Ionospheric Radiowave Propagation Effects Observed with a Large Aperture Antenna Array

by

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3. Experimental arrangement

Introduction

The antenna arrays

The large (Forward Look) array
The small (Verbena) array

Geographic location

The receiver

Hardware
Calibration

The Computer System

Hardware
Control software
Pulse sounder

The transmitter
The receiver and data recorder

Data digitisation

Concluding remarks

4. Equipment validation and initial experimental observations

Introduction

Equipment validation and measurement errors

Stability check
Amplitude measurements
Phase measurements
System errors

Amplitude and phase measurements

Spectral analysis of the received signal
5. Amplitude and phase measurements

Introduction 5.1
Short range signals 5.1
  Amplitude measurements 5.2
  Phase measurements 5.4
  Coherence ratio 5.7
  Summary 5.8
Long range signals 5.9
  Identification of single moded propagation 5.9
  Experimental results 5.10
Conclusions 5.12

6. Direction finding and single site location: the method

Introduction 6.1
Determination of the direction of arrival 6.1
  Sub-array notation 6.3
  Resolution of ambiguities 6.4
Expected deviations in the measured DOA 6.5
  Wave interference 6.5
  Ionospheric waves and tilts 6.6
Data selection 6.7
  Selection by phase front planarity 6.7
  Selection by amplitude equality 6.8
  Selection by phase front planarity and amplitude equality 6.9
7. Direction finding and single site location: experimental results

Introduction

DOA determination and data selection

Sarnen, Switzerland; 9.535 MHz
Madrid, Spain; 9.570 MHz
Moosbrunn, Austria; 9.770 MHz

Summary

DOA measurements and transmitter location results

Azimuth correction
Ionospheric soundings
Sarnen, Switzerland; 9.535 MHz
Copenhagen, Denmark; 15.165 MHz
Madrid, Spain; 9.570 MHz
Noblejas-Toledo, Spain; 11.920 MHz
Moosbrunn, Austria; 9.770 MHz

Summary

Conclusions

8. Summary, conclusions and suggestions for further work

Introduction

Single moded signals
Single site location
Suggestions for further work
APPENDICES

A. Summary of the data collected

B. Details of the calculation of DOA for a multi-element antenna array

REFERENCES
CHAPTER 1

INTRODUCTION

THE IONOSPHERE

The Earth's atmosphere can be subdivided into several layers or regions according to various criteria, the most usual being composition, temperature, and ionisation.

Up to 100 km the atmosphere is composed mainly of $N_2 (78\%)$, $O_2 (21\%)$ and small quantities of other constituents such as argon, helium, carbon dioxide and water vapour. Above 100 km $O_2$ becomes dissociated into atomic oxygen and there is a larger proportion of lighter constituents due to diffusive processes. This is illustrated in Figure 1.1. In terms of temperature five regions are usually identified. These are illustrated in Figure 1.2.

An alternative classification can be based on the ionisation state of the atmospheric gases. These are ionised mainly by incoming solar radiation and above about 50 km regions of free electrons can exist since a balance is reached between the solar production and losses due to recombination. Because the ionosphere is predominantly 'solar driven' it is subject to diurnal, seasonal, and 11 year solar cycle variations. Typical profiles of the electron concentration are reproduced in Figure 1.3. For a detailed explanation of the structure of the ionosphere it is necessary to take account of the solar spectrum and the detailed composition and photochemistry of the atmosphere. This detail is beyond the scope of this thesis, however investigations have shown that the important ionising solar
DAYTIME ATMOSPHERIC COMPOSITION

Medium sunspot number (C.I.R.A., 1965)

FIGURE 1.1
TEMPERATURE DISTRIBUTION WITH HEIGHT OF THE EARTH'S ATMOSPHERE
Regions of the atmosphere based on the gradient of the temperature profile are indicated
(After Rishbeth and Garriott, 1969)

FIGURE 1.2
Typical electron density profiles for mid-latitude ionosphere at sunspot maximum and minimum (After Hargreaves, 1979)

FIGURE 1.3
radiations are those in the X-ray band (10 - 1700 nm) and the extreme ultra-violet (1700 - 17500 nm) (see Figure 1.4).

The electron density height profile exhibits a number of maxima and the regions associated with these peaks are termed the D, E, and F layers. The lowest of these is the D region which extends from 60 km to 95 km with an electron density of approximately $10^{10} \text{ m}^{-3}$. This layer recombines completely at night.

The E region extends from approximately 95 km to 120 km with an electron density of the order of $10^{11} \text{ m}^{-3}$ and exhibits marked regular solar zenith angle variations. Under certain conditions a layer known as sporadic E ($E_s$) may develop. This is a thin layer of irregular intense ionisation in which the electron density can exceed that of the normal E layer by a factor of four or more. The creation of this layer is intermittent and is related to the presence of strong wind shears which can exist at these heights.

Above the E region is the F region extending upwards from about 120 km. During the summer months this may split into two layers known as the F1 and F2 layers. The F1 layer disappears at night, whereas the F2 layer persists. The F region is very sensitive to changes in solar activity.

An example of the diurnal variation of the electron density profile is presented in Figure 1.5. The electron density peak forms quickly after dawn but decreases slowly after dusk. In contrast to the expected solar control, the F region maximum electron density is greater in winter than in summer (see Figure 1.6). This is due to the increased proportion of atomic oxygen in the atmosphere in winter which increases the rate at which ions are produced, moreover the lower winter temperatures retard one of the recombination processes.
THE ROLE OF VARIOUS SOLAR EMISSIONS IN THE UPPER ATMOSPHERE
(After Hargreaves, 1979)

FIGURE 14
DIURNAL CHANGES IN IONOSPHERIC PROFILES
(after J. W. Wright, unpublished)

FIGURE 15
SEASONAL CHANGES IN ELECTRON DENSITY PROFILE
(after J. W. Wright, unpublished)

FIGURE 1.6
The dependence of the F layer on solar activity, as indicated by the sunspot number \( R \), is illustrated in Figure 1.7 by the close correlation between \( R \) and the F region maximum electron densities. As before, the summer months exhibit a reduced level of ionisation.

The F region is sensitive to geomagnetic storm activity which can result in an increase or decrease in the maximum electron density depending on the latitude. Furthermore, the F region electron density distribution can become irregular at these times resulting in a condition known as spread F.

**IONOSPHERIC RADIOWAVE PROPAGATION**

**Historical background**

On 31 December 1901 Marconi succeeded in receiving in Newfoundland, Canada, a radio signal \('S S S'\) in Morse code) transmitted from Cornwall, England. This proved conclusively that radiowaves could travel around the curvature of the Earth. Although this phenomenon was originally thought to be due to diffraction processes, Kennelly [1902] and Heaviside [1902] independently suggested that the signals were reflected by a conducting layer of ions at approximately 80 km altitude. This layer was for many years known as the Kennelly-Heaviside layer.

Appleton and Barnett [1925] employed a wave interference technique and Breit and Tuve [1925, 1926] a pulse sounding method to demonstrate the existence of reflecting layers and to establish their approximate heights. Appleton [1925] and (independently) Nichols and Schelleng [1925] drew attention to the fact that the Earth's magnetic field influenced the return of radiowaves from the ionosphere. This lead to the development of a magnetoionic theory [Appleton and Builder, 1932].
Representative electron density profiles at high, middle and low latitudes for levels of solar activity \( R = 0, 100, 200 \) (After Wright, 1962)

**FIGURE 1.7**
Radio developed rapidly and was employed for many purposes (eg. broadcasting, navigation and communication with ships). Most of these services required long distance communication and initially frequencies in the low and medium frequency (LF and MF) bands were employed (<3 MHz). In the 1930's the advantages of using higher frequencies became apparent and interest was concentrated on the high frequency (HF) band (3-30 MHz) where relatively simple equipment can provide communication over long distances via the ionosphere.

Radiowaves in ionised media

Full and detailed descriptions of the propagation of HF radiowaves through the ionosphere is available in many text books [eg. Davies, 1966]. A brief outline of the theory relevant to this investigation is now presented.

The passage of a radiowave through the ionosphere is influenced by many factors, the main ones being the electron density profile, the Earth's magnetic field and collisions between the free electrons and the neutral gas molecules. Initially consider a situation of an isotropic ionosphere with no magnetic field or collisions. In this case, the refractive index is given by:

\[
\mu^2 = 1 - \frac{Ne^2}{\varepsilon_0 mw^2} \quad 1.1(a)
\]

\[
= 1 - \frac{N}{\omega^2} \quad 1.1(b)
\]

where:

- \( N \) is the electron density,
- \( e \) is the magnitude of the electronic charge,
\( m \) is the electron mass,
\( \varepsilon_0 \) is the permittivity of free space,
\( \omega \) is the wave frequency, and
\( \omega_N \) is the angular plasma frequency, i.e., the natural angular frequency of oscillation of the electrons when displaced and then allowed to move freely.

When the wave frequency is equal to the plasma frequency the refractive index becomes equal to zero, and, for normally incident waves, the signal is reflected (note that for oblique angles of incidence reflection occurs when \( \mu = \sin \theta \), where \( \theta \) is the angle of incidence). Since there is a limit to the maximum electron density which occurs in the ionosphere, vertically propagating waves with a frequency greater than the plasma frequency \( \omega_N \) at the point of maximum electron density will not be reflected. This limiting frequency is known as the critical (or penetration) frequency, \( f_C \).

If the model is now modified to take account of collisions between the free electrons and the neutral gas molecules some of the energy transferred from the wave into kinetic energy of the electrons is lost in the form of thermal energy of the molecules. This leads to the radiowave being attenuated as it passes through the medium. In this case the refractive index is complex and is given by:

\[
n^2 = (\mu-i\chi)^2 = 1 - \frac{\omega_N^2}{\omega^2(1-i\nu/\omega)}
\]

where:

\( \nu \) is the collision frequency between an electron and the neutral gas molecules.
There is now no frequency, \( \omega \), such that \( \mu = 0 \). However, provided that \( \nu \) is not too high, strong reflections will still occur near regions of small \( \mu \).

It can also be shown that the absorption coefficient (absorption per unit length) is given by:

\[
\kappa = \frac{e^2}{2\varepsilon_0 mc \nu} \cdot \frac{N\nu}{\nu^2 + \nu^2},
\]

For regions of the ionosphere where the refractive index is approximately unity the absorption is said to be non-deviative. In general non-deviative absorption is greatest in the D region. Near to the reflection point, or anywhere along the path where significant refraction takes place, the absorption is said to be deviative.

A further important consideration is the influence of the Earth's magnetic field. When a charged particle moves in a magnetic field it tends to spiral around the magnetic field lines with an angular frequency (known as the angular gyrofrequency) given by:

\[
\omega_H = \frac{e}{m} B
\]

where:

- \( B \) is the magnetic flux density.

Typical values of the gyrofrequency \((= \omega_H/2\pi)\) are 1.4 MHz for an electron, 763 Hz for a hydrogen ion \((H^+)\), 27.2 Hz for a singly charged nitrogen molecule \((N_2^+)\) and 23.8 Hz for a singly charged oxygen molecule \((O_2^+)\). In this case the refractive index (neglecting collisions) is given by:
\[ \mu^2 = 1 - \frac{2X(1-X)}{2(1-X) - \gamma^2 + \gamma^2} \]

where:

\[ X = \frac{\omega_N^2}{\omega^2} \]

\[ Y = \frac{\omega_H}{\omega} \]

The positive sign solution to Equation 1.5 is associated with a wave reflected (at normal incidence) from a level where \( X = 1 \) (i.e.: \( \omega_N = \omega \)), and the negative sign solution with waves reflected at levels where \( X = 1 - Y \) and \( X = 1 + Y \). The characteristic wave which is reflected at the same level as when the magnetic field is absent (i.e.: the level at which \( X = 1 \)) is termed the ordinary (O) wave, the wave reflected at the level where \( X = 1 - Y \) being termed the extraordinary (X) wave, and the wave reflected at the level where \( X = 1 + Y \) is known as the Z wave. Although there are three possible levels of reflection there are only two types of polarisation (clockwise and anticlockwise). For waves originating on the Earth's surface in low and mid latitudes with the polarisation of the extraordinary wave reflection occurs at the level where \( X = 1 - Y \). In high magnetic latitudes it is possible for energy to be coupled from the O into the Z mode, and in this way reach a level where \( X = 1 + Y \) (the O and Z modes have the same polarisation).

In the case when both collisions and a magnetic field are considered (for non-deviative absorption) the absorption coefficient of the extraordinary wave is greater than that of the ordinary wave. Near to the gyrofrequency, and also near to the reflection point for vertical incidence, this difference becomes even more pronounced.
Equivalence theorems

There are several theorems which relate certain characteristics of an obliquely propagating wave to those of a wave which, when propagating vertically, is reflected at the same real height. This wave is known as the equivalent vertical wave. The notation used in these theorems is illustrated in Figure 1.8.

a) The secant law. The relationship between the frequency, $f_{ob}$, of the wave incident obliquely on a flat ionosphere and the equivalent vertical frequency, $f_v$, is given by:

$$f_{ob} = f_v \sec \phi_0$$

where:

- $f_{ob}$ is the frequency of the obliquely propagating wave,
- $f_v$ is the equivalent vertical frequency, and
- $\phi_0$ is the angle between the vertical and the ray at the bottom of the layer.

b) Breit and Tuve's theorem. This theorem states that the time taken to traverse the actual curved path TBR is the same as that which would be taken to traverse the triangular path TAR in free space.

c) Martyn's equivalent path theorem. This states that the virtual heights of reflection, $h'_r$, of the obliquely propagating wave and the vertical wave are equal.

Effect of the Earth’s curvature on oblique propagation

For distances greater than about 500 km the effect of the Earth’s curvature becomes important. With a thin layer the curvature of the Earth must be
MARTYN'S EQUIVALENT HEIGHT THEOREM.  
See text for explanation (After Davies, 1966)  

FIGURE 1.8
considered but that of the ionosphere can be neglected. From Figure 1.9 it can be seen that the Earth's curvature has the effect of shortening the distance between the transmitter and receiver (TCR < TBR), and also the effective height of the ionosphere is increased by the distance BC.

When the thickness of the ionospheric layer is not negligible compared with its height above ground the curvature of the layer itself must be taken into account. In this case the secant law can be written as:

\[ f_{ob} = f \sec \phi_r \]  \hspace{1cm} 1.7

where:

\[ \phi_r \] is the angle between the continuation of the unrefracted ray and the radius vector at the height of reflection (see Figure 1.10).

This situation is illustrated in Figure 1.10. Equation 1.7 is similar to the secant law for a flat ionosphere (Equation 1.6) except that the equivalent vertical frequency, \( f_V \), depends upon the true level of reflection and, hence, the electron density profile. For most practical purposes it is usually adequate to replace the \( \sec \phi_r \) of Equation 1.7 with \( k \sec \phi_0 \). The \( k \) factor can be approximately calculated using model ionospheres. It primarily depends upon ground distance and has values lying in the range 1.0 (for vertical incidence) to about 1.2. In general terms the secant law can be rewritten as:

\[ f_{ob} = k f_V \sec \phi_0 \]  \hspace{1cm} 1.8

The maximum frequency which can be propagated over any given path (the maximum usable frequency, MUF) is related (from Equation 1.8) to the
RAY PATH REFLECTION FROM A THIN CURVED IONOSPHERIC LAYER

FIGURE 1.9
RAY PATH GEOMETRY IN A THICKLY CURVED IONOSPHERE
(after Davies, 1966)

FIGURE 1.10
critical frequency (i.e., the maximum frequency which can be reflected vertically by the ionosphere) by the equation:

\[ f_m = f_c k \sec \phi \]  \hspace{1cm} (1.9a)

\[ = M f_c \]  \hspace{1cm} (1.9b)

where:

- \( f_m \) is the maximum frequency which will propagate,
- \( f_c \) is the critical frequency (in effect the maximum \( f_v \)), and
- \( M \) is a factor which relates the critical frequency to the MUF for a given distance.

**Oblique ray paths**

In practice, the path of a radiowave in travelling from transmitter to receiver may involve several reflections from the ionosphere with or without intermediate ground reflections. This is illustrated in Figure 1.11 for several (not exhaustive) possibilities. Furthermore, a given signal may travel by more than one route, for example both 1 hop F and 2 hop F modes may occur (Figure 1.12), the signals combining at the receiving antenna. In general, the constituent signals will not maintain a constant phase relationship, due to small ionospheric movements imposing a Doppler shift on the signal, and, as a result, the amplitude of the combined signal will increase and decrease with time (fading).

The situation is further complicated by the fact that the ionosphere cannot be considered as a perfectly smooth reflector and as such a single mode must be considered, to some extent, as being comprised of several (or many) signals reflected from nearby points in the ionosphere. This is illustrated in Figure 1.13 and again leads to fading of the signal at the receiver ('in-mode' fading).
EXAMPLES OF DIFFERENT PROPAGATION PATHS

FIGURE 1.11
EXAMPLE OF TWO MODED PROPAGATION

FIGURE 1.12
REPRESENTATION OF CONING OF IONOSPHERICALLY REFLECTED SIGNALS.

FIGURE 1.13
Arrays of spaced antennas are often employed in HF receiving systems to form a series of 'beams' and 'nulls' in the directional sensitivity pattern of the antenna system. The design of such systems usually depends upon the assumption that the radiowaves arriving at the receiving site have a linear wavefront (i.e. consist of one component reflected from a 'perfect' ionosphere). This is not, in general, the case and one of the principal aims of the present investigation was to examine the linearity of the wavefronts of HF waves reflected from the ionosphere. The phase and amplitude were sampled at points separated by up to 1.5 km for signals propagating over paths of between 100 km and 2000 km. The magnitude of the distortion of the wavefront is a critical factor in the design of multi-element receiving antenna.

Spaced antenna arrays are also used in direction finding (DF) systems to determine the direction of arrival of a signal. Such direction finders usually employ a circular array and measure the angle of arrival in azimuth only. Two or more direction finders are therefore required to locate the transmitter. If crossed linear antenna arrays are employed then simultaneous measurement of both azimuth and elevation angles of arrival are possible. The second major aim of this investigation was to examine the problems associated with this type of direction finder, and to evaluate the performance of such a system with a view to locating the transmitter from a single receiving site.
CHAPTER 2

REVIEW OF PREVIOUS WORK

INTRODUCTION

The material already published in the open literature relevant to the present investigation can be divided into the following two topic areas:

a) Fading characteristics of ionospherically propagated radio signals. Particular reference is made to measurements obtained using wide aperture antenna arrays.

b) Direction finding, in particular the use of amplitude and phase measurements on multi-element antenna arrays, together with appropriate ionospheric sounding measurements, to determine the location of a target transmitter from a single receiving site (single site location - SSL).

SIGNAL FADEING CHARACTERISTICS

It has been known since the earliest days of radio that the amplitude of an ionospherically propagated signal varies with time on scales ranging from less than a second to more than ten minutes. This variation of signal amplitude is known as 'fading' and the phenomenon is reviewed in a CCIR report [1970]. The main causes of fading are given as:

a) Variations in absorption.

b) Movement of ionospheric irregularities producing focussing and defocussing.
c) Changes of path lengths among component signals propagated via multiple paths and/or multiple modes.

d) Changes of polarisation involving multiple paths and/or multiple modes.

The relationship between multipath propagation and fading characteristics of ionospherically propagated signals has been demonstrated by several investigators [eg. Potter, 1930; Briggs, 1951; Price and Green, 1958; Ames, 1963]. Such work has led to the following conclusions [CCIR, 1970]:

Motions of non-uniformly ionised regions of the ionosphere, as well as motion of regular layers, produces effective changes of path length and Doppler shifts of frequency on each of the individual contributing signal components. The vector addition of these changing signal components gives rise to fluctuations of the composite received signal amplitude, observed at an antenna, which are functions of space, frequency and time. Short-period fluctuations can arise from the interference between components of a single mode and polarisation following closely separated paths, but at HF, they are more generally produced by interference between separate modes and between the ordinary and extraordinary components of each mode.

Long-period variations of field strength are found to depend upon variations of electron density and absorption over extensive ionospheric regions. Such changes exhibit regular variations (diurnal, seasonal, etc) which are modified by superimposed random variations. This thesis is not concerned with absorption effects, and these are not discussed further.

Amplitude distributions

Amplitude distributions measured over short intervals of a few minutes are found to approximate closely to either a Rayleigh distribution
(Equation 2.1) or to a Nakagami-Rice distribution (Equation 2.2) [Nakagami, 1943; McNichol, 1949; Nakagami, 1960].

A very good simulation of the Rayleigh distribution can be obtained by adding together \( n \) unit vectors with a rectangular phase distribution from \( 0 - 2\pi \) (ie: random phases). Norton et al [1955] showed that values of \( n \) greater than about 4 give a satisfactory approximation.

If a steady component is added to the random vectors then the Nakagami-Rice distribution is obtained. For \( A_s \ll A_r \) the Nakagami-Rice distribution approximates to the Rayleigh distribution, and for \( A_s \gg A_r \) the distribution approaches a normal distribution with mean \( A_s \) and standard deviation \( 0.707A_r \).

\[
\begin{align*}
p(A) &= \frac{2}{A_r^2} \int_A^\infty \exp\left(-\frac{A^2}{A_r^2}\right) dA \\
p(A) &= \frac{2}{A_r^2} \int_A^\infty \exp\left(-\frac{(A^2+A_s^2)}{A_r^2}\right) I_0\left(\frac{2AA_s}{A_r^2}\right) dA
\end{align*}
\]

where:

- \( p(A) \) is the probability that the amplitude exceeds \( A \),
- \( A_r \) is the rms value of the random component,
- \( A_s \) is the amplitude of the steady component,
- \( I_0 \) is a modified zero order Bessel function.

**Fading rates**

The rapidity of fading can be defined in various ways [eg. McNichol, 1949; Ratcliffe, 1956; Price, 1957; Rice, 1958]. For example, if the
HISTOGRAM OF CORRELATION TIMES
(after Balser and Smith, 1962)

FIGURE 2.1
autocorrelation function, $R$, of an amplitude record with time, $t$, is represented by a Gaussian curve, then:

$$R(t) = R(0) \exp \left( \frac{-t^2}{2 \sigma^2} \right)$$

The value of $\sigma$ giving the best fit to the observations is a useful measure of the fading period. Figures quoted for this parameter range from 0.5 to 2.5 seconds for some HF paths in multimoded conditions [McNichol, 1949; Grisdale et al, 1957].

