DIURNAL AND TRANSIENT COSMIC-RAY VARIATIONS

by

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PREFACE.

The Hobart Cosmic-Ray Group, comprising members of the University of Tasmania and of the Australian National Antarctic Research Expeditions (A.N.A.R.E.) under the leadership of Dr. A.G. Fenton, commenced synoptic observations of cosmic rays at ground level in 1953. By the beginning of the International Geophysical Year in July 1957 a comprehensive series of observations was in progress at a number of Australian and Antarctic sites. The observations were continued, and further extended, after the I.G.Y. with the intention of observing, if possible, variations in cosmic-ray behaviour over at least a complete solar cycle. The programme of data exchange with other cosmic-ray groups, which had been started during the I.G.Y., was also continued.

The handling and analysis of data of the type accumulated by these observations require the use of a number of more-or-less standard techniques. The data require correction for atmospheric variations before they can be used. They may subsequently be subjected to some form of ordering, or to harmonic or power spectrum analysis, with or without the prior application of numerical filtering. Analysis requires that the response characteristics of each detector be well determined, involving knowledge of its directions of viewing outside the influence of the terrestial magnetic field, and of its likely response to any particular anisotropy in the interplanetary cosmic-ray flux.

Investigators at the time of the I.G.Y., and for a few years thereafter, were generally restricted to desk calculators and slide rules for arithmetic purposes. This severely limited the size and scope of the investigations which could be undertaken. Under this restriction atmospheric correction is the only one of the above techniques which is easy to apply. Harmonic analysis takes about one hour per analysis; numerical filtering and power spectrum analysis are practical impossibilities; and directions of viewing must be based on primary particle trajectories calculated for dipole representations of the Earth's magnetic field. The lastmentioned problem was a particularly severe handicap as it meant that responses of detectors, in particular neutron monitors and high-latitude muon telescopes, could not be accurately determined.

Early in 1964 the Hydro-University Computing Centre, a joint undertaking by the University of Tasmania and the Tasmanian Hydro-Electric Commission, commenced operations with an Elliott 503 Digital Computer. This machine gave the Hobart Cosmic-Ray Group its first ready access to computing facilities, and it was immediately decided to develop computer programmes to carry out the various standard calculations. It would then be possible to undertake more precise analyses, and inter-station comparisons than had been feasible previously. This thesis is concerned with some of these investigations, into several aspects of the modulation of cosmic-rays, and with the development of the necessary computer programmes. Emphasis is given to the analysis of neutron monitor observations, but data from muon telescopes are also used where appropriate.

The work described in the following chapters was undertaken between 1964 and 1970. For the last four years of this period I have been a full-time member of the teaching staff of the University of Tasmania, initially as a Senior Demonstrator and latterly as a Lecturer. For the whole of this period I have had oversight of the Cosmic-Ray Group's Data Handling Assistants, and the methods and techniques used, and have acted as computing consultant - and often programmer - for the other members of the Group. I have been particularly responsible for the collection and reduction of data from all the neutron monitors operated by the Group, and for the fault detection and remedial action for the Hobart and Brisbane neutron monitors, and for all the equipment at the Lae observatory until its closure. In the course of these duties I have also developed a series of computer programmes for the computer handling, pressure correction, graphing, and error detection of data from all the Group's various detectors, and also for the preparation of data tapes in standard format for transmittal to the World Data Centres. Prior to undertaking this work I spent a year at Mawson in charge of the cosmic-ray observatory.

The draft of this report was completed early in 1971. Few papers published outside Australia after September 1970 reached Hobart in time for consideration. Unfortunately I was unable to attend the 11th International Cosmic Ray Conference held at Budapest in 1969, and the Proceedings of that Conference did not start to arrive in Hobart until late July 1971, too late for general consideration. Teaching duties, and preparations for the 12th International Cosmic Ray Conference held at Hobart in August 1971, have delayed the final stages of the production of this report until after the Hobart Conference. In these circumstances, only limited mention is made of a few matters discussed at that Conference.

This thesis contains no material which has been accepted for the award of any degree or diploma in any University or other institution. It presents the results of my own work, and so far as I am aware it contains no copy or paraphrase of any material written or published by any

other person except where this has been noted and acknowledged in the body of the text. All computer programmes used (except the trajectory calculation programme in its original form) are of my own design, and I have undertaken all my own programme writing, testing, and evaluation.

An investigation of this nature benefits greatly from the interchange of ideas between various investigators. I have been particularly fortunate in this regard. It is a pleasure to thank fellow members of the Cosmic-Ray Group, in particular my supervisor for this work, Dr. A.G. Fenton; and Mr. D.J. Cooke, Dr. K.B. Fenton, and Dr. R.M. Jacklyn, for many interesting and thought-provoking discussions. I am also most grateful for a number of stimulating discussions with Professor K.G. McCracken and Dr. L.J. Gleeson. I thank Drs. Gleeson, M.A. Forman, and G.B. Tucker for making their work available to me before publication. I am also indebted to the directors of the various cosmic-ray observatories around the world, who have made their data available. The staffs of the World Data Centres at Boulder and Tokyo have been most co-operative in providing data which were not available through data exchange.

One cannot process large quantities of data unaided, particularly when they arrive in a varied collection of formats whose only common feature appears to be that they cannot be presented to the computer without some form of pre-processing. The help rendered by the Group's Data Handling Assistants in this regard has been indispensible and is most gratefully acknowledged. I have particularly appreciated the cheerful responses of Mrs. P.E. James, Mrs. D. Chappell, Mrs. B.M. Jensen, Mrs. P.E. Bashford, and Miss J.J. Whelan when, individually or collectively, they have been presented with large quantities of data with the request that they be processed as soon as possible. Grateful thanks are also due to the staff of the Computer Centre, and particularly to Miss M. Dunlop, Miss M. Lane, Miss C. Lewis, and other operators for their patience and tolerance with my long and often complex runs. I also wish to thank Mrs. J. Scott and Mrs. J. McLeod for typing assistance.

I am deeply indebted to General Motors Holden's Pty. Ltd. for the award of a Research Fellowship, and to the Commonwealth of Australia for a Commonwealth Research Scholarship, which covered the earlier years of this work. Finally my thanks go to my wife, both for her invaluable drafting assistance and for putting up with long and peculiar hours of work over the past few years, and to Mrs. L. Shelton for typing the final draft of this thesis.

J.E. Humble

(J.E. Humble),

Hobart, December, 1971.

CHAPTER 1.

SUMMARY.

The investigations described in this thesis fall naturally into three main sections. The relevant introductory reviews and theory are presented at the beginning of each section, rather than being grouped in one or more separate introductory chapters.

The first section, covered by Chapter 2, considers some of the modulations which cosmic rays undergo between the entry of the primary particle into the magnetosphere and the detection of the secondary particle at ground level. The calculation of the primary particle's trajectory in a high order simulation of the magnetic field is described. This work is not new, but is a necessary precursor to much which follows. Some of the various available simulations of the field are reviewed in connection with these calculations.

The effects of modulation processes affecting secondary particles within the atmosphere are then considered, particularly in relation to the absorption of neutrons. It is emphasised that good pressure data are essential, and some factors which affect the accuracy of pressure readings are discussed. An investigation is reported into possible wind-induced errors in the Mawson barograph recordings. No significant errors were found until the barograph was moved to a new location in 1965. Large wind-associated errors were found at the new site, and the procedures adopted for the retrospective correction of the pressure recordings are detailed.

The main part of the studies reported here concerns the analysis of the mean annual solar diurnal variation observed in cosmic rays at ground

level. Chapter 3 presents relevant background material, whilst the investigations themselves, together with the calculation techniques employed are discussed in Chapters 4, 5 and 6. The conventional simple model, that the anisotropy $\frac{\Delta J(R)}{J(R)} = AR^{\beta}$ for Rigidity $R \leq R_u$, and equals zero for $R > R_u$, is examined for several years (1961 to 1966) around solar minimum. The method used is the intercomparison of observations from many different neutron monitors, and some underground muon telescopes, for different assumed values of the model's parameters.

Detailed investigations are undertaken into factors which can affect this type of analysis. As a result it now appears that the conclusions which can be drawn may not be as reliable as previously has been supposed. The selection of stations to be used is of crucial importance since some detectors display diurnal vectors which appear to include components quite unrelated to the cosmic-ray flux. Comparison and statistical techniques for the detection of such instruments are discussed. Doubt exists in some cases and the results of including or excluding such stations in analyses are considered. It is shown that the analysis is insensitive to the set of coupling coefficients employed, and also that the anisotropy has - at least at the lower rigidities - a cosine dependence on asymptotic latitude.

It is found that it is insufficient to consider only the amplitude or the phase alone of the diurnal variations observed by the various detectors. The final analyses consider differences between the free-space vectors predicted by each detector, on the basis of its full diurnal vector, as the model parameters are varied. Likewise it is found that it is not valid to treat β and R_u separately. Varying one whilst keeping the other fixed leads to incorrect results. Overall it is found that β may be slightly positive through the years considered, with a most likely value in the region 0.0 to +0.2. This is at variance with previously reported results, but is permitted by the recent theory of Forman and Gleeson. R_u appears to lie in the range 60 to 100 GV, with indications of the lowest values being reached at solar minimum.

The parameters of the model which give rise to the best agreement between various detectors still generally leave a bigger scatter between the estimates of the free-space anisotropy derived from observations by the different detectors than would be expected on purely statistical grounds. Either incomplete allowance has been made for terrestial modulation at some of the detectors or the model is inadequate. It is probable that both causes contribute, and possible further developments in the techniques and model employed are discussed.

The statistical methods employed are checked experimentally, and it is found that the variance observed in neutron monitor data is about twice its expected value.

The methods developed for the diurnal analysis may conveniently be used, with appropriate modifications, for the study of transient events such as Forbush Decreases. A study of a particularly unusual type of transient event is reported in Chapter 7. This event is a sudden decrease in cosmic-ray intensity, but displays a number of features which distinguish it from normal Forbush Decreases. Possible mechanisms for normal Forbush Decreases are discussed, and it is suggested that this event may have been associated with a situation in which the magnetically disturbed region of space was principally located to one side of the ecliptic plane.

CHAPTER 2.

TERRESTIAL MODULATIONS - DIRECT AND INDIRECT.

2.1 INTRODUCTION

Any measurement of cosmic ray intensity made within the earth's atmosphere represents the free space intensity in the direction of viewing of the detector only indirectly, since the incoming cosmic rays are modulated successively by the geomagnetic field, the atmosphere, and the detecting instrument itself. The total modulation will be a product of these effects and may be expected to depend on the magnetic rigidity of the primary particle and its direction of arrival at the top of the atmosphere, the type of secondary particle produced, the type and geographic location of the detector, and the atmospheric structure above it. Consequently before any deductions can be made concerning free space cosmic ray fluxes, both isotropic and anistropic, the effects of these modulations must in some way be eliminated. We are concerned in this thesis primarily with sea level neutron monitors and hence the main attention in this section will be devoted towards them. However, we will also use data from other surface and underground instruments, requiring appropriate adjustments to the correction procedures in such cases.

It should be noted that "Free-Space", as used in the above context, is used to describe the region outside the terrestrial magnetosphere. The terms free-space flux, free-space anisotropy, etc., refer to the flux, or anisotropy in the flux, observed outside the magnetospheric boundary by an observer in the frame of reference of the moving earth.

When dealing with the various corrections necessary to determine free space conditions from ground level observations, it is useful to divide the corrections into time-dependent and time-invariant groups.

The former comprise the corrections for varying atmospheric structure whilst the latter are those for deflections in the geomagnetic field and the energy and geometric sensitivities of the detector. The detector energy sensitivity incorporates the specific yield functions which essentially determine the transparency of the atmosphere for secondaries produced by specific primaries. It is not of course totally true to assume the magnetic field is time-invariant. However, for many cosmic ray purposes it can be so treated, at least to a first approximation, making appropriate corrections at a later stage in the analysis. In the case of the quiet time diurnal variation, allowance may need to be made for the deformation of the magnetosphere by the solar wind, compression on the upwind side and stretching out to a pear drop shape on the downwind side. Forbush decreases are usually accompanied by magnetic disturbances and these may need to be considered. Greater attention will be given to these matters at the appropriate points in the text.

2.1.1 Magnetic Observations

Primary cosmic rays, excluding the numerous but hard to detect neutrinos, are mostly protons, which form about 88% of the particle flux observed in free space near the earth. The majority of the remainder are alpha particles, together with a percent or so of heavier nuclei. There is some evidence for the existence of neutrons of solar origin during disturbed periods (Apparao, Daniel, Vijayalakshmi and Bhatt; 1966), but their proportion appears low and their energy seems insufficient to penetrate deep into the atmosphere, certainly not to sea level. In computing the path of an incoming cosmic ray we are therefore faced with the problem of the motion of a charged particle in a magnetic field.

Early investigators, attempting to define a mean direction of viewing of their cosmic ray detectors, made use of a centred dipole magnetic field and basic Störmer theory. It was found that this did not give really satisfactory agreement between observations made at various stations. Later the offset dipole field was employed and this too was found to have shortcomings when inter-station comparisons were made. More recently, more complex models of the geomagnetic field, involving spherical harmonic expansions to several orders, have become available, and these have formed the basis for most recent studies of cosmic ray variations. The present work is no exception.

A number of sets of such spherical harmonic coefficients now exist, the degree of expansion used, and consequently the number of coefficients obtained, varying somewhat. An analysis by Hurwitz, Knapp, Nelson and Watson (1966) goes to 12 degrees. Earlier expansions tended to be smaller. Those of Finch and Leaton (1957) and Jensen and Cain (1962), for example, went only to 6 degrees. All the analyses use common basic data, as many magnetic observations as can be obtained from various parts of the world, up to 450,000 observations. Rejection and preliminary smoothing techniques differ, as do the epochs to which the results apply. The degree of expansion used only partly reflects the extra data available to the later investigations, it is also based on criteria involving the investigators view as to the reliability of the higher order terms, the amount of computing time available, and the immediate likely use of the results.

From the cosmic ray viewpoint, all expansions have certain common, although unavoidable, disadvantages. Firstly, the observations on which the analyses are based are far from equally distributed over the surface of the earth. Naturally there is a preponderance of observations in the more populated regions, and from the more densely trafficked sea routes. This means, in effect, mid and low latitudes. The paucity of reliable data from Antarctic and Asian, and to a lesser extent Arctic, regions is commented on by all workers and they caution against unthinking use of their results in such areas. Even Hurwitz et al, having access to PROJECT MAGNET world-wide data gathered over several years by the United States Naval Oceanographic Office, find large areas of Antarctica inadequately covered. It is not a good assumption that a numerical description of the field which gives a good fit to the mid- and low-latitude observations will necessarily give an equally good fit to the actual field elsewhere on the earth's surface.

Secondly, the analyses are performed on observations of magnetic field intensity on the surface of one shell only, that comprising the earth's surface, unless some satellite data obtained at heights of one to a few hundred miles are included. Backus (1970) has shown mathematically that it is possible to construct, from magnitude data obtained on the surface of a sphere, two models which vanish at infinity, agree everywhere on the observational surface, but which differ throughout the intermediate region. It is therefore not possible to determine a uniquely correct set of harmonic coefficients from the available observations, even assuming that the latter are perfectly accurate and evenly distributed. In practice, fortunately, the various models obtained by different investigators are not disastrously different (compare, for example, the Finch and Leaton, and the Jensen and Cain, field expansions). Even so it is not valid to assume without qualification that these models will give as good a fit to the actual field at some distance above the earth's surface as they do at ground level. Care must therefore be taken when extrapolating upwards (Cain and Hendricks, 1964; Cain, Daniels, Hendricks and Jensen, 1965). Since we are interested in trajectories of charged particles incident at the top of the atmosphere at such places as Wilkes and Mawson in Antarctica, and further we require to calculate the trajectories inward from the magnetopause, we must take account of these limitations. Thirdly, we need some criterion to enable us to obtain the expansion best suited to this purpose.

There is at present nothing which can be done concerning the first objection. It is found in high latitude regions that strong magnetic focussing effects exist for particles of rigidity below about 20 GV, i.e. regardless of their zenith and azimuth angle on arrival, they all come from a restricted region of the celestial sphere. The effect of any field errors will therefore presumably be to shift such regions bodily. If appreciable such shifts, particularly in longitude, might show up in inter-station comparisons. Small errors of order a degree or two would not be easily detectable, except possibly during the onset phase of a flare of solar protons sufficiently energetic to be observed at ground level.

The lower reliability of the field expansion at increasing distances from the earth is compensated by the lower magnitude of the field, resulting in errors becoming proportionately less serious for particle trajectory calculations. The higher order terms, being relatively small even at ground level, become progressively less significant and are therefore gradually omitted from the calculations as the radial distance increases. This can be opposed by the increasing effects of any external magnetic sources such as ring currents.

Up to the present time most of the non-dipole trajectory calculations for cosmic ray studies have used the Finch and Leaton simulation, based on the 1955.0 epoch. This is, partly at least, a historic accident in that this field was available when the first such calculations were being performed. In the absence of any demonstration of the superiority of any of the other expansions, the use of this field has been continued by most investigators to facilitate intercomparison of results. It has been shown by Shea, Smart and McCracken (1965) that the use of other simulations, in particular that of Jensen and Cain, does not produce a significant difference in the effective vertical cut-off rigidity obtained, although the penumbral structure is notably different.

Table 2.1 compares asymptotic directions (section 2.1.2) calculated for vertically arriving particles at Mawson using different field expansions. The RMS differences between the two sets of directions are about 0.9 degrees in latitude and 0.4 degrees in longitude.

Very similar differences are found for particles arriving at Mawson from inclined directions. Such differences are insignificant.

Rigidity (GV)	Asymptotic Lat Lon FL	Asymptotic Lat Lon JC	Rigidity (GV)	Asymptotic Lat Lon FL	Asymptotic Lat Lon JC	Rigidity (GV)	Asymptotic Lat Lon FL	Asymptotic Lat Lon JC
0.9	9.0 61.5	6.9 60.4	8.5	-38.9 52.3	-39.7 51.8	35	-48.7 69.9	-49.1 69.5
1.5	-3.8 56.0	-5.1 55.7	9.5	-38.5 50.0	-39.3 49.6	45	-52.7 71.2	-53.0 70.8
2.5	-15.7 55.6	-17.2 55.3	11.0	-36.9 49.5	-37.6 49.2	55	-55.4 71.5	-55.7 71.1
3.5	-21.3 55.5	-22.6 55.3	13.0	-35.5 51.9	-36.3 51.6	65	-57.4 71.3	-57.6 71.0
4.5	-27.3 51.5	-28.0 51.1	15.0	-35.6 55.1	-36.3 54.8	75	-58.8 71.0	-58.9 70.7
5.5	-26.8 54.5	-27.8 54.4	17.0	-36.5 58.2	-37.3 57.8	85	-59.9 70.7	-60.0 70.4
6.5	-32.3 57.4	-33.4 57.2	19.0	-37.9 60.8	-38.6 60.4	95	-60.7 70.3	-60.9 70.0
7.5	-37.2 55.6	-38.1 55.2	25.0	-42.6 66.1	-43.2 65.7	150	-63.3 68.5	-63.5 68.3

Table 2.1

Asymptotic Directions of particles incident vertically at Mawson, calculated using Finch and Leaton (FL) and Jensen and Cain (JC) field expansions. The FL values are from McCracken et al (1965). JC directions by the author.

Since the calculation of the trajectories used in this thesis an International Geomagnetic Reference Field (IGRF) has been published (IAGA Commission 2, 1969). The field was chosen by a Working Group of the International Association of Geomagnetism and Aeronomy to represent the field of internal origin and its secular variation. The IAGA recommend the use of this field in future work for epochs 1955.0 to 1972.0. For later dates it will be updated as required. It seems clear that this should be used for future cosmic ray calculations.

2.1.2 Trajectory Calculations

It is possible to calculate the motion of a charged particle through any magnetic field provided the initial conditions of motion of the particle are known and the field is explicitly determined at all points. The relevant equation of motion is, in the Gaussian system,

$$m \frac{d^2\underline{r}}{dt^2} = \frac{e}{c}\left(\frac{d\underline{r}}{dt} \times \underline{B} \right) \qquad 2.1$$

where e and m are the particle's charge and inertial mass, c is the velocity of light, and $\underline{r}$ and $\underline{B}$ are the position and magnetic induction vectors. In the general case there is no analytic solution to this equation for a non-uniform field, and numerical integration becomes necessary.

In practice we wish to know the direction, termed the asymptotic direction of approach, from which the particle was travelling at entry to the geomagnetic field when it is observed to arrive at the top of the atmosphere at some particular geographic location λ,η with particular zenith and azimuth angles θ and ψ. If we calculate the trajectory of a negatively charged particle ejected from λ,η in a direction specified by θ,ψ and having energy E, equation 2.1 shows that the trajectory will be the same, but traversed in the opposite direction, as that of a positively charged particle of the same energy observed to arrive at λ,η from the direction θ,ψ. Clearly the direction of motion of the negative particle on exit from the field will give the required information.

The composition of primary cosmic rays has already been mentioned. Neutrinos do not affect normal types of cosmic ray detectors and can be completely ignored for the present purposes. For the charged particles with which we are concerned it would clearly be unsatisfactory to consider protons alone since a significant proportion are nuclei of helium and heavier elements. We may, however, define magnetic rigidity R in the usual way, as the momentum to charge ratio of any particle.

$$R = \frac{pc}{ze} \qquad 2.2$$

Particles of equal rigidity have equal gyro-radii and therefore identical paths in a magnetic field. All calculations and results in this thesis are in terms of rigidity unless otherwise noted.

McCracken, Rao and Shea (1962) published the first set of trajectory results, together with their Fortran computer programme. Since then, several other sets of results have appeared using the same programme, including those of McCracken et al (1965), Shea et al (1965, 1968), Kondo and Kodama (1966), Daniel and Stephens (1966), and Shea and Smart (1967). Doubtless publication of similar results will continue. In all cases, the end results are asymptotic directions of approach for various particles with specified E, λ, η, θ, and ψ. The directions are given as coordinate pairs in a terrestrial centred spherical polar coordinate system.

The programme performs numerical integration of the trajectory of a negative particle projected from the top of the atmosphere above the detector in the manner already described. It employs the fourth order Runge-Kutta method of integration. As the radial distance of the particle increases, the higher degree terms of the field become progressively less significant and therefore the field expansion is gradually truncated. Beyond 10 earth radii all terms of the third order and higher are disregarded. The calculation is stopped

(a) when the particle reaches a predetermined distance from the earth, the assumed position of the magnetopause, or

(b) when the particle re-enters the atmosphere, indicating a forbidden trajectory, or

(c) when a specified number of integration steps have been performed without either (a) or (b) eventuating.

For fuller details of the basic programme and its method of operation, reference should be made to McCracken et al's document.

Many of the asymptotic directions required for this thesis have been taken from the abovementioned publications. However, asymptotic directions other than those published have been needed, and in any case it was not known at the outset just what would become available elsewhere. It was therefore decided to calculate trajectories and asymptotic directions on the then newly available Hydro-University Elliott 503 computer using McCracken et al's basic programme. The only programming language available on the 503 is Algol and translation of the Fortran programme was therefore necessary. During the translation a number of additional features were added. These permit automatic calculation of one or a series of directions at fixed or individually specified rigidity intervals; more detailed internal back tracking if an excessive calculation error is detected; and facilities for automatic cessation of computation after a given time has elapsed and for manual interruption of the programme by the computer operator; in both cases a new data tape specifying the uncalculated trajectories being produced. The programme will also automatically stop if a pre-determined number of successive trajectories in the same direction but with different rigidities are re-entrant, for use in calculating cut-off rigidities. This feature has been particularly useful for viewing cone and penumbral studies (Cooke, 1971; Cooke and Humble, 1970).

It has been the practice of most authors to cease calculations at a distance of 25 er (earth radii). No explanation of this figure has been given. Possibly it originated as a likely mean value for the distance of the magnetospheric boundary. It is now known that, due to the effects of the solar wind, the magnetosphere is compressed on the sunward side with the boundary lying at 10 to 12 er, or less, whilst on the night side the magnetic field lines are drawn out into a tear drop shape, the boundary being rather ill defined but apparently extending at least some tens of earth radii. Calculations of asymptotic directions on the basis of a spherical magnetopause of radius 25 er therefore result in only approximate values of the true asymptotic directions. Ahluwalia and McCracken (1966) have demonstrated the local time dependence of the error, and noted the effect on the observed solar daily variation, using varying degrees of compression of the sunward side of the magnetopause. The problem is complicated by the dependence of this compression on general interplanetary conditions and the mean solar wind velocity.

In addition to the regular variations in the magnetosphere as the earth rotates beneath it, there are the more erratic variations in the real field due to terrestrial magnetic storms, sudden commencements, etc. Such events have their origin in solar disturbances, being transmitted to the earth by the solar wind. The precise configuration of the geomagnetic field cannot be determined at each instant under such conditions and hence detailed trajectory calculations are impossible. In any case even were the field known explicitly the computer time involved in calculating trajectories for each individual configuration would be prohibitive. We must therefore proceed by calculating average trajectories and then making corrections as best we can for individual departures of the field from the normal mean configuration. For compatibility with other results, trajectories calculated at Hobart for the present studies have been terminated at 25 er. All the trajectories used neglect the effects of a magnetospheric ring current.

The cessation of calculations when a particle re-enters the atmosphere is self evident. Such an occurrence indicates that the particular trajectory, and therefore the particular combination of rigidity and arrival direction, is inaccessible from outside the magnetopause; such an incoming particle first strokes the atmosphere at some other point, as shown in Figure 2.1. The decision when to cease calculations as a result of trajectory complexity is a little less straightforward, since a particle with such a trajectory may or may not finally be re-entrant. Ahluwalia and McCracken's figure 2, reproduced here as Figure 2.2, shows the trajectory of such a particle after carrying the calculation to 25,000 integration steps. The outcome is still indefinite, but inspection of the trajectory shows that it is likely that a small variation in the field could make a notable difference in the outcome. In consequence the value of carrying calculations to this length can be questioned, especially as the computer time involved is considerable.

The computers available to McCracken, Shea, and their co-workers run at about 1000 integration steps per minute on complex trajectories. In the early publications, they ceased calculations and reported "Integration Failure" after 3,000 integration steps; later publications have used limits of 10,000 and 15,000, partly for close determination of penumbral structure. They state that it is their experience that such

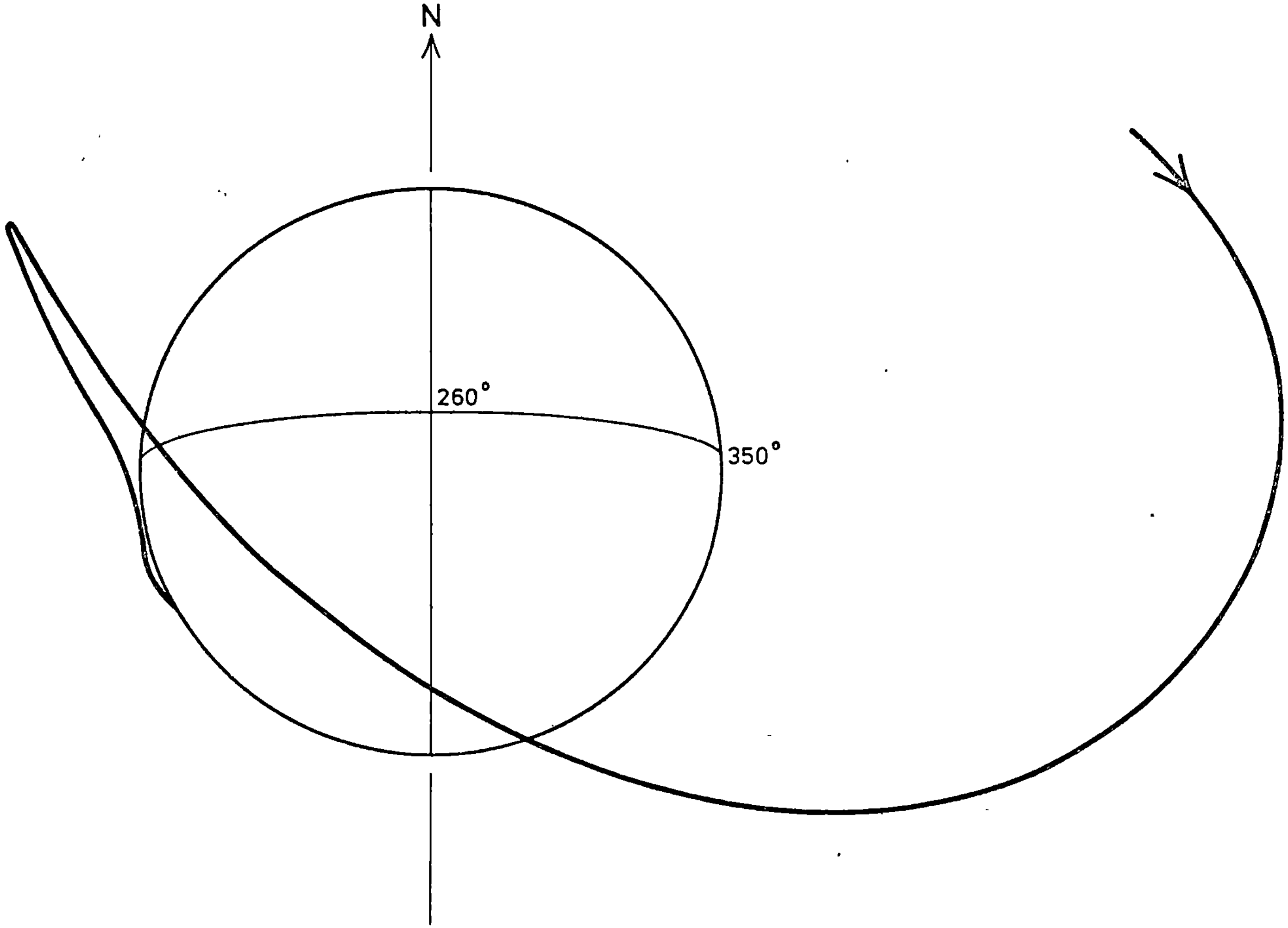


Figure 2.1. *Trajectory which just touches top of atmosphere at some distance from final entry point. 14.50 GV particle incident at Rockhampton, Australia (-23.37, 150.48 deg. geographic). Asymptotic direction at 10 er is (9.86°, 113.70°). Trajectory is viewed from point directly above point (-10°, 260°). This trajectory is allowed. A slightly closer approach to earth at initial approach point would result in capture at that point, and the combination of rigidity and arrival direction would be forbidden at Rockhampton. Plot due to D.J. Cooke.*

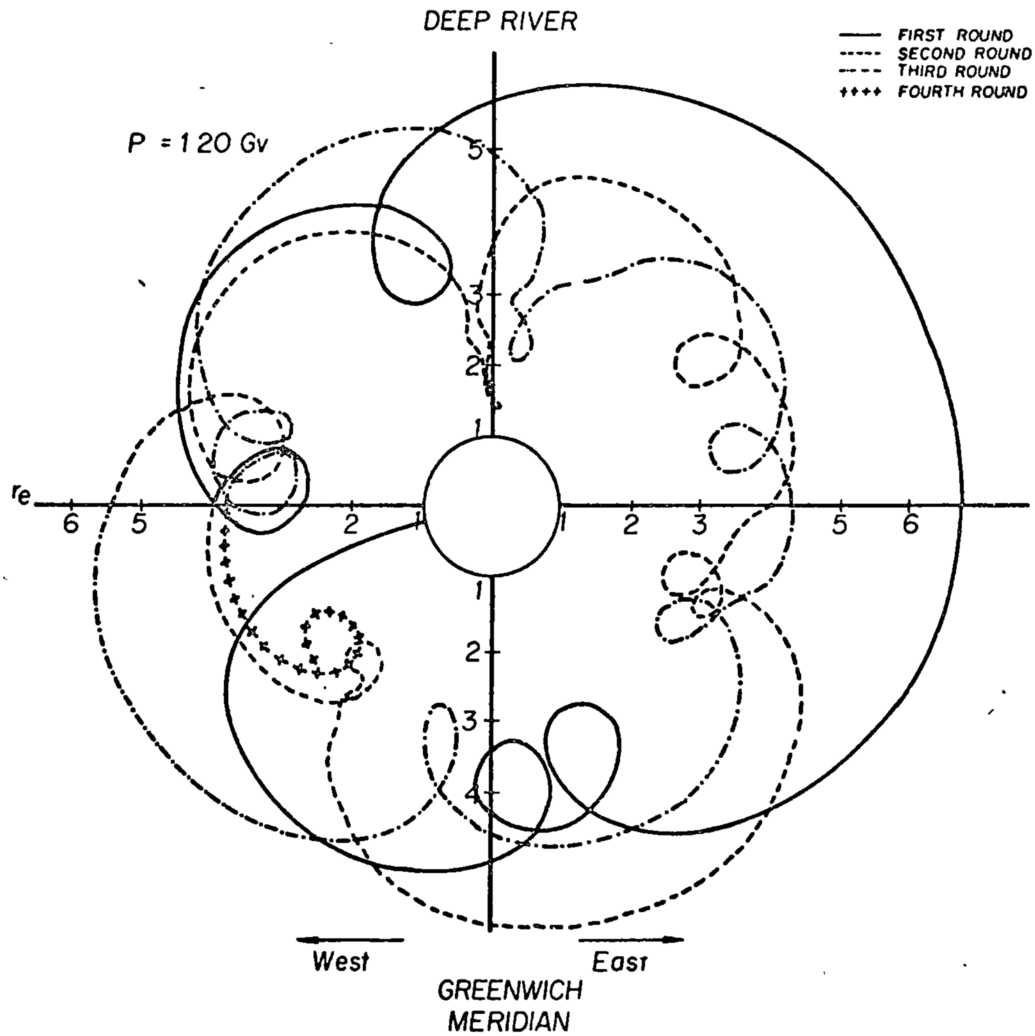


Figure 2.2. *Complex trajectory.* *Due to Ahluwalia & McCracken, 1966.*

long and complex trajectories are generally eventually re-entrant, and also that the cumulative errors inevitable in such calculations are still not serious. (This point can be demonstrated by reversing the sign of charge and velocity components of the particle on reaching the magnetopause, retracing the trajectory, and showing that the particle does in fact re-enter the atmosphere at its initial point of projection.) The Hobart computer is only capable of 300 integration steps per minute in such conditions when programmed in Algol, and hence a 3,000 step limit was applied. It was found that rewriting the field evaluation sub-routine and integration section in machine code raised the speed by a factor of about 2.8. The resultant programme is closely tailored to the available computer and could only be run elsewhere on computers of the same model. It should be noted that the run time of a programme of this type written in Algol, Fortran, or a similar language, will in general be longer than that of the same programme written in machine code, due to extra facilities provided by the general purpose compiler which the individual programme may not require.

Another method of calculating directions has been suggested. Webber (1963) has demonstrated that for geomagnetic latitudes greater than 45° in either hemisphere, and rigidities below 5GV, single parameter families of trajectories, called nullbahnen, may be utilised to provide asymptotic directions of all members after only one member has been calculated by numerical integration. Within the limits quoted, the asymptotic directions thus obtained usually agree within $\pm 2^{\circ}$ with those obtained by direct integration. The method has not been used here since relatively few of the required trajectories which were not available elsewhere fell within its limitations.

2.1.3 Asymptotic Cone of Acceptance and Viewing Region

The asymptotic direction of approach of a cosmic ray primary has been defined as the direction from which the particle appears to be travelling when it comes under the influence of the geomagnetic field. We have already seen that we have considered this to occur when the particle is located 25 er from the centre of the earth. We could, however, had we wished, have taken it to be the direction from which the particle appeared to be travelling when it entered the interplanetary magnetic field, or indeed at any other place where the direction of appearance is of interest. In this thesis, the term "Asymptotic Direction of Approach" will refer to the direction of appearance of the incoming particle at 25 er, unless otherwise specified.

The asymptotic cone of acceptance may be defined as the solid angle containing the asymptotic directions of approach of all particles capable of reaching the detector. As such, it is a most useful concept but is not easy to depict. It is perhaps easier to think of the Viewing Region, being the surface of intersection of the asymptotic cone and the celestial sphere. It is therefore the totality of the free-space directions which the detector sees. With individual directions plotted on an asymptotic latitude-longitude grid, the Viewing Region appears as the envelope of

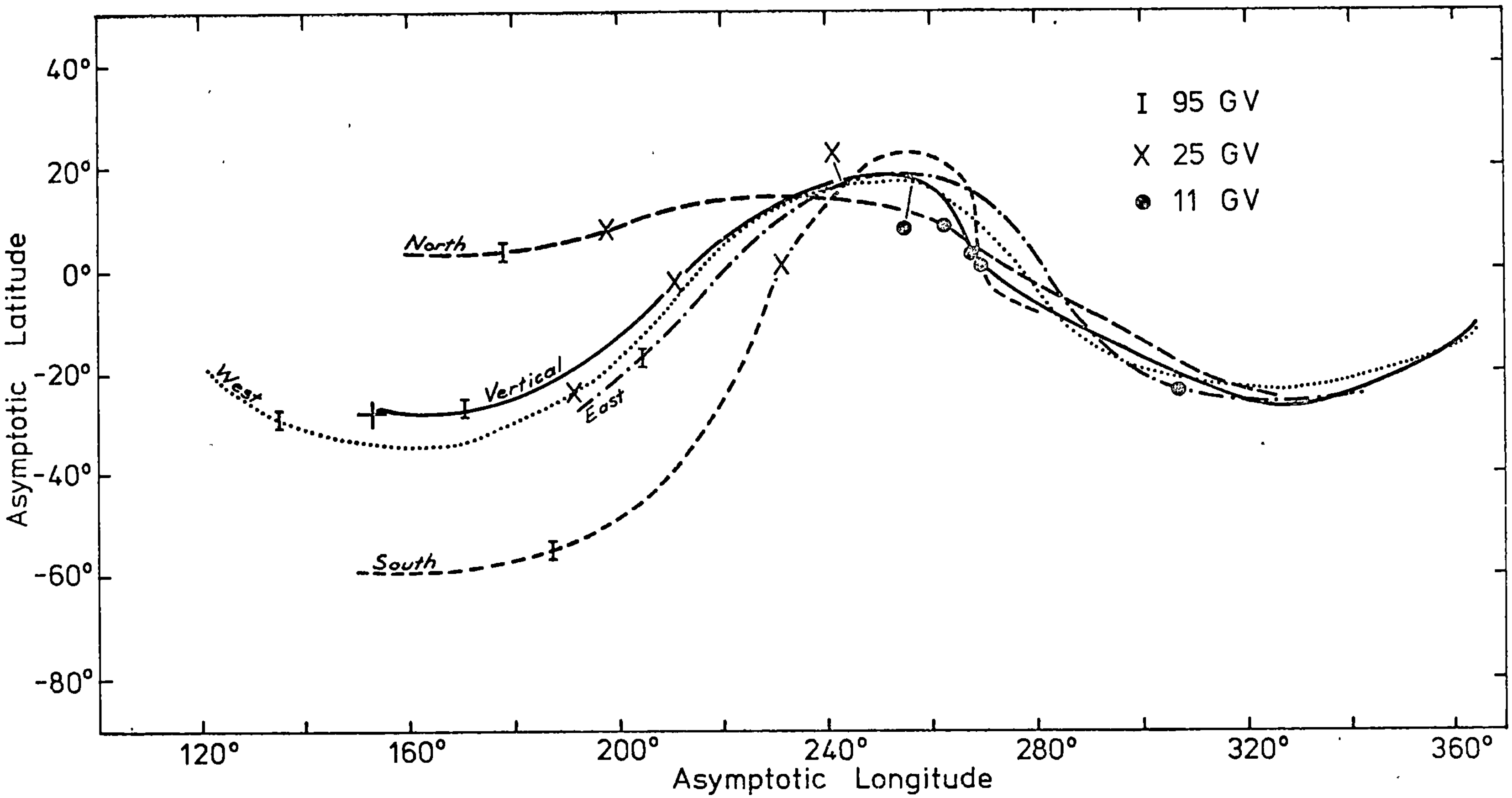


Figure 2.3. *Asymptotic Directions (at 25 er) for particles arriving vertically (solid curve) and at zenith angles of 32^{o} from various azimuths. Each curve starts at 750 GV.*

all such directions. Figure 2.3 shows asymptotic directions of approach for particles of various rigidities arriving at a mid-latitude station from five selected directions. Four of the arrival directions have zenith angles of 32° (see figure 2.5 and associated discussion) and the corresponding asymptotic directions lie near the edge of the viewing region. The latter may then be approximately obtained by sketching the envelope of the indicated directions (Figure 2.4b).

Even under conditions of completely isotropic flux, equal areas in the viewing region do not contribute equally to the instrumental count rate. Particles whose rigidities lie between 1 and 10,000 GV, corresponding to proton energies of 10^{9} to 10^{13} eV, contribute more than 99% of the sea-level neutron monitor count rate. In this range the primary spectrum varies as $E^{-1.7}$, and therefore those parts of the viewing region which are seen by means of the lower energy particles in the range will contribute a large proportion of the count rate. Even if this were not so, the non-uniform distribution of asymptotic directions within the viewing region would ensure non-equal contributions to the count rate. Typical viewing regions are shown in Figures 2.4a and 2.4b., where an attempt has been made to indicate the regions of major contribution to the count rate. These form relatively small parts of the entire region. This is particularly true for a high latitude station such as that shown in Figure 2.4a. The mid-latitude station shown in Figure 2.4b has a rather different distribution. In this situation the only possible approach to computing the response of a detector to any particular free-space flux is by numerical integration over the entire viewing region

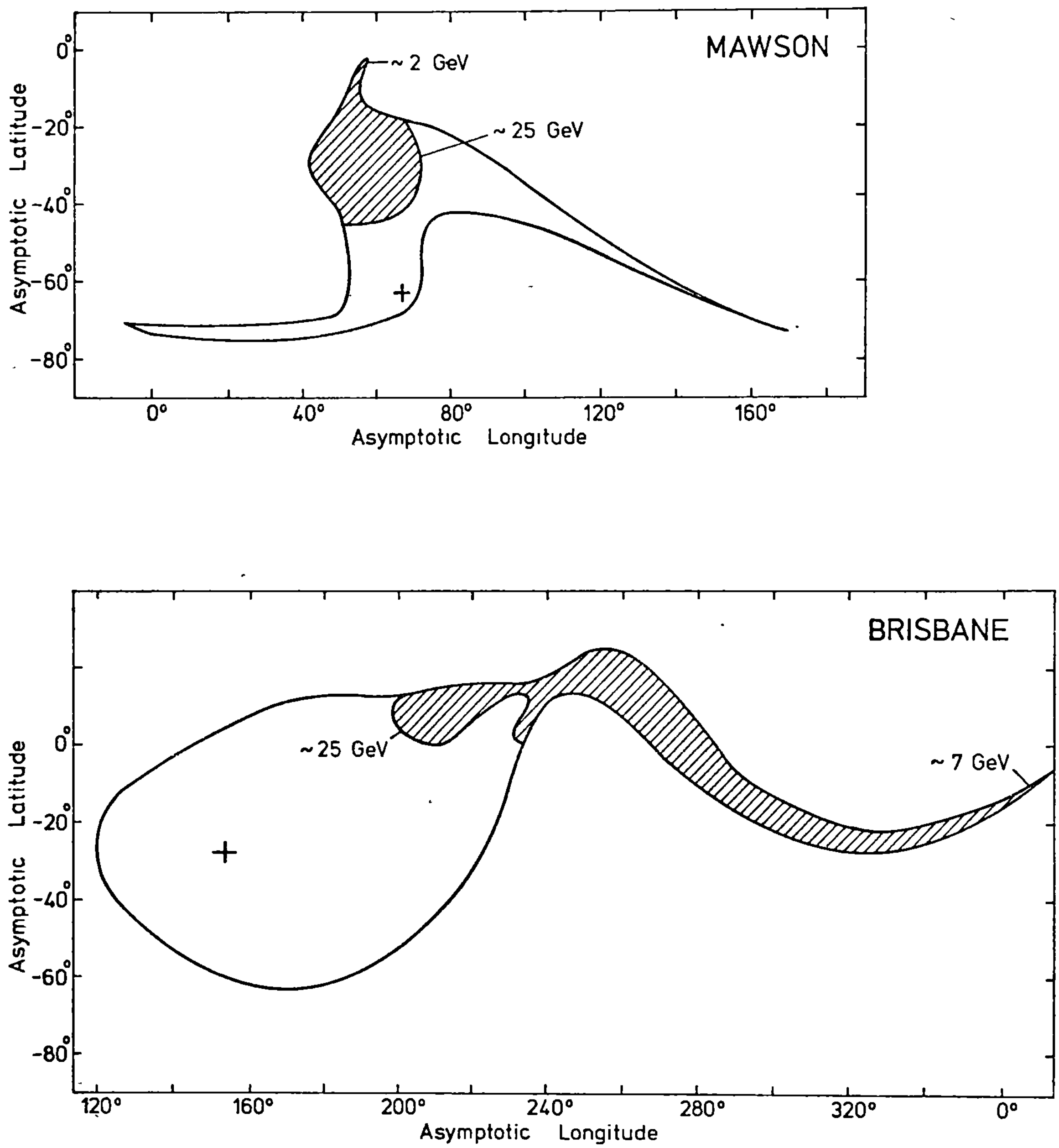


Figure 2.4. Viewing regions at Mawson and Brisbane. The regions due to particles of rigidity less than about 25 GV are shaded.

giving appropriate weight (according to primary spectrum and coupling coefficients) to each part of the region.

In figures 2.4a and 2.4b the edge of the viewing region is defined usually by single asymptotic directions. We shall see later that the choice of the particular trajectories giving rise to these directions is somewhat arbitrary, both in total number and arrival directions. In practice, the viewing region must be delineated with a relatively small total number of asymptotic directions, rather than the large number envisaged in the original definition. At low energies it is apparent, from these figures, that for a given rigidity below 10 GV the asymptotic direction is well-nigh independent of the arrival direction at the top of the atmosphere. At rigidities above about 100GV this is not true, and due to our arbitrary choice of arrival directions the viewing region is not clearly delineated at such rigidities, at least to within 5^o or 10^o. The percentage contribution to the count rate at such rigidities is, for a neutron monitor, low and the poor resolution is acceptable. In view of this, and other approximations which have to be made in the treatment which follows, it is sufficient to redefine the asymptotic cone of acceptance as being the solid angle encompassing all asymptotic directions which contribute significantly to the count rate. This is the definition usually found in the literature.

Having a knowledge of the asymptotic cone of acceptance, we may then determine the counting rate of a detector in the presence of any flux, if we can explicitly allow for the various modulations occurring in the atmosphere and detector. Following Rao, McCracken and Venkatesan (1963) we will divide the hemisphere above the detector into a number of small solid angles $\delta\omega$, in the direction θ,ψ where θ and ψ are the zenith and azimuth directions of arrival of a primary particle at the top of the atmosphere. Similarly, we will divide the whole 4π of possible asymptotic directions into a number of small solid angles $\delta\Omega$. If the cosmic ray differential rigidity spectrum for particles coming from $\delta\Omega$ is $J(\delta\Omega, R)$, then the flux observed at the top of the atmosphere in the direction $\delta\omega$ is, by Liouville's theorem, $J(\delta\Omega,R)$ if $\delta\omega$ is accessible from $\delta\Omega$, else it is zero. At the detector, in the accessible case the count rate due to this flux is

$$\delta C(\delta\omega,\delta\Omega,R) = \delta C(\theta,\psi,\delta\Omega,R) = J(\delta\Omega,R).T(R,\theta,\psi).\delta\omega \qquad 2.3$$

where $T(R,\theta,\psi)$ is a transmission factor of the atmosphere and detector. We will assume that the latter is a separable function of rigidity and direction and therefore

$$T(R,\theta,\psi) = S(R).D(\theta,\psi)$$

Considering that equation 2.3 holds for all particles in the rigidity range R to $R + dR$, and identifying the individual $\delta\Omega$ as Ω_i we may write

$$\delta C(\theta,\psi,\Omega_i,R) \;=\; J(\Omega_i,R).D(\theta,\psi).\delta\omega dR$$

and, summing over all $\delta\omega$,

$$\Delta C(\Omega_i,R) \;=\; J(\Omega_i,R).S(R).Y(\Omega_i,R)\;\; dR \qquad 2.4$$

where $Y(\Omega_i,R)$ is the sum of all $D(\theta,\psi)$ over all directions θ,ψ which are accessible from Ω_i for particles in the rigidity range R to R + dR.

If radiation is isotropic, $J(\Omega_i,R)$ becomes $J_o(R)$ for all Ω_i, and we may integrate equation 2.4 over R, obtaining the total instrumental count rate

$$N \;=\; \int_0^{\infty} J_o(R).S(R).Y(4\pi,R)\; dR \qquad 2.5$$

The actual differential count rate of a detector has been defined (Dorman, 1957) as

$$W(R) \;=\; \frac{dc}{dR}\cdot\frac{1}{N} \qquad 2.6$$

Tables of $W(R)$, called coupling coefficients, may be prepared by considering the results of experiments with mobile detectors operated in different sites for which the cut-off rigidities are known. Such tables have been published by Dorman (1957), Webber and Quenby (1959), Mathews and Kodama (1964), Lockwood and Webber (1967), and others. They incorporate the primary spectrum $J(R)$ and the atmospheric and instrumental modulation term $S(R)$, and therefore differ with different spectra. Mathews and Kodama produced sets of $W(R)$ for both solar maximum and solar minimum conditions. Since $W(R)$ contains atmospheric modulation, individual sets are valid only for the atmospheric depth for which they were prepared. Usually sets are given for sea level and some height around 700 gm.cm^{-2} (about 10,500 ft.).

Examination shows that dc in equation 2.6 equals the term inside the integral in 2.5. Therefore

$$S(R) = \frac{N.W(R)}{J_o(R).Y(4\pi,R)}$$

Equation 2.4 then becomes

$$\Delta C(\Omega_i,R) = N.W(R).\frac{J(\Omega_i,R)}{J_o(R)}\cdot\frac{Y(\Omega_i,R)}{Y(4\pi,R)}\cdot dR \qquad 2.7$$

We are interested in anisotropies in the primary radiation. These are generally observed as deviations from the normal count rate of a detector, and therefore are thought of usually in the form dN/N.

We may write $J(\Omega_i,R) = J_o(R) + \Delta J_i(R)$. Integrating equation 2.7 and making this substitution, we find

$$C(\Omega_i) = C_o(\Omega_i) + \Delta C_i(\Omega_i) = \int_0^\infty N.W(R) \left[1 + \frac{\Delta J_i(R)}{J_o(R)} \right] . \frac{Y(\Omega_i,R)}{Y(4\pi,R)}.dR$$

But $\dfrac{dN(\Omega_i)}{N} = \dfrac{\Delta C_i(\Omega_i)}{N}$

Therefore $$\frac{dN(\Omega_i)}{N} = \int_0^\infty W(R) . \frac{\Delta J_i(R)}{J_o(R)} . \frac{Y(\Omega_i, R)}{Y(4\pi,R)} . dR \qquad 2.8$$

and the observed quantity

$$\frac{dN}{N} = \int_0^\infty \sum_{i=1}^{n} W(R) . \frac{\Delta J_i(R)}{J_o(R)} . \frac{Y(\Omega_i,R)}{Y(4\pi,R)} . dR \qquad 2.9$$

where $$\sum_{i=1}^{n} \Omega_i = 4\pi$$

It follows that we can compute the response of any detector to a specified anistropy if we know the coupling coefficients and sufficient about the asymptotic cones. The accuracy of the calculation will depend on the number of directional elements Ω_i chosen.

To accurately evaluate equation 2.9, we obviously need as many areas Ω_i as possible, thus requiring a large number of asymptotic directions. We have already discussed the time consuming aspect of these calculations; individual directions take anything from 10 seconds to 1 minute to compute in reasonably straightforward cases, and can easily extend to 5 minutes for complex trajectories in the penumbral zone. It is therefore necessary to determine the smallest number of Ω_i which will adequately describe the response of the detector.

We have seen that, at least at low rigidities, the asymptotic direction of a particle is only slightly related to its arrival direction. About 78% of the count rate of a high latitude sea level neutron monitor is due to primaries of rigidity below 100 GV, and it is therefore apparent that it may be possible to use a fairly small number of Ω_i. Rao et al, employing the same assumptions used in deriving the Gross transformation (Janossy, 1948), have demonstrated that the counting rate of a neutron monitor as a function of zenith angle of arrival is roughly in the ratio 1:4:4 for the annuli $0^\circ < \theta < 8^\circ$; $8^\circ < \theta < 24^\circ$; and $24^\circ < \theta < 40^\circ$. This is grossly independent of whether the monitor response in a parallel beam of high energy nucleons is assumed to be independent of, or cosine dependent on, the zenith angle of arrival of the nucleons. It is reasonable to state that the sensitivity of a monitor is independent of azimuth, and Rao et al therefore divided the annular rings for $8^{o} < \theta < 24^{o}$, and $24^{o} < \theta < 40^{o}$, into four sectors centred on geomagnetic North, East South and West. They then approximate that if, for the rigidity R, a direction θ_o, ψ_o is accessible from Ω_i, then for all rigidities between $(R_{k-1} + R_k)/2$ and $(R_k + R_{k+1})/2$ all arrival directions specified by $\theta_o > 8^{o}$ and bounded by $\theta_o \pm 8^{o}$, and $\psi_o \pm 45^{o}$, are accessible from Ω_i. For $\theta_o < 8^{o}$, the approximation applies to the entire solid angle defined by $\theta_o < 8^{o}$, independent of ψ. The resultant sectors of arrival are depicted in Figure 2.5.

It must be decided whether the above is in fact a reasonable assumption. Phillips and Parsons (1962) have experimentally determined the zenithal dependence of count rate of a neutron monitor, using a stone quarry to intercept the incident flux in one direction. Their results are plotted, in differential and integral form, in Figure 2.6 together with the mean of the two rather similar theoretical curves used by Rao et al. The theoretical values assume there is no scattering of fast neutrons in the atmosphere, in that all members of the nucleon cascade are assumed to be travelling in the same direction as the primary. This is certain to be untrue. Such scattering would lead to a relatively higher contribution to the count rate from higher zenith angles, exactly the situation observed by Phillips and Parsons. Whether the extra contribution is as much as their evidence suggests is debatable. They remark the possibility of contamination by fast neutrons scattered in the quarry face, and also a possible contribution from thermal neutrons produced in the rock (Phillips, 1961). There is need for further work on this problem.

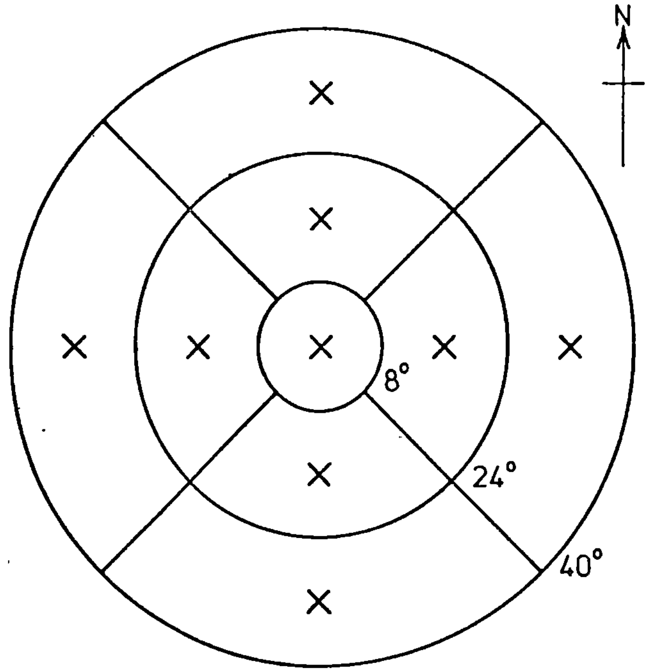


Figure 2.5. Sectors of equal contribution to neutron monitor count rates.

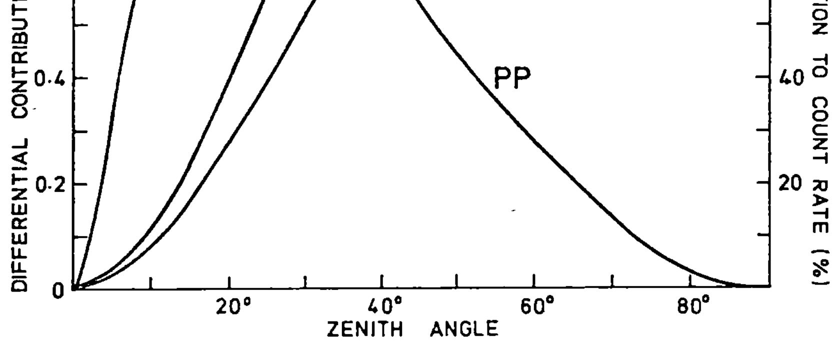


Figure 2.6. Zenithal dependence of neutron monitor count rate. PP, Phillips and Parsons (1962). RMV, Rao, McCracken and Venkatesan (1963).

Whilst the use of 9 arrival directions appear to be satisfactory for neutron monitors, it will not be so when detectors having a higher mean energy of response are involved. In the extreme case, for underground muon telescopes at 36 m.w.e., Jacklyn and Humble (1965) have shown that it is necessary for some purposes to consider more than 500 directions.

2.1.4 Variational Coefficients

In studying any anisotropy we are generally considering the case of a detector at a fixed location on the earth with its cone of acceptance sweeping across the anisotropic region as the earth rotates. We are therefore especially interested in the varying response of the detector in asymptotic longitude. It is useful therefore to consider an asymptotic longitude belt j, defined by the meridians $\psi_j \pm \Delta\psi$. We may then sum equation 2.8 over all Ω_i lying within j and obtain

$$\frac{dN(\psi j)}{N} = \sum_{\psi_j} \int_0^\infty W(R).J_A(R).\frac{Y(\Omega_i,R)}{Y(4\pi,R)}\,dR \qquad 2.10$$

where $J_A(R)$ is the spectrum of the anisotropy $\Delta J_i(R)/J_o(R)$.

The right hand side of equation 2.10 is frequently referred to as $v(\psi_j)$, the variational coefficient corresponding to the j^{th} longitude belt and the particular variation spectrum $J_A(R)$. Variational coefficients $v(\Omega_i)$ or $v(\Lambda_k)$ corresponding to the solid angle Ω_i, or latitude belt Λ_k may be calculated in a similar fashion. In this thesis, we shall be concerned exclusively with $v(\psi_j)$, and will refer to it as $v(j)$. It is emphasised that numerical values of variational coefficients have no meaning unless the particular variational spectrum to which they refer is also given.

For the reasons already mentioned in the discussion on arrival directions, we cannot compute asymptotic direction for an infinite number of rigidities. It is sufficient instead to calculate them for a number of rigidities, the intervals being chosen so that there is a relatively small change in asymptotic directions when going from one rigidity to the next. We can write, from 2.10,

$$v(j) = \sum_{\psi j} \sum_{k} W(R_k).J_A(R_k).\frac{Y(\Omega_i,R_k)}{Y(4\pi,R_k)} \cdot \frac{R_{k+1} - R_{k-1}}{2} \qquad 2.11$$

This equation is the basis for all subsequent work.

In order to obtain the various $v(j)$ we need to evaluate the terms $Y(\Omega_i,R_k)/Y(4\pi,R_k)$. They represent the fractional contribution to the count rate due to the primaries in the k^{th} rigidity group coming from the region Ω_i. In practice, however, we do not sum over all Ω_i but rather over ω_i, the arrival directions, of which we have considered 9 to be adequate. Equation 2.11 is evaluated by taking each rigidity in turn and computing the contribution to some $v(j)$ from each arrival direction The value of j is determined by the asymptotic longitude. In these circumstances, Ω_i is the asymptotic direction corresponding to ω_i, and $Y(\Omega_i,R_k)$ takes the value 1 if ω_i is accessible from Ω_i, or zero if it is not (implying in fact a forbidden arrival direction). $Y(4\pi,R_k)$ is then the number of arrival directions at rigidity R_k which are accessible from any asymptotic direction at all.

Tables of $v(j)$ have been published (e.g. McCracken, Rao et al, 1965) for various assumed spectra of the daily variation. The present work required the use of spectra and stations other than those published; it was therefore decided to compute all the variational coefficients required. Sample sets have been compared with McCracken et al's results and found to largely agree. The small differences are thought to be due to different treatments of the detector response close to cut-off.

Variational coefficients by themselves only appear to be useful in the study of transient anisotropies. In the diurnal (or semi-diurnal) case we are actually interested in the phase and amplitude of the vector due to the anisotropy. Sets of v(j) are tools for such determinations. It has been found preferable, for a particular station and variational spectrum, to generate sets of v(j) and then to use them, in the same programme without explicit output, to generate the required amplitude and phase information. The principal advantage of this approach is that the amount of data required to be output by the computer per station spectrum is reduced from 72 to 2 items.

One further approximation is necessary. In the penumbral region, the asymptotic directions can change very rapidly with small changes in either rigidity or direction of arrival. In particular, the assumption that, for a particular arrival direction θ,ψ if θ,ψ is accessible from Ω_i, then all $\theta \pm 8^{\circ}$, $\psi \pm 45^{\circ}$ is accessible is quite untenable, since a small change in arrival direction could easily result in that direction becoming totally inaccessible, or vice-versa. However, we can reasonably assume that, in most cases, the error so caused is small, and that greater error would be incurred by omitting such terms altogether. This last assumption has been made in the present work.

It is necessary to show that the various approximations made in obtaining the variational coefficients are in fact acceptable. To some extent, errors are going to be dependent on the form of the variation spectrum used : if the latter were of the form const. $R^{-1.5}$, for example, errors in determining asymptotic directions at high rigidities would be negligible, whereas penumbral errors could be serious; in the case of a const. $R^{+1.5}$ spectrum, the reverse would be the case. It is in fact found that, in the case of the diurnal variation, the spectral exponent is of order zero. In this case therefore errors in asymptotic directions or coupling coefficients at either end of the spectrum can in principle contribute to the overall error. It is found, however, that the variation is constrained to the region below about 100 GV, and most of the error will come from errors in the penumbral region.

2.2 ATMOSPHERIC EFFECTS

Reference will be made in Chapter 3 to the history of investigations concerning the correlation between atmospheric structural changes and observed ground level changes in cosmic ray intensity. It is sufficient here to detail the main effects.

The charged secondary flux observed at ground level is dependent on the quantity of air traversed (the mass absorption effect, sometimes called the barometric effect), on the height of the atmospheric layer where the majority of the secondaries are produced (negative temperature effect), and the actual temperature of that layer (positive temperature effect), as well as on variations in the incident primaries. The relative proportions of each of these effects differs according to the effective energy threshold of the detector. Approximate magnitudes are given in Table 2.2.

		High Latitude Vertical Cubic Muon Telescope	Underground (Hobart) Vertical Semi-Cube at 36 m.w.e.
Partial Pressure Coeff	(%/cm.Hg)	-1.55	-0.59
Negative Temp. "	(%/km)	-4.8	-0.46
Positive " "	(%/^{o}C)	+0.05	+0.02
Total Pressure "	(%/cm.Hg)	-1.87	-0.65

Table 2.2

Approximate values of some atmospheric correction coefficients. Since the parameters depend on the primary spectrum they are likely to vary slightly through the solar cycle.

Two pressure coefficients appear in table 2.2. The partial coefficient is obtained from 4-fold correlation analysis of observed cosmic-ray flux, atmospheric pressure, and temperature and height of the production layer. It is used for data correction when all these quantities are available. The total pressure coefficient is an attempt to summarise the effects of changes in atmospheric structure in a single measurement, for use on occasions when height and temperature measurements are unavailable or when, as in the case of underground observations, the temperature coefficients are small. These matters are further discussed in sections 3.2 and 5.2.

For the neutron component of the secondary flux the situation is, nominally, rather simpler. The only major effect is that of mass absorption, but unfortunately the coefficient is large, of the order 0.7 %/mb. Writing the corrected count rate N' which would be observed at a standard pressure $\bar{p}$ as a function of the observed count rate N and pressure p we have

$$N' = N \exp \left(\frac{p - \bar{p}}{\lambda} \right) \qquad 2.12$$

where λ is the attenuation length, usually given as around 138 gm/cm^2. $\bar{p}$ is normally the mean pressure at the station.

Whilst the use of this equation would appear simple enough, two problems arise. Due to the magnitude of λ, and the consequent large correction coefficient, the pressure measurement used requires high accuracy. In addition, doubt exists as to the correct value of λ to be applied to any particular instrument at any time. Use of this equation also makes the unavoidable assumption that the barometric pressure above the detector is a good representation of the mass of air traversed by all secondary particles, many of which reach the detector from inclined directions.

2.2.1 Mass Absorption Coefficients

Determination of a suitable pressure correction coefficient for neutron monitors is usually difficult due to the simultaneous occurrence of pressure and cosmic ray primary intensity variations. Error tails on the results obtained tend to be ± 2 or 3%. Various attempts have been made to obtain more accurate estimates, either by use of a number of short segments of data and assuming that no genuine primary variations occur during the period (e.g. Forman, 1965), by use of a second station as a control to eliminate such variations (e.g. McCracken and Johns, 1959), or by use of a filtering procedure to eliminate large primary intensity variations, usually in combination with a control station (e.g. Lockwood and Kaplan, 1967). Forman concluded that, for Climax and Chicago, there were no significant changes in the mass absorption coefficient between 1952 and 1963. Lockwood and Kaplan, on the other hand, found distinct trends for the Mount Washington monitor, with a minimum value of the coefficient occurring roughly coincidental with solar maximum. Bachelet, Dyring, Iucci and Villoresi (1967, 1968) have confirmed this view working with a combination of the above methods, and a number of stations. They obtain minimum values of the coefficients in various years between 1957 and 1960, according to the station, but indicate a definite rise in the values at each station, except Mawson and Ottawa, between solar maximum and solar minimum. They claim that the variation of these two instruments from the generally observed pattern could be attributed to instrumental changes. They are supported by Forman (1967, 1968), who also finds a solar cycle variation of about 0.04%/mm.Hg. to exist in sea level high latitude monitors.

The correction factor originally used for all Hobart Group monitors was −0.708 %/mb (−0.944 %/mm Hg). This corresponds to an attenuation length of 145 $gm.cm^{-2}$. It was realised subsequently that this was rather long, and on January 1, 1962, a new coefficient of −0.744%/mb (−0.992%/mm Hg, 138 $gm.cm^{-2}$) was introduced, based on the work of McCracken and Johns,

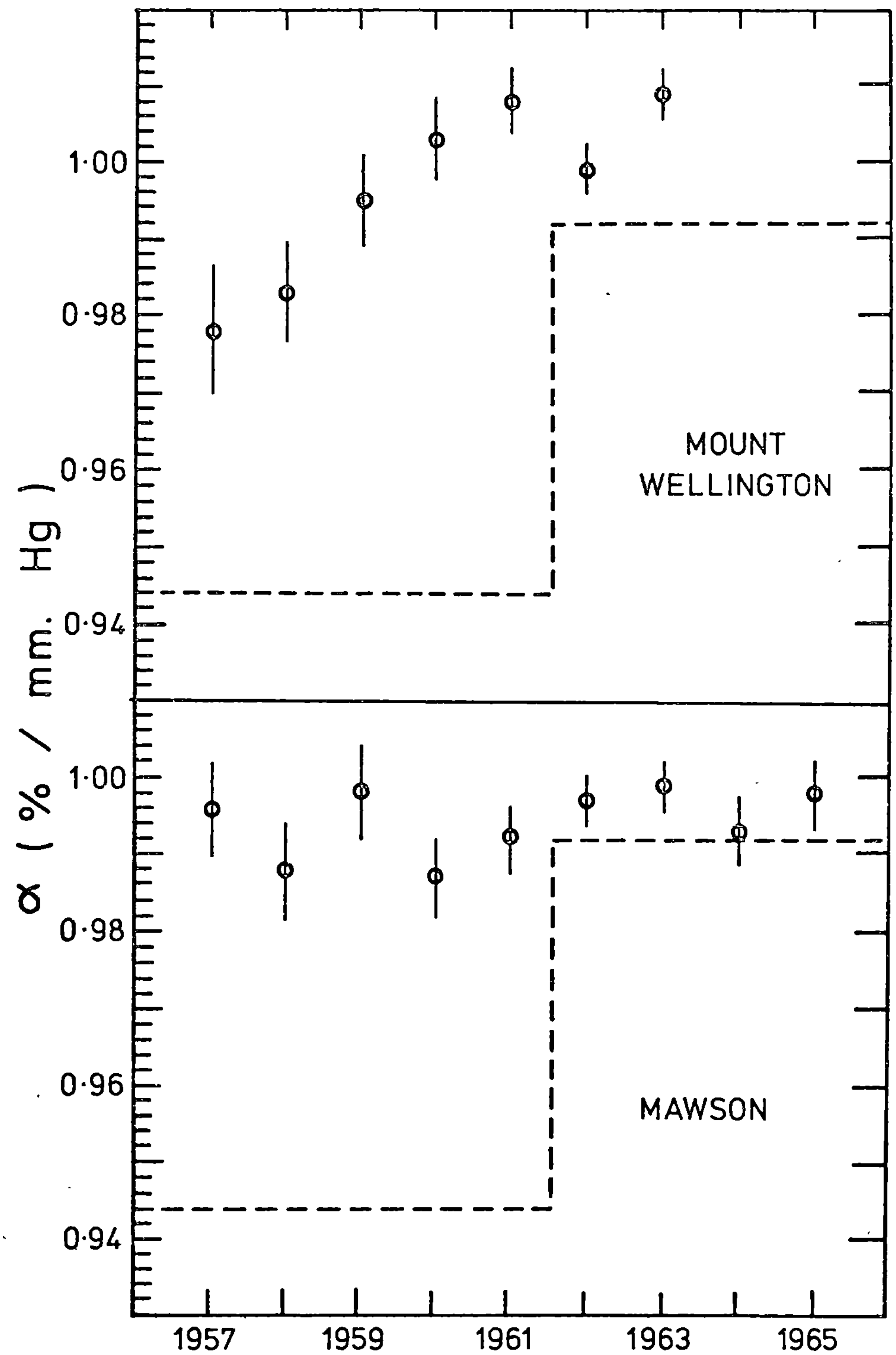


Figure 2.7. Barometer coefficients estimated by Bachelet et al (1967) for Mt. Wellington, compared with values actually used (dashed lines).

and Phillips (1961). Figure 2.7 shows the relationships between the values of the correction coefficients estimated by Bachelet et al and those actually used. Clearly, the attenuation length used up until December 1961 was in error by about 7 $gm.cm^{-2}$, about 5%, implying that residual pressure effects exist in the pressure-corrected data.

