STUDIES OF THE UPPER ATMOSPHERE

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The greater wave is covered with innumerable other waves which move in different directions; and these are deep or shallow according to the power that generated them........

LEONARDO DA VINCI

ABSTRACT

In an attempt to make synoptic observations of winds in the mesosphere and lower thermosphere, a simplified version of the correlation method for analysing spaced receiver ionosphere drift observations was developed. The new method makes possible the use of much simpler recording methods and eliminates the manual reduction of records. Drift observations made at noon between altitudes of 65 and 100 km, for summer 1963-4 and winter 1964 are presented. It is concluded that the mean monthly drift is a good estimate of the winds at these heights. The most prominent feature of the seasonal circulation is the upward progression of the height of reversal from westerlies (below) to easterlies (above) from 80 km in April to 100 km in July. The reversal height falls to 90 km in August and September.

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I also wish to thank Dr. J.B. Gregory, for the generous assistance and advice which he provided during the course of the experiment.

The technical assistance so necessary to the success of the experiments was provided primarily by Mr. A.W. Black and Mr. B.A. Perry with help from other members of the Physics Department Staff and occasional student labour.

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Since the computer is necessarily so much a part of the experimental technique I must thank Professor D.F. Lawden of the Mathematics Department and Mr. B.A.M. Moon of the University of Canterbury Mobil Computer Laboratory, for providing the computing facilities.

The illustrations in Volume 2 were photographically reproduced by Mr. E.R. Mangin. Many of the individual wind profiles were plotted by Mr. J. MacInnes.

Much of the credit for this thesis belongs to my wife who tolerated a confused domestic timetable in the interests of computation and field work, assisted with the analysis and plotting of results, did most of the drawings for Volume 2, and typed the draft and final versions of this thesis.

This thesis is, for convenience of reference, divided into two volumes. Volume 1 contains the text and Volume 2 contains the illustrations.

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SYMBOLS

		- introduced on page
A	output amplitude of receiver intermediate frequency amplifier	13
A_r	amplitude of coherent detector phase reference waveform	14
a	probability in tetrachoric correlation table	20
a	a constant (equation B.4 only)	123
a(x)	Gauss function of a normalised variable(x)	24
b	probability in tetrachoric correlation table	20
b	a constant (equation B.4 only)	123
C	reference level for tetrachoric correlation	19
c	probability in tetrachoric correlation table	20
D	delay bit from monostable multivibrator	131
d	probability in tetrachoric correlation table	20
d_a	apparent depth of reflecting layer	11
d_o	spacing between receiver aerials	32
d_s	thickness of spherical shell (determined by the width of the transmitted pulse)	10
E	electric field strength of electromagnetic wave	8
E_o	amplitude of reflected field strength at receiving aerial	12
$\underset{\sim}{F}$	$(= F_x, F_y, F_z)$ force acting on air mass	81
f	Coriolis parameter ($2h \sin \phi_1$)	83
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g	gravitational constant	80
H	atmospheric scale height	78
HG	height gate output bit	120

$H_n(x)$	Hermite polynomial	24
h	(in Section 2.3 only) height of reflecting layer	10
h	(in Section 3 only) normalised reference level	23
h	(Section 8) earth's angular velocity	81
h_{FE}	large signal short circuit forward current transfer ratio	124
I_a, I_1, I_2, I_3, I_4	input currents to NOR gate	119
I_c	collector current	125
I_{co}	base-collector junction leakage current	123
IN1, IN2, IN3, IN4	input bit to NOR gate	120
I_p	base bias current from base supply	125
i	suffix, usually used to distinguish between the three receiving aerials	15
j	suffix, usually used to distinguish between the three receiving aerials	15
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N_e	electron density at reflection height	78
N_o	electron density at ground level	78
n	phase refractive index of electromagnetic wave	8
OUT	output bit from NOR gate	120
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p	pressure	81
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r_m	maximum value of cross-correlation	31
r^o	cross-correlation when there is no differential phase error	56
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s	standard deviation	22
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t	time	12
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u_o	a constant	51
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V_{CC}	collector supply voltage	112
$V_{CE\ (SAT)}$	saturation collector-emitter voltage	125
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v	northward wind component	61
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$\underset{\sim}{v}'$	apparent drift velocity	33

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y	northward displacement co-ordinate	27
y	(in Section 3 only) normalised random variable	23
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z_o	real reflection height	78
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ξ_o	"size" of diffraction pattern	16
ϕ	phase of received wave	12
ϕ_l	latitude	81
ϕ_c	phase error in receiver	56
ϕ_v	angle between drift vector ($\underset{\sim}{v}$) and x-axis	36
θ_d	width of transmitter-receiver polar diagram	10
θ_v	angle used in definition of velocity parameters	34
ρ	air density	81

τ	time lag (argument of time correlation function)	15
τ_k	time lag for which the autocorrelation has fallen to r_k	31
τ_m	time lag for maximum cross-correlation	31
τ_o	"fading period"	16
τ_{o1}	"fading period" of reflection from a moving rigid surface	28
τ_{o2}	"fading period" of reflection from a randomly moving surface with no steady motion	29
τ_s	time lag for which the autocorrelation has fallen to r_m	31
τ_v	maximum time lag for a given correlation	33
ω_c	carrier frequency of received wave	12
$*$	complex conjugate	
$< >$	mean value	

Logic functions: $\cdot$ AND

$+$ OR

$-$ NOT

1. INTRODUCTION

Air movement in the upper atmosphere can be observed from the ground by watching the movement of characteristic features in the air mass. At lower levels clouds are the most common natural tracers in the air. Further up, at altitudes of about 80 km, noctilucent clouds have indicated atmospheric movement in that region. The height limitations of the meteorological sounding balloon have, until recently, prevented the meteorologist from taking soundings in the stratosphere above 30 km. The development of small solid fuel rockets has provided a much more satisfactory vehicle for carrying instruments to measure the physical properties of the atmosphere. Standard methods of measuring atmospheric pressure and temperature fail above 50 to 60 km because the sensitivity of aneroid barometers is inadequate for reliable low pressure measurements, and temperature-sensing devices become inaccurate- the heat energy transferred to the thermometer by radiation is no longer negligible compared with the energy transferred by molecular collisions.

Observations of natural tracers, in the form of meteor trails, can be made by radar systems operating on wavelengths of several metres. The meteor trails are formed at altitudes of 80 to 100 km. Two very thcrough investigations of upper atmosphere winds, based on this method, have been made by Greenhow and Neufeld (1961) at Jodrell Bank near Manchester in England and Elford (1959) at Adelaide, South Australia.

Artificial tracers are now extensively used to follow the air mction at these very high altitudes. Sodium vapour clouds, produced from burners carried in a rocket, or the smoke trails of rocket motors can be tracked optically. Radar equipment can be used to follow the motion of "chaff" (small pieces of metal foil), parachutes, balloon-supported corner reflectors, or falling spheres. The macroscopic objects are of little use above 60 km because the viscous force exerted on them by the moving air is less than the gravitational force~~s~~ and the objects do not follow the air movement. This difficulty does not arise with microscopic objects like the smoke particles, the vapour molecules, or the electrons and ions in the meteor trails.

One of the most successful radar targets which have been used at altitudes of about 80 km is the ROBIN (for rocket balloon instrumentation). A thin plastic sphere containing a collapsible corner reflector is carried up by a small solid fuel rocket, ejected, inflated and then followed by ground radar. Horizontal motion of the sphere indicates the horizontal component of the wind vector. Since the vertical component of the wind is negligible, the atmospheric density can be calculated from the vertical velocity of the sphere.

Extensive measurements of atmospheric density and winds have been made by Nordberg and his fellow workers (see, for example, Nordberg 1964). They observed the ray paths and velocity of the sound waves produced when a sequence of grenades is ejected from a rocket as it passes through the atmosphere. Results from various rocket experiments will be discussed in Section 8.

Electrons are the lightest tracers which can be used to study the motion of the ionised gas containing them. Solar radiation is the most common source of ionisation, and the consequent free electrons in the upper atmosphere. The ionosphere so produced appears as an inhomogeneous, anisotropic, dissipative medium to electromagnetic waves. The inhomogeneities in the ionosphere diffract electromagnetic waves passing through it, or reflected from it, and it is possible to deduce some properties of the medium from a study of the diffraction pattern formed on the ground. This fact is the basis of the experimental work described in outline in Section 2 and in more detail in Sections 3 to 7.

The intensity at any point in the diffraction pattern is a random function of space and time and various statistical parameters for describing its behaviour are defined in Section 3. Section 4 shows how the statistical parameters are used to determine the drift velocity of the diffraction pattern, and in Section 7 we investigate relationships between the diffraction pattern drift velocity and winds in the atmosphere between altitudes of 65 and 100 km. Section 5 is a brief description of the equipment (details are given in the appendices) and Section 6 discusses the records obtained from the equipment.

The ionosphere is only a small part of the whole atmosphere, which is a compressible, inhomogeneous fluid on a rotating sphere - the earth. The fluid is perturbed by tidal forces, thermally generated circulation systems and various forms of instability. The time scale and dimensions of atmospheric motion are considerably larger than any observation period, and of any practicable geographic positioning of experimental equipment. Consequently the observable atmosphere appears to be statistically non-stationary, i.e. even its "average" properties are not constant. Any theories of atmospheric motion, or explanations of experimental observations, are therefore severely limited by the approximations which are necessary to obtain a quantitative answer. In Section 8, the equations of atmospheric motion are considered and, with the help of certain approximations, used to interpret the experimental results.

The emphasis throughout this investigation has been to use the diffraction drift experiment as a tool for the synoptic investigation of atmospheric winds above altitudes of 65 to 70 km. The discussion in Section 8 shows that this aim was achieved. The principal techniques which have made this objective attainable are the

(i) use of simplified data recording methods, whose use became evident after an investigation of the <u>minimum</u> amount of information necessitated by the method of correlation analysis

(ii) the elimination of manual data reduction and

(iii) the conceptof on- and off- line computing equipment as forming an integral part of the experimental apparatus, making it possible to simplify the field equipment and thereby improve its reliability.

2. GROUND-BASED RADIO OBSERVATIONS OF AIR MOTION IN THE UPPER ATMOSPHERE.

2.1. PRINCIPLES OF THE METHOD.

After the establishment of radio communications in the early years of this century it soon appeared that there were short-term (compared with diurnal variations) variations in the amplitude of the electromagnetic waves received at a fixed point, from a fixed transmitter. This amplitude variation was called "fading". Appleton and Ratcliffe (1927) investigated the fading of waves received from a transmitter 150 km from the receiver. By using a loop and a vertical aerial to distinguish the ground wave from the wave reflected from the ionosphere, they were able to show that the principal cause of fading was the fluctuation in amplitude and phase of the reflected wave, the variation in polarisation and angle of incidence being negligible. Ratcliffe and Pawsey (1933) found that the amplitude variations of the reflected wave were not identical at two points a wavelength or so apart. The ionosphere was therefore producing a diffraction pattern across the ground, but at any point the intensity of the pattern was a random function of time. Pawsey (1935) then showed that although the amplitude variations at two separated points were similar there was often a time delay between corresponding maxima and minima, indicating a translational motion of the diffraction pattern. Mitra (1949) used three aerials in a triangular array to investigate the two-dimensional motion of the diffraction pattern. Figure 2.1 indicates the basic principles of this spaced receiver method of investigating a drifting diffraction pattern. Figure 2.1(a) is a vertical cross-section of the experiment. The transmitted waves are returned from the "rough" reflecting surface and produce the diffraction pattern on the ground. Figure 2.1(b) is a horizontal cross-section, with a hypothetical set of contours of constant electromagnetic field strength. As the pattern moves across the ground it intersects the receiving aerials and the variations in field strength can be recorded as a function of time at each of the three points. An analysis of the field strength variations yields the time delay between pairs of receivers, and enables the velocity of the pattern to be calculated. The methods used are discussed in Section 3 and 4.

2.2 THE NATURE OF THE REFLECTING SURFACE.

Two further approximations are implied in Figure 2.1(a) which shows a single, abrupt discontinuity in refractive index. Wave propagation in an inhomogeneous medium may be represented by the equation

$$\frac{d^2E}{dz^2} + n^2(z)\, E = 0 \qquad (2.1)$$

where n = refractive index

z = distance along the vertical axis

E = electric field strength.

The use of ray theory, or the Liouville (WKBJ) approximation, requires that

$$\frac{1}{n}\frac{dn}{dz} \approx 0$$

$$\text{and} \quad \frac{1}{n}\frac{d^2n}{dz^2} \approx 0 \qquad (2.2)$$

If the relative change in refractive index is not negligible there is a reflected wave. Equations (2.2) are rendered invalid by two conditions:

(i) $n = 0$ ("total" reflection)

and (ii) $\frac{dn}{dz} \sim n$ ("partial" reflections)

Most of the results to be described utilised partial reflections from the lower parts of the ionosphere where the electron density is low and the refractive index close to unity. Consequently the rate of change of refractive index with height must be quite large to generate a reflected wave. Since the fractional change in refractive index is not large, this change must occur in a very short distance. Albini and Jahn (1961) and Brekovskikh (1960) show curves for calculations on various (simple) theoretical models for a discontinuity in refractive index. They find that if the discontinuity extends over a distance of about a half-wavelength or less, the actual shape of the discontinuity is of secondary importance. The reflection coefficient depends primarily on the difference in refractive index on either side of the discontinuity. A step discontinuity in refractive index is therefore a reasonable model, and a very useful one because the (Fresnel) reflection coefficients are easily calculated.

There is evidence that even when the totally reflected waves are considered, irregularities close to the point of reflection are the principal source of fading. The experimental evidence is provided by Jones (1958) who measured the variation of wind velocity with height, using waves of frequency 2.0 and 2.5 Mc/s, each totally reflected from the E layer at an altitude of about 110 km. The physical separation of the reflection heights was about 4 km. Jones measured the directions of drift at the two heights and found that they were consistent with the physical separation in true reflection height. The results also agreed with Greenhow and Neufeld's meteor wind measurements at Jodrell Bank. The theoretical evidence is provided by Pitteway (1960).

It can therefore be assumed that the movement of the diffraction pattern on the ground depends on the movement of the irregularities within a small distance, probably of the order of several hundred metres, of the reflection height. This is well within the limits imposed by the height resolution of the equipment.

2.3. HEIGHT RESOLUTION OF THE RADIO METHOD.

In the experiment energy is radiated by the transmitter in the form of pulses 25 microseconds long, on a radio frequency of 2.4 Mc sec^{-1} (a wavelength of 125m). The reflected wave at any instant is therefore the superposition of waves returned from ionospheric irregularities lying within the 4 km thick walls of a spherical shell (see Figure 2.2). The movement of the ground diffraction pattern depends on the average movement of the irregularities contained in the spherical shell. An order of magnitude estimate of the shell's dimensions is possible since the pulse width determines d_s (about 4 km); the reflection height (h) is about 80 km; the angle (θ_d) within which the significant part of the reflected power lies, estimated from a typical value of cross correlation between two aerials spaced two wavelengths apart, is about 20° (the semi-angle subtended by the first Fresnel zone is 2.3°).

Thus $\quad h \sin \theta_d = 27$ km

and $\quad h \cos \theta_d = 75$ km

hence $\quad d_a = h - h \cos \theta_d$

$\quad = 5$ km

The height limits of the spherical cap are therefore $d_a + d_s = 9$ km. The height resolution for a uniformly dense scattering region is thus 9 km.

Because the atmosphere is horizontally stratified, with changes in the vertical dimension being much more rapid than changes in the horizontal direction, we can expect a resolution somewhere between 4 km, for an infinitely narrow reflecting region and 9 km, for an infinitely thick scattering region.

3. CORRELATION ANALYSIS OF THE GROUND DIFFRACTION PATTERN.

Standard techniques are available for the analysis of the fading records from spaced receivers. An excellent review of ionospheric diffraction has been given by Ratcliffe (1956). The most satisfactory techniques (described in Section 4) necessitates a considerable amount of computing. The purpose of the present study is to investigate synoptically the winds below 100 km, so that methods of analysis must be rapid and convenient. With some approximations and consequent simplifications, the ease of recording data and the subsequent analysis by correlation techniques can be made acceptable for use in synoptic wind observations. The simplified method is discussed in Section 3.2.

3.1. THE CORRELATION FUNCTIONS OF THE FADING RECORDS.

The physical variable actually measured in the spaced-receiver experiment is the electromagnetic field strength on the ground. The field induces in each aerial an e.m.f. which is amplified by the succeeding radio receivers. Let the electric field strength at an aerial be

$$E_o(t) \exp j\,[\omega_c t + \varphi(t)] \qquad (3.1)$$

Equation (3.1) is the usual expression for a randomly perturbed wave. It indicates an "almost simple harmonic" variation of field strength, with an angular frequency ω_c, and amplitude and phase terms which are random functions of time. If the ratio of receiver output voltage to electric field strength at the aerial is G_s, the receiver intermediate frequency amplifier output voltage must be

$$V_{if}(t) = G_s E_o(t) \exp j [\omega_c t + \phi(t)]$$

$$= A(t). \exp j \phi(t). \exp j \omega_c t \qquad (3.2)$$

If the receiver is a superheterodyne ω_c should be replaced by ω_{if}, the intermediate frequency, but translation of the carrier frequency will be neglected. Equation (3.2) then represents the output of the intermediate frequency amplifier in the receiver. Figure 3.1 is a tracing of the recording, originally on a paper chart, of the output from a pair of detectors, operating in the rectifying mode. The output of the detectors is A(t). The fading records are similar and there is a time lag between the similar parts of the records, indicating translational motion of the diffraction pattern.

The equipment, used in this experiment used coherent detectors to simplify the problem of determining

a reference level for recording (see Section 3.2).
The function

$$V(t) = \text{Real}\,[A(t) \exp j\, \varphi(t)] \tag{3.3}$$

is the output of a coherent detector with a signal input given by (3.2) and a phase reference signal of

$$V_r = A_r \exp j\, \omega_c t. \tag{3.4}$$

The waveform represented by equation (3.3) is similar in appearance to the fading records in Figure 3.1, except that the mean value is zero.

