CHAPTER II

INSTRUMENTATION

2.1 Super neutron monitor:

Regular monitoring of primary cosmic radiation through the measurement of secondary components such as neutrons and muons which occur as daughter products during the interaction of the incident primary cosmic ray particles with atmospheric nuclei, has been extensively carried out in the past two decades. The comparatively large magnitude of the latitude effect observed on the secondary neutron component, which is suggestive of their association with the lower energy part of the spectrum of cosmic radiation makes the monitoring of primary cosmic ray variations through nucleonic component very attractive (Simpson, 1948, 1949). However, it is only in 1952 that, an effective neutron monitor developed by Simpson and his co-workers become available which after a few minor changes was adopted as a standard cosmic ray monitoring equipment for IGY during 1957-58. In spite of very reliable results obtained from the data from a world wide network of about 50 IGY type of monitors, it was quite apparent that the counting rates obtained from those monitors were too low to permit an unambiguous interpretation of many aspects of cosmic ray time variations. Whereas the IGY monitors were quite adequate to study the large cosmic ray enhancements of solar origin and through them the interplanetary field configuration (McCracken, 1962), these monitors offered poor statistics for the study of
short term variations such as diurnal and semi-diurnal variation on a day to day basis. This led to the design of super neutron monitors (18-NM-64), which employ a total of 18 large size BF$_3$ counters giving a counting rate of $\sim 10^6$ counts/hour at a typical sea level station having a cut-off rigidity $\leq 2$ GV (Carmichael, 1964).

Even though more than $\sim 30$ (18-NM-64) super neutron monitors are operating at various parts of the world, conspicuous gaps in the longitude range 25° E to 180° E and an almost complete absence of equatorial monitors are still noticeable. The establishment of a super neutron monitor (NM-64) at Ahmedabad during 1968, a sea level station located at geographic latitude 23.01° N and geographic longitude 72.61° E having an upper cut-off rigidity $\sim 15.94$ GV has to some extent been responsible to fill this big gap in the longitude range 25° E to 180° E and provide an extremely valuable input to the world data coverage.

2.2 Description of the super neutron monitor at Ahmedabad:

The basic design of the super neutron monitor (18-NM-64) at Ahmedabad (India) essentially follows the standard design recommended by Carmichael (1964) during IQSY period. The neutron pile consists of 18 large size BF$_3$ gas filled copper proportional counters enclosed in a cylinder of paraffin wax moderator. Each counter along with its moderator cylinder is surrounded by 18 lead rings of purity
greater than $99.9\%$ cast in the form of cylinders each of length of $\sim 11.5\text{ cm}$, weighing about $\sim 89.3 \pm 0.6$ Kg ($\sim 200$ pounds).

The 18 counters are distributed in three identical arrays of 6 counters each, with the three individual arrays being completely shielded by a rectangular box of low density paraffin wax of thickness $\sim 7.5$ cm, which acts as a reflector and establishes a full albedo of neutrons inside the monitor. In addition the paraffin wax also diminishes the proportion of low energy neutrons arriving at the detector from outside the monitor, thus making it less susceptible to the variable environmental flux of thermal neutrons which can be often as high as $\sim 5\%$.

Fig. 2.1 shows one such array which forms a part of the neutron monitor assembly at Ahmedabad. The output of each counter after amplification and discrimination is fed to a mixer-amplifier. The output of the mixer-amplifier from each of the three sections (arrays) are separately counted and recorded.

2.3 The principles of neutron counter:

The proportional counters filled with Boron trifluoride ($\text{BF}_3$) gas enriched with Boron isotope $\text{B}^{10}$ are the most efficient detectors for detecting thermal neutrons. The large size counters used in the neutron monitor are filled with pure $\text{BF}_3$ gas enriched with $96\%$ $\text{B}^{10}$ isotope at a pressure of $\sim 20$ cm of Hg at $22\, ^\circ\text{C}$, when operated in the proportional region with a high voltage of about $\sim 2800$ V, the counters are found to have
Figure 2.1 - A section of the neutron pile of 18-EM-64 neutron monitor at Ahmedabad. The boxes projecting out of the proportional counters contain pre-amplifier and amplifier-discriminator assembly. The amplifier-mixer box and the box containing high voltage distribution points can be seen on the top of the neutron pile.
a gas multiplication $\propto 35$. These counters exhibit a plateau over a range of $\propto 500$ V with a slope $\propto 1\%/100$ V in the proportional region. A resonant exothermic reaction occurs when a thermal neutron collide with Boron ($B^{10}$) nucleus producing Lithium and Helium following the reaction,

$$\frac{10}{7}B + \frac{1}{0}n \rightarrow 3Li^7 + 2He^4 + 2.78 \text{ MeV}$$  \hspace{1cm} (2.1)

