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Matsushiro Underground Cosmic-Ray Observatory (220 m.w.e. Depth) and the Observation of High Energy ($\lesssim 10^{12}$ eV) Cosmic Ray Intensity Variation

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Abstract

A new underground cosmic-ray observatory was opened in Matsushiro, Nagano City, Japan on March 22, 1984, and a multi-directional muon telescope has been installed at an effective vertical depth of 220 m.w.e. underground. The telescope consists of 50 plastic scintillation detectors totally, arranged in two layers of 25 detectors each and has 17 directional channels of observation. We have made the continuous observation of the intensity variation of cosmic ray muons (median primary energies of detection $\lesssim 10^{12}$ eV) since that date. The intensity has been recorded every hour, and the average muon counting-rates are; $\sim 8.7 \times 10^4$ counts per hour for a wide-angle vertical telescope (two-fold coincidence between upper and lower arrays of detectors) and $\sim 2.0 \times 10^4$ counts per hour for a vertical component-telescope, for example. In the present report, we describe briefly the underground observatory of Matsushiro and its surroundings, including the underground tunnel, the muon detector, the multi-directional telescope constructed and some of its related characterristics. We also present some of the observed intensity variations of cosmic ray muons for a full five-year period from April 1984 through March 1989 and discuss preliminarily the analyzed results of them in solar and sidereal time.

Introduction

The continuous observations of the time variations of high energy galactic cosmic rays ($\gtrsim 10^{11}$ eV), particularly in sidereal time, provide information of its distribution and its propagation of cosmic rays inside and outside the heliomagnetosphere, and in turn information of the electromagnetic conditions in the magnetized space. For those purposes, the long-running observations of the comsic ray intensity variations have been performed by many researchers since the discovery of cosmic radiations, by means of a variety of detectors at various levels at the ground and underground (e. g., ELLIOT, 1952; DORMAN, 1974). Among those, at the present moment more than a dozen underground telescopes (its median energies of detection $>10^{11}$ eV) have been actively in operation and accumulated valuable data worldwidely. Those stations are shown in Fig. 1 and listed in Table 1. By using those data, a great many investigations of the anisotropy, particularly in sidereal time, of galactic origin has been performed, and some indications have been obtained about a nature of the anisotropic flows of cosmic rays around the inner and outer heliomagnetosphere (e. g., NAGASHIMA and MORI, 1976, references therein), cooperated with recently developed small air-shower measurements (its effective energies

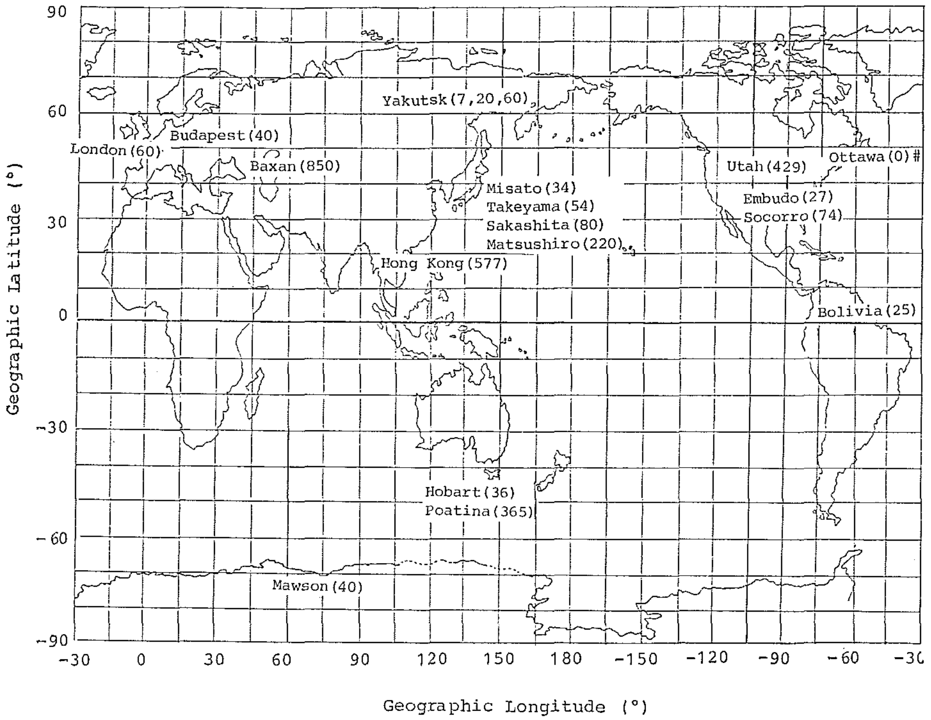


Figure 1 A worldwide location of the underground cosmic-ray observatories in operation (in parenthesis, each depth is indicated).

Table 1 List of worldwide underground cosmic-ray observatories and some of its characteristics.

Station	Geographic Lat. (°)	 Long. (°)	Depth* (m. w. e.)	E_{mp}§ (GeV)
Artyomovsk$^+$	48.8N	38.0E	575	1600
Baxan	43.0N	42.5E	850	2000
Bolivia**	16.3N	68.2E	25	117–180
Budapest**	47.5N	18.9E	40	187–209
Embudo	35.2N	106.4W	27	125–159
Hobrat	42.9S	147.2E	36	184–195
Hong Kong	22.0N	114.0E	577	1500
Kamioka$^+$	36.3N	137.5E	2700	7000
London**	51.5N	0.1W	60	261–421
Matsushiro	36.5N	137.8E	220	600–1300
Mawson	67.6S	62.9E	40	164–188
Misato	36.0N	137.8E	34	145–209
ottawa♯	51.0N	78.0W	0	80–900
Poatina	41.8S	147.9E	365	1400
Sakashita	35.6N	137.5E	80	331–595
Socorro	34.0N	105.6W	74	280–364
Takeyama**	35.2N	139.6E	54	212–299
Utah**	40.6N	111.5W	429	1300
Yakutsk	62.0N	129.5	7, 20, 60	80–264

* Vertical depth, ** ceased, ♯ at ground (inclined),
§ E_{mp} (median primary energy) for Matsushiro (IMAIZUMI, 1988), and for otherwise (FUJIMOTO et al., 1984), and
$^+$ originally not for modulation observation.

of response $>10^{13}$ eV) (e. g., SAKAKIBARA et al., 1984, references therein). A complete picture, however, of the anisotropies of galactic origin, including its three-dimensional nature, its energy spectrum, and further its modulation in the heliomagnetosphere, particularly in the energy regions $>10^{12}$ eV, have not yet been fully documented.

Here we can refer to one of the recent summaries of the observations of the sidereal anisotropy, given at the Moscow Conference (KRISTIANSEN, 1987), for example. That states that in the energy regions $10^{12}\sim10^{14}$ eV, to which the deep underground observations and small air-shower measurements may respond, the sidereal diurnal anisotropy obtained shows the amplitude approximately 0.1% and the phase around 2 hr LST, and that those are almost invariant with energy. On the basis of that observed constancy, some authors (e. g., KIRALY and KOTA, 1979) have interpreted that the anisotropic flows of cosmic rays may mainly be produced by the so-called COMPTON-GETTING effect;

a simple drift of cosmic rays through a smoothly flowing local (in some tens of Lamor radii for the energies in question) interstellar medium. We should also refer to the other important observational and theoretical views, given by JACKLYN (1970) and NAGASHIMA (1971). Those state that in addition to the diurnal term, the semi-diurnal and higher terms have definitely been observed in the sidereal wave, and that those terms may play an essential role for discussing the anisotropy model of cosmic rays.

We may further refer to a series of works, recently developed by NAGASHIMA et al. (1982, 1983, 1985; references therein). That concerns the heliomagnetospheric modulation of the sidereal time anisotropies, being presumably predominant in the energy regions less than 10^{13} eV, to which the underground observations at the depth of 200 m.w.e. or above may respond. They have made an extensive theoretical calculation of modifications of the anisotropy inside the heliosphere (its dimension roughly 100 AU), due to the orbital deflection of cosmic ray particles in the magnetosphere. Using models of the heliomagnetosphere, which may change its state every 11-year, particularly of the field polarities in the northern and the southern hemispheres with respect to the neutral current sheet with its different degrees of waviness. NAGASHIMA et al. (1983) have presented, in a tabular form, comprehensive predictions of the field modulated characteristics of the anisotropies of arbitary orientation, as functions of primary cosmic ray particle rigidity and latitude of the viewing.

The following reference may be added as a milestone of observation of the sidereal signal of cosmic rays, which is very recently reported by NAGASHIMA et al. (1989; references therein). That concerns an observational summary of the sidereal anisotropy and its modulation in the heliosphere, based on their long-running observations by means of small air showers at Mt. Norikura for almsot 20-year period (1970-1988). First, a significant sidereal diurnal variation has been well established with enough statistics, showing that an amplitude is $0.060 \pm 0.003\%$ and a phase 0.8 ± 0.3 h LST for $\sim 1.5 \cdot 10^{13}$ eV, together with statistically significant higher terms (semi- and tri-diurnal variations) in the sidereal wave. The results are definitely proved to be free from the atmospheric effects, with a method of the difference between two simultaneous directional (eastward and westward) air-shower measurements. We may regard the above result as a 'standard' of the anisotropic flows of cosmic rays outside the heliosphere. Secondly, the observation of the heliosphereic modulation of the sidereal daily variations have been discussed, showing that the annual variations of the observed phases of both sidereal and solar daily variations may respond significantly to the polarity reversal of the polar magnetic field of the Sun at the transition period 1979-1980. If that were the case, such modulation would be predominant in the energy regions $\gtrsim 10^{12}$ eV, then the observations at the deep underground depths of approximately 220 m. w. e. or above, may be expected to appreciably suffer that modulation in the heliomagnetosphere. Thirdly, a rather negative spectrum of the sidereal diurnal variations has been observed with their multi-fold air-shower measurements; the diurnal amplitudes may show a slightly decreasing form in the energy range of $\sim 10^{12}$ to $\sim 10^{14}$ eV. This may be rather strong contrast to a flat or rather increasing spectrum so far discussed (e. g., KIRALY et al., 1979; KRISTIANSEN, 1987). If that would be the case, greater amplitudes of about 0.1% or more might be expected to be observable in the energy regions of $\gtrsim 10^{12}$ eV, and the expectation of larger amplitudes will be referred to later.

In those observational and theoretical situations, we have been expecting the deep underground observations of cosmic rays promising, at the depths of 200 m. w. e. or above and much better with a multi-directional telescope in the following several reasons. First, the observations in the energy regions around 10^{12} eV, to which the present observations at Matsushiro may respond, may be important and interesting for establishing a sidereal anisotropy itself, particularly in a sense of a connective role of observations between the higher ($>2 \cdot 10^{12}$ eV) and the lower energy regions ($<5 \cdot 10^{11}$ eV). In the higher energy regions the measurements by means of air showers are available, and may give the anisotropic flows outside the heliosphere. In the lower energy regions there have been a great many observations at the ground and the shallow underground for a long period of time, but the observations themselves may be too severly modulated by the heliomagnetosphere to discuss the anisotropies of galactic origin. Secondly, as have been comprehensively predicted by NAGASHIMA et al. (1982, 1983, 1985), the heliomagnetospheric modulation of the galactic anisotropy of cosmic rays must be predominant in $\sim 10^{12}$ eV regions. This may imply that conversely, the observations of modulation of the anisotropies in the magnetized space make it feasible the electromagnetic diagnostics about the heliosphere. Such diagnostics using cosmic ray modulation observation may be promising for exploring the heliosphere, but this still be left fully unsolved yet (BERCOVITCH, 1984). Thirdly, a multi-directional observation may be certainly effective for confirming the observational facts themselves. With comparison of the observed results in a multi-directional way we may confirm them on a firm basis. Fourthly, the multi-directional telescope has a wide scanning ability over the celestial space; with the present telescope, from the north polar regions (70°～80°N) to the southern latitudes (～20°S), for example. The scanning around the Earth's rotational axis may lead to an observation with its small amplitude of the anisotropic flows of cosmic rays, and the viewings beyond the equatorial regions may reveal some of the southern characteristics, which may be different from the northern ones in the observation. Fifthly, on the basis of the multi-directional observation we may check and eliminate the inherent atmospheric effects to the observing muons by a method of the difference between the directional measurements (e. g., ELLIOT, 1952). With such a process we may check the spurious components of atmospheric origin, otherwise there would be no means to test for the possibility of that kind of effects.

Matsushiro underground observatory itself was completed in 1983. We started the observations of the intensity variations of cosmic ray muons on March 1984, and have continued them since that date, whose duty operation time rate (complete days/total days in operation) is as high as 95%. In this report we present a brief description of Matsushiro underground cosmic-ray observatory, the muon detectors, the multi-directional telescope constructed and some of its related characteristics. We also present some of the observed results of the daily intensity variations of cosmic ray muons in solar and sidereal times, and discuss the analyzed results of them preliminarily.

Underground site

Matsushiro underground cosmic-ray observatory is located in Matsushiro, Nagano City, Nagano Pref. in a central part of Japan, as shown in Fig. 2. Locality of Matsushiro is shown in Table 2; ~40 km northeast of Matsumoto

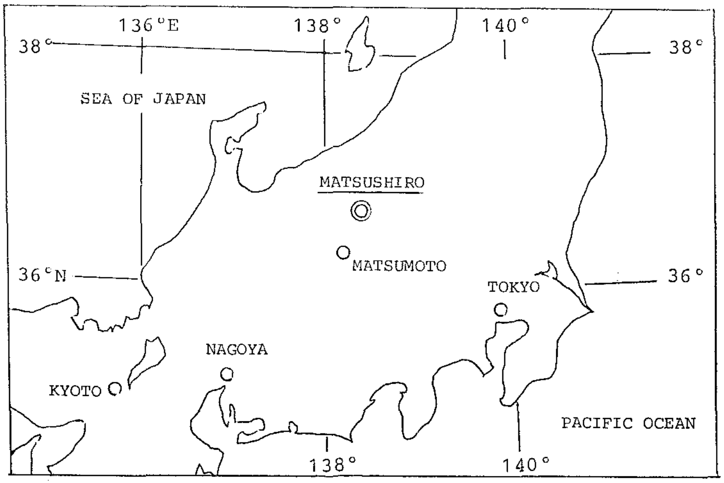


Figure 2 An outline map of a central part of Japan, showing Matsushiro, and other cities of Matsumoto, Tokyo, Nagoya, and Kyoto.