Figure 3.1 emphasises that the physical quantities are random functions of time. Consequently previous statements about "comparing the electric field strengths at two points in the diffraction pattern", and "measuring the time delay between the pairs of fading records" now have to be given a quantitative meaning in terms of the properties of random variables. Two random functions are compared statistically by calculating the correlation coefficient between them. This quantity is defined as

$$r = \frac{\langle V_1 \; V_2^* \rangle}{\left(\langle V_1^2 \rangle \langle V_2^2 \rangle\right)^{\frac{1}{2}}} \tag{3.5}$$

If the two random variables are identical, $r = 1$. If they are "mirror images" $r = -1$ and if they are independent functions, $r = 0$ (but if $r = 0$, they are not necessarily independent functions).

If two of the aerials in Figure 2.1(b) are in a line parallel to the velocity of the diffraction pattern, and the diffraction pattern does not change as it moves, the fading records of the two receivers connected to these aerials will be identical, but there will be a time displacement. Consequently $r \neq 1$. However if one fading record is shifted by an amount corresponding to the time delay, $r = 1$. Equation (3.5) is therefore generalised to allow for a time difference:

$$r_{ij}\ (\tau) = \frac{\langle V_i(t) . V_j^*(t+\tau)\rangle}{(\langle V_i^2(t)\rangle . \langle V_j^2(t)\rangle)^{\frac{1}{2}}} \tag{3.6}$$

Equations (3.4) and (3.5) are limiting forms of (3.6). The numerator of (3.6) is called the covariance; if $j = i$ it is the usual variance of V_i, sometimes called the autocovariance. A graph of r against τ is known as a correlogram; if $i = j$ it is an autocorrelogram, and if $i \neq j$ it is a cross-correlogram. The function $r_{ii}\ (\tau)$ is known as an autocorrelation function, and $r_{ij}\ (\tau)$ is a cross-correlation function, of the lag τ. (Examples of auto- and cross-correlograms are shown in Figure 4.2(a)). Accepting this short catalogue of jargon, we can now proceed to discuss quantitatively the characteristics of the diffraction pattern formed on the ground by electromagnetic waves reflected from the random irregularities in the ionosphere.

The diffraction pattern is two-dimensional and changes with time. The average characteristics of the time variations are described by the time correlation function (3.6), and the average characteristic of the spatial quantities can be described by the space correlation function,

$$r_{ij}(\delta) = \frac{\langle V_i(r) . V_j^*(r + \delta) \rangle}{(\langle V_i(r)^2 \rangle \langle V_j(r)^2 \rangle)^{\frac{1}{2}}} \tag{3.7}$$

Equation (3.7) describes the average properties of the diffraction pattern along a line in the ground plane. Both the time (3.6) and space (3.7) correlation functions provide a measure of the time and space scale of the diffraction pattern. Commonly the time lag, τ_o, such that $r(\tau_o) = 0.5$ is called the "fading period". Similarly the spatial displacement, δ_o, such that $r(\delta_o) = 0.5$ is called the "size" of the diffraction pattern. There is no reason why the diffraction pattern should be statistically isotropic, and consequently a different value of $r_{ij}(\delta)$ will be obtained for each orientation of the observation points. The calculations of all the time and space correlation functions which would be necessary to define the diffraction pattern in detail would occupy an unreasonable amount of time and require an enormous amount of experimental equipment to record the observations. The two space dimensions of the ground diffraction pattern and the time dimension can be combined to give a three-dimensional correlation function, with contours of constant correlation forming a three-dimensional surface.

3.2. THE APPLICATION OF TETRACHORIC CORRELATION TO THE ANALYSIS OF FADING RECORDS.

In the correlation analysis of the fading records from three spaced receivers the three cross- correlation functions must be computed for a large number of lags. At least one of the autocorrelation functions must also be computed, but a better estimate is obtained if all three are computed and their average used. A considerable amount of computing is necessary to produce all these correlograms and the purpose of this section is to consider how we may retain the advantages of the correlation analysis without the considerable amount of labour and computer time normally required.

The three steps traditionally required by the method are

(1) Recording of the three field strength variations on photographic film or pen recorder chart.

(2) Manual reading of these films or charts and the recording of the values in a form suitable for calculation or input to a computer.

(3) Computation of the correlation functions, manually or by means of an electronic digital computer.

We can eliminate the alternative in (3) because manual computation is out of the question. It takes several days to produce a set of correlograms from a 10 minute observation. The correlation analysis can only be used if a computer is available. The manual reduction of records (step 2) is as lengthy a process as the manual computation and is subject to error. This step can be eliminated altogether if the experimental apparatus records the information in a form suitable for input to a computer. Punched paper tape was selected as the recording medium because it is more satisfactory for field use than magnetic tape. Paper tape punches and the associated equipment are also cheaper to operate and more readily available than the equivalent magnetic recording apparatus.

Having concluded that the field strength variations shall be recorded on paper tape, we must decide on a method. An obvious approach is to use one or more digital voltmeters, with their accompanying scanning and programming units. However, apart from the high cost of such complex equipment, there is the problem of maintaining it at a field site.

Fortunately, the digital voltmeter(s) and associated equipment are unnecessary as investigations of the cross-correlation functions of distorted functions (Lawson and Uhlenbeck 1950, Bussgang 1952, Heaps 1962), show that, provided the joint probability distribution of the two waveforms is known, there is no information lost even if the two functions have been badly distorted by the receiving equipment. We shall consider only an extreme form of distortion - complete limiting (hard clipping) of the waveforms. Under these conditions the only information we retain is whether or not the waveforms exceed given reference levels (denoted by C_i and C_j) which are determined by the equipment. Consequently there is no need for any degree of accuracy in reading the records and the linearity of the receiving equipment is quite unimportant. However another problem is introduced by the necessity to realise C_i and C_j. These are constants which, translated into electrical circuits, must be constant voltages. The most convenient level for C_i and C_j is zero. In this case

V_i and V_j must be bi-directional signals and can be obtained from a coherent detector (equation 3.3). Tetrachoric correlation is commonly called polarity-coincidence correlation when $C_i = C_j = 0$, as the only information required is the sign, or polarity, of the waveform.

When the waveforms have each been limited the cross-product, $V_i(t)\ V_j(t + \tau)$, can only have one of four possible values, since V_i and V_j each have only two possible values, i.e. the waveform is now binary. The cross-correlation may therefore be expressed in terms of the probabilities of each of the four values occurring, as in Table 3.1.

TABLE 3.1.

PROBABILITY OF OCCURRENCE OF COMBINATIONS OF V_i AND V_j

	$V_i < C_i$	$V_i > C_i$	
$V_j < C_j$	a	b	a + b
$V_j > C_j$	c	d	c + d
	a + c	b + a	1

a is the probability that both V_i and V_j are less than their respective reference levels; b is the probability that V_i exceeds its reference level while V_j remains below its reference level, and so on. There is only one degree of freedom in this table since the determination of a,b,c, or d is sufficient to determine the other three quantities (the sums at the sides of the table are determined by the probability distributions of the individual waveforms).

We can, of course draw up a table like Table 3.1 even if we have no information at all about the joint probability distribution of V_i and V_j, or about the respective probability distributions. Comparisons of this nature are used extensively in analysing qualitative information like that obtained in the social sciences or where only two possibities are to be considered, such as the absence or presence of rain (Brooks and Carruthers 1953).

Early work on this type of comparison has been described by Yule (1900) and Pearson (1901). Table 3.1 is a form of contingency table and various coefficients which can be defined from its entries a, b, c, and d are

(1) Yule's coefficient of association

$$Q_1 = \frac{ad - bc}{ad + bc} \tag{3.8}$$

(2) Yule's coefficient of colligation

$$Q_2 = \frac{\sqrt{ad} - \sqrt{bc}}{\sqrt{ad} + \sqrt{bc}} \tag{3.9}$$

(3) Pearson (1901) defined several more coefficients, among them being

$$Q_3 = \sin \frac{\pi}{2} Q_2 \tag{3.10}$$

3.3. CALCULATIONS FOR A JOINT GAUSSIAN PROBABILITY DISTRIBUTION.

If we assume that the joint probability distribution of the output waveforms $(V_i(t), V_j(t))$ of a pair of receivers is the bivariate Gaussian distribution

$$p(V_i, V_j) = \frac{1}{2\pi\sqrt{1 - r^2}} \exp -\left[\frac{1}{2(1 - r^2)}\left(\frac{V_i^2}{s_i^2} - 2r\frac{V_i}{s_i}\frac{V_j}{s_j} + \frac{V_j^2}{s_j^2}\right)\right] \tag{3.11}$$

where s_i^2, s_j^2 are the variances of V_i and V_j respectively and r is the cross-correlation between V_i and V_j. It is implicit in (3.11) that V_i and V_j each have zero mean. A non-zero mean is easily dealt with by a suitable adjustment of C_i and C_j. From (3.11) it is possible to calculate the probability of V_i and V_j exceeding their given reference levels, C_i and C_j, i.e. calculate d in Table 3.1. Similarly a, b or c can be calculated. For simplicity, we will assume that the receiver output voltages and reference levels are defined in terms of their respective standard deviations, i.e. write

$$
\begin{aligned}
x &= V_i / s_i \\
y &= V_j / s_j \\
h &= C_i / s_i \\
k &= C_j / s_j
\end{aligned}
\tag{3.12}
$$

We will also adopt a simpler notation for the integral of the bivariate Gaussian distribution and write

$$L(h,k,r) = \int_h^\infty dx \int_k^\infty dy \; p(x, y) \tag{3.13}$$

Using this notation, the entries in Table 1 are

$$
\begin{aligned}
a &= L(-h, -k, r) \\
b &= L(h, -k, r) \\
c &= L(-h, k, r) \\
d &= L(h, k, r)
\end{aligned}
\tag{3.14}
$$

We can then, in principle, find the cross-correlation between the two fading records, $V_i(t)$ and $V_j(t)$, by using the experimental results to construct a tetrachoric table, and then looking up a suitable set of tables of $L(h, k, r)$ such as those in the National Bureau of Standards Applied Mathematics Series (NBS 1959). As the purpose of this thesis is to discuss rapid methods of finding values of correlation, the looking-up of tables is of no further interest. The necessary table look-up could be performed by a digital computer but the storage requirements are excessive. If a digital computer is available, it is possible to calculate $L(h, k, r)$ using a series expansion and to find r by an iterative process. A suitable series, which always converges, is (Kendall and Stuart 1961)

$$L(h,k,r) = \sum_{j=0}^{j=\infty} \frac{r^j}{j!} H_{j-1}(h).\ H_{j-1}(k).\ a(h).\ a(k) \qquad (3.15)$$

$$\text{where } a(x) = (2\pi)^{-1/2} \exp(-x^2/2) \qquad (3.16)$$

and the H's are the Hermite polynomials:

$$H_o(x) = 1$$
$$H_1(x) = x$$
$$H_2(x) = x^2-1$$
$$\cdots\cdots\cdots\cdots$$
$$H_n(x) = xH_{n-1}(x) - (n-1)\ H_{n-2}(x). \qquad (3.17)$$

The clipping reference levels h and k need not be measured in the equipment as they can be calculated from the mean values of x and y, once the gains of the receivers have been made equal.

In the limit, when $h = k = 0$, (3.13) reduces to

$$L(0,0,r) = \frac{2}{\pi} \sin^{-1} r \tag{3.18}$$

$$\text{whence } r = \sin \frac{\pi}{2} [L(0,0,r)]$$

and equations (3.14) become

$$a = L(-0, -0, r) = L(0, 0, r)$$
$$b = L(0, -0, r)$$
$$c = L(-0, 0, r) = L(0, -0, r)$$
$$d = L(0, 0, r)$$

Hence $a = d$

and $b = c$

The coefficients defined by Yule and by Pearson then become

$$Q_1 = \frac{a^2 - b^2}{a^2 + b^2} \tag{3.19}$$

$$Q_2 = \frac{a - b}{a + b} \tag{3.20}$$

$$Q_3 = \sin \frac{\pi(a - b)}{2(a + b)} \tag{3.21}$$

Pearson (1901) studied 15 sample data pairs and found that there was considerable disagreement between the correlation coefficient calculated in the normal way and the tetrachoric correlation defined by Q_1, the mean error over 15 samples being 24 per cent. He did not consider Q_2, but found that Q_3 had an error of only 4 per cent. Q_3 is exact for a joint Gaussian probability distribution, and many physical processes are known to approximately obey such a distribution law.

Rice (1944, 1945) deduced the probability distribution of a narrow-band random waveform. The in phase and quadrature components which are $A(t) \cos \varphi(t)$ and $A(t) \sin \varphi(t)$ respectively, using the notation of equation (3.2), each have a Gaussian probability distribution. The coherent detection system therefore has an output voltage with a Gaussian probability density function. The detector is then succeeded by the amplifiers and clippers necessary to generate the binary waveform. Equation (3.18) enables the correlation coefficient of the joint Gaussian probability distribution to be calculated from the tetrachoric correlation $L(0,0,r)$.

SECTION 4. THE DETERMINATION OF THE DRIFT VELOCITY

4.1. INTRODUCTION TO THE VELOCITY PARAMETERS.

The velocity of the drifting diffraction pattern can be determined from the correlograms by the method discussed below. The discussion is adapted from the paper by Briggs, Phillips and Shinn (1950).

The diffraction pattern moves over the ground as the properties of the diffracting screen vary. Its detailed structure is also subject to random changes. As the observable changes are confined to the two dimensions of the ground plane, it is convenient to represent the random changes as the result of a fictitious movement in the vertical direction. The random variations are really due to temporal changes in the diffraction pattern so that distances in the fictitious vertical direction must be measured in units of $v_c t'$, where t' is the actual time scale of the random variations and v_c is ~~a~~ proportionality constant with the dimensions of velocity. In this way the problem is reduced to the study of an unchanging diffraction pattern moving in three dimensions. Distances are measured in terms of the three cartesian components x, y, and $v_c t$ (see Figure 4.1a).

The true motion of the drifting diffraction pattern is given by the vector

$$\underset{\sim}{v} = (v_x, v_y) \qquad (4.1)$$

The proportionally constant v_c was labelled the characteristic velocity by Briggs, Phillips and Shinn (1950). They labelled the vector

$$\underset{\sim}{v}'_c = (v_x, v_y, v_c) \qquad (4.2)$$

the fading velocity (see Figure 4.1(b).

The signifiance of the fading velocity v'_c and its three components is best shown by considering an observer at the origin of the axes in Figure 4.1(a) (observations can of course, only be made in the ground (x, y) plane). If the diffraction pattern has no translational motion and there are no random variations with time (i.e. $v_c = 0$), the observer sees a constant amplitude. If the diffraction pattern is the result of reflections from a moving rigid surface with randomly varying reflection properties, the observer sees a randomly varying amplitude and could measure a fading period (as defined in Section 3.1). The observed fading period (τ_{01}) and the size (δ_0, also defined in Section 3.1) of the irregular amplitude variation parallel to the direction of motion are then related by the velocity of the drifting pattern

$$v = (v_x^2 + v_y^2)^{\frac{1}{2}}$$

$$= \delta_0 / \tau_{01} \qquad (4.3)$$

The higher the drift speed, the faster the fading.

In contrast we can consider reflections from a turbulent reflecting medium with no mean horizontal motion. Then $v_x = v_y = 0$. The observer measures a fading period (τ_{02}) characteristic of the random motion and the characteristic velocity is, by its definition, (δ_0 / τ_{02}). The diffraction pattern size (δ_0) will, in general, depend on the direction in the (x, y) plane along which the measurements are made.

In reality the diffraction pattern changes as it drifts past the observer and the ratio of pattern size (δ_0), measured parallel to the direction of drift, to the observed fading period (τ_0) defines the fading velocity.

$$v'_c = \delta_0 / \tau_0 \qquad (4.4)$$

The fading velocity is a function of the direction in which δ_0 is measured.

The fading velocity (v'_c) comprises two parts (see equation (4.2)) - a component (v) due to the drift motion of the diffraction pattern and a component (v_c) due to random changes in the diffraction pattern. Consequently if an observer moves across the ground plane, his speed relative to the diffraction pattern is a minimum when he moves with the same velocity as the drift component of the diffraction pattern and all he sees is the random fading represented by v_c. Conversely if the observer moves with such a velocity that he sees a maximum fading period, indicating a minimum fading velocity, his velocity must be equal to the drift velocity ($\underset{\sim}{v}$). This fact provides us with a definition of the drift velocity in terms of observable quantities. This definition of the drift velocity ($\underset{\sim}{v}$) also provides the definition of the characteristic velocity (v_c) because the minimum fading velocity, as measured by the moving observer, is just v_c.

4.2. DETERMINATION OF THE VELOCITY PARAMETERS FROM THE CORRELOGRAMS.

NOTE In the succeeding sections the distinction between the tetrachoric correlation, L(0,0,r), and the true correlation coefficient, r, is ignored since the actual shape of the correlation function is not required in the analysis.

The observable quantities in the correlation analysis are indicated in Figure 4.2(a) which shows the mean auto-correlogram and one cross-correlogram of data recorded on 15 December 1963 at a reflection height of 76 km. It will be assumed, as in the Briggs, Phillips and Shinn (1950) paper, that the diffraction pattern in the ground plane is statistically isotropic, i.e. the pattern size (δ_0) is independent of direction. It will also be assumed that the two receivers are parallel to the drift velocity vector ($\underset{\sim}{v}$). The latter assumption is invalid for the particular correlograms of Figure 4.2(a) but provides us with a simplified picture so that the principles of the correlation analysis may be more easily explained. The observable quantities used in the analysis are

τ_m	the time delay for maximum cross-correlation (r_m)
r_k	the cross-correlation at zero time delay
τ_k	the time delay at which the autocorrelation has fallen to r_k
and τ_s	the time delay at which the autocorrelation has fallen to r_m

These parameters are shown in Figure 4.2(a).

