EXPERIMENTAL STUDIES OF THE LOWER IONOSPHERE

USING

VERY LOW FREQUENCY RADIO WAVES

by

William George Woods

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CHAPTER 1

INTRODUCTION

This thesis is based on an experimental research programme carried out at the University of Leicester during the years 1967 to 1970. During this time recordings were made of the amplitude and phase of a number of Low and Very Low Frequency radio transmissions with a view to monitoring the behaviour of those regions of the ionosphere from which the radiowaves had been reflected.

The propagation of VLF waves has been of considerable interest since the earliest days of radio, since these waves propagate to great distances with little attenuation. With the recent advent of atomic frequency standards it has become possible to record the phase as well as the amplitude of these waves when propagated over long distance paths.

The propagation of VLF waves at steep incidence (short paths) has figured prominently in the study of the lower regions of the earth's ionosphere. A notable series of observations was undertaken by the group at Cambridge, England, and the results of these investigations have been summarised by Bracewell et al (1951). These investigations helped to provide a detailed understanding of the behaviour of the lower ionosphere, and established the propagation characteristics of VLF and LF waves out to distances of about 1000 km from the transmitter. The propagation of the waves
was, in general, found to be characterised by high stability in both phase and amplitude, due to the stability of the reflecting region, except during sunrise and sunset periods. Attenuation of the waves during the reflection process was found to be low, particularly in the VLF band, and changes in the apparent height of the reflecting layer were observed to be very regular. Changes observed in the signals beyond about 500 km have been interpreted as indicating the presence of a second reflecting layer in the D-region, which reflects waves received beyond this distance.

The group at Kuhlungsborn, East Germany have investigated the behaviour of LF waves of higher frequency (100 to 700 kHz), and found that it can be dissimilar to waves of lower frequency, with transient disturbances and fading of the signal at night being more prominent (Lauter, 1966).

Propagation of LF and VLF waves at high latitudes has been investigated by Belrose and co-workers, who observed large disturbances on these paths during geomagnetic storms, in addition to the effects caused by those parts of the path above the Arctic Circle remaining sunlit, or in darkness, for long periods.

The variation of signal strength as a function of distance from the transmitter has been investigated by a number of workers, following Hollingworth's (1926) discovery of a series of maxima and minima. Such results have been interpreted in terms of one reflecting layer out to about 500 km, and two beyond this distance.

The lower ionosphere is sensitive to a number of geophysical disturbances, of both long and short duration. Following a solar
flare the X-ray flux is enhanced and many workers have observed the resulting effects on both the phase and the amplitude of VLF and LF waves, VLF phase observations being considered to be a particularly sensitive indicator of this type of solar activity. Magnetic storm activity also affects long wave propagation by lowering the reflection height and changing the absorption. The exact effects depend on latitude and frequency, and have been discussed by, for example, Belrose and Ross (1962), and Lauter and Knuth (1967).

The present project has included an investigation of the effects of geophysical disturbances on VLF waves propagated over both long and short propagation paths.

For the short path studies in the present project VLF transmitters situated within the U.K. were employed. The frequency and location of these, and the respective path lengths, are indicated in Table A1 in the Appendix. The transmissions provide a range of "equivalent vertical frequency" and it was intended that they should be used to search for anomalous propagation effects such as those predicted theoretically by Jones and Wand (1969) to occur in the vicinity of the Brewster angle.

The stability of the phase and amplitude of VLF waves propagated to great distances has led to their extensive use in long range navigation and communication systems. It is of considerable practical interest therefore to investigate the phase and amplitude anomalies produced by geophysical disturbances, since these can lead to erroneous results in an operational system. Long path propagation of VLF waves was also used to study the characteristics of the TE and TM modes propagating in the spherical
waveguide formed by the earth as one wall, and the ionosphere as the other. The frequency, location, and path length of the long path transmissions monitored during the project are listed in Table A2 in the Appendix.

The recording programme at Leicester was conducted in conjunction with the Royal Aircraft Establishment, Farnborough, from whom much of the receiving and recording equipment was obtained on loan. Close co-operation enabled Leicester and RAE to benefit from the experience gained during the project and rationalize their efforts by introducing a joint programme of short and long path LF and VLF recording.

During the course of the project at Leicester additional aerials were needed, so design studies were undertaken and several new loop aerials were constructed and brought into use. These and the remainder of the equipment used during the project are described in detail in Chapter 3.

Before presenting the results obtained it will be useful to review current knowledge of the lower ionosphere as it relates to the work to be presented. The review follows immediately after this introduction, in Chapter 2.
CHAPTER 2

THE LOWER IONOSPHERE

2.1. Historical.

The concept of an ionised region surrounding the earth originated in the mid-nineteenth century. As early as 1839 for example, Gauss was of the opinion that the aurora might have its origin in "electricity in motion", and in 1860 Lord Kelvin thought that there might be a conducting region in the atmosphere at an altitude greater than 100 miles. This proved to be a more accurate figure than Balfour Stewart's 1878 estimate of 5 to 10 miles (Kaiser, 1962; Chalmers, 1962).

In the 1890's A.S. Popov in Russia, and G. Marconi in Italy, and then later in Britain, conducted experiments involving transmitting "Hertzian waves" over a distance, and in 1901 Marconi succeeded in transmitting signals across the North Atlantic, thus proving that the "rays" must deviate from a straight line to travel to this distance round the curve of the globe. In the following year Kennelley suggested that they were deviated by a conducting layer at an altitude of about 80 km; Heaviside made a similar suggestion independently in the same year. This view was not unanimously accepted however, some scientists preferring a theory based on diffraction. As late as 1926 in fact, protest could still be heard of the waste involved in "the pursuit of this academic myth of a useful ionised layer" (see Hollingworth, 1926).
In 1912 Eccles showed in laboratory studies that the refractive index of an ionised gas was less than unity, the implication of this result being that a radiowave travelling upwards into an ionised medium would tend to be bent away from the normal, or in other words, towards the horizontal.

The experimental evidence which conclusively proved the existence of a reflecting ionised layer was published independently by Appleton and Barnett (1925), and Breit and Tuve (1926), the former using a wave interference technique and the latter employing the pulse sounding method which subsequently became widely employed in ionospheric research.

Shortly before this experimental work was published Larmor, in 1924, had applied Eccles' theory to ionospheric radiowave propagation and had predicted the skip-distance effect. Theoretical progress continued with the extension of the Eccles-Larmour theory to a magneto-ionic medium by Appleton (1925) and later, independently, by Hartree (1929). In 1931 Chapman proposed his classic theory of ionospheric layer formation which, despite its simplifying assumptions, remained the basis of many later ionospheric models.

Radio techniques advanced rapidly during the Second World War after which, and in particular during the International Geophysical Year in 1957-58 (the IGY), world-wide cooperation in ionospheric radio and other geo-sciences developed. This continued during the IQSY (International Years of the Quiet Sun) in 1964-65, and the exchange of data on a global scale is now an established feature of ionospheric work. An important aspect of this international cooperation is the up-to-date information that is made available by
**TABLE 2.1 Ionospheric Regions (after Davies, 1969)**

<table>
<thead>
<tr>
<th>Region</th>
<th>Height (km.)</th>
<th>Layer</th>
<th>Approx Ht.</th>
<th>Approx. daytime N(e) m⁻³</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>50 to 90</td>
<td>C</td>
<td>65</td>
<td>10^8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D</td>
<td>75-80</td>
<td>10^9</td>
</tr>
<tr>
<td>E</td>
<td>90 to 120-140</td>
<td>E₁</td>
<td>110</td>
<td>10^11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E₂</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Eₛ</td>
<td>100</td>
<td>?</td>
</tr>
<tr>
<td>F</td>
<td>from 120-140</td>
<td>F₁, F₂</td>
<td>200</td>
<td>2.10^11</td>
</tr>
<tr>
<td></td>
<td>upwards</td>
<td></td>
<td>&gt;250</td>
<td>10^12</td>
</tr>
</tbody>
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![Figure 2.1: Ionospheric electron densities and nomenclature (Davies, 1965)](image-url)
solar astronomers - for example warnings of impending solar 

disturbances which are expected to affect the ionosphere - thus 
enabling many workers to concentrate their efforts simultaneously 
on chosen events. The data obtained on such occasions are more 
valuable that many sets of data which are not directly comparable.

Regarding the nomenclature of the main ionospheric regions, 
when Appelton first detected reflections from the ionosphere he 
used the letter E to represent the electric vector of the 
downcoming wave. Later, when he detected reflections from a 
higher level he used the letter F to denote the electric vector of 
that reflected wave. Occasionally he obtained reflections from a 
lower layer so these he identified by the letter D. He continued 
to use these letters to identify the layers, reasoning that this 
would permit the orderly naming of lower layers should any others 
be discovered. In modern usage reference is made to D, E and F 
regions within which sub-layers can sometimes be identified. 
Table 2.1 and Figure 2.1 illustrate the modern nomenclature and 
include typical temperatures and electron densities to be found 
at the various heights. These will be referred to in the next 
section.

2.2. The Undisturbed D-region.

The ionosphere is defined as that part of the Earth's 
atmosphere in which sufficient ionisation exists to affect the 
propagation of radiowaves. It is generally taken to exist 
between 50 km and one earth radius.

The D-region of the ionosphere extends from 50 km to about 
90 km, the E-region from about 90 km to 120 to 140 km, and the
F-region from this height upwards. At ionospheric heights, as is shown in Figure 2.1, the temperature falls above the Mesopause (which lies at about 50 km), to a minimum value of about 200° K at the mesopause between 80 and 90 km in the D-region, after which it increases again to a value of about 1500° K in the F-region.

The electron density \( N(e) \) generally increases upwards through the ionosphere from a value of a few electrons per \( \text{cm}^3 \) at the bottom of the D-region to a value of the order of \( 10^6 \) per \( \text{cm}^3 \) at the peak of the F-region, and then decreases again. The gradient is by no means regular but varies according to the time of day, latitude and longitude, season, and state of the sun. Irregular features such as sharp ledges of sporadic ionisation which appear during the night in the E-region contrast with the virtual disappearance of the D-region ionisation each night, and the close solar control of the E and F-regions during the day.

A representative selection of electron density profiles of the lower ionosphere is presented in Figures 2.2, 2.3, and 2.5 to 2.7. Figure 2.2 represents a collection of typical day time profiles of the upper part of the D-region measured at different locations, mostly with the solar zenith angle \( \chi = 50° \). It can be concluded from an examination of these profiles that, in general, the electron density increases from the order of \( 10^2 \) electrons/cm\(^3\) at about 65 km to about \( 5 \times 10^3 \) at 90 km. In Figure 2.3 the depletion of the D-region at night is evident, particularly below 80 km. Also evident is the ledge of ionisation or region of small gradient in the electron density between 80 and 90 km, and the thin layer of ionisation near 95 km. Figure 2.4 illustrates the diurnal variation of electron concentration at selected heights,
Figure 2.2. Typical measured electron density profiles of the lower ionosphere (Landmark, 1968)

Figure 2.3. Thomas and Harrison night time electron density profile (IV) and others. (Thomas, Harrison, and Horowitz, 1970).

Figure 2.4. Diurnal variations of electron concentrations at particular heights over Crete. (Thrane, 1969)
Figure 2.5. Deeks' (1966) model electron density profiles.

Figure 2.6. Bain & May's (1967) electron density profile together with others.

Figure 2.7. Bain & Harrison's (1972) model electron density profile.
derived from partial-reflection measurements at Crete. The strong solar-angle control of the daytime electron concentration is evident in this Figure, as is the fact that the changes in the concentration are greater above 80 km.

Figures 2.5, 2.6 and 2.7 show several interesting daytime profiles. Deeks (1966) derived his profiles for the middle latitude D-region by altering an assumed distribution until full wave calculations of reflection coefficients and reflection heights for VLF and LF propagation gave results in agreement with experiment. Mechtly and Smith (1968) in a series of rocket flights at solar angles $\chi = 108^\circ, 96^\circ, 94^\circ, 94^\circ$ and $85^\circ$ obtained profiles which were in agreement with the gross features of the Deeks' profiles, but not with the details. The observed night-time depletion below 90 km is reproduced in the Deeks profiles in Figure 2.5, but the electron concentration at the step between 80 and 90 km is an order of magnitude smaller than that shown in Fig. 2.3. The manner in which the concentration increases to fill out the region near 80 km during the morning is also illustrated, and although Figures 2.4 and 2.5 are not in close agreement quantitatively, both Figures show that the change in electron density at the higher levels is greater than at the lower levels, and that, particularly at the higher levels, it changes most quickly at high $\chi$ values. Bain and May (1967) using additional data proposed modifications to a Deeks noon profile, adjusted for different sun-spot conditions, and found that the modified profile (shown as a solid line in Figure 2.6) afforded satisfactory agreement with ground interference patterns (Hollingworth patterns) on 16 and 21 kHz. The modification consisted essentially of "lowering" the profile by several kilometres while retaining its essential
shape, including the C-layer bulge, now placed between 50 and 60 km. Also illustrated in Figure 2.6 are profiles by Smith, Belrose, and Krasnushkin and Kolesnikov (see Bain and May, 1967).

Bain and Harrison (1972) subsequently revised the Bain and May profile in the light of further data obtained from a simultaneous rocket flight and Hollingworth interference pattern measurements. The electron density was measured by the rocket from 68 km upwards and the profile thus obtained was adjusted slightly to give good agreement with the interference pattern measurements. A C-layer was again incorporated in the complete profile, reproduced in Fig. 2.7.

The Bain and Harrison profile was among those examined by Rowe et al (1974) who concluded that there was general agreement between the various profiles they examined at the upper and middle levels of the D-region, but less agreement at the lower levels where, for example, some profiles include a C-layer, and others do not.

Ionisation in the D-region is thought to be caused by solar radiation and galactic cosmic rays, mainly the former. Although the solar radiation may include very energetic particles during solar storms, the major contributing factor is electromagnetic radiation, particularly UV and soft X-rays.

In a review of current knowledge of the lower ionosphere Thomas (1971) concluded that near 80 km in daytime solar minimum conditions ionisation is produced principally by photoionisation of nitric oxide by Solar Lyman α radiation, and of O₂(¹Σg) by radiation of wavelength 1027 - 1118 Å (see Figures 2.8, 2.9). At solar maximum (and during solar flares) X-rays of λ < 10 Å become
Figure 2.8. Ionization rates (day).  
Figure 2.9. Ionization rates (night)  
(Thomas, 1971).

Figure 2.10. Height distribution of concentrations of electrons and negative ion species.  
(Thomas, Gondhalekar, & Bowman; 1972)

Figure 2.11. The variation of conversion coefficient with frequency.  
(Bracewell et al, 1951).

Figure 2.12. The seasonal variation of $R_\perp$ at 16kHz.  
(Bracewell et al, 1951)
more important. Satellite and rocket observations of the Sun have found that the X-ray emission is very variable, and observations of those variations in the X-ray spectrum by Poppoff et al (1964) indicate that the corresponding photo-ionisation rates can vary by more than three orders of magnitude over the solar cycle for non-flare conditions. At greater heights ionisation is produced by Lyman β, soft X-rays, EUV, and at lower heights by cosmic rays. During darkness ionisation is produced by Ly α in the airglow, cosmic rays, and possibly high energy particles, with Ly α being the most important source near 80 km. There is also some evidence that galactic X-ray sources may produce ionisation (see, for example, Kaufmann et al, 1970).

In a theoretical study of the height distribution of electrons and negative ions Thomas, Gondhalekar and Bowman (1972) suggest that it is necessary to take into account the photo-detachment of electrons from all the major ions throughout the day to account for the electron concentrations observed below 70 km. Including the ions $\text{CO}_3^-$, $\text{NO}_2^-$, and $\text{NO}_3^-$ in the calculations in addition to $\text{O}^-$, $\text{O}_2^-$, $\text{O}_3^-$, $\text{O}_4^-$ and $\text{CO}_4^-$ produced good agreement between the calculated and observed electron concentrations at these heights. This is illustrated in Figure 2.10. Thomas (1971) also concluded that marked differences between day and night at lower levels in the D-region result from day-to-night changes in $\text{O}$, $\text{O}_2(\text{^1}\Delta_g)$, $\text{NO}$ and $\text{NO}_2$.

Rocket observations by Johannessen et al (1972) indicate that water cluster ions, $\text{H}^+ (\text{H}_2\text{O})_n$, are dominant in the ion composition below 84 km. They observed cluster ions of higher order mass to increase with height, but after an abrupt change between 84 and 86 km $\text{NO}^+$ and $\text{O}_2^+$ and metal ions became predominant. Recombination of
electrons with water cluster ions is more rapid than with NO\textsuperscript{+}
or O\textsubscript{2}\textsuperscript{+} and it is thought that the marked change in the electron density gradient often observed near this height is linked to the abrupt changes in ion concentration between 84 and 86 km.

The proposed chains of reactions are complex and their rates are not always known to any accuracy: furthermore they are constantly being modified in the light of further measurements. A recent series of 6 papers by Mitra and his colleagues (J. Atmos, Terr. Phys. 34 pp. 211, 229, 243, 255, 267, 795; (1972)) cover this aspect of the lower ionosphere in detail. They also describe the behaviour of the lower ionosphere during solar induced disturbances, a topic which is considered in a later section of this chapter.

2.3 Long Waves and the D region.

Expressed simply, the effect of the D-region on radiowaves is to act as an imperfect reflector to waves of low frequency and to attenuate those of higher frequency as they pass through it, the degree of attenuation suffered being dependent on, among other things, the concentration of ionisation existing there at any given instant. Thus when D-region ionisation reduces at night, HF signal strength is enhanced and the phase of reflected low frequency signals is retarded due to an increase in the effective height of reflection. It should be noted that in the following discussion the terms VLF and LF will be used strictly to refer to the frequency bands 3 – 30 kHz and 30 – 300 kHz respectively, but for convenience the terms "low frequencies" and "long waves" will be used loosely to refer in general terms to frequencies in this
region. Also, the terms "advance" and "retard" when applied to the phase of reflected low frequency waves denote a decrease or increase, respectively, in the phase length of the path (i.e. the number of wavelengths). If one associates these phase changes with changes in the effective height of reflection of the waves then a phase advance corresponds to a decrease in this height, and vice versa.

Early radio communication was conducted on low frequencies exclusively, and although higher frequency transmissions later displaced long waves in many applications, long wave transmissions still have certain specific uses. They are used for example in geophysical research, particularly in respect of the lower ionosphere, in broadcasting (e.g. Droitwich, 200 kHz), in navigation systems such as the Decca Navigator system (70-130 kHz) Loran C (100 kHz) and Omega (10-14 kHz), in long-distance time and frequency transmissions (e.g. GBR, 16 kHz), in long-distance communication where high frequency propagation is unreliable, e.g. over high latitude paths or to submerged submarines.

VLF waves are particularly useful for uninterrupted long-distance transmissions because, in addition to being less affected by fade-outs than higher frequencies during solar disturbances, the distance attenuation suffered by long waves, for a given transmitted power, decreases with frequency to a minimum of a few dB's per 1,000 km in the region of 10 - 20 kHz. Consequently many of the VLF transmitters operate in or near this region.

When considering propagation over short distances the concept of a ground wave and one or more ionospherically reflected skywaves may be usefully employed, but for long distance VLF propagation, it
is necessary to use guided wave models in which the waves propagate in a waveguide bounded by the surface of the earth and the lower edge of the ionosphere. These models are discussed at greater length in Chapter 3 and in Chapter 7 respectively.

Direct measurement of the lower ionosphere using rocket-borne equipment to sample constituent ions etc. is a valuable aid in ionospheric research, but since each flight lasts only a matter of minutes the data obtained are of the nature of spot measurements. The use of a series of rocket flights compensates for this to some extent but is obviously very costly. Satellites are also extremely costly, and due to their short life at D-region altitudes they are not viable at lower ionospheric heights. Therefore for continuous or long term observations of the lower ionosphere the monitoring of LF and, particularly over long paths, VLF radiowaves which have been reflected from the lower ionosphere remains an essential and a relatively inexpensive tool. This remains so despite the weakness inherent in making what are essentially indirect measurements of the integrated effect of the D-region on the wave as it propagates along a path some hundreds or even thousands of kilometres long.

In addition to the methods which employ higher frequencies e.g. partial-reflection experiments and HF absorption measurements, there are several methods of probing the lower ionosphere using low frequency radiowaves. A number of workers have obtained results down to 50 kHz using low frequency ionograms despite the difficulties of operating pulse sounders successfully at such low frequencies; see, for example, Watts and Brown (1954) or Watts.
(1959). High-power high-frequency transmissions may be beamed at selected regions of the ionosphere to modify it by increasing the electron temperature and collisional frequency. The effects on the ionosphere may be monitored using low frequency waves reflected from the modified region; see, for example, Jones, Davies and Wieder (1972) who examined the modulation impressed on waves of 20 and 60 kHz. An examination of the signal from a distant low frequency transmitter during the transition between darkness and daylight may yield information on, for example, the relative signal strengths of the ground and skywaves, which at such times combine to produce an interference pattern due to the changing phase of the skywave or waves. The apparent height of reflection and the ionospheric reflection coefficient \( R_\parallel \) may be deduced from such data; see for example Belrose (1968) who used waves of 71 and 245 kHz. A variation of this technique is to measure the total field at different distances from a low frequency transmitter and from the values obtained construct the interference pattern. Hollingworth (1926) first used this method to deduce the reflection height of 20.9 kHz waves. Moving the receiver away from a fixed transmitter to obtain the interference pattern is possible if an aircraft is available; see for example Smeathers (1971) at 16 kHz, and Weekes and Stuart (1952) near 100 km, each of whom plotted the product of the field strength and distance from the transmitter against the distance from the transmitter to obtain a suitable interference pattern.

One of the more widely employed observational methods at low frequencies is to monitor both the phase and the amplitude of the received signal. At distances of several thousand
kilometres the total field is recorded and interpretation is
by means of wave-guide theory; see, for example, Walker (1965)
who examined the interference pattern generated by the different
modes at the transition between day and night. At short distances
from the transmitter the steeply incident skywave is generally
isolated using either a loop aerial or a loop and vertical aerial
combined in the manner described in Chapter 3. The ionospheric
reflection coefficient of the abnormally - and normally - polarized
skywaves respectively may then be determined. Bracewell et al
(1951) summarised the results of the early work which established
these techniques. Belrose (1968) describes a further variation
which involves oscillating a loop aerial through a small angle
about the plane of propagation to deduce the polarization of a
71 kHz downcoming skywave from a transmitter 860 km distant.

In short-path low frequency experiments the measurements
are often expressed in terms of the ionospheric reflection
coefficients (see Chapter 3 for an explanation of the various
coefficients). Figures 2.11 and 2.12 illustrate the variation of
the conversion coefficient $R_\perp$ with frequency for different
seasons, and the seasonal variation of $R_\perp$ at 16 kHz deduced by
Bracewell et al (1951). Belrose (1968) has revised these
diagrams and his graphs of the variation of $R_\parallel$ with frequency
at different seasons during sun-spot maximum and sun-spot minimum
years are reproduced in Figures 2.13 and 2.14. The graphs were
revised by including in them data obtained by several independent
groups of workers at both steep and oblique incidence at different
locations. This has been done by expressing all the data in terms
of equivalent frequency, the assumption being that the reflection
Ionospheric reflection coefficient $\nu$ equivalent frequency (Belrose, 1968).

Figure 2.13 (top) sunspot maximum years

Figure 2.14 (bottom) sunspot minimum years
and conversion coefficients will have the same value for all paths having identical values of \( f \cos i \). Effects resulting from changes in path direction relative to the Earth's magnetic field have been neglected. In Figures 2.13 and 2.14 data obtained at steep incidence are identified by letters and those obtained at oblique incidence by numbers. It was assumed also that at steep incidence \( nR_n = nR_\perp \), and at oblique incidence it was \( nR_n \) which was measured. The long wave recording programme at Leicester as originally formulated was intended in effect to provide data which would complement the information displayed in these Figures. However, subsequent theoretical work (Jones and Wand, 1969) has cast doubt on the validity of using the \( f \cos i \) theorem to compare dissimilar long wave data in the manner illustrated here, so if use is to be made of values of the reflection coefficients in, for example, modeling electron density profiles it would be necessary to examine the individual sets of data in addition to the summary displayed in these Figures to ensure that incorrect values are not inadvertently being employed. Nevertheless, it can be deduced from Figures 2.11 to 2.14 that the reflected wave becomes weaker as the frequency increases up to several hundred kHz, and it also becomes weaker as the solar angle decreases, i.e. the skywave is weaker in summer than in winter and weaker during the day than during the night.

The change in the reflected wave at day-break normally occurs in advance of ground sunrise. Bracewell et al (1951) noted that the strength of steeply incident waves of 16, 30, 43, 70 and 113 kHz all started to decrease about 1 hour before ground sunrise in summer, but the phase generally did not change until about ground
sunrise. With oblique incidence waves the changes in both phase and amplitude began in advance of ground sunrise when the Sun's zenith angle at the mid-point of the path was about 98°. The change in the total field records of more distant transmitters (500 - 900 km) also started to change at about this time. The effect was attributed by Bracewell et al to the illumination of the lower ionosphere by solar radiation, which would be expected to occur before ground sunrise. Thomas (1971) attributes the pre-sunrise increase in electron density to the arrival of solar UV radiation. Bracewell et al found also that the behaviour of 16 kHz reflected waves was quite regular from day-to-day in their solar angle dependent variation throughout the day, in contrast to the less regular behaviour of higher frequency waves. He calculated that for waves having a frequency less than 40 kHz the apparent height of reflection was 73 ± 2 km for $\chi = 0$, and at a latitude of 50° the heights at midday in midsummer and midwinter, and at night throughout the year, were approximately 1, 5 and 19 km greater, respectively. Skywaves of 16 - 50 kHz transmitted over distances between 100 and 300 km were all approximately circularly polarized, but at greater distances they became approximately linearly polarized.

VLF signals transmitted over long paths, i.e. several thousand kilometres, are fairly regular in their behaviour from day-to-day in the absence of major solar disturbances. In Figure 2.15 is reproduced a typical long path record - the phase and signal amplitude of GBR received at Nairobi over a 7000 km path (from Burgess and Jones, 1967). An SPA and accompanying SES are prominent features of the record. In long path VLF records at
Figure 2.15. Typical long path phase and amplitude record at 16kHz: GBR-Nairobi (7,000 km) and GBR-Rome (1500 km); (Burgess and Jones, 1967)

Figure 2.16. Typical VLF record at 18.0kHz showing modal interference pattern during dawn and dusk transitions (Walker, 1965)
this frequency and below the daily phase variation is quasi-trapezoidal in shape. The phase advances from its night-time value as the dawn line moves along the transmission path, exhibits some solar angle control during the time that all the path is sunlit, and retards to its night-time value as the dusk line moves along the transmission path. The signal strength decreases during the morning phase advance and increases again in the evening. At night the signal strength may be variable. In the record shown in Figure 2.15 the signal strength is rather higher when the sun is at its highest over the path than in the morning and afternoon.

The detailed shape of long path records varies with time of year, the path, and the frequency. At different seasons the dawn and dusk lines cross the transmission path at different speeds and directions causing changes in the steepness of the corresponding morning and evening phase changes. Different transmission paths will intersect the dawn and dusk lines at different angles, and high latitude paths may pass through areas which remain sunlit or in darkness during a complete 24 hour period. At higher frequencies in the VLF band modal interference effects become more noticeable. Figure 2.16 (from Walker, 1965) reproduces a record taken on the 18.0 kHz NBA-Nairobi path. On this record a series of maxima and minima in the signal strength coincide with step-like changes of phase. These are attributed to interference between modes as the dawn and dusk lines move along the transmission path following Crombies' (1964) theory which proposes that long distance VLF propagation is by way of two modes at night and one mode during the day, the second order
night-time mode converting to first order at the dawn line.

