SOLAR AND SIDEREAL DAILY VARIATIONS OF THE COSMIC RAY INTENSITY OBSERVED UNDERGROUND

A THESIS

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ABSTRACT

By making observations at a moderate depth underground, it has been possible to monitor the intensity time variations of the primary cosmic ray particles with energies of the order of 100 GeV during the period of minimum solar activity.

At the Holborn Underground Laboratory (51° $32'$N, depth 60 m.w.e.) the secondary muon flux has been detected with vertical, semi-cubic, scintillator telescopes (area 3 m^2, counting rate 50,000/hour) and with cubical telescopes inclined at 45° to the zenith, pointing due east and north (areas of 4.5 m^2 in each direction, counting rates 35,000/hour).

The day-to-day intensity changes were largely of meteorological origin, being well correlated with barometric pressure, upper air temperature and height of the 100 mb pressure level. The corresponding regression coefficients were found to be independent of telescope direction within the limits of statistical uncertainty, and it is shown that either no changes are expected on the basis of the physical processes underlying the atmospheric effects or the changes are too small to be detected by correlation analysis.

No seasonal intensity wave was observed which could be unambiguously interpreted as a primary variation. Seasonally, the pressure-corrected intensity was under the control of the upper air temperature.

The solar diurnal wave observed by vertical telescopes from November 1960 to the middle of 1964 had a time of maximum near 14 hours and an amplitude of 0.018%; the phase reversed to about 06 hours from the middle of 1964 to the middle of 1966. The early time of maximum was independently

confirmed by the east and north-pointing telescopes from October 1964. Later data indicate that from the middle of 1966 the phase is slowly recovering to later times of maxima. The changes are interpreted as a reduction in the upper limiting rigidity of the "corotation" solar anisotropy to such low values ($\simeq$70 GV) that the Compton-Getting effect due to the orbital motion of the earth became observable.

The atmospheric contribution to solar diurnal wave was found to be less than 0.02%.

The solar semi-diurnal wave exhibited no significant changes in amplitude or phase during the period November 1960 to September 1966.

The apparent sidereal wave observed by the vertical telescopes from November 1960 showed no significant changes during the solar minimum period. The apparent sidereal wave observed by the north-pointing telescopes was similar to those observed by vertical and east-pointing telescopes. This necessarily casts doubt on the interpretation of the apparent sidereal wave in terms of a galactic anisotropy.

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

The primary cosmic radiation may be considered as a means of carrying "information" from remote regions of the Galaxy to the vicinity of the earth. This information may be, for instance, the chemical composition or the energy spectrum of the cosmic radiation. This is analagous to the case of the optical and radio radiation received at the earth which give insight into the astrophysical processes involved in their generation and propagation. In the same way, the "information" carried by the primary cosmic rays tells us of the generation, acceleration and propagation processes involved.

Impinging on the atmosphere, the primary cosmic radiation quickly undergoes interaction with target nucleons present in the nuclei of gases such as oxygen and nitrogen. This produces a flux of secondary particles, e.g.

$$P + N \longrightarrow \pi^- + P + P$$

Since the primary particles, mainly protons, have energies up to 10^{19} to 10^{20} eV, they have provided a source of particles far in excess in energy of those produced by man (up to 3.10^{10} eV). Hence, the flux of secondary particles through the atmosphere has been used to identify hitherto unknown particles, e.g. the observation of the π meson predicted by Yukawa in 1935.

The "information" which is of prime importance in this thesis is that

of the time variations exhibited by the secondary particles observed at a depth of 60 m.w.e. In particular, we are concerned with the observation and interpretation of the solar and sidereal daily variations. This problem cannot be treated in isolation from other aspects of the cosmic rays and for this reason there follows a short discussion under the headings:-

(a) The Differential Energy Spectrum.

(b) The Chemical Composition.

(c) Geomagnetic Effects.

(d) Atmospheric Effects.

Where possible the relevance to the Holborn observations will be pointed out.

1.2 The Differential Energy Spectrum of Primary Cosmic Rays

Primary cosmic rays store vast amounts of kinetic energy and their spectrum covers a huge range of at least 12 orders of magnitude, i.e. from about 0.1 GeV/nucleon to about 10^{11} GeV/nucleon. Over most of this energy range the differential energy spectrum may be represented by a simple power law, viz $\frac{dJ(E)}{dR} = K_A E^{-\gamma}$ where J(E) is the intensity of particles per cm^2 - sterad - sec., E is the energy and K_A and γ are constants. K_A determines the differing absolute intensities of the chemical components of the primary flux; γ, the slope of the spectrum, is independent of Z the nuclear charge (Waddington, 1960).

However, γ is not independent of energy having a value of -2.6 for $10^{10} < E < 10^{15}$ eV; $\gamma \simeq -3.2$ for $10^{16} < E < 10^{18}$ eV; $\gamma \simeq -2.6$ again for $E > 10^{18}$ eV. The measurements above 10^{15} eV are of low statistical weight

and the γ values cannot be considered as final, but there does seem evidence for a change of γ with energy.

Below an energy of about 10 GeV, the power law relation does not hold and, in fact, the spectrum shows a peak at about 2 GeV. This peak varies with the solar cycle and is interpreted as being due mostly to solar modulation of the galactic spectrum. The changes of the differential spectrum for the different nuclei provides a means of studying the 11 year cycle of modulation. Courtier and Linney (1966) suggest that such modulation was present at the last solar minimum (1965) and that cosmic rays generated on the sun interfere with these measurements, especially at solar minimum. The sun, at times of powerful flares, can generate cosmic rays with energies up to several tens of GeV. Hence, there is overlapping of the galactic and solar spectra. Much more frequently, the sun generates low energy particles ranging from tens to hundreds of MeV.

In the range of primary energies producing most of the muons which are observed underground at Holborn (about 70 to 1000 GeV), the differential spectrum is well described by a simple power law with an exponent $\gamma = -2.6$. It is not thought that the sun generates particles of these high energies.

1.3 The Chemical Composition of Primary Cosmic Rays

Virtually all primary cosmic rays are nucleonic and of these, 85 to 90% are protons. The absolute intensities vary with the solar cycle and are approximately 0.2 proton/cm^2 - sterad. - sec; 0.03 α's/cm^2 - sterad. - sec; 0.003 nucleons with $z \geq 2$/cm^2-sterad. - sec. These measurements are for total intensities near solar minimum.

Of more importance are the relative abundances and their comparison with the cosmic abundances. Waddington (1960) shows that for measurement at Texas, i.e. for intensities above a rigidity of 4.5 GV, the cosmic radiation is relatively poor in light elements compared to the Universe in general.

If we classify the nuclei according to:-

GROUP	Z
L	3-5
M	6-9
H	10-20
VH	20-28

then the L group shows a small but finite intensity ($2 \pm .2$ m^{-2} - sterad.$^{-1}$ - sec.$^{-1}$) compared with an almost complete absence on a universal scale. M-nuclei ($5.6 \pm .2$ m^{-2} - sterad.$^{-1}$-sec.$^{-1}$) and H nuclei ($1.88 \pm .3$ m^{-2} - sterad.$^{-1}$ - sec.$^{-1}$) are both about five times more plentiful in cosmic rays than in the cosmic abundance. Finally, VH nuclei ($.69 \pm .16$ m^{-2} - sterad.$^{-1}$ - sec.$^{-1}$) are about 30 times more plentiful in cosmic rays, most nuclei in this range being Fe. The observed limit to Z is about 40.

A possible interpretation of the presence of L nuclei is that of fragmentation of VH nuclei (especially Fe) in traversing about 3 - 4 gms./cm.^{2} of material in interstellar space. This tends to be confirmed by the observed ratio of $He^3/(He^3 + He^4)$ of about 0.1 to 0.3 for kinetic energies of 100 to 400 MeV/nucleon. This represents a relatively high content of He^3 which <u>may</u> be interpreted as being due to fragmentation of cosmic rays in traversing about 3 - 7 gms./cm.^{2} of matter.

The above results cannot be considered final since most measurements were made at balloon altitudes with emulsion stacks. This means the results must be extrapolated back to the top of the atmosphere and the effect of "splash" albedo removed. Nonetheless, direct measurements by satellite-borne detectors (e.g. Comstock et al 1965) show general agreement with balloon results.

Since 1961 there has been direct evidence of primary cosmic electrons. Earl (1961) obtained a value of 32 ± 10 electrons/cm.^{2} - sterad. - sec. for $E > 0.5$ GeV. At the moment, electrons produced by interactions of the positive primaries with interstellar gas would appear to fit the observed differential spectrum (Simnett 1966). Other sources such as the sun cannot be ruled out, however.

Several discrete X-ray sources have now been discovered (e.g. McCracken 1965) which appear to coincide with sources of optical emission.

One discrete γ-ray source has been discovered by Duthie et al (1966) and obviously this awaits confirmation.

As yet, there is no experimental evidence of neutrinos in the primary cosmic ray flux. Similarly, antiparticles have not yet been observed down to a measuring limit of about 1% of the primary flux.

From the above, it can be seen that the primary particles responsible for the secondaries observed at Holborn are virtually all positively charged nuclei and of these about 85 - 90% are protons. As such, they undergo deflection in the geomagnetic field and this is described in the next section.

1.4 Geomagnetic Effects on Cosmic Rays

After analysing for a particular time-variation, we wish to know what

spatial anisotropy this corresponds to external to the geomagnetic field.

In the first approximation, the geomagnetic field may be considered as that due to a centred dipole of magnetic moment 8.1×10^{25} gauss-cm^3.

Störmer (1930) showed that in a dipole field there are allowed and forbidden regions close to the earth for a particle of given rigidity. This means that particles below a so-called "cut-off" rigidity cannot reach the earth with a given direction of arrival. This theory predicts an East-West asymmetry which was first observed by Johnson and Street (1933). It also gave the latitude dependence of the vertical cut-off rigidity as,

$$R_{min.} = 15 \cos^4 (\lambda) \text{ GV}$$

where λ is the geomagnetic latitude.

Latitude surveys of the cosmic ray intensity enabled the differential rigidity spectrum to be estimated and confirmed that the primary cosmic rays were indeed positively charged particles.

Lemaitre and Vallarta (1933) demonstrated the effect of the solid, finite earth, i.e. the "shadow" effect. From all this work using a centred dipole representation of the geomagnetic field, it appears that the sky can be divided into four regions where, for a given rigidity,

(a) All particles are forbidden (Störmer cone).

(b) All particles are allowed (Main cone).

(c) Particles are forbidden although allowed by the main cone (Shadow cone).

(d) Some arrival directions are allowed and some are not (Penumbral region).

Störmer's theory showed discrepancies with experiment (e.g. Rose et

al 1956) which were only slightly reduced by the use of an eccentric dipole field. Quenby and Webber (1959) introduced non-dipole components to the geomagnetic field to calculate much improved cut-off rigidities, and even further improvement was obtained by including penumbral effects (Quenby and Wenk 1962).

To calculate asymptotic directions of approach, model experiments have been performed. This involves observing electron orbits around a magnetised sphere (terrella) simulating the earth's magnetic field. Brunberg and Dattner (1953) have published a set of diagrams showing asymptotic directions obtained in such experiments. These results are limited in that only a simple dipole field is used and suffer from the difficulty of obtaining a very narrow beam of electrons in only a small rigidity range.

The best calculations of trajectories and cut-off rigidities have been made by numerical integration of orbits in the geomagnetic field represented by its first six spherical harmonics, e.g. McCracken (1962).

Comparisons of the Brunberg-Dattner results with some numerical integrations for Holborn show agreement within a few degrees in the range of rigidities of interest (70 - 1000 GV). Because of this, and the fact that numerical integration takes much costly computer time, the asymptotic directions have been taken from the relevant Brunberg-Dattner diagrams for Holborn. A typical easterly deflection would be 15^{o} for vertical incidence of a 100 GV particle.

Finally, it is to be noted that although the geomagnetic field may reduce the amplitude of any external cosmic ray variation by "smearing out" the viewing directions of detectors, it cannot by itself cause a spurious

variation. This is a consequence of Liouville's Theorem which states that the particle density in phase space is constant. Since the scalar magnitude of the particle momentum is a constant of the motion in a constant magnetic field, it follows that the differential directional intensity is constant along the trajectory. Hence, if a given trajectory is allowed, then the intensity observed at the detector will be the same as that at infinity. Therefore, the origins of the diurnal waves observed by the Holborn detectors are not associated with the geomagnetic field. Since time variations of the geomagnetic field have negligible effect on the relatively high energy particles observed at Holborn, these too cannot generate the observed diurnal waves.

1.5 The Atmospheric Effects on Cosmic Rays

A primary proton (E $\sim$100 GeV) undergoes nuclear interaction on impinging on the atmosphere with a typical path length of 60 - 70 gm.-cm.$^{-2}$. The resulting disintegration causes the emission of many energetic pions ($\sim$10) and several nucleons, often including one which has most of the initial energy. All are well collimated with the direction of incidence of the primary particle due to the relativistic energies involved.

The pions decay thus:-

$$\pi^{\pm} \longrightarrow \mu^{\pm} + \nu \quad \tau \simeq 2.6.10^{-8} \text{ sec.}$$

$$\pi^{0} \longrightarrow 2\gamma \quad \tau \simeq 10^{-16} \text{ sec.}$$

or interact to give further nucleons and pions. The nucleons emitted in the first interaction cause further interactions and so there is a nucleon cascade development through the atmosphere. The absorption path length for

nucleons is about 120 gm.- cm.$^{-2}$ due to this regenerative process.

The photons caused by π^0 decay can undergo pair production:-

$$\gamma \longrightarrow e^+ + e^-$$

The positrons can then produce more photons by annihilation and hence photon-electron cascades start. This is one way of obtaining the soft component (mostly electrons at s/l); this cannot penetrate to a depth of 60 m.w.e. and so does not contribute to the Holborn counting rate.

The pion production is at maximum at about 100 - 200 gm. - cm.$^{-2}$ atmospheric depth; in this region, decay of pions takes place more rapidly than interaction. Therefore, most pions decay to give a muon intensity which is at maximum in the same region.

Muons are weakly interacting and unstable with a lifetime, $\tau \simeq 2.2.10^{-6}$ sec., much longer than that of pions. Ionization loss ($\simeq$2.2 MeV/gm. - cm.$^{-2}$) slows the muons and therefore increases their probability of decay before reaching s/l. Slow muons and electrons from muon decay constitute another part of the soft component at s/l. Only those muons of energy $E \gtrsim 15$ GeV at production can penetrate to 60 m.w.e. depth underground. These constitute the vast majority of particles observed at this depth since the soft component at s/l is filtered out by only another 150 gm. - cm.$^{-2}$ of material. The s/l nucleon component suffers energy degradation in strong interactions with subsequent loss to the underground flux.

In general, we can describe the i th component of the directional intensity of secondaries by:-

$$N^i_{\lambda,\eta}(h_o, \theta, \varphi) = \int_{\varepsilon_{min.}}^{\infty} D(\varepsilon).m^i(\varepsilon, h_o).\, d\varepsilon \qquad .....1.1$$

where λ = Latitude of the observation point.

η = Longitude of the observation point.

θ = Zenith angle.

φ = Azimuthal angle.

h_o = Atmospheric pressure at the observation point.

$D(\mathcal{E})$ = Differential energy spectrum of primaries.

$m^i(\mathcal{E}, h_o)$ = Multiplicity.

$\mathcal{E}_{min.}$ = Geomagnetic threshold.

This assumes $D(\mathcal{E})$ is isotropic beyond the atmosphere, considers only the proton contribution to the primary flux and neglects the dependence on direction of arrival.

Allowing the variables in equation 1.1 to change by small amounts, we get

$$\frac{\delta N}{N} = -W^i_{\lambda,\eta}\ \delta\mathcal{E}_{min.} + \int_{\mathcal{E}_{min.}}^{\infty} \frac{\delta D(\mathcal{E})}{D(\mathcal{E})} \cdot W^i_{\lambda\eta}\ d\mathcal{E} + \int_{\mathcal{E}_{min.}}^{\infty} \frac{\delta m}{m} . W^i_{\lambda\eta}\ d\mathcal{E} \qquad \ldots\ldots\ldots 1.2$$

where $W^i_{\lambda,\eta} = \dfrac{D(\mathcal{E}).\ m^i(\mathcal{E}, h_o)}{N^i_{\lambda,\eta}(h_o)}$

The first term of equation 1.2 represents the effect of variations of the geomagnetic threshold; this may be ignored for the case of Holborn where the effective lower energy cut-off is due to absorption.

The second term represents the time variation of the primary cosmic rays. $\dfrac{\delta D(\mathcal{E})}{D(\mathcal{E})}$ is the energy spectrum of the primary variation and is the function we wish to investigate for the daily variation.

The third term represents the meteorological variations which obviously require detailed knowledge of the multiplicity to calculate theoretically.

This is discussed more fully in Chapter 3.

W^i, the "coupling coefficient", also requires m^i to be known. W^i is essential for the calculation of $\frac{\delta D(\mathcal{E})}{D(\mathcal{E})}$. Unfortunately, there is, as yet, no adequate theory for strong interactions; direct measurements of cross-sections and angular distributions etc. only extend up to machine energies of about 30 GeV. Hence, to obtain W^i for Holborn requires some other technique. For a sea-level neutron monitor or meson detector, it is relatively easy to conduct a latitude survey and compare the change in counting rate with latitude to that predicted by geomagnetic theory. This gives the percentage contribution to the counting rate in small rigidity ranges, i.e. W^i. Obviously this requires accurate knowledge of out-off rigidities, good long-term instrumental stability and careful correction for meteorological variations. Above the maximum cut-off rigidity of about 15 GV, extrapolation is performed using a formula which essentially asserts that the multiplicity increases exponentially with energy, i.e. the prediction of the Fermi and Landau models of nuclear interactions. Webber (1962) has given some results for such surveys for meson and neutron detectors and these have been extended to underground depths by the method of Dorman (1959). This involves the implicit assumption that the processes producing the muons observed at s/l and underground are not very different.

The coupling coefficients plotted against energy or "differential response curves" are shown in Appendix I (along with the relevant formulae) for the Holborn detectors. Comparison of the results for 40 m.w.e. with those obtained semi-theoretically by Fenton (1963) using the Fermi model for the nucleon interactions shows good agreement. Hence, the Dorman method has

been used for 60 m.w.e.

1.6 Results of Past Experiments at Holborn

MacAnuff (1951) in 1949 - 1950 made the first measurements of the solar daily variation at Holborn. Using three trays of closely packed geiger tubes to form a wide-angle telescope, he found a diurnal wave of amplitude 0.04% with a time of maximum at 14 hours L.Sol.T. This being for the declining phase of solar activity. His results were of low statistical weight but showed that if a solar daily variation was present at Holborn, it had an amplitude of 0.05% or less.

Mathews (1962) during November 1960 to October 1961 repeated MacAnuff's measurements using semi-cubical scintillator telescopes of total counting rate 50,000/hour. These operated in the vertical direction and showed a solar first harmonic of $0.025 \pm 0.011\%$ with $T_{max.} = 15.0 \pm 1.5$ hours L.Sol.T; again this is for the declining phase of solar activity. Dutt (1965) repeated the same measurements with the same equipment from November 1961 to October 1962; he obtained the same results within the limits of statistical error. With three times the counting rate, the vertical measurements were carried on during August 1963 - July 1964, again with the same results. Hence, the data were averaged between 1960 and 1964 to give a mean solar diurnal wave of amplitude $0.018 \pm 0.004\%$ with $T_{max.} = 13.6 \pm 0.8$ hours.

Similarly, the second harmonics were insignificantly different for the same yearly periods; the mean for the whole period was $0.014 \pm 0.004\%$ with the time of the first maximum at 1.5 ± 1 hours.

The apparent sidereal variation had only a significant first harmonic from 1960 to 1964 and again this was constant over this period with a mean amplitude of $0.015 \pm 0.004\%$ and $T_{max.} = 19.4 \pm 1$ hours L.Sid.T.

The results in the form of means for the period November 1960 to July 1964 are summarised in Table 1.1; the errors quoted are those due to Poissonian fluctuations only. The sidereal variation is corrected for seasonal modulation of the solar diurnal wave.

TABLE 1.1

SOLAR TIME				SIDEREAL TIME	
A_1 (%)	T_1 (Hrs.)	A_2 (%)	T_2 (Hrs.)	A_1 (%)	T_1 (Hrs.)
0.018 ± 0.004	13.6 ± 0.8	0.014 ± 0.004	1.8 ± 0.8	0.027 ± 0.006	19.4 ± 1

1.7 Aim of the Present Experiment

The above measurements are statistically significant but the errors quoted consider only the Poissonian fluctuations, i.e. the errors are calculated from the counting rates. Instrumental and atmospheric fluctuations may increase the observed error; more important, the variability of the daily variation itself will tend to increase the statistical error. The errors observed from the scatter of the results are, in fact, about 1.5 times those calculated on the basis of the counting rate (see Chapter 2, section 2.4.1). Part of this work is a re-appraisal of the significance of the results obtained so far.

Besides this, it is not clear what part is played by regular atmospheric

oscillations. For instance, Dutt (1965) finds that all of the observed solar diurnal wave may be explained by a stratospheric temperature oscillation of only 1.2°C.

For these reasons, it was decided to continue the vertical measurements to improve the statistics and to see if there was any appreciable change in results for the solar minimum period. At the same time, measurements by cubical telescopes inclined at 45° to the zenith were made in the east and north directions. Having similar responses, it was thought that both sets of inclined telescopes would react in the same way to daily atmospheric variations, but that only the East telescopes would observe an appreciable daily variation due to anisotropies external to the geomagnetic field. This is because the north-pointing telescopes "look" in a nearly fixed direction of space and therefore mostly observe the daily variation caused by the atmosphere. Using this "crossed telescope" technique, it was hoped to eliminate atmospheric effects and estimate the daily variations due only to cosmic ray anisotropies.

It was hoped to get the best estimates of the meteorological effects during the solar minimum period due to the low level of solar-induced cosmic ray intensity variations.

With knowledge of the atmospheric component and a re-appraisal of the statistical errors, it was hoped to test the sidereal results to see if a consistent picture emerged for the whole period 1960 to 1966.

CHAPTER 2

INSTRUMENTAL AND ANALYTICAL TECHNIQUES

2.1 General Instrumental Requirements

The simplest way to monitor the primary cosmic rays of energy $\sim$100 GeV is to detect the secondary muon flux penetrating to moderate depths underground. We require an efficient muon detector which is reliable and has good long-term stability. In the following, we outline the experimental requirements which virtually determine the choice of detector, then describe the apparatus used, and finally describe the performance and characteristics of this apparatus.

2.1.1. Counting Rate

The minimum expected sidereal diurnal amplitude can be calculated on the basis of an assumed isotropy of cosmic rays in the local system of stars. The local motion of the sun then causes a sidereal effect of about 0.02% (see Chapter 7, section 7.5.3).

Taking the yearly statistical error on the diurnal amplitudes to be 0.013% for a counting rate of about 50,000 per hour (see section 2.4.1), then 0.02% should be observable with such a statistical error after two to three years. A convenient laboratory at 60 m.w.e. depth was available; at this depth the maximum response is to primary energies of about 100 GeV, and is therefore suitable for this experiment. At such a depth, a total counting area of about $3m^2$ is required to obtain a counting rate of 50,000/hour.

2.1.2 Long-Term Stability

As part of the experiment, we wish to study the change of counting rate with season and solar cycle. It is not yet clear how large these effects are and so we require as great a stability as possible. A minimum condition is that the change in counting rate over the period of a day should be much less than the diurnal wave amplitude. Since the latter is about 0.02%, we require a stability better than, say, 0.005%/day, i.e. about 2% per year.

2.1.3 Reliability

Since the apparatus is operated at a remote position, absolute reliability is required. As a general rule, the Underground Laboratory was visited twice per week. Hence the need for reliability made the use of transistors a necessity. The further advantages of low heat dissipation and greater stability compared to valves were also useful. However, transistors are more sensitive to supply voltage and temperature variations, and also have a large spread in characteristics. Hence, care was taken at certain stages to select transistors for particular applications. The electronic circuits were designed for minimum temperature coefficient, while several stages of smoothing were used to eliminate the effect of supply voltage fluctuations.

As a general rule, scintillator counters have greater reliability than geiger counters, as well as having a longer lifetime. Hence, the former were favoured.

2.1.4 Instrumental Temperature Coefficients

The photomultipliers and transistorised electronics used with a scintillation counting system are liable to be temperature sensitive. However, the diurnal laboratory temperature wave was less than about 0.25°C. Since the observed solar daily variation is less than 0.05% (MacAnuff 1951), we require an instrumental temperature coefficient of less than about 0.02% per °C.

2.1.5 Directional Sensitivity

The purpose of the experiment was to compare the diurnal waves obtained by two sets of telescopes, equally inclined to the zenith, pointing due North and East. The North telescopes were to point in a nearly fixed direction in space and therefore a narrow cone of acceptance was required consistent with a sufficient counting rate for adequate statistical accuracy (i.e. about 0.01%/year for the daily harmonics). This need for directional sensitivity eliminated the use of ionization chambers. Cerenkov detectors would also have been rather bulky for inclination within the limitations of the tube tunnel size.

From the above considerations, transistorised scintillator detectors seemed the most obvious choice. Detection of the scintillations by photomultipliers operated in coincidence enabled the required opening angle to be obtained and helped in the discrimination between cosmic rays and natural background radioactivity. Since the detectors do define a certain opening angle, they will be called telescopes although no "magnification" is involved.



PLATE 2.1



PLATE 2.2 - GENERAL VIEW OF AN INCLINED TELESCOPE

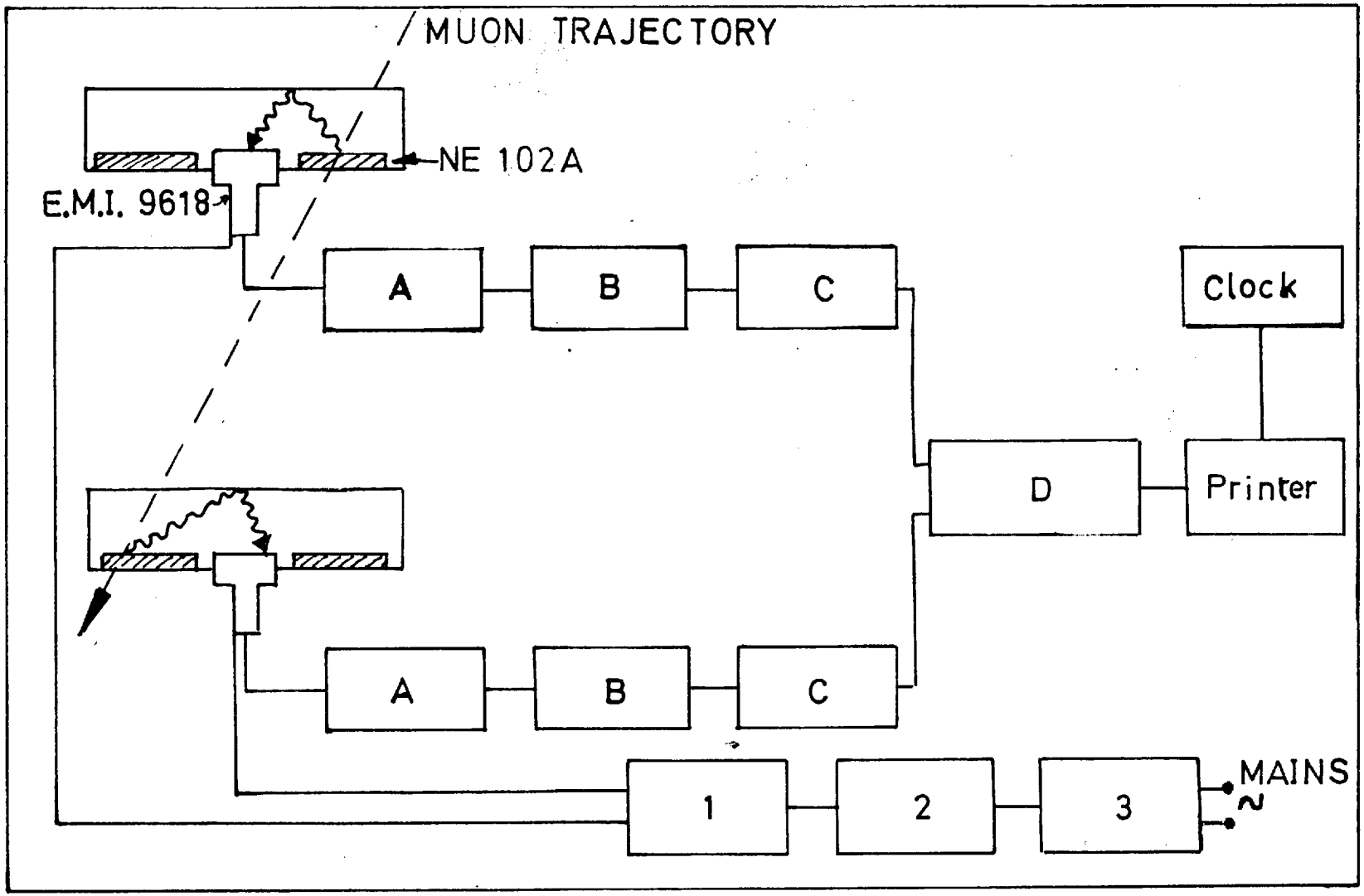


FIG. 2.1 BLOCK DIAGRAM OF A TYPICAL TELESCOPE. A - AMPLIFIER: B - PULSE HEIGHT LIMITER: C - DISCRIMINATOR: D - COINCIDENCE/SCALER UNIT: 1 - E.H.T. STABILISER: 2 - CONSTANT VOLTAGE TRANSFORMER: 3 - SERVOMEX STABILISER.

2.2 Description of the Scintillator Telescopes

The design of a scintillator telescope revolves around the problems of production, transmission and detection of the scintillation light pulses. For light production, we have used commercially supplied plastic scintillator slabs of dimension 2' x 2' x 1"; four of these slabs being contained in one light-tight box. Transmission of the light is by diffuse reflection from the darvic-lined boxes (darvic is a white, highly reflecting plastic material). The initial detection of the light pulses is by a photomultiplier tube, situated at the centre of the box, as shown in Plate 2.1. Fig. 2.1 is a block diagram of a complete telescope; it will be convenient to discuss the design under separate headings, covering the main points above:-

2.2.1 The Plastic Scintillators

These are slabs of polyvinyl toluene in which an organic scintillator, p-terphenyl, is dissolved. They are type NE102A supplied by Nuclear Enterprises Limited. Their light output is about 65% of that of anthracene under the same experimental conditions. The decay constant is $2.2 \cdot 10^{-9}$ sec. and is therefore more than adequate for achieving fast resolving times. The slabs were coated with white reflector paint on the edges only. Transparency to their own radiation is about 70%. This radiation had a wavelength of about 3800 Å for maximum emission. This was transferred to about 4250 Å by the presence of a wavelength shifter "Popop". Thus it was possible to match the output wavelength to the wavelength of maximum detection efficiency for the photomultiplier tubes used.

2.2.2 Light Transmission

With a scintillating area of about 1.5 m^2 per box, it is not possible to have direct light coupling to the 5" diameter photomultiplier tubes. Instead, one relies on diffuse reflection within the darvic-lined boxes. The box dimensions of 54" x 54" x 17" are relatively large compared to the light-collecting surface (about $4\frac{1}{2}$" diameter). Therefore, it is possible for there to be a big disparity between the light collection efficiences for light pulses emitted near the centre of the box and pulses emitted close to the edge. As a measure of this effect, Dutt (1965) monitored the photomultiplier dark current while a small tungsten lamp was moved to different positions within the box. The current fell by only 30% when the source was moved from the centre to the extreme corner of the box. Hence, the collection efficiency was found to be reasonably uniform with this sort of arrangement.

In practice, the minimum threshold of the discriminator following the photomultiplier was about 150 mV. The gain of the scintillation/transmission/photomultiplier system was adjusted until all muons passing through the edges of the scintillator slabs were being recorded. The adjustment was made varying the E.H.T. supplied to the photomultiplier.

2.2.3 The Photomultiplier Tubes (P.M. Tubes)

We require P.M. tubes with large sensitive areas and low noise characteristics. E.M.I. type 9618 were selected as covering these requirements as well as being "fast" for coincidence counting. These tubes are of 5" nominal diameter with a semi-transparent photo-cathode made of Sb-Cs-O (S11).

The 11 dynodes are coated with Cs Sb and have the venetian blind type of construction.

Typical photo-cathode sensitivities were 70-80μA/L with a dark current of about 20-30 mμA at 1500 V. As a test of the P.M. tubes and the light-tightness of the boxes, the anode currents were measured at an E.H.T. supply voltage of 2000 V. At this voltage, the anode current was required to be 1μA or less. Since the anode current fell exponentially with supply voltage, this corresponded to a dark current of only 30 mμA at the operating voltage near 1500 V. This procedure made certain that:-

(i) The boxes were light-tight.

(ii) The signal was superimposed on a minimum background current level.

(iii) Changes in the dark current with time could not affect the biasing current through the dynode resistor chain (since the latter was about 150μA).

The supply voltages to the dynodes were supplied by the chain of resistors shown in Fig. 2.2. The later stages were not de-coupled so that some space charge limiting occurred. This effectively reduced the range of pulse heights obtained and was therefore desirable from the electronic point of view.

The P.M. tubes were matched in pairs by the Manufacturers so that each pair had the same gain at the same operating voltage of about 1500 V. This allowed the use of only one E.H.T. power supply for each telescope.

The output pulses from the anode of the P.M. tube had a range starting from about 200 mV and rising to several volts. The time spread on the pulses

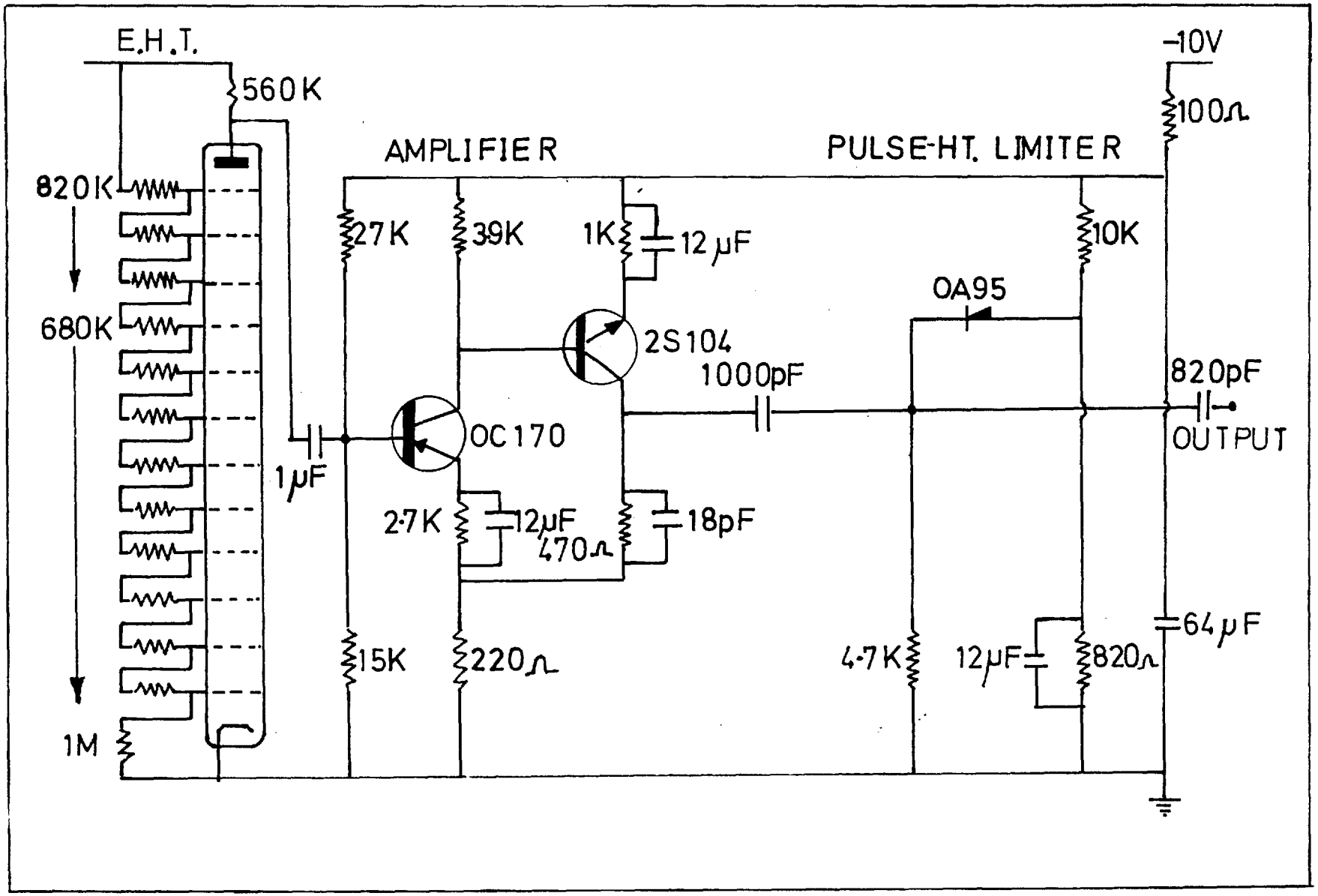


FIG. 2.2 CIRCUIT FOR INITIAL PROCESSING OF P.M. TUBE PULSES.

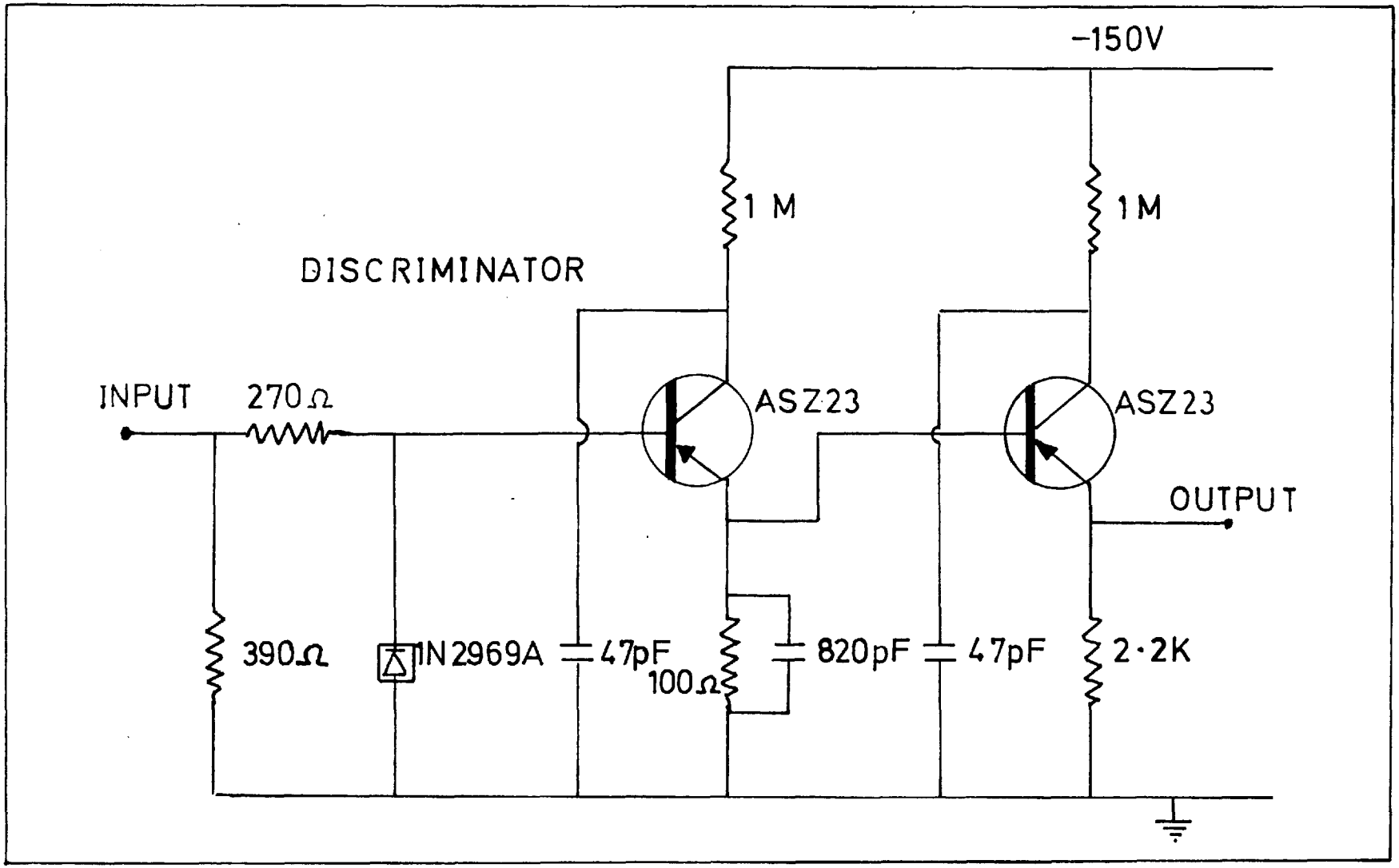


FIG. 2.3 CONTINUATION OF FIG. 2.2.