The space and time correlation functions can be represented, to a first approximation, as ellipses of constant correlation in the (δ,τ) plane, as shown in Figure 4.2(b). It is assumed that the time and space correlation functions have the same shape, although this shape (i.e. the exact form of the correlation functions) need not be known. The ellipses of constant correlation must therefore be concentric and have a constant axial ratio. Figure 4.2(b) can be thought of as a bird's-eye view of a hill whose horizontal cross sections are the correlation ellipses, and whose peak is the origin with a maximum correlation value of 1.0. The auto-correlogram of Figure 4.2(a) is thus a vertical cross section of the correlation hill in the plane $\delta = 0$, and the cross-correlogram is a vertical cross-section at $\delta = d_o$, the spacing between the two receivers whose output signals were compared. The outer ellipse in Figure 4.2(b) is the lower contour $r = r_k$ while the inner one is $r = r_m$. The position of the r_k ellipse is determined by its intercepts with the δ and τ axes at d_o and τ_k respectively while the inner ellipse must be tangential to the line $\delta = d_o$. δ_m is the intersection of the r_m ellipse with the δ- axis and is not an observable quantity. From the definition of v'_c (equation 4.4), and the assumption of similar space and time correlation functions, we see that

$$v'_c = \frac{d_o}{\tau_k} \tag{4.5}$$

The calculation of the characteristic velocity (v_c) follows from the definition given in the previous section i.e. v_c is the minimum fading velocity that can be observed. The minimum fading velocity corresponds to the maximum fading period for a given correlation value. This value is given by the point of contact between a line of constant time delay tangential to the ellipse for that value of correlation. This time delay is shown as τ_v in Figure 4.2(b). It is not an observable quantity. The correlation appropriate to the spatial separation of d_o in the ground plane must therefore be the same as that produced by a shift of $v_c \tau_v$ along the τ-axis. Thus

$$v_c = \frac{d_o}{\tau_v} \tag{4.6}$$

If there was no random component of fading the drift velocity would be that appropriate to the actual receiver separation (d_o) and the time lag for maximum cross-correlation (τ_m). The presence of the random fading makes this simple interpretation impossible but we may define another term with the dimensions of velocity.

$$v' = \frac{d_o}{\tau_m} \tag{4.7}$$

v' is called the apparent drift velocity (Briggs, Phillips and Shinn 1950) and its significance is indicated in

Figure 4.3. It is the velocity of point P in the ground plane (see equation (4.8) below).

The three-dimensional diffraction pattern passes the two receivers placed at O and P in the direction of the drift velocity vector (which is here assumed parallel to the x-axis). The characteristic velocity v_c has been defined so that the three-dimensional diffraction pattern is statistically isotropic. Maximum cross-correlation thus corresponds to the shortest distance in the diffraction pattern, i.e. to the perpendicular distance (PP' in Figure 4.3) between lines passing through the two receivers in the direction of $\underset{\sim}{v}'_c$. The point in the diffraction pattern which was at O when t = O has reached P' in a time τ_m; then

$$\begin{aligned} OP' &= v'_c \ \tau_m \\ O'P' &= v_c \ \tau_m \\ OO' &= v \ \tau_m \\ OP &= v' \ \tau_m \end{aligned} \tag{4.8}$$

$$\begin{aligned} \text{Now} \quad O'P' &= PP' \cos \theta_v \\ &= OP \sin \theta_v \cos \theta_v \end{aligned}$$

$$\text{where} \quad \theta_v = \tan^{-1} (O'P' \,/\, OO') \tag{4.9}$$

On substituting (4.8) in (4.9) we find that

$$vv' = v^2 + v_c^2$$

$$= (v'_c)^2 \tag{4.10}$$

v'_c and v' are defined by equations (4.4) and (4.7) respectively so that

$$v = \frac{(v'_c)^2}{v'}$$

$$= \left(\frac{x_o}{\tau_k}\right)^2 / \left(\frac{x_o}{\tau_m}\right)$$

$$= \frac{x_o \tau_m}{\tau_k^2} \tag{4.11}$$

The velocity defined by equation (4.11) is the true translational velocity of the diffraction pattern. The expression is of little use because its derivation was based on the assumption that the two receivers lay on a line parallel to the drift velocity ($\underset{\sim}{v}$). We must next consider how the analysis can be extended to cover the more general situation.

4.3. VELOCITY PARAMETERS WHEN THE RECEIVERS ARE NOT IN THE LINE OF DRIFT.

When the drift velocity $\underset{\sim}{v}$ is not parallel to the line joining the two receivers, its magnitude and direction can only be determined by using a second pair of receivers along a line in a direction not parallel to the first pair. To simplify the analysis it will be assumed that the second pair of receivers is at right angles to the first pair, but with suitable trigonometrical manipulation the analysis can be extended to any combination of receivers. Figure 4.4 shows the system of x, y, and $v_c t$ axis with receivers at 0, x_o and y_o. The analysis to determine the various parameters relative to the x-axis can be carried out as in Section 4.2, except that P is replaced by x_o and the suffix x is used to indicate that measurements are relative to the x-axis. The set of equations corresponding to (4.8) is

$$
\begin{aligned}
OO_x' &= v_x \; \tau_m \\
OP' &= v'_c \; \tau_m \\
O'_x P' &= v'_{cx} \; \tau_m \\
Ox_o &= v_x' \; \tau_m
\end{aligned}
\qquad (4.12)
$$

Now $\cos\,(P'Ox_o) = \cos\,\theta_v \,\cos\,\varphi_v$

$\therefore \quad OO'_x = OP' \cos\theta_v \cos\varphi_v$

and $\quad OP' = Ox_o \cos\theta_v \cos\varphi_v$

Thus $$OO'_x \cdot Ox_o = (OP')^2$$

$$OO_x' = OO' \cos \varphi_v$$

$$OO' = Ox_o \cos \varphi_v \tag{4.13}$$

or $$v_x v_x' = (v'_c)^2$$

$$v_x = v \cos \varphi_v$$

$$v_x' = v' / \cos \varphi_v \tag{4.14}$$

similarly $$v_y\ v_y' = (v_c')^2$$

$$v_y = v \sin \varphi_v$$

$$v_y' = v' / \sin \varphi_v \tag{4.15}$$

The angle (φ_v) between the drift vector ($\underset{\sim}{v}$) and the x-axis is given by

$$\varphi_v = \tan^{-1} (v_x' / v_y') \tag{4.16}$$

and the magnitude of the drift vector is

$$v = (v_x^2 + v_y^2)^{\frac{1}{2}}$$

4.4. THE ANALYSIS OF A STATISTICALLY ANISOTROPIC DIFFRACTION PATTERN.

Phillips and Spencer (1955) showed how the restriction of a statistically isotropic ground diffraction pattern could be relaxed. They used a procedure similar to that adopted by Briggs, Phillips and Shinn (1950) who, when dealing with the space and time variations, introduced a scale factor v_c. The ellipsoids of constant correlation which describe the statistically anisotropic pattern can be squeezed or stretched to a sphere by using suitable scaling factors. Phillips and Spencer (1955) used a dimensionless constant and a rotation angle. The intersection of the unmodified contours of constant correlation with the ground plane was an ellipse of variable orientation. It is shown in Section 6 that this extension of the analysis is not necessary for the results obtained in the current experiment.

5. OUTLINE OF EXPERIMENTAL METHOD.

The equipment used for the observation of the high altitude atmospheric winds by the diffraction drift method is conveniently divided into two parts

(a) the radio transmitter, receivers and associated apparatus at the Birdling's Flat field site

and (b) the computer (IBM 1620) and associated off-line equipment in the Mobil Computer Laboratory of the Department of Mathematics, University of Canterbury.

Only an outline of the apparatus is given here. Details of the electronic circuits are given in Appendices.

5.1. APPARATUS AT BIRDLING'S FLAT.

5.1.1 THE RADIO TRANSMITTING AND RECEIVING EQUIPMENT.

This is situated at the Birdling's Flat field site (43° 50' S, 172° 40' E, 30 km south of Christchurch), and comprises the following:

(a) A radio-frequency pulse transmitter generating a 25 micro-second pulse with a peak power of 120 kW at repetition rates of 25 or 50 sec^{-1}. The carrier frequency is 2.404 Mc/s, and the wavelength 125m.

(b) Transmitting aerial array of 8 half wave elements in a broadside array, with a calculated gain of 13.8 dB (relative to an isotropic radiator).

(c) Three receiving arrays, each of two in-phase half-wave elements with a calculated gain of 7.8 dB. They are connected to the receiver by way of 600 ohm open-wire transmission line. The arrays are in the form of a right-angle triangle with sides of 250m (two wavelengths). A spacing of two wavelengths was used. The scale of ionospheric diffraction pattern is so variable that any one spacing will cause rejection of some records in which the cross-correlation is too high or too low for satisfactory analysis. A spacing of two wavelengths ensures that the rejected observations would be of the smaller scale diffraction patterns, which could arise from a large random fading component and thus be a poor indication of atmospheric wind motion. It was felt that, should the diffraction pattern scale be too small for a significant correlation, digital smoothing could be applied to remove the high frequency components. An equilateral triangle is considered more satisfactory for the diffraction drift method (Barber 1957) but the receiving arrays were sited with the possibility of future interferometer experiments in mind.

(d) The three receivers are each preceded by a balun matching unit. For reliability, and with related experiments in mind, it was decided to use three independent receiver channels rather than one channel with diode switches at the input and output. The crystal-controlled local oscillator is common to all three channels to maintain a constant phase reference at the three coherent detectors. The phase reference signal for the coherent detector is derived from the transmitter crystal oscillator which runs continuously. The receivers also include a video amplifier designed to reproduce the bi-directional signals with negligible shift in the d.c. level.

(e) A phase calibration oscillator is necessary to eliminate any systematic phase differences between the three receiver channels. The oscillator and its loop aerial were placed equally distant from the three receiving aerials.

5.1.2. SIGNAL PROCESSING UNIT.

This collective term refers to the circuits between the receiver video stages and the recording device.

The video output signal is first limited about ground potential by cascaded diode and Schmitt limiter stages. A height gate pulse then selects the required part of the reflected waves. The gated signal is at this point a 10 microsecond bit with a repetition period of 20 milliseconds and an amplitude of 12V. Its average power is too low to drive a pen recorder, and it is too short to operate the low speed punch driving circuits. Each signal bit therefore sets a flip-flop which is used as a single-bit storage cell. The flip-flop is reset by each transmitter trigger pulse. In this way the duty cycle is increased from 0.05 per cent to about 97 per cent.

The fading period of the signals is about 1 to 5 seconds so that there is no need to sample the receiver outputs more frequently than about 2 sec^{-1}. In practice a sampling rate of 3.125 sec^{-1} was used (derived from a 50 sec^{-1} fork and a 4-stage binary divider). With a transmitter pulse repetition rate of 50 sec^{-1} there is therefore a considerable amount of redundancy in the receiver output signal. It is therefore possible to improve the signal-to-noise ratio by using an integrator circuit. The capacitor is switched to give integration time constants of 0.05 or 0.25 seconds. The integration increases the rise-time of the binary signal to 2.2 times the integration time constant. To reduce uncertainties in switching levels, this slow signal is again limited about its nominal mean level. A description of the signal processing unit, including a logic diagram appears in Appendix C. Appendix B gives details of the logic elements used.

5.1.3. RECORDERS.

The output from each channel of the signal processing unit has only two values, depending on the value of the limiting amplifier input voltage relative to the reference level. Each observation from each receiver may then be recorded as a single binary digit which has the value '0', say, when the limiter input is below the reference level, and the value '1' when it is above. The binary outputs of the three receivers may be recorded as three separate entities on a three-channel recorder, but the recording process is considerably simplified if the three digits are considered together as a binary coded decimal or octal number. A single digit, in the range 0 to 7, then specifies a unique state of the receiving systems outputs. When the correlation calculations are to be carried out this octal or decimal digit must of course be decoded to the original three binary digits so that the probabilities in the tetrachoric tables can be calculated. The recording process has been simplified although the calculations are complicated by the addition of a decoding operation, but this is of no consequence if a computer is available to carry out the decoding. The decoding required only a small fraction of the total time needed to compute the points for the correlograms.

While the paper tape punch control circuits were being constructed a two channel pen recorder was used to record the binary output data from the three receivers. The pen coils were driven by the bridge-connected transistor d.c. amplifiers. By the addition of shunt feedback these were used as summing operationsl amplifiers. As three bits had to be recorded on two channels, the '1' and '2' bits were combined through the resistive weighting networks of one amplifier to give a 0 to 3 indication on one channel. The '4' bit was recorded on the other channel. Even this simple type of chart recording required about 3 man-hours to read for a 10 minute recording time.

The paper tape punch is an IBM type 961 which is capable of punching 15 characters sec^{-1}. Eight tracks can be punched so that a considerable variety (256) of characters is available. However compatibility with the equipment in the Mobil Computer Laboratory made it desirable to use the standard IBM code, which also has the advantage of representing numbers by their binary-coded-decimal equivalents. The three outputs from the signal processing unit were therefore punched in the 1, 2, and 4 tracks on the tape punch. The punching is carried out by applying the three signals to three pulses gates which are driven by the 3.125 sec^{-1} sampling pulse. The outputs from the pulse gates set (or don't set) flip-flops in the punch buffer register which drive the punch. Once the character has been punched, a pulse from the punch resets the punch buffer register to await the next pulse. The logical diagram of the paper tape punch drive unit is given in Appendix D.

5.2. EQUIPMENT AVAILABLE IN THE MOBIL COMPUTER LABORATORY.

The computer is an IBM 1620 Model 1 with 40,000 digit storage and card input/output. An IBM 870 unit is also available for tape-to-card conversion and graph-plotting, in addition to its other functions.

The tapes which have been punched withthe binary information at the field site are first read on the 870 and the data digits punched into cards. The cards are then read into the 1620 and the decimal digits decoded to three time series of binary digits. The tetrachoric correlation function for each point of the correlograms is then calculated, usually from lags of -40 to +40 for the cross-correlation functions and 0 to + 40 for the autocorrelation functions, with increments of 2 units. The maximum lag and incremental lag can be varied by a program control card. The correlogram points are then punched on to cards in the format required by the IBM Library Autoplotter program which prepares a deck of cards for plotting the correlograms on the modified typewriter of the 870.

The correlation program is written in fixed-point SPS (a symbolic form of machine language) to obtain the maximum computing speed. Six correlograms with the lags specified in the previous paragraph, using 150 data digits, are computed in 110 seconds. The same calculation with a Fortran program takes 70 minutes, although no attempt was made to realise the shortest computing time with the Fortran program as it was obviously too slow. Normally 500 to 600 data points are used, with a computing time of 4 to 5 minutes.

An improvement in computing speed is obtained by using logical instructions for the binary data, instead of multiply instructions. As the 1620 is a serial binary-coded decimal machine logical operations on binary data are clumsy and inefficient. The program can be changed to produce the correlograms for 512 two-digit data points in $6\frac{1}{2}$ minutes, so that the logical instructions do shorten the computing time by about 25 per cent. The plotting of the correlogram set takes 17 minutes and is the weakest link (in terms of speed) in the chain of calculation. A high-speed line printer would be more efficient.

The appropriate data is read from the correlograms and punched on to cards, and the velocity parameters are calculated by the computer.

6. FEATURES OF THE EXPERIMENTAL CORRELOGRAMS.

A set of experimental correlograms is shown in Figure 6.1. The auto-correlogram and one cross-correlogram of this set were used as examples in Section 4.2. The mean auto-correlation function is used because it is found that the three individual auto-correlation functions from the three receivers are not identical. No selection of suitable fading conditions is made at the field site, so that many records consist merely of the noise between pulses reflected from the various altitudes in the atmosphere, and the percentage of useable records is fairly low (40 per cent). The results described in this thesis were obtained from 300 sets of correlograms derived from 740 fading records. It is possible to assess the minimum useable cross-correlation at zero time delay. In future the cross-correlation at zero time delay can be first calculated and if the value falls below the minimum the remainder of the correlogram points need not be computed.

6.1. SAMPLING ERRORS.

The purpose of the investigation is to simplify, as much as possible, the recording and analysis of data for the spaced receiver experiment. We must therefore consider the amount of detailed information which it is necessary to retain in the calculations. We have already seen (in Section 3.2) that the recording can be simplified because the use of tetrachoric correlation provides adequate information for the correlation analysis (the actual shape of the space and time autocorrelation functions is of no importance). It will now be shown that there is no need to consider a statistically anisotropic ground diffraction pattern and the refinements of the Phillips and Spencer (1955) analysis are unnecessary.

The three receivers are each sampling a random function - the amplitude of the electric field in the diffraction pattern - and sampling errors will be present. The differences between the three time autocorrelation functions have already been mentioned. The sampling errors also appear as small differences between the cross-correlation values calculated from samples of finite length. These differences are interpreted by the Phillips and Spencer analysis as anisotropy of the diffraction pattern, which will introduce errors in the drift velocity if the anisotropy is ignored. It is, however, unreasonable to attribute unusual features to the diffraction pattern when they do not exist. We can only be certain that the unusual features really exist in the physical system if the errors of observation are so small that the unusual features are significantly different from what we would expect.

A study of the experimental correlograms showed that fluctuations in the correlation coefficients of $\pm$ 0.1, about a nominal zero mean, were very common. We can tentatively take this figure to be the sample standard deviation of the correlation coefficient. The axial ratio is deduced from the calculated fading velocity (v_c') which is in turn derived from the correlograms, as follows:

(i) Find the cross-correlation (r_k) between one pair of receivers for zero time lag.

(ii) Find the time lag (τ_k) of the autocorrelation function which gives a correlation of r_k.