To account for discrepancies between this model and observations made during the early part of the sunrise transition, Kaiser (1968) proposed a one night-mode/two day-mode model. Mahmoud and Beal (1971) noting further discrepancies proposed a 2 night-mode/2 day-mode model which is claimed to have wider range of validity than either of the former models. In developing their model Mahmoud and Beal used NAA-Leicester and NSS-Leicester records supplied to them by the Physics Department at Leicester. VLF propagation by way of modes is discussed further in Chapter 7 which describes an attempt to record both TE and TM modes at Leicester.

2.4 D-region Disturbances.

For a few days each month the ionosphere may indeed behave in a regular and predictable manner consistent with that outlined in the previous sections. During the remainder of the time the "normal" behaviour is, to a greater or lesser degree, disrupted by the effects which follow the irregular and, on an individual scale at least, unpredictable burst of radiation and energetic particles from the sun, the most interesting disruptions from the standpoint of D-region observations being those following the appearance of a solar flare on the Sun's disc.

Solar flares were first observed as bursts of "light" occurring in the chromosphere near sunspots: they are most easily observed in $\mathbb{H}_\alpha$ light. A numerical relationship has been noted between solar flares and sunspots, namely:

$$N_f = \alpha (\bar{R} - 10)$$  
(Kuiper, 1953)
where $N_f$ = the number of flares occurring per solar rotation

$\bar{R}$ = the mean sunspot number

$\alpha$ = a proportionality factor, varying between 1.17 and 1.98

Flares are classified according to their importance, the classification currently in use being that illustrated in Table 2.2. An earlier classification based on the area of the flare seen in H$_\alpha$ light ranged from 1- to 3+. During a selected solar cycle Waldmeir (1948) observed the relative frequency of occurrence of flares of each class to be:

Class 1 73%; Class 2 23%; Class 3 4%.

Kuiper (1953) gave the mean duration of flares in each class as:

Class 1 20 mts; Class 2 33 mts; Class 3 62 mts.

although individual variation from the mean is wide.

The effects of a large solar flare on the ionosphere are extensive, and Figure 2.17 illustrates the main geophysical effects associated with such a flare. As this thesis relates to long wave radio experiments attention will be directed mainly to those effects which bear most closely on propagation at low frequencies.

Of the "instantaneous" effects listed in Figure 2.17 the SID (Sudden Ionospheric Disturbance) is the one most relevant to the present project. The term SID nowadays is used to denote those disturbances occurring on the sunlit part of the Earth which are closely associated with the occurrence of solar flares and the associated EM emissions. An SID is characterised by a rapid onset followed by a slow recovery to normal conditions within an hour or two.
### Table 2.2. Solar Flare Classification

<table>
<thead>
<tr>
<th>&quot;Corrected&quot; Area (in square degrees)</th>
<th>Relative Intensity</th>
<th>Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 2.0</td>
<td>Sf</td>
<td>Sn</td>
</tr>
<tr>
<td>2.1 - 5.1</td>
<td>lf</td>
<td>ln</td>
</tr>
<tr>
<td>5.2 - 12.4</td>
<td>2f</td>
<td>2n</td>
</tr>
<tr>
<td>12.5 - 24.7</td>
<td>3f</td>
<td>3n</td>
</tr>
<tr>
<td>&gt; 24.7</td>
<td>4f</td>
<td>4n</td>
</tr>
</tbody>
</table>

---

**Figure 2.17.** The main geophysical effects associated with a solar flare.
Budden and Ratcliffe (1937) noted that "catastrophic phase anomalies" occurred on the 16 kHz GBR - Cambridge path when Short Wave Fade-outs (SWF's) were reported, or magnetic anomalies noted. They attributed these phase changes to a decrease in the apparent height of reflection. No significant change in signal strength was observed to accompany them.

Bracewell and Straker (1949) investigated quantitative relationships between a large number of these SPA's (Sudden Phase Anomalies) and the importance of the flares with which they were associated. They reported that although there was a tendency for large SPA's to correlate with the larger flares, there were many obvious exceptions to this.

Bracewell et al (1951) examined SPA's on three paths at 16, 70 and 113 kHz and concluded that the change in apparent height of reflection deduced from the phase advance on each path was the same - about 7 km in the case of the selected event illustrated in their paper. They noted an appreciable decrease in signal strength on 70 and 113 kHz but not on 16 kHz. In a review Belrose (1968) concluded that "during an SPA the apparent height of reflection of long and very long waves, transmitted over a wide variety of distances and over a range of frequencies all exhibit approximately the same change of apparent height".

Before rocket and satellite measurements revealed that bursts of X-radiation accompany solar flares it had been assumed that Lyman a radiation from the flare was responsible for the excess ionisation created in the D-region during the flare. With the satellite data now available it is possible to correlate SID's with the X-ray burst which accompanies the flare. Deshpande,
Subrahmanyan, and Mitra (1972) found that SID's follow approximately 90% of X-ray flares in the 10 - 50 keV band, and in 80% of SID producing X-ray enhancements Hα flares as well as radio noise bursts occur concurrently. These are the major SID events. Arnoldy, Kane and Winckley (1967) reported that out of 30 X-ray bursts observed by the satellite OGO only 3 small bursts were not accompanied by a reported SWF. The onset times of the burst and the SWF were closely similar, but the peak and end of the SWF occurred later than that of the burst. Kaufmann and de Barros (1969) reported excellent correlation between SPA importance and the logarithm of the X-ray burst peak intensity. They expressed the importance of the SPA's in degrees per 1,000 km of path length. They also suggested that the negative correlation between X-ray bursts in the 0 - 8 Å band and SCNA's (Solar Cosmic Noise Absorption) reported by Landrini, Russo and Tagliaferri (1967) might be limited to bursts with energy below the threshold energy required for production of SCNA's, this threshold energy being higher, they say, than that necessary for the occurrence of SPA's.

Several workers have estimated the threshold energy of the X-radiation required for the occurrence of SPA's. Kreplin et al (1964) gave a value of 2.10^{-3} erg/cm²/sec in the 0 - 8 Å band. Kaufmann and de Barros (1969) suggested 4.3 10^{-5} erg/cm²/sec in the main ionising band of 0 - 3 Å. Deshpande, Subrahmanyan and Mitra (1972) deduced the threshold to be 2.10^{-5} erg/cm²/sec in the 0 - 3 Å band, and 1.10^{-3} erg/cm²/sec in the 0 - 8 Å band, and they suggest that the value 1.10^{-3} erg/cm²/sec in the 2 - 12 Å band given by Sengupta and Van Allen in an unpublished...
University of Iowa report (1968) is too low. Kaufmann and de Barros report also that a hardening of the X-ray burst spectra is evident for increasing importance of SPA's, and Deshpande, Subrahmanyan and Mitra conclude that what they call "the occurrence probability" of an SPA increases as the X-ray emission extends towards the shorter end of the spectrum. They give a figure of 89% for this probability for X-rays in the 10 - 50 keV range.

SPA's on long paths are a more sensitive indicator of SID's than the other SID effects. Sudden small increases in electron density in the lower levels of the D-region where the electron density is low and the collisional frequency high, are equivalent to a sudden lowering of the upper boundary of the Earth - ionosphere waveguide and are easy to detect as SPA's. On the other hand the low frequency SES (Sudden Enhancement of Signal) is not a sensitive indicator of SID's. It is related to changes in the conductivity of the waveguide boundary, which depends in turn on the relationship between changes in the electron concentration and collisional frequency during the burst. Often no SES is observed on long path transmissions in the 10 - 15 kHz region. When an SES occurs on a long path the signal level generally increases, as the name of the effect would suggest. This contrasts with the effect on steep incidence paths where the signal strength tends to decrease. An SPA has however a similar effect on both long and short paths - the phase advances in each case. An exception to this rule was reported by Burgess and Jones (1967) who observed that on the 16 kHz GHR-Rome path (1500 km) the phase retarded instead of advancing as expected. A theoretical
examination using satellite X-ray observations and an exponential model electron density profile indicated that at just this distance from the transmitter such an effect would be consistent with interference between 1st and 2nd modes in the waveguide when a lowering of the D-region is coupled with a steepening of the ionisation gradient due to the increased X-radiation.

Albee and Bates (1965) examined the decay phase of SPA's recorded on several different paths and frequencies. They attempted to fit exponential decay curves of the form \( \exp(-at) \) to the tails of the SPA's and observed that the value of the decay coefficient \( a \) was similar for SPA's on similar frequencies over different paths (NBA and NPM to College, Alaska) but different for different frequencies over the same path (18.0 and 10.2 kHz Panama to College). \( a \) was larger on the lower frequency. They accounted for the difference by suggesting that the X-ray flare spectrum softens as the intensity of the burst decreases. The excess ionisation would then diminish more rapidly at lower heights due to the continuing (softer) X-rays being absorbed at greater heights, and if the 10.2 kHz signal were reflected at a lower height than the 18.0 kHz signal the decay of the SPA on the 10.2 kHz signal would be expected to be more rapid than that on the 18.0 kHz signal. Their theory would appear to be supported by Donnelley's (1969) observations that the 8 - 20 Å X-ray flux rises, peaks, and decays slower than the 1 - 8 Å flux.

The effects of flares on high-latitude paths differs markedly from the effects on paths which avoid high latitudes. Thus, high-
latitude paths are less affected by solar X-rays than are mid-latitude paths, but they are more affected by the delayed (i.e. particle) effects which follow large flares. For example Albee and Bates (1965) report that SPA's are observed only rarely on the NAA-College path, and almost never on the GBR-College path.

In respect of the effects of aurora on VLF transmissions there is a lack of agreement. Bates and Albee (1965) reported that analysis shows that in general no strong direct connection is to be expected, and none was found. They state that magnetic disturbances and VLF phase disturbances can sometimes be connected, but concluded that the large night-time variations of phase which they observed were not caused directly by auroral or geomagnetic disturbances. On the other hand Egeland and Naustvik (1967) report that on high-latitude paths there is high correlation between auroral absorption (AA) and VLF disturbances. Furthermore, they also noted that waves of frequency 10 - 12 kHz are much more sensitive to moderate ionospheric disturbances than waves of frequency greater than 15 kHz. The effects they observed were (i) a reduction in signal strength and (ii) strong fluctuations in the signal. Egeland, Larsen and Naustvik (1969) reported that with every AA event anomalous phase and amplitude disturbances were seen on all VLF paths studied which had an appreciable path length North of 60° geomagnetic latitude. These occurred during both day and night.

The short period effects accompanying auroral absorption contrast with the effects accompanying a PCD (Polar Cap Disturbance) where no fine structure is observed. Auroral effects are thought to be caused by low-energy electrons, whereas PCD's follow certain
intense flares, referred to variously as proton flares or solar proton events. Totemara et al (1967) reported that an influx of 150 protons/cm\(^2\) with energy greater than 20 MeV produced a 10 km lowering of the daytime VLF reflection height, and on high-latitude paths phase disturbances occurred both day and night, and lasted three days. Following some intense proton flares the nighttime reflection height may be depressed to such an extent that the diurnal phase variation virtually disappears (Belrose, 1968). During a PCD the signal may be weakened to such a degree that it drops out altogether. Belrose (1968) states that the nighttime amplitude is always less than normal, but the daytime amplitude can be the same or greater than normal, depending on the magnitude of the disturbance. Normal conditions may not return until 5 to 15 days have elapsed.

Magnetic storms can also affect low frequency propagation for a period of several days or longer. Lauter and Sprenger (1952) summarised the effects on the 180 km Kalundborg to Kuhlungsborn path at 245 kHz to be: (1) the sudden commencement was not associated with any change of amplitude; (2) rapid and deep fading at night occurred during the main phase of the storm but (3) there was no disturbance on the daytime records; (4) when the storm was intense the signal strength at night was weak for a period beginning 3 to 4 days after the start of the storm and this continued for several days (the "after-effect"). King and Fooks (1969) add that the days most affected on a 600 km path from Kalundborg are the fourth day in the case of large storms and the third day for smaller storms. They also note that the signal strength on a path North from the transmitter may decrease by a factor of 7 during the storm after-effect, but the conversion coefficient on a path South from the
transmitter sometimes increases.

On steep incidence VLF paths the effects also last for several
days, beginning some hours after the Sudden Commencement (e.g. 20
hours, Bracewell et al, 1951). Violent fluctuations in phase and
amplitude occur at night and a return to normal is followed some
three days after the SC by a lowering of the reflection height,
particularly at night when it may be depressed almost to daytime
levels. These effects can last for several days and conditions may
not return to normal for another 10 days, or even 20 days on one
reported occasion (Bracewell et al, 1951).

The foregoing account of the various disturbances which
affect the lower ionosphere is not intended to be exhaustive, but
concentrates mainly on those effects following a solar flare which
are of particular interest in the present project. Various other
effects involving a disruption of the quiet D-region have been
reported. These range from disturbances following nuclear explosions
in the atmosphere (e.g. Chilton, Conner and Steele, 1965), to phase
disturbances attributed to meteors (e.g. Chilton, 1961), to increases
in ionisation attributed to celestial X-ray sources (e.g. Edwards
et al, 1969), but since they are not directly relevant to the subject
of this thesis they will not be discussed at length here. Many of
the other effects described in this section however have been observed
during the course of the project, and these observations will be
presented and discussed in the chapters which follow.
3.1. Introduction.

In this chapter both the equipment and the measuring techniques employed in the present project will be described. During the course of the project several loop aerials were designed and built so brief details will be given of the practical aspects of building and setting up such aerials. Some of the techniques necessary to obtain satisfactory measurements of ionospheric reflection coefficients will also be explained. It should be noted that the problems involved in measuring the relative strengths of long path TM and TE modes are somewhat similar to those encountered when measuring steeply incident abnormally polarised skywaves.

3.2. The Radiated Long Wave Field.

3.2.1. Introduction.

The following discussion is intended to apply when the distance separating the transmitter and the receiving site is of the order of tens of kilometres, although the concept of ground and skywaves may be usefully employed out to greater distances. The limiting distance for ground-wave reception is governed to a large extent by the conductivity of the ground. In Canada for example the conductivity of Arctic land is 0.5 millimhos/m whereas European pastoral land may be an order of magnitude
greater (Belrose, 1968). Thus at 750 km in Canada the skywave is 6 times greater than the groundwave whereas in Europe at this distance the groundwave predominates at noon in summer. (Belrose, 1968).

For distances of several Mm groundwave/skywave models are no longer applicable and it is necessary to use waveguide theory because at Very Low Frequencies the wavelength is comparable to the earth-ionosphere distance.

3.2.2. The Groundwave.

A long wave transmitter is generally, in principle at least, an electrically short vertical conductor. The radiated field, in this instance the groundwave, is therefore vertically polarised, i.e. the electric vector $E_o$ is vertical as shown in Figure 3.1. Although it is ignored in this simple treatment it should be mentioned in passing that the wavefront near the ground tilts forward slightly due to the finite conductivity of the ground. This effect is used to advantage in one type of aerial - the Beverage or long wave aerial.

If the field strength at unit distance from the transmitter (say 1 km) is denoted by $F_o$ then the field strength at a distance $d$ may be calculated using the formula

$$F_d = F_o \frac{d}{M}.$$  \hspace{1cm} (3.1)

where $M$ is an attenuation factor which takes into account the frequency, the earth curvature, and the effective conductivity and dielectric constant of the earth over which the wave is travelling. For short distances in Europe $M$ approaches unity.
The field at unit distance from the transmitter is given by

\[ F_0 = 3(10 P)^{\frac{1}{3}} \text{ mV/m} \]  \hspace{1cm} (3.2)

where \( P \) is the power radiated in watts. (Belrose, 1968).

3.2.3. The Skywaves.

For steep incidence propagation multiple reflection of the wave can occur. Even for a single hop the wave may have components of different polarization. Thus there is usually more than one skywave to be considered. When the vertically polarised incident wave is reflected from the ionosphere two components are present after reflection. These are the vertically polarised or normal component, and the horizontally polarised or abnormal component. Figure 3.1 shows the downcoming skywave as it is reflected at the ground with 180° change of phase.

The parameters which may be measured are also shown in Figure 3.1. The subscripts are used to identify the groundwave \((0)\), the normal skywave \((1)\), and the abnormal skywave \((2)\). The vertically resolved parts of the magnetic field cancel leaving only the horizontal components. These may be resolved parallel to and perpendicular to the plane of propagation respectively to give

\[ H_N = H_0 + 2H_1 \] \hspace{1cm} (3.3)

and

\[ H_A = 2H_2 \cos i \] \hspace{1cm} (3.4)
Figure 3.1 showing:

(top) the ground wave in the plane of propagation TABR,
(center) the skywave reflected at the ground with 180° change of phase,
(bottom) the measurable quantities $H_N$, $H_A$. 
The locus of the resultant is an ellipse, the horizontal field ellipse. The electric field may be resolved vertically giving

\[ E = E_o + 2E_1 \sin i. \]  \(\text{(3.5)}\)

The horizontally resolved parts of the electric field cancel.

3.2.4. Reflection Coefficients.

When a long wave is reflected from the ionosphere a partial change of polarisation occurs. As there are thus more than one reflected component the ionospheric reflection coefficient \( R \) is expressed in the form of a matrix

\[ R = \begin{bmatrix} R_{||} & R_{\perp} \\ R_{\perp} & R_{||} \end{bmatrix}. \]  \(\text{(3.6)}\)

The subscripts parallel (\( || \)) and perpendicular (\( \perp \)) placed before and after \( R \) refer to the polarisation before and after reflection, respectively. "Parallel" refers to vertical polarisation and "perpendicular" to horizontal polarisation. Since the incident wave at the first ionospheric reflection contains no horizontally polarised component the terms \( R_{||} \) and \( R_{\perp} \) do not apply in this case. The other two coefficients are known as the reflection coefficient (\( R_{||} \)) and conversion coefficient (\( R_{\perp} \)) respectively. At the second and subsequent reflections all four coefficients must in theory be taken into account. Often however the values of the coefficients are so small that in practice only one reflection
need be considered. In calculations involving waveguide theory and long distance propagation the complete matrix must be considered.

The reflection and conversion coefficients may be measured separately because it is possible to a first approximation to isolate the groundwave and each of the skywaves using different types of aerial systems. These systems will now be discussed in detail.

3.3. Long-Wave Receiving Aerials.

The two types of aerial described in this section are the two most commonly used in VLF work viz. the short vertical rod or whip aerial, and the loop or frame aerial. Only brief details of the properties of these antennae will be given here but a full treatment of the theory of both types may be found in "VLF Radio Engineering" Chapter 4 (Watt, 1967).

The vertical whip responds to vertically polarised waves and is sometimes referred to as an "E field aerial". When it is placed in a vertical electric field of strength E the voltage induced in it is given by

\[ V = E h_e \]  

(3.7)

where \( h_e \) is the effective height of the aerial. In practice, for a thin whip, this may be taken as being approximately equal to half the physical height of the aerial. For the conditions of this experiment, in the short vertical whip the skywave \( (2E \sin i) \) is much smaller than the groundwave, perhaps \(-20\) dB or less, so to a first approximation the signal picked up on a whip contains only
the groundwave.

Loop aerials have been used for many years and their properties are well known. Briefly, the polar diagram of a loop is a figure of eight so if \( V \) is the voltage induced in it when it is in the plane of propagation, the voltage induced when it is perpendicular to this plane will be \( V \cos 90^\circ = 0 \). This simple treatment is modified in practice because of the finite size of the loop as will be explained later. If the loop is placed in the plane of propagation (see Figure 3.1) the induced emf will be due to the normally polarised waves, \( H_0 + 2H_\perp \). As with the whip aerial \( H_0 \) is generally much greater than \( H_\perp \) so the emf will be approximately equal to that induced by the groundwave alone. If the loop is rotated through \( 90^\circ \) the emf induced in it by the normally polarised wave will reduce to zero thus enabling the abnormally polarised skywave to be isolated.

To isolate the normal skywave the signals from an in-plane loop and a vertical whip are combined. The whip signal is attenuated and phase shifted then subtracted vectorially from the loop signal. This in effect removes the groundwave and allows the normal skywave to be detected and measured.

When a loop with \( N \) turns each having an area \( A \) is placed in a field of intensity \( E \) the voltage induced in it is given by

\[
V = E \left( \frac{2\pi NA}{\lambda} \right) \quad (3.8)
\]

The term in the brackets is usually referred to as the effective height of the loop

\[
h_e = \left( \frac{2\pi NA}{\lambda} \right) \quad (3.9)
\]
If one side of the loop has a higher capacitance path to earth than the other the balance of the loop will be upset and the polar diagram will be distorted from a figure of eight. One way of avoiding this "vertical effect" is to use a screened loop (Haig, 1960).

3.4. Practical Aerials.

Additional loop aerials were required during the project so several new ones were designed and built. As there were residential areas adjoining the field station the new loop aerials had to be made as unobtrusive as possible. This limited their size and meant that shelters could not be erected to protect them from the weather. They had to be made sufficiently robust to be left free standing in all weathers as well as sensitive enough to isolate the very small abnormal skywave. Some guidelines found useful when constructing the aerials will be mentioned briefly at this point.

From equation (3.8) we see that for high sensitivity we need a large multi-turn aerial. For the reasons mentioned above the size of the loops was fixed at 1m square for short path loops and 2m square for long path loops. The latter did not need to be as rigid as the others because they were set for maximum signal pick up.

Although the sensitivity of a loop increases with the number of turns the number of turns is generally limited by losses due to proximity effects in the wires which increase with number of turns. An optimum figure of 40 turns is given in the Service Textbook, Volume 5 although some commercial loop aerials have 56 turns (e.g. those sold by Tracor Inc.)

A loop aerial is normally series tuned to resonate at the required frequency. In series tuned circuits the Q value should
be made reasonably large because it determines the magnification, the selectivity and the bandwidth. At resonance

\[ Q_0 = \frac{1}{R} \left( \frac{L}{C} \right)^{\frac{1}{2}} \]  

(3.10)

so to obtain large values of \( Q \), \( L \) should be large and \( R \) and \( C \) small. Now the resistance of a wire of a length \( L \) is given by

\[ R = \rho \frac{L}{A} \]  

(3.11)

so for small \( R \) we need thick wire \( \left( \frac{L}{A} \right) \) of low specific resistance \( (\rho) \). For a circular coil of \( n \) turns which has an inside radius \( r \) and an outside radius \( (r+d) \) and a thickness \( t \) (measured axially) the self inductance is given by

\[ L = F r n^2 \]  

(3.12)

where \( F \) is a function of \( \left( \frac{r}{t+d} \right) \) [Service textbooks, Volume 1]. Therefore for large inductance we need both \( n \) and \( r \) large and the wires wound close together. The capacitance between parallel conductors of area \( A \) separated by a medium of dielectric permittivity \( \kappa \) and thickness \( T \) is given by

\[ C = \kappa \left( \frac{A}{T} \right) \]  

(3.13)

so for small \( C \) we need small areas (thin wire) far apart in a medium of small dielectric constant. Some of these parameters are fixed \( (\rho, \kappa, n, A) \) so consider the others. Since capacitance is normally added to the loop to tune it, it is sufficient at
this point that $C$ should be small enough so that we may add
a capacitor to tune it to any frequency we require in the VLF
or low LF band. The remaining conditions are therefore :-
(i) for small $R$ we require short wire (i.e. small $n$), and (ii) for
large $L$ we require large $n$ and tight windings. But

$$Q = \frac{\sqrt{L}}{R} \sqrt{n^2} \frac{n}{n} \quad (3.14)$$

So the number of turns cancel as far as $R$ and $L$ are concerned,
The only remaining factor is the way in which the wire is wound,
$L$ being larger for a tightly packed coil.

Having established these guide lines it is necessary to
consider the ways in which the $n$ turns may be wound to form a
loop aerial. They may be wound (a) in the form of a cylindrical
coil of constant radius, or (b) in a flat spiral, or (c) in a
combination of the two. Type (a) is called a box loop (since the
loop is often square rather than circular for ease of construction)
and type (b) a flat loop, or occasionally a pancake loop. It is
important to distinguish between these two types because although
the flat loop gives zero signal when perpendicular to the plane
of propagation, the box loop does not. It presents to the normal
magnetic component $(H_N)$ the finite area of its vertical side.
This is equivalent to a small loop of area equal to half the area
of the vertical side of the box loop. [Admiralty Handbook of
Wireless Telegraphy]. Therefore although either type of loop may
be used to detect ground wave or to receive long path signals, it is
the flat loop which must be used to detect the weak abnormal
skywave in the presence of a strong groundwave.
Consider a 20 turn 1m square box loop of total thickness 10cm. The theoretical suppression of the groundwave afforded by this loop may be calculated by comparing the relative equivalent areas of the loop when set parallel and set perpendicular to the plane of propagation. The ratio of the equivalent areas is

\[
20 \text{ turns} \times \frac{1 \text{ m}^2}{0.05 \text{ m}^2} = 200 = 46 \text{ dB}.
\]

Now in summer the skywave of GBR at Leicester is about 46dB below the groundwave so obviously this loop would be unsuitable for short path work. If the thickness of the loop were reduced to 1cm the theoretical suppression would improve to about 66dB. Doubling the number of turns and reducing the thickness by half would give a figure of 78dB although in practice other factors might reduce this figure somewhat. So it is necessary that in this type of work the loop should be flat and not more than a few mm thick in the axial direction.

Of the loop aerials used in this project several were already available and several more were built. The former consisted of a thin screened multicore cable fixed in a groove in a wooden frame and had either 12 or 25 turns. They were lightly built and needed protection from the weather. Several larger loops of a similar design were built for long path work. These had 25 turns, were 2m square, strongly built and free standing and could be easily dismantled for transporting to other field sites. Several more free standing 1m² loops were built for short path work. They had 40 turns wound inside a strong aluminium frame which served as a screen, and their wooden legs were bolted to four 4" x 4" stakes in the ground.
as shown in Figure 3.2. Each of the short path loops was pivoted so that it could be rotated about a vertical axis when calibrating the system. A long threaded bolt abutting one leg allowed fine adjustments to be made to the orientation of the loop when it was set in the plane of propagation. It was then clamped in this position. One loop, used for the GYA transmissions which were difficult to monitor, was mounted on a rotatable plate which was supported on another fixed plate by ball bearings. By using a fine threaded bolt the angular position of this loop could be adjusted in very small increments. In tests in the workshop it was found that the increments could be as small as 20 seconds of arc. In practice, accuracy of this degree would not be expected outdoors at the field station.

3.5. Site Reradiation.

If an aerial can pick up VLF waves it can also reradiate some of the energy. Since any conductor will act as an aerial of sorts reradiated groundwave from conductors in the vicinity of the loop may contaminate the small skywave signal which is picked up on the loop. Consider several types of conductor. A vertical wire will respond to the vertically polarised ground-wave and will reradiate some of this energy. A horizontal wire lying perpendicular to the plane of propagation will be unaffected by ground wave but in any other position will act as a travelling wave aerial and so will pick up some groundwave. As it is horizontal it can reradiate horizontally polarised waves. A sloping wire will be able to detect both vertically and horizontally polarised waves and the current flowing along the wire may be
Figure 3.2. A VLF loop aerial at the Leicester University field site.
resolved into vertical and horizontal components. So even if it picks up only the vertically polarised groundwave a sloping wire can reradiate both horizontally and vertically polarised waves. Unless each of these wires lies in the plane of propagation containing the loop aerial, the reradiation from them will be picked up by the loop.

If all the reradiated components of the groundwave are added vectorially to the groundwave proper the resultant groundwave will appear to come from a direction which may differ by several degrees from the bearing of the transmitter. If the local reradiation pattern remains constant the loop may be rotated slightly and set to reject the resultant groundwave, thus overcoming the problem. However if the reradiation pattern changes the loop orientation will have to be reset. This was a problem which caused considerable difficulty in the earlier part of this project because the small field site was overcrowded with aerials which were moved from time to time. The problem was well illustrated on one occasion at the Leicester Field Station when a 20 ft. vertical aerial which had been in position for a long time was connected to a receiver using a coaxial cable laid along the ground. The feeder passed within 10 yards of a loop aerial at one point. When the vertical aerial was connected to the feeder the signal picked up on the loop increased by about 30dB. Disconnecting the aerial caused the signal to return to its usual level.