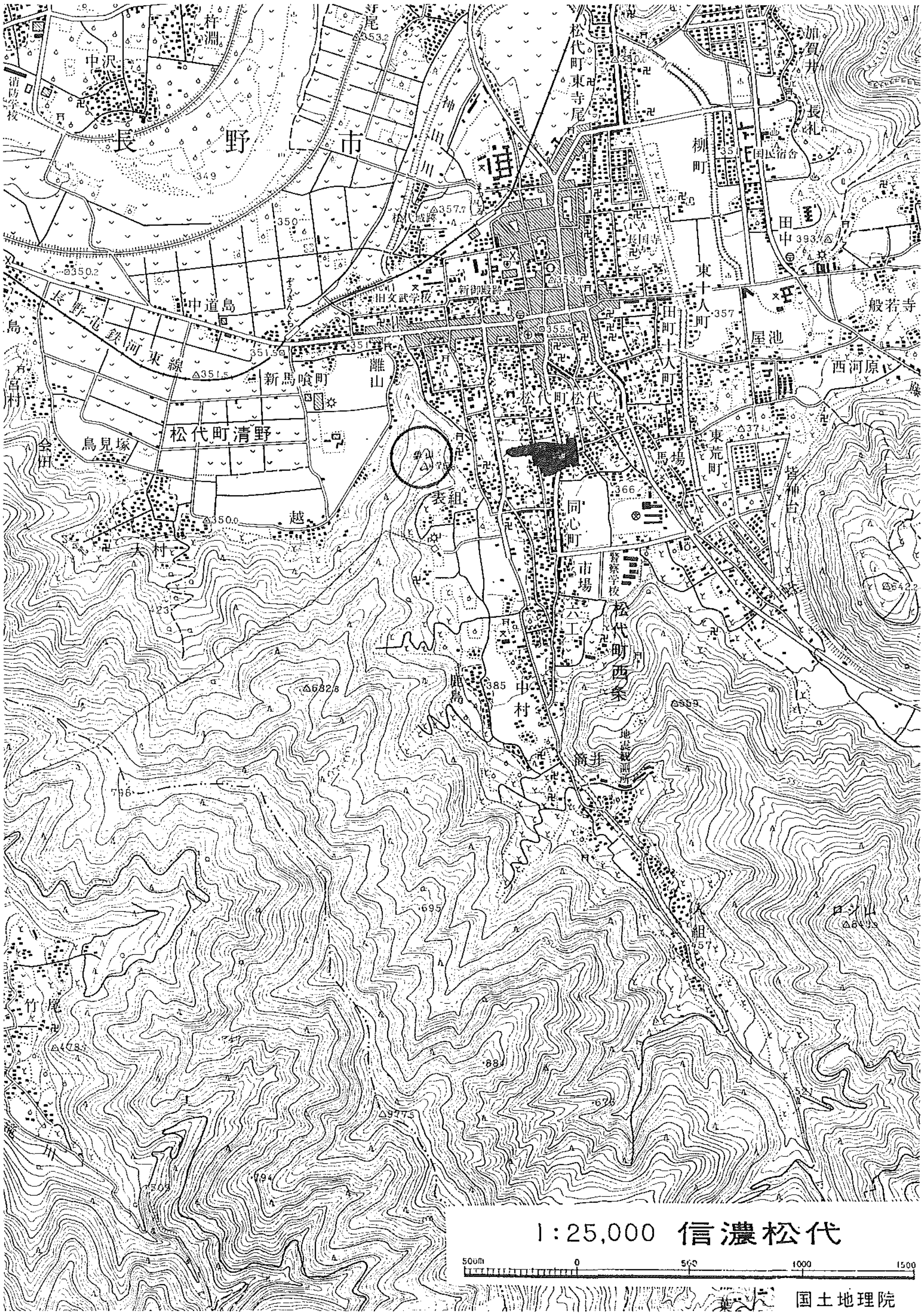


Figure 3 A detailed map around Matsushiro and the underground site area (printed by Geographical Survey Institute).

Table 2 Locality of Matsushiro underground observatory

Geographic		Height	Depth
Latitude	Longitude	(above sea level)	
36.53°N	138.01°E	360m	220m. w. e.

City, where our Department of Physics, Faculty of Science, Shinshu University is situated. Figure 3 illustrates a detailed map (printed by Geographical Survey Institute) of Matsushiro and the underground site. The present underground site is very close to the older Matsushiro underground observatory (~4 km in distance), which has been in operation since August 1980 (YASUE et al., 1979; 1981; 1983). Figure 4 (photograph) shows a distant view of an area (Mt. Zohzan) of the underground cosmic-ray observatory, for which the unused tunnel has been re-excavated and enlarged through the hill named Mt. Zohzan.

Figure 5 (a) shows the topography of the overburden (Mt. Zohzan), underneath of which the present cosmic-ray observatory is located, and Figure 5 (b) illustrated a cross-sectional profile along a line A−B of Mt. Zohzan in Fig. 5(a). As shown in the figure, the overburden rocks are mostly andesite (abbreviated to **Ad** in the figure) and shale (also to **Sh**). The rocks were sampled by boring at four points from the top (~450m above s. l.) to the bottom (~360m above s. l.) of the hill, and their average density is estimated at 2.54 $g \cdot cm^{-3}$. We also measured directly the rock depth and is as high as 92.8m vertically, being equivalent to 236 meter-water depth (Fig. 5 (b)).

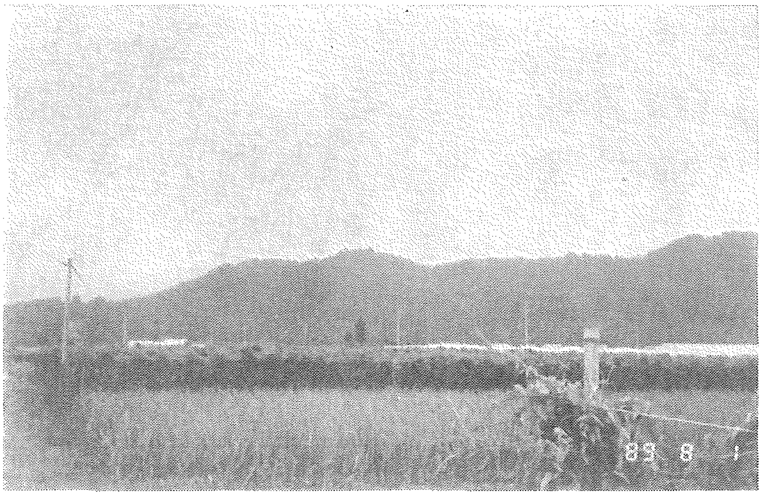


Figure 4 A distant view of Mt. Zohzan and the underground site area.

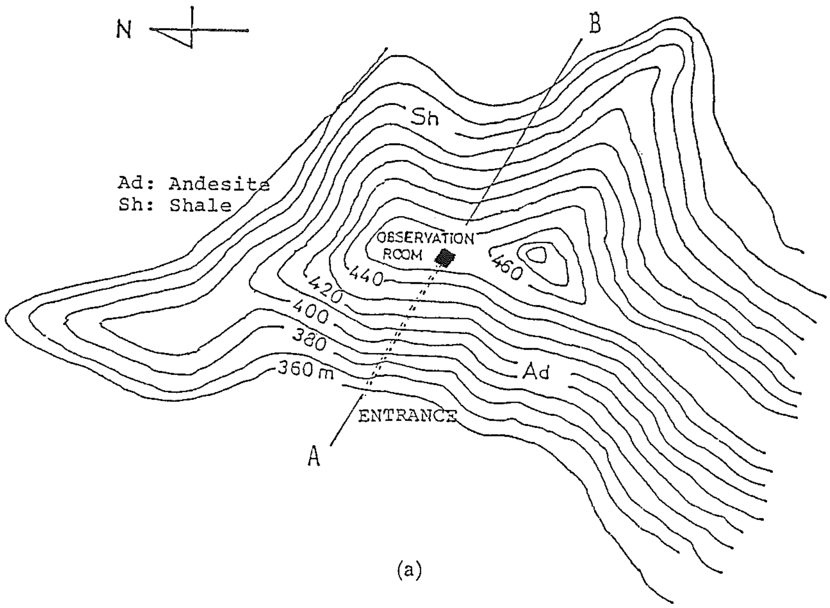
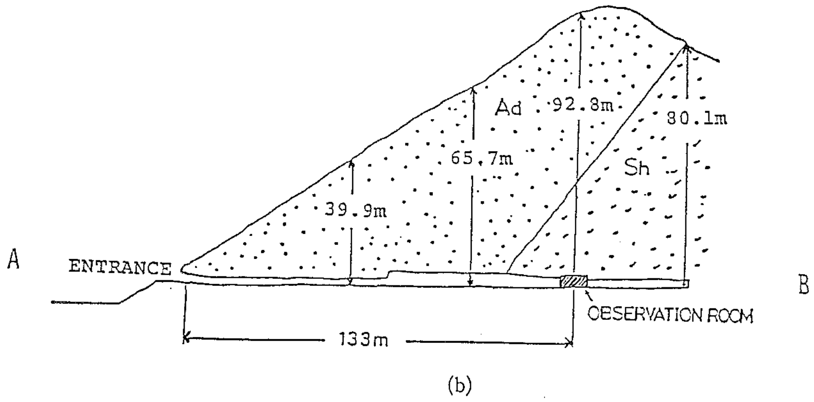


Figure 5 (a) A topography of the overburden (Mt. Zohzan), underneath of which the underground tunnel has been re-excavated and enlarged.



(b) One of the cross-sections of Mt. Zohzan along a line AB in Fig. 5(a).

Figures 6 (a) and 6 (b) demonstrate the simplified profiles of the cross-sections of the hill; (a) in the north-south (N-S) direction and (b) in the east-west (E-W) direction, for example. In the figure, the letters N, NN, N3, S, SS, S3,

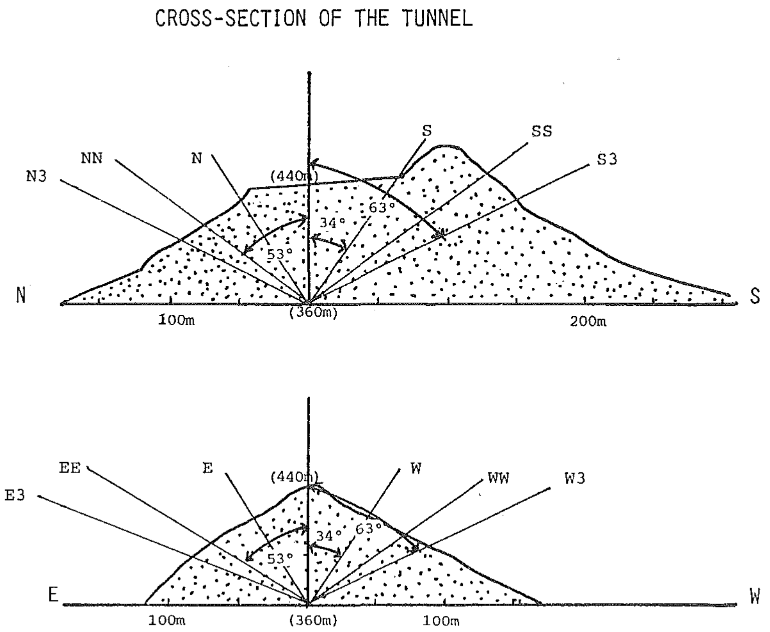
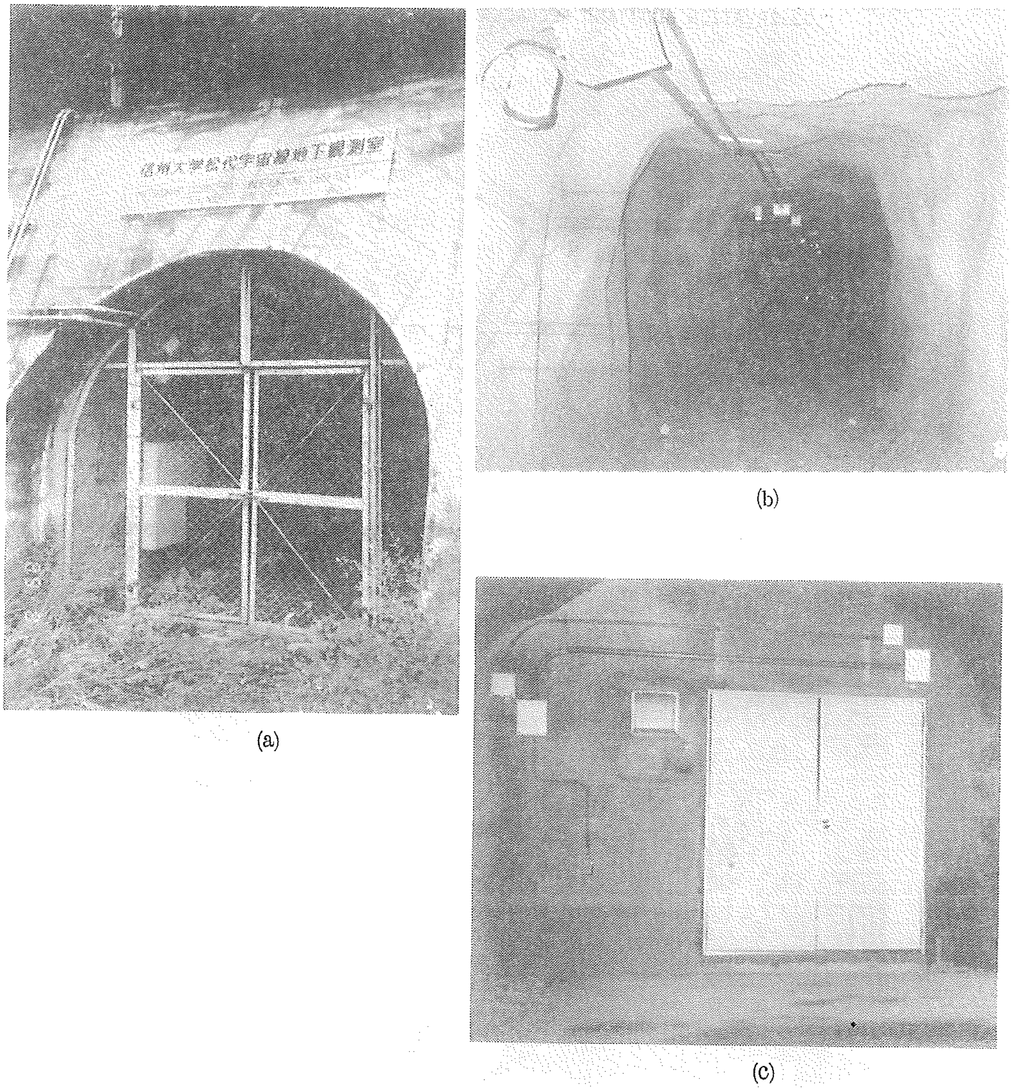