Then v_c' is calculated, using equations (4.14) and (4.15) for the respective values appropriate to each pair of receivers. To find the error introduced in each of steps (i) and (ii) above we must determine the relationship between the standard deviation of a correlation function and the standard deviation of its argument. We assume, as a first approximation, that the correlation functions are of the elementary form

$$r(u) = \exp(-|u|/u_o) \tag{6.1}$$

where u is either the space or time variable (δ or τ respectively) and u_o is a constant, then the fractional standard deviation of the correlation coefficient is

$$\frac{s(r)}{r} = \frac{s(u)}{u_o} \tag{6.2}$$

Equation (6.2) shows that the fractional standard deviations are equal. Let us assume that the correlograms indicate a value of $u = u_o$, so that $r = 0.37$. When $s(r) = 0.1$ the fractional standard deviation is 0.27, for each of steps (i) and (ii) above in the determination of the fading velocity. The fading velocity will therefore have a fractional standard deviation of 0.38. Each axis of the ellipse can be determined to this accuracy so that the axial ratio may have a fractional error of $\pm$ 0.53. The axial ratio is always defined to be greater than unity so that the variance will be doubled if the mean axial ratio is unity. Assuming that the ground diffraction pattern is statistically isotropic, the sampling errors would suggest correlation ellipses with axial ratios of 1.74 and random orientation.

This estimate of the sampling error has used some very crude approximations. For example, the standard deviations have been added as if they were derived from independent samples. The method of analysis is based on a finite correlation between the field strengths sampled at two points in the diffraction pattern. The assumption of independent samples is therefore only a rough approximation to the real situation, but will serve as a guide. The finite correlation between samples reduces the standard deviation of the axial ratio, and ratios as high as 1.7 would be observed infrequently. Conversely, the value chosen for the fractional standard deviation of the correlation is very common and values as high as 0.3 to 0.5 are often found, indicating a larger value then 1.7 for the "mean-axial-ratio-plus-one-standard-deviation".

Awe (1964b) conducted an experimental investigation on the errors present in similar correlograms and found that the deviation in the correlation coefficient (for confidence limits of 95 per cent) was $\pm$ 0.2. His mean value of the correlation was about 0.8 to 0.9 so that the fractional standard deviation is comparable with the value used in the rough calculation above.

The exact shape of the autocorrelation function is not known, but the importance of the shape can be estimated by considering another function for r(u).

Let $r(u)$ be the Gauss function:

$$r(u) = \exp - (u^2/2u_o^2) \qquad (6.3)$$

The fractional standard deviation of $s(r)$ is then

$$\frac{s(r)}{r} = (-2 \log_e r)^{\frac{1}{2}} \frac{s(u)}{u_o} \qquad (6.4)$$

The axial ratio determined from (6.4) with $r = 0.37$ and $s(r) = 0.1$ is 1.54. It can be seen that the shape of the autocorrelation functions only has a second-order effect on the axial ratio arising from random sampling errors.

Phillips and Spencer (1955), using a transmitter frequency of 2.4 Mc sec^{-1} to obtain reflections from the E region, found that the most common axial ratio was 1.3. From their histogram for the axial ratio we can calculate the mean value, which is 1.7. Fooks and Jones (1961) used frequencies between 2.0 and 4.5 Mc sec^{-1} to observe reflections from E region. They found a median axial ratio of 1.5. Lee (1962) investigated diffraction drifts on a frequency of 300 kc/s, with an estimated reflection height of 95 to 100 km. Lee's results agree in general with the observations made at higher frequencies, and he found axial ratios of 1.6. The observations reported by Fooks and Jones gave ellipses of constant correlation which had a slight tendency to be oriented in the northwest-southeast quadrants. Lee's ellipses, and those of Phillips and Spencer, do not show a preferred orientation. The E region work described in the references showed, at the most, only a slight tendency to non-random correlation ellipse orientation. If the apparent axial ratio is due to random sampling errors the ellipse orientation ought to be random, and such a hypothesis is reasonable for the E region, but not for the F region.

We shall therefore assume that the diffraction pattern is statistically isotropic, because the axial ratios observed by the other workers do not differ significantly from 1.0 and the ellipse orientation is almost random.

6.2. THE INFLUENCE OF PHASE DRIFT ON THE CROSS-CORRELOGRAMS.

Results from the current investigation have not been included in the previous section's discussion on axial ratios because of uncertainties about the cross-correlation analysis. The cause of the uncertainties is illustrated by Figure 6.2. Cross-correlograms from successive observations show a uniform progression in the height of the peak. In a phase sensitive system such a progression indicate a slow change of phase. Possible sources of this phase variation will now be discussed.

The output from the coherent detector of one receiver, when the mean phase difference between the signal and the local phase reference is zero, is given by (3.3)

$$\mathbf{v}(t) = \text{Real}\ [A(t) \exp j\ \varphi(t)] \tag{3.3}$$

If there is an arbitrary, but constant phase error in the receiver (relative to the reference signal) of φ_o

$$\mathbf{v}(t) = \text{Real}\ [A(t) \exp j\ (\varphi(t) + \varphi_o)] \tag{4.19}$$

Comparing the output signals from the detectors in two receiver channels, the cross-correlation coefficient is (3.6)

$$r_{ij}(o) = \langle A_i(t).\ A_j(t) \exp j\ [\varphi_i(t) - \varphi_j(t)] \rangle \exp j\ (\varphi_{oi} - \varphi_{oj}) \tag{4.20}$$

i.e. $$r_{ij}(o) = r^o_{ij} \exp j\ (\varphi_{oi} - \varphi_{oj}) \tag{4.21}$$

where r^{o}_{ij} is the correlation coefficient when the two phase errors φ_{oi} and φ_{oj} are equal. A phase comparison oscillator (Section 4.1.1 and Appendix A.9) provides a signal which enables the receivers to be adjusted so that $(\varphi_{oi} - \varphi_{oj}) = 0$. The values of φ_{oi} and φ_{oj} are unimportant: it is only their difference which is significant. The cross-correlograms in Figure 6.2 indicate that there is a slow change in the quantity $(\varphi_{oi} - \varphi_{oj})$, the mean phase difference. The correlation coefficient changes sign showing that the phase changes must be about 180^{o}. The phase calibration was found to be stable within 5^{o} to 10^{o} over a period of several weeks so that the differential phase change is not an instrumental effect.

A possible explanation of the variation is indicated in Figure 6.3(a). Very large scale, wave-like irregularities in the height of constant electron density contours have been observed. Landmark(1957) found that a "quiet" E layer can depart from the horizontal by 6^{o} or more (the method of observation which he used failed for deviations greater than 6^{o}). We may therefore assume that localised deviations from the horizontal of 10^{o} might occur, although perhaps not frequently. If a large scale irregularity of this nature passed over the receiving site in a time which is long compared with the fading period, the reflected wave will deviate from the vertical by 10^{o}.

The corresponding variation in the mean phase difference $(\varphi_{oi} - \varphi_{oj})$ is 120^{o}. This change in the mean phase difference is sufficient to reverse the sign of the correlation as the large scale irregularity drifts past.

An alternative explanation of the phase change can be derived from the same geometry. Landmark (1957) found that on occasion the phase and amplitude variations at one point on the ground could be explained by two rays, with angles of incidence 4^{o} and 6^{o} respectively on either side of the vertical (Figure 6.3(b)). The resultant interference fringes on the ground have a separation of about six wavelengths. The mean phase difference is then about 120^{o} for fringes oriented at right angles to either ofthe short sides of the triangular receiving array or about 170^{o} for fringes oriented at right angles to the hypotenuse.

In the absence of any detailed knowledge about the structure of the irregularities it is impossible to decide which of these hypotheses is correct. The second hypothesis seems more reasonable, since it calls for a smaller inclination of the reflecting surface. It is quite possible that the two effects should occur simultaneously, with the further complication that the phase changes introduced might well be independent. Further support for the fringe hypothesis is found in records which have occasionally been obtained where one pair of receivers had a low value of cross-correlation, but the pair at right angles has a much larger correlation, clearly indicating the presence of interference fringes.

The sign reversal in the cross-correlation produced by slow phase changes would not be "visible" to a receiving system with incoherent detectors. However interference fringes of quite reasonable visibility (up to 0.3) are even found with incoherent receiving systems (Awe 1964(a), 1964(b)).

6.3. INTERFERENCE BETWEEN ORDINARY AND EXTRA-ORDINARY WAVES.

The ordinary and extra-ordinary magneto-ionic components of the reflected wave will have increasingly different ray paths as they pass through higher and higher regions of the atmosphere. Consequently the fading imposed on the wave at the respective reflection levels may be quite different. Fortunately electron density measuring equipment associated with the diffraction drift apparatus has a visual display of the ordinary and extra-ordinary reflected waves. As would be expected, the fading of the two components from the lower heights is often well correlated, but independent fading occurs quite frequently, especially in the higher altitude observations.

The visual display, and the appearance of the correlograms, makes it apparent that there is negligible possibility of a systematic error in measurement due to interference between the two magneto-ionic components. Either the fading is well-correlated, and has little effect on the correlograms, or the fading is random and merely reduces the correlation without altering the time delay of maximum correlation.

The electron density measuring equipment also yields the ratio of the two components and there is only a limited range of heights (60 to 80 km) over which the components have comparable power (Manson 1965) and the interference between components might reduce the correlation. However the fading of the two components is usually well-correlated at these low heights.

6.4. CONCLUSION.

This section concludes with the observation that, since the behaviour of the cross-correlograms is frequently curious and unpredictable, the value of cross-correlation at zero time delay is too unreliable to be of use in the Briggs, Phillips and Shinn (1950) method of correlation analysis. The only consistently reliable parameter is τ_m, the time-delay for maximum cross-correlation (or minimum cross-correlation if the correlogram has been inverted by the presence of interference fringes). Consequently only the apparent drift velocity components (v_x' and v_y' in equations 4.14 and 4.15) can be calculated. As shown by equation (4.10)

$$v' = v + \left(\frac{v_c}{v}\right) v_c \qquad (4.10)$$

The apparent velocity (v') therefore exceeds the true velocity (v) by an amount depending on the ratio (v_c/v). This ratio is commonly (Fooks and Jones 1961) about 1.0 and the apparent velocity then exceeds the true velocity by about 100 per cent.

About 30 per cent of the correlograms were of sufficient quality to permit the calculation of all the velocity parameters. The correlograms must first be corrected for non-zero mean, as outlined in Section 3.3, but as the necessary computer program has not yet been written, parameters other then the apparent velocity are not available for the results discussed in this thesis.

7. ATMOSPHERIC WINDS BETWEEN 65 AND 100 KM.

The high sensitivity system has made possible the measurement of atmospheric winds down to 64 km. Observations at the lower altitudes (below 75 km) are possible only during the middle part of the day in winter. As most of the results were obtained during the winter, there is a relatively high proportion of low altitude observations.

Figure 7.1 shows the height profile of wind components obtained on 24 June 1964 between 1300 and 1400 hours local time. This day was selected because more observations were obtained over a wider virtual height range (64 to 120 km) than on other days. The east-west (zonal component, u) of the drift is from the west below 95 km. Above this height the drift is from the east. The north-south (meridional component, v) is from the north at all heights, except for two points which deviate considerably from the mean curve.

We must now consider the relationship between the translational motion of the ground diffraction pattern ("drift") and the translational motion of the neutral air ("wind"). An elementary correction which must be applied is the geometric factor introduced into the diffraction process by the use of spherical waves radiated from the transmitter on the ground. The ground diffraction pattern drifts at twice the speed of the ionospheric irregularities. This correction is allowed for in all the results: the drift velocities are quoted as the equivalent drift of the reflecting layer.

Other factors which confuse the relationship between the diffraction pattern drift velocity and the wind velocity include geomagnetic field effects (discussed in Section 7.2) and the nature of the diffraction process (discussed in Section 7.3). This Section concludes with a discussion of possible errors due to solar atmospheric tides and to radio wave group path delay.

7.1. A NOTE ON TERMINOLOGY.

Before discussing the results, and their interpretation in terms of atmospheric dynamics, it is necessary to consider the sign conventions and jargon associated with the topic. The work described in this thesis represents one of the few areas of common interest to both ionospheric physicists and meteorologists. Unfortunately the two groups of workers have adopted differing definitions of wind direction. The meteorologist describes a wind by the direction *from* which it is blowing. To a physicist the wind is represented by a velocity vector and is therefore described by the direction towards which the wind is blowing.

There is fortunately no disagreement about the sign of the vectors and their components. Figure 7.2 shows the right-handed Cartesian co-ordinate systems used in meteorology. The positive directions are eastward, northward and upward; displacements are respectively x, y and z. The corresponding velocity components are u, v and w. In Section 4, v_x and v_y were used as the horizontal components of the drift velocity, but were not at that time associated with any geographical direction. In the new terminology v_x becomes u, and v_y becomes v, which makes the symbol v ambiguous - it can represent either the north-south wind component or the magnitude of the velocity. In this and succeeding sections v will be taken to represent the north-south component of wind velocity and if the magnitude of the vector is discussed it will be written $|\underset{\sim}{v}|$.

Figures 7.3(a) and (b) show the relationship between the terminology and the vector components. The meteorological terms will be used because they are in everyday use. In Figure 7.1 therefore the wind is westerly (from the west, towards the east, u positive) below

95 km, easterly (from the east, towards the west, u negative) above 95 km.

7.2. THE INFLUENCE OF THE GEOMAGNETIC FIELD ON THE MOVEMENT OF IONISATION.

As a first approximation, consider isolated electrons in a region containing a magnetic field. Any translational motion imparted to the electrons by an applied force results in an average motion along the magnetic field. The resultant motion of the electron gives no indication of the magnitude or direction of the applied force.

As an alternative first approximation, consider the electrons in a weakly-ionised, dense gas in a magnetic field. The random collision process prevents the electrons from rotating around the magnetic field lines and the electrons follow the average motion of the neutral gas.

In the atmosphere, which at all times has the geomagnetic field passing through it, the neutral gas density decreases with height and the electron density increases with height. At the outer limits of the atmosphere, the former approximation is valid. At ground level the alternative approximation is valid. There is therefore some region of the atmosphere below which the influence of the geomagnetic field is negligible. Above this region, the geomagnetic field cannot be neglected.

There are various estimates of the height below which the geomagnetic field can be neglected. Clemmow, Johnson and Weekes (1955) deduced that a cylindrical cloud of charge, parallel to the geomagnetic field, would follow the motion of the neutral gas if the ratio of the collision frequency to the angular electron gyro-frequency exceeded 10^{-3}. The angular electron gyro-frequency is 10^{+7} sec^{-1}. Experimental data on the variation of collision frequency with height in the relevant part of the atmosphere (Bjelland, Holt, Landmark and Lied 1959; Kane 1961) gives a collision frequency of 10^{+4} sec^{-1} at 105 to 115 km. The cylindrical cloud would therefore move with the wind at altitudes of 105 km or less. It is, however, an unrealistic geometry as the nature of the diffraction drift experiment implies ionospheric irregularities spread over a large area in a horizontal plane. The problem was reconsidered by Villars and Feshbach (1963) who extended the analysis to a weakly ionised turbulent gas. They concluded that below 100 km the geomagnetic field has no effect on fluctuations in the ionisation density produced by turbulence. In the 110 to 120 km region the ionisation fluctuations are slightly modified by the geomagnetic field.

It is therefore reasonable to assume that the diffraction pattern drifts described in this thesis resulted from radio waves reflected, in the atmosphere below 110 km, by electrons whose motion is dependent on the neutral gas motion, and is unaffected by the geomagnetic field. The calculated velocities therefore refer to the neutral gas, but do not necessarily indicate the direction of the wind. This restriction on the interpretation of the results is discussed in the next section.

7.3. THE DIFFRACTION OF WAVES BY IRREGULARITIES IN A FLUID.

In the previous section we have seen that the radio waves are reflected from electrons which move with the neutral gas. We cannot observe directly the motion of the neutral gas, but we can interpret the results (Section 4) as horizontal motion of the reflecting surface. If atmospheric waves are perturbing the medium, the observed velocity is that of the wave profile, not that of the medium itself. The atmospheric motion is complicated and the point is best illustrated by an example drawn from a different field of geophysics - physical oceanography.

7.3.1. A RELATIVELY SIMPLE EXAMPLE.

The motion of waves on the sea's surface has a considerable effect on the propagation of acoustic waves underwater. This field of study is of considerable importance to various governments who have encouraged much research on the topic. Many of the results from this research can be applied to the diffraction of radio waves by reflecting surfaces in the ionosphere. The detailed diffraction theory is outside the scope of this thesis and the discussion will be confined to only those principles necessary to describe the problem of immediate interest.

Consider a transducer placed on the sea bed, directing acoustic waves vertically upwards; if the sea surface is perfectly smooth the waves appear to come from the image of the source. If there is a shallow swell (less than one-sixth of the acoustic wavelength) on the surface the diffraction pattern formed on the sea bed moves with the swell, and the diffraction pattern velocity and structure size correspond to the velocity and structure size of the surface waves. Even this simple example shows that the acoustic diffraction pattern does not reveal the movement of the ocean currents, but that of waves at the fluid interface.

If the depth of the swell is greater than about one-sixth of a wavelength, the velocity of the diffraction pattern corresponds to that of the surface waves but the structure size does not. We can still make no deductions about the movement of ocean currents. If the swell has a reasonably simple waveform we can never deduce the velocity of the underlying sea currents. If, however, the sea is so choppy that we can consider its movement to be (only) the resultant of a very large number of simple waves arriving from all directions with random phases, there is no drift motion apparent in the diffraction pattern on the sea bed and we could measure the characteristic velocity (v_c) as defined in Section 4.1. However, sea currents will bodily move this random profile and the mean motion will then be apparent in the diffraction pattern on the sea bed.

We see, therefore, that the diffraction pattern shows the movement of waves on the sea's surface but if the surface is perturbed by a set of random waves the mean velocity of the surface (due to ocean currents) can be measured by using the average motion observed over a time which is long compared with the period of the lowest frequency component in the wave spectrum.

7.3.2. REFLECTION FROM ATMOSPHERIC IRREGULARITIES.

The major difference between the problem of acoustic propagation, outlined in the previous section, and the atmospheric situation is the change in the density of the medium at the interface. In the atmosphere the fluid density changes slowly, although the radio waves are partially reflected by small changes in electron density which occur within a wavelength. There is no first-order change in the fluid motion across the reflecting layer, although there is obviously some mechanism responsible for the change in electron density, The slow density change is a source of complication because the wave motion is not simply a surface phenomenon but extends throughout the medium.