When loop aerials were used in DF equipment at medium frequencies large trees, buildings, metal towers, roads, rivers, hills, power lines and shore lines were known to cause bearing errors of up to 10° (R.A.F. Signal Manual, Volume II, 1939). The
field site used during the project was thus not an ideal one for recording VLF skywaves, but it was the only one available. It was on sloping ground between a metalled road and a small stream, both lined with mature trees. During the project several buildings together with a large metal link fence were constructed alongside the stream and new houses were under construction adjacent a third side of the site. On the site there were two metal and several wooden masts supporting HF arrays, and there were of course the various loops and the short vertical whip aerials. Metal feeding troughs also appeared from time to time to feed sheep which grazed on the site.

Not surprisingly therefore, there were many occasions, particularly during the first half of the project, when the records exhibited groundwave contamination after having been correctly set not long previously, and frequent adjustment of loop orientation was thus necessary. Fortunately, during the later part of the project, conditions on the site became more stable and more consistent records were thus able to be obtained.

3.6. **Installing Loop Aerials.**

Although in theory a flat loop correctly set does not pick up any groundwave, in practice in any given set of experimental conditions there is a residual amount of groundwave contamination present in the receiving system. The experimental problem is to reduce this to a level at which it is negligible compared to the skywave. If, as in winter, the skywave is some 20dB below the groundwave the task is relatively easy. During the summer however when the skywave is weaker, suppressing the
groundwave becomes more difficult and it may prove impossible
to achieve satisfactory suppression at this time. This situation
did occur at Leicester with GYA transmissions which proved
impossible to monitor satisfactorily during summer days.

When installing a loop aerial intended to operate under
difficult conditions such as those described above care must be
taken to ensure that groundwave pick up on the feeders is also
minimised. At Leicester 50Ω coaxial cable was used as feeder.
One test carried out on the site demonstrated that a 10dB
reduction in groundwave pick up could be obtained if the coaxial
feeder was moved so that it lay perpendicular to the plane of
propagation rather than parallel to it. Shortening the feeder
also helped to reduce the pick up. Appropriate positions for
the loops were therefore chosen to minimise feeder pick up.
Correct matching of the feeder to the aerial and to the receivers
was also of paramount importance.

Once the position for the loop has been chosen there are
several ways of finding the correct orientation. The approximate
orientation may be quickly found by setting the loop in the
position in which it picks up minimum signal. As the loop is
rotated by a few degrees in small increments through this position
the phase and amplitude of the received signal may be noted and
plotted as shown in Figure 3.3. At Leicester the loop was set
where the phase changed fastest. On subsequent days the morning
and evening phase and amplitude changes were noted. A polar
diagram was then plotted with the signal strength as the r coordinate
and the phase as θ. If the loop is set correctly the vector
diagram will show the locus of the signal to be a spiral, centred
Figure 3.3. Rotating a loop aerial through the null.

Figure 3.4. ABLIL of GBZ; 24th July 1970.
Figure 3.5. A set of model ABLILS and the accompanying phase records.
on the origin as shown in Figure 3.4. If groundwave contamination is present it is centred about a point displaced from the origin by the amount of groundwave present. There are more examples and further discussion of these ABLIL's (Abnormal Loop Induction Locus, after Bain et al., 1952) in Chapter 4. Since plotting these ABLILS can be long and tedious a set of model or artificial ablils may be constructed to assist immediate recognition of groundwave contamination in the records. Figure 3.5 shows such a set accompanied by sketches of the corresponding phase record. It is clear that the amplitude record would in each case include a series of maxima and minima instead of the smooth increase or decrease expected, with the minima coinciding in time with the point of fastest phase change. A more important reason for constructing these model ABLILS is concerned with identifying groundwave contamination when the received signal strength is very low. In these conditions it is not possible to record the amplitude changes accurately although the phase is still measured correctly. A set of model ABLILS is useful in these circumstances.

3.7. Receivers and Recorders.

Two types of VLF receiver were used in this project. One was a valve receiver built by the Plessey Company, the other was a solid state Tracer VLF/LF phase tracking receiver. Block diagrams of the complete systems using each of these receivers are shown in Figures 3.6 to 3.8.

The Plessey receiver consists of two almost identical channels, the groundwave (reference) channel which employs simple AGC and the skywave (signal) channel which employs amplified AGC.
Output 6-10v at 525 Hz

Additional amplification of signal IF. Output 10v constant for input > 1v.

Amplifies (x 10) and compares signal and reference IF's.

Potentiometer to adjust f.s.d. on pen recorder.

Figure 3.6. Block diagram of receiving system using the Plessey valve receiver for short paths signals.
Figure 3.7. Block diagram of receiving system using the Plessey valve receiver for long path signals.

VARIAN
FREQUENCY
STANDARD

INCREMENTAL
PHASE CHANGER

FREQUENCY
SYNTHESISER

PLESSEY
TWIN-CHANNEL RECEIVER

IF
AMPLIFIER

SERVO UNIT

FOSTER
SIX-CHANNEL RECORDER

Fb: vapour frequency standard:
Stability: parts in $10^{12}$.

Mechanically offsets the frequency
by 150 parts in $10^{12}$ from the
standard frequency to provide UT-2

Divides 100 kHz into
100 Hz pulses

Receiver selects the appropriate
harmonic of 100 Hz to use as a
reference frequency.

Additional amplification
of signal IF, if required

Each channel dots once
per minute.
Figure 3.8. Block diagram of receiving system using the Tracor phase tracking receiver.
The local oscillator is controlled by a crystal held at 40°C in an oven, and the operating frequency is 525 Hz above or below that of the RF amplifier. The RF stages are broadly tuned but the IF stages have a bandwidth of 1 Hz. This is achieved using a frequency selective feedback loop which includes "Twin T" filters held at constant temperature in a double oven. The two 525 Hz IF outputs are taken to a mechanical phase measuring servo. It was found that it was usually necessary to provide additional amplification of the signal IF output due to the very small signal input to the receiver. The output from this servo (representing the phase of the skywave) and the AGC voltage (representing the signal strength) were then recorded on either an Evershed twin-channel pen-recorder or a Foster potentiometric 6-channel dotting recorder. Some Evershed recorders were 5mA full scale, but these were later replaced by ones having 1mA full scale as the former were not sensitive enough to give acceptable records of the changes in signal strength which were observed. The 6-channel Foster recorders dotted 6 times each minute thus yielding one dot per minute on each channel. This proved to be very convenient for following the progress of SPA's on the long paths for which the Fosters were normally used.

When signals from distant transmitters were being recorded the Plessey receiver used as reference a signal derived from a Varian "5000" Rubidium vapour frequency standard. After adding the required offset to the Varian output to obtain UT-2 the sine wave output was divided into 100 Hz pulses. The receiver then selected the appropriate harmonic of 100 Hz, which in the case of 12 kHz Ω/Trinidad was the 120th, and used this as its reference
signal. At times when the received signal was very weak the IF output again required additional amplification to drive the servo motor.

The Tracor 599 J solid-state phase-tracking receiver is tunable in 50 Hz steps between 3.00 and 99.95 kHz. The phase tracking servo is electronic and the time constant may be switched between 5, 15, 50 and 150 secs (nominal) at 20 kHz. The phase output is accurate to ± 0.25μsec and may be set to 10μsec or 100μsec full-scale. The dynamic range is 40 dB of AGC plus a manual adjustment of 80 dB. The output representing the strength of the carrier is derived from the AGC and has a range of 40 dB. The phase and signal level outputs are linear and were displayed on the Foster recorder.

At the beginning of the recording programme only Plessey receivers were available, but later several Tracor receivers were added to the system. They were assigned to the long path transmissions which all used the same offset from UT-2. This was not the case for some of the short path transmissions.


The dynamic range of the Tracor receiver was 40 dB and this was indicated by a ± 20 dB scale on the meter. A Manual control of the gain could be used to bring the level within the meter range if necessary. The signal level output was taken from the meter. This range normally proved to be adequate and gave a convenient 0-40 dB scale on the paper trace. The servo time-constant was usually set to 5 sec (nominal) except in noisy conditions when it was necessary to smooth the record by selecting the 15 or 50 sec output.
The Plessey receiver was an obsolescent valve receiver that had a dynamic range of about 60 dB. The daily variation in signal level was usually much less than this so setting the gain to give 30 or 40 dB across the paper chart would normally have been quite sufficient. But due to the small signal input the receiver usually had to be set at maximum gain and even that proved to be insufficient at times. Moreover, overrunning its 23 valves continuously caused several to fail from time-to-time. Modifications to some of the receivers involving using different valves produced an improvement in gain, and this and the more sensitive aerials which were constructed enabled the changes in signal level to be monitored more accurately in the later half of the project.

To calibrate the short path system the loop was rotated into the plane of propagation to pick up the groundwave. A switched attenuator was inserted into the aerial feeder and the paper chart marked appropriately as the attenuation was adjusted in steps of 5 or 10 dB. The time constant of the Plessey receiver was quite short so the ink trace was smoothed by placing a capacitor across the input to the pen-recorder amplifier giving a time constant of about one minute.

The speed at which the servo-motor moves governs the time constant of the phase record. A servo with a tracking rate of 0.12 λ per second was later replaced by one with a faster response. The trace was so noisy on some paths that small SPA's could not be identified clearly so the slower servo was used on the Ω/Trinidad recordings and it proved to be adequate to record both the slow diurnal changes and the much faster SPA's.
When SPA's on the G/Trinidad-Leicester path were examined graphically by plotting the rise time against the size of the SPA, the fastest rising SPA observed averaged about 0.1 \( \lambda \) per minute. The above figures show that this speed was well within the capability of the equipment. On the short paths the faster servo which could track through 0.5 \( \lambda \) in about 12 seconds was used successfully during the later half of the project.

To determine the ionospheric conversion coefficient it is not necessary to know the absolute value of the field strength, only the ratio of the skywave and groundwave strengths (See Chapter 5). No attempt was thus made to determine the absolute value of the field strength of the various transmissions monitored. However during the earlier stages of the project calculations were carried out to determine the field strength of the skywaves of as many of the LF and VLF transmissions in the U.K. for which information on transmitted power etc. was available. The values of the ionospheric conversion coefficient used in these calculations were those found in Belrose's (1968) graphs of \( R_L \) vs. \( f \cos \theta \) reproduced in Figure 2.13. Having obtained the values of the field strength of these transmissions to be expected at Leicester, the magnitude of the input to the receiver was then calculated for each one. To do this it was also necessary to calculate the theoretical sensitivities of the loop aerials which were then available at the Field Station. This exercise proved to be very useful because it was immediately apparent that - assuming reasonably accurate values of the conversion coefficient had been used - some of the transmissions were below the sensitivity of the receivers. Included among these were some of the transmissions which it was proposed to monitor. At the same time the suppression necessary to
isolate the skywave of each transmission was calculated and again it was apparent that the aerials which were available were not good enough in this respect. With this information available the specifications for the new loop aerials described earlier could then be drawn up.

Tables of the calculated field strengths and the skywave/groundwave ratios of all these transmissions are included in the Appendix.

The data obtained using the equipment described in this chapter will now be presented.
CHAPTER 4

EXPERIMENTAL RESULTS: QUIET CONDITIONS.

4.1. Introduction

In this chapter the experimental results are examined to establish the normal behaviour of the various VLF and LF transmissions received at Leicester. For the purposes of this chapter "normal behaviour" means the characteristics of the received signals on those days which were not unduly disturbed by large solar or magnetic disturbances, and which therefore represent the normal conditions encountered during the project. It will be noted that these are not the 5 or 10 "Quiet Days" of each month identified in published geomagnetic activity indices, although where there was a choice the magnetically quieter day was preferred.

Complete details of frequency, path length, etc., of each of the transmissions monitored at Leicester have, for convenience, been gathered together in the Appendix.

Before examining the results obtained, the methods used in selecting and processing the records to obtain the normal behaviour of the signals will be described.

4.2 Selection and Processing of the Records.

During the three-year period 1967-1970 attempts were made at Leicester to detect fifteen different LF and VLF transmissions.
Some of these fifteen transmissions were in fact monitored almost continuously during the three-year period; others were monitored for shorter periods, ranging from one or two years to periods of a few weeks or less. Attempts to monitor several of the transmissions were unsuccessful, due mainly to their signals being too weak for the receivers available to detect. Where records were obtained over a long enough period of time, the normal behaviour of the phase and amplitude of the received signal was extracted by averaging records selected as follows.

To obtain the diurnal variation in the phase and amplitude of the signal at each season about a dozen undisturbed records were selected from those taken during the four week periods centred on mid-summer day, mid-winter day, and the two equinoxes. In making the selection records taken during periods of high geomagnetic activity were set aside, together with those having large gaps due to transmitter or receiver maintenance, and records disturbed by large solar flares. If the disturbance was small and the trace could be notionally smoothed and the undisturbed value estimated, the record was included. Care was also taken to ensure that as far as possible the records selected were evenly distributed on each side of the central day, particularly at the equinoxes.

Hourly values of the phase were then read off the selected records and transferred to punched tape and a standard library programme on an ICL 4130 computer computed the mean, median, and upper and lower quartile values at each sampling point. The amplitude of the steep incidence transmissions was determined from calibration marks put on to the paper chart in the manner
described in Chapter 3. On records taken using the Tracor receivers the relative signal strength, in decibels, could be read straight off the chart.

In this chapter the phase data for each of the four seasons have been summarised for ease of comparison by making one page represent a three year period on each path, with the layout of the years and seasons on each page being the same.

The way in which the short path signals changed during the course of a year was also examined by noting (a) the magnitude of the daily phase advance, (b) the phase of the skywave relative to the ground wave at (nominally) noon and midnight, and (c) the amplitude of the signal at (nominally) noon and midnight on each day of the year for which data were available. These data were not averaged but each value was plotted individually so that both the annual trend and normal spread of points were visible.

On the phase channel the daily phase advance could be measured to about ± 0.20λ, or at times ± 0.15λ. In, for example, the GBR records the "noon" value, i.e. the mean value between 11.00 and 13.00 h, could usually be estimated to within ± 0.05λ, and the night value to within ± 0.15λ, or sometimes 0.10λ. In the GBZ records the uncertainty was usually rather less than this, and in the GYA records it was usually rather greater. An attempt was made to estimate the notionally smoothed night time level by smoothing out small disturbances by eye when taking readings, but records with large or extensive disturbances were omitted.

In the amplitude records it was also the notionally undisturbed night time level which was estimated by ignoring small amounts of fading, or omitting the record if the fading was deep
or extensive. The value could often be read off the calibration marks to $\pm 1$ dB, but the smoothing of the record, particularly at night, could increase the uncertainty by a further 2 dB or so.

To achieve consistency, all records relating to one transmission were processed before processing those of another transmission, and the phase of each was examined before the amplitude. This method of working was found to be essential with the more difficult records e.g. of GYA, which posed particular problems which will be referred to later.

Three-day running means were calculated for certain sets of daily phase and amplitude data. Where there was a gap in the data of one data point the values on either side were averaged; if the gap was wider the values adjacent to the gap were weighted according to the width of the gap. In computing the three-day means, to establish the trend more clearly, a few isolated points well away from the normal spread have been disregarded.

In the following section it will be convenient to examine the data relating to each path in turn. The steep incidence data have been grouped together, as have the long path data. Within these groups the paths for which most data are available will be examined first.

It will be noted that the data in this chapter are presented in terms of the units in which the measurements were made. Conversion of the data to yield values of ionospheric parameters, and comparison of these with values derived from model ionospheres is the subject of Chapter 5 but for completeness of presentation values of $\mu R_\perp$ and the apparent height of reflection have been added to certain figures.
4.3. RESULTS: Short Paths.

GBZ: 19.6kHz.

The GBZ transmitter at Crippion in Wales came on the air in mid-1969 and it was monitored for nearly a year and a half. The signal was strong enough to enable satisfactory records to be taken all year round, and due to the strong reflection of the skywave in winter, multiple-hop transmission was observed on this path. The strength of the transmitted signal changed regularly, being high for two hours and low for one hour. The effect is clearly illustrated in Figure 4.1 which shows a typical GBZ record. As long as the skywave was not too small the instruments were able to continue tracking the phase through these low periods. The record was calibrated near midday when the vertically polarised skywave was weakest and least affected the groundwave used in calibration.

The diurnal variation of the GBZ phase at each of the four seasons is summarised in Figure 4.2. The number adjacent to each curve indicates the number of days used to establish that curve. It is evident that there is little difference between the form of the equinox and summer curves except that caused by the changing length of the day; the phase change is almost the same and the general shape is similar. The winter curve contrasts with the three others due to its much smaller phase change and way in which it reverts slowly to its night time level after sunset. It also begins to advance towards its day time level well before sunrise.

The phase curves are illustrated in greater detail in Figure 4.3. The discrete points indicate mean values at hourly intervals, and the dotted lines represent the upper and lower quartiles.
Figure 4.2  GBZ-Leicester: mean diurnal phase at each season.
Figure 4.3 GBZ-Leicester: diurnal phase at different seasons.
Figure 4.4. GBZ-Leicester; diurnal amplitude at different seasons.
The smaller curves in Figure 4.2 were constructed using median values. There are a few mean values in Figure 4.3 which do not lie within the quartile boundaries. These occur at night, and were caused by a few individual values lying well outside the usual spread of values weighing the mean in that direction.

The diurnal variation of the signal strength at each season is shown in Figure 4.4: the amplitude of the skywave is expressed in terms of decibels down on the ground wave. It is noted that the summer and the equinox curves are again similar to each other, and the winter curve exhibits a smaller variation than the others. The quartile boundaries on the autumn curve are more widely spaced than the others, indicating that there was a greater variation between the fifteen autumn days selected than there was at other seasons. The night time level is rather lower at the autumn equinox than it is at the spring equinox. The change from night to day and vice versa is not smooth, and the departures from the smooth change are considered below and attributed to multiple hop propagation on this path.

Figures 4.5 and 4.6 illustrate the way in which the noon amplitude varied over the 15-month period, September 1969 to November 1970. The amplitude of the signal rises to a maximum at mid-winter, and then falls again. From the middle of March until early October the mean level remains approximately constant at about 18 dB lower than the mid-winter peak. Towards the end of October it rises again abruptly - the so called "November effect". There is a noticeable departure from the smooth winter peak during December and January. This feature is also prominent in Figures 4.7 and 4.8 which illustrate the night time amplitude levels over
Figure 4.5  GBZ - Leicester: amplitude of horizontally polarized skywave at noon.
Figure 4.6 GBZ-Leicester: amplitude at noon, 3 day running mean.
Figure 4.7  GBZ - Leicester: amplitude of horizontally polarized skywave at night.
Figure 4.8 GBZ-Leicester: amplitude at night, 3 day running mean.
the same 15 month period. The night time amplitude does not exhibit the same clear seasonal change as the noon amplitude, but in Figure 4.8 it does appear to rise slightly between April and July or August, and then fall again towards the end of November 1970. There are a few weeks in September/October, in both 1969 and 1970, when the values are rather lower than those immediately before and after, and there also appears to be a slow fall between February and April.

The phase of the signal at noon and midnight, relative to the groundwave, is plotted in Figures 4.9 and 4.10. The annual trend in these phase measurements resembles the trends in the day and night amplitude levels in several respects. The noon phase retards in the autumn, and advances again in spring. From the beginning of March until mid-September it exhibits a consistent slow advance; in this it differs from the amplitude trend, which remains constant during the summer. It is also noted that there is an abrupt retardation of the phase in January which coincides with the sharp dip in the amplitude at this time. The night time phase is also retarded during the same period. Another noticeable feature in both the noon and midnight phase data is the spike-like retardation at the end of December. This coincided with a Stratwarm over Eurasia, first reported in the URSIGRAM service on 30th December, and which ended on 9th January 1970. With the exception of these two periods in December and January, the trend in the night time phase appears to suggest that the phase advances from October until mid-winter, and then retards slowly until mid-summer; it then appears to remain approximately constant until mid-October, when it starts to advance again. At the beginning of December in
Figure 4.9  GBZ - Leicester: phase of horizontally polarized skywave and apparent heights of reflection.
Figure 4.10  GBZ - Leicester: phase of skywave; 3 day running mean.
both 1969 and 1970 there is a short, abrupt retardation. One further point visible in Figure 4.9 is the level to which the night time phase advanced during the Polar Cap Disturbance in March - about half way to daytime level on one night included here.

The other variable which was measured was the daily phase advance, referred to here as $\Delta\phi$. It was independent of the calibrations used to measure the amplitude or the day and night phase levels, and to some extent it provided an indication of the consistency of the measurements. It was also the one variable which could usually be measured or estimated to within acceptable limits over the whole three year period.

The daily phase advance of the GBZ signal is illustrated in Figures 4.11 and 4.12. Those disturbances which recurred in both the noon and midnight phase data are largely absent, and so the form of the winter peak in particular is quite regular, and is symmetrical about mid-winter. Thus lines drawn through the two periods January - March and October - December intersect near the end of December, and the end of June. Overall, there appears to be a sinusoidal type of change which is interrupted in the summer months as though by some saturation effect. The changeover appears to occur about 25th March and 18th September, and the value of the solar zenith angle $\chi$ at both these times was about $50^\circ$. These are not the dates on which the noon phase and the amplitude appear to change however. The respective dates are set out in Table 4.1: they were taken from the original figures drawn on graph paper.
Figure 4.11  GBZ-Leicester : magnitude of daily phase advance ($\Delta \phi$)
Figure 4.12  GBZ - Leicester: magnitude of daily phase advance, 3 day running mean.
Figure 4.13  GBZ - Leicester: difference between day and night amplitudes (Δ Amp.)
Figure 4.14. GBZ-Leicester: difference between day and night amplitudes, 3 day running mean.
### TABLE 4.1

Dates of the beginning and end of the summer period in the GBZ records, 1970.

<table>
<thead>
<tr>
<th></th>
<th>Spring</th>
<th>Autumn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude</td>
<td>March 28 ± 4 days</td>
<td>October 15 ± 5 days</td>
</tr>
<tr>
<td>Noon phase</td>
<td>March 5 ± 3 days</td>
<td>September 10 ± 2 days</td>
</tr>
<tr>
<td>Δφ</td>
<td>March 26 ± 6 days</td>
<td>September 18 ± 2 days</td>
</tr>
<tr>
<td>Night phase</td>
<td>-</td>
<td>October 5 ± 5 days</td>
</tr>
</tbody>
</table>

The difference between the day and night amplitude levels was plotted in Figures 4.13 and 4.14. The annual trend is similar to, but does not exhibit such a clear form as the trend in the phase difference. It appears in Figure 4.13 to slope gradually downwards from January to July or August, and rises abruptly from September onwards, but Figure 4.14 could be interpreted as indicating two level periods during the summer months with a step of about 4 dB between them in June. The data available are not sufficient to resolve this point.

Figures 3.4 and 4.15 show ABLILS drawn using summer and winter data respectively. The former is a smooth spiral about the origin suggesting that only one component is present. The morning and afternoon branches are not coincident, and indicate that the phase does not begin to retard until some time after noon, and that the amplitude is smaller in the afternoon than in the morning. The two winter ABLILS in Figure 4.15 are more complex and suggest that more than one component is present. The gaps in the ABLILS are due to the 1 hour in 3 reduction in transmitter power. To interpret
Figure 4.15. Two ABLILS for the GBZ-Leicester path.

Top: 13 January 1970
Bottom: 29 November 1970
the winter ABLILS consider Figure 4.16. The top diagram shows the locus of the sum of three vectors $V_1$, $V_2$, and $V_3$ of decreasing magnitude, with $V_2$ and $V_3$ rotating twice and three times as fast, respectively, as $V_1$, and $V_1$ and $V_3$ being in phase and $V_2$ in antiphase at $\theta = 0^\circ$. During rotation the magnitudes of the vectors were kept constant, as indicated by the dotted circle, the locus of the end of $V_1$. The top diagram would therefore resemble the ABLILS of a signal which was the sum of the first, second, and third hops, with change of phase of $\pi$ at each ground reflection, and no change of phase at ionospheric reflection, and with the attenuation remaining constant as the phase advanced and retarded. The middle diagram has been modified to allow for change of amplitude with phase, as indicated by the spiral. The close similarity between this diagram and the GBZ ABLIL below it indicates that multiple hop propagation occurs on this path in winter, with at least the first three hops being significant. An exact correspondence between the two figures is not expected since the path lengths of the second and third hops will depart from exactly two and three times the path length of the first hop as the angle of incidence departs from zero.

The other ABLIL in Figure 4.15 relates to the following winter and, although more complicated in detail, its overall shape indicates that three components are present here also. The small loops indicate that the secondary vectors are larger in magnitude than they are in the January ABLIL. Reference to Figure 4.8 confirms that the amplitude of the signal was larger in November than it was in January.
Figure 4.16  Vector diagrams :-

(a) three components, amplitude remaining constant with $\theta$
(b) three components, amplitude increasing with $\theta$
(c) GBZ ABUL of 13 January, 1970.
In averaging the amplitude data to extract the mean diurnal variation the detail tends to disappear, and the day to night transitions exhibit only the gross features such as the step-like interruptions visible in Figure 4.4. These can thus be seen to be attributable to the multiple-hop propagation. From the shape of the summer curve in Figure 4.4 it appears that more than one hop is present then also, although the regular form of the summer ABLIL in Figure 3.4 would suggest that only the first hop was prominent on the day the ABLIL was drawn. This apparent discrepancy can be resolved by remembering that the amplitude of the \( n \)th reflected component will, to a first approximation, depend on \( (\frac{R}{R_\perp})^n \), and that the amplitude of the signal exhibits a day to day variability. The second and higher components will tend to reduce to an insignificant amplitude on a day when the magnitude of \( \frac{R}{R_\perp} \) is low. An ABLIL drawn on such a day will, to a first approximation, contain only one component and the locus will thus approximate to a smooth spiral, as it does in Figure 3.4.
GBR: 16.0kHz.

The Leicester field station is situated only 27 km from the GBR transmitter, (i.e. about \(1\frac{1}{2} \lambda\)) and consequently the groundwave is very strong. However, the vertical polar diagram of the transmitting aerial is such that little power is radiated vertically, and as the launching angle of the skywave received at Leicester is nearly vertical (about 80°) the skywave at Leicester is very weak. Isolating the skywave is thus a demanding task all year round, and especially so in summer. In the earlier part of the project only the phase was measured but later, with improved instruments, amplitude measurements were also undertaken. The phase measurements cover a three year period, the amplitude measurements about half this time.

Figure 4.17 shows a sample GBR record; the changes in the transmitter keying pattern are clearly evident in the amplitude trace. In winter the diurnal change in amplitude is small on the GBR-Leicester circuit, as indicated by the lack of appreciable change in the amplitude trace going from day to night.

The summary of the seasonal phase changes is presented in Figure 4.18. The close similarity of each season from year to year is striking, as is the similarity of the spring, summer, and autumn curves but for the different length of the day. As with the GBZ data, the winter curves differ from those of the other three seasons. One noticeable difference between the GBR and GBZ phase curves, however, is that the GBR phase changes very little around noon having almost reached its lowest value some time before, whereas the GBZ phase noticeably continues to advance until noon, and then begins to retard again.
Figure 4.1b  GBR - Leicester: mean climatological phase at each season.
Figure 4.19 illustrates four GBR seasonal phase curves in greater detail and includes upper and lower quartile values.

Due to the greater difficulty in recording the GBR amplitude satisfactorily and the apparently changing levels of the signal due to keying changes at the transmitter, it has not been possible to extract satisfactory curves to represent the mean diurnal amplitude variation at each season. However, examples of the diurnal variation on selected days at different times of the year are given in Figure 4.20. The smoothed amplitude of the signal at hourly intervals has been plotted. It should be noted that at times the signal can vary by 5 or even 10 dB between the hourly values, so these curves represent the general trend of the amplitude over the 24 hour period selected. The absence of substantial change in the signal between day and night in winter is evident in the January curve, and fading of the signal at night is a prominent feature in each of the curves. The absence of symmetry about noon is also marked in most of them. In September the signal became too small to be measured reliably for several hours around noon so this part has been omitted.