Experiments in which a true single mode consisting of one magneto-ionic component has been isolated for study are comparatively rare. Balser and Smith [1962] found some examples of very slow fading in such circumstances. Their results for a 35 µs pulse transmission in the frequency range 1-25 MHz over a 1566 km path in the USA for several ionospheric modes are reproduced in Figure 2.1. There appears to be no significant difference between the 1 hop E and 1 hop F results — both give a most probable fading time of between 10 and 20 seconds; the multiple hop F results, however, nearly always display fading times of several seconds.

More commonly, polarisation rotation when both $O$ and $X$ modes are present leads to fading rates for a single mode of several seconds per cycle. When two or more such modes are present then fading rates of several cycles per second are typical [Gething, 1978].

**Diversity distances**

Signals received at separated antennas are found to display differing fading characteristics, the signals becoming less well correlated as the antenna
separation is increased. This effect is known as 'space diversity'. A similar effect is observed if the signal is received on antennas of opposite polarisation sensitivity - this effect is known as 'polarisation diversity'.

Generally, a strong steady component and a slow fading rate can be considered as corresponding to a nearly plane wavefront. The diversity distance at which the cross-correlation coefficient drops to (say) 0.5 tends, under such conditions, to be comparatively large. For single moded signals, Balser and Smith [1962] found distances of the order of 40λ for single hop paths, and about 10λ for multi-hop paths. Their results are reproduced here as Figure 2.2. A similar, though somewhat shorter, correlation distance is obtained from the more extensive medium frequency data obtained by Brennan and Phillips [1957]. Diversity distances may drop to a few wavelengths in multi-moded conditions [Van Wambeck and Ross, 1951].

Specular and diffracted components

Single moded propagation is often regarded as consisting of a single specularly reflected ray from a smooth ionosphere, surrounded by a cone of subsiduary rays established due to the roughness of the ionosphere. The former is referred to as the specular component, and the latter as the diffracted, or random, components. The concept of specular and diffracted components in the angular power spectrum corresponds well with the 'steady' and 'random' phasors of the Nakagami-Rice fading model.

The origins of this model can be traced to early work on drifting ionospheric irregularities and to studies of amplitude fading at a single antenna element. Booker, Ratcliffe and Shinn [1950] treated the ionosphere as a diffraction grating and showed that the angular power spectrum of the scattered radiation should be proportional to the Fourier transform of the autocorrelation function of the complex amplitude of the emergent wave.
HISTOGRAM OF CORRELATION DISTANCES
IN WAVELENGTHS
(After Balser and Smith, 1962)

FIGURE 2.2
Their one dimensional analysis was extended to two dimensions by Briggs and Phillips [1950].

Three basic parameters can be associated with this model:

a) The coherence ratio, $B$, defined as the ratio of the power in the specular component to the power in the diffracted components (some investigators use the parameter $b = \sqrt{B}$).
b) The angular standard deviation in azimuth.
c) The angular standard deviation in elevation.

Experimental methods for investigating the fine structure of ionospheric modes can be classified as:

a) Measurements of amplitude fluctuations at one antenna.
b) Measurements of amplitude fluctuations at two antennas.
c) Measurements of the fluctuations in the phase difference between two antennas.
d) Measurements involving more than two antennas.

Several authors [eg. Hughes and Morris, 1963] have pointed out that measurements of the amplitude at a single antenna are limited since the shape of the Nakagami-Rice distribution is not very sensitive to the value of the coherence ratio, $B$. This is illustrated in Figure 2.3. Phase measurements are more useful, particularly if the specular component is small ($B << 1$) [Morris and Hughes, 1959, and Hughes and Morris, 1963]. The first authors to give reliable curves [Gething, 1978] for the phase difference distribution as a function of a correlation coefficient, $R$, and the coherence ratio, $B$, were Whale and Gardiner [1966]. Their curves are
NAKAGAMI-RICE AMPLITUDE DISTRIBUTION
(after Gething, 1978)

FIGURE 2.3
reproduced here as Figure 2.4, which differs in detail from the approximate curves given by Hughes and Morris [1963].

Briggs and Phillips [1950] found $B < 1$ from a pulsed experiments at vertical incidence at frequencies of 2.4 MHz and 4.8 MHz. Bramley [1951] conducted a series of experiments employing a pulsed signal at frequencies between 4 MHz and 7 MHz at near vertical incidence and measured values of $B$ in the range 1.7 to 64 with angular spreads of between 0.6° and 3.8°. His results are summarised here in Table 2.1. Hughes and Morris [1963] conducted a series of experiments employing CW signals in the frequency range 6-20 MHz on oblique paths of between 500 km and 1700 km and found values of $B < 3.6$ and angular spreads of between 1.5° and 4.5° in azimuth and between 2.5° and 8.0° in elevation. Their results are reproduced here in Table 2.2.

More recent investigations have cast doubt on the basic model of specular component together with a cone of diffracted rays. Whale and Boys [1968] made phase measurements on pairs of antennas and concluded that in many cases, especially when the propagation distance was only a few thousand kilometres, two or three distinct specular components could be identified. Boys [1968] regards the true coherence ratio as zero. Results obtained by Rice [1973] for a swept frequency CW signal transmitted over a 911 km path received on a 1.18 km broadside array show nearly plane wavefronts (see Figure 2.5) for some modes, leading to the conclusion that the signal is usually resolvable into a relatively small number of discrete signals, and that any random component must be at least 23 dB smaller than the discrete components. Thus a ray interference model better represents the data than a diffracting screen model. These results agree well with observations of vertical incidence (70 μs pulses) signals made on a large aperture (approximately 1 km x 1 km) well filled array made by Felgate and Golley [1971]. They concluded that their observations were produced by the
STANDARD DEVIATION OF PHASE DIFFERENCE BETWEEN TWO SPACED ANTENNAS
(after Whale and Gardiner, 1966)

FIGURE 2.4
Table 2.1 - Measurements of B and $\theta_0$ (angular spread) made by Bramley [1951]. Two antenna pairs were employed, labelled E-W and N-S here.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Frequency</th>
<th>Mode</th>
<th>Ant. pair</th>
<th>$\theta_0$</th>
<th>B</th>
<th>method 1</th>
<th>method 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 July</td>
<td>0940-1005</td>
<td>4.245 E</td>
<td>E</td>
<td>E-W</td>
<td>2.1°</td>
<td>6.76</td>
<td>5.29</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>N-S</td>
<td>N-S</td>
<td>3.8°</td>
<td>3.61</td>
<td></td>
<td></td>
<td>5.76</td>
</tr>
<tr>
<td>1105-1125</td>
<td>6.75</td>
<td>F2</td>
<td>E-W</td>
<td>&lt;0.6°</td>
<td>-</td>
<td>&lt;25.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1105-1125</td>
<td>6.75</td>
<td>F2</td>
<td>E-W</td>
<td>&lt;0.6°</td>
<td>-</td>
<td>&lt;25.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>22 July</td>
<td>0932-0947</td>
<td>4.43 F1</td>
<td>E-W</td>
<td>0.8°</td>
<td>5.76</td>
<td>7.84</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>N-S</td>
<td>N-S</td>
<td>0.9°</td>
<td>4.0</td>
<td>4.84</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1104-1133</td>
<td>4.48</td>
<td>E</td>
<td>E-W</td>
<td>0.8°</td>
<td>1.96</td>
<td>1.69</td>
<td></td>
<td></td>
</tr>
<tr>
<td>29 July</td>
<td>1018-1050</td>
<td>4.49 E</td>
<td>E-W</td>
<td>2.1°</td>
<td>4.84</td>
<td>4.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>N-S</td>
<td>N-S</td>
<td>1.4°</td>
<td>3.24</td>
<td>2.56</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 Aug.</td>
<td>1111-1127</td>
<td>6.76 F2</td>
<td>E-W</td>
<td>&lt;0.6°</td>
<td>-</td>
<td>&lt;16.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16 Aug.</td>
<td>1025-1052</td>
<td>4.43 F1</td>
<td>E-W</td>
<td>0.9°</td>
<td>4.0</td>
<td>12.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>N-S</td>
<td>N-S</td>
<td>0.6°</td>
<td>4.0</td>
<td>4.84</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1111-1134</td>
<td>5.38</td>
<td>F2</td>
<td>E-W</td>
<td>0.9°</td>
<td>5.29</td>
<td>9.61</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>N-S</td>
<td>N-S</td>
<td>0.6°</td>
<td>4.41</td>
<td>4.84</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18 Aug.</td>
<td>1103-1131</td>
<td>6.27 E</td>
<td>E-W</td>
<td>1.2°</td>
<td>7.29</td>
<td>11.56</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25 Aug.</td>
<td>1103-1123</td>
<td>4.69 E</td>
<td>E-W</td>
<td>0.9°</td>
<td>9.0</td>
<td>64.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.2 - Measurements of B, $\theta_a$, and $\theta_e$ (the angular spread in azimuth and elevation) made by Hughes and Morris [1963].

<table>
<thead>
<tr>
<th>Date</th>
<th>Station</th>
<th>Frequency</th>
<th>Range</th>
<th>B</th>
<th>$\theta_a$</th>
<th>$\theta_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.1.58</td>
<td>Luxembourg</td>
<td>6.090</td>
<td>510</td>
<td>1.96</td>
<td>-</td>
<td>6.0°</td>
</tr>
<tr>
<td>19.2.58</td>
<td>Luxembourg</td>
<td>6.090</td>
<td>510</td>
<td>1.69</td>
<td>4.5°</td>
<td>4.5°</td>
</tr>
<tr>
<td>13.3.58</td>
<td>Luxembourg</td>
<td>6.090</td>
<td>510</td>
<td>3.61</td>
<td>-</td>
<td>8.0°</td>
</tr>
<tr>
<td>16.1.58</td>
<td>Washington</td>
<td>20.000</td>
<td>5800</td>
<td>0.16</td>
<td>-</td>
<td>6.5°</td>
</tr>
<tr>
<td>10.2.58</td>
<td>Washington</td>
<td>20.000</td>
<td>5800</td>
<td>0.25</td>
<td>1.5°</td>
<td>6.0°</td>
</tr>
<tr>
<td>12.2.58</td>
<td>Washington</td>
<td>20.000</td>
<td>5800</td>
<td>0.25</td>
<td>-</td>
<td>6.0°</td>
</tr>
<tr>
<td>4.2.58</td>
<td>Nairobi</td>
<td>20.445</td>
<td>7000</td>
<td>0.64</td>
<td>2.0°</td>
<td>5.5°</td>
</tr>
<tr>
<td>24.2.58</td>
<td>Nairobi</td>
<td>20.445</td>
<td>7000</td>
<td>0.64</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>16.1.58</td>
<td>Melbourne</td>
<td>11.710</td>
<td>17000</td>
<td>0.16</td>
<td>2.0°</td>
<td>-</td>
</tr>
<tr>
<td>17.1.58</td>
<td>Moscow</td>
<td>13.710</td>
<td>2600</td>
<td>1.0</td>
<td>2.5°</td>
<td>-</td>
</tr>
<tr>
<td>13.3.58</td>
<td>Rome</td>
<td>20.890</td>
<td>1460</td>
<td>1.96</td>
<td>-</td>
<td>2.5°</td>
</tr>
</tbody>
</table>
Measured phase fronts across an antenna aperture of 1.18 km for six propagation modes at 8.35 MHz identified from an oblique ionogram over a 911 km path.

o, ordinary; x, extraordinary; H, high angle; L, low angle.

Path delays in a) are a, 4.77 ms; b, 4.26 ms; c, 4.19 ms; d, 3.98 ms; e, 3.82 ms; f, 3.25 ms.

(Reproduced from Rice (1973))

**FIGURE 2.5**
interference effects occurring between a small number of discrete rays returned from specular points, and that this is in sharp contrast to the continuous angular power spectrum assumed in most previous work.

DIRECTION FINDING AND SINGLE SITE LOCATION

Background

In principle any antenna with directional properties can be used to measure the direction of arrival of a radiowave. A vertical loop, for example, can be rotated about the vertical axis to give a signal minimum, and, provided that the waves from the transmitter have travelled horizontally, the normal to the loop should point to the transmitter. Such a system is not suited to skywave signals, giving errors in the order of tens of degrees due to the mixed polarisation of the signals after passage through the ionosphere. This source of error was greatly reduced in a system developed by Adcock [1919] consisting of four vertical monopoles at the corners of a square with sides of the order of a few tenths of a wavelength. Such a system was capable of providing both azimuth and elevation angle measurements. The Adcock DF was employed extensively during the Second World War, and considerable efforts were made to identify the various site and instrumental errors and to reduce their magnitudes.

As instrumental errors were reduced, the importance of errors arising from site imperfections and wave interference effects became greater. This led to the development of systems utilising a larger proportion of the incoming wavefront, for example the combination of two or more Adcock DFs in a group system was tried [Crampton, 1947]. Most research was, however, on systems employing wide aperture (greater than a wavelength) circular arrays, principally Wullenweber systems [Rindfleisch, 1956].
The Wullenweber was first introduced as a single ring system with an inner reflecting screen to improve the radiation pattern, the outputs from a sector of approximately one third of the elements in the ring being combined to form a directional pattern (Figure 2.6). In later systems the single monopole elements were replaced by doublets and the inner reflecting screen dispensed with [Byatt, 1967]. This directional pattern was rotated in azimuth by means of a spinning goniometer (a capacitive switch that selects which elements are in use at a given moment), the bearing (azimuth) measurement being made by noting the pointing angle of the goniometer when a minimum signal between the two maxima is observed. Attempts have been made at measuring both azimuth and elevation angles of arrival using a Wullenweber array [eg. Jones, Schlicht and Ernst, 1966].

Interferometer arrays

Interferometer arrays, which are capable of determining the direction of arrival (DOA) of a signal in both azimuth and elevation, have been widely employed in radio astronomy and HF propagation research, and have taken many forms. A review of such arrays for propagation research has been published by Sherrill [1971] in which thirteen different configurations are described, some of which are illustrated here in Figure 2.7. Data obtained from interferometer arrays is easier to interpret if the antennas in each arm are accurately positioned along a straight line and the two arms are orthogonal. Significant deviations from this configuration can make processing of the received signals more difficult.

Usually in such arrays the widest antenna spacing is greater than half a wavelength, and may extend to several wavelengths. Measurements of the phase differences are used to calculate the angle of arrival of the signal to each of the antenna arms. For spacings greater than half a wavelength ambiguities occur in the determined angle of arrival since it is not
RADIATION PATTERN OF A WULLENWEBER ARRAY
(After Gething, 1978)

FIGURE 2.6
EXAMPLES OF HF INTERFEROMETER ARRAYS
(after Sherrill, 1971)

FIGURE 2.7
possible to determine the precise phase difference (true phase difference = n2π + measured phase difference). For this reason additional antennas are employed at spacings of less than half a wavelength to resolve these ambiguities [Dodge and Martin, 1969; Gething, 1978]. The angles of arrival to each of the arms define 'cones of possible DOA', the line of intersection of these cones defining the DOA of the signal.

When access to both transmitter and receiver is available it is often possible to employ a pulsed transmission and to measure the individual time resolved modes [eg. Ross, Bramley and Ashwell, 1951]. This is not, however, the usual situation in operational DF systems where it is frequently required is to locate an unco-operative transmitter. Methods have been devised to overcome this problem under certain circumstances, for example, by taking measurements at the leading edge of an amplitude keyed signal - the so-called 'dot lock technique' [Wireless Engineer, 1938] - when only the component of the signal which has travelled by the shortest route is measured. The measurement is not, therefore, subject to interference by the longer-path components.

Wave front testing and mode resolution

Interferometer array measurement of the DOA are severely restricted by interference effects between multiple modes. Two approaches have been adopted by various investigators to overcome this problem: (a) restriction of measurements to times when a single mode is predominant, and (b) resolution of the several modes present.

Treharne [1967, 1973] suggests that the direction of arrival of a single mode can be determined by an interferometer, even when the signal is multi-moded. This technique relies on the relative fading between modes to produce periods of 'quasi uni-modal propagation' (QUMP) when the DOA of the
remaining mode can be determined. The probability of this situation occurring decreases rapidly if more than two significant modes are present [Gething, 1978]. The periods of QUMP can be selected by testing the phase linearity of the wave front of the received signal - eg. the phases measured on a linear array of antennas must have (to within reasonable limits) a linear relationship, indicative of a planar wave front. Rice [1982] undertook such measurements on both CW and modulated signals and concluded that amplitude modulation significantly shortens the interval between phase linear events. A more rigorous approach would test for both phase linearity and amplitude equality over the elements of the array.

An alternative to measuring during periods of QUMP is to resolve the constituent modes. One such technique was developed by Bailey and McClurg [1963]. Their method involved a 'sum and difference polygon display' in which the signals from pairs of antennas were combined in such a way (see Figure 2.8) as to display on a storage oscilloscope polygons, the angles of the parallel sides being equal to the angles of arrival of the constituent modes to the line between the antennas. The lengths of the sides of the polygon are proportional to the relative amplitudes of the modes. Details of the formation of these polygons are given by Gething [1978]. Sufficient time is required to build up a polygon and under unfavourable conditions (eg. changing mode content.) clear polygons will not be produced.

A further mode resolution technique which has been applied in experimental tests is that of wave front analysis (WFA). Several variations of this method have been reported in the literature, for example, Gething et al [1969] describe measurements on a vertical stack of three antennas to determine the elevation angle using a technique given by Wilkins and Minnis [1956]. Later experiments are reported by Clarke and Tibble [1978] in which a vertical stack of eight antennas were employed. In the WFA technique

2.11
Basic components of a radio direction finder incorporating sum-and-difference interferometer system techniques (after Bailey and McClurg, 1963)

FIGURE 2.8
[Gething, 1978] the complex signal amplitude is instantaneously sampled at several antennas. Equations are then solved to find complex coefficients to combine the signal samples to give a zero output. This is, in effect, postprocessing of the data to find a radiation pattern for the antenna which has nulls in the directions along which the signal components arrive at the antenna. Several sets of samples and solutions at different groups of antennas may be required to resolve all ambiguities.

Transmitter location

Traditional DF systems employ two or more receiving sites at well separated locations, each measuring the azimuthal direction of arrival (bearing) of a signal. The location of the transmitter is then determined by simple triangulation techniques.

If the DOAs of several rays from a distant transmitter have been determined, and that the state of the ionosphere is known in sufficient detail, then it is possible, in principle, to trace back along the ray paths to the transmitter. Ideally, all such rays should intersect, perhaps after one or more ground reflections, at the transmitter site.

Details of ray tracing techniques can be found in text books such as those by Budden [1966] and Kelso [1964]; a summary is given by Gething [1978]. A widely used three dimensional ray tracing program was developed by Jones [1966]. Full ray tracing techniques require a detailed knowledge of the ionosphere over the path of the radio wave. Over limited ranges and under favourable conditions simpler techniques can be employed, such as those discussed by Reilly [1983].

2.12
CONCLUDING REMARKS

Although much research effort has been devoted to the measurement of the directions of arrival of radio signals reflected from the ionosphere at oblique incidence several major problems still exist. It is evident that more detailed measurements of the wave front planarity are required for a range of propagation paths and ionospheric conditions. In this thesis an attempt is made to resolve some of these problems.
INTRODUCTION

To measure the temporal and spatial variations of the phase and amplitude of a radiowave reflected from the ionosphere a network of dedicated remote transmitters would, ideally, have been employed. Since this was not generally available, recourse was made to existing European broadcast transmitters in the frequency range 1 to 30 MHz. In additional experiments the mode structure of the signals received over a 122 km path was determined by means of a pulsed transmitter under our own control.

The spatial distributions of the signal characteristics were observed on one of two seven element antenna arrays located at the GCHQ Blakehill Radio Research Station in Wiltshire. One had a largest dimension of 1526 metres and the other a largest dimension of 294 metres. The phase and amplitude was measured by means of a seven channel receiver, each channel being phase coherent and connected to one of the antenna elements. The outputs of the receivers were sampled by a computer controlled interface and the data recorded on magnetic tape for subsequent processing and analysis on the mainframe computer at the University of Leicester. A separate wide bandwidth receiver and recording system was employed for the pulsed signal observations.

Some of the equipment had been constructed prior to the start of this investigation, details of which can be found by reference to Thomas [1986].
THE ANTENNA ARRAYS

Both antenna arrays were comprised of elevated feed vertical monopoles. This type of antenna element was adopted because it provides a large bandwidth and a low elevation angle of the main lobe. The elements were commercially supplied and installed on the site. Details of the antenna arrays are now given.

The large (Forward Look) array

This array consisted of seven vertical monopoles arranged in a V formation (see Figure 3.1). The four antennas along each arm (antenna 4 common to both arms) were arranged with separations approximately in the ratio 1:3:2 (a minimum redundancy configuration); this enabled all spacings in multiples of 200 m up to 1200 m (approximately) to be obtained along each arm. The relative positions of the antennas were determined to an accuracy of ±1 m by conventional site surveying techniques and are given in Table 3.1.

Each of the seven antennas was connected to its receiver by means of gas pressurised coaxial cable (several lengths to a total of approximately 1500 metres for each antenna). The final electrical lengths of the feeders were equalised by adding lengths of RG58 cable in order to preserve the relative phases of the signal as measured at each antenna element. The differences in the cable lengths were measured by means of a pulse reflection technique and equalised to within ±2 ns in the pulse reflection time (equivalent to an error of ±3.6° in phase at 10 MHz).

The small (Verbena) array

This array consisted of 24 vertical monopoles arranged in a Y formation (see Figure 3.2). Seven of these antennas were employed in a configuration
FORWARD LOOK ANTENNA POSITIONS

FIGURE 3.1
Table 3.1 - Forward Look antenna positions. Positions are given on a 1 m grid with the positive y-axis pointing north. Surveying accuracy ±1 m.