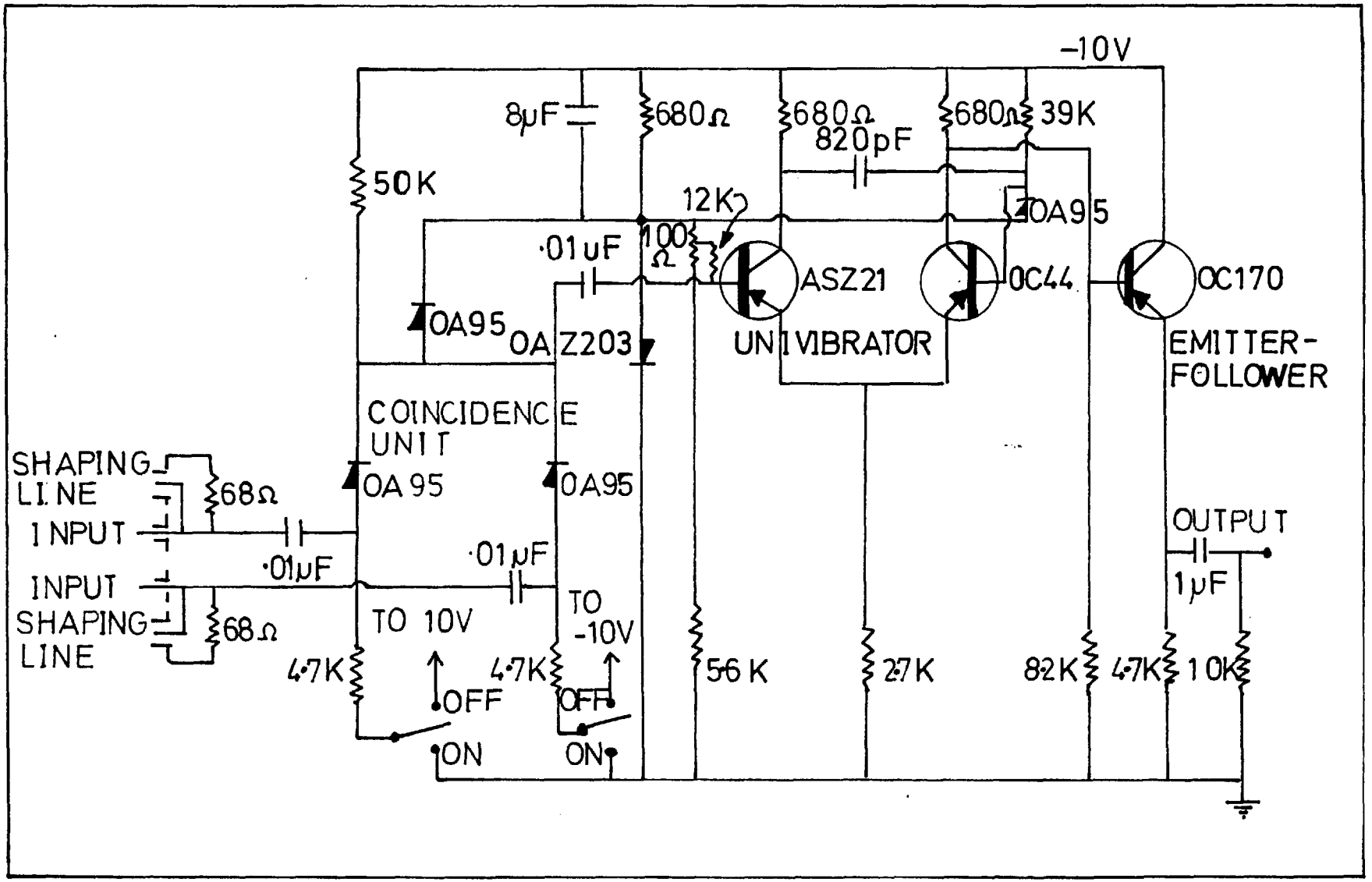


FIG. 2.4 THE CIRCUIT DIAGRAM OF THE COINCIDENCE UNIT, THE UNIVIBRATOR AND THE EMITTER-FOLLOWER.

was about 25.10^{-9} secs. and hence suitable for coincidence counting with a similar resolving time.

2.2.4 The Electronics

The Figs. 2.2 and 2.3 are circuit diagrams of the electronics associated with the initial processing of pulses from the P.M. tubes. The first stage of amplification acts as a buffer between the high output impedance of the P.M. tube and the low input impedance of the pulse height limiter and discriminator circuits. The amplifier has a gain of about x3 and employs negative feedback for stability against L.T. and temperature changes. After amplification, the pulses are clipped in a pulse height limiter to a maximum of about 1 V.

Pulses of less than 150 mV amplitude are effectively removed by a discriminator which does not "fire" below this level. This removes many of the smaller noise pulses. The discriminator uses a tunnel diode, which is very stable against temperature changes, to provide a very sharp pulse to initiate the current flow through two avalanche transistors, ASZ 23. These provide the current at a low output impedance to feed a 6 8 ohm coaxial cable. Thus we get pulses that are independent of temperature, having fairly constant amplitude (4V) with small width (30.10^{-9} secs.) and sufficient power to be transmitted along reasonable lengths of coaxial cable.

The output pulses are then fed to the coincidence units (Fig. 2.4) after "squaring" of the pulses by a shaping line. This doubles the width of the pulse with, therefore, some increase of resolving time. However, the "squaring" of the pulses provides for a more uniform input to the coincidence

unit, allowing it to give more reproducible results. The basic coincidence circuit requires two pulses of amplitude 1V to make the diodes conducting so that the univibrator switches states. A single pulse of 1V amplitude does not switch the state of the univibrator. An emitter follower matches the coincidence unit output impedance to the impedance of the coaxial cable leading to the recording system.

As a test of the coincidence unit, a telescope was operated with black cloth over the P.M. tubes. The chance coincidence counting rate was then observed; from the known singles rate from each tube (N_1 and N_2) it was possible to calculate the resolving time (τ) from:-

$$N_{CHANCE} = 2 \cdot N_1 \cdot N_2 \cdot \tau \qquad \ldots\ldots 2.1$$

This calculation gave $\tau \simeq 70.10^{-9}$ secs. which is comparable to the width of the pulses fed to the coincidence unit. Thus, the coincidence unit rejects most of the single counting rate due to background radioactivity, e.g. the singles counting rates were about 10,000/min. at the operating voltage, while the coincidence rate was about 400/min. The chance counting rate is, by equation 2.1,

$$N_{CHANCE} = 2 \cdot 10^4 \cdot 10^4 \cdot 60^{-1} \cdot 70 \cdot 10^{-9}$$

$$\simeq 0.2/\text{min.}$$

This represents a negligible contribution of only 0.05% to the total counting rate.

2.2.5 The Recording System

The univibrator of Fig. 2.4 provided square pulses of width greater than 6 μsecs. These pulses were capable of operating 2 Venner decade units

in series; thus the coincidence counting rate was scaled by a factor 100. The scaled output was made to operate relays which in turn operated electro-mechanical counters. The counters were made to print hourly by means of contacts mounted on a spring-operated clock.

The main requirements for the recording system were that it should count with 100% accuracy and be reliable. The former was relatively easy to achieve since the counting rates were low and the pulses to be counted rather long. To obtain reliability, all components were grossly overrated with regard to power dissipation. In fact, this technique was applied to all the electronics to aid reliability and to reduce the drifts in counting rate due to changes of circuit parameters.

2.2.6 The Power Supplies

The initial stage of mains smoothing was by means of a Servomex stabiliser. This reduced A.C. mains voltage fluctuations of 10% to less than 0.25%. Its long-term stability was about 1 or 2 volts per year, while short-term it greatly reduced the effect of supply fluctuations due to the daily peak demands.

The smoothed output from the Servomex unit was taken to a saturated core transformer. Since the Servomex stabiliser had a time constant of several seconds, it could not eliminate "spikes" or sudden troughs in the supply voltage. However, these are removed by the saturated core transformer.

To obtain the supply voltages for the P.M. tubes, Philips voltage stabilisers type PW4024/01 were used. For a 10% change in supply voltage to this unit the output voltage changed by less than 0.05%. As an example, we can imagine the mains supply to the Servomex stabiliser to decrease by 10 V

due, say, to increased load during the period of peak demand. This results in a variation of about 0.25 V applied to the constant voltage transformer; the transformer output changes by about 0.02 V (1% output change for a 15% input voltage variation). The resultant change in the voltage applied to P.M. tube is only 0.00075 volts. This causes a change of gain of about 0.0035%; hence, even in the most extreme case, we have eliminated the effect of A.C. mains variations.

The stability of the E.H.T. supply against temperature variations was better than 0.02%/°C. Since the diurnal temperature wave in the laboratory was less than 0.25°C the E.H.T. diurnal wave was 0.075 V, at most. The counting rate/voltage characteristics (described in section 2.3) show this to correspond to a maximum diurnal amplitude in coincidence counts of only 0.006%. Hence, this is small compared to the observed solar daily variations.

The L.T. supply was provided by a Venner unit type TS20 operated from the saturated core transformer. The 10 V stabilised output had a 50 c/sec. ripple of only 1 mV or less; this was insufficient to interfere with the operation of the transistor pulse circuits.

2.3 Performance and Characteristics of the Telescopes

The initial setting up of the telescopes involved the establishment of the plateau in the counting rate/voltage characteristic. A single counter tray of a telescope increased its counting rate with increase of E.H.T. without evidence of a plateau. This simply corresponds to an increasing efficiency of the scintillator/P.M. tube combination for detection of the natural background radioactivity. When the telescope counter trays were

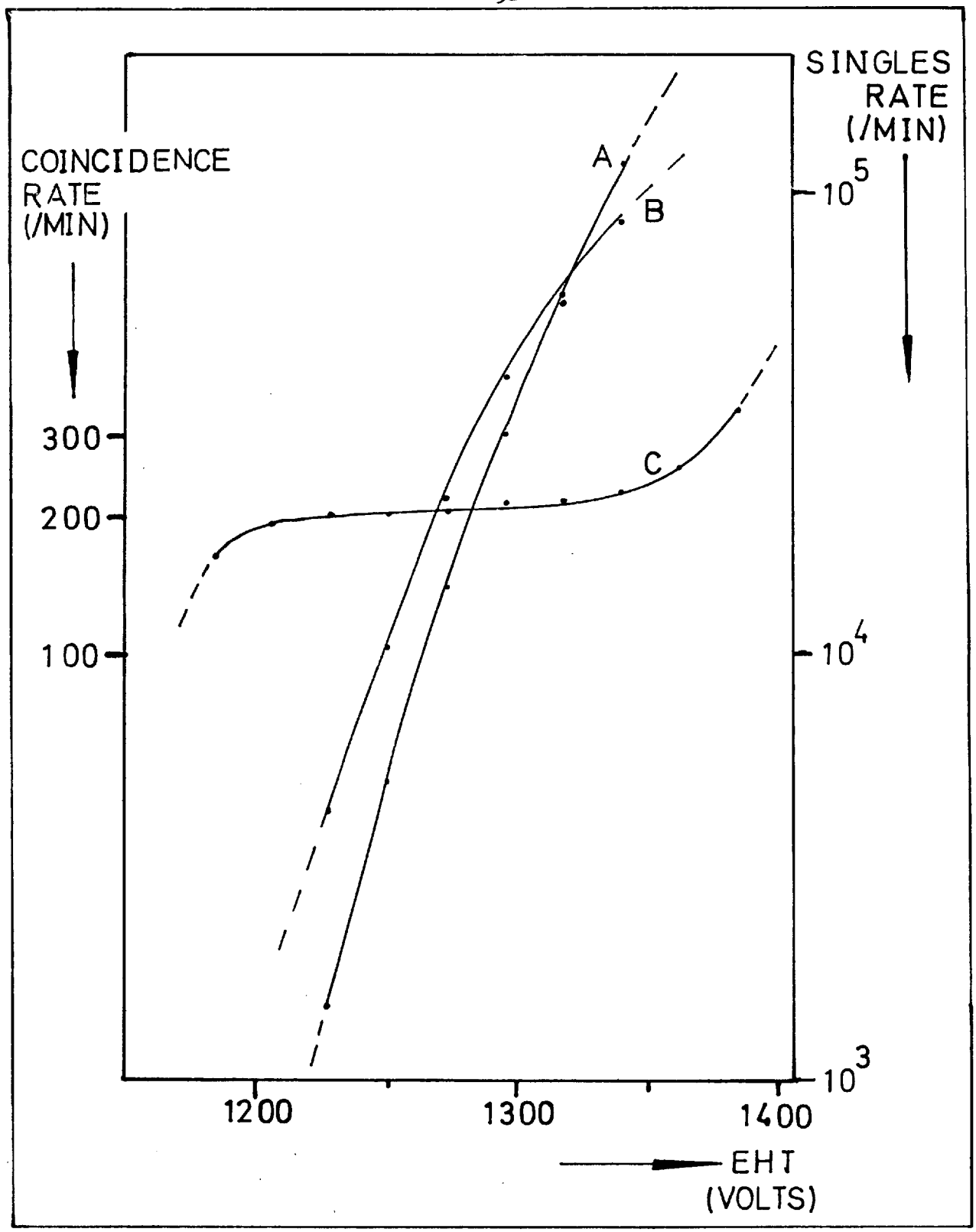


FIG. 2.5 SINGLE AND COINCIDENCE COUNTING RATES FOR A TYPICAL TELESCOPE.
A, B - SINGLES RATES
C - COINCIDENCE RATE

operated in coincidence and the E.H.T. increased, there was a relatively sudden increase in counting rate at about 1500 V (see Fig. 2.5). Beyond this voltage the counting rate increased only slowly (0.8%/10 V), indicating that in this plateau region the cosmic ray intensity was being adequately detected. The finite slope of the plateau was attributed to the increasing chance counting rate and the increasing efficiency for detection of the background γ-ray intensity.

After a plateau region extending about 80 V the counting rate increased rapidly with E.H.T. Again, this was most probably due to increased γ-ray detection, increased chance coincidence rate and possibly other spurious pulsing effects in the P.M. tubes due to application of too large a voltage.

The setting-up procedure was as follows:-

(i) Make sure the single counting rates were nearly equal at about 10,000/min., if necessary placing a resistor in series with the dynode resistor chain to reduce the P.M. tube gain. Care was taken to adequately de-couple this resistor.

(ii) Adjust the coincidence discriminator setting for maximum rejection of the single particle counting rate consistent with efficient counting of the coincidence rate.

(iii) With this discriminator setting, obtain the coincidence rate/E.H.T. characteristic and set the E.H.T. to the mid-point of the plateau.

For directional sensitivity, the telescopes were inclined at 45° to the zenith with a near cubical arrangement. Taking the secondary intensity

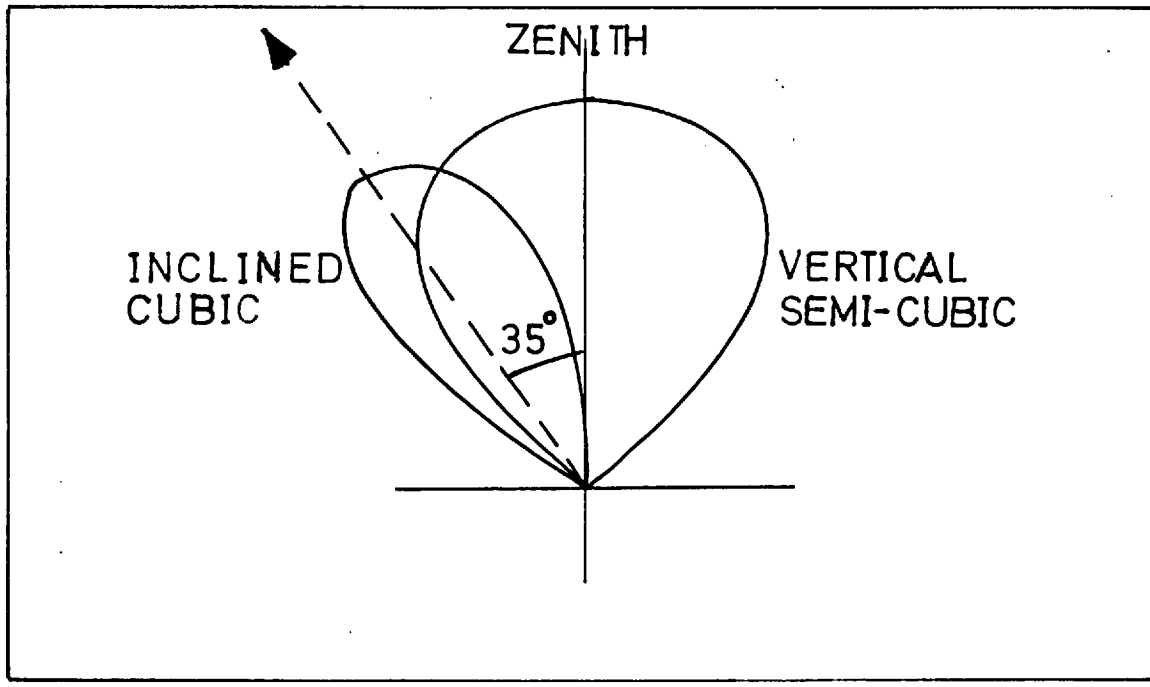


FIG. 2.6a SENSITIVITY PATTERNS FOR VERTICAL AND INCLINED TELESCOPES.

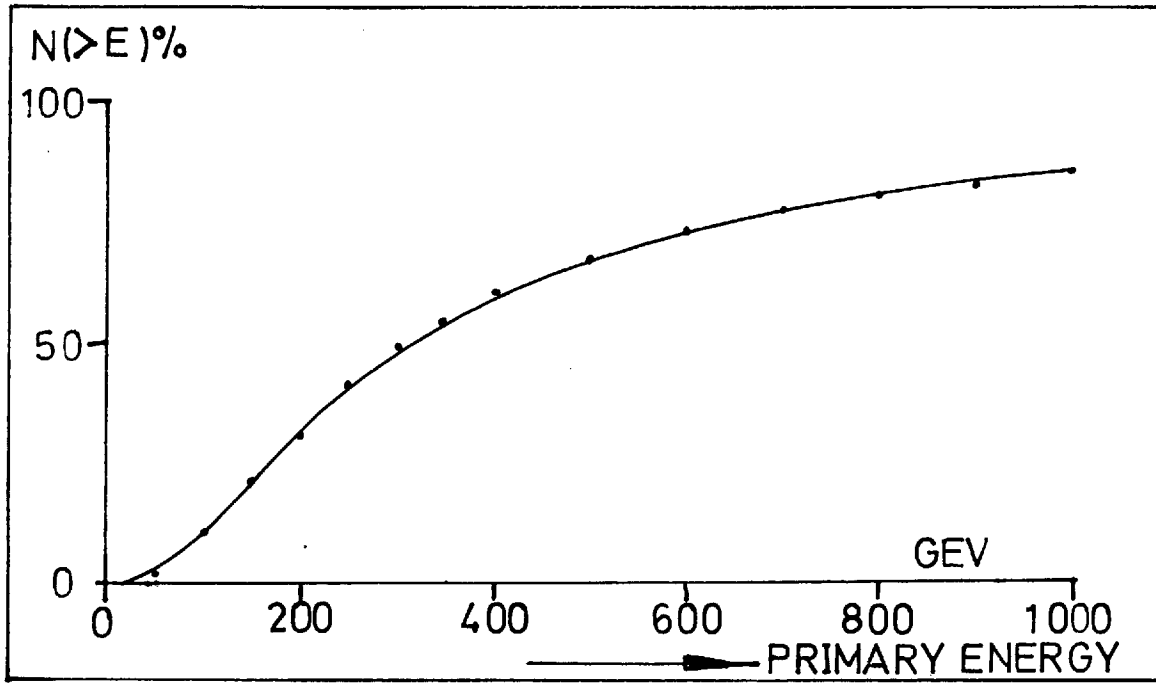


FIG. 2.6b INTEGRAL COUNTING RATE SPECTRUM FOR THE VERTICAL, SEMI-CUBIC TELESCOPES AT 60 M.W.E.

to decrease as $\cos^2 \lambda$ with zenith angle λ (George 1952), we can calculate the directional sensitivity patterns. These are shown in Fig. 2.6a; the peak responses are normalised to 100% and are at 0° and 35° for vertical and inclined telescopes respectively. In these directions, the main cones of acceptance of the telescopes intercepted the ground level in the Kingsway road rather than nearby buildings. Hence, the absorber above the detectors was composed of (a) the clay overburden, (b) the atmosphere and (c) people and traffic. The latter exhibited a daily variation and is considered further in Chapter 5, section 5.3.

Using the differential response functions derived in Appendix I, we can calculate the relative contributions to the counting rate from particles of different energy. Fig. 2.6b is a plot of counting rate (in percent) due to particles of energy greater than E against E. The median energy is about 300 GeV.

In operation, the reliability of the telescopes was limited by the electro-mechanical counters. In the two-year period October 1965 to September 1966, 90% of all possible data was obtained, most data being lost due to a failure of the clock (20 days) and a shut-down of the two older, vertical telescopes for transistorizing the electronics (40 days). Only one electronic failure occurred and this was a transistor supplying the power to drive pulses along a coaxial cable. Replacement of the transistor cured the fault. Although the dynode chains used high stability resistors, two failures occurred here. Presumably these correspond to the normal failure rate under these experimental conditions, in which case the rate is 1%/25,000 hours for $\frac{1}{2}$W resistors dissipating 0.2W.

The D.C. stabilised supplies were very satisfactory, only one L.T. unit developing a fault. The D.C. voltages were regularly checked.

The best check on the stability of the individual telescopes was the parallelism between pairs of recorders. The variations in the uncorrected counting rates were mostly due to atmospheric effects; since the telescopes all "view" through virtually the same section of the atmosphere, their counting rates are well correlated, with correlation coefficients of 0.95 to 0.99. This high degree of correlation indicates the short-term stability. Long-term stability was monitored by calculating the ratios of counting rates from different telescopes. From these ratios it was established that all telescopes were slowly decreasing in counting rate. The average rate was about 0.5%/year, and did not seem to be directly connected with the solar cycle. No doubt part of the decrease for the two older telescopes was due to "yellowing" of the white paint on the scintillator slabs (these older slabs were painted on all edges and the lower side). This could not be true of the scintillator slabs in the six newer telescopes since they are painted only on the edges and, by visual inspection, were not seen to be yellowing themselves. The fact that all counting rates were decreasing suggested a general loss of efficiency which might possibly be associated with ageing of the photocathode and/or dynode surfaces of the P.M. tubes.

2.4 Analytical Techniques

In common with other geophysical problems, we are concerned with establishing the presence or absence of periodicities in a time series of equidistant data points. In this case, we are concerned with 12 and 24-hour periodicities of the underground muon intensity in solar and sidereal time.

By the Fourier theory, any continuous function $\psi(t)$ is best fitted by the infinite trignometrical series:-

$$\psi(t) = a_0 + \sum_{n=1}^{\infty} [a_n \cos(nt) + b_n \sin(nt)] \quad \ldots \quad 2.2$$

where

$$\left.\begin{aligned} a_0 &= \frac{1}{2\pi}\int_0^{2\pi} \psi(t)\,dt \\ a_n &= \frac{1}{\pi}\int_0^{2\pi} \psi(t)\cos(nt)\,dt \\ b_n &= \frac{1}{\pi}\int_0^{2\pi} \psi(t)\sin(nt)\,dt \end{aligned}\right\} \quad \ldots\ldots\ldots 2.3$$

(See Chapman and Bartels, 1940).

In the practical case, a finite set of trignometrical functions may be used to approximate the given function to any degree of accuracy. Usually, only the first few harmonics give a good fit to $\psi(t)$. In our case, the 12 and 24-hour periodicities are to be fitted to the data, which is in the form of 12 bi-hourly counting rates. To fit 12 data points rather than the continuous function $\psi(t)$ the integrals of equation 2.4 become summations, viz:-

$$\left.\begin{aligned} a_0 &= \frac{1}{12}\sum_{i=1}^{12} y_i \\ a_n &= \frac{1}{6}\sum_{i=1}^{12} y_i \cos(nt_i) \\ b_n &= \frac{1}{6}\sum_{i=1}^{12} y_i \sin(nt_i) \end{aligned}\right\} \quad \ldots\ldots\ldots 2.4$$

where y_i are the data points.

Strictly speaking, the harmonic amplitudes should be corrected for the influence of smoothing, since each data point is the average of two hours data rather than an instantaneous measurement. However, the corrections are only about 1% and 5% of the diurnal and semi-diurnal amplitudes respectively. These

corrections were negligible compared to the statistical errors of about 30 to 50% and, hence, were not applied.

The harmonic coefficients a_n and b_n are most easily represented on harmonic dials where (a_n, b_n) are the co-ordinates of the end-point of the vector representing the wave in phase and amplitude.

Before harmonically analysing, it is desirable to remove non-cyclic variation from the data. In the present case, however, this amounted to only about 0.5%/year and therefore made only a negligible contribution to the daily harmonic coefficients.

More important is the estimation of errors on the harmonic amplitudes, and this is described in the next section.

2.4.1 Errors of Measurement on the Harmonic Amplitudes

As far as is possible, systematic errors have been eliminated by the design of the telescopes.

Experimentally small errors arise from (i) the finite coincidence time and (ii) the dead time of the electro-mechanical counters during the printing action. For (i) the spurious counting rate was shown in section 2.2.4 to be only 0.03% of the mean counting rate and was, therefore, negligible. For (ii), the printer dead time was about 0.2 secs. and with a scaled counting rate of 0.1/sec. this represented a loss of only 0.004% and again was ignored.

The more important contribution to the errors comes from the inherent randomness in the data itself. Even if the solar daily variation were constant in time, the harmonic coefficients would still have standard

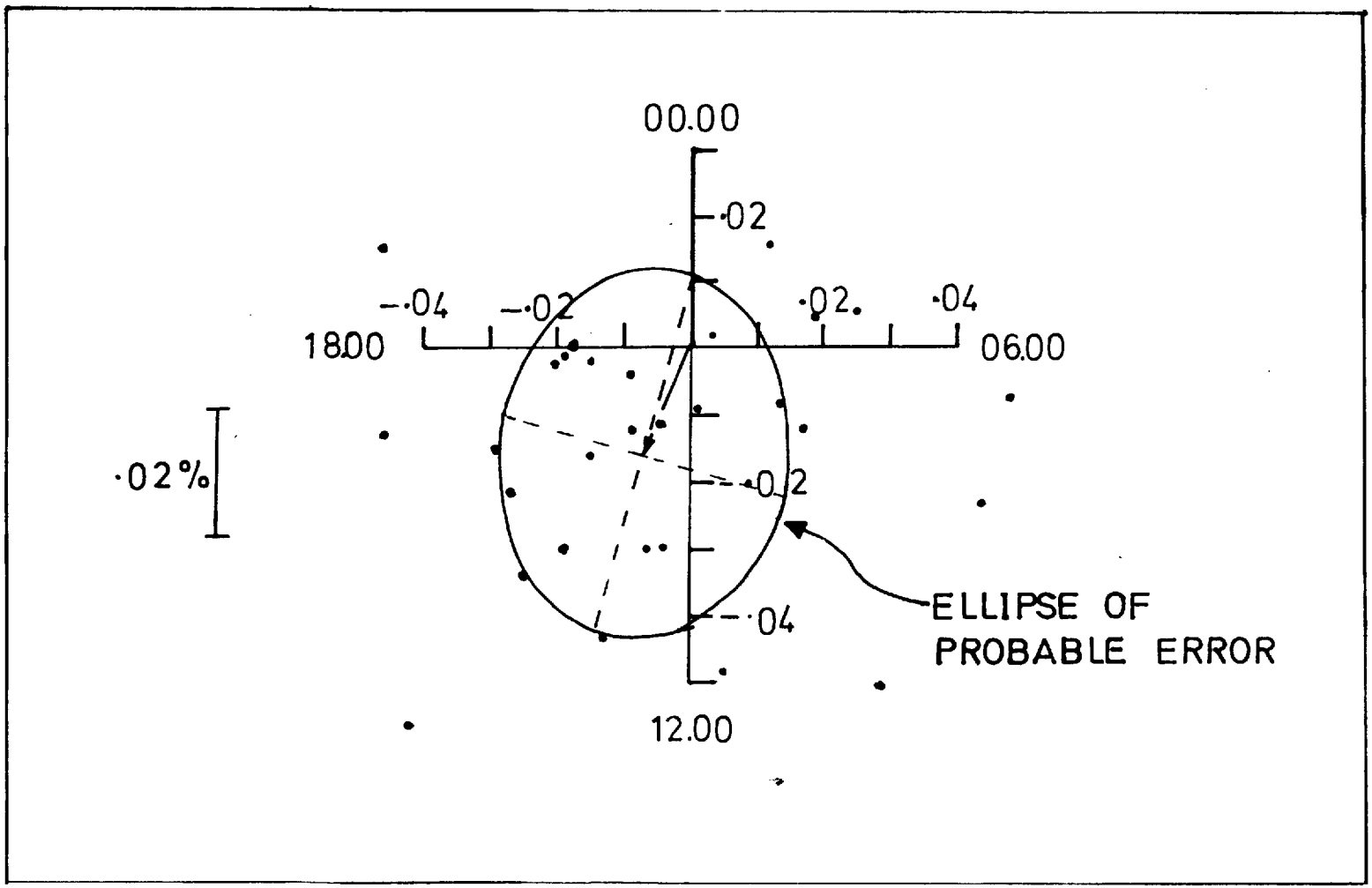


FIG. 2.7 SCATTER DIAGRAM OF THE VERTICAL SOLAR DIURNAL WAVE FOR THE PERIOD NOVEMBER 1960 - JULY 1964.

deviations associated with the Poisson fluctuations. With a counting rate of 50,000/hour, the standard deviation on the diurnal and semi-diurnal amplitudes is 0.007% for a year's data. However, to allow for variability in the solar daily variation, we adopt the experimental point of view and measure the scatter in the harmonic amplitudes on the basis of many individual estimates. For this purpose, the data were split into two groups, viz:-

Group I - Vertical data November 1960 to July 1964.

Group II - East, North and vertical data from October 1964 to September 1966.

Group I Data

The vertical data from November 1960 to October 1962 can be split into monthly batches with counting rates of 50,000/hour. For the yearly period August 1963 to July 1964 we can get, for each month, three independent estimates of the harmonic coefficients, each corresponding to a counting rate of 50,000/hour. Thus we get a total of 60 estimates of the solar daily variation. During this period, the yearly mean solar daily variations were very closely the same (see Chapter 4). Thus, apart from systematic variations caused by a possible daily variation in sidereal time, the separate estimates of the solar harmonics should randomly distribute about the mean for the whole period. To eliminate the sidereal effects, the monthly results were averaged in pairs separated by a gap of six months. Thus, we get 30 estimates of the solar harmonics including variability of the solar daily variation but without systematic variations. Fig. 2.7 is a typical "scatter" diagram showing the end-points of the vectors representing the bi-monthly solar diurnal waves during this period.

The probable error ellipse which best fits the data points does not have much eccentricity. Hence, we can take the R.M.S. deviations in the a and b directions and obtain an approximate two-dimensional error of

$$\sigma = \sqrt{\sigma_a^2 + \sigma_b^2}$$

$$= 0.031\%$$

If we calculate the corresponding standard deviation assuming a Poisson distribution about the mean counting rate, we get $\sigma = 0.017\%$. Presumably the extra contribution does come from variability of the solar daily variation itself. In this thesis, we shall use the standard deviation obtained, as above, from the scatter of the results. In the above example, the probability that the mean of all data is consistent with zero amplitude of the diurnal wave is less than $\frac{1}{2}\%$. Similar results were obtained for the 12-hour wave.

In this form of analysis, the ellipse of probable error is useful since it shows if phase or amplitude variations are more important. For the solar daily variation averaged from November 1960 to July 1964, both amplitude and phase variations were equally important. This is consistent with the initial hypothesis that the mean solar daily variation was constant over this period. If there had been some reduction in amplitude of the diurnal wave, we would have expected a more eccentric ellipse.

Group II Data

From October 1964 the Kew pressure data were available in punched card form. Hence, it was possible to pressure-correct the bi-hourly counting rates for each day and harmonically analyse these without too much time-

consuming labour. In any one month the solar daily variation does not show any appreciable systematic change due, for example, to a sidereal variation. However, the counting rate does vary rapidly during the day due to atmospheric effects. These non-cyclic variations were removed by taking the departure of the bi-hourly pressure-corrected intensity from the daily mean intensity centred on that bi-hourly value. This helped remove the effect of "curvature" and drift in the counting rate.

The scatter of the daily harmonics about the monthly means was averaged for the two-year period October 1964 to September 1966 for vertical, East and North telescopes. Again, the ellipses of probable error were not very eccentric, which is consistent with the solar daily variation not changing appreciably in any one month. The standard deviations on the amplitudes were found to be 0.013% compared to a calculated value of only 0.008% due to Poisson fluctuations. Table 2.1 summarises these results, including those for Group I data.

TABLE 2.1

PERIOD	DIRECTION	COUNTS/HR.	T = 24 HR.			T = 12 HR.
			σ_p (%)	$\sigma_{Scatter}$ (%)	σ_{sc}/σ_p	σ_{sc}/σ_p
Oct.1964-Sept.1966	East	35,000	0.008	0.013	1.6	1.6
Oct.1964-Sept.1966	North	35,000	0.008	0.013	1.6	1.6
Oct.1964-Sept.1966	Vertical	50,000	0.007	0.013	1.9	1.7
Nov.1960-July 1964	Vertical	50,000	0.007	0.012	1.8	1.9

σ_p is the standard deviation calculated on the basis of the counting rate shown for the period of one year. $\sigma_{scatter}$ is the corresponding observed standard deviation.

The results for the two methods of analysis are consistent inasmuch as the vertical data do not give significantly different standard deviations. It is obvious that 0.013% represents a good average of the standard deviation on the harmonic amplitudes for a year's data with a counting rate of $35 \cdot 10^3$ to $50 \cdot 10^3$ per hour.

CHAPTER 3

METEOROLOGICAL EFFECTS UNDERGROUND

3.1 Introduction

If the nuclear processes occurring in the diffusion of secondary particles through the atmosphere were fully understood, it would be possible to remove the effect of atmospheric variations on the secondary flux. Maeda and Wada (1954), Dorman (1957) and others have made such theoretical attempts with some success despite this lack of knowledge on high energy interactions. The main difficulty concerns the attenuation path length of pions since it is known that in pion-nucleon collisions further pions are produced so that the attenuation length (L) may be several times the interaction path length ($\ell \simeq 60$ gm.-cm.$^{-2}$). In fact, Dorman assumes $L = 2.\ell = 120$ gm.-cm.$^{-2}$. Other simplifying assumptions are made, such as the use of a model atmosphere, to reduce the equations to a convenient form. Dorman's final result for the hard component is:-

$$\frac{\delta N}{N} = \beta_p \, \delta P + \int_o^{h_o} W(h) . \delta T(h) \, dh \qquad \ldots\ldots\ldots 3.1$$

where $\frac{\delta N}{N}$ is the fractional change of counting rate.

β_p is the pressure coefficient.

δP is the pressure change.

$W(h)$ is the "density of the temperature coefficient" and gives the intensity change due to a 1°C variation in air temperature at a depth h.

In practice, the integration over the whole atmosphere is replaced by a summation over as much of the atmosphere for which there is data available.

Thus to apply this method to the Holborn results requires frequent, accurate measurements up to at least the 20 mb level since W(h) is still appreciable there. Unfortunately, the balloon ascents from the nearest station (Crawley, some 20 km. due S.W. of London) are only twice daily, do not always reach even the 100 mb level and above this region suffer from insolation errors to the temperature and height measurements. Hence, the "theoretical" method has not been used for correcting the Holborn results for meteorological variations.

The alternative method is to adopt the phenomological approach and describe changes in intensity in terms of atmospheric coefficients, viz:-

$$\frac{\delta I}{I} = \beta_p \delta P + \beta_T \delta T + \beta_H \delta H \quad \ldots\ldots\ldots 3.2$$

where β_p, β_T and β_H are pressure, temperature and height coefficients. δP, δT and δH are corresponding changes in pressure, temperature and height. Physically, this means that processes occurring throughout the atmosphere are well described by atmospheric parameters observed at one level or, at most, averaged over only a small region. This is true only if one or more of the following applies:-

(a) The measured parameter reflects the cumulative effect of the whole atmosphere, e.g. the pressure at a given level is a measure of the mass of air above that level. Therefore, $\beta_p \delta P$ gives the change due to absorption.

(b) The physical process involved occurs only in a small region of the atmosphere, e.g. the produotion of pions and subsequent loss by decay and nuclear interation takes place in about the first 200 gm.-cm^{-2} of the atmosphere. The average temperature in this region should be good enough

to describe the competing processes of decay and capture.

(c) The variations of the parameter used at a particular level are closely correlated with the variations at other levels in the range over which the physical process takes place, e.g. muons energetic enough to be observed at Holborn are produced in about the first 200 gms. cm.$^{-2}$ of the atmosphere where height variations are well correlated. Since the probability of muon survival down to the observation level depends on the distance travelled, it is possible to use the height of the 100 mb level to get an average μ-e decay coefficient, β_H, corresponding to muons produced at a variety of levels.

The above considerations and examples apply to the Holborn measurements and hence, the Duperier-type equation 3.2 was used to get the atmospheric coefficients. Before discussing these results, however, some results of other workers will be considered.

3.2 Results of Other Workers

Myssowsky and Tuwim first observed a barometric effect on the s/1 cosmic ray flux in 1928. Following this, a negative temperature effect was found which was interpreted by Blackett (1938) as being due to the instability of the muon. Duperier in 1949 discovered the positive temperature effect which was interpreted by him as being due to the competing processes of pion decay and capture in the upper atmosphere. These simple explanations did not suffice, largely due to the fact that the observed positive temperature effect is much larger than the theoretical value.

Trefall in a series of papers (1955 a, b and c) showed how the

decay effect contributed to the barometric and positive temperature effects as well as being the cause of the negative temperature effect. His main conclusions were:-

(i) The barometric effect has two major contributions, one being due to pure mass absorption and the other due to μ-e decay probability increasing as the muons lose energy through ionization losses. When this is taken into account, there is agreement between theory and experiment for s/l and underground measurements.

(ii) Other contributions to the positive temperature effect are (a) non-coincidence of the production layer of muons and the chosen reference level, and (b) the change in energy loss distribution and hence survival probability of the muons when the pressure and height remain constant and the temperature varies. These effects increase the positive effect for s/l measurements so that there is fair agreement between theory and experiment.

(iii) Underground only the π-μ decay effectively contributes to the positive effect so that there is simple agreement between MacAnuff's vertical results for 60 m.w.e. and theory. This is true assuming a pion attenuation length of 125 gm. cm.$^{-2}$ and neglects the temperature variations above the 100 mb level. Since the temperature above 100 mb is unreliably known, the agreement may only be fortuitous.

All results from Duperier-type equations suffer from the correlation between the atmospheric variables used. This leads to systematic errors and increased random errors. Because of this, Dorman and others made their

theoretical attempts.

Many workers have compared the different correcting procedures, one of the most recent being that of Carmichael, Bercovitch and Steljes (1965). They expressed changes in the ground level meson monitor rate (δM) in terms of the neutron monitor rate at the same location (Deep River), i.e.

$$\delta M = C_P \delta P + C_N \delta N + C_T \delta T + C_H \delta H \quad \ldots\ldots\ldots\ 3.3$$

δN is the change in primary intensity, assumed proportional to the pressure-corrected neutron intensity. Use of the neutron counting rate eliminated the effect of primary intensity changes. The best results are obtained by using the 100 mb height and the 800 mb temperature as suggested by Mathews (1959). However, it is not clear how significant is the improvement. Similar calculations using Dorman's and Maeda's weighting factors W_T show discrepancies between day-to-day and seasonal results in both cases. To overcome this, the authors use two more terms in the regression equation, one involving the 31-day running average in temperature and the other the 31-day running average in neutron intensity. Then the methods of Dorman, Maeda and Wada appear equally good. The use of running means to remove the discrepancy between day-to-day and seasonal coefficients would again tend to suggest that correlation methods are limited by non-independence of the atmospheric variables. In this case, the correlation between the atmospheric variables would be different day-to-day compared to seasonally to explain the above results.

3.3 Results at Holborn

3.3.1 Day-to-Day Analysis

The Duperier-type equation 3.2 has been applied to East, North and vertical telescopes over the two-year period starting in October 1964. East and North telescopes have counting rates of 35,000 per hour and the vertical telescopes 50,000 per hour.

The use of equation 3.2 was justified in section 3.1; because of this reasoning, the chosen atmospheric variables were:-

(1) Station-level pressure measured hourly at Kew, some 10 kms. from Holborn.

(2) Air temperature averaged between the 200 and 70 mb levels measured on twice daily (00.00 and 12.00 hours G.M.T.) balloon ascents from Crawley, some 40 kms. from Holborn.

(3) Distance between the 1000 and 100 mb levels measured on the Crawley balloon ascents. Use of this distance eliminated the effect of correlation between height and pressure when just the 100 mb height is used. So long as the air temperature remains constant, the distance between the 1000 and 100 mb levels remains constant even though the pressure may change with consequent change of the 100 mb height. This means that the pressure coefficient is the "total" coefficient since it contains a contribution due to μ-e decay effects which occur when the height of atmosphere varies with ground level pressure. Future reference to height in this thesis means the difference between the 1000 and 100 mb heights.

Day-to-day correlation was performed for 24 separate monthly periods

(22 in the vertical direction because of missing data). Use of nearly equal periods enabled the spread of the results to be obtained. This was preferable to calculation of errors from statistical theory since the latter assumes independence of the variables P, T and H, which does not necessarily apply.

A summary of results is given in Table 3.1. Correlation and regression coefficients are r and β respectively.

TABLE 3.1

	PRESSURE		TEMPERATURE		HEIGHT	
	r	β (%/mb)	r	β (%/°C)	r	β (%/km.)
East	$-.88\pm.01$	$-.038\pm.0012$	$+.64\pm.03$	$+.045\pm.003$	$-.21\pm.1$	$-.32\pm.12$
North	$-.85\pm.02$	$-.036\pm.0013$	$+.59\pm.04$	$+.043\pm.003$	$-.16\pm.1$	$-.32\pm.12$
Vertical	$-.75\pm.04$	$-.035\pm.002$	$+.47\pm.05$	$+.042\pm.006$	$-.17\pm.1$	$-.42\pm.18$

Errors are R.M.S. deviations taken from the results. It can be seen that the pressure and temperature regression coefficients are all significant whereas those for height are barely significant or insignificant. This is to be expected since the day-to-day temperature and pressure variations are large enough for the resulting intensity changes to be bigger than the statistical fluctuations. This is not true of the height fluctuations since for a typical month the R.M.S. deviation in H is only about 80 metres. With an expected β_H of -0.7%/km. this means the resulting daily intensity changes will be about 0.06% compared with statistical fluctuations of at least 0.1% hence, the correlation is poor.