2.2.2 Accuracy of Pressure Measurement

The accuracy required in individual pressure measurements varies according to the purpose for which the final results are required, and the statistical accuracy of the recorder involved. Since the majority of neutron monitor records are published for general use, these requirements involve the removal of all systematic errors from the pressure recording system and the reduction of statistical errors (such as reading the pressure transducer) to a level which will not seriously enlarge the normal statistical variations due to the recorders mean count rate. Typical correction coefficients lie in the range 0.68 to 0.72%/mb. The normal IGY type neutron monitor as used by the Hobart group has a count rate, at sea level and high latitudes, around 35,000 cts/hr, giving a standard deviation of about 0.5%/hr or 0.1%/day. A pressure accuracy of ± 0.2 mb in hourly readings is satisfactory in these cases, provided that no systematic error exists. In the case of Super Monitors, of the type now operating in many places, the pressure accuracy needs to be much better, say ±0.05 mb for an hourly average.

The pressure recording systems used by the Hobart group to date have been based, for all stations except Mt. Wellington, on visual averaging from a barograph chart which is changed daily. One hour's record on such a chart is 15 mm long, and the amplitude scale is 1 mb equals 1.5 mm. The charts are calibrated every 3 hours by readings from a mercury barometer at the local meteorological station. It is generally thought that inaccuracies in this system will be of the order ± 0.2 mb for reading the barograph trace, ± 0.1 mb for the calibrating barometer, ± 0.1 mb for trace width and ± 0.1 mb for hysteresis and sticking in the barograph pen assembly. A total error of ± 0.5 mb is therefore indicated. At Mt. Wellington, prior to the destruction of the old station by fire in February 1967, photographic recording was in use, and a 9" diameter dial aneroid barometer calibrated in hundredths of an inch of mercury was employed. Similar errors were likely with this instrument. It is clear that, for super monitors, better pressure recording systems are necessary. It is hoped at this stage to introduce digital recorders, which integrate over the recording period, to all stations run by the Hobart group. However the Mt. Wellington 6NM64 instrument still relies on a photographic system, using a 9" dial aneroid calibrated in half mm. of Hg., and readable to tenths mm. of Hg.

Systematic errors in pressure measurements can stem from three causes. These are faulty barometer calibration; correction to some pressure other than the mean for the station ; or systematic errors in the barometer readings due to outside influences.

The use of both barometer and barograph will detect any calibration errors apart from possible zero errors in the barometer. It is not conceivable that such zero errors could be large enough to affect the accuracy of pressure corrections, provided that they do not vary with time.

Use of an incorrect mean pressure for the station would be serious only if an incorrect attenuation length were used. It is known (section 2.2.1) that an incorrect length was used at Mawson for several years. In such a case, use of a grossly incorrect mean pressure for correction purposes would increase the amplitude of the deviation of observed pressure from the 'mean' value, and hence increase the error in the 'corrected' pressure. However, the annual mean pressure at Mawson generally lies close to 990 mb, which figure has been used as the correction mean.

Systematic errors in the barograph, and possibly the barometer, therefore remain as the major sources of possible error. Several authors have remarked on the possibility of hysteresis in the barograph giving rise to a false component of the observed semi-diurnal variation in pressure-corrected cosmic ray data. Whilst this possibility certainly exists, it is difficult to check accurately. Evidence obtained by the Hobart group, and others, from underground muon telescopes and surface neutron monitors suggests that a genuine semi-diurnal variation does exist. Contribution to this from hysteresis of the barograph cannot be ruled out, but does not appear large. The reading of a barometer may also be seriously affected by the flow of air past the instrument. The next section deals with the theory of this effect; subsequent sections will detail measurements made at Mawson, where high winds are prevelant.

2.2.3 Wind Induced Errors in Barometer Readings

A barometer measures the apparent atmospheric pressure in its immediate vicinity whereas we are, for cosmic ray purposes, interested only in the total air mass situated between the point of production of the secondary particles and the detector. The region of atmosphere through which most of the secondary particles pass, and in which many are absorbed, is roughly a right circular cone, of half angle 45°, and apex at the detector (Section 2.1.3). The assumption has therefore to be made that the reading obtained from a barometer situated at the detector is in fact representative of the air mass within this cone. In the presence of a reasonably homogeneous atmospheric structure this is generally true, although the passage of "fronts" can cause systematic errors at some stations (Jacklyn, 1954; Fazzini, Galli, Guidi, and Randi, 1968). When an air flow exists past the barometer or its housing, there will be a contribution to its reading due to the Bernoulli effect. We may write

$$P_o = P - \tfrac{1}{2} c\psi v^2$$

where P is the pressure reading obtained, P_o is the "static" pressure reading which we require, ψ and v are the density and velocity of the air and c is an arbitrary constant.

The error in pressure readings thus caused can be large unless either c or v is small. Table 2.3 shows the magnitude of errors which may be expected for $\psi = 0.0012$ gm.cm^{-3}, corresponding to $P_o = 1000$ mb and a temperature of 15°C.

	Wind Speed $v(\mathrm{m.sec}^{-1})$				
c	10	20	30	40	50
0.2	0.1	0.5	1.1	1.9	3.0
0.4	0.2	1.0	2.2	3.8	6.0
0.6	0.4	1.4	3.2	5.8	9.0
0.8	0.5	1.9	4.3	7.7	12.0
1.0	0.6	2.4	5.4	9.6	15.0
1.2	0.7	2.9	6.5	11.5	18.0

Table 2.3. Values of $\frac{1}{2} c\psi v^2$, in millibars (1 $\mathrm{m.sec}^{-1} \simeq 2.25$ mile hr^{-1})

Shimuzu and Kimura (1957), experimenting with various model rooms in a wind tunnel, demonstrated that c tended to take any value between +1.0 and -1.0, depending on the angle between the room and the air flow, the shape of the model, and the number and position of the orifices in it. They concluded that, in general, no reliable correction could be made for this effect.

Table 2.3 shows that, at stations where the wind speed frequently exceeds 10 $\mathrm{m.sec}^{-1}$, the problem may well be serious. At stations at mountain altitudes, such as Mount Washington; or Mawson, Casey, or Syowa on the Antarctic coastline, winds can exceed 40 $\mathrm{m.sec}^{-1}$ on occasion and winds of 30 $\mathrm{m.sec}^{-1}$ are frequent. Consequently correction becomes important.

Lockwood and Calawa (1957) have reported that the system used at Mount Washington, whereby the barometer is located in a sealed cistern connected to the outside of the building via a pitot tube and head (Falconer, 1947), appears to give satisfactory results. This system assumes a value of c of 1.0 and relies on the dynamic pressure in the pitot head to provide compensation for pressure errors due to airflow around the mountain. For the method to be satisfactory, it is essential that the pitot head be located well away from any other obstructions which could cause breakdown of laminar flow, since in such conditions c no longer necessarily has unit value. There is also the possibility that the design of the pitot head might cause trouble in this regard.

Taking the opposite view, Kodama, Ishida and Shimizu (1967) have attempted to design a static head which would register P_o without any correction and which would, in particular, be independent of wind direction. They produced a hexahedral design which, although in fact not a perfect static head since it has a c value of 0.04, is a considerable advance. It does however, require to be vaned into the wind.

In principle, either of these methods could well be employed at stations where high winds are a severe problem. A difficulty is that, at least as far as the Antarctic stations are concerned, high wind velocities are frequently accompanied by severe snow drift or full blizzard conditions. Under such circumstances, heads, bearings, etc., freeze up very rapidly and the requisite amount of electrical heating is not always available.

2.2.3.1 Studies at Mawson. Data

Mawson, by virtue of its location and local topography, experiences remarkably constant winds. The station, which is operated by A.N.A.R.E., is small, with a normal wintering party of 25 men. It is situated on a rocky outcrop, about half a mile long, 1/4 mile deep and 100 feet high, on the Antarctic coastline. Immediately behind the station, the continental ice shelf starts sloping upwards towards the high plateau. As a consequence, the station is subject to a strong daily katabatic wind, cold air travelling down the ice slope. A pronounced diurnal variation exists in the phenomenon, the wind frequently dying away around midnight local time and recurring in the late morning. The afternoon wind speed is up to 15 or 20 metre sec^{-1}, and by virture of its nature is constant in direction, blowing from directions between 130° and 140°. In winter, the katabatic wind is erratic. This state of affairs indicated that if a house effect with an appreciable c value existed, then systemic diurnal errors in pressure readings would result. Figure 2.8 shows a plot of typical monthly mean values of hourly wind speeds.

Additional high winds are caused at Mawson by the passage of regions of low pressure. A continuous series of such regions circulates around southern polar areas, passing to the north of Mawson at intervals between 7 and 14 days. They produce strong winds which can range anywhere between 25 and 50 metre sec^{-1}. The direction of these winds is strikingly constant being from around 90° to 105° prior to the passage of the low across the station meridian, and 110° to 130° subsequently. These directions more or less coincide with those of the katabatic wind. High winds from directions outside the ranges mentioned above are almost totally unknown, only one case being recorded between 1960 and 1967. In these circumstances, systematic alienation of pressure records seemed likely and studies of the problem were initiated.

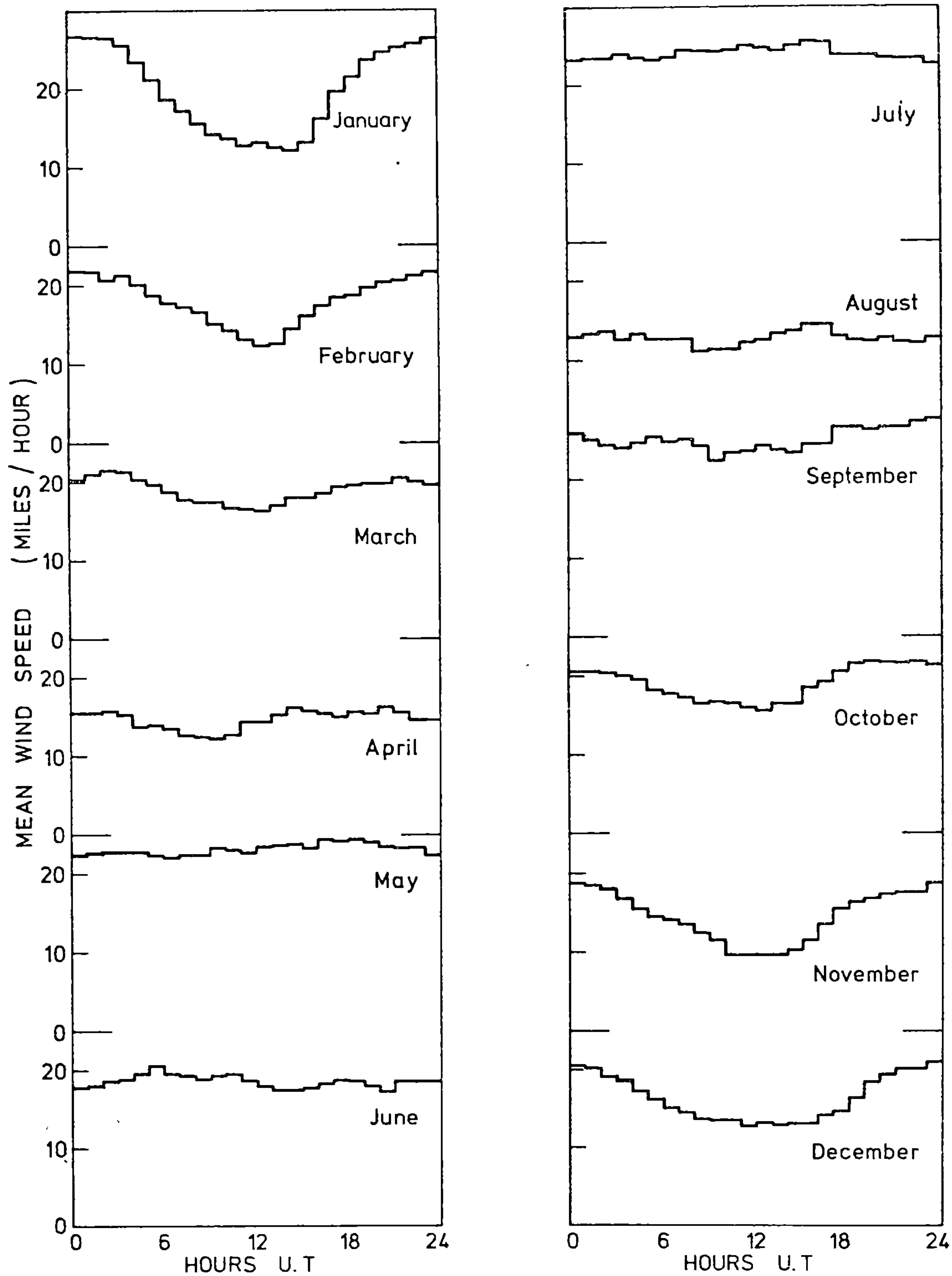


Figure 2.8. *Typical monthly mean hourly wind speeds, Mawson. There is little change in this pattern from year to year.*

2.2.3.2 Pressure Measurements at Mawson

From the founding of the station in February 1954, up until April 1965, all pressure measurements at Mawson were made in the original meteorological building. This building, now known as "old met" (Figure 2.9) is a hut of early ANARE design, and in fact was transported from Heard Island where it was first installed about 1948 or 1949. By the time the author came to know it, in 1960, it could not be described as weather-proof in any sort of strong wind. There were a considerable number of pin hole cracks and small slits through which snow drift could penetrate. No "dead bench" was provided, and perforce both barometer and barograph were mounted on one wall of the building on normal shelves, subject to some vibration during high winds, with consequent thickening of the barograph trace. On the face of it, it would be imagined that pressure measurements obtained under such conditions would be unreliable to say the least; however in practice this did not turn out to be so, as will be shown below.

In April 1965 a new meteorological building, of the current standard ANARE weatherproof pattern, was brought into use. This building is known as "new met". It was at once apparent from "pressure" corrected cosmic ray data that the pressure measured in this building was partly dependent on wind velocity. The cosmic-ray physicist immediately obtained permission to use the Bureau of Meteorology's spare barograph and barometer in the cosmic ray laboratory - known as "cosray". In February 1966, the incoming cosmic-ray physicist reverted, due to a misunderstanding, to obtaining his pressure records from new met and did not notice the resultant peculiarities in his results. During the year the only means of returning results from Mawson to Australia is by telegram, detailed results being brought back

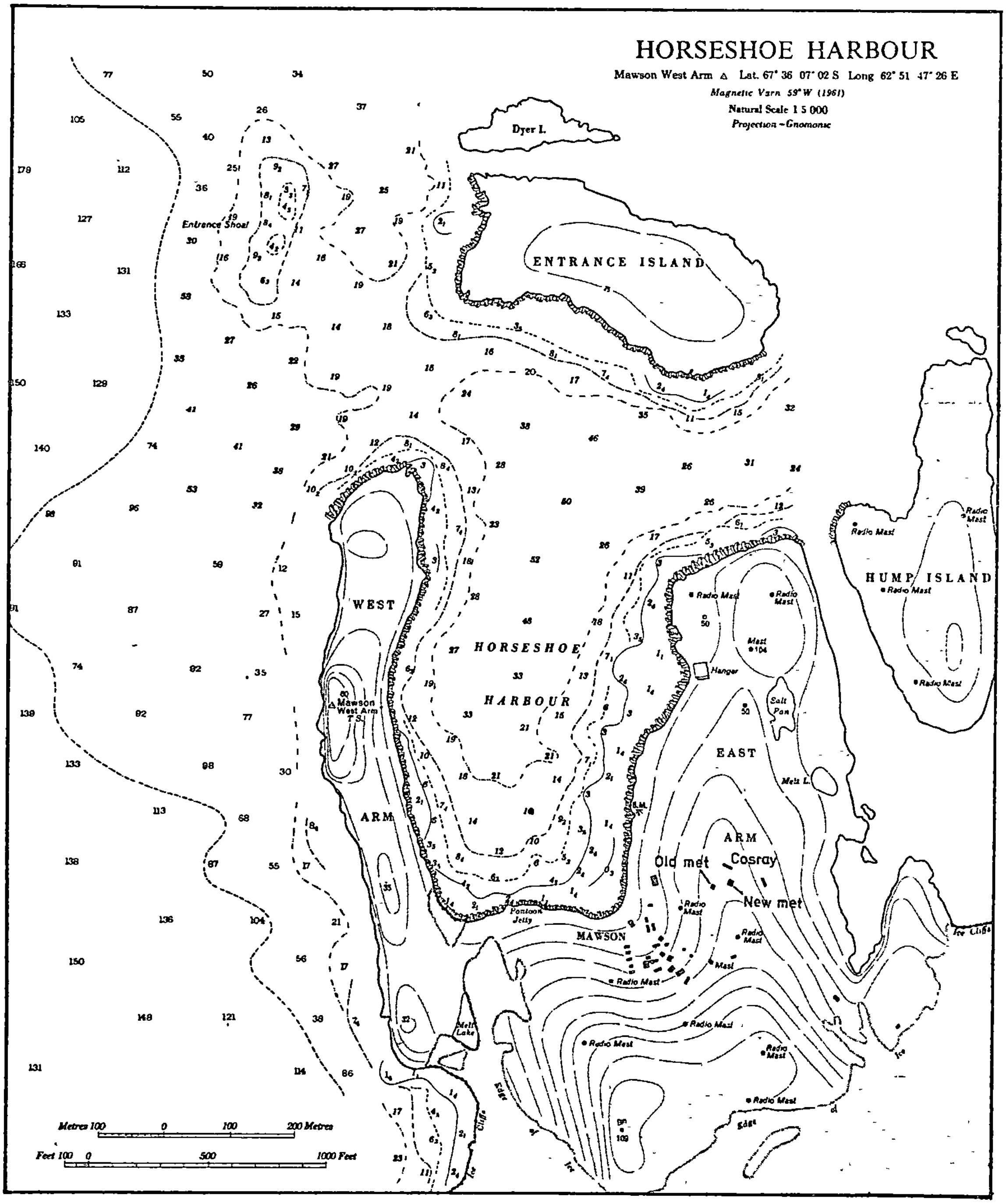


Figure 2.9. Map of Mawson.

with the returning operator at the summer changeover. The telegraphed results were, at that time, as a routine confined to pressure-corrected neutron hourly count rates, together with daily mean values of muon count rates and pressure records. In consequence, the correlation between pressure and nominally pressure-corrected neutron results was not detected at Hobart until the June data were examined, when it became apparent that considerable disagreement existed between results from Mawson and those from Wilkes. From then until January 1967 simultaneous pressure measurements were made in cosray, old met, and new met. Subsequently, all pressure measurements have been made in old met. Following these events both uncorrected neutron and pressure data are now telegraphed to Hobart for examination.

From the analysis aspect, it is clear that the problem requires treatment in two stages, prior to April 1965, and subsequent to it. We will first consider the earlier period.

2.2.3.3 Analysis, 1960-1964 data

Hourly values of mean wind speed and direction were obtained, and a correlation analysis carried out between wind speed and pressure-corrected neutron count rate on an hourly basis. Preliminary analyses were undertaken on a desk calculator, subsequent ones on the computer. It was necessary to eliminate secular drifts from the neutron data as the average wind speed varies through the year, being highest in summer. This was achieved by multiplying each hourly neutron count by a correction factor equal to the mean count rate for the entire period divided by the annual running mean hourly count rate centred on the day in question. The reference mean used was 555 scale counts per hour. To eliminate as far as possible the effects of genuine variations in the incident primary cosmic rays, all hours for which the data, after adjustment as described above, were five or more standard deviations different from the mean were rejected from the analysis.

This last procedure is open to criticism. The chances of obtaining a purely random deviation of 5σ from the mean are negligible. However, allowance must be made for deviations genuinely due to faulty pressure records as a result of high wind speeds and this figure was chosen as a compromise. The alternative procedure would have been to employ another neutron detector, whose cone of acceptance was similar to that of Mawson, in a threefold regression analysis. The choice of a station for such an analysis is difficult, although Ottawa or Churchill would probably be suitable. However, the extra data preparation involved and, more serious, the limited storage available on the 503 computer when the project was first tackled, caused the method to be rejected until such time as it was shown to be necessary. This did not eventuate. There is no reason to suppose that there is any significant correlation between those genuine cosmic ray variations which remained in the data after the 5σ limit had been applied and the wind data, except for the possibility of a connection between the diurnal variation in wind velocity due to the katabatic influence and the normal diurnal variation in cosmic ray intensity, which will be considered later. The only effect of any other cosmic ray variations present will be to decrease the signal to noise ratio of the calculations, thereby reducing correlation coefficients. It was necessary to use hourly, rather than daily, figures to get sufficient wind variability.

So far as could be ascertained from the preliminary calculations, the dependence of count rate upon wind speed was very small, if not zero, regardless of the direction of wind. It has already been pointed out that the winds at Mawson come mainly from two fairly similar directions, and accordingly the wind data were divided into three groups, corresponding to winds from directions between 90° and 120°, 120° and 180°, and all others. A fourth group, for all winds regardless of direction, was also established. Within each group the data were further classified in classes of width 5 miles hr^{-1} as depicted in Table 2.4. The mean wind speed within each class, the mean neutron count rate for the corresponding hours, and the number of hours involved were then computed and printed for each individual class.

Class Number	Wind Speed	Group 1 East	Group 2 South-east	Group 3 Other directions	Group 4 All directions (sum of groups 1 - 3)
1	0 to 4 mile hr^{-1}				
2	5 " 9 " "				
3	10 " 14 "				
4	15 " 19 "				
5	20 " 24 "				
6	25 " 29 "				
7	30 " 34 "				
8	35 " 39 "				
9	40 " 44 "				
10	45 " 49 "				
11	50 " 54 "				
12	55 " 59 "				
13	60 " 64 "				
14	65 " 69 "				
15	70 " 74 "				
16	75 " 79 "				
17	80 " 84 "				
18	> 85				

Table 2.4: Classification of breakdown of wind data. The choice of units, Mile hr^{-1} and 16 points of the compass, in the original analysis was dictated by the scales provided on the anemograph charts in the earlier years. More recent charts have been calibrated in knots (1 knot = 6280 feet hr^{-1} = 0.53 metre sec^{-1}) and tens of degrees. For simplicity of tabulation, data obtained on this scale have been converted to the original one before use.

The basic period used in the analysis was the calender month. For each month, the coefficients a_o, a_1 and a_2 of the equation

$$n_v = a_o + a_1 v + a_2 v^2 \qquad 2.13$$

where n_v is the apparent neutron rate corresponding to wind speed v were obtained by regression analysis for all winds regardless of their direction (group 4). Three separate sets of regression analyses were performed.

(a) Using all data points completely independently

(b) Grouping and averaging first, and then using the resultant mean values weighted by the number of hours involved in each class

(c) Grouping and averaging but not weighting, giving each point an equal value.

Every calendar quarter this process was repeated on the total results for the quarter, but on this occasion the analysis was performed on each of the groups 1 to 4, instead of on group 4 only. This procedure was adopted because in general there were insufficient hours in some groups in some months to justify individual statistical analysis.

For the total results for each year, and also for the total results for the four years 1960-63, and five years 1960-64, the quarterly procedure was repeated, this time using linear, quadratic, and cubic functions to test for best fit to the data, instead of merely assuming the quadratic case as for the shorter term data.

In the ideal case of no alienation of pressure data by wind speed one would expect a_o to equal n_v, and a_1 and a_2 - and a_3 if calculated - to be zero. However, any statistical analysis will invariably give non-zero values, and it must be determined if they are in fact significant. The choice of the quadratic expression was made on grounds that the Bernoulli effect was involved. In the case of a pure Bernoulli effect a_1 would be zero. The linear and cubic cases were added since it was obvious that more than a simple application of $\frac{1}{2} c\psi v^2$ could be involved. The significance or otherwise of the regression coefficients was tested using the standard "t" test on the simultaneously obtained correlation coefficient. All were found to be significant.

2.2.3.4 Results, 1960-1964

It is clear that no consistent major correlation between pressure-corrected neutron count rate and observed wind velocity existed during this period. Figure 2.10 shows the relationship observed between the two quantities averaged over each of the five years, the direction of the wind being disregarded. The average relation for all five years taken together is also shown. In each case, the value shown is that of the mean count rate for the period corresponding to the particular wind speed group. The 95% confidence limits, based purely on the total counts involved in the observation are also shown. The curve is the computed cubic curve of best fit, obtained using the individual points on the graph weighted according to their statistical accuracy. It is evident from the graphs that the situation may have been somewhat different during 1960 and 1961 than during the other three years. A definite upturn in neutron intensity is observable in 1960-61, except for the two rather low points at high velocities in 1960. The curve of best fit rises throughout. Curves for the other years tend to fall as the velocity rises. It may be therefore

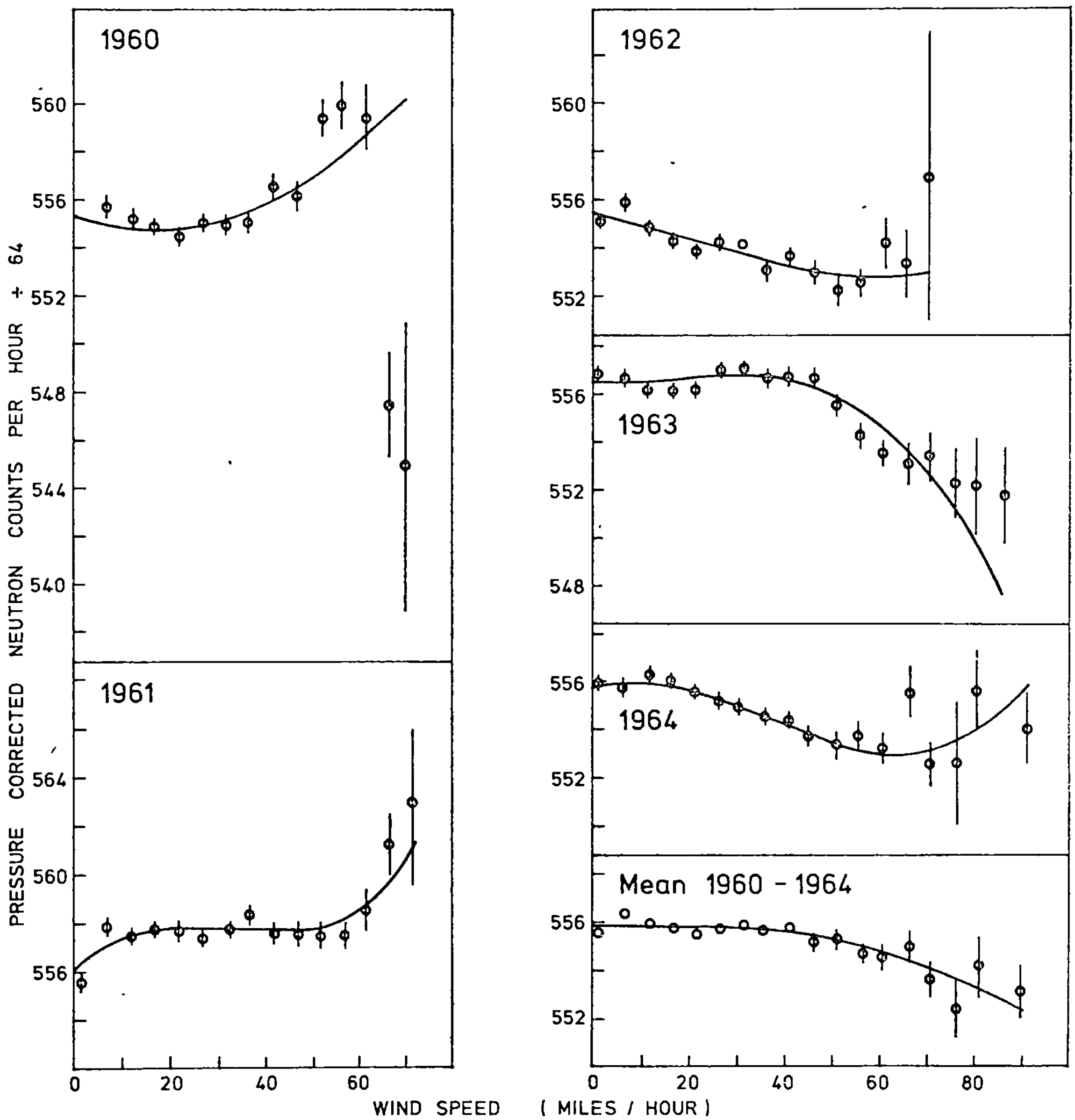


Figure 2.10. *Pressure-corrected neutron count rate as a function of wind-speed.*

that the apparently near horizontal graph for the five year average reflects the sum of two more or less equal and opposite effects, the fall away at highest velocities being due to the greater preponderance of high winds in the later years.

The error tails, being statistical, take no account of possible bias due to small cosmic ray events causing variations in count rate not exceeding the 5σ rejection limit. The two low count rates obtained in 1960 at high wind speeds are definitely due to this cause. Such variations are not eliminated by the running average technique employed unless they are of considerable duration. It is unlikely, however, that all cosmic ray data obtained during high winds would be biased in this way, and it is still less likely that it will all be biased in the same direction. It is thought that any accidental concurrence of high winds and genuine low neutron intensities would add no more than another 2σ to the error tails, and even in this event there would still be a definite tendency for the observed intensity to decrease with wind velocity during the final three years. It is therefore concluded that a definite relationship exists in the Mawson data between wind speed and apparent neutron intensity, and that the relationship varied between 1960-61 and 1962-64.

Turning to individual wind directions, the five-year averages for the East, South East, and Other, groups are shown in Figure 2.11. In the E and SE sets, the same sort of reduction of intensity at high velocity is observed. The reduction seen in the Other Directions set is not significant due to the very low incidence of high winds in these directions. From the graphs, it seems reasonable to deduce that the effect is independent of direction, at least within the accuracy attainable.

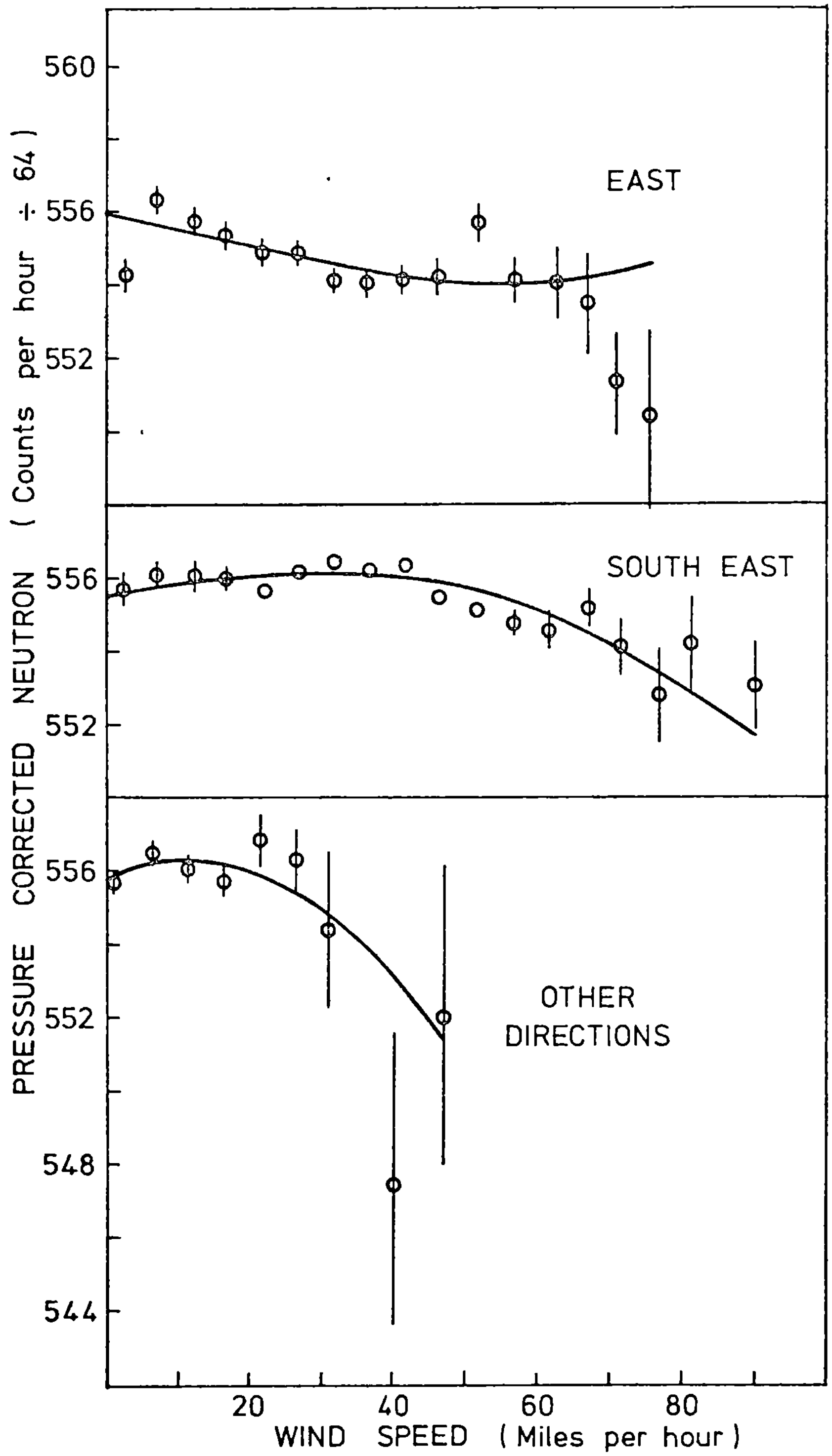


Figure 2.11. *Five year averages (1960–1964) of pressure corrected neutron count rate as a function of wind-speed and direction.*

The suggestion was put forward earlier in this chapter that any correlation observed may be due to the effects that high wind velocities may have on barometer readings. It was pointed out that, in general, the magnitudes of such effects are highly dependent on wind direction and local topography. It has been customary at Mawson to stack large quantities of weatherproof stores in close proximity to the old met hut. The exact location of these stacks tends to vary from year to year, and their size decreases more or less linearly between replenishment of the station supplies each February and the end of the tour of duty 12 months later. The store stacks are generally located downwind of the hut, although close enough to affect the air flow. High snow drifts form on the upwind side of the hut between March and December. In consequence, changes in the effects could be, although not necessarily must be, observed from year to year and season to season. This sort of thing could account, at least partially, for the variability of results from month to month.

Another possible explanation exists. It has already been mentioned that high winds at Mawson, those above the maximum katabatic velocity of 40 mile hr^{-1}, are invariably associated with the passage of regions of low pressure over the station. Generally the centre of the cyclone passes to the north of the station, and pressure will drop to around 950 mb, but at times it will pass overhead and a sea-level pressure of 937 mb has been recorded. The annual mean sea level pressure at Mawson is 990 mb. Conversely, periods of high pressure, up to 1030 mb, are generally characterised by relatively windless conditions. Consequently, an apparent relationship between wind speed and pressure- corrected neutron intensity could imply a failure to correctly compensate for pressure effects, i.e. the use of an incorrect pressure correction coefficient.

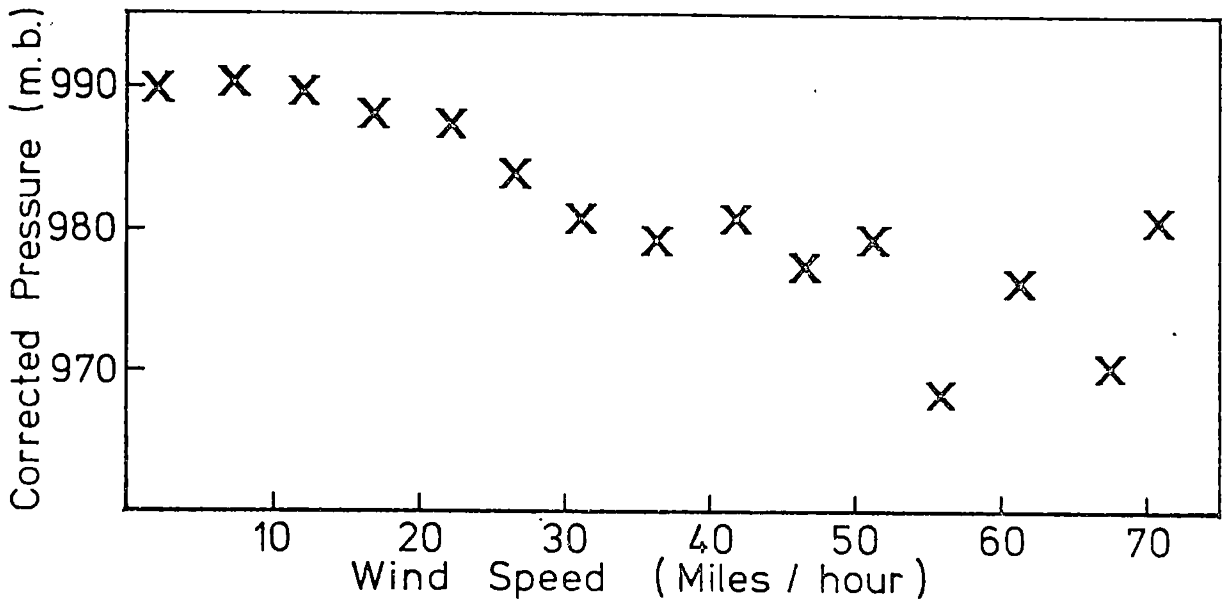


Figure 2.12. *Observed relationship between corrected pressure and wind-speed in 1966. The observation of lower pressures at times of high wind is well established.*

Figure 2.12 shows the correspondence between pressure and observed wind velocity for 1966. The pressure values are those obtained after correction for the known wind-induced errors in the barograph. The tendency for high winds to be accompanied by periods of low pressure is clear It was not thought necessary to repeat this calculation for other years since the general meteorological pattern repeats itself fairly closely from year to year, and no other pressure data were immediately available on tape. It should be an acceptable approximation to use the trends indicated in Figure 2.12 when considering data from earlier years.

2.2.3.5 Effects of Incorrect Mass Absorption Coefficient

The neutron data prior to January 1, 1962, were corrected using a faulty correction coefficient (see previous section). Figure 2.7 shows that an acceptable attenuation length for 1960 and 1961 would have been 138 $gm.cm^{-2}$ instead of the 145 $gm.cm^{-2}$ actually used. Successive substitution of the correct and faulty attenuation lengths in the correction equation (eqn. 2.12) reveals that the error caused by use of the incorrect value is given by

$$\varepsilon = -0.036\ (p - p_m) \qquad 2.14$$

where ε is in percentage, and the observed pressure p and mean pressure p_m are in millibars. Figure 2.12 reveals that the average pressure at a wind speed of 40 miles/hr is about 980 mb, and is lower at higher wind speeds. Therefore, on the average, the error in the pressure-corrected neutron count rate at this speed will be, from substitution in (eqn. 2.14), at least +0.36%. The error will be greater at higher wind speeds.

We can now return to the graphs of neutron intensity versus wind speed (figure 2.10). The discrepancy between the plots for 1960 and 1961, and those for the remaining three years, is explicable on the basis of faulty attenuation length. If we apply the above suggestion to the 1960 and 1961 plots, we find that they will indeed tend to turn downwards at wind speeds in the 40 to 50 mile/hr range, confirming the results of the other years.

2.2.3.6 Correction to Mawson Pressure, 1965-6

Pressure measurements at Mawson were different during 1965 and 1966 from those of other years (section 2.2.3.2). Details are shown in Table 2.5.

Period	Measurements made in
Prior to April 18, 1965	Old Met
April 19, 1965 to February 12, 1966	Cos Ray
Feb. 13 to Sept. 5, 1966	New Met
Sept. 6 to Nov. 22, 1966	Cos Ray
Nov. 23, 1966 onwards	Old Met

Table 2.5: Location of Mawson Barographs.

The use of this number of locations is unfortunate, and was due to misunderstandings between the several people involved at Mawson, Hobart, and Melbourne. The short period of observations in cosray late in 1966 followed the author's insistence of an immediate transfer away from new met as soon as he became aware that it was in use. It was not immediately known in Hobart whether old met was still available.

Study of the Forbush effects in the neutron data for the end of June 1966 revealed, when compared with data from elsewhere, discrepancies which could be explained by errors in pressure measurements of the order of 5 mb. A wind of average speed 50 to 60 mile/hr was blowing at the time. Simultaneous readings of pressure in new met, old met, and cosray, were then instituted and continued for several months.

Each set of readings was reduced to sea level pressure, and the differences taken. As expected there were no consistent differences between pressures measured at the three locations during periods of low wind. At higher wind speeds this was not so. The results are shown in Table 2.6.

Location	Wind Direction	Wind Speed Range (knots) 25-30	31-35	36-40	41-50	51-60	61-70	>70
Old Met - New Met	80°-124°	0.3	0.8	1.3	1.8	2.9	3.4	4.7
" "	125°-190°	0.3	0.4	0.8	1.2	1.7		
Old Met - Cos Ray	80°-124°		0.2	0.3	0.3	0.6	0.6	0.8
" "	125°-190°		0.2	0.4	0.7	0.9		

Table 2.6: Pressure difference, in mb, registered between new met, cos ray, and old met huts (1 knot = 6080 ft/hr = 0.514 metre sec^{-1}).

It was reported by the experimenters at Mawson that the barometer in old met suffered least 'pumping' during high winds, indicating that it probably had the least error. This was supported by the fact that this barometer always read higher than the other instruments, since it was already known from the cosmic ray data that the new met barometer was reading lower than the true pressure in high wind conditions. In view of this, and since the calculations referred to in previous sections had not revealed a serious bias of old met pressure with wind, the pressure measurements were finally returned to old met. This arrangement has been continued in subsequent years.

It was clear that the pressure obtained from new met could not be used to pressure correct cosmic ray data. Therefore it was decided to modify all 1966 pressure data to the old met standard, taking into account the wind speed and direction. The error, ΔP, is given by

$$\Delta P = av + bv^2, \tag{2.15}$$

where v is wind velocity in some specific direction or group of directions. The expression contains no constant term, since all instruments agreed at low wind speeds. Least squares analysis of the data in Table 2.6 produced the coefficients listed in Table 2.7.

	Direction	a	b
New Met data	80°–124°	-4.756×10^{-3}	6.941×10^{-4}
	125°–190°	-7.884×10^{-3}	5.478×10^{-4}
Cos Ray data	80°–124°	2.987×10^{-3}	7.301×10^{-5}
	125°–190°	-4.663×10^{-3}	3.032×10^{-5}

Table 2.7: Factors to obtain true pressure from pressure measured in Mawson cos ray and new met huts. For use with v expressed in miles/hr, and pressure in millibars.

All 1966 pressure data were then corrected to the old met standard using equation 2.15 and the appropriate coefficients from Table 2.7. No correction was applied for winds whose directions were outside the ranges indicated. Such winds are almost invariably light and the errors are therefore small. The 'corrected' pressure was then considered to be the best estimate of pressure available, although it undoubtedly still contains some errors, and was used to pressure correct the 1966 raw neutron data.

The 1965 pressure data, although partly obtained in cos ray, have not been treated in this fashion, since the pressure error is much smaller than that involving new met. Some errors will therefore remain in the 1965 pressure-corrected neutron data.

2.2.3.7 Errors at Wilkes and Casey

The ANARE station at Wilkes experiences even stronger winds than does Mawson. However close inspection of the pressure corrected neutron data obtained at Wilkes during periods of high wind showed no indication of a wind effect on the barometer, and consequently an analysis of the type undertaken on the Mawson data was not attempted.

Wilkes station was built in 1957 on a rocky outcrop on the Antarctic coastline. By the mid nineteen sixties the station was almost totally buried by snowdrifts, was in poor structural condition and judged to be a serious fire risk. The separate neutron monitor building, erected in 1961, did not suffer from these problems. Rather than repair the base an entirely new station, named Casey, was built a few miles away. Casey was commissioned in January 1969, and Wilkes was finally closed at the end of April 1969. The neutron monitor was moved from Wilkes to Casey between April 9th and 12th, 1969.

It was immediately apparent that extremely large wind associated errors existed in the Casey barograph. Visual inspection of telegraphed data suggested barometer errors of the order of 8 mb. at wind speeds of 80 mile/hour. Unfortunately extensive experimentation has failed to find any better site, around the station, for the barometer, and finance has not been available to install a suitable static head system. Recourse has had to be made to retrospective correction of the pressure data using the best possible estimation of the wind effect, the same technique as was used on the 1966 Mawson pressure data.

Co-incidence of several Forbush Decreases and periods of high wind at Casey during 1969 caused some difficulty in evaluating coefficients for use in eqn. 2.15. Elimination of Forbush Decrease periods led to elimination of too great a percentage of the high wind periods. Eventually pressure corrected Mawson data were used as a control to remove as much of the Forbush Decrease effects as possible from the Casey data. These revised data were then used in the usual way. This process must result in greater residual errors than if it were not necessary, and the revised pressure and pressure-corrected neutron data produced should be treated with caution wherever high winds are indicated on the data sheets.

There was no need to group the pressure data by wind direction at Casey, since all high winds were closely from the same direction. The coefficient values found were $a = 1.0817 \times 10^{-2}$, $b = 6.97 \times 10^{-4}$. They again refer to wind speed in miles/hr, and pressure in millibars.

The majority of the numerical work involved in the Casey analysis was carried out by Mr. G.G. Cooper, under the author's guidance.

CHAPTER 3.

THE SOLAR DAILY VARIATION - HISTORY AND THEORIES.

3.1 INTRODUCTION

The existence of a regular variation, of period 24 hours, in the ground level cosmic ray flux has been known for almost 40 years. Lindholm (1928), cited by Elliot (1952), reported the existence of such a variation, having an amplitude of something less than 0.5% and a maximum in the early afternoon, local solar time. This variation has come to be called the solar daily variation, which will generally be abbreviated to "d.v." in this report.

The variation has been shown by many investigators to be not a pure sine wave but best represented by the sum of two sine waves, of period 24 and 12 hours respectively, and having different amplitudes and phases. These components are termed the first and second harmonics of the d.v. and are obtained by Fourier analysis of the original data. Their amplitudes are small, typically between 0.2 and 0.4% for the first harmonic and 0.03 to 0.1% for the second. The exact figure depends on the type of recording equipment, its geographic location, and the state of solar activity. The time of maximum of the first harmonic is usually sometime in the afternoon, local solar time, and that of the second somewhere around noon. The phases are also dependent on the factors just mentioned. Recombining the two harmonics leads to a d.v. with peak to peak amplitude (as opposed to the zero to peak amplitude mentioned above) around 0.6 to 0.8%, maximum normally sometime in the local afternoon and minimum usually about 8 to 10 hours earlier.

A similar in appearance, although very different in character, d.v. exists in sidereal time. This will briefly appear in this investigation in Chapter 5 in relation to the results obtained underground, and will be mentioned only in passing elsewhere.

The classic approach to the daily variation problem is to obtain total counts for a period for each hour of the 24, after days containing recognisable cosmic ray events, and days of incomplete data, have been rejected. The period chosen depends on the aims of individual experiments but must always be long enough to obtain reasonable counting rate statistics. The resultant data have then sometimes been smoothed by some process, at least to remove any secular trends which may be present, and have then been subjected to Harmonic (Fourier) Analysis. Vectors of components of period 24 and 12 hours, and at times 8 or even 6 hours, have been obtained. The values thus obtained represent vectors of the mean d.v. for the period, as opposed to the mean of the vectors of the d.v. of individual days. The difference can easily be seen by considering a 12 day period during which the first harmonic vector has the same amplitude r1 each day, but occurs two hours earlier than on the preceding day. The summation dial is shown in Figure 3.1. Clearly, the mean amplitude of the individual vectors over this period is still r1, the mean time of occurrence being indeterminate. If, however, we add the data over the 12 days and then perform harmonic analysis we will obtain a first harmonic vector of zero amplitude, and therefore again of indeterminate time of occurrence; clearly a quite different result from that obtained by considering individual days.

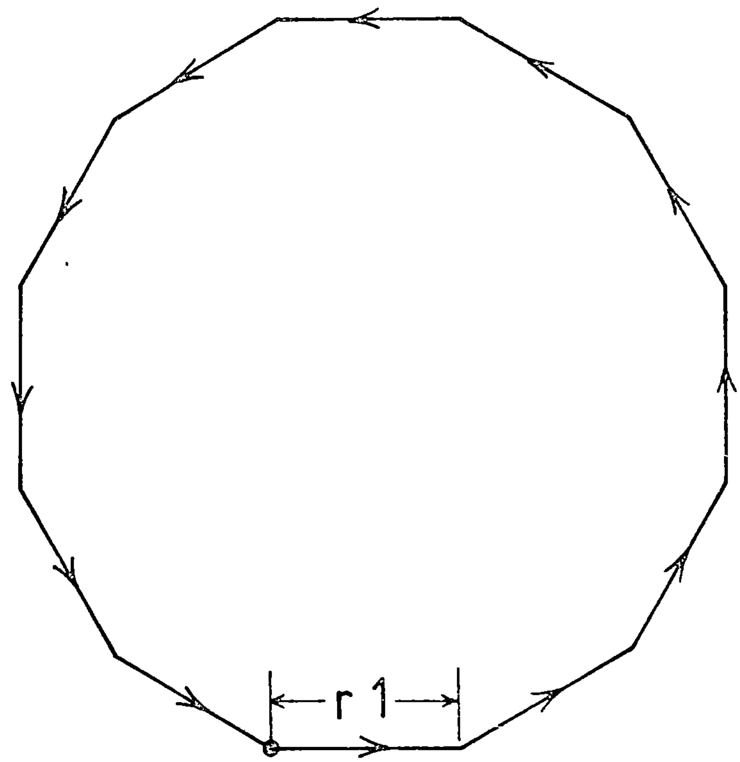


Figure 3.1. Summation dial of 12 vectors of equal amplitude and constant phase difference between adjacent vectors.

This classic approach is therefore a guide to the day-to-day daily variation only if it can be shown that the phases of the latter are reasonably constant; if they are not so, then it is necessary to dissociate the two effects entirely. Patel, Sarabhai, and Subramanian (1968), using NM64 Super monitors, have shown that the majority of individual days display diurnal maxima in free space directions between 225° and 285° but that a small number of days display maxima in all other possible directions. Additionally, series of days of enhanced diurnal variations (Duggal and Pomerantz, 1962; and others) exist. These have highly varied directions of maximum intensity, and amplitudes ranging up to 3 or 4%, ten times greater than the long term average amplitude. These effects are due to transient variations in interplanetary conditions. The long-term mean d.v. is therefore not simply an average of daily values, but rather a measure of the average (over the term) interplanetary magnetic conditions.

Two criteria must be applied when selecting the length of the period to be analysed. It must be of such a length as to make the resultant average physically meaningful, and must be long enough to enable reasonable statistical accuracy to be obtained in the results.

The first of these requirements depends somewhat on the question being asked of the data. In chapters 4 and 5, for example, we will be concerned with changes in the average diurnal variation through part of a solar cycle. Annual averages are convenient for this purpose. They have the added advantage of being free from contamination by any diurnal variations which exist in sidereal time. As part of the analysis we will also be concerned with internal consistency of the observed variations both between individual sections of a particular neutron monitor and also between various different monitors. For such tests monthly averages are appropriate.

Concerning the statistical accuracy it may be shown, based on Poisson statistics (e.g. Parsons, 1959), that the standard deviation σ of the amplitude of any harmonic of the daily variation equals $\frac{100}{\sqrt{12N}}$ %, where N is the mean hourly count total involved. If we require $\sigma \approx 0.02\%$, $N = 2 \times 10^6$ counts. A standard IGY type neutron monitor operating at mid-latitudes will require approximately two months' operation to achieve this figure. For one month's operation $\sigma \simeq 0.028\%$. The errors in the times of maximum of the individual harmonics depend on both the amplitude of the harmonic vector and on its standard deviation. In a typical case of a monthly vector $\sigma \simeq 0.028\%$ and the amplitude r1 of the first harmonic might equal 0.25%. The standard error of the phase of the first harmonic then equals 0.44 hours. In the same case r2 might equal 0.04% and the consequent standard error of the phase of the second harmonic is then 1.66 hours. In practice the standard errors will be larger than those indicated by Poisson statistics (section 4.7.2). Standard errors of such magnitude are as large as can be tolerated and therefore for work with such neutron monitors it is inadvisable to attempt this type of analysis for periods of less than one month.

For this reason primarily, very few attempts were made to study the d.v. on a day-to-day basis, except for enhanced variations, until the advent of very high counting rate recorders in the last three or four years. The largest neutron monitor now operating, as far as the author is aware, is the 48-NM-64 at Deep River, having a counting rate of 2×10^6 cts/hr. This meets the statistical requirements quoted above. Most other "Super" monitors have 18 counters and a count rate about 6×10^5 /hr at high latitudes. The high count rate scintillator muon telescopes at Massachusetts Institute of Technology, Deep River, and other places, have count rates around 1.3 x 10^6/hr. Such instruments have been used by some investigators for studies on a day-to-day basis.

The extensive studies of the time-averaged d.v., often, but not exclusively, the annual average, have had to answer three main questions since Lindholm's experiment was performed. These are:-

(a) Are the variations seen in the secondary component at ground level a reflection, true or distorted, of similar variations in the primary radiation incident on the top of the atmosphere?

(b) If a genuine variation is present in the primary radiation, does its source lie in modulation of a purely isotropic flux by geomagnetic effects or is it a reflection of a genuine flux anisotropy incident on the magnetosphere?

(c) If the latter alternative is correct, and a genuine anisotropy, regular in time, does exist in interplanetary space, what are its features and causes?

It is clearly necessary to treat these questions in the order given. The solution of the first problem took by far the longest time, up until the early 1950's. That of the second was a subject for debate until about 1960.

3.2 ATMOSPHERIC EFFECTS

The effect of the atmosphere on the incident cosmic radiation is complex, and dependent on the primary energy and secondary component involved. It is however useful to consider the charged and neutral, i.e. muon and neutron, components quite separately.

3.2.1 The charged component, 1911 to 1950

This was the first of the two components to be detected, the first real confirmation of the arrival of charged radiation in the atmosphere coming from the manned balloon flights of Hess and Kolhörster in 1911-14. Questions concerning the source of this radiation were at once raised. Several investigators tackled the problem but for some years their results appeared to be mutually contradictory. Eventually it became apparent that the radiation was largely isotropic, but that various irregular decreases, and less frequent increases, also existed. If the observations were averaged over a suitable length period it transpired that there was a regular variation in solar time having an amplitude of something less than 1% and a time of maximum generally in the range 1200 to 1800 hours local time. There was some suggestion that a seasonal variation existed in this effect.

Whilst these investigations were still in progress the barometer effect was discovered, in 1928, by Myssowsky and Tuwim. The cosmic-ray intensity, as measured by ionization chambers, was negatively correlated with changes in atmospheric pressure. Later a negative correlation with ground level temperature was also found. It was clear that both these effects would have a profound effect on the observed cosmic ray daily variation since both barometric pressure and ground level temperature have regular variations with period 24 hours. In theory therefore appropriate correction coefficients to eliminate these effects could be obtained. Correction of the observed data could then be undertaken and the residual d.v. should then represent the true d.v in the cosmic radiation incident at the top of the atmosphere.

It subsequently appeared that these corrections were insufficient. Blackett (1938) suggested that the ground temperature effect was actually a reflection of a change in the mean production height of the muons involved, since warming of the atmosphere at ground level would lead to a general warming at higher altitudes, and hence to the rise of any particular pressure level. The muon, which is the principal constituent of the charged secondary radiation, has a half life of 2.2×10^{-6} seconds, and any increase in its production height would increase the chance of it decaying before reaching ground level. It was considered unlikely that a one to one correspondence would exist between the ground level temperature and the height of any particular pressure level, and therefore corrections made to the observed d.v. on this basis could well be incorrect. This doubt was re-inforced when experiments revealed an apparent seasonal variation in the ground level temperature coefficient (Hogg, 1947).

Duperier (1944) meanwhile had investigated, also using partial correlation techniques, the correlation between the day to day observed intensity at ground level, the barometric pressure, and the heights of various fixed atmospheric pressure levels. From the mid 1940's onwards the last-mentioned had been available from regular daily balloon-borne radiosonde ascents. He found that if threefold correlation was carried out between the cosmic-ray intensity I, the barometric pressure B, and the assumed height of the production layer H, the partial correlation coefficients between I and B, holding H constant (written as $r_{IH.B}$) and between I and H with B constant ($r_{IB.H}$) both increased as H increased. They were still increasing at 100 mb., the highest level which he could investigate, and he concluded that the production region was above this height.

Duperier's first experiments were carried out using a geiger counter telescope having no absorber. It therefore detected both muons and electrons. The experiments were then extended to exclude the electron component by means of suitable absorber placed between the trays of geiger counters (Duperier, 1949). In this experiment internal inconsistencies were found between $r_{IB.H}$ and $r_{IH.B}$. Unlike the first experiment these quantities were now found to have maximum values at different heights. Duperier proposed that this could be due to a change of density in the production region affecting the rate of muon production. Since density is inversely proportional to temperature he proposed that an observed change ΔI in muon intensity due to atmospheric effects may be written as

$$\frac{\Delta I}{I} = \beta_{IB.HT} \, \Delta B + \beta_{IH.BT} \, \Delta H + \beta_{IT.BH} \, \Delta T \qquad 3.1$$

Here B and H have the same meanings as previously and T is the temperature of the production layer. The various coefficients are obtained by four-fold correlation analysis, considering the variation of only one variable at a time whilst the other two are held constant.

Much of the foregoing section is condensed from part of a comprehensive review by Elliot (1952).

3.2.2 The charged component, 1950 onwards

Other investigators have continued studies of this problem, in particular Dorman (1957, 1963) and Wada (1961). Both conclude that the matter is more complicated than indicated by Duperier, and they recommend the use of correction methods which take into account changes in atmospheric structure between the production layer and the recording instrument.

The differences between the various methods are not important from the viewpoint of d.v. studies. Most, if not all, investigators must rely for atmospheric data on radiosonde flights conducted by their local Bureau of Meteorology or equivalent organisation. Such flights are normally launched once, or at some stations twice, a day, with launchings being at the same time(s) each day. Useful information is thus obtained on day to day changes in atmospheric structure, but nothing is found about hour to hour changes therein. Information on the latter is required for correction of d.v. data by the Dorman, Wada, or Duperier techniques.

In this situation only two possibilities exist. Some sort of estimate of ΔH and ΔT may be made, and equation 3.1 used to correct the data. In this case ΔH must be known fairly accurately since the negative temperature coefficient ($\beta_{IH.B.T}$) is large for surface level muon detectors (Table 2.1). Alternatively a total barometer coefficient may be used in the equation

$$\frac{\Delta I}{I} = \beta_{total} \Delta B \qquad 3.2$$

β_{total} is larger than $\beta_{IB.HT}$ and to some extent compensates for the other two omitted terms. Neither possibility is really satisfactory and the direct use of surface level muon telescopes for d.v. studies has generally been regarded as of questionable value in recent years, although such results have been used at times in conjunction with neutron monitor studies.

There is at least on exception to this situation. Bercovitch (1966) has reported that it appears possible to satisfactorily reconcile the d.v.'s recorded by the Deep River neutron and muon detectors when due allowance is made for the d.v.'s in pressure and ground level temperature. He suggests two possible reasons for this apparent contradiction of the results of earlier workers. Firstly, temperature inversion conditions occur fairly frequently in the atmosphere above Deep River. The existence of such conditions inhibits the normal convective heat transfer between the lower and upper atmosphere which is characteristic of normal adiabatic lapse rate conditions. Secondly, he finds evidence that true day-night temperature differences in the atmosphere above 300 mb. are negligible above Canada, thus supporting conclusions reached by Teweles and Finger (1960) and Finger, Harris and Tewles (1964).

A quite different method of avoiding atmospheric contamination of observations was employed by a number of investigators in the nineteen fifties. This involves simultaneous observations with two (or more) telescopes whose azimuthal headings are in different, generally opposite, directions. The assumption is then made that the telescopes are looking through esentially the same air mass and that the secondaries each detects have therefore been subjected to the same atmospheric modulation. The difference between the intensities recorded by each instrument, after standardisation to the same detector efficiency, then represents the difference between the primary fluxes being sampled by each instrument. Assuming that the differences are purely a matter of direction of viewing, as is the case with the daily variation, the anisotropy giving rise to them may be determined.

A review of several such experiments is given by Sandström (1965), pp 242 et seq. Some conflicting results, which in retrospect were possibly due to insufficient knowledge of the detectors' asymptotic cones of acceptance, caused the technique to be largely ignored for several years. However some observations with crossed telescopes were continued by the Hobart group, and these have recently been shown to be rather useful in some aspects of d.v. studies (Jacklyn, Duggal, and Pomerantz, 1970).

3.2.3 The neutron component

The large mass-absorption effect in secondary neutrons, due to energy losses in neutron-hydrogen collisions in the atmosphere, has been discussed in section 2.2.1. The reduction in neutron intensity at any given atmospheric depth is a function of the total mass of hydrogen traversed. In turn this is represented by the total mass of air above the level of interest, one measure of which is the barometric pressure at the level. A significant d.v. exists in barometric pressure and if the data correction method is inadequate a residual d.v. will remain in the data after correction. The most probable cause of incorrect correction is use of an incorrect barometric coefficient; experimental estimations of the magnitudes of such errors are given in Section 4.7.3.

There are unfortunately other possible means of introducing spurious d.v.'s into neutron monitor data. Neither the positive nor negative temperature effects, so troublesome with muon data, should exist since the half-life of neutrons is long relative to their time of flight and the reaction with hydrogen is not, to first order, temperature dependent. However not all neutrons recorded by normal types of neutron monitors result from a pure neutron cascade through the atmosphere.

Table 3.1, due to Harman and Hatton (1968), indicates the state of affairs for normal neutron monitors.

Item	Component	IGY	NM64
1	Neutrons	83.2±4.8	83.3±4.0
2	Protons	6.2±1.2	6.7±1.5
3	Stopping muons	4.6±1.9	1.8±1.3
4	Fast muons (producing neutrons in flight)	1.8±0.4	1.9±0.5
5	Pions	1.2±0.3	0.8±0.2
6	Background and local production	3.0±1.0	5.5±0.5

Table 3.1 *Percentage contributions to the counting rates of IGY and NM64 monitors.*

It is evident that items 3 to 6 inclusive will all display some form of variation with temperature, due to variations in temperature of the monitor pile itself and in the atmosphere at and below the muon production level. Dorman (1957) calculated the magnitudes to be approximately $-0.01\%/^{\circ}C$ for the local temperature dependence of an IGY neutron monitor, and $-0.03\%/^{\circ}C$ for a uniform rise in atmospheric temperature throughout the region between the production layer and the site of a sea-level mid-latitude neutron monitor. The magnitude of this effect will be, according to Dorman, larger for an equatorial station and will decrease with station altitude. Clearly diurnal variations in pile or atmospheric temperature can lead to residual variations in neutron monitor data. These could be large enough to affect conclusions drawn from the data.

Harman and Hatton (1968), surveying the temperature effect, find that Dorman's atmospheric coefficients must be revised upwards to compensate for his incorrect estimate of the relative contributions to the detector count rate. They find that his coefficients should be multiplied by numbers of the order of 1.6 for IGY monitors and 1.2 for NM64 monitors, for Leeds near solar minimum. Bercovitch (1967), using older percentage contribution data, reached a similar conclusion.

The presence of water vapour in the atmosphere will also affect the counting rate of a neutron monitor since the attenuation length for neutrons in water differs from that in air. Thus varying amounts of water vapour will absorb varying amounts of the neutron flux. Bercovitch and Robertson (1966) found the resulting coefficient for observed neutrons to be $0.09 \pm 0.03\%/(\text{gm.cm}^{-2})$ water vapour.

Ground lying snow appears to have a significant effect on the counting rate of NM64 type monitors. The normal design for these detectors calls for a shield of polyethylene, 7.5 cm thick, around the pile. In contrast an IGY monitor is surrounded by a 30 cm thick paraffin wax shield. It has subsequently been shown (Bercovitch 1967; K.B. Fenton et al, unpublished, 1970) that the 7.5 cm is insufficient. When snow is lying on the ground in the vicinity of the monitor the number of locally produced albedo neutrons decreases. The monitor count rate is found to decrease in these conditions, indicating that a significant number of externally produced neutrons are penetrating the shield. In principle this difficulty is easily eliminated. However the shields are expensive, simply due to their large volume. To increase the shield thickness of the 6NM64 monitor at Mt. Wellington would cost about \$(Aus) 2000, (\$1 Aus = \$1.14 U.S.) and this sum has not been forthcoming. This particular monitor will therefore the subject to some snow effects in winter. Other investigators find similar financial problems.

Only some of the abovementioned effects significantly affect the observed d.v. in neutron intensity. Temperature changes in the monitor can be eliminated by control of the laboratory temperature. Cane (1971) has shown that temperature variations of at least $\pm 1^{\circ}C$ are tolerable. Ground snow thickness is not likely to show a consistent daily variation, although a regular sequence of overnight precipitation and daytime thawing can occur at temperate climate sites. Some effect would probably be detectable at Mt. Wellington. Snow falls of 3 or 4 inches occur a few times a year, followed by thawing in a couple of days. At this particular station the thin Aluminium walls of the building do not offer much in the way of additional shielding.

However atmospheric water vapour, being partly temperature dependent, may exhibit a daily variation, and atmospheric temperature itself certainly will, at least below the tropopause. Fortunately the effects on secondary neutrons are of opposite sense, although the degree of cancellation thus invoked will vary widely. Little can be done about these problems, except to hope - supported by some experimental evidence - that they are small. Bercovitch (1967) has stated that the atmospheric temperature effect in neutron monitors is about 20% of that in muon telescopes. This should make the effect detectable in NM64 monitor records if adequate temperature observations are available.

3.2.4 Conclusions, Atmospheric Effects

It had been shown conclusively by the early nineteen fifties, by crossed telescope experiments, that atmospheric effects were not the sole contributors to the observed cosmic ray daily variation, although they could give rise to large effects which could partially or completely obscure the genuine daily variation in radiation intensity at the top of the atmosphere. Most of the recent work, some of which has been outlined above, has been concerned with improving knowledge of the various coefficients involved.

3.3 POSSIBLE GEOMAGNETIC ORIGIN

For a period in the middle and late 1950's, there was considerable speculation whether the daily variation observed after the removal of atmospheric influences was of terrestrial or extra terrestrial origin. The main difficulty lay, prior to 1957, in the existence of only a handful of neutron monitors at Chicago, Mt. Washington, and one or two other places. Consequently the majority of d.v. work was done using muon telescopes. The pitfalls inherent in such experiments have been discussed in section 3.2.1 above. A full length review of the work at that time is not justified here, several such exist in the literature. The main difficulties lay in attempting to reconcile results of various experiments, some of which appeared at the time to be contradictory to others. Some of this confusion arose from an imperfect knowledge of the directions of viewing of the instruments employed, due in turn to the difficulties associated with trajectory tracing in the then imperfectly known earth's magnetic field. No one paper could easily be singled out as demonstrating conclusively that the observed daily variation was indeed non-geomagnetic in origin, but by the end of the decade it was generally thought that this was so, at least so far as the mean daily variation was concerned.

3.4 INTERPLANETARY ORIGIN

The daily variation observed in cosmic rays, after known atmospheric and geomagnetic effects have been removed, is not purely sinusoidal in character. Neither is it necessarily constant from one day to the next, although long period mean values do show remarkable constancy. We are at present concerned mainly with these long term mean values.

Plotting typical data reveals that there is a maximum of intensity in the late afternoon, local time, which corresponds to the 1800 direction outside the magnetosphere. A minimum in intensity occurs some 8 to 10 hours earlier, roughly in the 0900 direction. The observed variations can be well represented by taking the first and second harmonics from Fourier analysis of the data, and then recombining them (Fig. 3.2). The question then arises whether the physical causes of the observations are related to the first and second harmonics, or whether a virtual source and virtual sink exist in the appropriate direction. Both suggestions have received much attention in recent years. The mechanism invoked for both the virtual source and for the first harmonic is usually the same, and will be treated in the next section.