The properties of internal atmospheric gravity waves have been discussed (see, for example, Gossard and Munk 1954; Gossard 1962; Eckart 1960; Hines 1960, 1963(a)). Hines, whose discussions are characterised by a vigorous enthusiasm for gravity waves, has considered (1963(a), 1963(b), 1964) the influence of gravity waves on the motion of ionospheric irregularities. Much of his discussion concerns the interaction of ionisation with the geomagnetic field. The interaction can be ignored when considering motion below 100 km (Section 7.2). The remaining features discussed by Hines are best illustrated by the impression of a gravity wave created by Figure 7.4, which is a copy of Figure 2 of Hines' (1960) paper. Only a small portion of the wave in the horizontal direction is shown because the horizontal scale of the motion is considerably greater than the vertical scale. The increasing amplitude of the gravity waves with height is a characteristic of motion in the atmosphere, assuming a constant energy density and a decreasing mass density. Hines estimates that the dominant mode of oscillation at an altitude of 90 km has a vertical wavelength of about 10 km and horizontal wavelength of about 500 km. The corresponding period of oscillation is about 10 minutes. Irregularities of electron density, arising from turbulence or density fluctuations in the gas will be moved by the wave perturbation velocity and the horizontal velocity perturbations of the gas can be measured by the spaced receiver equipment.

On the other hand, the wave perturbation pressure will produce its own electron density irregularities. The latter will occur in horizontal layers separated by the vertical wavelength (about 10 km). As the sloping pressure perturbation passes through an already existing horizontal ionospheric layer the electron density fluctuations will pass along the layer. Hence the velocity measured by a diffraction drift experiment is neither the wave velocity nor the velocity of any physical body. In the hypothetical sea-wave investigation described in Section 7.3.1 we were at least able to measure the velocity of wave motion, but the atmospheric waves are not confined to a surface and the interpretation of their motion is correspondingly more difficult.

Meaningful results can be obtained by again invoking a random spatial and temporal distribution of simple waves. If the observation time is long enough, or the number of observations sufficiently large, the mean motion will be that of the medium in which the waves are propagated.

It is reasonable to suppose that, in the atmosphere, both velocity and pressure perturbations will occur and the velocity measured in a diffraction drift experiment will be a composite effect. However, if the gravity waves are random it is still possible to measure the mean horizontal component of the wind.

The sources of interval atmospheric gravity waves are unknown, but Gossard (1962) has shown that sufficient energy could propagate upwards from tropospheric disturbances to maintain the gravity waves at ionospheric heights as postulated by Hines. Tropospheric disturbances appear to be sufficiently irregular in space and time to generate random gravity waves. The waves could also be generated in the upper atmosphere, possible sources of energy being instability due to greater-than-adiabatic temperature gradients between 50 and 80 km (the mesodecline), or instability induced by tidal motion (Hines 1963).

7.4. THE DEDUCTION OF ATMOSPHERIC WINDS FROM THE EXPERIMENTAL RESULTS.

It is apparent that although atmospheric gravity waves introduce spurious components into the diffraction pattern drift velocity, there may be some significance in the mean value of a large number of drift observations. The reliability of the mean drift as an estimate of mean atmospheric wind depends on the assumption of randomly superposed gravity waves. There is no prospect of disentangling the gravity waves from the other innumerable physical effects also present in the atmospheric motion. The reliability of the mean drift can only be determined by comparing the diffraction pattern drift results with observations of atmospheric winds determined by other methods, such as meteorological rockets, or meteor trail motion.

The mean drift velocity profiles at noon were calculated for each month. The mean zonal and meridional components are shown, in Figures 7.5 to 7.12, for the period December 1963 to September 1964, except for February and March when the number of observations was negligible. No error bars indicating standard deviations are shown because the data available for a given height varied in reliability and number. The reliability of the mean curve is best indicated by the regularity with which the velocity components change with height. The drift profiles show a systematic change with height. It is reasonable to assume, following the discussion in Section 7.3.2, that Figures 7.5 to 7.12 show the mean monthly height variation of the atmospheric wind at noon over Birdling's Flat.

The height profile (Figure 7.13) of the zonal wind component (u) shows a systematic variation during the winter months, the height of reversal increasing from 80 km in April to just over 100 km in July. The height of reversal then decreases to 90 km in August, but drops no further in September. The corresponding Figure 7.14 for the meridional component (v) shows no systematic variation, although the wind is northerly during the winter (v negative) and southerly during the summer.

7.5. INFLUENCE OF SOLAR TIDES.

Although gravity waves may introduce considerable errors in a single observation, the assumed random superpostion of many waves allows the mean drift to be interpreted as the mean wind. Regular perturbations of the mean atmospheric flow cannot be eliminated in this manner. Since all the observations described in this thesis were made within an hour or two of noon, an averaging process will not eliminate the regular tidal components.

In a search for some way of allowing for the solar tides, it was necessary to consult the only adequate sources of information on atmospheric winds in the 65 to 100 km region - the meteor wind results from Jodrell Bank (latitude 53^{o}N) in England (Greenhow and Neufeld 1961) and Adelaide (35^{o}S) in South Australia (Elford 1959). Elford's data for the prevailing (mean over 24 hours), diurnal and semi-diurnal wind components was selected. There are differences between the two sets of data, which may be due to the latitude differences or to a difference between the hemispheres. Christchurch is, in terms of distance from the equator, half-way between Adelaide and Jodrell Bank. If the circulation differences are due to the latitude change, either the Adelaide or Jodrell Bank results would be satisfactory. Since there are major differences between the northern and southern circulation patterns in the troposphere and stratosphere it is more reasonable to use the Adelaide data in case the mesospheric behaviour is also asymmetrical.

Elford (1959) quoted the amplitude and phases of the tidal components in the meteor wind measurements for 1953, with some data from 1952 and 1954. The wind due to the three components was re-constructed from his data for each hour from 1000 to 1500 in an attempt to find a suitable correction for the drift results. There did not then appear to be any suitable technique for making the correction, until it was realised that the unsystematic behaviour of the wind was of considerable significance - the "regular" solar tidal components showed a most irregular variation over a period of several weeks. With randomly phased waves still in mind, the phase of Elford's semi-diurnal component was plotted for each month. The resultant graph (Figure 7.15) clearly showed that the semi-diurnal component was, on a monthly time scale, randomly phased. The amplitude also showed considerable variation.

This heartening conclusion led to an investigation of the diurnal component (Figure 7.16). The scatter in phase is not so pronounced. It would appear that the fluctuating quantity in the tidal motion is dependent on a time difference, not on a phase difference. The hypothesis of randomly phased tidal waves was put to the test, with the results shown in Figure 7.17, where the suffix "o" indicates the prevailing component in Elford's data and the other variable is the mean sum of the prevailing, diurnal and semi-diurnal components at noon. Only when the mean velocity components are small is the difference between the mean and prevailing values significant.

Thus we can safely assume that the monthly mean values shown in Figures 7.5 to 7.12 are a good approximation to the prevailing wind for each month. It is possible to use these mean wind components to investigate the high altitude atmospheric circulation over Birdling's Flat. This investigation is presented in Section 8.

7.6. GROUP PATH DELAYS IN HEIGHT MEASUREMENT.

Although the waves are partially reflected below 100 km the increasing electron concentration around 100 km causes the group path length (measured by the delayed gate pulse), or virtual height, to exceed the real path length.

Reference to the Ionospheric Data of the Christchurch Geophysical Observatory showed that the noon E region critical frequency was about 3.0 Mc sec^{-1} in the winter and 3.5 Mc sec^{-1} in the summer. The operating frequency was 2.4 Mc sec^{-1} and, allowing for variations in the observing time up to two hours either side of noon, it was found that many of the observations were recorded when the wave frequency was very close to the critical frequency. This was apparent at the time of recording in the increased height of the E reflection.

To provide an estimate of the height correction necessary, an exponential approximation to the average winter electron density profile (Manson 1965) was assumed, with 100 electrons cm^{-3} at 73 km and 1000 electrons cm^{-3} at 85 km. These figures correspond to a scale height of 5.3 km; the critical electron density occurs at 107 km. Since the extra-ordinary wave reflected from the E region is at least 30 dB below the amplitude of the ordinary wave the former may be neglected. Consequently the geomagnetic field may be neglected in an approximate calculation. The electron collision frequency will also be neglected as a finite collision frequency reduces the group refractive index and will reduce the magnitude of the height correction.

With these assumptions - an exponential electron density profile, no geomagnetic field, and no collisions, the virtual height of reflection can be calculated and the real height of reflection subtracted. The height correction is then

$$z'-z_o = 2H \log_e \left\{ \left(1 + \sqrt{1-(N_o/N_c)}\right) / \left(1+ \sqrt{1-(N_e/N_c)}\right) \right\} \quad (7.1)$$

where z' = virtual height

z_o = real height of reflection

H = scale height

N_e = electron density at reflection height

N_o = electron density at ground level ($z = o$)

N_c = critical electron density.

The height correction is 0.83 km for the assumed model, when the real height of reflection is 100 km, This is negligible, compared with the transmitter pulse width (4 km).

The assumed average winter profile has more ionisation below 88 to 90 km, and less at a higher level, than the average summer profile. The E region electron density is about 30 per cent greater in the summer and the reflection height 3 to 4 km lower. Consequently the height correction is larger, but as a negligible number of satisfactory records was obtained above 92 km during the summer, we shall again neglect the height correction. The occasional violent fluctuations in the electron density profile below 90 km in the winter may cause increases in the group path correction. The 1000 electron cm^{-3} contour has a mean height of 85 km during the winter (May, June and July); on 21 June 1964 it was at 89 km but on the following day it was at 82 km. These two values are the extremes observed during the period (Manson 1965). The sudden increases have such a short time scale compared with the monthly mean values used that they may be ignored, especially as the maximum height of useful diffraction drift observations on 22 June was only 96 km.

We assume therefore, that there is negligible group path delay on observations made below 100 km, but that most of the measurements at virtual heights of 100 to 124 km apply to a lower region of the atmosphere- probably 100 to 110 km.

8. THE DYNAMICS OF THE ATMOSPHERE BETWEEN 65 AND 100 KM.

In this section we consider equations of atmospheric motion relevant to the present study, using various approximations which the meteorologists have found adequate in descriptions of motion above the troposphere. The diffraction drift results are then related to the predicted motion, and to meteorological rocket observations. The discussion is limited mainly to measurements of motion below 100 km because of the uncertainties introduced above 100 km by group path delay (Section 7.6) and the geomagnetic field (Section 7.2).

8.1 BASIC EQUATIONS OF ATMOSPHERIC MOTION.

The acceleration of a mass relative to the geographic axes illustrated in Figure 7.2 is

$$\frac{\partial u}{\partial t} = (F_x/m) + 2\,(vh \sin\varphi_1 - w\,h \cos\varphi_1) \qquad (8.1)$$

$$\frac{\partial v}{\partial t} = (F_y/m) - 2\,uh \sin\varphi_1 \qquad (8.2)$$

$$\frac{\partial w}{\partial t} = (F_z/m) + 2\,u\,h \cos\varphi_1 - g \qquad (8.3)$$

where (u, v, w) = the velocity of the mass relative to the earth

m = mass

h = angular velocity of the earth

φ_1 = latitude

$\underset{\sim}{F}$ = the force acting on the mass

The principal source of energy in the atmosphere is solar radiation. The atmosphere therefore becomes heated and pressure gradients develop. If the force ($\underset{\sim}{F}$ in equations 8.1 to 8.3) acting is solely due to the pressure gradient the equations of motion become

$$\frac{\partial u}{\partial t} = 2(v\ h \sin \varphi_1 - w\ h \cos \varphi_1) - \frac{1}{\rho}\frac{\partial p}{\partial x} \qquad (8.4)$$

$$\frac{\partial v}{\partial t} = -2\ u\ h \sin \varphi_1 - \frac{1}{\rho}\frac{\partial p}{\partial y} \qquad (8.5)$$

$$\frac{\partial w}{\partial t} = 2\ u\ h \cos \varphi_1 - g - \frac{1}{\rho}\frac{\partial p}{\partial z} \qquad (8.6)$$

If we also assume that the vertical velocity is negligible ($w = o$) and that all motion is steady ($d\underset{\sim}{v}/dt = o$) equations (8.4 to 8.6) reduce to

$$2\ v\ h \sin \varphi_1 = \frac{1}{\rho}\frac{\partial p}{\partial x} \qquad (8.7)$$

$$2\ u\ h \sin \varphi_1 = -\frac{1}{\rho}\frac{\partial p}{\partial y} \qquad (8.8)$$

$$2\ u\ h \cos \varphi_1 = g + \frac{1}{\rho}\frac{\partial p}{\partial z} \qquad (8.9)$$

The equations (8.7 to 8.9), for the steady, horizontal motion of air subject only to pressure and Coriolis forces are known as the geostrophic wind equations. The wind (u, v, 0) so calculated is called the geostrophic wind. The type of motion can be illustrated by assuming that the pressure increases to the east ($\partial p/\partial x$ positive), with no variation in any other direction. Then equation (8.7) predicts a northerly wind in the southern hemisphere (see Figure 8.1(a)). The wind is therefore parallel to the isobars. Equation (8.8) predicts a westerly wind for a south to north pressure gradient. (See Figure 8.1(b)). In general, the geostrophic wind in the southern hemisphere flows parallel to the isobars, with the high pressure region to the left. The pressure gradient force on the air is balanced by the Coriolis force (see equations 8.7 and 8.8). The approximation is therefore invalid in regions where the Coriolis force is small, that is, in tropical latitudes. Elsewhere the geostrophic approximation is sufficiently accurate for most purposes (Hess 1959). The approximation cannot be used at very low levels in the atmosphere where there are viscous forces due to the fixed boundary of the earth's surface.

We may ignore the small Coriolis term in equation (8.9) since $u < 100$ m sec^{-1}, $h = 7.292 \times 10^{-5}$ sec^{-1} and thus $2u\, h \cos \varphi_1 = 2 \times 10^{-2}$ m sec^{-2}, which is negligible compared with the gravitational acceleration. This reduces (8.9) to the usual hydrostatic equation.

It is convenient to discuss atmospheric flow in terms of temperature gradients. We therefore substitute the "ideal gas" equation into the geostrophic-wind equation (8.7 to 8.9). Firstly we use the gas equation to eliminate the density equation (8.9), ignoring the Coriolis term. After some re-arranging and cross-differentation we obtain.

$$\frac{\partial u}{\partial z} = -(g/2h\ T \sin \varphi_1) \frac{\partial T}{\partial y} + (u/T) \frac{\partial T}{\partial z} \qquad (8.10)$$

and $$\frac{\partial v}{\partial z} = (g/2h\ T \sin \varphi_1) \frac{\partial T}{\partial x} + (v/T) \frac{\partial T}{\partial z} \qquad (8.11)$$

These equations are the basic equations for the present study, since the information provided by the diffraction drift experiment is just the height variation of the mean wind. The geostrophic wind approximation has eliminated all variables except the wind velocity components and the temperature. Integrating equations (8.10) and 8.11) between the limits z_1 and z_2, and writing the Coriolis parameter

$$2\ h \sin \varphi_1 = f$$

$$= -10^{-4}\ \sec^{-1} \text{ (at Birdling's Flat)} \qquad (8.12)$$

we have

$$u(z_2) = u(z_1)\,\frac{T(z_2)}{T(z_1)} - (g/f)\int_{z_1}^{z_2} \frac{1}{T}\left(\frac{\partial T}{\partial y}\right) dz \qquad (8.13)$$

and

$$v(z_2) = v(z_1)\,\frac{T(z_2)}{T(z_1)} + (g/f)\int_{z_1}^{z_2} \frac{1}{T}\left(\frac{\partial T}{\partial x}\right) dz \qquad (8.14)$$

The geostrophic wind shows an increase in amplitude with temperature. There is an additional term, due to the horizontal temperature gradient, which is called the thermal wind.

The factor (g/f) in equation (8.13) and (8.14) is -10^5 m sec^{-1} so that even a small horizontal temperature gradient is able to produce a significant thermal wind component. For example, a thermal wind of 10 m sec^{-1} is generated over a height interval of 1 km in an isothermal atmosphere at a temperature of 250° K, by a horizontal temperature gradient of 0.C25° K km^{-1}.

8.2. TEMPERATURES BETWEEN 65 AND 100 KM.

The importance of the temperature as a function of height and horizontal distance is immediately apparent from equations (8.13) and (8.14). The temperature and its spatial variation cannot be measured by ground based methods. The only technique for obtaining the information at the heights of interest is by the use of meteorological rockets which can carry temperature sensors and other instruments. No such information is available in New Zealand.

However a reasonable estimate of the temperatureprofile can be made if we neglect any possible asymmetry between the northern and southern hemispheres. We may then include data from the only southern hemisphere station at Woomera, South Australia (31° S) with the more numerous northern hemisphere results. In the upper stratosphere (around 50 km altitude) the summer hemisphere is warmer than the winter hemisphere. On the other hand the winter mesosphere is warmer than the summer mesosphere. Consequently there is a height range (60 to 65 km) in which the summer and winter temperature are much the same. This was pointed out by Kochanski (1963) and Nordberg (1964). This behaviour is also described in the summaries by Batten (1961) and Teweles (1964), and in the individual temperature profiles shown by Faust and Attmannspacher (1961), Groves (1963), aufm Kampe and Lowenthal (1963), Nordberg and Smith (1963), Maeda (1963). In all these sources, describing measurements over a wide latitude range, the mean temperature at 65 km was 230° K, within about 5 per cent, during both summer and winter. The mean temperature gradient between 50 and 80 km at mid-latitudes is about 3° K km^{-1} in the summer and less in the winter. Nordberg (1964) concluded that "the temperature profile between the ground and 90 km becomes more and more isothermal as one progresses from the tropics towards the winter pole". Nordberg found (1963) that the winter stratosphere and mesosphere above Wallops Island (latitude 38^{o}N) is almost isothermal with an average temperature of about 220^{o} K.