<table>
<thead>
<tr>
<th>Antenna</th>
<th>$x$</th>
<th>$y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-707.156</td>
<td>-838.594</td>
</tr>
<tr>
<td>2</td>
<td>-479.921</td>
<td>-572.604</td>
</tr>
<tr>
<td>3</td>
<td>-134.785</td>
<td>-151.365</td>
</tr>
<tr>
<td>4</td>
<td>0.</td>
<td>0.</td>
</tr>
<tr>
<td>5</td>
<td>156.113</td>
<td>-83.993</td>
</tr>
<tr>
<td>6</td>
<td>527.235</td>
<td>-497.364</td>
</tr>
<tr>
<td>7</td>
<td>815.292</td>
<td>-736.865</td>
</tr>
</tbody>
</table>
VERBENA ANTENNA POSITIONS

FIGURE 3.2
Table 3.2 - Verbena antenna array positions and feeder lengths. Positions are on a 1 m grid with the positive y-axis pointing north.

<table>
<thead>
<tr>
<th>Antenna</th>
<th>x</th>
<th>y</th>
<th>feeder length</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-167.46</td>
<td>-23.57</td>
<td>302.189 m</td>
</tr>
<tr>
<td>2</td>
<td>-104.03</td>
<td>-14.62</td>
<td>225.777 m</td>
</tr>
<tr>
<td>3</td>
<td>-21.76</td>
<td>3.06</td>
<td>127.224 m</td>
</tr>
<tr>
<td>4</td>
<td>3.02</td>
<td>7.46</td>
<td>111.341 m</td>
</tr>
<tr>
<td>5</td>
<td>13.40</td>
<td>-17.15</td>
<td>127.280 m</td>
</tr>
<tr>
<td>6</td>
<td>64.63</td>
<td>-82.73</td>
<td>225.734 m</td>
</tr>
<tr>
<td>7</td>
<td>104.57</td>
<td>-133.84</td>
<td>302.216 m</td>
</tr>
</tbody>
</table>
similar to that of the Forward Look array, but with a largest dimension of 294 m. The antenna positions and the electrical lengths of the feeder cables were determined by GCHQ and are given in Table 3.2.

**Geographic location**

The field site at which both of the antenna arrays were sited was located at geographic coordinates 51.63° N, 1.89° W.

**THE RECEIVER**

**Hardware**

The receiving arrangement, see Figure 3.3, was designed to measure the phase and amplitude of the signals received on each of the antenna elements simultaneously. The outputs were suitable for interfacing with a computer controlled data logging system, and facilities for computer controlled calibration were also provided.

Each of the signal inputs was connected to one of seven Racal RA117S slave receivers. The local oscillator signals were derived from common synthesised generators to enable accurate tuning of the system, and to allow meaningful comparative phase measurements. An eighth similar receiver driven from a synthesised reference frequency (against which the phases of the seven signals were determined) operating 2 Hz below the nominal signal was provided. This frequency offset enabled the small Doppler shifts imposed on a signal due to ionospheric movements around the reflection region to be observed (although complex samples of the received signal were recorded which would have enabled the frequency changes to be subsequently calculated without this offset, a spectrum analyser was directly connected to the equipment. Under these circumstances the frequency offset was
BLOCK DIAGRAM OF THE 7 CHANNEL RECEIVER

FIGURE 3.3
required to prevent ambiguities between positive and negative frequency changes).

The 100 kHz intermediate frequency (IF) outputs of the seven signal receivers were each connected to the inputs of two phase sensitive detectors (Aim PSD122A). The phase references were driven by two signals in quadrature derived from the 100 kHz IF output of the reference receiver. Each channel, therefore, had two outputs, R and I, in quadrature which can be described by Equations 3.1(a) and 3.1(b).

\[
R = a \cos(\theta - \theta') \quad 3.1(a)
\]
\[
I = a \sin(\theta - \theta') \quad 3.1(b)
\]

where:
- \(a\) is the amplitude of the IF signal,
- \(\theta\) is the phase of the IF signal, and
- \(\theta'\) is the phase of the IF signal from the reference receiver.

Hence:

\[
a = \sqrt{R^2 + I^2} \quad 3.2(a)
\]
\[
(\theta - \theta') = \tan^{-1}(I/R) \quad 3.2(b)
\]

Equations 3.2(a) and 3.2(b) indicate that both the amplitudes of the IF signals and their phases relative to the IF signal of the reference receiver can be determined.

**Calibration**

Equations 3.2(a) and 3.2(b) do not directly relate to the input signals since no account is taken of the amplitude and phase transfer.
characteristics of the individual receivers. Thus a calibration facility was provided whereby the signals from the antennas were replaced by a signal from the reference frequency generator fed via a switchable attenuator (both switching and attenuation level being controlled by the computer). In this way the amplitude and phase characteristics of each of the receivers were measured, and typical results are reproduced in Figure 3.4. The detected amplitude is on a scale of 0 to 511 corresponding to the digital output of the analogue to digital converter (ADC). Amplitude and phase calibration functions, $C_A(x)$ and $C_p(x)$ respectively, are defined by these measurements where $x$ is the calibration amplitude. From these calibration data the amplitudes of the input signals (relative to the maximum calibration signal level) and their phases (relative to the reference phase) were determined by post processing of the recorded data.

The phase, relative to the reference, and the amplitude of the signal are determined from the following relations:

$$A = C_A^{-1}(a)$$  \hspace{1cm} 3.3(a)

$$(\phi - \phi') = (\theta - \theta') - C_p(A)$$  \hspace{1cm} 3.3(b)

where:

- $A$ is the amplitude of the signal at the receiver input,
- $\phi$ is the phase of the signal,
- $\phi'$ is the phase of the reference signal,
- $C_A^{-1}$ is the inverse amplitude calibration function, and
- $C_p$ is the phase calibration function.

The calibration curves of Figure 3.4 were obtained with the receiver IF gain set manually. Figure 3.5 presents a similar curve but for automatic gain control (AGC), the flatness of the amplitude characteristic illustrates the
Typical calibration curves for one channel with the receiver set for manual gain control.

FIGURE 3.4
Typical calibration curves for one channel with the receiver set for automatic gain control.

**FIGURE 3.5**
unsuitability of this mode of operation for the measurement of signal amplitude.

Due to the valve based construction of the Racal RA117S receivers there was a noticeable tendency for the transfer characteristics to change slightly with time. This is illustrated in Figure 3.6 for several calibration curves taken at intervals of between 3 minutes and 5 hours. Little change occurs over periods of several minutes, whereas the changes in the amplitude characteristic become significant over periods of several tens of minutes. For this reason the system was calibrated at intervals of approximately 3 minutes.

THE COMPUTER SYSTEM

Hardware
The collection and logging of data, and the calibration of the receivers, was performed under the control of a minicomputer based system (Figure 3.7), the main components of which were:

a) DEC PDP8/E minicomputer containing 8 kwords of core memory and several interfaces to the other components of the system.
b) Visual display unit (VDU) for communication with, and control of, the computer.
c) Racal Digistore twin data cassette unit for program storage.
d) Potter MT-SW seven track write only magnetic tape drive. All signal and calibration data were recorded on this unit in a form suitable for transfer to the CDC Cyber 73 mainframe computer at Leicester University.
e) Time of day clock.
f) Programmable clock to provide timing functions for the time dependent software routines.
Typical calibration curves for one channel showing the time variability and illustrating the need for frequent calibration.

FIGURE 3.6
16 channel ADC

To phase sensitive detector outputs

To programmable attenuator

To antenna relays

7 channel magnetic tape unit

DK8-ES programmable clock

PDP8/E minicomputer

Calibration interface

Racial Digistore cassette deck

VDU

Time of day clock

**BLOCK DIAGRAM OF THE COMPUTER SYSTEM**

**FIGURE 3.7**
g) 16 channel, 10 bit analogue to digital convertor (DEC AD08) to measure the output voltages of the phase sensitive detectors. The conversion time of this unit was 10 µs, however due to software overhead the time taken to sample all channels and buffer them into memory was 300 µs.

h) Calibration interface to provide control of the programmable attenuator and the antenna relays allowing for computer controlled calibration of the receivers.

Due to speed restrictions imposed by the magnetic tape drive the maximum rate at which all the phase sensitive detector outputs could be sampled, and the data recorded, was 9 times per second.

Control software

To control the equipment a special version of DEC BASIC/RT [Digital Equipment Corporation, 1972] was developed which contained several additional commands to those of the standard language [Thomas, 1986]. This approach had several advantages:

a) Additional commands were provided for the control of the non standard peripherals, thus avoiding the need to use PEEK/POKE type commands.

b) Since BASIC/RT is an interpretive language all commands could be entered for immediate execution.

c) Time critical elements were written in assembler code and incorporated into the interpreter. Such functions could not easily have been implemented using the normal BASIC commands.

d) Different control sequences could easily be entered without the need for recompilation or assembly, both of which are lengthy and potentially awkward tasks on a small system without disc drives.
PULSE SOUNDER

Most of the measurements were of transmissions received from central European broadcast stations radiating continuous carrier signals. The mode content of the signals could only be estimated from prediction programs, or from vertical ionosonde measurements made at a limited number of locations, since direct measurements were not possible. Since the measured propagation characteristics are critically dependent upon the modal structure of the received signals a series of experiments was undertaken in which the mode content was measured directly. This required the transmission from Leicester of a normal continuous carrier which was replaced at regular intervals by a pulse transmission from which the mode structure was determined. A separate receiver and recording system was developed for the pulse signal.

The format of the pulse signal, reproduced in Figure 3.8, consisted of a 0.7 ms pulse in the centre of a 21.7 ms break in the carrier signal, repeated at 89.7 ms intervals. The long (68 ms) period of carrier was included between the pulses in order to operate the AGC of the receiver.

The transmitter

Figure 3.9 is a block diagram of the pulse transmitter, which consisted of the following major sections:

a) Synthesised frequency generator to give an accurate and stable transmission frequency (essential for the normal data collection).
b) 400W transmitter consisting of a Heathkit DX40 driving a Redifon GA406 power amplifier.
PULSE SIGNAL FORMAT

FIGURE 3.8
THE PULSE TRANSMITTER

FIGURE 3.9
c) Antenna system: KW107 antenna tuning unit and a half wave horizontal dipole.

d) Keyer based around a small dedicated M6800 microprocessor based system. Timing was provided by an external crystal controlled clock connected to one of the processor's interrupt lines.

The receiver and data recorder

A diagram of the equipment for the reception and recording of the pulsed signal is reproduced in Figure 3.10. The receiver, a Racal RA117 with 1.2 kHz bandwidth, was fitted with an amplitude detector which had a dc output, in the range 0 to 5 volts, proportional to the amplitude of the IF signal. A real time clock was also constructed, the time being output at minute intervals in a serial BCD format. Both of the signals were recorded on two separate channels of a Fenlow TR4 FM tape recorder for subsequent digitisation and analysis.

Data digitisation

The data recorded on the FM tape were digitised at Leicester and transferred to the University's mainframe computer via an interactive terminal service line. The digitising equipment, see Figure 3.11, was designed around an M6800 microcomputer system provided with an analogue to digital converter, a real time clock, and a serial link to the mainframe computer.

In order to reduce the amount of data to be transferred the beginning of a break in carrier was recognised by software and then 256 samples at 87.9 μs intervals taken. These data were then transferred in the form of a series of hexadecimal numbers to a file on the mainframe computer.
Dipole antenna

Racal RA117 HF receiver

100 kHz IF

Amplitude detector

0 - 5 V

Digital time of day clock

Serial data

FM tape recorder

RECEIVER AND DATA RECORDER

FIGURE 3.10
DATA DIGITISATION EQUIPMENT

FIGURE 3.11
CONCLUDING REMARKS

The equipment used to collect and record the data and diagnostic information (pulse sounder) has been described. A discussion of the measurement errors involved is included in Chapter 4 where several sets of test data are presented. A large quantity of data were obtained for several paths and frequencies, analysis of which is presented in subsequent chapters.
INTRODUCTION

During the period of the experimental work (1978-1981) an extensive set of data were collected for several different propagation paths and conditions (see appendix A). The locations of the principal transmitters employed are illustrated in Figure 4.1. These transmitters provide both ground wave and sky wave paths.

For signals received via ground wave propagation no distortion of the wave front occurs, as is the case for sky wave propagation. Ground wave signals were therefore employed to validate the correct operation of the equipment. A preliminary discussion of the sky wave observations is also presented, including the determination of the mode content by oblique pulsed sounding.

EQUIMENT VALIDATION AND MEASUREMENT ERRORS

Stability check

Several sets of data were collected for local medium wave broadcast stations (ground wave signals). For these signals no distortion of the wave front occurs, and the lines of constant phase are circular with their centres at the transmitter. Thus, from a knowledge of the separations of the transmitter and the measuring sites, the phase differences at each of
Gnomic zenithal projection of northern Europe with the locations of the transmitters referred to in the text marked.

FIGURE 4.1
the array elements can be accurately determined. A typical example of this type of signal, measured using the Forward Look antenna array, is presented in Figure 4.2(a) for BBC Radio Wales (882 kHz) from Washford. A similar example for the Verbena array, for BBC Radio 2 (693 kHz) from Droitwich, is reproduced in Figure 4.2(b). These diagrams represent: (a) the amplitude, plotted as a solid line on a scale in which the peak calibration amplitude is given as 100; and (b) the phase, plotted as a broken line, for each of the seven channels. To prevent an excessive number of phase cycles being displayed as a result of the -2 Hz offset of the reference signal the phase data had the linear trend removed prior to plotting. The trend was calculated for the channel 4 signal and this value was removed for each of the seven channels. The data presented in Figure 4.2(b) do, however, contain interference from a co-channel station with an amplitude of approximately 0.1 that of the desired signal. When allowance is made for this interference it is evident from Figure 4.2 that: (a) the amplitude remains constant on each channel, confirming that each receiver has a stable amplitude characteristic over the period between calibrations; and (b) the phase remains constant (after removing the linear trend) again confirming the stability of the receivers. This also demonstrates that the phase of the reference signal is stable relative to that of the transmitter.

Amplitude measurements

A somewhat unexpected effect, evident in Figure 4.2, is that the signal amplitudes measured at each of the antennas are different. These differences are more pronounced on data acquired from the Forward Look array. Typical examples of these measurements are reproduced in Table 4.1. Several features are apparent from these data: (a) the relative amplitudes are different for each of the test transmitters, and (b) slight differences occur between measurements made for the same transmitter on different days. There are several possible causes for these differences, all of which are
Transmitter location: Washford
Frequency: 0.882 MHz.
Date: 17/5/79

FIGURE 4.2(a)
Transmitter Location: Droitwich
Frequency: 0.685 MHz
Date: 2/2/61

PHASE (DEGREES) RELATIVE AMPLITUDE

CHANNEL NO. 7
180
90
0
360

CHANNEL NO. 6
180
90
0
360

CHANNEL NO. 5
180
90
0
360

CHANNEL NO. 4
180
90
0
360

CHANNEL NO. 3
180
90
0
360

CHANNEL NO. 2
180
90
0
360

CHANNEL NO. 1
180
90
0
360

TIME (GMT)
Table 4.1 - Comparison of the amplitudes measured at each of the antennas for several groundwave signals. The amplitudes have been scaled such that the amplitude on channel 4 is given as 100.

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Date</th>
<th>Array</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.693</td>
<td>17/05/79</td>
<td>FL</td>
<td>174</td>
<td>189</td>
<td>159</td>
<td>100</td>
<td>159</td>
<td>174</td>
<td>193</td>
</tr>
<tr>
<td>0.862</td>
<td>16/01/79</td>
<td>FL</td>
<td>262</td>
<td>315</td>
<td>290</td>
<td>100</td>
<td>246</td>
<td>292</td>
<td>290</td>
</tr>
<tr>
<td>0.882</td>
<td>19/01/79</td>
<td>FL</td>
<td>263</td>
<td>290</td>
<td>273</td>
<td>100</td>
<td>241</td>
<td>273</td>
<td>263</td>
</tr>
<tr>
<td>1.340</td>
<td>24/10/78</td>
<td>FL</td>
<td>121</td>
<td>137</td>
<td>102</td>
<td>100</td>
<td>*</td>
<td>117</td>
<td>120</td>
</tr>
<tr>
<td>0.693</td>
<td>02/02/81</td>
<td>V</td>
<td>130</td>
<td>130</td>
<td>90</td>
<td>100</td>
<td>149</td>
<td>109</td>
<td>90</td>
</tr>
</tbody>
</table>
probably present to some extent. They are as follows:

a) Differences in the cables and connectors.

b) Differences in antenna environment. This can produce variations in antenna gain and polar sensitivity pattern. Possible causes are: varying ground conductivity, local trees, buildings, adjacent antennas, etc.

These effects are also likely to affect the phase of the measured signal.

**Phase measurements**

As a check on the positions of the antennas from the site survey, the equality of the lengths of the feeder cables, and of the effects of the antennas' differing environments, the expected phases (relative to channel 4) were calculated assuming spherical wave fronts. These were compared with the measured values for several ground wave signals; the results are presented in Table 4.2 for the Forward Look array, and in Table 4.3 for the Verbena array.

**a) Forward Look antennas.** Good agreement was obtained between the measured and expected values for all of the test signals. In all but one case the agreement is within the accuracy of the phase sensitive detectors (±3°/channel = ±6° in the phase difference measurement).

**b) Verbena antennas.** In this case good agreement is obtained between the measured and expected phases with the exception of channel 5 which deviates by 21°. This is probably a consequence of the signal propagating in the line of sight of some of the other array elements, thus screening antenna 5 (NB: the array contained 24 elements of which 7 were employed for these tests). For these data a low level of
Table 4.2 - Comparison of measured and expected phases observed using the Forward Look array for several ground wave signals. The phases are expressed relative to channel 4.

<table>
<thead>
<tr>
<th>Antenna number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Expected phase</strong></td>
<td>210°</td>
<td>165°</td>
<td>160°</td>
<td>43°</td>
<td>0°</td>
<td>265°</td>
<td>78°</td>
</tr>
<tr>
<td><strong>Measured phase</strong></td>
<td>211°</td>
<td>160°</td>
<td>161°</td>
<td>42°</td>
<td>0°</td>
<td>261°</td>
<td>82°</td>
</tr>
<tr>
<td><strong>Phase error</strong></td>
<td>-1°</td>
<td>5°</td>
<td>1°</td>
<td>-4°</td>
<td>-4°</td>
<td>-5°</td>
<td></td>
</tr>
</tbody>
</table>

BBC Radio Swindon, 1.34 MHz.

BBC Radio Wales, Washford, 0.882 MHz.

<table>
<thead>
<tr>
<th>Antenna number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Expected phase</strong></td>
<td>358°</td>
<td>13°</td>
<td>201°</td>
<td>0°</td>
<td>265°</td>
<td>113°</td>
<td>321°</td>
</tr>
<tr>
<td><strong>Measured phase</strong></td>
<td>3°</td>
<td>13°</td>
<td>195°</td>
<td>0°</td>
<td>255°</td>
<td>107°</td>
<td>321°</td>
</tr>
<tr>
<td><strong>Phase error</strong></td>
<td>-5°</td>
<td>0°</td>
<td>6°</td>
<td>-1°</td>
<td>6°</td>
<td>0°</td>
<td></td>
</tr>
</tbody>
</table>

BBC Radio 2, Droitwich, 0.693 MHz.

<table>
<thead>
<tr>
<th>Antenna number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Expected phase</strong></td>
<td>151°</td>
<td>332°</td>
<td>259°</td>
<td>0°</td>
<td>265°</td>
<td>217°</td>
<td>328°</td>
</tr>
<tr>
<td><strong>Measured phase</strong></td>
<td>155°</td>
<td>329°</td>
<td>252°</td>
<td>0°</td>
<td>261°</td>
<td>213°</td>
<td>322°</td>
</tr>
<tr>
<td><strong>Phase error</strong></td>
<td>-4°</td>
<td>3°</td>
<td>7°</td>
<td>-2°</td>
<td>4°</td>
<td>6°</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.3 - Comparison of measured and expected phases obtained using the Verbena array for a ground wave signal. The phases are expressed relative to channel 4.

BBC Radio 2, Droitwich, 0.693 MHz.

<table>
<thead>
<tr>
<th>Antenna number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Expected phase</strong></td>
<td>2°</td>
<td>359°</td>
<td>355°</td>
<td>0°</td>
<td>338°</td>
<td>277°</td>
<td>229°</td>
</tr>
<tr>
<td><strong>Measured phase</strong></td>
<td>0°</td>
<td>359°</td>
<td>359°</td>
<td>0°</td>
<td>359°</td>
<td>270°</td>
<td>222°</td>
</tr>
<tr>
<td><strong>Phase error</strong></td>
<td>2°</td>
<td>0°</td>
<td>-4°</td>
<td>-21°</td>
<td>7°</td>
<td>7°</td>
<td></td>
</tr>
</tbody>
</table>
interference from a co-channel station was present, the effects of which were removed by averaging.

**System errors**

Several sources of error in the measurement of the signal parameters existed in the receiving system. These are identified below:

a) Differences in the efficiency and polar sensitivity pattern of each antenna due, for example, to ground conductivity, nearby obstacles (trees, etc) or nearby antennas. The latter is particularly apparent in the ground wave test data for the Verbena antennas (see Table 4.3) where the measured phase is $21^\circ$ in error for one of the antenna elements.

b) Positional inaccuracies of the antennas. The Forward Look array was surveyed by conventional site surveying techniques to an accuracy of \( \pm 1 \text{ m} \). The effect of this on the phase measurements is frequency and direction of arrival dependent (\( 1 \text{ m} \equiv 1.2^\circ \text{ at } 1 \text{ MHz} \); and \( 1 \text{ m} \equiv 12^\circ \text{ at } 10 \text{ MHz} \) for ground wave signals). The expected errors are less for greater elevation angles of arrival. The Verbena array positions were accurately determined to within several centimetres by GCHQ.

c) Inaccuracies in the cable lengths. The Forward Look cables were equalised in electrical length to \( \pm 30 \text{ cm} \) (\( \equiv 3.6^\circ \text{ at } 10 \text{ MHz} \)).

d) Changes in the characteristics of each of the receivers between calibrations. This source of error is in the region of \( \pm 1^\circ \) in phase and less than \( \pm 1\% \) in amplitude.

e) Inaccuracies in the phase sensitive detectors: \( \pm 3^\circ \)

f) ADC quantisation errors.
AMPLITUDE AND PHASE MEASUREMENTS

In this section several examples of the amplitude and phase measurements are presented, and specific characteristics of the observations discussed. The examples of ground wave (693 kHz and 892 kHz) data presented in Figure 4.2 have no interest other than as an equipment check and evaluation of the errors imposed by the system.