3.4.1 The Diurnal Component. The Virtual Source

Using a technique involving asymptotic cones of acceptance, Rao, McCracken and Venkatesan (1963) demonstrated that the mean diurnal variations observed by a world wide selection of neutron monitors during the IGY could be explained by an anisotropy of definite characteristics in the primary radiation. This had an amplitude of 0.4% in the 1740 hrs free space direction. In the range of rigidities 1.0 to 100 GV, they

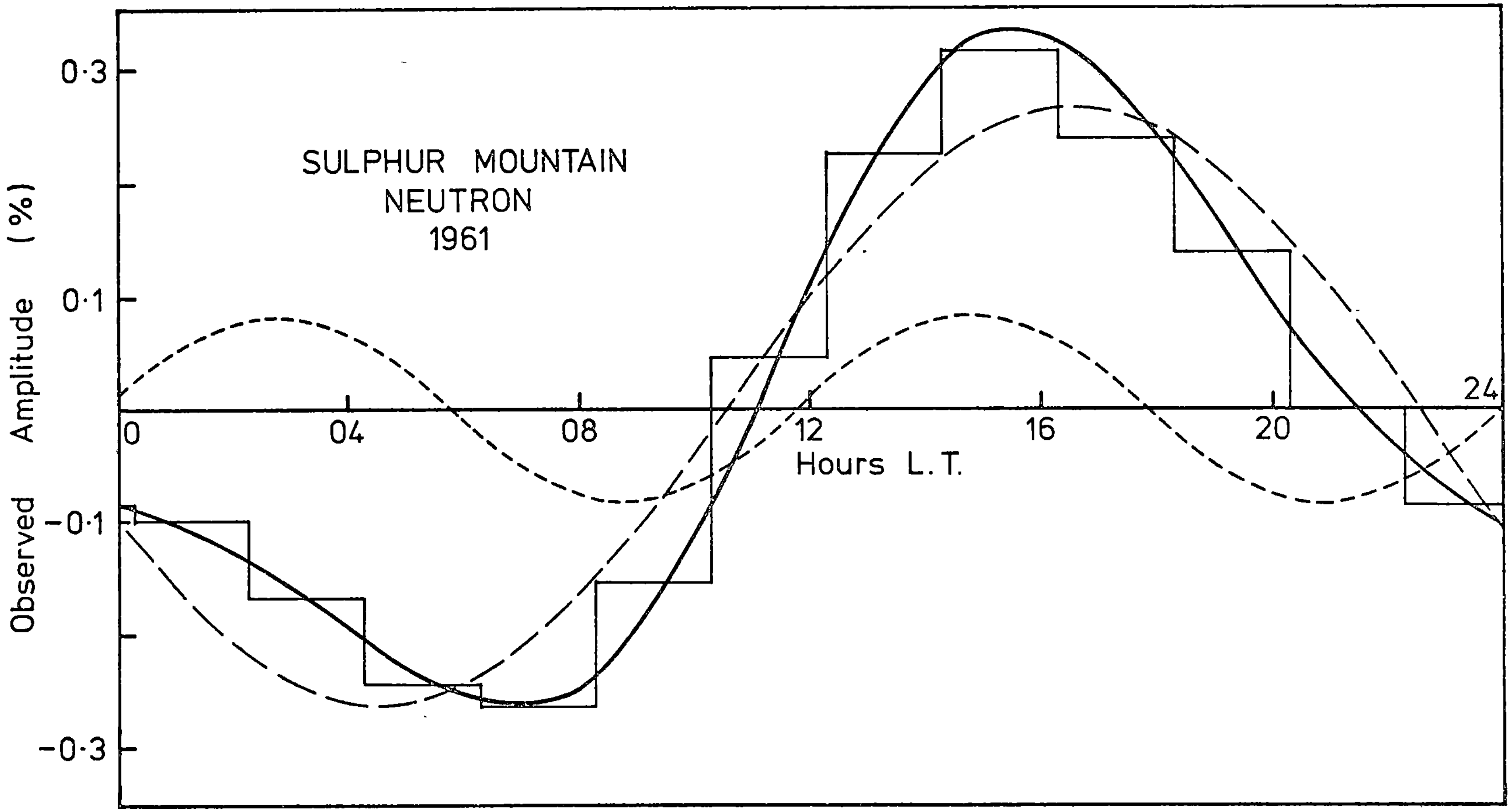


Figure 3.2. Mean annual pressure-corrected neutron monitor observations at Sulphur Mountain in 1961 (histogram). The first (0.254% at 16.44 hours L.T.) and second (0.085% at 2.63 hours L.T.) harmonics of best fit, and their sum, are also shown.

found that the anisotropy was independent of rigidity. Subsequent analyses, including that of the present author (Chapters 4 and 5), have shown that the anisotropy has remained constant, in gross features, through the solar minimum in 1965. There are, however, significant variations in some of the parameters involved.

The diurnal maximum in, approximately, the 1800 direction outside the magnetosphere, implies a maximum in the received radiation from a direction along the trailing side of earth's orbit. The problem is complicated by the variation of the observed free space diurnal vectors from day to day. In particular, large changes in the vector exist at geomagnetically disturbed times, and efforts to obtain explicit relationships between these vectors and other geomagnetic parameters have not always been successful. It seems then that several factors must influence the directions of motion of energetic particles in the vicinity of earth's orbit. A number of theories designed to account for the observations have appeared in the literature in recent years. Some are discussed in the remainder of this section.

Parker (1964, 1966) suggested that the difficulty of the day-to-day variability could be overcome when the non uniform, both in space and in time, nature of the interplanetary magnetic field, B, was considered. He demonstrated that in a completely stationary large scale B field no anisotropy could exist. In time varying fields, anisotropies could be observed due to non cancellation of cosmic ray density gradients and to streaming caused by the electric field created by the moving solar wind. However the long term field change is clearly zero, consequently no long term average anisotropy could exist from this cause. He also found that, if the B field is grossly (on the scale of the gyro-radii of the particles involved) regular inside earth's orbit, so that the guiding centre approximation holds, and if there are sufficient irregularities outside the earth's orbit to largely destroy the cosmic ray density gradient produced by the electric field inherent in the solar wind, then a net streaming of cosmic rays parallel to the earth's orbit will result. The mean value of the streaming velocity will be the solar co-rotation velocity at 1 a.u., 400 km/sec. Axford (1965) independently came to a similar conclusion.

McCracken and Rao (1966) showed that this effect should result in a mean annual diurnal variation of 0.7cos(lat)% and discussed reasons why the observed variation, although apparently following the cosine rule quite closely, has an amplitude of 0.4% instead of 0.7%. They postulated that this could be due to the existence of a time varying cosmic ray gradient normal to the ecliptic plane. Variations in the amplitude of the diurnal vector could, in the light of this suggestion, be due to variations in the perpendicular density gradient.

All the abovementioned authors agree that some upper rigidity limit must apply to the co-rotation model. Clearly particle gyro radii must be less than the scale dimension of the rotating system. Parker suggests around 100 GV, whilst Axford predicts that the limit may be solar cycle dependent, being lowest at solar minimum, as the result of variations in irregularity dimensions outside the earth's orbit. Chapters 4 and 5 of this thesis will present observational evidence for such changes. Axford suggests that at rigidities above this limit the observed daily variation will be in sidereal time, and below the limit will be in solar time.

Evidence exists for abrupt changes in the monthly mean diurnal vectors observed near the solar minima in 1932 and 1954. No such changes were observed at the 1943 or 1965 minima. This has been taken by some investigators as evidence for some form of 22-year cycle. That the actual changes in the vectors did occur is certain, that such changes must occur every other solar minimum is open to question on statistical grounds. Two 'successes' out of four 'tries' would scarcely convince a statistician that P necessarily equals 0.5!

The observed changes were mainly in the phase of the vector. The 1932 minimum occurred in the infancy of cosmic ray observations, when only a few ion chambers were operating, but the 1954 observations were made with all varieties of detectors, albeit not many being neutron monitors. The monthly mean vector at Huancayo rotated anti-clockwise by almost 2π radians during 1954 (Conforto and Simpson, 1957). The use of monthly vectors leads to possible confusion between diurnal variations in solar and sidereal time, and Conforto and Simpson showed that the observations were consistent if they were plotted in sidereal, rather than solar, time. The suggestion was made that the solar influence at that time could not extend as far out as Earth's orbit and hence the full galactic intensity and influences were being received. The direction they obtained for the sidereal anisotropy was π radians out of phase with subsequent northern hemisphere observations at higher energies, and was suspect for that reason. However they synchronised solar and sidereal time on 21st March instead of 21st September, and if this is corrected their sidereal explanation does fit in with other observations. The explanation could be that the solar wind outer limit had receded inside earth's orbit, leading to a cessation of the normal solar daily variation, or that the upper limiting rigidity had dropped to 25 or

30 GV. Since the monthly vectors, when plotted in sidereal time, are rather more consistent at Huancayo than they are at the lower cut-off rigidity statio Climax, the lower value of upper limiting rigidity seems a more attractive explanation, however the other cannot be ruled out. The matter is likely to remain open for speculation, at least until the 1976 solar minimum.

Forbush (1967, 1969) has propounded an entirely different interpretation, using observations obtained from the ion chambers at Cheltenham, Christchurch, and Huancayo. He finds that the 1800 LT vector may in fact be split into two components, one in the 1800 direction whose amplitude is linearly dependent on magnetic activity, and one in the 19.11 direction, approximately in the direction of the Archimedian spiral field, whose amplitude is independent of magnetic activity but demonstrates a sine wave with a period of two solar cycles. The last zero in this wave occurred, according to Forbush, in mid 1958 about the time of a reversal in the sun's general magnetic field. The magnitudes of the two effects are comparable, for ion chambers, and were this the case for neutron monitors also presumably a phase variation would be evident over a period of 3 or 4 years. This does not seem to be the case at first sight. If Forbush's interpretation of his observations is correct, it will be necessary to modify the Parker-Axford theories. On the other hand, one of the difficulties of the streaming model is to understand why the irregularities required to exist beyond the earth's orbit should remain so apparently constant throughout the solar cycle, since one would expect their frequency, size, and solar radial distance all to be dependent on the state of solar activity. Forbush's explanation would obviate this requirement. The variability which he observed in the diurnal vector component in the garden-hose direction may be understandable in view of observations of the variable direction of the field. Space probe observations by Rosenberg and Coleman (1969) appear to show that the polarity of the dominant field at a given heliolatitude is the same as the polarity of the weak solar dipole field in the same solar hemisphere. Since the annual mean heliolatitude of the earth is zero these observations imply that the nett annual B flux past the earth in the ecliptic may be close to zero, which argues against this particular explanation of Forbush's observations. The fact remains though that these observations must almost certainly be somehow connected with the 22 year solar magnetic cycle.

All the abovementioned work takes little account of conditions away from the ecliptic plane, partly because the majority of detectors at all the highest latitudes scan in that plane. The amplitude of the observed anisotropy due to azimuthal streaming should fall off with the cosine of the asymptotic latitude of viewing. The experimental results obtained have been generally taken as agreeing with this expectation. In some theories conditions have been laid down concerning the maximum cosmic ray density gradient perpendicular to the ecliptic plane, usually it is required not to exceed a few percent per a.u.

A theory of changing cosmic ray density with heliolatitude and solar cycle period has been developed (Sarabhai and Subramanian, 1966) and the consequences on the various observeable cosmic ray modulations have been explored (Subramanian and Sarabhai, 1967). The model predicts variations of cosmic ray density with heliolatitude, and possible non-symmetric density distribution North and South of the ecliptic plane, on the bases of latitudes of maximum solar activity, latitude distribution of the 5303Å green coronal line intensity, and other similar parameters. They suggest that at some heliolatitude θ_2 the cosmic ray density can be less than in the ecliptic plane, whilst at the solar poles the full galactic density should be observable. The latitude of the minimum is solar cycle dependent, and may or may not be the same on both sides of the ecliptic. Making various assumptions about the rigidity dependence of the 11-year variation in intensity, and interplanetary field strength, they show that, so long as the rigidity exponent is ≈ -1, and the density distribution is symmetric about the ecliptic, the effect on the diurnal vectors observed by the Huancayo and Deep River neutron monitors will be small, regardless of the shape of the distribution of density with heliolatitude. For a symmetric distribution about the equator, an 11-year cycle independent of rigidity, and a smoothly increasing density with heliolatitude, they predict amplitudes of 0.047% at 1.3 hrs LT for Deep River, 0.085% at 23.6 hrs LT for Huancayo, assuming a 5γ field. These vectors should be observable. For the case of symmetry about some heliolatitude $\theta_1 \neq 0$, they predict variations ranging from 0.3 to 1.2% at both stations in the general direction of midnight LT, depending on the exact field and exponent values assumed. Such variations would be clearly observable when compared with the vectors, approximately perpendicular to them and comparable im amplitude, which are due to azimuthal streaming. They do not appear in the annual mean or monthly mean observed vectors except as a possible explanation for the 1932 and 1954 anomalies. It must therefore be concluded that, at least on average, the cosmic ray density distribution is similar north and south of the ecliptic.

Forman and Gleeson (1970, not yet published) have joined other investigators in stressing the difficulty of reconciling the theoretical amplitude of the diurnal variation as predicted by the Parker-Axford model with the amplitude actually observed. Part of the difficulty lies in erroneous evaluations of the Parker-Axford model. Forman (1970) has shown that the McCracken and Rao (1966) estimate of 0.7% is too large owing to their incorrect evaluation of the Compton-Getting coefficient (Section 5.2.4). Use of the correct coefficient reduces the theoretical amplitude to about 0.6%, still 50% or more larger than that actually observed. The perpendicular density gradient postulated by McCracken and Rao to obtain this reduction has not been observed (Forman and Gleeson, op.cit).

Forman and Gleeson present in their paper a development of the Parker-Axford model which differs from its predecessors in its treatment of the density gradient and of the effects of magnetic field irregularities. They are able to show that the electric field drifts of cosmic-ray particles perpendicular to the interplanetary magnetic field combine with convection of the same particles parallel to the field to form a simple convective flow in the solar wind direction. The other bulk flows of particles are due to diffusion and to magnetic drifts. They obtain an expression for the differential (with respect to energy) streaming $\underline{S}$ of cosmic rays in interplanetary space. They find

$$\underline{S} = CU\underline{V} - \underline{\underline{\kappa}}\frac{\partial U}{\partial \underline{r}} - \frac{\omega\tau\kappa_{11}}{1+(\omega\tau)^2}\left(\frac{\partial U}{\partial \underline{r}} \times \frac{\underline{B}}{B}\right) \qquad 3.3$$

Here C is the Compton-Getting coefficient, U the differential number density, $\underline{V}$ the solar wind velocity, ω the gyro-frequency of the particles and τ the mean collision time. $\underline{B}$ is the magnetic field vector and $\underline{r}$ the displacement vector from the sun. The diffusion tensor is defined by

$$\underline{\underline{\kappa}}\ \frac{\partial U}{\partial \underline{r}} = \kappa_{11} \left(\frac{\partial U}{\partial \underline{r}}\right)_{11} + \kappa_{\underline{1}} \left(\frac{\partial U}{\partial \underline{r}}\right)_{\underline{1}} \qquad 3.4$$

where parallel and perpendicular refer to the direction of $\underline{B}$.

There is no direct relationship in a complex field situation between the parallel and perpendicular diffusion coefficients κ_{11} and $\kappa_{\underline{1}}$. $\kappa_{11} = \kappa = 1/3v^2\tau$, where v is the particle speed. In the case of a smooth field $\kappa_{\underline{1}} = \frac{\kappa}{1+(\omega\tau)2}$, but when random walk of the field lines (Jokipii, 1966) is taken into account $\kappa_{\underline{1}}$ becomes larger than this. Forman and Gleeson suggest that $\kappa_{\underline{1}}$ can become as large as the order of κ_{11}. Gleeson (private discussion) has suggested that the magnetic drift term is probably negligible, due to the low value of the coefficient. In the long term this term will vanish anyway, due to field reversal. We are therefore left with

$$\underline{S} = C U \underline{V} - \kappa_{11} \left(\frac{\partial U}{\partial \underline{r}}\right)_{11} - \kappa_{\underline{1}} \left(\frac{\partial U}{\partial \underline{r}}\right)_{\underline{1}} \qquad 3.5$$

The streaming manifests itself as a sinusoidal variation in intensity recorded by a detector rotating at uniform angular velocity, with the maximum occurring when viewing directly upstream against the direction of $\underline{S}$. When the detector is fixed on the earth's surface a diurnal variation will be observed.

No explicit co-rotation term appears in these equations, and Forman and Gleeson suggest that the notion of co-rotation should be abandoned. Instead they suggest that the observation of an anisotropy exactly in the cross-radial direction should simply be taken as confirmatory evidence of no radial streaming. It is customary to assume that, on average, there are no sources or sinks for high energy cosmic rays (having energies greater than, say, 1 GeV/nucleon) inside the earth's orbit. The few solar flares which emit particles in this range, and small convective flow which exists in particles in the few GeV/nuclear range through the solar cycle, are second order effects for this purpose. It follows therefore that an observation of strictly cross-radial streaming implies also that there is no nett energy gain or loss - on the average - for particles approaching the sun in the energy range of observation.

Short term sinks (e.g. Forbush Decreases) and sources (e.g. the subsequent diffusive replenishment of the depleted region) certainly exist. They have characteristic time scales of a few days, or less. As would be expected streaming in markedly different directions, with sizeable radial components, is observed. More surprisingly such streaming can also occur in magnetically quiet times. A possible explanation is that changes in the relative magnitude of κ_{11} and $\kappa_{\perp}$, related to variations in the degree of irregularity in the field, could be responsible.

3.4.2 The Semi-Diurnal Variation

Whilst there is now no doubt about the existence of an increase in radiation energy received from the direction 90°E of the sun and giving rise to the observed diurnal variation, there is still some dispute concerning the semi-diurnal variation. Katzman and Venkatesan (1960) observed such a variation in data from 16 neutron monitors through the IGY period. They felt that they could explain the observed semi-diurnal vectors on meteorological grounds in 13 cases. The three exceptions were all equatorial stations. This is significant in the light of more recent work. Ahluwalia (1962) attempted to show a relationship between the semi-diurnal vectors for individual days and values of relationship between the semi-diurnal vectors for individual days and values of K_p. He showed that considerable variability existed between vectors from different days. Rao, McCracken and Venkatesan (1963) applied the cone of acceptance/minimum variance technique, which they pioneered, to the mean semi-diurnal variation for the IGY period. They found that the minimum variance which they obtained greatly exceeded the value they expected on statistical grounds, and concluded that their work neither proved nor disproved the existence of a genuine semi-diurnal variation.

Sandström (1965) pointed out that the semi-diurnal vectors obtained from East and West pointing telescopes, at medium zenith angles, at Uppsala were considerably different, implying that their origin could scarcely be atmospheric. He drew the same conclusions from North and South pointing telescopes at Kiruna. The vectors which he obtained appeared to vary considerably from one short period to the next, and he suggested that the fairly small amplitudes observed for the annual mean vectors were due to the apparent random walk nature of the effect from day to day. Ables, McCracken and Rao (1966) found a definite, consistent, mean annual semi-diurnal variation in neutron monitors for the period 1953 to 1965. They obtained an average amplitude of the annual vectors of approximately 0.1% directed approximately perpendicular to the interplanetary field direction, approximately at 0400 and 1600 hours L.T. This result was obtained by a numerical filter technique, the time of maximum allocated to each station being the most probable time of maximum, not necessarily the same as the mean time obtained from conventional harmonic analysis. The author's remark that the effect could be rigidity dependent, however the direction was calculated on the basis of its being rigidity independent.

The theory of the semi-diurnal variation is not clear at the present time. Parker (1964) put forward a possible two-way streaming in the ecliptic plane perpendicular to the magnetic field direction. The term in his expression for cosmic ray transport varies as $\underline{B} \times (W_{11}{}^2 - \frac{1}{2}W_{\underline{1}}^2)$ where W_{11} and $W_{\underline{1}}$ are the velocity components of cosmic rays parallel and perpendicular to the B field. Since the average value of $(W_{11}{}^2 - \frac{1}{2}W_{\underline{1}}^2)$ will be approximately constant, and the direction of B reverses every few days so that the average value of $|B|$ goes to zero over a period of a year, this mechanism can scarcely give rise to an annual mean semi-diurnal variation, although it can certainly produce one on individual days.

Subramanian and Sarabhai (1967) have put forward the consequences of their perpendicular density gradient theory as it applies to the semi-diurnal variation. They find various rather complicated changes in the expected vectors as the density distribution and field strength change. In general the vectors, which they predict to denote the times of maximum, lie either approximately radially or cross-radially with respect to the earth-sun line, and do not therefore appear to agree too well with observational results (Section 4.9).

Lietti and Quenby (1968) proposed two possible models for the semi-diurnal variation. Both require the existence of a cosmic-ray density gradient perpendicular to the ecliptic, but make different assumptions concerning the relative magnitudes of the diffusion coefficients in and perpendicular to the ecliptic plane. Both lead to prediction of a rigidity dependent semi-diurnal anisotropy with a direction of maximum in the solar equatorial plane perpendicular to the "garden-hose" direction. They expect the latitude dependence to be as $\cos^3$ (asymptotic latitude) and approximate asymptotic latitude above the equatorial plane with geographic asymptotic latitude. They suggest that the model assuming $\kappa_{11} >> \kappa_{\perp}$ gives a better fit to the observations. This is taken further by Quenby and Lietti (1968) in the rigidity range 1 to 15 GV, and confirmed at higher rigidities by Hashim, Peacock, Quenby, and Thambyahpillai (1969). The latter authors, utilising data from the London 60 m.w.e. underground directional muon telescopes, show that a rigidity dependent variation up to an upper limiting cut-off between 60 and 100 GV is consistent with their observations, both in amplitude and phase.

3.4.3 The Virtual Sink

Combination of the first and second harmonics of analysed data results in a quasi-sinusoidal curve of the type shown in Figure 3.2. A typical curve will have a minimum between 0600 and 0900 LT and a maximum between 1400 and 1700 LT, some 8 to 10 hours later. Sarabhai, Pai and Wada (1965) noted the consistency of this time lag from day to day and compared details of the lag with changes in the B field direction. They suggested that the daily variation might be composed of two components, a virtual source in the 1800 direction due to azimuthal streaming, and a virtual sink in the direction looking sunward along the B field. They suggested the possibility of sunward bound particles, spiralling along the field lines following the guiding centre approximation, having maximum chance of scattering if irregularities of scale size equal to the particle gyro-radius exist near the mirroring point. If a significant proportion of particles are scattered at that point, a decrease in radiation coming from the sun along the field lines should be observed. Irregularities of order 10^5 to 10^6 Km are required.

At first sight this effect might be thought of as sinusoidal, when observed by a detector on the rotating earth, in the same manner as the sinusoid obtained from azimuthal streaming. The sum of two sine waves of equal period but different phases is also a sine wave, of the same period. However the streaming gives rise to a true maximum in the 1800 direction and a true minimum in the 0600 whereas the virtual sink is non-sinusoidal, having a definite minimum at 0900 but no corresponding maximum from the anti-solar 2100 direction. Thus the combination can give rise to the type of effect observed.

Another suggestion was made by Mercer and Wilson (1965). They discussed the solar capture of the inward bound protons which, due to their pitch angles on entering the interplanetary field, nominally mirror below the solar surface. They computed that only 0.01% of all primary cosmic rays are so captured, however due to the finite opening angle of a neutron monitor (or any other detector), this would result in a decrease of about 0.6% when looking inward along the field direction. The decrease would vary from day to day, both in amplitude and direction, as the average solar wind velocity, and therefore field direction, changed.

3.5 CONCLUSION

The review, and comments, presented above, particularly in sections 3.4.1 to 3.4.3, do not attempt to cover all of the vast amount of work which has been done in this field in recent years. However, an attempt has been made to present most of the work which seems relevant to the author's investigations. The omission of comment on many papers, particularly by Japanese and Russian authors, does not mean that they have not been read, rather that the line must be drawn somewhere. Were one to rigorously mention every paper published on this subject over the past five years, one would end up with a thesis the size of 12 months' issues of Scientific Abstracts - or so it at times seems!

Many details of the solar daily variation are not yet fully known. Clear knowledge of rigidity exponents, latitude dependence, and upper and lower effective rigidity limits for both harmonic components, is essential to permit the various theories to be verified. The next chapters present investigations into methods of obtaining these parameters, into the values of the parameters themselves, and into some of the pitfalls which strew the investigator's path.

CHAPTER 4.

PARAMETERS OF THE SOLAR DAILY VARIATION

4.1 INTRODUCTION

The parameters of the solar daily variation are, as indicated in the previous chapter, of paramount importance in investigation of interplanetary magnetic conditions, in particular at the higher energies where satellite data are not useful. By late 1964 it was apparent that the daily solar variation was relatively invariant over the solar cycle, at least in the energy range to which neutron monitors primarily respond. However results from the underground muon telescopes at Hobart indicated some decrease in amplitude at higher energies, and furthermore the first harmonic appeared to be decreasing proportionately more than the second. Such changes could be due to an alteration in the spectral exponents involved, or a reduction in the upper rigidities at which the components ceased to be effective, assuming that such limits existed. The changes might or might not be evident in the neutron data. It therefore appeared reasonable to investigate whether the solar daily variation in the range 1 to 200 or so GV was in fact as invariable as it appeared.

Rao, McCracken, and Venkatesan (1963) showed that in 1958 the first harmonic had a free-space amplitude around 0.4% with the maximum in the direction 265°. It was independent of rigidity, up to an estimated 200 GV. Their results for the second harmonic were inconclusive since they found such variations only in data from low latitude stations. The amount of clerical work involved in a study such as this is considerable, and to keep within reasonable bounds it was decided to restrict the main analysis to the period 1961-3. If the 1961-3 results were not similar to those of

Rao et al then further work would be necessary. 1963 was originally taken as the final year for which data files at Hobart were essentially complete. It was however hoped from the onset that work could be continued through solar minimum, to determine if any effects similar to those of 1954 could be seen.

4.2 CALCULATION TECHNIQUES

Rao et al showed how the response of any particular detector to specified anisotropies could be predicted, and how the results could then be used in a least squares analysis to determine which, if any, of the assumed anisotropies in fact fitted the actual observations. The method depends on the different forms of the asymptotic cones for various detectors. It has been used, with variations, in the present analysis.

4.2.1 Calculation of Modulation Coefficients

From a knowledge of the asymptotic cones of acceptance we may, by the appropriate use of variational coefficients, calculate the expected response of a detector to any specified anisotropy. In particular we can predict the time variation to be observed in the count rate as the Earth rotates relative to the anisotropy.

Let the rigidity spectrum of the anisotropy be given by

$$J_A(R) = \begin{cases} f(\Lambda).R^{\beta} & \text{for } R_1 \leq R \leq R_u \\ 0 & \text{for } R < R_1 \text{ and } R > R_u \end{cases}$$

where R_1 and R_u are the lower and upper rigidities between which the anisotropy is effective (called the lower and upper limiting rigidities respectively), and $f(\Lambda)$ is a function of asymptotic latitude. For $f(\Lambda)$ we will take the function $\cos^p(\Lambda)$, where p remains to be determined. Note that the case $p = 0$ corresponds to an anisotropy independent of asymptotic latitude, and $p = 1$ is the direct cosine dependence generally predicted for the diurnal variation. It remains to determine $g(\eta)$, the response to this anisotropy of a detector viewing in the direction η.

The angles used to define the direction of viewing are shown in figure 4.1, where η is the direction of viewing relative to the earth-sun line. All angles are in degrees, T is universal time in hours. Any anisotropy will be a function, as seen by the detector, of η, and may be expressed as a Fourier series,

$$g(\eta) = J_A(R) \sum_{m=1}^{\infty} A_m \cos m(\eta - \eta_m)$$

where A_m and η_m are amplitude and phase constants.

A consequence of this should be noted. Analysis of any cosmic-ray data which contain departures from isotropy, including departures due to the statistical fluctuations inherent in finite count rates, will reveal apparent harmonics at any specified frequency. If, for example, a severe Forbush decrease occurs during the period under analysis, it may contribute markedly to the calculated first and second harmonics without being connected in any way with genuine periodicities in the data. Care must therefore be taken to eliminate such events before harmonic analysis is undertaken.

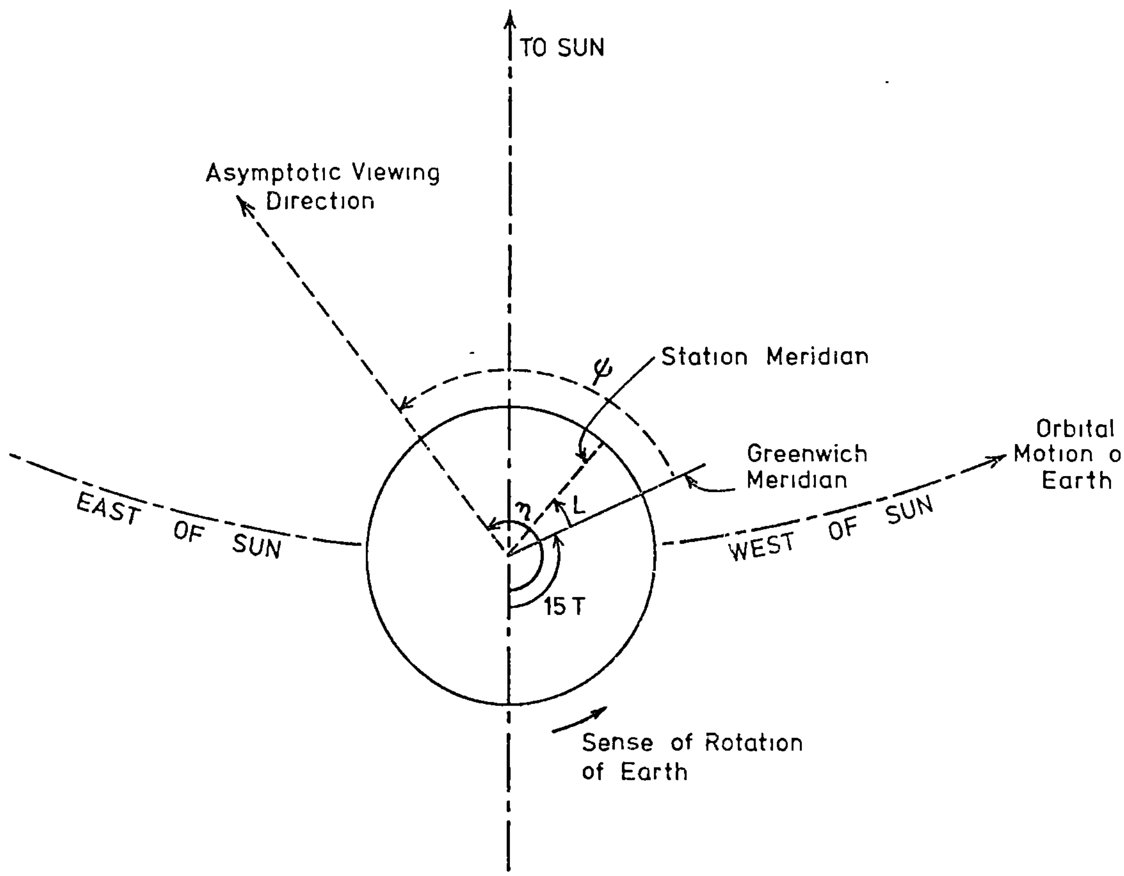


Figure 4.1. *Definitions of angles employed.*

From figure 4.1 , $\eta = \psi + 15T$, where ψ is asymptotic longitude.

$$\therefore \quad g(\psi) = J_A(R) \sum_{m=1}^{\infty} A_m \cos m(\psi + 15T - \eta_m) \qquad 4.1$$

From eqn. 2.11 we find, for a longitude-varying anisotropy

$$\frac{\Delta N(\psi_j)}{N} = g(\psi_j) \cdot v(j) \qquad 4.2$$

where $\frac{\Delta N(\psi_j)}{N}$ represents the counting rate from a longitude belt defined by the meridian planes $\psi_j \pm \Delta\psi$. Assuming 72 such longitude belts, each of width 5°, and combining equations 4.1 and 4.2, we find the counting rate of the detector at time T varies from the isotropic rate by $\Delta N(T)$, where

$$\frac{\Delta N(T)}{N} = \sum_{j=0}^{71} v_j \cdot \frac{g(\psi_j)}{J_A(R)}$$

Since $\psi_j = 5j + 2.5$

$$\frac{\Delta N(T)}{N} = \sum_{j=0}^{71} v_j \cdot \sum_{m=1}^{\infty} A_m \cos m(5j + 15T + 2.5 - \eta_m)$$

$$= \sum_{m=1}^{\infty} A_m B_m \cos \left[m(15T - \eta_m) + \gamma_m \right] \qquad 4.3$$

$$\text{where } B_m = \left[\left(\sum_{j=0}^{71} v_j \sin m(5j + 2.5) \right)^2 + \left(\sum_{j=0}^{71} v_j \cos m(5 + 2.5) \right)^2 \right]^{\frac{1}{2}} \qquad 4.4$$

$$\text{and} \quad \gamma_m = \arctan \left[\frac{\sum_{j=0}^{71} v_j \sin m(5j + 2.5)}{\sum_{j=0}^{71} v_j \cos m(5j + 2.5)} \right] \qquad 4.5$$

From eqn. 4.3 the observed amplitude of the m^{th} harmonic is equal to $A_m\ B_m$, and maximum intensity is observed at time

$$T_m = \frac{m\eta_m - \gamma_m}{15m} \quad \text{hours U.T.}$$

The local time of maximum, at a station whose geographic longitude is L is, therefore

$$t_m' = \frac{m\eta_m - (\gamma_m - mL)}{15m} \quad \text{hours L.T.} \qquad 4.6$$

Since B_m is rigidity dependent it follows from eqn. 4.3 that A_m, the amplitude constant of the anisotropy, only becomes the actual free-space amplitude in the case $\beta = 0$.

In eqn. 4.6 the term $(mL - \gamma_m)$ is the correction for primary particle deflection in the geomagnetic field. If, as is usually the case, γ is greater than mL the intensity maximum of the m^{th} harmonic will be observed earlier at a given station than it would be if no geomagnetic field existed. We will let

$$G_m = \frac{(\gamma_m - mL)}{15m}$$

Due to the dependence of asymptotic cones on assumed variational spectrum and on type and location of the detector we would expect the calculated values of B_m and G_m to change for each different detector and assumed spectrum. This is indeed found to occur. We may therefore calculate sets of values of B_m and G_m for each detector, using different parameters in the assumed variational spectrum used to calculate each pair. B_m and G_m are referred to as the modulation coefficients of the detector.

Subjecting the observed data for some period from each station to Fourier analysis we find values P_m and t_m for the observed amplitude and local time of maximum of the m^{th} harmonic.

From eqn. 4.6

$$t_m = \frac{\eta_m}{15} - G_m$$

$$\therefore \quad \eta_m = 15(t_m + G_m)$$

A free-space direction is often described in terms of the local time associated with it, defined as the time τ at which the direction η lies in the local meridian plane. $\tau = \eta/15$. Free-space directions are described in terms of τ in this thesis where

$$\tau_m = t_m + G_m$$

$$= T_m + G_m + \frac{L}{15} \qquad 4.7$$

This is illustrated in figure 4.4.

The anisotropy is clearly the same regardless of the means with which we view it, and therefore the estimates $(A_m)_s$ and $(\tau_m)_s$ of A_m and τ_m obtained using the s^{th} detector should be the same as those obtained using predictions and data for all other detectors if we have selected the correct form of the anisotropy and if all the detectors are perfect. In practice detectors have finite count rates, imperfect meteorological corrections, and instrumental troubles and the values of $(A_m)_s$ and $(\tau_m)_s$ are therefore subject to statistical and quasi-statistical fluctuations. If the values of $(A_m)_s$ and $(\tau_m)_s$ obtained have a variance which can be attributed purely to statistics we may claim that the spectrum used is compatible with the observations. It is not necessarily the only spectrum which will give such a fit. We can proceed therefore by obtaining estimates of $(A_m)_s$ and $(\tau_m)_s$ using various spectra, taking as most likely the spectrum giving minimum variance of these estimates. We then enquire whether the minimum variance so obtained is in fact attributable to the differences in the observed data which must be expected on purely statistical grounds.

A computer programme has been written to calculate values of B_m and G_m for use in this process. It is generally found that only the first and second harmonics of the solar daily variation are significant and hence the programme functions for m = 1 and 2 only. Variational coefficients are essentially only an intermediate step in calculations of this type and are of little direct use apart from illustrative purposes. They were not therefore normally obtained as computer output.

In the spectrum assumed above there are four parameters, β, R_u, R_1, and p. If we follow the method suggested to the letter it would be necessary to calculate sets of predictions for every possible combination of these. In practice this is neither necessary nor desirable. It is necessary to use a sufficient number of values of each parameter to ensure bracketing the correct value and at the same time maintaining intervals between successive values which are reasonably consistent with the resolving power of the method. Twelve values of each variable appeared to be a reasonable compromise. If all possible combinations were computed this would result in 12^4 (= 20736) sets of predictions being required per detector. The observed run-time to calculate each set varies, according to station cut-off rigidity, between about 3 and 4 seconds on the Elliott 503. At an average of 3.5 seconds/set this is about 20 hours. Quite apart from this objection the greatly increased amount of data for the variance calculation programme could not have been easily handled since the total available computer storage, for both programme and data, is only 23000 words. No discs or magnetic tape were available. If, on the other hand, the four parameters are all independent then it is sufficient to give three of them arbitrary, but reasonable, values and calculate modulation coefficients for 12 values of the remaining one, and perform this operation for each parameter in turn. The resultant 48 sets of coefficients are quickly produced and easily handled

The initial programme was based on the assumed independence of the parameters, and also on the likelihood of the spectral parameters of the two harmonics being of the same order. It was immediately evident that neither assumption was justified within the accuracy of the calculations. It was obvious that the spectral exponent β of the first harmonic was in the near zero region as reported by Rao et al (1963), whilst that for the second harmonic appeared markedly positive. Furthermore the values of R_u obtained for the second harmonic were very low, not at all consistent with the underground measurements at Hobart. These values were obtained with an assumed spectral exponent of 0.0, thus giving a strong suggestion that R_u at least could not be treated as independent of β. The programme was therefore modified to produce 4 groups of coefficients. The first

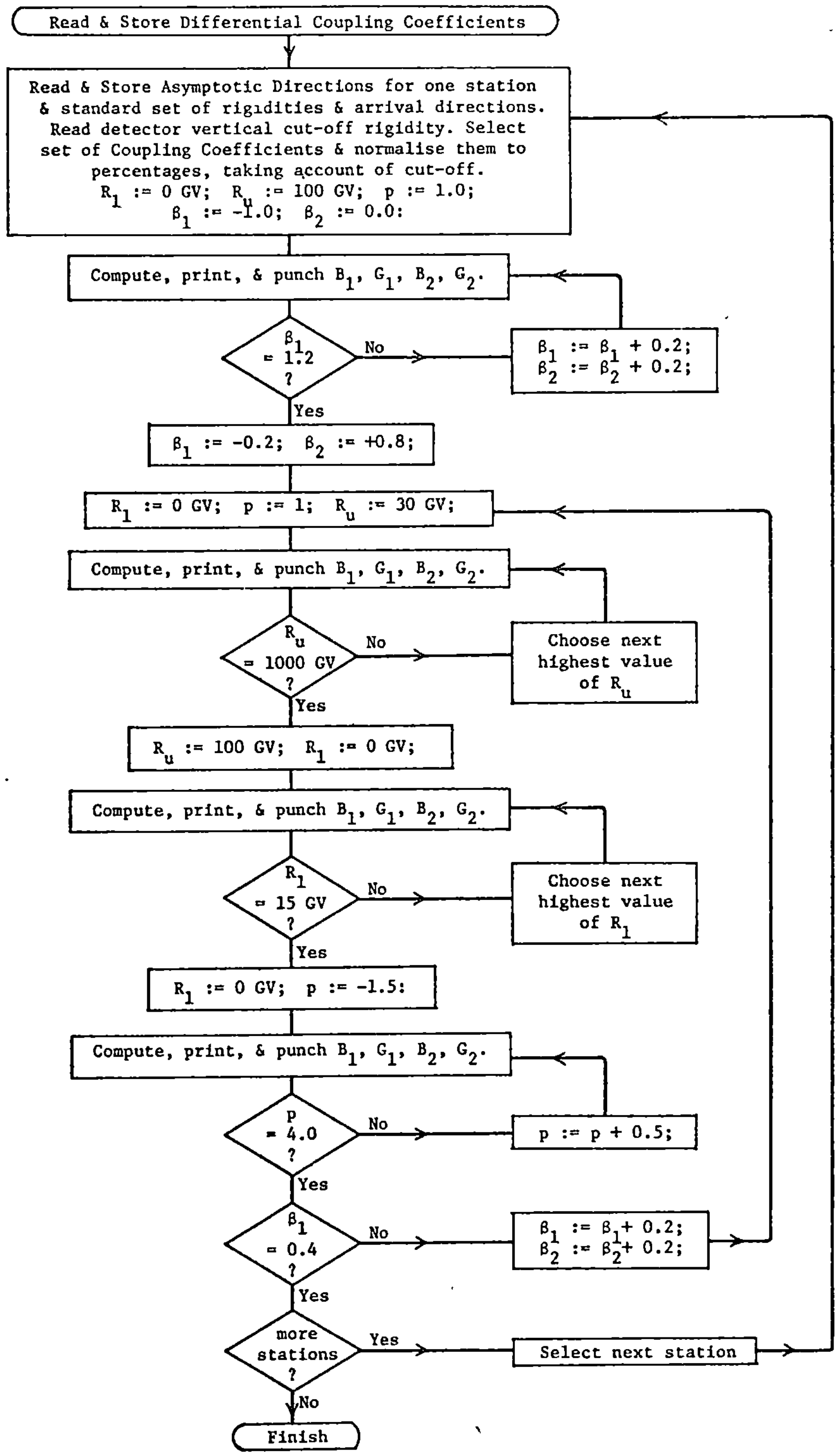


Figure 4.2. Flow chart of programme for calculation of modulation coefficients.

Group	R_u Gv	R_1 Gv	P	β_1	β_2
	100	0.0	1.0	-1.0	0.0
				-0.8	0.2
				-0.6	0.4
				-0.4	0.6
				-0.2	0.8
A				0.0	1.0
				0.2	1.2
				0.4	1.4
				0.6	1.6
				0.8	1.8
				1.0	2.0
				1.2	2.2
	30	0.0	1.0	Sub-Group 1	
	40			-0.2	0.8
	50				
	60			Sub-Group 2	
	70			0.0	1.0
	80				
B	90			Sub-Group 3	
	100			0.2	1.2
	150				
	250			Sub-Group 4	
	500			0.4	1.4
	1000				
	100	1.0	1.0	Sub-Group 5	
		2.0		-0.2	0.8
		3.0			
		4.0		Sub-Group 6	
		5.0		0.0	1.0
C		6.0			
		7.0		Sub-Group 7	
		8.0		0.2	1.2
		9.0			
		10.0		Sub-Group 8	
		12.0		0.4	1.4
		15.0			
	100	0.0	-1.5	Sub-Group 9	
			-1.0	-0.2	0.8
			-0.5		
			0.0	Sub-Group 10	
			0.5	0.0	1.0
			1.0		
D			1.5	Sub-Group 11	
			2.0	0.2	1.2
			2.5		
			3.0	Sub-Group 12	
			3.5	0.4	1.4
			4.0		

Table 4.1 Spectral parameter values used in initial investigations of daily variation.

group involved varying β, with R_u, R_1, and p held constant at reasonable values. The remaining groups were divided into four sub-groups each; β being given a different value in each sub-group whilst R_u, R_1, or p were varied. The values of β chosen were judged, on the basis of the preliminary runs, to cover the most likely values. To overcome the difference in exponents β_2 was put equal to $\beta_1 + 1.0$. The flow chart of the programme in this form is given in figure 4.2, whilst the actual paramete values used are listed in table 4.1.

4.2.2 Calculations of Harmonics

The Fourier coefficients in polar form R_1, T_1, R_2 and T_2 of the actual data have been obtained by conventional harmonic analysis, of which a brief description follows.

The basic assumption is that the count rate of a detector at any instant, after correction for atmospheric effects and the removal of Forbush decreases, flares, and like effects will be describable by the function

$$f(t) = \sum_{m=1} r_m \cos \frac{2m\pi}{24}(t - t_m) \qquad 4.8$$

where t is in hours. It may be shown that this expression is the same as

$$f(t) = \sum_{m=1} (a_m \cos \frac{2\pi mt}{24} + b_m \sin \frac{2\pi mt}{24}) \qquad 4.9$$

where $r_m = (a_m^2 + b_m^2)^{\frac{1}{2}}$ and $t_m = \frac{24}{2m\pi} \arctan \left(\frac{b_m}{a_m}\right)$

The expansion may be taken as high an order of m as seems desirable.

Whittaker and Robinson (1944) have shown that, for a system of equally spaced (as in this case in time) observations of magnitude U_k the expression f (t) is the closest fit to the observations, as determined by a least squares method, when

$$a_m = \frac{2}{n} \sum_{k=0}^{n-1} U_k \cos\left(\frac{2mk\pi}{n}\right) \text{ and } b_m = \frac{2}{n} \sum_{k=0}^{n-1} U_k \sin\left(\frac{2mk\pi}{n}\right) \qquad 4.10$$

We have therefore a method of obtaining the amplitude and phase of any periodicity, of frequency m, in our data.

When used in the conventional manner for cosmic-ray work two correction need to be made to these expressions. Whittaker and Robinson took their ordinates U_k to be instantaneous samples of f(t) and also took their time origin at the first such ordinate, U_o. Neither of these assumptions are true when dealing with time averaged cosmic-ray data.

Cosmic-ray results are usually presented as a set of 24 hourly or 12 bi-hourly count accumulations. The published figure for H01 in hourly tabulations in fact refers to the total accumulated between 0000 and 0100, usually universal time. It must therefore be considered as the average value for that period, and be deemed true at 0030. Similarly the bi-hourly total for H01/2 is centred at 0100. The phase obtained when using the method outlined above must be corrected for this shift by the addition of ½ hour in the hourly case and 1 hour in the bi-hourly; in general this amounts to $\frac{12}{n}$ hours.

The effect of time averaging in production of the ordinates is to reduce the amplitude of the sine wave obtained by a factor of $\frac{\sin\omega}{\omega}$ where $\omega = \frac{m\pi}{n}$, m and n having the meanings assigned above (Parsons, 1959).

Therefore the amplitude of any harmonic obtained from time averaged data may be corrected for the averaging effect by multiplying by $\frac{\omega}{\sin \omega}$. We finally find therefore that

$$R_m = \frac{m\pi(a_m^2 + b_m^2)^{\frac{1}{2}}}{n \sin (m\pi/n)} \quad \text{and} \quad \tau_m = \left\{\frac{12 \arctan (b_m/a_m)}{m\pi} + \frac{12}{n}\right\} \text{ hours}$$

In these expressions R_m represents the conventional amplitude of a sine wave, the displacement of the peak from the mean, and not the peak-to-peak amplitude. Throughout this thesis amplitude is taken as the peak-to-mean displacement.

A computer programme was written, using the above technique, to obtain values of R_1, T_1, R_2 and T_2 from any suitable set of hourly or bi-hourly data. It also produces the standard errors of these quantities and a statistical indication of the closeness of fit of the individual harmonics to the data. The values and times of occurrence of the maximum and minimum of the function

$$f(t) = R_1 \cos \frac{2\pi}{24} (t - T_1) + R_2 \cos \frac{4\pi}{24} (t - T_2) \qquad 4.11$$

representing the maximum and minimum amplitudes of the daily variation, are found and a statistical indication of the closeness of fit of this expression to the data is given. All amplitudes are given in percent and times in both hours and decimals of hours, and degrees, the latter to facilitate the plotting of harmonic dials. The mean count rate of the supplied data is noted and, as an option, the percentage deviations (the deviates) of individual ordinates from the mean may be produced. The programme internally checks the data in all cases for a statistically unlikely difference between adjacen ordinates, and in such cases automatically prints all deviates in the data concerned to permit checking to be carried out.

The programme is arranged to produce monthly mean values of the various quantities indicated. It also, by internal averaging of the deviates, produces annual values and values covering the entire period for which data is supplied. Percentage deviates are always produced in these cases. The programme will also, on optional command from the computer console; produce percentage deviations of all monthly data, with or without output of the harmonic coefficients; inhibit the calculation of monthly harmonics, only producing annual and total period values; produce annual-running-mean harmonic coefficients, and deviates, in solar time; or re-arrange the data in sidereal or anti-sidereal time and again produce annual-running-mean harmonic coefficients and deviates. Table 4.2 shows part of a typical set of results.

It has been suggested (Ables, McCracken and Rao, 1966) that the use of a numerical filter on the data before analysis leads to an improvement in the statistical accuracy. However Forbush, Duggal, and Pomerantz (1968) have shown that, in the limited case of data which does not contain persistent variations whose periods are non-harmonic to the periods under review, no such improvement results and the two methods have identical statistical accuracy. It is just this case which is met in practice. Straightforward harmonic analysis was originally chosen for the present project on the basis that it appeared to give satisfactory statistical accuracy for both harmonics in trial analyses, and that the data preparation required was substantially easier, with the available facilities, than would be the case were filtering

CHICAGO NEUTRON STN 111

YEAR	MON	ACT	DAYS POSS	%	MAG	ERROR. T1	T2	R1%	TMAX1	ANG	VAR	R2%	TMAX2	ANG	VAR	MAXAM	TMAX	ANG	MINAMP	TMIN	ANG	VAR	MEAN	SF
						TIME IN DECIMAL HOURS GMT, ANGLES IN DEGREES.				FROM *HOURLY DATA														
1961	JAN	28	31	90	.023	0.61	0.85	.146	20.49	307	.29	.054	08.53	256	.91	.200	20.52	308	-.105	05.35	80	.20	3421.0	16
	FEB	25	28	89	.025	0.77	6.00	.123	20.04	301	.44	.023	04.81	144	.98	.128	18.80	282	-.132	09.13	137	.43	3427.0	
	MAR	29	31	94	.023	0.82	2.29	.108	21.11	317	.42	.025	04.50	135	.97	.099	19.32	290	-.129	09.77	147	.39	3433.5	
	APR	24	27	89	.025	1.45	6.00	.068	19.20	288	.70	.021	08.56	257	.97	.086	19.95	299	-.063	04.87	73	.68	3430.8	
	MAY	25	30	83	.025	0.79	1.80	.120	21.63	324	.48	.030	06.40	192	.97	.130	20.08	301	-.135	10.97	165	.45	3439.0	
	JUN	28	30	93	.023	0.63	1.27	.143	22.29	334	.33	.038	06.28	188	.95	.142	20.40	306	-.171	11.30	169	.28	3429.5	
	JUL	21	21	100	.027	1.41	1.28	.075	23.14	347	.66	.044	07.04	211	.89	.090	20.25	304	-.112	12.47	187	.55	3392.3	
	AUG	24	31	77	.025	0.43	1.27	.224	22.08	331	.13	.041	03.87	116	.97	.184	22.62	339	-.265	09.98	150	.10	3418.8	
	SEP	27	29	93	.024	0.66	2.02	.138	21.60	324	.26	.027	08.26	248	.97	.162	21.02	315	-.126	11.13	167	.23	3434.3	
	OCT	29	29	100	.023	1.06	0.89	.083	20.00	300	.59	.051	02.47	74	.85	.077	15.98	240	-.133	08.33	125	.45	3457.2	
	NOV	29	30	97	.023	0.89	1.45	.099	21.34	320	.38	.033	08.21	246	.93	.129	20.70	310	-.089	11.92	179	.32	3482.7	
	DEC	19	27	70	.028	1.73	0.71	.064	18.28	274	.82	.077	06.75	203	.74	.141	18.67	280	-.092	01.53	23	.56	3478.4	
	TOT	308	344	90	.007	0.24	0.61	.111	21.17	318	.10	.022	06.55	196	.96	.122	20.05	301	-.115	10.53	158	.07	3437.5	
1962	JAN	29	31	94	.023	0.53	2.67	.163	20.97	315	.18	.023	06.74	202	.98	.176	20.22	303	-.160	10.05	151	.16	3484.5	16
	FEB	24	24	100	.025	0.51	6.00	.188	21.92	329	.23	.023	08.68	260	.99	.208	21.52	323	-.173	10.77	162	.22	3468.2	
	MAR	29	30	97	.023	1.32	6.00	.067	20.79	312	.73	.020	07.79	234	.98	.086	20.25	304	-.058	11.20	168	.70	3472.6	
	APR	27	28	96	.024	0.84	2.02	.109	23.29	349	.31	.027	09.08	272	.96	.127	22.22	333	-.110	13.03	195	.27	3455.2	
	MAY	31	31	100	.022	0.71	6.00	.120	22.82	342	.28	.019	06.80	204	.98	.115	21.62	324	-.132	11.55	173	.26	3459.6	
	JUN	29	30	97	.023	0.71	1.66	.124	20.98	315	.31	.030	06.72	201	.96	.143	19.90	299	-.126	10.65	160	.27	3455.5	
	JUL	26	29	90	.024	0.66	6.00	.140	22.45	337	.24	.011	07.96	239	1.0	.145	21.93	329	-.139	11.05	166	.24	3454.5	
	AUG	28	29	97	.023	0.51	2.04	.176	22.38	336	.19	.026	07.64	229	.98	.186	21.45	322	-.180	11.45	172	.18	3454.1	
	SEP	28	30	93	.023	0.69	0.68	.130	21.64	325	.42	.067	08.17	245	.85	.190	20.65	310	-.138	12.70	191	.27	3449.5	
	OCT	30	31	97	.022	0.82	6.00	.105	22.02	330	.36	.017	03.86	116	.98	.089	22.30	335	-.122	09.95	149	.35	3454.0	
	NOV	27	30	90	.024	0.47	1.73	.190	22.54	338	.17	.030	08.36	251	.98	.209	21.73	326	-.187	11.73	176	.15	3471.7	
	DEC	29	31	94	.023	0.46	6.00	.187	20.37	305	.19	.009	02.82	85	1.0	.179	20.27	304	-.196	08.43	126	.19	3480.1	
	TOT	337	354	95	.007	0.18	0.65	.138	21.84	328	.05	.020	07.72	232	.98	.150	21.10	316	-.135	10.95	164	.03	3463.3	
1963	JAN	0																						
	FEB	18	28	64	.029	1.06	1.28	.105	21.57	323	.43	.046	07.16	215	.89	.138	20.03	301	-.123	11.83	178	.32	3514.5	16
	MAR	31	31	100	.022	1.51	1.32	.057	17.38	261	.66	.034	06.06	182	.88	.090	17.87	268	-.055	01.53	23	.54	3503.4	
	APR	24	30	80	.025	0.74	1.40	.129	20.32	305	.38	.037	06.89	207	.95	.161	19.55	293	-.120	10.52	158	.33	3504.0	
	MAY	27	31	87	.024	0.93	0.71	.098	19.61	294	.51	.065	07.06	212	.79	.162	19.22	288	-.096	11.68	175	.30	3488.7	
	JUN	27	30	90	.023	1.03	0.60	.089	22.51	338	.53	.076	06.02	181	.66	.121	18.95	284	-.160	11.68	175	.19	3493.9	
	JUL	31	31	100	.022	0.59	2.17	.143	19.86	298	.28	.024	04.64	139	.98	.148	18.70	280	-.152	08.90	134	.25	3492.0	
	AUG	31	31	100	.022	0.56	6.00	.150	21.00	315	.22	.014	02.89	87	.99	.137	21.07	316	-.164	08.97	135	.22	3491.2	
	SEP	21	23	91	.027	1.19	6.00	.087	23.28	349	.50	.025	07.02	211	.96	.085	21.22	318	-.107	12.20	183	.46	3489.1	
	OCT	26	28	93	.024	1.58	6.00	.060	22.33	335	.46	.018	11.23	337	.95	.077	22.82	342	-.051	07.92	119	.41	3494.3	
	NOV	25	30	83	.024	0.91	6.00	.104	21.26	319	.39	.016	03.40	102	.99	.088	21.05	316	-.119	09.32	140	.38	3504.5	
	DEC	30	31	97	.022	0.60	1.13	.142	19.79	297	.29	.040	06.23	187	.95	.176	18.97	284	-.135	09.90	149	.23	3520.6	
	TOT	291	355	82	.007	0.28	0.49	.099	20.78	312	.11	.028	06.36	191	.93	.117	19.52	293	-.105	10.58	159	.04	3499.4	
1961-63A		936	1053	89	.004	0.13	0.35	.116	21.34	320	.05	.022	06.82	204	.97	.127	20.30	305	-.118	10.68	160	.02	3466.0	
CHECK SUMS			1200.731			1290.582																		

DEVIATIONS IN THOUSANDTHS %

1961 TOT	85	-6	-4	23	-23	-31	-107	-65	-93	-125	-119	-78
	-78	-80	-60	14	52	83	107	152	90	123	76	66
1962 TOT	70	32	65	6	-18	-68	-81	-81	-100	-144	-139	-117
	-132	-80	-63	-59	42	62	116	112	156	144	162	115

Table 4.2. Typical set of results from Harmonic Analysis programme.

used. It now seems that this choice was better than it at one time appeared

4.2.3 Calculation of Variance

It is necessary to obtain a measure of the scatter of the various estimates $(A_m)_s$ and $(\tau_m)_s$ obtained using each set of parameters, and then to decide which set of parameters gives the minimum scatter in these quantities. A suitable measure of the scatter for this purpose is the sample variance S^2 of the estimates. If only a few such calculations are involved it is quickest to perform them on a desk calculator. If, as in the present case, large numbers of estimates are involved and the process must be carried out for each harmonic coefficient and several different sets of data, computer operation is essential. It was decided that the amplitude and phase estimates would initially be dealt with separately.

A computer programme was written to produce the required information from knowledge of the various sets of predictions and the actual observations To this end it accepts as data result-tapes from the prediction and harmonic analysis programmes. Each tape bears a detector identification number for computer recognition. Taking one group of predictions at a time the programme calculates the variance of the estimates of $(A_m)_s$ associated with each set of predictions in the group. The minimum value of the variance is found, and the parameter set giving rise to it is determined. The mean value of A_m for this set is calculated, together with the consequent value of τ_m. Standard errors of A_m and τ_m, and of the minimum variance itself, are printed. The same operations are then repeated for the variance of the estimates of $(\tau_m)_s$. The entire process is then repeated for each of the variable parameters in turn, for both harmonics, and for as many periods of data as required. In every case the probable value of β_m was obtained

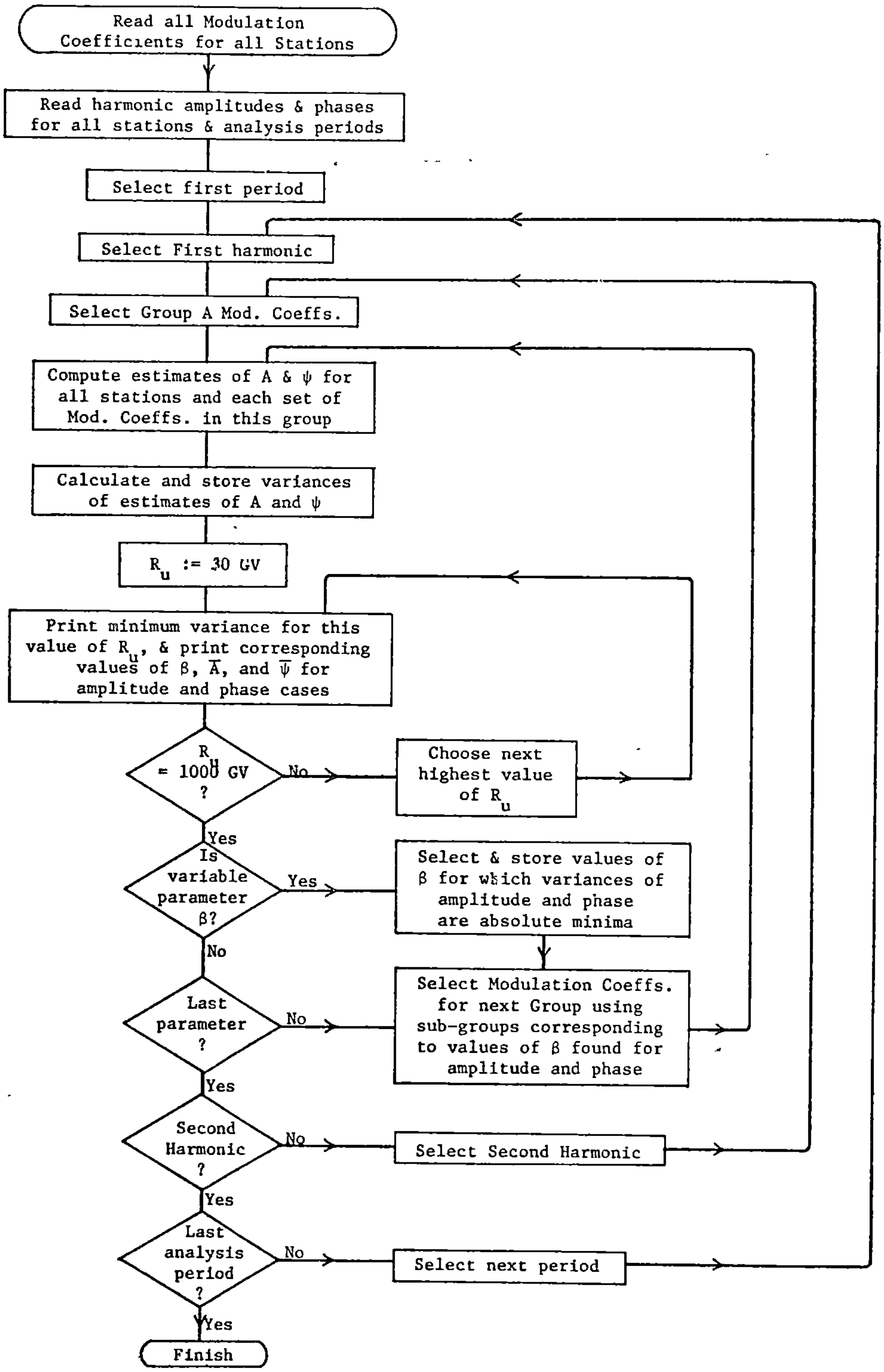


Figure 4.3. *Flow chart of programme for calculation and minimisation of variance of estimates of amplitude and phase.*

first and the sub-group of predictions (Table 4.1) using this, or the nearest available, value was used when obtaining values of the other three parameters.

The programme flow chart is given in figure 4.3. All data are read in before computation starts. Sum checks are used on the data tapes, even though the latter are computer produced, to guard against possible reader errors.

The sample variance, S^2, of n estimates x_i of a quantity is defined as $\frac{1}{n} \sum_{i=1}^{n} (x_i - \bar{x})^2$

where $\bar{x}$ is the mean of the values of x_i. Expansion shows that

$$S^2 = \frac{1}{n} \sum_{i=1}^{n} x_i^2 - \bar{x}^2 \qquad 4.12$$

In this form S^2 is well suited to computation. However its value depends on the magnitude of the variable as well as on the scatter of the various x_i about $\bar{x}$, and its use in the manner outlined is therefore justified only if the various values of x_i obtained are of closely similar magnitude. The restriction is largely obeyed in the case of the phase calculations, where the mean value of phase varies by only an hour or two over the whole range of parameters considered, but is violated when the amplitude constant is being investigated. The amplitude constant can vary by several orders of magnitude in the parameter range. To obtain a measure of relative scattering under these conditions it is necessary to use the coefficient of variance, v^2, defined as $\frac{100S^2}{\bar{x}^2}$ whose magnitude is independent of $\bar{x}^2$.

For computational uniformity this quantity has been used in all variance calculations.

The minimum value of v^2 obtained in these calculations will not be zero even if one of the sets of chosen parameters does fit the freespace anisotropy exactly. The estimates $(A_m)_s$ and $(\tau_m)_s$ will still show a scatter due to

(a) The finite count rates of the individual detectors.

(b) Possible errors in corrections for geomagnetic deflection or meteorological modulation.

(c) Any systematic errors present in data from one or more stations.

The factors (b) and (c) can cause errors in the estimates which may or may not be serious. Suppose an estimate $(A_m, \tau_m)_s$ of the free space harmonic is obtained using data contaminated by factors (b) and (c). The estimate may be represented as a vector (figure 4.4). The possible error in this vector due to purely statistical causes may be represented by a circle whose radius ε_s is the standard error associated with the detector count-rate. The vector $(A_m, \tau_m)_s$, corresponding to the true estimate obtained from station s without effects from (b) and (c) being present may also be drawn. If the point of this vector lies within the error circle of the $(A_m, \tau_m)_s$ vector then the two vectors may be regarded as statistically indistinguishable and the contamination caused by (b) and (c) may be disregarded. The argument is reversible since the error circles of the two vectors have the same radius. Note that the argument is true for any value of the rigidity exponent, and that vectors of the form shown in figure 4.4 represent the amplitude constant, only becoming the actual free-space amplitude if the rigidity exponent is zero.

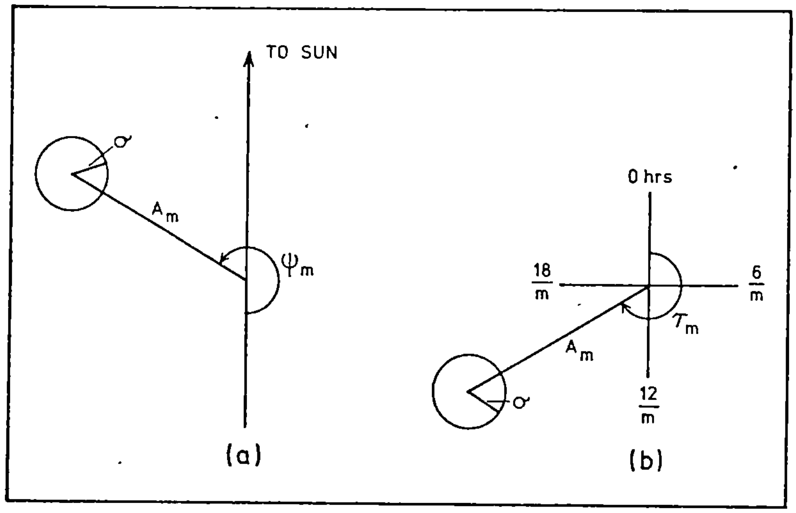


Figure 4.4. Vector representations of free-space m^{th} harmonic

(a) Relative to Earth-Sun line

(b) On a harmonic dial, relative to local midnight.

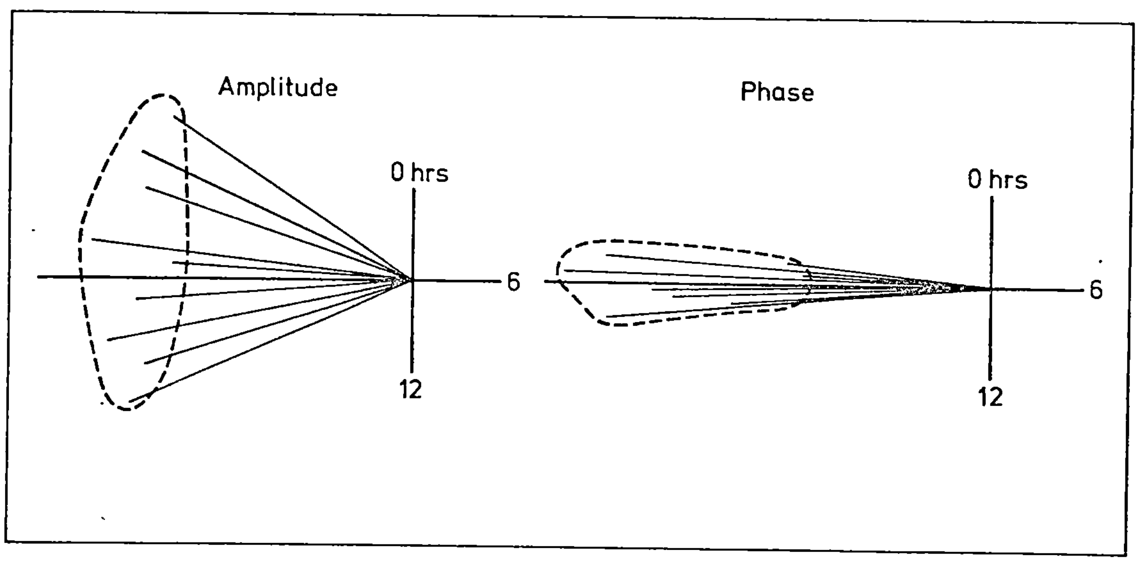


Figure 4.5. Hypothetical estimated free-space vectors obtained by separate minimisation of the variance of estimates of amplitude and phase.

We have seen that, so far as can be ascertained, the errors due to (b) are indeed small. Those due to (c) are less easy to determine. Whilst the obvious ones are easy to eliminate (section 4.4.2) some systematic errors are not easy to detect. For instance a systematic advancement of phase at a station by, say, one hour, cannot easily be detected by an examination of the data either before or after harmonic analysis. Such errors can be caused by, for instance, the use of an erroneous barometer coefficient, the taking of spot barometer readings instead of averages from a barograph, wind effects on the barometer (Section 2.2.3; Chiba and Kodama, 1969), or hysteresis in a barograph pen. Other possible causes certainly exist.

A different class of errors, affecting the amplitude but not the phase, can also occur. An example would be some instrumental effect proportional to the count rate. Whilst this seems unlikely at first sight an apparent case has been observed. At one station for which data from individual sections were analysed separately the observed ratio of the amplitudes, of both harmonics, recorded by the two sections were in the ratio 1.35:1, consistently through the three years considered. The phases recorded by the two sections were statistically the same. No satisfactory explanation has been found. Clearly these data are unsuitable for use in an analysis based on minimising the variance of amplitude estimates but could possibly be used in minimising phase estimates.

If the amplitude and phase are treated independently we should, if no such quasi-statistical effects are present, obtain the same result in both cases. In particular the plots of the end points of the $(A_m \, \tau_m)_s$ vectors will be the same and form a more or less circular pattern. The expected variance of these estimates will be that due to statistics alone and will equal $\frac{1}{n}\sum_{i=1}^{n}(\varepsilon_i)^2_{A \text{ or } \tau}$, depending on whether phase or amplitude has been minimised. In both cases the expected figure should be achieved. If, however, systematic errors are present in either amplitude or phase observations we may find that minimising the phase variance does not automatically minimise the amplitude variance, and vici-versa. Indeed it generally happens that minimisation of one results in a far from minimum value of other. Figure 4.5 shows this in exaggerated form; it can be seen that the end points of vectors determined in this manner tend to lie within elliptical regions of the harmonic dial.

4.2.4 Variance of Vectors

Estimated values of the free-space parameters of both harmonics obtained by separate variance analyses of phase and amplitude proved, perhaps not surprisingly, to produce different results. Possible reasons for this have been discussed in the previous section. There being no physical reason to prefer one of these analyses to the other a "vector variance" technique has been devised to avoid placing undue emphasis on amplitude or phase alone. It involves the minimisation of the length of the difference vectors which result from vectorially subtracting the mean free-space vector obtained from a given set of stations from the actual free-space vectors obtained from each of the stations. For this purpose it is preferable to revert to the orthoganal a and b components of the daily variation harmonics, from which the usual polar components are derived (Section 4.2.2).