The cross-section of this reaction is inversly proportional to the velocity $V$ of the captured neutron ($\frac{1}{V}$ dependence) is found to be $\propto 3820$ barns for thermal neutrons of energies $1/40 \equiv V$. In 94% of the reaction $3Li^7$ nucleus is left in an excited state ($\propto 0.48$ MeV) and the remaining 2.30 MeV energy is shared between $3Li^7$ and $2He^4$ nuclei. In the remaining 6% of the reaction, $3Li^7$ nucleus is left in the ground state and $3Li^7$ and $2He^4$ nuclei have a total kinetic energy of $\propto 2.78$ MeV. The output pulse of about $\propto 1$ milli-volt due to the neutrons captured can be suitably amplified and discriminated from the relatively small pulses produced by muons, electrons and $\gamma$-rays passing through the counter.

A high energy incident secondary neutron interacts with lead and produces a large number of evaporation neutrons, the number being proportional to the energy of the incident interacting particle. Typically a parent secondary nuclei of energy of $\propto 200 - 300$ MeV produces on an average 10 evaporation neutrons. In the neutron monitor a spectrum of excitation...
energies of the lead nuclei results because (a) the incident nucleons have a wide range of energies and (b) the nucleus with a given energy produces a range of excitation energies due to the statistical nature of the intranuclear cascades. The evaporation neutrons produced are decelerated due to collisions in the moderator and give rise to slow or thermal neutrons, which are easily captured by $^{10}$B isotope present in the counter gas. The absorption losses of thermal neutrons in the moderator and the counter walls is almost negligible and the detection efficiency of the evaporation neutrons in the NM-64 neutron monitor is found to be of $\sim 6\%$ (Hatton and Carmichael, 1964).

2.4 Neutron production by nucleons:

The nucleon-nucleus interaction is found to develop in two stages. In the first "cascade phase" the pions and the knock on nucleons are emitted with a broad energy spectrum with an angular distribution peaked along the direction of motion of the incident nucleon. The residual nucleon at the end of the first phase are left in an excited state and further emission of particles that is the production of evaporation neutrons follow during the second "de-excitation" or evaporation phase. It has been shown theoretically (Shen, 1968) and experimentally (Hughes et al, 1964) that the production of evaporation neutrons increases with the energy of the incident particle and also with the increase of the producer thickness.
The stochastic nature of the processes leading to the production of the evaporation neutrons which results in a broad and exponential neutron production spectrum, essentially limits the use of neutron monitor as an energy spectrometer.

2.5 Data recording system:

Fig. 2.2 shows the data recording system of the super neutron monitor at Ahmedabad. A block diagram shown in Fig. 2.3 gives complete details of the data recording system. The millivolt pulses produced due to the passage of thermal neutrons in the counter are fed to a pre-amplifier followed by a three stage amplifier and a simple tunnel diode discriminator which will reject the small pulses produced by other secondary particles such as muons, electrons and X-rays. The counting rate of each counter at Ahmedabad is of \( \sim 10,000 \text{ counts/hour} \). The discriminator output from the six counters in each section are separately amplified and suitably mixed in the mixer-amplifier and the combined output from each section is accumulated in intervals of 4 minutes duration. At the end of each 4 minute interval, the accumulated counts are transferred to a temporary discrete memory system which introduces a known dead time of \( \sim 6 \mu s \) during which period the decades are reset and kept ready for continuing the accumulation for the next interval of time. The data from the buffer memory of all the three sections, together with the exact time information from a crystal clock and the atmospheric pressure data from a digital
Figure 2.2 - The automatic data recording system of the super neutron monitor at Ahmedabad. The first rack from the left contains all the high and low voltage power supplies, the middle one all the decades, memory storage systems and the serial converter and the third rack contains the electronic typewriter and punchers used for recording the data.
Figure 2.3 - A block diagram of the data recording system at Ahmedabad. The 18 counters and the pre-amplifier and amplifier-discriminator assembly are also shown.
servo-barometer with an accuracy of \( \pm 0.1 \) mm are then serially transferred in BCD form on to a paper tape punch recorder and in digital form or to an electronic typewriter. The entire recording operation is controlled by a crystal clock which produces command pulses at the end of each 4-minute interval. The hourly and daily mean cosmic ray intensity at Ahmedabad is derived from this 4-minute basic data.