Amplitude and phase measurements for the 909 kHz BBC Radio 2 transmission from Droitwich (path length: 76 km) are reproduced in Figure 4.3. Regular amplitude fading is present together with rapid phase changes at the times of amplitude minima. This type of fading is consistent with that produced by interference between two signals of approximately equal amplitude with a slight difference in frequency (in this case approximately 0.03Hz). This situation has been modelled and the resulting amplitude and phase changes are presented as Figure 4.4 for 3 values of the relative amplitudes. The amplitude and phase variations obtained in this way are similar to those observed experimentally. This situation would correspond to a ground wave component received together with a single sky wave component of about equal amplitude which would be expected in the case of the Droitwich/Blakehill path.

The major objective of this study was to investigate the characteristics of signals received from distant HF transmitters via the ionosphere. As a typical example of this type of propagation a series of measurements for the 9.535 MHz Swiss Radio International signal from Sarnen, Switzerland between 18:15 and 19:10 GMT on 21 November 1979 is presented in Figure 4.5. Vertical ionograms taken at Slough at 18:00 and 19:00 GMT indicate that the following modes of propagation were possible for the oblique path:
Transmitter Location: Droitwich
Frequency: 0.909 MHz.
Date: 17/5/79

FIGURE 4.5
Model of two mode interference effects. The amplitudes of vector $T$ (relative to vector $S$) are: (a) 0.2, (b) 0.6 and (c) 1.0. The phases are shown relative to vector $S$.

**FIGURE 4.4**
Transmitter location: Sarnen, Switzerland
Frequency: 9.535 MHz.
Date: 21/11/79

FIGURE 4.5(a)
Transmitter location: Sarnen, Switzerland

Frequency: 9.555 MHz.

Date: 21/11/79
Transmitter location: Sarnen, Switzerland
Frequency: 9.535 MHz.
Date: 21/11/79
Transmitter location: Sarnen, Switzerland
Frequency: 9.535 MHz.
Date: 21/11/79
Transmitter Location: Sarnen, Switzerland
Frequency: 8.355 MHz
Date: 21/11/79
Transmitter location: Sarnen, Switzerland
Frequency: 9.535 MHz.
Date: 21/11/79
Several features are apparent from these data and are noted below:

a) Fading is always present.

b) Both the fading rate and depth vary, some records (Figure 4.5(a), (e) and (f) particularly) exhibit several fading rates (i.e. fast fading superimposed on a slower fading). Reference to the type of model illustrated in Figure 4.4 suggests that at least three components are probably present, although some of the longer period fading may also be due to in-mode effects.

c) The vertical ionograms only give an indication of the modes likely to be present, and not the number of components actually present at a given time. It appears that the relative strengths of the signal components can change on very short (< minute) time scales.

A more detailed discussion of sky wave signals is contained in Chapter 5, particular attention being given to periods of single moded propagation.

SPECTRAL ANALYSIS OF THE RECEIVED SIGNAL

In the previous section the marked fading due to multi-moded propagation was discussed and the problems of determining the mode content of the signal at any specific time was noted. The vertical ionograms from Slough can only give an approximate guide to the possible modes present, and the relative amplitudes of the modes can vary appreciably on time scales much shorter than the interval between routine soundings. Since the modes combine to produce temporal fading there must be a small frequency difference between them due to the motions of the ionosphere around the reflection points. It
appears therefore that the relative amplitudes and frequencies of the constituent modes could be determined by Fourier analysis of the recorded signal using a FFT routine.

The results of this type of analysis on the data of Figure 4.5 are presented in Figure 4.6, in which 1024 data points taken over approximately 112 seconds are analysed by the FFT procedure. As expected the resulting frequency spectra contain several peaks, this feature is particularly evident in Figure 4.6(b) and (f). However, the peaks are not always discrete, indicating that the constituent modes are of an almost identical frequency. In these cases it is difficult to employ this technique for mode identification. A further problem arises since the 1024 point transforms were calculated on data collected over a 112 second interval. During this interval the relative amplitudes and phases of the constituent modes may change several times as illustrated in Figure 4.5. To overcome this problem fewer points can be input to the transform, but this leads to a corresponding reduction in the frequency resolution. This limitation implies that the spectral analysis technique can only provide a guide to the likely mode content and may not provide unambiguous information regarding the modal activity at any given time.

**PULSE SOUNDING**

To overcome the problems outlined in the previous sections in determining the mode content of the signals, a dedicated transmitter operating on 4.7925MHz was set up in Oadby, Leicester (see Chapter 3 for details). This radiated a continuous carrier signal which was interrupted at approximately 3 minute intervals (the period between receiver calibrations) and a series of 0.7 ms pulses were radiated (see Chapter 3 for precise format). Although this system did not allow sounding of the path at the same time as the
AMPLITUDE SPECTRA FOR CHANNEL 7. 112 SECOND TIME WINDOW.
(a) Corresponds to the data in Figure 4.5(a) at 18:16 GMT
(b) Corresponds to the data in Figure 4.5(b) at 18:22 GMT

FIGURE 4.6
AMPLITUDE SPECTRA FOR CHANNEL 7. 112 SECOND TIME WINDOW.
(c) Corresponds to the data in Figure 4.5(c) at 18:33 GMT
(d) Corresponds to the data in Figure 4.5(d) at 18:39 GMT
AMPLITUDE SPECTRA FOR CHANNEL 7. 112 SECOND TIME WINDOW.

(e) Corresponds to the data in Figure 4.5(e) at 18:55 GMT
(f) Corresponds to the data in Figure 4.5(f) at 19:08 GMT
amplitude and phase data were being acquired, only 3 minutes elapsed between sounding periods. Thus a very considerable improvement was achieved over the results obtained from vertical ionograms which were taken some distance from the path mid-point and at only hourly intervals. Care should be taken in interpreting the pulse returns, however, since the higher amplitude pulses may be limiting in the receiver (the continuous carrier inserted between the pulses to operate the receiver AGC may have an amplitude less than that of the higher amplitude pulses due to destructive interference between the constituent modes). At times when the O and X components are reflected from similar virtual heights they are not distinguishable as separate peaks, but cause slight broadening of the received pulse.

Four examples of pulse sounding returns together with the corresponding amplitude/phase plots (for the Forward Look array) and FFTs are presented as Figures 4.7, 4.8, 4.9, and 4.10, and are discussed individually below:

a) Figure 4.7. Two pulse sounding sequences acquired at 14:26 GMT and 14:29 GMT indicate predominantly single moded propagation with (on the 14:29 GMT sounding) a small secondary mode present. Each frame of the figures represents the pulse returns at 180 ms intervals. The small secondary mode is fading, reaching a peak amplitude of, at most, 0.25 that of the main mode. The time delay between the pulses (approximately 1.5 ms) is consistent with 1 and 2 hop propagation from the F region at 225 km. This is also consistent with the modal content/ reflection heights estimated from the ionogram taken at Slough at 14:59 GMT. The amplitude of the signal recorded on each element of the receiving array between these two sounding sequences remains essentially constant (see Figure 4.7(b)), although some of the channels do exhibit fading (eg. channel 2 at 14:27:15 GMT) consistent with two modes of relative
OSDBY PULSE SOUNDING, FREQUENCY=4.9725 MHZ. 22/1/80.

Data corresponds to sounding immediately before and after the phase and amplitude data in Figure 4.7(b).

FIGURE 4.7(a)
Transmitter location: Dadby
Frequency: 4.7925 MHz.
Date: 22/1/80
AMPLITUDE SPECTRA FOR CHANNEL 7. 112 SECOND TIME WINDOW.
Corresponds to the data in Figure 4.7(b)

(c)
amplitude 3:1. No definite conclusion can be drawn regarding the mode content from a spectral analysis of this data set.

b) Figure 4.8. In this case two sounding sequences acquired at 15:44 GMT and 15:47 GMT indicate the presence of 2 modes of approximately equal amplitude. The time delay between the pulses is consistent with 1 and 2 hop F region propagation, the ionograms again confirming this situation. The signal amplitudes recorded on the elements of the receiving array in the interval between soundings exhibit deep fading, reaching zero at times, with varying fading rates. A superimposed faster fading of small amplitude is also apparent. The spectral analysis contains several non-discrete peaks, some of which may have been caused by changes in the Doppler shifts of the signals.

c) Figure 4.9. The two pulse sounding sequences indicate the presence of 4 modes at 16:47 GMT and 3 modes at 16:50 GMT with time separations consistent with multiple hop F region propagation. This situation is confirmed by the ionogram taken at 16:59 GMT. The amplitude records exhibit long period but irregular fading, the amplitude occasionally reaching zero. The long period of the fading suggests that the Doppler shifts between the modes are small, this being confirmed by the spectral analysis which exhibits only a moderate frequency spread with a single peak.

d) Figure 4.10. In this case the two pulse sounding sequences indicate the presence of 2 strong and 1 weak modes at 15:54 GMT and the presence of 4 modes exhibiting rapid fading at 15:57 GMT. Again the time separations are consistent with multiple hop F region propagation. This is confirmed by the corresponding Slough ionogram. The amplitude record for these times exhibit very rapid fading of the signal implying a large

4.9
OADBY PULSE SOUNDING. FREQUENCY=4.9725 MHZ. 22/1/80.
Data corresponds to sounding immediately before and after the phase and amplitude data in Figure 4.8(b)

FIGURE 4.8(a)
Transmitter location: Oadby
Frequency: 4.7925 MHz.
Date: 22/1/80
AMPLITUDE SPECTRA FOR CHANNEL 7. 112 SECOND TIME WINDOW.
Corresponds to the data in Figure 4.8(b)

(c)
OADBY PULSE SOUNDING. FREQUENCY=4.9725 MHZ. 31/10/79.
Data corresponds to sounding immediately before and after the phase and amplitude data in Figure 4.9(b)

FIGURE 4.9(a)
Transmitter location: Geddy
Frequency: 4.7925 MHz.
Date: 5/10/79

PHASE (DEGREES) ------

RELATIVE AMPLITUDE

- CHANNEL NO. 7 180
- CHANNEL NO. 6 90
- CHANNEL NO. 5 90
- CHANNEL NO. 4 90
- CHANNEL NO. 3 90
- CHANNEL NO. 2 90
- CHANNEL NO. 1 90

TIME (GMT)
AMPLITUDE SPECTRA FOR CHANNEL 7. 112 SECOND TIME WINDOW.
Corresponds to the data in Figure 4.9(b)
OADBY PULSE SOUNDING. FREQUENCY=4.9725 MHZ. 29/11/79.
Data corresponds to sounding immediately before and after the phase and amplitude data in Figure 4.10(b)  

FIGURE 4.10(a)
Transmitter location: Oadby
Frequency: 4.7925 MHz.
Date: 29/11/79
AMPLITUDE SPECTRA FOR CHANNEL 7. 112 SECOND TIME WINDOW.
Corresponds to the data in Figure 4.10(b)
Doppler shift between the constituent modes. This is confirmed by the spectral analysis which indicated a widely spread spectrum containing multiple peaks.

The results presented indicate that the pulsed soundings provide a useful method of determining the mode content of a received signal. Periods have been identified of near single moded propagation, however such times are infrequent and of short duration (tens of minutes). For the majority of the soundings at least 2, and often 3 or 4, modes of comparable amplitude could be identified.

CONCLUDING REMARKS

Data have been presented for several transmissions for a variety of propagation conditions. Amplitude and phase measurements of signals from local MF broadcast transmitters were employed to validate the operation of the equipment. Observations of sky wave signals from a distant HF transmitter (901 km) indicated that fading was always present. The depth and rate of fading was found to vary, several fading rates often being observed for the same signal (ie. fast fading superimposed on a slower fading) indicative of the presence of several modes.

Fourier analysis of the received signals displayed spectra containing several peaks. The peaks were not always discrete, indicating that the components are not always well separated in frequency (this is also apparent from the amplitude fading records). Furthermore, the spectra obtained for consecutive data sets were often found to differ, indicating that the components present in the signal change over short periods.
To obtain an indication of the mode content of the received signals a series of experiments were conducted over a short range (122 km) path in which a series of short pulses were transmitted during the receiver calibration periods. The results obtained indicate that the fast amplitude fading was due to interference between 2 or more modes, and that when only one mode was present the fading rate was much slower (several tens of seconds). Periods of single moded propagation were found to occur infrequently and to be of relatively short duration (10-20 minutes).
Chapter 5

Amplitude and Phase Measurements

Introduction

In the previous chapter some of the features observed in the measured signals were briefly discussed. More detailed consideration is now given to the observations with particular emphasis being placed on periods of single moded propagation. Two cases are considered: a) short range, near vertical incidence signals for which pulsed sounding over the path was available; and b) long range (approximately 1000 km) signals for which pulsed soundings were not available. All of the measurements presented in this chapter were made using the large (Forward Look) antenna array.

Short Range Signals

Approximately 8.2 hours of data were collected for the pulsed signal transmitted on 4.7925 MHz from Oadby, Leicester (122 km range). Full details of the format of this signal are given in Chapter 3. The pulse width of this signal (0.7 ms) was too great to enable resolution of modes/components with closely separated group path lengths (10 km ≈ 33 μs). O/X components, when present, may only lead to a slight broadening of the reflected pulses and therefore may not be resolved. The pulse technique is, however, useful in identifying periods when single hop propagation is dominant. Particular attention will be paid in this section to periods of single hop propagation.

5.1
Amplitude measurements

When several pulse returns are received, indicative of multiple hop propagation, fast fading is often observed. The rate of fading is dependent upon the relative Doppler shifts between the constituent modes, and generally the fades occur at different times on each of the receiving channels (e.g. see Figure 5.1). This effect arises simply as a result of interference between the constituent modes, and has frequently been exploited in spaced diversity receiving systems. In these systems an approximately constant signal is obtained since the probability of receiving a fade at two separated antennas simultaneously is much less than the probability of receiving a fade at a single antenna.

When only a single dominant pulse is received the fading differs markedly from that observed during periods of multiple hop propagation. In these circumstances fast fading is not observed, but is replaced by long period variations (e.g. see Figure 5.2). These long period variations are not perfectly correlated between the channels.

Variations in the signal amplitude may be characterised in several ways, for example, by the amplitude distribution, fading rate, fading depth, etc. The amplitude distributions for a 141 s period when single pulses were being received (corresponding to the data presented in Figure 4.7) are presented in Figure 5.3. The amplitudes having been normalised to the mean value for each channel and standard deviations of between 0.23 and 0.8 were observed in each of the channels. A similar plot for a 10 minute period (including the above 141 s period) is presented as Figure 5.4. In this case standard deviations of between 0.13 and 0.26 are observed. Longer periods are not presented since times when only a single dominant pulse was received were comparatively rare and only of several minutes duration. The difference in values of standard deviation between the channels suggests that the sample
AMPLITUDES MEASURED AT EACH OF THE SEVEN ANTENNAS.

(Each channel has been given an arbitrary amplitude offset)

FIGURE 5.1
Example of long period fading at a time of single pulse reception.

**FIGURE 5.2**
NORMALISED AMPLITUDE DISTRIBUTION

Transmitter location: Oadby
Frequency: 4.7925 MHz.
Start at: 14:26 GMT on 22/1/80
Sample length: 2.5 minutes.

FIGURE 5.3
NORMALISED AMPLITUDE DISTRIBUTION

Transmitter location: Oedby

Frequency: 4.7925 MHz.

Start at: 14:26 GMT on 22/1/80

Sample length: 10 minutes.

FIGURE 5.4
did not extend over several signal fades and did not adequately represent the fading statistics. Furthermore, the distributions of amplitude are not sufficiently well formed to make an estimate of the coherence ratio, B, which is, in any case, relatively insensitive to the amplitude distribution (see Chapter 2).

Amplitude distributions for the multiple hop propagation conditions illustrated in Figures 4.8, 4.9 and 4.10 are presented as Figures 5.5, 5.6 and 5.7 respectively. For the cases when several comparable modes were observed, the standard deviations were typically between 0.4 and 0.5. Differences between the channels are again apparent. Similar long period effects to those observed for the single moded case must still be present, each mode individually exhibiting long period fading.

The cross correlation of the amplitudes as a function of effective antenna separation measured for the 'single pulse' period of Figure 4.7 are presented in Figure 5.8(a). The effective antenna separations for these plots were determined by projecting the true antenna positions onto a plane perpendicular to the expected direction of arrival of the signal, and as such, represent the antenna separations observed in the direction of the incoming signal. This technique is illustrated in Figure 5.9, which shows the foreshortening of the array in the direction of the wave front. The correlation coefficients calculated for the various antenna pairs are indicated by different symbols depending upon the orientation of the antenna pairs (arm 1-4, arm 4-7, etc.) and this enables orientation dependent effects to be readily identified. The data points mainly lie on a line representing high correlation coefficients, such that the correlation would be expected to drop to 0.5 at an effective aperture of approximately 1600 m. All of the points for pairs incorporating channel 1 indicate a very poor correlation. Data for the 141 s period immediately following that of

5.3
NORMAlISED AMPLITUDE DISTRIBUTION
Transmitter location: Oadby
Frequency: 4.7925 MHz.
Start at: 15:45 GMT on 22/1/80
Sample length: 2.5 minutes.

FIGURE 5.5
NORMALISED AMPLITUDE DISTRIBUTION

Transmitter location: Dadby

Frequency: 4.7925 MHz.

Start at: 16:48 GMT on 31/10/79

Sample length: 2.5 minutes.

FIGURE 5.6
NORMALISED AMPLITUDE DISTRIBUTION

Transmitter location: Oadby
Frequency: 47925 MHz.
Start at: 15:55 GMT on 29/11/79
Sample length: 2.5 minutes.

**FIGURE 5.7**
CROSS CORRELATION OF SIGNAL AMPLITUDE WITH ANTENNA SEPARATION.
Transmitter location: Dadby
Single mode propagation conditions
Frequency: 4.7925 MHz. Date: 22/1/80.

FIGURE 5.8
ILLUSTRATION OF THE FORESHORTENING OF THE ARRAY. Irregularities in the wavefront separated by a distance $d$ are observed on the ground by antennas separated by a distance $D$.

FIGURE 5.9
Figure 5.8(a) is presented in Figure 5.8(b). In this case less scatter is apparent, and the correlation coefficient decreases more rapidly with aperture, a value of 0.5 occurring for an effective antenna separation of approximately 600 m.

If a propagation model consisting of a specular and diffracted component is assumed for single moded propagation, the rate at which the correlation coefficient decreases with effective aperture should be related to the scale of irregularities in the ionosphere at the reflection point. Separation values ranging from 500 m to 5 km for a correlation coefficient of 0.5 have been determined.

Figure 5.10 is a similar plot for two consecutive 141 s periods during which 2 modes were present. In these cases the correlation decreases more rapidly with antenna separation than for the single moded cases. Effective antenna separations for which the correlation coefficient drops to 0.5 are typically several hundred metres. In the presence of 2 or more modes the decrease of correlation coefficient with effective antenna separation cannot easily be related to the size of ionospheric irregularities since the fading will be dominated by the interference between the constituent modes.

Phase measurements
Phases measured at a single antenna, relative to a local reference signal, are difficult to interpret and would be more useful if the local reference signal were 'locked' to the transmitted signal. Measurements of the phase differences between pairs of spaced antennas yield more information, and may be employed to estimate the coherence ratio of the signal [eg. Hughes and Morris, 1963; Whale and Boys, 1968].
CROSS CORRELATION OF SIGNAL AMPLITUDE WITH ANTENNA SEPARATION.
Transmitter location: Dadby
Two mode propagation conditions
Frequency: 4.7925 MHz.
Date: 22/1/80.

**FIGURE 5.10**
Phase difference distributions for the single moded period of Figure 4.7 are presented in Figure 5.11. Channel 4 was selected as the reference signal due to its location at the centre of the antenna array, thus enabling comparative measurements along each arm of the array. The width of the distributions was found to increase with aperture, but by differing amounts along each of the two antenna arms. The variations in the phase values presented in Figure 4.7(b) appear (by eye) to be well correlated over short intervals, however, over several minutes the variations are not well correlated. For example, for channel 4 there is no net phase change over the interval (due to the detrending process described in Chapter 4), however, the phase for channel 7 differs at the end of this interval by approximately 180° from its starting value. One possible explanation of these longer period differences is that the direction of arrival of the specular component may be varying due to large scale (compared with the array size) tilts in the ionosphere near the reflection point. The phase changes observed are those to be expected from a change in azimuthal angle of arrival of approximately 0.7° and a change in elevation angle of arrival of approximately 0.8° over the interval. An attempt has been made to compensate for this type of variation in order to examine any residual random variations. The linear trends of the phase values were therefore removed individually from each channel and the phases adjusted to give a mean value of approximately zero (to prevent the distribution 'wrapping around' at 180°/-180°). The resulting phase difference distributions are presented in Figure 5.12, and differ considerably (much narrower) from those presented in Figure 5.11.

The procedure adopted above is of limited value since the changes in the individual phase paths due to ionospheric motions producing variations in the DOA of the specular component will not, in general, vary linearly with time. Distributions obtained for shorter analysis intervals (14 s) during
PHASE DIFFERENCE DISTRIBUTION
Transmitter location: Oadby
Start at 14:26 GMT on 22/1/80
Frequency: 4.7925 MHz. Sample length: 141 s.

FIGURE 5.11
PHASE DIFFERENCE DISTRIBUTION
Transmitter location: Oadby
Start at 14:26 GMT on 22/1/80
Frequency: 4.7925 MHz. Sample length: 141 s.
the period presented in Figure 5.11 are presented as Figures 5.13 and 5.14 (linear trends were not removed). The distributions in these cases are considerably narrower than the previous examples, however, the values of the phase differences at each antenna separation changes by up to 45° in the 28 s interval between these 14 s periods.

The variations of phase differences relative to channel 4 for these single moded data are presented in Figure 5.15. The long period trends in the phase differences noted earlier are clearly illustrated. For antennas 1, 2 and 3 the phase differences decreased and for antennas 5, 6 and 7 the phase differences increased. The overall changes along each antenna arm are in proportion to the antenna separations, consistent with the presence of an extensive ionospheric tilt affecting the whole of the reflection region.