The change in the noon signal amplitude over the period 1968-1970 is shown in Figures 4.21 and 4.22. As was evident in the previous Figure the signal was near the limit of the equipment's capability during the summer and decreasing reliance must be placed on the accuracy of values below about 50 dB. They are included in Figure 4.21 for completeness and to indicate that the measurements were in this region, but values below 54 dB have been omitted from Figure 4.22. The general trend in the 1970 data is similar to the GBZ data, with the noticeable exception of the sharp
Figure 4.19  GBR - Leicester: diurnal phase at different seasons.
Figure 4.20 GER-Leicester : amplitude on different days.
Figure 4.21 GBR-Leicester: amplitude of horizontally polarized skywave at noon.
Figure 4.22 GBR-Leicester: noon amplitude, 3 day running mean.
dip in January, which is absent from the GBR data. Instead, there is a small spike in the GBR data. The amplitude decreases until about mid-April and remains at about this level until it increases abruptly at the beginning of October. The GBR measurements were most difficult to obtain some weeks after midsummer, about August, suggesting that the amplitude was rather lower then than at midsummer. However, as the instruments were working at the limit of their capability throughout the summer, this does not necessarily indicate a large change in signal level, although the accuracy of the measurements at this time probably decreased somewhat.

Figures 4.23 and 4.24 illustrate the night time amplitude measurements of the GBR signal during 1970 and parts of 1968 and 1969. The sharp dip in the GBZ amplitude in January is not reproduced in those data, but there appears to be a seasonal trend with the level rather lower at the equinoxes, and midsummer and midwinter.

The amplitude of the GBR signal at night appears to be mostly in the region 28 to 38 dB throughout the two year period covered by Figure 4.23.

The phase of the signal relative to the groundwave is shown in Figures 4.25 and 4.26. The gross features resemble those of the GBZ phase, and the phase retardation in January is present in both the day and the night data, as is the spike which coincides with the December/January Stratwarm. These two features mask the normal trend during the 1969/70 winter period, but during the remainder of the year both day and night phase levels follow the GBZ trends quite closely. If tracings of the GBR and GBZ data are overlaid one on the other it can be seen that some of the detail is also common to both sets of data.
Figure 4.23 GBR-Leicester: amplitude of horizontally polarized skywave at night.
Figure 4.24  GBR-Leicester; night amplitude, 3 day running mean.
Figure 4.26  GBR-Leicester: phase of skywave, 3 day running mean.
The variation in the daily phase advance $\Delta \phi$ between November 1967 and November 1970 is illustrated in Figures 4.27 and 4.28. The drift upwards in mid-1968 is due to instrumental drift: after repair the phase reading returns to normal again. Apart from this period, the similarity of the data from year to year is marked, particularly in Figure 4.28. If the 1970 data in Figure 4.28 are compared with the GBZ data by overlaying tracings of these figures, marked similarities in the detail can be observed, with the exception of the July-August period when it became very difficult to make accurate measurements on GBR. Thus, a downward trend in the GBR data between March and September 1970, identical to that in the GBZ data, becomes evident, and the magnitudes of $\Delta \phi$ throughout the year can be seen to be very similar in both sets of data. Furthermore, there appears to be closer agreement between the 1970 GBR and 1970 GBZ data than between the 1970 GBR and earlier GBR data. It is also noted that, as in the GBZ data, the peak in the GBR data during the winter months is quite regular, and is symmetrical about midwinter: lines drawn through the spring and autumn data intersect near the end of December and the end of June each year. The dates on which the summer level period appears to begin and end in the 1970 data are set out in Table 4.2.

**TABLE 4.2**

Dates of the beginning and end of the summer period in the GBR records, 1970

<table>
<thead>
<tr>
<th></th>
<th>Spring</th>
<th>Autumn</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Amplitude</strong></td>
<td>April 15 $\pm$ 3 days</td>
<td>September 25 $\pm$ 3 days</td>
</tr>
<tr>
<td><strong>Noon Phase</strong></td>
<td>March 7 $\pm$ 5 days</td>
<td>September 15 $\pm$ 3 days</td>
</tr>
<tr>
<td>$\Delta \phi$</td>
<td>March 15 $\pm$ 10 days</td>
<td>September 20 $\pm$ 5 days</td>
</tr>
<tr>
<td><strong>Night Phase</strong></td>
<td>-</td>
<td>October 8 $\pm$ 6 days</td>
</tr>
</tbody>
</table>
Figure 4.27  GBR-Leicester: magnitude of daily phase advance ($\Delta \phi$)
Figure 4.28 GBR-Leicester: daily phase advance, 3 day running mean.
In 1968 and 1969 the summer period in the $\Delta \phi$ data begins on March 20th ($\pm 5$ days) and March 20th ($\pm 3$ days) respectively, and in 1968 it ends on September 26th ($\pm 4$ days). It thus begins and ends each year on about the same dates. Reference to Table 4.1 shows that in 1970 it appears to begin about 11 days earlier than in the GBZ data, but that it ends at about the same time. In the noon phase data the summer periods begin and end at nearly the same times. In the night phase data the summer periods end about the same time also. In the amplitude data however there is a difference of about 2½ weeks at each end: the GBZ summer period begins earlier and ends later than the GBR summer period.

The difference between the day and the night amplitudes is plotted in Figure 4.29. The general trend exhibited by these data is similar to that of the GBZ data, but no detailed conclusions can be drawn from the relatively few data available.
Figure 4.29
GBR - Leicestart: difference between day and night amplitudes (dB).

Difference between Day and Night amplitudes (dB)

1969 N D J F M A M J J A S O N D

0 10 20
GYA: 45 kHz.

The observations of the GYA transmissions extended the measurement into the LF band. Higher attenuation at these frequencies resulted in a weak skywave, and changes in transmitted power during the project caused even the groundwave to drop to a level some 50 dB smaller than the GBR groundwave at times. Being a military transmitter, little information was readily available regarding changes in the GYA transmissions. Finally the transmitter went off the air at the end of 1969 for some months, and monitoring of this frequency ceased. Continuous monitoring from 1967 until this time yielded valid data during the winter months, and a limited amount of data during the summer months. A few measurements were taken in September 1970, after transmissions had recommenced.

A sample GYA record is shown in Figure 4.30. The cos x type variation of the amplitude during the day is visible, as is the variability of both the phase and amplitude during the night.

The summary of the phase measurements in Figure 4.31 shows the three winter curves and in addition, parts of the two autumn curves. The gaps in the autumn curves indicate that the signal became too small to be recorded at these times. Allowing for the shorter wavelength of GYA making the quantity $\Delta \phi$ larger, there is quite a close similarity between these LF winter curves and the corresponding VLF curves, particularly in the evening when all three sets of curves exhibit a slow drift upwards for some hours after sunset. The reverse effect in the morning is quite pronounced in the GYA and GBZ curves (both taken at oblique incidence) and to a lesser extent in the GBR curves (taken near vertical incidence).

Figure 4.32 illustrates an autumn and a winter phase curve.
Figure 4.30. A typical GWA record; 15 December 1968. Top: phase, f.s.d. = 360°; bottom: amplitude.
Figure 4.31  GYA-Leicester: mean diurnal phase at each season.
Figure 4.32 GYA-Leicester: diurnal phase at different seasons.
in greater detail.

During December 1968 some measurements of the daytime amplitude were made, and these are shown in Figure 4.33, together with a few made in February, April and December 1969, and a few in September 1970. These GYA amplitude measurements are probably not as accurate as those elsewhere in this section, but they give some indication of the magnitude of the signal at these times. They also indicate that the GYA amplitude appears to follow an annual trend similar to that in the VLF data.

Measurements of the night-time amplitude were made during parts of 1969, and these data are illustrated in Figures 4.34 and 4.35. The points lie almost entirely within the range 10 to 20 dB. No annual trend is discernible in the data.

The variation of $\Delta \phi$ during the winter months is illustrated in Figures 4.36 and 4.37. The solid dots in Figure 4.36 indicate definite readings and the open circles indicate estimated values which were obtained as follows. When processing the records it was noticed that as one moved away from midwinter the signal amplitude decreased until a point was reached where, in the morning, the phase advanced, turned sharply, and then advanced again in a manner similar to that shown in the artificial $\text{ABLUR}$ in Figure 3.5. The total phase advance on those days was therefore estimated using vector diagrams similar to those in Figure 3.5. In this way the observations of $\Delta \phi$ could be extended by up to several weeks further from midwinter than otherwise possible.

The data plotted in Figures 4.36 and 4.37 are in general agreement with the VLF data, and some similarities in the detail also became evident if tracings of the GYA and GBR diagrams are superimposed.
Figure 4.33 GVA-Leicester: amplitude of horizontally polarized skywave.
Figure 4.34 (top) GYA-Leicester: amplitude of horizontally polarized skywave at night.

Figure 4.35 (bottom)
Figure 4.36 GYA-Leicester: daily phase advance (Δφ)
Figure 4.37  GVA - Leicester: daily phase advance, 3 day running mean.
Thus, about November 1968 there are many days in both with unusually low values of $\Delta \phi$. In February 1969 the trend of dots in both moves upwards before dropping sharply, the trends being clearer in the 3-day running means. About October/November 1969 both have days with unusually high values of $\Delta \phi$: GBZ has fewer data points than usual about this time but one of these is also anomalously high. In mid-December all three sets of data exhibit an interruption in the upward trend for about two weeks in their 3-day running means, the GBZ data even move in the opposite direction for a time. Thus there is a marked correspondence between both the gross features and the detail of the LF and the VLF data.
This transmitter was the most distant of the short path transmissions monitored, being 300 km distant from Leicester. It was monitored for several months in 1970. The transmitted power changed regularly, being high for 1 hour and low for 2 hours as shown in the sample GQD record in Figure 4.38. During the low periods the receiver did not track the phase, so it could not be followed during the morning and evening changes.

The noon amplitude was observed from January to April 1970 and the variation during this time is shown in Figure 4.39. The familiar downward trend between January and March is evident in the data and in this respect they are consistent with the data from the other transmissions. After the downward trend the position of the data points during April appears to suggest the beginning of a level summer period. From the grouping of the data the summer amplitude would thus appear to lie in the region 18 to 26 dB.

The noon phase level, relative to the groundwave, is illustrated in Figure 4.40. The grouping of the points in January followed by an abrupt advance is consistent with the retardation evident in the other VLF phase levels at this time.

No reliable measurements of the night phase and amplitude were made because of the variability of the signal during the short times that the transmitter was on high power.
Figure 4.38  A typical record of G&Q (19.0 kHz), 10 April 1970.
Figure 4.39 (top): amplitude
Figure 4.40 (bottom): phase
Puckeridge: 85kHz.

The Decca Navigator transmitter at Puckeridge transmits on a frequency of 85.00kHz and is phase stable, so a Tracor receiver was used for tests on transmissions from it during February 1969. The Decca Navigator system is described in the Appendix, where it is explained how groundwave pulses from other transmitters in the chain normally swamp the skywave being sought. To overcome this problem during these tests the aerial feeder was unplugged during each pulse.

Rotating the loop aerial through the null indicated that the amplitude of the Puckeridge signal at the null was 37 dB smaller than the groundwave in daytime. This suggests that the skywave at this time was of the same order of magnitude as the calculated value in Table A.4 and Figure A.1 in the Appendix.

MSF: 60kHz.

Attempts were made on several occasions to monitor the MSF transmissions from Rugby, but on each occasion the skywave proved to be too weak for the instruments available. This would suggest that, as expected, the conversion coefficient is smaller at 60kHz than at 16kHz on this path.
4.4. RESULTS: Long Paths.

In this section the normal behaviour of the phase, and to a lesser extent the amplitude, of the long path transmissions will be presented. These transmissions were monitored mainly to investigate particular aspects of their propagation, so their normal propagation characteristics have not been studied in detail. Each transmission has been examined merely to determine the normal behaviour of the phase during the periods when they were being monitored. Examples of the diurnal variation of the amplitude will also be presented. Other aspects of the propagation of several of these transmissions will be examined in greater detail in later chapters, in particular the effects of solar disturbances on the received signal and the characteristics of TE and TM modes at great distances from the transmitter.

Where a transmission was monitored for long enough the mean diurnal phase variation was extracted by averaging selected records in the manner described earlier. If the period was too short for averaging purposes a record taken on a magnetically quiet day at the appropriate part of the year was selected for inclusion in the three-year phase summary. Such occasions are identified by the numeral "1" alongside the corresponding curve.

Ω/Trinidad: 12.0kHz.

The US Navy Omega transmitter at Trinidad radiated a frequency of 12.0kHz for 6 seconds in every 10, and the transmissions on this frequency were monitored at Leicester continuously from 1967 to 1970. A Plessey receiver was used for most of the time, and because of the low level of the signal only the phase was monitored accurately.
These transmissions were monitored (a) as a flare patrol at Leicester and (b) to compare with transmissions over higher latitude paths when investigating the latitude variation of Polar Cap Disturbances.

A sample $\Omega$/Trinidad record is reproduced in Figure 4.41; on this occasion an unusually large number of clearly defined SPA's were present in the record. In Figure 4.42 are displayed the mean diurnal phase curves for each season during the 3-year period Winter 1967 - Autumn 1970. Figure 4.43 shows four phase curves in greater detail. The stability of the phase from day to day, particularly during summer, is evident from the closeness of the quartile boundaries. Higher order mode effects are evident in the morning but not in the afternoon. The change in the angle between the transmission path and the dawn and dusk lines at different times is reflected in the change in the steepness of the morning phase advance and the evening phase retardation. In contrast to the short paths the diurnal phase change in winter is not substantially smaller than at other times. Also the changing length of the day at Leicester during the year does not change the curve to the same extent as it does the short path curves due to the Trinidad transmitter being within 11° of the equator. The difference in the length of the night is more evident, especially in the summer and winter curves, and it is noted that it is the autumn curves, and not the summer curves, that exhibit the largest phase change. The winter curves exhibit the smallest change. The day to night change in the amplitude is not large.

One interesting point which emerges from a close inspection of Figure 4.42 is that the magnitude of the diurnal phase change
Figure 4.41. A typical Ω/Trinidad record; 15 May 1970.
Figure 4.42  \( \Omega \)/Trinidad - Leicester: mean diurnal phase at each season.
Figure 4.43 $\Omega$/TRINIDAD - Leicester: diurnal phase at different seasons.
becomes smaller from year to year between 1967 and 1970. With one exception (summer 1970) the magnitude of the phase change in any season is slightly smaller than in the corresponding season of the preceding year. The extent of the trend is indicated in Tables 4.1 and 4.2; the data in these tables were obtained by inspection of the original curves drawn on graph paper.

**TABLE 4.1**

Magnitude of the Diurnal Phase Change
(expressed in wavelengths)

<table>
<thead>
<tr>
<th></th>
<th>Winter</th>
<th>Spring</th>
<th>Summer</th>
<th>Autumn</th>
</tr>
</thead>
<tbody>
<tr>
<td>1967/68</td>
<td>.72</td>
<td>.82</td>
<td>.78</td>
<td>.89</td>
</tr>
<tr>
<td>1968/69</td>
<td>.68</td>
<td>.77</td>
<td>.74</td>
<td>.84</td>
</tr>
<tr>
<td>1969/70</td>
<td>.64</td>
<td>.72</td>
<td>.80</td>
<td>.80</td>
</tr>
</tbody>
</table>

**TABLE 4.2**

Diminution in the Diurnal Phase Change from Year to Year

<table>
<thead>
<tr>
<th></th>
<th>Winter</th>
<th>Spring</th>
<th>Summer</th>
<th>Autumn</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.04 (5.5%)</td>
<td>-0.05 (6.1%)</td>
<td>-0.04 (5.1%)</td>
<td>-0.05 (5.6%)</td>
<td></td>
</tr>
<tr>
<td>-0.04 (5.8%)</td>
<td>-0.05 (6.5%)</td>
<td>+0.06 (8.1%)</td>
<td>-0.04 (5.0%)</td>
<td></td>
</tr>
</tbody>
</table>

As an additional check both the median and the mean values of the phase were inspected, and the same trend was evident in each set of data.
It is noted that Solar Cycle 20 (beginning October 1964) was at its peak during 1968-1970 but, as can be seen in Figure 4.44, the peak of this cycle was relatively flat. Furthermore, with the exception of Winter 1967 and Autumn 1970, the smoothed sunspot number remained in the region 105 to 110 during the whole of this time, and the sunspot number was not higher in June 1970 (the one exception to the diminishing phase trend) than it was in June 1968 or June 1969. The trend is thus not correlated with the sunspot number. The solar radio flux is also reproduced in Figure 4.44 and it is evident that the diminishing phase trend does not correlate with these data either. At the lower levels in the D-region from which the 12.0 kHz waves would be reflected the solar U.V. and X-radiation flux plays an important role in ion production (Thomas, 1971). Now the sunspot number and the solar radio flux over a solar cycle provide an indication of the general state of activity of the sun. If the changes in the flux of the short wavelength radiations over the solar cycle were similar to the changes in the sunspot number and in the radio flux then the short wavelength fluxes might also be expected to exhibit a flattened peak rather than a downward trend over the period in question. The flux of galactic cosmic rays also changes during the solar cycle, though in an inverse manner: if the solar cycle has a flattened peak the change in this flux would also be expected to exhibit a similar feature. Thus it is not clear that the diminishing phase trend is the result of changes in ionizing radiation. Furthermore inspection of Figure 4.18 reveals that the diurnal phase of GBR, the only other set of phase data covering this three year period, does not exhibit a consistent diminution in its diurnal phase. The effect would thus
Figure 4.44. Top: solar cycle 20.
Bottom: Solar radio flux 1946-74
(reproduced from the ESA Bulletin.)
seem to be confined to either levels lower than those from which the steeply incident GBR waves were reflected, or to lower latitude portions of the Trinidad to Leicester transmission path. A change in the ionosphere of the magnitude sought would be unlikely to result from man-made effects. It is not clear to what the change in the Ω/Trinidad diurnal phase may be attributed. A closer study of all the sources of ionization and the factors which influence the ionization density at the reflection heights of 12.0 kHz waves over the period in question would appear to be necessary as a first step to solving this problem.
NSS: 21.4 kHz.

This transmitter, in Maryland, U.S.A., was monitored for several long periods in 1968 and 1969. Its transmission path passes through the auroral zone and it was monitored mainly to observe the effects of polar disturbances on it. Also, NSS was one of the transmitters monitored during the TE/TM mode experiment described in Chapter 7.

A typical NSS-Leicester record is reproduced in Figure 4.45. The phase is steady during the day and exhibits mode interference effects in the morning, but they are not evident in the evening. The amplitude trace is also steady during the day and exhibits the corresponding mode interference minima in the morning. They are present to a lesser extent in the evening also.

Figure 4.46 illustrates the diurnal phase change at different seasons. The main difference between these curves is the different length of the day and night portions at different times of the year. The phase change in winter, like that of Ω/Trinidad, is not appreciably smaller than at other seasons. The seasonal phase curves are illustrated in greater detail in Figure 4.47 and, as with the Ω/Trinidad transmissions the phase appears to be rather less stable at night in Autumn than at most other times. There was also a wider than usual spread of points in the summer evenings in 1969.

NAA: 17.8 kHz.

The NAA transmitter in Maine, U.S.A., is situated on the NSS-Leicester transmission path, so transmissions from it also pass through the auroral zone. It is about 12 times more powerful

75
Figure A.4.6 NSS-Leicester: mean diurnal phase at each season.
Figure 4.47  NSS-Leicester: diurnal phase at different seasons.
than NSS and during the later part of the project it tended to be monitored in preference to NSS. It also was monitored during the TE/TM mode experiment, and will be discussed in greater detail in Chapter 7.

The NAA records resembled those of NSS in many respects, as may be seen from the typical record reproduced in Figure 4.45. The phase is steady during the day and exhibits mode interference effects both in the morning and in the evening. Mode interference effects are present in the amplitude trace morning and evening but the minima are not as deep as in the NSS records.

The diurnal phase change at different seasons is illustrated in Figures 4.48 and 4.49. It tends to be rather smaller than NSS but otherwise similar.

NBA: 24.0kHz.

This transmitter at Panama had the highest frequency of the long path VLF transmissions monitored. It was monitored for periods during 1969 and 1970, and during the TE/TM experiment in the winter of 1968/69.

The typical record shown in Figure 4.50 exhibits extensive mode interference effects both morning and evening. The step-like changes in phase are sometimes sufficiently large and fast to cause the receiver to retard rather than advance when tracking the phase, as can be seen in Figure 4.51.

In Figures 4.52 and 4.53 the morning phase change is assumed to advance despite steps backwards on some days, so it is dotted over the portions where this occurred. As with the other long path transmissions the changing length of the day and night portions
Figure 4.49  NAA - Leicester: diurnal phase at different seasons.
Figure 4.52. NBA - Leicester: mean diurnal phase at each season.
Figure 4. 53 NBA-Leicester: diurnal phase at different seasons.
of the curves is the main difference between them. In these curves the modal interference pattern in the evening phase retardation can be seen to change from one season to the next.

*

Transmissions from several other transmitters were monitored for shorter periods of time. No mean curves have been extracted from these records, but some examples of the daily phase and amplitude records are reproduced in Figures 1.54 to 1.56.

*

NLK: 18.6kHz.

The NLK transmitter is situated in the state of Washington on the West coast of the USA, so the NLK to Leicester path passes through the polar cap region and crosses part of the Greenland ice cap. The NLK transmissions were originally selected for monitoring to observe the effects of Polar Cap Disturbances on this path. However, the signal suffered considerable attenuation in crossing the ice cap and during PCD's, when the amplitude decreased even further, the receiver was unable at times to continue tracking the signal reliably. Despite this some records were taken during a Polar Cap Disturbance in October/November 1968 and these will be discussed in detail in Chapter 6.

The severe attenuation on the NLK path contrasts with the much lower level of attenuation suffered by transmissions on other paths which are restricted to crossing only water e.g. the Trinidad to Leicester path. The 100 KW NLK transmissions fell below the threshold of the receiving equipment at times while the less
Figure 4.54. A typical NLK, 18.6kHz, winter record; 7 November 1969.
powerful 1 KW Ω/Trinidad transmissions could be monitored throughout.

* NPM: 23.4kHz.

The NPM (Hawaii) to Leicester path was interesting as it also passed through the polar cap region, but as this path traversed the Greenland ice cap near its widest part the signal received at Leicester was even weaker than the NLK signal. Consequently the NPM transmissions could not be monitored reliably using the equipment available at the time.

* NWC: 22.3kHz.

Some test recordings of the NWC (North West Cape, Australia) transmissions were made and it was found that they could be monitored reliably. In the sample record reproduced in Figure 4.55 it can be seen that due to its length the path was in total darkness, or total daylight, for only short periods. Modal interference effects are quite prominent on the NWC transmissions.

* Ω/Norway: 12.3kHz.

The Ω/Norway to Leicester path was of intermediate length (1,800 km) and it was of interest because the transmitter was situated at auroral latitudes. Monitoring of the Ω/N transmissions commenced during the latter part of the project. Because the path is at such a high latitude the night is quite short during the summer months, and the diurnal phase change is quite small. The amplitude during the day tended to be rather less constant than the amplitude of the other long path VLF transmissions.
Figure 4.56  A typical Ø/NORWAY summer record; 3 June, 1970.
Some interesting observations regarding the response of this path during solar flares were made: these observations are reported in Chapter 6.

*

**OMA: 50kHz.**

Some test recordings of the OMA (Czechoslovakia) LF transmissions were also made. Several SPA's occurred during this time and these will be referred to in Chapter 6.
5.1. Introduction.

In this chapter the customary approach to modeling electron density profiles will be examined in the light of the experimental results presented in Chapter 4 and the findings of other workers in the field. Well known model ionospheres and variations of them will be discussed, and the limitations of using a small quantity of data to produce model electron density profiles will be emphasised.

The measurements in Chapter 4 were presented in terms of the units used in calibrating the instruments. In converting VLF phase and amplitude measurements to yield values of the conversion coefficient various approximations and unknowns are introduced. The presentation adopted in Chapter 4 ensures that the observations are available uncontaminated by such degrading factors. These factors will be considered in this chapter.

5.2. Determining the Conversion Coefficient.

As was explained in Chapter 3 if the field strength of a long wave transmitter at unit distance from the transmitter is \( F_0 \) then at a distance \( d \) from the transmitter the amplitude of the ground wave will be

\[
\frac{F_0}{d} \cdot M
\]

(5.1.)

where \( M \) is a factor which takes account of the conductivity and
curvature of the earth. For the conditions obtaining in this project it approximates to unity. The polar diagram of the transmitting aerial approximates to that of a short dipole so the intensity of the transmitted skywave will vary with the angle it makes with the vertical: at steep incidence this approximates closely to the angle of incidence at the ionosphere so the intensity varies with \( F_d \sin i \). If the difference between the angles of incidence at the ionosphere and at the ground is neglected the downcoming skywave arriving at the receiver will have travelled a distance \( \frac{d}{\sin i} \), and the amplitude of the abnormal component at the receiver will be (from Figure 3.1)

\[
H_A = 2 H_2 \cos i = 2 \left( \frac{F_0 \sin i \sin i}{d} \right) R_\perp \cos i = 2 \frac{F_0}{d} \sin^2 i \cos i \cdot R_\perp \tag{5.2}
\]

The ratio of the abnormal skywave to the groundwave at the receiver will be

\[
\frac{H_A}{H_0} = \frac{2 \sin^2 i \cos i}{M} \cdot R_\perp \tag{5.3}
\]

At Leicester the signal picked up by the loop when rotated into the plane of propagation was taken as approximating to the groundwave. When the normally polarized skywave is small this is an adequate approximation.

At this point it is worth examining some of the approximations made in converting amplitude measurements into values of \( R_\perp \).

First, the asymmetrical top loading of some long wave transmitting aerials will cause the assumptions of a \( \sin i \) type of vertical polar diagram to be less true for some transmission paths than others. Hopkins and Reynolds (1954) suggested that the ratio of the horizontally
to vertically polarized components of the GBR transmissions can be of the order of 10% at certain azimuths. They advanced azimuth dependence of the transmitter polar diagram as one possibility to account for unexplained systematic differences between measurements of GBR transmissions at Cambridge and Slough over paths of similar length but different azimuth. Correspondence with the staffs of the transmitters monitored during the present project has not revealed any further information regarding the polar diagrams of these transmitters. The errors introduced into the measurements from this source are thus not quantifiable at present.

Another factor which may affect the present steep incidence measurements is the setting of the Leicester field station so relatively close to the powerful GBR transmitter. The field site is about 1½ wavelengths from the transmitter, which produces 450 kW of power. Of this about 65 kW is radiated from the aerial system and these transmissions are known to affect some of the other long wave signals monitored at Leicester. For example, when at one point during the project an improved loop aerial (having a bandwidth of about 2kHz) was installed at the site for the Ω/Trinidad signal, modulation of the Ω/Trinidad signal by the GBR signal was observed in the records. Rotating the loop through approximately 20° to reject the GBR signal overcame this problem, but in the case of the steep incidence transmissions the aerials cannot of course be rotated from their fixed positions. The error introduced into the steep incidence measurements from this source is not known at present.

In another approximation the signal detected by a loop set in the plane of propagation is taken as representing the groundwave.
But the signal detected by a loop in this position is (from Figure 3.1)

$$H_N = H_0 + 2H_1$$  \hspace{1cm} (5.4)

When \(2H_1 \ll H_0\) this is a valid approximation, but if this condition is not fulfilled a correction should be made. To make the correction requires a knowledge of the magnitude of \(H_1\), which in turn requires a knowledge of \(R_H\), which is itself not known accurately for all paths. One group of workers sought to minimise this problem by using the signal received on a short vertical aerial to represent the groundwave, and calibrated their loop aerial against this. (Bracewell, Harwood and Straker, 1953). But the signal picked up by a vertical whip is proportional to

$$H_0 + 2H_1 \sin i$$  \hspace{1cm} (5.5)

so at anything other than steep incidence the factor \(\sin i\) remains a large fraction. At, for example, \(i = 30^\circ\) which was the condition in several previous observations, the signal on the whip will still be \((H_0 + H_1)\). If \(R_H = 0.1\) the error introduced by this alone will be of the order of 10\%, and it will increase with the value of \(R_H\).