2.6 Zenith angle dependence of a neutron monitor:

The relative contribution of the secondary nucleon incident at a zenith angle varying between \( \Theta \) and \( \Theta + d\Theta \) to the counting rate of a detector is given by

\[
N(\Theta) d\Theta \propto J(\Theta) S(\Theta) \sin \Theta \cdot d\Theta
\]

Where \( J(\Theta) \) is the zenith angle distribution of the nucleonic component and \( S(\Theta) \) is the sensitivity of the detector to this component is a function of zenith angle. \( S(\Theta) \) is found to be approximately a constant indicating that the neutron monitor essentially behaves as an omnidirectional detector. Phillips and Parsons (1962) using a mobile IGY monitor showed that the zenith angle distribution of the nucleonic component can be expressed as \( J(\Theta) \propto \cos^5 \Theta \) over a range of \( \Theta \), varying between \( 0 - 40^\circ \) and at larger angles \( \Theta > 40^\circ \) the function decreases very slowly. The largest contribution to the counting rate of a neutron monitor is from zenith angles \( \Theta \approx 25^\circ \) and less than 7% of the counting rate being accounted for by neutrons arriving at large zenith angles \( \Theta > 60^\circ \) (Carmichael et al, 1969).
2.7 **Plateau and pulse height characteristics:**

The proportional region of a neutron counter can be determined by a typical plot of the variation of the counting rate with applied voltage. It is found that in the proportional region the pulses due to various secondary particles such as muons, electrons and \( \gamma \)-rays (noise pulses) are relatively smaller compared to the pulses due to thermal neutrons, thus making it possible to discriminate between the two. A number of authors have investigated the relative contributions made by various secondary components to the counting rate of both IGY and NM-64 monitors. (Simpson et al, 1953; Hughes and Marsden, 1965; Harman and Hatton, 1968; Hatton, 1971). Table 2.1 gives the relative contribution by different secondary cosmic ray components to the counting rate of a typical IGY and NM-64 monitor. The proportional region of a NM-64 neutron counter typically extends from 2700 to 3200 Volts with a plateau of 100 - 500 V and a slope of \( \sim 1/100 \) V. McCracken et al (1966a) pointed out that a periodical examination of the pulse height characteristics of a neutron counter can be effectively used to detect a slowly deteriorating counter. Since then, this method of monitoring the health of a neutron monitor has been well accepted as a general practice. The pulse height analysis of each counter using a 400 channel analyser has been regularly carried out and the resolution of each counter is periodically measured. The typical full-width
### Table 2.1

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Components</th>
<th>Percentage contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>IGY Monitor</td>
</tr>
<tr>
<td>1.</td>
<td>Neutrons</td>
<td>83.6 ± 2.0</td>
</tr>
<tr>
<td>2.</td>
<td>Protons</td>
<td>7.4 ± 1.0</td>
</tr>
<tr>
<td>3.</td>
<td>Pions</td>
<td>1.2 ± 0.3</td>
</tr>
<tr>
<td>4.</td>
<td>Stopping muons</td>
<td>4.4 ± 0.8</td>
</tr>
<tr>
<td>5.</td>
<td>Interacting muons</td>
<td>2.4 ± 0.4</td>
</tr>
<tr>
<td>6.</td>
<td>Background</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 2.1 - The relative contributions (percent) made by various secondary cosmic ray components to the counting rate of an IGY and NM-64 monitor.
at half-maximum of a good NM-64 counter is found to be of 
11% at the operating voltage and varies from 9 to 20% for 
all the 18 counters used in Ahmedabad neutron monitor.