The phase differences observed between two pairs of antennas (3/4 and 1/2) along the same arm of the array are presented in Figure 5.16. These pairs have approximate separations of 200 m and 400 m respectively and are separated by approximately 600 m. Again, the overall trend is apparent, the changes for pair 1/2 being twice that for pair 3/4 (i.e. in proportion to the antenna separations). Short term variations on both pairs appear to be uncorrelated and for pair 1/2 are approximately twice the magnitude. Similar results were obtained for other antenna pairs within the array. These results indicate that the phase differences are not entirely due to bulk changes affecting the whole of the array and smaller scale uncorrelated effects are also present.

The variations in phase differences presented in Figures 5.15 and 5.16 suggest the presence of two effects. Firstly, the direction of arrival of the signal appears to vary slowly leading to well correlated changes in the phase differences measured across the array, and, secondly, shorter period
PHASE DIFFERENCE DISTRIBUTION
Transmitter location: Oadby
Start at 14:26 GMT on 22/1/80
Frequency: 4.7925 MHz. Sample length: 14 s.

FIGURE 5.13
PHASE DIFFERENCE DISTRIBUTION
Transmitter location: Oadby
Start at 14:26 GMT on 22/1/80
Frequency: 4.7925 MHz. Sample length: 14 s.

FIGURE 5.14
Phase (degrees)

Channel NO. 7

Channel NO. 6

Channel NO. 5

Channel NO. 4

Channel NO. 3

Channel NO. 2

Channel NO. 1

Time (GMT)

PHASE RELATIVE TO CHANNEL 4.
Transmitter location: Oadby
Frequency: 4.7925 MHz.
Start at 14.26 GMT on 22/1/80

FIGURE 5.15
Transmitter location: Oadby. Frequency: 4.7925 MHz.
Start at 14:26 GMT on 22/1/80

FIGURE 5.16
variations are present which are not well correlated between antennas separated by several hundred metres. Two possible explanations for this latter effect are: a) small scale tilting leading to localised changes in the direction of arrival, and/or b) the presence of a specular component together with a diffracted component which varies on a time scale of several seconds.

Coherence ratio
The coherence ratio is defined as the ratio of the power in the specular component to the power in the diffracted (random) components for a single mode. Several authors have defined a correlation function which is a function of antenna spacing and which decreases from 1 to 0 as the antenna separation is increased from zero. Whale and Gardiner [1966] derived a relationship between the standard deviation of the phase differences ($\sigma$) measured between pairs of spaced antennas, the coherence ratio (B) and the correlation coefficient (R), which is reproduced diagramatically in Figure 5.17(a) (see also Chapter 2). The coherence ratio may be determined from measurements of $\sigma$ obtained from widely separated antennas where $R=0$ (see Figure 5.17(b)). The variation of R with separation can be determined from measurements of $\sigma$ at smaller apertures.

The variation of $\sigma$ with antenna separation for this model should take the form indicated in Figure 5.18(a) in which the antenna separations are on an arbitrary scale. The important feature of the diagram is that $\sigma$ increases from zero with increasing antenna separation and reaches a limiting value at a point when $R$ becomes zero. For the case when the DOA of the specular component varies due to bulk ionospheric motions, the variation of $\sigma$ with antenna separation should take the form shown in Figure 5.18(b), the intercept of the linear portion of the curve with the y-axis giving the value of $\sigma$ which would have occurred for large apertures had the specular
a) Standard deviation of phase difference between two spaced antennas (after Whale and Gardiner, 1966)

(b) Relationship between the standard deviation of phase difference for large antenna separations ($R=0$) and coherence ratio. (after Thomas, 1986)
Expected variation of standard deviation of phase difference with antenna separation for a signal comprised of a specular and diffracted components
(a) Steady specular component,
(b) Wandering specular component
(c) Steady specular component with uncorrelated interference.

\[ \sigma = \text{standard deviation} \]
component maintained a constant DOA. Interference and noise which is uncorrelated across the array should lead to larger values of $\sigma$ being measured for all antenna separations (except those very close to zero). This is illustrated in Figure 5.18(c).

The variation of $\sigma$ with effective antenna separation for three consecutive 141 s intervals are presented in Figures 5.19(a), (b) and (c). The points on these graphs are coded to indicate the geometrical arrangement of the antenna pairs to enable identification of orientation dependent behaviour. Figure 5.19(b) corresponds to the data presented in Figure 4.7. The data points are well scattered in these figures and show a general increase in $\sigma$ with increasing separation with no limiting value being apparent. Different behaviour between arms 1-4 and 4-7 of the array can also be identified, this being consistent with a varying DOA of the specular component. In all cases straight lines fitted through the data intercept the y-axis at values of $\sigma$ between 0° and 12°.

Figures 5.20 and 5.21 are plots of the first 70 and 28 seconds respectively for the data presented in Figure 5.19. As the analysis interval is decreased, the scatter is reduced and the slope of the 'best fit' lines become less, the curves approximating more closely to those corresponding to a steady specular component. In all cases the 'best fit' lines intercept the y-axis at values of $\sigma$ less than 10°.

**Summary**

Data have been analysed for a short period (10 minutes) over which time the pulsed soundings indicated predominantly IF propagation (resolution of O/X components not possible). Some evidence of a small secondary mode is evident in the pulsed soundings taken at 14:29 GMT, of peak relative amplitude 0.25.
STANDARD DEVIATION OF PHASE DIFFERENCES AGAINST ANTENNA SEPARATION.

Transmitter location: Oadby
Frequency: 4.7925 MHz
Date: 22/1/80

**FIGURE 5.19**
STANDARD DEVIATION OF PHASE DIFFERENCES AGAINST ANTENNA SEPARATION.
Transmitter location: Oadby
Frequency: 4.7925 MHz.
Date: 22/1/80

FIGURE 5.20
Phase difference SD (degrees)

Effective antenna separations (metres)

Key: Arm 1-4  Arm 4-7  Sample length: 28 s
    E-W pairs  other pairs

STANDARD DEVIATION OF PHASE DIFFERENCES AGAINST ANTENNA SEPARATION.
Transmitter location: Dadby
Frequency: 4,7925 MHz.
Date: 22/1/80

FIGURE 5.21
The cross correlations of the amplitudes measured at each of the antennas decreases approximately in a linear manner at times of 1-hop propagation. For a correlation coefficient of 0.5 the effective antenna separations range between 500 m and 5 km. When the pulsed soundings indicated the presence of several modes of comparable amplitude (1F, 2F, 3F, etc.), the cross-correlation coefficients decreased rapidly as a function of antenna separation, a value of 0.5 occurring for separations of several hundred metres.

Phase difference measurements indicate two effects: (a) variations in the direction of arrival of the signal of approximately 1° in both azimuth and elevation, (b) uncorrelated variations which may be due to small scale tilting (which may lead to the reception of a small number of 'specular-like' signals at each antenna) or the presence of a large number of diffracted components, or (c) contamination by a small secondary mode.

Interpretation of the results in terms of a specular and diffracted component model leads to measured values of coherence ratio often in excess of 40, indicative of a dominant specular component. The presence of a small secondary mode (or an interfering signal) may lead to the measured values being less than the true value.

**LONG RANGE SIGNALS**

**Identification of single moded propagation**

For the measurements of long range transmissions, the pulsed sounding employed to identify single moded periods on the short range path was not available. An attempt to identify single moded periods was initially made from ionospheric predictions. These predictions are based on average
ionospheric parameters and are not, on a day-to-day basis, sufficiently accurate to select periods of single moded propagation. To overcome this difficulty of selecting single modes, a large quantity of data were collected for several transmitters and frequencies, and the data subsequently examined to select suitable periods for further analysis. It has been established earlier that periodic fading of the signal is due to interference between different modes and/or magneto-ionic components. Periods where such fading was not present (or at least at a minimum) were therefore assumed to be predominantly single moded.

**Experimental results**

Two periods are now considered which displayed the least amount of periodic fading. Both are for the 9.535 MHz transmission from Sarnen, Switzerland. The first (period A) was recorded on 21 November 1979 and the second (period B) on 3 June 1980. These two sets of data are now considered individually.

**a) Period A.** The phase and amplitude records for these data are presented in Figure 5.22. During the first frame of this figure a small amount of fast fading is present together with a longer period fading. The fast fading is not present in the subsequent two frames of this period, but the long period fading is still present. This may be indicative of interference between the magneto-ionic components.

The correlations of the amplitudes for the different antenna pairs are presented in Figures 5.23(a), (b) and (c) for the three time periods. Considerable scattering is apparent in all three frames, the correlation coefficient obtained from the best fit line reducing to 0.5 at an effective antenna separation of between 340 m and 576 m. Different behaviour between the two antenna arms can be identified in frames (b)
Transmitter location: Sarnen, Switzerland
Date: 21/11/79
Data corresponds to period A described in the text.

*FIGURE 5.22*
Transmitter location: Sarnen, Switzerland
Date: 21/11/79
Data corresponds to period A described in the text.
CROSS CORRELATION OF SIGNAL AMPLITUDE WITH ANTENNA SEPARATION.
Transmitter location: Sarnen, Switzerland.
Results for period A described in the text.

FIGURE 5.23
CROSS CORRELATION OF SIGNAL AMPLITUDE WITH ANTENNA SEPARATION.

Transmitter location: Sarnen, Switzerland.

Results for period A described in the text.

and (c), higher correlation being observed for arm 4-7 (approximately in the direction of the incoming signal) than for arm 1-4.

Plots of the standard deviation of the phase differences (\( \sigma \)) with effective antenna separation, corresponding to data for the three frames of Figure 5.22, are presented in Figures 5.24, 5.25 and 5.26 for periods of 141 s, 70 s and 28 s respectively. The 'best fit' straight lines applied to the data points at the greater effective antenna separations intersect the y-axis for values of \( \sigma \) between 0° and 50°, corresponding to coherence ratios of greater than 2. The lower values correspond to frame (a) for which a small amount of fast fading was observed, indicative of an interfering mode.

b) Period B. The amplitude and phase records for these data are presented in Figure 5.27. Frames (a), (b) and (c) are consecutive and are separated by a 15 minute interval from frames (d), (e) and (f) which are also consecutive. The amplitude correlations (see Figure 5.28) display considerable scattering for frames (a), (b) and (f), the remaining frames ((c), (d) and (e)) indicate good correlation, decreasing approximately in a linear manner, a correlation coefficient of 0.5 occurring for effective antenna separations of approximately 1250 m. The corresponding variations of \( \sigma \) with effective antenna separation are presented in Figure 5.29. For frames (a) and (b), \( \sigma \) appears almost constant. For frames (c), (d), (e) and (f), the curves approximate to those expected for a single moded signal with a slight variation of the DOA of the specular component (see Figure 5.18). The 'best fit' straight lines applied to the data at the greater effective antenna separations intersect the y-axis for values of \( \sigma \) between 8° and 22°, corresponding to coherence ratios of between 40 and 8.
STANDARD DEVIATION OF PHASE DIFFERENCES AGAINST ANTENNA SEPARATION.

Transmitter location: Sarnen, Switzerland
Frequency: 9.535 MHz.
Date: 21/11/79

FIGURE 5.24
Phase difference SD (degrees)

Time, 18.29 GMT

Time, 18.32 GMT

Time, 18.35 GMT

Effective antenna separations (metres)

Effective antenna separations (metres)

Effective antenna separations (metres)

Key: Arm 1-4  Arm 4-7  Sample length, 70 s
   E-W pairs  other pairs

STANDARD DEVIATION OF PHASE DIFFERENCES AGAINST ANTENNA SEPARATION.
Transmitter location: Sarnen, Switzerland
Frequency, 9.535 MHz.
Date: 21/11/79

FIGURE 5.25
STANDARD DEVIATION OF PHASE DIFFERENCES AGAINST ANTENNA SEPARATION.

Transmitter location: Sarnen, Switzerland
Frequency: 9.535 MHz.
Date: 21/11/79

FIGURE 5.26
FIGURE 5.27

Transmitter location: Sarnen, Switzerland
Date: 3/6/80
Data corresponds to period B described in the text.
Transmitter location: Sarnen, Switzerland
Date: 3/6/80
Data corresponds to period B described in the text.
Transmitter location: Sarnen, Switzerland
Date: 3/6/80
Data corresponds to period B described in the text.
Transmitter location: Sarnen, Switzerland
Date: 3/6/80
Data corresponds to period B described in the text.

PHASE (DEGREES)

RELATIVE AMPLITUDE

CHANNEL NO. 1

CHANNEL NO. 2

CHANNEL NO. 3

CHANNEL NO. 4

CHANNEL NO. 5

CHANNEL NO. 6

CHANNEL NO. 7

TIME (GMT)
Transmitter location: Sarnen, Switzerland
Date: 3/6/80
Data corresponds to period B described in the text.
Transmitter location: Sarnen, Switzerland
Date: 3/6/80
Date corresponds to period B described in the text.
CROSS CORRELATION OF SIGNAL AMPLITUDE WITH ANTENNA SEPARATION.
Transmitter location: Sarnen, Switzerland.
Results for period B described in the text.

FIGURE 5.28
CROSS CORRELATION OF SIGNAL AMPLITUDE WITH ANTENNA SEPARATION.
Transmitter location: Sarnen, Switzerland.
Results for period B described in the text.
CROSS CORRELATION OF SIGNAL AMPLITUDE WITH ANTENNA SEPARATION.

Transmitter location: Sarnen, Switzerland.

Results for period B described in the text.

STANDARD DEVIATION OF PHASE DIFFERENCES AGAINST ANTENNA SEPARATION.

Transmitter location: Sarnen, Switzerland
Frequency: 9.535 MHz.
Date: 3/6/80
STANDARD DEVIATION OF PHASE DIFFERENCES AGAINST ANTENNA SEPARATION.

Transmitter location: Sarnen, Switzerland
Frequency: 9.535 MHz
Date: 3/6/80
CONCLUSIONS

Data have been presented for both long (1000 km) and short range (122 km) paths for periods of near single moded propagation. Two factors affecting the phase differences measured between pairs of antennas have been identified: (a) well correlated changes occurring across the array indicative of variations in the direction of arrival of the signal due to large scale tilting of the ionosphere, and (b) changes which are not well correlated across the array which may be caused either by small scale tilting of the ionosphere (ie. on a scale smaller than the array) or by the presence of diffracted components.

Assuming a signal is comprised of a specular component which has a variable direction of arrival, surrounded by a cone of diffracted (random) components, coherence ratios greater than 10 and often greater than 40 are usually found. The measured coherence ratios may, however, be lower than the true values due to the presence of both magneto-ionic components and/or the presence of a small secondary mode, for which there was some evidence in both the pulsed soundings and in the amplitude records. It would seem likely, therefore, that the true coherence ratio for a single mode consisting of one magneto-ionic component is somewhat higher than the measured values. This result agrees well with the later results reported in the literature [eg. Felgate and Golley, 1971; Rice, 1973] in which the wave fields were considered to consist of a small number of 'specular-like' components. If the coherence ratio is calculated assuming a steady specular component (ie. one that does not have a variable DOA) then coherence ratios of between 0 and 7 are obtained. These results agree with measurements reported in the early literature [eg. Bramley, 1951; Hughes and Morris, 1963].
Arrays of spaced antennas are often employed in HF receiving systems (e.g. direction finders and adaptive arrays) to form a series of 'beams' and 'nulls' in the directional sensitivity pattern of the antenna system. The evaluation of the performance of such systems requires an understanding of the characteristics of the incident wave field. The results presented in this chapter indicate that the wave field can be considered as the sum of a small number (corresponding to the different modes present in the signal) of components with large coherence ratios (i.e. essentially planar wavefronts) and slowly varying directions of arrival (approximately 1 or 2 degrees over periods of several minutes). Modelling of the array performance can be achieved using the knowledge of the signal form gained from these investigations.
CHAPTER 6

DIRECTION FINDING AND SINGLE SITE LOCATION: THE METHOD

INTRODUCTION

Measurements of the amplitudes and phases observed on pairs of spaced antennas can be used to determine the direction of arrival (DOA) of a signal, both in azimuth (bearing) and elevation. Furthermore, a knowledge of the ionosphere, obtained, say, from vertical soundings, can be combined with the DOA measurements to estimate the location of the transmitter.

To investigate the above technique of transmitter location, several hours of data were collected using the small (Verbena) antenna array. The methods adopted in this investigation are described in this chapter, and experimental results are presented in Chapter 7.

DETERMINATION OF THE DIRECTION OF ARRIVAL

The receiving equipment enabled the simultaneous measurement of the amplitude and phase at each of seven antennas, nine such measurements being made per second. The basic technique for determining the direction of arrival of a signal assumes a single mode and planar wavefront and requires the phase to be measured at two pairs of antennas arranged such that lines drawn through each pair are well separated in azimuth (see Figure 6.1). This situation can be realised with only three antennas, one antenna being common to each pair.
Typical antenna configuration required to measure the direction of arrival.

FIGURE 6.1
For a given phase difference between antennas A and B (referring to Figure 6.1), one or more possible angles of arrival to arm AB of the antenna array can be calculated. These directions describe a 'cone of possible DOA' along which the signal may arrive to produce the measured phase differences. Similarly, a 'cone of possible DOA' can be determined for arm CD of the array. The true DOA of the signal is along the intersection of the cones, as illustrated in Figure 6.2.

Details of the calculation of the DOA are contained in appendix B of this thesis, and the results are reproduced here as Equations 6.1, 6.2, and 6.3.

Two possibilities exist for the phase differences measured at each antenna pair: A leads B, or B leads A. These two possibilities must be considered separately for each antenna pair, leading to four overall possibilities. In the following equations angles are measured, relative to an antenna pair, such that 0° is in the direction of the line joining the 'phase lagging' antenna to the 'phase leading' antenna. Similarly, angles between antenna pairs are measured between the above directions.

\[
\cos \theta = \left( n + \frac{\Delta \phi}{2\pi} \right) \frac{\lambda}{\delta} \quad 6.1 \ (B.1)
\]

where:

- \( \theta \) is the cone angle to an antenna pair,
- \( \Delta \phi \) is the positive phase difference between the antennas,
- \( n \) is a positive integer, or zero,
- \( \delta \) is the antenna separation, and
- \( \lambda \) is the wavelength.
ILLUSTRATION OF THE INTERSECTION OF TWO 'CONES OF POSSIBLE DOA'.

FIGURE 6.2
\[
\tan \theta = \frac{\cos \theta_2 - \cos \theta_1 \cos \alpha}{\cos \theta_1 \sin \alpha}
\]

where:

- \( \theta \) is the azimuth angle of arrival measured from pair 1 towards pair 2,
- \( \theta_1 \) is the cone angle to antenna pair 1,
- \( \theta_2 \) is the cone angle to antenna pair 2, and
- \( \alpha \) is the angle between the antenna pairs.

\[
\cos \theta_e = \frac{\cos \theta_1}{\cos \theta_a}
\]

where:

- \( \theta_e \) is the elevation angle of arrival.

Substitution of phase differences into Equation 6.1 will give the cone angles for each of the antenna pairs, which can then be individually substituted into Equations 6.2 and 6.3 to yield possible directions of arrival. If the arm length exceeds one half wavelength, ambiguities in the angle of arrival occur since it is not possible to determine whether the signal at antenna A leads that at antenna B, or vice versa. Furthermore, if the arm length exceeds one wavelength then additional possible angles of arrival occur due to \( 2\pi \) ambiguities (\( n \) in Equation 6.1 is non-zero).

**Sub-array notation**

For the remainder of this chapter it is convenient to consider the array as being comprised of several sub-arrays - these are numbered 1 to 6 (1 corresponds to the smallest aperture and 6 to the largest). This notation is summarised in Table 6.1.
Table 6.1 - Sub-array notation.

<table>
<thead>
<tr>
<th>Sub-array</th>
<th>Antenna numbers arm 1</th>
<th>arm 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3, 4</td>
<td>4, 5</td>
</tr>
<tr>
<td>2</td>
<td>1, 2</td>
<td>6, 7</td>
</tr>
<tr>
<td>3</td>
<td>2, 3</td>
<td>5, 6</td>
</tr>
<tr>
<td>4</td>
<td>2, 4</td>
<td>4, 6</td>
</tr>
<tr>
<td>5</td>
<td>1, 3</td>
<td>5, 7</td>
</tr>
<tr>
<td>6</td>
<td>1, 4</td>
<td>4, 7</td>
</tr>
</tbody>
</table>
Resolution of ambiguities

At larger apertures many possible directions of arrival may be determined from one set of phase measurements. These ambiguities can be resolved, in principle, by comparison with measurements (either of cone angles for a linear antenna arm, or of DOAs determined for groups of antennas) obtained at a smaller aperture, non-corresponding determinations being rejected. In the experiments described in this chapter the DOAs for the smallest antenna separations are determined. Possible DOAs are then determined for the next larger spacings and the DOA closest in both azimuth and elevation selected (minimum of $\sqrt{(Az_{n+1} - Az_n)^2 + (El_{n+1} - El_n)^2}$); this procedure is then repeated for increasing apertures. This method was chosen since antenna 4 was not collinear with antenna groups 1/2/3 or 5/6/7.

The smallest aperture sub-array which could be formed with the Verbena array consisted of antenna pairs 3/4 and 4/5. Since the spacings between these antennas are greater than half a wavelength at all frequencies observed in these experiments, ambiguities existed in all the determined DOAs. The first $2\pi$ phase ambiguity occurred at around 11.5 MHz. Below this frequency a restriction was placed on the determined bearings to be within $\pm 45^\circ$ of the true bearing; above 11.5 MHz the ambiguities were resolved by reducing the bearing acceptance to within $\pm 20^\circ$ of the true bearing.

The restriction on the acceptance of determined bearings to within a specified range of the true (known) bearing would be a severe restriction for an operational system where the true bearing is not known beforehand. However, in such a system additional antennas could be employed to overcome this limitation.
EXPECTED DEVIATIONS IN THE MEASURED DOA

A brief consideration of the expected deviations in the measured DOA is now presented. Three topics are considered: random errors in the measured phase differences; effects of multimoded propagation; and the presence of waves and tilts in the ionosphere which deflect the signal path from the great circle route.

Random errors.