For any given observation and allotted set of free space parameters a particular free-space vector $\underline{r}_{m,s}$ having amplitude $A_{m,s}$ and phase $\tau_{m,s}$ will be obtained for the m^{th} harmonic at the s^{th} station. Introducing unit vectors $\hat{\underline{i}}$, $\hat{\underline{j}}$, in the directions 0 and $\pi/2$ on the harmonic dial it follows that

$$\underline{r}_{m,s} = r_{m,s}\,\hat{\underline{r}} = a'_{m,s}\cos\theta_{m,s}\,\hat{\underline{i}} + b'_{m,s}\sin\theta_{m,s}\,\hat{\underline{j}} \qquad 4.13$$

$$\text{where } \theta_{m,s} = \tau_{m,s}\frac{2\pi m}{24}$$

The angular conversion is from hours to radians, and unit vector $\hat{\underline{r}}$ is in the direction of $\underline{r}$. The coefficients a' and b' in the expression should be distinguished from the coefficients a and b in equation 4.10, which refer to the variation actually observed by the particular detector.

$$\left.\begin{aligned} a'_{m,s} &= f_a\,(m,s,\beta,R_u,R_1,p)\;\; a_{m,s} \\ b'_{m,s} &= f_b\,(m,s,\beta,R_u,R_1,p)\;\; b_{m,s} \end{aligned}\right\} \qquad 4.14$$

They are related as indicated in eqns 4.14, the functions f_a and f_b being fully determinable at all points.

The subscript m may be dropped, for clarity, at this stage, since the work which follows applies indifferently to either harmonic.

A mean vector $\overline{\underline{r}}$ is now defined, such that

$$\overline{r} = \left\{\overline{a'}^{\,2} + \overline{b'}^{\,2}\right\}^{\frac{1}{2}}$$

$$\text{where } \overline{a'} = \frac{1}{n}\sum_{s=1}^{n} a'_s \text{ and } \overline{b'} = \frac{1}{n}\sum_{s=1}^{n} b'_s \qquad 4.15$$

In order to minimise the scatter of the end points of the various estimated free-space vectors we actually need to minimise the variance of the amplitudes of the various difference vectors

$$\therefore \quad S^2 = \frac{1}{n}\sum_{s=1}^{n} \left| (\underline{r}_s - \underline{\bar{r}}) \right|^2$$

$$= \frac{1}{n}\sum_{s=1}^{n} \left[\left(a'_s - \overline{a'} \right)^2 + \left(b'_s - \overline{b'} \right)^2 \right] \qquad 4.16$$

The sample variance may readily be calculated in this form. However it should be noted that eqn. 4.16 reduces in the following manner. Expanding we have

$$S^2 = \frac{1}{n}\sum_{s=1}^{n} \left(a'^2_s + b'^2_s + \overline{a'}^2 + \overline{b'}^2 - 2\overline{a'}a'_s - 2\overline{b'}b'_s \right)$$

$$= \frac{1}{n}\sum_{s=1}^{n} \left(a'^2_s + b'^2_s \right) + \overline{a'}^2 + \overline{b'}^2 - 2\overline{a'}^2 - 2\overline{b'}^2$$

$$\therefore \; S^2 = \overline{r^2} - \bar{r}^2 \qquad 4.17$$

This expression reveals that there is little difference between the variance of the amplitudes of the difference vectors and the variance of the amplitudes of the estimated vectors themselves if, and only if, the estimated vectors do not display a great scatter in directions. The amplitude of the mean vector will necessarily always be less than the mean of the amplitudes of the individual vectors, but the difference will be small if the latter are all in similar directions. This is likely to apply in the case of the first harmonic, and it is therefore possible that similar results may be obtained from both the amplitude and vector techniques in this case. For the second harmonic, where the statistical accuracy is relatively poorer and the directional scatter greater this conclusion may not apply.

The value of S^2 obtained in practice from eqn 4.16 will depend, as before, on the numerical values of the various $\underline{r}_s$, and consequently for comparison purposes the coefficient-of-variance form must again be used.

$$v^2 = \frac{100S^2}{\bar{r}^2}$$

$$= 100\left(\frac{\overline{r^2} - \bar{r}^2}{\bar{r}^2}\right)$$

$$= 100\left(\frac{\overline{r^2}}{\bar{r}^2} - 1\right)$$

$$= 100\left(\frac{\overline{a'^2} + \overline{b'^2}}{\bar{a}'^2 + \bar{b}'^2} - 1\right) \qquad 4.18$$

This expression has been used for all calculations on this topic.

4.2.5 Selections of Parameters for Vector Variance

The initial analyses of phase and amplitude variance were completed prior to commencement of the vector analysis. They had shown that R_1 was indeterminate below 5 GV, and that p, for the first harmonic at least, equalled 1 (a pure cosine dependence). The arguments leading to these conclusions are given in Section 4.4.5. It was also apparent at this stage that consideration of β and R_u independently was not satisfactory.

In the vector analysis, therefore, the parameters R_1 and p were set at 0 and 1 respectively, and advantage was taken of the reduction in number of varying parameters to investigate in greater detail the effects of changes in β and R_u. 12 values of each were selected, chosen to bracket the likely values, and modulation coefficients calculated for each possible pair, 144 pairs in all. A computer programme was written to utilise this information and obtain, and compare, the vector variance derived from each value pair.

4.2.6 Standard Errors of Estimates, and Expected Variance

Since cosmic-ray detectors have finite count-rates, any quantity derived from them must have an associated statistical standard error. It is assumed that the original data, on which analysis is performed, is composed of n hourly, or bihourly (24 or 12 respectively) count totals; each of these is a Poisson variate, having standard deviation $\sqrt{U_k}$.

Since amplitudes of the diurnal and semi-diurnal vectors are small, and the differences between the various U_k are also small, it is possible to regard each U_k as having magnitude N and standard error $\sqrt{N}$, where $N = \frac{1}{n} \sum_{k=0}^{n} U_k$.

Equation 4.10 gives that $a_m = \frac{2}{n} \sum_{k=0}^{n-1} U_k \cos \left(\frac{2mk\pi}{n} \right)$

Since the only statistical variate on the right hand side is U_k we may write the variance of a_m as

$$\sigma^2_{a,m} = \sigma^2_{U_k} \left(\frac{2}{n}\right)^2 \sum_{k=0}^{n-1} \cos^2 \left(\frac{2mk\pi}{n}\right) \qquad 4.19$$

$$= \sigma^2_{U_k} \cdot \frac{2}{n}$$

Similarly $\sigma^2_{b,m} = \sigma^2_{U_k} \cdot \frac{2}{n}$

Note that $\sigma^2_{a,m} = \sigma^2_{b,m}$ and that $\sigma^2_{a,1} = \sigma^2_{a,2}$

Now $\sigma^2_r = \sigma^2_a \frac{(\partial R)^2}{(\partial a)} + \sigma^2_b \frac{(\partial R)^2}{(\partial b)}$ where σ^2_r is the estimated variance of the vector amplitude of either harmonic.

$$\therefore \quad \sigma^2_r = \sigma^2_a \left[\frac{a^2}{R^2}\right] + \sigma^2_b \left[\frac{b^2}{R^2}\right]$$

$$\therefore \quad \sigma^2_r = \sigma^2_a \qquad 4.20$$

The variance of the amplitude of the observed vector equals the variance of its a or b components. The above work follows Parsons (1959).

Consequently we have that the standard error of estimate, or standard deviation, of r is

$$\sigma_r = \sigma_a = \sqrt{\frac{2}{n}} \; \sigma_{U_k} \qquad 4.21$$

$$= \sqrt{\frac{2N}{n}}$$

Expressed in percent we have

$$\sigma_r = \frac{100}{N} \sqrt{\frac{2N}{n}}$$

$$= 100 \sqrt{\frac{2}{nN}}$$

If G is the grand total of recorded counts for the period we have, for each harmonic

$$\sigma_r = 100 \sqrt{\frac{2}{G}} \; \% \qquad 4.22$$

Since only the total count appears in eqn 4.22 it follows that σ_r is the same regardless of whether hourly or bihourly data have been used. The standard deviation of the phase is then obtained by supposing that the true end point of the vector defined by r_m, θ_m, lies, to 67% confidence, within a circle of radius σ_r drawn at the end of the vector. The angle subtended by this circle at the origin will represent the standard error of the phase, $\sigma_{\theta,m}$.

$$\text{Thus} \quad \sigma_{\theta,m} = \arcsin\left\{\frac{\sigma_r}{r_m}\right\} \qquad 4.23$$

and will be different for each harmonic.

The variance of the amplitudes and phase will then be $\sigma^2_{r,m}$ and $\sigma^2_{\theta,m}$ respectively. $\sigma^2_{\theta,m}$ may be used as it stands, but $\sigma^2_{r,m}$ requires multiplication by a scaling factor to convert it to a free-space estimate of variance.

The variance, σ^2_v, of the amplitude of the difference vector is also required for use with the vector variance analysis. Eqn 4.16 shows that the free-space sample variance in this case reduces to $S^2 = S^2_{a'} + S^2_{b'}$ where $S^2_{a'}$ and $S^2_{b'}$ are the sample variances of the a' and b' components respectively. Since a and b are statistically independent and each pair a' and a, b' and b, are related through completely determined functions, knowledge of the estimates of variance σ^2_a and σ^2_b means that $\sigma^2_{a'}$ and $\sigma^2_{b'}$ can also be obtained.

The ratios $\frac{a'}{a}$ and $\frac{b'}{b}$ will not be very different and thus to a first order the estimate of the free-space vector variance will be given by

$$\sigma^2_v \simeq \sigma^2_{a'} + \sigma^2_{b'}$$

$$\therefore \sigma^2_v \simeq 2\sigma^2_{a'}$$

$$\therefore \sigma^2_v \simeq 2\sigma^2_{r'} \qquad 4.24$$

The latter quantity is known, and σ_v^2 can therefore be approximately calculated. It will have the same value for each harmonic. In practice σ_v^2 may be somewhat greater than $2\sigma_r^2$, if many equatorial stations, for which $\frac{a'}{a} \neq \frac{b'}{b}$ are included.

4.2.7 Presentation of Variance Results. The "Z" Parameter

Writing the variance, of amplitude or phase, of the free-space vector obtained from the s^{th} station as σ_s an average estimated variance can be obtained, given by

$$\sigma^2 = \frac{1}{n} \sum_{s=1}^{n} \sigma_s^2$$

This may be calculated readily, either in this or in coefficient of variance form, and may be compared with the observed sample variance S^2 of the component involved. It is convenient to define a new quantity Z such that

$$Z = \frac{S^2}{\sigma^2} \qquad 4.25$$

According to Weatherburn (1949, p169) the quantity $\frac{1}{2}nZ$ is a Gamma variate of parameter $\frac{1}{2}(n-1)$. The expected value E(x) of a variate which follows a Gamma distribution equals the parameter of the distribution.

$$\text{Thus} \quad E(\tfrac{1}{2}nZ) = \tfrac{1}{2}(n-1)$$

$$\therefore \quad \tfrac{1}{2}n.E(Z) = \tfrac{1}{2}(n-1)$$

$$\therefore \quad E(Z) = \frac{n-1}{n} \qquad 4.26$$

Thus for large n the expected value of $Z \simeq 1$. In such a case the distribution of Z will be approximately normal, with a standard deviation of $\sqrt{\frac{2}{n}}$.

In the case of vector variance the approximation of eqn 4.24 has been taken as an equality. In this case σ_v^2 becomes calculable, and E(Z) follows eqn 4.26.

4.3 METHOD OF HANDLING DATA

It was decided at the onset that the analysis would be confined to data obtained from the world-wide neutron monitor network either by regular exchange or from one of the World Data Centres for Cosmic Rays at Minneapolis (later Boulder), Moscow, and Tokyo. These data would be supplemented by data from the underground muon telescopes at Hobart. Surface level muon detectors have not been used due to the uncertainties inherent in the correction of their data for atmospheric modulation (section 3.2.2).

Unfortunately uniformity is only now being achieved in the presentation of published cosmic ray data, and data for the periods analysed were published in several different formats. Neutron data are usually published both as raw data and after correction for changes in barometric height, together with the appropriate barometric readings. In some cases only raw data and barometric readings are available; in such cases pressure correction is necessary before the data can be used. A "most probable" barometric co-efficient was used for this purpose. Most data are published as count totals, but there are exceptions. Some earlier data especially are published as percentage departures from some stated mean. These may be used directly. Other data, notably from Japanese stations, are published in logarithmic form. These must be converted back to count totals before analysis. Both these systems have gradually been abandoned in favour of straightforward count totals.

When large scale interchange of cosmic ray data commenced at the beginning of the IGY in July 1957 bihourly tabulations were in general use. With the advent of higher counting rate detectors almost all stations have now changed to hourly tabulations. The differences in the value of the harmonic coefficients obtained when the same data are expressed in hourly or bihourly form are within the statistical limits involved (Section 4.2.6). To avoid unnecessary arithmetic the harmonic analysis programme was designed to function with either hourly or bihourly data, giving an indication of which form was used on the result sheet. The majority of data are tabulated in hours, or bihours, Universal Time, and all analysis has been carried out in this frame, thus eliminating possible confusion between 'local' time based on actual detector longitude, 'local' time based on local zone time, local summer time, etc.

The data were organised by summing all data for each given hourly or bihourly period for a month for each detector. Sums for hour 25 and hour 26 (or bihour 13), defined in the usual way as hour 01 and hour 02 of the following day, were also obtained. As many days data as possible were used in each month.

In the analysis of data of this type for periodic effects it is important that the final results are not contaminated by the presence of non-recurrent effects in the data which would have frequency components at the frequency of interest. Data containing abrupt forbush decreases, solar flares and what are loosely known as "other anomalous effects" must therefore be rejected. In the present case, where intercomparison of data from different stations is being undertaken, it is also highly desirable that only data covering the same days at all stations be employed. To this end hourly plots of data from three low cut-off neutron monitors at widely separated longitudes were examined for the type of events mentioned above. When any such event was found the day on which it occurred was eliminated from the data of all stations before the addition of the monthly sums. In the case of Forbush decreases the days immediately before and after the main decrease day(s) were also rejected, as were any obviously disturbed days in the recovery period. In addition to such global rejection, days from individual stations were also rejected when it was apparent that the data were anomalous in some way, due possibly to instrumental trouble or undefined causes, or when more than 2 hours data was missing altogether. If only one or two hours data were missing, and the remaining data for the day looked normal, they were replaced by figures obtained by linear interpolation between the four hours bracketing the missing data. The rejection of certain days at some stations only is undesirable but inevitable. Power failures, particularly at the more remote stations, are distressingly frequent and if one rejected all stations' data because of a 3 hour recording gap in the data from one station only, one would eliminate a high percentage of the available data, if not nearly all of them.

These techniques do not affect any secular changes which may be present. Figures 4.6 depicts the apparent daily variation which will be observed in data which increase at a uniform rate throughout the day. The data from hours 25 and 26 are used to eliminate such changes by multiplying data for each hourly group by appropriate factors such that, after such multiplication, H01+H02 = H25+H26, data from intermediate hours being multiplied proportionally. This process is carried out in the harmonic programme. A slight error is introduced due to the statistical variability

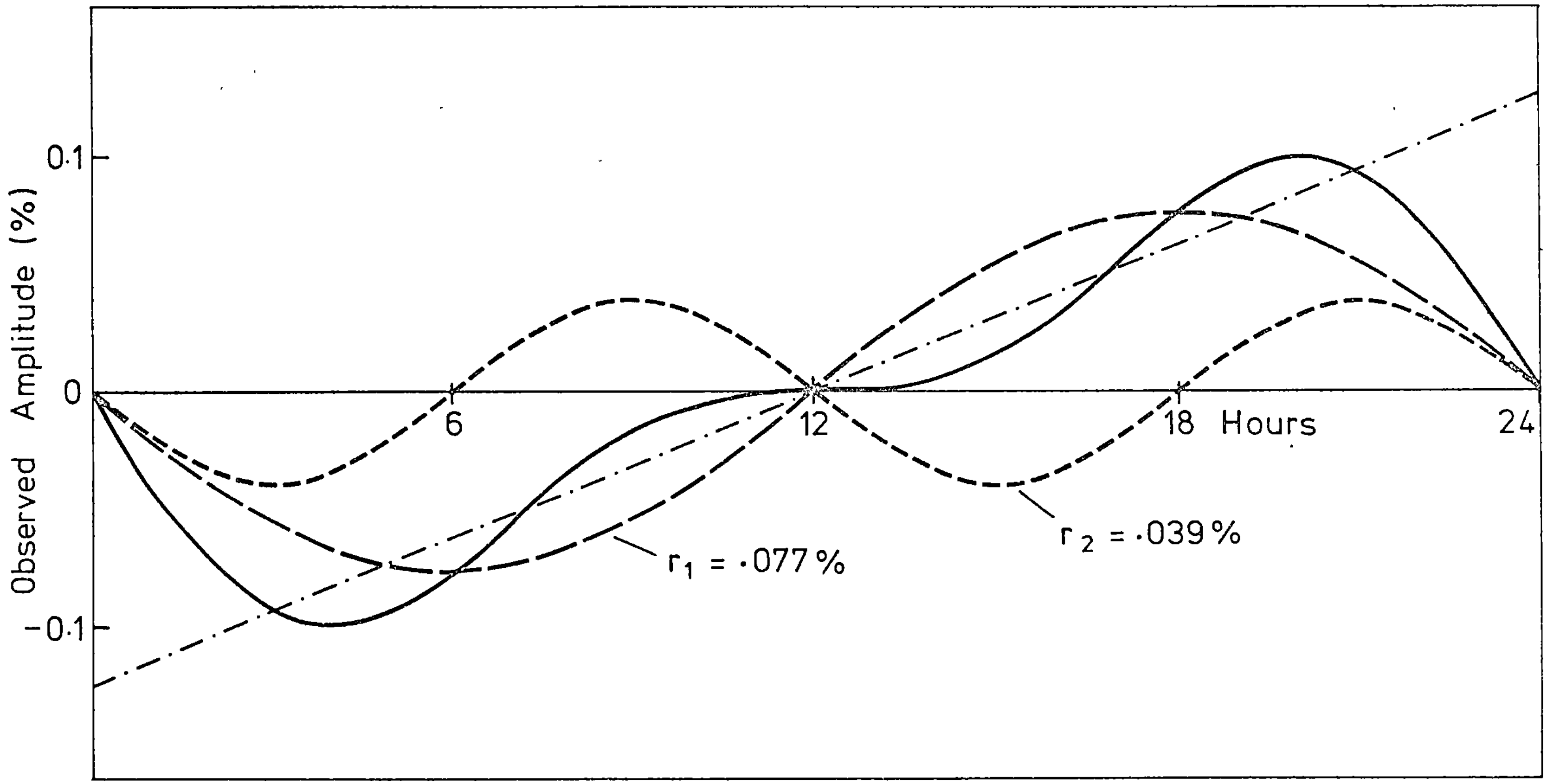


Figure 4.6. *Apparent daily variation resulting from a uniform rate of change of intensity of 0.25%/day (7.5%/month).*

between the H01 + H02 and H25 + H26 totals, but in monthly means this error is negligible.

Data prepared in the above manner were tabulated in yearly groups. Listed for each month were the number of days' data actually used, the possible number of days - defined as the total number of days in the month minus the number of days rejected from all stations on cosmic ray grounds - which could have been used, and the sum of these two quantities. The 26 hourly or 13 bihourly count totals followed, followed in turn by a check total of the sum of these.

After the first few sets of data had been produced in this way it was found desirable to provide sum checks over each column of data over the 12 months, in order to detect accidental transposition of numbers in a row by the typists during data tape preparation. Such errors have been found occasionally, and are more reliably detected by cross sum-checking than by proof reading of typescripts. The omission or repetition of a complete month of data by an inattentive typist is also detected in this fashion. Cross checking of this variety was also used in the manual preparation of the monthly hour sums.

A further cause of typing errors was the inevitable use of rather similar 5 or 6 digit numbers for each hourly monthly sum. A suitable large number was therefore subtracted from each hourly sum for any given month, the figure so subtracted being added to the actual plus possible days sum check, and detected and re-added to the hourly values in the harmonic analysis programme. This reduced the number of digits to be typed per hourly group to 2 or 3, with a very significant improvement in typing accuracy.

Data set out in the above fashion were typed and simultaneously punched on paper tape using Friden Flexowriters, normally with three years data to a tape together with sufficient additional information to enable the computer to identify the station and year(s) involved, scale factor, station longitude, and whether the data were in hourly or bihourly format. The longitude was included for standardisation with other Hobart group projects which used the same, or similar, data in the same programmes and which required conversion to local solar or sidereal time.

The enforced use of paper tape as the only available medium of data input to the computer was felt to be a considerable disadvantage. When the inevitable punching errors are found the whole tape has to be repunched, copying the good sections automatically and correcting the errors individually. This is a time-consuming process. Worse, if it is required to update a tape by addition of more recent data the whole of the original must be copied and then the extra data added. Tapes could not be spliced and then presented to the computer, for reasons of computer hardware, until after this part of the analysis had been completed. A proliferation of small tapes is also a disadvantage as they cannot be stacked neatly and consequently it is difficult to ensure that they are presented to the computer in the correct order. Also, the computer readers require manual loading for each tape. A punched card system, preferably with magnetic tape or disc storage, would have made the data processing much simpler.

4.4 DIURNAL VARIATION, 1961-3. INITIAL ANALYSIS.

4.4.1 Availability and grouping of stations.

At the onset, data from 24 neutron monitors were available for the period 1961-3, mostly from the Hobart files but in one or two cases direct from the investigator concerned. For the purpose of this analysis they were divided into two groups, as listed in Table 4.3. So far as practicable the distribution of cut-off rigidities and mountain stations within the groups was kept similar.

	Station	Cut-off GV	Altitude m	Altitude gm/cm^2	Missing data
Group A	Resolute	< 0.05	S.L	1033	
	Mawson	0.22	S.L	1033	
	Deep River	1.02	145	1015	
	☆ Sulphur Mt.	1.14	2283	783	
	Mt. Wellington	1.89	725	949	
	London	2.73	S.L	1033	
	Munich	4.14	S.L	1033	May-Dec 1963
	☆ Jungfraujoch	4.64	3550	669	Jan-Feb 1963
	Hermanus	4.90	S.L	1033	Feb. 1963
	Brisbane	7.00	S.L	1033	Jan-Apr 1963
	☆ Mt. Norikura	11.39	2770	736	
	Kampala	14.98	1196	896	Jan-Jul 1961, Mar. 1962
Group B	Thule	< 0.04	S.L	1033	All 1963
	Churchill	0.21	S.L	1033	
	Ottawa	1.08	100	1020	
	Uppsala	1.43	S.L	1033	
	Leeds	2.20	100	1020	
	Kiel	2.29	S.L	1033	
	Lindau	3.00	S.L	1033	
	☆ Pic du Midi	5.36	2860	728	
	Rome	6.31	S.L	1033	
	Buenos Aires	10.63	S.L	1033	
	☆ Mina Aguilar	12.51	4000	630	
	☆ Huancayo	13.49	3400	684	

Table 4.3. Neutron monitors used in 1961-3 analysis. ☆ indicates mountain stations. Cut-off indicated is vertical, taken from McCracken, Rao, Fowler, Shea, and Smart (1965).

For many analyses there are some unfortunate features in the geographical distribution of available stations. There has been a strong tendency for cosmic ray observatories to be established primarily in the more affluent areas of the world, particularly North America and Western Europe, both areas of relatively low geomagnetic cut-off. A number of stations have been established in other areas, however some of them seem to suffer a good deal of instrumental trouble, and some are situated at mountain altitudes, consequently being more awkward to use in this type of analysis (section 4.4.7). It appears that tropical stations in general are more difficult to maintain than those in more temperate regions. It has been the experience of the Hobart group that the detectors at Lae, New Guinea (cut-off 15.5 GV, latitude 6° 44'S) have been less reliable than identical equipment at other stations, due to a combination of climatic and logistic problems, and in spite of the best efforts of the local operator. The finance necessary to remedy this state of affairs has not been forthcoming. It seems likely that other operators of tropical stations have met similar problems.

It can be seen from the table that the two highest cut-off stations in each group are at mountain altitudes. Good experimental coupling coefficients applicable to the exact altitude of each station are not available. The best that could be done in the initial analyses was to use the general mountain altitude coefficients of Dorman (1957) or Webber and Quenby (1959). These in themselves are less precise than the sea-level coefficients due to the paucity of available measurements. Consequently results from mountain stations must be considered with some caution, and in fact analyses have been performed with and without their inclusion (section 4.4.7).

It is also evident from table 4.3 that no stations are available with cut-offs between 7.0 and 10.6 GV, a very serious gap. The author is aware of only one existing station in this range, that at Mexico City at 9.5 GV, but the data are not generally available and the station is in any case at mountain altitude. There is a strong need for a number of sea-level neutron monitors to be installed at different locations with cut-offs ranging from 7.0 GV upwards. They should preferably be of the NM64 type, although for this type of analysis this is not critical and a well maintained IGY monitor is quite adequate.

The ideal analysis would use data for exactly the same periods for each station. However from time to time almost all stations have a few hours or a day or two of data missing due to power failures, routine maintenance, and the like. Whilst frequent data gaps could possibly indicate serious instrumental troubles the existence of the occasional short gap can have no such implication. At the same time such gaps do destroy the hope for totally simultaneous data since there is a good chance of such a short gap occurring in the data from at least one of the 24 stations in any given day. The rather lenient view was taken that the data from a station were usable if at least 69% of the 'possible' data (section 4.3) were available in the period under consideration. This corresponds to requiring that at least 21 days' data be available for each possible 30 days' data. In consideration of monthly mean daily variations the application of this criterion is unambiguous, but in the case of the annual mean d.v. one may require simply that 69% of the possible data are available (which permits three consecutive months to be completely missing) or that 69% of each individual months' potential data are available. The latter is clearly the best principle but in practice, due to the relative invariance of the d.v. from month to month, the former consideration was generally used with the added restriction that stations with two or more consecutive months missing from their data were rejected for the year in question. Care was also taken that any single missing months were in fact average months according to the majority of stations.

4.4.2 Consistency of observed harmonic vectors

It is unfortunately true that some stations' data, whilst fulfilling all criteria concerning availability, and looking satisfactory on an hour by hour plot, still produce harmonic coefficients which are quite considerably different from those obtained from other stations. Provided the harmonic coefficients for the station in question are consistent from month to month there is no reason to suppose, a priori, that the observations are faulty. However the phenomena under discussion are small, and spurious variations due to such things as temperature effects, either in detectors themselves or in barometric instruments, (Katzman and Venkatesan, 1960); regular changes in atmospheric structure such as large humidity changes (Bercovitch, 1967); and a number of other possibilities may all, in principle, completely alter the observed d.v at any one station. If this spurious modulation is consistent through many months it will reveal itself as an isolated, clearly erroneous, point on a scatter diagram of estimated free-space vectors from various stations. If however the spurious modulation is inconsistent from month to month it will be revealed, visually, on a suitable harmonic dial plot, when compared with observed vectors from other stations. Rao, McCracken, and Venkatesan (1963) have shown, in their Table 1, that the differences in the observed diurnal variation at stations with similar cut-off rigidities viewing the same free-space anisotropy will not be great, and that inter-station comparison is therefore of value. The modulation coefficients calculated for the present analysis confirm this view. There is however a possibility that such comparisons are not necessarily valid for polar region stations whose asymptotic cones have been calculated purely on the basis of internal (to the earth) magnetic field sources (Gall, Jiménez, and Orozco, 1969).

Summation dials were plotted for each calendar year and all available stations (Figures 4.7, 4.8 and 4.9). For convenience of plotting they are presented in Universal Time. Figures 4.10 and 4.11 depict the summation plots of the three annual mean diurnal and semi-diurnal vectors for each station plotted in local time. The individual monthly semi-diurnal vectors for each station are not presented here. Inspection of these figures immediately shows certain stations displaying inconsistent behaviour. We will deal with each year separately.

4.4.2.1 1961 Results

From figure 4.7 the vectors at Kiel are clearly of abnormal length in the first few months and severe phase alterations occur in May and December. Since there is ample confirmation of more consistent behaviour from other European stations it was rejected. There was a temptation also to reject Brisbane, Hermanus, and Buenos Aires, due to the marked clockwise swing in their vectors through the year. This however could not be done as all three stations plainly have a lot in common, being medium-latitude southern-hemisphere stations with cut-offs in the range 5 to 10 GV. It must be assumed therefore that a genuine effect may be present. The vectors of the two highest latitude stations, Resolute and Thule, are somewhat less regular than many others. This is due in part to the low count rate of, and small expected observed d.v at, each station, and may be made worse by external

Figure 4.7a.

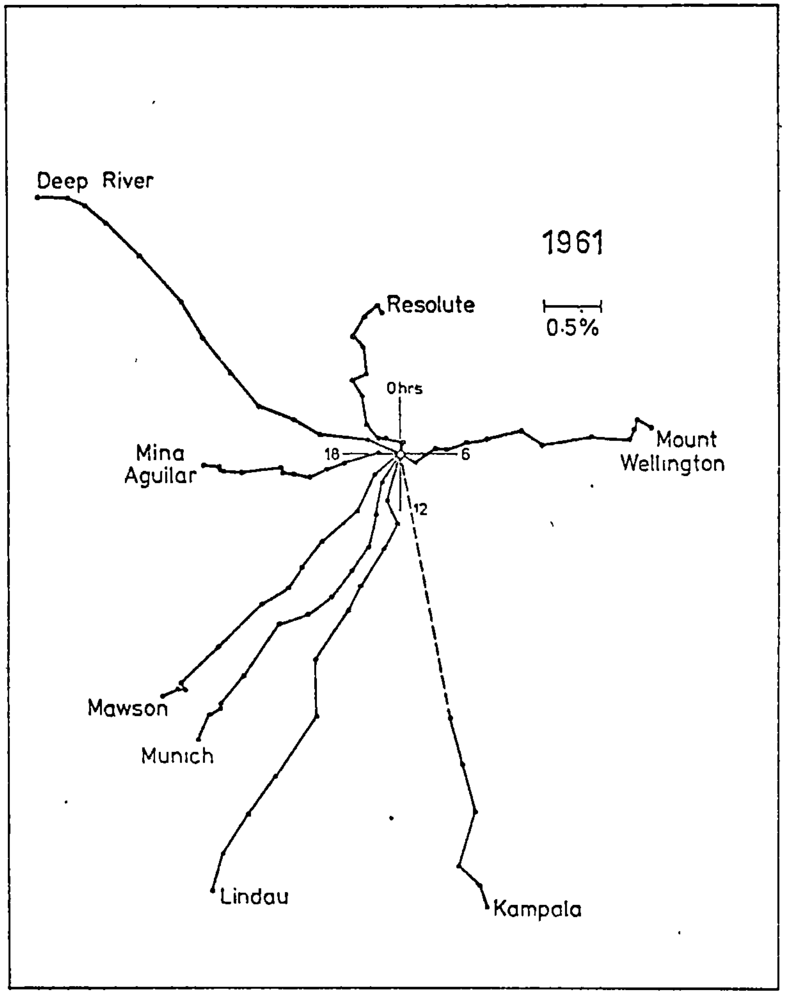
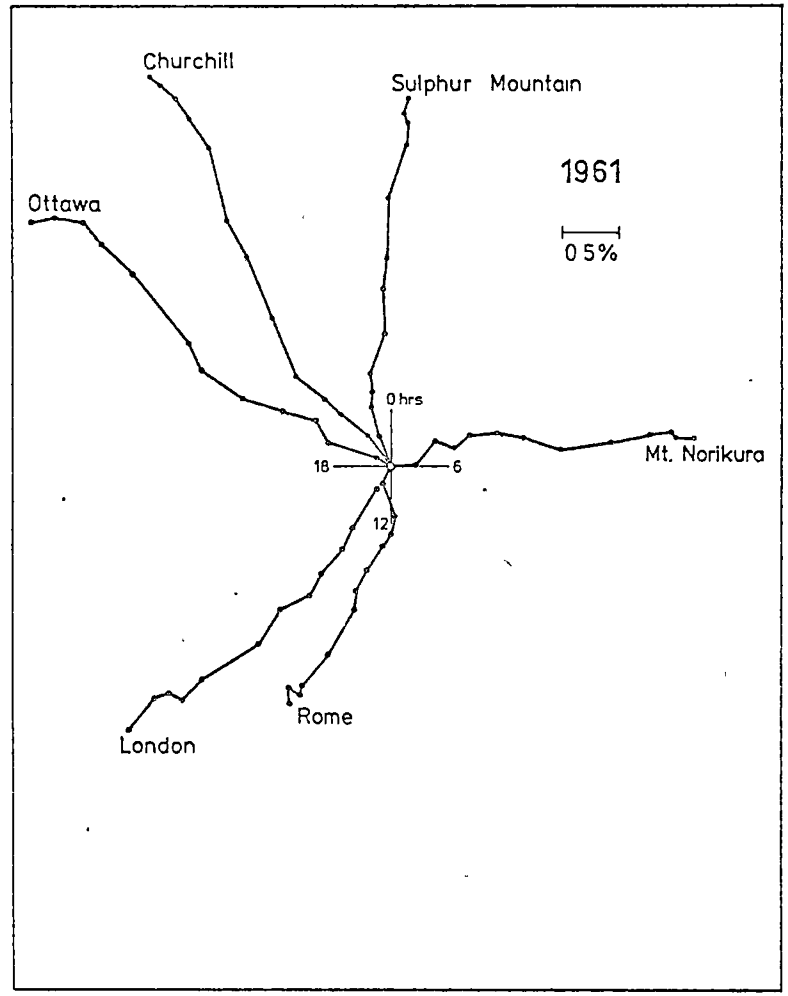


Figure 4.7b.



Figures 4.7a and 4.7b. Observed, pressure corrected, monthly mean diurnal vectors.

Figure 4.7c

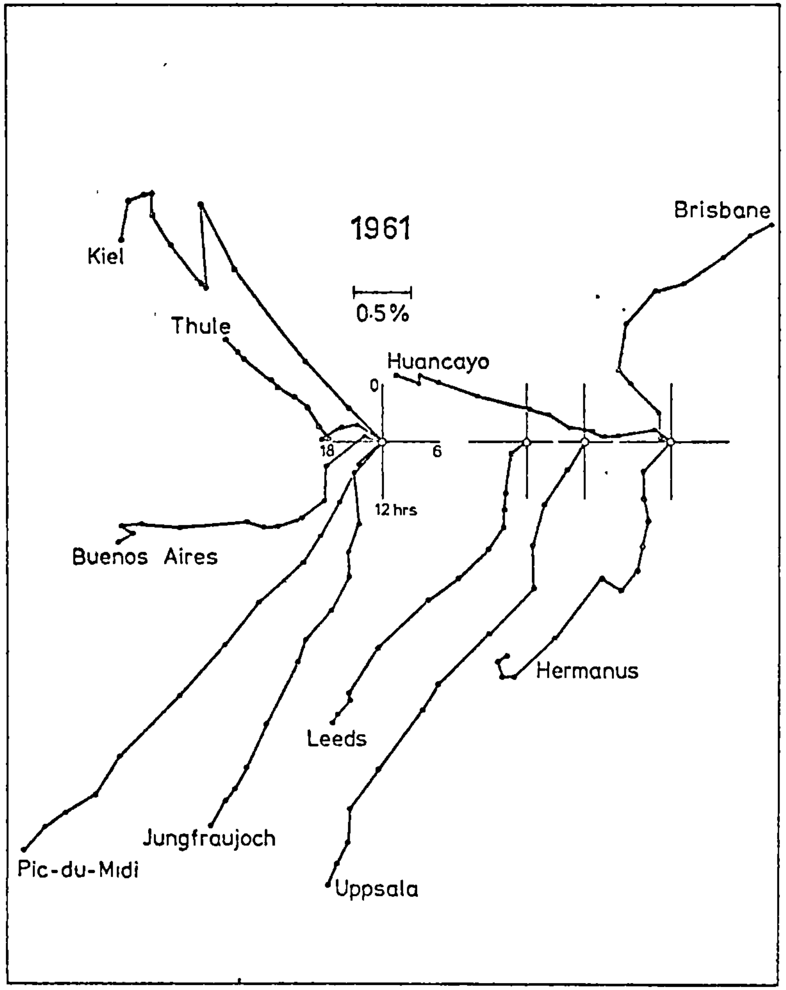
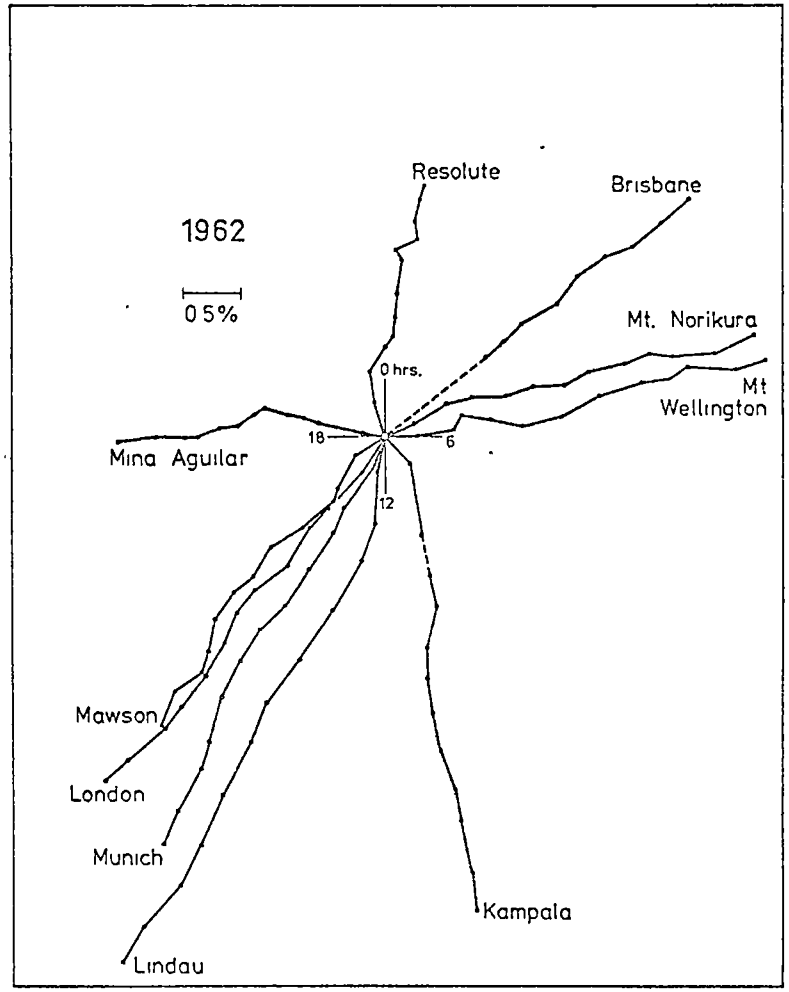


Figure 4.8a.



Figures 4.7c and 4.8a. *Observed, pressure corrected, monthly mean diurnal vectors.*

Figure 4.8b.

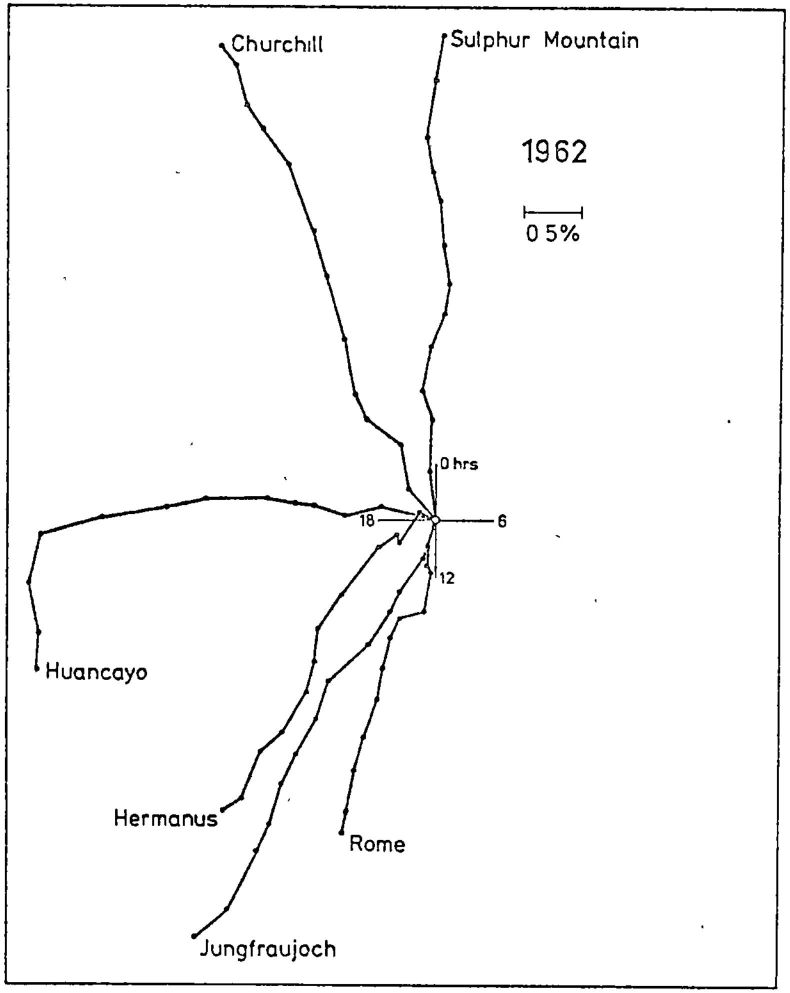
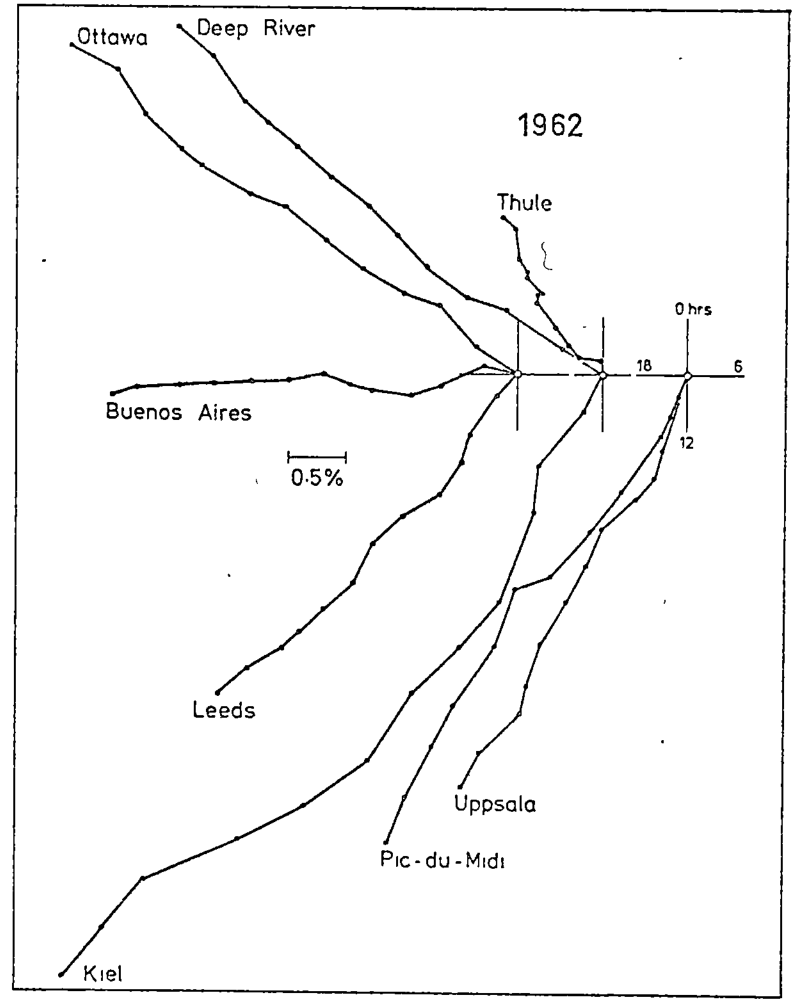


Figure 4.8c.



Figures 4.8b and 4.8c. *Observed, pressure corrected, monthly mean diurnal vectors.*

Figure 4.9a.

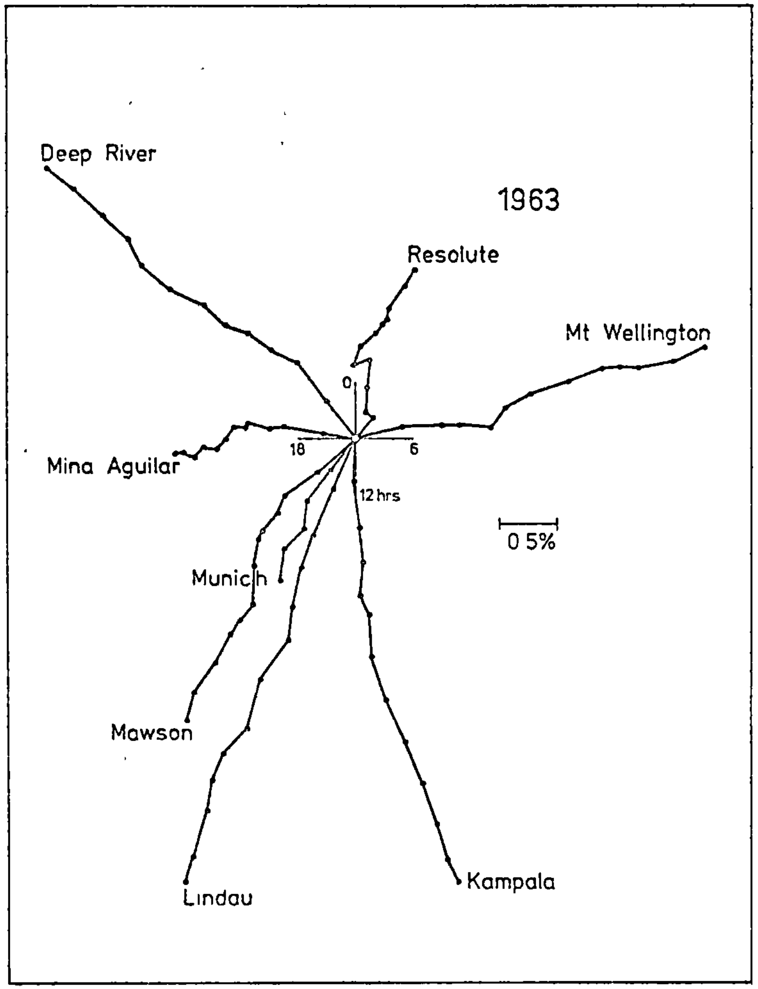
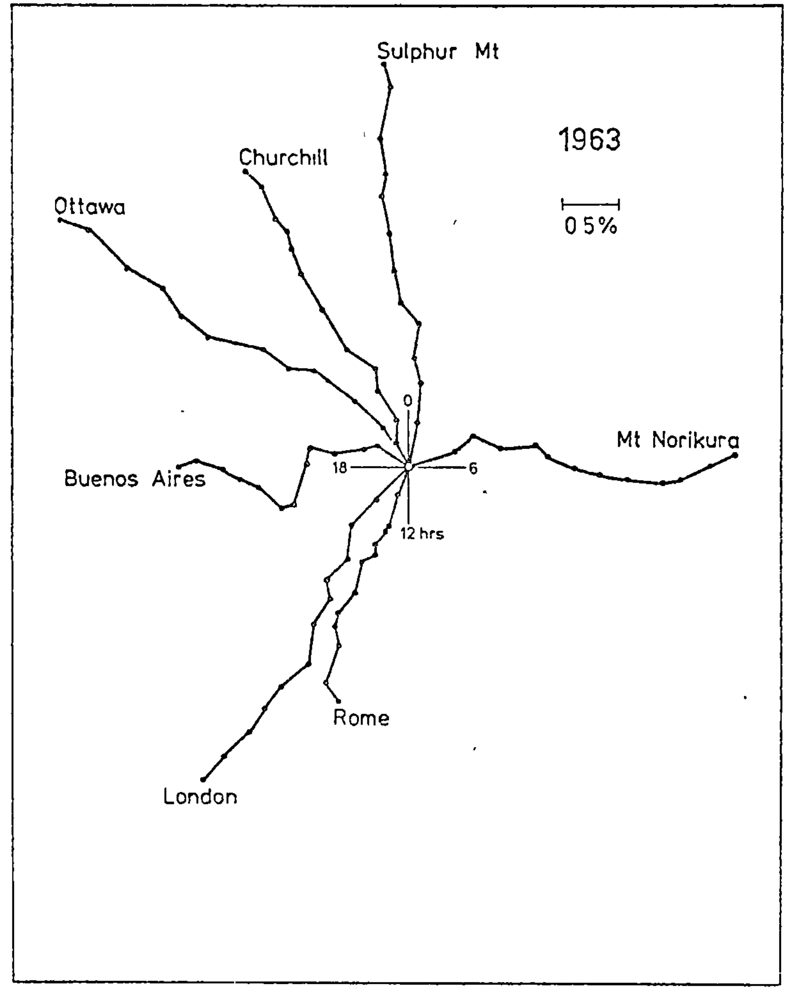


Figure 4.9b.



Figures 4.9a and 4.9b. *Observed, pressure corrected, monthly mean diurnal vectors.*

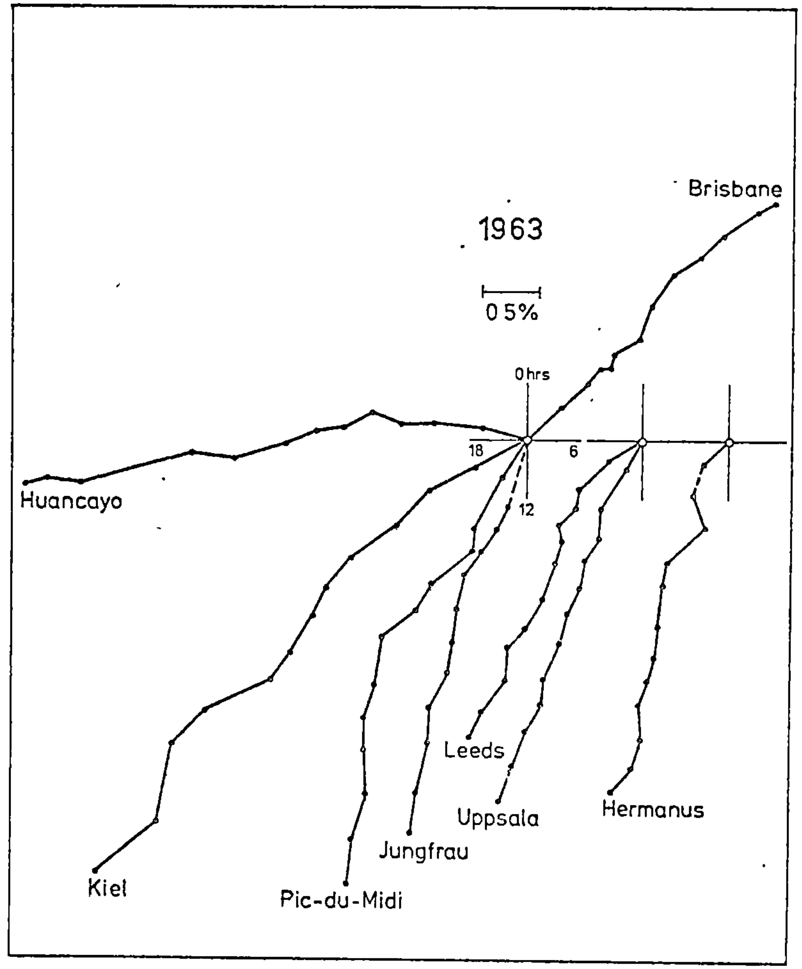


Figure 4.9c. Observed, pressure corrected, monthly mean diurnal vectors.

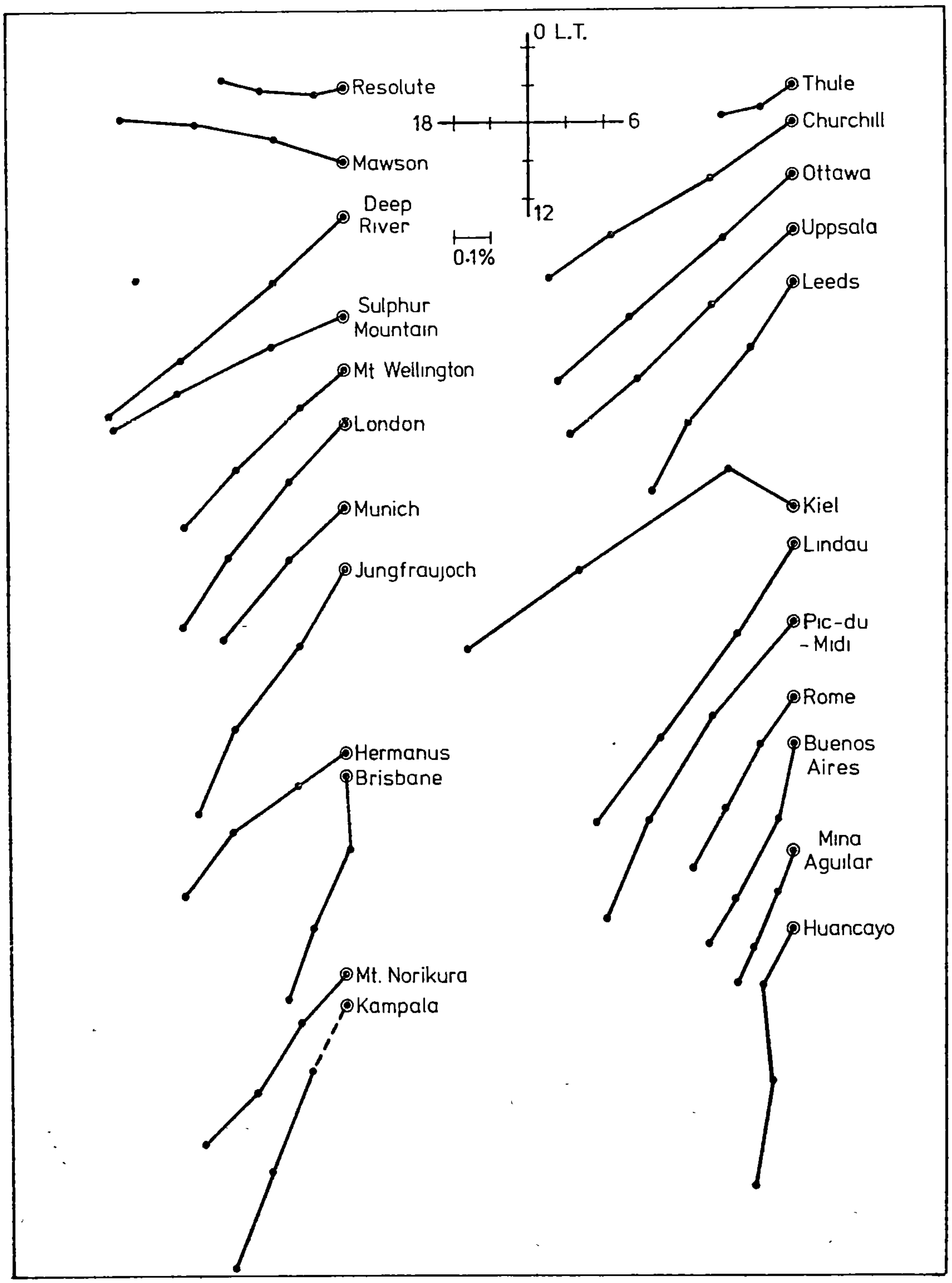


Figure 4.10. *Observed, pressure corrected, annual mean diurnal vectors, 1961 to 1963.*

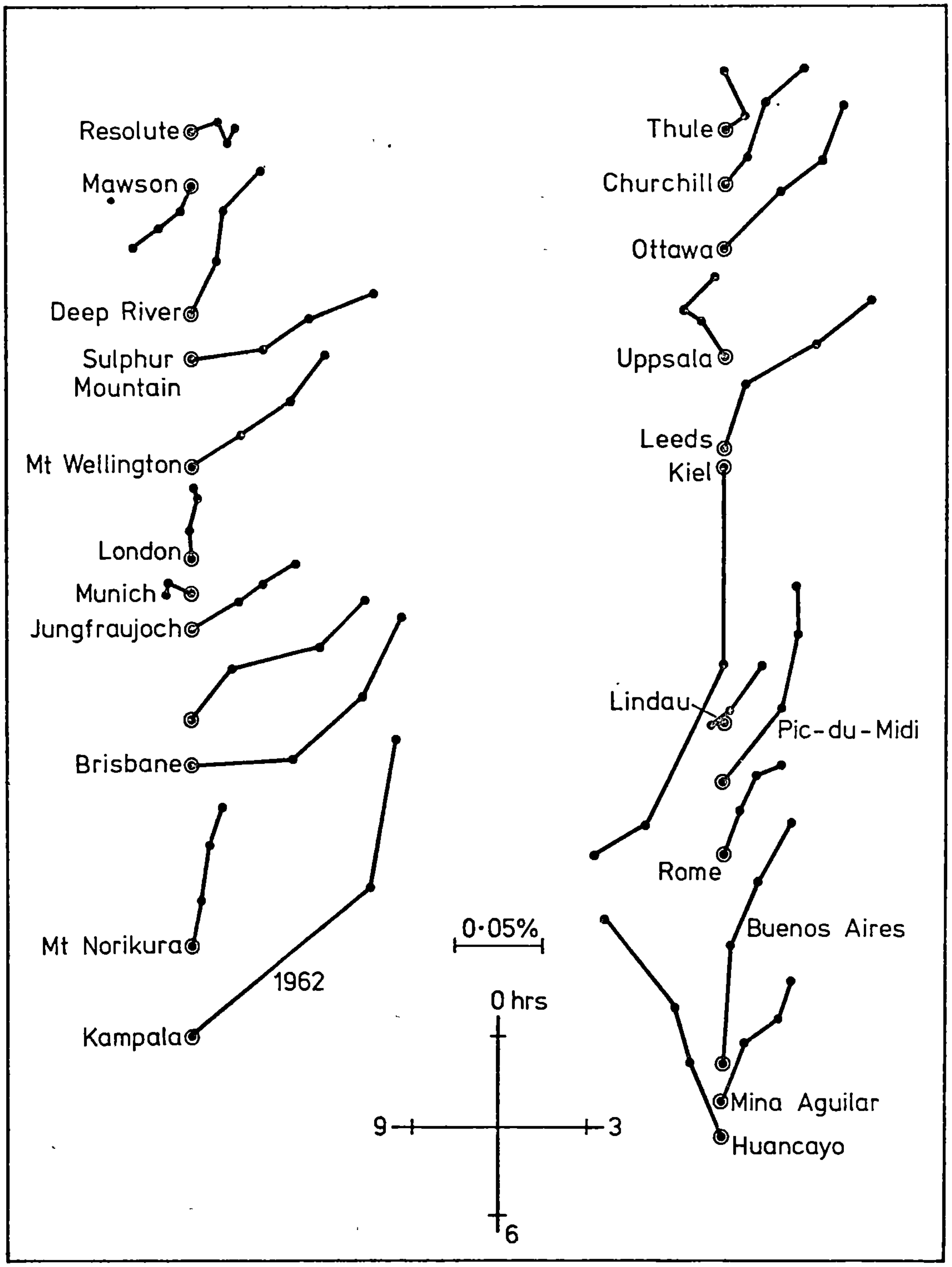


Figure 4.11. *Observed, pressure corrected, annual mean semi-diurnal vectors, 1961 to 1963.*

magnetospheric effects. These stations have considerable significance in determinations of the latitude dependence parameter p and were therefore retained in the analysis at this stage.

An interesting feature of the 1961 observations concerns the small irregular vectors present at a number of stations in the final few months of the year. It was at first thought that these might represent some form of data contamination, since no common feature could be found to isolate these stations from the remainder. Later analysis from data obtained from further stations showed that the short vectors were definitely genuine and apparently have extra-terrestial origin. No stations were rejected from the analysis from this cause.

4.4.2.2 1962 and 1963 Results

In 1962 it is apparent that Huancayo is quite faulty, and in 1963 Buenos Aires appears to be seriously inconsistent. In both years the vectors at Kiel were abnormally long. The necessary rejections were made. Data for each year which are rejectable for the above reasons have been termed 'doubtful' data in following sections.

4.4.2.3 General Comments

The summation dials in Figure 4.10 depict the mean annual diurnal variation in local time for each of the three years. The stations are arranged in the two groups, in order of increasing cut-off rigidity. Certain common characteristics are evident. As the cut-off increases the observed time maximum becomes earlier. In general the directions of the vectors at any particular station do not change much during the three years, although there is a slight tendency for them to become a few minutes earlier. The

1962 vectors generally have larger amplitudes than those of the other years. The observed amplitudes decrease markedly at both high and low cut-offs. At the low cut-off Polar stations this is expected for any set of parameters since the axial direction of the cone of viewing is well away from the ecliptic plane. The long spread in longitude of the cone of viewing of equatorial high cut-off stations tends to reduce their observed amplitudes, and this may be aided by a relatively low upper limiting rigidity. Brisbane, Huancayo, and Kiel flagrantly oppose these generalities in certain years, and as in each case there are other reasons for suspecting their accuracy for the years in question (see above) they have been rejected for those years Regrettably Huancayo was in any case rejected automatically by virtue of the large amount of missing data in all three years, the percentage available ranging from 53 to 63%.

Figure 4.11 depicts the semi-diurnal vectors in the same manner, using an enlarged amplitude scale. It is evident that these vectors also become earlier with increasing cut-off rigidity. The amplitudes, in contrast to the diurnal case, increase with cut-off. Again some stations show inconsistent behaviour, notably Kiel with relatively enormous vectors roughly six hours out of phase with the remainder, and Huancayo roughly three hours out of phase. It is interesting that these two stations have already been eliminated on other grounds. Munich appears to disagree rather with the general pattern, and in any case has one year of data unavailable. The Mawson vectors are rather later than those for the other stations, but this is explicable by the position of the cone of viewing, the centre of which lies nearly directly overhead, rather than 30 to 60 degrees east of the station as is generally the case. The explanation is valid almost regardless of which rigidity exponent is assumed for the primary variation. There is also a rather surprising disagreement between the Leeds and London vectors, the cause of which is not known. It appears, from considerations of consistency, that the London vectors are probably in error.

No attempt has been made to plot statistical error circles in figures 4.10 or 4.11. Even in figure 4.11 circles of radius one standard deviation are about the size of, or smaller than, the 'origin' circle at the commencement of each vector set. Since the standard deviations of the amplitudes of both diurnal and semi-diurnal components are the same this is even more applicable to figure 4.10. Thus the majority of the semi-diurnal, and all the diurnal, vectors plotted are of considerable statistical significance. The semi-diurnal vectors at Mawson, for instance, are about four standard deviations in length, and for most of the other stations the statistical significance of the semi-diurnal vectors is higher. This, together with the consistency in local time of plots from many stations points to a genuine non-statistical origin of the semi-diurnal variation, although it does not of course prove that the variation exists in the primary flux.

4.4.3 Results of Variance Analyses

A number of sets of analyses were undertaken, to test the effect of various data and coupling coefficient changes. For each run the variances of A_1, A_2, τ_1 and τ_2 were minimised separately for a suitable range of the four parameters β, R_u, R_l and p. The analyses were performed for each of the three years involved, and for the data combined over the three years. Details of each run are listed in table 4.4.

Run No.	Selection of Stations	Possible No of stations	Doubtful Data	Coupling Coefficients
1.	All	12 (Group A)	Included	Webber and Quenby
2.	"	12 (Group B)	"	" "
3.	"	24 (Both Groups)	"	" "
4.	Sea level only	17 " "	"	" "
5.	" " "	17 " "	Excluded	" "
6.	" " "	17 " "	"	Dorman
7.	" " "	17 " "		Mathews & Kodama Solar Minimum
8.	" " "	17 " "	"	Mathews & Kodama Solar Maximum
9.	All	24 " "	"	Dorman
10.	"	24 " "	"	Webber and Quenby

Table 4.4. Details of analyses performed using the separate variance analysis programme, U579.

The following effects can be studied using appropriate combinations of these analyses:

(a) Differences between analyses based on phase and analyses based on amplitude (All runs).

(b) Internal consistency of data (runs 1, 2, and 3).

(c) Variations due to use of different coupling coefficients (runs 5, 6, 7 and 8).

(d) Variations due to inclusion of mountain altitude data (Runs 6 and 9)

(e) Variations due to inclusion of suspect data (Runs 4 and 5, and 3 and 10).

4.4.4 Differences between analyses based on phase and amplitude constant minimisations.

It has already been pointed out (section 4.2.3 and figure 4.5) that obtaining the minimum variance of the estimates of the free-space amplitude constant and phase separately need not necessarily lead to the same values of the various parameters. This has been amply borne out in practice, especially for the years 1961 and 1962. Table 4.5 lists typical values of β obtained for the first harmonic from run 7.

Period	Minimisation of:-	Value of β obtained	Corresponding values of Z Amplitude	Z Phase
1961	Amplitude Constant	−0. 2±0.2	15.1	20.9
	Phase	+0. 6±0.3	28.8	13.3
1962	Amplitude Constant	+0. 1±0.15	12.5	13.6
	Phase	+0. 4±0.2	16.4	10.9
1963	Amplitude Constant	+0. 2±0.2	8.5	13.6
	Phase	+0.25±0.3	8.5	13.6
1961-3	Amplitude Constant	−0.15±0.15	31.3	50.0
	Phase	+0. 5±0.1	28.0	46.7

Table 4.5. Estimates of β for diurnal variation obtained from minimisation of estimates of amplitude and phase. R_u = 100 GV, p = 1.0, coupling coefficients Mathews and Kodama Solar Minimum. Sea level stations only with all doubtful stations excluded. The same stations were used in each analysis for any given period.

Figure 4.12 depicts the variance curves for 1961 with β as a parameter, on which the results in table 4.5 are partly based. The individual curves are steep enough to produce reasonably unambiguous results but the results disagree and the minimum values of Z obtained are too high for the scatter in the estimates to be attributable purely to statistical fluctuations. This could be due to errors in the model; to the inclusion of data which are corrupt in one way or another; to the impracticability of averaging by this type of technique over periods when there are undoubtedly changes in the mean monthly free-space diurnal variation; or to underestimation of the standard deviations inherent in each detector's observa-

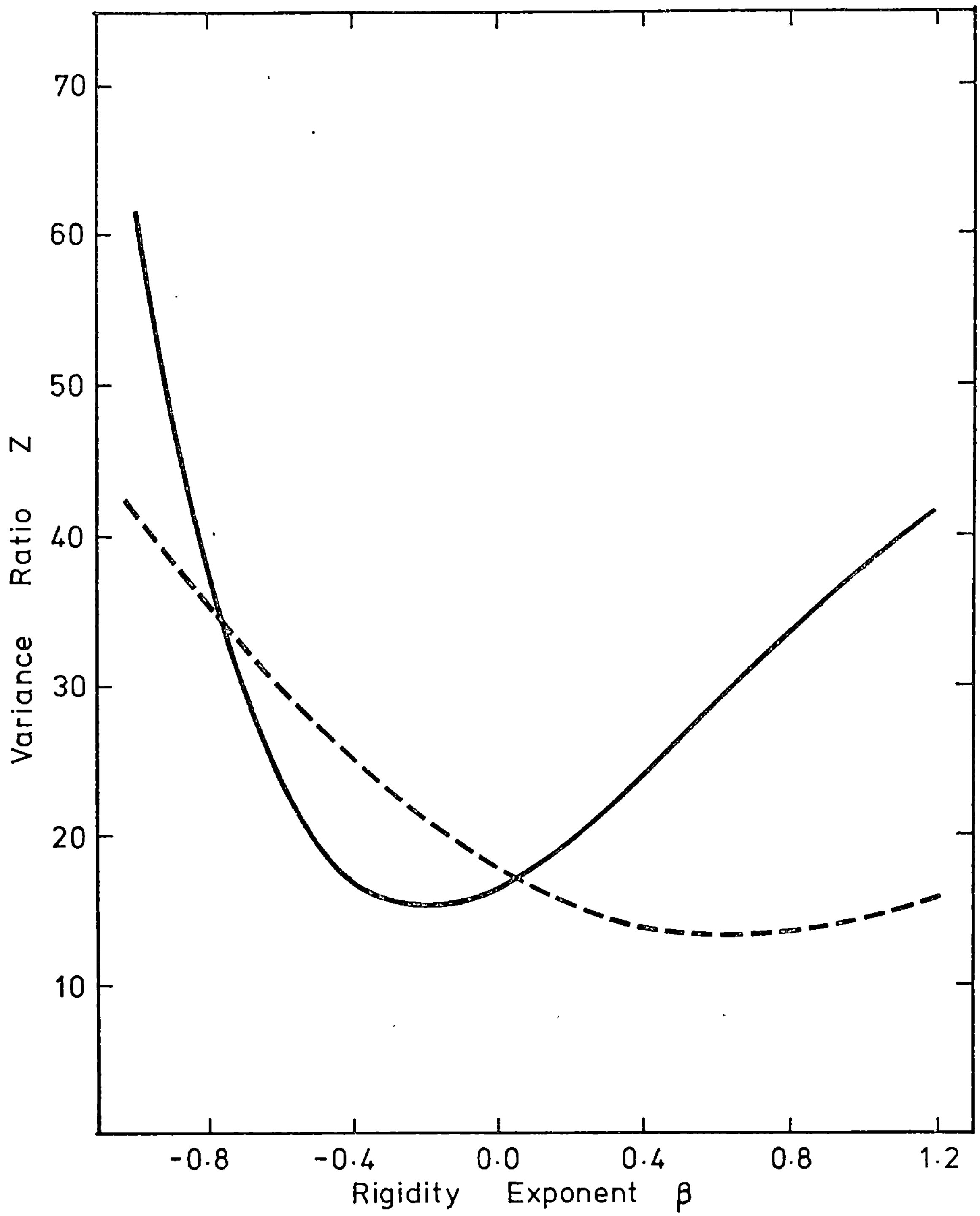


Figure 4.12. Variance of estimates of amplitude (solid line) and phase (dashed line) of 1961 free-space diurnal vector. Sea-level stations only, with doubtful rejected (from run 7, tables 4.4, 4.5).

tions. None of these possibilities can be instantly dismissed, and it is likely that the discrepant values of Z observed are due to a combination of them. A discussion of these factors appears in section 4.7 but one is worth mentioning at this stage.