To return to the loop aerial, by rearranging equation (5.3) we get

$$R = \frac{M}{2 \sin^2 i \cos i} \cdot \frac{H_A}{H_0}$$  \hspace{1cm} (5.6)

$$= \kappa \cdot \frac{H_A}{H_0} \text{ where } \kappa = \frac{M}{2 \sin^2 i \cos i}$$

But in the present observations the quantity measured was
\[ Q = \kappa \frac{H_A}{H_0 + 2H_1} \]  
\[ = \kappa \frac{H_A}{H_0 (1 + \frac{2H_1}{H_0})} \]  
\[ = (\kappa \frac{H_A}{H_0}) \frac{1}{\gamma} \]  

where \( \gamma = (1 + \frac{2H_1}{H_0}) \)  
\[ \therefore \gamma = (1 + \frac{2H_1}{H_0}) \]  
\[ \therefore \gamma = (1 + \frac{2H_1}{H_0}) \]  
\[ \therefore \gamma = (1 + \frac{2H_1}{H_0}) \]  
\[ \therefore \gamma = (1 + \frac{2H_1}{H_0}) \]  

Now \( \frac{R_1}{H_0} = \frac{F_d}{d} \sin^2 i \cdot \frac{d}{F_d M} \cdot \mu R_\parallel \)  
\[ \therefore \gamma = (1 + 2M^{-1}) \mu R_\parallel \sin^2 i \]  
\[ \therefore \gamma = (1 + 2M^{-1}) \mu R_\parallel \sin^2 i \]  

If we know the value of \( \mu R_\parallel \) at the time the calibration was performed then the correction can be made. On the GEZ path when the calibration was performed near noon in summer \( i = 42^\circ \) and \( \mu R_\parallel = 0.1 \) (Spracklen, 1973). If \( M = 0.95 \) then \( \gamma = 1.09 \). In winter near noon \( i = 40^\circ \) and \( \mu R_\parallel = 0.2 \) so \( \gamma = 1.17 \). For the GBR path \( i = 10^\circ \) and assuming the polarization to be circular and \( \mu R_\parallel \) to be about 0.08 in summer and 0.2 in winter (from the present measurements) then \( \gamma = 1.00 \) all year. For the GYA path in winter \( i = 49^\circ \), and if \( \mu R_\parallel = 0.1 \) and \( M = 0.9 \) then \( \gamma = 1.13 \), but if \( \mu R_\parallel = 0.2 \) then \( \gamma = 1.25 \). In summer \( i = 51^\circ \) and taking \( \mu R_\parallel \) to be 0.01, then \( \gamma = 1.02 \). Reliable measurements of \( \mu R_\parallel \) over a path comparable to the GQD-Leicester path are not available so an accurate estimate of \( \gamma \) cannot be made, but if \( \mu R_\parallel \) is assumed to be about the same magnitude as it is on the other paths then \( \gamma \) would be about 1.1 to 1.2. Neglecting the correction factor \( \gamma \) could thus introduce an error of up to 25% in the case of some
of these paths. In placing the scales on the various figures in Chapter 4 the correction factor $\gamma$ has been taken into account. With the night time amplitude data two scales have been provided, one for measurements made during the summer and the other for measurements made at midwinter.

In the phase data only the GBR and GBZ data have the apparent height indicated alongside. Earth curvature has been neglected, but there is close agreement between these two sets of data in respect of the apparent height of reflection both day and night. Because the phase is ambiguous by $2\pi$ the heights are also ambiguous: those indicated here were selected as being closest to those found by other workers.

In the GQD phase data the simplified approach indicates that the skywave and groundwave will be in phase if the apparent height of reflection is approximately 63, 81 or 97 km. This could indicate a reflection height of near 80 km in winter and near 65 in summer. The winter value corresponds to the GBR and GBZ winter values, but the summer value seems rather low. It is possible that the measurements are in error by $\pm \pi$ depending on the sense in which the loop aerial was rotated during calibration. Moving the reflection levels by this amount would give values of 73 - 74 km in summer and near 90 km in winter. Although the summer values would then be close to the GBR and GBZ reflection levels the winter value would now seem to be rather high. There is a further possibility. Because the signal was recorded only one hour in three the phase could not be followed from day to day, so each estimate of the noon phase was independent of measurements on other days. Therefore if the noon phase should change by, say, $\pi$ from one day to the next, or over a period when no records were taken, it would not be known whether the phase had
advanced or retarded. Now there was an abrupt disruption of both the amplitude and the phase of all the short path VLF transmissions in January, and if this had caused errors to be made in estimating the GQD phase levels then the winter values might be $2\pi$ too high. Lowering the highest values by this amount would place the winter reflection level near 80 km and both the summer and winter levels would then correspond to the GBR and GBZ levels.

Having converted the data to values of $R_\perp$ several model ionospheres will now be examined to see if they are consistent with the measurements presented here.

5.3. Model Ionospheres.

A number of model electron density profiles for the D-region have been constructed on the basis of radiowave propagation data alone. Deeks (1966) altered an assumed distribution until full-wave calculations of the reflection coefficients and reflection heights gave results in agreement with experiment. Bain and May (1967) adopted a more stringent approach in testing their distribution against a Hollingworth type ground interference pattern. Bain and Harrison (1972) based their model on rocket measurements of the electron density and pointed out that these other models are open to at least one of two objections: either it is impossible to show that the electron density distribution obtained was uniquely determined by the propagation data alone, or the parameters defining the distribution were too few to give a satisfactory fit to the observations. Bailey and Jones (1974) have demonstrated by calculation the limited degree of accuracy to be expected in such profiles when
derived from, for example, the phase and amplitude of two different frequencies each measured at two different locations, a total of eight measurements.

Although it should be possible to construct a set of model electron density profiles consistent with the measurements presented in Chapter 4 to represent, say, the lower ionosphere each month of the year, this has not been attempted. In view of the lengthy process involved in deriving such a set of distributions - Bain and May reported testing about 100 models in their derivation of a single summer profile - and the fact that the resulting models would still suffer from the fundamental deficiencies outlined above, a different approach has been adopted here. In effect, a number of models known in the literature have been tested against the results presented in Chapter 4. In addition, the effect of systematically altering parts of these models has been examined. The results of these tests proved to be quite interesting.

5.4. Testing the Model Ionospheres.

The model ionosphere proposed by Bain and Harrison (1972) is based on an electron density distribution obtained by rocket in June 1969 in the U.K. The final distribution is claimed to be valid for 4 hours centred on local noon, for the months May to September, and for the four years around the maximum of the solar cycle. It would seem to be the most suitable summer day model available. Thomas and Harrison (1970) used LF and VLF propagation data to deduce a night time electron density profile whose main features were found to be very similar to directly measured night time distributions. This model would appear to be the most suitable night time model.
available. These two electron density profiles are reproduced in Figure 5.1 together with others proposed by Deeks (1966) for noon and night at different seasons and different sunspot conditions. Some of the modifications to the Bain and Harrison day profile and the Thomas and Harrison night profile are illustrated in Figure 5.2: summer, winter, and night profiles are identified by GS, GW, and GN respectively.

Full wave calculations were performed on the Leicester University CYBER 72 computer using these distributions. Two different collision frequency profiles were used during the calculations. One of them was available at Leicester and had been calculated from the CIRA model atmosphere (COSPAR, 1965) by means of the equation

\[ \nu = (0.11n(N_e) + 0.07n(O_2)) \mu \text{ sec}^{-1} \]

where \( \nu \) is the electron energy in electron volts and \( n \) is the number density of each species (m\(^{-3}\)). The other was published by Bain and Harrison with their electron density profile.

The results of the calculations are presented in Figure 5.3 to 5.11. From inspection of these figures it is evident that although the different profiles yield different values of \( \mu R_\perp \), the differences are in many cases not significantly greater than the day to day variability of the ionosphere as expressed by the spread in the experimental values, and quite dissimilar profiles yield values of \( \mu R_\perp \) which are within the spread of the measurements. Also, in some instances, altering the assumed angle of incidence by as little as 0.5° causes a greater change in \( \mu R_\perp \) than does altering the electron density profile by a substantial amount. Furthermore, it is clear that the choice of collision frequency profile is as significant as the choice of electron density profile,
Figure 5.1. Electron density profiles: Deeks (unless marked otherwise); Bain & Harrison (day); Thomas & Harrison (night).
Figure 5.2  Electron density profiles tested:
GS: summer; GW: winter; GN: night.
and in some instances more so.

In the GBR data the Bain and Harrison model (subsequently abbreviated to the B & H model) produces excellent agreement in both phase and amplitude with the measurements. But the Deeks summer profile for sunspot minimum conditions (subsequently abbreviated to the Deeks summer minimum profile) gives results nearly as close in the phase data and closer to the centre of the spread in the amplitude data. In addition, none of the variations of the B & H profile resulted in a substantial change in either the phase or the amplitude. Calculated values on the GBR-Leicester path are therefore insensitive to quite substantial changes in the gradient and concentration of the electron density profile. Using a different collision frequency profile results in a small change in amplitude and about 35° change of phase. The CIRA based profile yields larger values of $|R_L|$ and values of the argument in advance of the B & H collision frequency model in all instances tested, except at night when there is no difference.

Calculations using the Deeks March profiles give reasonable agreement with measurement in the amplitude data, but less so in the phase data. There is a difference of about 3dB between the Deeks March maximum and minimum profiles, but no significant difference in phase although changing the collision frequency profile produces a measurable change of phase.

The Deeks winter profile does not give results in close agreement with experiment. Some other winter profiles were therefore constructed and of these GW-10 and particularly GW-6 gave results which came reasonably close to the experimental values.
Figure 5.3  GBR - Leicester: noon amplitudes, calculated and measured values.
Figure 5.4  GBR-Leicester: night amplitudes, calculated and measured values.
In the GBR-Leicester test, the data and profiles gave results which
lay outside the expected and measured values. In the phase
profiles, the observations of the B & H profile gave results which were
not consistent with the measured values as expected. Using the Deeks
minimum profile. On this path, the values of phase changed
relatively with the expected angle of incidence, producing
larger changes in 
phase. The variations of the B & H profile
produced phase changes, and the collision frequency profile
results, as large as those caused by temperature
variations in the Deeks winter profile. The
Deeks winter profiles do not give the results along the
median line of the Deeks maximum profile, and the Deeks winter
profile profiles 3-5, 7 and 10. The values of only 1°
magnitude data, but only 76% of the
measured phase.
Although the earth's rotation has been neglected in the GBR
measurements, it is thought that it will not give rise to large
traits of the data. These traits are large because they are separated
by a factor of only 1° between
longitudes; a rotation of only 1° between
angles of incidence at the bow of the Deeks at the ground. Although
predicted phase changes yield.
The change of 1° is not
to materially alter the conclusions drawn here.

All the night-time profiles tested gave results in agreement
with the GBR magnitude measurements. Of the Deeks profiles only 2
the winter Deeks profile gave results in agreement with

Figure 5.5
GBR-Leicester: comparison of calculated and measured values of phase.
In the GBR night time data no profile gave results which lay outside the spread of observed amplitude values. In the phase data however only two profiles—GW-1 and the Deeks minimum—gave results in agreement with the observations.

On the GBZ path the B & H profile gave results which were not as close to the measured values as were those of the Deeks summer minimum profile. On this path the calculated phase changed rapidly with the assumed angle of incidence; a variation of 0.5° in the angle of incidence producing larger changes in phase and amplitude than did any of the variations of the B & H profile. Furthermore, changing the collision frequency profile produced changes in $|\Pi R_\perp|$ as large as any of those caused by the variations of the B & H electron density profile.

The Deeks March profiles do not give results close to the measured values, but the Deeks winter profile does. Of the other winter profiles GW-6, 7 and 10 give values close to the measured amplitude data, but only GW-6 and 10 give values close to the measured phase.

Although the earth's curvature has been neglected in the GBZ measurements it is thought that this will not give rise to large errors in the data since the transmitter and receiver are separated by only 2° of longitude, resulting in a difference of only 1° between the angle of incidence at the ionosphere and at the ground. Although the calculated phase changes rapidly with $i$ a change of 1° is not sufficient to materially alter the conclusions drawn here.

All the night time profiles tested gave results in agreement with the GBZ amplitude measurements. Of the Deeks profiles only one, the winter maximum profile, gave results in agreement with the
Figure 5.6  GBZ-Leicester: noon amplitude, comparison of calculated and measured values.
Figure 5.7. GBZ-Leicester: night amplitude, comparison of calculated and measured values.
Figure 5.8  GBZ-Leicester: comparison of calculated and measured values of phase.
phase measurements. Of the constructed profiles those closest in form to the Deeks winter maximum profile gave results close to the experiment values.

Calculations for the GYA to Leicester path indicate that the angle of incidence is approximately equal to the Brewster angle, so relatively small modifications to the electron density profile can change $|\mathbf{R}_\perp|_H$ by more than an order of magnitude. The B & H and the Deeks summer profiles yielded similar values for $|\mathbf{R}_\perp|_H$, as did several of the B & H profile variations. Due to the lack of observations at midsummer it is not possible to determine which of these profiles gives the most accurate results on the GYA path.

Of the two Deeks March profiles the minimum profile would appear to give values of $|\mathbf{R}_\perp|_H$ closer to the extrapolated measurements. The Deeks winter minimum profile and the GW - 6 and 10 profiles gave results closest to the measured amplitude at this time of year. At night the variations of the Thomas and Harrison profile came closest to the centre of the spread of measurements and of these GN-1 came closest.

On the GQP to Leicester path multiple hop propagation and earth curvature are expected to influence the measurements. Close agreement is thus not expected between the calculated values and the observations which are not extensive and have not taken these factors into account. Multiple hop propagation is expected to strengthen the received signal, and the results illustrated in Figure 5.11 are consistent with this: all the values of $|\mathbf{R}_\perp|_H$ calculated assuming single hop propagation are smaller than the observed values. The variations of the B & H profile do not result in large changes in $|\mathbf{R}_\perp|_H$, but calculations using the Deeks March minimum profile

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Figure 5.9  GVA - Leicester; noon amplitude, calculated and measured values.
Figure 5.10 GVA-Leicester: height amplitude, calculated and measured values.

Figure 5.11 G&V-1-Leicester: noon amplitude, calculated and measured values.
show a Brewster angle near the angle of incidence assumed at this
time of year. Of the winter electron density profiles GW-6 and 10
again give the values which are closest to the observed values.

Several main points emerge from this series of tests. First,
\[ \left| \begin{array}{c} R \parallel \end{array} \right| \] is not sensitive to major modifications of the electron
density profile; but the argument of \( \begin{array}{c} R \parallel \end{array} \) is rather more
sensitive to such changes. Second, the steep incidence path (where
\( i = 10^\circ \)) is not as sensitive to variations in the angle of incidence
as the paths with \( i = 40^\circ \) to \( 50^\circ \). Third, \[ \left| \begin{array}{c} R \perp \end{array} \right| \] is insensitive
to substantial changes in the night time electron density profile
regardless of the angle of incidence tested here, but the argument
of \( R \perp \) is sensitive to relatively small modifications to the profile.
Minor modifications to the Thomas and Harrison night time profile
did not produce results in agreement with experiment; only when
the step at 83-90km was moved from \( N(e) = 10^2 \text{cm}^{-3} \) to about \( N(e) =
3 \times 10^2 \text{cm}^{-3} \) did the phase measurements agree with experiment. The
Deeks night time profile closest in form to this (the winter minimum
profile) often gave phase results reasonably close to experiment.
Of the winter profiles tested GW-6 and 10 gave results closest to
the experiment values with GW-6 being the better of the two. Finally,
selection of the appropriate collision frequency profile is often
as important as the selection of the correct electron density profile
for the paths and frequencies tested. These results therefore
emphasise the limitations of using this type of long wave propagation
data to verify the accuracy or otherwise of model electron density
profiles, especially when the data are few.
5.5. Comparison with Earlier Measurements.

It remains now to compare the measured values of \( R_x \) with those determined by other workers. Belrose (1968) has collated many measurements and expressed them in the form illustrated in Figures 2.13 and 2.14, his \( f \cos i \) vs. \( \tan \phi \) reflection coefficient curves. A convenient way of comparing the present results with the others is to place the new values of \( |R_x| \) on Figure 2.14, the figure relating to sunspot maximum conditions. This has been done in Figure 5.12. No equinoctial values have been placed in Figure 5.12, because in the present project they have been found to be usually very close to the summer values. Also, the behaviour of the ionosphere at the spring and autumn equinoxes has been shown to be not identical.

In Figure 5.12 the spot values indicate estimated mean values and are taken from the 3-day running mean data: the bars indicate the limits within which the bulk of the 3-day mean values lie.

The night time values all lie quite close to Belrose's night time line, but the winter values are all rather lower than his winter day line. It is noted that the one spot measurement of the Puckeridge amplitude in February lies between Belrose's winter and equinoctial lines. Of the measured summer values only those of GBR and GQD lie close to Belrose's summer day line, the GBZ value lies well below it and the GYA bar lies above it. Only the estimated spread of the GYA summer values has been indicated here: the mean value is uncertain. The upper limit of the possible MSF amplitude was obtained by estimating the amplitude of the smallest signal on the Rugby to Leicester path which the instruments could detect: it is known that the MSF signal was smaller than this; it is not known by how much.
Figure 5.12 Belrose's (1968) $R_\perp$ is equivalent frequency curves for sunspot maximum conditions, with the Leicester measurements placed in position.
Reference to Figure 2.14, the figure relating to sunspot minimum conditions, indicates that in some instances the present values lie between Belrose’s sunspot maximum and sunspot minimum curves. This is not unexpected since, as indicated in the previous chapter, the 1967-70 sunspot maximum period was considerably less active than the previous sunspot maximum periods. What is interesting is that despite the doubt cast on the validity of Belrose's use of the \( f \cos i \) theorem to compare long wave measurements by the presence of Brewster angles (Jones and Wand, 1969) the present set of measurements is in broad agreement with Belrose's mean values.

The annual trend in the noon amplitude data is consistent with the trend exhibited in other data, see e.g. Figure 2.12: the trend in the night data is not so well defined as that illustrated in Figure 2.12.

The apparent height of reflection reported by Bracewell et al (1951) who summarised a series of long wave measurements, was 74, 79 and 92 km respectively, for midsummer and midwinter days, and night throughout the year. The present measurements are in close agreement with these values. It is interesting to note that the annual trend in the phase data is in agreement with that found by Belrose (1968; p IV-63) for 1954-55 (sunspot minimum years), and the retardation of the noon phase during the month of January is present in Belrose's data also. This phenomenon would thus appear to be a feature of the lower ionosphere in January and not an isolated event in 1970. It is obviously not linked with the solar zenith angle and so would probably be related to the major atmospheric changes which occur in the northern hemisphere in winter.
6.1. Introduction.

Two distinct types of ionospheric disturbance are associated with solar flare activity as may be seen from Figure 2.17. The first is produced by the enhancement in the flux of short wavelength ionizing radiations and results in a rapid increase in the electron density: it is known as a Sudden Ionospheric Disturbance (SID) and occurs only on the sunlit side of the earth. Some hours after an SID a further disturbance sometimes occurs. Energetic streams of protons and other charged particles ejected during the flare arrive at the Earth and are deviated by the Earth's magnetic field so that they impinge on the low ionosphere within limited areas round the geomagnetic poles. The resulting Polar Cap Disturbance (PCD) is long-lived and disturbances can occur both day and night down to magnetic invariant latitudes (A) of about 55° (Belrose et al., 1956). Both types of disturbance were observed in records taken at Leicester, and in this chapter the effects of both these types of disturbance on paths ranging from 27 km. to 8,600 km. will be presented. For the purposes of this chapter the paths monitored may conveniently be considered as falling into four main groups:

1. Local steep incidence paths;
2. Caribbean - UK paths (Ω/T, NBA);
3. USA - UK paths (NAA, NSS, NLK);
4. Norway - UK path (Ω/N);
The location of each of these paths is indicated in Figure 6.1. The first type of disturbance to be examined here will be the short lived anomalies resulting from the increased flux of short wavelength radiation.

6.2. Sudden Phase Anomalies.

On VLF waves reflected from the ionosphere the most clearly marked effect of an SID is a Sudden Phase Anomaly (SPA). The effect on the amplitude is less marked and although referred to as a Sudden Enhancement of Signal (SES) an enhancement is not always observed. The amplitude of the signal may in fact decrease.

The most sensitive and reliable circuit monitored during this project in respect of SPA's was the 12.0kHz O/Trinidad to Leicester path: it was therefore used as a flare patrol and was the path on which most data were accumulated. A card index of all SPA's observed on this path was compiled and the histograms in Figures 6.2 and 6.3 have been produced after a study of 140 SPA's observed during the 16 month period December 1967 to March 1969. From Figure 6.2 it can be seen that in 40% of these SPA's the initial phase advance lasted between 4 and 6 minutes (inclusive), in 72% it lasted between 4 and 10 minutes, and in 81% it lasted between 4 and 12 minutes. A few SPA's had an initial advance lasting over 20 minutes: these were usually large SPA's, but the initial advance of a few, smaller, SPA's was rather slow. The resulting SPA then had a 'V' shape.

Figure 6.3 represents the number distribution of the SPA's as a function of the magnitude of the phase advance. A more detailed examination of the data indicates that approximately 30%
Figure 6.1 Map showing location of distant transmitters and the transmission paths to Leicester.
Figure 6.2 Distribution of rise times of SPA's.

Figure 6.3 Distribution of sizes of SPA's
of the SPA's had magnitudes between .05 and .10λ, 25% were between .10 and .15λ, and 20% between .15 and .20λ. The smallest SPA's were masked by the background noise: of those large enough to emerge above the background noise, the frequency of occurrence falls off smoothly with increasing size until a small number of very large SPA's distorts the trend. The duration of the recovery phase was almost invariably much longer than the phase advance, often lasting up to several hours, but because the trace reverted to its normal level in the manner of an exponential curve and the recovery was often interrupted by the occurrence of another SPA or by the sunset phase retardation, the end of the event could not often be determined accurately.

In Figure 6.4 the magnitude of the phase advance has been related to the rise time according to an expression of the form

$$\text{rise time} = (\text{size of SPA})^m$$

The rather wide spread of the data points indicates that although there is a trend for larger SPA's to have longer rise times there are many exceptions to this. The broken line represents the best straight line fit to the data: its gradient $m$ is approximately 0.5 indicating that the rise time tends to increase as the square root of the size of the SPA.

The relationship between the size of the SPA and the peak intensity of the X-radiation in three different bands is illustrated in Figure 6.5. The X-ray data were taken from SOLRAD 9 X-ray Memory Data published in the ESSA Bulletin. The events occurring in two separate months have been plotted separately. The arrows indicate minimum values, signifying that the X-ray detector saturated or stopped registering at this value: the peak intensity
Figure 6.4 Distribution of time of phase advance with size of SPA
was greater than this by an unknown amount. In both months there is a clear indication that the size of the SPA increases as the peak intensity increases, but the size of the SPA correlates more closely with the shorter wavelengths, particularly in March when the intensity in the $3 - 20 \, \text{Å}$ band does not rise much above the background level for the smaller SPA's. A comparison of the two months suggests that the gradients in the $0 - 3$ and $1 - 8 \, \text{Å}$ bands respectively are not the same in these two months. To produce an SPA of say $0.20 \, \text{Å}$ in November appears to require a rather greater peak intensity in these two bands than it does in March, although the difference is not great.

In studying the records to compile the card index it was noted that the effects of a solar flare on the different paths as reflected in the change in the received signal were not the same. The following observations were made:

1. appreciable changes in the $\Omega$/Trinidad amplitude records were rarely observed at the time of SPA's;
2. amplitude changes in the NLK records during an SPA were small;
3. the NBA, NAA, and NSS records all exhibited increases in the field strength during SPA's, the increase in the NBA records usually being quite marked;
4. SPA effects were often quite small or sometimes absent on the NSS path;
5. the response of the NAA path was similar to that of the NSS path;
6. in the NSS and NAA records, after the peak of the SPA had passed, the phase occasionally retarded beyond its
pre-flare level before returning to the pre-flare level;

7. the response of the Ω/Norway signal was not consistent:
on different occasions the signal was observed to exhibit
(a) the expected features i.e. SPA, SES, (b) no observable
effects, or (c) an initial phase retardation followed by
a phase advance, then a return to the pre-flare level;

8. the Ω/Trinidad phase exhibited a slower recovery to its
pre-flare level than the phase of the short path signals
on occasions;

9. the short path records show a decrease in amplitude
during SPA's;

10. the onset of an SPA was not always simultaneous (to our
timing accuracy) on all paths being monitored;

Examples of these observations are illustrated in Figures
6.6 to 6.10. Figure 6.6 illustrates the response of the phase and amplitude on five paths to a flare starting at 17.05
on 12 April 1970. The amplitude of NAA, Ω/Norway, and NBA increased but the amplitudes of Ω/Trinidad and OMA (50kHz) were unaffected.
A small precursor caused NBA to increase and Ω/Norway to decrease, but did not affect NAA. The precursor caused the phase of Ω/Trinidad and NBA to advance and Ω/Norway to retard but did not affect NAA.
The main burst caused the phase on all paths to advance. OMA was not monitored for long enough to establish the pattern of its response; on this occasion the phase suffered an appreciable retardation, but on other occasions the change was observed to be small or absent.
It should be noted that the scale used for Ω/Trinidad phase anomalies is not the same as that used with the others. The Ω/Trinidad records were taken using a different type of receiver which indicated phase
Figure 6.6 Phase and amplitude anomalies on five long paths

12 April 1970
Figure 6.7. Comparison of SPA's on three long paths.
Figure 6.8 Phase and amplitude anomalies on three long paths; 15 May 1970.
Figure 6.9. SPA's on GBR (top, phase and amplitude) and GBZ (bottom, phase and amplitude)
Figure 6.10  Comparisons of SPA's on various paths.
changes in different units to the other receivers. The short path scales are also different.

Figures 6.7 and 6.8 emphasise the fact that of the long path transmissions monitored the $\Omega$/Trinidad phase was the most sensitive indicator of flare activity although the response of its amplitude was not consistent. The NBA transmissions yielded the largest amplitude changes. On May 26th the $\Omega$/Norway records exhibited the classic response of a VLF transmission to a solar flare - an SPA and an SES - but only during the second burst; no disturbance was recorded during the first burst. On May 15th despite the presence of large anomalies on the other paths only two small anomalies were observed on the $\Omega$/Norway path. The SPA's in the GBR and GBZ records of this day are reproduced in Figures 6.9. The amplitude traces are also shown here for the sake of completeness but when the signal amplitudes decreased during these SPA's from their already low levels the receivers were unable to record the changes faithfully. On such occasions the output from the amplitude channels fell to zero. Other examples of amplitude changes during SPA's on steep incidence circuits will be given later.

From an inspection of the long path disturbances illustrated in these figures it appears as if the $\Omega$/Norway records exhibit an SPA only when the SPA in the $\Omega$/Trinidad records is about 18μsec or greater, but the precise threshold has not been definitely established. For example on May 26th (Figure 6.7) an SPA of 20μsec in the Trinidad records coincided with an SPA of 4μsec in the Norway records, and on April 10 the SPA's in the Trinidad and Norway records were 27μsec and 4μsec respectively. On May 15th however (Figure 6.8) the Norway records remained undisturbed when the Trinidad records
showed SPA's of 13, 15, 7 and 18 μsec, but SPA's of 22 and 18 μsec in the Trinidad records coincided with small disturbances of 3 μsec and 1 μsec respectively in the Norway records. No examples were found of an SPA substantially smaller than 18 μsecs in the Trinidad records coinciding with an SPA in the Norway records, nor any examples of SPA's greater than this threshold on the Trinidad path which did not coincide with an SPA on the Norway path. The apparent inconsistency in the response of the Q/Norway to Leicester path can therefore be attributed to a lack of sensitivity to small flares. The Norway path is at a much higher latitude than the Trinidad path (the mid points of these paths lie at approximately 60° North and 35° North, respectively) and it would always suffer from having a greater solar zenith angle. Hence it would always receive a weaker flux of radiation per unit length than would the Trinidad path. It is also much shorter, being 1,800 km compared to 7,200 km for the Trinidad path.