On the basis of the above data we can use the crude temperature profile shown in Figure 8.2. The above references were used as a source of information, with some help from the U.S. Standard atmosphere (COESA 1962). A notable feature of Nordberg's (1964) summer profile is the lack of a mesopause, although his data is only available up to 90 km. The assumed winter profile in Figure 8.2 has a mesopause but Nordberg's comments (referred to above) suggest that an isothermal atmosphere (at 230^{o} K) would be adequate.

8.3. THE MERIDIONAL TEMPERATURE GRADIENT.

The meridional temperature gradient, at heights of 65 to 100 km above Birdling's Flat, was calculated by using a crude finite - difference approximation to equation (8.10), assuming that $(\partial T/\partial y)$ is constant. No great accuracy is necessary because of uncertainties in both the experimental data and the assumed temperature profile. However the calculated gradients contained an excessive amount of fluctuation because of the large errors in the differences taken from the raw data. The raw data used is shown in Figures 8.3 and 8.4, the average winter profile being obtained from the data for May, June, July and August, 1964. The fluctuations were reduced by smoothing with weights of $\frac{1}{4}$, $\frac{1}{2}$, $\frac{1}{4}$. The smoothed curves are shown in Figure 8.5. The consequent horizontal temperature gradient, as a function of height, is shown in Figure 8.6. The temperature gradient $(\partial T/\partial y)$ in units of $(^{\circ}K/10^{\circ}$ latitude) is plotted against height. Between 70 and 100 km the air is cold towards the equator, but below 70 km the air is warm towards the equator. The temperature gradient above 100 km is uncertain.

An alternative method of analysis was also investigated. A least-squares straight line was fitted to the zonal wind profile for each month. The gradients of these straight lines, as a function of time of year, are shown in Figure 8.7. The average gradient for the four winter months was then calculated. The average gradient, and an assumed isothermal atmosphere at 230° K, gave the meridional temperature gradient shown in Figure 8.6 as a vertical dashed line. Such large scale averaging does not do justice to the data, and cannot be considered of much significance.

The winter meridional temperature gradient at

95 km agrees with the values calculated by Kochanski (1963) from Elford's meteor wind data at Adelaide. The value found here is slightly larger (-5° K/10° latitude compared with -3.5° K/10° latitude) but this may indicate a genuine difference due to the differing latitudes for the two stations or merely reflect the systematic error in the wind calculations due to neglect of the random component (see Section 6.4).

The zonal temperature gradients have not been calculated from the height variation of the meridional wind component. None of the references used indicated any interest in the topic. This is, perhaps, because the diurnal component is so large that no significance can be attached to the results. It can be seen, from Figures 8.3 and 8.4 and equation (8.11), that the zonal temperature gradient is positive in the summer and negative in the winter.

The most reasonable way of quantitatively investigating the variation of the wind component with height and time of year is to make a two-dimensional plot of the raw data and then apply smoothing factors in the height and time dimensions. This approach has been foiled by the non-availability of a technique for two-dimensional smoothing which will allow for large gaps of missing data. The simple monthly, equalweight, averaging used seems to be adequate but destroys much of the time resolution available.

8.4. THE CIRCULATION BETWEEN 65 AND 100 KM.

The general atmospheric circulation revealed by the diffraction drift experiment is in general agreement with current reviews of the subject (Batten 1961, Kochanski 1963). The principal features of the middle-latitude zonal wind system are:

(i) the dominant westerly circulation throughout the atmosphere in winter, with strong westerlies between 60 and 70 km;

(ii) the decreasing velocity above this height, culminating in a reversal to easterly winds;

(iii) the seasonal variation of this height of reversal;

(iv) the pronounced variation in the circulation in spring and autumn; and

(v) the change in the summer to an easterly circulation at some heights.

Each of these points will now be discussed, briefly, in a quantitative comparison with the diffraction drift results.

8.4.1. THE 60 TO 70 KM WINTER WESTERLIES.

Batten (1961) deduced a westerly wind component of 60 to 70 m sec^{-1} at 60 to 70 km in the winter. Kochanski (1963), using Batten's work and some later experimental work, principally the Jodrell Bank meteor wind results (Greenhow and Neufeld 1961), shows values of 80 to 85 m sec^{-1}. The diffraction drift results for the four winter months (Figures 7.8 to 7.11) show westerly velocity components of 40 to 60 m sec^{-1}. The average velocity reaches a maximum of 48 m sec^{-1} at 72 km, which is slightly higher (by 5 to 10 km) than the heights of maximum shown by Batten and Kochanski. The difference is negligible.

8.4.2. THE MID-WINTER HEIGHT OF REVERSAL IN THE ZONAL WIND.

The diffraction drift results clearly show the upward trend of the westerly circulation early in the winter, and the subsequent downward trend. Batten places the mid-winter height of reversal at 95 to 100 km; Kochanski places it at 100 km. The diffraction drift results show a reversal at 100 to 105 km, but allowing for group path delay (Section 7.6) a height of 100 km is a good estimate.

8.4.3. THE VARIATION IN THE HEIGHT OF REVERSAL.

The downward trend (see Figure 7.13) in the spring is a well-known phenomenon associated with large variations in the polar circulation system (Batten, 1961; Miers, 1963; Finger, Teweles and Mason, 1963). There does not yet appear to be any satisfactory explanation of the downward progression of the circulation system. As discussed in Section 9, such a downward progression may indicate an upward progression of energy. Conversely, the upward trend in the autumn may indicate a downward movement of energy. This behaviour was not found in the work reviewed by Batten (1961) and Kochanski (1963), or in the observations reported by Miers (1963). Mier's results show considerable variability in the behaviour of the circulation system from one season to the next. The downward progression is not at all smooth. Consequently it would be unwise to assume that the trend of the height of reversal indicated in Figure 7.13 is correct. The true variation might well be a downward progression beginning above 100 km in the summer with the April and May increases in height being major upward perturbations. The lack of data for February and March makes it impossible to specify the autumn change in circulation.

8.4.4. EQUINOCTIAL VARIATIONS IN THE CIRCULATION.

The equinoctial behaviour of the height of reversal described in the previcus section, is accompanied by increases in the east-west and north-south velocity components. Figure 8.8 shows the anual trend of the mean zonal wind, for virtual height ranges of 64 to 76 km, 80 to 88 km, 92 to 100 km and 104 to 124 km. Figure 8.9 is the corresponding plot for the mean meridional wind. It is apparent from these two figures that the behaviour of the wind is similar for all heights above the reversal height. Figure 8.10 shows the annual trend of the components averaged for all heights above, and all heights below, the reversal height.

Near the equinoxes both the zonal and meridional winds below the reversal height increase. There is also a change in the components above the reversal height but these components are more variable and the increases are not quite so obvious. It is possible that the increase in velocity is only apparent and may be caused by an increase in the random velocity component, due to turbulence or increased gravity wave activity. It is obviously desirable that the characteristic velocity be calculated for as many records as possible. This has not been done quantitatively, but a prominent feature of the late April, early May and the September results is a large fading period and high cross-correlation. These characteristics suggest a very low random component in the fading so that the increases in apparent velocity would correspond to even larger increases in the true drift velocity.

The February-March gap has not been crossed in Figure 8.10 as there is no clear indication of the trend on either side of the gap. The summer winds are easterly and southerly at all heights observed (72 to 92 km). A prominent feature of Figure 8.10 is the abrupt, but temporary, change in the meridional wind above the reversal height. This change is una ccompanied by any change in the winds below the reversal height, but there is a slight change in the zonal component above the reversal height, and the start of a pronounced decrease in the reversal height (Figure 7.13). This feature suggests an instability in the circulation. Such a pronounced change in circulation ought to be accompanied by corresponding effects in the lower stratosphere, and in electron density and ionospheric absorption. However a detailed comparison must await the acquisition of the relevant data, and the discovery of an adequate method for the treatment of the unevenly spaced diffraction drift data.

8.4.5. THE SUMMER CIRCULATION.

The only summer observations available are between 72 and 92 km. The zonal wind is easterly and the meridional wind is southerly. The meridional wind is in accordance with the meteor wind results quoted by Kochanski (1963). Batten (1961) and Kochanski (1963) both show zonal winds from the east, in the summer, below 75 km. The diffraction drift results show that easterly winds exist up to at least 92 km.

Meteorological rocketsonde investigations also suggest that the easterlies extend to much higher altitudes than Batten and Kochanski indicate. aufm Kampe, Smith and Brown (1962), Smith (1962) and Finger, Teweles and Mason (1963) show summer easterlies of 50 to 60 m sec^{-1} up to 70 km, the limit of their observations. In neither set of data does the wind show any indication of the steep gradient necessary to cause a reversal at 75 km. In both cases the wind near 70 km shows little variation with height, indicating that the easterly circulation extends well above 80 km. These meteorological rocketsonde observations were made near latitude 38^{o} N and are therefore comparable with the diffraction drift results. The conclusions of Batten (1961) and Kochanski (1963) must therefore be modified to allow for the higher extent of the summer easterly circulation in the mesophere at middle latitudes.

9. A DISCUSSION OF MOTION IN THE MESOSPHERE.

The height range of 65 to 100 km which has been studied by the diffraction drift method includes the mesosphere (from the temperature maximum around 50 km to the temperature minimum, or mesopause, just above 80 km) and the lower thermosphere (the region of increasing temperatures above the mesopause). The experimental results discussed in Sections 7 and 8 can be interpreted to some extent by existing theories of motion in the upper atmosphere.

The height of reversal of the mean monthly zonal wind component increases (Figure 7.13) during the early part of the winter and decreases after July. Kantor and Cole (1964) have calculated the day and night geostrophic zonal wind components for January, and latitudes between 30° and 45° N. Their curves are very similar to those shown in Figures 7.7 to 7.12, except that the profile shows a reversal at 88 km in the daytime, and at 82 km in the night-time. Their calculations were based on temperature changes due to solar heating and nocturnal cooling. It is reasonable to interpret the winter variation in the height of reversal as indicative of a similar variation in the mesospheric temperature contours. This interpretation assumes that there are no major changes in the mesospheric and thermospheric circulation in the winter. The winds measured by the diffraction drift method show no major variations over the winter. There is no information available on temperature variations above Birdling's Flat, but it can be assumed that the general behaviour will be much the same as that a comparable latitudes in the northern hemisphere.

The basic feature of the region is the mesopause itself. The summer mesosphere is much cooler than the winter mesosphere so that the temperature gradients are large and the mesopause is well-defined. In winter there is little, if any, variation in the mean temperature between 65 and 100 km. The references quoted in Section 8.2 showed minimum temperatures at various heights between 65 and 90 km, while the temperature profile assumed by Kantor and Cole was isothermal from 80 to 85 km at night and 80 to 95 km during the day. Using this limited data it is possible to link the height of reversal (in Figure 7.13) with the bottom of the thermosphere. The geostrophic wind equations (8.10) and (8.13) show that the relationship between the height of reversal and the bottom of the thermosphere includes the meridional temperature gradient. Kantor and Cole used the geostrophic equations and their results show the bottom of the thermosphere to be about 6 km above the height of reversal, but the difference depends on the variation of temperature with height and latitude.

Manson (1965) shows that there is a minimum electron density in summer at 82 km, but in the winter there is no minimum of electron density at the commonly accepted mesopause height of 80 to 85 km. The relationship between the electron density and the meteorological parameters is obscure, but the electron density profiles do indicate the existence of a discontinuity in the summer, and its absence in the winter. The summer minimum of electron density at 82 km is not accompanied by any characteristics of the zonal winds, which are easterly at all heights between 70 and 90 km. Three different physical quantities (the winds and electron density measurements at Birdling's Flat, and the northern hemisphere temperature measurements) show that the winter mesosphere is more uniform and more variable than the summer mesosphere. It is known (Charney and Drazin, 1961; Hines 1963(a)) that the mesopause is a barrier to wave propagation on the planetary (periods of several days), tidal (periods of one day and harmonics) and gravity wave (periods of tens of minutes) scale. Consequently in summer, there may be little wave energy above the mesopause, but there could be considerable energy below the mesopause because of the reflected energy, with a consequent disturbance of atmospheric pressure, temperature and winds. Such disturbances are, however, characteristic of the winter mesosphere. The paradox was partly resolved by Charney and Drazin (1961) who showed that the summer stratospheric wind system reflects the planetary waves and it is likely (Hines 1963(a)) that the tidal and gravity wave motion is similarly reflected.

The average mesospheric structure is more uniform in the winter and the temperature barrier is small or non-existent. Energy may be propagated upwards and thus give rise to perturbations of pressure, temperature, winds and, presumably, electron density. Indivdual diffraction drift results can not easily be interpreted as an atmospheric wave motion (Section 7) but Gregory (1961, 1964) found that reflections of 2.4 Mc/s radio waves could be obtained over a much greater thickness of the mesosphere in winter than in summer. Gregory attributed these thick scattering regions to turbulence but it seems equally likely that the electron density fluctuations are caused by the increased transmission of a wide spectrum of atmospheric waves. There does not seem to be any simple way in which the source of the electron density fluctuations might be revealed since a wide spectrum of waves and the turbulence would each produce random electron density fluctuations. It is conceivable that there is no fundamental difference between high-frequency gravity waves and turbulence since both forms of motion represent pressure and velocity variations in a fluid, and can be generated by fluid instabilities. Discussions of turbulence usually assume fluids of uniform density in the absence of gravity, and the inclusion of gravity and the hydrostatic equation might well eliminate the distinction. There is little point in pursuing this topic, as even Hines can only speculate (1964) on the link between gravity waves and turbulence.

Moving now to the very-low-frequency end of the atmospheric wave spectrum, we return to a topic first mentioned in Section 8.4.3. The downward progression of the reversal height in the late winter (Figure 7.13) may be associated with the increasing amount of energy absorbed below the mesosphere, and the subsequent upward propagation of this energy. It is known (Hines 1963(a)) that tidal and gravity wave motion is characterised by a downward progression of phase when there is an upward progression of energy. If it is assumed that the height of reversal is a velocity node of a seasonal "wave" with characteristics similar to the tidal and gravity waves, then the difficulty of finding an upper atmosphere driving force for the equinoctial reversals in circulation may be avoided.

It is clear that a more detailed interpretation of the experimental results requires considerable extension of current theories for wave motion to include models more nearly like the real atmosphere.

10. CONCLUSION.

The comparison of the diffraction drift results with the information obtained from meteor trail wind measurements and meteorological rocket-sondes show that the high sensitivity diffraction drift techniques is a most useful tool for the synoptic investigation of atmospheric motion above altitudes of 65 to 70 km. The diffraction drift results do require various corrections, which can be made for suitable records, and, although the significance of an individual drift observation has been questioned by Hines, there can be no doubt that the average velocity profiles show excellent agreement with the results obtained by other methods. Most of the individual drift velocity profiles show good agreement with the appropriate mean profile and atmospheric gravity waves appear to have only a second-order effect. The results obtained show, in particular, the upward movement of the mesospheric westerlies during the early part of the winter. This is followed by their subsequent downward movement, apparently irregular, in the late winter.

The diffraction drift method does reveal the effects of gravity waves and, combined with suitable phase path and group path measurements, could provide information on the characteristics of the internal gravity waves themselves.

A careful analysis of correlation techniques has shown that the reliability and usefulness of the diffraction drift experiment is considerably improved by using tetrachoric correlation. The principal improvement is in the simplification of the recording process, with the consequent improvement in reliability of the field equipment. The high sensitivity depends on high-gain aerial systems, which are also simple and reliable pieces of apparatus.

The spaced receiver diffraction drift method is thus a simple, reliable, ground-based method for the synoptic observation of atmospheric circulation in the mesosphere and thermosphere. It enables observations to be made over a much longer period than any rocket technique, and certainly enables the observations to be made much more cheaply.

APPENDICES A to E

CIRCUIT DETAILS OF THE WINDS EQUIPMENT.

Details are first given in Appendix A (and Figure A.1.) of the radio receiver (up to and including the video stages) used for the reception of 2.4 Mc/s. pulses reflected from the moving irregularities in the upper atmosphere.

Then follows :

APPENDIX B. A description of the digital circuit elements which were developed for use in various parts of the winds equipment, and have also been used in apparatus for associated experiments.

APPENDIX C. The logical design of the signal processing unit which accepts the three video signals from the receivers, limits them, selects the appropriate height in a gate driven by the height gate pulse generator, stores the resultant binary digit until the next one is received, integrates the stored digits, and reshapes the d.c. level.

APPENDIX D. The logical design of the paper tape punch drive unit which accepts the d.c. levels from the signal processing unit and controls the tape punch so that the information is suitably recorded on the punched paper tape.

<u>APPENDIX E.</u> The logical design of the height gate pulse generator which supplies a height gate pulse every 4 km from 32 to 128 km.

A. RADIO RECEIVER.

The receiver consists of three independent channels with a common local oscillator and a phase reference channel. All circuits are conventional and so detailed circuit diagrams are not given. Only the basic circuit functions and any features unique to the present use of binary signal information are described.

A.1. "BALUN" TRANSFORMER.

The balanced-to-unbalanced transformer was required to perform two functions:

(a) to convert the balanced input from the transmission lines to the unbalanced radio frequency amplifier stages, and

(b) to transform between the standard impedance levels of 600 ohms balanced and 75 ohms unbalanced.

The transformer has a parallel tuned primary and a series-tuned secondary separated by a Faraday shield. The design was assisted by the graphical method given by Sandeman (1953).

A.2. RADIO FREQUENCY AMPLIFIER.

The 75 ohms input impedance level is stepped up to the 0.1 Megohms grid resistance (external to the valve) by a pi-network. The 6BA6 plate impedance is a single-tuned circuit shunted by back-to-back silicon diodes (OA202) to reduce receiver overloading when the transmitter pulse is radiated. The diodes limit the mixer grid voltage to 1 V peak-to-peak.

A.3. MIXER.