Figure 6 A simplified profile of the cross-sections in the directions; (a) north-south (N-S) direction and (b) east-west (E-W) direction, for example. Numerical values (m) in parenthesis represent a height.

etc. represent the center directions of viewing of the component-telescopes constructed, which will be referred to later. One can see that the rock depths are different from each direction and the median primary energies of detection of each directional component-telescope are, therefore, different from each other (see Table 4). Figures 7 (photograph) shows the underground tunnel, in which the cosmic-ray observatory is located; (a) the entrance of the tunnel, and (b) and (c) the paths inside. Figure 8 illustrates the room arrangement of the observatory in the tunnel; the observation room (10×10m in area) and the recorder room, where the electronics circuits and the recording system have been installed as shown in Fig. 9 (photograph). As mentioned earlier, the present underground tunnel has been constructed by re-excavating and enlarging the unused tunnel for the sake of the cosmic ray observation. The environmental conditions in the tunnel therefore, have been kept in an excellent state; inside the tunnel it has been rather dry and in almost constant atmospheric temperature throughout the year; the temperature in both observation and recorder rooms has been kept constant at 18.0±0.1°C throughout the year with some heating sources. The daily variation of the temperatue has been too small (~0.01°C) to produce any significant effects to the cosmic ray detectors and the



(a)

(b)

(c)

Figure 7 Matsushiro underground cosmic-ray observatory; (a) the main entrance, and (b) the path in the tunnel, and (c) the entrance of the observation room.

electronics circuits. The humidity in both rooms has been kept constant at 50 ± 1 % (routinely measured) all the year round by using four dehumidifiers.

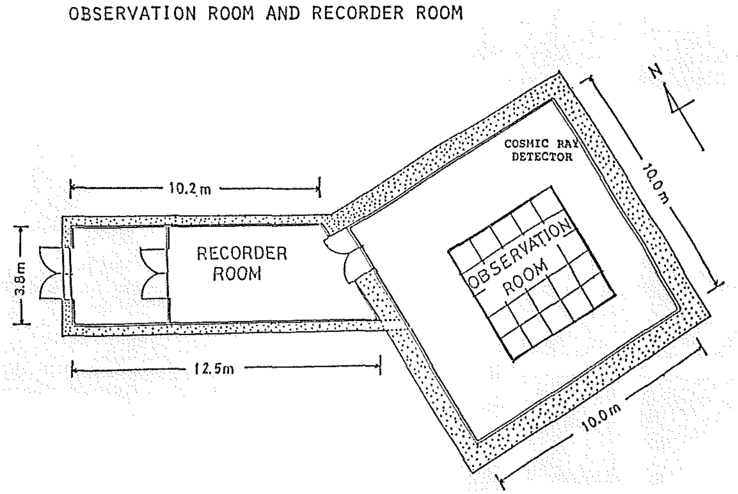


Figure 8 An arrangement of the room in the observatory; the recorder room and the observation room (10×10 m in area).

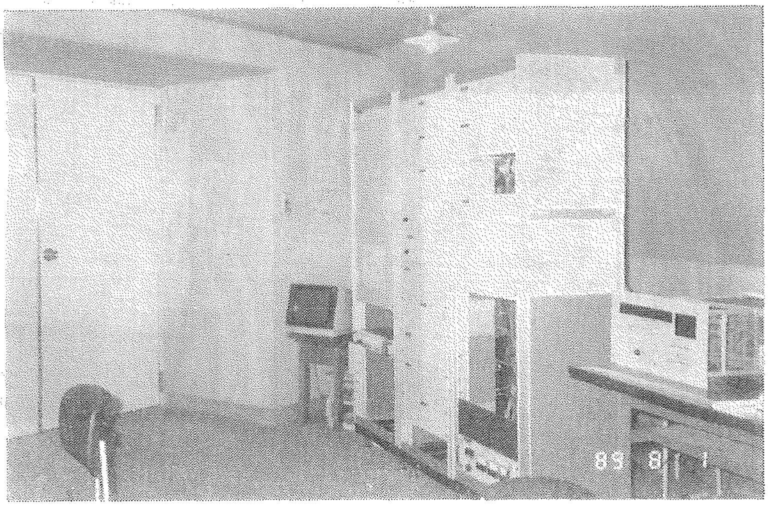


Figure 9 The recorder room, where the electronics circuits and the recording system are installed.

Multi-directional cosmic ray muon telescope

1. *Cosmic ray muon detector*

In the present observation, we have used plastic scintillation detectors for detecting the cosmic ray muons. The detector itself is of the same type as that being used in the older Matsushiro underground observatory, some detaild of which have already been discussed by YASUE et al. (1979). The detector of a piramid-shaped iron box of 1×1 m in area, as shwon in Fig. 10, contains four plastic scintillators, each of which has 50×50 cm in area and 10 cm thick. Inside the iron box we have coated white paint (Marine Paint) for reflecting and collecting as much scintillation light as possible (~90% in efficiency) to the photomultipliers (PMs, 5" in diameter; Hamamatsu Photonics). It is worthwhile noting here that in the present detector we have adopted a new optical system, which we call 'double PMs system', as shown in Fig. 10.

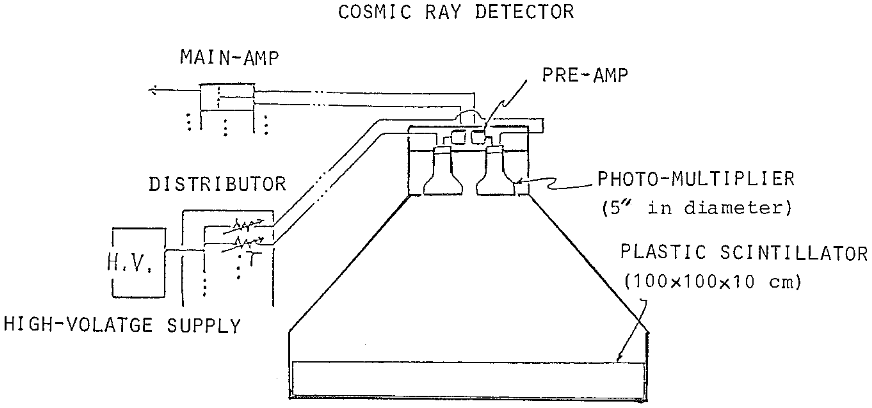


Figure 10 The cosmic ray detector, including the plastic scintillators (each being 100×100×10 cm slab), double photomultipliers (PMs; 5″ in diameter), and some electronics connection.

As can be seen in the figure the scintillators are viewed with 'one set of two PMs' instead of a single PM, placed at the apex of the iron box. We then take two-fold coincidence between those two output pulses out of the twin PMs as an output of each detector. With this 'double PMs system' we have succeeded in obtaining a better signal-to-noise ratio (S/N ratio), detection uniformity in the scintillators, and finally excellent HV-characteristics (output counts vs. high-voltage applied to PMs) of the component-telescopes as shown later (see Fig. 13). We have carefully selected four plastic scintillators as well as double PMs and their combination in each detector so as all the detectors to have fairly equal detection sensitivity.

2. *Multi-directional muon telescope*

The present telescope consists of 50 detectors totally. We have arranged these detectors in two layers (upper and lower) of 25 detectors each, spaced by 150 cm verically as illustrated in Fig. 11. Figure 12 (photograph) shows the

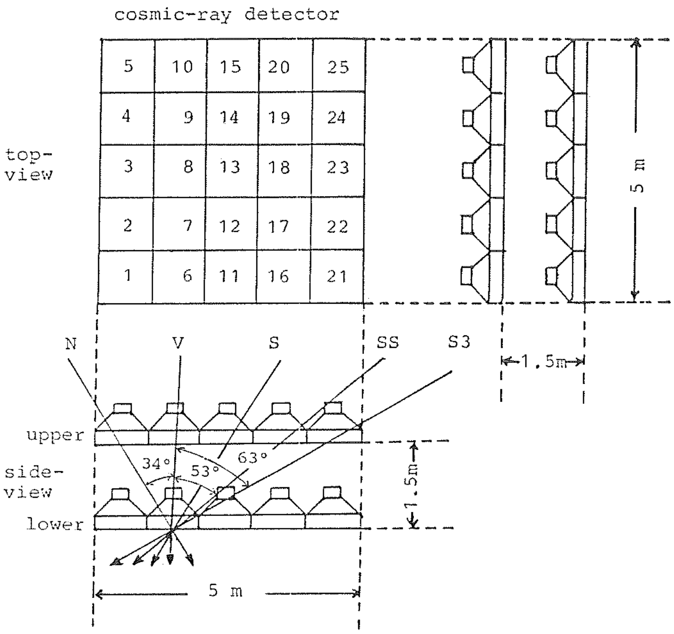
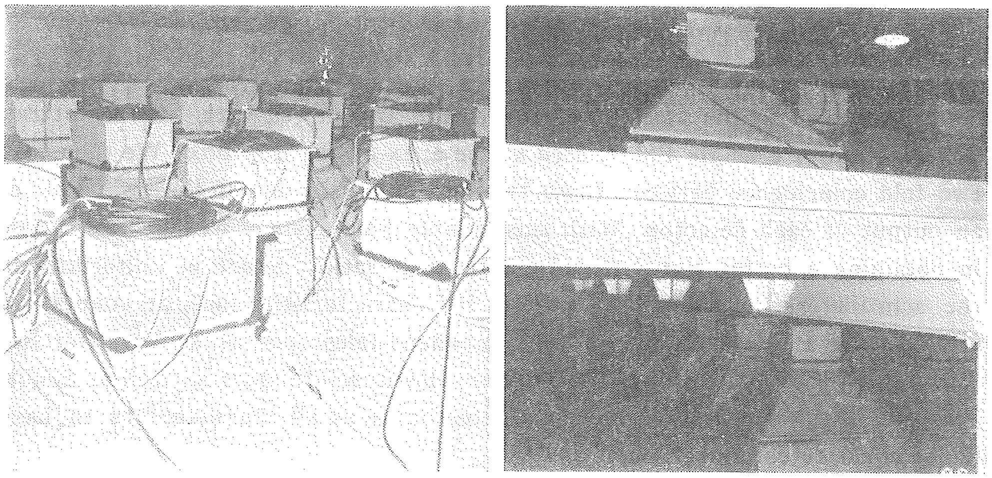


Figure 11 An arrnagement of the cosmic ray muon detectors in the two (upper and lower) layers of 25 detectors each, spaced by 150 cm vertically. Some of the component-telescopes; V-telescope, the inclined N-, S-, SS-, and S3-telescopes are illustrated.



(a) (b)

Figure 12 The settings of the cosmic ray muon detectors; (a) in the upper layer (exactly the same setting as the lower layer; not shown here) and (b) in the upper and lower layers.

setting of the detector arrays; (a) the upper layer in the observation room (and in the lower layer also set in the same manner as the upper; not shown here) and (b) two layers. On the basis of this arrangement of the detectors, whose numberings are shown in Fig. 11, we have constructed 16 directional component-telescopes as well as the vertical telescope, by taking two-fold coincidence between the pulses out of appropriate pairs of the detectors in the upper and lower layers. In Table 3, we summarize the present coincidence system between them. Figure 11 also shows some of the component-telescopes thus constructed in a front view; the vertical telescope (abbreviated to V-telescope hereafter), the south-pointing telescopes (S-, SS-, and S3-telescopes) and one of the north-pointing telescopes (N-telescope), for example. As is seen in the figure and as tabulated in Table 3, a geometrical settings of the component-telescopes are as follows; the center directions of viewing of the inclined telescopes, N-and S-telescopes (also E and W-telescopes) are inclined at the angle of ~34° to the vertical (with angular resolution of ~±20° in latitude λ_{cd} and

Table 3 The present coincidence system at Matsushiro

Component telescope	Coincidence-system	Number of sub-telescope
V	= (U1×L1) + (U2×L2) + (U3×L3) + (U4×L4) + (U5×L5) + ………………………	(25)
N	= (U1×L6) + (U2×L7) + (U3×L8) + (U4×L9) + (U5×L10) + ……………………	(20)
S	= (U6×L1) + (U7×L2) + (U8×L3) + (U9×L4) + (U10×L5) + ………………………	(20)
E	= (U2×L1) + (U7×L6) + (U12×L11) + (U17×L16) + (U22×L21) + ……………	(20)
W	= (U1×L2) + (U6×L7) + (U11×L12) + (U16×L17) + (U21×L22) + ……………	(20)
NE	= (U2×L6) + (U3×L7) + (U4×L8) + (U5×L9) + ……………………………………	(16)
SE	= (U7×L1) + (U8×L2) + (U9×L3) + (U10×L4) + …………………………………	(16)
NW	= (U1×L7) + (U2×L8) + (U3×L9) + (U4×L10) + …………………………………	(16)
SW	= (U6×L2) + (U7×L3) + (U8×L4) + (U9×L5) + …………………………………	(16)
NN	= (U1× (L11+L12+L13+L14+L15)) + (U2× (L11+L12+L13+L14+L15)) +…	(15)
SS	= (U11× (L1+L2+L3+L4+L5)) + (U12× (L1+L2+L3+L4+L5)) +……………	(15)
EE	= (U3× (L1+L6+L11+L16+L21)) + (U8× (L1+L6+L11+L16+L21)) +………	(15)
WW	= (U1× (L3+L8+L13+L18+L23)) + (U6× (L3+L8+L13+L18+L23)) +………	(15)
N3	= (U1× (L16+L17+L18+L19+L20)) + (U2× (L16+L17+L13+L19+L20)) +…	(10)
S3	= (U16× (L1+L2+L3+L4+L5)) + (U12× (L1+L2+L3+L4+L5)) +……………	(10)
E3	= (U4× (L1+L6+L11+L16+L21)) + (U9× (L1+L6+L11+L16+L21)) +………	(10)
W3	= (U1× (L4+L9+L14+L19+L24)) + (U6× (L4+L9+L14+L19+L24)) +………	(10)
WV	= US×LS	
US	= (U1+U2+U3+………+U24+U25)	
LS	= (L1+L2+L3+………L24+L25)	

For numbering the detectors, see Fig. 11.
× denotes coincidence and + denotes mixing of the pulses.