The response of the phase on the other long paths as set out earlier can now be seen to be consistent with this explanation. The NSS path is in effect the NAA path extended, and as these two paths lie, both in latitude and in length, between the Trinidad and the Norway paths they would be expected to exhibit smaller phase anomalies than the Trinidad path but larger anomalies than the Norway path. This was in fact what was observed. Also, no SPA's appeared in the NAA or NSS records when the SPA in the Trinidad records was very small. An example of this is illustrated in Figure 6.10.

The NBA to Leicester path extends over substantially the same latitudes as the Trinidad to Leicester path and these two
paths would therefore be expected to respond in a similar manner. The NBA records did in fact always exhibit a phase anomaly when one was observed in the Trinidad records.

To account for the anomalous behaviour of the N/Norway path and the NSS and NAA paths in exhibiting the oscillating type of phase disturbance illustrated in Figure 6.10 one would undoubtedly have to take into account the response of higher order modes on these paths as was done by Burgess and Jones (1967) in explaining a sudden phase retardation observed on the Rugby-Rome path.

The response of each of the steep incidence paths to solar flare activity was similar, i.e. the phase advanced and the amplitude of the signal decreased. There was often a close similarity in the disturbances observed in the different records. In Figure 6.10 further examples are given to illustrate these observations. On January 14th, 1969 the disturbances in the GYA and GBR amplitudes can be seen to be very similar. On June 6th 1970 despite the GBR amplitude channel dropping to zero at times the close similarity between both the phase and amplitude of the GBR and GBZ transmissions is evident. Also evident from this example is the fact that the minimum in the amplitude trace during the disturbance does not always coincide with the maximum phase advance. It was often observed to be delayed, particularly in the GBZ records. A clear example of this effect on July 27th, 1970 is also illustrated in Figure 6.10. In Figure 6.9 also it can be seen that the times when the amplitude drops to zero do not coincide with the times of maximum phase advance. Modeling electron density profiles as described in Chapter 5 indicated that appreciable changes in the phase accompanied by small changes in the amplitude of $R_\perp$ could
be obtained by suitable adjustment of the profile at selected heights. Such changes in the ionosphere caused by different rates of decay in the X-radiation flux at different wavelengths causing recombination at different heights to proceed at different rates could probably account for the lack of similarity in phase and amplitude changes.

Another interesting observation noted earlier was that during some disturbances the phase of the short paths transmissions recovered much more quickly than the phase of the Trinidad signal. Several examples of this occurred in early March 1970 and these are illustrated in Figure 6.19. The dissimilarity between the response of these paths will be referred to later.

After noting the general characteristics of these short period disturbances on each of the different paths several SPA's were selected for closer study. A number of these coincided with sharp spike-like bursts of solar X-radiation in the three bands 0-3, 1-8, and 8-20 Å. These spike-like bursts were taken as approximating, in this instance, to square-waveform bursts so that the response of the ionosphere following the "switch-off" of the ionizing radiation could be observed.

In Figure 6.11 the phase of the O/Trinidad signal during three SPA's has been redrawn alongside the X-ray flux which accompanied each one. On each occasion the flux returns to its pre-flare value much sooner than the phase does. Now after the peak of an SPA the phase is often observed to return to its pre-flare value in a manner resembling an exponential decay. If we therefore assume that a relationship of the form

\[ \phi = k e^{-\gamma t} \]  

(6.1)
Figure 6.11. X-ray flux and accompanying phase anomalies in the Ω/Trinidad to Leicester transmissions.
holds during the decay period and we redraw the SPA on semi-
logarithmic graph paper, as has been done in Figure 6.12, then the
slope during the decay period will be constant if this relationship
holds and the time constant $\tau$ may be determined by inspection of
the gradient. In Figure 6.12 it is evident that the excess flux
in the two January 17th events decays faster than the flux in the
January 18th event. The phase, however, decays at about the same
rate on each occasion, indicating that during these three events
the phase of the Trinidad signal returned to its pre-flare value
at a rate governed by the rate at which the excess ionization is
removed by ionospheric processes and not solely by the rate at
which the ionizing radiation is reduced. In the second January
17th event and in the January 18th event the ionosphere clearly
does not follow the rate of decay of the flux closely since the
structure evident in the flux change is not reproduced in the phase
changes. The values of time constant $\tau$ for the three bursts are,
in chronological order, 0.018, 0.020 and 0.017 min.$^{-1}$ The
corresponding values of $\tau$ for the decay of the main burst of the
X-radiation are approximately 0.15, 0.50, and 0.15 min.$^{-1}$
respectively, an order of magnitude or more greater. It is noted
that the magnitude of the time constants of the SPA decay is
comparable to those reported by Albee and Bates (1965) who employed
a curve fitting technique to determine the time constants.

Other instances of SPA's occurring simultaneously with sharp
burst of X-radiation were studied and it was noted that SPA's
occurring simultaneously on different paths did not always decay at
the same rate. In Figure 6.13 are reproduced two examples of SPA's
occurring simultaneously on three long paths in winter: it should be
noted that on both occasions NAA decays fastest, \( \Omega/T \) next, and NBA is the slowest. In Figure 6.14 is shown an example of SPA's occurring simultaneously on three long paths in summer. On this occasion all three decayed at about the same rate. Inspection of the X-ray data (Figure 6.15) indicates that the X-ray flux decayed more slowly during this event that in the earlier examples. Moreover the rate of decay decreased with time.

The recombination of the flare enhanced radiation is known to depend on several factors as shown below:

\[
\frac{dN}{dt} = q - \alpha_{\text{eff.}} N_0^2 \tag{6.2}
\]

where \( N_0 \) indicates the pre-flare electron density, and \( \alpha_{\text{eff.}} \) is the effective recombination coefficient. For flare conditions

\[
\frac{d}{dt}(N_o + \Delta N) = (q_o + \Delta q) - \alpha_{\text{eff.}} (N_o + \Delta N)^2 \tag{6.3}
\]

\[
\therefore \frac{d}{dt}(\Delta N) = \Delta q - \alpha_{\text{eff.}} (2\Delta N N_o) \tag{6.4}
\]

Until the excess X-ray flux has decreased to a negligible level the production term \( \Delta q \) will continue to affect the rate of change of \( N \), and if the flux decreases slowly then \( \Delta q \), and hence the excess ionization, will also decrease slowly. The similarity between the recovery rates exhibited by the three paths in Figure 6.14 is thus consistent with a slower rate of recovery of the flux.

Earlier in this section it was reported that in winter the higher latitude long paths responded to solar flares only when the SPA in the \( \Omega/\text{Trinidad} \) records was greater than a certain threshold value. This indicates that in the X-ray flux there is a threshold value above which the flux is sufficient to cause a phase anomaly.
on such paths, but below which it is not sufficient to cause an SPA. In Chapter 2 it was noted that several estimates of such a threshold have in fact been given in the literature. From the observations reported here the threshold would appear not to be constant but to change with the solar zenith angle, being higher in winter on paths in the Northern Hemisphere. The raising of this threshold in winter means that, in effect, only the higher levels of the flux during an X-ray burst will effect the phase of the signal on such paths in winter. It will be recalled that a close examination of Figure 6.5 suggested that a similar flux in November and March would produce SPA's of different magnitudes on the Trinidad to Leicester path. This observation is consistent with the threshold being higher in November than in March. Although the Ω/Trinidad transmitter is situated at an equatorial latitude the solar zenith angle of the mid-point of the path changes appreciably between summer and winter.

It was also reported earlier in this section that following certain solar flares, the phase of the short path transmissions recover more quickly than the phase of the Ω/Trinidad transmissions. If all these observations are combined a possible explanation of the faster recovery on the short paths and the different rates of recovery of the long paths in winter emerges.

Consider the different rates of recovery of the phase of GEZ and Ω/T following the flare at 9.40h on 1st March 1970 (Figure 6.19). The higher levels of the X-ray flux at this time (Figure 6.15) exhibit a sharp spike-like form, but after the flux has fallen from its peak value there is a marked change in the rate of decay: it becomes much slower. If, as we have seen above, the higher latitude paths
Figure 6.12 Phase & flux changes plotted logarithmically to obtain time constants. (Arbitrarily moved for clarity here)
Figure 6.13 Two examples of dissimilar decay rates in winter.

Figure 6.14 An example of similar decay rates in summer.
Figure 6.15. Solrad 9 X-ray data for 1 March 1970 (top) and 3 July 1969 (bottom): (ESSA Bulletin)
(in this instance the GBZ path) respond to only the higher levels of the flux which, in this instance, decay very rapidly, then these paths will be able to recover more quickly than the Trinidad path whose recovery will be delayed by the continuing, weaker, flux of X-radiation. If this explanation is valid then SPA's exhibiting different rates of recovery on the steep incidence paths and the Trinidad path would not be expected to occur often in summer because the threshold would be lower then and the response of the higher latitude paths would be expected to be closer to that of the Ω/Trinidad path. In fact no such occurrences have been observed near midsummer: the occasions when different rates of recovery have been observed tended to be in the winter or in the early part of the year. Although the study of the SPA's observed in the records taken at Leicester during this project has not been exhaustive, no events which contradict this proposed explanation have been observed.

Other factors may of course also play a part in causing the records to exhibit different phase recovery rates on different paths. Examination of equation 6.4 shows that the loss term \( \alpha (2 \Delta N N_0) \) depends on the pre-flare electron density \( N_0 \) and the effective increase in electron density \( \Delta N \) as well as the effective recombination coefficient. The 12kHz Ω/Trinidad waves are reflected from lower levels than the steep incidence 16 and 19kHz waves and the difference between the ambient electron densities at these heights might be expected to cause recombination to proceed more slowly at the reflection level of the 12kHz waves. In addition, if the increase in electron density \( \Delta N \) were greater at greater heights this also would be expected to cause recombination at the steep incidence
reflection levels to proceed more rapidly than at the 12kHz reflection level. It is interesting to note that such an event was observed, by coincidence, on the same day eight years earlier than the event considered here (Belrose, 1968; page IV,81). The increase $\Delta N$ in the region 75 to 78 km was about twice the increase in the region 65 to 68 km. The third element in the loss term is $\alpha_{\text{eff}}$, the effective recombination coefficient: it is unlikely that this would decrease with decreasing height.

To conclude then, the differences in the response of the different paths would appear to be explained by a combination of several factors, viz. the dependence of the threshold on the solar zenith angle $\chi$, the unusual decay in the X-radiation flux on certain occasions, the different initial electron density $N_0$ at different heights, and possibly a different degree of enhancement in the electron density $\Delta N$ at different heights. The mix of these factors would probably change from one occasion to the next.
6.3. **Polar Cap Disturbances.**

The three long path transmissions originally selected for monitoring at Leicester (NLK, NSS, and Ω/T) were chosen because these transmission paths covered a wide range of geomagnetic latitudes. Reference to Figure 6.1 shows that one (NLK) passes through the polar cap region, one (NSS) skirts it, and one (Ω/Trinidad) does not approach close to it at any point. Observations on these and other paths during the project have indicated that the response of the Trinidad path is anomalous during Polar Cap Disturbances and that short and long path transmissions respond in different ways.

Two Polar Cap Disturbances have been selected for presentation here: one occurred in October-November, 1968, and the other occurred in March, 1970. During the first event all three long paths were monitored and in addition some data were obtained on the NAA path. Two short paths, GBR and GYA were also monitored for part of the time.

On the 26th October and 1st November, 1968, Sudden Commencement geomagnetic storms occurred; prior to each Sudden Commencement SPA's were observed in the records. The dates and approximate times of the SPA's are tabulated in Table 6.1. Several of these SPA's were quite large; the largest have been underlined.

The diurnal phase variations of the three long path transmissions NLK, NSS and Ω/T for the period October 25th - November 8th are reproduced in Figure 6.16, and those of NAA and the short paths GBR and GYA in Figure 6.17. The level of the solar proton flux during this time is reproduced in Figure 6.18.
TABLE 6.1. Dates and Times of SPA's

<table>
<thead>
<tr>
<th>Date</th>
<th>Times</th>
</tr>
</thead>
<tbody>
<tr>
<td>October 21st</td>
<td>11.20; 13.10; 14.20; 17.35;</td>
</tr>
<tr>
<td>22nd</td>
<td>13.30; 17.00;</td>
</tr>
<tr>
<td>23rd</td>
<td>13.10; 16.00;</td>
</tr>
<tr>
<td>25th</td>
<td>13.00</td>
</tr>
<tr>
<td>26th (Sudden Commencement)</td>
<td></td>
</tr>
<tr>
<td>October 28th</td>
<td>13.50;</td>
</tr>
<tr>
<td>29th</td>
<td>8.55; 12.10; 14.05; 18.50;</td>
</tr>
<tr>
<td>30th</td>
<td>12.30; 13.30;</td>
</tr>
<tr>
<td>November 1st (Sudden Commencement)</td>
<td></td>
</tr>
<tr>
<td>2nd</td>
<td>9.50; 15.20;</td>
</tr>
<tr>
<td>3rd</td>
<td>12.35;</td>
</tr>
<tr>
<td>5th</td>
<td>13.40; 16.00;</td>
</tr>
</tbody>
</table>

The first feature of interest is the diminution of the diurnal phase variations of the long path transmissions and the lowering of the NSS day time phase levels following the first Sudden Commencement on October 26th. On the night of the 28th (i.e. the 28th/29th) the Trinidad phase retards to a higher level than usual. On the following night it is normal again but there is a downward shift in the NSS phase and to a lesser extent in the NAA phase; this feature is not well defined in the NLK records. On the night of the 30th all three signals are slightly higher than on the previous night, and on the following two nights, the sixth and seventh after the Sudden Commencement, all three are lower, NLK and NSS considerably so, the lowering of these two being
Figure 6.17 Phase records of NAA (17.8 kHz), GBR (16.0 kHz), and GYA (45 kHz); 25 October - 3 November, 1968.
Figure 6.18. Solar proton flux in 3 energy bands 22 October - 22 November 1968.
(Reproduced from the ESSA Bulletin).
accompanied by extensive disruption of the night-time phase.
The second Sudden Commencement occurred on the 1st November, but
the disturbances on the NLK and NSS paths on the night of the
1st can probably be attributed to (a) the high level of the solar
proton flux and (b) the so-called "storm after-effects" following
the earlier Sudden Commencement. This is consistent with the
depressed NLK phase level on the nights of the 5th and 6th November,
the fifth and sixth full nights after the second Sudden Commencement,
following the recovery of the NLK phase between the 2nd and 4th
November. The after-effects in the NLK phase records thus occur
on the sixth and seventh nights following the first Sudden
Commencement, but on the fifth and sixth nights following the
second Sudden Commencement. The NSS records show a depression
of the night phase level on the fourth, sixth and seventh nights
following the first Sudden Commencement, but no delayed after­
effects following the second Sudden Commencement. The disturbances
in the NSS records would therefore appear to be the result of the
enhanced solar flux at these times. The Trinidad phase does
however change after the second Sudden Commencement: it is higher
on the night of November 2nd than on the two previous nights. It
is therefore higher than expected following each Sudden Commencement,
on the third night after the first Sudden Commencement and on the
second night after the second Sudden Commencement. Both the Trinidad
and the NLK signals therefore exhibit an apparent difference of one
day in their respective responses after the first and second Sudden
Commencements; they respond one day sooner after the second Sudden
Commencement than after the first Sudden Commencement. This
apparent difference can probably be attributed to the different times
of the day at which the first and second Sudden Commencements occurred, the first Sudden Commencement occurring much later in the day than the second one.

The level of the daytime phase was also depressed in the NLK and NSS records, the depression in both being greatest on October 31st and coinciding with the first major peak in the solar proton flux. Observations on NLK became difficult at times due to a weakening of the signal but the phase appeared to be very depressed on the 29th also. This depression coincided with the first small peak in the proton flux. The faintness of the signal at times precluded an accurate estimate of the extent of the depression of the phase on November 1st, a time when the NSS phase was very depressed. A further interesting feature noted in Figure 6.16 is the close similarity between the movement of the NLK and the NSS phase levels from the afternoon of the 30th until about midnight of the 2nd, suggesting close control of both these paths by the incident proton flux which was at its highest levels during this period. This feature is not present in the Trinidad records.

On the short paths the phase levels of both GBR and GYA were depressed during the night of the 30th, a night when the long paths are less depressed than on the nights preceding and following this one. The GYA phase became very disturbed on the nights of the 1st and 2nd November with fast fluctuations of the phase being evident throughout both nights although the mean levels of the phase were not depressed. These disturbances in the LF short path thus coincided with the most disturbed nights on the northern long paths. On the night of the 6th November the storm after-effects became evident on both short paths with depression of the phase for two periods during
the night, each lasting 2 to 3 hours. These after-effects thus coincided with the after-effects on the NLK path. The phase of both short path transmissions appeared to be normal on the night of the 7th, but on the 8th and 9th, and to a lesser extent on GYA alone until the 12th, there were periods of depression of the phase in the early evening, delaying the evening phase retardation in the manner familiar on short path VLF recordings after a geomagnetic storm. There was a small increase in the proton flux during the night of the 11th, but the occurrence of the GYA disturbances on several nights in succession indicates that they were the after-effects of the earlier, larger, disturbances. The diurnal phase records of these days are not reproduced here. Ground wave interference occurred during this period and distorted the diurnal phase patterns, but as the signal increased in the evening the interference was less obtrusive and the above noted features were clearly discernible.

One may therefore conclude that during this solar proton event the response of the short paths differed at times from the response of the two northern long paths, which themselves did not respond in an identical manner during the after-effects of the storm. The Trinidad path was anomalous in several respects; in general it did not respond at all like the other long paths, and on two occasions, the second full night after each Sudden Commencement, its response was contrary to that expected with the phase being elevated rather than depressed. The two main peaks in the solar proton flux coincided with the most severe disturbances on the northern paths, on one occasion during the night and on the other occasion during the day. The third large peak did not disturb the
records to the same extent as the two earlier peaks. These three peaks were the same size in the $E > 60$ MeV channel, but the third peak was smaller in the other two channels. It would therefore appear that it is the large flux of lower energy protons rather than the smaller flux of higher energy protons which control the disturbances on the northern paths.

The second solar proton event to be considered occurred during the first half of March 1970. There were two Sudden Commencement geomagnetic storms during this period also and a large number of SPA's were observed in the records of each path. The dates and approximate times of these are given in Table 6.2; the largest have again been underlined.

<table>
<thead>
<tr>
<th>TABLE 6.2. Dates and Times of SPA's</th>
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<tbody>
<tr>
<td>February 28th</td>
</tr>
<tr>
<td>March 1st</td>
</tr>
<tr>
<td>2nd</td>
</tr>
<tr>
<td>4th</td>
</tr>
<tr>
<td>5th (Sudden Commencement)</td>
</tr>
<tr>
<td>6th</td>
</tr>
<tr>
<td>7th</td>
</tr>
<tr>
<td>8th (Sudden Commencement)</td>
</tr>
<tr>
<td>9th</td>
</tr>
</tbody>
</table>

Tracings of three of these days, March 1st, 5th, and 6th are reproduced in Figure 6.19. On March 1st four large SPA's or groups of SPA's occurred in both the long and the short path records. The first and
Figure 6.19. SPA's on 1, 5 and 6 March, 1970.
last on this day were particularly interesting because of the markedly different rates of recovery on the short and long paths referred to earlier. The large event starting at 11.05 U.T. exhibits a structure which corresponds to the structure in the X-radiation flux.

On March 5th the long and short paths again exhibit different recovery rates, the second SPA in the Trinidad record does not recover until about 18.40; SPA's lasting this length of time (~ 140 mins) were not common in the records. The long lasting SPA starting at midday on the 6th is also a rather rare type with a slow advance and a slower than usual recovery, the duration of the disturbance being about four hours on both the long and the short paths. Inspection of the X-ray data indicates a high flux of X-radiation during these extended SPA's.

Marked disruption of the regular day to night phase variation occurred during 7th-18th March, and smaller, less well defined anomalies were present in the signal amplitude. Changes in the phase fluctuation rates were also observed at night during this period. Hourly values of the phase of the various VLF signals are presented in Figure 6.20 and 6.21; other relevant geophysical data are presented in Figure 6.22. The night time phase recordings for 4th to 14th March are reproduced in Figures 6.23 to 6.27 in order to illustrate the changes in the phase fluctuation rate. Figure 6.28 illustrates in a schematic manner the relationships between the various disturbances which occurred during the event. In view of the marked differences in the anomalies observed on the long, intermediate, and short propagation paths these are described separately below.
Figure 6.21. Phase recordings of OBR (16.0kHz) and GBZ (19.6kHz); 1-18 March, 1970.
Figure 6.22 (a) Solar proton flux; 4-16 March, 1970 (reproduced from the ESSA Bulletin)
Figure 6.22 (b) $A_p$, $K_p$, and Neutron Monitor levels:

4 - 16 March 1970 (reproduced from the ESSA Bulletin)
Short Paths:

The phases of the GBR and GBZ signals behaved in a broadly similar manner during the March event and the following comments apply equally to the observations on both frequencies. No disturbances were detected before the night of 4th March, indicating that the high level of $K_p$ and the small but significant increase above background level of the 5 - 21 MeV solar proton flux had little effect on these paths. Following the Sudden Commencement at 08.05 U.T. on the 5th, large fluctuations were present during the following night. The night-time disturbance is associated with the initial response of the neutron monitor and also the rise in Ap. The phase was abnormal during the next day and for most of the following night. On the 7th the phase returned to normal but the phase disturbance resumed on the night of the 8th, possibly as a result of the Sudden Commencement at 14.15 U.T. on this day although it is probable that the storm after-effect following the first Sudden Commencement contributes to this disruption. The night-time phase levels then gradually recover until the evening of the 12th, when there occurred a small but significant depression of the phase for some hours. This disturbance was less intense than those of the 5th and 9th and was not preceded by a Sudden Commencement. It reappeared on the 13th and 15th. The depression of the night-time phase diminished gradually and the normal pattern had reappeared by about the night of the 18th.

The very large increases in the solar proton flux at 17.00 U.T. on the 6th did not apparently produce marked changes in the phase of the GBR and GBZ signals, although any effects could have been masked by disturbances resulting from the first Sudden Commencement.
The small decrease in phase on the evenings of March 12th, 13th, and 15th, the fifth, sixth, and eighth nights after the second Sudden Commencement, correspond to the storm after-effects. As was the case during the disturbances of October/November, 1968, the occurrence of a second Sudden Commencement a few days after the first one makes it difficult to distinguish between the effects occasioned by each one. However it is noted that the nights when the phase was depressed following the second Sudden Commencement in March 1970 correspond to the fourth and subsequent nights after the first Sudden Commencement.

Intermediate range path:

The 1800 km Ø/Norway to Leicester path is of particular interest since the transmitter is situated at an auroral latitude. During undisturbed conditions the diurnal phase change is relatively small, amounting to only about 1/4 wavelength. During the Polar Cap Disturbance of early March, the night-time phase pattern was severely disrupted but little change occurred during day-time. Although no recordings were available prior to 5th March, it is evident from Figure 6.25 that some departure from the normal variation occurred during the night of the 5th. The magnitude of the phase irregularities increased on subsequent nights, becoming greatest on the night of the 8th. There followed a fairly rapid recovery, the disturbances having disappeared by the night of March 10th. The greatest phase disturbances on this propagation path appear to occur at the time of the greatest enhancement of the solar proton flux. The Sudden Commencement of 5th March does not seem to be followed by any clear disturbances in the night time phase pattern which can
be attributed to storm after-effects.

Long paths:

Phase disturbances were observed on both the NAA and the G/Trinidad transmissions during early March. Phase disturbances were first observed on both the NAA and the Trinidad transmissions during the night of 6th March, i.e. 24 hours later than on the steep incidence circuits, and these phase changes on the night of the 6th probably resulted from the marked increase in the solar proton flux observed on the preceding day. The intermediate and long propagation paths all show disturbed conditions during the night of 7th March in contrast to the normal undisturbed phase levels recorded on the steep incidence transmissions. On the 6th and 7th March, the second and third nights after the first Sudden Commencement, the day to night phase changes of the Trinidad signals are larger than normal resulting in greater retardation of the night-time phase.

Following the second Sudden Commencement the night phase levels of both NAA and Trinidad were depressed, and for several days the day-time phase levels were depressed also. Bearing this in mind it can be seen that the day to night phase retardation of the Trinidad signal on the 10th and 11th were greater than on the previous two days. These increases occurred on the third and fourth nights after the second Sudden Commencement. On the fifth and subsequent nights the phase change is rather smaller again. The diurnal pattern in the Trinidad phase appears to have returned to normal by the 16th, but the NAA phase does not return to normal until about the 18th. Although the response of the phase is
complicated by the spacing of the two Sudden Commencements
close inspection shows that the NAA phase was depressed on the
fourth, sixth, and seventh nights after the first S.C. and
on the third, fourth and sixth nights following the second S.C.
Unfortunately the sixth and seventh nights of the first group
coincide with the third and fourth nights of the second group so
the after-effects of the two Sudden Commencements cannot be
separated here one from the other.

Night-time phase fluctuation rates:

An interesting feature of the VLF disturbances was the marked
changes in the rate of fluctuation of the phase during night-time,
this being particularly noticeable on the long propagation paths.
Rapid phase changes occurred in the GBR transmissions during the
night of 4th March, and there was some indication of phase
fluctuations in both the GBR and GBZ records for the following
night. Further disturbances occurred on both short paths on the nights
of the 8th and 9th, and in the GBR records these were of greater
magnitude than those of the 4th March.

The changes in night-time phase oscillation rates are most
easily seen on the N/Norway and NAA recordings (Figures 6.25 and
6.26). Small fluctuations in the phase of the N/Norway signal were
present during the night of the 5th March. The amplitude of the
irregularities increased on the night of the 6th March and the
following night a large "bay-like" feature is present on both the
N/Norway and the NAA phase recordings from about 02.00 - 05.00 U.T.
This feature persists during the following night on both frequencies
and can still be detected on the NAA records until the night of the
Figure 6.25. Fluctuations in the night time phase of the \( \Omega \)/Norway transmissions; March, 1970.
Figure 6.27 Fluctuations in the night time phase of the Ω/Trinidad transmissions; March, 1970.
10th March. The night of the 7th is also noteworthy due to the marked increase in the magnitude of the phase fluctuations in the η/Norway signal. The fluctuations continued on both frequencies until the night of the 9th March and to a lesser extent until the 11th in the NAA records. Long-period disturbances of small amplitude in the nocturnal phase pattern occurred again on the 13th and 14th March.

The phase fluctuations in the Trinidad transmissions were not so marked as in the NAA and η/Norway transmissions. Some short period fluctuations were present throughout the event but the difference between these nights and other undisturbed nights was not as great as on the other paths. The short period fluctuations did tend to occur, however, more on the nights of the 8th to the 8th than on other nights.

The fast fluctuation rates on the long paths were thus observed during the large influx of solar cosmic ray particles and so appear to be associated with the particle precipitation events. It is unlikely that these particles will penetrate to any great extent to the lowest ionospheric levels at the geomagnetic latitudes of the Trinidad-Leicester circuit, which would account for the limited degree to which the fast phase fluctuations occurred in phase recordings of this and the short path transmissions.

Several broad conclusions can now be drawn from this examination of the records taken during the P.C.D's of October/November, 1968, and March, 1970. First, both these geophysical disturbances produced anomalies in the phase of VLF transmissions monitored over a wide range of propagation paths. Second, in general the normal day-to-night phase variation was disrupted and changes also occurred in
the phase fluctuation rates at night. Third, the response of the short and long propagation circuits to the disturbances differed, especially during the initial period. Furthermore, the conclusions which were drawn following the examination of the first P.C.D. are confirmed by the examination of the second P.C.D. In particular, the anomalous response of the Trinidad path during the first event when it exhibited an elevation of the night time phase level following each Sudden Commencement was repeated during the second event. These observations therefore illuminate one more aspect of the anomalous behaviour of the 12.0 kHz transmissions on the Trinidad to Leicester circuit. They also indicate that these events had a marked influence on LF and VLF propagation down to magnetic latitudes of $A = 50^\circ$ (the magnetic latitude of the receiver and the short paths).
Figure 6.28. Schematic diagram of the disturbance during the PCD of early March, 1970.
CHAPTER 7

THE TE/TM MODE EXPERIMENT

7.1. Introduction.

Long distance VLF propagation is usually interpreted in terms of waveguide models in which one or more predominant modes together with others of lesser intensity propagate in a waveguide, the walls of which are formed by the surface of the Earth and the lower edge of the ionosphere (see, for example, Budden, 1961; or Wait, 1962). Several models, which differ in their detail, have been advanced to account for the observed characteristics of long distance VLF propagation. Three of these models have already been mentioned in Chapter 2.