The mixer is a dual-triode, cathode coupled circuit to provide maximum isolation between the oscillator and signal inputs. The oscillator injection input is applied to the mixer stage through a transformer with an untuned low impedance primary and a high impedance tuned secondary.

A.4. INTERMEDIATE FREQUENCY (4.5 Mc/s) AMPLIFIER.

The three amplifier stages are coupled with synchronous single-tuned circuits. The overall bandwidth of the three channels is 90 to 110 kc/s (there are small differences between channels). This is twice the optimum (Lawson and Uhlenbeck 1950) bandwidth for the pulse length used.

A.5. DETECTOR.

The phase-sensitive detector was required to have, for convenience, unbalanced inputs and output. A satisfactory circuit has been described by Villard (1949). The detector is not a true multiplier ("product detector") because when no phase reference input is applied to the detector it functions as conventional rectifier detector. This is a considerable advantage since the receivers can be used to measure A(t) (equation 3.2) simply by switching off the phase reference channel.

The phase-reference signal is applied to the detector by way of a coupling transformer (from the low-impedance input to the receiver chassis), cathode follower, grounded-grid amplifier, and a tuned transformer.

A.6. VIDEO AMPLIFIER.

The video amplifier (two grounded cathode stages and a cathode follower) were designed to handle bi-directional signals with the minimum shift in d.c. level. The bi-directional operation was simply obtained by biasing the valves to the mid-point of their linear operating characteristic i.e. as conventional audio amplifiers, rather than as the more common type of video amplifier in which the valves are biased to one end of the linear operating characteristic (because only signals of one polarity are to be amplified). The d.c. level of a normal video signal is easily maintained by diode d.c. clamping circuits but with bi-directional signals this is impossible. Consequently coupling capacitors were eliminated wherever possible. The second stage is directly coupled to the cathode-follower output stage. Large time constants are used in the coupling circuits between the first and second stages, and between the output cathode and the output terminal. In this way the sag in receiver mean level is reduced to a minimum. There only remains a negligible variation in d.c. level caused by the fading signal.

A.7. PHASE REFERENCE CHANNEL.

The 2.4 Mc/s sine wave from the transmitter crystal oscillator and the 6.9 Mc/s sine wave from the local crystal oscillator in the receiver are each amplified by a grounded-grid stage before being applied to the mixer. The mixer and intermediate frequency amplifier stages are identical with those in the signal channels. Cathode followers provide low impedance outputs.

A.8. LOCAL OSCILLATOR.

The electron-coupled Pierce crystal oscillator (International Crystal Mfg. Co., 1962) is followed by a pentode buffer amplifier. Four cathode followers provide low impedance outputs for the four mixers in the three signal channels and the phase reference channel.

A.9. PHASE COMPARISON OSCILLATOR.

A small (one metre square) loop antenna is driven by a crystal oscillator using a grounded-base transistor circuit. The oscillator and antenna are mounted on the same pole, equidistant from the three receiving aerial arrays, so that there can be no spurious radiation from radio frequency feeder cables. The oscillator could have been battery-powered but, to avoid a 500 yard walk over rough ground whenever a phase calibration was required, a cable was laid to the apparatus site. The power is supplied through a switch located in the caravan containing the receiving equipment. A small amount of radio-frequency radiation from this power lead was eliminated with series r.f. chokes and by-passing capacitors.

APPENDIX B. DIGITAL LOGIC ELEMENTS.

The digital logic elements used to realise the logical functions required in the equipment were designed on the following premises;

(i) All circuits should be as simple as possible.

(ii) All components must be readily available from local sources.

(iii) All components must be as inexpensive as design considerations allow.

(iv) Each circuit should use as few components as possible, and as small a variety of components as possible.

(v) The mechanical design should be based on plug-in modular units.

(vi) The maximum operating temperature will be 40° C (104° F).

(vii) Only low speeds of operations are required (the transmitter pulse repetition rate is 50 sec^{-1}, or less, and the data punching rate is 3.125 sec^{-1}).

(viii) "Worst case" design limits give best reliability. In this application there is no increase in cost or circuit complexity because of the low operating speed and low loading of individual elements.

These features make possible equipment which is inexpensive, easy to maintain and easy to replace. The use of standardised circuit elements eliminates much of the construction work necessary when changes are to be made in the equipment - only the inter-element wiring need be changed. The transistor circuits were constructed on commercially available plug-in printed circuit matrix board.

<u>NOTE:</u> All voltages are assumed relative to ground, so that, for example, -48V is a <u>lower</u> voltage than -12V. In the diagrams all resistances are marked in units of ohms, and all capacitances in picofarads.

B.1. DESIGN CRITERIA FOR DIGITAL LOGIC ELEMENTS.

The above premises led to the following conclusions:

(i) The common emitter configuration has more power gain and a smaller ratio of input/output impedances than the other configurations. Diode logic circuits do not amplify and must be used in conjunction with transistor amplifiers. They are not therefore economical in this application. The grounded-emitter transistor configuration permits quite a large amount of interstage power loss, allowing a greater freedom in design.

(ii) Saturated operation of transistors is permissible since minority carrier storage delay times are negligible compared with the required operating times in the circuits.

(iii) Audio or slow-speed switching pnp germanium transistors have adequate switching speed, are readily available, cheap, and the base-collector leakage current is still reasonably low at 40° C.

(iv) There is quite a bit of latitude in the definition of the "1" and "0" logic level voltages. The minimum value of a "1" level is the supply voltage (-12V or -48V) and the maximum will depend on how heavily the source is loaded. A maximum level of -6V was chosen as this allows the load on a 12V logic element to be as low as the element's equivalent resistance. A correspondingly lower load resistance can be used on a -48V element. The maximum value of a "0" is ground for the electromechanical elements but the output from a saturated transistor is limited to about -0.25V.

(v) Conclusions (ii) and (iv) indicate that diode clamping of the voltages levels is unnecessary.

(vi) The resistor-transistor NOR gate (Figure B.1.) is the most satisfactory basis for the system of logical elements since the transistor is only about twice the cost of a diode, provides amplification, and all other logical functions can be derived from it. As an example of economy, the 4-input NOR gate requires 4 resistors and a transistor; whereas a 4 -input diode gate would need 4 diodes and, after a few logical operations, at least one transistor amplifier to compensate for the power loss in the diodes. As an example of the NOR gate's versatility, a flip-flop (bistable multi-vibrator) can be constructed from the two NOR gates with the input of each connected to the output of the other; and a monostable multivibrator can be derived from the two NOR gates, with the addition of a timing capacitor and resistor.

(vii) A resistance tolerance of $\pm$ 5 per cent is adequate.

(viii) For maximum reliability all collector load resistances exceed the limit set by the maximum supply voltage and maximum transistor power dissipation.

(ix) Dual-voltage supply biasing is used as it permits greater d.c. stability, and it is sometimes more convenient to operate a circuit between ground and a supply voltage of, say, $+V_{cc}$ than between $-V_{cc}$ and ground. The dual voltage supply also makes available a 24V supply for any electromechanical elements which require this operating voltage. The dual supply, and definition of logic levels in (iv) above, ensure that no inter-stage level shifting is necessary as the emitters can be directly grounded without the saturation collector emitter voltage falling outside the limits for a "0" as defined in (iv).

B.2. DEFINITION OF LOGIC LEVELS AND PULSES.

The distinction between "0" and "1" was specified in the previous section as $V > -0.25V$ and $V < -6V$ respectively. Standard supply voltages of -12V, with a complementary +12V, were available. A supply delivering -48V was also required for the tape punch and various uniselectors and relays. The positive terminal of this supply is grounded to permit the use of the pnp power transistors to drive these electromechanical devices. Logical "1" levels derived from the electromechanical devices are also -48V with respect to ground. Before entering a transistor logic circuit a -48V level is clamped to -12V as illustrated in Figure B.11.

The apparatus at Birdling's Flat also contains many valve circuits, including all the transmitting equipment. A trigger pulse of about +50V is required to trigger this equipment. Fortunately this waveform is readily obtainable from a grounded-emitter pnp amplifier (Figure B.6.) operating from the -48V supply.

We must also consider how the timing of various circuit functions is to be achieved. All the above discussion relevant to the transistor logic is independent of time and the bits may exist for as long as we wish or as short as the rise, fall and storage times of the transistors permit. This type of digital logic is termed "level" logic because functions are determined by a d.c. level. On the other hand "pulse logic" is not related to the length of time for which a bit is present or absent; the term is used when a bit must pass through a capacitor or transformer. The output voltage is proportional to the rate of change of input voltage (assuming the sources and loads have finite resistance and negligible reactance). Timing functions can therefore be performed by either level logic or pulse logic. A pulse of finite width can be used to define time but it is ambiguous as there are two pieces of information available - the leading edge and the trailing edge. If the leading edge of a pulse is used to define a time instant it is sometimes possible for the trailing edge to interfere with circuit operation. A time instant is therefore best defined by a step function. We have two choices, but a positive going step is preferable because

(i) it implies that the pnp grounded emitter stage generating the pulse is being switched ON and with a reasonable amount of overdrive the transition can be made very quickly (in less than 0.5 microseconds for the transistors used, which are nominally restricted to audio applications)

(ii) apart from the increased speed internal to the transistor, the overdriven transistor has a very low output impedance (about 3 ohms) and any capacitance across the transistor is rapidly discharged.

(iii) the uncertain delay due to minority carrier storage is completely eliminated.

These considerations determine the various definitions of the bits as they arise in various parts of the equipment, and are summarised in the Table B.1.

In Table B.1 the nominal values of the bits are taken to be either the relevant supply voltage or ground. The minimum and maximum values depend on the following assumptions (the numbers refer to the rows in the table):

1. <u>MINIMUM:</u> This is the lowest value of base-emitter

TABLE B.1.

ADOPTED DEFINITIONS (IN VOLTS) OF BINARY DIGITS.

	CIRCUIT ELEMENT	BIT	MIN.	NOM.	MAX.
1	Transistor (level logic)	0	-0.25	0	0
2	" " "	1	-12	-12	-6
3	Electromechanical (level logic)	0	-0.25	0	0
4	" " "	1	-60	-48	-40
5	Transistor (pulse logic)	1 (=pos.step	+6	+12	+12
6	Electromechanical and valve (pulse logic)	1 (=pos.step)	+24	+48	+60

voltage or saturation collector to emitter voltage which can be expected

MAXIMUM: Positive voltages are not necessary and have not been allowed for.

2. **MINIMUM:** No lower voltage is obtainable with a -12V supply.

MAXIMUM: The output voltage available when the element has a load equal to its internal resistance, (see (iv) in Section B.1).

3. **MINIMUM:** The clamping circuits do not operate above -12V so that the minimum is determined by the low voltage transistor circuits.

MAXIMUM: This level is also determined by the low voltage transistor circuits.

4. **MINIMUM:** This is the maximum voltage rating for the power transistor. The -48V supply is unregulated, and the primary power source is a self-regulating diesel alternator set. On some occasions the supply voltage surges below -48V by a few volts, but never falls as low as -60V.

MAXIMUM: The relays, uniselectors and tape punch will operate with 35V applied to the solenoids but 40V was selected to give a greater margin for unforeseen mechanical misbehaviour.

5. MINIMUM: This is the lower limit for reliable operation of the flip-flop.

MAXIMUM: The maximum reverse base-emitter voltage of the low-power transistors is +12V.

6. MINIMUM: This voltage allows the series resistance of a diode clamp circuit to have a maximum value equal to the resistance of one NOR gate input. It is also equal to the minimum resistance of the pulse gate.

MAXIMUM: No greater pulse amplitude could be obtained with the supply available. It is also the largest pulse otainable from the power transistors.

NOTE ON SYMBOLS USED FOR LOGICAL DIAGRAMS.

There are only a few standard circuit elements, with common positive, and negative power supply and ground connections. It is therefore convenient to describe the equipment by its logical functions, rather than be detailed circuit drawings. There is a great variety of curious hieroglyphs used to represent logical elements in the literature, including several "standards". To avoid the necessity of "learning" any of these systems another variety is here offered. The element is represented by a box with the logical function as a mnemonic label on the box. Arrows show the sequence of events. A d.c. input is attached directly to the box; an input to a coupling capacitor is separated from the rest of the box by a straight line. Each box symbol, with its set of connections, is defined below its circuit diagram.

B.3. DETAILED DESCRIPTION OF THE BASIC NOR GATE. (FIGURE B.1).

The circuit of the basic NOR gate is shown in Figure B.1. The transistor will conduct if I_1 or I_2 or I_3 or I_4 is sufficient to turn the transistor ON. When the transistor is On the output voltage is the saturation collector-emitter voltage of the transistor (typically 50mV).

In the discussion of logical functions in this and succeeding sections the following abbreviations will be used:

A and B abbreviated to A.B

A or B abbreviated to A+B

A = not B abbreviated to $A=\overline{B}$ (B.1)

With the definitions of logic levels given in Table B.1, we see that the NOR gate performs the logical function

$$\mathrm{OUT} = \overline{\mathrm{IN1+IN2+IN3+IN4}} \qquad (B.2)$$

or, in English, an output is present if neither input 1 nor input 2 nor input 3 nor input 4 is present - hence the name given to the circuit.

The NOR gate is able to perform any logical function and this feature is made use of in the signal processing unit (Appendix C). A given height of observation is selected by a delayed gate pulse. The gating operation corresponds to the logical function and. If we denote the signal by SIG and the delayed pulse of the height gate by HG, the quantity X, which we require is

$$X = \mathrm{HG.\ SIG}$$

or (De Morgan's Theorem) $\overline{X} = \overline{\mathrm{HG}} + \overline{\mathrm{SIG}}$

$$\text{or } X = \overline{\overline{\mathrm{HG}} + \overline{\mathrm{SIG}}} \qquad (B.3)$$

We obtain the desired function by applying $\overline{\mathrm{HG}}$ and $\overline{\mathrm{SIG}}$ to the inputs of a NOR gate. The two inverse functions are obtained by applying the original levels HG and SIG to individual NOR gates, which are therefore being used as logical inverters.

Before considering the design details, the transistor characteristics need to be known. In the circuit diagrams, Figures B.1 to B.11, the transistor labelled ACY21 in fact may be one of the following three types - 2N1380, ACY20 or ACY21. It is hoped that the latest one used, the ACY21 will remain readily available from local sources. Each of the first two seemed, at the time to be in adequate supply, but eventually supplies became difficult to obtain. The ACY21 was used wherever possible but it was occasionally necessary to substitute an ACY20. These two transistors are in the same manufacturing series which begins with the ACY17, used in this apparatus in the high-voltage (-48V supply) inverter or NOR gate (see Figure B.6). The ACY20 and ACY21 are very similar, the ACY20 having slightly lower gain and cut-off frequency. Equipment based on a "worst case" ACY20 will always be satisfactory if an ACY21 is substituted, and the following analysis is therefore based on the ACY20, although the ACY21 is shown on the circuit diagrams. The characteristics of these three transistors are relevant and are quoted for reference in Table B.2. For convenient reference the characteristics of the power transistor (ASZ16/OC29) are also given. Copies of Tables B.1 and B.2 are included immediately before Figure B.1 in Volume 2.

TABLE B.2.

SUMMARY OF TRANSISTOR PARAMETERS.

(Grounded emitter operations. Ambient temp. = $40^{o}C$, I_c = 50mA)

PARAMETER	ACY17	ACY20	ACY21		ASZ16	
V_{CE} max (V_{BE} iV)	-60	-32	-32	V	-60	V
V_{BE} max (reverse)	+12	+12	+12	V	+20	V
V_{CE} (SAT) min	-500 (I_c = 300mA)	-200	-200	mV	-1.0 (I_c = 6A)	V
V_{BE}(ON) min	-750 (I_c = 300mA)	-380	-380	mV	-800	mV
V_{BE} (ON) max	-315 (I_c = 300mA)	-230	-230	mV	-400	mV
V_{BE} (OFF) max	+200	+200	+200	mV	+500	mV
V_{BE} (OFF) min	-100	-100	-100	mV	-300	mV
I_c (AV) max	500	500	500	mA	8	A
I_b (AV) max	25	25	25	mA	1	A
I_{co} max *	16	16	16	μA	3.5	mA
P_c max	180	180	180	mW	30	W
h_{FE}	50 - 210	50 - 130	90 - 250		45-130 (I_c = 1A)	
$f_1 \approx f_\alpha$	1.1 (f_1)	1.1 (f_1)	1.1 (f_1)	Mc/s	0.25 (f_α)	Mc/s
τ_s	3.5	3.5	3.5	μs	50	μs

* see over

TABLE B.2. (Cont.)

*The collector-base leakage current for the ACY17, ACY20 and ACY21 was not available for the required maximum temperature (40° C) and supply voltage (-12V). The leakage current of alloy junction transistors has two components. The first, due to the thermal generation of hole-electron pairs, is almost independent of voltage, while the second component, due to surface leakage, is almost proportional to voltage, but independent of temperature (GEC 1962). A linear relationship therefore seems to be a reasonable approximation for the leakage current as a function of voltage. This assumption is supported by the behaviour shown in a graph (with unlabelled axes) in the GEC publication (1962). The linear relationship seems valid except at very low voltages and near the breakdown point.

$$\text{Let } I_{co} \max = a + b\,(V_{cc} + 10) \qquad \text{(B.4)}$$

With the quoted values for the ACY20 and ACY21

a = 10 microamperes

b = -3 microamperes/volt

The leakage current with V_{cc} = -12 V is therefore 16 microamperes

It will be assumed that each NOR gate is being driven by the maximum number of NOR gates (or their equivalent) and is in turn driving the maximum number. This maximum is assumed to be, at worst, five. The five-input NOR gates are required for the decoding matrix in the height gate unit (Appendix E). The first parameter to be determined is the collector load resistance. Too high a resistance will increase the rise time, if this is being determined by the shunt output capacitances, and aggravate the difficulties associated with leakage current. A low resistance requires much larger power supplies. The minimum load resistance (for maximum power dissipation) is 200 ohms. A load resistance of 1000 ohms was chosen, so that the ON collector current is 12mA. At this value of collector current the current gain (h_{FE}) of the transistors is up to 10 per cent lower than it is at a current of 50mA. The maximum potential difference across the load resistance due to leakage current (in a maximum gain ACY21) is 4V. The collector voltage is then -8V which still represents a "1". This situation could only arise under the catastrophic conditions of an open base circuit or complete failure of the +12V supply. If these equipment failures have not occurred, so that we only have to deal with worst case leakage current, the collector voltage can only rise to -11.9V.