According to Rao et al (1963), the standard deviation of the annual mean phase of an IGY neutron monitor is about 5°, and they comment that this is probably an underestimate. The standard deviation calculated in the analysis purely on the basis of Poisson statistics is a little less than 3°, giving a mean expected variance of 8.3 square degrees, exactly 1/3 of the value used by Rao et al. Since Rao et al just managed to reduce their observed variance to the order of 25 square degrees it is apparent that the value of the expected variance used in this analysis is unlikely to be matched by the calculated sample variance. It is probable on this basis alone that the minimum achievable Z will not be less than 3 in the case of phase variance. Similar arguments will apply to amplitude and vector variance. Experimental results reported in section 4.7.6 support this conclusion. Other authors have also reported that the statistics of neutron monitor observations are worse than those estimated from the count rate alone (e.g. Sandstrom, 1965).

There were severe changes in the monthly mean diurnal variation in the last few months of 1961, and it is noteworthy that the highest value of minimum Z_{amp} was in that year, as was the largest discrepancy between the two values of β obtained. In 1963, for which year later analyses have shown much better agreement between stations than in 1961, a much lower value of minimum Z_{amp} is found. However the lowest values of Z_{phase} remained rather constant over the three years, and represent a variance of about 110 square degrees.

When the three-year mean diurnal variation is considered the minimum values of Z found are much higher than for the individual years. This is due to the reduction in the expected variance, reduced from the annual value by $\sqrt{3}$, whilst the observed maximum variance goes up slightly, due partly to the greater likelihood of inclusion of faulty data and also, possibly, to averaging over a longer period.

There remains the possibility of the retention of faulty data, even after the previously described checks have been made. There is evidence that a number of stations show consistent differences from average values of the free-space vectors over several successive years (section 4.5.3) and one or two of these stations are included in the above analyses. The differences may be either in amplitude or phase, or both, and would therefore be expected to affect the two analyses separately.

Figures 4.13 and 4.14 present the distribution of the estimates of the first harmonic free-space vectors based on minimisation of amplitude and phase variance separately for 1961, corresponding to the top lines of table 4.5. The various vector estimates are represented by circles of radius one standard deviation drawn around their end points. The mean vector, defined as a vector of average length directed in the mean direction, is also plotted. Its error circle is dashed for ease of recognition. Plus and minus one standard deviation limits are also shown for the amplitude and phase respectively in the two figures. The figures take on the general elliptical appearance, perpendicular and parallel to the mean vector respectively, predicted in figure 4.5.

It is not possible to determine which is the more valid analysis,

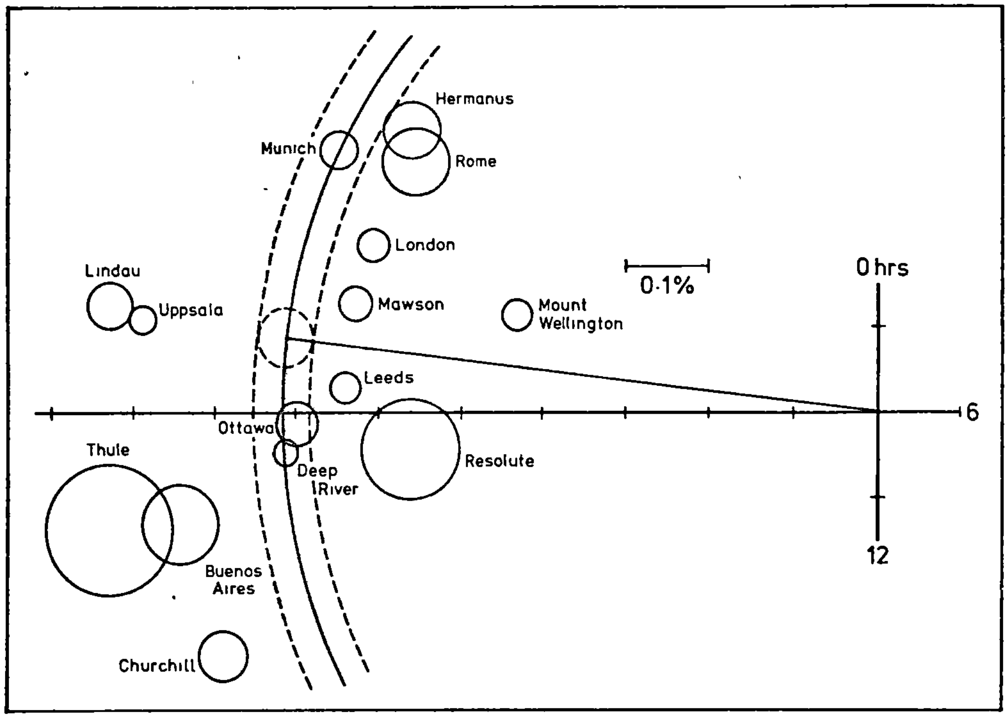


Figure 4.13. Estimated free-space vector end-points which give minimum variance of estimates of amplitude, 1961. (From run 7, tables 4.4, 4.5). The dashed lines indicate the 67% standard error limits of amplitude, regardless of phase.

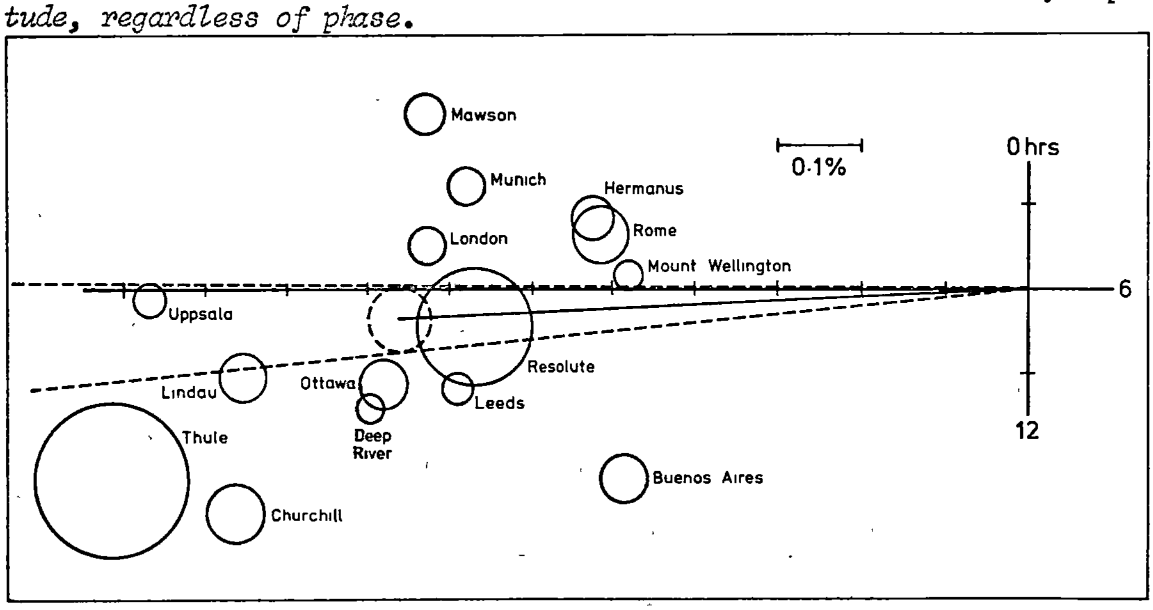


Figure 4.14. As figure 4.13 but showing vectors which give minimum variance of estimates of phase.

and the question arises as to whether it is legitimate to minimise the amplitude and phase variance separately. The different results obtained are partly due to the fact that the two analyses utilise different parts of the available information, although they also reflect the possibility that either the model or the correction of the observations for environmental effects may be inadequate. In order to make use of all available information later analyses (sections 4.5 and 4.6) minimise the length of the difference vectors between the estimated vectors for each station and their mean (section 4.2.4). However the present technique is sufficient for differentiating between coupling coefficients, investigation of mountain stations, etc. as reported in sections 4.4.5 to 4.4.8.

4.4.5 Sensitivity to evaluation of the various parameters, and internal consistency of data.

The two groups of stations (table 4.3) were analysed separately in runs 1 and 2 (table 4.4), and jointly in run 10, for comparison purposes. Doubtful data were included in runs 1 and 2, and excluded in run 10. Furthe analyses of the individual groups of stations were carried out using vector variance (section 4.5.1), but some conclusions could be made at this stage.

Different values of β and R_u were obtained for the same periods from the two groups. This must be due, in part at least, to the inclusion of suspect data. However the values of p and R_1 obtained are in agreement throughout. Figure 4.15 shows the set of variance curves from run 10 for all stations, with doubtful excluded, for 1962. They are typical of those obtained from either of the individual groups of stations and the other years. They show that the phase estimates are quite insensitive to changes in R_1 or p, and that the amplitude estimates are insensitive to

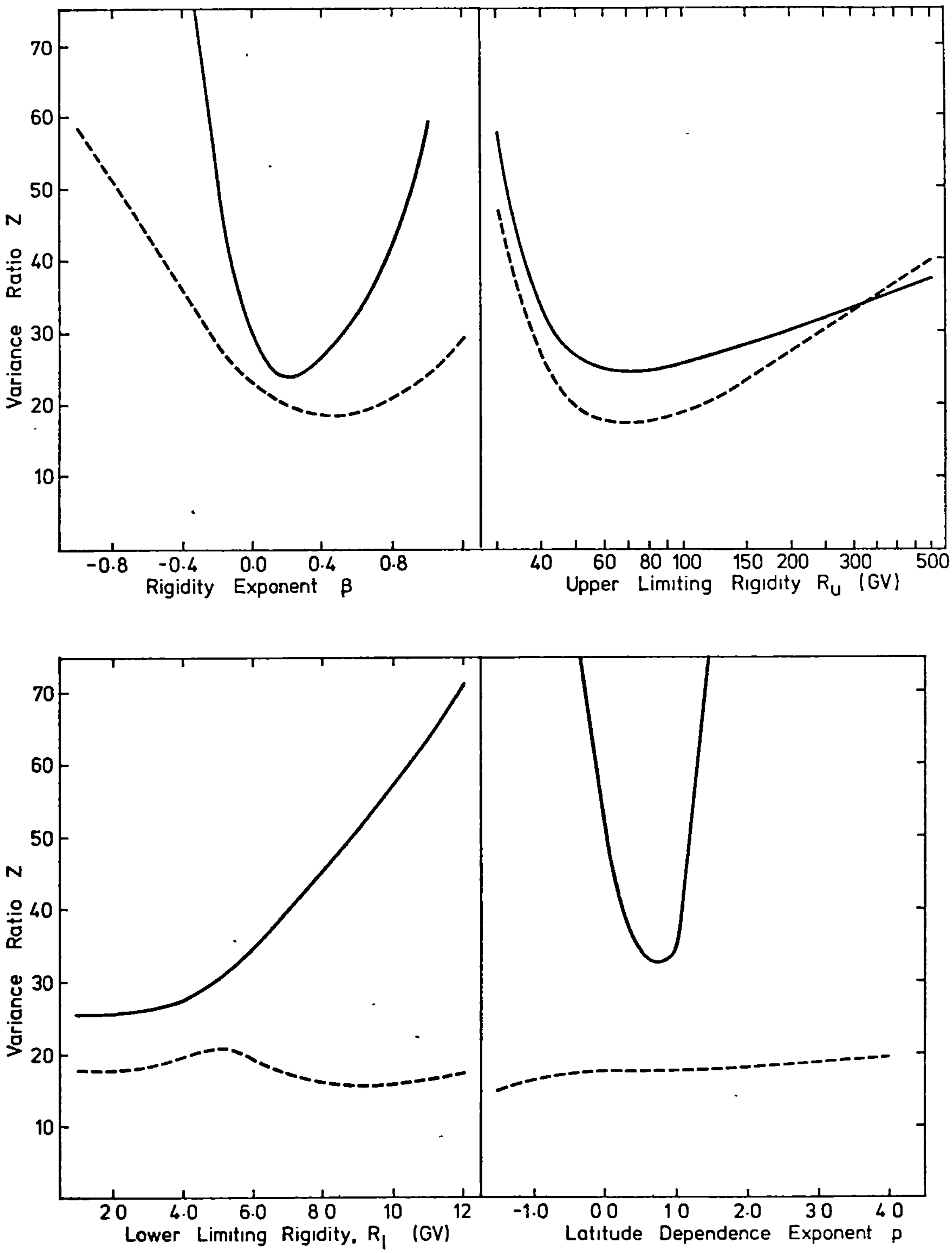


Figure 4.15. *Variance of estimates of free-space amplitude (solid curves) and phase (dashed curves) as each parameter changes whilst the remainder are held constant. 1962. (Run 10, table 4.4).*

changes in R_1 below 5 GV. Consequently R_1 is indeterminate by this technique. Similarly p is indeterminate by minimisation of phase estimates. However the variance of the amplitude estimates is extremely sensitive to the value of p in the, admittedly large, range scanned, and in every case except one the value of p obtained was either 0.5 or 1.0. In the exceptional case data from the high latitude stations were missing and the amplitude variance plot was broad and shallow. The modulation coefficients (section 4.2.1) are highly sensitive to changes in the cosine dependence exponent only at the highest latitude stations, Thule, Resolute, and Mawson, and only mildly sensitive for other stations even as high in latitude as Deep River (figure 4.16). The dependence is so sharp for the high latitude stations, relative to the remainder, that the sharp variance curve shown in figure 4.15 results and an unambiguous result may be obtained, independent of possible slight errors in the observations at these stations.

It is possible therefore to state that the latitude dependence of the first harmonic in each of the three years 1961, 1962, and 1963 is approximately cosine or a little less, and certainly lies in the range $(\text{cosine})^{0.5}$ to cosine, with a mean exponent value of about 0.8 ± 0.2. Subsequent vector analyses have been carried out using a value of 1.0.

It is not possible to give a value for R_1, except to note that it is probably less than 5 GV, and that the method is insensitive to alterations below this limit. It has therefore been taken as 0 GV in subsequent work.

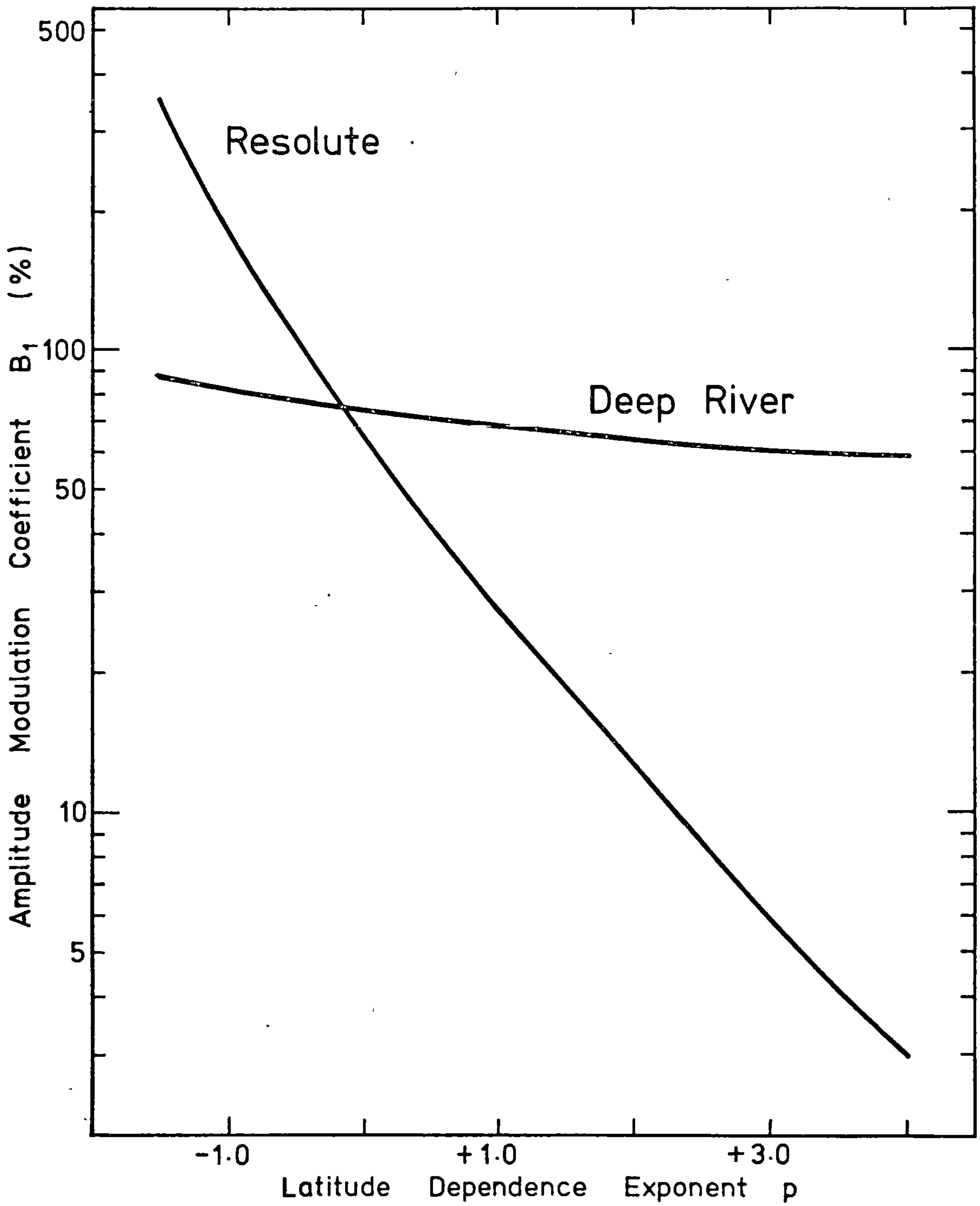


Figure 4.16. *Variation of modulation coefficient B_1 with change in latitude dependence exponent p for high- and mid-latitude stations. $\beta = 0.0$. $R_u = 100$ GV. $R_l = 0$ GV.*

4.4.6 Sensitivity to coupling coefficients.

Four sets of coupling coefficients were used, those due to Dorman (1957), Webber and Quenby (1959), and the coefficients for both solar maximum and solar minimum conditions published by Mathews and Kodama (1964). There were no significant differences between the results obtained with any of these sets (table 4.6).

Coupling Coefficients Parameter	Webber and Quenby	Dorman	Mathews and Kodama Solar Minimum	Mathews and Kodama Solar Maximum
β	-0.2	-0.2	-0.2	-0.2
Corresponding Z	15.06	15.10	15.05	15.96
R_u	30	30	30	30
Corresponding Z	16.48	16.79	17.02	17.43
R_1	1.0	1.0	1.0	3.0
Corresponding Z	22.22	22.25	22.13	22.94
p	0.5	0.5	0.5	0.5
Corresponding Z	22.05	25.60	26.03	24.72

Table 4.6. Parameter and corresponding values of Z obtained from minimisation of the variance of amplitude estimates for each set of coupling coefficients. First harmonic 1961, 15 sea-level stations with doubtful rejected.

The only set which shows an appreciable difference from the remainder are the Mathews Kodama solar maximum set, and even then the difference is slight. There is no significance in the different value of the R_1 found. 1961 was probably closer to solar maximum than solar minimum, but the reverse applies to the other two years. Considerable simplicity resulted from use of only one set of coupling coefficients to cover all three years of data, and in view of these results it was considered adequate to use one or other of the solar minimum sets. The Mathews and Kodama coefficients are for sea-level stations only, whereas the other sets also include coefficients for mountain altitude detectors. Before the vector variance computations were made the three-altitude coefficients of Lockwood and Webber (1967) became available, and in view of the above results and the 3 altitude (sea level, 828 $gm.cm^{-2}$, and 680 $gm.cm^{-2}$) advantage these have been used in all vector analyses.

4.4.7 Inclusion of mountain stations.

The investigations described above have made use solely of sea level, and approximately sea level (e.g. Mt. Wellington, 725 metres), detectors. Mountain altitude stations have much higher count rates, and consequently better statistical accuracy, than identically equipped stations at sea level, but this advantage is countered by several problems:-

(a) The difficulty of computing coupling coefficients considering the relatively few stations involved and their scatter in altitude.

(b) The altitude of the detector which is, in general, different from the mean altitude used for the coupling coefficients. The difference either can be ignored or some rather uncertain extrapolation made.

(c) The probability of difficulty in relating barometric height at such stations to the air mass above the detector, due to dynamic pressure effects resulting from high winds around the mountain (Section 2.2). This difficulty has been reported for Mt. Washington (Lockwood and Calawa, 1957) and for Mt. Norikura, (Chiba and Kodama, 1969), and is likely at other exposed sites such as Pic-du-Midi and Jungfraujoch.

Table 4.7 illustrates the effects of including mountain altitude stations in the analyses.

Minimisation of Parameter	Sea Level Stations only		Sea Level plus Mountain Stations	
	Amplitude	Phase	Amplitude	Phase
β	0.2	0.2	0.4	0.4
Corresponding Z	8.55	13.87	27.58	21.25
R_u	60	100	90	90
Corresponding Z	8.42	13.78	27.58	21.25
R_1	4.0	1.0	4.0	1.0
Corresponding Z	8.40	13.78	26.12	20.92
p	1.0	1.5	1.0	1.5
Corresponding Z	8.66	9.77	27.58	16.34

Table 4.7. Comparison of 13 sea-level stations (run 6) and the same 13 sea-level plus 6 mountain-level stations (run 9). 1963. Coupling coefficients : Dorman.

The 1963 results were by far the most closely ordered in that the lowest values of Z were found that year. The inclusion of the extra 6 mountain stations, whilst not appearing to make a great difference to the results, clearly shifts Z from statistically probable to statistically improbable values, particularly in the amplitude case. Introducing these stations has therefore introduced some sort of contamination to the data, but at this stage it is not possible to determine which of the various possibilities is involved, or whether perhaps one of the individual mountain stations is itself faulty. Further consideration is given to this problem in connection with the variance of vectors (Section 4.5.3).

4.4.8 Inclusion of Doubtful Stations.

Doubtful stations have been defined (section 4.4.2.2) as those stations whose monthly mean vectors appear to display peculiar features when plotted on summation dials (figures 4.7 to 4.9). In 1963 Buenos Aires and Kiel were placed in this category (section 4.4.2.2) and table 4.8 compares results obtained from analyses including and excluding these stations in that year. All available sea-level stations were used in the comparison.

Minimisation of Parameter	Accepted Stations (run 5) (13 stations)		Accepted plus Doubtful Stations (run 4) (15 stations)	
	Amplitude	Phase	Amplitude	Phase
β	$0.2^{+0.4}_{-0.2}$	0.2 ± 0.3	0.0 ± 0.2	0.2 ± 0.3
Corresponding Z	8.5	13.6	20.0	14.0
R_u	60^{+200}_{-30}	80^{+70}_{-30}	30 to 45	80^{+70}_{-30}
Corresponding Z	8.3	13.7	17.3	13.9
R_1	$4.0^{+1.5}_{-4.0}$	$1.0^{+3.5}_{-1.0}$	$4.0^{+1.5}_{-4.0}$	$1.0^{+4.5}_{-1.0}$
Corresponding Z	8.1	13.8	25.0	14.1
p	1.0 ± 0.2	-1.5 ± 0.5	1.0 ± 0.2	-1.5 ± 0.5
Corresponding Z	8.5	9.4	25.8	10.6

Table 4.8. 1963 First Harmonic, Coupling Coefficients:- Webber and Quenby. Sea level stations only. 95% Confidence Limits.

Kiel was rejected because of abnormally long vectors, and the table shows that inclusion of these stations causes a major change in the minimum Z values obtained from variance of the phase estimates. The Kiel vectors appear to be in approximately the correct direction, and the mean Buenos Aires vector appears likewise, so this result is reasonable. In consequence the parameter estimates obtained from amplitude variance differ in the two cases whilst the estimates obtained from phase variance do not. Inclusion of such obviously doubtful data may be expected to increase the minimum variance to non-statistical values, thereby producing false estimates of the parameters sought.

4.4.9 Conclusions, initial analyses.

In general minimising the variance of the amplitudes and of the phases of the free-space vectors, estimated from each stations' observations gives different results. It is usually possible to reduce the minimum variance in each case to a value which, whilst usually somewhat larger than one would hope for on a purely statistical basis, is not so large as to suggest that the approach is basically incorrect. This conclusion is supported by the fact that the statistical estimates used above are under-estimates of the actual statistical fluctuations of the observations of each detector (section 4.7.2).

The exponent p of the cosine (latitude) dependence is found to lie in the range 0.5 to 1.0, probably nearer the higher value. R_1 is indeterminate below 5 GV, and can therefore be taken as zero, since the detectors used have no significant response below the atmospheric cut-off about 2 GV. For sea-level stations at least the analyses are relatively insensitive to the coupling coefficients used. Inclusion of mountain stations increases the variance to somewhat larger values. The best estimates of the parameters from these analyses are therefore obtained from the sea-level stations only, with all doubtful stations excluded, and with p set equal to 1.0 and R_1 set at zero. Estimates obtained in this way are listed in table 4.9.

		From Minimisation of Amplitude		From Minimisation of Phase		No. of stations actually used	Excluded Stations
		Parameter Value	Corresponding Z	Parameter Value	Corresponding Z		
1961	β	-0.1 ± 0.2	15.1	0.6 ± 0.5	12.7	15	Brisbane, Kiel
	R_u	30 to 50	16.5	90^{+150}_{-45}	15.2		
1962	β	$0.2^{+0.1}_{-0.3}$	12.3	0.4 ± 0.3	11.7	15	Brisbane, Kiel
	R_u	50^{+70}_{-15}	13.4	90 ± 40	11.4		
1963	β	0.3 ± 0.3	8.5	0.2 ± 0.3	13.6	13	Buenos Aires, Munich, Kiel, Thule
	R_u	60^{+200}_{-30}	8.3	80^{+70}_{-30}	13.6		
1961-3 (Average)	β	-0.1 ± 0.2	30.4	0.5 ± 0.2	28.6	12	All above
	R_u	30 to 40	31.6	100^{+100}_{-25}	28.6		

Table 4.9 *Final results, first harmonic, from individual minimisation of amplitude and phase variance. The 17 sea-level stations only, less those indicated. Coupling coefficients : Webber and Quenby. $R_1 = 0$. $p = 1.0$. β estimates made with $R_u = 100$ GV, R_u estimates with β at available value nearest to that just found (table 4.1). The corresponding variance curves are shown in figure 4.17.*

There is no strong evidence as to which of the two sets of results presented are the more reliable, although one might suspect that the β

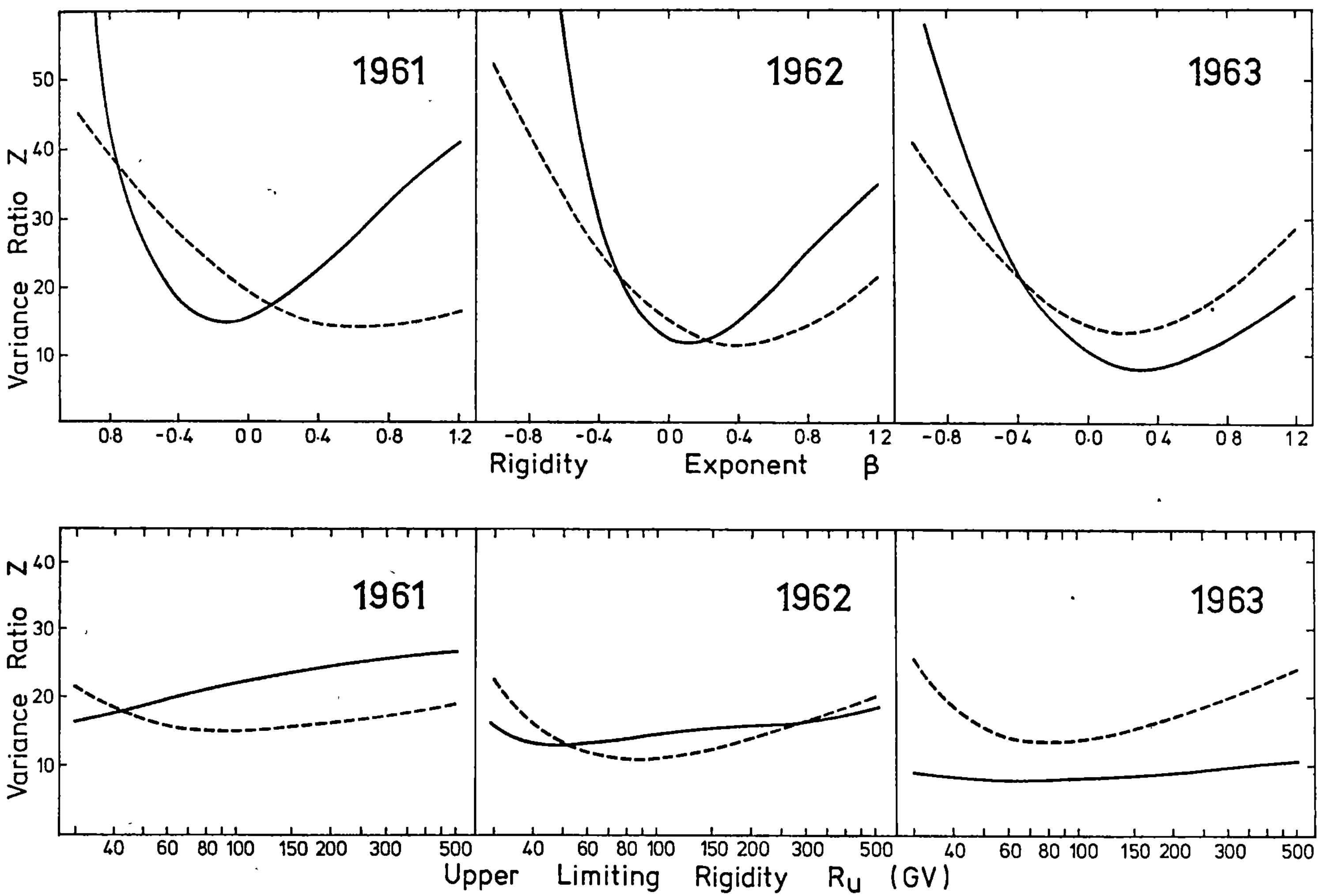


Figure 4.17. *Variance of estimates of free-space amplitude (solid curves) and phase (dashed curves) for varying β and fixed R_u, and vici-versa. Sea-level stations only, with doubtful excluded.* $p = 1.0$, $R_l = 0$ GV.

values obtained from amplitude minimisation, and the R_u values obtained from phase minimisation, are the more reliable, since the variance curves tend to be more sharply defined - and therefore less sensitive to individual station error - in the amplitude case for β and the phase case for R_u (figures 4.15 and 4.17). The tendency is not strong, however.

4.5 VECTOR VARIANCE ANALYSIS, 1961-1963.

The disagreement between the results achieved from the phase and amplitude analyses led to analyses based on minimisation of the amplitudes of the difference vectors, defined for each station as $\underline{r}_{s,m} - \bar{\underline{r}}_m$ (Section 4.2.4). Values of R_1 and p were set at 0 and 1.0, respectively as indicated by the previous results, and the 3-altitude coupling co-efficients of Lockwood and Webber (1967) were used in the hope of improving the usefulness of the mountain stations. To avoid the possibility of erroneous results due to use of an incorrect value of R_u (Section 4.5.5) 12 x 12 matrices (Section 4.2.5) of modulation coefficients were prepared to cover each possible combination of values, the sample variance of the difference vectors being found for each combination.

4.5.1 Comparison of different station groups.

Group A and Group B stations (table 4.2) were first studied separately It happens that the only doubtful station in Group A is rejected automaticall due to shortage of data but that this does not apply to Group B. Group B was therefore analysed including and excluding the doubtful stations. The results from the two groups (Table 4.10) differ, as the earlier work had predicted.

	Group A No doubtful Stations			Group B Including doubtful Stations			Group B Excluding Doubtful Stations		
	β	R_u	Corresponding Z	β	R_u	Corresponding Z	β	R_u	Corresponding Z
1961	0.4	80	14.1	0.0	50	58.4	0.0	60	28.2
1962	0.4	80	15.5	0.0	80	30.2	0.2	70	19.7
1963	0.6	70	14.9	-0.4	1000	29.5	-0.2	500	32.8

Table 4.10. Values of β and R_u for minimum variance of difference vectors. All stations used except those which do not meet the minimum percentage of data criterion (section 4.4.1.)

The Z values for Group B when doubtful stations are included are enormous; and there is a significant reduction when these stations are removed from the analysis. Even in this case however the Z values obtained are still too large to be attributable to statistical fluctuations, and it is noticeable that the parameter values obtained do not differ greatly whether or not the doubtful stations are included. The increase in Z for Group B in 1963 when the doubtful stations are excluded results from the elimination of Buenos Aires, whose vector, although suspect, was close to the mean vector for the year. Excluding stations regarded as doubtful, from study of their monthly vectors, does not bring Group A and Group B into agreement, although the discrepancies in the parameter estimates are marginally reduced in all 3 years.

All stations have been allotted equal weight in the analyses, disregarding differences in statistical accuracies due to differing count-rates.

Since the majority of the detectors involved are more or less standard IGY type monitors this seems a reasonable approach. However two stations in particular, Resolute and Thule, do have much lower count rates than the others and in consequence the standard deviations of their vectors are comparatively large. To eliminate possible errors due to the inclusion of such stations both groups were re-analysed with those stations eliminated whose individual standard deviations were greater than 2.0 times the mean standard deviation for all detectors in the group. The process generally made no difference to the estimated parameters but increased the minimum Z values obtained, since removal of such stations did not materially lower the observed variance but did considerably lower the expected variance, by removing the largest components of the latter.

Some stations have estimated vectors which appear to be considerably different from the mean. Automatic rejection of such stations was tried by eliminating from the analysis all those stations whose difference vector was greater than 5 standard deviations in length, on the grounds that such a difference vector was unlikely to be statistical in origin. For this purpose the standard deviation of the detector itself was used. The technique certainly eliminated the really discrepant stations but also tended to exclude high count rate detectors having small standard deviations Deep River and Jungfaujoch, for example, were excluded by this method. There is no justification for the exclusion of high count rate stations, and the method was abandoned. Results from these two trials for Group A stations in 1963 are presented in table 4.11, the corresponding vectors being displayed in figure 4.18. The low Z value obtained when stations were eliminated on the above grounds cannot be taken too seriously, due

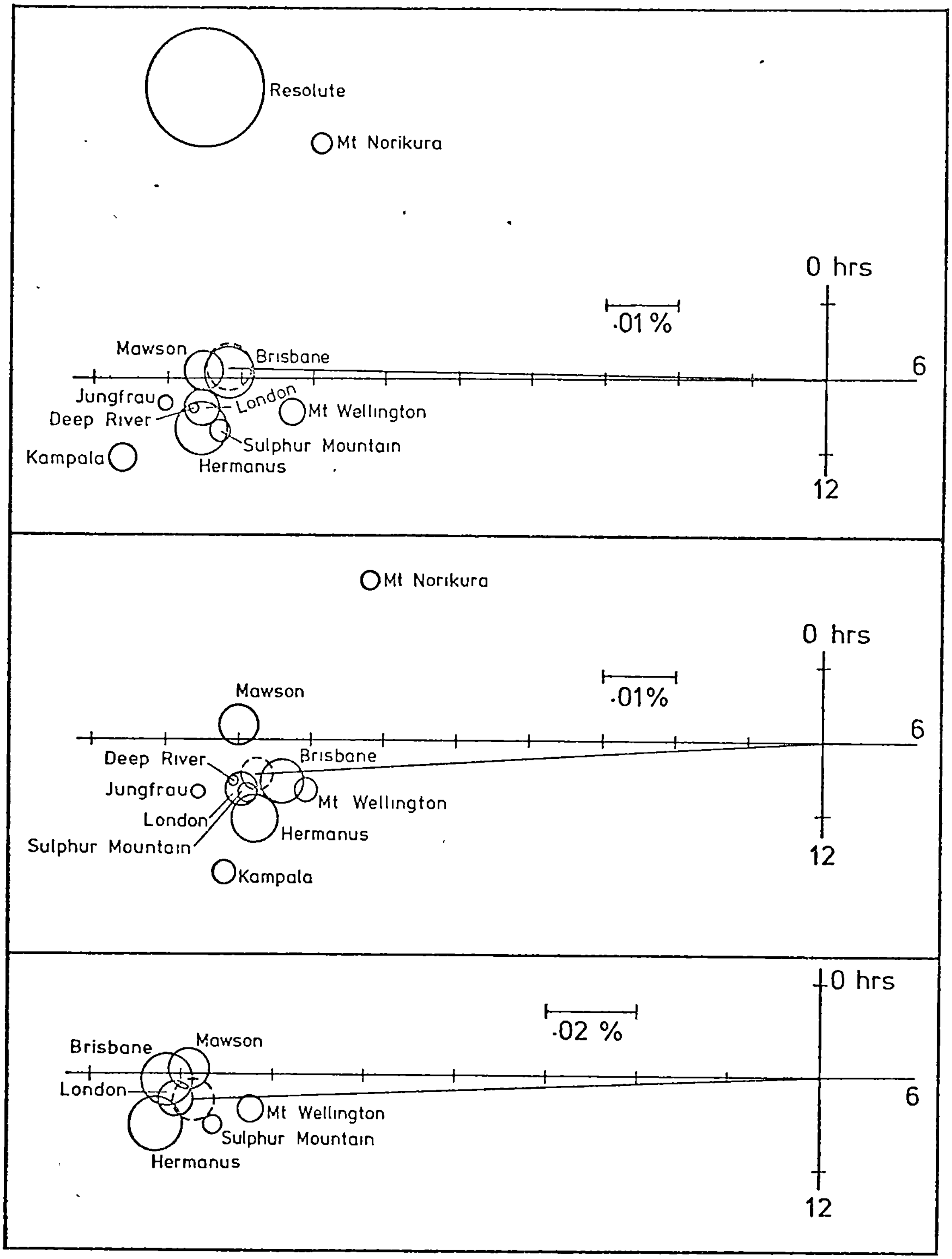


Figure 4.18. *Estimated free-space vector end-points which give minimum variance of difference vectors, Group A stations 1963.* Top - *all stations.* Centre - *Stations whose s.d. is greater than twice mean s.d. eliminated.* Bottom - *Stations in above group and also those whose difference vector > 5.0 times the station s.d. eliminated. The mean vector and its standard error circle (dashed) are also shown.*

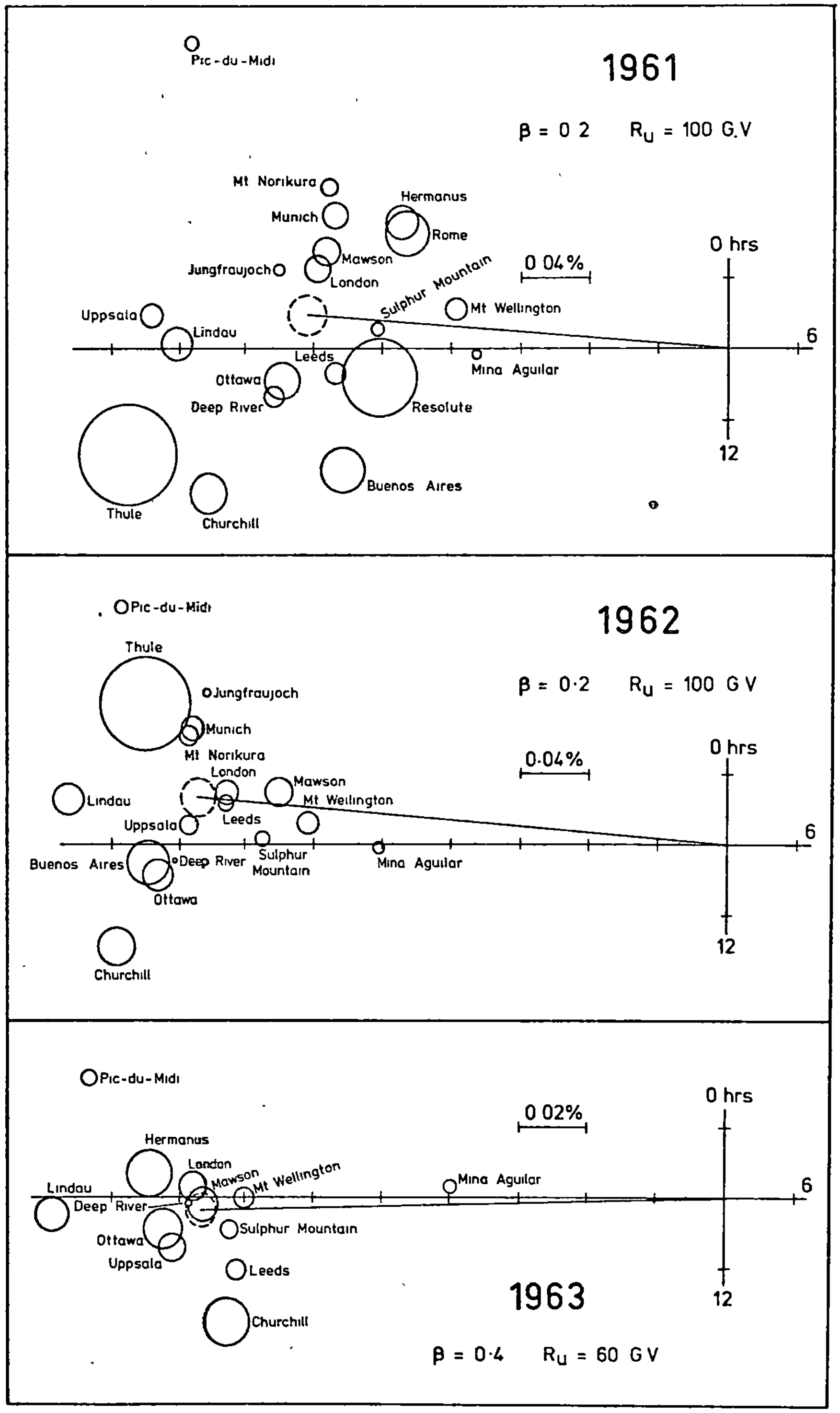


Figure 4.19. End points of estimated free-space vectors which give minimum variance of difference vectors for each year 1961 to 1963.

to the elimination process used. For the other years for Group A, and for all years for Group B, only 2 or 3 stations remained after elimination, supporting the view that the method is not useful.

Eliminated Groups	No. of stations remaining	Parameter Estimates β	R_u	Corresponding Z
None	11	0.6	70	13.93
Standard deviation) $\geq$ 2.0 x mean s.d.)	10	0.6	90	16.77
Ditto plus difference) vectors over 5.0 s.d.)	6	0.4	100	1.67

Table 4.11. Effect of removal of various groups of stations from analysis. Group A 1963.

4.5.2. 24 Stations analysis.

It is evident from Table 4.10 that the results obtained from the two groups are inconsistent. In consequence all stations were combined in one analysis in order to determine, if possible, causes of this discrepancy. Stations known to be doubtful were excluded at the outset. Analyses were performed including and excluding mountain stations. The initial results are summarised in table 4.12, and the estimated free-space vectors when mountain stations are included are presented in figure 4.19.

Year	Mountain Stations	No. of stations used	Parameter Estimates β	R_u	Corres-ponding Z
1961	Included	20	0.2±0.2	100	27.1
"	Excluded	15	0.0±0.2	500	17.6
1962	Included	17	0.2±0.2	100	23.5
"	Excluded	12	0.2±0.2	100	11.9
1963	Included	13	0.4±0.3	60	24.5
"	Excluded	10	1.2±0.8	40	6.5

Table 4.12. Estimates of β and R_u using data from all 24 stations except those classified as doubtful. Quoted limits are 95% confidence, based on counting rate of detectors.

It is noteworthy that the Z values are very significantly lower when the mountain stations are excluded. In 1963 this reduction appears to be accompanied by a tremendous change in β. This is the result of an abnormally flat variance curve.

4.5.3. Discrepant vectors.

Certain strange features are apparent in figure 4.19. There is a marked tendency for certain stations to occupy more or less the same relative positions on the plots from year to year, and some of these are drastically removed from the mean vector. The vector estimated from Pic-du-Midi is, for each year, significantly longer and later than the the mean vector for the year. In 1961 it is about 1.5 times longer than, and 100 minutes later than, the mean vector, and is about 1.25 times longer than, and 50 minutes later than, the mean vector in the other two years. Similarly the vector estimated from Mina Aguilar agrees reasonably well with the mean direction in all 3 years but is only about half the length of the mean vector in each year. Other less marked examples exist, Churchill for instance is always earlier than the mean vector, but about the same length, whilst Lindau and Mt. Wellington indicate the correct direction but give vectors which are somewhat long and somewhat short respectively. Mt. Norikura is generally rather later than other stations.

It is not possible to produce definitive explanations for these phenomena, although possibilities can be put forward. Pic-du-Midi, at 728 $gm.cm^{-2}$ atmospheric depth, is 48 $gm.cm^{-2}$ below the level of the coupling coefficients used, which will cause undue weight to be given to the rigidities around 5 to 10 GV in comparison with higher rigidities. This will result in β appearing to be a little more negative than it really is, which will have the effect of lengthening the estimated free-space vector by, qualitatively, about the right amount. This should not however have more than a 4° or 5° effect on the vector direction. The reverse argument applies at Mina Aguilar, which station is at a notably higher altitude than the coupling coefficient level. The estimated vector here may reasonably be expected to be short, as found. Against this argument however the estimated vector obtained from Sulphur Mountain is very close to the mean vector on each occasion, although, by accident, the 680 gm.cm.$^{-2}$ coupling coefficients were used although the station's atmospheric depth is 783 gm. cm^{-2}. The only practical solution appears to be the rejection of all mountain stations.

The consistent discrepancies of the other stations mentioned are rather smaller. The probability that they are statistical in origin is small. Gall, Jiminez, and Orozco (1969) have pointed out that for particles of rigidity less than about 5 GV the directions of approach at the magnetospheric boundary are not equal to the asymptotic directions of approach at 25 earth radii. The error increases as rigidity decreases, being very large below 2 GV. Furthermore they point out that the direction of approach is time dependent due to the asymmetric shape of the magnetosphere. The errors introduced by ignoring such deflections will affect about 10 to 12% of the particles recorded by a detector such as Churchill.

Ahluwalia and McCracken (1966) dealt with this problem in respect to the diurnal and semi-diurnal variations, and McCracken and Rao (1966) interpret their results as meaning that, on the average, the estimated free-space vector found assuming a spherical magnetosphere underestimates the actual free-space direction by 2 or 3 degrees. The correction is likely to vary from station to station and will tend to become larger at low cut-off stations. It need not however be consistent for different stations at similar cut-off rigidities; Gall et al have demonstrated that the differences between directions of approach and asymptotic directions vary very considerably for similar rigidities at different stations in the same general invariant latitude range. Without considerable computation it is not practicable to forecast the phase error which would be introduced into the estimated vector, but it does not seem likely that the deflection could reach 15° or 20°, which would be necessary to bring the Churchill vector into line with other stations, and there is no sign of any consistent discrepancies in the vectors obtained from the other high latitude stations used. This explanation for the anomalous result from Churchill is therefore probably incorrect. However no other plausible explanation is evident.

There is no reason to suspect any geophysical abnormality at Lindau, and in practice only the 1963 vector, which is excessively long, was rejected. The short Mt. Wellington vectors may be due to the use of sea-level coupling coefficients. The altitude of this detector is 725 metre. It was also found that Rome and Mt. Norikura were very much later than average in 1963, and these also were rejected.

4.5.4 Effect of excluding discrepant stations

The 1963 data were then analysed with and without the mountain stations and with and without the stations Lindau, Mina Agiular and

Churchill. Rome, Pic du Midi and Mt. Norikura were excluded throughout on the grounds of their discrepant vectors, and several other stations were missing due to lack of data. The results are summarised in table 4.13.

Mountain Stations	Questionable Stations	No. of Stations used	Parameter Estimates β	Parameter Estimates R_u	Corresponding Z
Included	Included	13	0.4	60	24.5
Excluded	Included	10	1.2	40	6.5
Included	Excluded	10	-0.2	1000	15.0
Excluded	Excluded	8	0.4	80	3.7

Table 4.13. 1963 data. Effect of excluding questionable stations.

Elimination of mountain and questionable stations enabled a reasonable Z value to be obtained for 1963. However the rather arbitrary elimination of some stations on the grounds that they disagree with the majority is not a valid procedure unless corrobative evidence is available. The above review demonstrates that, for 1963 at least, this evidence is only partially available. The difficulty then arises of rejecting some stations purely on the grounds that their results are not supported by other similar stations. The view has been taken that this is permissible if only a minority of stations do disagree for inexplicable reasons.

In 1961 and 1962 the matter is not so straightforward. These years, particularly 1961, were much more geomagnetically disturbed than was 1963, and the stations show a bigger general scatter in these years than they do in 1963 (figure 4.19). The detection and rejection of discrepant stations is much harder in such circumstances. The view has been taken that, as in 1963, the extremely low count-rate stations should be eliminated, together with the stations with the longest difference vectors, being for each year Churchill, Mina Aguilar, and Pic du Midi.

The results are presented in table 4.14. Note the difference between the table 4.13 and 4.14 results for 1963. Brisbane, against which no suspicion was laid, was inadvertently rejected from the table 4.13 run but has been included in the table 4.14 calculations.

Year	Mtn Sts	No. of Sts used	Parameter β	Parameter Range	Estimates R_u	Estimates Range	Minimim Z	Free Space Amp Const	Free Space Phase (LT)
1961	Inc	16	0.2	0.1 to 0.3	80	50 to 125	28.5	.243±.009	18.42±.15
1961	Exc	13	0.2	0.1 to 0.5	50	40 to 70	23.3	.268±.011	18.53±.16
1962	Inc	16	0.4	0.35to 0.7	90	75 to 105	23.5	.171±.004	18.17±.10
1962	Exc	12	0.4	0.2 to 0.45	90	65 to 120	20.4	.171±.005	18.16±.11
1963	Inc	12	0.8	0.6 to 0.85	60	55 to 90	5.0	.050±.002	17.70±.10
1963	Exc	9	0.4	0.2 to 0.5	100	75 to 500	3.3	.140±.004	17.73±.11
Mean 1961 -63	Inc	12	0.2	0.2 to 0.4	150	70 to 200	38.5	.248±.004	18.14±.06
	Exc	10	0.2	0.0 to 0.2	150	100 to1000	34.4	.248±.004	18.11±.07

Table 4.14. All doubtful and questionable stations rejected.

These results appear surprising in that β appears to remain positive for all periods. They correspond quite reasonably to the results obtained from minimisation of phase alone in table 4.9, but disagree with previously published results which indicated that β = 0.0, (McCracken and Rao, 1966) or possibly −0.1 or −0.2 (Faller and Marsden, 1966). The difference appears to arise from the assumptions of these authors that the upper cut-off rigidity is not a significant factor. In their original analysis of the IGY period Rao et al (1963) set R_u = 500 GV, and this value has been used in the various tables of variational coefficients published at, and since, that time (e.g., McCracken, Rao, Fowler, et al, 1965).

4.5.5 Effect of varying R_u

Figure 4.20 depicts a typical contour diagram, as a function of β and R_u, for variance values obtained in one of the analyses. It shows the trough which invariably runs across these diagrams. There are no statistical means for distinguishing between any of the (β, R_u) value pairs which fall within the trough. If a value of R_u is arbitrarily selected then a particular value of β will be obtained. However as the value of R_u is altered so the value of β obtained will alter, in the sense that β becomes more positive as R_u is decreased.

The contours in figure 4.20 are plotted at intervals equivalent to twice the statistically expected variance of the data, the innermost one being at this level above the minimum calculated variance anywhere in the diagram. There is therefore, on purely statistical grounds, a 95% probability that the actual value pair will lie within the confines of the innermost trough. It will be argued later (section 4.7) that the total errors inherent in this type of analysis should be assessed at not less than twice the apparent purely poisson statistical error, and in this event 95% probability applies to the region within the second contour.

Contour plots similar to figure 4.20 have been drawn for many of the combinations of stations which have been discussed in the preceeding sections

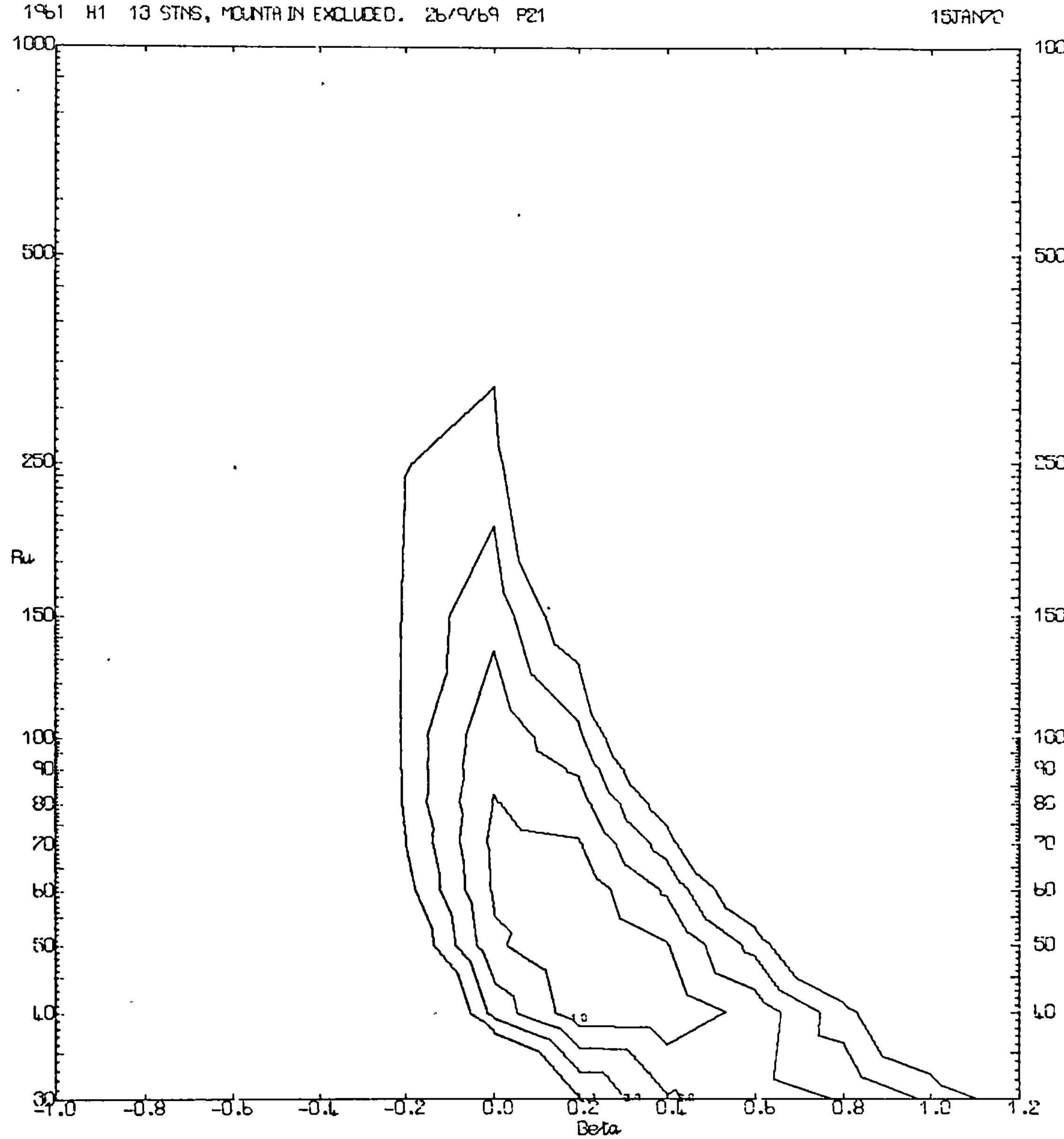


Figure 4.20. *Contours of constant variance of free-space difference vectors. The contour irregularities result from the coarse sampling employed (section 4.2.5).*

In most cases the major part of the region inside the innermost contour lies in the range of positive β, generally within an R_u range from 150 to 50 GV, thus indicating that the likely situation should in practice be represented by a positive value of β associated with an R_u value in the above range. The conclusion is not altered by using a greater estimate of error (except that the range of R_u is increased) since the second contour is generally approximately concentric with the innermost one.

The difference between the β values obtained from the fixed R_u and variable R_u assumptions is clearly shown in table 4.15. The values are obtained from minimum variance in the normal way.

Year	Mountain Stations	No. of Stations used	Column A β for R_u 500 GV	Column B β found for variable R_u in this analysis u_β	Range
1961	Included	16	0.0 ±.05	0.2	0.1 to 0.3
1961	Excluded	13	-0.1 ±0.1	0.2	0.1 to 0.5
1962	Included	16	0.2 ±.05	0.4	0.35 to 0.7
1962	Excluded	12	0.1 ±.05	0.4	0.2 to 0.45
1963	Included	12	0.25±.05	0.8	0.6 to 0.85
1963	Excluded	9	0.15±.05	0.4	0.2 to 0.5
Mean)	Included	12	0.00±0.1	0.2	0.2 to 0.4
1961-3)	Excluded	10	0.00±.05	0.2	0.0 to 0.2

Table 4.15. Comparison of rigidity exponents found for R_u = 500 GV and for variable R_u.

The β values found in column A are slightly more positive than those previously reported by other observers. However the difference is insignificant in 1961, and only barely significant in 1962 and 1963. In contrast the column B values are significantly different from earlier results.

The ranges of β quoted in table 4.15 are calculated from Poisson statistics. Substitution of more realistic error calculations (section 4.7.6) widens the ranges without altering the basic conclusion.

4.5.6 Estimates of Errors

In the simple case of variation of variance with only one variable a curve is obtained from which the minimum value of the variance, the corresponding value of the variable, and its likely statistical error, can be read directly (figure 4.17). When two variables are involved the situation depicted in figures 4.20 arises. Whilst it is easy to locate the point of minimum variance, and read off the corresponding values of the variables, there must be some confusion about the errors to be associated with each variable. Figure 4.21 depicts the innermost contour associated with a bi-variate variance plot. The position of minimum variance is indicated. Errors could be specified as the displacement of the particular variable from its minimum variance value whilst the other variable is held constant, as represented by the cross in the diagram. Alternatively it is possible to quote error limits of one variable as the extreme limits of values of that variable which are statistically insignificantly different from the minimum variance value, regardless of changing values of the other variable. This situation is represented by the bars on the outside of the contour in figure 4.21. Clearly the two extreme possible values of one variable, β say, are necessarily not associated with the same value of R_u.

The error limits quoted in tables 4.14 and4.15 are calculated on the lastmentioned basis, and can therefore be regarded as extreme limits. Due

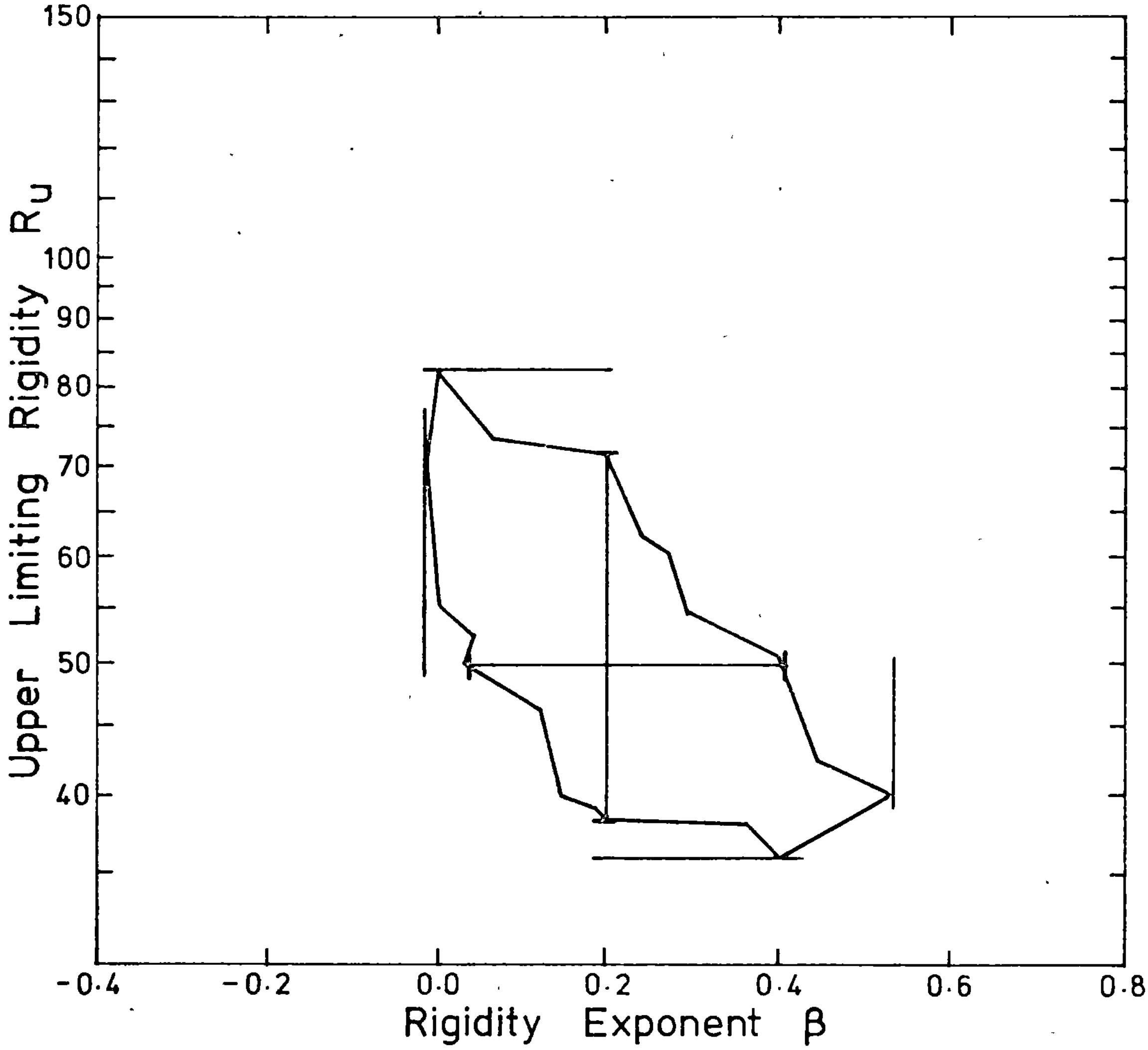


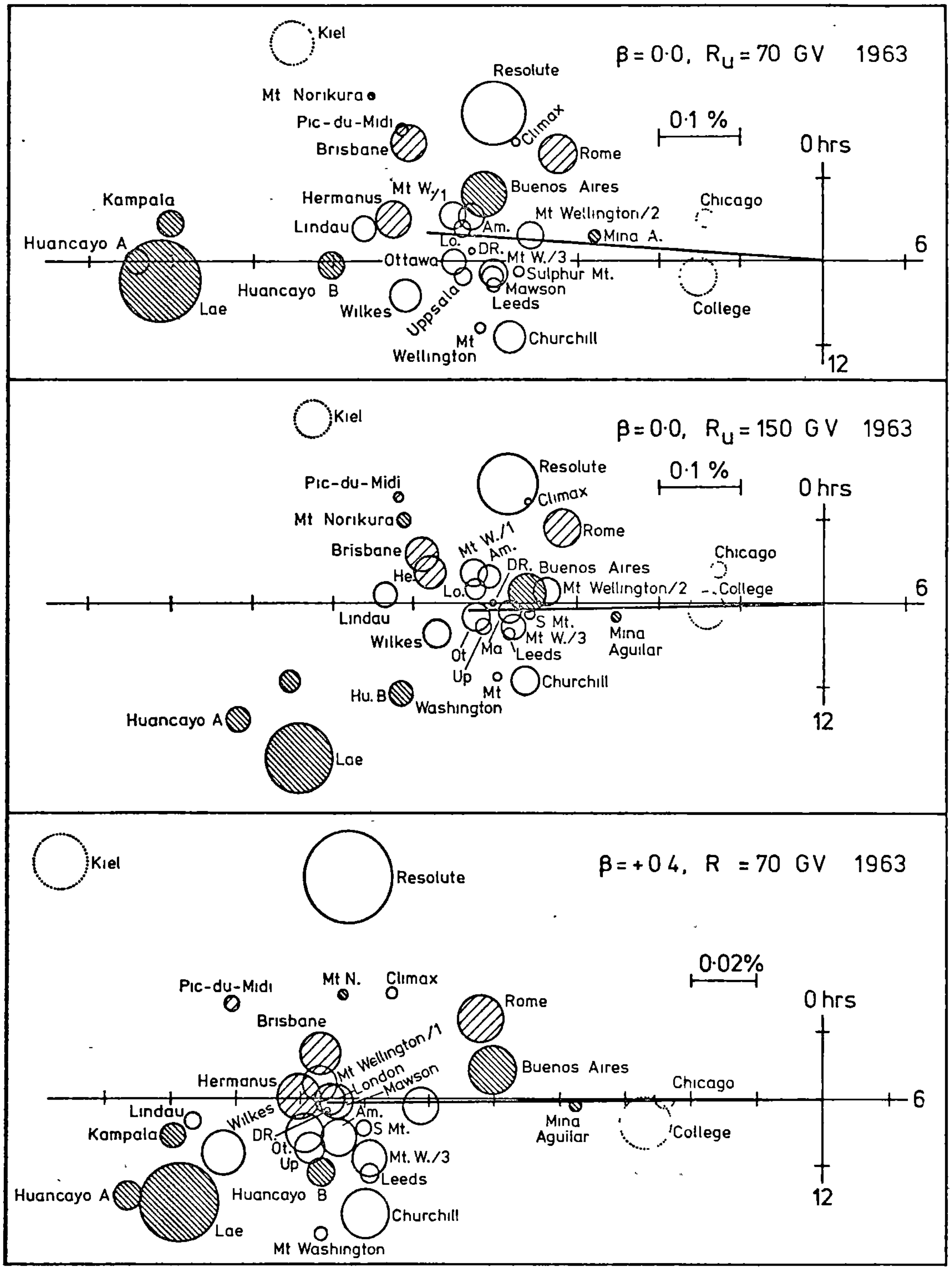
Figure 4.2.1. *Possible descriptions of statistical limits of parameters (see text).*

to the awkwardness of expression the statistical errors have not been quoted in most of the comparitive tables in this chapter, but it may be generally understood that in most cases the statistical limits are of order ± 0.15 for β and ± 15% for R_u.

4.5.7 Effect of inclusion of further neutron data

The stations used in the analyses described in section 4.5.4, after stringent tests to exclude possible faulty data, were limited both in number and geographic distribution. Elimination of the mountain stations excluded all stations with vertical cut-offs above 7 GV, and in fact only Brisbane and Rome had cut-offs above 3 GV. This was manifestly unsatisfactory, as the responses of most of the remaining stations tended to vary in rather similar fashion as the parameters were varied. The variance curves were therefore flatter than is desirable.

A further study of the 1963 diurnal variation was therefore carried out, incorporating every item of data which was available in Hobart. These included data from Lae and Wilkes, both excluded from the original analyses since no 1961 or 1962 data were available; Amsterdam, Chicago, Climax, College, and Mt. Washington. Huancayo, excluded from the original analyses by virtue of its poor percentage availability of data, was also included. Both sections of the Huancayo monitor, and all three sections of the Mt. Wellington monitor, had been harmonically analysed separately, and these were included as separate observations. Figure 4.22 shows the free-space vector end points, and their associated error circles, for three different combinations of β and R_u in 1963. Vectors are plotted from all available stations, regardless of their suspected accuracy. Individual sections of some detectors are plotted separately. A total of 31 estimated



<u>Figure 4.22.</u> End-points of free-space vectors estimated for three different combinations of β and R_u in 1963. The mean vector is indicated in each case, for clarity, without its error circle.

vectors, obtained from 28 different observing sites, appear in each section of the figure. The cut-off range of each detector is indicated by the degree of shading, or lack of it, in the error circle. The vectors for Mt. Norikura are advanced by one hour from their apparent direction to compensate for wind-induced errors on the barograph at the station (Chiba and Kodama, 1969). Comparison of this figure with figure 4.18, in which the Mt. Norikura vectors are not corrected in this way, suggests that the correction, which was derived by Chiba and Kodama in a quite different way, is approximately correct.

In figure 4.22 the vectors for Kiel, College, and Chicago, are very different from those of other similar stations. Their error circles are dotted for identification, and the vectors have been omitted from subsequent analyses, Kiel for the reasons discussed earlier in this chapter and College and Chicago since the vectors appear to be anomalously short.

The pairs of parameters employed in these figures are ($\beta = 0.0$, $R_u = 70$ GV); ($\beta = 0.0$, $R_u = 150$ GV), and ($\beta = 0.4$, $R_u = 70$ GV). Visual inspection of the diagrams indicates that the first of these provides the poorest fit, there being perhaps not much to choose between the second and third possibilities. This is confirmed by variance calculations.

Indication of the detector vertical cut-off range demonstrates the greater scatter of amplitudes of the high-cut-off stations as compared with those of low cut-off. There is a curious anomoly in that whilst the vectors associated with Huancayo Section A, Kampala, and Lae, appear to be unreasonably long they all agree so well as to make it impossible, in the lack of further evidence, to reject them. It is certain that these long vectors cannot be due to incorrect air mass correction coefficients (section 4.7.3) and it seems unlikely that barographs would display equal errors at all these stations. However a triple co-incidence cannot be ruled out, particularly as there is no means of knowing which of the two Huancayo sections is correct. Of the three sets of vectors plotted the variance of the vectors is least for the case ($\beta = 0.4$ $R_u = 70$ GV) both when the above stations are included and when they are excluded.

The results of full-scale analyses including and excluding these three detectors are compared in table 4.16 with the results obtained previously (table 4.14) following the most rigorous of the station selection procedures. The values obtained using the large number of stations differ only marginally from those obtained in the original analysis, except that the observed value of Z is much higher.

Analysis	No. of stns used	β	Range	R_u	Range	Z	Amp Const	Phase (Hours, LT)
Final Original Analysis, Mountain Excluded	9	0.4	0.2to0.5	100	75to500	3.3	.140±.004	17.73±.11
All available stations	28	0.6	0.4to0.8	70	50to 70	13.5	.088±.004	17.92±.18
All available stations except Lae, Kampala, Huancayo A	25	0.2	0.1to0.5	70	60to150	11.9	.243±.011	18.07±.18

Table 4.16. *Effect of including all stations, 1963 only.*

4.6. VECTOR ANALYSIS, 1964-1966.

As a result of the analyses of the 1961 to 1963 data it was decided to proceed directly to a vector variance analysis of the 1964 to 1966 observations, without studying the effects of separate variance analyses of amplitude and phase of the free-space estimated vectors. For the same reason the lower cut-off rigidity, R_1, was set at zero and the latitude dependence was assumed to be pure cosine.