This type of error is caused by interfering signals, measurement errors, noise, etc., and will cause the cone angles determined for the antenna pairs to vary. The amount by which the cone angle varies for a given error in the measured phase difference is dependent upon several factors associated with Equation 6.1, i.e. the values of $\Delta \phi$, $n$ and $\lambda/\delta$. Errors are much more pronounced for small cone angles than for signals arriving near-broadside to the antenna pair. For example, considering the case of $n=0$ and $\lambda=\delta$, for a signal arriving broadside to the antenna pair an error in $\Delta \phi$ of 5° causes an error in the determined cone angle of 0.8°, whereas for a signal arriving along the boresite of the antenna pair the same error in $\Delta \phi$ produces a cone angle error of 9.5°. Furthermore, since the cone angles will, in general, be different for each antenna pair employed in a DOA determination the scatter of the determined DOAs will not be symmetrically placed about the true position. This effect will depend upon the frequency and DOA of the signal and the array geometry, and is illustrated in Figure 6.3 for two cases corresponding to signals with elevation angles of arrival of 30° and 15°.

Wave interference.

Under ideal conditions the signals would consist of single modes presenting a planar wave front to the array, and, using the techniques described
Illustration of errors in measured DOA which can occur: (a) at large elevation angles the cones of possible DOA intersect at a large angle (b) at low elevation angles the cones of possible DOA intersect a small angles, leading to a large uncertainty in the measured elevation angle.

FIGURE 6.3
earlier in this section, it would be relatively easy to determine the
directions of arrival. When two modes are present the wavefront is no
longer planar, but becomes corrugated, as illustrated in Figure 6.4. For
the case when both components arrive from the same bearing but at different
elevation angles, the corrugations are such that the cone angle is correctly
determined for antenna pairs broadside to the azimuthal DOA of the signal
(i.e. the cone angle, $\theta = 90^\circ$), but not for any other angle, the greatest error
occurring for antenna pairs in-line with the azimuthal DOA. The depth and
separation of the corrugations is dependent upon the relative amplitudes of
the constituent modes and their relative angles of arrival. The error in
the determined DOA will depend upon the antenna separation and the direction
of arrival. In this context it is assumed that the correct DOA is that of
the dominant mode, and that any deviation from this is classed as an error.
More accurate measurements are to be expected at larger apertures since the
effect of any small corrugations in the wave front will be minimised. The
constituent modes may also arrive at slightly different bearings, causing
wavefront corrugations in both azimuth and elevation. For a given
corrugation depth the 'scatter region' will be contained within that
expected for random errors of the same magnitude, except that the phase
difference errors are now correlated and, therefore, the DOA will not vary
randomly, but follow a path within the error limits.

Ionospheric waves and tilts.
Long term variations in the bearing are known to be caused by ionospheric
tilts, both static and travelling, which deflect the signal from the great
circle path [Tedd, 1982]. The variations associated with travelling
ionospheric disturbances (TIDs) have quasi-periods ranging from about ten
minutes to more than an hour. Deviations due to static tilts are
predominant during sunrise and sunset periods, and can persist for two to
three hours. Examples of these types of error are reproduced in Figure 6.5
TWO RAY WAVE FIELD, HORIZONTAL PLANE
(after Gething, 1978)

FIGURE 6.4
The diurnal variation of bearing error obtained experimentally for the 6.09 MHz Luxembourg transmission (true great-circle bearing = 109.3°, path length = 633 km) for 18-23 October 1979. Bearing error is defined as the difference between the observed and true bearing of the transmitter. Local sunrise and sunset times are indicated by vertical lines, and were determined for the 15th day of the month at 250 km altitude for the path midpoint. The thick curve is a mean of the other curves, which thus represents the average variation of the days considered.

(a) Example of bearing errors due to TIDs
(b) Example of bearing errors due to systematic tilts

(after Tedd, 1982)
DATA SELECTION

Wave interference effects cause considerable spreading of the snaps in both azimuth and elevation, and lead to a failure of the methods adopted to resolve the \(2\pi\) ambiguities. Several methods were investigated to select snaps which are accurate and are not in error due to wave interference effects.

Selection by phase front planarity.

When a plane wave front is incident onto a linear array of antennas, the phase differences measured between pairs of antennas should display a linear relationship with antenna separation (after making allowance for \(2\pi\) ambiguities). Under multimoded conditions, or when interference is present, the wave front is no longer planar and, therefore, the phase differences measured between the antennas will, in general, no longer display a linear relationship. This can be used as a simple test of wavefront planarity which can be applied to linear antenna configurations. Problems do, however, occur if initial \(2\pi\) ambiguities cannot be resolved, unless the antenna separations at larger apertures are an integer multiple of the smaller aperture - under such circumstances the \(2\pi\) ambiguities cancel out. To overcome this problem with the Verbena array the techniques described below were adopted.

The phase difference between antennas 3 and 5 was determined and the phase difference expected for a separation of 31 times the aperture calculated. The phase difference for antennas 1 and 7 was also determined (aperture approximately 7.75 times that of antennas 3 and 5) and the expected phase difference for a separation of 4 times the aperture (31 times that of antennas 3 and 5) was calculated. Since these two pairs of antennas were...
parallel (to within $0.23^0$) the two calculated phase differences for the extrapolated apertures should agree for a plane wave front. The (positive) difference between the two calculated values was adopted as a measure of the wave front planarity. Due to the large multiplications of the phase differences, leading to ambiguities in the resultant phases, this method is expected to only have a useful affect for near plane wave front conditions. The extrapolated antenna positions determined from the two antenna pairs differed in position by approximately 0.12 m, an error equivalent to $1.5^0$ of phase at a wavelength of 30 m.

The second method tried in these experiments was, in effect, a direct test of the signal wave front planarity. Under plane wave front conditions the DOAs determined for the larger aperture sub-arrays should agree exactly with those obtained at smaller apertures - this being the assumption made in the method employed to resolve ambiguities. Under non-plane wave front conditions this agreement will degrade; the degree of mismatch between sub-array 2 and sub-array 3 $\sqrt{(Az_2-Az_3)^2+(El_3-El_2)^2}$ was employed as a measure of wave front planarity.

It is possible, under adverse conditions, for such tests to be coincidentally satisfied for non-planar wavefronts, but occurrences will be minimised by the use of a larger number of antennas.

Selection by amplitude equality.

Under single moded conditions, the amplitudes measured at each of the antennas should be identical. When several modes are present then fading occurs differentially at each antenna. Amplitude testing can be employed as a further test of single moded conditions (or conditions of QUMP). This method does not require any particular antenna configuration and can be applied when only three antennas are employed.
To compensate for the different sensitivities of each of the antennas (see Chapter 4), the signal levels were first normalised to the mean level observed in each channel.

Selection by phase front planarity and amplitude equality.
Both of the above methods of signal testing can be combined to provide a more rigorous test. When such a test is employed it is unlikely that good confidence levels will be assigned to bad snaps.

RANGE DETERMINATION
The accurate determination of the location of a distant transmitter from measurements of the direction of arrival at the receiving site requires a detailed knowledge of the ionosphere over the entire path through which the signal travels so that a suitable ray tracing analysis can be applied. Over relatively short paths, when the curvature of the ionosphere can be neglected and assuming that significant refraction only takes place near to the reflection point, the equivalence theorems can be applied and the following simple technique adopted. For longer range paths, and for high angle paths for frequencies near to the critical frequency [Reilly, 1983], a more rigorous approach is required.

Figure 6.6 illustrates a situation where Martyn's equivalent path theorem is assumed to hold (ie: the virtual height of reflection, h', of an obliquely propagating wave and the equivalent vertical wave are equal). Referring to Figure 6.6:

\[ \cos \gamma = \frac{f_y}{f} \]  
(the secant law) 6.4

6.9
Diagramatic illustration of the signal path, assuming a thin, curved ionosphere.

FIGURE 6.6
where:

- \( \gamma \) is the angle of incidence (in degrees) at the point of reflection (see Figure 6.6),
- \( \theta_e \) is the elevation angle of arrival at the antenna array (in degrees),
- \( R \) is the Earth's radius,
- \( r \) is the range from receiver to transmitter, and
- \( h' \) is the virtual height of reflection.
- \( f \) is the signal frequency, and
- \( f_v \) is the equivalent vertical frequency.

Due to the curvature of the Earth the equivalent vertical frequency varies with virtual height, the two parameters are related by Equation 6.6 for a given elevation angle, \( \theta_e \) (this equation was obtained by squaring and adding Equations 6.4 and 6.5 and rearranging).

\[
\frac{180 - 2(\theta + \gamma)}{2\pi R} \]

where:

\[
\sin \gamma = \frac{R \cos \theta}{R + h'}
\]

\[
r = \frac{[180 - 2(\theta + \gamma)]2\pi R}{360}
\]

\[
h' = R \left( \frac{f \cos \theta_e}{f_v} - 1 \right)
\]

Reflection will occur at the virtual height where the frequency of the equivalent vertical wave \( f_v \) is equal to the frequency of a vertically propagated signal reflected from the same virtual height. Curves formed from Equation 6.7 can, therefore, be considered as a family of transmission
curves which may be overlayed onto an ionogram (ie. a plot of $h'$ against vertical sounding frequency), the virtual height of reflection being found as the intersection of the transmission curve with the ionogram trace. This method is illustrated in Figure 6.7.

Ideally the ionospheric soundings should be taken frequently beneath the reflection point. This was not possible in the experiments described in this thesis and recourse was made to hourly soundings taken at Slough, UK.

CONCLUDING REMARKS

The methods by which the DOA of a signal can be determined have been described, together with a simple method of relating the elevation angle measurements to the range, given vertical sounding measurements. The methods described were tested for several HF paths and the results of these tests are given in Chapter 7.
Example of transmission curves overlayed onto a vertical sounding trace. Each of the transmission curves, described by Equation 6.7, is identified by the elevation angle.

FIGURE 6.7
CHAPTER 7

DIRECTION FINDING AND SINGLE SITE LOCATION: EXPERIMENTAL RESULTS

INTRODUCTION

To investigate the technique of transmitter location several hours of data were collected, using the relatively small (Verbena) antenna array. Five HF broadcast transmitters on a range of frequencies were monitored and details of these are summarised in Table 7.1.

In the following sections the term 'snap' is used to mean a DOA determined from a single (instantaneous) set of signal samples (this term is analogous to a 'snapshot' taken by a camera - the scene is recorded at one instant). Several snaps may be combined (eg. by averaging, from peaks in a distribution, etc.) to produce 'determined directions of arrival' (DDOAs). Both of these terms should be distinguished from the true DOAs of the signal components - under ideal conditions the DDOAs should be identical to the DOAs.

The presentation and analysis of the experimental results is divided into two parts, dealing separately with (a) the determination of the DOA, and (b) with the estimation of the location of a distant transmitter from a single receiving site.
Table 7.1 - Transmissions received using the Verbena antenna array.

<table>
<thead>
<tr>
<th>Transmitter</th>
<th>Frequency</th>
<th>Range</th>
<th>Bearing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copenhagen, Denmark</td>
<td>15.165 MHz</td>
<td>1015 km</td>
<td>60.2°</td>
</tr>
<tr>
<td>Noblejas-Toledo, Spain</td>
<td>11.920 MHz</td>
<td>1339 km</td>
<td>185.1°</td>
</tr>
<tr>
<td>Moosbrunn, Austria</td>
<td>9.770 MHz</td>
<td>1375 km</td>
<td>99.9°</td>
</tr>
<tr>
<td>Madrid, Spain</td>
<td>9.570 MHz</td>
<td>1278 km</td>
<td>185.4°</td>
</tr>
<tr>
<td>Sarnen, Switzerland</td>
<td>9.535 MHz</td>
<td>901 km</td>
<td>121.9°</td>
</tr>
</tbody>
</table>
DOA DETERMINATION AND DATA SELECTION

In this section the technique of DOA determination described in Chapter 6 is tested on experimental data. Typical examples of contour plots of the frequency of occurrence of snap values of azimuth and elevation angles are presented for data sets of 15 minutes duration for three of the test transmissions. Contours are plotted for frequency of occurrence values of 20%, 50% and 80% of the peak frequency of occurrence. Additionally, values of the percentage of data available (some snaps may have 'failed' due to non-intersection of the cones of possible DOA at sub-array 1) and the percentage of successful snaps lying within the bounds of the 20%, 50% and 80% contours are quoted. To give an indication of the signal conditions, amplitude plots for the corresponding periods are also presented.

Sarnen, Switzerland: 9.535 MHz.

Shown in Figure 7.1 are plots of amplitude against time for a 141 second period commencing at 19:21:51 GMT on 25 March 1981 for each of the seven channels. The amplitude fading is indicative of a dominant mode together with a smaller interfering mode (or interference) of approximate relative amplitude 0.3 and frequency difference of approximately 1.2 Hz.

Presented as Figure 7.2 are a sequence of skymaps showing the distribution of the frequency of occurrence of DOA values for four of the sub-arrays corresponding to some of the various apertures available. The snaps obtained from sub-array 1 (smallest aperture) are spread such that the 20% contour occupies some 9° in azimuth and 20° in elevation. As the aperture is increased the spreading reduces, and at the largest aperture (sub-array 6) the 20% contour occupies approximately 3° in azimuth and 5° in elevation. Approximately 93% of the array samples result in successful snaps (ie. 93% data availability), the majority of which lie within the
Transmitter location, Sarnen, Switzerland
Frequency, 8.535 MHz.
Date, 25/3/81

FIGURE 7.1

PHASE (DEGREES) ------

CHANNEL 180
NO. 7 90

CHANNEL 180
NO. 6 90

CHANNEL 180
NO. 5 90

CHANNEL 180
NO. 4 90

CHANNEL 180
NO. 3 90

CHANNEL 180
NO. 2 90

CHANNEL 180
NO. 1 90

RELATIVE AMPLITUDE
Sub array 1
Data selection test limits:
- Maximum phase linearity error: 180 degrees
- Maximum amplitude standard deviation: 100%
- Maximum DOA determination error: 1000.0 degrees

Distribution statistics:
- Data availability: 93.2%
- Data above 20% contour: 59.5%
- Data above 50% contour: 31.4%
- Data above 80% contour: 10.3%

Transmitter: Sarnen, Switzerland. Frequency: 9.555 MHz.
Date: 25 March 1981. Time: 19:20 GMT.
Sub array 1. No data selection. Duration: 15 minutes.

FIGURE 7.2(a)

Sub array 2
Data selection test limits:
- Maximum phase linearity error: 180 degrees
- Maximum amplitude standard deviation: 100%
- Maximum DOA determination error: 1000.0 degrees

Distribution statistics:
- Data availability: 93.2%
- Data above 20% contour: 50.9%
- Data above 50% contour: 21.0%
- Data above 80% contour: 5.0%

Date: 25 March 1981. Time: 19:20 GMT.
Sub array 2. No data selection. Duration: 15 minutes.

FIGURE 7.2(b)
Sub array 4
Data selection test limits:
Maximum phase linearity error: 180 degrees
Maximum amplitude standard deviation: 100%
Maximum DOA determination error: 1000.0 degrees
Distribution statistics:
Data availability: 93.2%
Data above 20% contour: 73.7%
Data above 50% contour: 49.3%
Data above 80% contour: 14.4%

Date: 25 March 1981. Time: 19:20 GMT.

(c)

Sub array 6
Data selection test limits:
Maximum phase linearity error: 180 degrees
Maximum amplitude standard deviation: 100%
Maximum DOA determination error: 1000.0 degrees
Distribution statistics:
Data availability: 93.2%
Data above 20% contour: 77.4%
Data above 50% contour: 62.4%
Data above 80% contour: 41.4%

Date: 25 March 1981. Time: 19:20 GMT.

(d)
Selection of the snaps by applying the phase linearity test results in little change in the shape or size of the snap distribution (eg. see Figure 7.3). The data availability is reduced from 93.2% for no selection, to 5.1% for a maximum allowed phase linearity error of 10°, with a corresponding increase in the percentage of the successful snaps within the bounds of the 20% contour from 77.4% to 83.8%.

Similar results are obtained when the data are selected by the DOA agreement test (eg. see Figure 7.4). For this selection technique the data availability is reduced to 9% for a maximum DOA agreement error of 2° with a corresponding increase in the percentage of successful snaps within the bounds of the 20% contour from 77.4% to 84%. Very little change in the size of the snap distribution is apparent.

Selection of the data by the amplitude equality test (eg. see Figure 7.5) leads to a reduction in the size of the snap distribution to approximately 2° in azimuth and elevation, for a maximum amplitude standard deviation of 5%. A corresponding increase in the percentage of successful snaps contained within the bounds of the 20% contour to 94.3% occurs. At this value of maximum allowed amplitude standard deviation the data availability is reduced to 2.5%. For a maximum amplitude standard deviation of 20% little change in the size of the distribution of snaps was observed, but the number of snaps within the bounds of the 20% contour increased to 83.4%.

For this transmission the application of the selection techniques resulted in a small improvement in the snap distribution, a larger percentage of the successful snaps lying within the 20% contour - this is indicative of a reduction in the number of 'wild' DOA determinations. With the exception of
Sub array 6

Data selection test limits:
- Maximum phase linearity error: 10 degrees
- Maximum amplitude standard deviation: 100%
- Maximum DOA determination error: 1000.0 degrees

Distribution statistics:
- Data availability: 5.1%
- Data above 20% contour: 83.8%
- Data above 50% contour: 95.6%
- Data above 80% contour: 90.9%

Date: 25 March 1981. Time: 19:20 GMT.
Selection by phase linearity test. Duration: 15 minutes.

FIGURE 7.3

Sub array 6

Data selection test limits:
- Maximum phase linearity error: 180 degrees
- Maximum amplitude standard deviation: 100%
- Maximum DOA determination error: 2.5 degrees

Distribution statistics:
- Data availability: 14.5%
- Data above 20% contour: 92.6%
- Data above 50% contour: 71.9%
- Data above 80% contour: 54.0%

Date: 25 March 1981. Time: 19:20 GMT.
Selection DOA agreement test. Duration: 15 minutes.

FIGURE 7.4
Sub array 6
Data selection test limits:
- Maximum phase linearity error: 180 degrees
- Maximum amplitude standard deviation: 10%
- Maximum DOA determination error: 1000.0 degrees

Distribution statistics:
- Data availability: 18.4%
- Data above 20% contour: 89.5%
- Data above 50% contour: 76.7%
- Data above 80% contour: 44.6%

Date: 25 March 1981. Time: 19:20 CMT.
Selection by the amplitude test. Duration: 15 minutes.

FIGURE 7.5
the results obtained from applying the amplitude test no reduction in the spread of the snaps was observed.

Madrid, Spain: 9.570 MHz.

Presented in Figure 7.6 are plots of the signal amplitude for the 141 second interval starting at 16:35:27 GMT on 26 March 1981 for each of the seven channels. The amplitude fading is indicative of a dominant mode together with a smaller interfering mode of relative amplitude 0.5 or less.

Presented in Figure 7.7 are a sequence of skymap plots showing the distribution of the frequency of occurrence of DOA values for four of the sub-arrays. The spreading of the snaps obtained for sub-array 1, as indicated by the 20% contour, is considerably greater in elevation (32°) than in azimuth (4°). This feature was anticipated (see Figure 6.3) for cases where the cones intersect at a low angle. For increased apertures the spread is reduced to some 2.5° in azimuth and 14° in elevation. The data availability (69.4%) is considerably less than the previous case, however the majority of snaps lie within the bounds of the 20% contour.

For sub-arrays 3-6 additional peaks occur in the contour plots. This effect is first apparent for sub-array 3, the secondary peak having a bearing of approximately 169° and elevation angle of 42°. As the aperture is increased the position of the secondary peak 'moves' to an approximate bearing of 182° with an elevation angle of 31°. This wandering is indicative of an incorrect DOA determination. This is confirmed by overlaying the azimuth/elevation plot with lines of the possible DOAs obtained for each of the antenna pairs such that an intersection occurs coincident with the main peak of the frequency of occurrence distribution (bearing approximately 192°) (see Figure 7.8); intersections of these lines indicate the azimuth/elevation coordinates for all the possible DOAs for the sub-array.
FIGURE 7.6

Transmitter location: Madrid, Spain
Frequency: 9,570 MHz.
Date: 26/5/81
Sub array 1
Data selection test limits:
- Maximum phase linearity error: 180 degrees
- Maximum amplitude standard deviation: 100%
- Maximum DOA determination error: 1000.0 degrees
Distribution statistics:
- Data availability: 69.4%
- Data above 20% contour: 52.7%
- Data above 50% contour: 33.6%
- Data above 80% contour: 13.1%

Date: 26 March 1981. Time: 16:33 GMT.
Sub array 1. No data selection. Duration: 15 minutes.

FIGURE 7.7 (a)

Sub array 2
Data selection test limits:
- Maximum phase linearity error: 180 degrees
- Maximum amplitude standard deviation: 100%
- Maximum DOA determination error: 1000.0 degrees
Distribution statistics:
- Data availability: 69.4%
- Data above 20% contour: 52.7%
- Data above 50% contour: 33.6%
- Data above 80% contour: 13.1%

Date: 26 March 1981. Time: 16:33 GMT.
Sub array 2. No data selection. Duration: 15 minutes.

FIGURE 7.7 (b)
Sub array 4
Data selection test limits:
Maximum phase linearity error: 180 degrees
Maximum amplitude standard deviation: 100%
Maximum DOA determination error: 1000.0 degrees
Distribution statistics:
Data availability: 69.3%
Data above 20% contour: 60.8%
Data above 50% contour: 29.9%
Data above 80% contour: 11.5%
Date: 26 March 1981. Time: 16:33 GMT.

(c)

Sub array 6
Data selection test limits:
Maximum phase linearity error: 180 degrees
Maximum amplitude standard deviation: 100%
Maximum DOA determination error: 1000.0 degrees
Distribution statistics:
Data availability: 69.3%
Data above 20% contour: 58.2%
Data above 50% contour: 40.0%
Data above 80% contour: 9.1%
Date: 26 March 1981. Time: 16:33 GMT.

(d)
Sub array 6

Data selection test limits:
- Maximum phase linearity error: 180 degrees
- Maximum amplitude standard deviation: 100%
- Maximum DOA determination error: 1000.0 degrees

Distribution statistics:
- Data availability: 69.3%
- Data above 20% contour: 58.2%
- Data above 50% contour: 40.0%
- Data above 80% contour: 9.1%

Data as for Figure 7.7(c) with 'lines of possible DOA' for each of the antenna arms added.