~±45° in azimuth φ_{cd}). More inclined SS-telescope (also NN-, EE-, and WW-telescopes) are inclined at ~53° (with angular resolution ~±10° in λ_{cd} and ~±68° in φ_{cd}), and most inclined S3-telescope (also N3-, E3- and W3-telescopes) are inclined at ~63° (with angular resolution ~±10° in λ_{cd} and ~±59° in φ_{cd}), respectively, Four more component-telescopes are also constructed, which are pointing towards the intermediate directions between N-, S-, E- and W-telescopes and inclined at ~40° to the vertical with angular resolution ~±20° in λ_{cd} and ~±45° in φ_{cd} (abbreviated to NE-, NW-, SE-, SW-telescopes).

Figure 13 illustrates the so-called high-voltage (HV-) characteristics; the output counting rates vs. high-volatge applied to PMs, for some of the component-telescopes; V-telescope, mixed countings in the upper (US) and the lower detector arrays (LS), and also the wide-vertical telescope (WV; two-fold

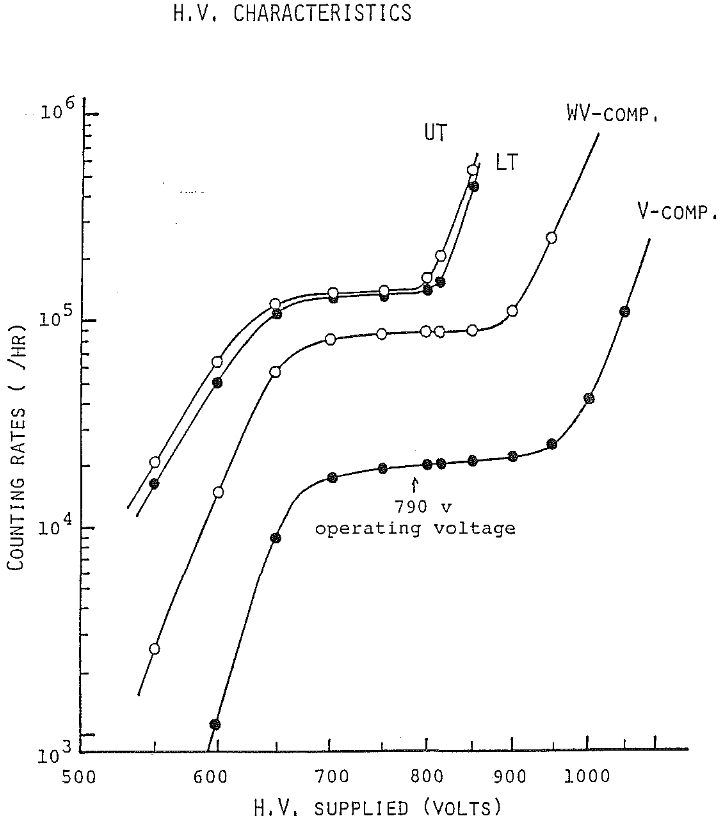


Figure 13 High-voltage characteristics (recorded counts vs. HV applied to PMs), for some component-telescopes; V-, WV-telescopes and US and LS.

coincidence between US and LS). Note again here that in the present system, the above US and LS themselves are the resultant outputs of two-fold coincidence and also the 17 component-telescopes are the resultant outputs of four-fold coincidence, thus accidental coincidence rates are very rare and negligible. In Fig. 13 we can clearly recognize a wide plateau region in the recorded counting-rates ranging approximately 200 volts or so. We have finally operated the detectors with a common high-voltage at 790 volts, with a further fine adjusted-voltage to each of 100 PMs through resistance-network of HV-distributor (see Fig. 10). As mentioned earlier, with an aid of the present improved detection system of 'double PMs' we have succeeded in obtaining much improved HV-characteristcs of the detectors and of the telescopes even in the deep underground, which may ensure the present continuous observations stable and reliable.

Figure 14 plots the asymptotic orbits of the 17 component-telescopes calculated for the primary particle energies of 250, 350, 450, and 750 Gev (INOUE, personal communication, 1985). As can be seen in the figure, the present multi-directional telescope may scan the celestial space from ~80° N to ~20° S in latitude and~130° wide in longitude. Among the 17 component-telescopes, three north-pointing telescopes; N-, NN-, and N3-telescopes, can view in the directions which are almost parallel to the Earth's spin axis, while three south-pointing telescopes; S-, SS-, and S3-telescopes can view the equatorial plane

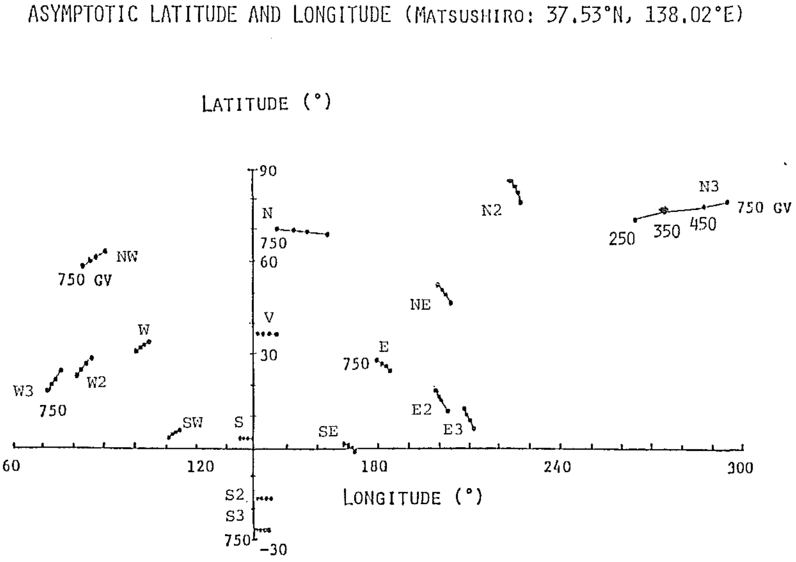


Figure 14 The asymptotic orbits for the 17 component-telescopes, calculated for primary energies of 250, 350, 45, and 750 GeV.

or rather southern latitude regions (~20°S). Such a wide scanning ability and the present multi-channels of observation and also with its relatively high energies of detection (as described below) may be the merits of the present muon telescope at Matsushiro as emphasized in Introduction. In Table 4 we summarize some of the characteristics of the 17 component-telescopes; the center directions of viewing (in geographical latitude and longitude), averaged hourly counting-rates, and median primary energies of detection (Mori et al., 1984, 1985, 1987).

Figure 15 shows the so-called integral response functions for some of the component-telescopes; V-telescope (in shallower depth among the 17 component-telescopes), S-, SS- and S3-telescopes (in deeper depth among the 17 telescopes). The calculations have been made by referring to the table of the response functions prepared by Murakami et al. (1979) and by taking into account rather realistic shape of the overburden (Mt. Zohzan) of each directional telescope (Imaizumi, 1988). As is summarized in Table 4 and shown in Fig. 15, the median primary energies of detection of the present component-telescopes lie in the range of $6 \cdot 10^{11}$~$1.3\ 10^{12}$ eV, and the corresponding Lamor radii are 3~5 AU for ~5nT of the magnetic field strength around the Earth's orbit and ~50 AU around the Saturn's orbit.

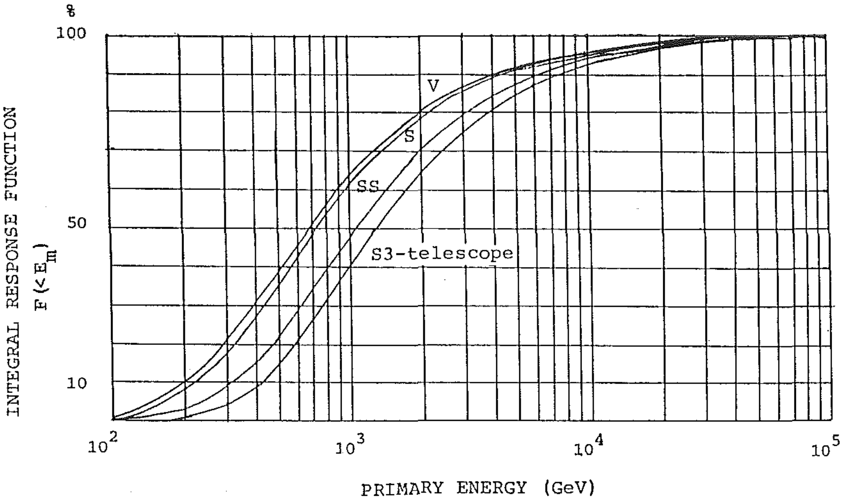


Figure 15 The integral response functions giving the percentage of the countrate $F(<E_m)$ due to primaries of energies E_m for some of component-telescopes; V-, S-, SS- and S3-telescopes, for example.

Observational Data of Cosmic Ray Muons

We started the observations on March 22, 1984, and have continued them since that date, whose duty operation time-rate (complete days/total days in operation) is as high as 95%. We have recorded real counts of the muons on an hourly basis on paper tape, (and now in preparation on other recording mediums, such as magnetic tape and floppy disk), for the 17 component-telescopes as well as for the WV-telescope and the upper (US) and lower (LS) arrays, whose hourly countings are tabulated in Table 4. At persent we are also in preparation of the data-sendings and the electronics monitoring by means of the remote-sensing with micro-computer and public telephone system between the remote observatory (~40 km in distance) and our laboratory in Matsumoto, a full system of which has been in operation between the older Matsushiro and Matsumoto (YASUE et al., 1979). In the followings, we will show some of

Table 4 Characteristics of 17 component-telescopes of multi-directional muon telescope of Matsushiro underground observatory

Comp.	λ_{cd}(°)	ϕ_{cd}(°)	n($\times 10^4$/h)	E_{mp}(GeV)	D_{eff}(m. w. e)
V	36.5	140.6	20.0	660	214
N	70.8	146.9	9.2	710	230
S	3.4	134.1	7.4	730	240
E	28.1	174.6	9.6	770	255
W	31.3	100.5	10.6	630	200
NE	52.7	199.5	4.7	700	228
NW	58.0	82.6	6.5	640	208
SE	1.5	168.7	4.5	730	240
SW	3.5	110.6	5.6	660	216
NN	86.2	223.6	6.0	870	265
SS	−16.7	139.6	3.8	1050	328
EE	18.5	198.6	5.1	720	235
WW	27.4	80.9	4.3	660	216
N 3	79.1	294.5	1.6	980	320
S 3	−26.9	139.7	0.9	1300	410
E 3	12.6	207.7	1.7	770	255
W 3	18.4	71.6	2.4	710	230
WV	—	—	87.5	660	214
US	—	—	141.3	660	214
LS	—	—	138.0	660	214

λ_{cd} and ϕ_{cd}, asymptotic latitude and longitude in geographic coordinate system of center direction for 750 GeV; n, counting rate (as to January, 1986); E_{mp}, effective median primary energy (GeV); D_{eff} (m. w. e.), effective depth.

the observed intensity variations of cosmic ray muons and its analyzed results, on the basis of the hourly data without any correction for the meteorological effects of both the barometric pressure and the atmospheric temperature.