4.6.1. Availability and grouping of stations.

This period was one of change of equipment in cosmic ray observatories throughout the world. Some old detectors were closed down, other new observatories were opened, and some installations were changed from IGY type to NM64 type Neutron monitors. These changes had a restrictive effect on the availability of some stations through the period.

The analysis of the 1961-3 data has appeared to show that increasing the number of detectors beyond a dozen or so does not produce a significantly different result, nor, apparently, a more highly significant result. Since the data preparation time and computer run time are both directly proportional to the number of stations in the analysis there are good reasons for using as few stations as possible, consistent with the use of a good distribution in cut-off rigidity of reliable detectors. These considerations led to the choice of 14 detectors, as listed in table 4.17.

Station	Vertical Cut-off Rigidity (GV)	Altitude	Notes
Wilkes	<0.05	Sea level	
Mawson	0.22	" "	
Deep River	1.02	" "	
Kerguelen	1.19	" "	
Mt. Wellington	1.89	725 m	
Leeds	2.20	Sea level	
Lindau IGY	3.00	" "	
Lindau NM64	3.00	" "	Commenced Nov 1964
Pic du Midi	5.36	2860 m	
Rome	6.31	Sea level	
Brisbane	7.20	" "	
Mina Aguilar	12.51	4000 m	
Haleakala	13.30	100 m	
Lae	15.52	Sea level	Some data missing

Table 4.17. Neutron detectors used, 1964-1966. Due to the small number of stations used no attempt was made to divide them into two groups.

4.6.2. Consistency of observed harmonic vectors

Visual inspection of annual summation dials of monthly vectors was again carried out. As in earlier years some stations did not appear to agree with the remainder. Those stations which were, by inspection, clearly erroneous were classified as rejection stations whilst others, concerning which some doubt could clearly be expressed, were classified as doubtful.

In 1964 Lae was rejected, due to 4 months of missing data and some erratic vectors. Erratic mid-year vectors at Brisbane and Mina Aguilar caused these stations to be considered doubtful in the same year. In 1965

Mina Aguilar was rejected, due to erratic short monthly vectors, and Lae was classified as doubtful as the mean annual vector appeared to be much too early. In 1966 Haleakala (erratic vectors) and Lae (early time of maximum) were classified doubtful.

4.6.3. Results of variance analysis

Year	No. of Sts	Classifi-cations Excluded	β	Range	R_u	Range	Corresponding Z	Mvar	Evar	Amp	Phase
1964	13	None	1.2	>1.1	30	<35	17.3	6.63	.38	.022	18.04
"	12	Reject	1.2	>1.1	30	<40	35.4	6.56	.18	.021	18.08
"	10	Reject & doubtful	1.2	>1.1	30	<35	23.3	3.72	.16	.023	17.99
"	8	Reject & doubtful & mtn.	0.2	0.15to0.9	40	35to90	12.9	2.57	.20	.263	18.33
1965	14	None	1.2	>1.1	30	<35	39.4	16.5	.42	.017	17.88
"	13	Reject	1.2	>1.1	30	<35	31.4	12.8	.40	.018	17.80
"	12	Reject & doubtful	1.2	>1.1	30	<35	24.1	6.58	.28	.017	18.08
"	10	Reject & doubtful & mtn.	0.4	0.0to0.8	50	30to150	18.1	6.35	.36	.176	18.18
1966	14	None	1.2	>1.1	30	<35	56.5	17.7	.32	.016	17.77
"	12	Doubtful	0.0	-0.1to0.3	50	35to65	20.9	3.80	.18	.464	18.61
"	10	Doubtful & mtn.	0.6	0.2to0.8	30	<45	20.5	3.89	.18	.120	18.47

Table 4.18. Results of variance analysis 1964 to 1966. Mvar is the measured variance of the estimates of the free-space vectors, evar is the statistically expected value of this quantity.

Seven of the analyses listed in table 4.18 appear to produce ridiculously high values of β. These analyses all include observations from Haleakala, whereas the other analyses in the table omit this station. Inspection of the free-space vector estimates shows that the vectors estimated from the Haleakala observations are too long, in each of the three years, when compared with those from other stations. The only way to bring the vectors down to an acceptable length is to impose a higher value of R_u, the effect of which is to further increase Z but to decrease the value of β. Such a parameter change shortens the vectors obtained from high cut-off detectors, and shifts them to earlier times of maximum. In 1965, for instance, changing R_u from 30 to 60 GV, and minimising β alone, alters the value of β obtained from 1.2 to 0.6 whilst altering the phase obtained from the Haleakala detector from average (compared with the other stations) to $1\frac{1}{2}$ hours earlier than average. The corresponding change in Z is from 24.1 to 27.3. Omitting Haleakala entirely (together with Pic-du-Midi) reduces Z to 18.1, corresponding to ($\beta = 0.4$, $R_u = 50$ GV).

This example illustrates the importance of accurate phase information from equatorial detectors. Figure 4.23 shows the variation of estimated phase with β for several detectors and it is clear that the effect is most pronounced at the higher cut-off detectors. Unfortunately, as mentioned earlier, it is just these stations which appear to be most prone to instrumental and other troubles. It is known that the Lae instrument appears to have an unduly early time of maximum, which is tentatively attributed to local temperature effects. Whilst one must sincerely hope that most detectors are more adequately housed than is the one at Lae one must wonder whether some such effect is a possibility at Haleakala. Whatever the reason for the apparent discrepancy Haleakala was rejected from the final analyses in all years on the grounds of the apparently discrepant vectors and the reduction in Z achieved by its exclusion.

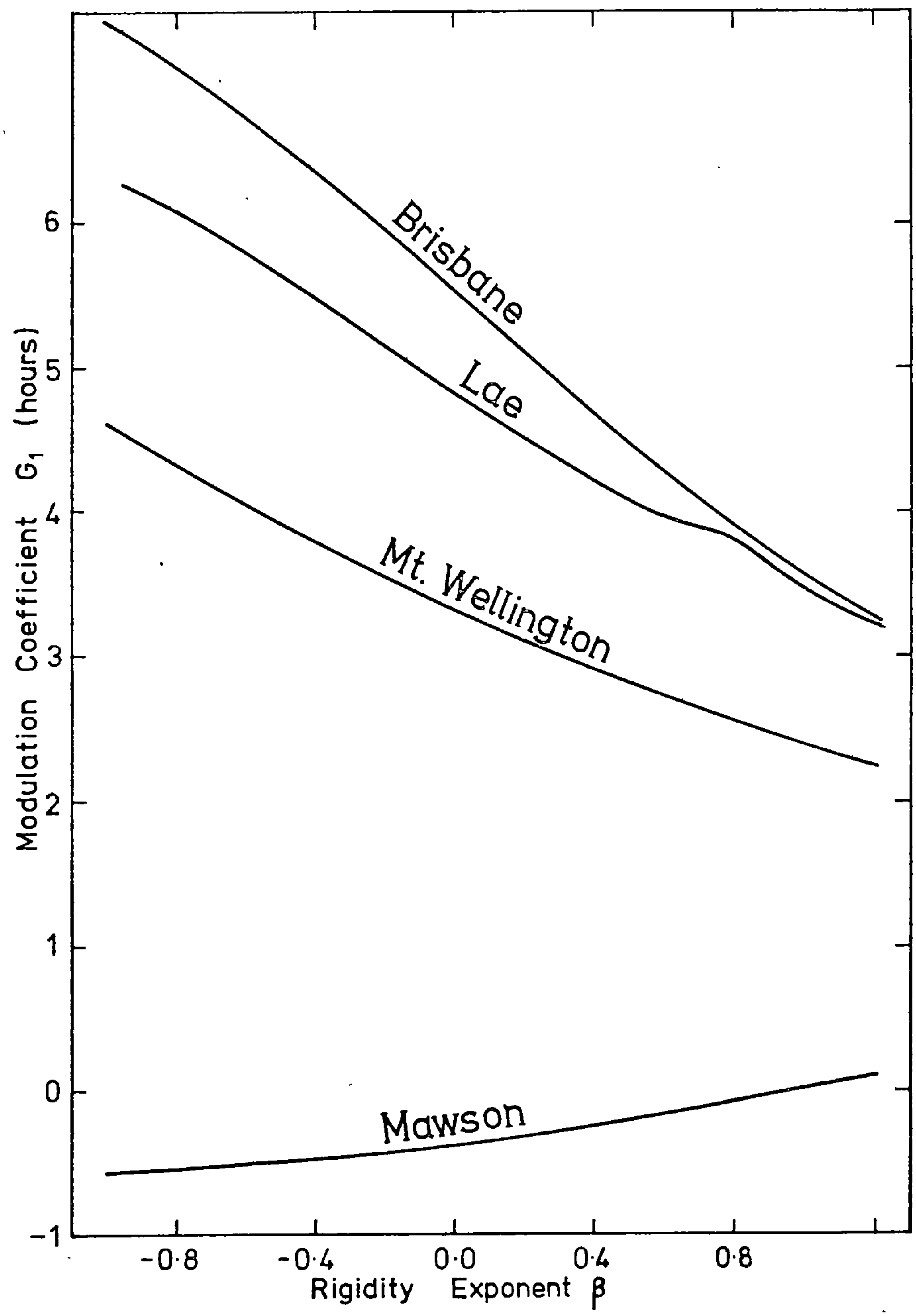


Figure 4.23. *Variation of phase modulation coefficient with* β *for various neutron monitors.*

It was later found that the scatter in the data at Haleakala is much greater than would be expected on purely statistical grounds (section 4.7.6), thus justifying its exclusion here.

4.7. POSSIBLE ERRORS IN THE ANALYSES.

If the data fit the model exactly, and no unaccounted factors exist, the minimum values of Z obtained in the final analysis for each year should be of order unity. Table 4.20 lists the values actually obtained in each year. The model clearly does not absolutely account for the observations. Either the model is incorrect, either wholly or in part, computation of the estimated variance is in error, or other spurious effects exist.

	1961	1962	1963	1964	1965	1966
Minimum Z	23. 3	20. 4	3.3	12.9	18.1	20.5
Measured Variance	7.34	2.98	.595	2.57	6.35	3.89
Estimated Variance	.31	.15	.18	.20	.36	.18

Table 4.20 Variance of best fit results, 1961 to 1966.

4.7.1. Possible criticism of the model.

Evidence obtained by other authors, both with neutron detectors (e.g. McCracken & Rao, 1966), and various combinations of muon telescopes and neutron detectors (e.g. Jacklyn, Duggal, & Pomerantz, 1970), together with the evidence from the Hobart underground muon telescopes (chapter 5), suggests that the basic model is likely to be sound. It is, however, an oversimplified description of the free-space anisotropy, on two counts. It is an averaging model, which represents an attempt to gain gross information about a phenomenon which is known to be quite strongly time dependent The averaging process is necessarily crude, and, due to the very fact of varying responses at different stations, will not have quite the same effect at each station. A certain amount of "noise" will therefore be introduced to the analysis.

Secondly, the assumption of a sharp upper cut-off rigidity is obviously not a physically justifiable procedure. In practice the mechanism responsible for the diurnal variation is likely to gradually lose efficiency as particle rigidity rises beyond a particular value. It may be speculated that the mechanism will have no effect at rigidities higher than twice the characteristic rigidity at which it ceases being fully effective. The efficiency may or may not decline in a linear manner. Regardless of the actual form of the diurnal variation dependence at these rigidities, substitution of a sharp cut-off will cause an error in the free-space vector computed from the observations of any particular detector. Since equatorial neutron monitors are more sensitive to changes in R_u than are higher latitude detectors it may be expected that this effect will cause greater errors at equatorial than at high latitude detectors, thereby introducing more noise to the analysis.

This point requires further investigation. It has deliberately not been probed at present due to limitations of time and computer facilities. This thesis is primarily concerned with determining, if possible, a value of R_u for the model used, rather than with detail refinements of the model.

4.7.2 Statistical accuracy of detectors

The expected variance of the free-space vectors is obtained from the purely poisson statistics of the individual detectors (Section 4.2.6).

$\sigma^2 = \frac{1}{n} \sum_{s=1}^{n} \sigma_s^2$ where σ_s^2 is the variance associated with the vector recorded at the s^{th} Station. It is possible to test whether this expression does or does not correspond to the variance of the actual diurnal or semi-diurnal vectors observed by a detector.

Most neutron monitors are operated in two or three sections, generally arranged side by side in a single laboratory. The monitors operated by the Chicago and Hobart groups, and probably most others, have totally separate electronic and recording systems for each section. The ratios of the counting rates of the various sections are used to detect instrumental and electronic faults as they occur, and also to attempt to keep track of changes in the overall detection efficiency of the monitors. The only coupling between the sections arises from a small percentage, estimated at about 4% for a duplex IGY monitor (McCracken, 1958), of thermal neutrons which originate in the producer of one section and are detected by the BF_3 counters in an adjacent section. This has an insignificant effect on the standard error of the section.

In normal operation the readings from a single barometer are used to pressure-correct the data obtained from all sections. Any residual pressure related vector would therefore be the same for all sections. Likewise atmospheric temperature changes will effect each section equally. For any given period therefore the scatter between the vectors recorded by the various sections should be purely statistical in origin, unless the sections have, for some reason, different sensitivities to periodic changes in laboratory temperature, a.c. supply voltage, or some other environmental factor.

A suitable test of the accuracy of the estimated variance of, say, the amplitude of the vectors recorded by a given detector is to compare the sample variance, S^2, between the amplitude recorded by each section for a given period, with the estimated variance, σ^2, of the amplitude for the same period. In the absence of errors of the types discussed above the value of Z obtained by this process should belong to a population which has a Gamma distribution, as outlined in section 4.2.7. A number of independent estimates of Z may be obtained using data from non-overlapping periods. The distribution of Z obtained will be extremely skewed, since the number of observations, n, contributing to each sampling of Z corresponds to the number of sections in the detector, normally 2 or 3. A mean value of Z, $\overline{Z}$, may be obtained, and if sufficient observations are available this should approach the value E(Z) expected from the properties of the distribution (Eqn 4.26).

Diurnal and semi-diurnal vectors have been obtained for each section of the Huancayo, Mawson, and Mt. Wellington monitors for each month of the period 1961 to 1963. Values of Z have been calculated for the scatter of amplitude, phase, and vector, for each month, station, and harmonic. Thus 36 values of Z are available for each station and quantity. The means of these values, averaged over the 36 months, provide experimental estimates of the mean values of Z. They are presented in table 4.20, together with the expected values, E(Z).

In computing the results the same days of data have been used for all sections at Mawson, and at Mt. Wellington. Frequent gaps in the data prevented this being done at Huancayo, where there are some differences between the days used for each section in most months. However this does not account for the very large Z value observed for the first harmonic

Station	Pressure Corrected	No. of sections	E(Z)	First Harmonic Amplitude	First Harmonic Phase	First Harmonic Vector	Second Harmonic Amplitude	Second Harmonic Phase	Second Harmonic Vector
Huancayo	Corr.	2	0.5	7.47	1.09	4.29	2.28	2.55	2.33
Mawson	Uncor	3	0.67	1.09	1.07	1.15	0.76	1.25	1.15
Mt. Well.	Uncor	3	0.67	1.31	1.62	1.47	1.07	1.13	1.09
Mt. Well.	Corr.	3	0.67	1.40	1.59	1.17	0.94	0.94	1.11

Table 4.20. Mean of 36 independent observations of Z for various quantities.

amplitude, and also vector, at Huancayo. This is primarily due to the systematic manner in which the diurnal amplitude recorded by section A of the Huancayo instrument is generally larger than that observed by section B. The average value, from 1961 to 1963, of the ratio of the amplitudes recorded by the two sections is 1.35. Very large ratios are observed for some months, leading to correspondingly large Z values. It must be assumed that this is an instrumental effect, particularly since the variance of the phase observations appears to be normal.

The relatively small differences between the values obtained from pressure corrected, and uncorrected, data at Mt. Wellington bear out the assertion above that effects common to all sections will have only small effects on the scatter of vectors.

It is noticeable that every value of $\overline{Z}$ is greater than its expected value. The average ratio $\overline{Z}/E(Z)$ for Mawson and Mt. Wellington (uncorrected) amplitude and phase, both harmonics, is 1.8 whilst the same ratio for the vectors at these stations is 1.9. Two points emerge from this result. Firstly, the normal poisson statistics appear to persistently underestimate the errors inherent in the calculation of harmonics, as has been reported previously (e.g. Sandstrom, 1965). Secondly, the approximation (section 4.2.6, eqn. 4.24) that the variance of the difference vectors is approximately twice the variance of the amplitudes of the estimated vectors themselves, is verified. The predicted equality of the variance of each harmonic for a given detector is also confirmed.

The first of these points may be confirmed by inspection of the distribution of Z. Since Z is a Gamma variate, (nZ) is distributed like χ^2 with (n-1) degrees of freedom (Weatherburn, 1949), and the chi-square test can therefore be applied. For a single observation of (3Z), corresponding to the value of 3Z obtained for a single month, there is a probability of 0.2 that the value observed will exceed 3.22 in random sampling (χ^2 Probability Table, op. cit.). Therefore the probability that an observation of Z will exceed $\frac{1}{3}(3.22)$, i.e. 1.07, will also equal 0.2 in random sampling. However study of the distribution of Z obtained for the amplitude of the first harmonic at Mawson shows that 17 out of the 36 observations exceeded 1.07, and at Mt. Wellington 16 out of the 36 exceeded it. Similar results are found from the distributions of Z for phase observations. Likewise the expected median value of Z, which has a probability of 0.5 of being exceeded in random sampling, is in fact exceeded by 25 out of the 36 first harmonic amplitude Z values at each station.

The variate of the distribution is now rescaled, such that the new variate, Z', is given by

$$Z' = \frac{Z}{1.8} \qquad 4.27$$

This is done on the basis of the observed ratio of E(Z) to $\overline{Z}$, and is equivalent to defining Z' as $S^2/(\sqrt{1.8}\sigma)^2$, in effect increasing the estimated standard error of the quantity involved by $\sqrt{1.8}$, that is, 1.36. The distribution of Z' should now fit the distribution originally predicted for Z above.

Combining the Z' values for first harmonic amplitude at Mawson and Mt. Wellington it is found that 16 out of 72 (22%) of observations of Z' exceed 1.07, compared with 20% to be expected from random sampling, and 35 out of 72 (49%) exceed the expected median value. The separate distributions for each station give results which are statistically indistinguishable from these figures. It therefore appears that the distributions do have their predicted shape, thus confirming that the observed standard error of amplitudes of the vectors appears to exceed the statistically predicted value by a factor of order 1.36 at both Mawson and Mt. Wellington.

It is thought that this is due to the combined effect of a number of factors which are in themselves small. The estimated 4% coupling between the sections has already been referred to. About 12% of the thermal neutrons recorded by an IGY type neutron monitor are products of multiple events in which a single nucleon incident in the pile gives rise to two or more detected thermal neutrons. Both these effects will slightly lower the effective number of independent secondary neutrons recorded by each section, thereby increasing the standard error of observation. McCracken (1958) has shown that random errors in pressure measurements contribute to increasing the observed variance of hourly and daily mean data; these will have a proportional effect on data averaged over longer terms.

Considerable care has been taken with both installation and operation of the Mawson and Mt. Wellington monitors, and it is hoped that their performance is at least average when compared against other detectors of the world-wide network. On these grounds, a realistic estimate of the variance of the harmonic vectors, or of their amplitudes or phases, is double the statistically expected variance of these quantities.

4.7.3 Effect of use of an incorrect barometer coefficient

Variations in atmospheric pressure tend to be almost entirely irregular in polar regions, gradually taking on a more regular character as the observer moves towards the equator. The regular variations are principally semi-diurnal but diurnal variations do exist at some stations. At any given station the mean annual vectors, both diurnal and semi-diurnal, are remarkably consistent from year to year.

Station	Approximate Latitude	Diurnal		Semi-diurnal	
		Amplitude (mb)	Time of Maximum (Hours L.T)	Amplitude (mb)	Time of Maximum (Hours L.T)
Godhavn *	69^o	.13			
Mawson	-63^o	.07	18.8	.03	9.0
Prague	50^o	.32	4.7	.39	10.2
Christchurch *	-44^o	.47			
Hobart	-43^o	.39	2.2	.62	9.3
Mt. Wellington	-43^o	.12	19.4	.53	9.4
Rome	41^o	.23	3.9	.47	10.1
Cheltenham *	38^o	.67			
Kula	20^o	.21	3.5	.92	9.5
Chacaltaya	-16^o	.20	8.7	.77	10.1
Huancayo *	-12^o	1.3			
Kodaikanal	10^o	.28	13.2	1.31	11.7
Lae	-6^o	.84	4.4	1.25	9.6

*Table 4.21. Average annual mean Diurnal and Semi-Diurnal Pressure Vectors at various stations. Amplitudes for stations marked * due to Forbush (1969). Remaining values from analyses by the author. Variations from year to year generally do not exceed ±0.5 mb and ± 0.4 hours.*

The semi-diurnal vectors presented in table 4.21 show consistency of phase throughout, and steadily increasing amplitude as the detector latitude becomes lower. This effect is well known to Meteorologists and is connected with atmospheric tidal effects. However the irregularity of the diurnal vectors between stations suggests that these vectors may be due either wholly or partly to local effects, such as undetected temperature variations in the barometers, or diurnal air-flow changes causing Bernoulli effects on the pressure readings. This suggestion is partially supported by the differences shown between the Mt. Wellington and Hobart barometers, which are separated by about 8 km. horizontally and 700 m. vertically and which show very similar semi-diurnal vectors but totally different diurnal ones. The Hobart records are corrected for instrumental temperature variations, the Mt. Wellington aneroid instrument was temperature compensated, and both were operated under a moderate degree of temperature control. Nevertheless the fact remains that it is not conceivable that the diurnal variation in the air mass over two stations 8 km. apart should be so different, and the discrepancy must be attributed either to local air movement effects or to instrumental problems. It is not immediately possible to say which, if either, set of results represents the true diurnal variation of the air mass over Hobart. In the following discussion therefore, concerning errors due to such variations, the larger of the two figures has been employed.

The difficulties involved in obtaining a correct value of the barometer coefficient for any given neutron monitor have already been discussed (section 2.2.1). A retrospective study of the type carried out by Bachelet, Dyring, Iucci, and Villoresi (1967), hereafter called the BDIV study, is really necessary if accurate coefficients are to be obtained.

The BDIV study presented the first definite evidence that barometer coefficients are solar cycle dependent. It also shows quite clearly that the statistical error tails on coefficients derived during the IGY are greater than those derived in later years (figure 4.24). As a consequence of these two facts most investigators determined coefficients for their instruments during the IGY, and retained the same coefficients for some years, regarding the values they were using as being the best obtainable. At some stations a single change in coefficient was made at some time between 1961 and 1966. Such changes have all tended to reduce the discrepancy between the coefficient actually used and the BDIV value, even though in several cases the analyses on which the changes were based were quite independent of the BDIV study. This was the case with the Hobart group, which changed the coefficient employed at all its stations from 0.944%/mm to 0.992%/mm on January 1, 1962.

The pressure variations at tropical localities are, in general, much smaller than those in temperate and polar areas. Barometer coefficients determined for such stations therefore have larger error tails than those determined for instruments of similar counting rate located in other regions. This is apparent in the BDIV analyses at Mina Aguila and Huancayo (figure 4.24). For this reason the Hobart group have employed the same coefficient at Lae as for their other detectors, being aware that this is

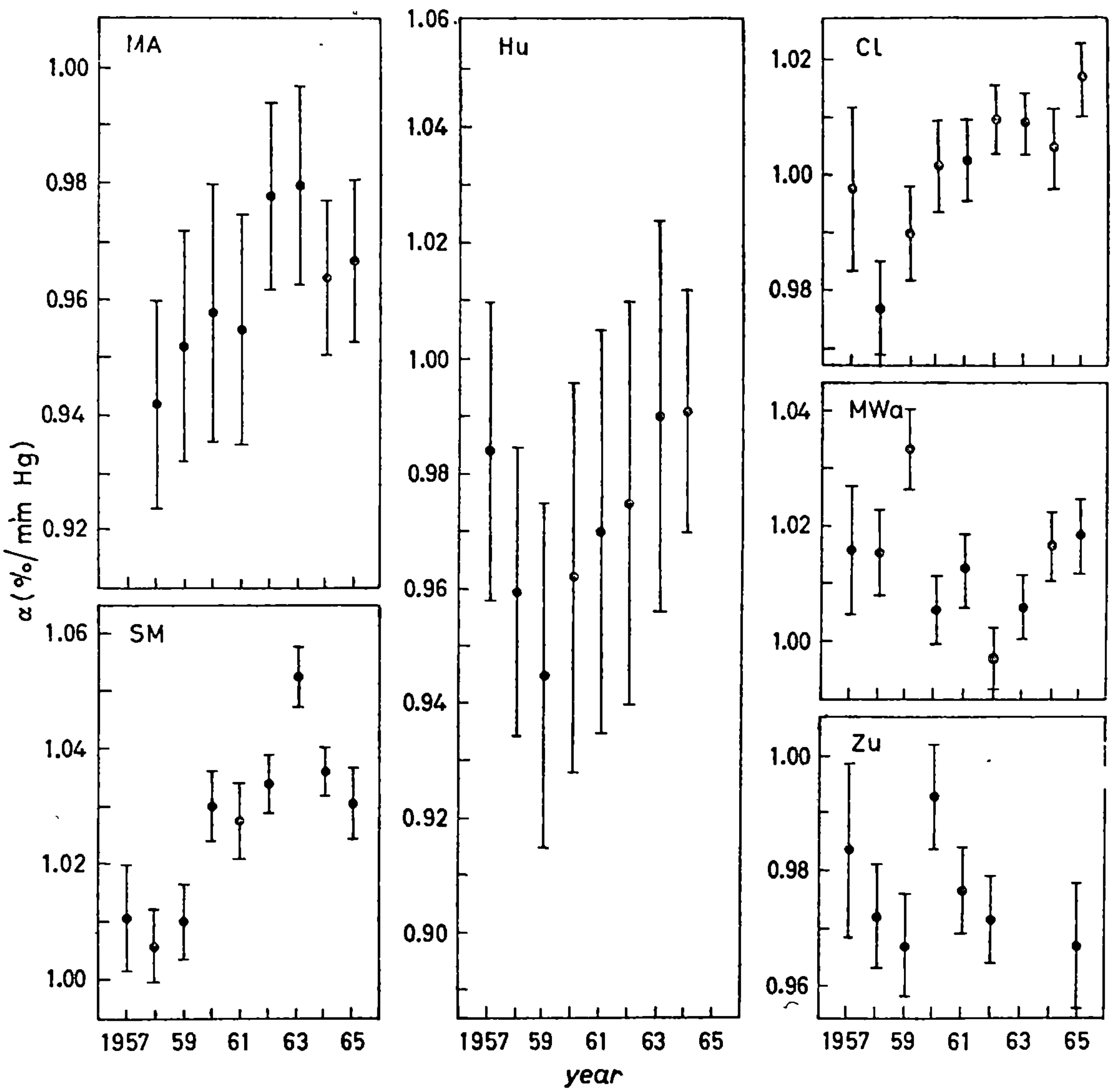


Figure 4.24. *The yearly mean values of the attenuation coefficient for some mountain stations (due to Bachelet et al, 1967).*

not necessarily the best coefficient for the station but deciding that it is the best available.

The BDIV coefficients for each of the 21 stations which they considered have been averaged over the years 1961, 1962 and 1963. Denoting pressure coefficients by α the mean coefficient thus obtained has been compared with the coefficient actually used at the station to produce an error $\delta\alpha = \alpha_{used} - \alpha_{BDIV}$. The r.m.s. value of $\frac{\delta\alpha}{\alpha}$ for the 21 stations, expressed in percent, is 4.2. The major part of this is accounted for by discrepancies at 4 stations; Kiel, where $\frac{\delta\alpha}{\alpha}$ equals 10%, Zugspitze and Sulphur Mountain (each 8%) and Buenos Aires (7%). The r.m.s. value of $\frac{\delta\alpha}{\alpha}$ for the remaining 17 stations is 2.3%. This compares with an average uncertainty in the BDIV coefficients of ±2% (Huancayo), ±1½% (Mina Aguilar), ±1% (Kiel and Hermanus), and ± ½% at the remaining stations. The value of 0.5% found for $\frac{\delta\alpha}{\alpha}$ at Huancayo is clearly fortuitous.

The combination of an erroneous barometer coefficient and a diurnal or semi-diurnal pressure vector will lead to residual pressure-associated vectors forming part of the vectors obtained from pressure corrected data. Ideally one would wish to subtract the residual vectors from the observed vectors. This requires knowledge of both $\delta\alpha$ and the pressure vectors. Alternatively the raw neutron data should be recorrected using a retrospectively determined value of α, the determination being carried out for each individual year and station. The labour involved in either procedure would be substantial as BDIV coefficients are not available for a number of stations used in this survey, and pressure vectors are available for very few of them. The alternative is to make, from the available data, the best possible estimate of the likely errors involved in ignoring the effect.

Bearing in mind that generalisation may be dangerous in this case it is apparent, from table 4.21 and Forbush's data that the stations may be grouped into low, medium, and high latitudes for consideration of pressure vectors. This is done in table 4.22 where the corresponding

Latitude Group	Amplitude Range of Diurnal Pressure Vector (mb)	Amplitude of Residual Vectors for $\delta\alpha/\alpha = 5\%$	$\delta\alpha/\alpha = 2.3\%$
Polar	0.0 to 0.2	.000 to .007	.000 to .003
Temperate	0.2 to 0.7	.007 to .025	.003 to .011
Tropical	0.2 to 1.3	.007 to .047	.003 to .021

Table 4.22. Possible amplitudes of residual vectors for observed pressure vectors.

amplitudes of the residual pressure associated vectors for hypothetical stations for which $\frac{\delta\alpha}{\alpha}$ is 5% are also listed. Such values of $\delta\alpha/\alpha$ have been observed, but with certain obvious anomalies removed the r.m.s. value of $\delta\alpha/\alpha$ drops to 2.3% as mentioned above. In this case the majority of the residual vectors have amplitudes around .01%, only slightly greater than the standard error of amplitude of the observed annual vectors for most IGY type monitors.

Four stations exist for which BDIV coefficients and pressure vectors are both available. For these stations the amplitude of the residual vector is, as depicted in table 4.23, less than the standard error of amplitude except at Mt. Wellington in 1961. The exceptional case has a fairly large $\delta\alpha$ and moderate pressure vector, a combination that might be thought fairly bad. The observed diurnal vector in the pressure-corrected data is .187 ± .007% at 15.41 ± .14 hours L.T. The corrected vector, with the residual pressure associated vector removed, is .203 ± .007% at 15.53 ± .14 hours L.T. The amplitude difference is statistically insignificant at the 95% confidence level.

Station	Amplitude, Pressure Diurnal Vector (mb)	$\frac{\delta\alpha}{\alpha}$(%)	BDIV Coeff (%/mb)	Amplitude of Residual Vector (%)	Standard error of observed vectors %
Mawson (1961)	.07	-5.3	.749	.003	.008
(1962/3)	.07	0.0	.746	.000	.008
Mt. Wellington (1961)	.39	-5.9	.756	.017	.007
" " (1962/3)	.39	-1.2	.753	.003	.007
Rome	.23	+4.2	.689	.007	.012
Huancayo	1.3	-0.5	.734	.005	.007

Table 4.23. Effect of faulty barometer coefficient at some stations.

It may be concluded that the use of an incorrect barometer coefficient is not a major problem at most stations, although it may well be so at a few. Some errors are definitely introduced to the diurnal vectors observed, they will be systematic both in time at one station and between stations at the same time (due to the relatively constant directions of the pressure vectors). This can cause small errors, of order a few degrees, in the estimated direction of the free-space anisotropy, but is more likely to affect its estimated amplitude since, roughly speaking, the diurnal pressure vectors tend to be out of phase with the observed vectors at many stations. The overall effect will be to introduce a quasi-statistical scatter in the free-space vectors estimated from various stations. If the amplitude of the residual vector is comparable with the standard error of amplitude of an IGY monitor, as it appears to be, and if the residual vector is in phase with the observed vector at some stations (e.g. Mawson, Mt. Wellington, and Kodaikanal), and out of phase at others, the uncertainty in the amplitude of the estimated free-space vectors will be approximately doubled. Thus, from this cause alone, the expected variance of the estimates of the free-space amplitudes could be up to four times the statistically expected value.

4.7.4 Other Errors

Other factors, besides those mentioned, will intrude into the vectors recorded at any individual station. Those which are common to all sections will not be detected by inter-section comparison, and may not be revealed by residual variance tests. Uncompensated diurnal environmental effects come into this category. Such factors will contribute to the scatter of the free-space estimates in an unestimable fashion, but it seems reasonable to expect that the variance of these estimates could easily be doubled by the combination of these effects and the errors inherent in the computational processes (Section 4.7.1).

4.7.5 Combined effects

Since all of the factors discussed in the previous sections are independent of one another their combined effects are multiplicative. Taking a factor of 2 from the pseudo-Poisson instrument-associated effects, of 2 to 4 from the residual barometer associated vectors and a further 2 from the other possible errors we find that a realistic value of Z could well be between 8 and 16 times the statistically expected value, E(Z). Consequently the likely values of Z could range up to 8 to 16, in all cases.

4.7.6 Practical Errors

The standard deviation σ_r of the amplitude of a vector $\underline{r}$ has been directly derived from the total number of counts recorded in the period to which the vector refers (Section 4.2.6). It has been shown in section 4.7.2 that the use of σ_r so calculated leads to an underestimate of the variance of the vectors observed by the different sections of the same neutron monitor.

An alternative method of estimating σ_r exists. Dyring & Rosen (1961), using data from the neutron monitors at Uppsala and Murchison Bay, have shown that the residuals which remain in some cosmic-ray data after the first and second harmonics of best fit have been subtracted, follow a random distribution. Thus the variance of the residuals can provide an estimate of the variance of the original data. If quasi-statistical variations are present in the data, or if all the counts contributing to the data are not statistically independent, the variance estimated in this way will be higher than that estimated on the basis of Poisson statistics alone. An estimate of σ_r, which we shall call σ_r', may be made from this variance.

By analogy with eqn. 4.21

$$\sigma_r' = \sqrt{\frac{2}{n}}\,\sigma_e \qquad 4.27$$

where σ_e is the standard deviation associated with each residual, and n is the number of observations (12 bi-hourly or 24 hourly) employed.

Sandstrom (1965) cites Guest (1961) as stating that an unbiased estimate of the variance, σ_e^2, of the residuals is given by

$$\sigma_e^2 = \frac{\sum_{k=1}^{n} (e_k - \bar{e})^2}{n-2j-1} \qquad 4.28$$

where e_k is the amplitude of the k^{th} residual and j is the order of the highest harmonic removed. In the present case $j = 2$.

Values of σ_r' have been obtained for all data employed in the diurnal analyses. It is found that, except for occasional statistical fluctuations in individual months of data, σ_r' is always greater than σ_r for the same period, except at one station.

It is convenient to define the ratio of the variances of the amplitudes, as computed by the two methods, as

$$Y = \frac{\sigma_r'^2}{\sigma_r^2} \qquad 4.29$$

This ratio will also apply to the variance to be associated with the vector end-points, since this quantity is twice the variance of the vector amplitudes regardless of how it is calculated (section 4.2.6).

Sandstrom (1965) has noted that the ratio of σ_r' to σ_r varies between different detectors. This is confirmed by the present work (Table 4.24). However it also appears that this ratio, and therefore Y, depends to some extent on the total number of counts included in the data. Most IGY monitors studied yield Y values, for annual mean harmonics, in the range 1.5 to 3.5. NM64 type monitors have slightly higher values of Y as do some (but not all) high altitude detectors. For any particular monitor the annual Y values are generally greater than the average of the Y values of the contributing months; the Y value of a multi-year average harmonic is greater than the values associated with the individual years; and the Y value associated with the vector obtained from the entire monitor for any given period is greater than the average of the values associated with the harmonics obtained from each section for the same period. These results for the Mawson IGY monitor appear in figure 4.25, where the ordinate is plotted as $y, = \sqrt{Y}$, the ratio of the standard errors.

Station	$\overline{Y}$	Station	$\overline{Y}$
Brisbane	2.3	Mawson	2.4
Buenos Aires	3.3	Mina Aguilar	7.6
Churchill	2.6	Mt. Norikura	4.2
Deep River	3.7	Mt. Wellington	1.8
Hermanus	3.3	Munich	2.2
Huancayo (Section A)	4.6	Pic-du-Midi	9.9
Jungfraujoch	4.1	Ottawa	1.6
Kampala	20.5	Resolute	1.4
Kiel	9.6	Rome	.55
Leeds	2.4	Sulphur Mountain	2.3
Lindau	2.6	Thule	2.4
London	2.9	Uppsala	2.3

Table 4.24 Average annual values of Y (eqn 4.29) for 24 stations 1961-1963. The average value of $\overline{Y}$ for 16 Sea level stations (excluding Kiel) is 2.4 and for 6 Mountain stations (excluding Kampala) is 5.5.

The Deep River neutron monitor has been enlarged twice. The annual y values associated with the various count rates are also shown in figure 4.25. It is clear from both the Mawson and Deep River examples that the observed variance, and therefore standard error, of the residuals decreases more slowly than does their expected variance as a larger number of counts

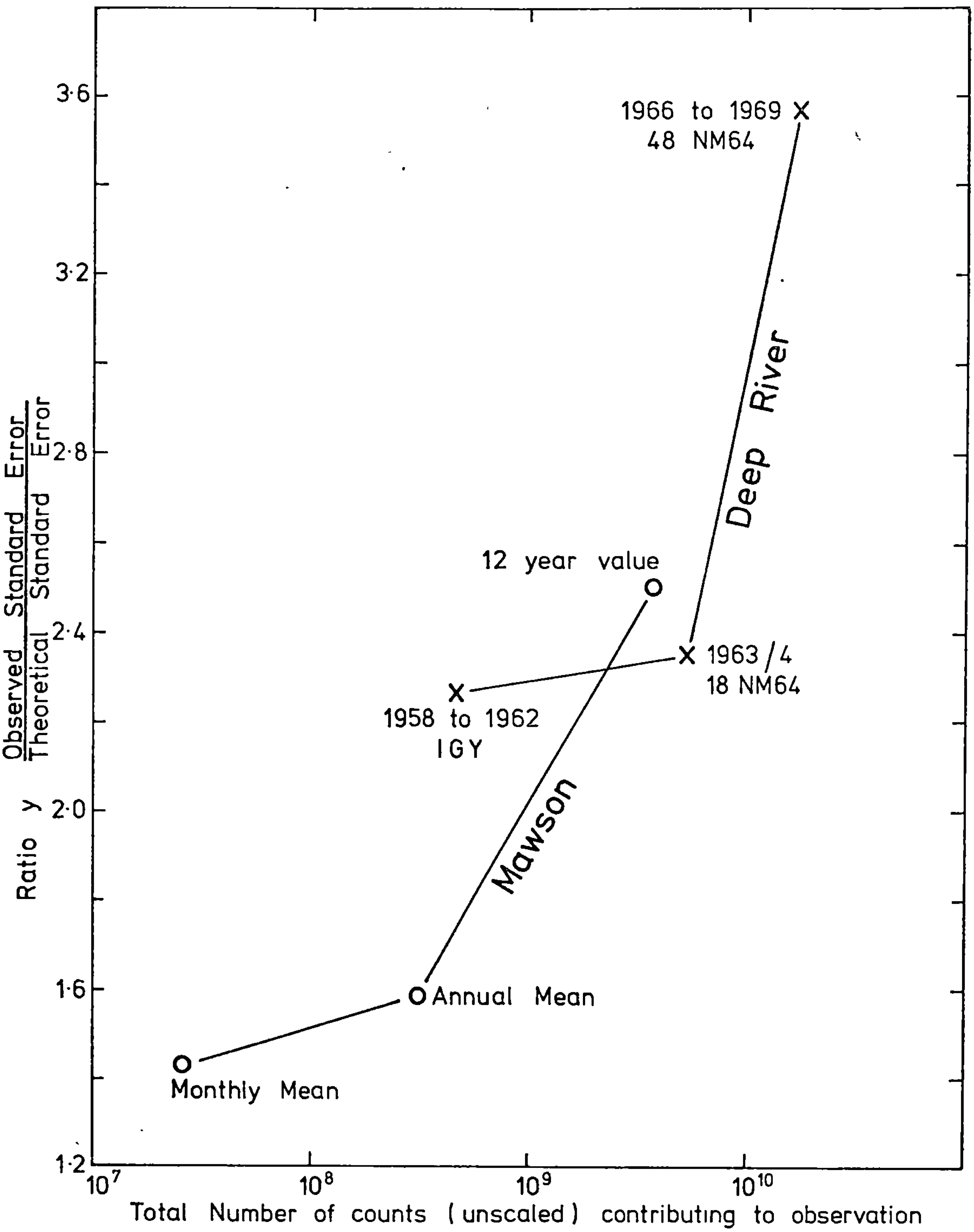


Figure 4.25. Relationship between ratio of observed to expected standard error of data, and contributing number of counts. The Deep River values are all mean annual values for the periods indicated. The Mawson values are from varying periods of analysis of the IGY monitor.

are included in the analysis.

Increase in Y with increase in counts could indicate the possible existence of small harmonics in the data, of order 3 or higher. Regular variations other than harmonics of 1 cycle per day would not be revealed by these results, due to the superposition of data on a daily basis before analysis (Section 4.3).

For relatively small count totals the extra, non-statistical, scatter introduced into the residuals by ignoring possible higher order harmonics will also be relatively small if the amplitudes of the ignored harmonics are small compared with their standard errors of amplitude. In such cases the residuals will appear to be random variates, as found by Dyring and Rosen, and Y should asymptotically approach a minimum value, theoretically unity but in practice probably a little higher (section 4.7.2)

The proportion of the scatter in the residuals due to the ignored harmonics, and consequently the value of Y, will increase with increase in included counts. Once the amplitudes of the ignored harmonics become large compared with their standard errors $\sigma_r'^2$ will become effectively constant. In this condition we have

$$Y \propto \frac{1}{\sigma_r^2}$$

$$\text{i.e. } Y \propto N$$

where N is the total number of included counts.

From figure 4.25 the first signs of this occur, at the two stations, in the region $N = 10^9$ to 10^{10}. A first assumption is to consider that the amplitudes of the ignored harmonics can be no greater than the standard error associated with the lower of these limits, approximately 0.005%. Such harmonics could not usefully be investigated on an annual basis using the methods outlined in this thesis for studies of the diurnal variation, and the matter has not been pursued further. *

Very high annual Y values associated with lower-count-rate instruments (such as averages of 20 at Kampala and 32 at Haleakala) suggest severe fluctuations in the data of other than cosmic-ray origin. These could be due to large high-order harmonics in the data but are more likely to be due to repetitive sudden fluctuations in counting rate. This view is supported by the discrepant vectors found for these stations (sections 4.4.2 and 4.6.3); by private discussions with Dr.M.A. Shea concerning Haleakala; and by observations at Kiel, whose average annual Y value (table 4.24) is 9.6. The diurnal vectors for this station have been found discrepant (section 4.4.2) and inspection of the residuals after subtraction of the first and second harmonics reveals that the residual for the bi-hour period 2200 to 2400 U.T. is frequently too large to be explicable on purely statistical grounds.

The averages of the monthly Y values for the individual sections of the Mawson and Mt. Wellington neutron monitors from 1961 to 1963 are 1.6 and 2.0 respectively. There are no significant differences between the sections of the same monitor. It was shown in section 4.7.2., by a quite different technique, that the ratio between the observed and expected

* *Observations of 3rd harmonics in Mt. Norikura muon and Deep River neutron data were reported at the Hobart Cosmic-Ray Conference by Fujimoto, Nagashima, Fujii, Ueno, and Kondo (1971) and Mori, Yasue, and Ichinose (1971).*

variance of the first harmonic amplitudes (i.e. Y) was 1.8. The good agreement between the two methods indicates that, for these stations at least, the scatter between the vectors recorded by the different sections is entirely due to quasi-statistical noise inherent in the data, and not to systematic differences between the sections. Neither does this level of Y value appear to be associated with non-random components remaining in the residuals. It is probable, but not certain, that these conclusions apply also to other detectors whose annual Y values are less than about 2.5 or 3.

One station consistently displays low values of Y. The average of the annual Y values at Rome for the period 1961 to 1966 is 0.97. For 1961 to 1963 the average was 0.55 (table 4.24). The counting rate for this detector is of the order of 17,000 counts per hour, rather low for a standard IGY monitor at its latitude and altitude. A more likely figure would be in the range 26,000 to 30,000 counts per hour. One possible explanation could be that an abnormally long dead-time was used in the recording equipment to guard against the possibility of recording multiple events arising from a single incident neutron. However the reduction in count-rate is rather large for this explanation, and N. Iucci (private communication) reports the use of a dead-time of 20 μsec with a resulting multiplicity of 1.13. This compares with a dead-time of 5 μsec and multiplicity of 1.2 (McCracken, 1958) of the Hobart group neutron monitors.

Fieldhouse, Hughes, and Marsden (1962) have reported the mean life-time of thermal neutrons in an IGY monitor to be about 170 μsec. There is therefore no essential difference between the Rome and Hobart group neutron monitors in this regard, a conclusion supported by the similarity of their observed multiplicities. The reason for the low values of Y found for Rome remains unknown.

4.7.7 Effect of use of practical errors

Sandstrom (1965), and others, have suggested that the error limits quoted in cosmic-ray observations should be computed on the basis of the observed variance of the data rather than on its estimated variance. This is strongly supported by the results presented in sections 4.7.2 and 4.7.6. Accordingly a number of the inter-station comparisons discussed in sections 4.5 and 4.6 have been recomputed in order to obtain new, practical, error limits for the various quantities which have been determined. The process does not alter the central values of β and R_u, nor the free-space amplitude constant and phase, obtained from a given set of stations. Neither does it affect the comparisons carried out in section 4.5 between the various coupling coefficients, effect of retention and rejection of mountain stations, etc., except to make the differences which were observed somewhat less significant.

As expected the minimum Z values obtained using practical errors are about half those found using Poisson statistics when all doubtful stations have been rejected. This ratio tends to be larger when all stations are used. Table 4.25 shows the various values obtained in the two cases in a typical year.

Errors	β	Range	R_u GV	Range	Amplitude Constant	Phase L.T.	Z
Poisson	0.2	0.0to0.6	40	30to60	.263±.016	18.33±.26	12.9
Practical	0.2	-0.2to0.9	40	< 120	.263±.034	18.33±.38	5.9

Table 4.25. Comparison of Poisson and Practical Errors for 1964. The same eight stations were used in each case. Quoted limits are 95% confidence.

4.8 CONCLUSIONS, DIURNAL ANALYSIS OF NEUTRON DATA

Table 4.26 presents the final results obtained in each of the years 1961 to 1966. The error limits quoted in this table, and also in tables 4.25 and 4.27, are the limits of the variable concerned on the assumption that the other variable is invariant at the value stated. (Section 4.5.6, figure 4.21).

Year	No. of Sts	β	Range	Estimated Values of R_u(GV)	Range	Amplitude Constant	Phase(LT)	Z
1961	13	0.0	-0.2to+0.5	70	35to300	.430±.073	18.55±.45	10.4
1962	13	+0.2	+0.1to+0.4	500	> 130	.264±.029	17.95±.31	11.0
1963	9	+0.4	+0.2to+0.7	100	50to250	.140±.017	17.73±.32	1.6
1964	8	+0.2	-0.2to+0.9	40	< 120	.263±.034	18.33±.38	5.9
1965	10	+0.2	-0.2to+0.8	60	< 300	.185±.033	18.24±.49	8.0
1966	10	+0.2	-0.1to+0.9	40	< 80	.296±.040	18.54±.39	8.3

Table 4.26. Final results for diurnal variation. All doubtful and mountain stations rejected. 95% confidence limits based on practical errors.

The results in table 4.26 are presented graphically in figure 4.26. Most of the ranges found for β include zero, and thus cannot be said to definitely mean that β is other than zero. However all the error ranges for β are clearly biased towards the positive and there is therefore some indication that β may be, on the average, slightly positive. The values of R_u, whilst rather wide-ranging, are consistent with currently accepted values. Similar values of R_u would have been obtained had β been arbitrarily fixed at 0.0. The directions of maximum are not significantly different from 18.00 L.T., except possibly in 1961, even then the differ-

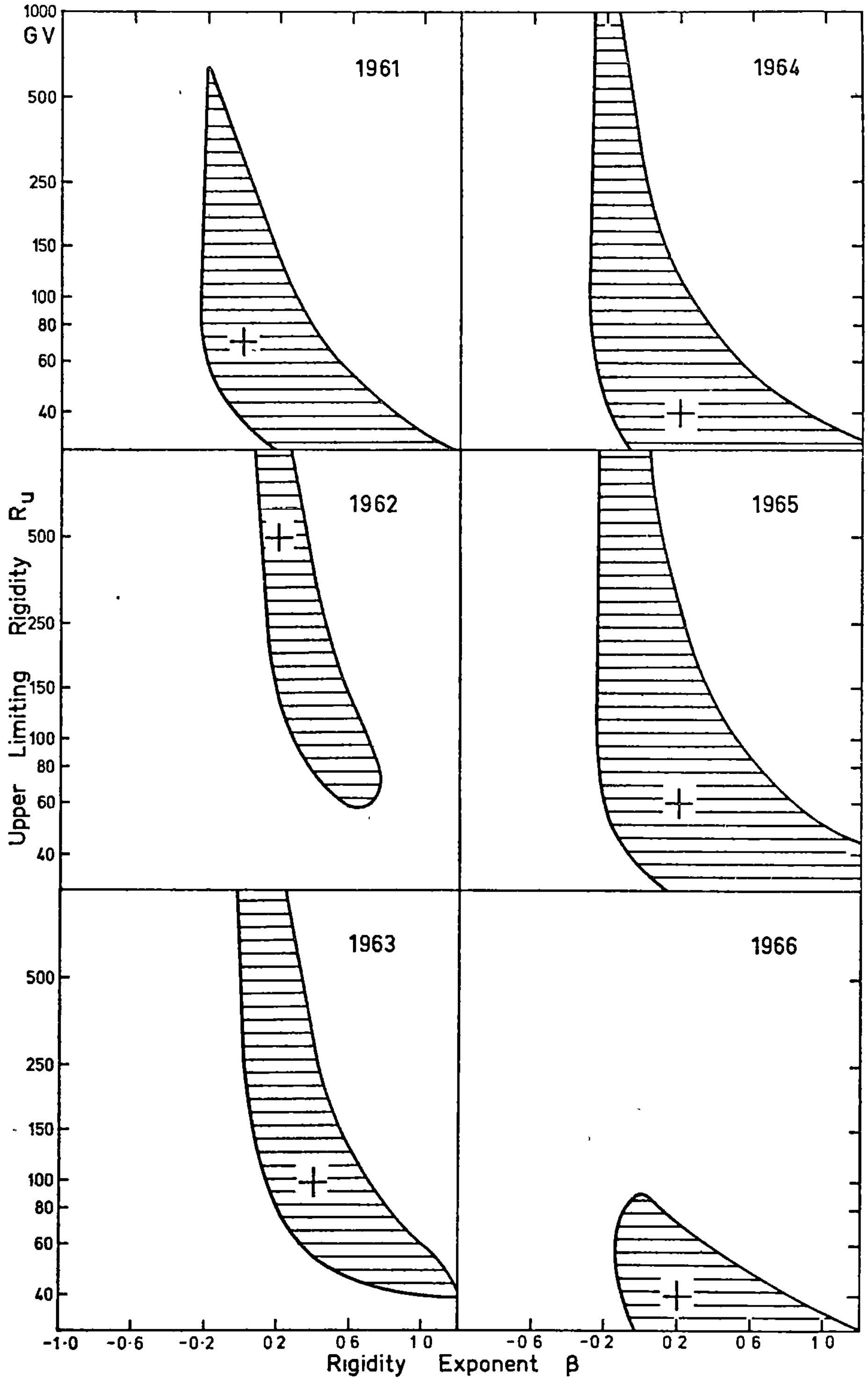


Figure 4.26. *Possible combinations of* β *and* R_u *(hatched regions) for diurnal variation, to 95% confidence based on practical error estimates. The smooth contours of this and subsequent diagrams result from visual smoothing of computer produced contours (figures 4.20, 4.21).*

ence is not great. The values of the amplitude constants depend critically on both R_u and β and thus the wide range in values is not necessarily as significant as it appears at first sight.

These conclusions must be qualified by the large value of Z in all years except 1963. Possible reasons for these high values have been put forward, and it must be assumed that these are the best attainable. They appear to be the major shortcoming of this type of analysis.

The principal difference between this and previous analyses is the simultaneous determination of β and R_u, combined with the use of the full vector information available from each detector. At the time of previous investigations (e.g. Faller and Marsden, 1966; McCracken and Rao, 1966) it was thought that R_u was rather higher than has subsequently proved to be the case. These investigators consequently felt justified in regarding variations in R_u as unimportant, and assigned arbitrary high values to it, usually 500 GV. They then concluded that the average value of β is indistinguishable from zero. The effect of setting R_u = 500 GV in the present analysis, and subsequently determining β, has been discussed (section 4.5.5), and is further illustrated in figure 4.27. The stations used in figure 4.27 correspond exactly to those used in figure 4.26 and table 4.26, and it is seen that the average value of β obtained in this way is indeed approximately zero. However figure 4.17 shows that, whilst the neutron observations are not as dependent on R_u as they are on β, a definite value of R_u is indicated, particularly by the phase information. It is thus important that this be taken into account in determinations of β.

The analyses presented in this chapter show that the errors inherent

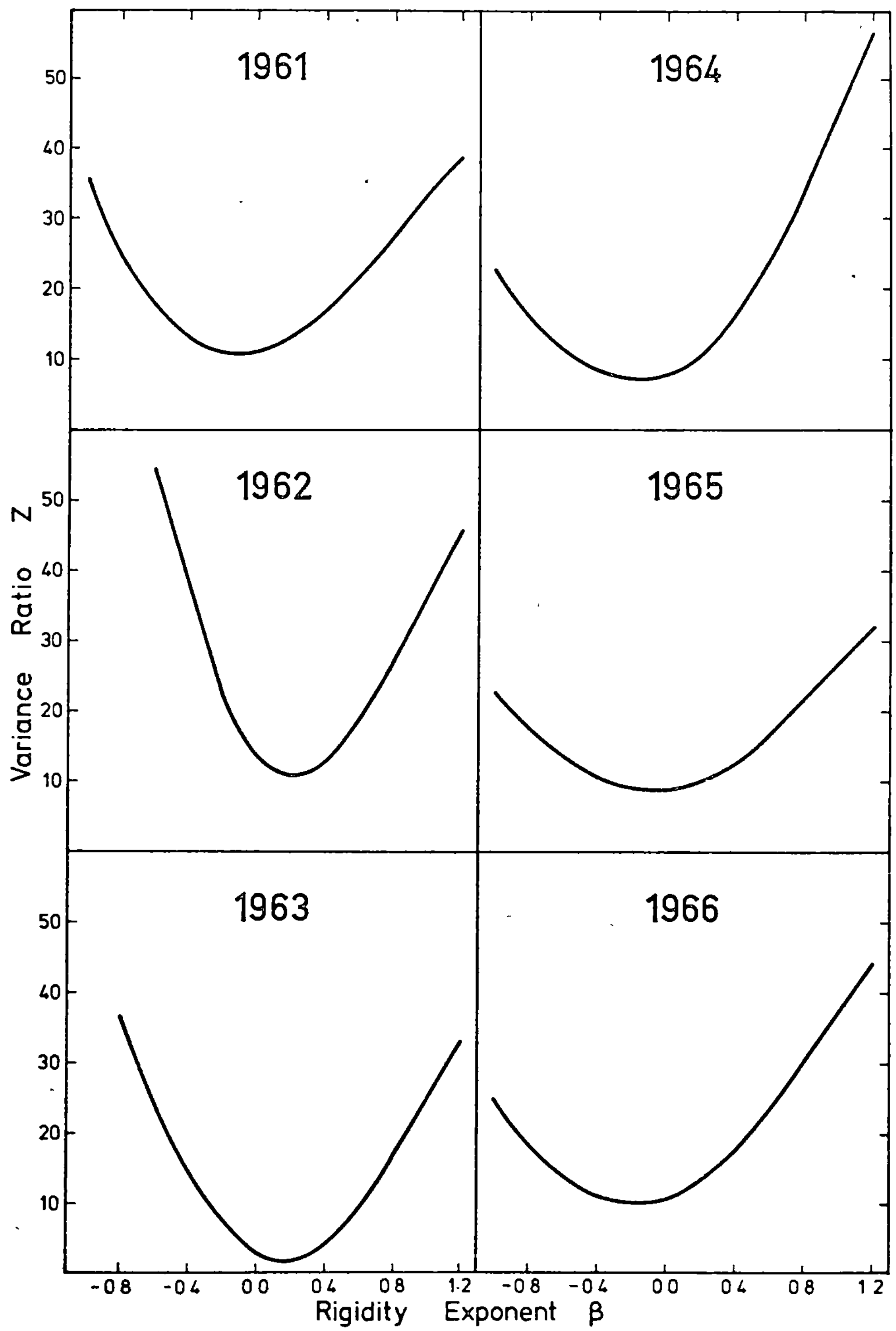


Figure 4.27. *Variance of estimated free-space difference vectors with varying* β *for* R_u *fixed at 500 GV.*

in determinations of the parameters involved are larger than has previously been believed, resulting in rather wide ranges of possible parameter values. In chapter 5 we will consider how observations from underground muon detectors can be used to reduce these ranges.

4.9 THE SEMI-DIURNAL VARIATION IN NEUTRON DATA

The analysis techniques applied to the diurnal variation may also be applied to the semi-diurnal variation. For data-handling reasons it has been convenient to consider both harmonics, for any given set of stations, in the same computer run. This has been done for many of the diurnal analyses reported earlier in this chapter.

The amplitudes of the semi-diurnal variations observed by neutron monitors are much smaller than those of the diurnal variations seen by the same detectors (figures 4.10 and 4.11). The standard errors, however, have the same magnitude for both harmonics (section 4.2.6). Consequently the second harmonic has a much lower signal-to-noise ratio than does the first. This is reflected in the variance curves and contour plots obtained. The variance curves similar, for example, to figure 4.27, are very shallow since changes in the estimated free-space vectors caused by quite large changes in β are of the same order as the standard error of the vectors. This is also evident in figure 5 of Rao and Agrawal (1970). The contour plots are therefore broad and shallow, and it is not possible to put very precise limits on the parameter values. In these circumstances only the final results obtained are presented (table 4.27, figure 4.28), with no discussion of the intermediate stages of the analysis.

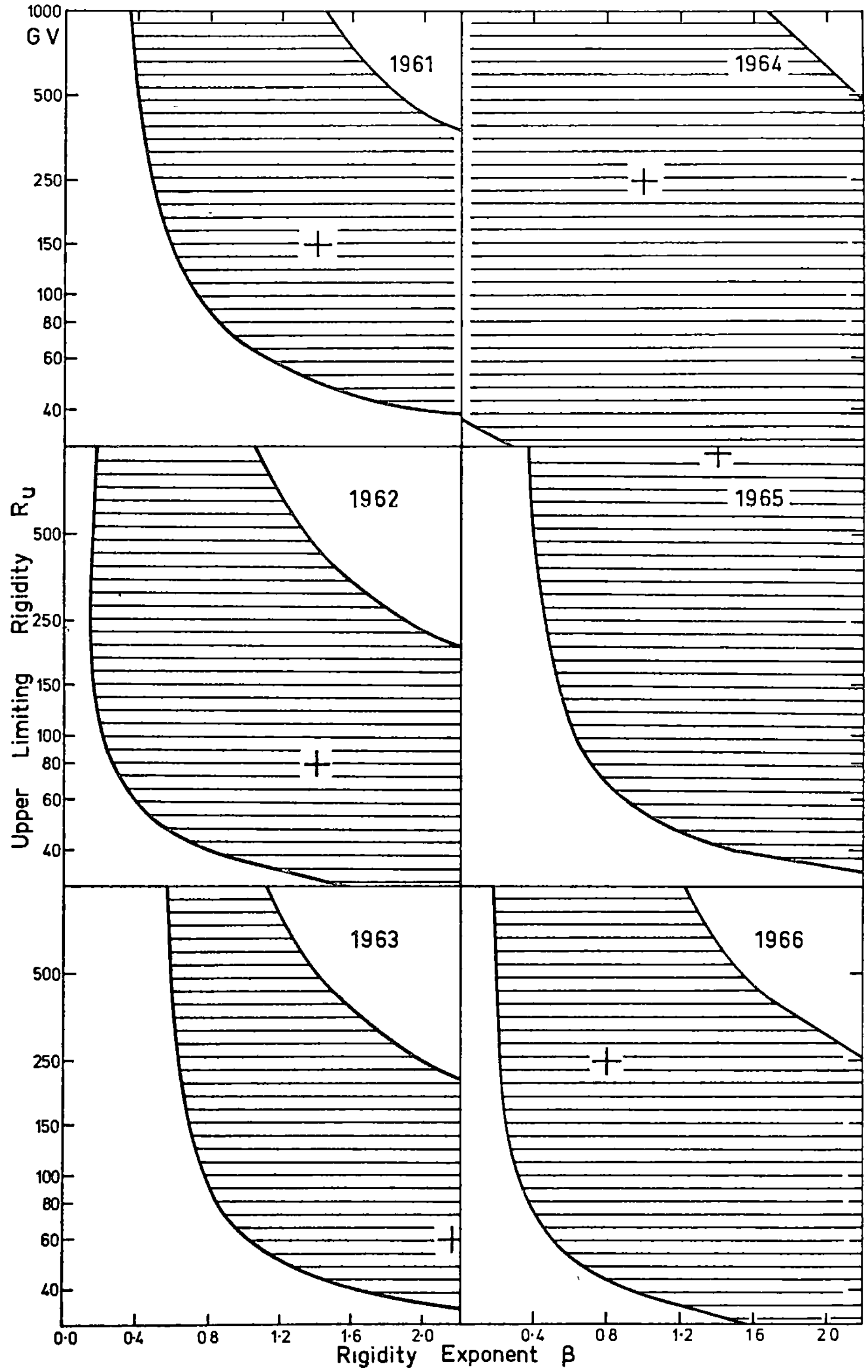


Figure 4.28. *Possible combinations of β and R_u (hatched regions) for semi-diurnal variation, to 95% confidence based on practical error estimates.*

Year	No. of Sts	β	Range	R_u(GV)	Range	Amplitude constant	Phase L.T.	Z
1961	13	1.2	$\geq$ 0.6	150	60to1000	.0010±.0004	2.6±1.7	2.7
1962	13	1.4	$\geq$ 0.2	80	35to 500	.0012±.0005	4.0±1.8	3.7
1963	9	2.2	$\geq$ 1.0	60	35to 250	.0001±.00005	3.8±2.0	8.7
1964	8	1.0	indeterminate	250	indeterminate	.003 ±.001	3.3±2.2	2.7
1965	10	1.4	$\geq$ 0.4	1000	$\geq$ 40	.0001±.0001	2.4±2.9	0.8
1966	10	0.8	$\geq$ 0.2	250	$\geq$ 45	.005 ±.003	3.3±2.2	1.8

Table 4.27 Final results, semi-diurnal analyses. 95% practical confidence limits.

The stations used in these analyses are the same as those employed in the final diurnal analyses. From the semi-diurnal viewpoint these need not necessarily be the best available set. However there is evidence that those stations which are reliable in the diurnal context are also reliable for semi-diurnal studies. The wide limits found for the parameters, regardless of which particular set of stations was used, support the view that it was not worthwhile to make a separate selection of stations for the semi-diurnal case.

Preliminary investigations showed that the lower limiting cut-off was not an effective factor in determining the scatter of the estimated free-space vectors, provided it was less than a few GV. It was therefore set at zero.

The exponent of the cosine dependence on asymptotic latitude was also investigated. As in the diurnal case the useful information comes from the scatter of the estimated free-space amplitude constants. Whilst the results are not quite as clear-cut as in the diurnal case (figure 4.15), and there is rather more variability from year to year, a value in the range 0 to 1.5 is strongly indicated. The value 3 proposed by Lietti and Quenby (1968), (section 3.4.2), appears to be excluded. The exponent was accordingly set at unity in the calculations leading to the results of table 4.27.

Figure 4.11 shows that the observed second harmonic amplitudes are larger at equatorial than at polar stations. This has been noted previously (e.g. Katzman and Venkatesan, 1960; Rao et al, 1963). It was found in the initial analyses that the rigidity exponent is clearly positive, and the range investigated was therefore set at 0.0 to 2.2.

Lietti and Quenby (1968) have proposed a direct rigidity dependence for the semi-diurnal variation, at least in the range below around 100 GV. Some confirmatory experimental evidence is available (Ables, McCracken, and Rao, 1966; Hashim, Peacock, Quenby and Thambyahpillai, 1969; Rao and Agrawal (1970); Subramanian (1971). The present results confirm that the rigidity exponent is positive, and encompass the value unity without distinguishing it from other positive values. They also show that the upper limiting rigidity cannot be reliably determined from the neutron data used, except that it is clearly greater than 35 to 40 GV. This is in agreement with the 70 to 100 GV range found by Hashim et al for the period 1965 to 1967 using inclined underground muon detectors.

The amplitude constants found are small, and dependent as the value of β obtained. Quenby and Lietti (1968) predict an amplitude constant, for a direct rigidity dependence, of approximately 0.0025, in good agreement with the results obtained here for 1964. If β is set equal to 1.0, within its possible range of values, similar values of the amplitude constant are found for the other years, except in 1965 when it is rather smaller.

The times of maximum found appear consistent from year to year. The average value over the six years is 3.2±2.1 hours. The radial or cross-radial directions predicted by Subramanian and Sarabhai (1967) appear to be excluded. Instead the directions found are approximately perpendicular to the average direction of the interplanetary magnetic field, as predicted by Quenby and Lietti, and found by themselves and by Rao and Agrawal.

The minimum values of Z obtained are reasonable, in fact better than those found for the first harmonic. This contrasts with the result reported by Rao et al (1963), (section 3.4.2) for 1958. Their conclusion is drawn using a rather small value, 25 square degrees, for their expected variance. More likely figures would be of order 100 (Poisson errors) or 200 (Practical errors) square degrees. The latter reduces their Z value to about 6, comparable with some of the values in table 4.27.

There does not seem to be any useful information on solar cycle trends in the semi-diurnal variation obtainable from the present results.

CHAPTER 5.

THE HOBART UNDERGROUND MUON TELESCOPES.

5.1. INTRODUCTION

The conclusions reached in the previous chapter leave fairly wide limits on the possible values of β and R_u for the first harmonic of the solar daily variation in cosmic-ray intensity. This is partly due to the rather similar rigidity responses of all neutron monitors, regardless of their geomagnetic location. The limits can be considerably reduced by the combination of neutron monitor results with those from other types of detectors which are more sensitive to primary particles of higher rigidities. Such instruments respond in different ways to changes in β and R_u than do neutron monitors. A suitable instrument for this purpose is the underground muon detector installed near Hobart.

This instrument is a vertically aligned semi-cubical duplex muon telescope, having a count rate of 65,000 counts per hour in its original condition. It has operated in a disused railway tunnel at Cambridge, on the outskirts of Hobart, since October 1957. A full description of the observatory and its equipment has been published, (Fenton, Jacklyn, and Taylor, 1961). Since their paper appeared a more detailed survey of the area has revealed that the effective instrumental depth is 36 metres water equivalent (m.w.e.) below the surface (Jacklyn, 1970), and not 42 m.w.e. as originally believed. A third section was added in mid 1966, raising the count rate to 95,000 counts per hour.