FIGURE 7.8
prior to the removal of the ambiguities. The peak at 182° is coincident with an adjacent intersection indicating that this peak originated from incorrect ambiguity resolution.

Selection of the snaps by the phase linearity test results in little overall change to the size of the distributions (eg. see Figure 7.9), although for a maximum allowed linearity error of 10° the elongated distribution 'breaks up' into two adjacent distributions and several other small peaks are apparent. As the maximum allowed linearity error is reduced the percentage of the successful snaps lying within the bounds of the 20% contour remains at approximately 59%. No major affect on the erroneous peak is apparent.

Application of selection by the DOA agreement test at a maximum allowed difference of 20° results in the removal of the erroneous peak present in the unselected data. The data availability is reduced from 69.3% to 59.6%, with 53.3% of the successful snaps lying within the bounds of the 20% contour. Further reduction of the maximum allowed mismatch (eg. see Figure 7.10) leads to a decrease in the data availability and an increase in the percentage of the successful snaps lying within the 20% contours. No significant change in the overall size of the distributions occurred.

Selection of the snaps by the amplitude standard deviation test (eg. see Figure 7.11) leads to a reduction in the data availability, a removal of the erroneous peak and a reduction in the overall size of the distribution. For a maximum allowed amplitude standard deviation of 10% the data availability was reduced form 69.3% to 16.7%, the percentage of the snaps within the 20% contours increased from 58.2% to 80.3%, and the elevation angle spread reduced from 15° to less than 10°.
Sub array 6
Data selection test limits:
- Maximum phase linearity error: 10 degrees
- Maximum amplitude standard deviation: 100%
- Maximum DOA determination error: 1000.0 degrees

Distribution statistics:
- Data availability: 3.7%
- Data above 20% contour: 57.3%
- Data above 50% contour: 32.1%
- Data above 80% contour: 9.0%

Date: 26 March 1981. Time: 16:53 GMT.
Selection by phase linearity test. Duration: 15 minutes.

FIGURE 7.9

Sub array 6
Data selection test limits:
- Maximum phase linearity error: 180 degrees
- Maximum amplitude standard deviation: 100%
- Maximum DOA determination error: 2.5 degrees

Distribution statistics:
- Data availability: 11.9%
- Data above 20% contour: 77.2%
- Data above 50% contour: 50.9%
- Data above 80% contour: 14.7%

Date: 26 March 1981. Time: 16:33 GMT.
Selection by DOA agreement test. Duration: 15 minutes.

FIGURE 7.10
Sub array 6

Data selection test limits:
- Maximum phase linearity error: 180 degrees
- Maximum amplitude standard deviation: 10%
- Maximum DOA determination error: 1000.0 degrees

Distribution statistics:
- Data availability: 16.7%
- Data above 20% contour: 80.3%
- Data above 50% contour: 47.9%
- Data above 80% contour: 10.9%

Date: 26 March 1981. Time: 16:33 GMT.
Selection by the amplitude test. Duration: 15 minutes.

FIGURE 7.11
In this case the application of the DOA matching test or the amplitude standard deviation test resulted in a significant improvement in the distribution of the snap values. In particular, the amplitude test resulted in a smaller distribution of determined DOAs.

Moosbrunn, Austria: 9.770 MHz.

In Figure 7.12 plots of signal amplitude for a 141 second interval commencing at 10:12:40 GMT on 26 March 1981 for each of the seven channels are presented. The severe amplitude fading is indicative of two or more signal components of similar amplitudes.

For this case the distributions of the snaps are far more spread than in the previous examples. Presented in Figure 7.13 are a sequence of skymaps for four of the sub-arrays with no data selection applied. The spreading, as indicated by the 20% contour, for sub-array 1 is some 12° in azimuth and 28° in elevation, and, unlike the previous examples no well determined peak exists. As the aperture is increased the spreading first of all increases to some 75° in azimuth and 60° in elevation for sub-array 2, and many localised peaks are present. Further increase in the aperture results in the formation of two main and several subsidiary peaks. The spreading around the main peaks (i.e. peaks above the 80% contour) is approximately 8° in azimuth and 6° in elevation. Data availability is 86.3% and approximately 36% of the successful snaps lie within the bounds of the 20% contour.

As in the previous example (the 9.570 MHz transmission from Madrid) the multiple peaks are consistent with a failure to correctly resolve the 2π ambiguities. The 'correct peak' has a bearing of approximately 103° and an elevation angle of 40°.
Transmitter location: Moosbrunn, Austria
Frequency: 9.770 MHz.
Date: 26/3/81

FIGURE 7.12
DATA SELECTION TEST LIMITS:

- Maximum phase linearity error: 180 degrees
- Maximum amplitude standard deviation: 100%
- Maximum DOA determination error: 1000.0 degrees

DISTRIBUTION STATISTICS:

- Data availability: 86.3%
- Data above 20% contour: 50.7%
- Data above 50% contour: 18.4%
- Data above 80% contour: 3.5%

Transmitter: Moosbrunn, Austria. Frequency: 9.770 MHz.
Date: 26 March 1981. Time: 10:10 GMT.
Sub array 1. No data selection. Duration: 15 minutes.

FIGURE 7.13 (a)

DATA SELECTION TEST LIMITS:

- Maximum phase linearity error: 180 degrees
- Maximum amplitude standard deviation: 100%
- Maximum DOA determination error: 1000.0 degrees

DISTRIBUTION STATISTICS:

- Data availability: 85.3%
- Data above 20% contour: 51.5%
- Data above 50% contour: 10.6%
- Data above 80% contour: 1.5%

Transmitter: Moosbrunn, Austria. Frequency: 9.770 MHz.
Date: 26 March 1981. Time: 10:10 GMT.
Sub array 2. No data selection. Duration: 15 minutes.

FIGURE 7.13 (b)
Sub array 4
Data selection test limits:
- Maximum phase linearity error: 180 degrees
- Maximum amplitude standard deviation: 100%
- Maximum DOA determination error: 1000.0 degrees

Distribution statistics:
- Data availability: 84.6%
- Data above 20% contour: 50.2%
- Data above 50% contour: 16.7%
- Data above 80% contour: 1.2%

Transmitter: Moosbrunn, Austria. Frequency: 9.770 MHz.
Date: 26 March 1981. Time: 10:10 GMT.

Sub array 6
Data selection test limits:
- Maximum phase linearity error: 180 degrees
- Maximum amplitude standard deviation: 100%
- Maximum DOA determination error: 1000.0 degrees

Distribution statistics:
- Data availability: 84.7%
- Data above 20% contour: 35.7%
- Data above 50% contour: 12.0%
- Data above 80% contour: 5.1%

Transmitter: Moosbrunn, Austria. Frequency: 9.770 MHz.
Date: 26 March 1981. Time: 10:10 GMT.
Selection of the snaps by the phase linearity test results in little significant change in the size or shape of the snap distributions (eg. see Figure 7.14). As the maximum allowed phase linearity error is decreased, the data availability drops from 84.7% for no selection to 4.7% for a maximum allowed linearity error of 10°.

Application of the DOA agreement test has little affect on the overall size of the main peaks as indicated by the 20% contour. For a maximum allowed DOA agreement error of 20° the data availability is reduced from 84.7% for no selection to 71.2% and no data occurs above the 80% contour for the erroneous peak at a bearing of approximately 115°. Further reduction of the maximum allowed DOA agreement error leads to some reduction in the size of the peak distributions, but has little affect on the presence of several peaks well displaced from the 'true' peak (eg. see Figure 7.15).

Selection of the snaps by the amplitude equality test (eg. see Figure 7.16) has little affect on the size of the peaks in the distribution, or on the presence of 'wild' peaks. The peaks show a tendency to split into several closely spaced peaks. Further reduction of the maximum allowed amplitude standard deviation results in the rejection of the majority of the snaps.

None of the selection techniques produced a significant reduction in the spread of the snap distributions, or the rejection of the erroneous peaks resulting from incorrect ambiguity resolution, for these data. Figure 7.17 is a skyplot for the same data presented above, but with a restriction placed on both the maximum allowed amplitude standard deviation (18%) and on the maximum allowed DOA agreement error (18°). A significant reduction in the size of the 'correct' peak and in the size of the 'erroneous' peaks is apparent. 73% of the successful snaps lie within the bounds of the 20% contours, however the data availability is only 2.9%.
Sub array 6
Data selection test limits:
  Maximum phase linearity error, 10 degrees
  Maximum amplitude standard deviation, 100%
  Maximum DOA determination error, 1000.0 degrees
Distribution statistics:
  Data availability, 4.7%
  Data above 20% contour, 100.0%
  Data above 50% contour, 30.5%
  Data above 80% contour, 6.3%
Transmitter: Moosbrunn, Austria. Frequency: 9.770 MHz.
Date: 26 March 1981. Time: 10:10 GMT.
Selection by phase linearity test. Duration: 15 minutes.

FIGURE 7.14

Sub array 6
Data selection test limits:
  Maximum phase linearity error, 180 degrees
  Maximum amplitude standard deviation, 100%
  Maximum DOA determination error, 10.0 degrees
Distribution statistics:
  Data availability, 21.0%
  Data above 20% contour, 42.2%
  Data above 50% contour, 10.5%
  Data above 80% contour, 4.0%
Transmitter: Moosbrunn, Austria. Frequency: 9.770 MHz.
Date: 26 March 1981. Time: 10:10 GMT.
Selection by DOA agreement test. Duration: 15 minutes.

FIGURE 7.15
Sub array 6
Data selection test limits:
- Maximum phase linearity error: 180 degrees
- Maximum amplitude standard deviation: 20%
- Maximum DOA determination error: 1000.0 degrees

Distribution statistics:
- Data availability: 5.8%
- Data above 20% contour: 72.5%
- Data above 50% contour: 29.2%
- Data above 80% contour: 11.5%

Transmitter: Moosbrunn, Austria. Frequency: 9.770 MHz.
Date: 26 March 1981. Time: 10:10 GMT.
Selection by the amplitude test. Duration: 15 minutes.

FIGURE 7.16

Sub array 6
Data selection test limits:
- Maximum phase linearity error: 180 degrees
- Maximum amplitude standard deviation: 18%
- Maximum DOA determination error: 18.0 degrees

Distribution statistics:
- Data availability: 2.9%
- Data above 20% contour: 73.0%
- Data above 50% contour: 21.6%
- Data above 80% contour: 6.1%

Transmitter: Moosbrunn, Austria. Frequency: 9.770 MHz.
Date: 26 March 1981. Time: 10:10 GMT. Duration: 15 minutes.
Selection by both the amplitude and DOA tests.

FIGURE 7.17
In this case the application of the selection techniques individually yielded little improvement in the size of the snap distributions, nor did they lead to a removal of the erroneous peaks. Application of both the DOA and amplitude tests lead to a significant reduction in the size of the distributions, however, the majority of the data were rejected. The amplitude fading for this interval was more severe than for the other cases considered above.

Summary

The results of measurements of the DOA for three of the test transmissions, each of which displayed different characteristics (probably due to the different levels of multi-mode interference) have been presented. Significant reduction in the spreading of the snaps and presence of erroneous peaks caused by the failure to correctly resolve ambiguities was obtained by selection of snaps by the amplitude equality test and by the DOA agreement test. The selection processes also resulted in the reduction of the percentage of 'wild' determinations. The performance of these two tests in terms of the data availability and the percentage of the remaining points lying within the bounds of the 20% contours are presented in Tables 7.2 and 7.3. The phase linearity test, however, lead to no significant reduction in the spreading of the distributions, probably due to the limitations expected from this test described in Chapter 6. Although the selection techniques were not successful in preventing erroneous peaks in the case of the transmission from Austria (worst fading case), these peaks were recognised by their tendency to 'move' as the aperture was changed and could, therefore, be identified and rejected.
Table 7.2 - Summary of the effect of data selection by the DOA agreement test on the data availability and on the percentage of available data lying within the bounds of the 20Z contour.

<table>
<thead>
<tr>
<th>Maximum DOA error:</th>
<th>20°</th>
<th>10°</th>
<th>8°</th>
<th>6°</th>
<th>4°</th>
<th>2°</th>
</tr>
</thead>
</table>

**Sarnen**
- Data availability: 93% 84% 77% 64% 38% 9%
- Within 20% contour: 78% 80% 82% 82% 83% 84%

**Moosbrunn**
- Data availability: 71% 21% 14% 8.5% 3.7% 0.6%
- Within 20% contour: 31% 42% 37% 38% 46% 100%

**Madrid**
- Data availability: 60% 47% 40% 31% 20% 9%
- Within 20% contour: 53% 67% 72% 75% 74% 83%

Table 7.3 - Summary of the effect of data selection by the amplitude agreement test on the data availability and on the percentage of the available data lying within the 20Z contour.

<table>
<thead>
<tr>
<th>Maximum amplitude SD:</th>
<th>80%</th>
<th>60%</th>
<th>40%</th>
<th>20%</th>
<th>10%</th>
<th>5%</th>
</tr>
</thead>
</table>

**Sarnen**
- Data availability: 93% 93% 90% 58% 18% 2.5%
- Within 20% contour: 77% 78% 80% 83% 90% 94%

**Moosbrunn**
- Data availability: 84% 81% 55% 5.8% - -
- Within 20% contour: 36% 36% 44% 73% - -

**Madrid**
- Data availability: 69% 67% 58% 38% 17% 8.1%
- Within 20% contour: 58% 60% 67% 80% 80% 70%
DOA MEASUREMENTS AND TRANSMITTER LOCATION RESULTS

In this section measurements of the DOA made over several hours are presented together with results of combining the DOA measurements with ionospheric soundings to obtain an estimate of the location of the transmitter. The methods employed in this chapter are those previously described in Chapter 6.

Azimuth correction

No attention has, so far, been paid to the 'correctness' of the determined DOAs, a good determination having been assumed to be invariant with aperture and not spreading by more than one or two degrees. The bearings determined from the measurements are subject to error from several sources, in particular tilts in the ionosphere and incorrect array orientation. Table 7.4 lists the values of the true bearing for each of the test transmitters together with the average measured bearing. All of the measured bearings are between $2^\circ$ and $6.5^\circ$ greater than the true bearings, with an average error of approximately $4.1^\circ$. In an attempt to correct for array orientation errors, all bearings subsequently presented will be adjusted by this amount.

Ionospheric soundings

To estimate the location of a distant transmitter from DOA measurements made at a single site, accurate information concerning the reflection heights near to the reflection point is required (see Chapter 6). Ideally a network of ionosondes operating at frequent time intervals near to the reflection points of the test signals would have been employed. Such a network was not available and recourse was made to hourly soundings made at Slough, UK.
Table 7.4 - Comparison of measured and true bearings.

<table>
<thead>
<tr>
<th>Transmitter</th>
<th>True bearing</th>
<th>Measured bearing</th>
<th>Measured - true</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copenhagen</td>
<td>60.2°</td>
<td>63.7°</td>
<td>3.5°</td>
</tr>
<tr>
<td>Noblejas-toledo</td>
<td>185.1°</td>
<td>190.3°</td>
<td>5.2°</td>
</tr>
<tr>
<td>Moosbrunn</td>
<td>99.9°</td>
<td>102.0°</td>
<td>2.1°</td>
</tr>
<tr>
<td>Madrid</td>
<td>185.4°</td>
<td>191.7°</td>
<td>6.3°</td>
</tr>
<tr>
<td>Sarnen</td>
<td>121.9°</td>
<td>125.4°</td>
<td>3.5°</td>
</tr>
</tbody>
</table>

Mean 4.1°
The F-region traces on the ionograms were digitised across the frequency range required for these experiments. Typical examples are presented in Figure 7.18. For some periods very little change occurs between consecutive hourly soundings (eg. see Figure 7.18(a) and (b)), however, other periods exhibit a considerable change between consecutive hourly soundings (eg. see Figure 7.18(c) and (d)). To take account of these changes in determining the reflection height, the following procedure was adopted: A value of the reflection height was calculated from the soundings taken both before and after the DOA measurements. The variation in reflection height was assumed to vary linearly with time and thus a value for the reflection height at the time of the DOA measurement calculated. Since the reflection point was not at the same longitude as Slough (the location of the ionosonde) a correction was made for the time difference between the path mid-point and Slough (see Table 7.5).

Due to the trace thickness on the ionograms the reflection heights could not be determined to better than approximately ±10 km. This error will lead to a positional error of approximately ±40 km at a range of 1000 km.

Sarnen, Switzerland: 9.535 MHz.

Five periods of data were collected:

a) 17:14 - 17:35 GMT, 25 March 1981  
b) 17:45 - 13:02 GMT, 25 March 1981  
d) 09:11 - 09:33 GMT, 26 March 1981  
e) 14:53 - 15:13 GMT, 26 March 1981

The digitised F region ionogram traces and appropriate transmission curves are presented in Figure 7.19. Plots of the bearing and elevation angles
Digitised F region traces from Slough ionograms. Date: 25/3/81.

FIGURE 7.18
SLOUGH IONOGRAM AND TRANSMISSION CURVES.
(a) 17:00 GMT. (b) 18:00 GMT. (c) 19:00 GMT

FIGURE 7.19
SLough Ionogram and Transmission Curves.

Frequency: 9.535 MHz.

(d) 20.00 GMT, 25/3/81
(e) 09.00 GMT, 26/3/81
(f) 10.00 GMT, 26/3/81
SLOUGH IONOGRAM AND TRANSMISSION CURVES.
(g) 14:00 GMT. (h) 15:00 GMT. (i) 14:00 GMT
Table 7.5 - Time differences between Slough and the path mid-points for the transmitters employed in the SSL experiments.

<table>
<thead>
<tr>
<th>Transmitter</th>
<th>Time difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copenhagen</td>
<td>24.4 minutes</td>
</tr>
<tr>
<td>Moosbrunn</td>
<td>32.9 minutes</td>
</tr>
<tr>
<td>Madrid</td>
<td>-6.9 minutes</td>
</tr>
<tr>
<td>Noblejas-Toledo</td>
<td>-6.9 minutes</td>
</tr>
<tr>
<td>Sarnen</td>
<td>16.4 minutes</td>
</tr>
</tbody>
</table>
with time and contour plots of the position fixes for these data sets are presented as Figures 7.20 to 7.24, each of which are discussed below.

a) Figure 7.20. In this figure approximately 22 minutes of data are presented. Spreading of several degrees is apparent in both the bearing and elevation angles of arrival. The overall position fix has good azimuthal accuracy, but the peak of the distribution lies some 50 km short of the transmitter - this is, however, within the accuracy to be expected from a ±10 km error in measuring the reflection height from the ionograms.

b) Figure 7.21. Presented in this figure are data for a 78 minute period following shortly after that of Figure 7.20. Similar spreading of the bearing and elevation angles to those of the previous data set are apparent. A wavelike variation of magnitude approximately 1° and period of several tens of minutes is also apparent. Two main peaks in the position fix distribution occur, one approximately 25 km short of the transmitter, the other some 75 km short. A smaller secondary peak, some 225 km beyond the transmitter is also present. Again, good bearing accuracy was obtained.

c) Figure 7.22. Data for a 25 minute period starting approximately 20 minutes after the end of the previous data set. Spreading of 1 or 2 degrees in both bearing and elevation angles is again apparent. There is a steady increase in elevation angle of arrival from approximately 24.5° at the start to approximately 29° at the end. At this time the ionograms indicate a large increase in the reflection height between consecutive soundings. This effect is unlikely to occur in a linear manner throughout the 1 hour period between soundings and, therefore, large errors in the calculated reflection height are likely. The peak
Transmitter location: Sarnen, Switzerland.
Frequency: 9.535 MHz.
17:14 GMT - 17:35 GMT on 25 March 1981

FIGURE 7.20
Transmitter location: Sarnen, Switzerland.
Frequency: 9.535 MHz.
17:45 GMT - 19:02 GMT on 25 March 1981

FIGURE 7.21
Transmitter location: Sarnen, Switzerland.
Frequency: 9.535 MHz.
17:45 GMT - 19:02 GMT on 25 March 1981
Transmitter location: Sarnen, Switzerland.
Frequency: 9.535 MHz.

FIGURE 7.22
in the position fix is located approximately 150 km beyond the transmitter, again with good azimuthal accuracy.

d) Figure 7.23. Data are presented in this figure for a 22 minute period starting at 09:11 GMT on the morning following the previous periods. Again, spreading of both the bearing and elevation angles of arrival is apparent. A wavelike variation of amplitude approximately 1° and period of several tens of minutes is apparent. The positional fix distribution is much smaller than in the previous examples, it has good bearing accuracy but lies approximately 125 km beyond the transmitter. The ionograms for this period display a very steep trace making it difficult to determine the reflection height to the required accuracy. At this time of day ionospheric tilts are to be expected which would lead to an over-ranging effect.

e) Figure 7.24. Presented in this figure are data for an 18 minute period. Spreading of several degrees in the determined angles of arrival is apparent. The positional fix distribution displays both good azimuthal and range accuracy.

Copenhagen, Denmark: 15.165 MHz.

Two periods of data were collected for this transmission:

a) 15:05 - 15:49 GMT, 25 March 1981

The digitised F region ionogram traces and appropriate transmission curves are presented in Figure 7.25. Plots of the bearing and elevation angles with time and contour plots of the position fixes for these data are presented as Figures 7.26 and 7.27, both of which are discussed below.
Transmitter location: Sarnen, Switzerland.
Frequency: 9535 MHz.
09:11 GMT - 09:33 GMT on 26 March 1981

FIGURE 7.23
Transmitter location: Sarnen, Switzerland.
Frequency: 9535 MHz.

FIGURE 7.24
FIGURE 7.25

SLOUGH IONOGRAM AND TRANSMISSION CURVES.
Frequency: 15.165 MHz. Date: 25 March 1981.
(a) 15.00 GMT. (b) 16.00 GMT. (c) 17.00 GMT
a) Figure 7.26. In this figure approximately 44 minutes of data are reproduced, and spreading of between 1° and 2° in both bearing and elevation angle of arrival is apparent. A wavelike variation in the bearing is present, with magnitude approximately 0.5° and period of approximately 25 minutes. The elevation angle of arrival decreases throughout the interval from 34° to 29°. The position fix distribution peaks at some 125 km short of the transmitter, but good bearing accuracy is obtained.