1. *Observed intensity variations of cosmic ray muons*

As is well known the observed intensities of cosmic ray muons at the ground and underground are affected not only by the primary cosmic rays themselves in free-space but also by the atmospheric effects through its production and propagation processes in the atmosphere. In addition to the above, the recorded intensity variations may further be contaminated with some unknown effects such as those of the instrumental, of background radiations, etc. Figure 16 shows the example of the observed intensity variations of muons, showing its monthly averages for WV-telescope, for example, during the period from April 1984 through July 1989. In the figure, first we can find a gradual decreasing trend in the intensity with a rate of approximately 0.3% per year. Such decreasing may be largely due to decreasing detection efficiency of the PMs used. Superposed on it, we can also find a trend of the semi-annual intensity variations, that is, there would be two peaks in a year; one peak locates at around mid-summer (June-July) and the other at around mid-winter (December-January). The present semi-annual variation may be an identical phenomenon to that already observed at the older Matsushiro underground by our group (YASUE et al., 1981). These semi-annual variations may be of atmospheric origin, and in order to understand the atmospheric effects on the intensity variations of muons, here we summarize in brief the basic idea developed by one of the present authors (SAGISAKA, 1986; references therein). The observed

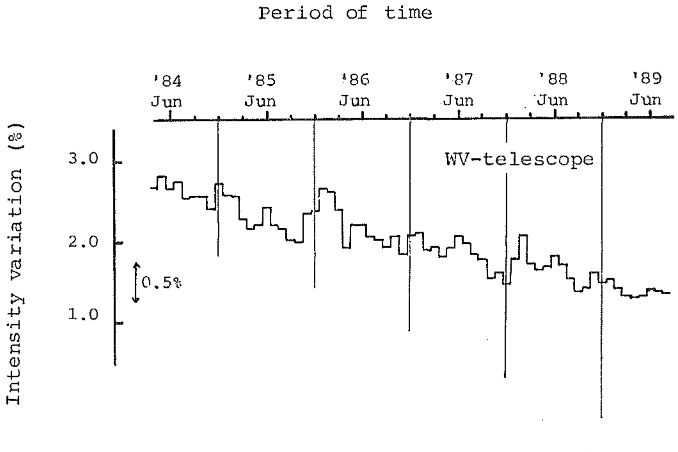


Figure 16 The monthly averaged intensity variations of WV- for the period April 1984 through July 1989, for example..

intensity variation (ΔI_{atm}) may be produced by at least two types of atmospheric variations; one is due to the barometric variations (ΔI_P) and the other to the atmospheric temperature variations (ΔI_T), and these are formulated as

$$\Delta I_{atm} = \Delta I_P + \Delta I_T \tag{1}$$

where $\Delta I_P = \beta \cdot \Delta P$

and
$$\Delta I_T = \int_o^{xo} \alpha(x) \cdot \Delta T(x) dx \tag{2}$$

In the above Eqs. β denotes the barometric coefficient, $\alpha(x)$ is the partial temperature coefficient at x (gr/cm^2) from the top of the atmosphere and $\Delta\mathrm{T}(x)$ the hourly deviations of the atmospheric temperature. On the basis of the data $\Delta\mathrm{T}(x)$ of direct temperature soundings (routinely four times a day at the meteorological stations in Japan), we can make a computation of Eq. (2) and can apply them to the atmospheric effects on the observing muons. SAGISAKA (1986) has made an extensive calculation of the partial temperature coefficients of muons for various situations; rock depths, muon threshold energies, and incident directions (see text in detail). With the computed results and the meteorological data, he has given a satisfactory explanation of the observed semi-annual variation of muon intensities at the older Matsushiro underground observatory. Figure 17 illustrates an example of the present analyses along SAGISAKA's manner, showing a comparison between the observed and the theoretically calculated variations for WV-telescope (KAJIYA, 1988). In the figure those variations are plotted in a relative form (in %) on a monthly basis, normalized

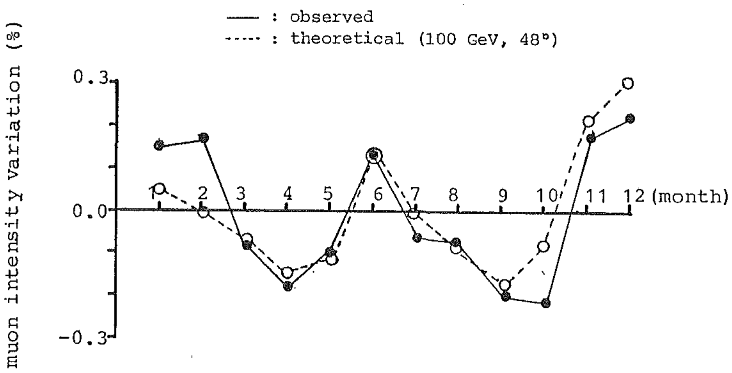


Figure 17 A comparison between the observed intensity variations (connected with the solid line) and the theoretically calculated variations (with the dotted line) of muons for WV-telescope, plotted on a monthly basis for the year 1985.

on June, for the year 1985; the observed variations are connected with the solid line and the calculated with the dotted line, whose calculations are tentatively made for primaries incident by 48° in zenith and with muon threshold energy of 100 GeV. In the figure we can find a fairly satisfactory agreement between the two variations. We can summarize here that as discussed by SAGISAKA such a semi-annual variation may be one of the characteristic features of the observed intensity variations of high energy muons at the deep underground (>100 m. w. e. depth), and that this can be satisfactorily explained in terms of the upper atmopsheric temperature effect on the observing muons.

2. *Barometric effect on muon intensity variation*

We have also examined the baromeric effect on the observed muon intensity variations at Matsushiro, based on Eqs. (1) and (2). Figure 18 gives an example of comparisons between the observed and the theoretically calculated barometric coefficients for WV-telescope for the year 1985 (KAJIYA, 1988). The calculated coefficients are obtained by taking into account two terms; one is the term from the partial temperature coefficient and the other from the so-called barometric coefficient. By combining these two terms and the meteorological data, the calculated coefficients can be finally obtained. In Fig. 18 the observed coefficients are connected with the solid line and the theoretical ones with the dotted line, on a monthly basis for the year 1985. We can find a fair agreement with each other (and the yearly average of the observed coefficient $\beta = -0.020 \pm$

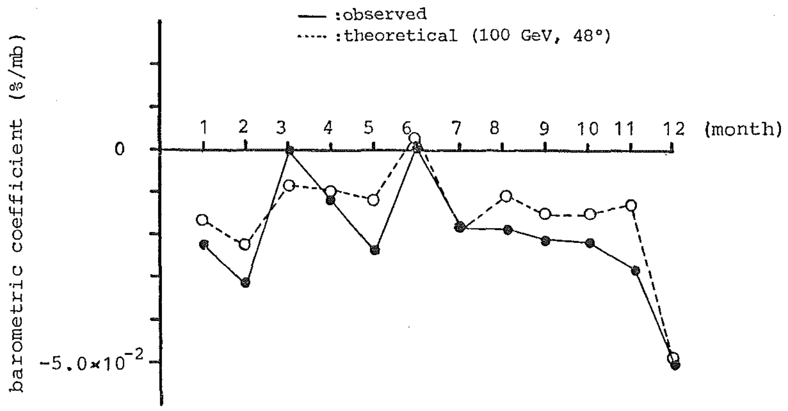


Figure 18 A comparison between the observed barometric coefficents (connected with the solid line) and the theoretically estimated coefficients (with the dotted line) for WV-telescope, plotted on a monthly basis for the year 1985.

0.004%/mb in 1985). The present result may be consistent with those characteristics of anomalously large coefficients ($\beta \sim -0.05\%$/mb) obtained by the older Matsushiro (YASUE et al., 1981) and by Poatina in Australia (365 m.w.e. depth) (FENTON et al., 1979). We may summarize here that the barometric effects on the muon intensity variations can be well explained in two terms of the apparent temperature effect in the upper atmosphere and the so-called barometric effect, as discussed by SAGISAKA (1986).

We have further analyzed the atmospheric temperature effect on the observed solar diurnal intensity variations of cosmic ray muons at the deep underground, Matsushiro, some of which have already been discussed by our group (MORI et al., 1988). Here we present a brief summary of their analysis and show the resultant temperature effect vectors of the daily variations of muons in the high energy regions $\lesssim 10^{12}$ eV. They have examined the temperature effect on an assumption that the observed solar diurnal variations may be produced with at least two kinds of the effect; one is the effect by the cosmic ray anisotropies themselves including the so-called COMPTON-GETTING effect and the other is the atmospheric temperature effect. First the solar diurnal an-

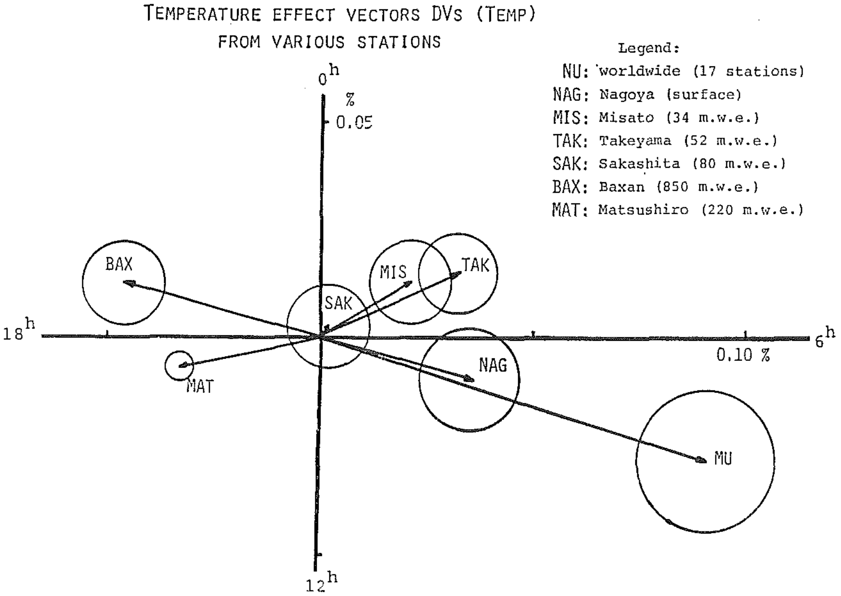


Figure 19 The atmospheric temperature vectors at Matsushiro, together with those from the underground stations at Baxan (850 m.w.e. depth), Sakashita (80 m.w.e. depth), Takeyama (54 m.w.e. depth), and Misato (34 m.w.e. depth) and the surface stations at Nagoya and at the worldwide location, reproduced from Mori et al. (1988).

isotropy has been determined, and obtained as ~0.35% in ~18 hr LT direction, after correcting for the COMPTON-GETTING effect. The temperature vectors are then derived for the 17 component-telescopes at Matsushiro, and those vectors are reproduced in Fig. 19, together with those in both lower energy regions and higher energy regions. We can well recognize that in the high energy regions ($>6 \cdot 10^{11}$ eV) the results from Matsushiro ($\gtrsim 6 \cdot 10^{11}$ eV) and Baxan (850 m.w.e. depth and $\gtrsim 2 \cdot 10^{12}$ eV; ANDREYEV et al., 1987) are in good agreement with each other, being directed towards the evening time (~20 hr LT). On the contrary, the corresponding vectors in the lower energy regions ($\gtrsim 3 \cdot 10^{11}$ eV) from the shallower underground stations are directed towards the morning time (~7 h LT). At the present stage we may summarize that the temperature vectors in the low and high energy regions may be different from each other and of reversed characters. Both of them, however, could not be fully understood in terms of the temperature effect only, but may be rather owed by the residuals of the barometric effect (NAGASHIMA, personal communication, 1989).

3. *Daily intensity variations of cosmic ray muons*

Figures 20 (a) and (b) show the observed daily intensity variations of cosmic ray muons by the present 17 component-telescopes, averaged over a full five-year period 1984–1989, plotted in the time-coordinate systems of the solar time (SO), the sidereal time (SI) and the anti-sidereal time (AS), respectively. In the figure the statistical error σ of the counting-rates is given for each component-telescope. In comparison we also plot the best-fitted curves to the above observed variations in Figs. 21 (a) and 21 (b), which are constructed with the first (1st) and the second (2nd) harmonic terms, some of which will be referred to later. In the figure also counting-rates error σ is given for each component-telescope.

Figure 22 shows the 1st and the 2nd harmonic vectors of the above daily variations in the solar time (SO), the sidereal time (SI), and the anti-sidereal time (AS), for the 17 component-telescopes. These vectors are averaged over a full five-year period of 1984–1989, but are left uncorrected for any spurious effects such as the meteorological effects of the barometric pressure and the atmospheric temperature. The statistical errors are derived from dispersion of yearly vectors. In what follows, we will present a pereliminary result of each daily intensity variation in solar (SO) time and in sidereal (SI) and anti-sidereal (AS) times, and the results of the detailed analysis of them will be reported in the near future.

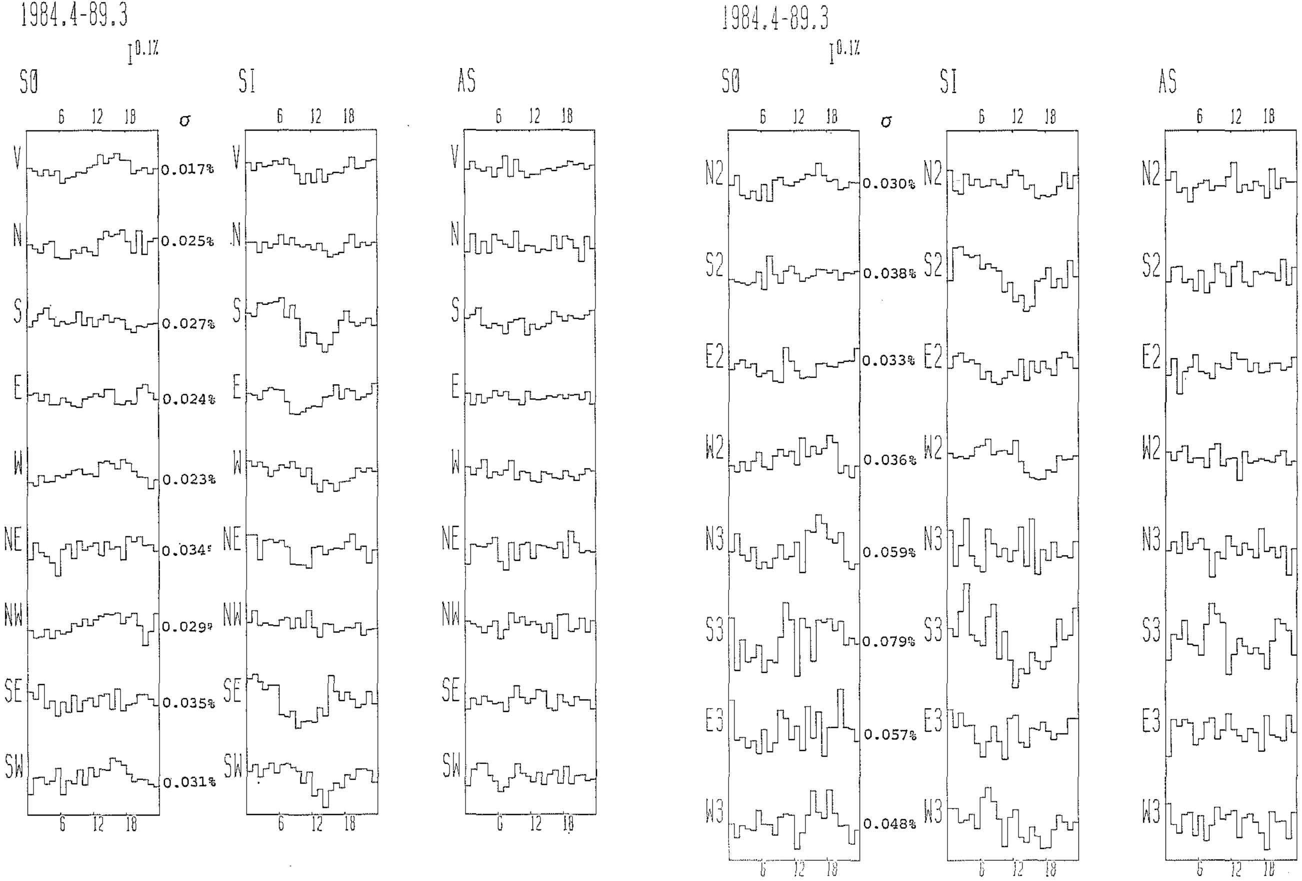


Figure 20 The observed daily intensity variations of cosmic ray muons of the 17 component-telescopes at Matsushiro, averaged over five-year period 1984–1989, and plotted in solar (SO), sidereal (SI), and anti-sidereal times (AS), respectively. Counting-rate error (σ) is given for each component-telescope.