Depending on the convention used the modes associated with these models are identified simply by numbering them 1 and 2, or else as the first and second TM modes. The latter convention will be the one adopted here. In that convention three main types of mode are identified, viz. TM or Transverse Magnetic, TE or Transverse Electric, and TEM - Transverse Electric and Magnetic. In their pure forms these modes can be distinguished one from the other by reference to the directions of their electric and magnetic fields. Thus

- a TEM mode has no axial field components, i.e. it has none in the direction of propagation;
- a TE mode has no electric field in the direction of propagation;
- a TM mode has no magnetic field in the direction of propagation.

The terms Quasi-TM and Quasi-TE are also used, for modes not completely one or the other of these types.

Normally most of the energy launched by a vertical VLF transmitting aerial will propagate in the form of TM modes of first and higher orders. Since the higher order modes generally have lower excitation factors and higher attenuation rates, at distances of several thousand kilometres from the transmitter the lowest order TM mode will usually predominate. That the higher order modes can also carry significant amounts of energy in certain circumstances is demonstrated by the interference effects referred to earlier chapters.

Calculations by, for example, Pappert (1968) indicate that TE modes will generally have smaller excitation factors and higher attenuation rates than TM modes in the model ionospheres used in his calculations. This is borne out by experience, and consequently loop aerials set to receive long distance VLF signals are set to respond to TM modes, i.e. the plane of the loop is in the plane of propagation.

Now the experimental VLF work at Leicester can be thought of as comprising two branches, viz. (i) using loop aerials set in the plane of propagation to pick up TM modes of long path signals and (ii) using loop aerials set perpendicular to the plane of propagation to pick up weak, horizontally-polarized, skywaves in the presence of strong, vertically-polarized, groundwaves. It was decided to combine the expertise acquired in these two areas in an attempt to detect long path TE modes using loop aerials set perpendicular to the plane of propagation. Preparations were thus made to detect the TE modes
of three long path transmissions in the following manner.

7.2. The Experiment.

Four identical loop aerials were constructed for the experiment. Each consisted of a wooden frame two metres square supporting a screened 25-strand multicore cable with the ends joined to form a screened 25 turn coil. As is usual a gap was made in the screen at the top of the loop and the loops were tuned to the selected frequency in the manner described in Chapter 3. Each wooden frame stood on cross-members which acted as feet and could be secured by pegs driven into the ground. The loops were constructed to be easily assembled and taken apart for transport between the two receiving sites used in the experiment. Two loops were used simultaneously at each site, one set in the normal manner, parallel to the plane of propagation, and the other set perpendicular to it. They will be identified hereafter as the "parallel" and the "perpendicular" loops, respectively.

The four loops used in the experiment were calibrated relative to each other and the induced signal in any loop was within 1 dB of that in any other. In a further test at the Leicester field station one loop was moved about the site to see how the signal varied with position while using a second loop as a reference. The signal remained the same except (i) when the loop was placed close to a metal fence at/boundary of the side, when the signal level increased by approximately 4 dB, and (ii) when the loops were placed within 1 metre of each other. Each loop then registered an increase of about 1 dB. In the experiment the loops were positioned away from the fence and each other.
Recordings were taken simultaneously at two dissimilar sites to ensure that the site re-radiation patterns would be different. It was hoped that any effects caused by site re-radiation would then be dissimilar and so, hopefully, could be distinguished from the effects sought. One of the sites was the Leicester University field site described in Chapter 3, and the other was an isolated area on an airfield at Lasham in the South of England. The nearest object there was a caravan containing the receiving equipment; the next building was several hundred metres away.

To minimise the effects on the perpendicular loop of TM re-radiation from the parallel loop, the parallel loop was set about 10m from the perpendicular loop on the axis of the coil forming that loop.

The receiving equipment at each site was the same. In addition to the two loop aerials there was one VARIAN Rubidium Vapour frequency standard, two TRACOR 599 phase-tracking receivers, and one FOSTER six-channel recorder. The systems were thus similar to that shown in Figure 3.8. The Leicester receivers were 599-J models, those at Lasham were earlier models with different tuning systems.

A list of possible long path VLF transmissions was compiled and the three transmitters listed in Table T.1 were selected as being the most suitable for recording.

<table>
<thead>
<tr>
<th>Transmitter</th>
<th>Location</th>
<th>Frequency (kHz)</th>
<th>Distance (km)</th>
<th>Radiated Power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAA</td>
<td>Maine, USA</td>
<td>17.8</td>
<td>4,800</td>
<td>1,000</td>
</tr>
<tr>
<td>NSS</td>
<td>Maryland, USA</td>
<td>21.4</td>
<td>5,800</td>
<td>85</td>
</tr>
<tr>
<td>NBA</td>
<td>Panama</td>
<td>24.0</td>
<td>8,400</td>
<td>150</td>
</tr>
</tbody>
</table>

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These three transmitters offered the following advantages:

(i) each was a high power phase-stable transmitter;

(ii) each transmission path was West-to-East, or more accurately each path left each transmitter in a North-Easternly direction and arrived at the receiver from a Westerly direction;

(iii) these three transmitters afforded a reasonable spread of frequencies in the VLF band;

(iv) the NAA transmitter lay on the NSS-Leicester great circle path; and

(v) preliminary recording had indicated that it was possible to obtain good records of the TM modes of each of the transmissions at Leicester.

The Omega/Trinidad transmitter also offered many of the above advantages, but it was rejected because its transmitted power was too low, it being only 1 kW. U.S. Navy Time Service Announcements, Series 3

Each transmission was monitored for about two weeks, and recording of each, in turn, was carried out simultaneously at each site. Although it was possible to set up the equipment personally at both sites, a continuous watch could not be maintained at both, so personnel from RAE, Farnborough visited the Lasham site weekly to check the equipment and re-tuned it when required.

At this point the practical difficulties presented by large loop aerials should be recalled. First, a practical loop cannot completely reject the unwanted signal. Even an ideal, perfectly flat loop misaligned by a small angle $\theta$ from the null point will pick up an unwanted signal proportional in strength to $\cos \theta$. If for example the ideal loop were misaligned by $2^\circ$ when set to
detect a TE mode 30 dB smaller than the TM mode, both signals would be picked up, and the voltages excited in the loop by them would be equal. For say 50 dB suppression the ideal loop would need to be set to within $\pm 0.2^\circ$ of the null. It must be accepted therefore that the signal picked up on a 2m square wooden loop erected out of doors in winter will be contaminated to some degree. In steep-incidence work where the groundwave (the contaminating signal) is constant, regular diurnal changes in the signal can be attributed to the skywave. In the long path experiment however, both the contaminating signal (the TM mode) and the wanted signal (the TE mode) vary.

An examination of Pappert's (1968) calculations suggests that there might still be a way of distinguishing between the modes. The calculations indicate that the phase velocities and attenuation rates of TE and TM modes differ, but more importantly the diurnal changes which occur in these parameters are not the same for TE and TM modes. Furthermore the calculated diurnal changes in the TE mode parameters are greater than those in the TM mode parameters. It should therefore be possible to determine whether the signal picked up on a perpendicular loop is attributable to the TE mode or is merely TM mode contamination by examining the records to see if the diurnal changes in the perpendicular records are identical to, or greater than, those in the parallel records. The results obtained during the experiment and presented in the following section would seem to suggest that this is the case and that both TE and TM modes are present.
7.3. The Results.

The diurnal variation in the phase and amplitude of the signal recorded on the parallel channel was compared with that recorded on the perpendicular channel. The mean diurnal variation of each of these parameters, at each site, was extracted from the records as follows. First, unduly disturbed days were rejected, and then the remaining days' records were averaged to yield hourly sampling points. As far as possible records taken during the same period at each site were chosen for averaging, but where this was not possible the same number of days at each site were chosen. Nine days' records of the NAA signals were averaged and four days' records of the NSS signals were averaged. For reasons explained later only the night time periods of five NBA records were averaged.

It will be convenient to consider the results relating to each path in turn, starting with NAA for which most data are available. It is worth noting that of the three transmitters NAA is the most powerful, the nearest, and has the lowest frequency.

The mean diurnal variation in the phase and in the amplitude on the NAA-Lasham circuit is illustrated in Figure 7.1. For convenience, the curves in each figure are labelled A to F. Curves A and B are the parallel and perpendicular phase variation, and curve C indicates the difference between these two. Curves E and F are the parallel and perpendicular amplitude variation, and curve D indicates the difference between these two. Curves A and B and curves E and F are separated on the page by an arbitrary amount for clarity.

Inspection of Figure 7.1 reveals that curve A exhibits the normal NAA quasi-trapezoidal phase variation. It is similar to
Figure 7.1 NAA - Lasham; winter 1968/69

TE and TM mode propagation.
many others taken at Leicester during this project. Curve B is very similar to curve A except for the period just before and during the early part of the evening retardation. This is one of the periods when higher order modes are expected to be excited. In these average curves higher order mode effects are not immediately obvious during the morning phase advance, but in the individual records step-like phase advances indicate their presence. Comparison of curves A and B in Figure 7.1 also reveals that the magnitude of the diurnal change in curve B is rather greater than that in curve A. Curve C emphasises this point. It was obtained by plotting the difference between the hourly values in curves A and B. The scale has an arbitrary zero. It is evident from curve C that the difference between curves A and B remains constant while the whole path is in darkness, but decreases as the path becomes illuminated, and then remains approximately constant at this new level for some 5 to 6 hours. The late afternoon divergence of curve B from its expected shape causes a further change in curve C before it returns to its nighttime level again.

For the purposes of this experiment the best periods to compare in curve C would seem to be the two level periods 01 to 06h. and 10 to 15h. Comparison of these periods suggests that the diurnal change in the perpendicular phase exceeds that of the parallel phase by about 6μsec. The diurnal change in the parallel phase is about 41μsec so the perpendicular change exceeds that by nearly 15%.

Curve E in Figure 7.1 exhibits the expected features of an NAA amplitude curve. The signal strength is high at night, becomes
weaker as the path becomes sunlit, remains low during the day, and increases again in the evening. Although the use of hourly sampling points does not bring out the modal interference effects well in this curve either, the expected minima are present in the individual records, both morning and evening. Curve F has the same overall form as curve E, but the day-to-night change is obviously much greater, and a "step" suggesting modal interference effects is more evident. These effects are clearer on the individual records where the finer detail indicates a series of minima. Curve D represents the difference in strength between the parallel and perpendicular signals. An interesting point to note in curve D is that the difference between the parallel and perpendicular field strengths remains constant until about 11h, i.e. until most of the path is sunlit. This contrasts with curve C in which the change occurs some two to three hours earlier.

The sharp evening change in curve D does not occur until near the end of the evening transition. To avoid the evening changes from 16h onwards the two periods chosen for comparison in curve D are 01-11h and 12-15h. Comparing these periods suggests that the diurnal change in the perpendicular field strength is greater than that in the parallel field strength by about 6 dB. The diurnal change in the parallel field strength is about 10 dB so this is a significantly larger change.

One further point should be made regarding curves D and F. At Lasham the apparatus was left to run unattended for about a week at a time after setting the gain to a suitable level. The night time increase in the perpendicular field strength proved to
be greater than expected and on occasions the trace moved off the upper edge of the chart. When averaging these records it was the value at the upper edge of the chart which was adopted for averaging purposes, to obtain a minimum value. The 6 dB difference is therefore the minimum figure by which the perpendicular exceeded the parallel diurnal variation. Inspection of the individual records suggests that the true figure might be 2 to 4 dB greater than this.

Figure 7.2 illustrates the variation of the parameters on the NAA-Leicester circuit. Curve A is very similar in shape to that in Figure 7.1 although the day-to-night change is smaller by a few microseconds. The perpendicular phase has not been reproduced here. Inspection of the records reveals it to be rather erratic, particularly at night when the trace was very noisy on occasions. Another interesting feature in the individual records was the large and rapid phase change in the perpendicular records, both morning and evening. This coincided with a very deep and quite sharp minima in the perpendicular amplitude records, which often caused the receiver to drop out of lock and cease tracking the phase for a short time. It was not possible to follow the phase change across these gaps.

In Figure 7.2, curve E is very similar to curve E in Figure 7.1, but it is slightly smaller, by about 1 dB. The deep morning minimum in the perpendicular amplitude trace is evident in curve F because it happened to occur close to 09h, but the evening minimum is not so evident. At night the amplitude trace was noisy and the reading was usually taken about the middle of the band of dots.
Figure 7.2  NAA-Leicester; Winter 1968/69
TE and TM mode propagation.
In curve D there is no long stable period in the afternoon so the period 13-15h will be used to compare against the period 01-08h. The difference between these two is about 5 to 6 dB. As the diurnal change in the parallel field strength is about 9 dB this represents a significant difference between the two channels.

Before leaving Figure 7.2 it is worth noting that but for the minimum at 09h in curve F, and hence also in curve D, it seems as if curve D would have remained at its night time level until nearly midday, as it did in Figure 7.1.

Prior to running the experiment at two sites some test runs had been made at the Leicester site during the summer months. Figure 7.3 shows the results of a 6-day run on NAA in early August, taken on smaller loops but otherwise using the same receiving system. Curve A is the typical NAA-Leicester summertime phase curve. The step-like mode interference effects at about 07 and 22h are rather more visible than in the winter curve. Curve B is strikingly similar to curve A except that the day-to-night change is rather larger and the step at 06-07h is more prominent. In curve C the difference between the day and night levels is not as clear cut as it is in the winter curves, nor is the transition between the day and night levels as clear. This appears to be due in part to the shortness of the night. The change to the daytime level seems to start soon after the first part of the path becomes sunlit, at about 04h. The timing of this change is thus similar in summer and winter, i.e. in both cases it occurs as the first part of the path becomes sunlit. By comparing the period 00-04h with the period 12-21h the diurnal change in the
Figure 7.3  NAA - Leicester; summer 1968
TE and TM mode propagation.
perpendicular phase can be seen to exceed that in the parallel phase by 6\mu\text{secs}. If we take the parallel phase change to be about 44\mu\text{secs}, then the perpendicular phase change exceeds this by just under 14\%, almost the same margin as NAA-Lasham in Winter.

In curve E there is a prominent dip in the mean parallel signal level between 01 and 03h. Inspection of the individual records reveals that this feature varies somewhat from night to night but the effect was so marked on two of the six nights averaged that the dip appears prominently in the mean curve.

In general however, in the individual records the signal level at night was not much higher than it was during the day. The peak at 05h occurred not during darkness but some time after ground sunrise at the receiver. Curve F stands in contrast to curve E by not having a prominent dip during the night. It also shows that the perpendicular signal strength falls to a comparatively much lower level during the day, and there appears to be a \cos \chi type variation in curve F not evident in curve E. It should be noted that the 'steps' in curves E and F in Figure 7.3 cannot be attributed solely to mode interference because when these summer records were taken the transmitter was changing its transmitted power periodically as explained in Chapter 4 and at times when the received signal level was changing due to ionospheric changes, and particularly when the trace was noisy, it was not easy to identify and allow for these changes in transmitted power. Hence one cannot be certain that the 'steps' in these curves are due solely to mode interference.
If the night time level of curve D in Figure 7.3 is taken to be about 23 dB (to make some allowance for the excessive dip in curve E) and is compared to the day time level between 12 and 16h, then the perpendicular diurnal variation is seen to exceed the parallel variation by about 14 dB. The peak-to-peak diurnal variation in the parallel signal is itself only about 12 dB, and if the peak at 05h is ignored, the night to day change is only about 3 dB.

From the data presented here one can therefore conclude that on both the NAA-Leicester circuit and on the NAA-Lasham circuit the diurnal variation of both the phase and the amplitude of the perpendicular signal is greater than that of the parallel signal, and by a significant margin in every set of data.

The NSS curves will be examined next. They are illustrated in Figures 7.4 and 7.5. The curves in these Figures resemble the NAA curves in their gross feature although there are differences in the detail. One difference was that the minima in the NSS amplitude records were deeper than those in the NAA records. In the evening this usually caused the perpendicular receivers to lose the signal for a time and so each perpendicular curve in Figures 7.4 and 7.5 has a gap between 19 and 23h. For convenience of presentation the time scale in these two Figures runs from 21h to 21h.

In Figure 7.4 curve A resembles the familiar NSS winter phase variation curve. Curve B resembles curve A but the diurnal variation is greater in magnitude. From curve C it can be seen that the difference is about 12μsec. Taking the day-to-night change in the parallel phase to be about 57μsec, this represents a margin of 21%
Figure 7.4  NSS-Lasham; winter 1968/69

TE and TM mode propagation.
Figure 7.5  NSS - Leicester; winter 1968/69

TE and TM mode propagation.
From Curve E it can be seen that the NSS parallel field strength remains at its high night time level for a longer time that did the NAA field strength, and that the change to the day time level is more abrupt, although this is partly due to a minimum occurring close to 10h. An afternoon minimum is also evident in curve E. Curve F indicates that the perpendicular signal starts to weaken much earlier in the morning than does the parallel signal. It also reverts to its night time level later. At other times the form of the curve is remarkably similar to curve E although the diurnal change is again much greater.

Comparing the periods 01-06h and 10-15h in curve D indicates that the perpendicular diurnal variation exceeds the parallel by about 6 dB. The peak-to-peak diurnal change in the parallel field strength is 9 dB; if the two minima are ignored the change is about 7 dB. The difference between the channels is thus again significant.

In Figure 7.5 the general shape of curve A is similar to that of curve A in Figure 7.4 although the magnitude of the variation is smaller, being only about 46μsecs. compared to 57μsecs. Part of this difference may be due to the fact that the four days averaged at Leicester were not the same four that were averaged at Lasham, and part can be attributed to small errors at the ends of the scale in the dotting recorders where the trace in effect disappears off one edge of the paper chart and re-appears on the other edge. Part of a typical NSS record is reproduced in Figure 7.6 and this type of fault is visible between 10.30 and 11.00h on the green trace. In Figure 7.6 the perpendicular signal is lost between 07.30 and 07.45h causing
Figure 7.6. Part of a typical NSS winter time record; 7 December 1968.

parallel channel: orange - amplitude; green - phase.

perpendicular channel: blue - amplitude, black - phase.
an error in the black phase trace. This type of gap occurred frequently both morning and evening in the NSS-Leicester records so no mean perpendicular phase curve was obtained. However if the parallel and perpendicular phase changes between 08h and 13.30h in Figure 7.7 are measured it can be seen that the advance in the perpendicular phase during this time is about 47μsecs whereas that in the parallel phase is only 38μsecs. Even if 4μsecs were added to the 38μsecs. parallel phase advance to allow for the full scale deflection error in the parallel trace it is still evident that the perpendicular exceeds the parallel phase advance by at least 5μsecs. This is a margin of about 12%.

Curves E and F in Figure 7.5 are similar to those in Figure 7.4. The parallel field strength does not decrease by a large factor in daytime, but the perpendicular field strength does. It also begins to decrease earlier, on average. The large rise between 08.30 and 09.30h in the sample record reproduced in Figure 7.6 is not typical and is not present on other days, as curve E in Figure 7.5 shows. Curve D shows that the perpendicular diurnal variation is greater than the parallel by about 9 dB. The parallel variation is itself only about 6 dB if the minima at 11.00 and 17.00h are ignored.

During the summer months test runs were carried out on the NSS-Leicester circuit but the quality of the records was not as good as that of the NAA records mentioned earlier. Nevertheless some conclusions can be drawn from an examination of individual records. One such NSS-Leicester record is reproduced in Figure 7.6. The mode interference minima are clearly visible on the black parallel field strength trace. The minima are also
Figure 7.7. Part of a typical NSS summer time record; 8 June 1968.

parallel channel: black - amplitude, green - phase.

perpendicular channel: blue - amplitude, red - phase.
evident on the blue perpendicular field strength trace, and it can be seen that the perpendicular receiver loses the signal for periods between 05.30 and 08.30h, causing errors in the red perpendicular phase trace. Nevertheless it is clear that the red perpendicular phase is advancing at a much faster rate than the green parallel phase. This is evident on other days also, but due to the gaps in each record one cannot follow the phase to its daytime level to measure the magnitude of the change accurately. The changes in the field strength can however be measured. Comparing the periods 01-04h and 12-18h on the parallel trace reveals a difference of about 4 dB. Comparing the periods 00.30-02.30 and 12-18h on the perpendicular trace reveals a difference of about 19 dB. Diurnal changes of this order were observed on other records also.

From these results one can conclude that in the NSS records, as in the NAA records, the magnitudes of the diurnal changes in the perpendicular parameters are significantly greater than those in the parallel parameters, in both winter and summer.

The third transmissions to be monitored were those of NBA. They yielded fewer and less satisfactory data than did the other two. The NBA carrier frequency is higher than both NAA and NSS and modal interference effects are more intrusive. Due to the presence of deep minima in the NBA amplitude records the daily range in the parallel signal strength was greater than 40 dB, the AGC range of the receiver. Consequently the trace either went off the top of the chart at night, or dropped out during the deep morning and afternoon minima. Thus the phase could not be tracked accurately as it advanced and retarded each day. Also,
the perpendicular signal, being much weaker than the parallel signal, was lost frequently during the day at Leicester, even with the receiver at maximum gain. Consequently the magnitude of the night-to-day amplitude changes could not be measured accurately either. Because of these difficulties the curves in Figures 7.8 and 7.9 relating to the NBA results are restricted to the hours of darkness.

The curves in Figure 7.8 relate to the Leicester site. Unfortunately curve B does not extend far enough to enable one to see if it moves to and from its daytime level faster than curve A. The rise at each end of curve C is due to curve B remaining at its nighttime level longer than curve A. Because of the gaps in the phase records no conclusion regarding the relative magnitudes of the diurnal phase changes can be drawn.

Curves E and F are also unable to resolve which of the diurnal amplitude changes is greater. Curve E remains at its nighttime level longer than curve F, and this observation is consistent, so far as it goes, with curves E and F in Figure 7.5 (the NSS-Leicester curves). The dotted sections in Figure 7.8 indicate that data from less than 5 days was used to establish these sections. On several days the perpendicular signal had dropped below the working threshold of the receiver at these times.

In Figure 7.9 the mean night time phase levels at the Lasham site have been plotted. The curves do not represent the same days as those in Figure 7.8 so one cannot draw conclusions about the differences of detail between them. Fortunately, the Lasham curve C extends one hour longer than the Leicester curve C and it suggests the beginning of the change to the daytime level.
Figure 7.8  NBA - Leicester; winter 1968/69.

TE and TM mode propagation.
Figure 7.9  NBA - Lasham; winter 1968/69

TE and TM mode propagation
The timing of this change, i.e. after 08h would be consistent with that of curve C in Figure 7.5 (NSS-Leicester) which moved to its daytime level between 08 and 09h. The tentative conclusion drawn from curve C in Figure 7.9 is therefore that the perpendicular diurnal phase change would appear to be greater than the parallel diurnal phase change.

No worthwhile mean amplitude curves could be prepared from the Lasham NBA records.

In Figure 7.10 an example of part of a typical NBA-Leicester record is reproduced. The deep fading in the orange parallel field strength is clearly visible, as is the rapid decrease in the blue perpendicular field strength after sunrise to such a low level that the receiver frequently failed to track the signal. The green parallel phase advances in steps and is lost between 11 and 11.15h. Due to the low strength of the signal the black perpendicular phase is not reliable beyond about 08.30h. Comparison of the night and the mid-afternoon amplitude levels of each channel shows that the blue perpendicular trace drops further than the red parallel trace.

One further interesting feature in Figure 7.10 is the occurrence of a solar flare at 12.22h and the striking increase in both the parallel and perpendicular field strengths which it caused. The parallel field strength rose by 21dB$^{\frac{1}{2}}$ in approximately 5 minutes. Just before the flare occurred the perpendicular receiver had lost its signal, so the increase in perpendicular field strength cannot be measured accurately. However the distance that the blue trace moved across the chart from the zero mark once the receiver had captured the signal again, represents an increase in signal strength of 24 dB. The parallel phase advance
Figure 7.10. Part of a typical NBA record; 19 January 1969.

parallel channel: orange-amplitude, green-phase.

perpendicular channel: blue - amplitude, black - phase
during the SPA was 11μsec. The perpendicular phase advance cannot be measured accurately. However if it is assumed that both the parallel and perpendicular phases had retarded to their normal values by 14.30h, one can estimate the magnitude of the retardation suffered by each signal between the time of maximum of the SPA and the time at which the phases returned to their normal levels, and from that estimate the magnitude of the perpendicular phase advance. Between 12.28h and 14.30h the parallel phase had retarded by 12½μsec and the perpendicular phase had retarded by 16μsec ± 5. Assuming that the middle of the band of black dots represents the perpendicular phase level, the perpendicular phase retarded by 16μsec, i.e. about 30% more than the parallel phase. If the relative magnitudes of the retardation can be assumed to represent the relative magnitudes of the phase advances, then during the SPA the perpendicular phase advanced by about 14μsec compared to the parallel phase advance of 11μsec.

Another large solar flare occurred on the day preceding that shown in Figure 7.10 and it caused the parallel field strength to increase by 20 dB ± ½ and the perpendicular field strength trace to rise from the zero mark to a level 25 dB above it. It was not possible to compare the phase changes on that occasion.

Thus the data available on the NBA transmissions, though not as complete as those on NAA and NSS, are consistent with the NAA and NSS data. There is a limited amount of evidence suggesting that phase changes on the NBA perpendicular channel are greater in magnitude than those on the parallel channel, and there is somewhat stronger evidence suggesting that changes in the
perpendicular field strength during both the night-to-day transition and during SID's are greater in magnitude than the corresponding changes in the parallel field strength.

Before leaving the NBA results it should be noted that both the NBA and the Ω/Trinidad transmitters are situated in the Caribbean area and transmissions from these two transmitters arrive in the U.K. from approximately the same direction - the bearing of NBA from Leicester is 266°, that of Ω/Trinidad 252°, a difference of 14°. The Ω/Trinidad frequency is 12.0 kHz, exactly half the NBA frequency of 24.0 kHz. At the end of the recording run on the NBA frequency a test was carried out to see if the loop aerials could pick up sufficient energy from harmonics of the 12.0 kHz transmissions to affect the NBA results.

For the test both the parallel and perpendicular systems were left as they were except that both transmitters were tuned to 12.0 rather than 24.0 kHz. Over the 24 hour test period the parallel system did in fact pick up the 12.0 kHz transmissions. During the night the Ω/Trinidad trace was about 45 dB lower than the usual NBA level, and during the day it was about 38 dB lower. (Diurnal changes in the NBA and Ω/Trinidad signals are dissimilar). At no time during the 24 hour period was any 12.0 kHz signal detected by the perpendicular receiver, even though it was set at its maximum gain.

From these measurements it is clear that the Ω/Trinidad signal was too weak to have any noticeable effect on the NBA results presented above.
7.4. Discussion.

The results presented in the previous section are all in qualitative agreement with Pappert's (1968) calculations. Those calculations relate to a specific path, viz. Hawaii-San Diego which, although a West-to-East path, is shorter than each of the paths in this experiment. Quantitative comparisons would therefore probably not be valid. Recent calculations by Galejs (1972) are more general, and comparison between these data and the experimental data is thus possible.

The values of the attenuation factor $\alpha$ in Tables 7.2 and 7.4 are taken from Galejs' graphs and relate to first order modes on West-to-East paths. $\alpha$ is in dB's per 1,000 km, and in the tables the calculated attenuation on path lengths of 4,800 km (NAA) and 5,800 (NSS) has been placed immediately below the corresponding value of $\alpha$. In Tables 7.3 and 7.5 are the corresponding measured values of attenuation. Since these values are only relative they have been normalised by setting the attenuation of the night time TM mode to 0 dB in each case.