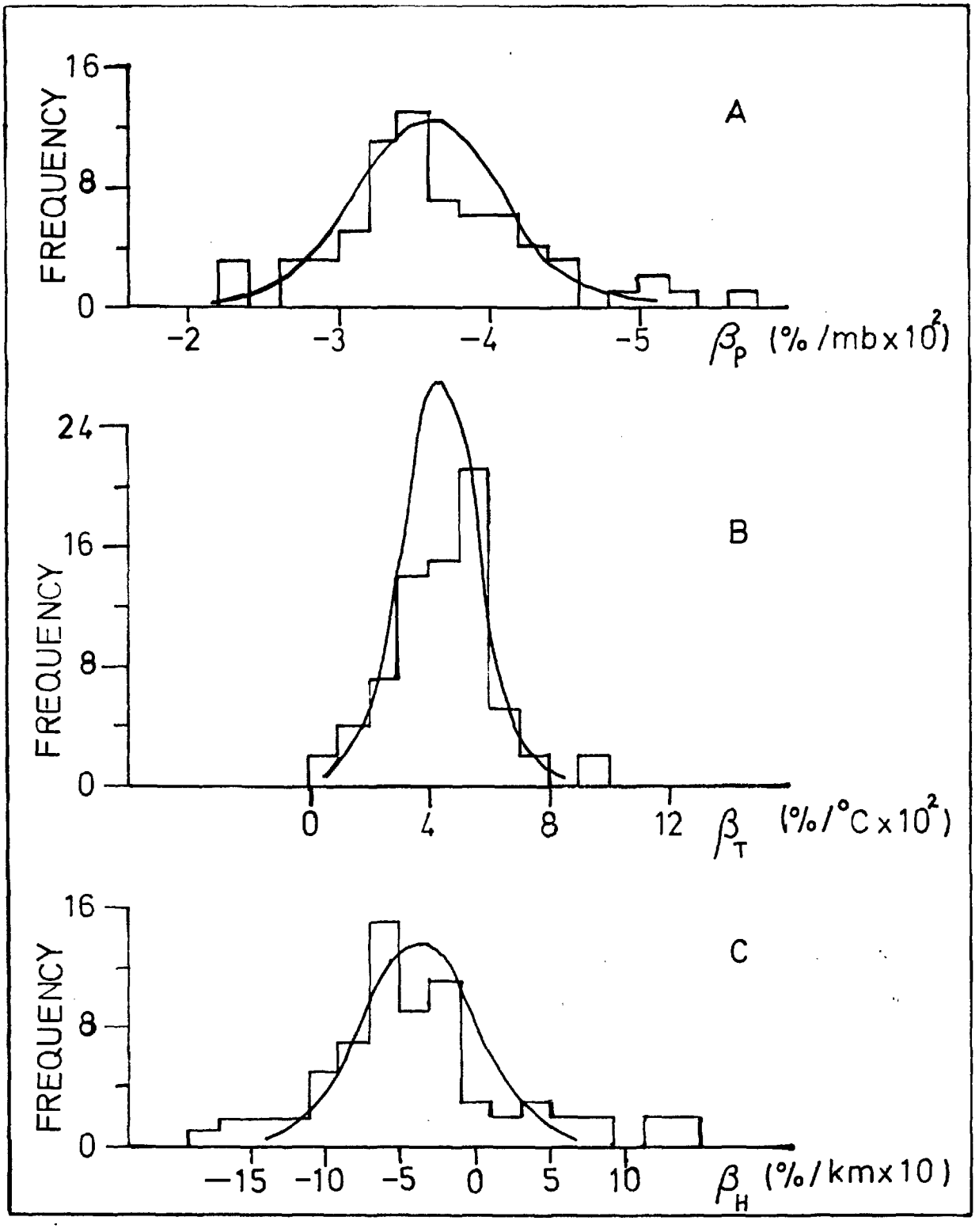


FIG. 3.1 A - PRESSURE COEFFICIENT/FREQUENCY
B - TEMPERATURE COEFFICIENT/FREQUENCY
C - HEIGHT COEFFICIENT/FREQUENCY

The pressure and temperature regression coefficients, although highly significant, are not significantly different for the three directions. Therefore, it was possible to collect together the three sets of directional data and show them in the form of frequency/coefficient plots for P, T and H. (See Fig. 3.1). Although the total frequency is low (70) there is in each case fair agreement between the experimental distribution and the normal distribution with the same mean and standard deviation. More important, there seems to be a definite peak in the height distribution. To reduce the large spread in β_H, the data were re-analysed so that only those months were used where:-

(i) The R.M.S. deviation in height exceeded 80m.

(ii) At least 20 days of data were available.

(iii) The correlation coefficient $r_{IH,PT}$ satisfied

$$|r_{IH,PT}| > 0.2$$

When (i) was applied, only 12 months were then available and of these, two months were omitted for the vertical direction because of (ii). Of the remaining 34 estimates for the three directions, only one had a positive correlation of intensity with height, and that was negligibly small ($r_{IH,PT}$ = 0.06). Application of (iii) reduced the number of estimates to 27, which tended to confirm that when the data had greater statistical weight, $r_{IH,PT}$ was of one sign and relatively large. From this total of 27 estimates the means became:-

EAST	NORTH	VERTICAL
-0.71 ± 0.07%/km.	-0.59 ± 0.05%/km.	-0.76 ± 0.13%/km.

It can be seen that the spread is much reduced even with less data.

Again, there is agreement between east and north directions but there is not enough resolution to detect any difference between inclined and vertical directions. Previous work at Holborn by MacAnuff, Mathews and Dutt could not detect a height coefficient although the method of analysis has not substantially changed. Most probably, the increased stability and statistical accuracy of the latest telescopes have combined with the more frequent and accurate temperature and height measurements to give this improvement in results.

Table 3.2 compares all Holborn measurements available so far.

TABLE 3.2

EXPERIMENTER	DIRECTION	β_p (%/mb)	β_T (%/°C)	β_H (%/km.)
MacAnuff	Vertical	-0.034 ± 0.002	$+0.055 \pm 0.005$	-
Mathews	Vertical	-0.043 ± 0.004	$+0.037 \pm 0.01$	-
Dutt	Vertical	-0.037 ± 0.001	$+0.041 \pm 0.003$	-
Present	Vertical	-0.035 ± 0.002	$+0.042 \pm 0.006$	-0.42 ± 0.18
	East	-0.038 ± 0.001	$+0.045 \pm 0.003$	-0.32 ± 0.12
	North	-0.036 ± 0.001	$+0.043 \pm 0.003$	-0.3 ± 0.12

The vertical measurements agree within the statistical limits and are not significantly different from the inclined measurements. This apparent lack of dependence on zenith angle will now be discussed.

3.3.2 Zenith Angle Dependence of the Pressure Effect

The muon intensity, $I(h, \theta)$, can be closely represented by:-

$$I\ (h, \theta) = A\ h^{-\gamma} \cos^{\gamma}\theta \qquad \ldots\ldots\ldots 3.4$$

where θ is zenith angle, h is vertical depth in m.w.e., A and γ are constants. Equation 3.4 implies that the rate of energy loss is independent of depth. At a depth of 60 m.w.e. most energy loss is by collision processes and these depend only weakly on energy in this region. Hence, γ is constant in the region of 60 m.w.e. depth and in fact has a value of about 2.

Now the pressure coefficients given by:-

$$\beta_p = \frac{1}{I}\frac{dI}{dP} \qquad \ldots\ldots\ldots 3.5$$

$$\therefore\ \beta_p = \frac{1}{I} \cdot \frac{dI}{dh} \cdot \frac{dh}{dP}$$

$$= -\frac{\gamma}{h} \cdot \frac{dh}{dP} \qquad \ldots\ldots\ldots 3.6$$

$\frac{dh}{dP}$ is a constant giving the effective change of depth/unit change of pressure.

Since $P \propto \frac{h}{\cos\theta}$

it follows that $\frac{1}{h}\frac{dh}{dP} \propto \frac{\cos\theta}{\cos\theta}$

i.e. β_p is independent of θ.

This has considered only that contribution to the pressure coefficient caused by mass absorption effect. If z is the vertical distance from the muon production level to detection level, then there is an extra component to the pressure coefficient due to μ-e decay given by:-

$$\frac{1}{I}\frac{dI}{dP} = \frac{1}{I}\frac{dI}{dz} \cdot \frac{dz}{dP} \qquad \ldots\ldots\ldots 3.7$$

$\frac{1}{I}\frac{dI}{dz}$ is the "height" coefficient caused by μ-e decay which is shown later to be independent of θ and to have a value -0.72%/km. $\frac{dz}{dP}$ is effectively

the change of vertical muon path length per unit change of ground level pressure. It is given by the normal condition for atmospheric equilibrium, i.e.

$$\frac{dP}{dz} = -\rho g$$

$$= -\frac{gP}{RT} \qquad \ldots\ldots\ldots\ldots 3.8$$

where ρ is air density, R is the gas constant, and g is the acceleration due to gravity. Therefore, the total pressure coefficient is:-

$$\beta_p = -\frac{\gamma}{h}\frac{dh}{dP} - \beta_H \cdot \frac{R.T}{g\,P} \qquad \ldots\ldots\ldots\ldots 3.9$$

Taking $\gamma = 2$

$h = 70$ m.w.e.

$\frac{dh}{dP} = 10^{-2}$ metres-mb^{-1}

$R = 8.3 \cdot 10^{7}$ ergs - deg^{-1} - mole^{-1}

$T = 280^{\circ}$ A

$g = 981$ dynes-cm^{-2}

$P = 1013$ mb

we get

$$\beta_p = -.029 - 0.006$$

$$= -.035\%/\text{mb} \qquad \ldots\ldots\ldots\ldots 3.10$$

This value agrees with the observed values within the limits of experimental error. The lack of dependence of β_p on θ seems natural in view of this simple theoretical approach.

3.3.3 Zenith Angle Dependence of the Positive Temperature Effect

We have used the average temperature between the 200 to 70 mb layers

and this should show a positive effect on the underground intensity, i.e. if this temperature increases the air density decreases, consequently increasing the probability of pion decay rather than capture. Since pion decay corresponds to muon production, this is a possible origin for a positive temperature effect.

The mean muon energy increases with increasing zenith angle and therefore the parent pion energy also increases. The pion lifetime increases with energy so that nuclear capture becomes more important so increasing the positive effect. Dorman (1957) shows this for a depth of 55 m.w.e; this work also shows that for inclined directions the region of maximum effect shifts to higher altitudes. Physically, one expects this since the first interaction occurs higher up for inclined directions.

If one assumes that the layer 0 - 200 mb changes temperature, as a unit one would expect (from Dorman's diagrams) the temperature coefficients to be about 25% bigger for the East and North measurements compared to the vertical. Such a difference is not detectable with the statistics available up to now and, in fact, the experimental results for the different directions are not significantly different.

Dorman estimated a temperature coefficient of +0.055%/°C for the 0 - 200 mb layer assuming uniform temperature changes. This assumption does not appear to be true since an analysis of four months Crawley data shows the temperature variations increasing rapidly as the altitude increases from the 200 mb level (See Fig. 3.3a). This behaviour tends to reduce the observed temperature coefficient compared to the theoretical value. It also reduces the difference between vertical and inclined coefficients. Hence, it appears

that the +ve temperature coefficients should be comparable in the different directions and somewhat less than 0.055%/°C. This is consistent with the observed estimates of β_T.

3.3.4 Zenith Angle Dependence of the μ-e Decay Effect

The decrease of muon intensity due to μ-e decay is given by:-

$$I = I_o \; e^{-\frac{z}{L}} \qquad \ldots\ldots\ldots\ldots \; 3.11$$

where I_o is a constant and L is the decay path length.

Then $\beta_H = \frac{1}{I}\frac{dI}{dz} = -\frac{1}{L}$ 3.12

For relativistic muons

$$L = \tau_o \cdot \gamma_o \cdot c \qquad \ldots\ldots\ldots\ldots \; 3.13$$

where τ_o is the muon lifetime in the rest frame

c is the velocity of light

$\gamma_o = (1-\beta^2)^{-\frac{1}{2}}$ where β is the muon velocity in units of c.

From 3.12 and 3.13

$$\beta_H = -\frac{1}{c\,\gamma_o\,\tau} = -\frac{m_\mu}{P_\mu \cdot \tau \cdot c}$$

where P_μ and m_μ are muon momentum and rest mass respectively.

For inclined directions, the path length increases to $z/\cos\theta$ while the cut-off momentum increases to $P_o/\cos\theta$ where P_o is the vertical cut-off momentum. Integrating over all momenta $\geq P_o/\cos\theta$ using the s/l differential momentum spectrum, n (p), as a weighting function, we get the average height coefficient:-

$$\beta_H(\theta) = -\frac{\int_{P_o/\cos\theta}^{\infty} \frac{m_\mu \cdot n(p_\mu)}{p_\mu \cdot \tau \cdot c} \cdot \frac{1}{\cos\theta}\, dp_\mu}{\int_{P_o/\cos\theta}^{\infty} n(p_\mu)\, dp_\mu} \qquad \ldots\ldots\ldots \; 3.14$$

We assume

(a) $n(p_\mu)$ is well represented by

$$n(p_\mu) = A_0 p_\mu^{-\gamma-1}$$

for $p_\mu \sim 100$ GeV/c where γ is independent of p_μ.

(b) The differential spectra for inclined directions up to about $\theta = 60^\circ$ have the same form as for the vertical.

Then 3.14 becomes:-

$$\beta_H(\theta) = \frac{-m_\mu}{N(P_0/\cos\theta, \theta)} \cdot \frac{A_0}{\gamma+1} \left[\frac{P_0}{\cos\theta}\right]^{-\gamma-1} \cdot \frac{1}{\cos\theta} \quad \ldots\ldots\ldots 3.15$$

where $N(p_\mu, \theta)$ is the integral momentum spectrum.

$$\therefore \frac{\beta_H(\theta)}{\beta_H(0)} = \frac{N(P_0, 0)}{N(P_0/\cos\theta, \theta)} \cdot [\cos\theta]^{\gamma+1} \cdot \frac{1}{\cos\theta} \quad \ldots\ldots\ldots 3.16$$

Now $$N\left(\frac{P_0}{\cos\theta}, \theta\right) = N(P_0, 0) \cos^\gamma\theta \quad \ldots\ldots\ldots 3.17$$

$$\therefore \frac{\beta_H(\theta)}{\beta_H(0)} = 1 \quad \ldots\ldots\ldots 3.18$$

Hence, we expect the height coefficients to be the same. This, in fact, was true within the statistical limits.

A detailed calculation was performed by Dutt and Thambyahpillai (1965). In this the muon momentum loss during flight was allowed for by averaging the coefficient obtained for three levels, namely the 100 mb level (assumed to be that of muon production), the 550 mb level and sea level. The resulting coefficient as a function of momentum was averaged using the differential momentum spectrum as a weighting function. This gives β_H = - 0.72%/km. which compares well with the observed values so long as we consider only selected data according to the three previously given conditions.

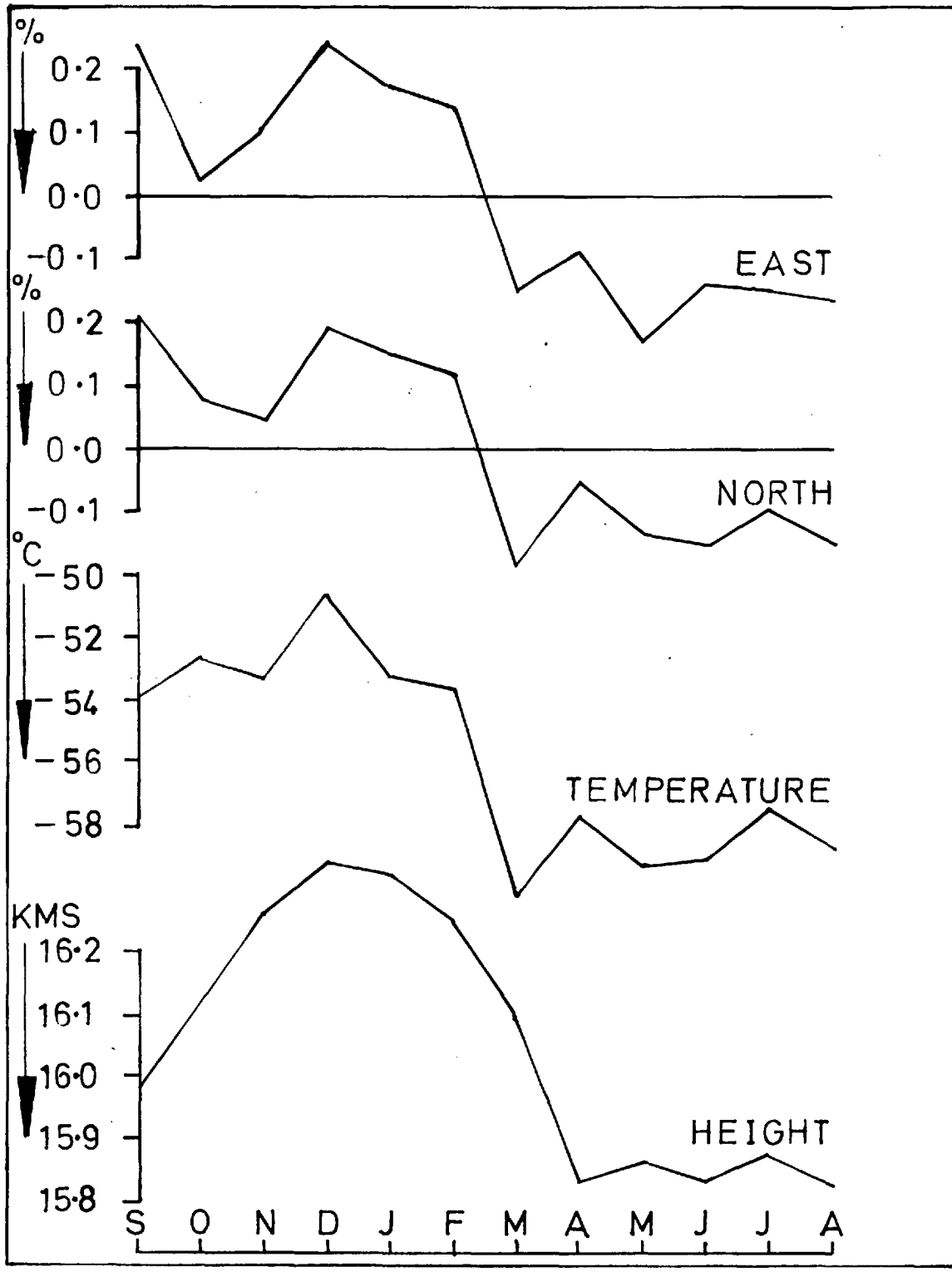


FIG. 3.2 MONTHLY INTENSITY DEVIATIONS (%) AND TEMPERATURE (200 - 70 MB) AND HEIGHT (1000 - 100 MB).
INTENSITIES ARE PRESSURE-CORRECTED.

3.4 Seasonal Wave Underground

A semi-annual wave in the corrected cosmic ray intensity has been predicted by models of the solar cavity which are not spherically symmetric. For instance, Sarabhai and Subramanian (1965) postulate a reduced galactic cosmic ray intensity at approximately 10° to 30° heliographic latitude compared to the intensity in the solar equatorial plane. This latitude corresponds to maximum sunspot activity on the sun and possibly enhanced magnetic irregularities flowing with the solar wind from this region. The ecliptic plane and solar equatorial plane are inclined at 7° so one expects maximum intensity at about September and March. If the cosmic ray intensity gradient normal to the solar equatorial plane is such that there is a minimum intensity in this plane, then the maxima in the semi-annual wave would be expected at about December and June. Similar reasoning can be applied to the diurnal variation.

It is difficult to observe small seasonal changes of intensity because of instrumental instability and inteference by the strong seasonal waves in atmospheric variables. The counting rates drifts at Holborn were about 0.5%/year and were thought mainly due to ageing of the photomultipliers. To overcome this, the yearly running average was used as a baseline to obtain the monthly percentage departures in counting rate. The vertical data suffered serious loss in two monthly periods and was therefore not used in this analysis.

Fig. 3.2 shows the seasonal trend of intensity, temperature and height. Since the pressure has no obvious seasonal wave, the pressure-

corrected intensities are shown in Fig. 5.2. It can be seen that the intensity seems to be largely under the control of temperature rather than height. Both T and H do not seem to be simple functions of time, e.g. both show big departures from a sinusoidal variation with a period of 12 months. For this reason, harmonic analysis was not used and again correlation analysis was used to estimate the atmospheric coefficients. Because the temperature and height are well correlated, care must be taken to avoid the consequent errors arising in correlation analysis. Hence, the intensity was pressure and height corrected ($\beta_H = -0.7\%/\text{km.}$) and then correlated with temperature, with the following results:-

North $r_{IT} = 0.93$; $\beta_{IT} = 0.074 \pm 0.010\%/^{\circ}C$

East $r_{IT} = 0.91$; $\beta_{IT} = 0.081 \pm 0.010\%/^{\circ}C$

The temperature coefficient are about $1\frac{1}{2}$ to 2 times bigger than the corresponding day-to-day results. This is in agreement with the previous results of MacAnuff and Dutt. However, it was thought that part of this discrepancy may arise in the use of air temperature data contaminated with insolation errors. For this reason, the data was re-analysed using only the night flight measurements of T. This reduced the seasonal coefficient by about 10%, viz:-

North $r_{IT} = 0.9$; $\beta_{IT} = 0.063 \pm 0.01\%/^{\circ}C$

East $r_{IT} = 0.88$; $\beta_{IT} = 0.069 \pm 0.01\%/^{\circ}C$

Since this is insufficient to account for the discrepancy, the source must lie elsewhere. The most likely explanation seems to be one or more of the following:-

(a) Day-to-day changes of temperature decrease with increasing altitude

above the 200 mb level whereas seasonally the reverse is true. Hence, use of an average temperature causes the seasonal coefficient to be larger than the day-to-day value because the more important levels producing the positive temperature effect lie above the 200 mb level.

(b) The levels above 70 mb may be important but have not been considered because of lack of data.

(c) A seasonal wave in intensity external to the atmosphere may be present so interfering with the interpretation of the seasonal data.

To eliminate the first two of these, Dutt (1965) used Dorman's W(T) values and the results of Berlin balloon ascents (which regularly reached 10 mb) and obtained agreement between the observed and expected intensities. So long as the results from Berlin are applicable to London, the conclusion is that the seasonal wave observed at Holborn can be entirely of atmospheric origin.

From Fig. 3.2 it appears that the pressure-corrected intensity is mostly temperature controlled. We have made the implicit assumption that external effects are absent to obtain a seasonal temperature coefficient. It is impossible to correct the data using that coefficient and assert that the residual variation is a "true" seasonal wave in intensity. Clearly, atmospheric data up to 10 mb is needed from a station close to London. This is, unfortunately, not available.

3.5 Daily Atmospheric Oscillations

We wish to obtain the solar and sidereal daily variations of under-

ground intensity so good correction must be made for the atmospheric oscillations.

3.5.1 Daily Pressure Variation

This virtually has only two components for London, viz:-

PERIOD	AMPLITUDE (mb)	TIME OF MAX. (Hrs.)
24 Hrs.	0.14	02
12 Hrs.	0.35	10

the second harmonic being more steady than the first. The pressure correction is well known and when applied to the data, there is no obvious correlation remaining of intensity with pressure. However, there is a difficulty in that it is now thought that the driving force exciting the pressure oscillations is thermal rather than gravitational. Part of this is due to heat transfer from the surface of the earth and another is due to direct absorption of sunlight by ozone and water-vapour. It is the latter source which might affect the 100 mb region where most of the positive temperature effect takes place. Hence, there is the possibility of a temperature-induced solar daily variation. Besides this, the first harmonic in pressure shows a systematic amplitude modulation with a maximum of 0.32 mb in April-May and a minimum in November-January. Amplitude modulation results in harmonic components appearing in sidereal and anti-sidereal time. This may be reflected in the behaviour of the stratospheric temperature since it is known that the ozone concentration also has a maximum in April whereas the temperature wave at the earth's surface has a mid-summer maximum. Hence, computed and observed temperature oscillations are discussed.

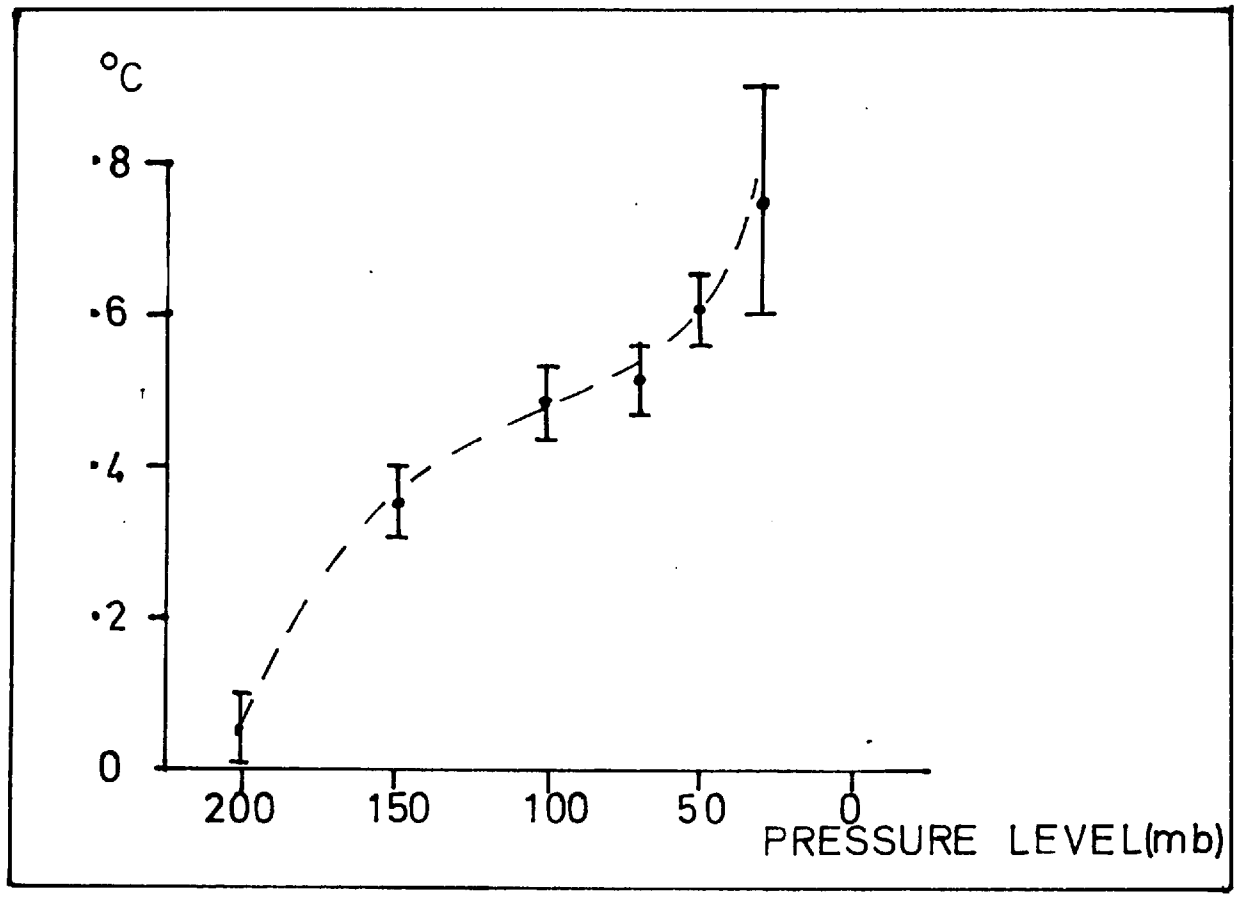


FIG. 3.3.a DAY-NIGHT TEMPERATURE DIFFERENCE/PRESSURE LEVEL.

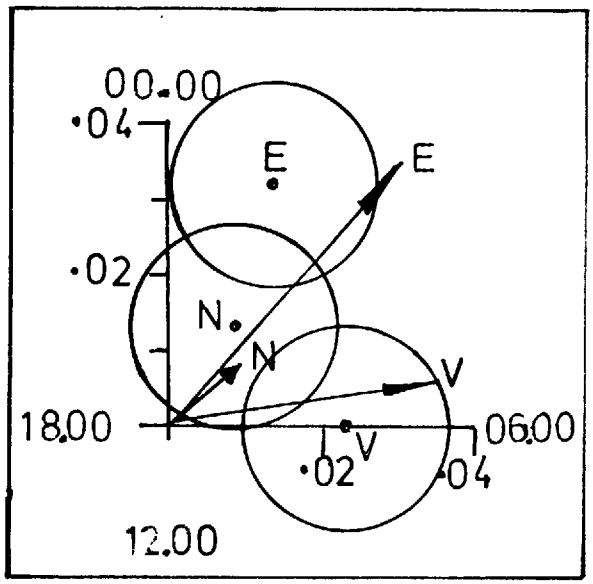


FIG. 3.3.b OBSERVED AND PREDICTED DIURNAL VECTORS FOR THE PERIOD OCT. 1964 - SEPT. 1965.

E - EAST: N - NORTH: V - VERTICAL

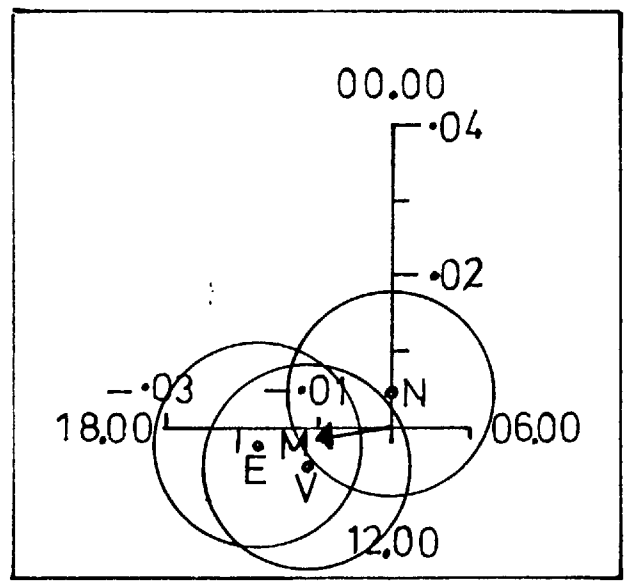


FIG. 3.3.c DIFFERENCE VECTORS FROM FIG. 3.3.b AND MEAN DIFFERENCE (M).

3.5.2 Daily Temperature Variation

Harris et al (1962) compared measured and computed stratospheric diurnal temperature waves and found that the measured values were much larger than the computed ones. The temperatures were computed on the basis of the diurnal wind variation, measurement of which is not affected by insolation errors. Also, the computed time of maximum was later than the observed value, which was around local noon. They conclude that insolation errors contaminate the observed values and that the true diurnal variation in the region 250 to 20 mb is on average less than $0.2^{\circ}C$.

In an effort to test these figures, the day-night differences in air temperature were averaged for two stations, Crawley and Hemsby. The results are shown in Fig. 3.3a, where it can be seen the difference increases rapidly with increasing altitude. This behaviour is consistent with the Harris conclusion that large insolation errors contaminate diurnal measurements. A measured day-night temperature difference of $0.5^{\circ}C$ should lead to an intensity change of about 0.025% assuming $\beta_T = 0.05\%/^{\circ}C$. But the Holborn results over the solar minimum period were consistent with a temperature-induced daily variation of less than 0.02%. These results will be described more fully later but it was found that the phase of the first harmonic of the daily variation for the vertical direction changed from $T_{max.} \simeq 14$ hours to $T_{max.} = 06$ hours. This early time was maintained from about July - September 1964 to May - June 1966 and was interpreted as being due only to the orbital motion of the earth plus any atmospheric effects, i.e. the solar anisotropy was absent. The inclined measurements only started in October 1964 but they showed the early time of maximum until May - June 1966 when

$T_{max.}$ appeared to return to later hours. (1200 - 1800 hours). With the same interpretation, it was possible to compare the prediction of an orbital effect with the three observed vectors as in Fig. 3.3b. All agree well, the differences between observed and predicted vectors being shown in Fig. 3.3c together with the mean vector difference. This mean value can be taken to be the remnant atmospheric contribution and is less than the observational limit of about 0.02%. This is consistent with Harris' estimate of $\Delta T < 0.2^{\circ}C$, since if we take $\beta_T = 0.05\%/^{\circ}C$ we get an intensity variation $< 0.01\%$.

We conclude that the spurious effect of temperature on the solar daily variation is less than the statistical limitation of about 0.02%.

If the atmospheric-induced solar component is only 0.02% or less, it follows that the spurious sidereal and anti-sidereal sidebands caused by amplitude modulation of this wave will be even less. Phase modulation is not expected since the maximum solar heating occurs at local noon all the year round.

There is a possibility that the average atmospheric component is small because of balancing of the positive temperature effect with the negative effect due to μ -e decay. Therefore, the latter is considered next.

3.5.3 Daily Height Variation

Observed diurnal height variations are again much larger than those computed from wind data (Harris 1962). The measurement of wind velocity is thought to be free of insolation errors in which case the daily variation of height is only about 15 m . with a time of maximum near 13 hours.

Taking $\beta_H = -0.7\%/km$. we get an intensity variation of 0.01% with $T_{max.} \simeq 01$ hours. This would tend to balance the positive temperature effect which has a time maximum that varies from 12 hours to 19 hours in the region 250 to 20 mb. Hence, it is reasonable to suppose that the averaged atmospheric contribution to the solar daily variation observed at Holborn is negligible compared to the statistical uncertainty. However, it is possible that seasonal variations of the temperature and height-induced components to the daily variation can cause spurious sidereal and anti-sidereal sidebands of amplitude up to 0.01%.

3.6 Conclusions

(i) Significant results were obtained when the intensity underground was correlated day-to-day with pressure, temperature averaged over 200 to 70 mb, and height of the atmosphere as measured by the distance between the 1000 and 100 mb levels.

(ii) East, North and vertical atmospheric coefficients are not significantly different from one another and this was shown to be natural in terms of the physical processes behind the effects and the limitations of statistical accuracy.

(iii) Discrepancies were again noticed between the positive temperature coefficients obtained by seasonal and day-to-day analysis. This was found to be only partly due to insolation errors in atmospheric data. Rather, the most plausible explanations seem to be the limitations to the use of the Duperier-type equation and lack of air data above 70 mb. The latter also prevented the estimation of the "true" seasonal wave.

(iv) The atmospheric contributions to the solar, sidereal and anti-sidereal daily variations at Holborn were shown to be most probably less than 0.02%.

CHAPTER 4

SOLAR DAILY VARIATION - EXPERIMENTAL

4.1 Introduction

The solar daily variation (S.D.V.) of the secondary cosmic ray intensity corrected for atmospheric and geomagnetic effects is of interest because it reflects the spatial anisotropy of the primaries in the vicinity of the earth. Since this is thought to be largely under the control of the solar "wind" and its associated magnetic field, it follows that an understanding of the S.D.V. tells us something of the electromagnetic conditions in interplanetary space. In particular, the S.D.V. of the underground intensity at Holborn corresponds to solar modulation of primaries of $\sim$100 GeV. energy. Hence, Holborn results are complementary to the surface data of meson and neutron monitors which respond to primaries of lower energy, perhaps up to 40 GeV.

The results of shielded ionization chambers for several stations from 1936 onwards indicated the presence of a S.D.V. After pressure correction, the data showed a 12-hour wave which had about one-third of the amplitude of the 24-hour wave, i.e. 0.05% compared to 0.15%. Neither harmonic could be explained entirely in terms of an atmospheric temperature effect.

The introduction of geiger counters enabled directional measurements to be made which removed the uncertainty due to atmospheric effects. Alfvén and Malmfors (1943), Elliot and Dolbear (1951) and others showed that there

were significant differences between the S.D.V.'s obtained by counter telescopes pointing North and South at the same zenith angle of about 45°. Assuming both counters observe the same atmospheric effect, the difference between them may be attributed to a non-isotropic distribution of the primary cosmic rays. Both the diurnal and semi-diurnal waves were shown to be extra-terrestrial in origin with phases about 1400 hours and 0200 hours respectively (uncorrected for geomagnetic deflection). Furthermore, the extra-terrestrial component increased after some magnetic storms and during periods of enhanced magnetic activity, as measured by the Kp index. Thus the S.D.V. seems to be connected with the plasma clouds emitted from the sun which can cause magnetic disturbances.

Thambyahpillai and Elliot (1953) combined data from eight stations operating ionization chambers or counter telescopes to show that there was a systematic change of phase of the diurnal variation from 1932 to 1952. The phase went progressively later from 1932 to 1942 and then earlier until 1952. The authors suggest that if this is a periodic effect then it can be fitted with a 22-year wave whose phase is such that the earliest times of maximum (of the diurnal wave) are associated with the solar minimum periods of 1933, 1955, etc.

Possener and V.Heerden (1956) and others found that the phase and amplitude of the diurnal wave changed remarkably during the solar minimum period of 1953 to 1955. North-South counter measurements at a zenith angle of 45° in Manchester (1948 - 1954) and vertical measurements at London (1954) showed the amplitude to decrease and the phase to go to early hours ($\sim$0600 L.Sol.T.). This was confirmed by hard component

measurements at Huancayo, Cheltenham, Christchurch, Hobart, Tokyo and elsewhere. Possener and V.Heerden compared the hard component measurements with neutron monitor data at London and Manchester and found that the neutron diurnal amplitude decreased virtually to zero during the periods when an early time of maximum was observed for the hard component. Since the neutron intensity is independent of atmospheric temperature, it would appear that the anisotropy disappeared during certain periods of the solar minimum of 1953 - 1955.

The advent of the neutron monitor (Simpson 1955) enabled the S.D.V. to be studied free from the perturbing influence of atmospheric temperature. The use of many neutron stations during the I.G.Y. and after has enabled the latitude and longitude dependence of the S.D.V. to be studied. The amplitude of the diurnal wave was found to increase from the equator ($\sim$.25%) to medium latitudes ($\sim$.35%) and then to decrease again at high latitudes ($\sim$.15%) (e.g. see Kane and Thakore 1960). The semi-diurnal wave amplitude decreased with increasing latitude. At the same geomagnetic latitude, the times of maxima were the same in L.Sol.T.

McCracken and Rao (1965) using neutron monitor data carefully corrected for geomagnetic deflection found that the mean annual diurnal variation was constant in phase and amplitude from 1957 to 1965. Furthermore, they find the amplitude to vary as the cosine of the declination from the solar equatorial plane, and to be independent of primary energy. The direction of anisotropy was very close to 90° East of the Earth-Sun line. This was confirmed by a similar analysis by Faller and Marsden (1965) using substantially the same data, i.e. neutron monitor data from a

dozen or so medium latitude stations, with one or two low latitude stations included.

However, Ahluwalia et al (1965) found that the diurnal wave amplitude decreased between 1958 and 1964 as shown by the neutron monitor data from Mt. Norikura and Huancayo. Similarly, East-West total component measurements at Mt. Chacaltaya show the same phase but significantly reduced amplitude between the two years. It is to be noted that the total component data were temperature corrected. East-West measurements of the total component at Makerere likewise show a greatly reduced anisotropy in 1965-1966, whereas North-South measurements at London show a small reduction of the normal anisotropy (Hashim 1967). Thus it appears that low latitude stations (i.e. those with high cut-off momenta) show a significant reduction in amplitude of the diurnal variation from solar maximum 1957-1958 to minimum in 1965. This indicates that it is in the relatively high momentum region ($P \gtrsim 15$ GeV./c) where secular changes may be important. Hence, underground results are useful and will be presented for Holborn 1961 to 1966.

4.2.1. Reduction of Holborn Data

The coincidence counting rates were scaled by a factor 100 and summed in electro-mechanical counters which printed hourly. The hourly values were added in pairs so that 12 bihourly values were obtained for each day. These were corrected for pressure using the Kew data and a coefficient of -0.037%/mb. No temperature or height corrections were made for lack of sufficient data.

The corrected values were averaged monthly using all data in the first case, and then secondly using only those complete days in which all

telescopes worked perfectly. In the latter case, an attempt was made to eliminate the effect of drift and curvature in the intensity by using the bihourly departures from the daily means centred on the bihourly value in question. Monthly averages were then harmonically analysed in the two cases; it was found that there was no significant difference between the two methods. This indicates that instrumental drifts, the "curvature" of the intensity and genuine intensity variations have little effect on the mean S.D.V. In fact, the instrumental drift was about 0.5%/year corresponding to 0.0015%/day compared to a statistical uncertainty of about 0.012% for a year's data.

The statistical error was calculated by the scatter in the daily harmonic components, as described in Chapter 2. The following % values were obtained for yearly means for October 1964 - September 1966:-

	Diurnal	Semi-diurnal
East	0.013	0.013
North	0.013	0.013
Vertical	0.013	0.012

It is to be noted that the standard deviation obtained from the scatter is about 1.5 times that obtained from the counting rate assuming just Poissonian fluctuations. It is possible that the variability of the S.D.V. itself causes this increase in the scatter of the results. A re-appraisal of the data from 1960 to 1964 also showed that the standard deviation on a year's data was 0.013% (for a counting rate of 50,000 per hour). Thus the standard deviations on the year harmonic coefficients are 1.5 to 2 times the values expected purely from statistical fluctuations.

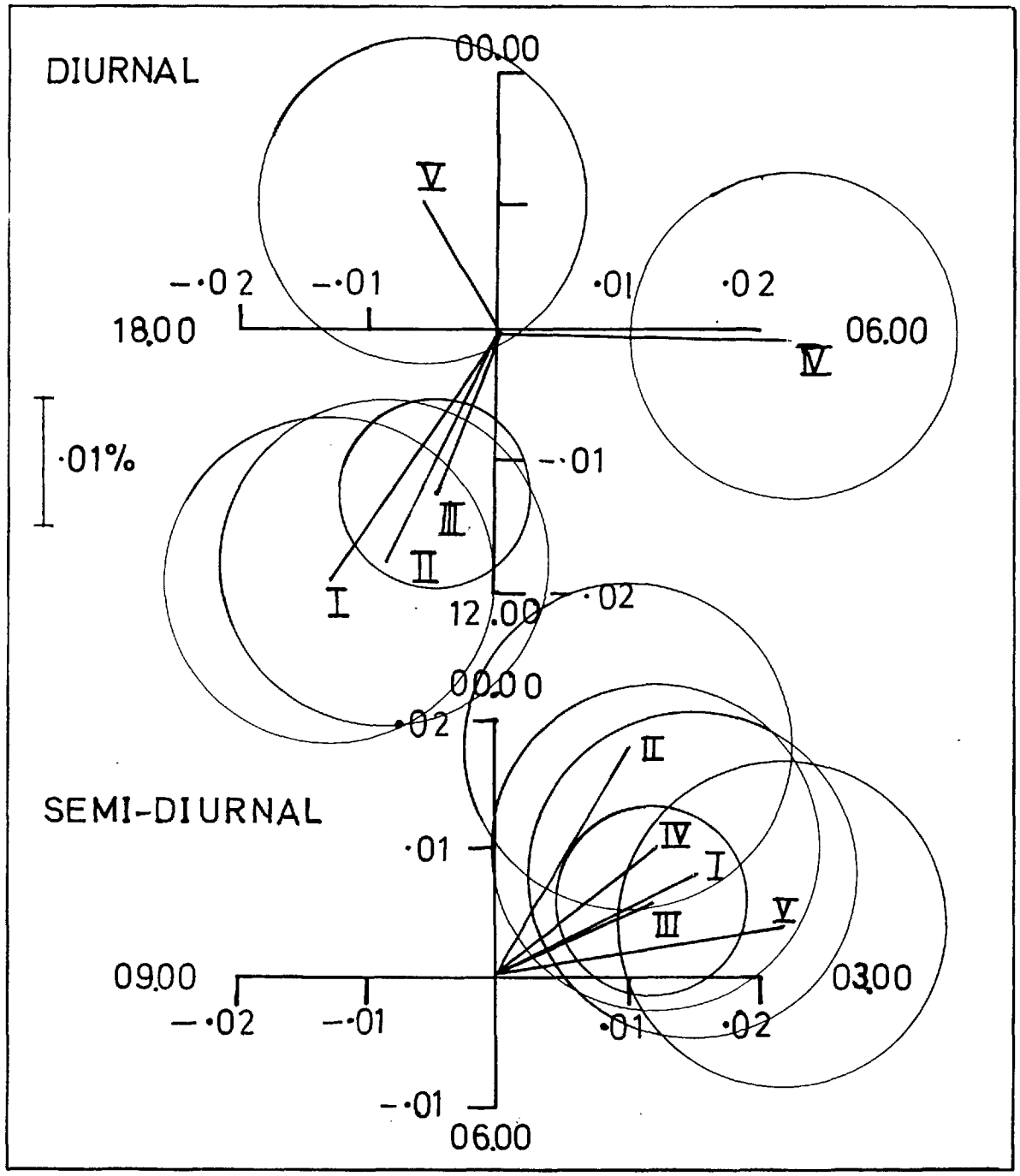


FIG. 4.1 DIURNAL AND SEMI-DIURNAL COMPONENTS OF THE VERTICAL DAILY VARIATION FOR THE PERIOD 1960 - 1966.