2.3 Data processing:

The ratio's of the counting rates obtained by three 
independent sections of the neutron monitor both on an hourly 
as well as on a daily basis is regularly monitored and used 
to determine the self consistency of the data. Since both the 
cosmic ray primaries and secondaries show a random distribu­
tion in time, they can be assumed to obey Poisson distribu­
tion. The statistical error associated with the 4 minute 
count rate $N$ is given by

$$\sigma = M/(N)^{1/2} \quad (2.3)$$

Where $M$ is the multiplicity which is of ~ 1.4 for Ahmedabad 
monitor. The error associated with the ratio can be written as

$$\sigma_r = \sigma^r (2)^{3/2} \quad (2.4)$$

Knowing the count rate obtained by the individual sections, 
the errors associated with any two sections can be calculated. 
Using a 4 $\sigma$ limit as the minimal acceptable level for both 
the ratio's and the actual count rate difference between any 
two sections, the pressure corrected data is then computed 
from which the hourly mean and daily mean pressure corrected 
cosmic ray intensity at Ahmedabad has been obtained. The
total counts over each day is also computed for each individual
section and is used to compute the daily ratio's between differ­
ent sections and these ratio's are used for checking the long
term stability of the monitor.

2.9 Pressure correction of neutron monitor data:

Before using Ahmedabad neutron data for any further
analysis it is very essential to correct the data for meteoro­
logical variations, as most of the secondary neutrons are pro­
duced during the interaction of primary cosmic ray particles
with the atmospheric nuclei. Earlier observations clearly
indicated that the neutron intensity at the ground is signifi­
cantly affected by pressure variations, whereas the temperature
corrections for neutron component is almost negligible. The
neutron intensity $N$ at any atmospheric pressure $P$ can be
expressed as,

$$N(P) = \exp(-P/L) \quad (2.5)$$

Where $L$ is the absorption mean free-path of the neutron
component, which depends on the mean energy of the recorded
neutron component. Differentiating equation (2.5) with
respect to $P$ it can be shown that

$$\alpha = -\frac{1}{L} \frac{dN}{dP} \quad (2.6)$$

Where $\alpha = \frac{1}{L}$ is known as the barometric attenuation co­
efficient. Extensive investigations have shown that the
The attenuation coefficient \( \alpha \) of a neutron monitor is a function of both latitude and altitude (Bachelet et al., 1965, 1972; Carmichael et al., 1958) and varies with solar cycle having a maximum value during solar minimum. The attenuation coefficients obtained for various sea level neutron monitoring stations having different cut-off rigidities for the period 1964-1965 (Bachelet et al., 1972) and those obtained for 1965 by Carmichael and Bercovitch (1969) from latitude surveys show that there is a good agreement in the values of the attenuation coefficient derived for low latitude stations having cut-off rigidities \( \geq 8 \) GV. Following well established methods, the attenuation coefficient \( \alpha \) for Ahmedabad NM-6 neutron monitor has been estimated by performing a complex regression analysis of successive differences (Lapointe and Rose, 1962) of the logarithm of the daily mean intensity \( N \) and the daily mean pressure \( P \) using equations

\[
\ln(N_2) - \ln(N_1) = - \alpha (P_2 - P_1)
\]  

(2.7)

Using the data of Ahmedabad neutron monitor during the period 1968-73, after adequately correcting for the changes in the efficiency of the monitor with time, the attenuation coefficient appropriate to Ahmedabad monitor \( P_c \sim 15.9 \) GV has been derived is found to be \( \sim 0.84 \pm 0.02/\text{mm} \) and is in good agreement with the results reported by Forman (1968) and Bachelet et al. (1972). Since the solar cycle variation of \( \alpha \) at
stations with $P_c \geq 15.9$ GV is quite negligible, we have used the same attenuation coefficient for correcting Ahmedabad neutron monitor data for the entire period 1968-73. The pressure corrected neutron intensity $N$ has been derived using the relationship

$$N = N_0 \exp\left\{\alpha(P - P_0)\right\} \quad (2.8)$$

Where $N_0$ is the observed neutron intensity at pressure $P$ and $(P - P_0)$ is the difference between the observed pressure $(P)$ and the standard pressure $(P_0)$ which is basically chosen as the yearly mean pressure at a particular station. The yearly mean pressure $(P_0)$ at Ahmedabad is found to be $\sim 750.08$ mm (1000 mb), and the attenuation coefficient is $\sim 0.84\%$/mm Hg. The pressure corrected hourly neutron data at Ahmedabad has been used for all further analysis.