5.2. THE OBSERVATIONS.

The magnitude of the solar daily variation observed in underground muon data is small compared with that seen by surface neutron or muon

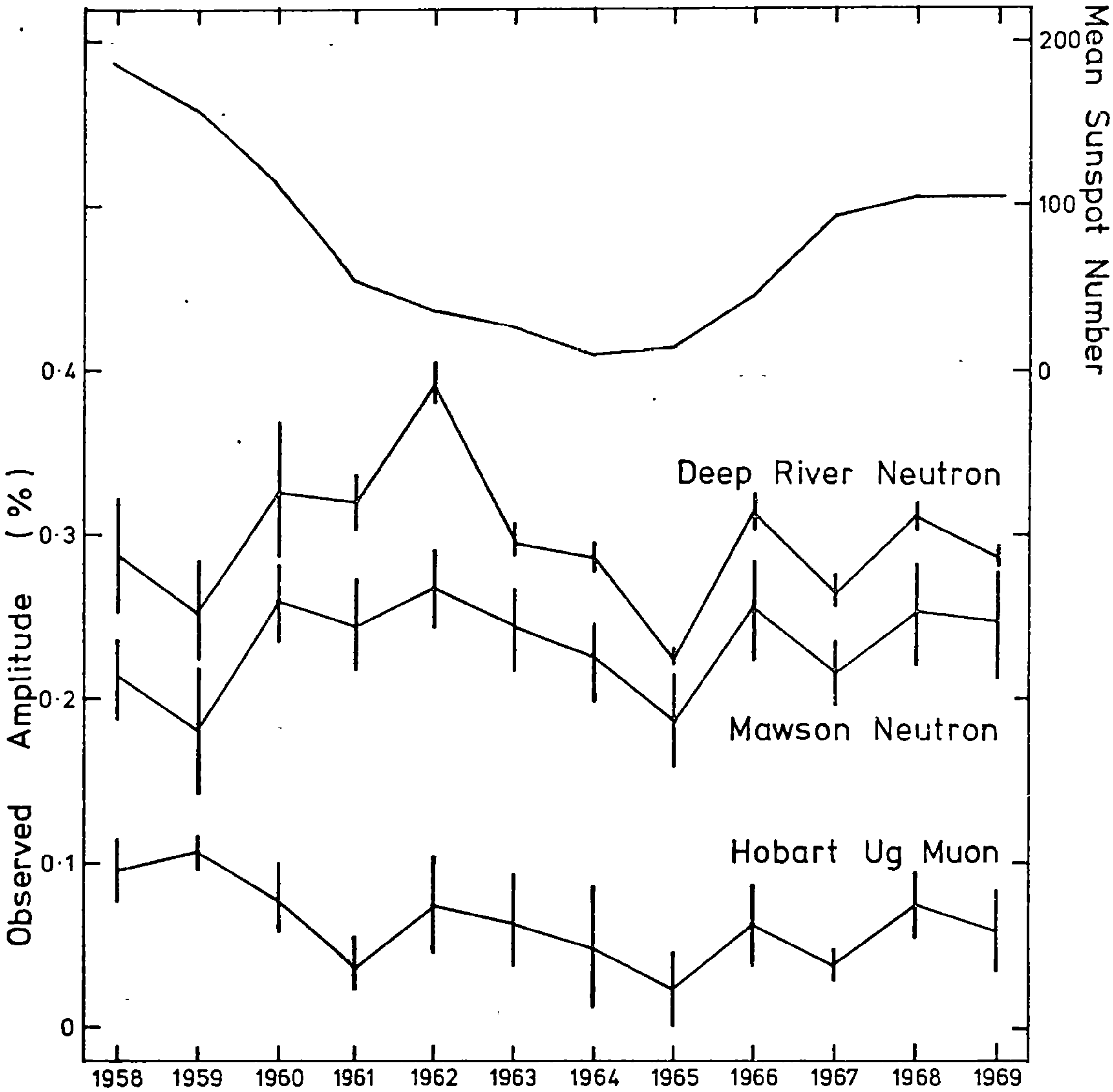


Figure 5.1. Solar cycle variation of pressure-corrected observed amplitudes of the annual mean diurnal variation. 95% practical confidence limits are indicated. The high Deep River observation in 1962 is supported by other neutron monitors.

detectors. Figure 5.1 shows the amplitudes of the mean annual solar diurnal variations observed over a number of years by the Deep River and Mawson neutron monitors and the Hobart underground telescope. All data are corrected for pressure changes only. Annual mean sunspot numbers are also plotted. There is a noticeable correlation between the underground amplitude and the sunspot numbers, indicating that solar-cycle-related changes occur in the annual diurnal variation at higher rigidities. Irregular variations from year to year are also evident, consistent between all three instruments. Both observations oppose the suggestion (McCracken and Rao, 1966) that the mean annual solar diurnal variation is relatively invariant from year to year.

Before discussing the results obtained from the underground telescope we first consider some of the factors which may affect the observations.

5.2.1. Atmospheric Effects.

The difficulties which are associated with the use of surface level muon detectors for daily variation studies (section 2.2) are much less severe in the case of underground instruments. The various atmospheric effect coefficients are relatively small, the partial barometer and negative temperature coefficients falling as the mean rigidity of response of the detector rises. Dutt and Thambyahpillai (1965) indicate that the Duperier formula (section 3.2.1, eqn. 3.1) is adequate for the correction of underground data. Table 5.1 lists the Duperier coefficients obtained for the Hobart and London underground instruments. The London temperature coefficients are greater than those for Hobart, in spite of the greater depth of the London observatory (60 m.w.e.). The figures are well substantiated, being very similar to values found earlier by Dutt and Thambyahpillai. They are still small however, particularly the negative temperature coefficient, compared with values found for surface instruments (table 2.2).

		Hobart 36 m.w.e.	London 60 m.w.e.
Total Barometer Coefficient	%/cm.Hg.	−0.655±0.042	−0.495±0.026
Partial " "	" " "	−0.591±0.044	−0.467±0.026
Negative Temperature "	%/km.	−0.459±0.250	−0.76 ±0.13
Positive " "	%/°C	+0.020±0.010	+0.042±0.006

Table 5.1. Atmospheric correction coefficients for underground muon detectors. Hobart values from Fenton et al (1961); London total barometer coefficient from Dutt and Thambyahpillai (1965); other London values from Peacock (1969).

In normal usage the underground data are corrected for pressure variations only, using a total barometer coefficient. The practical use of these corrected data for solar daily variation studies then rests on the likely amplitudes of the daily variations in the height and temperature of the secondary particle production region.

To some extent such variations are a function of regional meteorological conditions. The necessary observations are difficult to make, and few studies are available. Bercovitch (1966, 1967) has concluded that there is no significant daily variation in upper atmosphere temperatures above the 300 mb. level over Canada. Teweles and Finger (1960) reached a similar conclusion. Harris, Finger, and Teweles (1962) observed an annual average diurnal temperature variation of amplitude about 0.5°C at 100 mb. over the Azores. They believe their observations may contain diurnal insolation errors, and a separate derivation in the same paper, from wind data, gives an amplitude of 0.2^{o}C. Hashim, Peacock, Quenby, and Thambyahpillai (1969) state that an upper limit of 0.2^{o}C can be put on the diurnal temperature wave amplitude, corresponding to a variation of amplitude less than 0.01% in the cosmic-ray flux, with time of maximum close to local noon.

A series of observations, covering a 28 day period in September and October 1966, have been made near Melbourne, Australia (Commonwealth Bureau of Meteorology, 1968), and have been analysed by Tucker (1971). The direct temperature observations, made with an exposed white-painted thermistor, reveal a diurnal variation in the 100 mb. region of amplitude 0.8^{o}C, with maximum close to local noon. In contrast to the results of Harris et al., Tucker's analysis of wind data suggests a slightly larger amplitude, about 1.0^{o}C, with a maximum near 1800 L.T. However he warns that considerable errors are involved in the derivation of temperature from wind observations, due to the large random component in the wind data.

The Melbourne observing site is about 420 miles from Hobart, and the results should be applicable there. They suggest a diurnal variation of amplitude about 0.02% in the Hobart underground data from this cause. However Tucker's results appear much larger than have been observed elsewhere, and it is not clear whether they represent annual averages.

Concerning the negative temperature effect Thambyahpillai, Dutt, Mathews, and Romero (1966) quote the annual mean diurnal variation in the height of the 100 mb. level above southern England to be 42 metres, with a maximum at 1300 L.T., which would give rise to a variation of amplitude of 0.03% in the London underground data. Tucker's observations of diurnal pressure waves at fixed altitudes over Melbourne imply a diurnal variation of amplitude 35 metres in the height of the 100 mb. level, with maximum around local noon. These results agree well with those of Thambyahpillai et al., and suggest a diurnal variation of amplitude 0.016%, with maximum about midnight, in the Hobart data. This variation almost cancels that predicted from the positive temperature effect. Tucker's pressure data are directly derived from the temperature observations using a hydro-static equation. Hence any insolation errors should affect both results equally, and the conclusion of a negligible resultant cosmic-ray effect at Hobart is still valid.

Some direct evidence that the atmospheric diurnal waves in underground data are small is also available. Peacock (1969) has shown, using data from the inclined underground telescopes at London during solar minimum, that the upper limit for the atmospheric vector in both inclined and vertical detectors is 0.015%. Jacklyn (1970) concludes from a study of several years' data from Hobart that there is no persistent significant variation out-of-phase with the solar diurnal variation. In effect this means that the negative temperature effect cannot be significant or, alternatively, that it is significant but is effectively cancelled by the positive temperature effect in the manner outlined above. His analysis does not exclude the possibility of an atmospheric associated resultant vector approximately in phase with the genuine cosmic-ray variation, as would happen were the positive temperature effect dominant.

For the reasons outlined above data from the Hobart underground detectors have been used without further correction for atmospheric effects.

5.2.2. Coupling Coefficients.

It is not possible to obtain coupling coefficients for underground detectors in the manner normally employed for surface instruments, i.e. latitude surveys taking account of geomagnetic cut-off rigidities at the various observing sites. However Fenton (1963) has obtained a set of differential coupling coefficients for the Hobart underground detectors using a theoretical treatment to obtain the rate of pion production from primary protons. A quite different treatment by Mathews (1963) employing extrapolation of existing surface latitude surveys, together with an empirical response curve for a muon detector at 312 $gm.cm^{-2}$, has led to similar coefficients. With no known reason to prefer one of these sets of coefficients to the other Fenton's results have been used in the present work. They are calculated for a depth of 40 m.w.e., and therefore slightly under-estimate the contribution from the lower rigidities.

5.2.3. Modulation Coefficients.

The computer programme used to obtain modulation coefficients for neutron monitors (section 4.2.1) is not suitable for use with muon telescopes due to the latter's more complex geometric sensitivity (Parsons, 1959). Before the necessary modifications to the programme were undertaken Dr. R.M. Jacklyn kindly made available values of B_1 and G_1 (section 4.2.1) which he had calculated in the course of his own work. These values have been used throughout the present chapter.

The range of β covered by Jacklyn's coefficients is smaller than that employed in the previous chapter for neutron monitors. However the likely values of β are bracketed. A potentially more serious problem is that they have been calculated for an assumed latitude independent diurnal variation, whereas the neutron coefficients assume the cosine dependence found in section 4.4.5. There is evidence (Jacklyn, Private Communication) that the variation may be latitude independent at higher rigidities. The effect on the coefficients of introducing a cosine dependence has been estimated by the present author. The results obtained using the two sets are compared in section 5.4.1.

5.2.4. The Orbital Doppler Effect.

High rigidity cosmic-ray particles cannot be trapped by the interplanetary magnetic field, and therefore cannot take up any motion, such as co-rotation, associated with the interplanetary field. To a first approximation such particles are all those having rigidities greater than R_u. The earth's movement through the gas comprised of these particles, as the earth orbits the sun, causes a Compton-Getting type of solar diurnal variation to be observed (Compton and Getting, 1935). The maximum of the variation, in free-space, is at 0600 L.T., in the forward direction along the orbit. The effect is generally referred to as the Orbital-Doppler effect, shortened to OD in the following discussion.

There has been uncertainty in the literature concerning the correct expression to be used in calculating Compton-Getting vectors, apparently due to the complexities of the co-ordinate transformations involved. The matter seems to have been settled by Forman (1970), who derives the anisotropy which will be observed in particles of energy E to be

$$\underline{\partial_{CG}}\,(E) = (2 + \alpha\,\gamma)\,\frac{\underline{V}}{v} \qquad 5.1$$

where $\alpha = \dfrac{E + 2mc^2}{E + mc^2}$

and γ is the magnitude of the exponent (assumed negative) of the energy spectrum of the particles,

v is the average speed of the particles, and

$\underline{V}$ is the velocity of the body moving past them.

The relativistic cosmic-ray particles involved in the OD effect have minimum energies of order 50 to 100 GeV. For such particles, observed from the earth, $\alpha = 1$, $\gamma \simeq 2.5$, and $\left| \frac{\underline{V}}{v} \right| = 10^{-4}$.

$$\therefore \quad \partial_{OD}(E) \simeq 4.5 \times 10^{-4} \qquad 5.2$$

The free-space OD vector, $\underline{OD}$, depends solely on the value assigned to R_u. For any particular detector $\underline{OD}$ is modulated, both geomagnetically and by the response characteristics of the detector, to give rise to an observed vector $\underline{od}$. For neutron monitors, which have a proportionally small response at high rigidities, $\underline{od}$ is negligibly small compared with the observed diurnal vector $\underline{r_1}$. However for instruments which respond more to the higher rigidities $\underline{od}$ becomes significant. For the Hobart underground telescopes r_1 varies between 0.025% and about 0.10%, and od is of order 0.02%. To enable valid comparisons to be made between the diurnal vectors observed by this and similar detectors and those observed by neutron monitors an OD-free vector, $\underline{r_1'}$, must be used such that

$$\underline{r_1'} = \underline{r_1} - \underline{od} \qquad 5.3$$

Evaluation of $\underline{od}$ requires assumption of a value of R_u, one of the quantities being sought by the analysis. Fortunately the dependence is not great, and the assumption of a likely value suffices. Dr. Jacklyn (private communication) has calculated values of $\underline{od}$ for the Hobart data and has consequently obtained mean values of $\underline{r}_1'$ for each of a number of years. His results, extended by the author to the end of 1969, are listed in table 5.2.

Year	Observed $\underline{r}_1$ Amplitude (%)	Observed $\underline{r}_1$ Phase (deg)	Assumed R_u (GV)	$\underline{od}$ Amplitude (%)	$\underline{od}$ Phase (deg)	Corrected $\underline{r}_1'$ Amplitude (%)	Corrected $\underline{r}_1'$ Phase (deg)
1958	.081	251	120	.017	084	.099	253
1959	.110	249	120	.017	084	.127	251
1960	.087	260	120	.017	084	.104	260
1961	.044	229	120	.017	084	.060	240
1962	.071	245	120	.017	084	.088	249
1963	.064	234	75	.022	081	.085	241
1964	.049	222	75	.022	081	.069	234
1965	.023	205	60	.025	079	.042	234
1966	.062	208	60	.025	079	.079	222
1967	.039	225	75	.022	081	.059	238
1968	.074	243	90	.020	082	.094	247
1969	.059	229	100	.018	083	.076	237

Table 5.2. Removal of Orbital Doppler effect from Hobart underground results. The quoted observations for the years 1958 to 1962 are averages of the vectors recorded by the Hobart and Budapest underground observatories. The differences between the observations made by the two detectors, which are at similar depths, are within statistical limits in all years.

5.3. METHODS OF ANALYSIS.

Analysis of vector information is not as important with underground detectors as it is with neutron monitors. The majority of the information required for the present purpose is contained in the amplitude of the observed vectors, and in any case the statistical errors in the observed phases are proportionately rather large. Consequently it seems preferable to consider amplitude and phase information separately. It will be shown, in the following sections, that the results from each are mutually consistent.

5.3.1. Analysis of Amplitudes.

Jacklyn and Humble (1965) have shown that it is practicable to determine R_u, for a given period, by comparing the results from an underground telescope with those from a suitable neutron monitor. Using the Hobart underground telescopes, and Mt. Wellington neutron monitor, they obtained a value of 95 ± 15 GV for R_u in 1958, after setting $\beta = 0.0$ according to the results of Rao, McCracken, and Venkatesan (1963). No account was taken of the Orbital Doppler effect in that analysis.

The method involves the estimation of the free-space-amplitude constant, A, for different assumed values of R_u for each detector. The values of A obtained from the neutron monitor are rather insensitive to changes in R_u, whereas those obtained from the underground telescopes are highly sensitive to such changes. Curves of A v R_u for the two instruments therefore intersect at a steep angle, indicating fairly precisely a value of R_u. For the same reason the value thus obtained is relatively insensitive to small errors in the amplitudes of the diurnal vectors observed by either instrument. Figure 5.2 shows the case for the Hobart/Budapest combined underground telescopes, after correction for the OD effect and the Deep River neutron monitor in 1958, assuming $\beta = 0.0$. The error limits are 95% practical, the value of R_u obtained being 88^{+26}_{-18} GV, which is consistent with the earlier value.

In the present instance it is required to allow for the case of a

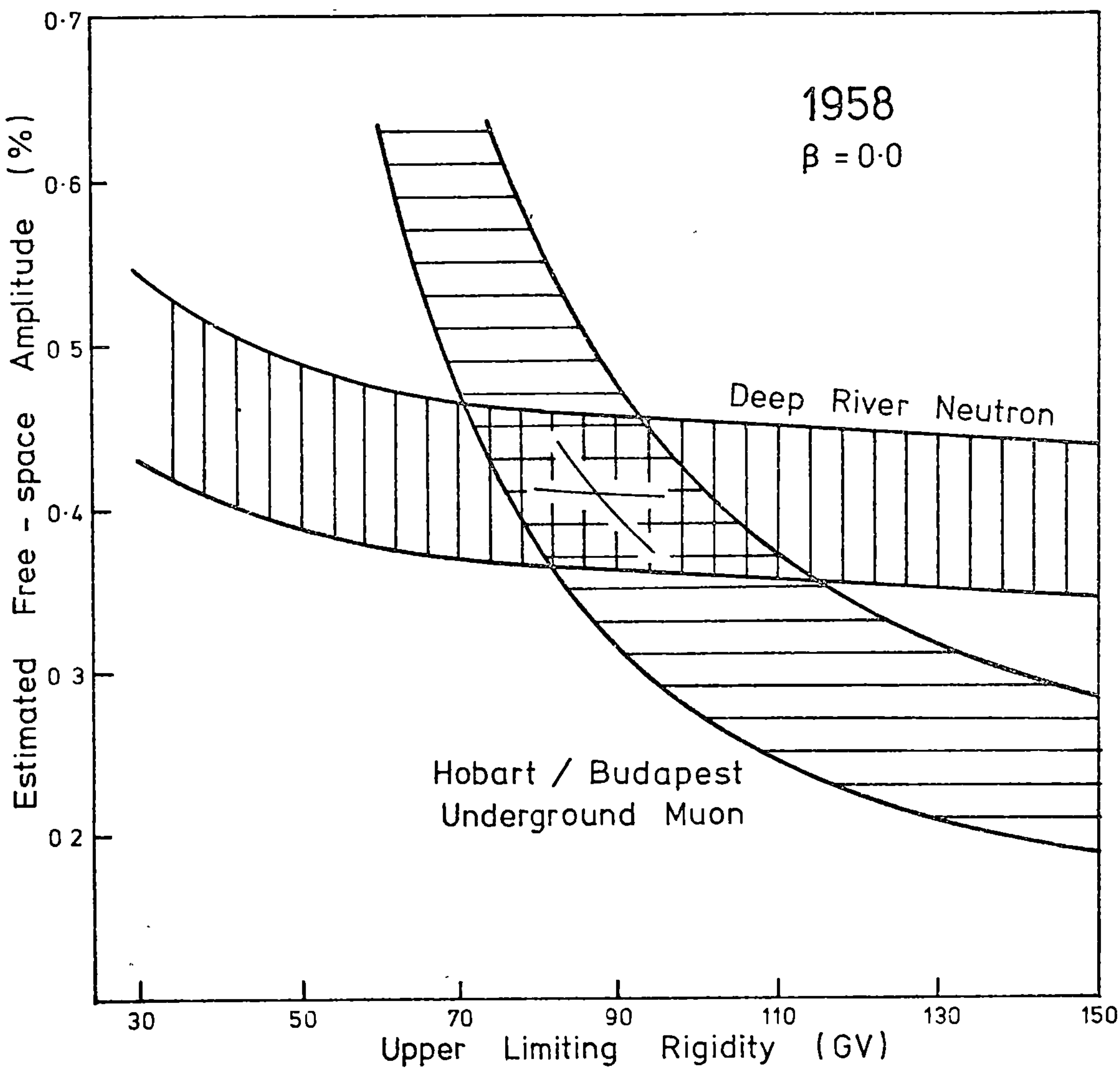


Figure 5.2. *Ranges, to 95% confidence, of possible values of the free-space amplitude constant according to the observations of different detectors for* $\beta = 0.0$ *and range of values of* R_u.

varying β. Families of A v R_u curves may be drawn, for each instrument, with β as a parameter. The intercept of the curves for corresponding β gives a value of R_u which could be associated with that particular value of β.

The plotting of families of A v R_u curves is a tedious business, requiring to be repeated for each new period of observation. Fortunately a much simpler technique exists.

For each point on the curves $A = \frac{R}{B}$

where R is the amplitude of the vector observed by the detector and B is the amplitude modulation coefficient for the particular instrument and assumed values of β, R_u, coupling coefficients etc. (Section 4.2.1).

For two particular detectors X and Y, we have

$$A_x = \frac{R_x}{B_x} \quad \text{and } A_y = \frac{R_y}{B_y}$$

The required condition is that $A_x = A_y$ and therefore

$$\frac{R_x}{B_x} = \frac{R_y}{B_y}$$

$$\therefore \quad \frac{B_x}{B_y} = \frac{R_x}{R_y} \qquad 5.4$$

Thus the necessary ratio of the response constants equals the ratio of the amplitudes of the observed vectors.

Sets of values of B for various stations and conditions have been computed (section 4.2.1). These are then plotted, on a logarithmic scale, as functions of R_u. Using β as a parameter, families of curves are obtained for each detector (Figure 5.3). Such plots, from different detectors, may be overlaid, with the B scale of one set superimposed on, but displaced along, the B scale of the other (Figure 5.4). The use of logarithmic scales ensures that, for a given displacement of the B_x scale relative to the B_y scale, the ratio B_x/B_y is constant throughout the combined diagram regardless of the absolute values of either quantity. The displacement of the two plots is adjusted such that B_x/B_y equals the observed value of R_x/R_y for the period under consideration. The values of R_u consistent with this ratio for various values of β may then be read directly from the intercepts of the appropriate β curves. Obtaining results for other periods then only entails altering the relative displacement of the two sets of plots.

The statistical uncertainties associated with each vector lead to a range of possible values of B_x/B_y. To 95% confidence the true value of this ratio lies in the range

$$\frac{R_x - 2\sigma_x}{R_y + 2\sigma_y} \quad \text{to} \quad \frac{R_x + 2\sigma_x}{R_y - 2\sigma_y}$$

Possible combinations of β and R_u which satisfy each of these relations are obtained as described above and their locii plotted as a β v. R_u graph (Figure 5.5a). The region between the two curves represents a swathe of possible β, R_u combinations consistent with these particular observations. The region is of quite different shape to that obtained from the neutron data alone in the previous chapter. Superposition of the two regions on the same diagram puts considerable constraints on the

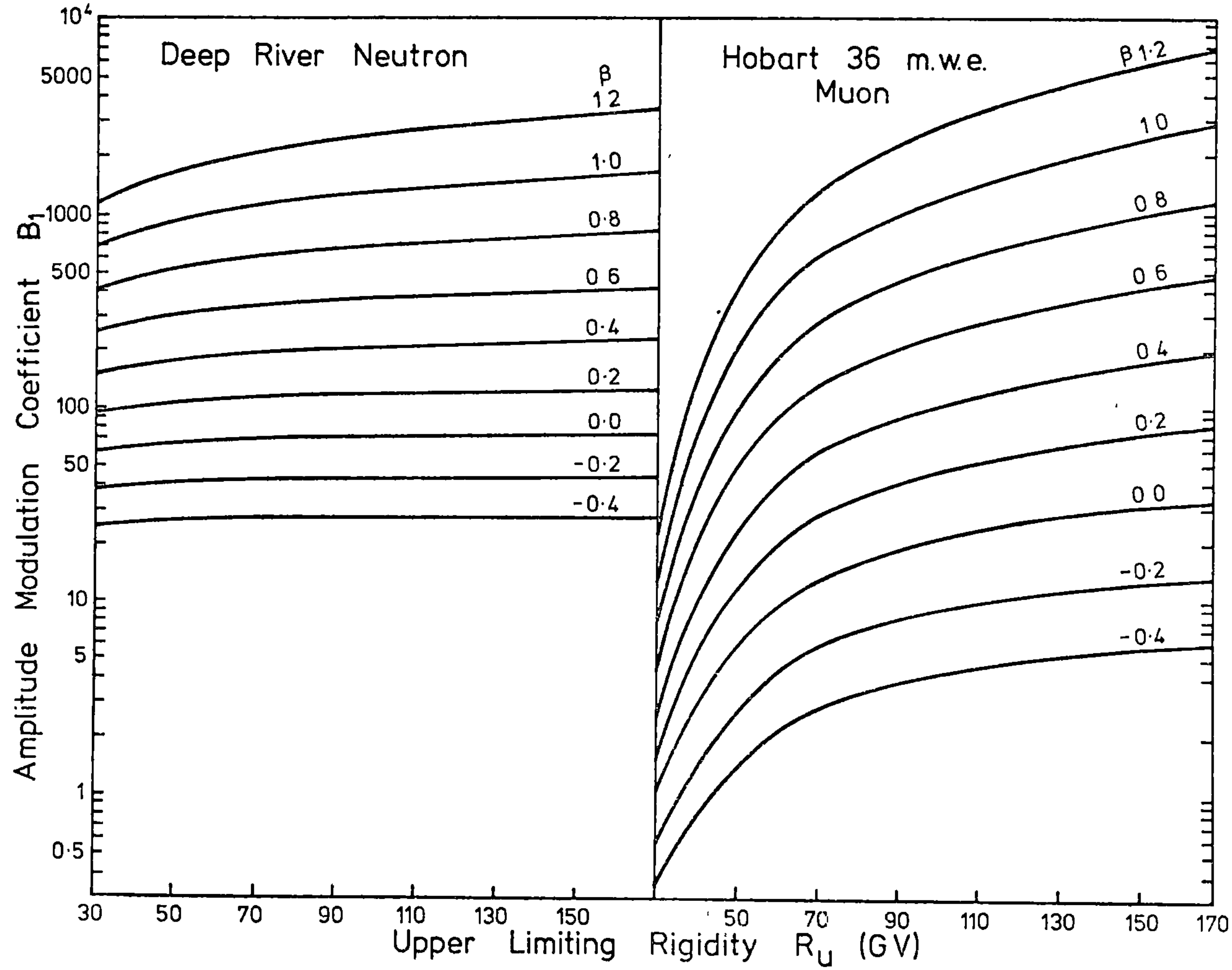
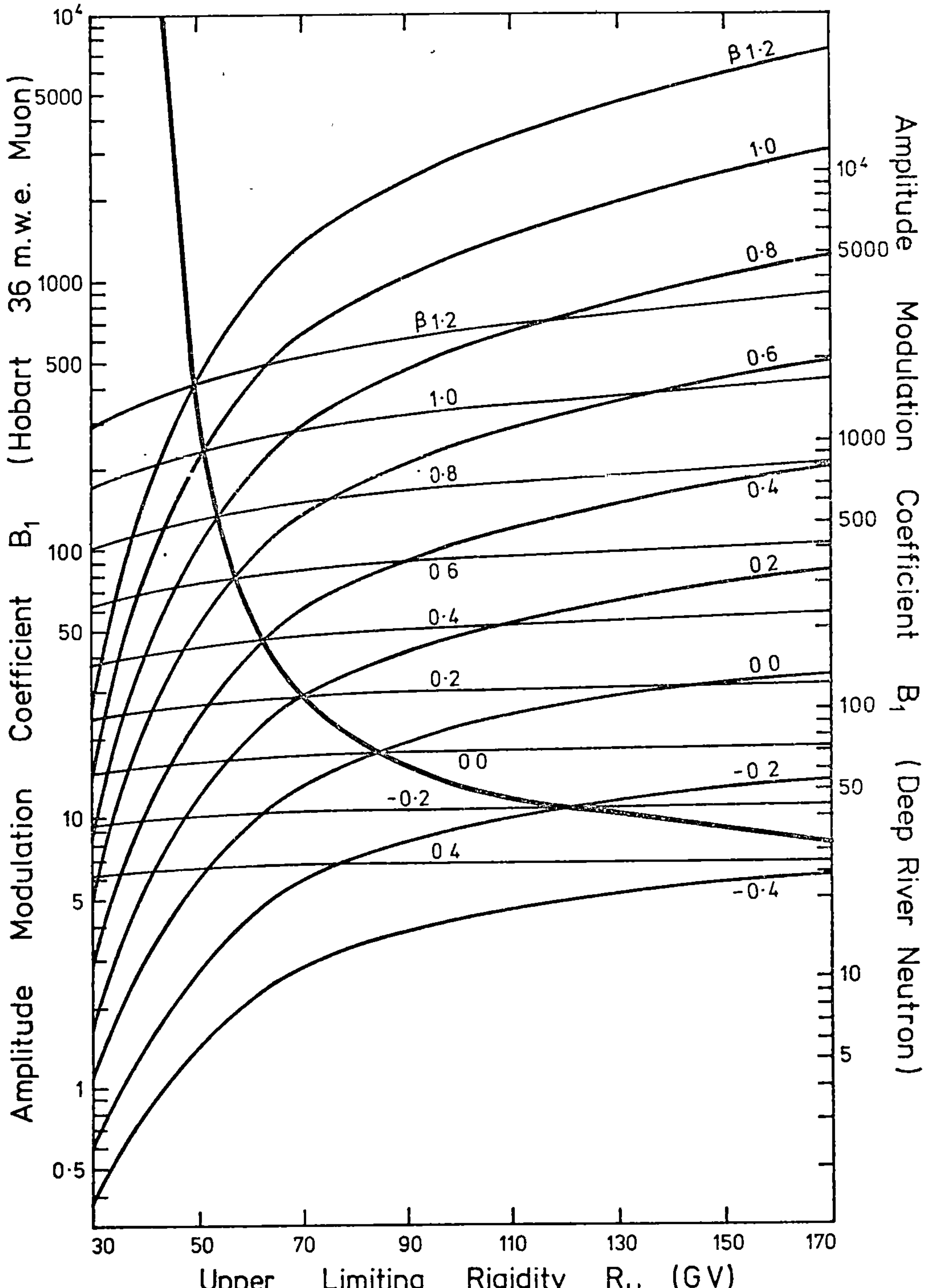


Figure 5.3. *Variation of amplitude modulation coefficient B_1 with R_u and β, for different detectors.*



<u>Figure 5.4.</u> *Superposition of Families of B_1 curves for Deep River and Hobart Ug muon. The heavy line represents the locus of all combinations of β and R_u which are consistent with the ratio of the observed amplitudes, in this case 4.0 : 1.*

Figure 5.5a *Figure 5.5b*

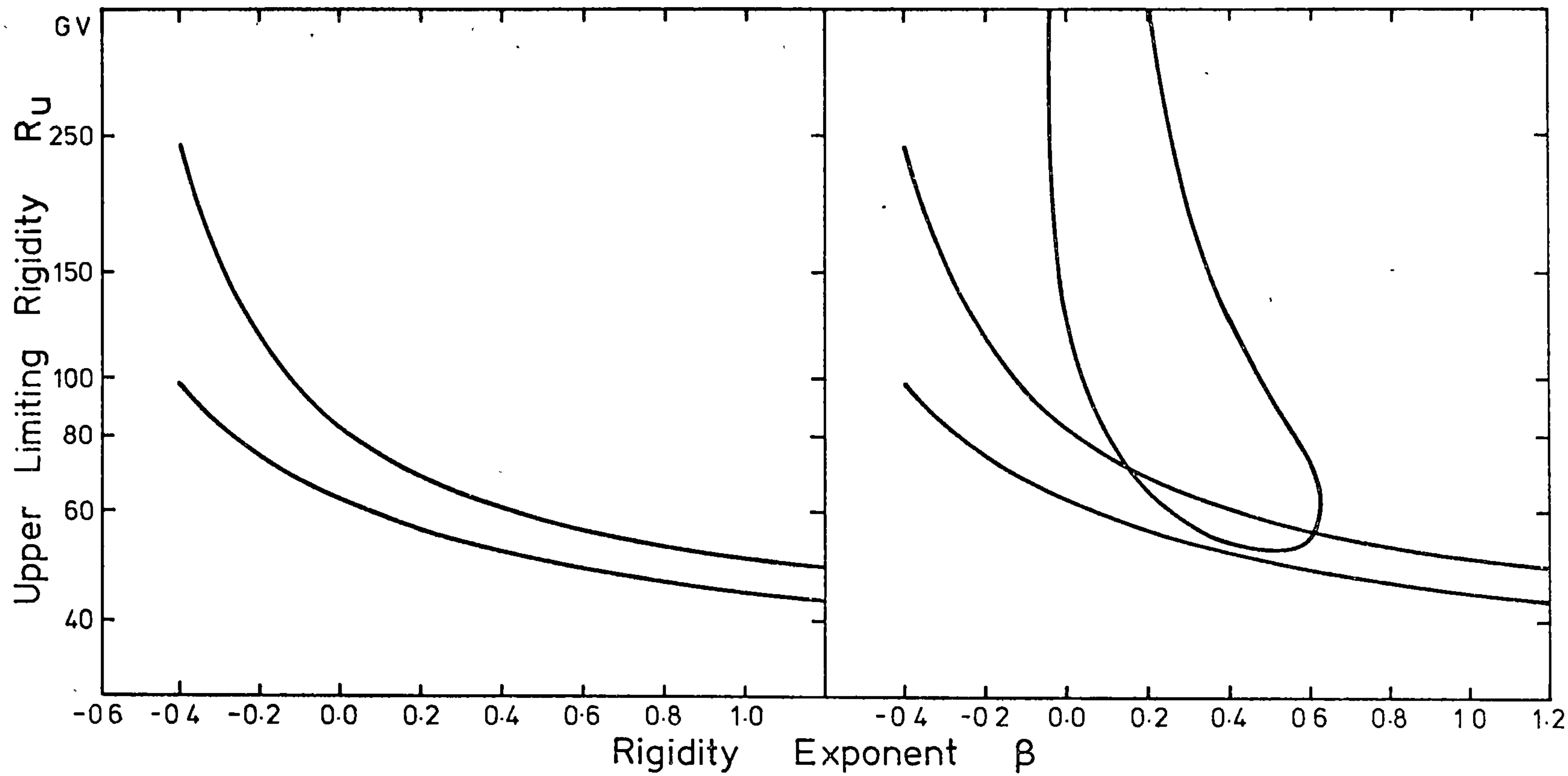


Figure 5.5a. *Possible (β, R_u) combinations as determined by ug muon v. neutron analysis.*

Figure 5.5b. *As figure 5.5a with addition of possible combinations as determined from neutron intercomparisons (figure 4.26).*

possible ranges of β (Figure 5.5b).

5.3.2. Analysis of Phase.

A similar process to that described above can be carried out using the phases ϕ_x and ϕ_y recorded by two dissimilar detectors. The phase modulation coefficients G_1 (section 4.2.1) are available for a variety of neutron monitors and combinations of β and R_u. Jacklyn (private communication) has computed similar coefficients for the Hobart underground telescopes. Both sets are in units of hours. Converting to angular measure let the coefficients for two particular detectors be Γ_x and Γ_y respectively. For observed vectors in directions ϕ_x and ϕ_y we have estimates

$$\eta_x = \phi_x + \Gamma_x \quad \text{and} \quad \eta_y = \phi_y + \Gamma_y$$

for the directions of the free-space vectors. Applying the condition that $\eta_x = \eta_y$ we have

$$\phi_x - \phi_y = \Gamma_y - \Gamma_x \qquad 5.5$$

Families of curves of Γ v. R_u, with β as a parameter, are plotted for each station. A linear scale is used for Γ. The same overlay technique, and subsequent plotting, as used in the amplitude case can then be employed to delineate a further region of possible combinations on a β v. R_u plot.

In practice the technique is of little use since the geomagnetic deflection associated with the Hobart underground telescope is relatively insensitive to quite large changes in R_u and is almost totally insensitive to changes in β (figure 5.6). The maximum change in Γ between the extreme

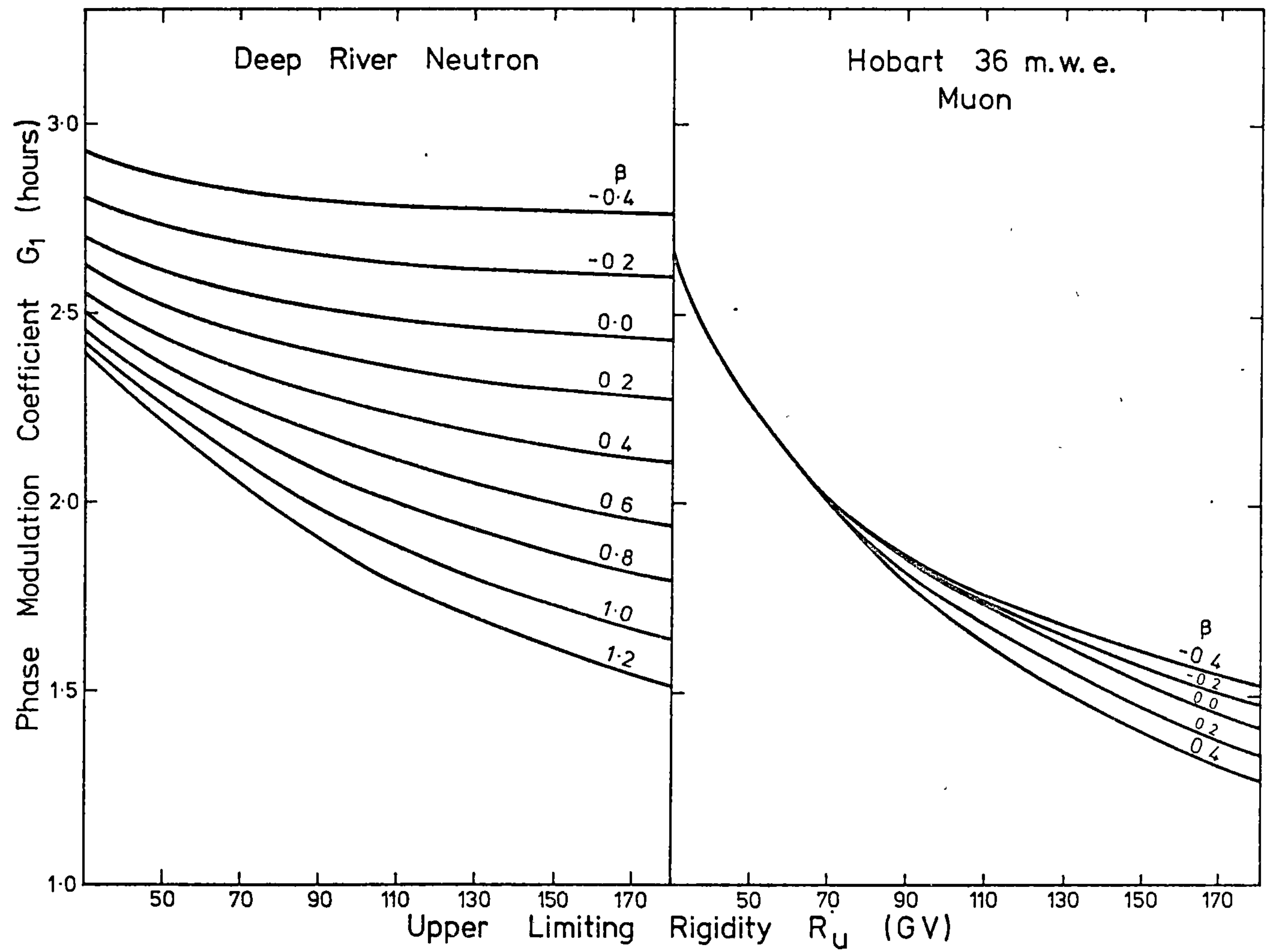


Figure 5.6. *Variation of phase modulation coefficient G_1 with R_u and β, for different detectors.*

likely values of R_u is only of order 10°. This must be compared with the 95% confidence limits on the phase observations, which average $\pm 30^{\circ}$. In consequence very large regions of possibility are obtained on β v. R_u diagrams by this method.

5.4. RESULTS.

5.4.1. Combined Observations.

The precise meaning of tabulated errors, discussed in section 4.5.6 in connection with results obtained from neutron intercomparisons, becomes even more uncertain when such results are compared with those obtained from the underground muon studies. For this reason results in this section are presented graphically.

Figures similar to figure 5.5a have been obtained for each year 1961 to 1966. They are obtained from the Hobart underground muon amplitude observations, corrected for the orbital-doppler effect, and the Deep River neutron monitor. The latter instrument is used since it displays estimated free-space vectors close to the mean free-space vector, averaged over a number of neutron monitors, in each year. It also has a low statistical error, even on a practical basis. The resulting regions of possible combinations of β and R_u are plotted in figures 5.7 and 5.8, where they are labelled muon regions. The regions of possible β and R_u combinations obtained from the final neutron analyses (figure 4.26), and here labelled neutron regions, are plotted in the same figures superimposed on the muon regions.

The regions of possibility obtained from the Hobart underground phase observations, when combined with those from Deep River, entirely

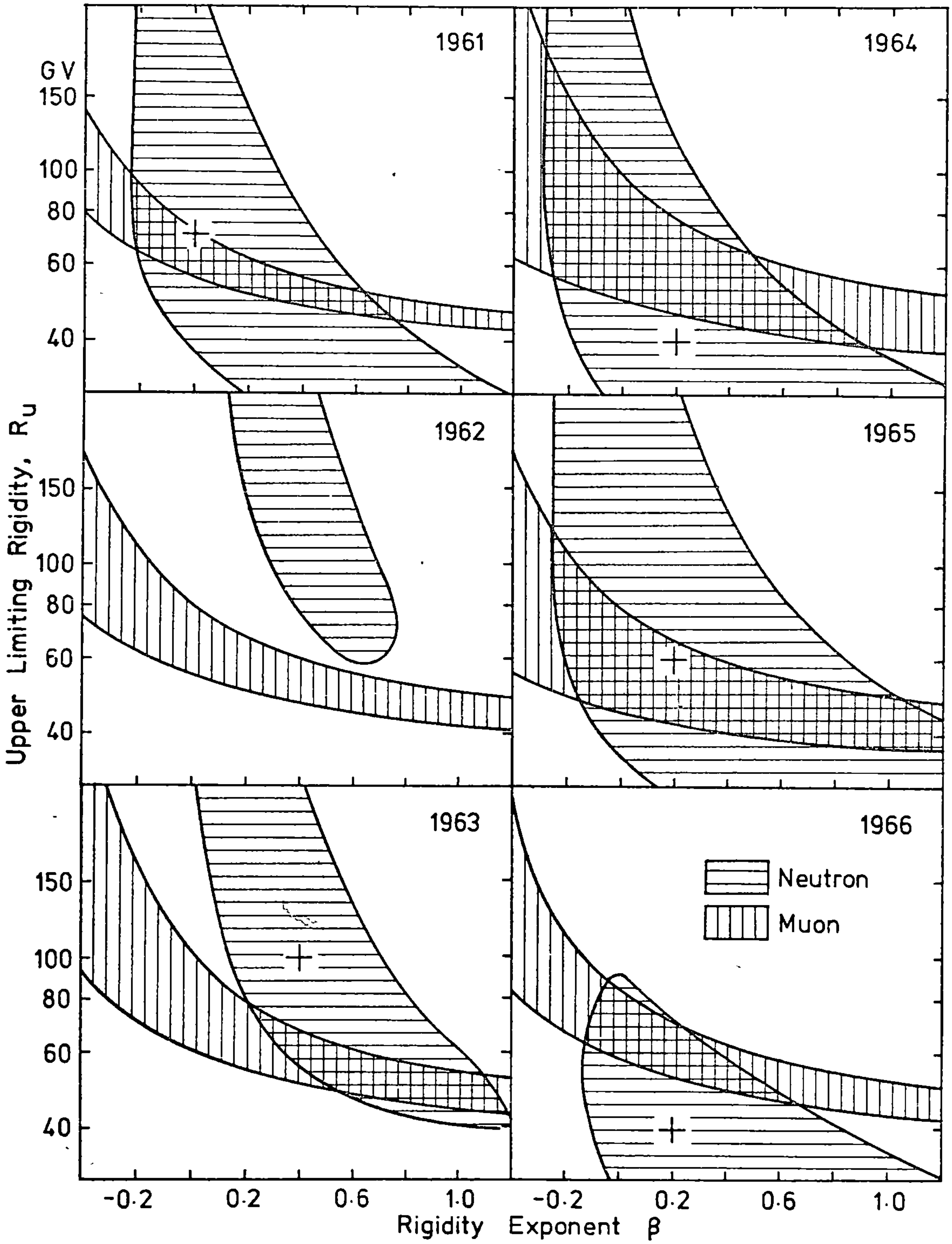


Figure 5.7. Possible combinations of β and R_u, to 95% confidence based on practical errors. The muon regions are computed for a latitude independent anisotropy.

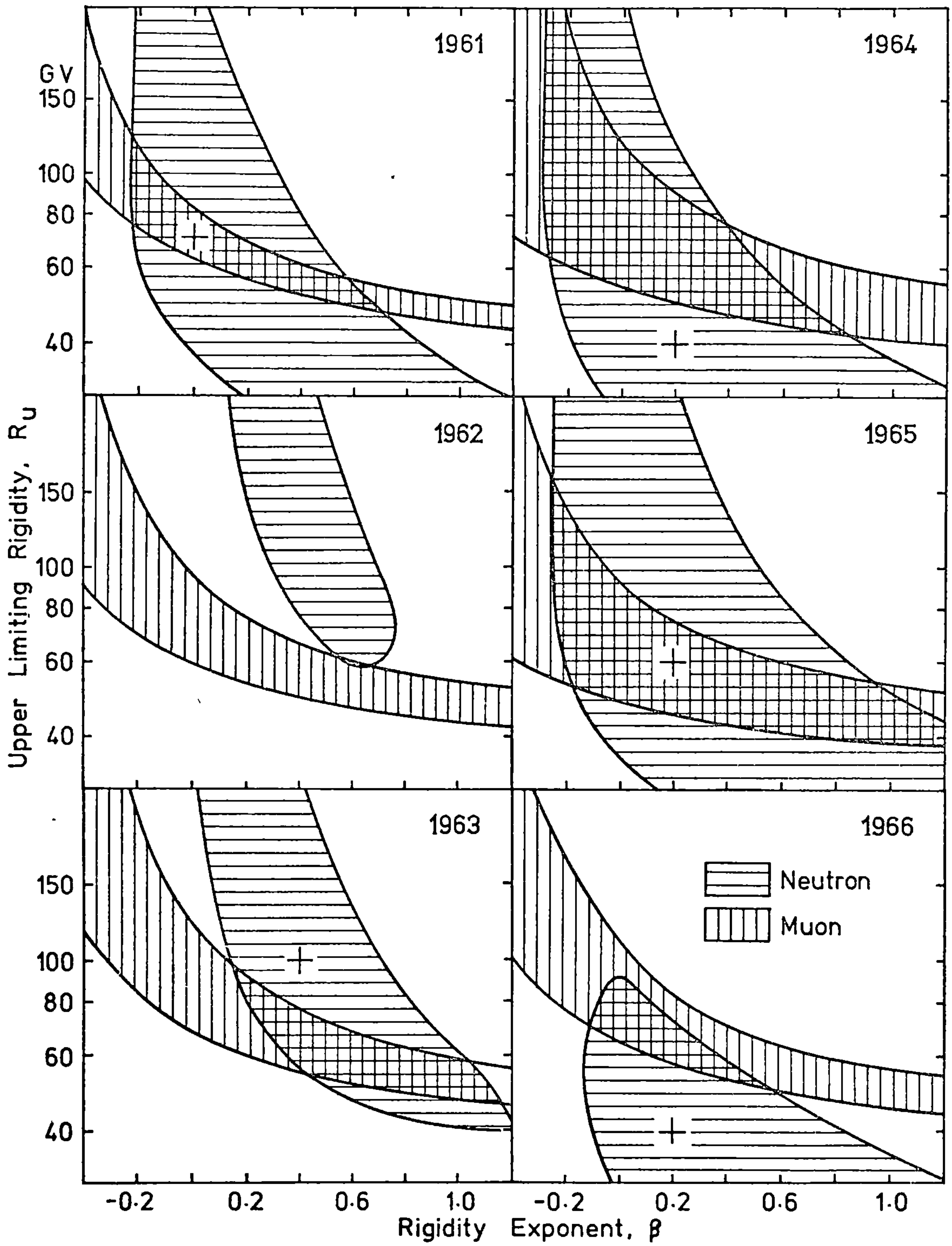


Figure 5.8. *Possible combinations of* β *and* R_u*, to 95% confidence based on practical errors. The muon regions are computed for an anisotropy varying as cosine (asymptotic latitude).*

encompass the regions derived from the other two methods in every year (section 5.3.2). They are not presented in figures 5.7 and 5.8 since they provide no further useful information. They do, however, indicate that the conclusions reached from the neutron and muon amplitude techniques are not inconsistent with the diurnal phases observed underground at Hobart.

Figures 5.7 and 5.8 show basically similar results. In figure 5.7 the muon regions have been computed on the basis of a latitude independent of anisotropy at higher rigidities (section 5.2.3). In figure 5.8 the muon regions refer to a cosine (latitude) dependence at all rigidities. In each case the neutron results principally delineate a range of possible β values, the muon results then determining the range of R_u and imposing further restraints on β.

The values of R_u obtained in figure 5.8 are a little higher than those in figure 5.7. This is to be expected Compared with the errors inherent in the measurement the difference between the two sets of results is not large. The values of β obtained are essentially the same for each case. For all years the central value of the range of β is positive, in some cases surprisingly so.

In 1962 and 1963 the combined analyses appear to exclude the possibility that $\beta = 0.0$. Jacklyn, Duggal, and Pomerantz (1970) demonstrated that $\beta = 0.0$ was a likely result for all years 1958 to 1966 (although their analysis does not definitely exclude non-zero values), and they evaluated R_u on this basis. It is interesting to put $\beta = 0.0$ in the present analysis, and compare the values of R_u thus obtained with those found by Jacklyn et al. The values are listed in table 5.3.

Analysis	Underground Latitude Dependence	1961	1962	1963	1964	1965	1966
Jacklyn et al	Independent	90	80	70	70	55	60
Present work	"	56to74	-	-	50to98	45to77	59to85
" "	cosine (latitude)	62to82	-	-	53to117	48to90	66to90

Table 5.3. Values of R_u, in GV, obtained by different analyses assuming β = 0.0.

Jacklyn et al did not attempt to specify the possible errors in their results, but they must be at least a few GV. The differences between theirs and the present values of R_u are therefore statistically significant only in 1961, although it could be argued that the consistently higher values obtained through solar minimum by the present work imply either that R_u was higher, or that β was more positive, than was found by Jacklyn et al for that period.

5.4.2. Solar cycle changes derived from muon analyses.

The year to year changes in observed diurnal variations are represented, in the Deep River neutron monitor (figure 5.1) for instance, by amplitudes varying over a range of up to 2 to 1, and times of maximum normally varying by only a few minutes, although variations of up to one hour are observed. The amplitude changes could, in principle, be due to changes in β, in R_u, in amplitude constant, or in varying combinations of the three. A considerable number of combinations of these variables appear to fit the observations (figures 5.7, 5.8). It is, however, possible to put limits on the likely year to year changes in these quantities.

Neutron monitors are too insensitive to changes in R_u, (figure 5.3) for such changes to be the prime cause of the observed year to year changes in amplitude. For a free-space vector with unchanging amplitude constant, A, but with varying β, the diurnal vector observed by a typical neutron monitor will approximately double in amplitude for each 0.2 rise in β. The observed phase of the vector will change by only 5 or 6 minutes in most cases. Thus the observations imply that the range of possible values of β is also about 0.2. Larger changes in β would require simultaneous large changes in A, in the opposite sense, a rather unlikely process.

The relative constancy of β permits the solar cycle changes in R_u to be assessed, by assigning an arbitrary, but possible, constant value to β and determining the value of R_u which then fits each year's observations. If the value of β selected is too low then the resulting value of R_u will be too high, and vici-versa, but the error will not be large and should not mask any cyclic changes in R_u.

In addition to the analyses reported in the previous section the Hobart underground muon and Deep River neutron observations have also been used to prepare further plots, similar to figure 5.5a, for each of the years 1958 to 1960 and 1967 to 1969. Utilising the similar results already obtained for 1961 to 1966, values of R_u, and consequent free-space amplitude and phase, have then been obtained for each year *on the assumption that* $\beta = 0.0$ (table 5.4). These values are compared with the sunspot numbers in figure 5.9. Results from the 1961 to 1966 neutron analyses have been entirely ignored in these calculations. The free-space phase and amplitude for each year have been estimated directly from the Deep River observations once the range of R_u has been determined. They differ

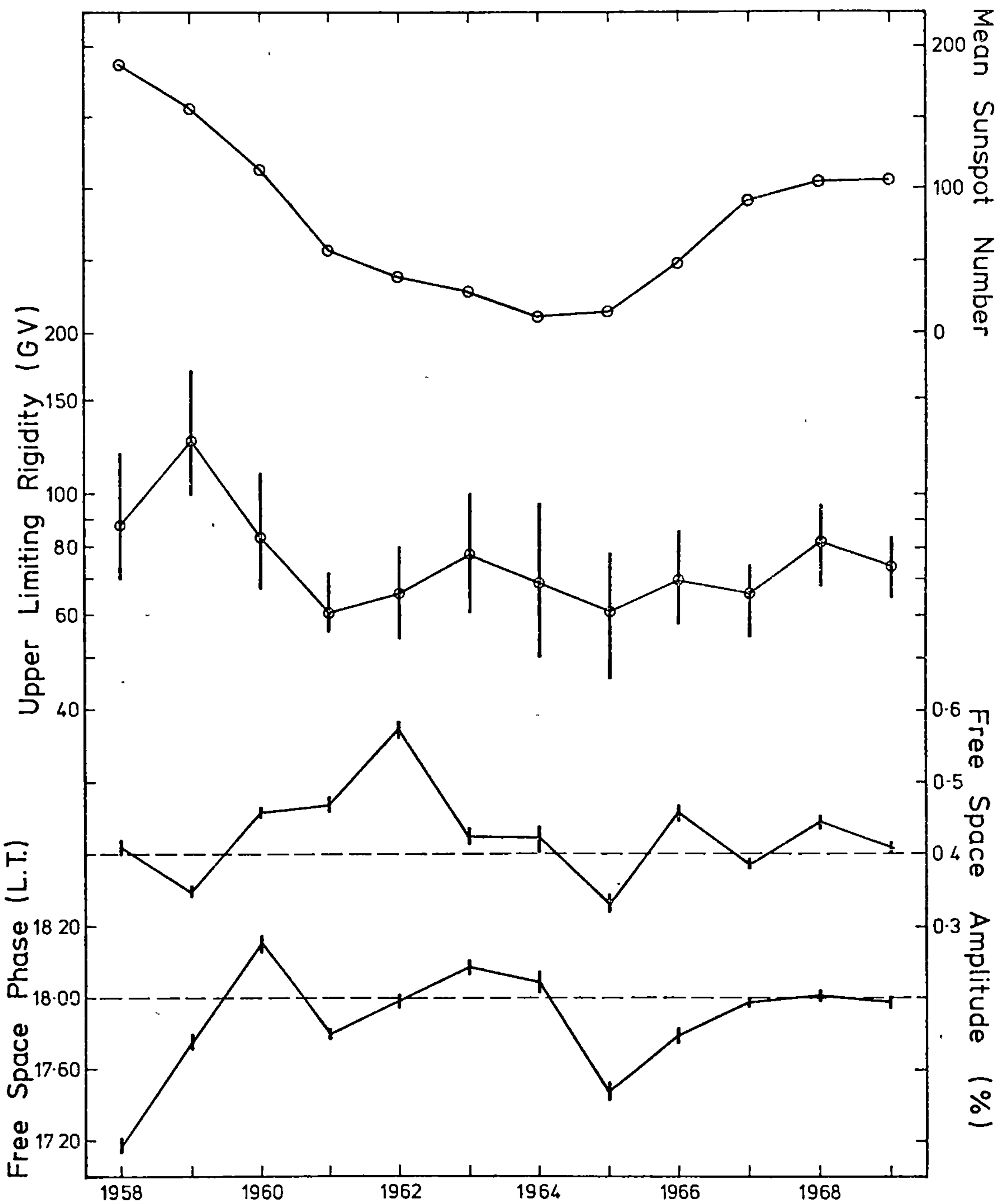


Figure 5.9. *Solar cycle variation of R_ν and free-space amplitude and phase, as estimated from comparison of Deep River neutron and Hobart underground muon observations,* assuming that $\beta = 0.0$.

to some extent from the values obtained by Jacklyn et al, who obtained values for those quantities from the average of observations of a number of detectors. A similar scatter in amplitudes from year to year, and early time of maximum in 1958, is indicated by both analyses.

Year	Most Probable Value	R_u (GV) Range		Estimated Free-Space		R_u (GV) JDP	R_u (GV) AE
		From	To	Amplitude (%)	Phase (L.T)		
1958	88	70	118	.41	17.18	100	
1959	126	100	170	.35	17.76	100	
1960	84	68	109	.46	18.31	100	
1961	61	56	72	.47	17.81	90	
1962	66	55	80	.58	17.99	80	
1963	78	61	100	.42	18.17	70	
1964	69	50	96	.42	18.10	70	
1965	61	46	78	.33	17.48	55	43 ± 2
1966	70	58	86	.46	17.79	60	) 60^{+5}_{-3}
1967	66	55	74	.39	17.98		)
1968	82	68	96	.44	18.02		90
1969	74	65	84	.41	17.99		

Table 5.4. Values of R_u, amplitude constant, and phase, of the free-space diurnal anisotropy. Results obtained from direct comparison of Hobart underground muon and Deep River neutron observations assuming $\beta = 0.0$, and disregarding information available from neutron analyses in some years. Errors are 95% practical, those for amplitude and phase being small (figure 5.9). Values of R_u found by Jacklyn et al (1970) and by Ahluwalia and Ericksen (1970), labelled JDP and AE respectively, are also listed.

A small solar cycle variation probably exists in the above tabulations of R_u. The large errors involved make it rather uncertain, however and a value of 70 GV agrees with the observations in all years except 1959. What variation there is appears to be rather smaller than the variations suggested by Jacklyn et al and by Ahluwalia and Ericksen (1970).

5.4.3. Discussion of observations of R_u.

The values of R_u obtained in the present analysis depend on the accuracy of the underground vector amplitudes. As indicated in table 5.2 the vectors used up to, and including, 1962 are in fact averages of the vectors recorded at Hobart and at the underground observatory at Budapest (40 m.w.e., 47^o N geographic). The amplitudes recorded by the two stations are consistently similar, and well within likely statistical variations. In 1961 in particular (see discussion below) the two amplitudes are almost identical. It is therefore likely that the amplitude used is correct. The phase difference of about 30^o between the phases observed by the two stations in 1961 is statistically possible. Since the two stations are situated at quite different longitudes and in totally different geographic locations any meteorological effects in the results would be expected to reveal themselves by causing greater differences between the result vectors than are actually observed. It can thus be provisionally concluded that serious meteorological contamination does not exist at either station.

5.4.4. Observations in 1961.

The diurnal variations observed by many (but not all) neutron monitors in October and November 1961 were abnormally short (of order 0.1%), and were often in unusual directions (section 4.4.2.1). The underground vectors also displayed unusual behaviour in this period, and the value of R_u found for 1961 is rather low.

High energy detectors observe diurnal variations in sidereal as well as in solar time. The existence of the sidereal variation is well established but there is some dispute in the literature concerning its origin. This does not concern us here for, whatever its origin, it is likely that the sidereal variation will be more or less constant from month to month in sidereal time. The same may broadly be said of the solar variation in solar time. This being so then at some part of the year the two vectors will re-inforce, resulting in a large monthly vector in solar time. Six months later partial cancellation will occur, resulting in a shorter vector in a different direction. These effects do not appear in the annual vectors since the total sidereal contribution to an annual solar diurnal variation is zero if the sidereal variation is time-invariant.

In the Southern Hemisphere re-inforcement occurs early in the year. The monthly vectors thus show a steady shortening and anti-clockwise rotation until September, after which clockwise rotation recommences. Figure 5.10 shows the 12 year (1958 to 1969) average monthly vectors observed underground at Hobart, and compares them with the individual monthly vectors observed by the same instrument in 1961. The unusual behaviour of the vectors in the last three months of 1961 is clearly seen. It indicates that the variation in solar time was much smaller than normal in those months, the observed vectors presumably largely comprising the sidereal component. This is quite contrary to the position earlier in the year.

A reduction in R_u to abnormally low values during these months provides one possible explanation of these observations. However inter-comparison of the observed neutron monitor vectors appears to favour a

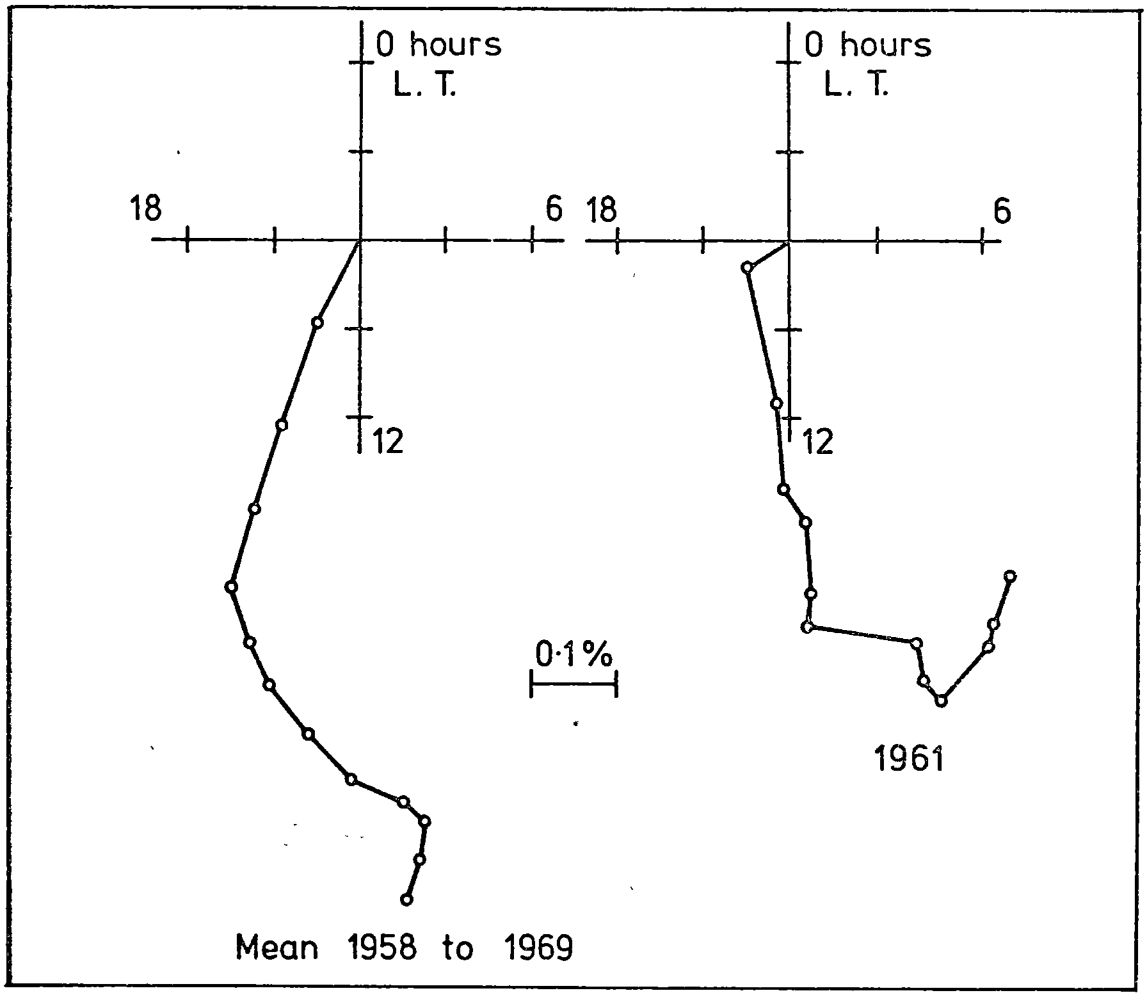


Figure 5.10. *Mean monthly pressure-corrected diurnal vectors observed by Hobart underground muon telescopes over 12-year period, compared with monthly mean vectors observed in 1961.*

very low amplitude constant associated with values of β and R_u in their normal range. With the small observed amplitudes the errors involved in this estimation are large and the results are therefore rather doubtful.

It does seem, however, that it may not be physically meaningful to discuss a mean diurnal variation in 1961, and that for analysis purposes the year should be divided into two periods, January to September, and October to December. The technique of analysis employed is necessarily restricted to complete years of data, to avoid contamination by variations in sidereal time, and consequently no attempt has been made to consider these periods on their own account.

CHAPTER 6.

THE SOLAR DIURNAL VARIATION - DISCUSSION AND CONCLUSIONS

6.1 DISCUSSION

The most recent model for the diurnal variation is that due to Forman and Gleeson (1970, not yet published), which was briefly outlined in section 3.4.1. They derive an expression for the average streaming $\underline{S}$ of cosmic rays in interplanetary space, as a result of which an anisotropy ξ will be observed. They find that

$$\underline{S} = C U \underline{V} - \kappa_{\parallel} \left(\frac{\partial U}{\partial \underline{r}} \right)_{\parallel} - \kappa_{\perp} \left(\frac{\partial U}{\partial \underline{r}} \right)_{\perp} \qquad 3.5$$

The quantities in this expression are defined in section 3.4.1, and the component vectors are illustrated in figure 6.1.

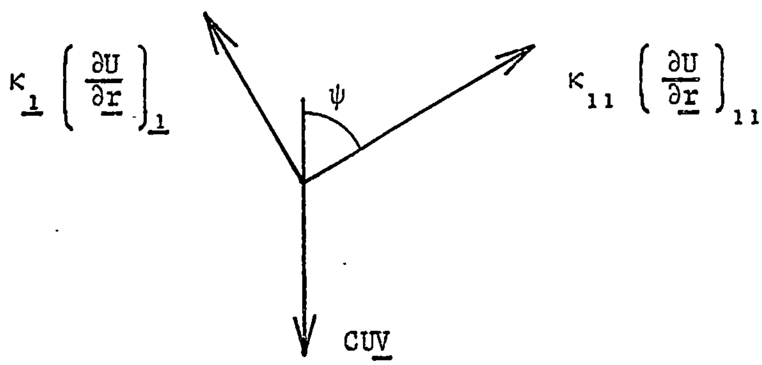


Figure 6.1. *Streaming components.*

In a solar centred spherical co-ordinate system the streaming may be expressed as

$$\underline{S} = \underline{S_r} + \underline{S_\phi} + \underline{S_\theta}$$

the sum of the radial, azimuthal, and perpendicular streamings. It is observed that $\underline{S_r} = 0$ on average.

$$\text{Now } \underline{S_r} = CU\underline{V} - \kappa_{11}\left(\frac{\partial U}{\partial \underline{r}}\right)_{11} \cos\psi \cdot \underline{\hat{r}} - \kappa_{\perp}\left(\frac{\partial U}{\partial \underline{r}}\right)_{\perp} \sin\psi \cdot \underline{\hat{r}} \qquad 6.1$$

where ψ is the angle between the magnetic field and the unit radial vector $\underline{\hat{r}}$.

By observation $\frac{\partial U}{\partial \phi} = 0$, and if $\frac{\partial U}{\partial \theta}$ is small compared with $\frac{\partial U}{\partial r}$ we have

$$CU\underline{V} - \kappa_{11}\left(\frac{\partial U}{\partial r}\right) \cos^2\psi \cdot \underline{\hat{r}} - \kappa_{\perp}\left(\frac{\partial U}{\partial r}\right) \sin^2\psi \cdot \underline{\hat{r}} = 0 \qquad 6.2$$

$$\text{Now } S_\phi = \kappa_{11}\left(\frac{\partial U}{\partial \underline{r}}\right)_{11} \sin\psi - \kappa_{\perp}\left(\frac{\partial U}{\partial \underline{r}}\right)_{\perp} \cos\psi$$

$$\therefore S_\phi = \kappa_{11}\left(\frac{\partial U}{\partial r}\right) \sin\psi\cos\psi - \kappa_{\perp}\left(\frac{\partial U}{\partial r}\right) \sin\psi\cos\psi \qquad 6.3$$

Eliminating $\frac{\partial U}{\partial r}$ we have

$$S_\phi = \frac{CUV\ (\kappa_{11} - \kappa_{\perp}) \sin\psi\cos\psi}{\kappa_{11}\cos^2\psi + \kappa_{\perp}\sin^2\psi} \qquad 6.4$$

The corresponding anisotropy is (Gleeson and Axford, 1968; Gleeson, 1969)

$$\xi = \frac{3\underline{S}}{vU}, \quad \text{where v is particle speed.}$$

$$\therefore \underline{\xi} = 3C\,\frac{V}{v}\,\frac{(\kappa_{11} - \kappa_{\perp})\tan\psi}{\kappa_{11} + \kappa_{\perp}\tan^2\psi} \cdot \underline{\hat{\phi}} \qquad 6.5$$

Gleeson and Axford show that, as particle kinetic energy $T \to \infty$, $C \to (2 + \gamma)/3$, where γ is the spectral exponent of the particles. This is the Compton-Getting expression (eqn. 5.1), and consequently C is often referred to as the Compton-Getting coefficient.

Gleeson and Axford have evaluated C for both protons and alpha particles over a wide range of kinetic energies. They find, for protons, a value of 1.2 at 2 GeV, rising to 1.6 at 100 GeV, confirming the approximation to the Compton-Getting relation at high energies. Setting C at 1.5, V at 400 $km.sec^{-1}$, and v at 3×10^8 $m.sec^{-1}$ we have, since $\psi \simeq 45^o$,

$$\underline{\xi} = 6 \times 10^{-3} \left(\frac{1 - \chi}{1 + \chi} \right) \underline{\Phi} \qquad 6.6$$

where $\chi = \kappa_{\perp}/\kappa_{11}$

The rigidity dependence of ξ rests on the dependence of C and χ. In the range 2 to 50 GeV / nucleon C increases slightly. The C,T relation is not exponential, however in this range the overall change in C is equivalent to an $R^{+0.1}$ relationship for protons.

In 1965 κ_{11} was observed to vary as Rv, with a value of 10^{22} $cm^2.sec^{-1}$ for 6 GeV protons (Gleeson, 1969). $(\omega\tau)$ is then independent of rigidity, and $\simeq 2.5$.

Now $\kappa_{\perp} \geq \dfrac{\kappa_{11}}{1 + (\omega\tau)^2}$ (section 3.4.1) with the minimum value occurring if there is no contribution to the scattering from random walk of the magnetic field lines (Jokipii, 1966; Jokipii and Parker, 1969).

Should this contribution indeed be negligible then $\kappa_{\perp}$ would also be rigidity dependent and χ would be rigidity independent.

Substituting $(\omega\tau) = 2.5$ we have $\kappa_{\perp} \gtrsim \frac{1}{7.25}\,\kappa_{11}$,

i.e. $\chi \geq 0.14$.

In 1965 the estimate for the free-space amplitude is 0.33 (table 5.4). Jacklyn et al (1970) find a similar value. Eqn. 6.6 then requires that $\chi \simeq 0.29$. Thus in that year the contribution to the perpendicular diffusion from random walk of the field lines approximately equalled the contribution from the scattering in a smooth field, and no direct statement can be made about the rigidity dependence of χ.