I	NOVEMBER 1960 - OCTOBER 1961
II	NOVEMBER 1961 - OCTOBER 1962
III	AUGUST 1963 - JULY 1964
IV	OCTOBER 1964 - SEPTEMBER 1965
V	OCTOBER 1965 - SEPTEMBER 1966

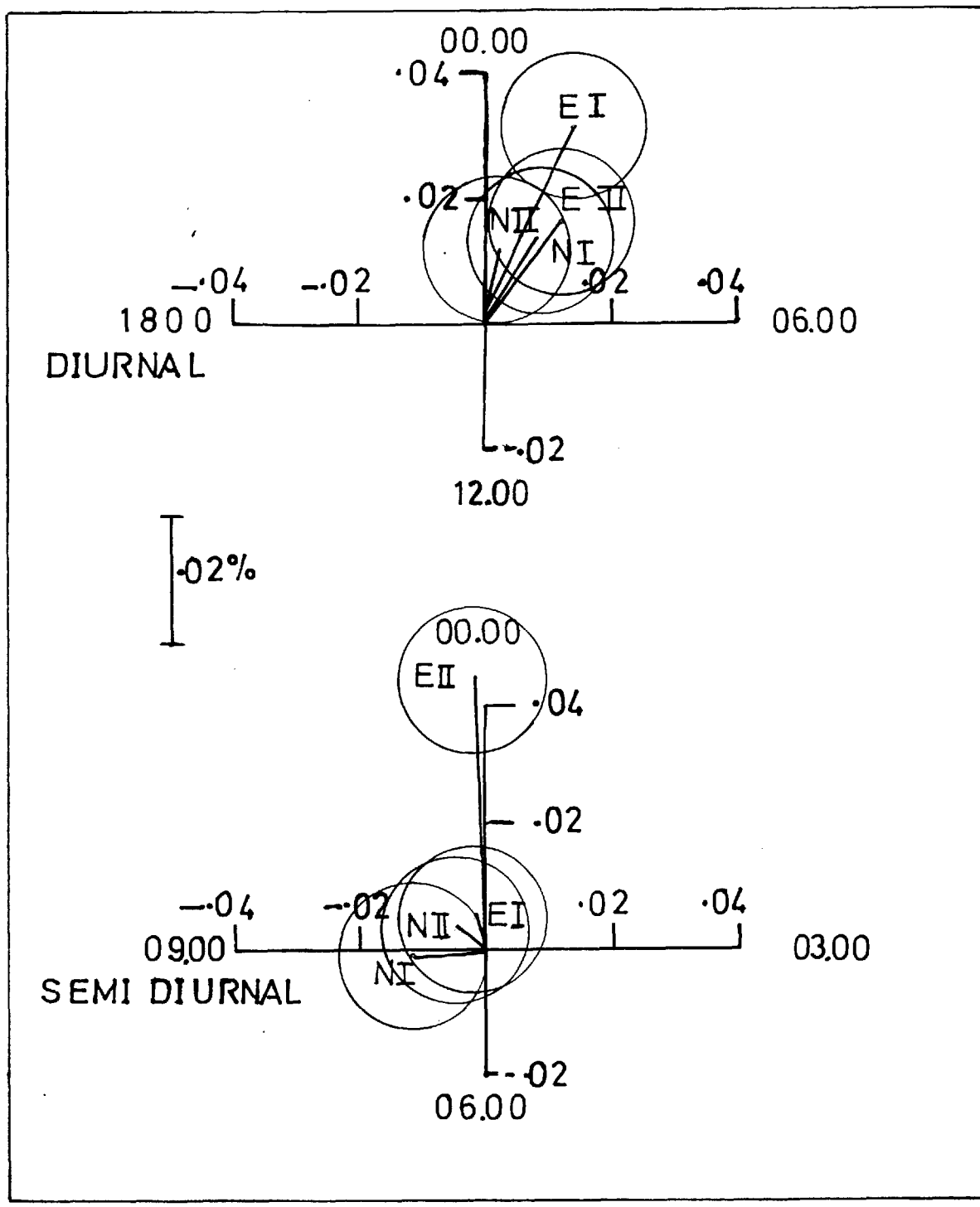


FIG. 4.2 DIURNAL AND SEMI-DIURNAL COMPONENTS OF THE INCLINED SOLAR DAILY VARIATION AT HOLBORN FOR OCTOBER 1964 - SEPTEMBER 1966.

EI	EAST	OCTOBER 1964 - SEPTEMBER 1965
EII	EAST	OCTOBER 1965 - SEPTEMBER 1966
NI	NORTH	OCTOBER 1964 - SEPTEMBER 1965
NII	NORTH	OCTOBER 1965 - SEPTEMBER 1966

Wherever possible, yearly averages of the S.D.V. were obtained thus eliminating the effect of any possible sidereal variation or seasonal wave in the S.D.V.

4.2.2. Results from Holborn 1960 to 1966

The mean S.D.V. has been found as a series of yearly averages of the diurnal and semi-diurnal waves which are tabulated in Table 4.1 for the vertical direction only:-

Period	DIURNAL		SEMI-DIURNAL	
	Amplitude %	$T_{Max.}$(L.Sol.T.)	Amplitude %	$T_{Max.}$(L.Sol.T.)
Nov. 1960 - Oct. 1961	0.023	14.3	0.017	2.0
Nov. 1961 - Oct. 1962	0.020	13.8	0.021	1.0
Aug. 1963 - July 1964	0.016	13.3	0.013	2.1
Oct. 1964 - Sept. 1965	0.023	6.0	0.016	1.6
Oct. 1965 - Sept. 1966	0.012	22.00	0.023	2.6

These same results are plotted in Fig. 4.1 where it can be seen the data from 1960 to 1964 show no appreciable change for either harmonic. However, in October 1965 to September 1966 the average diurnal wave was significantly earlier in phase than in the previous periods. East and North data available only from October 1964 show a similar early time of maximum (see Fig. 4.2) although the North S.D.V. is not significantly different from zero.

The vertical semi-diurnal wave appears constant throughout the whole period 1960 - 1966. Although the yearly amplitudes are only about twice the

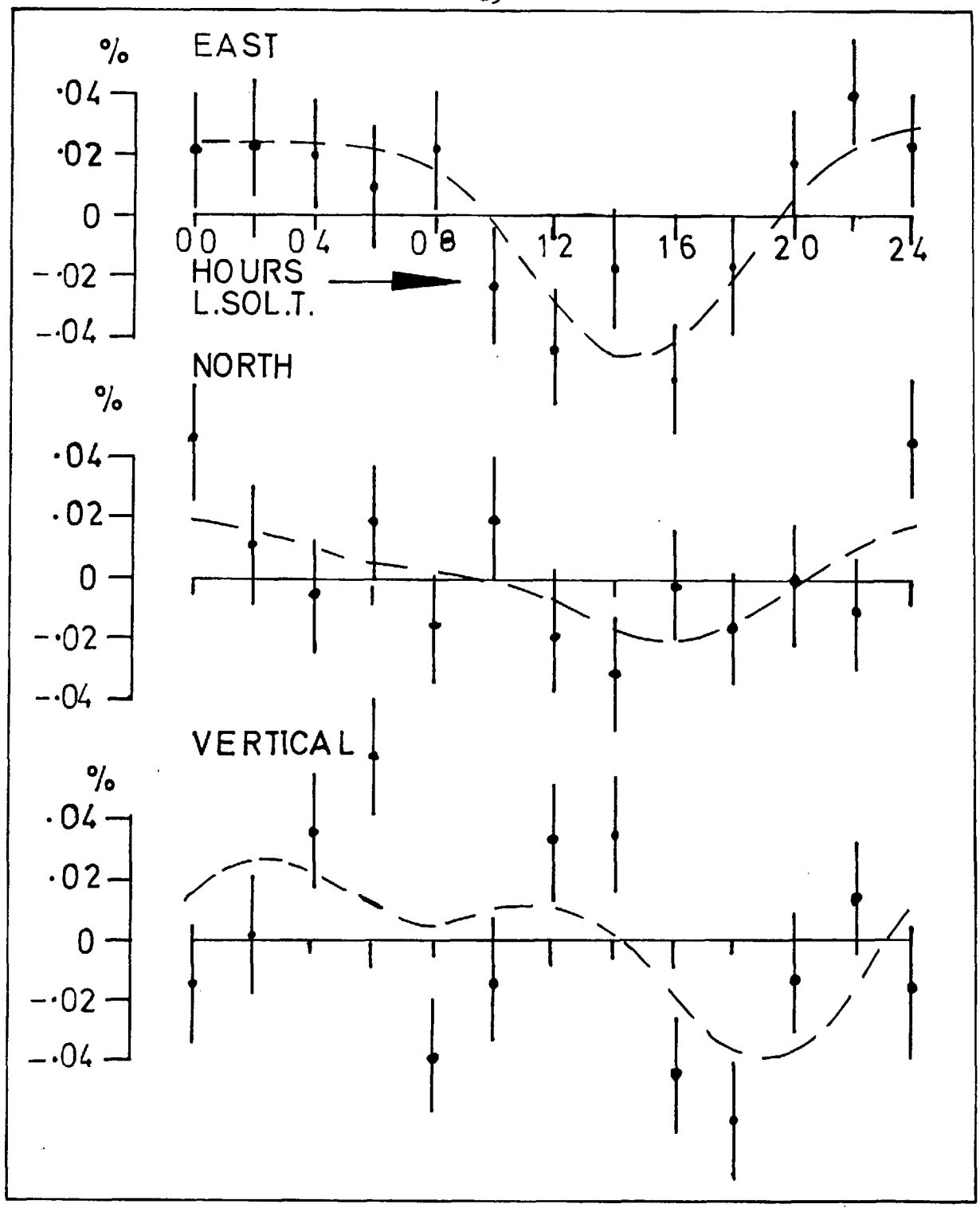


FIG. 4.3 DIURNAL AND SEMI-DIURNAL WAVES FITTED TO THE EAST, NORTH AND VERTICAL TELESCOPE DATA FOR THE PERIOD OCTOBER 1964 - SEPTEMBER 1965.

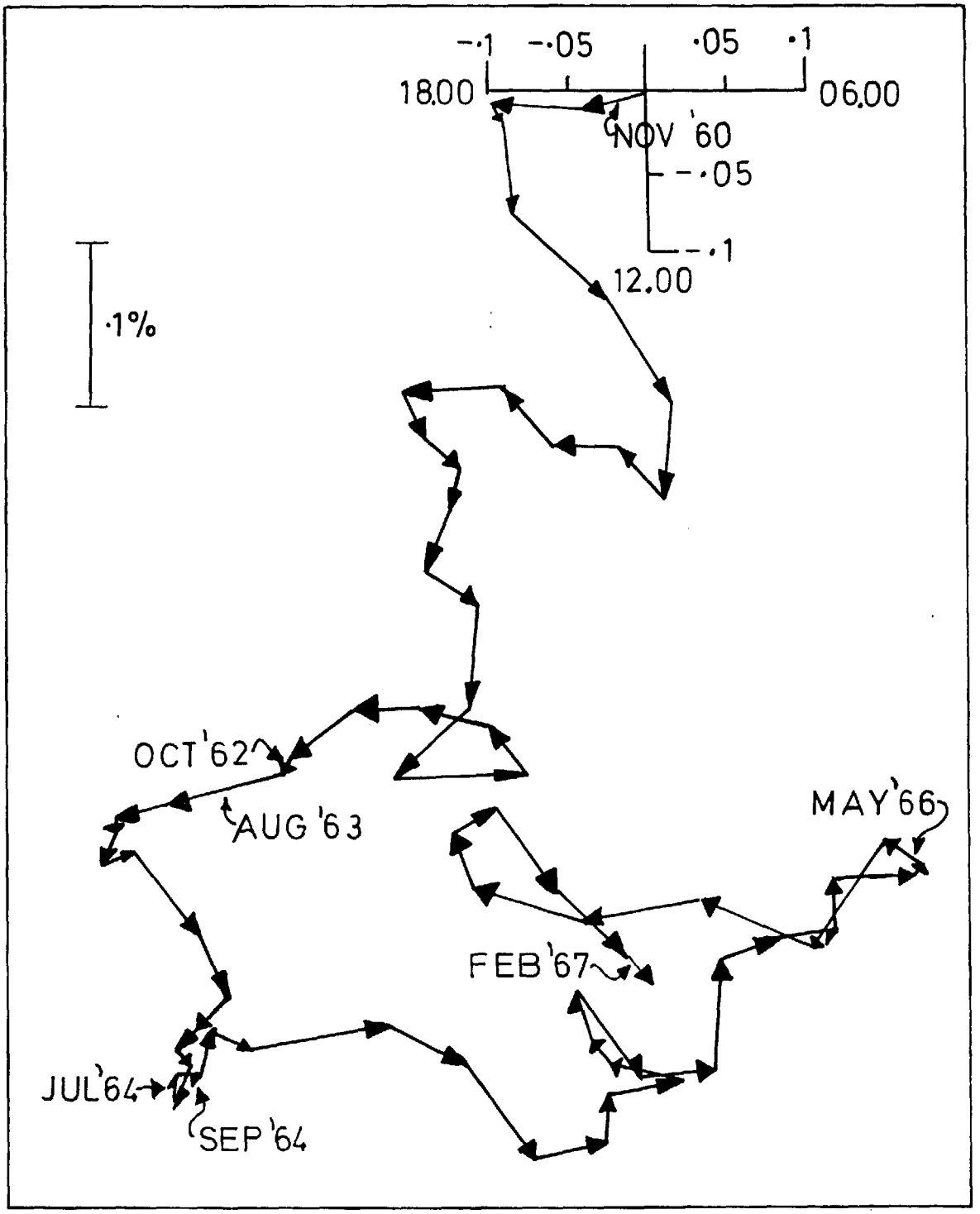


FIG. 4.4 SUMMATION DIAL FOR THE VERTICAL SOLAR DIURNAL WAVE AT HOLBORN FROM NOVEMBER 1960 - FEBRUARY 1967.

standard deviation (a significance level of ~95%) the grouping is impressive, and in fact the mean for the whole period is 0.015% at $T_{max.}$ = 2.0 hours with a significance level of 99.5%. The East and North semi-diurnal waves are insignificant except for the East in October 1965 to September 1966.

The diurnal wave for the East is early throughout the whole period October 1964 to September 1966 while the North is insignificant. The vertical diurnal wave seems to show some sign of recovery to later hours in the period October 1965 to September 1966, although since its amplitude is only one standard deviation, it cannot be considered a reliable estimate of the diurnal wave phase.

The period October 1964 to September 1965 shows the largest diurnal amplitudes with the early times of maximum; Fig. 4.3 therefore shows the data for this period fitted with the diurnal and semi-diurnal waves. All three directions seem to show a maximum in intensity in the 2000 to 0600 hours L.Sol.T. region. The significance levels for the East, North and vertical diurnal waves are 99%, 70%, 95% respectively.

Although yearly averages are useful in eliminating sidereal effects, it is of interest to study the diurnal amplitudes in finer detail to see if the change to early times of maximum can be observed. Fig. 4.4 is a summation dial showing the monthly diurnal vectors plotted consecutively for the vertical direction; the origin of any vector is made coincident with the end-point of the previous month's vector (in the case of missing data, the nearest earlier month is used). The phase seems to be mostly between 1200 and 1800 hours L.Sol.T. from October 1960 to June 1964 when a fairly rapid transition takes place. After this time, the phase is mostly between 0000 and

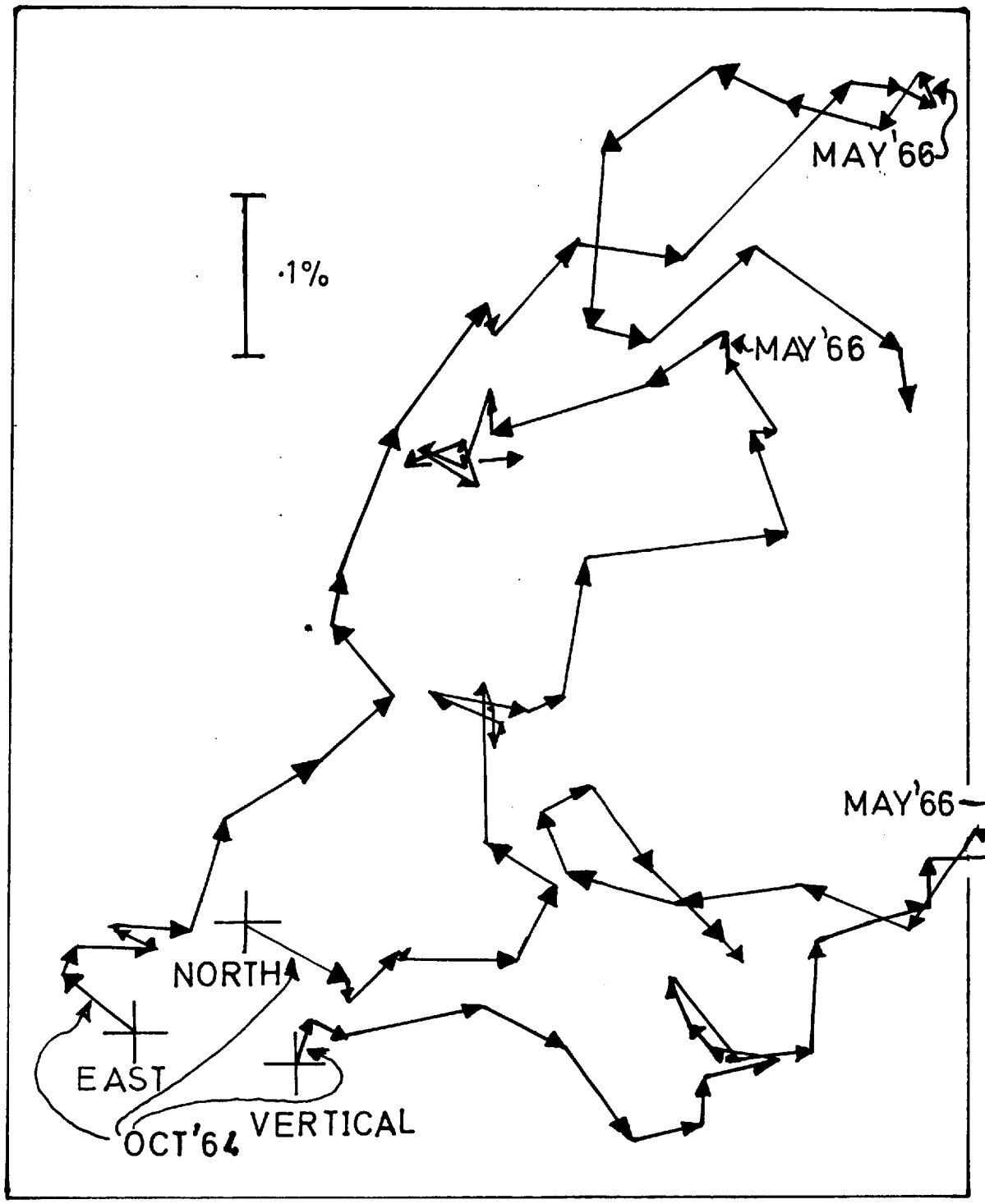


FIG. 4.5 SUMMATION DIAL OF THE SOLAR DIURNAL WAVES FROM OCTOBER 1964 - FEBRUARY 1967 FOR EAST, NORTH AND VERTICAL TELESCOPES.

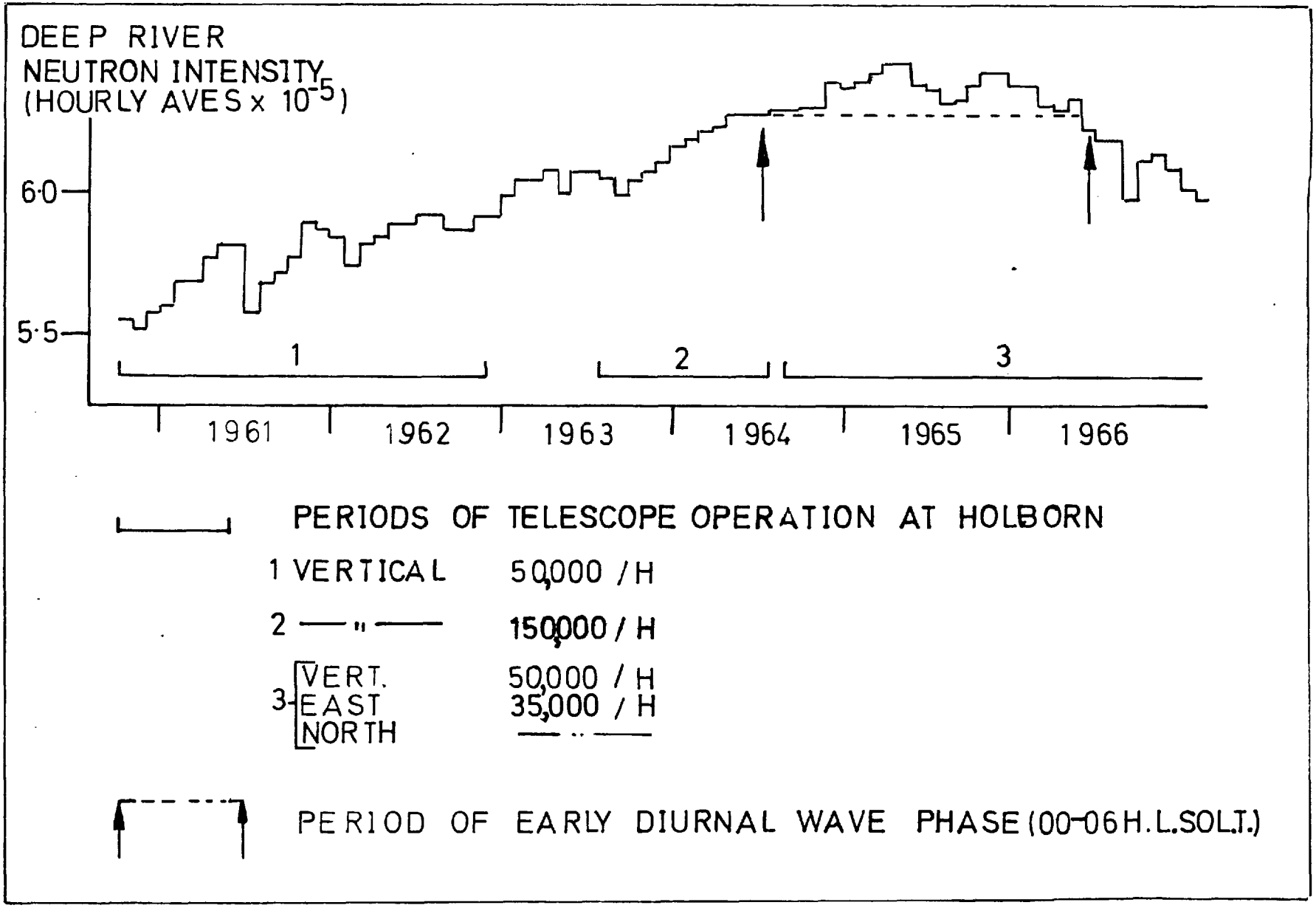


FIG. 4.6 DEEP RIVER NEUTRON INTENSITY OCTOBER 1960 - FEBRUARY 1967.

0900 hours L.Sol.T. until about May - June 1966. Then the phase again is about 1200 to 1800 hours L.Sol.T. These transition times are very approximate due to the large statistical fluctuations in monthly data. Similar "phase transitions" occur at various times lasting for 2 to 3 months and can be regarded as statistical in nature. The change from about July 1964 to about June 1966 is so long as to make it different from other transitions and to be much more significant. Thus the yearly averages for the vertical direction were significantly different as discussed earlier.

A similar summation dial for East and North from October 1964 is shown in Fig. 4.5 with the vertical repeated from the same time for comparison. All three show the rapid phase reversal near June 1966. East and North show the early time of maximum from October 1964 onwards which suggests they have already taken part in transition observed by the vertical telescopes in mid-1964.

The early phases seem to straddle the solar minimum period around 1965. Fig. 4.6 shows the maximum in Deep River neutron intensity corresponding to the minimum in solar activity. The arrows mark the period (approximately) when the diurnal phase was early. Considering the approximate nature of the estimation of this period, it is interesting that the transitions occur at times of equal neutron intensity on the ascending and descending parts of the solar cycle. This suggests that the long-term diurnal wave changes are associated with the same processes which exclude galactic cosmic rays from the earth giving rise to the 11-year cycle in intensity.

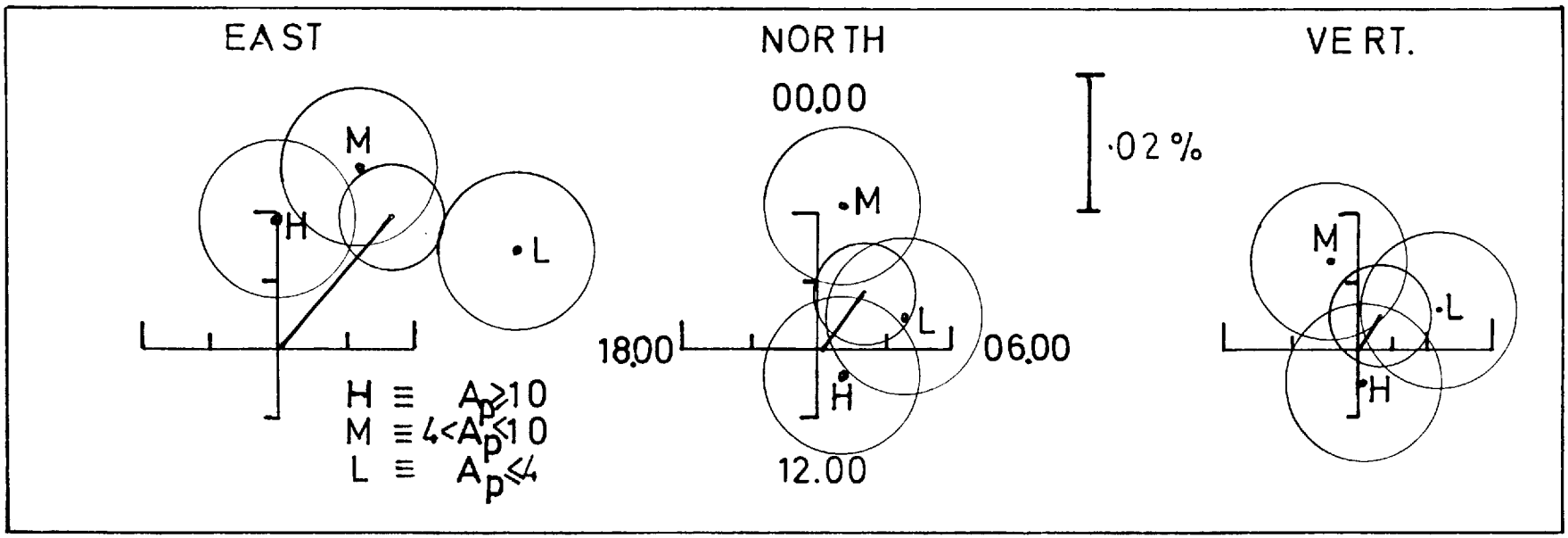


FIG. 4.7a SOLAR DIURNAL WAVES FOR SELECTED DAYS ACCORDING TO GEOMAGNETIC ACTIVITY (OCTOBER 1964 - SEPTEMBER 1966)

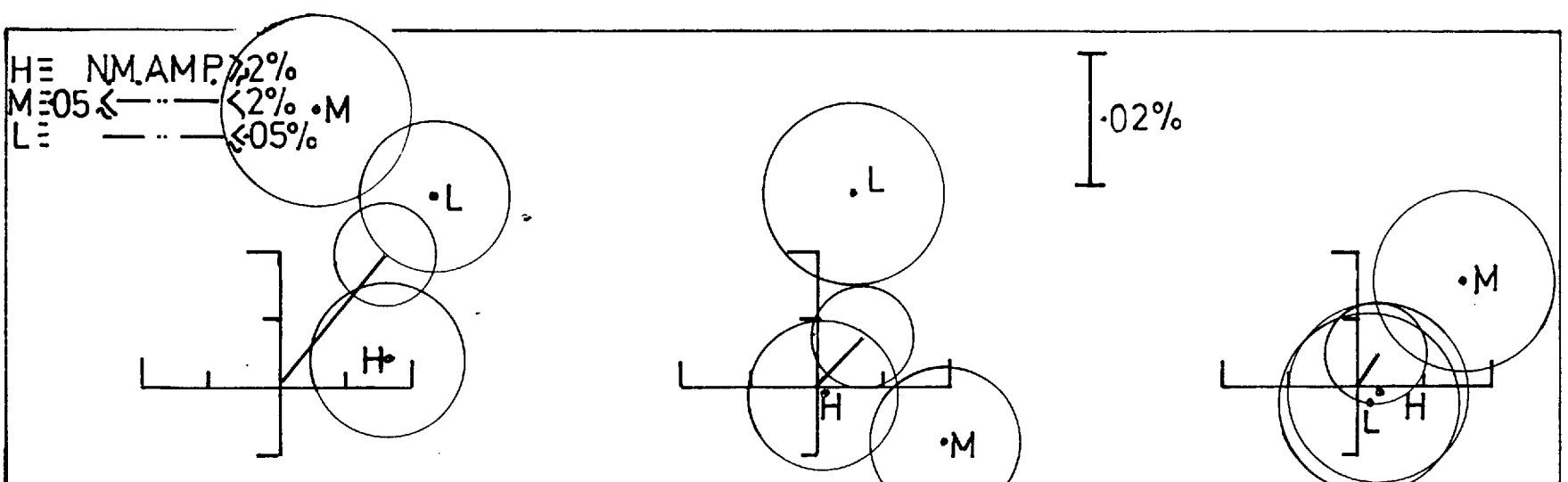


FIG. 4.7b SOLAR DIURNAL WAVES FOR SELECTED DAYS ACCORDING TO DEEP RIVER NEUTRON INTENSITY (OCTOBER 1964 - SEPTEMBER 1966).

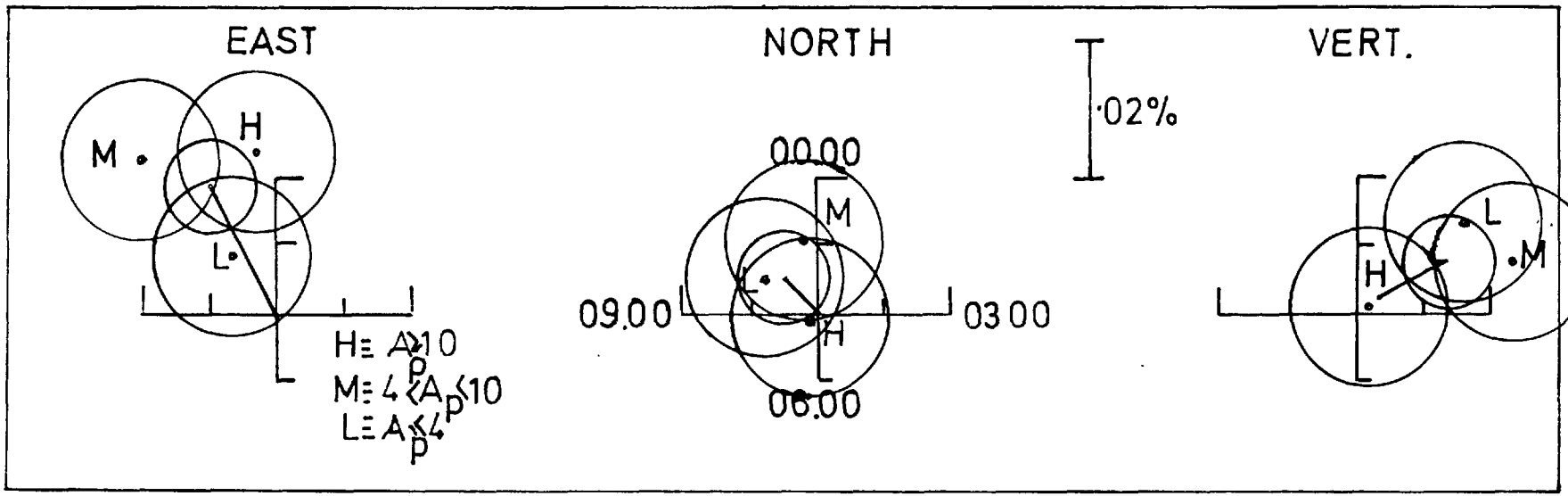


FIG. 4.8a SOLAR SEMI-DIURNAL WAVES FOR SELECTED DAYS ACCORDING TO GEOMAGNETIC ACTIVITY (OCTOBER 1964 - SEPTEMBER 1966).

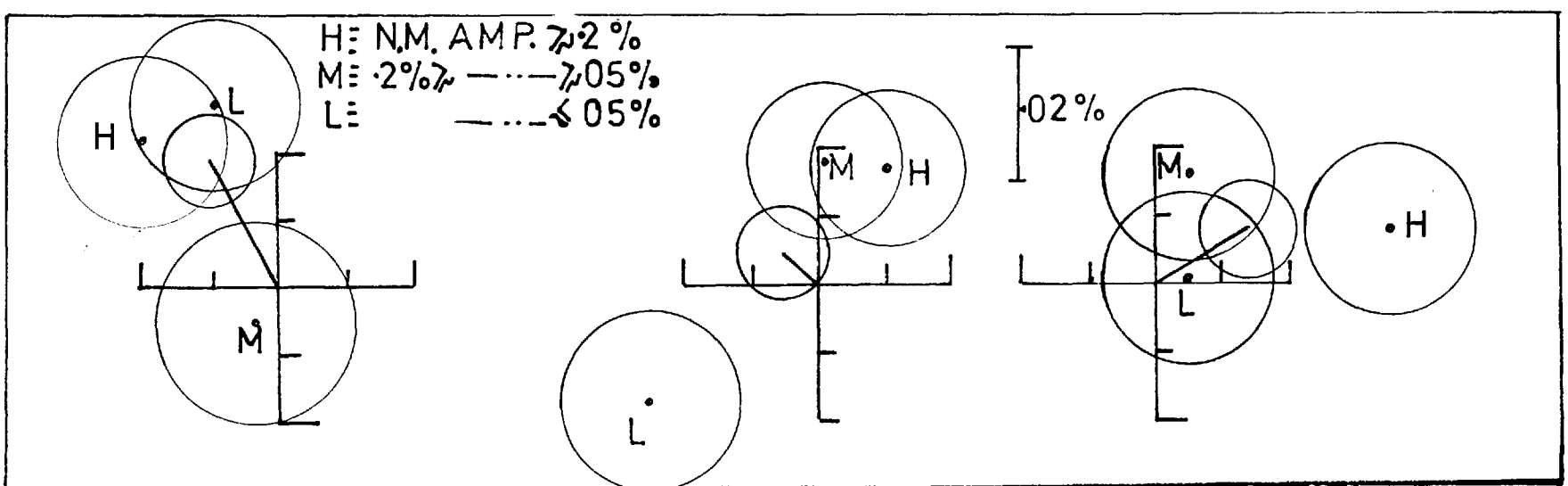


FIG. 4.8b SOLAR SEMI-DIURNAL WAVES FOR SELECTED DAYS ACCORDING TO DEEP RIVER NEUTRON INTENSITY (OCTOBER 1964 - SEPTEMBER 1966).

The North telescopes "look" roughly along the rotational axis of the earth and hence would not be expected to "see" any S.D.V. of external origin. Since the North diurnal and semi-diurnal components were observed to be insignificant for the period October 1964 to September 1966, one assumes that a S.D.V. of internal origin, e.g. a diurnal temperature effect can have only a very small contribution to the observed East S.D.V. The same is most probably true of the vertical telescopes since we have already seen (Chapter 3) that the atmospheric effects are very similar for inclined and vertical directions.

The most obvious agent for extra-terrestrial control of the S.D.V. is that of the plasma emitted from the sun. The plasma and its "frozen-in" magnetic field modulate the terrestrial field and hence may be monitored for activity by means of the magnetic Ap index. Effectively, the Ap index is a daily measure of the departure of the terrestrial magnetic field, at many selected stations, from the mean quiet field, after removal of secular and local influences. We classify days according to:

$Ap \leqslant 4$	Low Activity
$4 < Ap < 10$	Medium Activity
$Ap \geqslant 10$	High Activity

Corresponding means of the diurnal and semi-diurnal waves were obtained with the above classification over the 2 year period from October 1964 to September 1966. The results are displayed in Figs. 4.7a and 4.8a. No consistent, significant differences could be obtained between days of low, medium and high activity for the three directions.

A similar selection was made on the basis of the S.D.V. shown by the

Deep River neutron intensity. From a plot of intensity against time published in "Solar-Geophysical Data", days were chosen where the S.D.V. was $\geq 0.2\%$ as the days of "high activity. Days of smooth constant intensity were chosen as "low" days, all others being classed as "medium". A plot of the 2 year averages (Figs. 4.7b and 4.8b) shows no consistent pattern emerging for the three directions. Again, the large statistical errors make conclusions of doubtful value; any differences present with the above selection criteria were impossible to observe.

A more useful consequence of an extra-terrestrial origin to the S.D.V., such as the solar wind, is that stations all over the world should observe similar long-term changes. For this reason, the results from other stations are discussed in the next section.

4.3 Results from Other Stations

(i) Surface

We have seen that there is some contradiction in the results published so far. McCracken et al and Faller et al observe that the time averaged S.D.V. for mostly mid-latitude neutron stations remained constant in phase and amplitude from 1958 to 1965. Ahluwalia et al find a reduced amplitude in 1964 compared to 1958 for some equatorial neutron and meson monitors. This is confirmed by the results from Mawson (Hashim). Thus it seems that <u>if</u> any change in the diurnal wave took place, it involved only a change in amplitude and then only for equatorial and underground stations. This contrasts drastically with the solar minimum of 1954 when even high latitude surface stations saw big changes in amplitude and earlier phases for the diurnal variation, e.g. see Dattner and Venkatesan (1959).

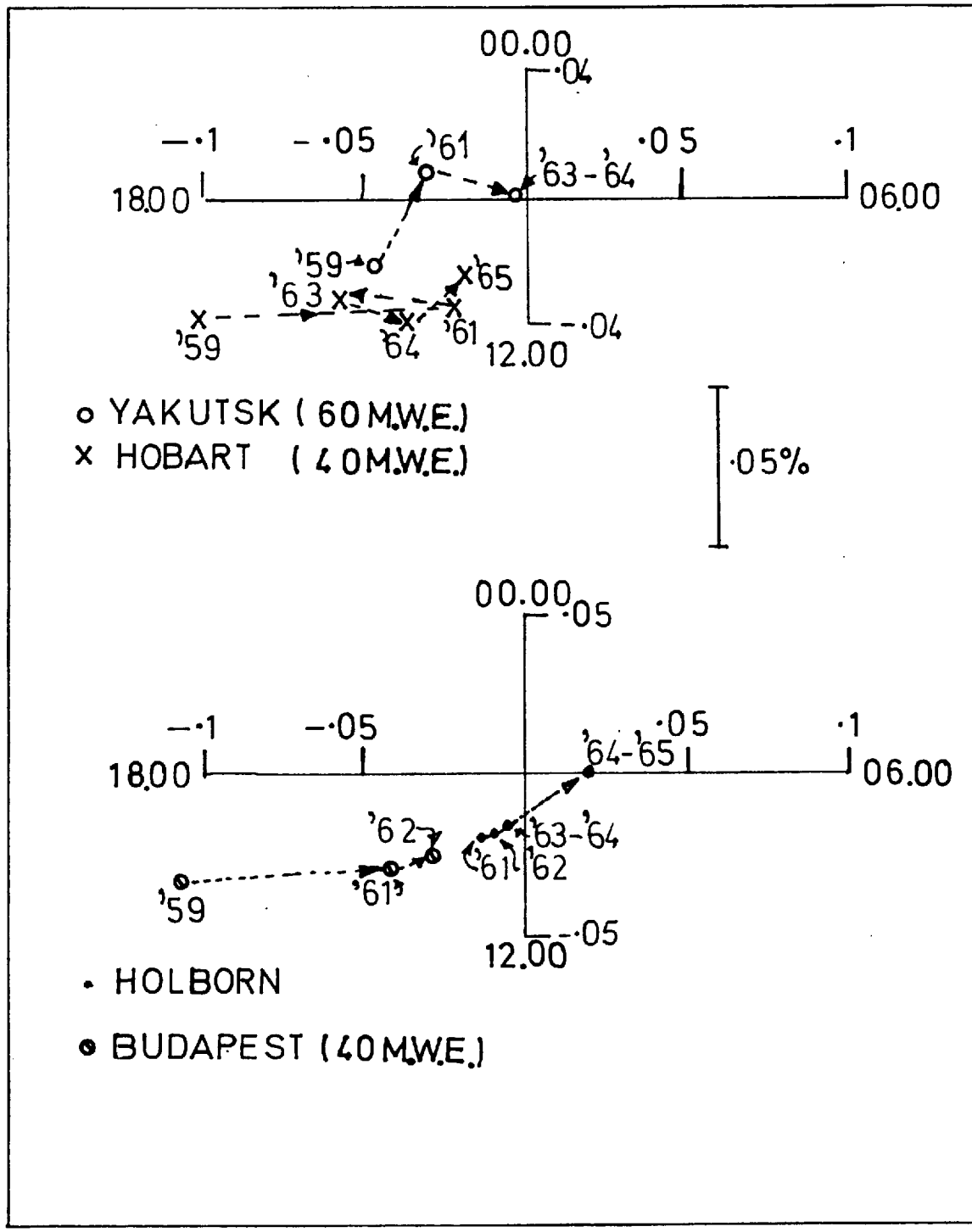


FIG. 4.9 END-POINTS OF SOLAR DIURNAL VECTORS FOR UNDERGROUND STATIONS (VERTICAL).

The semi-diurnal wave situation is not so clear and in fact, Venkatesan and Dattner (1958) can find no world-wide agreement for the long-term changes. This may be consistent with the conclusion of Forbush and Venkatesan (1960) that the semi-diurnal wave may be in error, at least at some stations, due to frictional lag in the barographs used. This results in inadequate pressure correction.

Ables et al (1965) found that the time averaged semi-diurnal wave for several mid-latitude neutron monitors showed no change from 1958 to 1965. The mean amplitude was $\sim$0.1% with a time of maximum 4.0 hours after correction for geomagnetic bending.

(ii) Underground

Results are available for only three other stations, viz Yakutsk (60 m.w.e.), Budapest (40 m.w.e.) and Hobart (40 m.w.e.). The end points of the diurnal wave vectors are plotted in Fig. 4.9 with Holborn included for comparison. The arrows show the progression from 1958 onwards. The stations are paired for clarity but it can be seen that the two 40 m.w.e. stations show similar amplitudes ($\sim$0.1%) and phases ($\sim$ 1600 hours L.Sol.T.) in 1959 reducing rapidly in 1961 to corresponding values of $\sim$ 0.05% at $\sim$ 1500 hours L.Sol.T. Further data in the case of Hobart shows that not much change takes place after that. The point marked 1965 for Hobart is, in fact, for the period September 1964 to August 1965 (being the latest data available) and covers a substantial part of solar minimum period (which may be taken as the calendar year 1965).