2.10 Determination of solar daily variation:

Even though the solar daily variation can be studied using different methods (Rao and Sarabhai, 1964; Kane, 1966) most of the qualitative information on the daily variation obtained so far has been through the study of the diurnal (I harmonic) and the semi-diurnal (II harmonic) components derived from a Fourier analysis (Chapman and Bartels, 1940) of the cosmic ray intensity observed over a period of 24-hours (1 day). The amplitude and time of maximum of the diurnal and semi-diurnal anisotropy vectors derived from the harmonic
coefficients implicitly assumes that the anisotropy remains constant over a period of 24 hours. Therefore whenever large world wide variations and short term variations (< 24 hours) occur, the harmonic coefficients and the diurnal and semi-diurnal vectors derived from above method nave to be viewed with caution. In order to derive the 12 hour and 24 hour periodic components, it is customary to employ the well known 24-hour moving average method (Dorman, 1957) to remove the effects of slowly varying components (> 24 hours). The data obtained after removing the slowly varying components are then subjected to Fourier analysis.

2.11 Harmonic analysis:

Any periodic function $Y(t)$, over a finite interval $t = 0$ to $t = 2\pi$, with 24 equidistant points within the interval, can be expressed in the simple form of a Fourier's series as,

$$Y(t) = A_0 + \sum_{n=1}^{24} (A_n \cos nt + B_n \sin nt)$$  \hspace{1cm} (2.9)

where $A_0$ is the mean value of $Y(t)$ in the interval 0 to $2\pi$ and $A_n, B_n$ are coefficients of the $n^{th}$ harmonic given by

$$A_0 = \frac{1}{24} \sum_{i=1}^{24} R_i, \quad A_n = \frac{1}{12} \sum_{i=1}^{24} R_i \cos nt_i$$  \hspace{1cm} (2.10)

$$B_n = \frac{1}{12} \sum_{i=1}^{24} R_i \sin nt_i$$
The amplitude $R_n$ and phase $\Theta_n$ of the $r^{th}$ harmonic can be obtained from the equation

$$R_n \cos (nt - \Theta_n) = A_n \cos nt + B_n \sin nt \quad (2.11)$$

Where

$$R_n = \left( A_n^2 + B_n^2 \right)^{1/2} \quad \text{and} \quad \Theta_n = \text{Arc tan} \left( B_n / A_n \right) \quad (2.12)$$

Assuming that the hourly counts follow a standard Gaussian distribution, the standard error in the determination of various harmonics is given by

$$\sigma_{A_n}^2 = \sigma_{B_n}^2 = \sigma_{R_n}^2 = \sigma^2 / 12 \quad \text{and} \quad \sigma_{\Theta_n} = \sigma_{R_n} / R_n \quad (2.13)$$

Where $\sigma$ is the standard error associated with the hourly count rate of the observed cosmic ray intensity.

2.12 Corrections for geomagnetic field:

Before interpreting the secondary cosmic ray variations observed at a ground based monitor in terms of primary cosmic ray variations in the interplanetary space, it is very essential to correct the observations for the effects of geomagnetic field. A number of investigators (McCracken et al., 1962, 1965; Rao et al., 1963; Shea et al., 1965, 1968) using a six degree simulation for the earth's magnetic field, have numerically computed the 'asymptotic directions' (the direction before entering the earth's magnetic field) of primary
c
d
cosmic ray particles having different rigidities varying from 1 - 500 GV, which are incident at different zenith and azimuth angles at the top of the atmosphere. The concept of an asymptotic cone of acceptance of a detector developed by them has been found extremely useful in interpreting most of the secondary cosmic ray variations observed at a ground based monitor. From an extensive study of ground based neutron monitor observations Rao et al. 1963 and McCracken and Rao (1965) further showed that the cosmic ray variations observed at a ground based detector corrected for the width and declination of the asymptotic cone of acceptance of the detector and geomagnetic bending at each station can be effectively used for deriving the characteristics of cosmic ray anisotropies in the interplanetary medium. A brief discussion of the variational coefficients and their application to diurnal variation are presented.

2.13 The concept of variational coefficients:

If \( J_0 \) is the isotropic cosmic ray intensity from all directions, then the anisotropic cosmic ray intensity from within the solid angle \( \Omega_1 \) can be represented in a simple form \( J_0 (1 + A_1 R^{\beta}) \), where \( A_1 \) is a function of asymptotic directions, \( R \) is the rigidity (in GV) and \( \beta \) is the spectral exponent. This anisotropy will essentially produce a fractional change in the counting rate of a ground based
detector given by (Zao et al, 1963; McCracken et al, 1965)

\[ \frac{\Delta N}{N} = v(\Omega_1, \beta) A_1 \]  

(2.14)