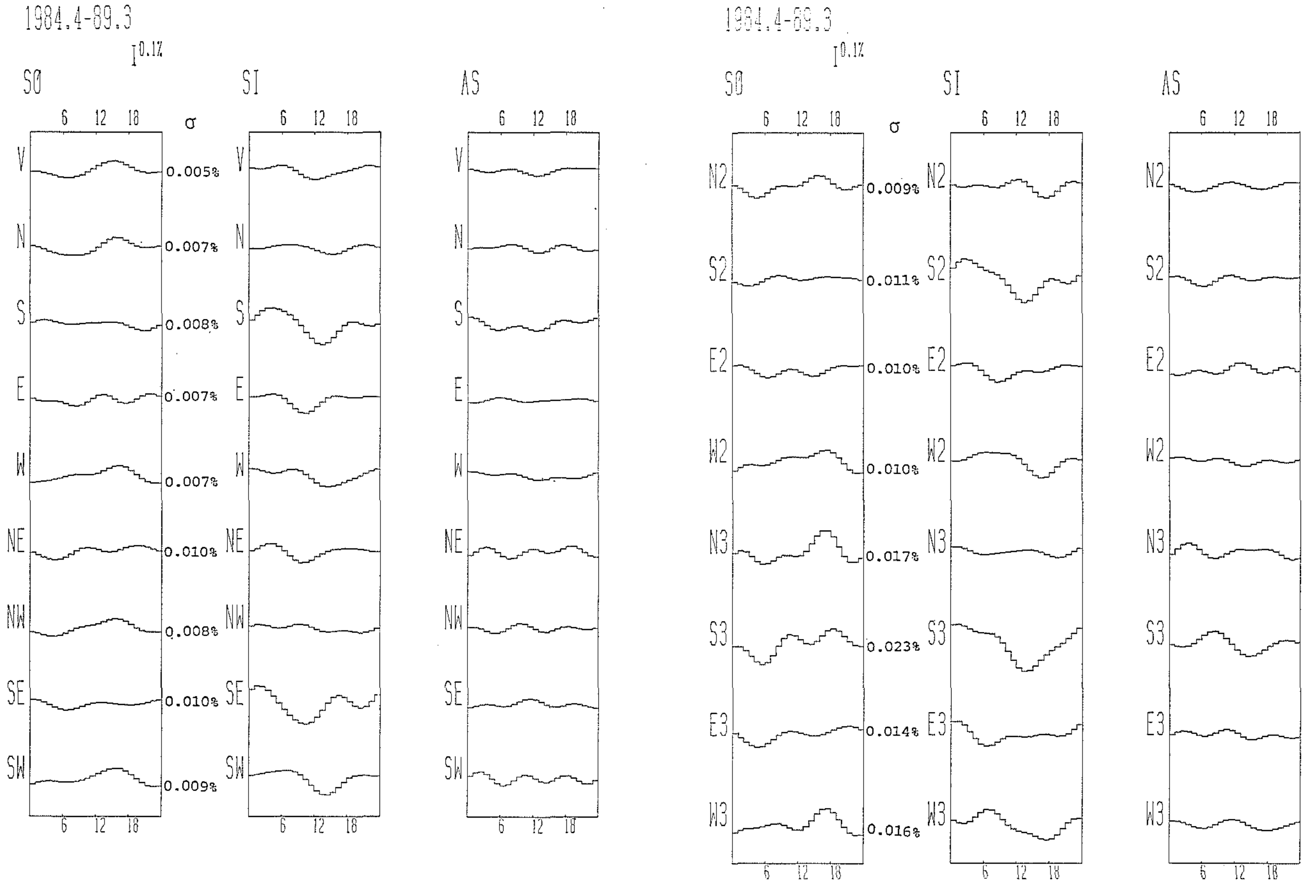


Figure 21 The Best-fitted curves to the above intensity variations of each component-telescope in Fig. 20, constructed with the 1st and the 2nd harmonic terms. Counting-rate error (σ) is given for each component-telescope.

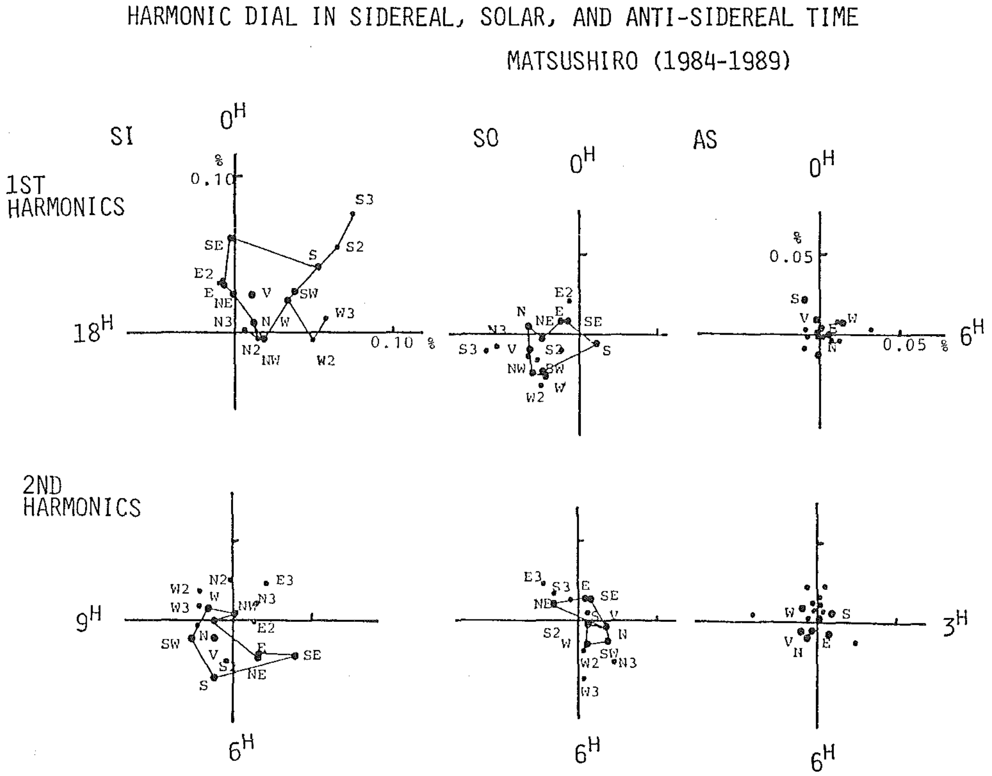


Figure 22 The five-year averages over 1984–1989, of the 1st and 2nd harmonic vectors of the daily intensity variations at Matsushiro in Fig. 21, plotted in sidereal (SI), solar (SO) and anti-sidereal (AS) times, resspectively. For AS, only five component-telescopes (V–, N–, S–, E–, W–telescopes) are indicated to avoid confusion.

3.1 *Solar daily variation of cosmic ray muons*

As mentioned earlier, our group (MORI et al., 1988) have already discussed some of the solar diurnal variations and its atmospheric temperature effect for the period 1984-1987. Figure 23 reproduces an example of the observed solar diurnal variations (after correcting for the COMPTON-GETTING effect) at Matsushiro, together with some others in the lower energy regions at the ground (Nagoya) and the underground stations (Misato; 34 m. w. e. depth and Takeyama; 54 m. w. e. depth). In the figure it seems highly likely that a common, significant anisotropy responsible for the observed variations exists in free-space for the period 1984-1985. The analysis by means of a method of best-fitting with the difference between the directional vectors of V–, N–, S–telescopes, etc., has shown that the solar diurnal anisotropy has such characteristics that the amplitude is approximately 0.35% in around 18 hr LT direction in free-space.

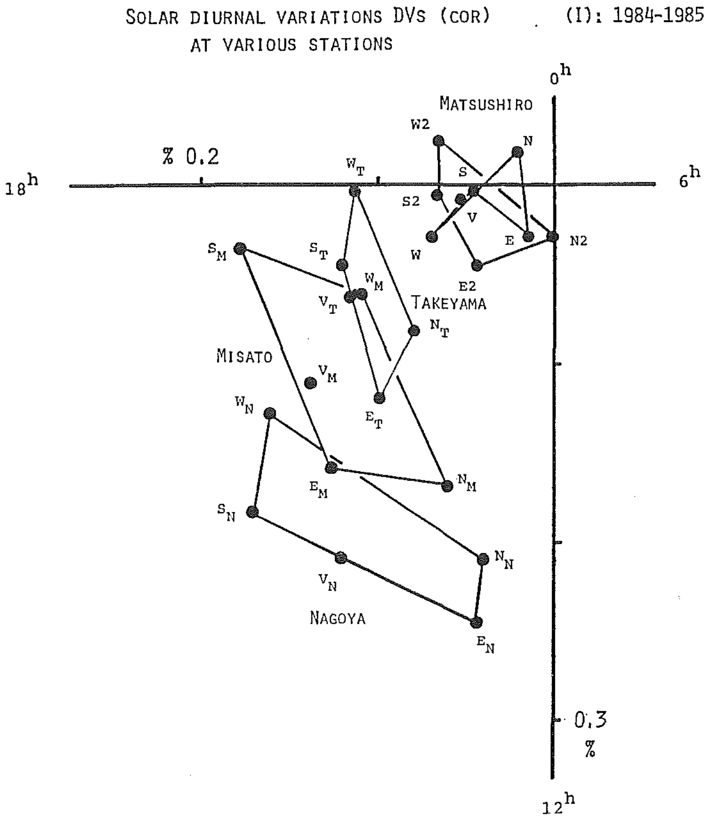


Figure 23 The observed solar diurnal vectors of some of the 17 component-telescopes at Matsushiro, together with those at Nagoya (surface), Misato and Takeyama (underground) for the year 1984-1985, reproduced from Mori et al. (1988).

This result may be consistent with those so far obtained in the lower energy regions ($<5 \cdot 10^{11}$ eV), with a rather higher cut-off (~300 GeV) of solar modulation during the last declining period of solar activity (UENO et al., 1985; NAGASHIMA et al., 1987; KUDO et al., 1987). Note that the solar daily variations at Matsushiro have certainly decreased and diminished during the following years of solar activity minimum (1986-1987).

It may be interesting to mention about another result analyzed by means of the power spectral analysis of the intensity variation at Matsushiro (YASUTANI, 1989). Figure 24 shows the power spectral density calculated for WV-telescope for the frequency range 10^{-7}—10^{-4} Hz (in a period of 1 hr to 40 days). The three-year (1985-1987) average is plotted, together with that at the Misato underground (34 m. w. e. depth; MORI et al., 1976). In the figure the power

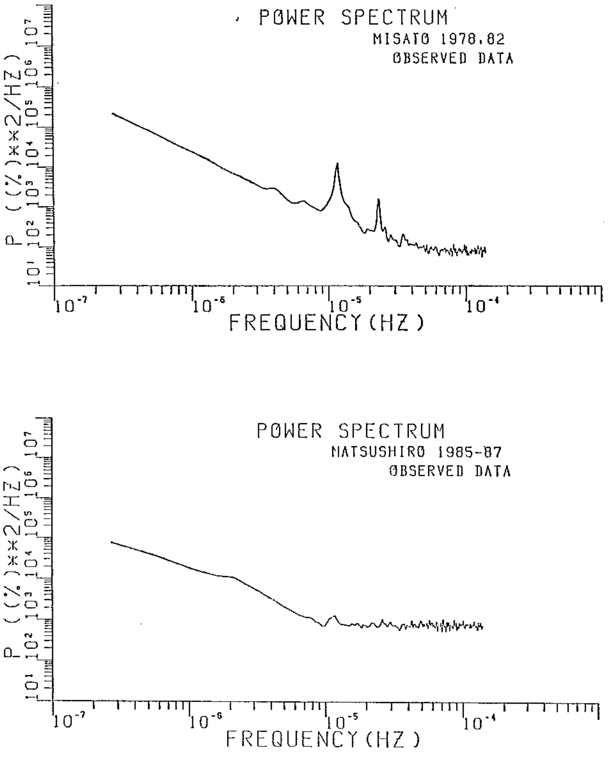


Figure 24 The averaged power spectral densities over 1985–1987 of WV-telescope at Matsushiro, together with that at Misato for 1978 and 1982.

density at the flat level may correspond to that expected from the counting-rates (white noises), indicating that the present observations at Matsushiro have been well operated for those periods of time in a statistical point of view. Detailed analysis of the observed intensity veriations of muons at the underground as well as those of the nucleonic components, have been going on by our gruop (YASUE, personal communication, 1989), and will be published elsewhere.