The transistor OFF conditions are determined by the lowest potentials ($V_{CE(SAT)}$ min) applied to the input terminals, the maximum leakage current (I_{co} max) and the maximum base-emitter voltage ($V_{BE(OFF)}$ min). The current through each input resistance R_a is

$$I_{a(OFF)} = (V_{BE(OFF)} \text{ min} - V_{CE(SAT)} \text{ min})/R_a \qquad (B.5)$$

R_a cannot be accurately calculated until R_B is known, and vice-versa. Consequently one of the values has to be assumed, and later modified if necessary. The initial estimate for R_a is based on the required collector current (12mA) the current gain (45 at worst, for the ACY20) and the maximum voltage for a "1" (-6V). Thus R_a ($=h_{FE} V_{"1"}$ max $/I_c$) is 22,500 ohms, say 10,000 ohms for quicker iteration. If R_a = 10,000 ohms then

$$I_{a(OFF)} = 8.7 \text{ microamperes}$$

The maximum input current for up to five possible inputs is therefore 43.5 microamperes

$$\text{Now} \quad I_p \text{ min} = I_{co} \text{ max} + I_{inputs} \qquad (B.6)$$
$$= 60 \text{ microamperes}$$

$$\text{Hence } R_b \text{ max} = (V_{BB} - V_{BE(OFF)} \text{ max}) / I_p \text{ min}$$
$$= 197{,}000 \text{ ohms} \qquad (B.7)$$

and the nominal value of R_b is R_b max less 5 per cent so that

$$R_b = 187{,}000 \text{ ohms.}$$

Since the resistance R_b completely determines the OFF stability of the gate, and the estimate of I_{co} max might be slightly in error, R_b was reduced to a nominal value of 100,000 ohms. The assumed minimum voltage for a "0" is -250mV, which is 50mV lower than the output from a saturated ACY20. $I_{a(OFF)}$ is therefore 14 microamperes. With these currents, R_b max is 137,000 ohms, a nominal value of 130,000 ohms. The gate is therefore stable with the standard "0" level input. If fewer than five inputs are used, even lower minimum values for the "0" level are permissible. The single-input gate can tolerate a "0" level as low as -0.96V. In various prototype developments non-standard logic levels were used temporarily, with a single-input NOR gate used as a standardising element. A single input NOR gate is also used as a logical inverter and a buffer amplifier.

The worst transistor ON conditions are determined by

(i) The least number of inputs (= 1)

(ii) The maximum input voltage for a "1" (-6V)

(iii) The minimum base-emitter voltage

$(V_{be(ON)}$ min = -380mV)

(iv) The worst minimum of leakage current

$(I_{co}$, assume = 0)

(v) The maximum input voltage for a "0"

$(V_{"0"}$ max = -0.25V)

(vi) The maximum value of current through R_b, namely

$$I_p \text{ max} = (V_{BB} - V_{BE(ON)} \text{ min}) / R_b \text{ min} \qquad (B.8)$$

$$= 0.13\text{mA}$$

Thus

$$I_a(ON) \text{ min} = I_p \text{ max} + I_B \text{ max} + 4\,(V_{"0"} \text{ max} - V_{BE(ON)} \text{ min})/R_a \qquad (B.9)$$

where I_b max = I_c max / h_{FE} min

$= V_{cc}/(h_{FE}$ min. R_c min)

= 0.28mA (B.10)

The last term represents the current passing through the other four inputs which are grounded. The current represented by this last term is 0.15mA

$\therefore$ $I_{a\ (ON)}$ min = 0.83mA

$\therefore$ R_a max = $(V_{BE(ON)}$ min - $V_{"1"\ max})/\ I_{a(ON)}$ min

= 10,300 ohms

$\therefore$ R_a = 10,000 ohms.

This completes the analysis of the ON and OFF states of the transistor in the NOR gate. All that remains to be done is the analysis of the transition between the two states. Since "worst-case" design has been used, the minimum drive current to the transistor is that which is just sufficient to cause saturation (the minimum overdrive factor is 1). Assuming the worst values of all parameters except the current gain, the overdrive factor for a best ACY21 (h_{FE} = 250) is 5.5. If the other parameters also reach their best limit, the overdrive factor will be even higher. The average overdrive factor for an ACY20 will be about 2, corresponding to a rise time improvement factor of 4, and a rise time of about 2 microseconds. This represents a possible ambiguity in time which is rather large compared with the shortest pulse lengths used in the system. Consequently 220pF speed-up capacitors were added. These make available a minimum charge of 1300pC to provide temporary overdrive at the beginning of the pulse. There is also a charge of 1300pC available at the end of the pulse to remove the minority charge from the base, with a consequent decrease in fall and storage times.

The influence of the speed-up capacitor is shown in the following table (B.3).

INFLUENCE OF SPEED-UP CAPACITOR ON SWITCHING SPEED.

VALUE OF SPEED-UP CAPACITOR	0	220	250	470 pF
RISE TIME	4	2	1	0.7 μs
FALL TIME	7.5	4	1.5	1 μs

If the speed-up capacitor is 470 pF or greater, the charge transferred on switching off is sufficient to temporarily (for about 3 μs) switch off a transistor which is otherwise saturated by the current from another input. With a 250 pF capacitor there is occasionally a 0,5V "spike" at the collector but with 220 pF there is no detectable switching transient.

The NOR gate is constructed, like the other logic elements, on plug-in printed circuit matrix board. The standard board contains two four-input and two three-input NOR gates.

B.4. ADDITIONAL DIGITAL LOGIC ELEMENTS.

Although all logical functions can be performed by a suitable combination of NOR gates it was found more economical to provide some additional logic elements. These will now be described briefly.

B.4.1. FLIP-FLOP. (FIGURE B.2).

The basic binary storage element is shown in Figure B.2. The standard card contains four flip-flops, each equivalent to two single input NOR gates. They can be SET by applying a positive pulse or level to the S input or a negative pulse or level to the R input. The positive pulse is provided by the pulse gate (Figure B.3). The standard binary counter is obtained by connecting a pair of pulse gates to the flip-flop, with pulse inputs in parallel (forming the trigger input) and the level inputs connected to the appropriate collectors. When the flip-flop is used as a level-controlled SET/RESET element the inputs are applied through 10,000 ohm base resistors.

B.4.2. PULSE GATE. (FIGURE B.3).

The pulse gate provides a positive output pulse to switch off a transistor when a positive-going step is applied to the capacitor <u>and</u> a "0" is present at the level input. No output is obtained when the level input is "1" or when a negative-going step is present. The gate therefore makes available, under the control of the level input, a timing pulse from the standard time-defining positive-going step.

B.4.3. MONOSTABLE MULTIVIBRATOR. (FIGURE B.4).

This element is also based on a pair of NOR gates, with the unnecessary input network removed. Thetiming resistor (R) and capacitor (C) which produce the appropriate delay time (≈ 0.7 CR) are external to the board. R is often a variable resistor in series with a fixed current limiting resistor.

Normally triggering is provided by a positive-going step applied to the capacitor. The differentiated pulse cuts off the first transistor and for the duration of the delay a "1" is available from the D output. The complementary output is available at $\bar{D}$. A negative going step cannot trigger the delay unit because it merely drives the first transistor further into saturation. If the negative-going step arrived during the unstable part of the cycle, it could prematurely terminate the cycle. No such negative-going trigger steps appear in the equipment, but to allow flexibility, the direct base connection (B) has been made available. A pulse gate connected to this input triggers the delay unit only when a positive-going step <u>and</u> a "0" level are present at the gate inputs, thus eliminating the possibility of false triggering.

B.4.4. SCHMITT LIMITER. (FIGURE B.5).

The Schmitt limiter is used in the signal processing unit to limit the bi-directional receiver video output to the desired binary signal. It is used elsewhere in the equipment as a pulse shaping circuit.

B.4.5. 48V PULSE AMPLIFIER. (FIGURE B.6).

This inverting voltage amplifier converts a standard -12V level or pulse to the complementary -48V level or pulse. It is also used to generate the 48V positive pulse required for triggering associated valve-operated equipment. The minimum permissible collector load resistance is 3,200 ohms. The closest standard value of resistance is 3,900 ohms.

B.4.6. PULSE CONVERTER. (FIGURE B.7).

This element supplements the 48V voltage amplifier in that it converts a positive-going 48V step with any mean value, to a positive-going 12V step starting at -12V. The subsequent exponential decay time depends on the resistance connected to the output, but this variability is of no significance.

B.4.7. EXCLUSIVE OR CIRCUIT. (FIGURE B.8).

This circuit performs the logical function

$$\overline{\text{OUT}} = (\text{IN 1 } \underline{\text{OR}} \text{ IN 2}) \ \underline{\text{BUT}} \ \underline{\text{NOT}} \ (\text{IN 1 } \underline{\text{AND}} \text{ IN 2})$$

$$= (\text{IN 1 } \underline{\text{AND NOT}} \text{ IN 2}) \ \underline{\text{OR}} \ (\underline{\text{NOT}} \text{ IN 1 } \underline{\text{AND}} \text{ IN 2})$$

i.e. $\text{OUT} = \overline{\text{IN 1} \cdot \overline{\text{IN 2}} + \overline{\text{IN 1}} \cdot \text{IN 2}}$

$$= (\overline{\text{IN 1}} + \text{IN 2}).(\text{IN 1} + \overline{\text{IN 2}})$$

This function is required for the parity check operation in the paper tape punch drive unit.

The EXCLUSIVE-OR function based on the basic NOR element is most uneconomical and this circuit, using both emitters and bases of the transistors is preferable.

B.4.8. EMITTER FOLLOWER. (FIGURE B.9).

The emitter follower is a non-inverting amplifier, in contrast to the NOR gate.

B.4.9. DIODE LIMITER. (FIGURE B.10).

The diode limiter is used before a Schmitt limiter if the input is likely to exceed the ratings of the first transistor in the Schmitt limiter. The output is limited to 1.2V peak-to-peak.

B.4.10. DIODE CLAMP. (FIGURE B.11).

The clamp reduces any negative input level or pulse of less than -12V to a standard level or pulse of -12V.

B.4.11. THE POWER FLIP-FLOP. (FIGURE B.12).

This circuit was designed to perform the functions of a flip-flop, but have adequate voltage and current ratings to drive an electromechanical element. For economy only one power transistor (ASZ16/OC29) is used and the design is similar to that of the basic flip-flop. Standard pulse gate inputs (S and L) are used to turn ON the power transistor. However a standard pulse gate driven from a standard logic element cannot provide sufficient charge to turn the power transistor OFF. Consequently a non-standard (reversed polarity) pulse gate is used to switch the ACY21 ON, switching the ASZ16 OFF. Inputs to either base are also available for additional SET/REST functions.

B.4.12. SOLENOID DRIVER. (FIGURE B.13).

This element is used to drive the solenoid motors of the uniselectors in the height gate generator unit. Two transistors connected in parallel act as current amplifiers for the solenoid. An ACY17 is adequate in low duty cycle operation but in some applications, the power dissipation is excessive. The second transistor, an ASZ16/OC29, has been added to cope with high duty cycle operation. This type of operation arises in the present equipment only when a uniselector is homing. A damping diode is connected across the solenoid.

APPENDIX C. SIGNAL PROCESSING UNIT. (FIGURE C.1).

This unit, like the receivers, contains three independent signal channels, with common control circuits. Channel A will be used as an example in the following discussion, and the corresponding signals in the other two channels are indicated by substituting "B" or "C" for "A" in the abbreviations of Figure C.1.

The receiver output voltage, V_A, can reach 70V peak-to-peak, so that it must first be limited by the diode limiter (LIM). The resulting limited waveform ($\overline{A}$) only has a peak-to-peak amplitude of about 1V so that some amplification is necessary. A NOR gate is modified to act as an amplifier and also provide the necessary d.c. shift for input to the Schmitt limiter. The modification is quite simple - the emitter is disconnected from ground and taken to a potentiometer so that the emitter potential can be altered slightly to centre the collector voltage on the mean input level for the Schmitt limiter. The output (A) from the modified NOR gate is shaped by the Schmitt limiter (SCH) to the standard (-12V, 0V) levels. A single-input NOR gate is used as a buffer amplifier. Its output ($\overline{A}$) and the inverted height gate pulse ($\overline{HG}$) are fed to a NOR gate whose output is therefore A.HG. The latter digit is applied to the S terminals of a flip-flop. The "1" output of the flip-flop is $\overline{A.HG}$. if digit A was present, i.e. the input waveform V_A was negative. The flip-flop is reset by the transmitter trigger pulse (TO). Except for the short time between the TO and HG pulses, $\overline{A.HG}$. is applied to the RC integrating network as long as the input (V_A) is negative. The output of the integrating network is roughly limited about its mean value by a 6V zener diode and a NOR gate. The output of the signal processing unit comprises three d.c. levels representing the average (over the integration time) of A.HG, B.HG and C.HG.

Two NOR gates are connected to act as phase meters for use in the phase calibration of the receiving system.

APPENDIX D.

PAPER TAPE PUNCH DRIVE UNIT. (FIGURE D.1).

The punch drive unit comprises three main parts:

(i) The punch buffer register where the three d.c. levels (A.HG, B.HG and C.HG) from the signal processing unit are sampled and stored.

(ii) The program pulse generator provides pulses which sample the input levels, set the parity bit and start the punching cycle.

(iii) The parity check unit produces a "1" parity check level if there is an even number of incoming "0" signal levels, maintaining the required (odd) parity on the paper tape.

The punch buffer register consists of one power flip-flop for each of the eight tape channels. Only the 1, 2, 4, and C channels are used at present. The input d.c. levels, A.HG, B.HG and C.HG are applied to the level inputs of the 1, 2, and 4 (respectively) power flip-flops. The STORE pulse from the program pulse generator sets the flip-flop if the relevant level (L) is at ground. Holes are therefore punched on the 1, 2, and 4 tracks of the tape if A.HG = 0, B.HG = 0 or C.HG = 0 respectively, i.e. if the respective receiver outputs were positive for the duration of the STORE pulse.

When the bits have been stored in the buffer register and the interposer solenoids energised the parity check unit provides the appropriate level to the level input of the parity check power flip-flop (C). The power flip-flops are relatively slow speed circuits, the rise times being about 100 microseconds, so that during this interval spurious pulses are emitted by the parity check unit. The program pulse generator delays the PUNCH pulse for 0.5 milliseconds to allow the power flip-flops to settle. Diodes are connected across each interposer solenoid to absorb the energy released by the magnetic field when the power transistor is switched OFF.

The program pulse generator is driven by a 50 c/s tuning fork. The simple harmonic output of the fork amplifier is limited to a square wave by a Schmitt limiter which is followed by a NOR gate buffer amplifier. The frequency is then divided in a four-stage binary counter which uses flip-flop and pulse gate elements. The output of the counter chain is a 3.125 sec^{-1} square wave. The square wave is applied through a NOR gate to the SET terminal of the punch control flip-flop, a power flip-flop modified to use a -12V supply to the power transistor.

The NOR gate is used as a pulse mixer so that punching can also be controlled externally. The 3.125 sec^{-1} square wave switches ON the power transistor producing a positive-going step at the "O" output. The positive step sets both the digit flip-flops of the buffer register and the monostable multivibrator with a delay of 0.5 milliseconds to allow the parity check output to reach its final state. The trailing edge of the delay pulse sets the check bit flip-flop and the punch clutch flip-flop. The parity check interposer and the punch clutch are energised simultaneously and the character representing the receiver outputs is punched on the tape.

The punching cycle proceeds and one of the cams available on the punch is used to signal the end of the punching operation. The cam opens at 60° on the punching cycle, providing a negative-going step which resets the punch control flip-flop. The corresponding negative-going step at the flip-flop output resets the punch buffer register.

APPENDIX E.

HEIGHT GATE GENERATOR. (FIGURE E.1.)

This unit provides height gate pulses every 4 km up to 128 km. The 37.5 kc sec^{-1} oscillator is triggered by the +50V transmitter trigger pulse which is converted to a standard 12V pulse by the pulse converter stage (PC), and then delayed by the adjustable (20 to 250 microseconds) delay multivibrator (MONO) to allow for the built in transmitter delay, time base starting time delay cable propagation times, and oscillator transient phase shift.

The trailing edge of the first delay multivibrator output triggers a second delay (3ms) multivibrator whose output gates ON the 37.5 kc sec^{-1} sinewave oscillator (Lambert 1963). The oscillator output is turned into a square wave by the succeeding Schmitt limiter (SCH) and NOR gate. The trailing edge of the first delay multivibrator output is inverted by a NOR gate and resets a counter control flip-flop which opens a NOR gate to allow the 37.5 kc sec^{-1} square wave to pass through to the binary counter stages (5 flip-flops).

The five-stage binary counter thus indicates the time delay (in units of 26.7 microseconds) equivalent to the virtual height of the received signal, in 4 km steps up to a maximum of 128 km. The output is decoded by a resistor matrix which has outputs ($\overline{T1}$ - $\overline{T32}$) which are at a level of -12V unless the counter contains the output appropriate to that time. The last output level ($\overline{T32}$) is amplified by an emitter folower, inverted by a NOR gate and sets the counter control flip-flop so that the counter retains a count of 32(= 0) until the next transmitter trigger pulse.

The required height level is selected by a uniselector which is driven by a solenoid driver (SD) and controlled by conventional homing circuits (not shown). The selected output is amplified by an emitter-follower, inverted by a NOR gate and then changed to a +50V pulse, 4 km wide, by the voltage amplifier (VA) or to a -12V pulse, nominally 1 km wide, by a delay multivibrator.

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