The Yakutsk results show a considerable reduction from 1959 to 1964.

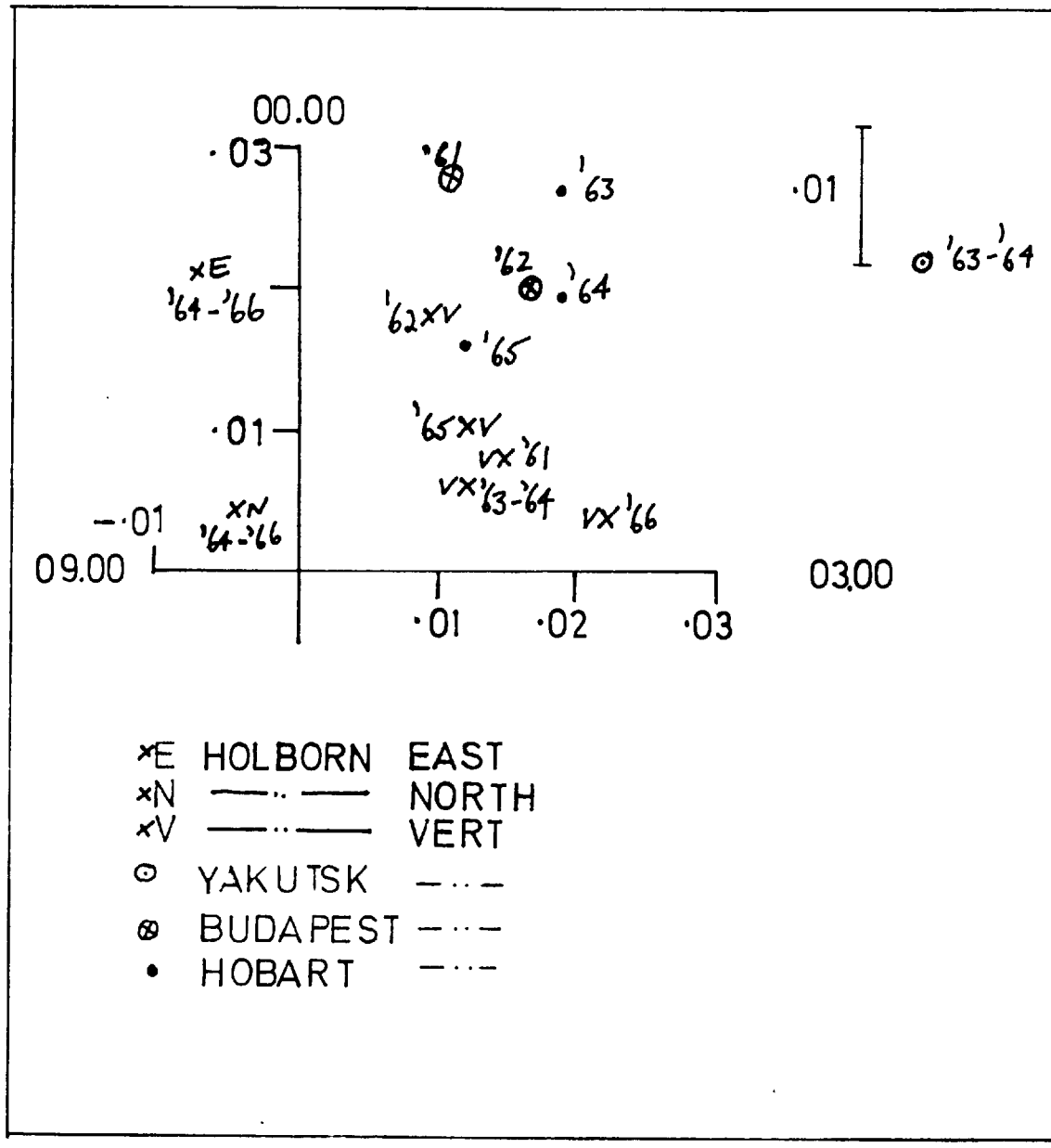


FIG. 4.10 SEMI-DIURNAL VECTORS FOR UNDERGROUND STATIONS 1960 - 1966.

The point marked 1963 - 1964 being a 2 year average to reduce the statistical error. This point is very closely zero and not inconsistent with the 1963 - 1964 value for Holborn considering the errors involved ($\sim$0.01%).

Thus there is considerable agreement that the amplitude at 40 m.w.e. and 60 m.w.e. decreased from 1959 onwards with some evidence that at 60 m.w.e. the amplitude went to zero (Yakutsk 1963 - 1964) and to early times of maximum (Holborn 1964 - 1965). There seems to be no disagreement between similar stations in Northern and southern hemispheres (Budapest 40° N. and Hobart 40°S.) establishing the world-wide nature of the effect.

Results on the semi-diurnal wave are not readily available compared to the diurnal wave. Fig. 4.10 summarises just a few results for Yakutsk, Hobart and Budapest with Holborn results repeated for comparison. No conclusions can be drawn with regard to the secular variation due to the scarcity of data. However, it is clear that the semi-diurnal wave was present at 40 m.w.e. and 60 m.w.e. from 1961 to 1966. Only the Hobart and Holborn results are available for the solar minimum of 1965; from these two it appears that the semi-diurnal wave did not reduce to zero or undergo large phase changes at this time.

The underground vertical semi-diurnal amplitudes are comparable to the diurnal amplitudes, suggesting that the energy dependences of the two effects are different, since at s/l the semi-diurnal wave is much smaller than the diurnal. The small North amplitude suggests that there is a latitude dependence similar to that for the diurnal effect. The underground times of maximum are the same as those at s/l; geomagnetic correction makes these about 0300 hours L.Sol.T.

4.4 Conclusions

(a) Solar Diurnal Wave

The mean diurnal wave has shown energy dependent systematic changes of phase and amplitude in the declining period of solar activity 1958 - 1965. At 60 m.w.e. the phase went from~1400 hours to~0600 L.Sol.T. for approximately 2 years (July 1964 to June 1966). Latest data show a recovery to ~1400 hours. The amplitude was roughly constant from 1961 to 1966, being about 0.02%. These effects were observed by vertical pointing telescopes and confirmed by east-pointing telescopes from October 1964 onwards. North pointing telescopes showed insignificant variations, suggesting that all three directions observe only a small daily temperature variation.

(b) Solar Semi-Diurnal Wave

At 60 m.w.e. the semi-diurnal wave was approximately constant from 1961 to 1966. The amplitude was about 0.02%, being comparable to that of the diurnal wave. The time of maximum corresponded to that observed at s/l, i.e. about 0300 hours for the vertical direction.

CHAPTER 5

SOLAR DAILY VARIATION - THEORETICAL

5.1 Introduction

The existence of an anisotropy in cosmic rays in the region of the earth is now established beyond doubt. The main features of the average diurnal effect are:-

(i) A small amplitude of about 0.4% in the solar equatorial plane.

(ii) A cosine λ dependence of the amplitude with inclination λ from the solar equatorial plane.

(iii) A maximum amplitude (0.4%) 90° east of the Earth-Sun line with a $\sin\theta$ dependence on azimuthal angle θ .

(iv) An energy independent variation below about 20 GeV.

The above summarises the results of McCracken and Rao (1965) and seemed to obtain in the period 1957 - 1965. We also know that:-

(v) The anisotropy shows long-term variations of amplitude and phase (before geomagnetic correction) with possibly an 11 or 22-year period.

(vi) There are short-term variations in amplitude and direction which may last a few days. Basically, it appears that after magnetic storms and during the main phases of Forbush decreases, the amplitude increases and the direction of maximum moves nearer to the Earth-Sun line.

(vii) There is some evidence (Sarabhai and Bhauser 1958) that there are 27-day periodicities in the amplitude, thus connecting the anisotropy with the rotational period of the sun.

The semi-diurnal wave is less well understood but it most probably has an amplitude of about 0.1% at 10 GeV. and increases with energy. The minima are along a line 60^{o} west of the Earth-Sun line and are therefore associated with the mean direction of the interplanetary magnetic field lines.

We wish to discuss possible physical processes causing modulation and then try to understand the Holborn results 1961 - 1966 in terms of detailed models which incorporate the seven points outlined above.

5.2 Physical Processes Causing Modulation

The most obvious forces for modulation of the primary galactic particles are (i) gravitational, (ii) electric and (iii) magnetic. Gravitational forces are too small considering the large energies of the particles and their relatively small mass. Electric and magnetic forces both seem possible and models using them may be conveniently classified into (a) Geocentric and (b) Heliocentric.

(a) Geocentric Models

There is a geocentric magnetic field of internal origin which is largely static showing only a small long-term change. As a consequence of Liouville's Theorem, stationary magnetic (and electric) fields cannot by themselves generate anisotropies. More important is the fact that large anisotropies have been observed by detectors in space probes far from the earth where geocentric fields are too weak to be effective (McCracken 1966). Similar measurements of the Forbush effect far from the earth are contrary to the predictions of geocentric models for modulation. Thus the geomagnetic field and the geoelectric fields postulated by Nagashima (1953) and others

do not seem likely candidates for the origin of the S.D.V.

(b) Heliocentric Models

An electric field centred on the sun has been postulated to explain the 11-year cycle in cosmic ray intensity. Emission of conducting plasma streams from the sun could distort the electric field near the earth to generate anisotropies. However, the predictions of electric field models are at variance with the data in the presence of low energy particles at earth during the solar maxima in sunspot activity (Dorman 1963). Moreover, the 11-year, 27-day and Forbush effects are described by a magnetic rigidity dependence rather than an energy dependence. This suggests a magnetic rather than electric modulation.

Direct magnetometer measurements of the interplanetary magnetic field showed it to be inconsistent with a dipole field centred on the sun. Thus the early models of Alfvén (1954) and Elliot (1960) using a solar dipole field seem wrong observationally. Likewise, the field-free region surrounding the sun suggested by Davis is untenable.

The best fit between theory and observation is obtained by Parker's (1958) model for the interplanetary magnetic field. He demonstrates that radial emission of neutral ionised plasma is dynamically possible from the sun. The surface field of the sun ($\sim$ 1 gauss) is drawn out radially; rotation of the sun causes the field lines to take the form of an Archimedian spiral. This underlying pattern of spiral field and radially flowing plasma ($v \simeq$ 300 to 400 km/sec.) has been verified by Ness (1965), Bonetti et al (1963) and others. Fluctuations in plasma emission velocity can cause perturbations in the magnetic field; such perturbations or "kinks" act as scattering centres

which are thought to generate cosmic ray modulation. These kinks have been observed and have typical separations of $10^{11} - 10^{12}$ cms. The kinks are thought to remove galactic cosmic rays from the solar cavity by outward convection; with the assumption of a range of scattering lengths, Dorman (1963) showed that this model fitted the observational facts on the 11-year variation. Twenty seven day and short-term variations follow naturally from the assumption of plasma streams of enhanced velocity. The generation of the anisotropy is less clear.

Ahluwalia and Dessler (1962) consider particles spiralling around magnetic field lines which have the configuration of the Parker model without scattering centres. In this smooth field, the particles' guiding centres drift past the earth with a velocity of several hundred kms./sec. generating a diurnal variation with a maximum at about 1500 hours L.Sol.T. This is somewhat earlier than the observed phase of about 1800 hours L.Sol.T. More important, the steady field cannot generate such an effect as a consequence of Liouville's Theorem (Stern 1964). In practice, a density gradient is generated as well which causes just enough streaming to balance the electric field drift.

To overcome this, Parker (1964) assumes that scattering centres superimposed on the Archimedian spiral field wipe out density gradients beyond the orbit of the earth. This effectively eliminates the radial streaming, leaving only the azimuthal component. The streaming velocity of 400 km./sec. corresponds to rigid rotation of the cosmic ray gas with the sun, hence the term "corotation".

With the same model, Axford (1964) obtains the same result, i.e.energy

independent corotation up to some upper energy limit near 100 GeV. Since the effect is similar to that of Compton and Getting (1935), with a cosmic ray gas overtaking the earth, there is a typical cosine λ dependence on heliographic latitude. Thus the Parker model fits the requirements for the steady component of the diurnal variation so long as scattering centres are superimposed on the stationary magnetic field.

An extension of the above model is that due to Krimsky (1965). The Archimedian spiral field is assumed in the solar equatorial plane allowing for the existence of two diffusion coefficients, viz (i) $K_{\perp}$ for diffusion across field lines and (ii) $K_{\parallel}$ for diffusion along field lines where $K_{\parallel} \gg K_{\perp}$. Effectively, $K_{\parallel}/K_{\perp}$ is assumed to have some large value near 10. With certain simplifying assumptions, Krimsky obtains a diurnal amplitude A where

$$A = 0.6 \quad \frac{b}{b + E} \quad \% \quad \text{with } T_{max.} = 1800 \text{ hours}$$

where b is a constant and E is energy. It is of interest that the direction of the interplanetary field at the orbit of the earth corresponds to the minima in intensity observed in the semi-diurnal wave. Thus the semi-diurnal wave has a simple interpretation in terms of "sinks" along the field lines.

5.3 Comparison Between Holborn Results and the Predictions of Interplanetary Field Models

Since the Parker field model is well verified experimentally, we will discuss two versions, one with isotropic diffusion of cosmic rays and the other, due to Krimsky, including anisotropic diffusion.

5.3.1 Isotropic Diffusion

We take the diurnal amplitude to be

$$A(R) = 0.4 \quad \cos(\lambda) \qquad R \leqslant R_{max.}$$

$$A(R) = 0 \qquad\qquad\qquad R > R_{max.}$$

where λ is angle between the solar equatorial plane and the particle trajectory beyond the influence of the geomagnetic field. Since the telescopes have fairly symmetrical sensitivity patterns (Fig. 2.6, Chapter 2), we use mean directions of 32° and 0° to the zenith for the inclined and vertical telescopes, respectively. Deflections in the geomagnetic field were obtained from the Brunberg-Dattner diagrams (1953). These describe deflections in a simple dipole approximation to the geomagnetic field; at relatively high rigidities these are accurate to within about 5° and are therefore adequate for Holborn. The energy responses of the detectors were taken to be the W(R) functions derived in Appendix I.

In the small rigidity interval δR the components to the diurnal vector are:-

$$\delta a_1 = A \cos(\lambda). \sin(\gamma_E). W(R). \delta R$$

$$\delta b_1 = A \cos(\lambda). \cos(\gamma_E). W(R). \delta R$$

where γ_E is the particle deflection east of the meridian through the Holborn station. Thus the normalised amplitude integrated over all energies is

$$A_1 = \frac{\left\{\left[\int_0^{\infty} A.\cos(\lambda).\sin(\gamma_E). W(R).dR\right]^2 + \left[\int_0^{\infty} A.\cos(\lambda).\cos(\gamma_E). W(R).dR\right]^2\right\}^{\frac{1}{2}}}{\int_0^{\infty} W(R).dR}$$

The phase advance (in degrees) over that of the anisotropy in space is

$$\Psi_E = \tan^{-1}\left[\frac{\int_0^{\infty} A.\cos(\lambda).\sin(\gamma_E). W(R).dR}{\int_0^{\infty} A.\cos(\lambda).\cos(\gamma_E). W(R).dR}\right]$$

A_1 and Ψ_E have been calculated for Vertical, East and North telescopes

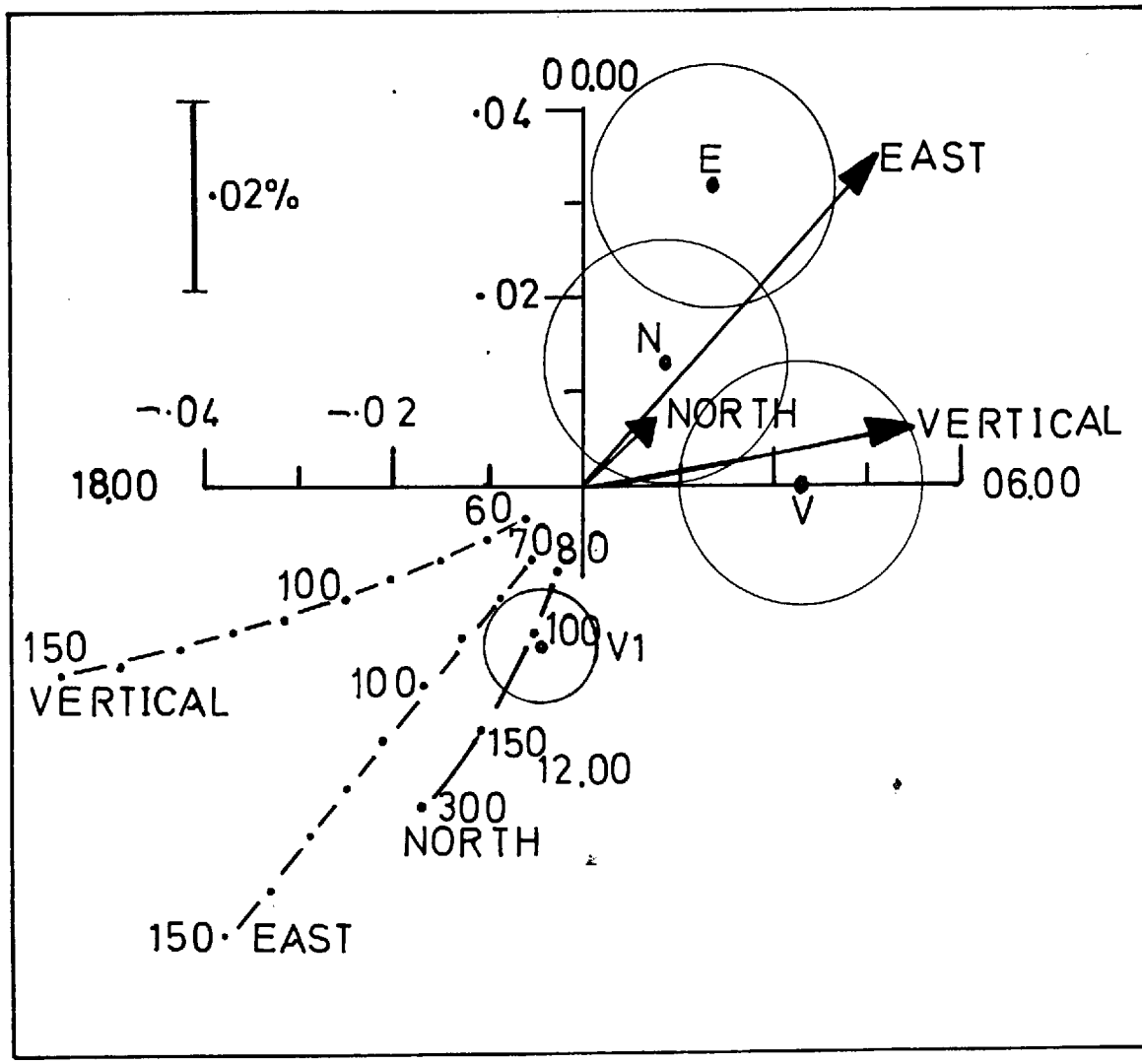


FIG. 5.1 OBSERVED AND PREDICTED SOLAR DIURNAL WAVES AT HOLBORN.
VECTORS MARKED EAST, NORTH AND VERTICAL ARE THE EXPECTED ORBITAL MOTION EFFECTS.
POINTS MARKED E, N AND V ARE THE OBSERVATIONS FOR THE EAST, NORTH AND VERTICAL TELESCOPES FOR THE PERIOD OCTOBER 1964 - SEPTEMBER 1965.
THE DOT-DASH CURVES ARE THE END-POINTS OF THE PREDICTED VECTORS DUE TO THE COROTATION EFFECT. THE DOTS ARE MARKED WITH THE CORRESPONDING R_{MAX}. VALUES.

for $R_{max.}$ = 0 to 300 GV. The results are plotted in Fig. 5.1 along with the observed vectors from 1960 to 1966. Since no appreciable change occurred in the observed diurnal wave from November 1960 to July 1964, the diagram shows the average for that period(V1).

The diurnal wave for 1960 to 1964 is just consistent with this model if $R_{max.} \simeq$ 70GV. However, the East and vertical data for 1964 to 1965 are inconsistent with this corotation model, the phases being completely opposite to what one expects. It is difficult to imagine how the phase can reverse since basically the effect arises due to the rotation of the sun. Hence, one suspects that the corotation model may have been ineffective in the solar minimum period and that the early time of maximum has some other origin.

The most obvious other sources are:-

(i) atmospheric temperature oscillations

(ii) a Compton-Getting effect due to the earth's orbital motion through the cosmic ray gas.

For (i) we would expect the North amplitude to be as large as the East and vertical amplitudes which is contrary to the observations. The North vector is close to zero and may be taken to represent the atmospheric component. Besides this, there are phase differences between the East and Vertical vectors which suggest an origin external to the geomagnetic field.

For (ii) we would expect a time of maximum of 0600 hours L.Sol.T. external to the geomagnetic field. With geomagnetic correction of about 1 - 3 hours, the observed vectors agree with an orbital motion effect. Thus a detailed calculation is performed in order to compare the results with those obtained for the solar minimum and then, if there is agreement, to use those

results to correct the S.D.V. observed in 1960 to 1964. A better comparison between the observations and the Parker model productions can then be made.

Diurnal Wave Due to the Earth's Orbital Motion

From the point of view of an observer situated on the Earth, the cosmic rays appear as a gas with random particle velocities close to c, with virtually no collisions and a relatively small mass motion from the 0600 hour direction of velocity 30 km./sec. There are two effects of this motion:-

(a) a change of energy of the particle, from E to E^{1}, as seen from the earth, where

$$E^{1} = \frac{E}{1-\beta\cos\theta}$$

where θ is the angle between the particle trajectory and the line of motion of the earth. This results in a change in the differential energy spectrum of an amount δn where

$$\begin{aligned}\delta n(E) &= n(E^{1}).\delta E \\ &= n\left[E\,(1-\beta\cos(\theta)\right]\delta E \\ &= n(E).(1-\beta\cos(\theta))^{-\gamma-1}\,E\end{aligned}$$

$$\therefore \quad \frac{\delta n(E)}{n(E)} \simeq \beta\cos(\theta)\;(\gamma+1).\,\delta E \text{ for small } \beta$$

(b) a change in the differential energy spectrum of amount δn where

$$\begin{aligned}\delta n(E) &= n^{1}(E)\,\delta E \\ &= \frac{n(E)}{(1-\beta\cos(\theta))^{3}}\,\delta E \\ &= 3\beta.\cos(\theta).\delta E \text{ for small } \beta\end{aligned}$$

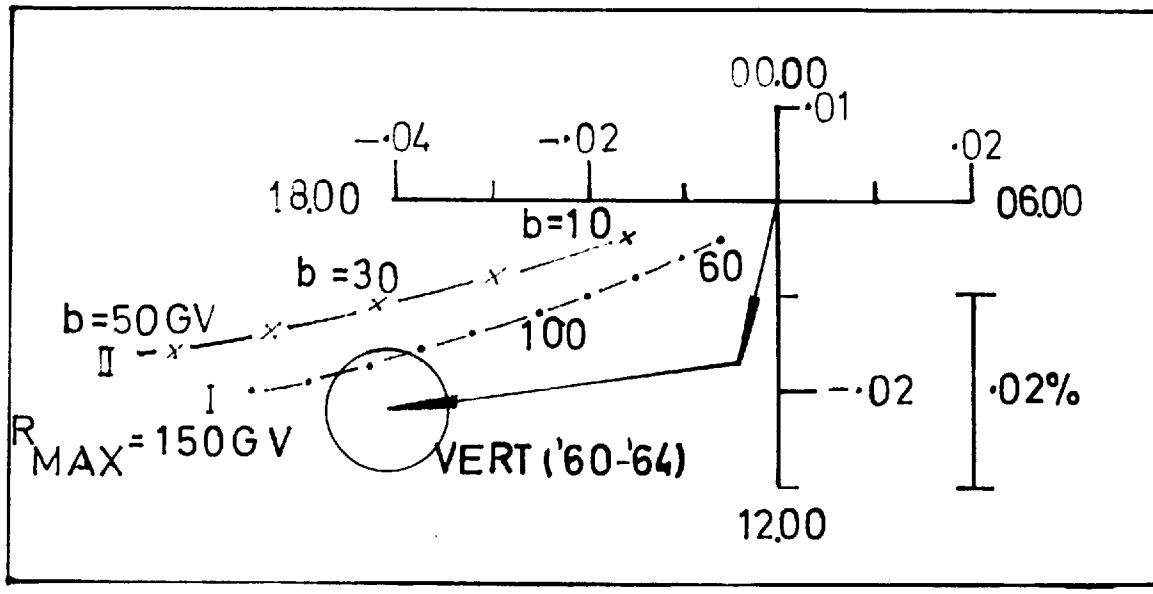


FIG. 5.2a VERTICAL SOLAR DIURNAL WAVE CORRECTED FOR THE ORBITAL MOTION EFFECT.

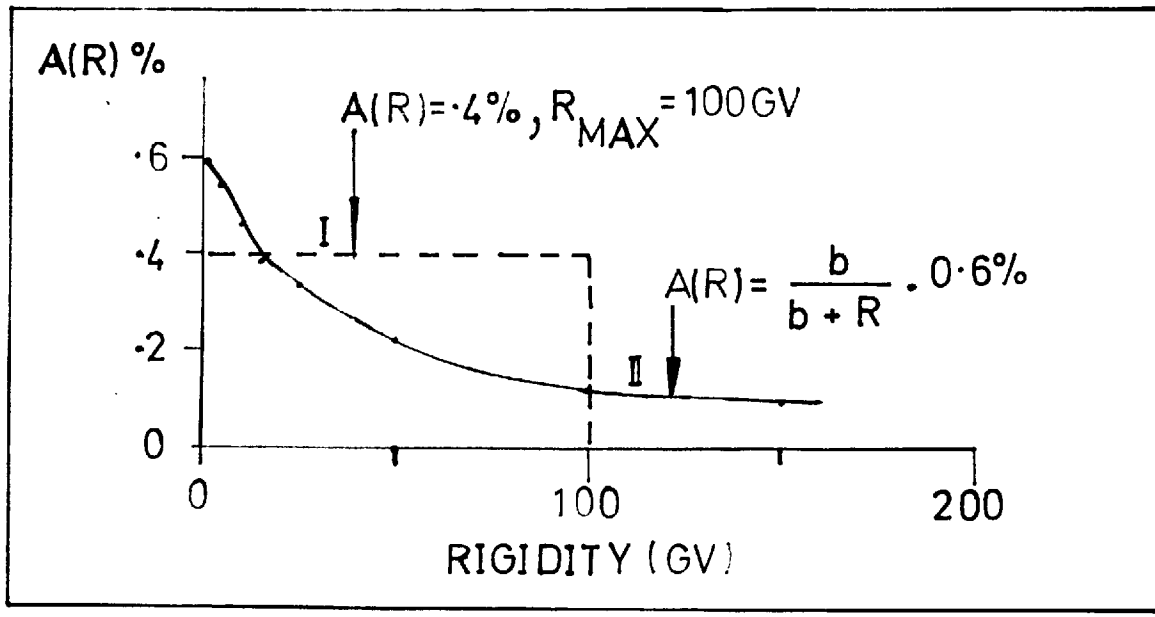


FIG. 5.2b RIGIDITY DEPENDENCES OF DIURNAL WAVE FOR CURVES I AND II IN FIG. 5.2a.

Thus, the total effect of (i) and (ii) is:-

$$\frac{\delta n(E)}{n(E)} = (4+\gamma).\beta.\cos\theta \qquad \text{where } \gamma = 1.5$$

$$\text{and } \beta = \frac{v}{c} \simeq 10^{-4}$$

Thus we get a diurnal wave with a time of maximum at 0600 hours L.Sol.T. with amplitude 0.055% and cosine θ dependence on angle θ between the ecliptic plane and the arrival directions of the particles.

Integrating over all energies in a similar way to the calculation for the corotation effect we get the orbital motion vectors shown in Fig. 5.1. There is excellent agreement between these vectors and the observations for the period January 1965 to December 1965. This period corresponds to the maximum in neutron intensity observed at Deep River (plotted in Fig. 4.6, Chapter 4). The use of a complete year eliminates possible sidereal effects. This suggests that :-

(i) the temperature contribution is less than the statistical error of about 0.02%.

(ii) the corotation present between November 1960 and July 1964 disappeared leaving only the orbital motion effect. Recent results suggest that the corotation has again become important as solar activity increases.

The data for November 1960 to July 1964 have been corrected for the orbital motion effect and shows better agreement with the predicted corotation anisotropy if we take $R_{max.} \simeq 130$ GV. (Fig. 5.2a). Before discussing this further, we will derive the predicted effects when anisotropic diffusion is allowed in the Parker model.

5.3.2 Anisotropic Diffusion

Skripin et al (1965) suggest that the diurnal amplitude A(E) given by

$$A(E) = 0.6 \quad \frac{b}{b + E} \quad \%$$

fits the observed data from four levels at Yakutsk, viz. surface, 7, 20 and 60 m.w.e. They found that

b = 60 GeV. at solar maximum (1958)

b = 40 GeV. in 1962 - 1963

The Holborn results for November 1960 to July 1964 fit this spectrum with b = 20 to 40 GeV. (after correction for the orbital motion effect). Curve II in Fig. 5.2a shows the predicted values for b = 10 to 50 GV. Physically this model may not have a strong foundation; the point of interest is that it allows the corotation effect to decrease slowly with energy rather than have the artificial transition at $R_{max.}$ predicted by the simple Parker Model. Fig. 5.2b shows the spectrum of the daily variation, A(R), for the two models discussed for typical values of $R_{max.}$ = 100 GV. and b = 30 GV. (We have converted from energy to magnetic rigidity for the sake of convenience since W(R) is determined in terms of R. Numerically E and R are nearly the same at $E \gtrsim 2$ GeV. for protons).

The results of the two models can both be made to fit the Holborn data despite the big differences in energy dependence. Thus Holborn results alone are not a sensitive test of the model used and therefore we shall apply these models to some surface stations. Before doing so, it must be pointed out that we have not considered a contamination of the Holborn results by small local effects. For the sake of completeness, we consider briefly four most obvious possibilities below:-

(a) Rainfall

This shows no obvious S.D.V. and is rapidly drained from the surface

anyway.

(b) Water-Bearing Strata Above the Laboratory

These have largely been removed in the Holborn area so that the overburden is mostly clay. The latter is fissured and contains appreciable quantities of water but it is difficult to see how this water can exhibit an S.D.V. since it is under a large pressure and is therefore not freely connected to outside sources.

(c) People/Traffic

Both exhibit large S.D.V.'s. MacAnuff (1951) estimates a maximum possible "population" effect of 0.025% but this assumes a density of people which seems too high. A detailed diagram showed the cones of maximum sensitivity of the detectors not to intercept local buildings but the road surface. Thus the traffic seems more important than people in this respect. From a study of the traffic flows in the Holborn area, it was possible to estimate the maximum "traffic" effect. This was 0.004% and as such, significantly less than the statistical errors involved in this experiment.

(d) Local Instrumental Effects

Laboratory temperature and mains voltage fluctuations could both cause a local, spurious S.D.V. The former could be eliminated since the laboratory temperature varied less than one degree C. in a year. Mains voltage fluctuations were removed by several stages of smoothing.

We conclude that the observed S.D.V. at Holborn is most probably due to anisotropies and atmospheric temperature effects. The latter were considered small for the reasons given earlier and therefore we conclude that the diurnal

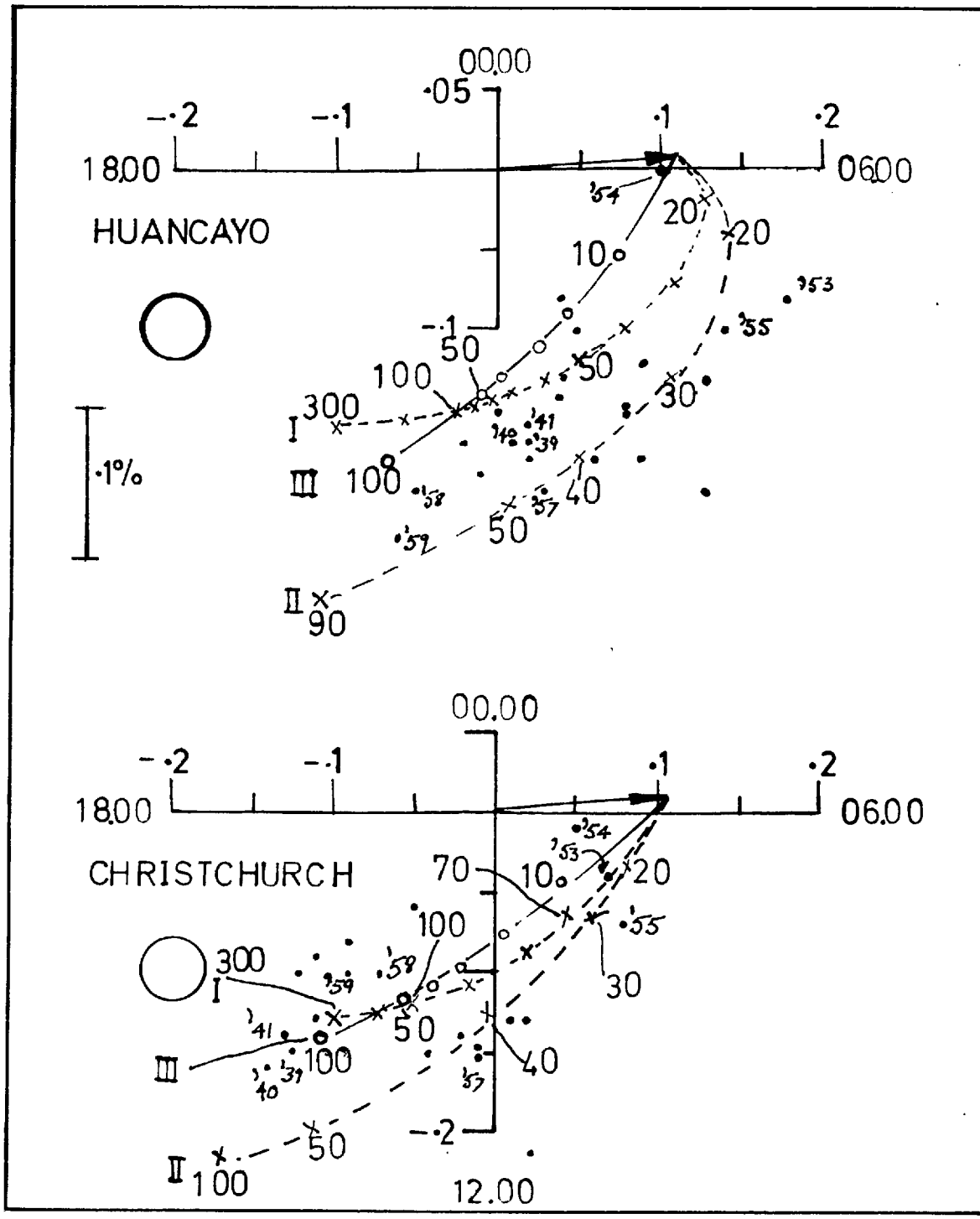


FIG. 5.3 OBSERVED AND PREDICTED DIURNAL WAVES FOR HUANCAYO AND CHRISTCHURCH IONIZATION CHAMBER STATIONS. SEE TEXT FOR DESCRIPTION OF DIAGRAM.

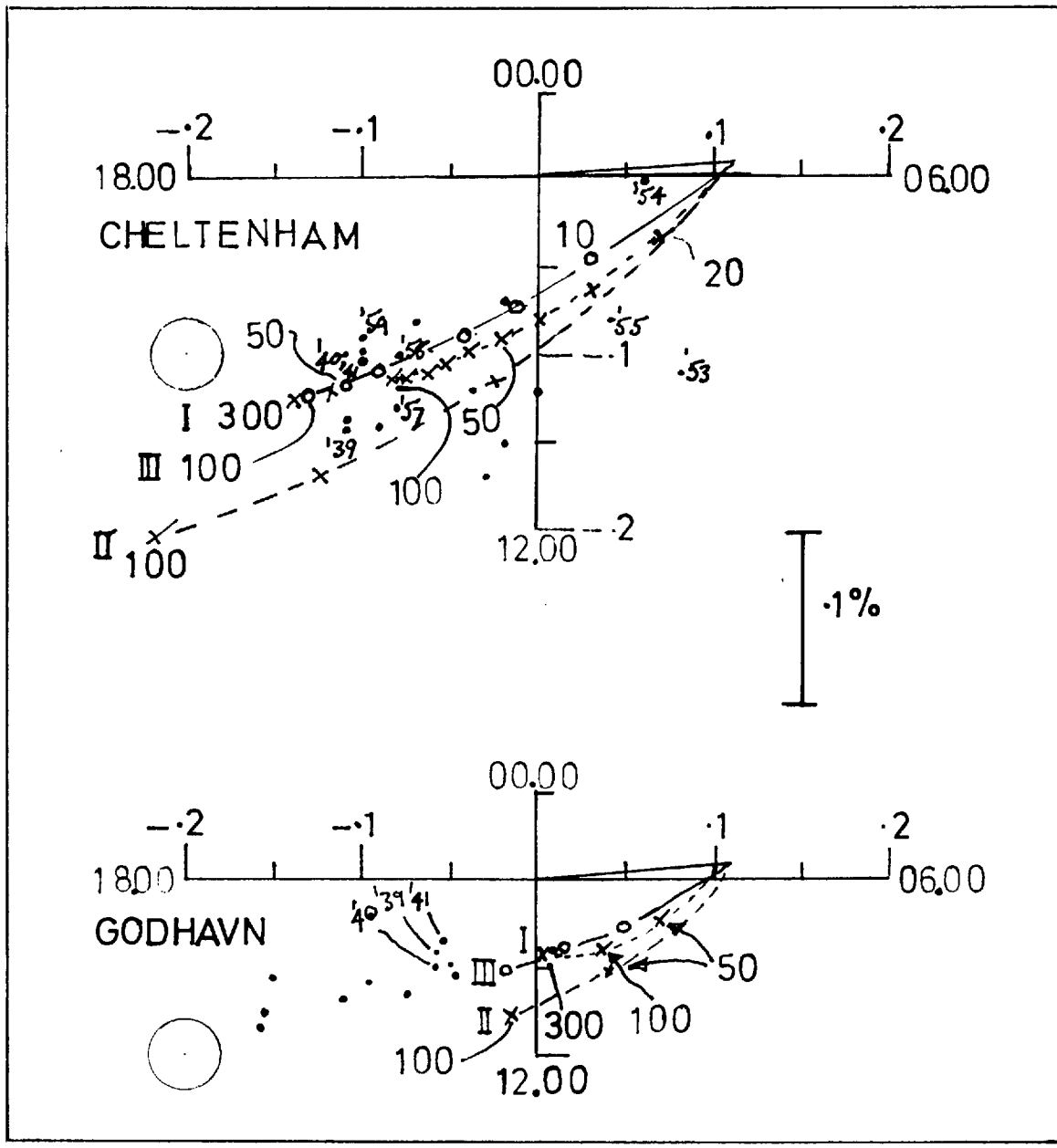


FIG. 5.4 OBSERVED AND PREDICTED DIURNAL WAVES FOR CHELTENHAM AND GODHAVN IONIZATION CHAMBER STATIONS. SEE TEXT FOR DESCRIPTION OF DIAGRAM.

variation at Holborn is accounted for by the two forms of Parker's model. If the amplitude of the corotation effect remains constant with time, the reversal of phase (of the diurnal wave) observed in the solar minimum period can be explained as a reduction of $R_{max.}$ to $\sim$70 GV. or less. With the model incorporating anisotropic diffusion, the same effects are described by b reducing to 10 GV. or less.

5.4 Comparison Between the Results of Some Surface Stations and the Predictions of Parker's Model

Long periods of continuous recording of the ionizing component have been obtained by the stations operated by the Carnegie Institute:-

		Geomagnetic Latitude
(1)	Huancayo	$- 0.6^{\circ}$
(2)	Cheltenham	50.7°
(3)	Christchurch	-48.6°
(4)	Godhavn	79.8°

All operate shielded ionization chambers, the results of which have been analysed for diurnal and semi-diurnal waves by Forbush and Venkatesan (1960). The end points of the vectors representing the mean yearly diurnal variation from 1937 to 1954 have been plotted in Figs. 5.3 and 5.4. For Godhavn, only 1939 to 1950 results are available.

For each station, three predicted curves are shown using the following amplitudes:-

Curve I $\quad A = 0.4\% \quad R \leqslant R_{max.}$

$\quad\quad\quad A = 0 \quad\quad R > R_{max.}$

$R_{Max.} = 10 - 300$ GV.

Curve II $\quad A = 0.7\% \quad R \leqslant R_{max.}$ $\quad A = 0 \quad R > R_{max.}$ $\quad R_{max.} = 10 - 300$ GV.

Curve III $\quad A = 0.6 \quad \frac{b}{b + R} \quad b = 10 - 100$ GV.

In the case of Christchurch and Cheltenham, nearby stations (Invarcargill and Swarthmore respectively) have been used to obtain the predicted amplitudes. This is because trajectory calculations are not available for Christchurch and Cheltenham; asymptotic directions of approach using a six degree simulation of the geomagnetic field are available for Invarcargill and Swarthmore. Since the corresponding stations are located within a few degrees of one another, no appreciable error will be introduced by this method. Differential response functions used were those of Webber (1962) for sea level. Since Huancayo is at an altitude of $\sim$ 3000 metres, there will be a small error introduced. Only the vertically arriving particles will be considered so that we do not expect exact results anyway. Rather, the predicted amplitudes should be correct to within $\sim$ 10%.