Figures 25 illustrates a summation dial showing year-to-year variation of the observed solar semi-diurnal vectors at Matsushiro for the periods 1984 through 1989. In the figure the statistical errors for each component-telescope are derived from counting-rates. Figure 26 shows its five-year averages over 1984-1989. The statistical significance may be rather less but the present results of its ~3 hr LT phases are in accordance with those well established in the lower energy regions (MORISHITA et al., 1984).

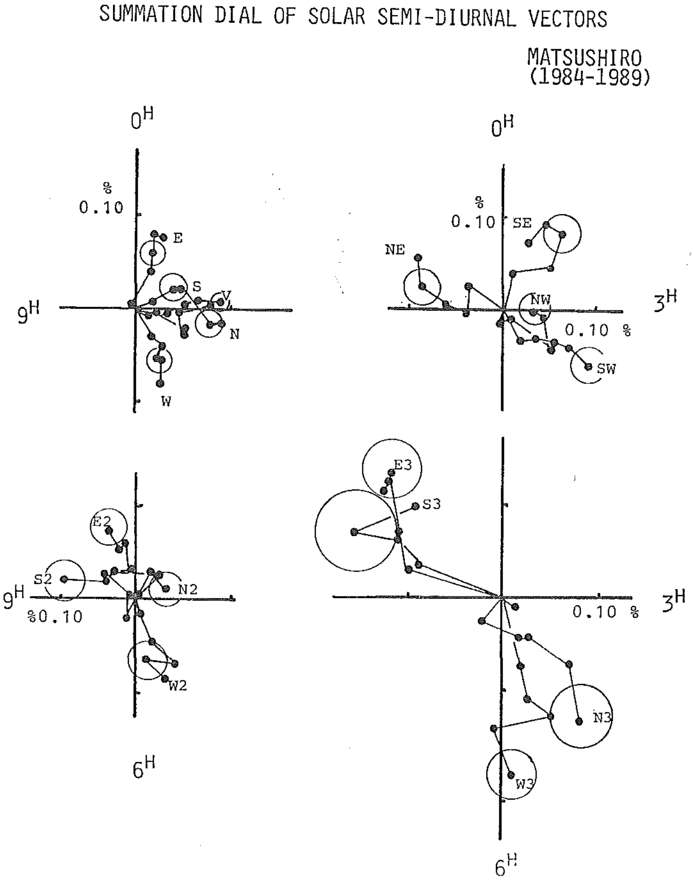


Figure 25 A summation dial showing year-to-year variations of the observed solar semi-diurnal variations of the 17 component-telescopes at Matsushiro for the period 1984 through 1989. Statistical errors are derived from the counting-rates.

3.2 *Sidereal daily variations of cosmic ray muons*

Figures 27 shows the same summation dial as that in Fig. 25 but for the observed sidereal diurnal vectors of the 17 component-telescopes at Matsushiro during the period 1984 through 1989. In the figure the statistical errors are derived from counting-rates. In this figure we can well recognize that the observed diurnal vectors are statistically significant and persistent over years. Figures 28 shows its five-year averages, whose errors are derived from dispersion of yearly averages. In the figure we can find that the present observed vectors may be reasonable and reliable on the basis of their mutual consistency of the phase configuration for the directional telescopes. Among

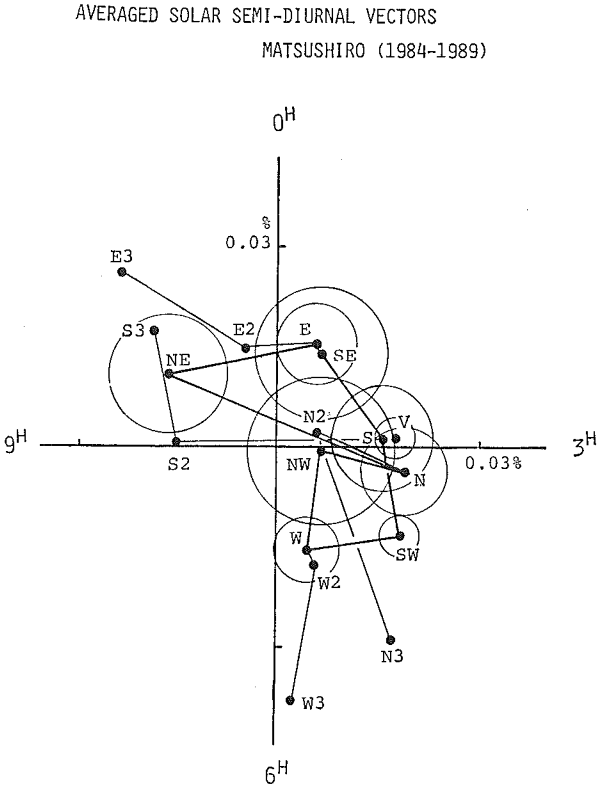


Figure 26 The five-year averages of the observed solar semi-diurnal vectors over the period 1984–1989. Statistical errors are derived from dispersion of yearly averages.

the 17 vectors the phases of the east-pointing telescopes (E-, EE-, and E3-telescopes, for example) locates in the earlier directions, while the phases of the west-pointing telescopes (W-, WW-, and W3-telescopes, for example) in the later directions, and the south-pointing telescopes (S-, SS-, and S3-telescopes) and V-telescope are in the intermediate phases within statistical errors. Such comparison may be one of the merits of the multi-diretional measurement for confirming the reliability of the observed results. In Fig. 28 we can also find that the observed amplitudes by the three north-pointing telescopes (N-, NN-, N3-telescopes) are small (0. 01~0. 02%) and not statistically significant. This is reasonably expectable on the basis of their directions of viewing (70°~80° N), which are almost parallel to the Earth's spin axis. From this it seems highly likely that the spurios effects such as those of atmospheric

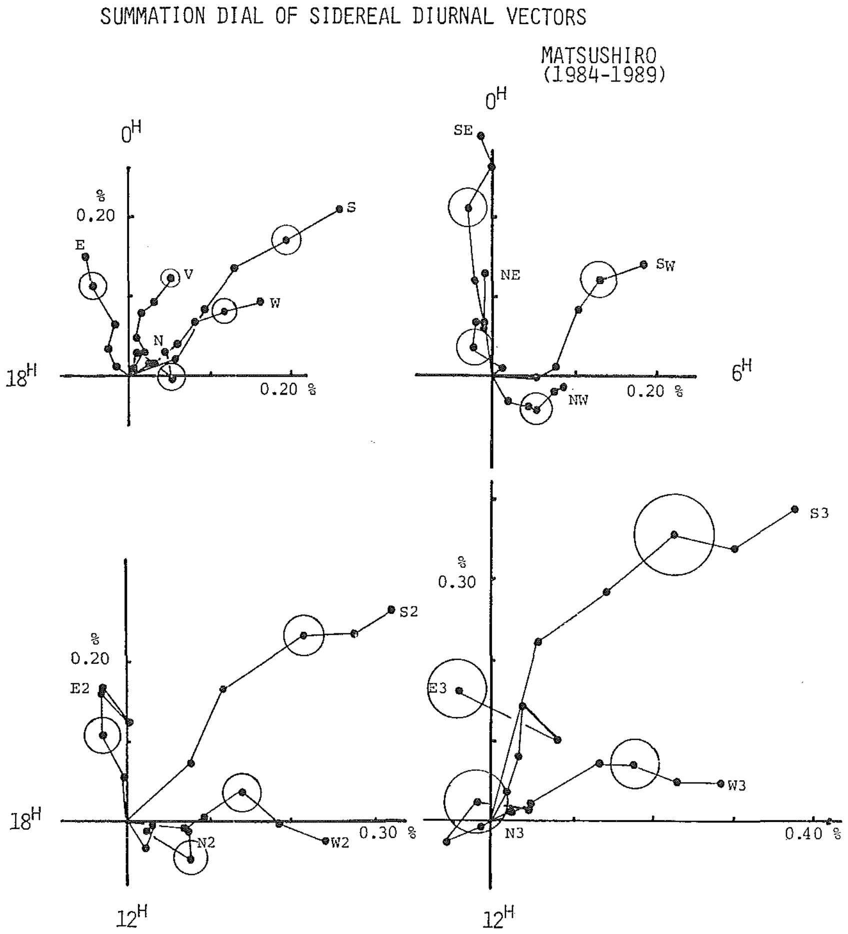


Figure 27 The same summation dial but for the observed sidereal diurnal vectors of the 17 component-telescopes at Matsushiro for the period 1984–1989. Statistical errors are derived from the counting-rates.

origin and of other environmental and instrumental causes, may be small and insignificant to the present observations. We can positively draw a conclusion that the observed sidereal diurnal vectors of all the component-telescopes are free from the contribution of atmospheric origin, because the above spurious effects, if exists, may be common to all. We can further note that the observed anti-sidereal diurnal vectors are small (0.02% or less) for all the component-telescopes as shown in Fig. 22, and this may be consistent with the above argument and also with the present significant sidereal diurnal vectors.

We have tentatively determined the direction of the observed sidereal diurnal

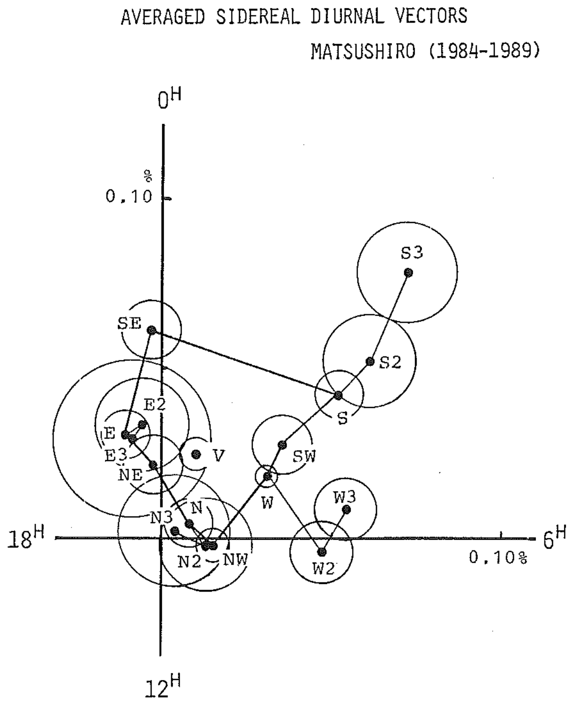


Figure 28
The five-year averages of the observed sidereal diurnal vectors of the 17 component-telescopes over the period 1984–1989. Statistical errors are derived from the dispersion of yearly averages.

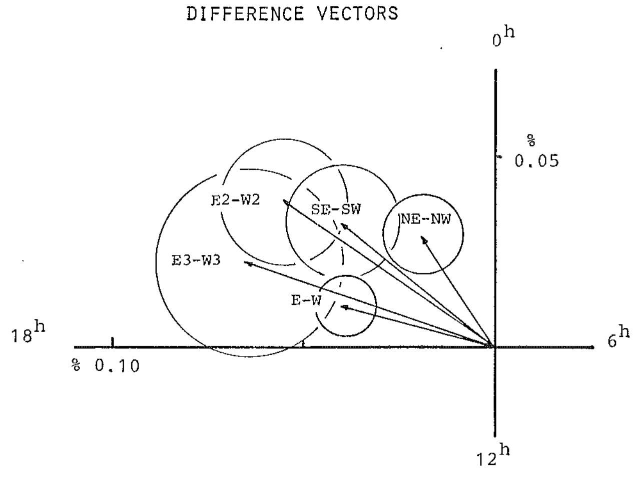
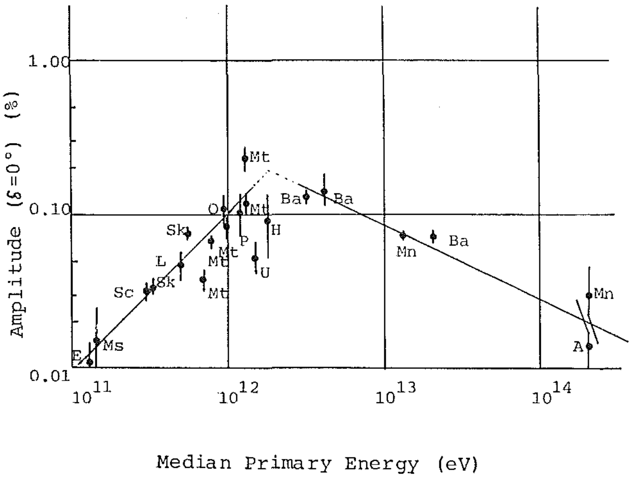


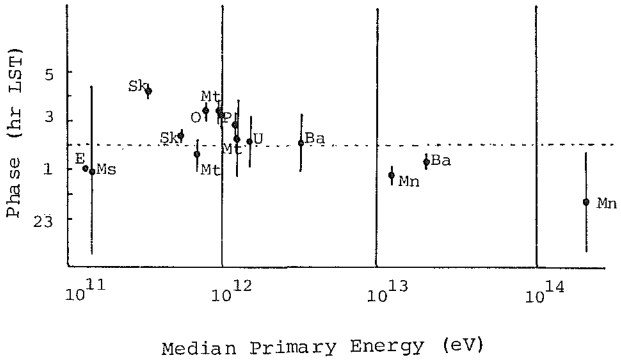
Figure 29 The difference vectors of the observed sidereal diurnal variations between five pairs of the east-associated and the west-associated telescopes at Matsushiro. The statistical errors are derived from the dispersion.

vectors by means of a method of difference between appropriate pairs in the 17 component-telescopes. Figure 29 shows the difference vectors thus derived for five pairs between the east-pointing telescopes (E–, EE–, and E3-telescopes, NE– and SE– telescopes) and the west-pointing telescopes (W–, WW–, and W3-telescopes, NW– and SW–telescopes). In the figure we can see that all the differences lie in almost the same direction around 19 hr LST within errors, which may be certainly free from the atmospheric effects. By rotating the vectors by 90°, we obtain the average direction as 2.2±0.3 hr LST, which is in coincidence with those of the present V–, S–, SS– and S3–telescopes within statistical errors (see Fig. 28). We can also note that the present phase of 2.2 hr may also be in coincidence with those at the similar energies above 500 GeV; the older Matsushiro (YASUE et al., 1985) and the south-pointing (SS–) telescope at Sakashita (UENO et al., 1985).