If κ_{11} is not rigidity dependent the rigidity dependence of χ becomes even more uncertain, but the observational evidence suggests that any such dependence must be weak.* There appears however to be no theoretical requirement that the observed diurnal anisotropy should be entirely independent of rigidity. If χ is rigidity independent then the anisotropy should show a slight rigidity dependence, about $R^{+0.1}$, due to the increasing value of C in the energy range of the anisotropy.

There is no explicit mention of an upper limiting cut-off rigidity in the Forman/Gleeson model. However the model only holds for particles staying entirely within a magnetic sector (Ness and Wilcox, 1964; Wilcox and Ness, 1965), in the interplanetary magnetic field. Particles

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* *During discussion following a paper (Humble, 1971) presenting some of the results of the present work to the Hobart Cosmic-Ray Conference Dr. J.J. Quenby stated that magnetic field power spectra give χ independent of rigidity even if κ_{11} does not vary as Rv. (Discussions, 12th Int. Conf. Cosmic Rays, Hobart, Conference Papers (University of Tasmania), 7, to be published).*

traversing a sector boundary are scattered out of, or into, the sector. Thus it could be assumed that R_u would be related to the characteristic size of sectors during the year. There is evidence to the contrary.

The sector structure in late 1963 and early 1964, at a time of low solar activity, was a well substantiated system with four more or less equal sized sectors distributed around the solar periphery. In two of these the magnetic field vectors were directed away from the sun, and in the other two towards it. The sectors co-rotated with the sun, their dimensions being determined by the time they took to pass an interplanetary space probe. There were also small regions of varying magnetic field directions, occupying about 2 or 3 days of each 27 day solar rotation period. Thus the characteristic dimensions of a sector, in the azimuthal direction at the earth's orbit, was $\frac{6}{27} \cdot 2\pi$ ($\approx$ 1.4) a.u. A particle having gyro-radius 0.7 a.u. could not be contained in such a sector. At the reported average field strength of 6 γ (6×10^{-5} gauss) this corresponds to a maximum possible particle rigidity, for retention in the sector, of 190 GV.

Such a particle would remain in the sector only if its gyro-centre were on the sector axis of symmetry. A reasonable value of R_u might correspond to a rigidity at which 50% of particles would be retained in a sector for a significant period. This corresponds to 95 GV in this particular case, the upper limit of the range observed for 1964.

The argument above assumes that the characteristic sector dimension (or more properly a product of sector dimension times field strength in the region traversed by the particle) is no smaller in directions perpendicular to the ecliptic than it is in the azimuthal direction. The assumption is questionable.

The sector structure apparently changes during the solar cycle. Ness (1969) reports that in 1966 only two sectors existed, one of 19 or 20 days and the other of 8 days, duration. At first sight this contradicts the requirement of div $\underline{B} = 0$. Presumably the field lines return at some other helio-latitude. These sectors persisted between March and September, 1966, but interchanged polarity in that time. There is some evidence, from data supplied by Dr. Ness to Dr. A.G. Fenton, that the pattern of alternate long and short sectors continued until at least mid 1968.

Such changes in the large-scale structure of the interplanetary magnetic field could reasonably be expected to have significant effects on cosmic ray behaviour. The surprising thing is that, at least as far as the diurnal variation is concerned, the effects are so small. A sector of angular width approximately $\frac{3\pi}{2}$, corresponding to the larger of the two sectors reported by Ness, has infinite dimensions in the azimuthal direction, so far as particles likely to be involved in the solar diurnal variation are concerned. The perpendicular dimension of such a sector must be the factor which controls the maximum rigidity for retention of particles. For the smaller sector the azimuthal direction will probably be the controlling factor. However this applies, at least in 1966, only to around one quarter of each month, and will have a correspondingly small effect on the mean diurnal variation observed for the month.

Schatten, Wilcox, and Ness (1969) have suggested that the magnetic sectors have their origin in relatively small regions on the solar disc, and that fairly substantial cross-radial propagation takes place. An azimuthal source to sector ratio of about 1 to 3 is suggested. There is evidence that the sources are at relatively high solar latitudes in 1966, around 35° to 40°, compared with their essentially equatorial location at the end of the previous solar cycle a year or so earlier. The inference is that the sources may follow the normal pattern of the sunspot cycle. The cross-radial spread, and high latitude source, reported suggest that the perpendicular sector diameter in the region of the earth's orbit will be at least 2 a.u., and probably nearer 3 a.u., corresponding to the retention of particles of 135 GV or 205 GV respectively in the larger sectors. These values are considerably higher than the observed values of R_u, and the mechanism can therefore only explain the observations if there is a considerable reduction in $|B|$ in regions well away from the ecliptic.

6.2. CONCLUSIONS

The errors involved in determining the parameters of the solar diurnal variation are larger than have been estimated by previous investigators. The present work excludes the likelihood of the rigidity exponent β having a negative value in any of the years 1961 to 1966, and suggests that, on average, β may be slightly positive. It is experimentally difficult to distinguish between zero and slightly positive values, and zero is not excluded in four of the six years. These observations are in agreement with the theory of Forman and Gleeson, which does not require β to be identically zero. The highly positive value found for β in 1962, whilst apparently satisfactory in terms of neutron data consistency, is rendered further suspect by its failure to agree with the underground/ Deep River analysis. There is no noticeable pattern in the changes observed in β, and it is not statistically possible to determine whether it remains constant from year to year. However large year to year changes are improbable.

The upper limiting rigidity, R_u, shows some tendency towards a solar cycle variation, with the lowest values occurring around solar minimum. Irregular variations from year to year are superimposed on this pattern. Some of these are undoubtedly statistical in origin, others may well be genuine. The observed values of R_u are consistent with the Forman/Gleeson theory, and with observed magnetic field sector structure, but are somewhat smaller than the latter would indicate, suggesting that some other controlling mechanism exists. The large ranges found in the determinations of R_u arise from the counting rates of the instruments used and the nature of the comparisons employed. They are believed realistic.

There is no evidence for regular solar-cycle variations in the phase, or amplitude constant, of the free-space diurnal vector. The times of maximum observed are close to 1800 L.T. It is not clear whether the departures from this are statistical or physical in origin. The considerable variability in the amplitude constants from year to year may be genuine or may reflect small changes, of order ±0.1, in β from year to year.

CHAPTER 7.

A TRANSIENT EVENT.

7.1 INTRODUCTION.

November 1960 was one of the most interesting and active months of Solar Cycle 19 from the viewpoint of cosmic radiation. Large radiation fluxes of solar origin were observed at ground level on November 12th and 15th, and to a lesser extent on November 20th. They were accompanied by intense magnetic activity and by Forbush Decreases in the recorded intensity of galactic cosmic rays. These events have been considered by a number of investigators (Lockwood and Shea, 1961; Mathews, Thambyahpillai and Webber, 1961; and several papers in the Proceedings of the Kyoto Conference, Vol.II, 1962), but no consideration appears to have been given to the sharp and short-lived decrease which occurred on November 30th and December 1st 1960. This is surprising, as the nature of the decrease appears to be unique as far as IGY and subsequent records are concerned.

The event superficially appears to resemble the pre-decrease sometimes seen prior to normal Forbush Decreases (McCracken and Parsons, 1958); however, in this case no following decrease was observed. The event was only obvious at stations whose asymptotic cones are centred between 50° and 180° East of the Greenwich meridian. It was short-lived, four to five hours, and had intensities of depression ranging up to 5.9%. Some, possibly related, effects were also observed two or three hours later at certain American stations.

The methods used to study the daily variation may also be used, with suitable modifications, to study transient events. The December 1st event is particularly suitable for such an analysis by reason of its rapid onset and ending. The following sections discuss a study of this event. A preliminary report of this work has been published (Humble, 1968), however some of the conclusions reached here differ slightly from those suggested at that time.

7.2 OBSERVATIONS

7.2.1. Cosmic Ray Observations

Data have been obtained from a number of stations in the global network; a detailed list appears in table 7.1. A number of stations, including several in the equatorial region, were unavailable due to equipment troubles.

The stations have been divided into four groups on the basis of longitude of the major portion of their viewing regions. The regional names adopted refer only to the approximate longitude and not necessarily the latitude of the recording station. The hourly or bihourly intensities recorded by each instrument are shown in figure 7.1, with amplitudes expressed as a percentage of the mean count rate for the particular instrument for H01 to H22 inclusive on November 30th (U.T.). It can be seen that the Australasian stations saw no marked event on either November 30 or December 1, whereas the European group stations all show a marked decrease with a minimum occurring during H01 and H02 U.T. on December 1. This corresponds to a decrease in the incident galactic cosmic radiation in directions η between 0 and 120° from the Sun-Earth line, i.e. in the morning side of the anti-solar hemisphere (figure 4.1). Some sign of the decrease is to be seen in the Eastern American stations, with the minimum being less pronounced and occurring mainly around H03 U.T. on

Station	Vertical Cut-off Rigidity (GV)	Geographic Longitude (degrees)	Altitude (metres)	Type of Detector
A. Australian Group				
Lae	15.52	147.00	S.L.	M
Mt. Norikura	11.39	137.56	2770	N
Brisbane	7.00	153.01	S.L.	N
Mt. Wellington	1.89	147.24	725	N
Hobart	1.88	147.33	S.L.	M
B. European Group				
Kodaikanal	17.47	77.46	2343	N
Rome	6.31	12.52	S.L.	N,M
Pic-du-Midi	5.36	0.25	2860	N,M
Jungfraujoch	4.48	7.98	3550	N
Zugspitze	4.24	10.98	2960	N
London	2.73	359.91	S.L.	N
Leeds	2.20	358.45	100	N
Uppsala	1.43	17.58	S.L.	N
Kerguelen	1.19	70.22	S.L.	N,M
Mawson	0.22	62.88	S.L.	N,M
C. Eastern American Group				
Huancayo	13.49	284.67	4000	N
Rio-de-Janeiro	11.73	316.78	S.L.	N
Climax	3.03	253.82	3500	N
Mt. Washington	1.24	288.70	1900	N
Ottawa	1.08	284.40	100	N,M
Deep River	1.02	282.50	145	N
D. Western American Group				
Sulphur Mountain	1.14	244.39	2283	N,M
Churchill	0.21	265.91	S.L.	N,M
Resolute	< 0.05	265.09	S.L.	N,M

Table 7.1. Stations used in analysis of December 1st event. N = neutron monitor, M = vertical muon telescope.

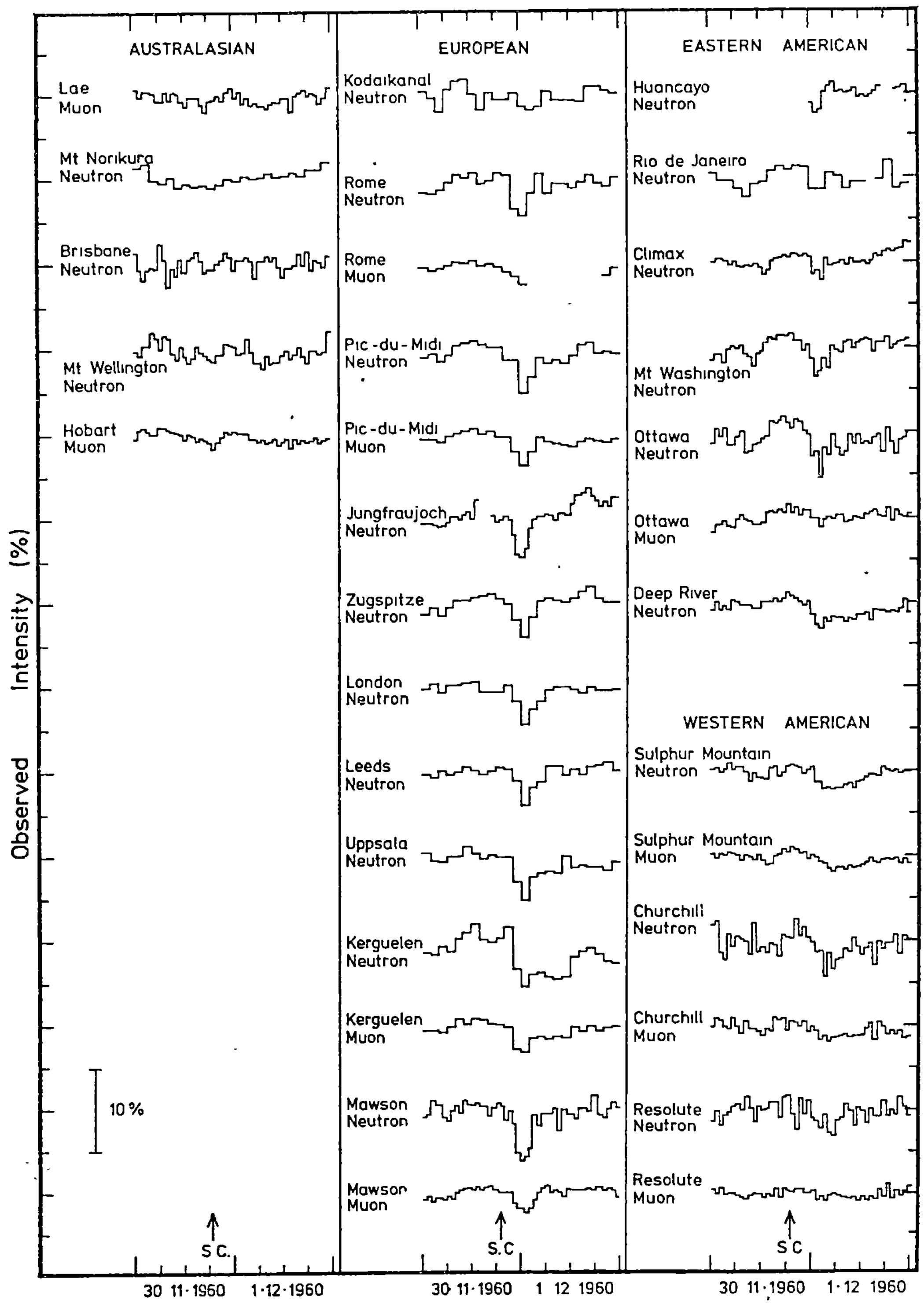

Figure 7.1. *Mean hourly or bi-hourly intensities recorded by various detectors, expressed as percentages of the mean intensity for hours 01 to 22, November 30, 1960.*

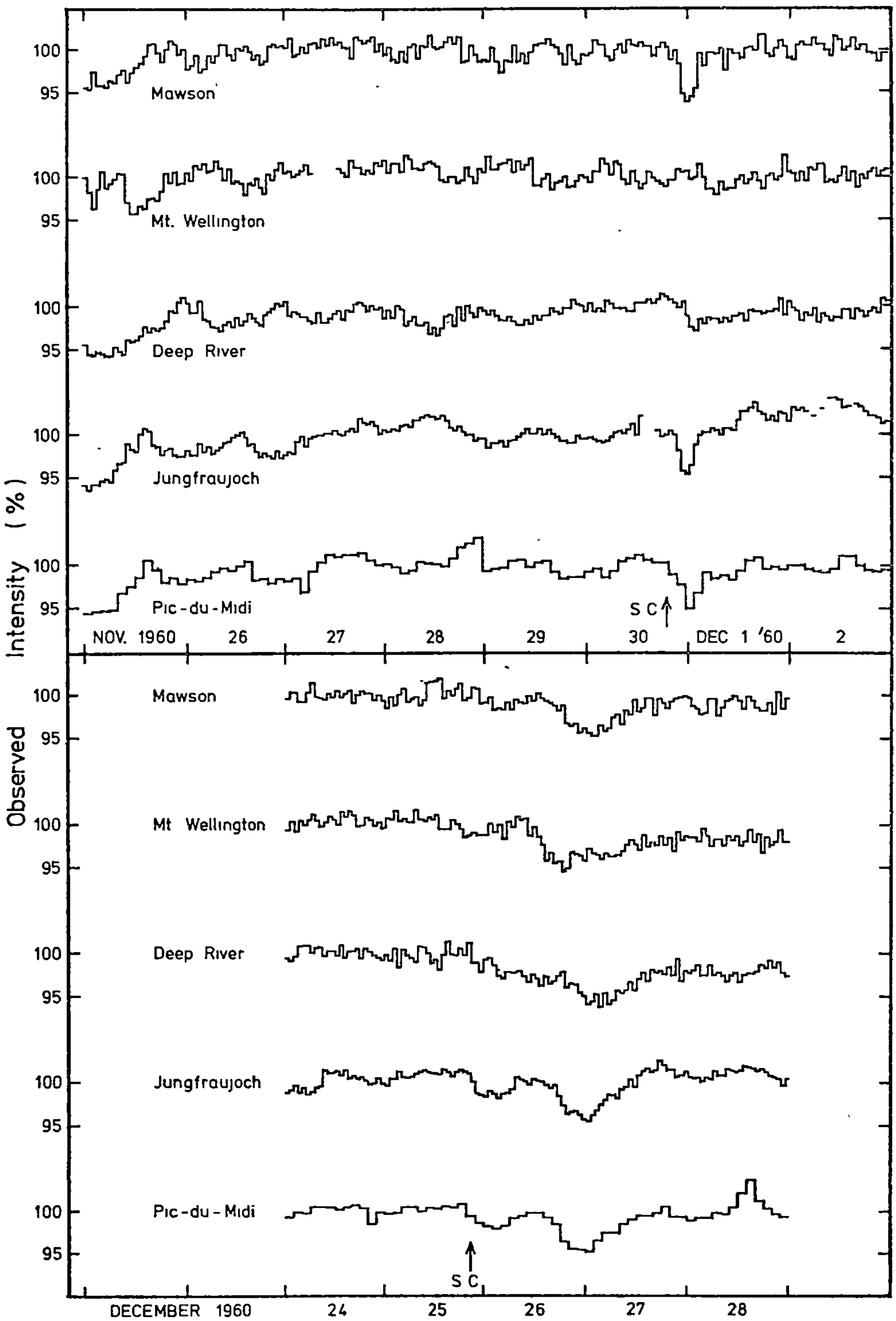

Figure 7.2. Mean hourly or bi-hourly intensities recorded by various neutron monitors, expressed as percentages of the daily mean intensity for November, 25, 1960 (upper diagram) or December 24, 1960 (lower diagram).

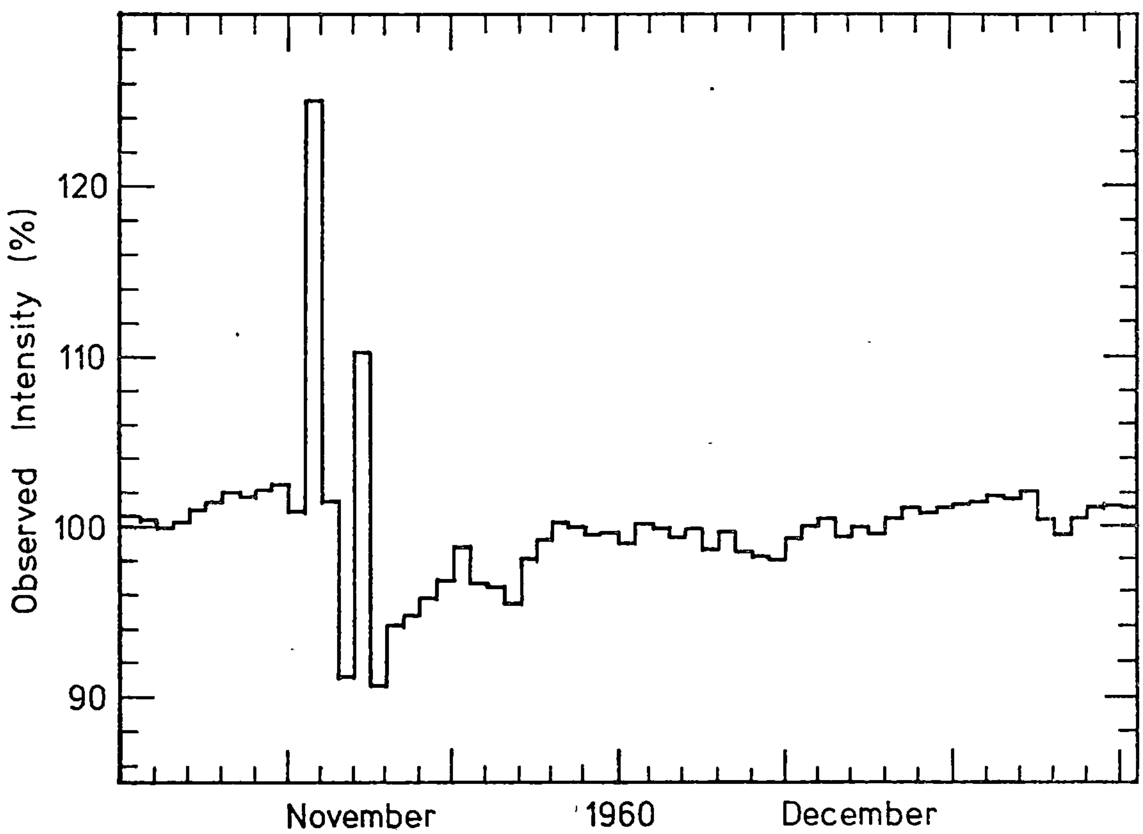

Figure 7.3. *Daily mean intensities observed by Mawson Neutron Monitor, November and December 1960, expressed as percentage of average intensity for October 1960.*

December 1. The Western American stations show only a slight depression, rather gradual and amounting to only 1 to $1\frac{1}{2}\%$ centred around H06 or H07 U.T. The behaviour of the American stations suggests that the effective sink moved if anything slightly further round to the night side and rapidly weakened. The whole event was over in about five hours.

The upper section of figure 7.2 shows the more general cosmic ray picture at the time, depicting the hourly intensities recorded by several neutron monitors, situated at different longitudes, between November 25 and December 2. It is seen that November 27 was fairly quiet, following many days of intense activity, and that there is some evidence of enhanced diurnal variations commencing on the following day. The magnitude of these was much less than the magnitude of the December 1 decrease. Figure 7.3 shows the daily mean neutron amplitudes recorded at Mawson throughout November and December. The neutron intensity at Mawson on November 30 was, if anything, still slightly depressed following the Forbush Decreases earlier in the month. There is no sign of a decrease or other anomaly 27 days prior to the event, however a decrease was observed 26 days later, on December 26, and this is depicted in greater detail in the lower section of figure 7.2. It is a normal-looking event. There was no further recurrence in the next solar rotation.

7.2.2. Solar Conditions

The sun was particularly quiet during this period. A class 2 flare was reported on November 28, at 1611 U.T. (maximum) from McMath-Hulbert plage region 5953 at S09 E72, and two class 1 flares were seen on each of November 29 and 30. There were only short gaps in the flare patrol at the time, ensuring that no major flares could have escaped detection. No exceptional ionospheric activity or solar radio emission were reported (CRPL, 1961). The two flares on November 29 may be different observations of the same flare, the only difference between them being exactly one hour in the times reported by the two observatories concerned. The peak of this flare was reached at 0109 (or 0209) U.T. It emanated from a solar position N10 E08, in plage 5948. This plage was new since the previous solar rotation, having been born on the invisible disc. Its first CMP (Central Meridian Passage) was at November 29.8, when its intensity was rated at 3.5, the highest noted for the month. The region subsequently split into two and lasted, at reduced intensity, a further two solar rotations. Apart from the high intensity on its first passage, there seems little to distinguish this region from others present at the time. Of the latter, No. 5946, CMP November 29.2, was making its second appearance and weakening. It died on the invisible disc. No. 5945, CMP November 28.8, intensity 2, was also making its second rotation. It survived until January. There are no flares listed for this region during the November transit. Region 5953 made its first CMP at December 04.2, intensity 3. It made a further CMP at January 01.3, intensity 3 and again at January 27.7, intensity 1.

7.2.3. Terrestial Magnetic Conditions

Figure 7.4 presents the magnetic observations during the period. A sudden commencement (S.C.) of activity was noted at 1915 U.T. on November 30, before the cosmic-ray event started. The planetary magnetic disturbance index, K_p, rose to a value of 8 by H05 on December 1, and then gradually decayed. Prior to the S.C. K_p had been fairly steady between 2 and 3. Subsequent S.C.'s occurred on December 7 and then at 2100 U.T.

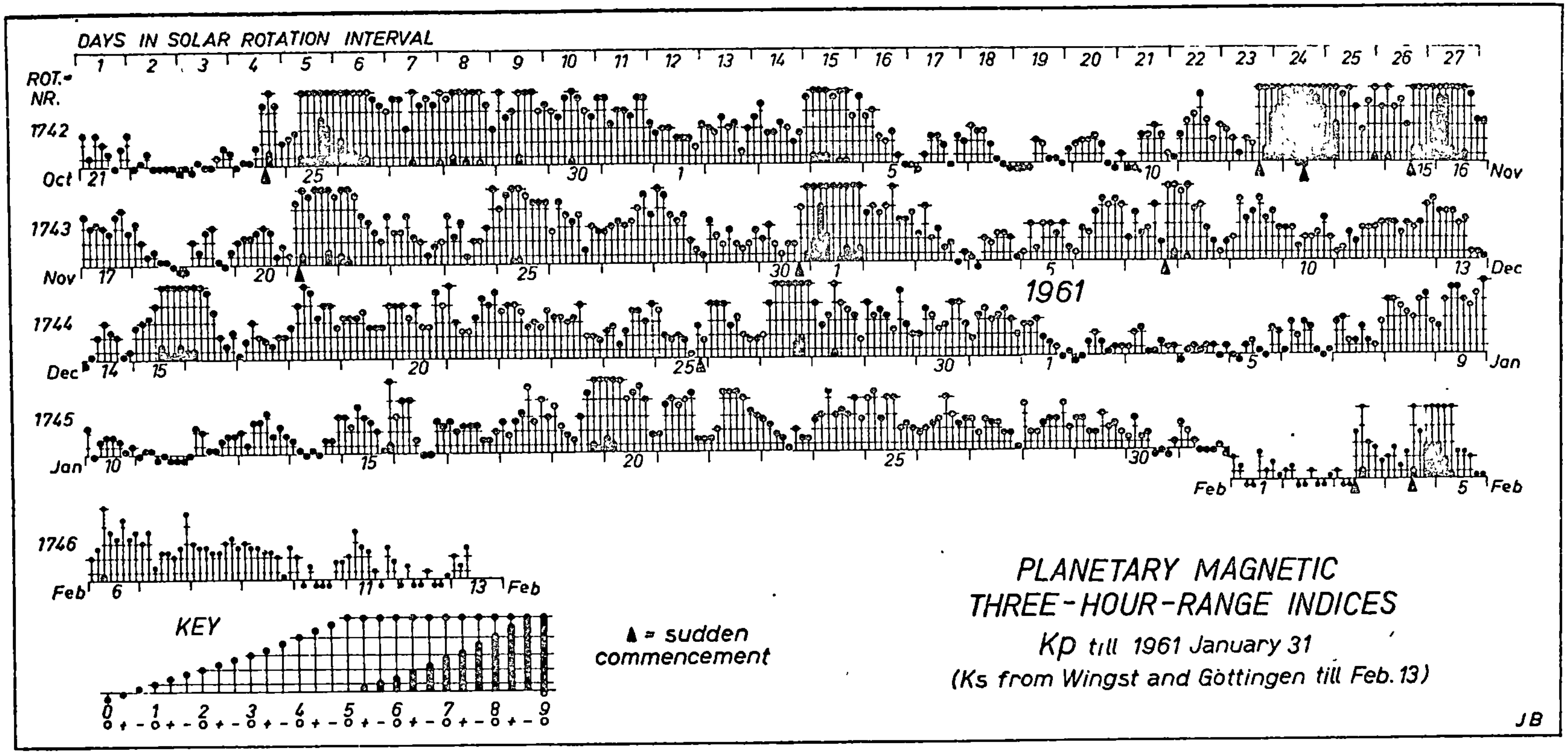

Figure 7.4. *Magnetic Observations, November and December 1960.*

December 25. The latter was followed by weak magnetic activity on December 26, after which K_p rose to 6+ by 2100 U.T., December 27.

7.3 NEUTRON MONITOR RESPONSE CHARACTERISTICS.

The viewing regions (section 2.1.3) of medium and low latitude neutron monitors are wide in longitude, whereas those of higher latitude monitors are much more sharply defined over only a few degrees of longitude (Rao, McCracken and Venkatesan, 1963). Provided the geomagnetic latitudes of the monitors are less than about 60 or 65°, the viewing regions are located at low asymptotic latitudes (section 2.1.3). It follows that if an event is observed to have rather similar characteristics in Universal Time at stations having similar geographic longitudes but different latitudes, it must be a genuine time variation in the incident radiation, rather than a time invariant spatial anisotropy. The estimated effect of the latter as seen by neutron monitors at Huancayo, Rome, Kerguelen and Mawson is shown in figure 7.5a. The responses, in local time, of the four detectors are seen to be quite different. Figure 7.5b shows the responses of the same monitors to the same anisotropy, but presented in U.T. The anisotropy assumed was a depression of intensity from a sector of angular width 60°. The model used fits the Mawson observations for the event under consideration quite well; it does not fit the observations at Rome and Huancayo. It can also be seen from these Figures that, as pointed out by Rao et al, any encroachment of the acceptance cone of a detector into an already depressed region as the earth rotates, results in only a gradual diminution of the count rate, the steepest drop occurring at the highest latitude stations.

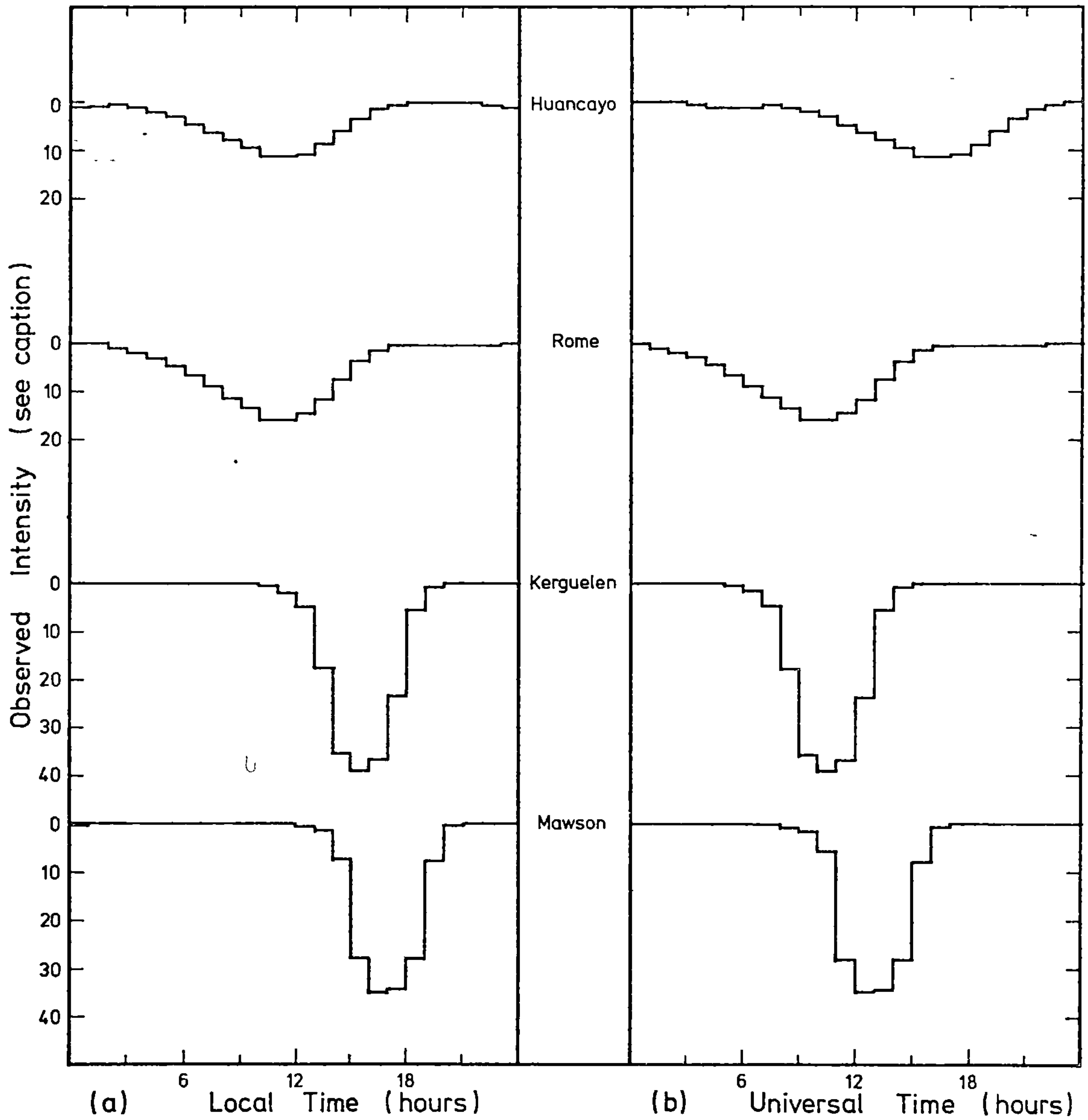

Figure 7.5. Computed hourly intensities which would be observed by some neutron monitors in the presence of a reduction $\Delta J(R)$ in free-space intensity from directions η between 210° and 270°, where $\Delta J(R) = AR^{-0.5}$, $J(R)$, for $R \leq 50$ GV. The amplitude scales are expressed as a percentage of the amplitude constant A.

This latter feature is observable in data from the American stations, which do indeed rotate in towards the already depressed region and consequently show a smaller amplitude than observed at the European stations and a slightly later, more gradual, minimum. During H01, U.T., the approximate time of minimum of the event, only limited portions of the leading edges of the American stations' acceptance cones were receiving radiation from the depressed region. An hour or two later more sensitive parts of the cones were covering the depressed region, just at the time that intensity was starting to recover. By the time, two or three hours later still, that the Western American stations were looking in the relevant direction, the depressed intensity had all but disappeared. It will be shown that, during its existence, the angular width of the depressed sector enlarged, but it is not certain whether this was the cause of the slight minimum observed by the Western American stations about H08 or whether this was mainly due to the enhanced diurnal variation already mentioned.

7.4. DELINEATION OF THE ANISOTROPY.

Before the physical cause of the anisotropy can be established it is necessary to determine its angular extent and spectrum. The extent can be determined from the responses of various stations and, in principle, the spectrum may be found by examining the ratios of the neutron and muon responses at stations where the viewing regions for the two instruments are similar. In the present case, only three pairs of neutron and muon records were available. Instrumental uncertainties existed in two of the pairs and conflicting values of the spectral exponent were obtained.

A preferable technique is to combine the calculation of spectrum with the determination of angular extent and to calculate the response of each detector to a number of likely models for the anisotropy. Since the response of each detector to any given model will be different, different estimates of the amplitude constant will be obtained for each station, and the model giving minimum variance in these estimates may be selected.

The model chosen for the anisotropy is

$$\frac{\Delta J(R)}{J(R)} = AR^{\beta}\cos\lambda \text{ for } (0 \le R \le R_u \text{ and } 0 \le \eta \le \eta_u)$$

$$= 0 \text{ for } R > R_u \text{ regardless of direction}$$

$$= 0 \text{ for } \eta > \eta_u \text{ regardless of rigidity.}$$

In these expressions λ is asymptotic latitude and η is the free-space direction (figure 4.1).

A computer programme, similar to that used to calculate modulation coefficients for the daily variation, and based on the calculation of variational coefficients, calculates the hourly - or bihourly if appropriate - response of a station as the earth rotates relative to a spatially and temporally fixed anisotropy, giving the depression (expressed as a percentage of the free-space amplitude constant A) which would be observed in each hour or bihour U.T. If the anisotropy is located at some other position, the effect is merely to change the Universal time at which the event is seen, by a fixed amount at all stations. In use, the parameters β and η_u are varied and sets of responses are calculated for each station. The minimum variance technique is then used to single out the model giving best fit to the observations.

In a study of this type it is clearly preferable to use hourly count rates. However, in 1960 a considerable number of stations, particularly those in the European group, were still reporting their results in bihourly form. Consequently bihourly figures have been used throughout the analysis, and the event has been treated in three stages, assuming it to be time invariant over the three periods H23-4, November 30; and H01-2, and H03-4, December 1. This is unfortunate since it appears from the Mawson record that the event started sometime during H23, probably around 2230. Cessation of the main phase seems to have been either late in H03 or early in H04, but this is less certain since no station with a reasonably narrow viewing region was looking in the appropriate direction at the time.

These definite changes in the form of the anisotropy during periods when the calculations have required it to be stationary will certainly contaminate the results. The calculated value for the amplitude constant will be too small, and uncertainties will result in the exact location of edge of the anisotropy. The errors are thought not to be serious, since the model itself is certainly in error in assuming uniform amplitude of reduction inside the affected region. It would possibly be more realistic to write the amplitude constant as $A \cos a(\eta - \eta_o)$ where η_o is the centre direction of the anisotropy and a is not necessarily integer. In view of these factors it has been thought reasonable to persist in using bihourly data.

A preliminary inspection of the data indicated that the rigidity spectrum was probably of the form $R^{-0.5}$, or thereabouts. This value was therefore used in determination of the angular width of the event. No underground muon observations were available, but it was apparent from sea-level muon detectors (figure 7.1) that quite high rigidity particles must have been involved. An upper limiting rigidity of 50 GV was selected, based on the above value of the rigidity exponent and on the muon observations. The errors introduced into analyses of neutron data by the use of this value of R_u, which could be 10 or 20 GV too low, are comparable with the errors of observation for this type of spectrum.

Use of the above values of β and R_u showed that the best fits to the observations are given by intensity reductions in the sectors specified by $\eta = 0^o$ to $(135\pm15)^o$ for H 23-4, by 0^o to $(120\pm15)^o$ for H 01-2, and by $(300\pm30)^o$ through 0^o to $(180\pm30)^o$ for H 03-4. It is therefore likely, smoothing these results, that the anisotropy was stationary in the sector 0^o to 135^o from 2230 to about 0200 U.T., and then gradually extended round to the evening direction whilst maintaining a slowly weakening depression on the morning side. The amplitude constants for the three periods, assuming the −0.5 spectrum, were 1.4, 2.5 and 1.3 respectively for the three periods. These features are indicated in figure 7.6. So far as can be determined, the intensity from directions in the 1200 to 1800 L.T. sector never became depressed. After H04 it is not possible to clearly delineate a definite anisotropy; although there are small depressions at some American stations, they could be due to the fairly large diurnal variations operative at the time.

Having determined the extent of the anisotropy, the spectrum could be checked. Minimum variance of the estimates was found for a spectrum varying as $R^{-0.4}$, remarkably flat for an event of this general type.

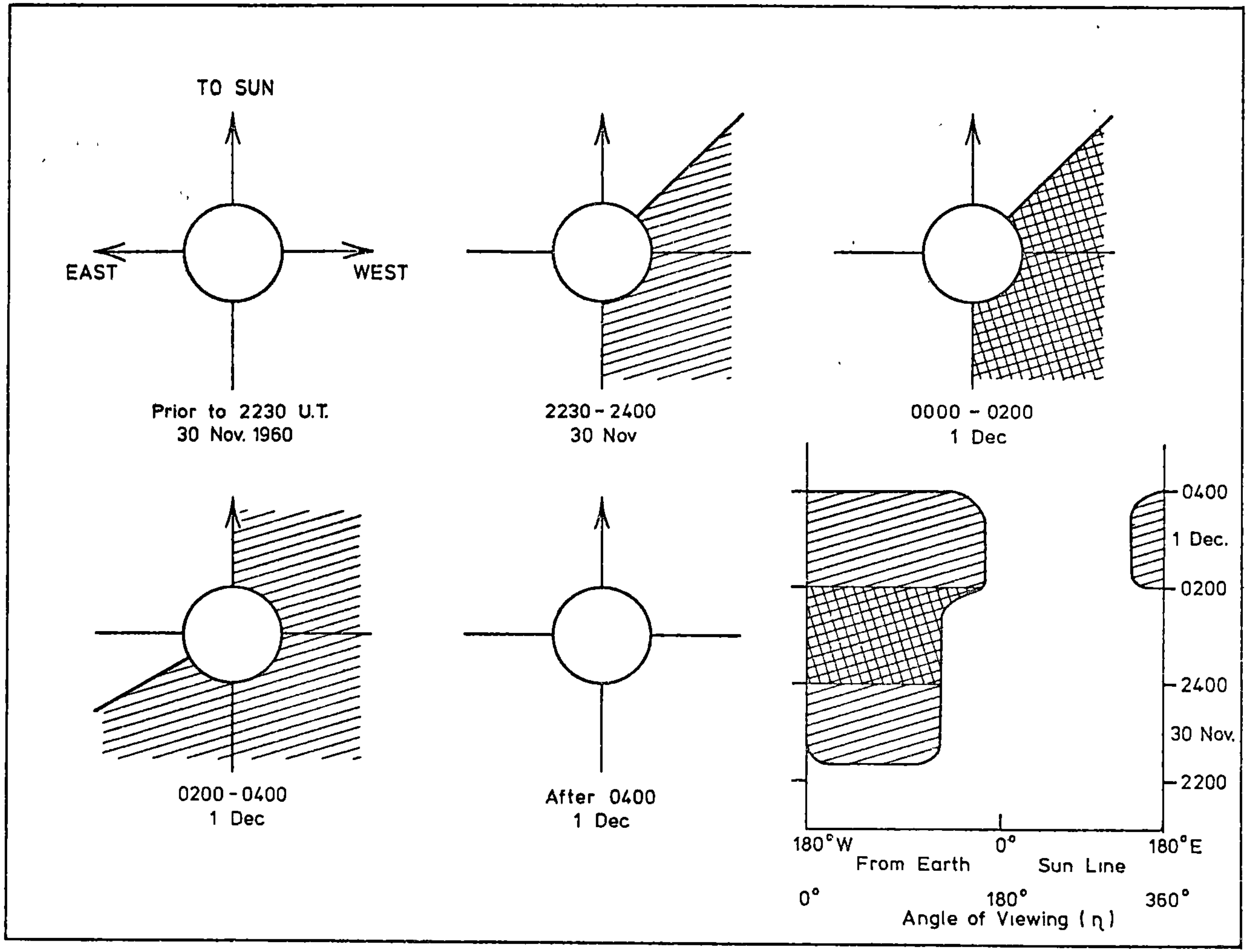

Figure 7.6. Representation of directions from which the decrease was observed. Light shading indicates amplitude constant $A \simeq 1.4$. Heavy shading indicates $A \simeq 2.5$.

7.5 FORBUSH DECREASES.

Forbush Decreases (hereafter called F.D.'s) in observed cosmic radiation appear to be related to shock fronts in the interplanetary medium. Such fronts occur at points of collision between fast and slow plasma emitted from the sun. They may occur either when fast plasma from a solar flare overtakes the slower material which precedes it (Parker, 1963), or at the glancing collision between plasmas emitted with different speeds from adjacent solar regions (Sarabhai, 1963). The latter type of shock front can be long-lived, and examples have been observed over two or more solar rotations (McCracken, Rao, and Bukarta, 1966).

Several attempts have been made to classify F.D.'s on phenomenological grounds (e.g. Bachelet, Balata, Conforto, and Marini, 1960 a, 1960 b; Sandstrom, 1965). Some of the findings conflict, possibly due in part to different typical behaviour of events arising from the two causes. However Fedchenko (1966) has found it possible to describe an average flare-associated F.D. having a pronounced initial anisotropic phase (figure 7.7; McCracken and Parsons, 1958; Fenton, McCracken, Rose, and Wilson, 1959; Mathews, Mercer, and Venkatesan, 1968).

Fedchenko found that the intensity in the anisotropic, pre-decrease, phase was depressed only from directions between 0300 and 0900 L.T., whereas Fenton et al found the depressed directions to lie between 0600 and 1200 L.T. The latter sector is centred on the "garden-hose" direction, looking towards the sun along the archimedian spiral of the quiet-time magnetic field. The differences in the observed directions may arise from different estimates of the viewing regions of the detectors employed. Asymptotic directions calculated for a high-order simulation of the terrestial magnetic field

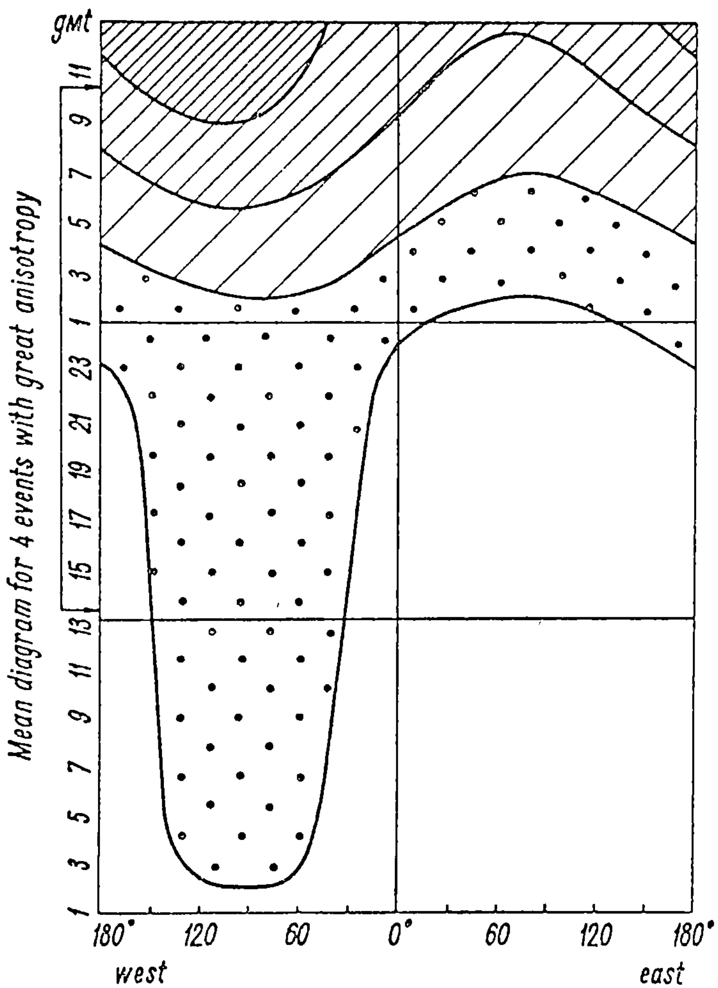

Figure 7.7. Space-time representation of average F.D. The lower arrow represents average time of S.C., the upper arrow indicates mean end of active magnetic period. The different degrees of shading represent different intensities of depression. (Due to Fedchenko, 1966).

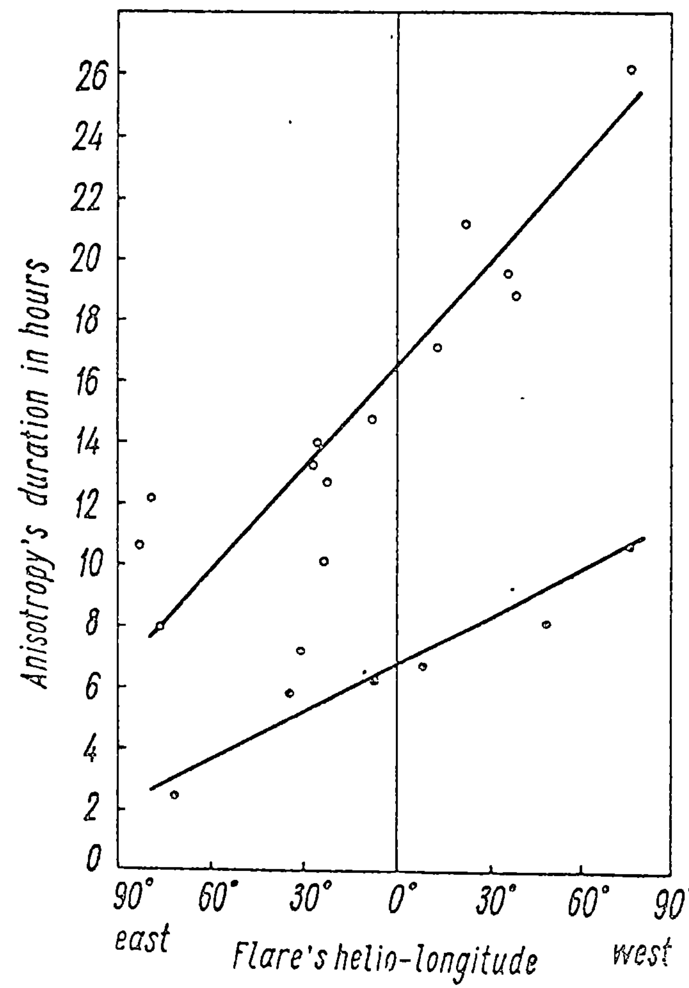

Figure 7.8. Duration of anisotropy of F.D.'s as a function of the helio-longitude of the associated solar flare. Open circles, class 2 or lower flares, closed circles class 3 or 3+ flares. (Due to Fedchenko, 1966).

were not available to Fenton et al, but had been published (McCracken, Rao, and Shea, 1962) prior to Fedchenko's investigation. However he does not state the source of his directional information.

Fedchenko also found that the duration of the anisotropic phase was related to the importance and helio-longitude of the related flare. The shortest duration was observed for flares near the eastern limb (figure 7.8). A significant corollary of these observations is that there does not seem to be any preferred longitude for flares which give rise to F.D.'s observed at the earth. Towards the end of the anisotropic phase an S.C. was observed, after which a world-wide isotropic decrease ensued (figure 7.7).

The recovery of intensity following an F.D. usually starts a few hours after the onset of the isotropic phase. The time scale of the recovery varies from one to a few days, with the rate of recovery varying from one event to another. At least one case of an abrupt recovery, occurring in less than two hours on July 15, 1960, has been reported (Sandstrom, 1965).

7.6 POSSIBLE MECHANISMS FOR FORBUSH DECREASES.

There is evidence (section 7.7.1) that the F.D. of November 30/ December 1 1960 is associated with a particular solar flare. In this section, therefore attention is restricted to possible mechanisms for events arising from such flares. The mechanisms suggested are based on the proposals of Parker (1963).

7.6.1 Steady-State Interplanetary Conditions.

The basic motion of charged particles in a smooth magnetic field is helical, around the field lines. The simple motion of the guiding centre of the helix, together with its pitch angle, are often used to characterise the particle's actual motion. If the field is non-uniform some drift across it will be observed, and this drift will be re-inforced by scattering if magnetic irregularities also exist. It has been estimated (section 6.1) that the contribution to the perpendicular diffusion coefficient $\kappa_{\perp}$ in the interplanetary field was about $\kappa_{\parallel}/7$ from each cause for particles of rigidity less than 50 or 60 GV in 1965. The guiding centre approximation is therefore valid for the qualitative discussion of the motion of such particles.

Particles of galactic origin enter regions of stronger field as they approach the sun. Their pitch angles therefore increase and, neglecting the small percentage which suffer solar capture, they are eventually reflected, or mirrored, back out again.

7.6.2. Flares at Western Solar Longitudes.

Figure 7.9 shows a schematic representation of the effects arising from a flare occurring at helio-longitude W 50. The fast plasma from the flare creates a blast wave where it overtakes the slower quiet-time solar wind plasma, here assumed to have a radial velocity of 300 km./sec. Cosmic-ray particles penetrating the wave will suffer both scattering and energy-loss, and a reduction in flux will therefore be observed behind the wave in any fixed energy interval.

No cosmic-ray effects should be observed at the earth until the wave reaches the quiet time field line (hereafter called the qfl) which intersects the earth. Particles whose guiding centres are on the qfl,

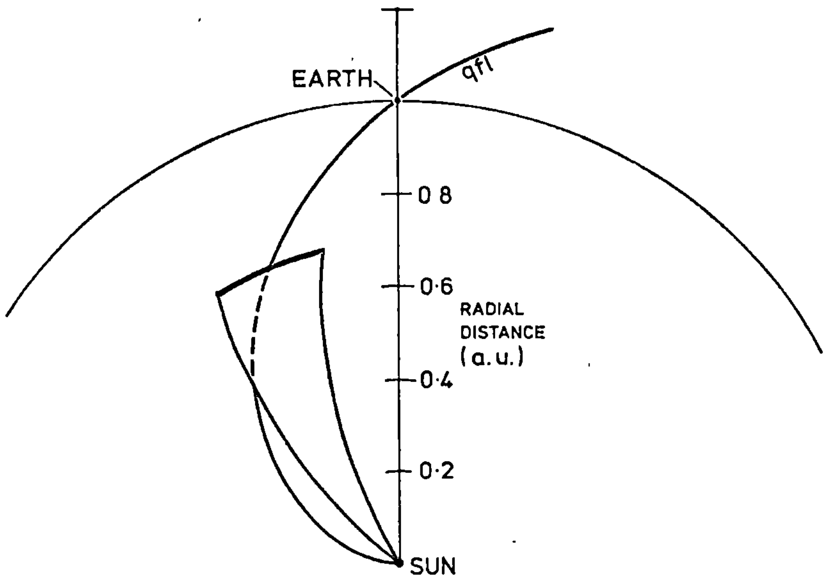

Figure 7.9. Disruption of quiet-time field line (qfl) by blast wave originating from a flare at helio-longitude W 50. Blast wave speed 900 km/sec.

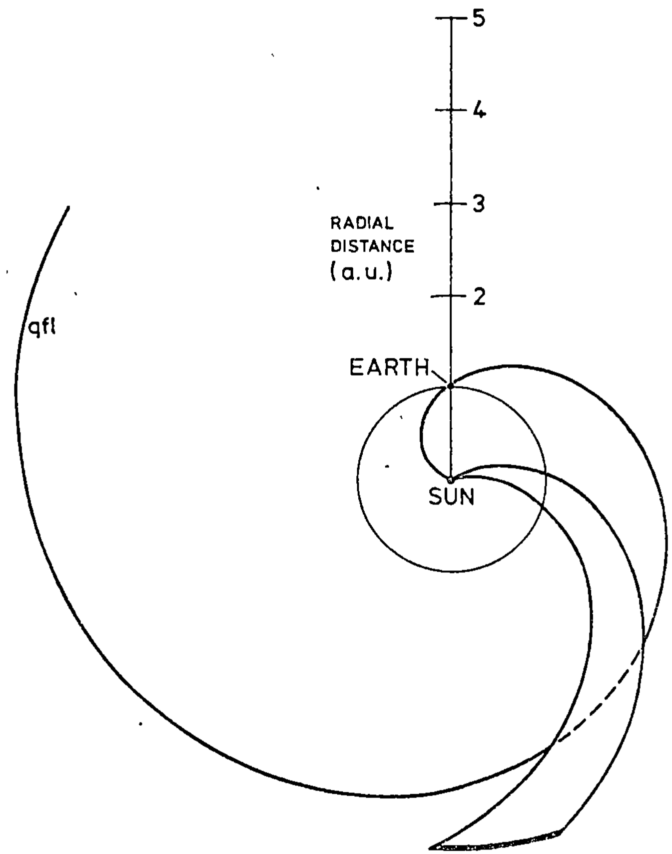

Figure 7.10. Disruption of qfl by blast wave originating from a flare at helio-longitude E 70. Blast wave speed 900 km/sec.

and which are therefore observed at earth, are then affected only if they would normally mirror closer to the sun than the point where the qfl is disrupted. Such particles will be doubly affected, since they must make two passages of the blast wave. The flux of particles mirroring between the earth and the blast wave will be unaffected, as will observations made by terrestial magnetometers. The qfl is disrupted, in this example, 23 hours before the blast wave reaches 1 a.u. Should the wave then envelop the earth (which is not the case with the example of figure 7.9) an S.C. will be observed. An isotropic decrease in cosmic ray intensity should then follow since all particles reaching the earth will have penetrated the wave.

7.6.3. Flares at Eastern Solar Longitudes.

As the site of the flare moves towards the east on the sun the qfl will be disrupted nearer to the earth for the same plasma speed. Consequently a shorter period of anisotropy should be observed, as found by Fedchenko. Figure 7.10 shows the case for a flare similar to that considered above but situated at E 70. The blast wave passes well behind the earth, and no anisotropic phase will occur. In this particular example the qfl will be disrupted (if it still exists at that distance) at 3 a.u. from the sun, 140 hours after the flare. Once disruption occurs an isotropic F.C. will be observed at the earth. Since the blast wave never comes close to the earth an S.C. should not occur.

7.6.4. Wide-angle Blast Waves.

The preceding sections have discussed effects arising from blast waves of angular width $\simeq 20^{\circ}$. The fact that F.D.'s are seen at the earth apparently independently of the helio-longitude of the associated flare (figure 7.8) requires that extensive regions of space be affected. Satellite observations suggest that the size of the regions over which F.D.'s occur was of order 60° in 1965 (Webber, 1967), comparable with the size of the sector structure at that time. The study of Schatten, Wilcox, and Ness (1969) also suggests that the fast plasma, and hence the blast wave, is likely to be spread widely in azimuth.

Figure 7.11 shows the schematic for a blast wave which just passes behind the earth, and which originates from a flare at E 70. The wave has the same radial velocity as that of figure 7.10, but the angular spread is now 180°. A very slight increase in plasma speed would cause such a wave to envelop the earth, in which case a very short anisotropic period, followed by an S.C., would be expected. A smaller angular spread but higher plasma speed would have the same result. Waves of similar, or rather smaller, spread emanating from western hemisphere flares would lead to the S.C. and isotropic phase which were absent from the example discussed in section 7.6.2. Waves of 60° in spread would explain some, but not all, of the observations and larger waves could well be possible in view of the large sectors observed between 1965 and 1968 (section 6.1).

7.6.5. Blast Waves out of the Ecliptic Plane.

The above work assumes that the blast waves are in, or symmetrical about, the ecliptic plane, and takes no account of their perpendicular spread. As an extreme example we now consider a blast wave passing close to the earth but constrained entirely to one side, say the southern, of the ecliptic plane.

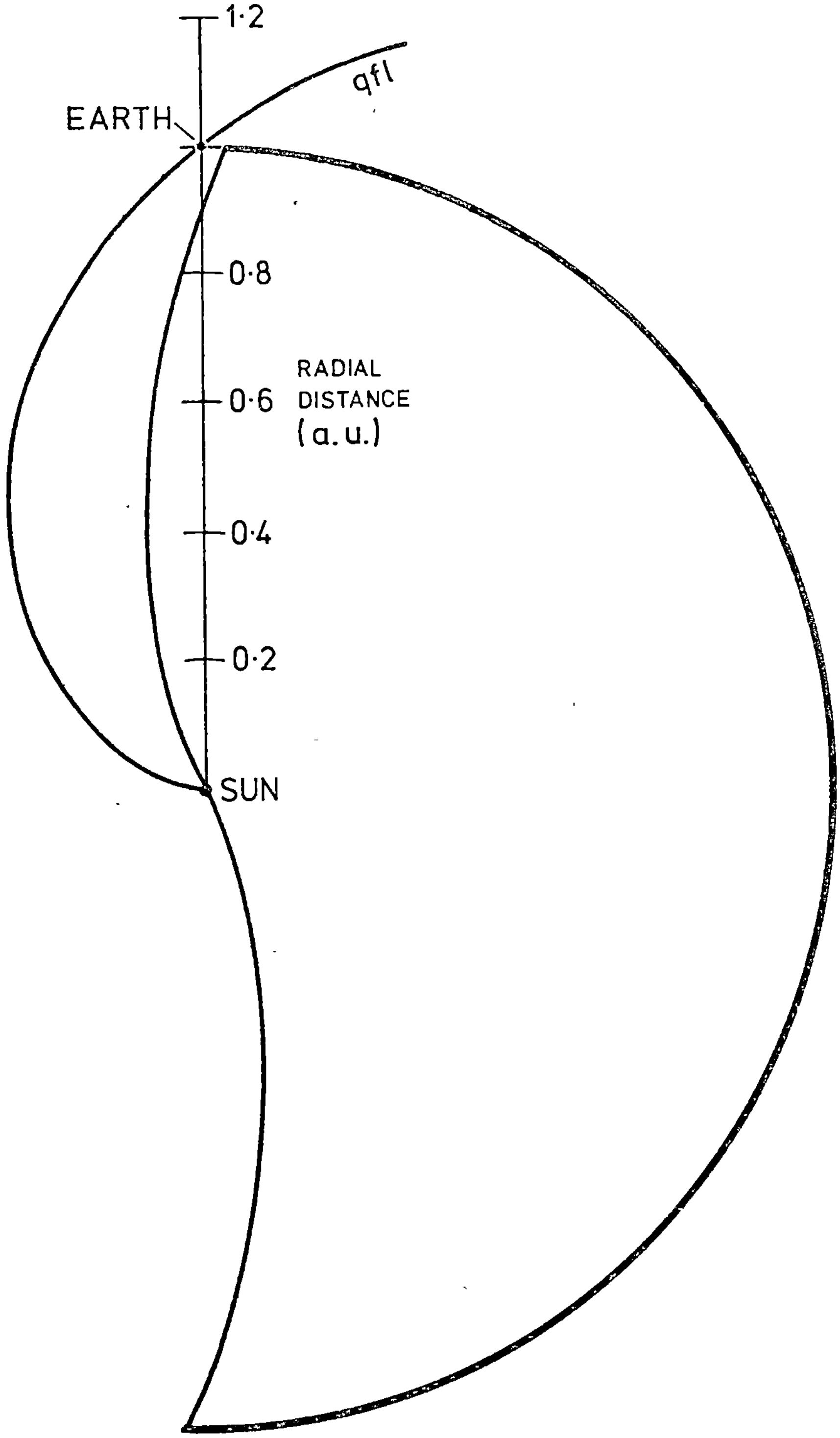

Figure 7.11. *Effect near earth of blast wave originating at heliolongitude E 70. Blast wave speed 900 km/sec. Angular width of blast wave is 180°. A wave of smaller angular dimension will not approach close to the earth with this source and speed.*

Primary cosmic rays with rigidities observable by surface detectors are positively charged. It follows that particles observed to arrive at the morning side of the earth from directions in the ecliptic plane and perpendicular to the magnetic field have their guiding centres travelling along field lines south of the ecliptic, if the field is directed away from the sun. Such particles will be affected by the blast wave and a decreased flux will be observed.

Particles arriving from the opposite direction, on the evening side of the earth, have been travelling on the northern side of the ecliptic plane, for the same field direction, and will be unaffected. An anisotropic decrease will be seen in approximately the 0300 L.T. direction. An inward directed field with this blast wave, or an outward directed field and a wave above the ecliptic, would result in an anisotropic decrease from the 1500 L.T. direction. Depending on the helio-longitude of the parent flare a decrease might or might not also be observed in the garden-hose direction. Any such decrease would affect high rigidity particles to a greater extent than those of lower rigidities, and a fairly flat spectrum should result.

7.7. The November 30 / December 1, 1960 Event.

Comparison of figures 7.6 and 7.7 shows that this event differs considerably from the type of F.D. commonly observed. The major differences are:-

(a) The S.C. occurred before the anisotropic phase of the event;

(b) No isotropic phase was observed;

(c) The recovery was very rapid;

(d) The direction of the anisotropy was unusual.

7.7.1. Flare Identification.

Two solar flares could possibly be associated with the event (section 7.2.2). The class 1 flare at 0209 U.T., November 29 is an unlikely candidate. Class 1 flares are more frequent than ground-level F.D.'s, suggesting that there is no close relationship between them. The required blast wave speed of 1000 km./sec is also extremely high for such a flare.

The class 2 flare at 1611 U.T., November 28, at helio-longitude E 72, requires the more reasonable average blast wave speed of 820 km./sec. The magnetic observations after the S.C. may support this speed.

Snyder, Neugebauer, and Rao (1963) obtained a relationship between the daily average magnetic activity as measured by ΣK_p, and the solar wind speed measured by Mariner 2 in late 1962. Their relation, when applied to the present event, gives an average plasma speed of 727 ± 52 km./sec between 1900 U.T. November 30 and 1900 on December 1. If the maximum observed value of K_p is used a speed of 870 ± 64 km./sec is indicated. These values are not incompatible with the required speed, particularly as considerable scatter is present in the individual observations of Snyder et al. Their result has, however, been called into question.

Wilcox, Schatten, and Ness (1967) present a scatter diagram of K_p v. solar wind speed observations made by IMP 1 in late 1963 and early 1964. These observations have been applied to the present event using a regression equation derived from them by Mansurov and Mansurova (1969). They yield an average plasma speed, for the same period as above, of 436 km./sec, and a maximum speed of 496 km./sec. However Mansurov and Mansurova find that the relationship between K_p and solar wind speed appears to be itself a function of average solar wind speed at the time, the averaging being carried out over a period of order a few weeks. At times of relatively high solar activity, and consequently high average solar wind speed, a given plasma speed will result in a lower value of K_p than would result from the same plasma speed at times of lesser solar activity. Extrapolation of this finding back to 1960 suggests that the Snyder et al. (SNR) equation will be more applicable than will that of Wilcox et al., and that, in view of the intense solar activity during much of November 1960, the SNR equation will, if anything, underestimate the true solar plasma speed at the end of the month. The magnetic observations therefore appear to suggest that the November 28 flare could well have been responsible for the November 30 S.C. Sandstrom and Troncoso (1965a, 1965b) have reported that every S.C. is accompanied by some form of cosmic-ray disturbance at ground level, and it is therefore likely that this flare was the cause of the present cosmic-ray event.

7.7.2. Discussion.

The event becomes similar to those outlined in section 7.6.4, caused by wide angle eastern hemisphere flares, if it is considered that the observed anisotropic phase merely represents incomplete development, for whatever reason, of the normal isotropic phase. In such a case the S.C. should precede the onset, as observed, provided that the blast wave actually reached the earth. Since no decrease was seen from the garden-hose direction the qfl could not have been disrupted any significant distance from the earth in the sunward direction.

The anisotropy can now be explained if the blast wave was located almost entirely on one or other side of the ecliptic plane (section 7.6.5).

No magnetic field direction data are available to determine which side, but since the flare (assuming the identification is correct) was at heliolatitude S 09 the wave would probably be below the ecliptic. In this case the observed decrease in the 0300 L.T. direction implies that the magnetic field was directed outward. No decrease should ever occur in the 1500 L.T. direction in these circumstances, but some reduction may be observed in both directions along the qfl. Such reductions could be small if the blast wave penetrated only a short distance beyond the ecliptic on the northern side, as many particles would then be able to get around it. A small reduction in intensity was observed in the 2100 L.T. direction, looking outwards along the qfl, late in the event.

The remaining observation which requires consideration is the rapid recovery to pre-event level. A region whose particle density (at a particular rigidity) has been decreased following the passage of a blast wave usually recovers to normal intensity over a day or two. Recovery is by diffusion into the affected region by particles which have passed around, rather than through, the blast wave. The time scale of the recovery will be related to the distance through which the diffusion must take place, as well as to the degree of reduction in intensity in the affected region. If the hypothesis put forward above is correct, and the blast wave was almost totally restricted to one side of the ecliptic, a region of normal particle density was close to the earth as soon as the blast wave had passed. Also, the observed amplitude of the decrease was not as large as many F.D.'s, amounting to a little less than 6% at Mawson when the station's viewing region was almost totally enveloped by the decrease. In these circumstances rapid recovery, by scattering from the unaffected side of the ecliptic, could occur. Residual anisotropies, particularly at higher rigidities, would probably continue for some hours, but these would not be detectable with the observations available for the December 1 event.

On these grounds it is suggested that the event of November 30 / December 1, 1960 was associated with the passage of a blast wave which was largely restricted to one side, probably the southern, of the ecliptic plane. The wave also included the ecliptic plane, and intersected the earth, but did not penetrate far into the unaffected side. It originated in a class 2 flare at solar longitude E 72 on November 28, and had a wide azimuthal spread in interplanetary space. There is no reliable information on whether the F.D. observed on December 26 is related to this event; in view of the 26 day recurrence it is quite possible that the two are entirely separate.

APPENDIX.

AVAILABLE COMPUTING FACILITIES.

The Elliott 503 computer operated by the Hydro-University Computing Centre has been used exclusively for all computing undertaken for the purposes of the work described in this thesis. Only 25 computers of this type were ever produced, and so far as I am aware no other cosmic-ray group has access to one. Most of the larger programmes written have been very closely tailored to this machine, with many machine-code inserts to save both running time and store space. For these reasons the programmes are not incorporated with this thesis.

The computing problems have been made both harder and easier by the nature of the installation. The Computing Centre is located in the Physics Department building, and is a small installation, not yet work saturated. These factors have enabled personal contact with the operating staff, my own presence for the more complicated runs, and short turn-around times both for programme testing and production runs. These are major advantages, as is the availability of an excellent Algol compiler having only a few minor restrictions (Hoare, Hoare, Hillmore, & Grover, 1963; Wooldridge & Ractliffe, 1963) on the full generality of Algol 60 (Naur, 1963).

However a number of hardware and software restrictions have considerably hindered rapid progress, particularly in the early years. A Fortran compiler has never been available and any available Fortran programmes have to be manually translated. In practice this has only been done once, with the basic part of the trajectory programme. The input-output devices have also been a hindrance at times.

The 503 is a fast medium-sized computer designed for use in scientific and engineering applications, having a cycle time of 1.6 μ sec. and an 8192 word, each of 39 bits, random access main store. There is only one arithmetic unit; multi-programming and remote access are not possible. In its original form the installation was extremely basic, consisting of the machine itself, two 1000 character/second high speed 8 channel paper tape readers and two 110 character/second paper tape punches. The readers are still the only available input medium. The computer operating system, standard functions etc., occupy about 2000 words of store. The compiler occupies about 5000 words, leaving around 1000 words for programme plus data. In the original configuration any programme in excess of this length (in practice this meant all programmes) was compiled onto paper tape, and then fed back in on a second pass, overwriting the compiler. This severely hindered the alteration of programmes, and in any event there was still a 6000 word limitation on programme plus data. Such a size is quite satisfactory for straightforward computational jobs like trajectory calculations or harmonic analysis, but does not permit large scale data comparisons.

The installation remained in this form for 2 years. In January 1966 a 16k random access core backing store was added, almost quadrupling the available storage and obviating the two-pass compilation requirement.

The two punches cannot reliably be used simultaneously, due to cross-talk problems, and output of results in any quantity remained a major problem until a 300 line/minute Line Printer was installed in August 1967, followed four months later by an X - Y plotter. The installation has remained in this form, the only changes being steady improvements to the software. It has been possible to fit, just, the largest of the required programmes into the installation in this form, with the use of machine-coding to conserve programme - and occasionally data - storage requirements.

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