The large change in reflection height between the soundings taken at 15:00 GMT and 16:00 GMT is unlikely to occur in a linear manner, leading to potentially large errors in determining the reflection height. If the range is calculated from the first 20 minutes of these data (i.e. during the period of relatively constant elevation angle) and the height calculated from the 15:00 GMT ionogram, then a range value of 1011 km is obtained (true range 1035 km).

b) Figure 7.27. Data for the 35 minute period starting 34 minutes after the end of the previous data set are presented in this figure. Steady bearings and elevation angles of arrival were observed, with some evidence of small wavelike variations. Two main peaks occur in the position fix distributions: which are approximately 40 km and 125 km short of the transmitter respectively.

Examination of the ionograms for this period indicates that between 17:00 GMT and 18:00 GMT the reflection height for this signal is reduced by approximately 20 km. If the 17:00 GMT ionogram is employed for the range determination then the position fix distribution is as illustrated
Transmitter location: Copenhagen, Denmark
Frequency: 15.165 MHz.

FIGURE 7.26
Frame (b) shows the position fixes obtained using both the 17:00 and 18:00 GMT ionograms. Frame (c) shows the position fixes obtained using only the 17:00 GMT ionogram.

FIGURE 7.27
Transmitter location: Copenhagen, Denmark
Frequency: 15.165 MHz.
in Figure 7.27(c). In this case the distribution peak is approximately 50 km short of the transmitter. Good bearing accuracy is obtained.

**Madrid, Spain: 9.570 MHz.**

Two periods of data were collected for this transmission:

a) 16:36 - 17:02 GMT, 26 March 1981  
b) 17:13 - 18:10 GMT, 26 March 1981

The digitised F region ionogram traces and appropriate transmission curves are presented in Figure 7.28. Azimuth and elevation angle plots and position fixes are presented in Figures 7.29 and 7.30.

**a) Figure 7.29.** For these data very little spreading in bearing was observed, there is, however, a large spread in elevation angles, approximately 10°. Good bearing accuracy was achieved. The peak of the position fix distribution lies approximately 80 km beyond the transmitter, but considerable range variation was observed - the 20% contour ranged from 50 km short of the transmitter to 370 km beyond the transmitter. The large spread in range is expected from geometrical considerations since: (a) the error in measured elevation angle was relatively large due to the small intersection angle of the 'cones of possible DOA', and (b) a small error in measured elevation angle results in a much larger range error than is the case for the shorter paths.

**b) Figure 7.30.** The data presented in this figure were collected for a 57 minute period starting 11 minutes after the end of the previous example. Very similar results were obtained.
SLOUGH IONGRAM AND TRANSMISSION CURVES.
(a) 16:00 GMT. (b) 17:00 GMT. (c) 18:00 GMT

FIGURE 7.28
Transmitter location: Madrid, Spain
Frequency: 9.570 MHz.
16:36 GMT - 17:02 GMT on 26 March 1981

FIGURE 7.29
Transmitter location: Madrid, Spain
Frequency: 9.570 MHz.
17:13 GMT - 18:10 GMT on 26 March 1981

FIGURE 7.30
Noblejas-Toledo, Spain: 11.920 MHz.

Three data sets were collected for this transmission:

a) 12:08 - 12:33 GMT, 26 March 1981
b) 13:08 - 14:12 GMT, 26 March 1981
c) 15:36 - 16:30 GMT, 26 March 1981

The digitised F region ionogram traces and appropriate transmission curves are presented in Figure 7.31. Plots of the bearing and elevation angles with time and contour plots of the position fixes for these data are presented as Figures 7.32, 7.33 and 7.34, each of which are discussed below.

a) Figure 7.32. Large scattering (10°) was observed in the measured elevation angle of arrival, but with much less spread in the bearings (approximately 1°). The position fix distribution is positioned with the peak some 230 km beyond the transmitter. The ionogram and transmission curves for this interval show a large variation of $h'$ with $f_v$ or $\theta_e$. Under these circumstances a small change in the ionospheric profile between Slough and the path mid-point would lead to large errors in the calculated reflection height, and consequently large range errors.

b) Figure 7.33. Very similar results to those presented in Figure 7.32 are observed for these data.

c) Figure 7.34. Similar variations in bearing and elevation angles to the previous examples for this transmission are observed. Good bearing accuracy was obtained, however the peak of the position fix distribution lies some 140 km beyond the transmitter, a large spread in range...
SLOUGH IONOGRAM AND TRANSMISSION CURVES.
Frequency: 11,920 MHz. Date: 26 March 1981.
(a) 12:00 GMT.  (b) 13:00 GMT.  (c) 14:00 GMT

FIGURE 7.31
SLOUGH IONOGRAM AND TRANSMISSION CURVES.
Frequency, 11.920 MHz. Date: 26 March 1981.
(d) 15.00 GMT. (e) 16.00 GMT. (f) 17.00 GMT
Transmitter location: Noblejas-Toledo, Spain.
Frequency: 11.920 MHz.
12:08 GMT - 12:33 GMT on 26 March 1981

FIGURE 7.32
Transmitter location: Noblejas-Toledo, Spain.
Frequency: 11.920 MHz.
13:08 GMT - 14:12 GMT on 26 March 1981

FIGURE 7.33
Transmitter location: Noblejas-Toledo, Spain.
Frequency: 11.920 MHz.
15:36 GMT - 16:30 GMT on 26 March 1981

FIGURE 7.34
occurring. In this case the variation of $h^*$ with $f$ was less than for the previous two examples.

Moosbrunn, Austria: 9.770 MHz.

Several data sets were collected for this transmission, three typical examples of which are presented here:

b) 10:57 - 11:10 GMT, 26 March 1981
c) 11:43 - 11:55 GMT, 26 March 1981

The digitised $F$ region ionogram traces and appropriate transmission curves are presented in Figure 7.35. In order to remove the additional peaks in the azimuth/elevation measurements due to a failure to correctly resolve the $2\pi$ ambiguities (see Figure 7.13), careful selection of the allowed bearing and elevation angles were made for these data.

a) Figure 7.36. Data for one hour are presented in this figure. Considerable spreading was observed in both the measured bearings and elevation angles. The peak of the position fix distribution lies some 70 km beyond the path mid-point indicative of predominantly 2-hop propagation. No peaks were observed near to the transmitter location. Good azimuthal accuracy was obtained.

b) Figure 7.37. Considerable spreading was, again, observed in the measured bearings and elevation angles of arrival. The peak of the position fix distribution lies some 150 km beyond the path mid-point, no peaks being observed near to the transmitter location.
SLough IONOGRAM AND TRANSMISSION CURVES.
(a) 13:00 GMT. (b) 14:00 GMT. (c) 15:00 GMT

FIGURE 7.35
SLOUGH IONOGRAM AND TRANSMISSION CURVES.
Frequency, 9.770 MHz. Date, 26 March 1981.
(d) 10.00 GMT. (e) 11.00 GMT. (f) 12.00 GMT
Transmitter location: Moosbrunn, Austria.
Frequency: 9.770 MHz.

FIGURE 7.36
Transmitter location: Moosbrunn, Austria.
Frequency: 9.770 MHz.
10:57 GMT - 11:10 GMT on 26 March 1981

FIGURE 7.37
c) Figure 7.38. Very similar results to those presented in Figure 7.37 were observed for these data.

Summary

Data have been presented for five transmissions; several features are apparent from these data. For the two transmissions at ranges of approximately 1000 km position fixes were obtained to within the accuracy expected from the reflection height measurements from the ionograms (+10 km, over Slough). Errors in range were observed for these paths when the slope of the $h'(f)$ curve was large - under such circumstances the height determination may have been inaccurate since small changes in ionospheric profile between Slough and the path mid-point would result in a significant error in determining the virtual reflection height. Also under such circumstances the assumption that significant refraction occurs only near to the reflection point breaks down and incorrect ranging is to be expected.

At larger ranges (Spain and Austria, approximately 1300 km) the position fixes obtained were not as accurate, and, in the case of the Austrian transmission were located at approximately the path mid-point, indicative of 2-hop propagation. The large range spread in the case of the Spanish signals was to be expected from geometrical considerations since: (a) the error in measured elevation angle was large due to the small intersection angle of the 'cones of possible DOA', and (b) a small error in measured elevation angle results in a much larger range error than is the case for the shorter range paths. The measured range was, however, nearly always 100 km or more greater than the true range.
Transmitter location: Moosbrunn, Austria.
Frequency: 9.770 MHz.

FIGURE 7.38
CONCLUSIONS

The measurements presented in this chapter indicate that simple interferometer techniques can be effectively employed to yield an accurate measure of the DOA. However, care must be taken not to include data which does not satisfy the phase and/or amplitude tests for identifying plane wave conditions.

It has also been demonstrated that if accurate information is available concerning the reflection heights, then the DOA can be employed for single site location (SSL) of the distant transmitter. A number of SSL determinations have been presented and the errors influencing the measurements discussed in detail. It is concluded that a simple spaced element array can produce accurate DOAs and SSL determinations provided care is exercised in selecting the data so as to exclude erroneous determinations due to the effects of multi-moded propagation.

The results of these tests indicate that accurate bearings are obtained, however, range errors can occur either as the result of multi-moded propagation or, at larger ranges, due to geometrical effects. Furthermore, if two or more co-channel signals are present then good DOA measurements will not be achieved. A well filled interferometer array could be employed with a mode resolution technique to individually measure to DOA of each of the modes and/or signals. Under these circumstances a conventional Wullenweber system may be able to resolve the individual bearings (dependent upon the bearing separation, frequency, etc.) although no elevation angle information would be available.

SSL requires an accurate knowledge of the reflection height in order to achieve accurate results and ideally an ionosonde located beneath the signal
reflection point(s) would be employed. A conventional Wullenweber system, however, requires two (or more) well separated receiving sites. In view of the potentially large range errors obtained with the SSL system, a conventional Wullenweber network should achieve a more accurate position location. However a suitable network of receiving sites may not always be available and under such circumstances useful results may be obtained with a simple interferometer array and local ionosonde.
CHAPTER 8

CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

INTRODUCTION

Measurements have been made of the phases and amplitudes of ionospherically propagated HF radio waves received on widely separated antennas. Two seven element arrays were employed with the antennas arranged (approximately) along the arms of a V. The larger of the arrays had a maximum aperture of 1526 m, and the smaller, a maximum aperture of 294 m. Measurements of signals propagating over both long range (1000 km) and short range (122 km) paths were undertaken for both single and multi-moded propagation.

The following three major studies have been undertaken:

a) The determination of the characteristics of the signals received on a large aperture antenna array after reflection from the ionosphere.

b) An evaluation of the interferometer technique for measuring the direction of arrival (DOA) in both azimuth and elevation.

c) An investigation of the accuracy of transmitter location obtained from a single site from the DOA measurements and ionospheric soundings to obtain the reflection height.

SINGLE MODED SIGNALS

Several problems were encountered in obtaining measurements for single moded signals, primarily since for most of the observing periods several modes
could be identified. A series of pulsed soundings were taken over a short (122 km) path to help overcome this problem by identifying periods of predominantly single moded propagation. Resolution of the magnetoionic components was not, in general, possible because the width of the pulse available (0.7 ms) was too great. However, periods of data of approximately 10-20 minutes duration which were considered to be predominantly single moded were examined. Two features were identified which affected the signals measured at each of the elements of the antenna array. The first was a variation in the DOA of the signal of approximately 1-2° in both azimuth and elevation. The second was the presence of small amplitude and phase changes which were not well correlated across the array. These appeared to be related to the presence of a diffracted component in addition to the specular component. Coherence ratios of greater than 10, and often greater than 40 were measured. These ratios may, however, be lower than the true values due to the presence of both magnetoionic components and/or the presence of a small secondary mode, for which there was some evidence in both the pulsed soundings and in the amplitude records. It seems likely that the true coherence ratio for a single mode consisting of one magnetoionic component is somewhat higher than the measured values.

SINGLE SITE LOCATION

The measurements indicate that simple interferometer techniques can yield accurate values of the direction of arrival of a signal in both azimuth and elevation provided that the wave front is not distorted by secondary modes and interfering signals. Techniques were developed which can recognise periods when the wave front is planar. Both amplitude and phase measurements can be employed for these tests. Application of these tests did not result in the rejection of all 'wild' measurements, however, a significant improvement in accuracy was achieved by the selection process.
If accurate information is available regarding the reflection heights it proved possible to determine the location of a distant transmitter from DOA measurements at a single receiving site. In all the cases examined good bearing accuracy was achieved, however, range errors occurred either as the result of multi-moded propagation or due to geometrical effects at larger ranges. It appears that small simple interferometers could provide a significant target location capability when multi-station DF nets composed of large Wullenweber arrays are not available.

SUGGESTIONS FOR FURTHER WORK

From the results of the present investigation it appears that there are a number of topics which require further investigation. These are outlined below.

a) A limitation of the present experimental arrangement is its inability to receive pulse sounding signals which are required for mode identification and resolution. A facility for pulse sounding should therefore be incorporated into any future measuring system so that the modal structure of the signal can be resolved.

b) There are advantages, such as the ability to resolve modes, in observing with a well filled array. Some part of any future interferometer array should therefore contain closely spaced elements.

c) A more extensive evaluation of the interferometer as a single site location system should be undertaken. There are evidently difficulties associated with long range 1-hop signals and with 2-hop signals and these should be resolved.
d) There is a need to develop a mathematical model for the ionospheric propagation based on the spaced element array observations. It seems that existing models could be adapted if the necessary development work were undertaken.

e) The data collected contains valuable information for the development of 'diversity' receiving systems. The benefits of diversity reception, obtained with various combinations of the array elements employed, should be examined.

f) The special problem of SSL for steep incidence propagation should be examined.
APPENDIX A

SUMMARY OF DATA COLLECTED

A summary of the data collected using both the Forward Look and Verbana antenna arrays is given below. The locations given (with the exception of the pulse sounder at Oadby, Leicester) are those claimed by the appropriate broadcasting authorities. It is possible that, on occasion, reserve transmitters were in use from alternative sites.

BBC Radio 2
Location: Droitwich
Frequency: 0.693 MHz
Range: 75.6 km
Bearing: 348.5°
Forward Look: 0.5 hours
Verbena: 0.1 hours

BBC Radio Wales
Location: Washford
Frequency: 0.882 MHz
Range: 116.0 km
Bearing: 243.0°
Forward Look: 0.3 hours

BBC Radio Swindon
Location: Swindon
Frequency: 1.34 MHz
Range: 11.5 km
Bearing: 140.5°
Forward Look: 4.6 hours
<table>
<thead>
<tr>
<th>Station</th>
<th>Location</th>
<th>Frequency</th>
<th>Range</th>
<th>Bearing</th>
<th>Forward Look</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swiss Radio International</td>
<td>Lenk</td>
<td>3.985 MHz</td>
<td>890.6 km</td>
<td>126.6°</td>
<td>0.5 hours</td>
</tr>
<tr>
<td>Oadby (Pulse sounder)</td>
<td>Oadby, Leicester</td>
<td>4.7925 MHz</td>
<td>122.2 km</td>
<td>25.1°</td>
<td>8.2 hours</td>
</tr>
<tr>
<td>Swiss Radio International</td>
<td>Lenk</td>
<td>6.165 MHz</td>
<td>890.6 km</td>
<td>126.6°</td>
<td>1.6 hours</td>
</tr>
<tr>
<td>French Radio International</td>
<td>Issoudun</td>
<td>6.175 MHz</td>
<td>870.3 km</td>
<td>162.9°</td>
<td>3.4 hours</td>
</tr>
<tr>
<td>Swiss Radio International</td>
<td>Sarnen</td>
<td>9.535 MHz</td>
<td>901.4 km</td>
<td>121.9°</td>
<td>31.1 hours</td>
</tr>
</tbody>
</table>

A.2
**Spanish Foreign Radio**

Location: Madrid  
Frequency: 9.570 MHz  
Range: 1259.2 km  
Bearing: $186.0^\circ$

Verbena: 1.0 hours

**Austrian Radio**

Location: Moosbrunn  
Frequency: 9.770 MHz  
Range: 1375.0 km  
Bearing: $99.9^\circ$

Verbena: 1.8 hours

**Spanish Foreign Radio**

Location: Noblejas-Toledo  
Frequency: 11.920 MHz  
Range: 1295.7 km  
Bearing: $185.9^\circ$

Verbena: 1.8 hours

**Radio Denmark**

Location: Copenhagen  
Frequency: 15.165 MHz  
Range: 1015.2 km  
Bearing: $60.16^\circ$

Verbena: 1.0 hours

**Miscellaneous**

Approximately 11.3 hours of data were collected using the Forward Look antenna array for several other transmissions.
APPENDIX B

DETAILS OF CALCULATION OF THE DIRECTION OF ARRIVAL
OF A SIGNAL TO A MULTI-ELEMENT ANTENNA ARRAY

Calculation of cone angle

Consider a signal arriving at an angle, \( \theta \), to the arm AB of the antenna array (see Figure B.1).

\[
\delta = n\lambda' + \frac{\Phi_B - \Phi_A}{2\pi} \frac{\lambda'}{\lambda}
\]

where:

\[
\lambda' = \frac{\lambda}{\cos \theta}
\]

\( \delta \) is the antenna separation,

\( n \) is a positive integer or zero,

\( \Phi \) is the phase measured at antenna A,

\( \Phi_B \) is the phase measured at antenna B,

\( \lambda \) is the signal wavelength, and

\( \theta \) is the angle of arrival of the signal to the antenna arm.

\[
\Rightarrow \cos \theta = \left| n + \frac{\Delta \phi}{2\pi} - \frac{\lambda}{\delta} \right|
\]

Equation B.1 applies to a single pair of antennas, and gives the 'cone angle' for that pair (see Figure 5.2).
Direction of arrival of the signal.

\[ \theta \]

\[ \lambda \]

\[ \lambda' \]

\[ \delta \]

FIGURE B.1
Calculation of DOA from two cone angles

Now need to combine results from two pairs of antennas to determine the true DOA. Referring to Figure B.2:

The signal arrives along D'DA

Antennas at A, B and C

DE and D'E' are verticals from line of arrival

Angles ACF and BCD' are 90°

θ₁ is measured cone angle to AC

θ₂ is measured cone angle to AB

α is angle between AB and AC

θₑ is the elevation angle, and

θₐ is the azimuth angle measured from AC towards AB.

Considering the points on the ground (ACD'E'F)

\[ CF = \delta_1 \tan\alpha \]
\[ CE' = \delta_1 \tan\theta_a \]
\[ E'F = CF - CE' = \delta_1 (\tan\alpha - \tan\theta_a) \]

\[ AF = \delta_1 / \cos\alpha \]
\[ AE' = \delta_1 / \cos\theta_a \]
\[ CD' = \delta_1 \tan\theta_1 \]

Considering ACD'E'

\[ \cos\theta_e = \frac{AE'}{AD'} = \frac{\delta_1}{\cos\theta_a AD'} \]
FIGURE B.2
\[ AD' = \frac{\delta_1}{\cos a \cos e} \]

\[ \tan \theta_e = \frac{D'E'}{AE'} = \frac{D'E'}{\delta_1} \]

\[ D'E' = \frac{\delta_1 \tan \theta_e}{\cos a} \]

\[ (AD')^2 = (AC)^2 + (D'C)^2 \]

\[ \delta_1^2 = \delta_1^2 + \delta_1^2 \tan^2 \theta_1 \]

\[ 1 = 1 + \tan^2 \theta_1 = \frac{1}{\cos^2 \theta_1} \]

\[ \cos \theta_1 = \cos a \cos e \quad (B.2) \]

Considering \( AD'E'F \)

\[ AD' = \frac{\delta_1}{\cos a \cos e} \]

\[ AE' = \frac{\delta_1}{\cos a} \]

\[ D'E' = AE' \tan \theta_e = \frac{\delta_1 \tan \theta_e}{\cos a} \]

\[ E'F = \delta_1 (\tan \alpha - \tan \theta_a) \]

\[ (FD')^2 = (E'F)^2 + (D'E')^2 \quad (B.3) \]
\[ AF = \frac{\delta}{\cos \alpha} \]

Applying the cosine rule to \( AD'F \)

\[ (FD')^2 = (AF)^2 + (AD')^2 - 2(AF)(AD')\cos \theta_2 \]

\[ \delta_1^2 (\tan \alpha - \tan \theta_a)^2 + \frac{\delta_1^2 \tan \theta \tan \theta_1}{\cos^2 \theta \cos^2 \theta_1} = \frac{\delta_1^2}{\cos^2 \alpha} + \frac{\delta_1^2}{\cos^2 \theta_1} - \frac{2\delta_1^2 \cos \theta_2}{\cos \alpha \cos \theta_1} \]

\[ \Rightarrow \tan \theta_a = \frac{\cos \theta_2 - \cos \theta_1 \cos \alpha}{\cos \theta_1 \sin \alpha} \]

\[ B.3 \]
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Ionospheric radiowave propagation effects observed with
a large aperture antenna array

Edward Michael Warrington

Abstract

The wavefronts of high frequency (HF) radio waves received after reflection from the ionosphere exhibit both spatial non-linearities and temporal variations which limit the performance of large aperture receiving arrays. The first objective of this investigation was to measure the phase and amplitude of ionospherically propagated signals at several widely spaced antennas in order to relate these parameters to the reflection process.

From the amplitudes and phases measured at pairs of spaced antennas, the direction of arrival (DOA) of the signal in both azimuth and elevation was determined. Furthermore, by combining the DOA and reflection height measurements the transmitter location can be estimated from a single receiving site. The second objective of this study was to investigate the ability of the system to determine DOA and transmitter locations correctly.

Two seven element antenna arrays were employed with maximum apertures of 1526 m and 294 m respectively. The associated multi-channel receiving and data logging equipment is described together with a pulsed sounding system employed for mode identification.

Signals received from several European transmitters exhibited widely differing behaviour and this was interpreted in terms of their modal content. For predominantly single moded signals the observations indicate that the diffracted components normally contribute less than 10% of the received power, moreover the DOA varies in both azimuth and elevation by approximately 1-2° over time periods of several minutes.

The use of the smaller array for DF and SSL applications is discussed in detail. In particular, the performance of the system was severely affected by multi-moded propagation. Techniques were developed for recognising periods of single moded propagation, when accurate measurements are to be expected. Good position fixes were obtained when measurements were restricted to these periods provided accurate reflection height information was also available.