It was noted in Section 7.2 that the receivers at Lasham were older models than those at Leicester, and so the quantity $|TM-TE|$ was not determined as accurately there as it was at Leicester. There is consequently a difference between the sites of between 4 and 7 dB in this quantity. Even allowing for this difference it is noted that at each site the margin between the TM and the TE signals was much greater than predicted from calculations using $\alpha$ alone, particularly at night. The magnitude of the diurnal variation could be determined accurately at both
### TABLE 7.2

NAA: Calculated Values of $a$ and path attenuation

<table>
<thead>
<tr>
<th></th>
<th>Night</th>
<th>Day</th>
<th>Diurnal Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_{TM}$</td>
<td>2</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>(10dB)</td>
<td>(10dB)</td>
<td>(0dB)</td>
</tr>
<tr>
<td>$a_{TE}$</td>
<td>2½</td>
<td>6½</td>
<td>3½</td>
</tr>
<tr>
<td></td>
<td>(12dB)</td>
<td>(30dB)</td>
<td>(18dB)</td>
</tr>
<tr>
<td>$</td>
<td>a_{TM}-a_{TE}</td>
<td>$</td>
<td>½</td>
</tr>
<tr>
<td></td>
<td>(2dB)</td>
<td>(20dB)</td>
<td>(18dB)</td>
</tr>
</tbody>
</table>

### TABLE 7.3

NAA: Experimental Values (in dB)

<table>
<thead>
<tr>
<th>Mode</th>
<th>Night</th>
<th>Day</th>
<th>Diurnal Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>TM Lasham</td>
<td>0</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>* Leicester</td>
<td>0</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>* Summer</td>
<td>0</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>TE Lasham</td>
<td>31</td>
<td>47</td>
<td>16</td>
</tr>
<tr>
<td>* Leicester</td>
<td>27</td>
<td>42</td>
<td>15</td>
</tr>
<tr>
<td>* Summer</td>
<td>18</td>
<td>35</td>
<td>17</td>
</tr>
<tr>
<td>$</td>
<td>TM-TE</td>
<td>$ Lasham</td>
<td>31</td>
</tr>
<tr>
<td>* Leicester</td>
<td>27</td>
<td>33</td>
<td>6</td>
</tr>
<tr>
<td>* Summer</td>
<td>23</td>
<td>37</td>
<td>14</td>
</tr>
</tbody>
</table>

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### TABLE 7.4

NSS: Calculated Values of $a$ and Path Attenuation

<table>
<thead>
<tr>
<th>Mode</th>
<th>Night</th>
<th>Day</th>
<th>Diurnal Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_{TM}$</td>
<td>1 (6dB)</td>
<td>2$\frac{1}{2}$ (13dB)</td>
<td>1$\frac{1}{2}$ (7dB)</td>
</tr>
<tr>
<td>$a_{TE}$</td>
<td>2$\frac{1}{2}$ (13dB)</td>
<td>5$\frac{1}{2}$ (32dB)</td>
<td>3$\frac{1}{2}$ (19dB)</td>
</tr>
<tr>
<td>$</td>
<td>a_{TM} - a_{TE}</td>
<td>$</td>
<td>1$\frac{1}{2}$ (7dB)</td>
</tr>
</tbody>
</table>

### TABLE 7.5

NAA: Measured Values (in dB)

<table>
<thead>
<tr>
<th>Mode</th>
<th>Night</th>
<th>Day</th>
<th>Diurnal Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>TM</td>
<td>Lasham</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>&quot;</td>
<td>Leicester</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>&quot;</td>
<td>Summer</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TE</td>
<td>Lasham</td>
<td>20</td>
<td>34</td>
</tr>
<tr>
<td>&quot;</td>
<td>Leicester</td>
<td>25</td>
<td>39</td>
</tr>
<tr>
<td>&quot;</td>
<td>Summer</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$</td>
<td>TM - TE</td>
<td>$</td>
<td>Lasham</td>
</tr>
<tr>
<td>&quot;</td>
<td>Leicester</td>
<td>25</td>
<td>33</td>
</tr>
<tr>
<td>&quot;</td>
<td>Summer</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
sites, and the sites agree with each other on this value to within 1 dB in each instance, in winter. The summer value, measured at only one site, differs from the winter values. In his calculation Galejs used Deeks' summer day and winter night electron density profiles and, as might be expected, the measured summer NAA values are in closer agreement with the calculated values than are the measured winter values. It is also noted that calculations using a alone predict no diurnal change in the NAA TM mode attenuation in summer, whereas measurement indicates that there is a change in signal strength although it is only about 3 dB. In the NSS data the measured diurnal change in summer is only a spot measurement on one record, but in respect of the TE mode the measured and calculated values agree exactly, and in respect of the TM mode they differ by only 3 dB. In winter it is the other way round with the TE values differing by 5 dB and the TM values being in agreement.

In general therefore (i) on both the NAA and NSS transmission paths the magnitude of the diurnal variation in signal strength of both the TM and TE modes is in agreement with the calculated values, but (ii) on both paths the TE modes are weaker relative to the TM modes than would be expected from the differences in the attenuation factors. This apparent discrepancy is to be expected however, and can be attributed to the excitation factor of the TE mode being smaller than the excitation factor of the TM mode. Furthermore, Galejs' calculations indicate that at night the 2nd order TM mode becomes relatively much stronger, more so than the 2nd order TE mode.
This would therefore reinforce the signal on the TM channel more than the signal on the TE channel, and would thus increase the margin between the parallel and perpendicular channels at night.

To conclude, it has been demonstrated that the experimental data are in agreement with the calculations of Pappert and Galejs, both qualitatively and quantitatively, and confirm that the signals detected on the TE channel during the experiment were not merely contamination by TM modes, but indicate the existence of TE mode propagation at great distances from the transmitter.
CHAPTER 8

SUMMARY AND CONCLUSIONS

8.1. Introduction.

In this final chapter some comments will be made regarding the performance of the equipment used during the project, and the results of the work will be summarised briefly. The chapter will end with a few comments on the future of this type of experimental programme, particularly at Leicester.

8.2. General.

During this experimental project at Leicester measurements have been made on VLF transmissions propagation over a wide range of paths. The abnormally polarised skywave on six short paths was isolated and measured, and TM mode propagated on eight long paths was examined. TE mode propagation on three long paths was also examined. On occasions up to eight transmissions were being monitored simultaneously to enable selected events to be examined in greater detail.

Calculation and subsequent tests indicated that several other local long wave transmissions cannot be monitored successfully using the equipment which was available during the project. Also, tests carried out on long path transmissions indicated that transmissions on two paths which pass through the polar cap region and are therefore of particular interest in the study of high latitude disturbances,
cannot be satisfactorily monitored using the obsolete twin-channel valve receivers. One of these transmissions (NLK) is marginal and the other (NPM) is below the working threshold of these receivers. Both these transmissions can however be monitored using the TRACOR solid state receivers.

Although all the short path data presented in this thesis were obtained using the valve receivers two serious deficiencies in the performance of these receivers emerged during the project: these were their inadequate sensitivity and the frequent need to replace the valves. The latter necessitated frequent and time consuming recalibrations of the system. One deficiency noted in the performance of the solid state receivers, which were otherwise generally satisfactory, was that the 40dB of AGC which was provided was, on some occasions, not sufficient to allow the receiver to continue tracking during the morning and evening amplitude minima in some long path transmissions.

The loop aerials were generally satisfactory, but frequent and irregular changes in the site re-radiation pattern proved to be a major handicap in monitoring the steep incidence transmissions. These re-radiation changes do not of course affect the monitoring of long path transmissions propagating via TM modes, but might prove to be a problem in some circumstances when monitoring TE mode propagation.

8.3. Short Paths.

The angles of incidence of the six steep incidence transmissions measured lay in the range $i = 10^\circ$ to $i = 60^\circ$, and at times up to four of these transmissions were being monitored simultaneously. Subsequent
analysis of the records taken enabled the diurnal changes in the
phase and amplitude to be extracted and the annual trends in the
data to be examined in greater detail than hitherto.

In particular, the very regular quasi-sinusoidal trend in
the day-to-night phase change during the winter months has been
highlighted, and the daily measurements have enabled differences
in the lengths of the period of "saturation" during the summer
months to be observed. Also, the quality of the observations has
enabled the dissimilar trends in each of the parameters measured
to be observed. Observations such as these are likely to become
more important as interest develops in the study of solar/ionospheric/
meteorological relationships as, for example, Thomas (1975) has
demonstrated in his comparison of temperature changes in the
stratosphere and changes in the D-region.

In a further analysis of the data obtained on the short
paths full wave calculations have demonstrated the lack of sensitivity
of some short path transmissions to what would be expected to be
significant modifications to important electron density profiles.
The calculations also brought out the greater sensitivity of some
of these short paths to changes in the collision-frequency profile. When
the available electron density profiles for night time and for winter days were
found to yield values of \( R_\perp \) not consistent with those measured,
new electron density profiles were derived which did yield results
consistent with experiment. It is recognised however that the validity
of these profiles in circumstances other than those obtaining during
the measurements remains to be tested.
8.4. Long Paths.

The long paths were monitored to investigate particular aspects of long path propagation and on occasions up to five of them were being monitored simultaneously. In addition, for periods of a few weeks the TM and TE modes of three transmissions in turn were being monitored at two sites. Analysis of these records indicated that the diurnal changes in the phase and amplitude of the signals were consistent with theoretically predicted values of the phase velocity and attenuation rates for the TE and TM modes on these paths.

Analysis of records of the 12.0kHz Ω/Trinidad to Leicester transmissions indicated a diminution in the day-to-night phase change over the three year period 1967-1970. As yet no explanation for this has been found although several possible sources have been eliminated.

In addition the disturbances observed on many of these paths were examined.

8.5. Disturbed Conditions.

Solar flare induced anomalies were observed on all the paths monitored. To assist in the analysis of these SPA's a card index was compiled and histograms of the size, rise times, etc. of SPA's on the Ω/Trinidad path prepared. The response of the different paths to solar flare activity was compared, and with the aid of satellite measurements of the incident X-ray flux an explanation was found for the differences in the response of the different paths. In addition, the threshold value in the incident X-radiation flux below which SPA's are not observed was shown to be related to the different solar
zenith angle $\chi$ at different seasons.

The effects of Polar Cap Disturbances on the different paths has been examined and the disturbances have been shown to extend to $\Lambda = 50^\circ$. The response of the 12.0kHz transmissions on the Trinidad to Leicester path have been found to be anomalous at these times, and short period fluctuations in the nocturnal phase records of both the long and the short paths have been correlated with the arrival of solar cosmic rays. The different response of the long and short paths during these geophysical disturbances has also been noted.

8.6. **Future Work.**

Long wave radio transmissions are finding increasing use in long range navigation systems, such as the VLF Omega system. There is therefore a need to understand in greater detail the geophysical phenomena which affect the working of these systems, in particular the ionospheric effects of solar flares. Monitoring VLF transmissions is a relatively inexpensive and convenient way of studying these effects.

Recording the total field or the TM modes of long wave transmissions is relatively easy given suitable receiving equipment, but isolating the TE modes or one of the components of a steeply incident skywave is much more demanding. The limitations imposed by the aerials, the site and the weakness of the skywave require to be taken into consideration in planning such work. The knowledge gained during this project of all three will help to identify which areas in this field may be profitably explored at Leicester.
This Appendix lists the transmissions which were monitored at Leicester during the project, together with Tables of the calculated field intensity at Leicester of many long wave transmitters, and other data which were used during the project.

In Table A.1 are listed all the steep incidence transmissions monitored or originally selected for testing because of their convenient $f \cos i$ values. The angles of incidence in Table A.1 were read off charts published by Belrose (1968) and relate to day and night reflection levels of 75 and 90 km respectively.

Those transmitters in Table A.1 marked "Decca" are Decca Navigator transmitters, and those in Table A.2 marked "Omega" are transmitters in the U.S. Navy "Omega" navigation system. In the Decca system each transmitter in a chain of four transmits not only on its own frequency, but in addition sends short pulses on each of the other frequencies used in the chain. Thus unless it is especially modified to receive the Decca transmissions the receiving equipment will pick up groundwave pulses arriving every few seconds from the other three transmitters in the chain. The time constants used in the Leicester equipment did not permit the equipment to revert to the skywave signal level between each groundwave pulse, and consequently the skywave was swamped. After tests had shown that the Decca skywaves were in any case very weak, the receivers were switched to monitoring other transmissions.
When monitoring long path Omega transmissions the loop aerial is set parallel to the plane of propagation to pick up the maximum signal, so interference from other transmitters is less of a problem. Furthermore each Omega transmitter transmits on its own exclusive frequency in addition to transmitting on the other shared frequencies. It was usually this exclusive frequency which was monitored at Leicester, but when any of the shared frequencies were to be monitored the special timing equipment needed was made available on loan from RAE, Farnborough.

It is noted in Table A.2 that transmissions from NWC (Australia) may propagate in both directions round the globe to the U.K., one great circle path passing for most of its length over water, the other passing over Europe and Asia. When monitoring this transmitter a Tracor "Cardiod Unit" was inserted in the aerial feeder to reject the unwanted signal.

Table A.3 lists the various VLF and LF transmissions in the RAE/Leicester joint monitoring programme mentioned in Chapter 1.

Tables A.4 to A.6 relate to short path transmissions. When tests indicated that some of the transmissions originally selected for monitoring were unsuitable a list was drawn up of all the local LF and VLF transmissions on which information was available. The groundwave/skywave ratios of each were calculated using values of \( \mu R_\perp \) taken from Figure 2.13 (Belrose's curves of Reflection Coefficient \( \mu \) Equivalent Frequency). The field strength at Leicester of each transmitter was also calculated if the transmitted power was known or could be estimated. The voltage induced in a loop aerial of the type used at Leicester was also estimated.
The data obtained in this way are listed in Tables A.4, A.5 and A.6 and plotted graphically in Figure A.1. With this information available it was possible to estimate which transmissions were within the capabilities of the receiving equipment, and which were not.

Finally, in Table A.7 are listed details of the various loop aerials used at Leicester during the project. The bandwidths of the 1 and 4m² loops were generally in the range 1 - 2 kHz when tuned to a frequency in the VLF band,
<table>
<thead>
<tr>
<th>Transmitter</th>
<th>Location</th>
<th>freq.(kHz)</th>
<th>Path Length (km)</th>
<th>Angle of Incidence Day</th>
<th>Angle of Incidence Night</th>
<th>$f \cos \theta$ Day</th>
<th>$f \cos \theta$ Night</th>
</tr>
</thead>
<tbody>
<tr>
<td>GBR</td>
<td>Rugby</td>
<td>16.0</td>
<td>27</td>
<td>10</td>
<td>8</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>GQD</td>
<td>Anthorn</td>
<td>19.0</td>
<td>300</td>
<td>62</td>
<td>58</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>(2nd Hop)</td>
<td></td>
<td>2 x 150</td>
<td>44</td>
<td>39</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(3rd Hop)</td>
<td></td>
<td>3 x 100</td>
<td>29</td>
<td>33</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GBZ</td>
<td>Criggion</td>
<td>19.6</td>
<td>135</td>
<td>42</td>
<td>37</td>
<td>15</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>(2nd Hop)</td>
<td></td>
<td>2 x 67</td>
<td>24</td>
<td>21</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(3rd Hop)</td>
<td></td>
<td>3 x 45</td>
<td>17</td>
<td>14</td>
<td></td>
<td></td>
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<tr>
<td>GYA</td>
<td>Inskip</td>
<td>44.993</td>
<td>185</td>
<td>51</td>
<td>45</td>
<td>28</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>(2nd Hop)</td>
<td></td>
<td>2 x 97</td>
<td>33</td>
<td>28</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(3rd Hop)</td>
<td></td>
<td>3 x 62</td>
<td>23</td>
<td>19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MSF</td>
<td>Rugby</td>
<td>60.0</td>
<td>27</td>
<td>10</td>
<td>8</td>
<td>59</td>
<td>59</td>
</tr>
<tr>
<td>Decca</td>
<td>Llanlcarfen</td>
<td>70.233</td>
<td>205</td>
<td>53</td>
<td>48</td>
<td>42</td>
<td>47</td>
</tr>
<tr>
<td>Decca</td>
<td>Puckeridge</td>
<td>85.00</td>
<td>107</td>
<td>36</td>
<td>32</td>
<td>69</td>
<td>72</td>
</tr>
<tr>
<td>Decca</td>
<td>Neston</td>
<td>126.967</td>
<td>140</td>
<td>43</td>
<td>38</td>
<td>91</td>
<td>100</td>
</tr>
</tbody>
</table>

155
<table>
<thead>
<tr>
<th>Transmitter</th>
<th>Location</th>
<th>freq.(kHz)</th>
<th>Path length (km)</th>
<th>Bearing from Leicester</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAA</td>
<td>Maine, USA</td>
<td>17.8</td>
<td>4,900</td>
<td>287°</td>
<td></td>
</tr>
<tr>
<td>NLK/NPG</td>
<td>Seattle, USA</td>
<td>18.6</td>
<td>7,700</td>
<td>323°</td>
<td>Over Greenland ice cap</td>
</tr>
<tr>
<td>NSS</td>
<td>Maryland, USA</td>
<td>21.4</td>
<td>5,850</td>
<td>287°</td>
<td></td>
</tr>
<tr>
<td>NBA</td>
<td>Panama</td>
<td>24.0</td>
<td>8,600</td>
<td>266°</td>
<td></td>
</tr>
<tr>
<td>NPM</td>
<td>Hawaii</td>
<td>23.4</td>
<td>11,700</td>
<td>338°</td>
<td>Over Greenland ice cap</td>
</tr>
<tr>
<td>NWC</td>
<td>North West Cape, 22.3 Australia</td>
<td>13,750</td>
<td>23,250</td>
<td>84°</td>
<td>Propagates in both directions round the globe</td>
</tr>
<tr>
<td>Ω/N</td>
<td>Aldra, Norway</td>
<td>12.3</td>
<td>1,780</td>
<td>22°</td>
<td>Omega</td>
</tr>
<tr>
<td>Ω/T</td>
<td>Trinidad</td>
<td>12.0</td>
<td>7,200</td>
<td>252°</td>
<td>Omega</td>
</tr>
<tr>
<td>OMA</td>
<td>Czechoslovakia</td>
<td>50.0</td>
<td>1,160</td>
<td>100°</td>
<td></td>
</tr>
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</table>
## TABLE A3

### Joint VLF/LF Monitoring Programme

<table>
<thead>
<tr>
<th>RAE, Farnborough</th>
<th>Leicester University</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>VLF Long Paths</strong></td>
<td></td>
</tr>
<tr>
<td>NLK/NPG (Seattle, USA)</td>
<td>18.6 kHz</td>
</tr>
<tr>
<td>NWC (Australia)</td>
<td>22.3 kHz</td>
</tr>
<tr>
<td>(\Omega)/Norway</td>
<td>10.2 kHz</td>
</tr>
<tr>
<td></td>
<td>11(\frac{1}{2}) kHz</td>
</tr>
<tr>
<td></td>
<td>13.6 kHz</td>
</tr>
<tr>
<td>(\Omega)/Trinidad</td>
<td>10.2 kHz</td>
</tr>
<tr>
<td></td>
<td>11(\frac{1}{2}) kHz</td>
</tr>
<tr>
<td></td>
<td>13.6 kHz</td>
</tr>
<tr>
<td>(\Omega)/New York</td>
<td>10.2 kHz</td>
</tr>
<tr>
<td></td>
<td>12.5 kHz</td>
</tr>
<tr>
<td></td>
<td>13.6 kHz</td>
</tr>
<tr>
<td><strong>VLF Short Paths</strong></td>
<td></td>
</tr>
<tr>
<td>GBR (Rugby)</td>
<td>16.0 kHz</td>
</tr>
<tr>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>LF Short and Medium Paths</strong></td>
<td></td>
</tr>
<tr>
<td>MSF (Rugby)</td>
<td>60.0 kHz</td>
</tr>
<tr>
<td>MSF (Rugby)</td>
<td>68.0 kHz</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
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</table>
TABLE A4

Groundwave/Skywave Ratios in dB

<table>
<thead>
<tr>
<th>Transmitter</th>
<th>Summer</th>
<th>March</th>
<th>Winter</th>
<th>Night</th>
</tr>
</thead>
<tbody>
<tr>
<td>GBR</td>
<td>47</td>
<td>37</td>
<td>35</td>
<td>33</td>
</tr>
<tr>
<td>GYA</td>
<td>46</td>
<td>24</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>MSF</td>
<td>78</td>
<td>61</td>
<td>48</td>
<td>40</td>
</tr>
<tr>
<td>GBZ</td>
<td>17</td>
<td>12</td>
<td>9</td>
<td>9</td>
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<tr>
<td>GQD</td>
<td>8.6</td>
<td></td>
<td></td>
<td>1.6</td>
</tr>
<tr>
<td>Llancarfen</td>
<td>58</td>
<td>44</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>Puckeridge</td>
<td>60</td>
<td>44</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>Neston</td>
<td>65</td>
<td>47</td>
<td>31</td>
<td>18</td>
</tr>
<tr>
<td>Warwick</td>
<td>68</td>
<td>42</td>
<td>36</td>
<td>30</td>
</tr>
<tr>
<td>Norwich</td>
<td>54</td>
<td>38</td>
<td>24</td>
<td>16</td>
</tr>
<tr>
<td>Lewes</td>
<td>53</td>
<td>36</td>
<td>23</td>
<td>14</td>
</tr>
<tr>
<td>Kidscale</td>
<td>75</td>
<td>60</td>
<td>32</td>
<td>27</td>
</tr>
<tr>
<td>Stirling</td>
<td>28</td>
<td>14</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>Droitwich</td>
<td>77</td>
<td>61</td>
<td>44</td>
<td>29</td>
</tr>
</tbody>
</table>

GBR-Cambridge (  21 Day
(  12 Night
(  14 Day
(  16 Night
## TABLE A5

Field Intensities at Leicester (Calculated) in \( \mu \text{V/m} \)

<table>
<thead>
<tr>
<th>Transmitter</th>
<th>Groundwave</th>
<th>Skywave Day</th>
<th>Skywave Night</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Summer</td>
<td>Equinox</td>
<td>Winter</td>
</tr>
<tr>
<td>GBR</td>
<td>( 6.6 \times 10^4 )</td>
<td>280</td>
<td>680</td>
</tr>
<tr>
<td>GYA</td>
<td>( 4.9 \times 10^3 )</td>
<td>23</td>
<td>324</td>
</tr>
<tr>
<td>MSF</td>
<td>( 1.1 \times 10^4 )</td>
<td>1.3</td>
<td>10</td>
</tr>
<tr>
<td>GQD</td>
<td>( 10^4 )</td>
<td>( 3.7 \times 10^3 )</td>
<td></td>
</tr>
<tr>
<td>Llancafen</td>
<td>186</td>
<td>0.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Puckeridge</td>
<td>840</td>
<td>0.8</td>
<td>5.5</td>
</tr>
<tr>
<td>Neston</td>
<td>360</td>
<td>0.2</td>
<td>1.8</td>
</tr>
<tr>
<td>Warwick</td>
<td>( 1.7 \times 10^3 )</td>
<td>0.7</td>
<td>4.3</td>
</tr>
<tr>
<td>Lewes</td>
<td>560</td>
<td>1.3</td>
<td>8.6</td>
</tr>
<tr>
<td>Norwich</td>
<td>660</td>
<td>1.3</td>
<td>8.4</td>
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<tr>
<td>Kidsdale</td>
<td>740</td>
<td>0.1</td>
<td>0.8</td>
</tr>
<tr>
<td>Stirling</td>
<td>( 1.2 \times 10^3 )</td>
<td>50</td>
<td>246</td>
</tr>
<tr>
<td>Transmitter</td>
<td>Groundwave</td>
<td>Skywave Day</td>
<td>Skywave Night</td>
</tr>
<tr>
<td>-------------</td>
<td>------------</td>
<td>-------------</td>
<td>---------------</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Summer</td>
<td>March</td>
</tr>
<tr>
<td>GBR</td>
<td>$1.2 \times 10^3$</td>
<td>5.3</td>
<td>12.9</td>
</tr>
<tr>
<td>GYA</td>
<td>314</td>
<td>1.5</td>
<td>21</td>
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<tr>
<td>MSF</td>
<td>777</td>
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<td>0.7</td>
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<td>GQD</td>
<td>220</td>
<td>82</td>
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</tr>
<tr>
<td>Llancarfen</td>
<td>15</td>
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<td>1.1</td>
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<tr>
<td>Puckeridge</td>
<td>84</td>
<td>0.09</td>
<td>0.6</td>
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<tr>
<td>Neston</td>
<td>60</td>
<td>0.03</td>
<td>0.3</td>
</tr>
<tr>
<td>Warwick</td>
<td>170</td>
<td>0.06</td>
<td>0.35</td>
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<tr>
<td>Lewes</td>
<td>85</td>
<td>0.2</td>
<td>1.3</td>
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<tr>
<td>Norwich</td>
<td>63</td>
<td>0.1</td>
<td>0.8</td>
</tr>
<tr>
<td>Stirling</td>
<td>100</td>
<td>4.1</td>
<td>20</td>
</tr>
<tr>
<td>Kidsdale</td>
<td>70</td>
<td>0.01</td>
<td>0.08</td>
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</table>

**TABLE A6**

*Voltage Induced in a 40 Turn Loop Aerial (in µV)*
### TABLE A7

Characteristics of Leicester Loop Aerials

<table>
<thead>
<tr>
<th>Loop</th>
<th>Turns (N)</th>
<th>Area ($m^2$)</th>
<th>$N \times A$</th>
<th>Resistance (Ω)</th>
<th>Suppression (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wooden</td>
<td>12</td>
<td>1</td>
<td>12</td>
<td>4</td>
<td>69</td>
</tr>
<tr>
<td>Wooden</td>
<td>25</td>
<td>1</td>
<td>25</td>
<td>32</td>
<td>78</td>
</tr>
<tr>
<td>Small Wooden</td>
<td>40</td>
<td>0.1</td>
<td>4</td>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td>Large Wooden</td>
<td>25</td>
<td>4</td>
<td>100</td>
<td>9</td>
<td>64</td>
</tr>
<tr>
<td>Metal (Box)</td>
<td>40</td>
<td>1</td>
<td>40</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>Metal (Flat)</td>
<td>40</td>
<td>1</td>
<td>40</td>
<td>40</td>
<td>98</td>
</tr>
</tbody>
</table>

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Figure A1 Groundwave/shywave ratios (suppression) at Leicester: calculated values.
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During the period 1967-1970 the phase and amplitude of twelve LF and VLF radiowave transmissions were monitored at Leicester for periods ranging from three years to a few weeks; the path lengths varied between 27km and 8,600km. The records taken were analyzed to extract the diurnal and seasonal behaviour of the signals.

The horizontally polarized skywave of six local (U.K.) transmissions were isolated using loop aerials designed and built during the project, and the value of the ionospheric conversion coefficient $n_R$ at noon and midnight throughout the year was obtained from the records. The apparent height of reflection was also measured.

Full-wave calculations were performed to test several published models of the ionospheric D-region for consistency with the measurements. Modified models were also tested and new models for winter days, and for nights throughout the year were derived.

TM mode propagation of VLF transmissions on eight long paths was examined, and TE mode propagation on three long paths was also examined at two receiving sites using orthogonal loop aerials to isolate the TE and TM modes. Measurements were found to be consistent with published predicted values of relevant ionospheric parameters.

Disturbances resulting from solar flare activity were observed on all the paths and the anomalies present in the records were examined in detail. The contrasting response of the different paths was noted. Comparison of selected anomalies with the incident flux of X-radiation enabled an explanation for the different response of the various paths to be found. The effect of Polar Cap Disturbances and the influx of solar cosmic rays on transmission paths at different magnetic latitudes was also examined, and the anomalous response of a low latitude path during these geophysical disturbances was discovered.

W.G. Woods