Where \( N \) is the counting rate observed, when the cosmic ray intensity is \( J_0 \) from all the directions and \( v(\Omega_1, \beta) \) is defined as the variational coefficients corresponding to a solid angle \( \Omega_1 \) and spectral exponent \( \beta \). The variational coefficients however can be expressed in a simple form as

\[ v(\Omega_1, \beta) = \int W(R) R^{\beta} Y(\Omega_1, R) / Y (1-\pi, R) \, dR \]  

(2.15)

Where \( W(R) \) is the coupling coefficient (Dorman, 1957) or differential response function of a detector (Lockwood and Webber, 1967) and \( Y(\Omega_1, R) \) is the fraction of hemisphere above the detector which is accessible from asymptotic directions within the solid angle \( \Omega_1 \).

2.14 Evaluation of variational coefficients:

Using spherical harmonics up to and including 6th degree simulation of the earth's magnetic field (McCracken et al, 1962, 1965; Shea et al, 1965, 1968) and defining the elementary solid angle \( \Omega_1 \) by planes of constant geographic longitude at 0, 5 and 10 degrees and by surfaces of constant geographic latitude spaced every 5 degrees on either side of the equator, it is possible to determine the fraction of the hemisphere above the detector which is accessible from asymptotic directions included within \( \Omega_1 \), if the asymptotic directions corresponding to all directions \( (\Theta, \Phi) \).
and for all rigidities \((R_k)\) are known. For evaluating the variational coefficients, cosmic ray particles of various rigidities arriving from nine specific directions namely vertical, geomagnetic north, south, east and west and at zenith angles 0, 16 and 32 degrees are used. Further it is assumed that for \(R^\text{th}\) rigidity \((R_k)\), if a direction \((\Theta_o, \Phi_o)\) is accessible from some elementary solid angle \(\Omega_1\), then for \(\Theta_o \neq 0\) all directions within the solid angle \(\Theta_o \pm 8^\circ\) and \(\Phi_o \pm 45^\circ\) are accessible from \(\Omega_1\) for rigidities in the range 
\[
\frac{R_k - 1}{2} \leq R \leq \frac{R_k + R_{k+1}}{2}.
\]
An acceptable estimate of \(Y(\Omega_1, R)\) is the number of above nine directions \((\Theta_o, \Phi_o)\) which are accessible from infinity. The variational coefficients then simplify to

\[
v(\Omega_1, \beta) = \sum_k W(R_k) \cdot \frac{Y(\Omega_1, R_k)}{Y(\Omega_1, R_k)} \cdot \frac{(R_{k+1} - R_k - 1)}{2}
\]  
(2.16)

Where the summation extends from near cut-off rigidity to a value \(R_{\text{max}} \approx 500\) GV.

Expressing the anisotropy as a power law in rigidity, we have

\[
\frac{\Delta J_{\lambda}}{J_o} = A R^\beta = f(\psi) R^\beta \cos \lambda
\]  
(2.17)

Where \(A\) is the amplitude of the anisotropy which is a separable function of the asymptotic latitude \(\lambda\) and longitude \(\psi\) and varies as the cosine of declination. The fractional change in the counting rate produced by the radiation from \(\Omega_1\) can be written as,
\[
\frac{dN (\Omega)}{N} = f(\psi \cdot \nu(\Omega, \beta) \cos \Lambda \quad (2.18)
\]

and summing over all \( \Omega \), equation 2.15 gives
\[
\frac{dN (\psi)}{N} = f(\psi \cdot \sum \nu(\Omega, \beta) \cos \Lambda
= f(\psi \cdot \nu(\psi, \beta) \quad (2.19)
\]

Where \( dN(\psi) \) is the solid angle defined between two meridional planes 2.5 degrees on either side of the meridional plane at geographic longitude \( \psi \). Using the above expression (2.19) the variational coefficients \( \nu(\psi, \beta) \) for different asymptotic longitudes and for a wide range of spectral exponents \( \beta \) ranging from 1.0 to 1.2 have been evaluated for a large number of stations (McCracken et al., 1965; Shea et al., 1968) are available in the literature (IQSY Instruction Manual No.10).