The S.D.V. caused by the atmospheric temperature effect was assumed to be that found by Quenby and Thambyahpillai (1960) for Huancayo, i.e. 0.11% at 0540 hours L.Sol.T. The calculated amplitudes were plotted using end point of the temperature vector as the "origin". The curves I to III in Figs. 5.3 and 5.4 then represent the trace of the end-point of the diurnal vectors for varying values of $R_{max.}$ and b. The use of the same temperature correction at all stations is justified on the grounds that Mori et al (1965) using many stations at all latitudes find a similar temperature vector to that of

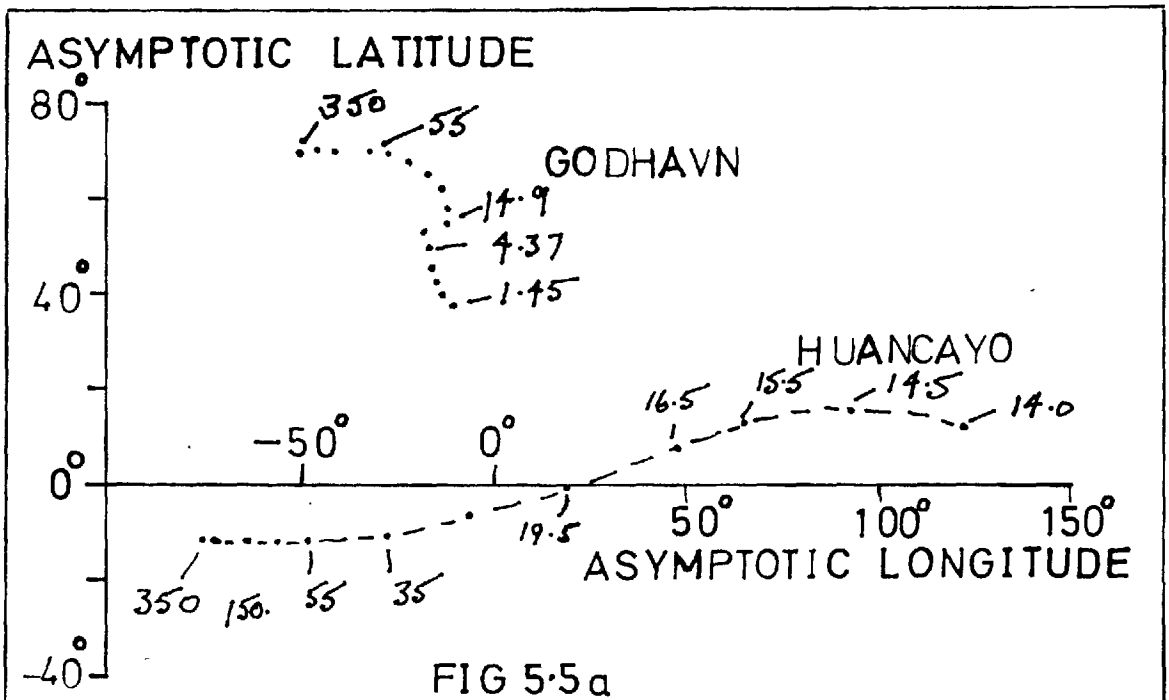


FIG 5·5a

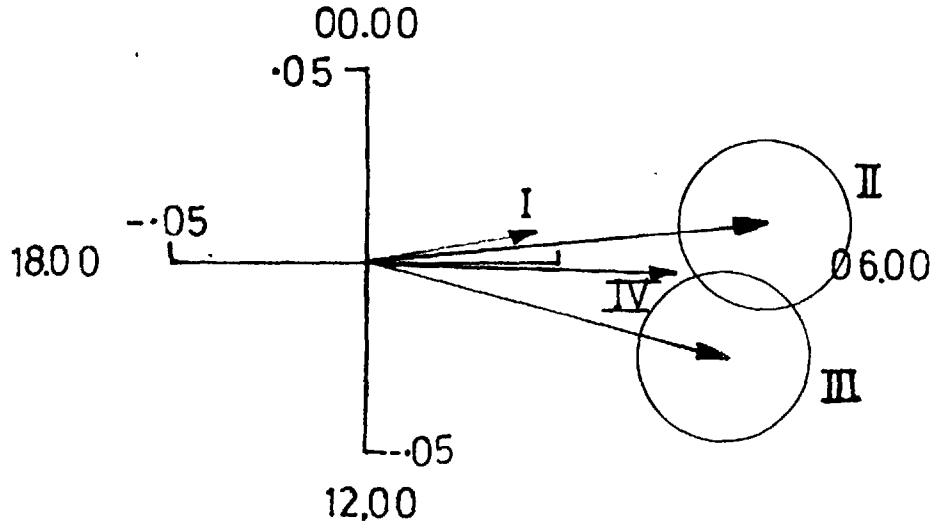


FIG 5·5b

FIG. 5.5.a ASYMPTOTIC LAT./LONG. FOR HUANCAYO AND GODHAVN.

FIG. 5.5.b OBSERVATIONS OF THE HARD COMPONENT TEMPERATURE EFFECT.

I BERCOVITCH ET AL
II QUENBY ET AL
III MORI ET AL
IV MEAN OF I TO III

Quenby and Thambyahpillai. Most recent results on the temperature effect are summarised in Fig. 5.5b. There is some agreement on the phase at least.

The main points of interest in Figs. 5.3 and 5.4 are:-

(a) The data points are spread around curves I and II. Neither curve can, on its own, account for all points at all times and this suggests that the diurnal amplitude varies between ~ 0.4 and 0.7% while $R_{max.}$ varies between 0 and ~ 100 GV. While these assumptions account for the observations at three stations, they are inadequate for Godhavn. For the latter station, the temperature vector seems grossly overestimated; this may be so, since the station is far enough North for surface snow and ice to effectively reduce the diurnal ground wave temperature. Thus convective heating of the lower atmosphere may be greatly reduced. Besides this, at high latitudes the daily variation in solar declination reduces to a yearly variation. Thus we expect some reduction of the temperature effect. To fit experiment and theory, we must assume the temperature effect is negligible. Curves I, II and II re-plotted from the true origin would then fit the data points within the limits of statistical error.

(b) Curve III for Huancayo does not fit the data points. Thus the "anisotropic" diffusion version of Parker's model cannot account for the phase advances seen in the period 1953 to 1955. These early times of maxima are most probably caused by a reduction in the mean energy of the particles taking part in the corotation. This is most easily understood by considering Fig. 5.5a. This shows the asymptotic directions of approach for vertically arriving particles at Huancayo and Godhavn for various rigidities. The asymptotic

longitude rapidly goes to the east as the rigidity decreases (for Huancayo); therefore, the diurnal time of maximum becomes earlier as $R_{max.}$ decreases. This is not so for Godhavn, where the asymptotic longitude is virtually independent of rigidity. Unfortunately, Godhavn data is not available for 1954 when the solar anisotropy reduced to a very small value. Thus we cannot be certain that at this station the phase is almost independent of the amplitude.

(c) In view of the discussion of point (b), it can be seen that the systematic phase changes observed by Elliot and Thambyahpillai (1953) and others may be interpreted as a geomagnetic effect caused by the reduction in amplitude (and hence mean energy). Such reductions occurred during the solar minima of 1933, 1944, 1954 and 1965, being much greater in 1954 and 1933. Thus the 22-year variation suggested by Thambyahpillai and Elliot may just be an expression of the fact that the 1954 solar minimum was much deeper (in terms of sunspot activity) than those in 1944 and 1965. This behaviour may repeat, with every other minimum being relatively deep but many cycles are required before such an effect can be verified. However, we suggest that, whether the periodicity is one of 11 years or 22 years (or both), the effect is due to a reduction of amplitude with virtually no phase change external to the geomagnetic field.

(d) Although the stations Huancayo, Christchurch and Cheltenham show agreement near solar minimum, there are important differences at other times. For example, the data points are clustered together in 1939, 1940 and 1941 and for 1957, 1958 and 1959 at the three stations. For Huancayo, the amplitudes are larger in the latter period compared to the former; the reverse

is true at Christchurch, while at Cheltenham the amplitudes are roughly the same. The simple corotation model cannot explain such local differences. This may be consistent with large solar disturbances being so frequent near sunspot maximum that the spiral field may be permanently disturbed. Experimentally, the Parker model for the interplanetary field has been verified only at relatively quiet times in the sunspot cycle, i.e. from 1962 onwards.

(e) If corotation does account for the diurnal wave at solar minimum, and we take 0.4% to be the amplitude at these times, we can estimate $R_{max.}$ for these periods:-

	$R_{Max.}$
1944	40 - 60 GV.
1954	$<$ 20 GV.
1965	40 - 70 GV.

The value for 1965 comes from a consideration of Holborn and Hobart underground data. We have seen that corotation can account for surface results from three ionization chamber stations for 1937 to 1959 and for Holborn underground results from 1961 to 1966. Work by Jacklyn and Humble (1965) showed that this same model can account for the solar diurnal wave at 40 m.w.e. (Hobart). Now, the amplitude at Hobart reduced to 0.029% for the period September 1964 to August 1965 with a time of maximum at about 1600 hours L.Sol.T. From Fig. 5. of Jacklyn and Humble this is consistent with $R_{max.}$ $\simeq$40 GV. At the same time, the Holborn results suggest that $R_{max.} \leqslant$70 GV. Hence we know that $R_{max.} \simeq$ 40 - 70 GV. in 1965. Thus the Carnegie Institute stations should have observed an amplitude reduction in 1965 similar to that

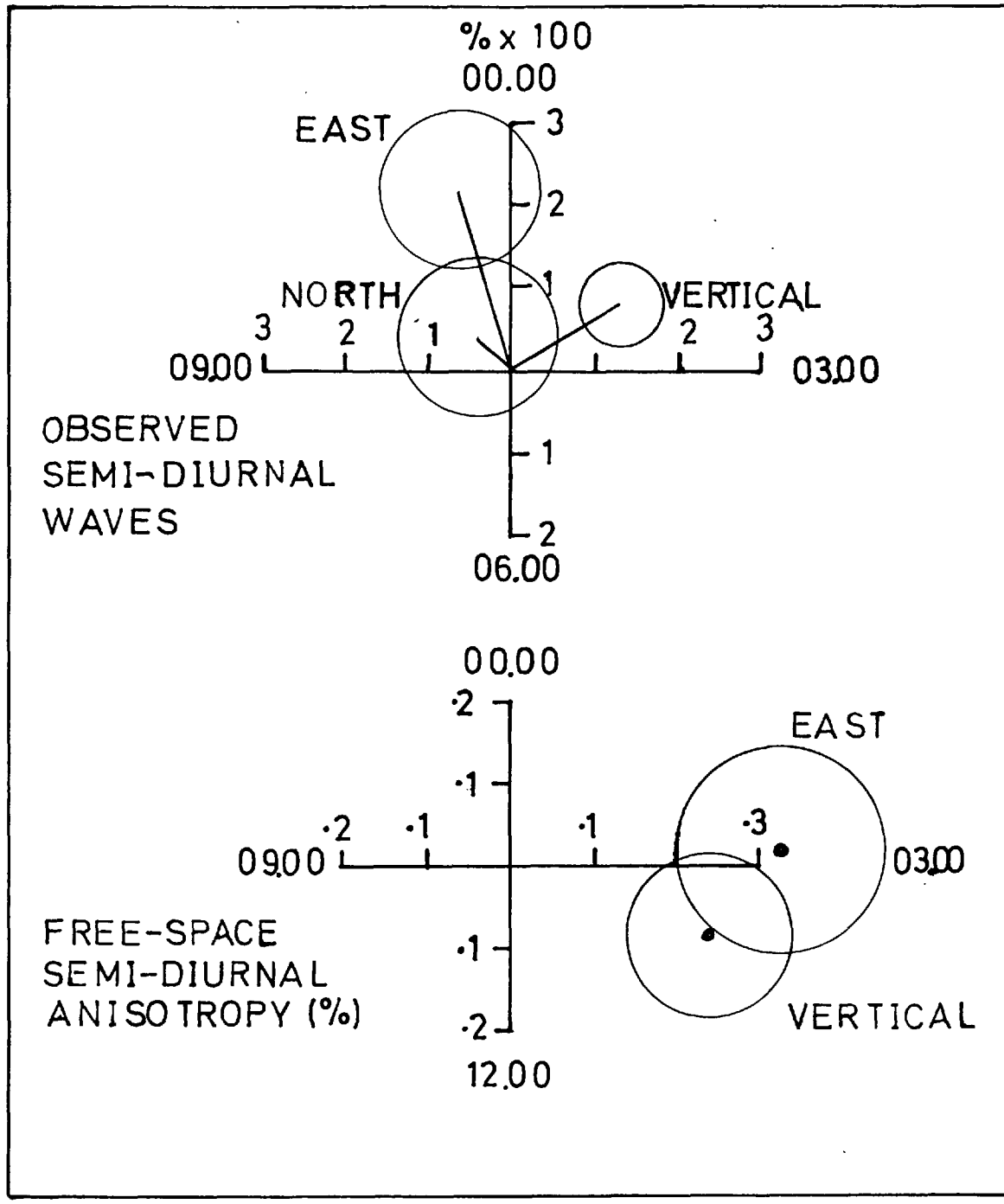


FIG. 5.6 OBSERVED AND GEOMAGNETICALLY CORRECTED SEMI-DIURNAL WAVES FOR HOLBORN.

EAST) OCTOBER 1964 - SEPTEMBER 1966
NORTH)

VERTICAL NOVEMBER 1960 - SEPTEMBER 1966

in 1944; preliminary analysis by Duggal et al (1967) confirms that such an effect has been observed.

5.5 Interpretation of the Semi-Diurnal Wave

As yet, no firm quantitative theory has been proposed for the semi-diurnal wave. In order to correct the Holborn results for geomagnetic deflection, we need to know the energy dependence of the effect. We shall assume a similar model to that for the diurnal wave, i.e. an energy independent effect up to some upper cut-off rigidity of $\sim$ 100 GV. The correction of the semi-diurnal wave is shown in Fig. 5.6; the lower diagram gives the estimated free-space amplitudes (0.2 - 0.3%). The North result has not been corrected since it is negligibly small; this in fact supports the use of the cosine λ dependence on heliographic latitude .

Applying the same sort of analysis to Huancayo, Cheltenham and Christchurch, the predicted amplitudes would be 0.13%, 0.14% and 0.13% respectively; in fact, they are observed to be 0.05%, 0.036% and 0.025% respectively (averaged from 1937 to 1959). Thus it seems that the semi-diurnal free-space anisotropy increases from about 0.1% at 10 GV. to about 0.3% at 100 GV.

The phase of the semi-diurnal wave after geomagnetic correction is the same underground and at the surface, being about 0300 hours L.Sol.T. This suggests particle sinks along the interplanetary field lines and/or sources perpendicular to the lines. Sarabhai and Subramanian (1965) suggest that scattering particles from the solar equatorial plane to higher heliolatitudes causes loss of particles along the field lines. Scattering into the solar equatorial plane is thought to be insufficient to destroy the density

gradient which is generated perpendicular to this plane (the gradient causes a maximum intensity in that plane). Thus the earth samples a reduced intensity along field lines, although not necessarily in both directions on a particular day.

An intensity gradient with a minimum intensity in the solar equatorial plane can also cause a semi-diurnal variation. Particles spiral around field lines so that in directions perpendicular to the field lines the earth samples the larger intensities from higher heliolatitudes. Hence maxima occur at 0300 hours and 1500 hours L.Sol.T. when this mechanism is effective. Thus there is a basic difference between this and the Sarabhai model. At the moment, Sarabhai et al (1965) favour the presence of one minimum per day on many days.

If we take the semi-diurnal amplitudes to be 0.1% and 0.3% at 10 GV. and 100 GV. respectively, then the corresponding density gradients are 1%/A.U. and 0.3%/A.U. approximately. This assumes that the interplanetary field away from the solar equatorial plane is still $5.\ 10^{-5}$ gauss in the region of the earth.

All models using a density gradient generated by scattering centres imply a solar cycle intensity variation. Thus if such gradients are the cause of the semi-diurnal wave at Holborn, then there should also be an 11-year intensity variation. So far this apparatus has not spanned a period from solar minimum to solar maximum and it is therefore not possible to estimate the effect. It is hoped to do this by 1969.

5.6 Conclusions

(1) Corotation associated with Parker's model for the interplanetary magnetic field can provide the basic mechanism for the diurnal variation in the rigidity range 0 - 100 GV.

(2) Long-term changes in $R_{max.}$ can account for the systematic amplitude and phase changes observed by ionization chambers at the surface between 1937 and 1954 and by muon detectors at Holborn between 1961 to 1966.

(3) Other sources of S.D.V. may be present at solar maximum, at least for surface stations.

(4) Corotation effectively disappeared during the approximate period July 1964 to May 1966 for primary energies $\gtrsim$ 50 GeV. At this time the Compton-Getting effect due to the orbital motion of the earth was observed. This effect must be present at all times and for all stations, although it is relatively unimportant at sea level.

(5) The semi-diurnal wave observed at Holborn and at the surface is consistent with an energy dependent effect associated with the spiral interplanetary magnetic field lines described by the Parker model.

CHAPTER 6

SIDEREAL DAILY VARIATION - EXPERIMENTAL

6.1 Introduction

It seems probable that cosmic rays are generated in many discrete sources, rather than in some general way throughout the Universe. The subsequent acceleration of the cosmic rays, and their propagation through galactic magnetic fields to the earth, tends to destroy the initial spatial anisotropy. Any remaining anisotropy should be observed at the earth as a sidereal daily variation (Sid. D.V.).

Work from the very beginning of time variation studies showed that the Sid. D.V., if present, was very small, being less than 0.1% for primary energies of about 10 GeV. It soon became obvious that solar modulation interfered with the observation and interpretation of such small effects, and so underground and air-shower experiments are performed. By going to a depth of 60 m.w.e. the S.D.V. is reduced by a factor 10 from the s/l amplitude. On the other hand, the Sid. D.V. may even increase with depth because of the increase in the mean energy of response of the detectors. Since primaries of higher energy suffer smaller deflections in the solar and galactic magnetic fields, it follows that the Sid. D.V. may increase with primary energy and hence with depth.

By doing air-shower experiments one may attain energies of up to $10^{19} - 10^{20}$ eV, but one must balance the improvement in the data with the loss of statistical accuracy due to the great reduction in counting rate.

As a design consideration for Holborn, the worst possible situation was assumed to be isotropy of the cosmic rays in the frame of reference centred on the Galaxy and rotating with it. Since the sun has a 20 km/sec. motion relative to nearby stars there should, at least, be a sidereal Compton-Getting effect of about 0.02% amplitude. With a yearly statistical accuracy of about 0.013%. it should be possible to observe 0.02% with a significance level of 95% in about three years, always assuming the absence of other contaminating influences.

6.2 Aim of the Present Experiment

This present work compares the Sid. D.V. for the yearly periods:-

		COUNTS/HOUR		
		Vertical	East	North
I	November 1960 - October 1961	50,000	-	-
II	November 1961 - October 1962	50,000	-	-
III	August 1963 - July 1964	150,000	-	-
IV	October 1964 - September 1965	50,000	35,000	35,000
V	October 1965 - September 1966	50,000	35,000	35,000

We wish to ascertain whether there is consistency between the vertical results for the five periods and to see if the data from vertical, East and North telescopes are consistent for the later periods, taking into account geomagnetic bending of the particle trajectories. Any significant results will be compared with other underground and s/l observations.

6.3 Reduction of the Data

The monthly averages of the pressure-corrected bi-hourly intensities

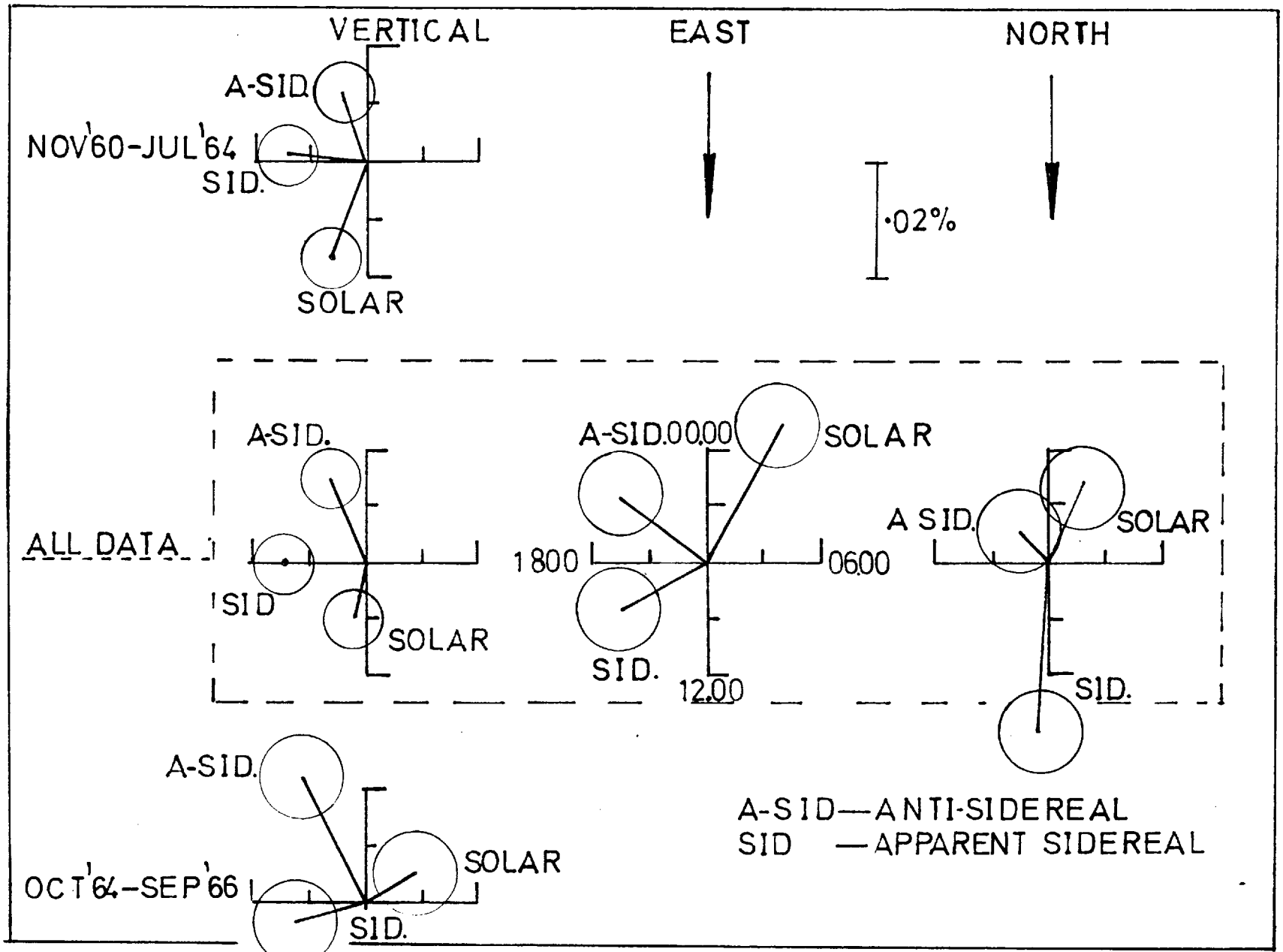


FIG. 6.1 SOLAR, APPARENT SIDEREAL, AND ANTI-SIDEREAL DIURNAL WAVES FOR THE PERIOD NOVEMBER 1960 - SEPTEMBER 1966.

were arranged in sidereal and anti-sidereal time. (A sidereal clock gains two hours/month and an anti-sidereal clock loses two hours/month when compared with a solar clock. Sidereal time is a natural consequence of the earth orbiting the sun once/year; anti-sidereal time has no physical significance except in the imaginary world where the earth's direction of spin is reversed). The yearly averages of the bi-hourly intensities were then harmonically analysed; the use of a yearly period effectively eliminates the constant part of the S.D.V.

The statistical errors were taken to be those found for the solar wave, i.e. 0.013%/year for each set of directional telescopes. This was justified on the grounds that the solar, sidereal and anti-sidereal waves differ by less than 1 per cent in frequency. Hence, the variability in sidereal time naturally includes the variability in solar time. In other words, we cannot separate the fluctuations of the sidereal and solar components and therefore the estimated error applies equally well to both.

6.4 Results for Holborn 1960 to 1966

6.4.1. Diurnal Wave

Fig. 6.1 summarises the Holborn results for the diurnal wave for the periods 1960 to 1964 and 1964 to 1966. In the former, only the vertical telescopes were operating and these observed nearly constant solar, apparent sidereal, and anti-sidereal waves. Similarly, in 1964 - 1966 the solar wave had mostly an early time of maximum, at about 0 - 0900 hours L.Sol.T., for the three directions. Therefore, as a first step, the latter

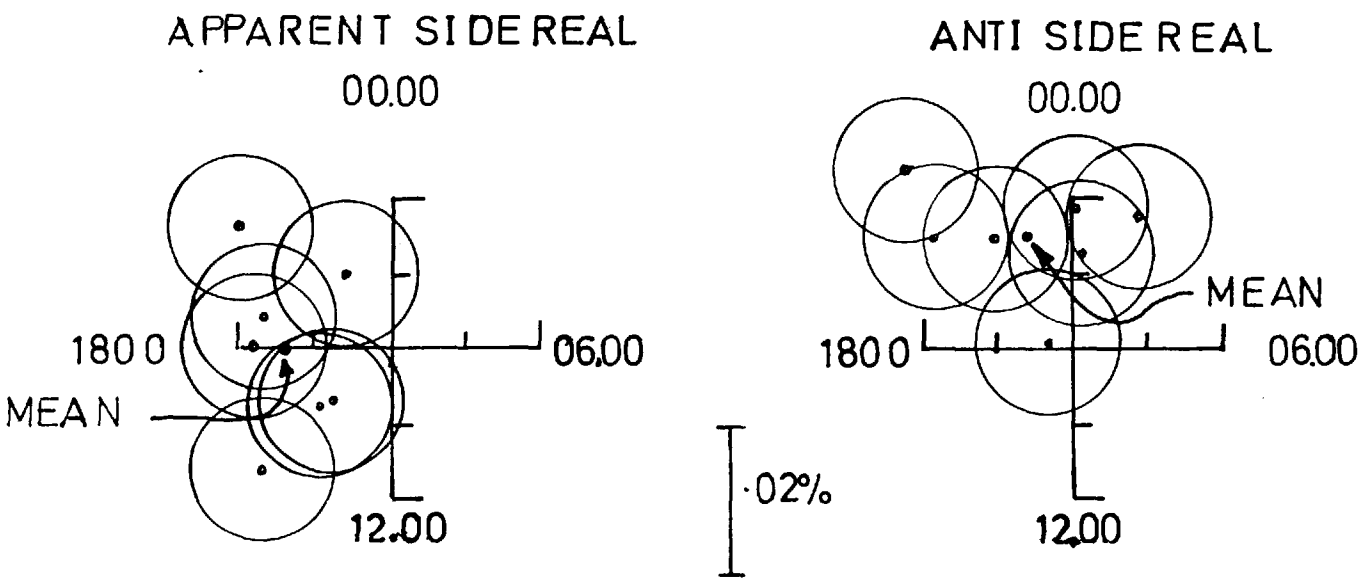


FIG. 6.2 YEARLY AVERAGES OF THE APPARENT SIDEREAL AND ANTI-SIDEREAL DIURNAL WAVES NOVEMBER 1960 - SEPTEMBER 1966.

two years of data were averaged. The main points to be noted from Fig. 6.1 are:-

(a) The apparent sidereal and anti-sidereal vectors have amplitudes of about 2 to 3 standard deviations apart from those for the North. Surprisingly, the North apparent sidereal wave amplitude is about 3.5 times standard deviation, while the solar wave is only 1.5 times standard deviation.

(b) The vertical apparent sidereal and anti-sidereal waves are very similar for the periods 1960 to 1964 and 1964 to 1966, while the corresponding solar waves have totally different phases.

To look at the vertical results in more detail, the data for August 1963 to July 1964 were split into three channels, which were then analysed separately. This gives a total of seven independent estimates of the apparent sidereal and anti-sidereal components. These are plotted in Fig. 6.2a and b; the grouping of the data seems impressive, all points being within an angular range of less than π radians about the origin. To test the significance of the means of these points, we assume first that the seven points represent random samples of a normal population distributed about zero as mean. We then calculate:-

$$t = \bar{a} \sqrt{\frac{n'(n'-1)}{\sum_i (\delta a_i)^2}}$$

where a is the amplitude and $n' = 7$. The probability of a given t value can be found from Fisher (1938) for six degrees of freedom. Table 6.1 summarises the results of such calculations.

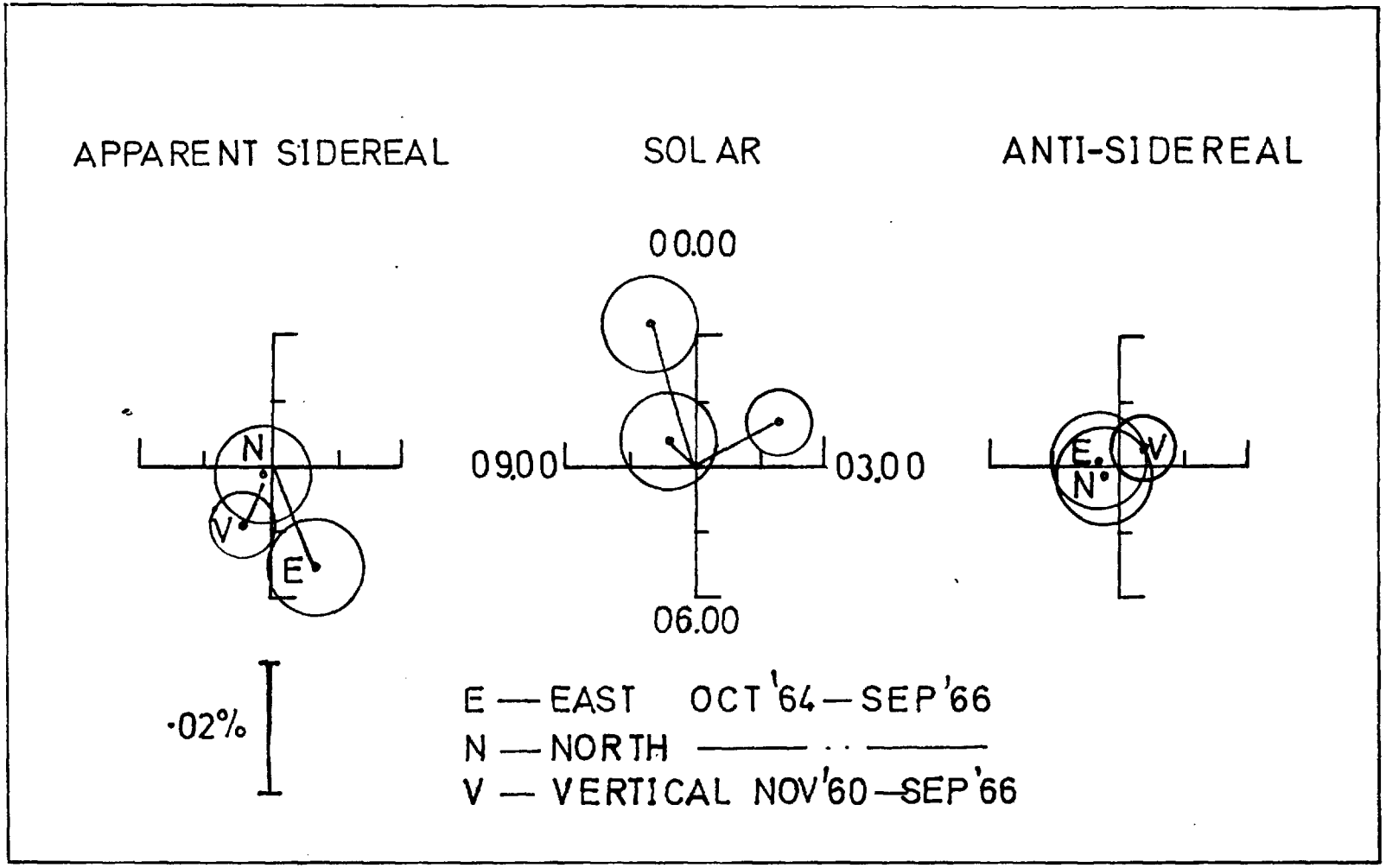


FIG. 6.3 SOLAR, APPARENT SIDEREAL, AND ANTI-SIDEREAL SEMI-DIURNAL WAVES.

TABLE 6.1

	a (%)	S (%)	$n' - 1$	t	P (%)
Apparent Sidereal	0.014	0.012	6	3.1	1
Anti-Sidereal	0.016	0.013	6	3.4	< 1

The estimated standard deviations (S) are in agreement with those found for the solar component, i.e. about 0.013%. The probabilities that these two componenets arise by chance are 1% or less and therefore we do not seriously doubt their presence.

A similar analysis is not possible for the East and North directions because of the limited amount of data. The best one can do is to assume that 0.013% does represent the true standard deviation and that the observations are part of a normal distribution. Then the East apparent sidereal and anti-sidereal waves are both significant at about the 95% level; the North anti-sidereal wave is insignificant while the apparent sidereal wave was significant at better than the 99% level. As such, the North apparent sidereal wave was over twice as large as the solar wave.

6.4.2 Semi-Diurnal Wave

Fig. 6.3 summarises the solar, apparent sidereal and anti-sidereal semi-diurnal results for the whole period 1960 to 1966. The anti-sidereal component seems consistently close to zero while the apparent sidereal components for East and vertical telescopes are significant at about the 95% level, the North component being insignificantly different from zero. As a more rigorous test of significance, the same analysis as for the vertical

diurnal wave was repeated. This showed a 7% probability that the vertical semi-diurnal variation in sidereal time arose by chance. Thus, there is much less confidence in the existence of the semi-diurnal wave than in the diurnal.

Spurious semi-diurnal (and diurnal) waves may arise from a seasonal modulation of the S.D.V. and for this reason the correction for such effects is discussed in the next section.

6.5 Correction for Seasonal Modulation of the S.D.V.

The probability that the vertical anti-sidereal diurnal wave arises by chance is less than 1% and yet it can have no real physical significance. In the simplest case, we imagine it to be caused by yearly amplitude modulation of the S.D.V. Following Farley and Storey (1954) the fractional intensity as a function of time t is given by:-

$$\frac{\delta I(t)}{\overline{I(t)}} 100 = \left[A + B \cos 2\pi \left(\frac{n_1 t}{365} - \varphi_1 \right) \right] \cos 2\pi (n_2 t - \varphi_2) + C \cos 2\pi (n_3 t - \varphi_3) \quad \ldots\ldots 6.1$$

where the first term represents seasonal modulation (with frequency n_1/year and amplitude B) of the solar component with frequency n_2/day; the second term represents a sidereal component with amplitude C and frequency n_3. Re-arranging equation 6.1, one gets for the first term:-

$$A \cos 2\pi (n_2 t - \varphi_2) + \frac{B}{2} \cos \left[\left(\frac{n_1}{365} + n_2 \right) t - \varphi_1 - \varphi_2 \right] + \frac{B}{2} \cos 2\pi \left[\left(n_2 - \frac{n_1}{365} \right) t + \varphi_1 - \varphi_2 \right]$$

i.e. the carrier wave (the solar component of frequency n_2/day) is modulated to give side-bands of amplitude $\frac{B}{2}$ and frequencies $\left(n_2 + \frac{n_1}{365} \right)$ and $\left(n_2 - \frac{n_1}{365} \right)$/day .

The most probable combinations of n_1 and n_2 would be:-

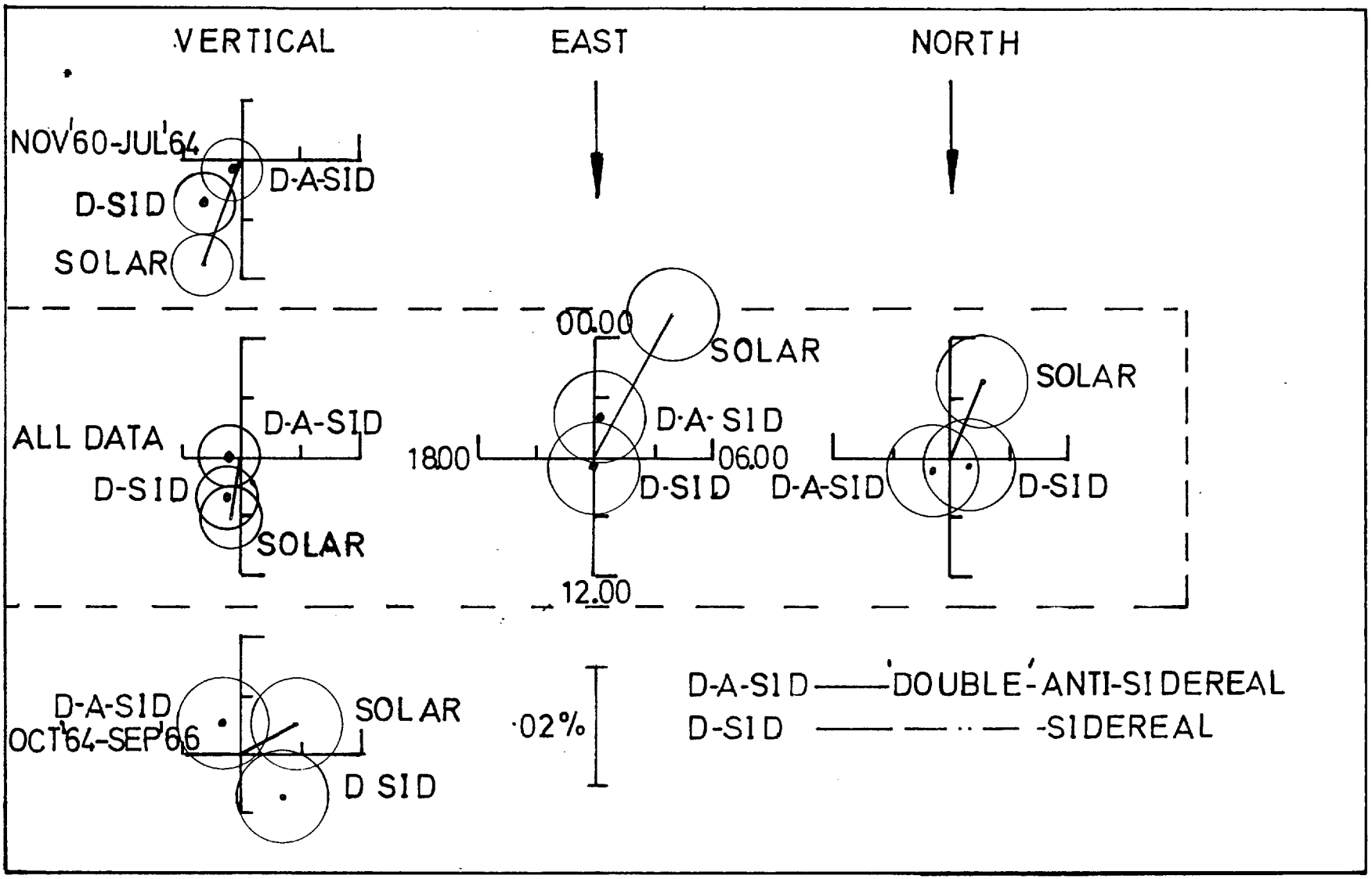


FIG. 6.4 DIURNAL WAVES IN "DOUBLE SIDEREAL" AND "DOUBLE ANTI-SIDEREAL" TIME.

(a) Solar Diurnal Wave, $n_2 = 1/\text{Day}$

Case (1) Yearly Modulation

$n_1 = 1/\text{year}$ then side-band frequencies are 366 and 364 cycles/year, i.e. spurious sidereal and anti-sidereal diurnal variations respectively.

Case (11) Twice-Yearly Modulation

$n_1 = 2/\text{year}$ the spurious frequencies are then 367 and 363 cycles/year. These would be observed as diurnal waves using clocks that gain and lose about 4 hours/month respectively. The time measured by such clocks we shall call "double-sidereal" and "double-anti-sidereal".

Physically we might expect a twice-yearly modulation if the source of the diurnal variation is strongly dependent on displacement from the solar equatorial plane, e.g. if it were due to a density gradient perpendicular to this plane. Since the earth has a twice-yearly variation in displacement from this plane, one might reasonably expect a twice-yearly modulation frequency.

To test such a hypothesis, the data were arranged and analysed in double-sidereal and double anti-sidereal time. The results are shown in Fig. 6.4, along with corresponding solar vectors. Not one of the spurious side-bands was significantly different from zero and we conclude that if any such component was present, its amplitude was less than about 0.01%.

(b) Solar Semi-Diurnal Wave, $n_2 = 2/\text{day}$

Case (1) Yearly Modulation $n_1 = 1/\text{Year}$

The side-band frequencies are now 731 and 729 cycles/year and have no simple interpretation in any of the clock times mentioned above.

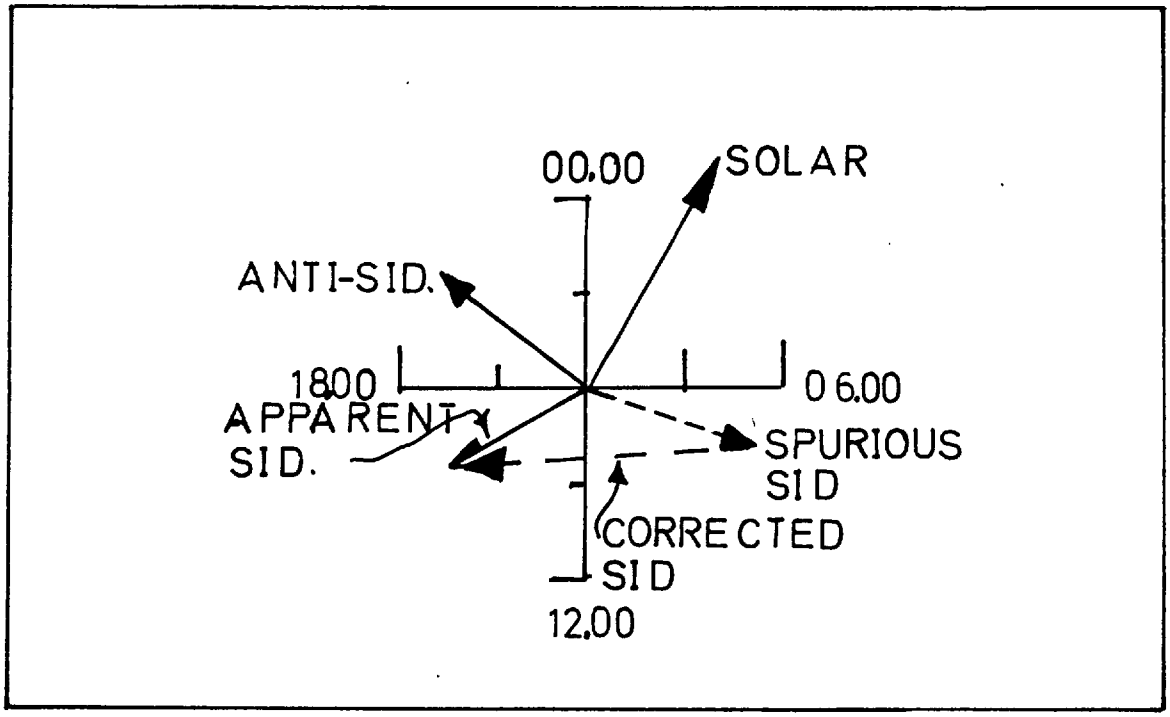


FIG.6.5a EXAMPLE OF THE CORRECTION OF THE APPARENT SIDEREAL WAVE FOR SEASONAL AMPLITUDE MODULATION OF THE SOLAR DIURNAL WAVE.