2.15 Application to diurnal variation:

From a detailed knowledge of the variational coefficients and cosmic ray observations at various stations, the amplitude and phase of the cosmic ray anisotropy in space can be easily predicted. Any anisotropy can be expanded as a function of \( \gamma \) in the form of a Fourier's series as
\[
f(\gamma) = J_0 (B) \sum_{m=1}^{\infty} \alpha_m \cdot \cos \{ m (\gamma - C_m) \} \quad (2.20)
\]

Where \( \alpha_m \) and \( C_m \) are the arbitrary amplitude and phase constants and \( C_m \) is also the direction from which a maximum of the \( m \)th harmonic is seen. Referring to figure 2.4 the intensity from
Figure 2.14 - Defines the angles employed to specify the asymptotic direction of viewing of an arbitrary station.
the asymptotic longitude $\psi$ can be written as

$$f(\psi) = J_0 (R) \sum_{n=1}^{\infty} \alpha_n \cos \left\{ m (\psi + 15T - 80 - C_m) \right\}$$

(2.21)

Where the asymptotic longitude $\psi = (5i + 2.5)^0$ is the mean longitude of all the particles arriving from solid angles lying between $\psi = 5i^0$ and $\psi = 5(i + 1)^0$. Inserting this value of $f(\psi)$ and summing over $i$, the deviation of the counting rate of a detector at time $T$ from the mean value is given by,

$$\frac{\Delta N(T)}{N} = \sum_{i=0}^{71} V(\psi_j, \beta) \sum_{m=1}^{\infty} \alpha_m \cos \left\{ m (5i + 2.5 + 15T - C_m - 180) \right\}$$

(2.22)

$$= \sum_{m=1}^{\infty} \alpha_m \sum_{i=0}^{71} \cos \left\{ m (15T - 180 - 2m) + \psi_m \right\}$$

(2.23)

where

$$B_m^2 = \left[ \sum_{i=0}^{71} V(\psi_j, \beta) \sin \left\{ m (5i + 2.5) \right\} \right]^2 + \left[ \sum_{i=0}^{71} V(\psi_j, \beta) \cos \left\{ m (5i + 2.5) \right\} \right]^2$$

(2.24)

and

$$\tan \gamma_m = \frac{\sum_{i=0}^{71} V(\psi_j, \beta) \sin \left\{ m (5i + 2.5) \right\}}{\sum_{i=0}^{71} V(\psi_j, \beta) \cos \left\{ m (5i + 2.5) \right\}}$$

(2.25)
Where \( \alpha_m B_m \) and \( -mC_m + \gamma_m \) represents the amplitude and phase constants of the \( m \)th harmonic. The local time of maximum intensity at a station whose geographic longitude \( L \) is given by

\[
T_m = \frac{180m + mC_m - \gamma_m}{15m} \text{ hours} \quad \text{(2.26)}
\]

The terms \( (\gamma_m - mL)/15m \) makes due allowance for the deflection suffered by cosmic ray particles in their passage through the geomagnetic field. The amplitude and phase of the diurnal variation observed at each neutron monitoring station are corrected both on an average as well as on a day to day basis using the amplitude and phase constants of the \( 1 \)st harmonic assuming an energy independent spectrum \( (\beta = 0) \) to derive the diurnal anisotropy vectors in the interplanetary space during the period 1965-72.

2.16 Space-time diagrams:

As the earth spins on its axis, a ground based neutron monitor which looks into a narrow region in space, will effectively scan the entire celestial sky in a period of one day \((24 \text{ hours})\). By using a large number of high latitude neutron monitoring stations \((P_c \leq 2 \text{ GV})\) well distributed in longitude and having a narrow asymptotic cone of acceptance, it is always possible to separate the cosmic ray spatial variations (anisotropic) from time variations (isotropic) and
to monitor continuously along each asymptotic direction the cosmic ray intensity variations as a function of time. A space-time diagram essentially represents the cosmic ray intensity variations observed in different asymptotic directions at any instant of time. The space-time contour diagrams essentially provide an integrated three dimensional view of the cosmic ray intensity profile in space and hence can be effectively utilized to derive the space and time evolution of cosmic ray anisotropies in the interplanetary medium. The method of constructing three dimensional space-time diagrams developed by a number of workers (Fenton et al, 1959; Ables et al, 1967; Mercer and Wilson, 1968; Carmichael and Steljes, 1969) is ideally suited for studying rapidly evolving cosmic ray anisotropies, for distinguishing the presence of sinks and sources of cosmic ray particles and also to understand the physical processes which leads to redistribution of cosmic ray particles in the interplanetary medium.

In this thesis, we have used this technique to understand particularly the trains of days having enhanced diurnal amplitude. The average daily mean cosmic ray intensity observed three days prior to the commencement of the enhanced diurnal variation event are used for normalization purposes. In order to derive the three dimensional cosmic ray intensity profile in space, the space is divided into 8 equal sectors, each covering a longitude of width $\sim 45^\circ$ (3 hours). After
correcting the observed cosmic ray intensity at each station for the width and declination of the asymptotic cone of acceptance and geomagnetic bending, the 3 hourly average cosmic ray intensity deviation in each sector are then computed for a number of selected high latitude neutron monitoring stations ($P_c \leq 2$ GV). Combining similar informations from a large number of neutron monitoring stations well distributed in longitude, the average intensity deviation in each sector is then derived for each day. The average intensity deviation observed in all the 8 sectors covering the entire space are used to construct three-dimensional space-time diagrams on a day to day basis during enhanced diurnal amplitude days. The results are discussed in chapter III.

2.17 Power spectrum analysis:

Though most of the cosmic ray time variations observed at ground based monitors can be understood in terms of the cosmic ray particle propagation in the large scale (Archimedean spiral) magnetic fields present in the solar system, when one deals with the short term cosmic ray variations of periodicity $\leq 1$ day, it is very essential to have a detailed description of the magnetic fields present in the interplanetary medium. As the field fluctuations ($\leq 1$ day) are frozen into the solar wind plasma, the observed time variation of the magnetic field at any point in space can be easily transformed into spatial variations. From a detailed power spectrum
analysis of the magnetic field obtained from direct spacecraft measurements a number of authors (Jokipii, 1966; 1967; Coleman Jr., 1966; Jokipii and Coleman, 1968; Siscoe et al, 1968; Sari and Ness, 1969) have clearly demonstrated that the large scale interplanetary magnetic fields are associated with irregularities of all scale sizes and these irregularities manifest themselves as deviations in the observed IPMF. These irregularities act as scattering centres for cosmic ray particles making them isotropic and also cause significant transverse diffusion in the interplanetary medium.

The observed fluctuations in time at a fixed point in space can be regarded as a pattern which is stationary in the frame of the solar wind, which is convected past the point of observation. Any variable $B(t)$ as a function of time, generated by a random (or stochastic) process is one of an ensemble of random functions which might be generated by the process. The value of the function at any particular point in time is thus a random variable with the probability distribution induced by the ensemble. If we assume that the random process is Gaussian, then for every $n$, $t_1, t_2, \ldots, t_n$, the joint probability distribution of $B(t_1), B(t_2), \ldots, B(t_n)$, is an $n$-dimensional Gaussian or normal distribution. The ensemble average is then given by

$$
\bar{B}(t_1) = \text{ave} \left\{ B(t_1) \right\} \quad (2.27)
$$

and the covariance $C_{ij} = \text{ave} \left\{ B(t_1) \times B(t_j) \right\}$

$$
(2.28)
$$
The random process is stationary and it is not affected by translation of origin in time, the covariance \( C_{ij} \) depends only on the separation \((t_i - t_j)\) such that

\[ C_{ij} = C(t_i - t_j) \quad (2.29) \]

The covariance at any time lag \( \tau \) in single function terms is given by

\[ C(\tau) = \text{ave} \left\{ B(t) x B(t + \tau) \right\} \quad (2.30) \]

Where \( C(\tau) \) is called the auto correlation function. If the averages of all random process are assumed to be zero, then \( C(\tau) \) is called as the auto-covariance function. The auto-covariance function can be reduced to the form

\[ C(\tau) = \int_{-\infty}^{\infty} P(f) e^{2\pi if \tau} df \quad (2.31) \]

Where \( P(f) \) is the power spectrum of the stationary random process as a function of frequency. \( P(f) \) is also called spectral density or power spectral density. The power spectrum can also be expressed as a Fourier transform of the auto-covariance function given by

\[ P(f) = 2 \int_0^{\infty} C(\tau) \cos 2\pi f \tau d\tau \quad (2.32) \]

Using the radial component of the hourly average IPMF vectors obtained from 'in situ' space-craft observations for nearly 5 days, the power spectral density at each frequency was obtained using a Nyquist frequency of \( \sqrt{4.6 \times 10^{-6}} \) Hz.
(\sim 60 \text{ hours}) \text{ and applying Blackman and Tukey window in equation 2.32. The power density distribution as a function of frequency is studied for a number of non-field aligned trains of days as well as for a number of completely field aligned trains of days. The results are discussed in chapter IV.}