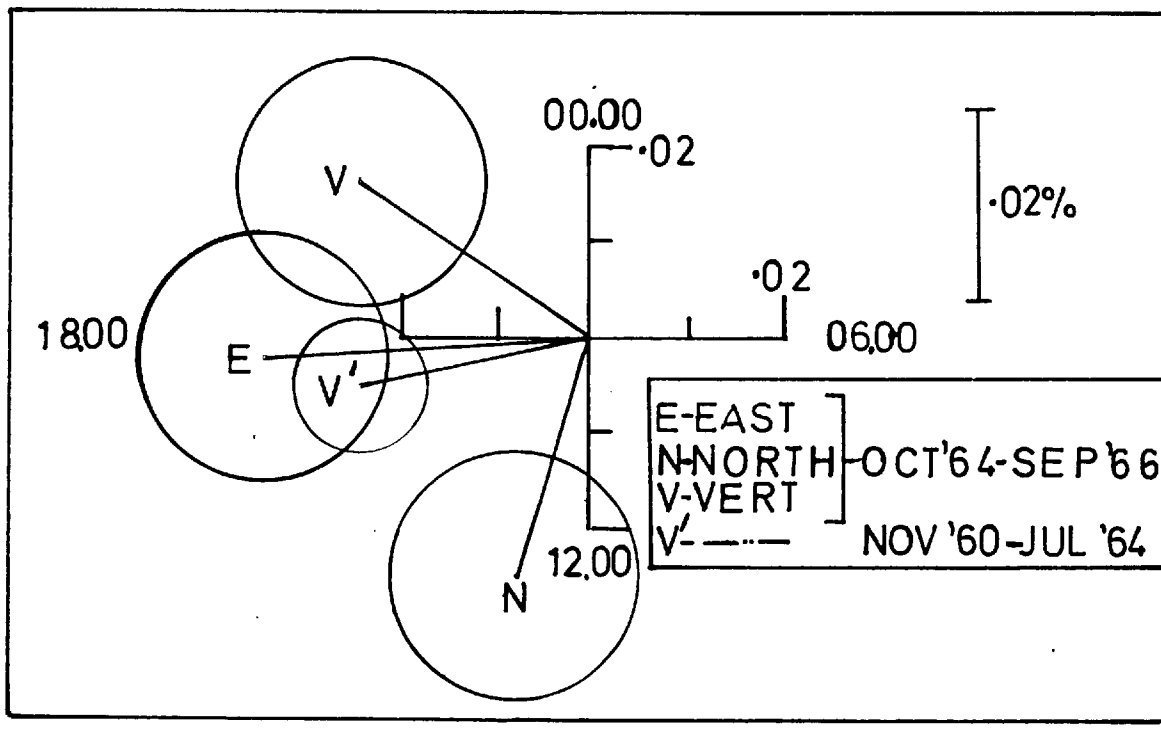


FIG. 6.5b CORRECTED SIDEREAL VECTORS.

Case (11) Twice-Yearly Modulation n_2 = 2/Year

Simple interpretation is available here since the side-band frequencies of 732 and 728 cycles/year correspond to the semi-diurnal waves in sidereal and anti-sidereal times respectively. The semi-diurnal results have already been discussed in section 6.4 where it was shown that the probability of the vertical sidereal component arising by chance was 7%. If this does reflect a genuine variation, then its origin must lie somewhere other than amplitude modulation of the solar sem-diurnal wave. This is because according to the above theory, one expects equally large spurious side-bands in sidereal and anti-sidereal time, and observationally the anti-sidereal components were negligibly small.

Of the four cases outlined above, (a) (1) seems to be the most important since it might be possible for yearly modulation of the solar diurnal wave to cause the observed sidereal and anti-sidereal variations. To test this hypothesis, the spurious sidereal component was described by the reflection of the anti-sidereal vector in the solar vector as in Fig. 6.5a. The true sidereal vector is then the difference between the apparent and spurious sidereal components. Fig. 6.5a shows the arrangement for the East as an example, while Fig. 6.5b shows the results for the three directions. The main features to be noted are:-

(a) The amplitudes are <u>increased</u> rather than decreased as one might expect if their origin is entirely spurious.

(b) Since the errors are increased by a factor $\sqrt{2}$, the significance levels remain about the same. The probability that the vertical observations for November 1960 to July 1963 arose by chance is less than ½%; the

corresponding chance probability for the other observations is rather larger at about 5%. Even so, it does not seem probable that amplitude modulation by itself can explain the observed sidereal effects.

(c) The two vertical results agree within the limits of experimental error. This is despite the very different phases of the solar diurnal waves during these two periods.

(d) The North amplitude is as large as those for the East and vertical directions. Since the North telescopes point in a nearly fixed direction in space, it follows that such a sidereal effect is not expected.

(e) The errors are so large as to make a discussion of phases almost meaningless. Normally, one expects the East time of maximum to be some 2 - 3 hours in advance of that of the vertical. The results do not disagree with such a phase difference, neither do they disagree with there being a common time of maximum. Thus it is difficult to tell if these effects have an origin external to the geomagnetic field (this is discussed more fully in the next chapter). However, one can state definitely that the data are inconsistent with a sidereal variation of amplitude 0.01% or greater with a time of maximum at about 0600 hours L.Sol.T. This is of importance in discussing the results from Hobart (40 m.w.e.) in Section 6.6.2.

All the above has come from the assumption of a seasonal amplitude modulation of the S.D.V. This could arise from, say, the geometrical properties of the sun-earth system. There is the further complicating problem of the mean S.D.V. exhibiting long-term changes in amplitude and phase. Adequate correction for this is not possible since the changes seemed to occur rapidly over the period of only a few months. Therefore, to correct

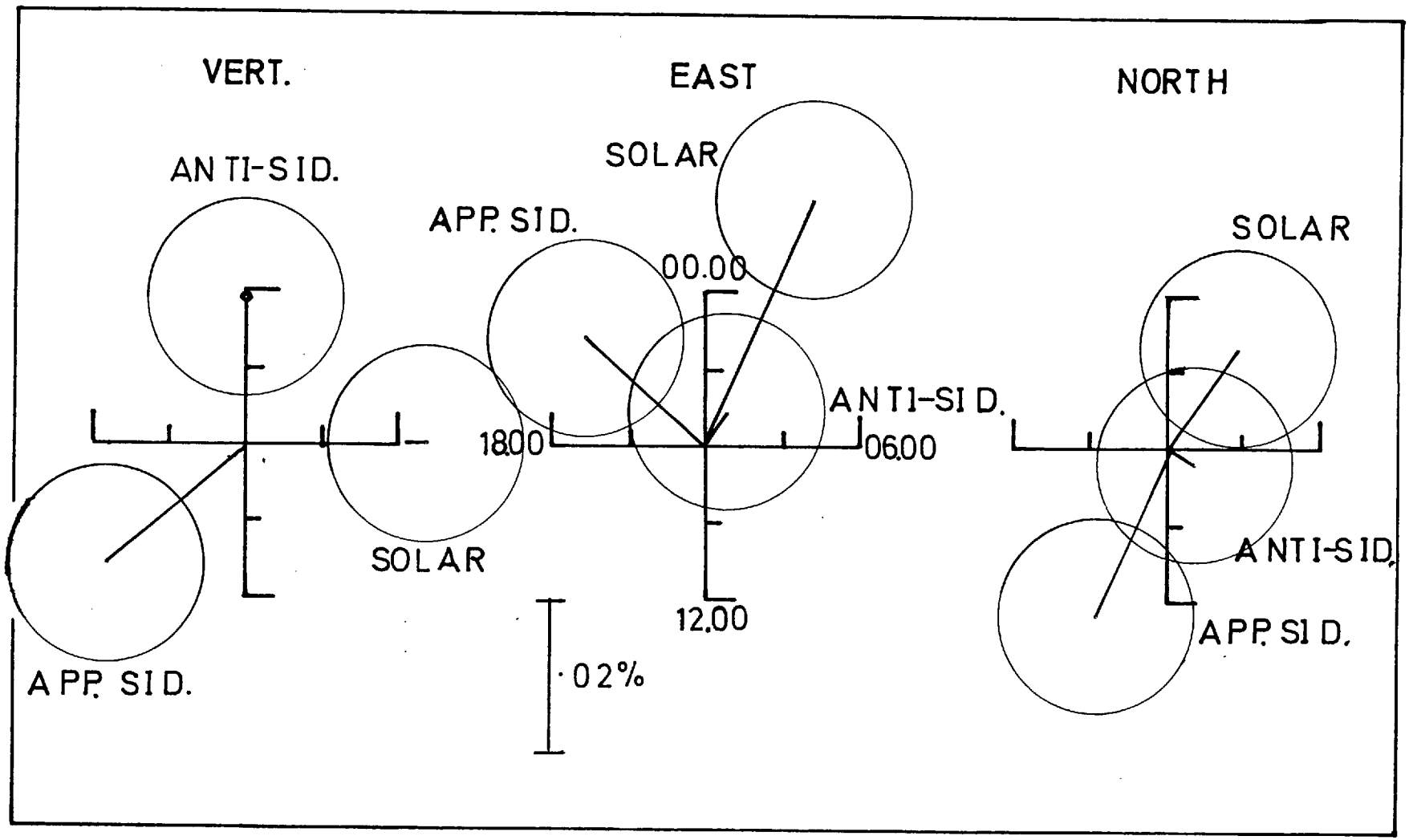


FIG. 6.6 SOLAR, APPARENT SIDEREAL AND ANTI-SIDEREAL DIURNAL WAVES FOR THE PERIOD OCTOBER 1964 - SEPTEMBER 1965.

for these changes by subtracting the running mean of the S.D.V. averaged over only 3 to 4 months would effectively eliminate the sidereal effect. Ideally, the running mean should be averaged over yearly periods and then subtracted from the relevant monthly data, thus leaving the sidereal effect untouched. This was not possible since the S.D.V. changed significantly in less than one year.

As an alternative approach, the period October 1964 to September 1965 was selected as one in which the solar diurnal wave was consistently early ($T_{max.} \simeq$ 0 - 0900 hours) and November 1960 to August 1963 when Tmax. was late (0900 - 2000 hours). Fig. 6.6 shows the solar, apparent sidereal and anti-sidereal diurnal waves for October 1964 to September 1965; these are to be compared with the results for the two-year period October 1964 to September 1966 shown in Fig. 6.1. No significant differences are present but since the statistical errors are increased, the results for just one year are not very significant in themselves. Thus there is the possibility that the North apparent sidereal effect was due to changes in the solar component. However, if this is true then the East and vertical telescopes should have observed even larger, spurious sidereal effects (since their S.D.V.'s were correspondingly larger than those for the North telescopes). But the North apparent sidereal wave was observed to be larger than the corresponding East and vertical waves. We conclude that only part of the apparent sidereal wave observed during October 1964 to September 1966 may have been due to changes in the S.D.V. Thus, the significant apparent sidereal and anti-sidereal waves observed by the vertical telescopes from November 1960 to July 1964 were not necessarily corroborated at a time

thought by some workers to be ideal for the observation of such effects (i.e. at the minimum of solar activity in 1965).

6.6 Comparison with other Stations

The results from other stations may be conveniently classified by the location and type of observation, viz.

(i) Sea-Level (Ionization Chamber, Meson and Neutron Monitors).

(ii) Underground.

(iii) Sea-Level (Extensive Air-Showers, E.A.S.).

This also roughly classifies the relevant primary particles in ascending energy:-

$$\begin{array}{rcl} & \text{(i)} \lesssim & 5.10^{10}\ \text{eV} \\ 5.10^{10}\ \text{eV} \lesssim & \text{(ii)} \lesssim & 5.10^{11}\ \text{eV} \\ & \text{(iii)} \gtrsim & 10^{11}\ \text{eV} \end{array}$$

6.6.1 Sea-Level (Ionization Chambers, Meson and Neutron Monitors).

Early work to establish the sidereal anisotropy soon showed its amplitude to be less than 0.1%. This seemed to rule out the possibility of an obvious connection between cosmic ray origin and the distribution of stars in the Galaxy. Similarly, it excluded the possibility of an isotropic extra-galactic flux since this would produce a large sidereal anisotropy due to the rotation of the Galaxy (Compton and Getting 1935).

Further work (summarised by Elliot 1952) showed inconsistencies in phase and amplitude between stations using either ionization chambers or counter telescopes. This was no doubt partly due to the seasonal changes in the meteorological contributions to the observed S.D.V. To

eliminate this, Elliot and Dolbear (1951) combined the ionization chamber data of Christchurch (latitude 43.5°S) and Cheltenham (latitude 38.7°N) on the assumption that these stations suffer the same seasonal temperature effects with a six-month difference in phase. The result showed a sidereal variation of about 0.02% with a time of maximum near 0500 hours L.Sid.T. This compared well with the result for Huancayo (latitude 0.6°S) for a roughly comparable period. Being equatorial, Huancayo might be expected not to see a large seasonal effect.

The development of the neutron monitor virtually eliminated the atmospheric temperature problem enabling Conforto and Simpson (1957) to observe a large sidereal effect in 1954 at Huancayo and Climax (48°N). In effect, these authors saw a systematic phase shift in solar time of about 2 hours/month. This they attributed to the presence of a sidereal effect and the absence of a S.D.V. since 1954 was a period of low solar activity. This also appeared in ion chamber data for Freiburg (48°N) and for a counter telescope in Rome (42°N). Other stations also observed in 1954 a reduction in neutron S.D.V. and phase and amplitude changes for the hard component S.D.V. e.g. see Possener and V.Heerden (1956).

Baliga and Thambyahpillai (1959) obtained the sidereal variation for 1954 at Huancayo, Cheltenham, Christchurch, Colombo, Hobart and Tokyo (all using ion chamber or counter telescopes). They conclude that at least part of the effects in 1954 were spurious.

More recently, large sidereal effects have been observed by Standil and Bukata (1964). Using rotating, narrow angle counter telescopes, responding to primary particles of mean energy $\sim$ 30 GeV, they observe a

10% anisotropy. This is definitely not confirmed at ~100 GeV by the Holborn results which limit the anisotropy to a maximum of about 0.03%. Since the Standil and Bukata data are uncorrected for meteorological effects, have only a small statistical weight (counting rate~30/hour) and are not confirmed by other stations, their interpretation is presumably something other than galactic anisotropy.

Baker, Chasson and Kisselbach (1966) report that crossed counter telescopes at Denver indicate apparent minima in the galactic intensity at 0400, 0900 and 1100 hours L.Sid.T. The amplitudes are about 0.06% which compares with other sea-level measurements but is too large in comparison with the limit set by the Holborn results. The Denver results are for one year only and must be shown to repeat from year to year before being accepted as a genuine effect. It may be that the technique of crossed telescopes inadequately corrects for the meteorological and S.D.V. effects since the directional telescopes respond to particles of slightly different mean energy.

We can generalise the sea-level results by noting that either (i) the sidereal amplitude found is small compared to the statistical error, or (ii) the significant sidereal amplitudes found are larger than the minimum set by Holborn, i.e.~ 0.03%. Thus it is probable that the significant sea-level variations (which tend to have a time of maximum at~ 2000 hours L.Sid.T.) are not due to a spatial anisotropy but are possibly associated with any or all of the following:-

(i) Seasonal modulation of the S.D.V.

(ii) Long-term modulation of the S.D.V.

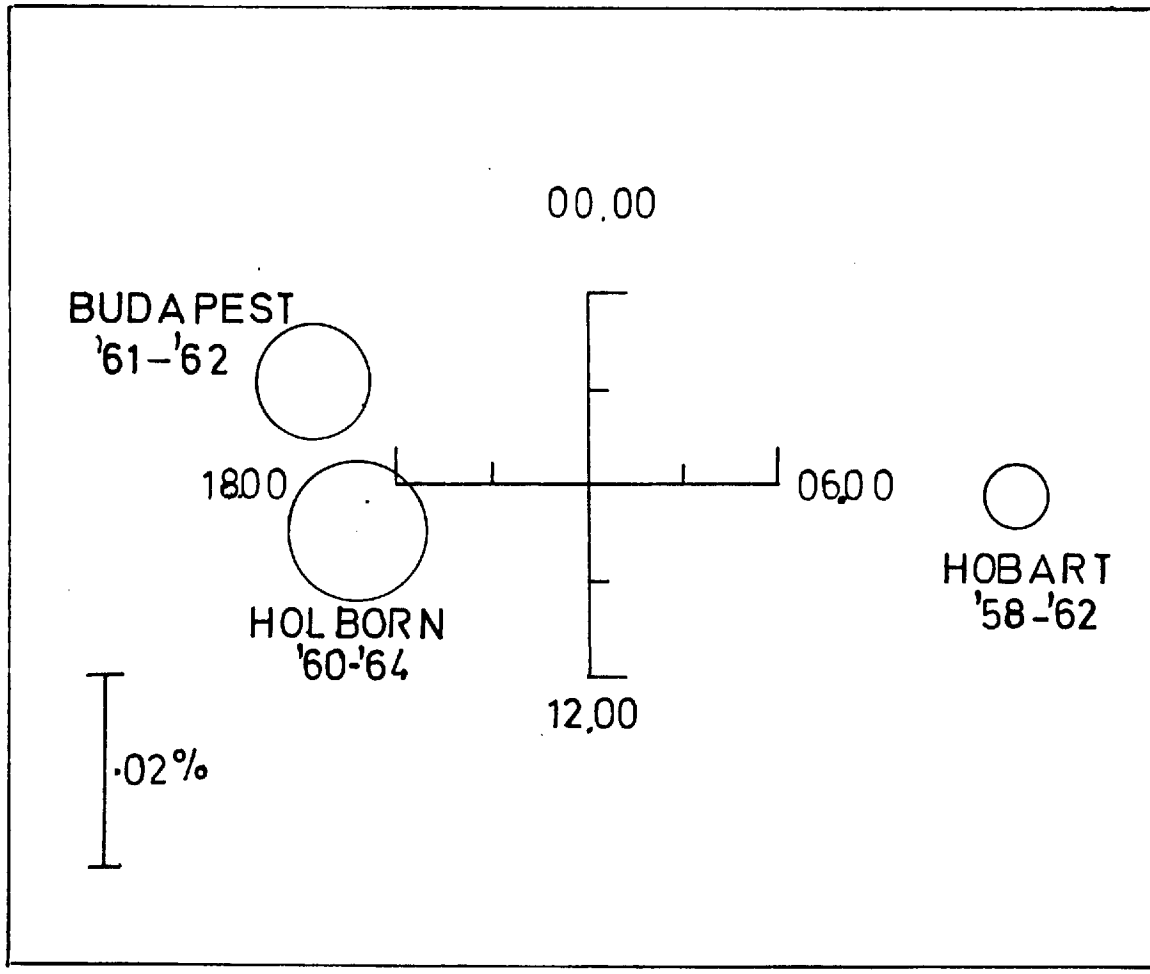


FIG. 6.7 SIDEREAL DIURNAL WAVES FOR UNDERGROUND STATIONS. (ONLY HOBART DATA ARE UNCORRECTED FOR SEASONAL MODULATION OF THE SOLAR DIURNAL WAVE BECAUSE NEGLIGIBLE ANTI-SIDEREAL WAVES WERE OBSERVED AT THIS STATION).

(iii) Inadequate correction for meteorological effects for ion chambers and counter telescopes.

The tendency for $T_{max.}$ to be $\sim$ 2000 hours L.Sid.T. (at least in the northern hemisphere) does compare with the Holborn results for the vertical direction. In the southern hemisphere, the time of maximum tends to be about 0800 hours L.Sid.T. for both sea-level and underground stations. This difference between northern and southern hemispheres is discussed more fully in the next section.

6.6.2. Underground Results

The results from only two other underground stations are freely available, and they are:-

(i) Hobart (35^{o}S, 40 m.w.e.) and

(ii) Budapest (47.5^{o}N, 40 m.w.e.).

These are plotted in Fig. 6.7 for the vertical direction, corrected for amplitude modulation as above. The two northern stations show good agreement in amplitude and phase while the southern station shows a larger amplitude and a phase some 12 hours in advance of the others. The amplitude at Hobart has been consistently large from 1958 to 1965, while during 1961 - 1962 Jacklyn (1963) observed a regular phase change of the S.D.V. of about 2 hours/month. The latter was attributed to a galactic anisotropy superimposed on a greatly reduced solar anisotropy. Similar effects were observed by Conforto and Simpson (1957) during the 1954 solar minimum at sea-level. However, no such effects were confirmed in the Holborn and Budapest data during 1961 - 1962 when normal S.D.V.'s were observed with no systematic phase shifts of 2 hours/month.

The sidereal amplitude of 0.07% observed at Hobart in 1961-62 would have easily been observed at Holborn; no such large effect was observed. Furthermore, Jacklyn (1965) reports a large apparent sidereal diurnal amplitude of $0.10 \pm 0.05\%$ for a narrow angle telescope inclined at 70°N to the vertical at Hobart. These results, for 1964, are directly comparable in energy and mean direction of view to the Holborn results. No such large amplitude is observed. Finally, one further contradiction between the Holborn and Hobart results is to be noted. In the yearly period October 1964 to September 1965, a much reduced solar anisotropy was observed at Holborn (compared to 1961 - 1962). If the phase changes of the solar diurnal wave observed at Hobart in 1961-1962 were significant and due to a genuine sidereal effect, then similar behaviour should have occurred in 1965. No such effect was observed in the Hobart data for September 1964 - August 1965 (Fenton 1965).

The differences between the results for the two hemispheres have been interpreted by Jacklyn (1965) as being due to a "2-way sidereal anisotropy". This implies that the two hemispheres observe different sidereal offects associated with the inward and outward directions along the galactic spiral arm.. It is not clear why the amplitudes should be much larger for observations in the southern hemisphere, nor why the amplitude should apparently vary.

6.6.3. Extensive Air-Shower (E.A.S.) Results

Since the larger sidereal effects are expected at higher energies, many E.A.S. experiments have been performed with a view to establishing the amplitude of the galactic anisotropy. Most have been unsuccessful due to

the large increase in uncertainty associated with the decreased intensity and only upper limits have been set by any particular experiment. A fairly typical result is that of Farley and Storey (1954) for E.A.S. observed at Auckland (37^{o}S):-

PRIMARY ENERGY (eV)	AMPLITUDE (%)	$T_{MAX.}$ (L.Sid.T.)
10^{15}	1.1 ± 0.26	19.8 ± 0.9
$1.4.10^{15}$	0.52 ± 0.41	19.7 ± 3.5
2.10^{11}	0.52 ± 0.61	20.7 ± 4.7

The non-significance of the individual E.A.S. experiments has been brought out by Delvaille (1959) who plotted amplitude (a) against standard deviation (σ) for many different E.A.S. results. The points distribute around the straight lines $a = 1\sigma$ and $a = 2\sigma$, thus indicating the statistical nature of the individual results.

However, Sakakibara (1965) taking virtually the same results as Delvaille finds that the times of maximum of the sidereal diurnal waves are not randomly distributed, as one expects for a purely statistical origin. She finds that the phase is energy dependent, being:-

(a) 2000 hours L.Sid.T. for $5.10^{13} \lesssim E \lesssim 5.10^{15}$ eV.

(b) 1200 hours L.Sid.T. for $5.10^{15} \lesssim E \lesssim 5.10^{17}$ eV.

She interprets (a) as being due to diffusion along the spiral arm of the galaxy and (b) due to diffusion radially outwards from the centre of the arm in the plane perpendicular to the arm. It is interesting that the change of phase occurs at $E \simeq 5.10^{15}$ eV, which is also the energy where the slope of intensity spectrum tends to increase.

Delvaille, on the other hand, suggests that the slight tendency

for a 2000 hour time of maximum is an atmospheric effect. McCusker et al (1960) have observed large solar semi-diurnal variations of about 10% amplitude in E.A.S. experiments; they attribute these to fluctuations in the height of the first interaction in the chain of events leading to an E.A.S. This emphasises that large atmospheric effects could possibly lead to a consistent, spurious sidereal variation.

6.7 Summary of Holborn Results 1960 to 1966

(i) Significant apparent sidereal and anti-sidereal diurnal waves were observed in the two-year period October 1964 to September 1965. The sidereal amplitudes corrected for amplitude modulation of the solar diurnal wave are shown in Table 6.2.

TABLE 6.2

		DIURNAL AMP. (%)	TIME OF MAX. (HRS. L.Sid.T.)
East	Oct. 1964 - Sept. 1966	0.034 ± 0.013	1740 ± 0130
North	Oct. 1964 - Sept. 1966	0.026 ± 0.013	1310 ± 0200
Vertical	Oct. 1964 - Sept, 1966	0.029 ± 0.013	2020 ± 0130
Vertical	Nov. 1960 - July 1964	0.024 ± 0.006	1710 ± 0100

(ii) The solar diurnal wave was very different in phase for the two periods of vertical data shown above; there was no significant difference between the corresponding apparent sidereal waves.

(iii) Amplitude modulation of the solar diurnal wave cannot entirely account for the apparent sidereal waves.

(iv) Semi-annual amplitude modulation of the solar diurnal wave was not observable and therefore was less than 50% of the mean solar anisotropy.

(v) The apparent sidereal amplitudes were no larger at solar minimum than at an earlier part of the solar cycle (i.e. 1960 - 1964). In fact, the changes in the S.D.V. with solar cycle may inhibit the recognition of a true sidereal effect or may be misinterpreted as such at solar minimum.

(vi) All data are inconsistent in phase and amplitude with that of Hobart, Tasmania.

(vii) No regular phase changes of the solar diurnal wave were observed at solar minimum which could be attributed to a large galactic anisotropy superimposed on a small solar anisotropy.

(viii) The north-pointing telescopes observed a significant apparent sidereal wave which was much larger than the anti-sidereal and solar waves. Therefore, it could not have been due to modulation of the solar wave and yet it is not expected to be due to genuine galactic anisotropy because these telescopes point in a nearly fixed direction in space. This is important when interpreting the above results in the next chapter.

CHAPTER 7

SIDEREAL DAILY VARIATION - THEORETICAL

7.1 Introduction

With regard to the sidereal daily variation observed at Holborn, there seem to be three distinct possibilities:-

(i) The Sid. D.V. is entirely genuine, i.e. is due only to a galactic anisotropy external to the solar cavity. Since we observe a significant anti-sidereal variation, this is hardly likely, although there is just the slim possibility of a pure sideral wave being modulated by the orbital motion of the earth, thus causing the anti-sidereal wave.

(ii) The Sid. D.V. is entirely spurious. This in itself is interesting since it would imply either that the cosmic rays in the region of the solar system are isotropic or that the anisotropy is largely destroyed in diffusing from the boundary of the solar cavity to the earth.

(iii) The Sid. D.V. is part spurious and part genuine. Even if cosmic rays were isotropic in the local group of stars, we would expect a small sidereal effect due to the local motion of the sun. On the other hand, the evidence from sea-level stations suggests that spurious effects can easily arise, e.g. from a seasonal temperature effect. Thus, genuine and spurious components may contribute to the Holborn results.

We wish to discuss these three possibilities in the light of the experimental results from Holborn and elsewhere.

7.2 Entirely Genuine Sid.D.V.

Any modulation of the S.D.V. tends to produce spurious sidereal and anti-sidereal components; thus, for only a genuine Sid.D.V. to exist, we must assume that the S.D.V. is constant and that modulation of the Sid.D.V. causes the observed anti-sidereal waves. This modulation would have to be of a rather special form, e.g. semi-annual amplitude modulation of the Sid. D.V. Such an effect seems unlikely, although not impossible, since the orbit of the earth has maximum displacement from the heliographic equator twice per year. However, the anti-sidereal amplitude would have to be a relatively small fraction of the sidereal amplitude whereas they are observed to be nearly the same. Besides this, we know that the S.D.V. is not constant in time, being observed to change greatly at the solar minimum period near 1965. This latter effect may account for part of the apparent sidereal diurnal wave observed by the north pointing telescopes from October 1964 to September 1966. That such a large effect as $0.03\% \pm 0.01\%$ should be observed by telescopes pointing in a nearly fixed direction in the sky is also contrary to the assumption of a pure sidereal effect and thus we reject it as untenable.

This contrasts with the Hobart underground results, where insignificant anti-sidereal effects are seen. Jacklyn (1963) considers only a genuine galactic anisotropy to be present, i.e. there is no regular modulation of the S.D.V.

Budapest data averaged for the years 1961 and 1962 show similar apparent sidereal and anti-sidereal diurnal waves to those at Holborn. Thus the spurious effects are confirmed, at least for the northern hemisphere.

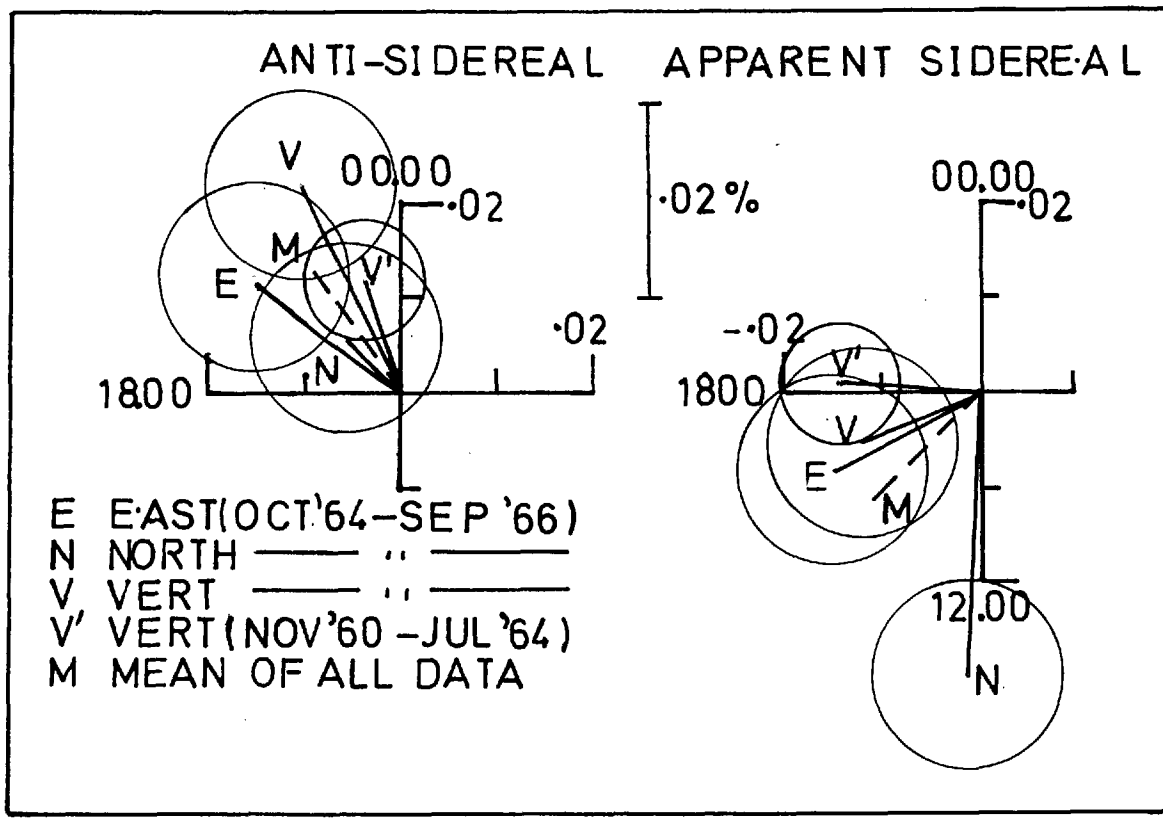


FIG. 7.1a APPARENT SIDEREAL AND ANTI-SIDEREAL DIURNAL WAVES - ALL DATA.

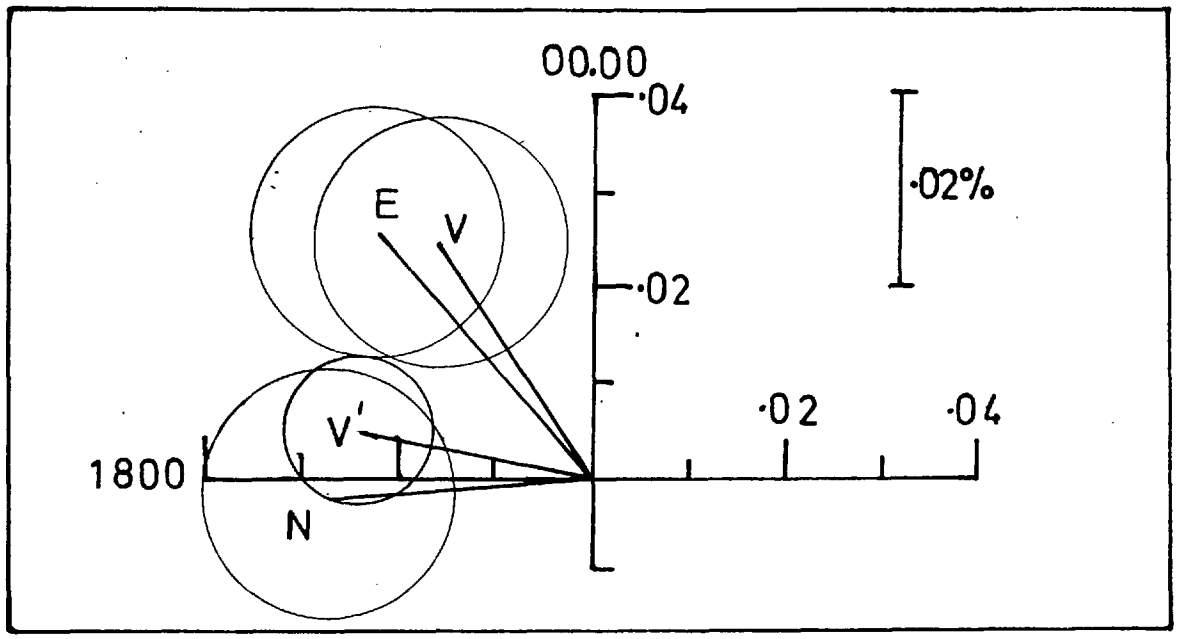


FIG. 7.1b SIDEREAL DIURNAL WAVES CORRECTED FOR AMPLITUDE MODULATION OF THE S.D.V. AND GEOMAGNETIC BENDING. PERIODS AS FOR FIG. 7.1a.

7.3 The Sid.D.V. is Entirely Spurious

This hypothesis can be tested by reconsidering all Holborn data on the assumption that the spurious sidereal and anti-sidereal effects have the same origin. Fig. 7.1a shows the diurnal results collected together and averaged independent of telescope direction of view. Points to be noted are:-

(i) All the anti-sidereal observations are less than one standard deviation away from the mean. Since there are no significant differences in phase and amplitude, we can assume that all telescopes observe the same effect whose origin is internal to the geomagnetic field.

(ii) Of the apparent sidereal waves, three agree very well while the North result is significantly different in phase and amplitude. If we take the mean of the three consistent results as the predicted effect, then the probability that the North observation arose by chance, but is consistent with this mean, is less than 1%.

Thus the data are not consistent with a single, spurious origin to both the apparent sidereal and anti-sidereal waves. However, this conclusion rests on the observations for only one direction, i.e. the north-pointing telescopes, while the other 90% of the data agrees with the hypothesis of a single, spurious origin.

It is not clear what part the long-term changes in the S.D.V. played in producing spurious sidereal and anti-sidereal components nor why the north-pointing telescopes should observe relatively large diurnal amplitudes. Since the North telescopes point in a nearly fixed direction in space, one does not expect large diurnal waves except from possible atmospheric effects.

Thus, the North observations are suggestive of an atmospheric effect, while on the other hand they are inconsistent with a purely local origin to the spurious apparent sidereal and anti-sidereal waves. With regard to long-term changes of the S.D.V. causing spurious effects, one expects larger contributions for the East and vertical telescopes compared with the North, since the latter observe only a small S.D.V. As the North apparent sidereal wave is larger than the corresponding East and vertical waves, it follows that long-term changes in the S.D.V. cannot entirely account for these observations.

We conclude that:-

(i) The data are not consistent with a single, local origin to the apparent sidereal and anti-sidereal diurnal waves.

(ii) Long-term changes of the S.D.V. cannot entirely account for the apparent sidereal waves observed during the solar minimum period. This is confirmed by the corresponding vertical results being virtually constant during the whole period November 1960 to September 1966.

7.4 The Sid.D.V. is Part Spurious and Part Genuine

We have seen from section 7.2 that the apparent Sid.D.V. cannot be entirely genuine. Section 7.3 showed that the apparent sidereal and anti-sidereal effects could not be reconciled with an entirely spurious origin internal to the geomagnetic field. Chapter 6, Section 6.5 showed that amplitude modulation of the observed S.D.V. cannot entirely account for the apparent sidereal and anti-sidereal diurnal waves. Phase modulation of the corotation and orbital motion effects seems unlikely to account for

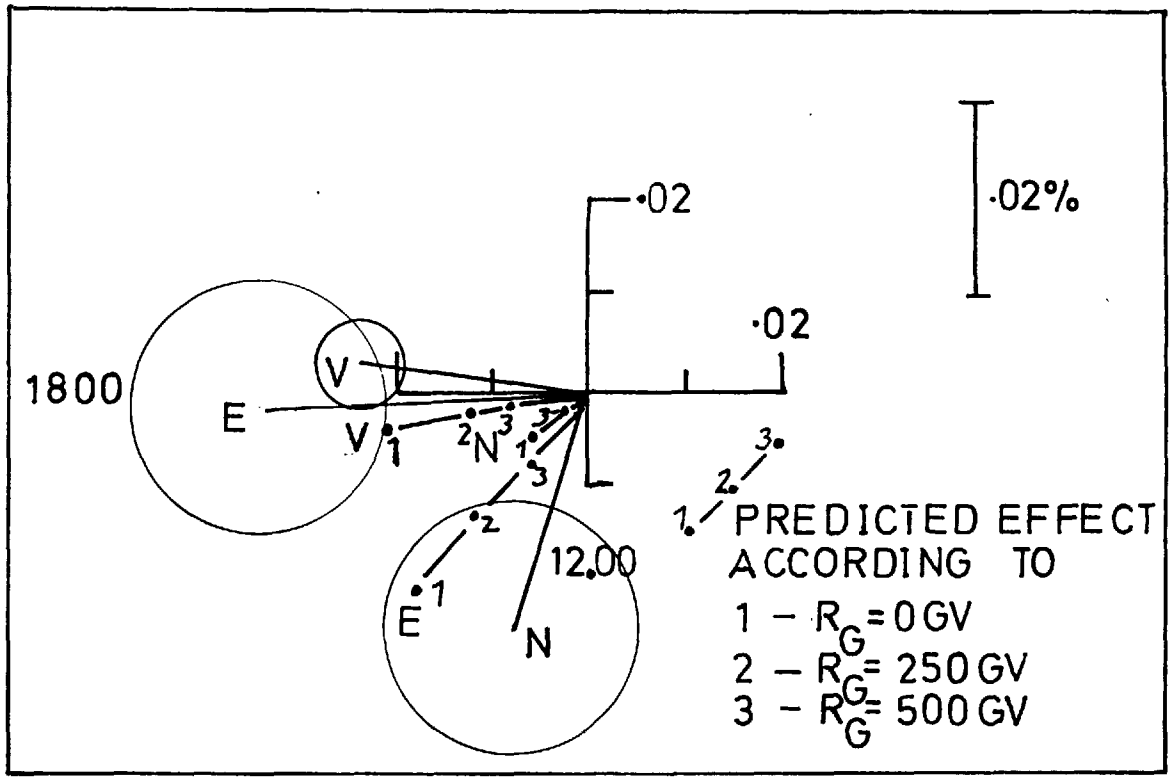


FIG. 7.2.a PREDICTIONS OF THE SIDEREAL EFFECT DUE TO LOCAL MOTION OF THE SUN COMPARED TO OBSERVATIONS.

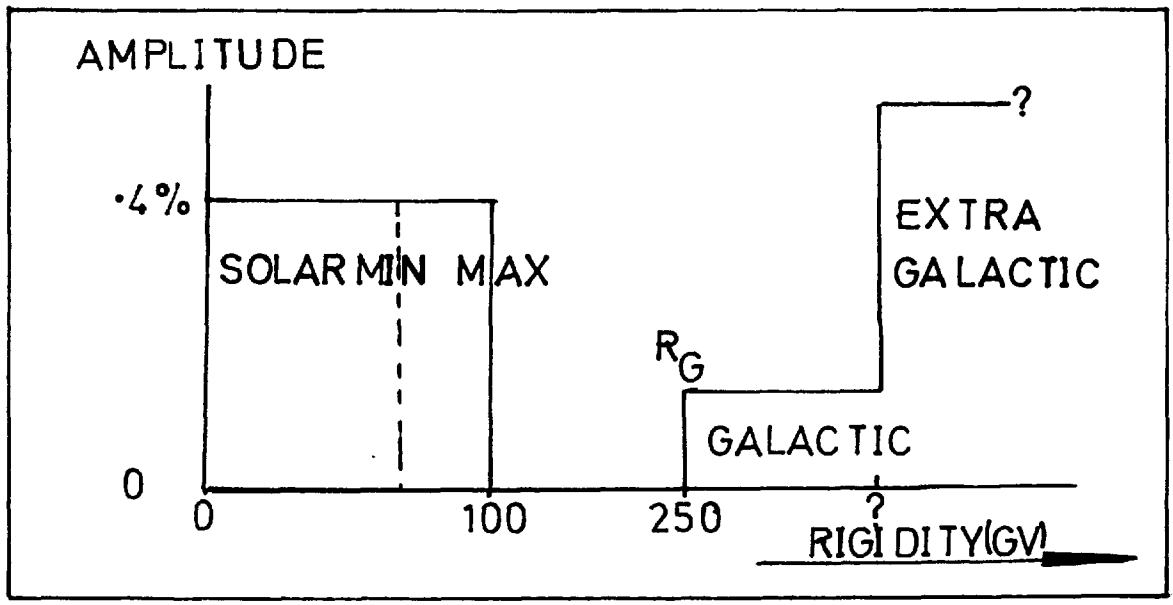


FIG. 7.2b SCHEMATIC ARRANGEMENT OF POSSIBLE SOLAR, GALACTIC AND EXTRA-GALACTIC ANISOTROPIES.

the observations, since the corresponding times of maxima are fixed at 1800 and 0600 hours L.Sol.T. all the year round. We are forced to conclude that the apparent sidereal diurnal wave has spurious and genuine components.

Neglecting a possible small atmospheric effect, we can take the genuine galactic anisotropy to be the apparent waves corrected for amplitude modulation of the S.D.V. This is justified on the grounds that the anti-sidereal waves of Fig. 7.1a are consistent with a phase difference of about three hours between East and vertical observations. Hence, the origin of the spurious effects may be external to the geomagnetic field.

We wish to interpret the corrected sidereal waves (shown in Fig.7.2a) in terms of solar, galactic and extra-galactic effects.

7.5 Interpretation of the Observed Sid. D.V.

There seem to be three main types of sources of sidereal diurnal variations:-

(i) Compton-Getting effects due to the motion of the sun-earth system through largely isotropic cosmic ray distributions. These affect particles of all energies.

(ii) Galactic anisotropy caused by the guidance of particle orbits along galactic magnetic field lines. An example would be the diffusion along the spiral arm of the Galaxy in which the earth is situated. If we take the dimension of the arm to be $\simeq 1.5.10^{21}$ cms. and the associated magnetic field to be $H \simeq 10^{-6}$ gauss, then particles of energy up to $\sim 10^{17}$ eV would exhibit this effect.

(iii) Galactic anisotropy caused by a nearby discrete source of energetic

cosmic ray particles. The energy dependence of this effect would depend on the nature of the source. The amplitude of the effect is greatly reduced due to the interstellar magnetic field. If we take $H \simeq 10^{-6}$ gauss and E = 300 GeV as the mean energy of response of the Holborn detectors, then the source must be no further than $\sim 10^{-3}$ light years. Since even the nearest star is several light years from the earth, it would appear that the dimensions of the Galaxy are too great to enable the Holborn detectors to observe discrete sources of cosmic rays.

Hence, we shall test the predictions of (i) and (ii) with the observations at Holborn for 1961 to 1966. Before doing so, we must consider the reduction of the galactic anisotropy caused by particle scattering in the interplanetary field. Both magnetic irregularities and the large-scale sectored magnetic field seem capable of modulating the incoming particles. It is convenient to treat these separately:-

7.5.1 Particle Scattering by Magnetic Irregularities

After Parker (1958), we can consider cosmic rays entering the solar cavity and diffusing to the earth by way of many "collisions" with radially moving "kinks" in the Archimedian spiral field.

In the approximation of "thin" scattering centres, where kink separations (ℓ) are much smaller than the particle Lamor radii (ρ), we get typical deflections of θ, where

$$\theta \simeq \frac{\ell}{\rho(E)} \qquad \ldots\ldots\ldots\ldots 7.1$$

In n collisions, the particle suffers a total deflection of

$$\Theta = n^{\frac{1}{2}}\,\theta \qquad \ldots\ldots\ldots\ldots 7.2$$

For the galactic anisotropy to be destroyed, the incident particles must suffer a deflection of about $\frac{\pi}{2}$ radians.

Thus,

$$n^{\frac{1}{2}}\theta = \pi/_2 \qquad \ldots\ldots\ldots\ldots 7.3$$

In diffusing a distance R_o from the edge of the solar cavity to the earth, the particle undergoes n small angle scatterings where

$$n = \frac{R_o}{\ell} \qquad \ldots\ldots\ldots\ldots 7.4$$

Combining equations 7.1, 7.3 and 7.4, we get

$$R_o = \ell . n$$
$$= \frac{\ell . \pi^2}{4.\theta^2}$$
$$= \frac{\pi^2 \rho^2}{4\ell}$$

Now
$$\rho = \frac{P}{300\ H} \qquad \ldots\ldots\ldots\ldots 7.5$$

where P is momentum in units of eV/c

$$\therefore \quad P = \sqrt{R_o \ell} \cdot \frac{2}{\pi} \cdot 300 \cdot H \qquad \ldots\ldots\ldots\ldots 7.6$$

For typical values of $\ell = 5.10^{11}$ cms. and $R_o \simeq$ 30 A.U. we get $P_{min.}$ = 150 GV/c. This represents the limit below which scattering by "kinks" in the interplanetary magnetic field effectively eliminates the sidereal variation.

7.5.2 Particle Deflection in the Large-Scale, Sectored Interplanetary Magnetic Field

Ness et al (1965) have found that the interplanetary magnetic field

has a sectored, spiral structure of inwardly and outwardly directed magnetic field. During the Imp. I satellite observations of 1964, there were seven sectors, thus their dimensions were approximately 1 A.U. at the region of the earth. Since a proton of momentum 225 GV/c has a Larmor radius of 1 A.U. in a magnetic field of 5.10^{-5} gauss, we expect severe deflection of the particle trajectories below this momentum in the region of the earth. Thus, the galactic anisotropy is "smeared" out and effectively reduced to zero for particles with momenta below about 225 GV/c.

Since the critical momentum obtained in (a) is associated with scattering by kinks, it most probably represents the upper limit to the solar anisotropy. For particles of greater momenta density gradients are operative which reduce the corotation effect (Parker 1964). Above P $\simeq$ 225 GV/c, the galactic anisotropy may still be present. This is summarised in schematic form in Fig. 7.2b. It is suggested that there is a momentum region which exhibits neither solar nor galactic anisotropies. We may now apply these ideas to the predictions of the two effects discussed earlier viz:-

(i) Compton-Getting effects. (ii) Galactic diffusion.

7.5.3 Compton-Getting Effect Due to Motion of the Earth

As a consequence of galactic rotation, the sun-earth system has a velocity of $\sim$300 kms./sec. relative to nearby galaxies. If the primary cosmic rays observed at Holborn are extra-galactic in origin, then we expect a sidereal diurnal wave of amplitude $\sim$0.3%. Such large amplitudes are inconsistent with the observed values of about 0.03% (see Fig. 7.2a for the diurnal waves corrected for amplitude modulation of the S.D.V.)

If we allow that the interplanetary field destroys the effect below about 250 GV/c, then since about 50% of the Holborn counting rate is due to particles of $P \rangle 250$ GV/c, we still expect a variation of about 0.15%. This is still inconsistent with the observations. Thus we conclude that the majority of particles monitored by the Holborn detectors originate within the Galaxy.

This is apparently confirmed by radio-astronomical data on synchrotron emission by energetic electrons. There is more emission in the disk and halo of the Galaxy than from inter-galactic sources. By implication, the proton intensity is assumed to be greater within the Galaxy. Since the magnetic field within the Galaxy is capable of containing particles of momentum up to 10^{17} to 10^{18} eV/C, it follows that only above this region will extra-galactic particles be able to enter our Galaxy.

Even if there is no Compton-Getting effect due to rotation of the Galaxy, there should be a small effect due to the motion of the sun relative to nearby stars. This motion is towards galactic latitude $\ell = 20^{\circ}$ at 1800 hours R.A. with a velocity of $\sim$ 20 kms./sec. Even if the galactic cosmic ray flux were isotropic right down to the local level of neighbouring stars, we still expect a small sidereal diurnal wave. We have calculated the predicted amplitudes for Holborn using the theory of Chapter 5, section 5. Theory and experiment are compared in Fig. 7.2a. Taking $R_{min.} \simeq 250$ GV, we can calculate the probability that the results of each set of telescopes are consistent with the predictions of a local motion effect. If this is the only galactic anisotropy present, then the probabilities that the results agree with this effect are 8%, 10%, 4% for East, North and vertical

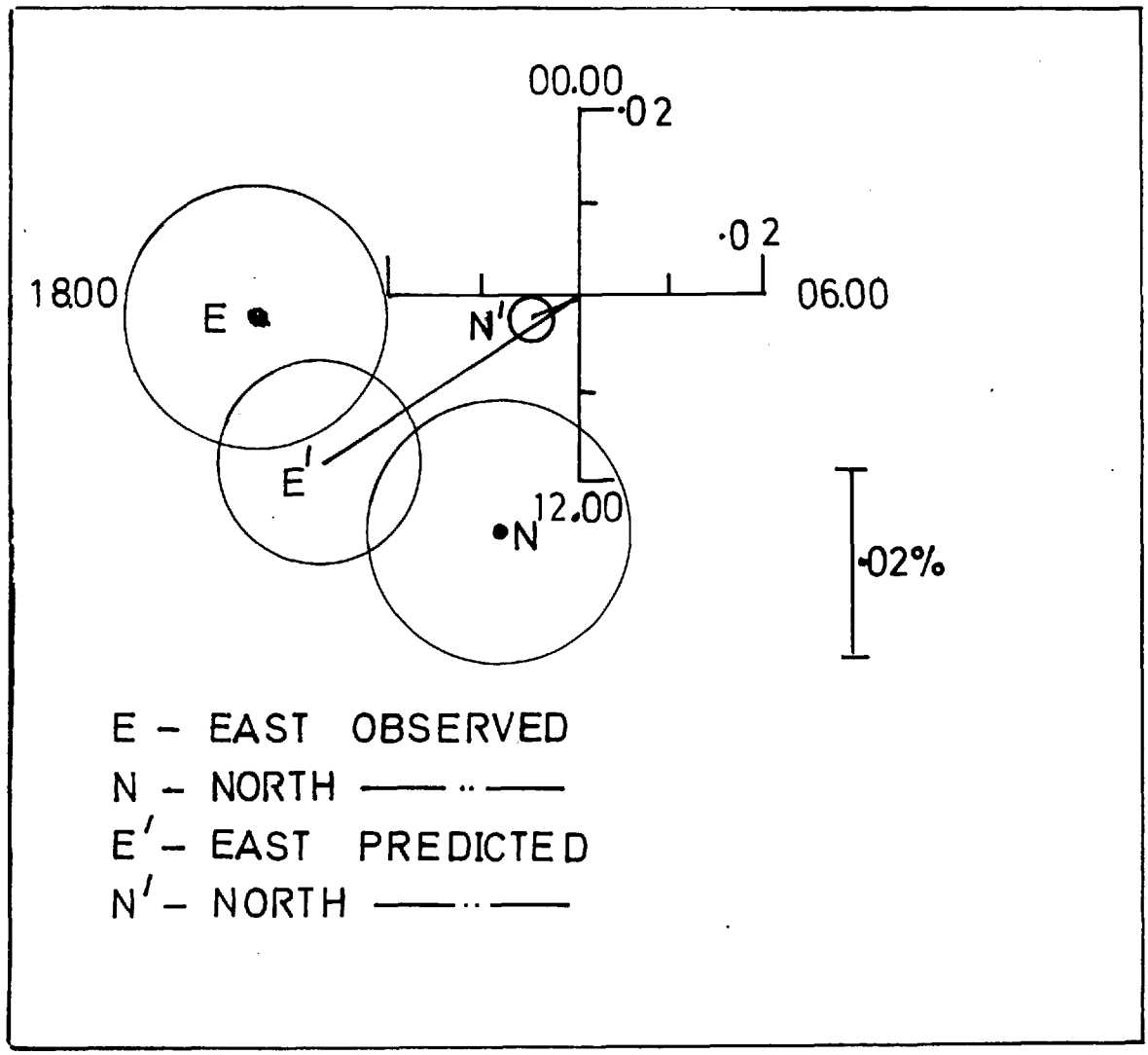


FIG. 7.3 OBSERVED SIDEREAL WAVES FOR EAST AND NORTH TELESCOPES CORRECTED FOR AMPLITUDE MODULATION OF THE SOLAR DIURNAL WAVE. PREDICTED WAVES ARE ACCORDING TO A POSSIBLE DIFFUSION EFFECT OBSERVED BY THE VERTICAL TELESCOPES.

telescopes respectively. The probability that all of the data is consistent with a local motion effect is only 0.03%. There is, therefore, the possibility of another sidereal effect.

The Hobart underground data are also at variance with a local motion effect. The observed phase being about 0800 hours L.Sid.T. compared to a predicted value of 1800 hours. Similarly, the observed amplitudes are about 0.05% compared to a predicted value of only 0.02%. We shall therefore consider the consequence of galactic diffusion of cosmic rays.

7.5.4 Galactic Diffusion

The galactic cosmic rays of energy 100 to 1000 GeV will all be more or less constrained to diffuse along observed galactic fields of about 10^{-5} to 10^{-6} gauss. For simplicity, we take the diffusion effect to be energy independent for the particles monitored by the Holborn detectors. Taking the vertical data for the whole period November 1960 to July 1966 we get the best estimate of the sidereal diurnal wave (corrected for amplitude modulation of the S.D.V., see Fig. 7.2a). If this represents a diffusion effect, we can predict the East and North sidereal diurnal waves. These are shown in Fig. 7.3. The probability that the east and north-pointing observations collectively agree with their respective predicted values is then about 10%. Again, this largely depends on the relatively large amplitude observed by the north-pointing telescopes. Although the probability is low, we cannot reject the hypothesis that galactic diffusion is responsible for the Holborn results. Neglecting a possible energy dependence, we can correct for geomagnetic bending by taking the mean energy of response of the Holborn detectors to be about 500 GeV. Corrections

for geomagnetic deflection are then 4, 4 and 1 hours for East, North and vertical telescopes respectively. The corrected results are shown in Fig. 7.1b, where it can be seen that the times of maxima tend to be about 2000 $\pm$ 0200 hours L.Sid.T. This direction corresponds to that of the "Orion" spiral arm directed towards the galactic centre.

If we accept that the sidereal diurnal wave is due to a diffusion of particles along the spiral arm, we can then estimate the particle mean free path. The sidereal diurnal amplitude of about 0.03% corresponds to a mean particle drift velocity (v_d) of about 40 kms./sec. if we assume that the anisotropy is destroyed below about 250 GeV. Taking a mean energy of response of 500 GeV, then v_d is given by:-

$$v_d = \frac{r_H}{\ell} \cdot c \qquad \text{(Alfvén 1949)}$$

where r_H is the Larmor radius of a particle of energy 500 GeV in a galactic magnetic field of about 3.10^{-6} gauss, ℓ is the m.f.p., and c is the particle velocity ($\simeq 3.10^{10}$ cms./sec.).

Hence ℓ is calculated to be about 4.10^{18} cms. on the basis of the Holborn results. This compares with a minimum separation of magnetised gas clouds of about 10^{19} cms. (according to Ginzburg and Syrovatskii 1964). However, considering the approximate nature of the calculation, we cannot say that the two estimates are significantly different. Thus we conclude that the data are not inconsistent with diffusion along the spiral arm containing the sun.

7.6 Conclusions

(i) The apparent sidereal diurnal wave is composed of spurious and

genuine components. But for the north-pointing telescopes, the data would be consistent with a single local origin to the anti-sidereal and apparent sidereal waves. On the other hand, the significant apparent sidereal wave observed by the North-pointing telescopes suggests the presence of a local spurious effect. We conclude that there is a genuine component to the apparent sidereal wave and that the spurious component is most probably local in origin.

(ii) The genuine component may not be entirely attributed to galactic rotation, nor to local motion of the sun relative to nearby stars. Thus, the cosmic rays in the energy region 100 to 1000 GeV are probably not extra-galactic in origin, nor are they isotropic in the local system of stars including the sun.

(iii) The data are not inconsistent with a model of particle diffusion along the spiral arm of the Galaxy containing the sun. If we allow that the resulting anisotropy is reduced by a factor 2 in the interplanetary field, then we can estimate the galactic anisotropy to be $0.1 \pm 0.03\%$ for particles of energy about 500 GeV.

CHAPTER 8

DISCUSSION AND SUGGESTIONS FOR FURTHER WORK

8.1 Discussion

Two of the more important objectives of this experiment were:-

(a) To continue the study of solar and sidereal daily variations exhibited by particles of energy of the order 100 GeV through the period of minimum solar activity (1965).

(b) To apply the "crossed telescope" technique to estimate the contribution to the daily variation due to stratospheric temperature variations. It will be convenient to discuss the results with these two aims in mind.

The minimum sunspot activity, as measured by the Zurich sunspot number, occurred about the middle of 1964, while the maximum in the cosmic ray intensity, as measured by the Deep River neutron monitor, occurred in about the middle of 1965 (see Solar-Geophysical Data 1964 - 1965). The long-term changes in the solar diurnal wave observed at Holborn were correlated with neutron counting rate rather than sunspot activity, e.g. see Fig. 4.6, Chapter 4. The time of maximum of the solar diurnal wave was observed to change from about 14 hours to about 06 hours during 1965. We have interpreted this as an absence of a solar anisotropy with $T_{max.}$ = 18 hours for particles with energies greater than 50 - 70 GeV. This allowed for the first time the direct observation of the diurnal wave due to the orbital motion of the earth; this has a maximum free space amplitude of 0.055% at 06 hours.

Duggal et al (1967) found from a study of many neutron monitor stations

that the mean solar diurnal amplitude was reduced by about 30% in 1965 compared to 1958. This smaller change at s/l compared to underground can be attributed to the vastly different energy responses. Thus the minimum solar diurnal variation observed at s/l and underground occurred at a time when there was least exclusion of the lower energy primary cosmic rays from the earth. The reduction of the galactic primary intensity to the lower values observed near the earth is normally associated with outward convection of the galactic particles by radially moving scattering centres embedded in the spiral interplanetary magnetic field (Parker 1965). As such, the 11-year variation may depend on any or all of the following:-

(i) u , the mean solar wind velocity.

(ii) λ , the scattering m.f.p.

(iii) R, the size of the modulating region.

On the other hand, the diurnal wave would appear to be independent of u and R if its origin is due to corotation of the galactic primaries with the sun. The long-term changes in the diurnal wave have a simple interpretation in terms of changes in λ e.g. in 1965 the larger kinks with separations of about 3.10^{12} cms. and greater may have been absent. Since the long-term changes in the diurnal wave and the intensity were well correlated during the solar minimum period there is the hint that the 11-year intensity variation may be associated with changes of λ. In direct contrast to this suggestion, the behaviour of the diurnal wave during the solar minimum of 1954 was vastly different from that of 1965. But the cosmic ray intensities observed by neutron monitors were approximately the same during 1954 and 1965, suggesting that the processes responsible for the 11-year intensity variation were equally effective in 1954

and 1965. However, if we interpret the data on the diurnal wave in terms of corotation theory, then $R_{max.}$ must have reduced to very low values approaching zero during many months of 1954 compared to a reduction to about 50 GV during 1965. Besides, it is known that even at solar minimum in 1954 there was still residual modulation even though the solar anisotropy was effectively zero. Thus the long-term variation in the solar diurnal wave and the 11-year intensity variation are not intimately related as suggested at first sight.

The solar diurnal wave has been observed to have a reduced amplitude during the last four solar minima. Hence, an 11-year variation can be considered well established, e.g. see Duggal et al (1967) and others. At the same time, it is to be noted that the amplitude reductions were greater in 1933 and 1954 and were associated with phase advances of several hours, Thambyahpillai and Elliot (1953). This may reflect a 22-year variation although it is suggested in this thesis that the phase advances can be interpreted in terms of corotation theory as being partly due to both

(a) reduction of the mean energy of the particles corotating as $R_{max.}$ decreases. Hence, there is greater geomagnetic deflection causing the solar diurnal phase to advance to even earlier times of maxima.

(b) a residual atmospheric contribution to the diurnal wave observed by s/l muon detectors which causes the phase to advance to near 06 hours when the anisotropy tends to zero.

If the diurnal wave were to continue to show a 22-year variation in amplitude, then it could possibly be associated with the 22-year variation observed in sunspot magnetic polarity. Sunspots are observed in pairs with

opposite magnetic polarities; in any 11-year cycle the leading spots (in terms of solar rotation) have the same polarity which changes sign at every solar minimum. It is interesting to note that the 1953 and 1954 minima were "quieter" in respect of sunspot activity than the minima of 1944 and 1965. One further point of interest on the possible relationship between cosmic ray modulation and sunspot activity is the asymmetry shown by the sun. In any one cycle either the northern or southern solar hemisphere exhibits greater sunspot activity than the other. This may be reflected in asymmetric cosmic ray modulations and is an obvious incentive to look for such effects. Recent work by Sarabhai and Subramanian (1965) has shown asymmetry in the intensity of the coronal line at $\lambda = 5303\text{Å}$ which again may reflect an asymmetric cosmic ray density gradient across the ecliptic plane, as pointed out by Marsden (1967). It must be emphasized that so far no direct relationship has been established between these solar surface phenomena and cosmic ray modulations.

The corotation model for the solar diurnal anisotropy was shown to account for the Holborn results if $R_{max.} \simeq$ 130 GV and the free space amplitude was 0.4% during 1960 - 1964. Long-term changes were accounted for by $R_{max.}$ reducing to less than 50 - 70 GV during 1965. Data from crossed meson telescopes at the surface in London and Makerere suggest that $R_{max.}$ was about 40 GV at this time (Hashim 1967). Corotation theory predicts a maximum free-space amplitude of 0.7% whereas the mean value is observed to be 0.4% (McCracken 1965). This discrepancy may only be a consequence of the interplanetary magnetic field not always conforming to the idealised model proposed by Parker. In fact, the interplanetary field is only observed to

have the Archimedian spiral pattern on average, and does show great variability in strength and direction (Ness 1965). However, corotation theory cannot account for local differences between results from surface ionization chamber stations described in Chapter 5. Besides this, it is known that the daily variation has great variability when studied on a day-to-day basis, e.g. Sarabhai and Subramanian (1965) found that the diurnal wave had an energy dependence of E^{β} where $-1 < \beta < +1$ and β varied from day to day. Again, this may be due to the variability in the interplanetary magnetic field. At the moment, statistical limitations do not allow the study of the daily variation at 60 m.w.e. for periods of less than one month.

The solar semi-diurnal wave was constant at 60 m.w.e. from 1960 to 1966. Similarly, the semi-diurnal wave did not show any significant changes during the solar minima of 1944 and 1954 according to the ionization chamber data of Forbush and Venkatesan (1960). This is consistent with the interpretation of the semi-diurnal wave in terms of a density gradient perpendicular to the heliographic equator if residual modulation was present in 1944, 1954 and 1965, as seems to be the case. It can be argued that as solar cycle modulation varies one might expect the gradient to change and hence the semi-diurnal amplitude to vary. From the work of Rao and McCracken (1965), the semi-diurnal amplitude was constant from 1957 to 1965. On the other hand, Lietti and Quenby (1967) suggest a solar cycle dependence which increases the semi-diurnal wave at solar maximum, thus suggesting that the gradient increases at solar maximum. Both agree that the phase is invariant with time; since the phase is associated with the presence and direction of the spiral interplanetary magnetic field, this is a piece of indirect evidence that the Parker

model applies even at solar maximum. This is of interest since no direct magnetometer measurements are available for the solar maximum period. Likewise, the presence of the semi-diurnal wave during 1954 would tend to indicate that the spiral field pattern was present at this time.

With regard to the atmospheric temperature contribution to the Holborn observations, we can assert that:-

(a) The two-year averages (October 1964 - September 1966) of solar diurnal and semi-diurnal waves observed by the North telescopes were insignificantly different from zero, and therefore the atmospheric contributions were insignificantly small.

(b) The solar diurnal waves for East and vertical telescopes were due only to an orbital motion effect and any atmospheric contribution during the solar minimum period. The year 1965 saw the maximum cosmic ray intensity and during this year the data were consistent with the atmospherically-induced wave being less than 0.02% (Peacock and Thambyahpillai 1967). Taking the observed positive temperature coefficient of 0.04%/^{o}C, this corresponds to a mean stratospheric temperature wave of less than 0.5^{o}C, a figure which seems reasonable from the recent wind measurements of Harris et al (1962).

The situation with regard to the apparent sidereal and anti-sidereal variations is still far from clear. The presence of the anti-sidereal wave at 60 m.w.e. was established even during the solar minimum period. In correcting for this effect, we have assumed that the observed solar diurnal wave undergoes seasonal amplitude modulation even during solar minimum. Since during this period the solar wave was thought to be due only to an orbital motion effect, we do not expect any appreciable seasonal modulation. Furthermore,

the large apparent sidereal waves observed by the North telescopes cannot be explained in terms of seasonal modulation since both the corresponding solar and anti-sidereal waves were insignificantly small. Despite this large apparent sidereal wave observed by the north-pointing telescopes, we cannot reject the hypothesis that the data were consistent with a galactic anisotropy of 0.03% with $T_{max.} \simeq$ 20 hours L.Sid.T., although this is subject to the limitation that the correction of the apparent sidereal waves was not fully understood. Apart from the data from the North telescopes, all other data were consistent with a local spurious origin of the anti-sidereal and apparent sidereal waves. This would also be consistent with the observed waves being constant even during the solar minimum period.

It is suggested that the existence of a large-scale sectored interplanetary magnetic field will reduce any galactic anisotropy observed at the earth below a primary energy limit of about 250 GeV. It is interesting that even though the solar anisotropy was effectively zero during the solar minimum period, no increase in the apparent sidereal wave was observed. This contrasts with the situation at the previous solar minimum (1954) when even surface stations observed a negligible solar diurnal wave during some months. Comforto and Simpson (1957) and others interpreted the phase changes observed in 1954 in terms of a possible galactic anisotropy. If this were correct, it would imply some sort of break-down in the large-scale interplanetary field. However, as pointed out previously, the presence of a semi-diurnal wave with $T_{max.} \simeq$ 03 hours in 1954 might suggest that the interplanetary field direction corresponded to the normal "garden hose" angle. A possible alternative explanation to the effects observed both at the surface in 1954 and underground

in 1965 would involve a second contribution to the solar diurnal wave which has only a small mean amplitude but undergoes a relatively large seasonal variation. In this respect, observations on the asymmetry of cosmic ray modulations across the ecliptic plane will be important. At the moment, there is some evidence (Dorman and Fischer 1965) for a seasonal variation in cosmic ray intensity consistent with a density gradient perpendicular to the ecliptic of about 5%/A.U. (for particles of energy$\sim$10 GeV in 1964).

One final point to be made on the sidereal daily variation is the disagreement between results at Hobart (40°S) and Holborn(50°N). The relatively large amplitude of 0.045% at $T_{max.} \simeq$ 06 hours L.Sid.T. was observed at 40 m.w.e. for the period 1958 - 1962 (Jacklyn 1965). The amplitude at Holborn was found to be 0.03% or less with $T_{max.} \simeq$ 20 hours L.Sid.T; considering that scattering in the interplanetary magnetic field becomes relatively more efficient at lower energies, one might reasonably expect larger sidereal variations at Holborn, contrary to observation. The large sidereal variation of 0.1% observed at Hobart by a telescope inclined at 70° to the zenith and pointing due north was not confirmed by the Holborn telescopes. Neither was it found that the sidereal daily variation increased as the solar daily variation decreased (Jacklyn and Humble 1965). We can only conclude that the suggested "2-way galactic anisotropy" is not yet confirmed.

8.2 Suggestions for Further Work

Obviously, the telescopes must continue in operation to fully confirm the return of the solar diurnal wave with a time of maximum near 14 hours.

The very latest data indicate that the yearly average solar diurnal waves (June 1966 to May 1967) are insignificantly different from zero for all three sets of directional telescopes. Correction for the orbital motion effect means that $R_{max.}$ has increased to about 100 GV for this latest period.

Continuation of the experiment will confirm or deny the large apparent sidereal wave observed by the North telescopes at solar minimum. At the moment, these apparent sidereal waves are not yet understood, but it is of interest to know if they are a permanent feature of the observations or merely associated with the solar minimum.

Since it is suggested that the galactic anisotropy is present only for primaries of energy greater than about 250 GeV, it would be of interest to repeat these measurements excluding primary particles with $E < 250$ GeV. This could be done by an E.A.S. experiment at mountain altitudes or by muon detectors at a depth of about 300 m.w.e. At a depth of 300 m.w.e., the solar diurnal wave will consist only of the orbital motion effect plus any atmospheric wave. A diurnal wave due to corotation of the primaries should be absent at all times of the solar cycle and this represents a further reason for going to these higher primary energies. At these depths, the positive temperature coefficient may increase to a value of about $0.2\%/^{\circ}C$ (according to Trefall 1958) compared to $0.04\%/^{\circ}C$ at 60 m.w.e. On the other hand, the stratospheric temperature wave was shown to be less than $0.5^{\circ}C$ and may reasonably be expected to be only a few tenths of a degree. If $\Delta T = 0.2^{\circ}C$ the corresponding intensity wave of 0.04% would, in all probability, be less than the statistical uncertainty, bearing in mind the great reduction of counting rate at 300 m.w.e. Thus, the problems reduce

to those of size and cost of the apparatus required to obtain a statistical accuracy of, say, 0.05% in a reasonable period of time.

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APPENDIX I

DIFFERENTIAL RESPONSE FUNCTIONS

With the notation of Chapter 1, we defined the differential response functions as:-

$$W^{i}_{\lambda,\eta}(h_o,\theta,\varphi) = \frac{\partial N^{i}_{\lambda,\eta}(h_o,\theta,\varphi)}{\partial \mathcal{E}_{min.}} \cdot \frac{1}{N^{i}_{\lambda,\eta}(h_o,\theta,\varphi)}$$

For a surface detector, e.g. meson or neutron monitor, we can obtain $N^{i}_{\lambda,\eta}$ as a function of $\mathcal{E}_{min.}$ by performing a latitude survey. In principle we then know $\frac{\partial N^{i}_{\lambda,\eta}}{\partial \mathcal{E}_{min.}}$ and $\frac{1}{N^{i}_{\lambda,\eta}}$ and, therefore, $W^{i}_{\lambda,\eta}$ up to a rigidity of about 15 GV. In practice, the detecting instrument integrates over all possible θ and φ with its own peculiar geometrical sensitivity and hence $W^{i}_{\lambda,\eta}$ applies only to that detector. Above 15 GV the response function is extrapolated, e.g. see Webber and Quenby (1959).

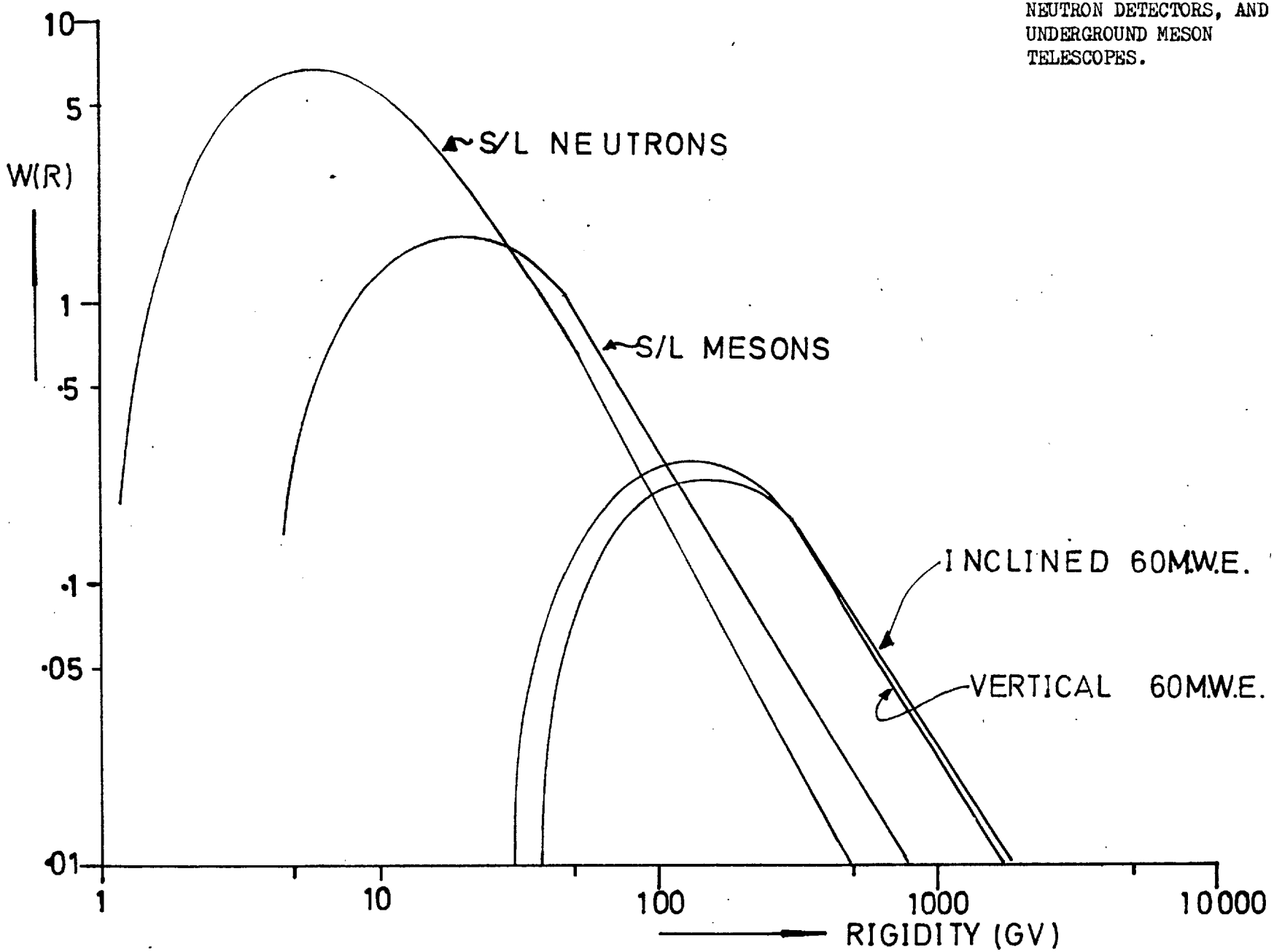
Such a latitude survey is not possible with underground detectors for obvious reasons. Therefore, Mathews (1962) obtained the response functions for 60 m.w.e. by a method due to Dorman (1959). The latter showed that the relationship between the response functions of a meson detector at two different atmospheric depths, x_1 and x_2, is given by:-

$$\frac{dN}{dP}(P, x_1) = \frac{E(x_2)}{E(x_1)} \cdot \frac{dN}{dP}\left(P.\frac{E(x_2)}{E(x_1)}, x_2\right)$$

where $\frac{dN}{dP}(P, x_1)$ is the differential response at a rigidity P and depth x_1

$\frac{E(x_2)}{E(x_1)} \cdot \frac{dN}{dP}\left(P.\frac{E(x_2)}{E(x_1)}, x_2\right)$ is the differential response at rigidity $P.\frac{E(x_2)}{E(x_1)}$

FIG. A1 RESPONSE FUNCTIONS FOR SEA LEVEL MESON AND NEUTRON DETECTORS, AND UNDERGROUND MESON TELESCOPES.



and depth x_2.

$E(x_1)$ is the minimum energy at production of muons capable of reaching depth x_1.

$E(x_2)$ is the minimum energy at production of muons capable of reaching depth x_2.

According to Dorman, this relationship holds if the exponent of the differential energy spectrum and the multiplicity for muon generation are both constant in the range of primary energies of interest, i.e. 10 - 1000 GeV.

We have used this method to extrapolate the cubical s/l meson detector response functions obtained by Webber (1962) (using Quenby-Wenk (1962) threshold rigidities) to a depth of 60 m.w.e. For inclined directions we have made the implicit assumption that a detector inclined at 45° to the zenith, having a mean direction of view at 35°, is equivalent in terms of response, to a vertical detector at a depth of 70. sec. $(35^{\circ}) \simeq 80$ m.w.e. (from the top of the atmosphere). This was justified on the grounds that the directional sensitivity patterns of the detectors (Fig. 2.6a, Chapter 2) were reasonably narrow and fairly symmetrical; at these large muon energies ($E \geqslant 15$ GeV) large geomagnetic deflections in the atmosphere are not expected and at 35° to the zenith the curvature of the atmosphere is not important. The calculated curves are shown in Fig. A.1 along with the curves for s/l meson and neutron monitors.

Considering the approximate nature of the calculation of response functions, we cannot expect accurate results; errors may be as large as 20%. This may not be so important with regard to random errors since the main experimental limitation here is that of statistical accuracy. But if the response functions involve some systematic error (due, for instance, to the method of calculation) then there results a systematic bias in, say, the estimation of $R_{max.}$ in Chapter 5.

REFERENCES

Ables, J. G., K. G. McCracken and U. R. Rao, 1965, Proc. Int. Conf. Cosmic Rays, Lond., 1, 208
Ahluwalia, H. S., V. I. Escobar, M. Zubieta, R. Anda, M. Schreier and O. Troncoso, 1965, Proc. Int. Conf. Cosmic Rays, Lond., 1, 190
Ahluwalia, H. S. and A. J. Dessler, 1962, Planet. Sp. Sc., 9, 195
Alfven, H., 1949, Phys. Rev., 75, 1742
Alfven, H., 1954, Tellus, 6, 232
Alfven, H. and K. G. Malmfors, 1943, Ark. Mat., Ast., Fys., 29A, 24
Axford, W. I., 1965, Planet. Sp. Sc., 13, 115

Baker, P., R. L. Chasson and V. J. Kisselbach, Nature, 211, 354
Baliga, S. P., and T. Thambyahpillai, 1954, Phil. Mag., 4, 973
Blackett, P. M. S., 1938, Phys. Rev., 54, 973
Bonetti, A., H. S. Bridge, A. J. Lazarus, B. Rossi, and F. Scherb, 1963, J. G. R., 68, 4017
Brunberg, E. A. and A. Dattner, 1953, Tellus, 5, 135

Carmichael, H., M. Bercovitch and J. F. Steljes, 1965, Proc. Int. Conf. Cosmic Rays, Lond., 1, 492
Compton, A. H. and I. A. Getting, 1935, Phys. Rev., 47, 817
Comstock, G. M., C. Y. Fan and J. A. Simpson, 1965, Proc. Int. Conf. Cosmic Rays, Lond., 1, 383
Conforto, A. M. and J. A. Simpson, 1957, Nuo. Cim., 6, 1052
Courtier, G. M. and A. D. Linney, 1966, Planet. Sp. Sc., 14, 503

Dattner, A. and D. Venkatesan, 1959, Tellus, 11, 239
Delvaille, J., F. Kendziorski and K. J. Greisen, 1959, Proc. Int. Conf. Cosmic Rays, Moscow, 3, 143
Dorman, L. I., 1957, "Cosmic Ray Variations" (Moscow)
Dorman, L. I., 1959, Section 7, I.G.Y. Prog. (C.R.), No. 1 Publ. House Acad. Sci., U.S.S.R.
Dorman, L. I., 1963, Prog. in Elem. Particles, Cosmic Ray Phys., N-Holland Publ. Co., Vol. 7
Dorman, L. I., and S. Fischer, 1965, Proc. Int. Conf. Cosmic Rays, Lond., 1, 239
Duggal, S. P., A. Pomerantz, S. E. Forbush, 1967, Nature, 214, 154
Duperier, A., 1949, Nature, 163, 364
Duthie, J. G., R. Cobb and J. Stewart, 1966, Phys. Rev. Lett., 17, 263
Dutt, J. C., 1965, Ph.D.Thesis, Lond. Univ.
Dutt, J. C. and T. Thambyahpillai, 1965, J. Atmos. Terr. Phys., 27, 349

Earl, J. A., 1961, Phys. Rev. Lett., 6, 125
Elliot, H., 1952, Prog. in Elem. Particles and Cosmic Ray Phys., N-Holland Publ. Co., Vol. 1
Elliot, H., 1960, Phil. Mag., 5, 601
Elliot, H. and D. W. N. Dolbear, 1951, J. Atmos. Terr. Phys., 1, 205
Fallar, A. M. and P. L. Marsden, 1965, Proc. Int. Conf. Cosmic Rays, Lond., 1, 231
Farley, F. J. M. and J. R. Storey, 1954, Proc. Phys. Soc., A67, 996
Fenton, A. G., 1963, Proc. Int. Conf. Cosmic Rays, Jaipur, 2, 185
Fenton, A. G., 1965, Private Comm.
Fisher, R. A., 1938, Stat. Methods for Res. Workers, Publ. Oliver and Boyd
Forbush, S. E. and D. Venkatesan, 1960, J. G. R., 65, 2213

George, E. P., 1952, Prog. in Elem. Part. and Cosmic Ray Phys., N-Holland Publ. Co., Vol. 1
Ginzburg, V. L. and S. I. Syrovatsky, 1964, "The Origin of Cosmic Rays", Pergamon Press

Harris, M. F., F. G. Finger and S. Teweles, 1962, J. Atmos. Sc., 19, 136
Hashim, A. 1967, Private Comm.

Jacklyn, R. M., 1963, Nature, 200, 1306
Jacklyn, R. M., 1965, Nuo Cim., 36, 1135
Jacklyn, R. M. and J. E. Humble, 1965, Aust. J. Phys., 18, 451
Johnson, T. H. and J. C. Street, 1933, Phys. Rev., 43, 381

Kane, S. R. and J. R. Thakore, 1960, Proc. Ind. Acad. Sci., A52, 122
Krimsky, G. F., 1965, Geo and Aero., 4, 977

Lemaitre, G. and M. S. Vallarta, 1933, Phys. Rev., 43, 87
Lietti, B. and J. J. Quenby, 1967, Proc. Int. Conf. Cosmic Rays, Calgary, to be published in Canad. J. of Phys.

MacAnuff, J. W., 1951, Ph.D.Thesis, Lond. Univ.
Maeda, K. and M. Wada, 1954, J. Sci. Res. Inst., 48, 71
Marsden, P. L., 1967, Written contribution to IV I.Q.S.Y. Assembly, London
Mathews, P. M., 1959, Canad. J. Phys., 37, 85
Mathews, T., 1962, Ph.D.Thesis, Lond. Univ.
McCracken, K. G., U. R. Rao and M. A. Shea, 1962, Tech. Report No. 77, M.I.T.
McCracken, K. G. and N. F. Ness, 1966, Pioneer VI Symposium, Washington
McCracken, K. G. and U. R. Rao, 1965, Proc. Int. Conf. Cosmic Rays, Lond. 1, 213
McCusker, C. B. A., D. E. Page and R. A. Reid, 1960, Proc. Int. Conf. Cosmic Rays, Moscow, 4, 280

Mori, S., H. Ueno and K. Nagashima, 1965, Proc. Int. Conf. Cosmic Rays, 1, 498
Myssowsky, L. and L. Tuwim, 1928, Z. Phys., 50, 273

Nagashima, K., 1953, J. Geomag. and Geoelec., 5, 141
Neas, N. F., 1965, Proc. Int. Conf. Cosmic Rays, Lond., 1, 14

Parker, E. N., 1958, Phys. Rev., 110, 1445
Parker, E. N., 1964, Planet. Sp. Sc., 12, 735
Parker, E. N., 1965, Proc. Int. Conf. Cosmic Rays, Lond., 1, 26
Peacock, D. S. and T. Thambyahpillai, 1967, Proc. Int. Conf. Cosmic Rays, Calgary, to be published in Canad. J. of Phys.
Possener, M. and I. J. V.Heerden, 1956, Phil. Mag., 8, 253

Quenby, J. J. and W. R. Webber, 1959, Phil. Mag., 4, 90
Quenby, J. J. and T. Thambyahpillai, 1960, Phil. Mag., 5, 585
Quenby, J. J. and G. J. Wenk, 1962, Phil. Mag., 7, 1457

Rose, D. C., K. B. Fenton, J. Katzman and J. A. Simpson, 1956, Can. J. Phys., 34, 968

Sakakibara, S., 1965, Proc. Int. Conf. Cosmic Rays, Lond., 1, 135
Sarabhai, V. and P. D. Bhauser, 1958, Nuo Cim., 8 (Suppl.), 299
Sarabhai, V. and G. S. Subramanian, 1965, Proc. Int. Conf. Cosmic Rays, Lond., 1, 170
Simnett, G., 1966, Ph.D.Thesis, Lond. Univ.
Simpson, J. A., 1955, "Neutron Monitor", Chicago
Skripin, G. V., 1965, Geo and Aero, 5, 635
Solar-Geophysical Data, U.S. Dept. of Commerce
Standil, S. and R. P. Bukata, 1964, Phys. Rev. Lett., 12, 487
Stern, D. J., 1964, Planet. Sp. Sc., 12, 973
Störmer, S., 1930, Z. Phys., 61, 237

Thambyahpillai, T. and H. Elliot, 1953, Nature, 171, 918
Trefall, H., 1955a, Proc. Phys. Soc., A68, 625
Trefall, H., 1955b, Proc. Phys. Soc., A68, 893
Trefall, H., 1955c, Proc. Phys. Soc., A68, 953
Trefall, H., 1958, Proc. Int. Conf. Cosmic Rays, Mexico, 215

Venkatesan, D. and A. Dattner, 1958, Tellus, 11, 116

Waddington, C. J., 1960, Prog. Nucl. Phys., 8, 1
Webber, W. R., 1962, Prog. Elem. Particle and Cosmic Ray Phys., N-Holland Publ. Co., Vol. VI
Webber, W. R. and J. J. Quenby, 1959, Phil. Mag., 4, 654