In Fig. 30, we tentatively plot; (a) the observed diurnal amplitudes and (b) the observed phases, as functions of median primary energies of detection for 10^{11} eV to 10^{14} eV from various underground stations and air-shower measurements. Note that the data periods are different from each other, and the statistical errors are their own. The quoted vectors in the lower energy regions ($<5 \cdot 10^{11}$ eV) are corrected by means of NAGASHIMA method (1984). In the figure the projected amplitudes onto the equatorial plane are shown, divided by $\cos\delta$ (δ denotes the viewing latitude of each telescope and apparatus) (ALEXEENKO et al., 1981; BERCOVITCH and AGRAWAL, 1981; CUTLER et al., 1981; DAVIES et al., 1979; FENTON and FENTON, 1975; GOMBOSI et al., 1975; HUMBLE et al., 1984; KOTA, 1985; LEE and NG, 1987; SAKAKIBARA et al., 1984; SPELLER et al.,



(a)



(b)

Figure 30 (a) The observed diurnal amplitudes projected onto the equatorial plane ($\delta=0$) and (b) the observed phases, as functions of median primary energies, from various underground stations and by air-shower measurements, including the present results at Matsushiro. The data periods are different from each other, and the statistical errors are taken from their own.

1972; UENO et al., 1985; MURAKAMI, personal communication, 1989). In the figure we may find some energy dependent nature of both the amplitudes and phases. First, we can note that the amplitudes range from 0.02% to 0.10% or more; the former corresponds to the energy ~100 GeV at the shallower underground (Embudo and Misato, for example), and the latter correspond to the energy ~1000 GeV at the deep underground (Matsushiro, for example). Such an energy dependent nature, particularly in the lower energy regions, $<10^{12}$ eV, might represent the so-called lower energy cut-offs, which would result from severe modifications by the heliomagnetosphere (NAGASHIMA et al., 1982, 1983a). It may be interesting to note here that the greater amplitudes have been observed by the south-pointing telescopes, S-, SS- and S3-telescopes at Matsushiro, in particular, S3-telescope showing its amplitudes of 0.11~0.20% in ~2 hr LST phase, whose asymptotic directions of viewing are around 20°S. That might not be far from understandable but rather consistent with the negatively decreasing spectrum proposed by NAGASHIMA et al. (1989) mentioned earlier. A precise detemination of the spectrum may be most important for exploring the nature of the sidereal anisotropy of galactic origin, for which a further observation and detailed analysis will be required. Secondly, the phases may also depend on energies of detection (KOTA, 1985); the earlier phase of ~1 hr LST for air-shower measurements (represented by AS in Fig. 30), the later phase of~5 hr LST for the lower energies and the intermediate of 2~3 hr LST for the intermediate energies of detection including the present.

We can point out another interesting observed fact from Fig. 30 (and also Figs. 27 and 28) that the present V-telescope at Matsushiro seems likely to be rather smaller than those of other directional telescopes, the south-pointing telescopes, for example. This tendency may be seen in those observed results by V-telescopes at the older Matsushiro (YASUE et al., 1985), at Sakashita (UENO et al., 1985) and at Utah (CUTLER et al., 1981). In the present observation, the fact of less than one-half amplitude of V-telescope relative to S-, SS-, and S3- telescopes may not be explained by merely considering each viewing latitude; a factor of ~ 1.2 $(=1/cos\ 36.5^{\circ})$ difference at most. This may suggest that the above facts would not be necessarily due to the energies of detection, but be due partly to the nature of the anisotropy itself, one of which constituents may be of the north-south (N-S) asymmetric nature. From this point of view, UENO et al. (1981, 1983, 1985) have analyzed the observed results in the lower energy regions (Nagoya Misato, and Sakashita) in terms of two-way anoisotropy (JACKLYN, 1970); one is of the N-S symmteric type and the other of the N-S asymmetric type. They have succeeded in separating each contribution in the observed sidereal variations, to some extent, and have discussed the N-S asymmteric term in the sidereal signal. Their analysis in the energy region $<5 \cdot 10^{11}$ eV, however, may be still lacking the consideration about predominant modifications by the heliomagnetosphere to discuss the sidereal anisotropy of galactic origin. The model of the anisotropy; of one-way, two-way or more may also be another target to be explored in the near future.

The analysis concerning 'toward-away' field dependent sidereal daily variations may provide important information about modulation of the sidereal anisotropy in the heliosphere as comprehensively predicted by NAGASHIMA and MORISHITA (1983). As has been well known for some times, SWINSON (1969) has suggested and given a definitive example of the sidereal diurnal variations of solar origin, which critically depend on the IMF sense of 'toward or away' from the Sun, being apparently produced by the anisotropic flows (SWINSON flows) perpendicular to the ecliptic plane, due to the radial heliocentric density gradient of cosmic rays in the presense of the IMF. That IMF-sense dependent anisotropy has been certainly shown, as expected, being directed towards ~ 18 hr LST direction for 'toward (T) sense' of the IMF, while towards ~ 6 hr LST for 'away (A) sense', respectively, because the radial gradients of cosmic rays are always positve (outward from the Sun) and the IMF essentially lies in the ecliptic plane. The observed IMF-sense dependent sideresl diurnal variations; usually the difference being taken, that is, the T-A vectors between

T- and A-vectors, show the resultant phases of 18 hr LST direction, at the ground and the shallow underground, and have perfectly supported the predictions (e. g., UENO et al., 1989; SWINSON, 1988). Note that in the above SWINSON's flows there may be an underlying assumtion that the Lamor radii of cosmic ray particles of interest may be less than the scale of the IMF concerned. If that were the case, for Matsushiro observation we would expect the T-A vectors being some different from that of SWINSON's because our median energies of detection are high eonugh ($\sim 10^{12}$ eV) and its Lamor radii are greater than 5 AU or so for 5nT IMF. Figure 31 shows an example of such sidereal diurnal T-A vectors obtained for five-directional telescopes (V-, N-, S-, E-, and W-telescopes) at Matsushiro, which are sorted according to 'toward-away' sense of the magnetic field as usualy made in the analysis. In the present case, we refer to the field polarity from the table prepared by Stanford Solar Observatory (Solar-Geophysical Data, 1989). We can find in the figure that irrespective of their large statistical uncertainty the T-A vectors for these five directional telescopes may be, on the average, directed towards $\sim$21 hr LST direction; being somewhat deviated from that of $\sim$18 hr LST direction so far established in the lower energy regions. Note here that to

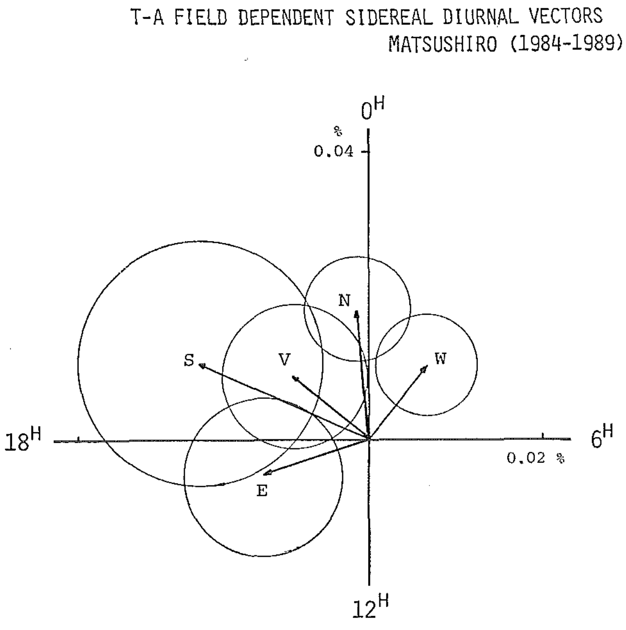


Figure 31 The sidereal diurnal T-A vectors for five directional telescopes, averaged over the period 1984–1989. The statistical errors are derived from dispersion of yearly averages.

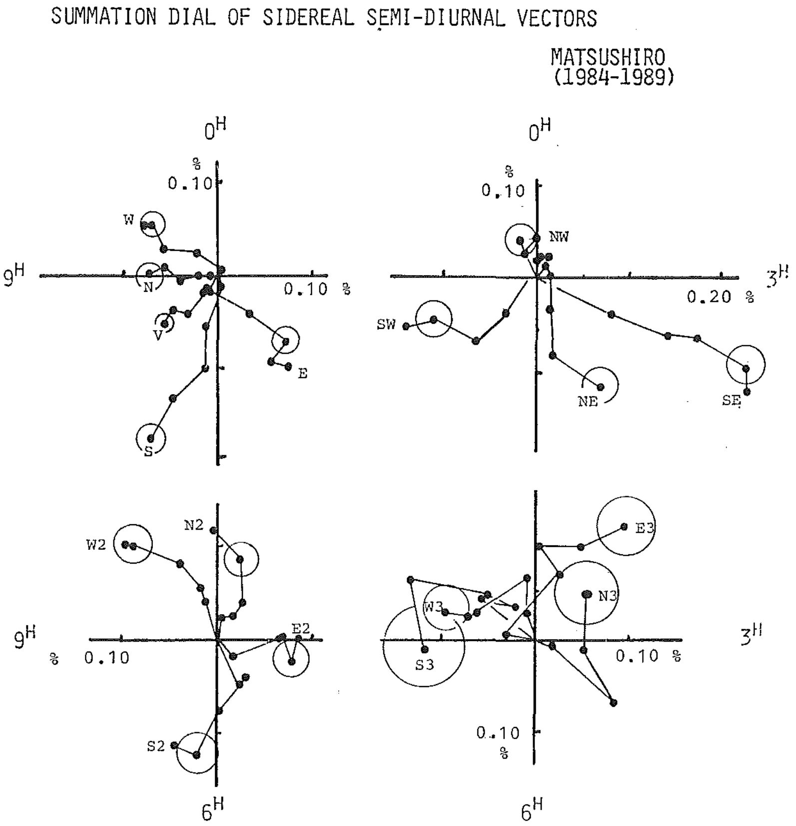


Figure 32 The same summation dial as that in Fig. 27 but for the sidereal semi-diurnal vectors for the 17 component-telescopes for the period 1984 through 1989. statistical errors are derived from the counting-rates.

increase statistics we derive these N-, S-, E-, and W-vectors by averaging two vectors of N- and NN telescopes for N-vector, S- and SS-telescopes for S-vector and so on. To determine the observed fatcs themselves and identify the anisotropic flows responsible for them a further analysis would be required.

Figure 32 gives the same summation dial as Fig. 27 but for the observed sidereal semi-diurnal vectors of the 17 component-telescopes for the five-year period 1984-1989. In the figure the statistical errors are derived from counting-rates. We can see that the sidereal semi-diurnal vectors are statistically significant and persistent over years for almost all the component-telescopes. Fig. 33 shows its five-year averages, whose errors are derived from dispersion of yearly average. We can also find that the observed vectors are reliable, showing their mutual consistency in the phase configuration for each directional

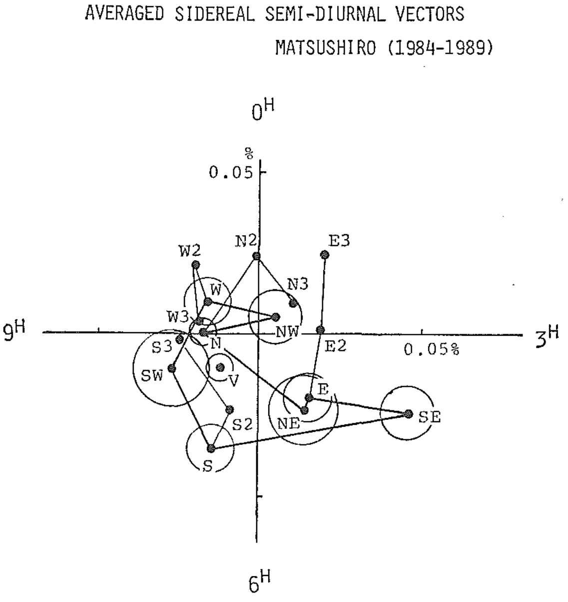


Figure 33
The five-year averages of the sidereal semi-diurnal vectors of the 17 component-telescopes over the period 1984–1989. Statistical errors are derived from dispersion of yearly averages.

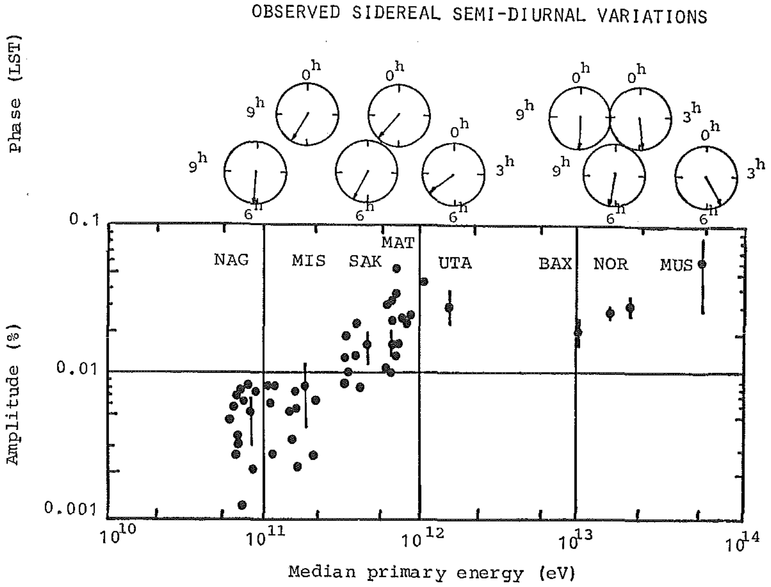


Figure 34 The observed amplitudes and phases of the sidereal semi-diurnal vectors, as functions of median primary energies, from various underground stations and by air-shower measurements. The errors for underground stations are indicated to each V-telescope only.

telescope, similarly to the diurnal vectors mentioned earlier. In Fig. 34, the

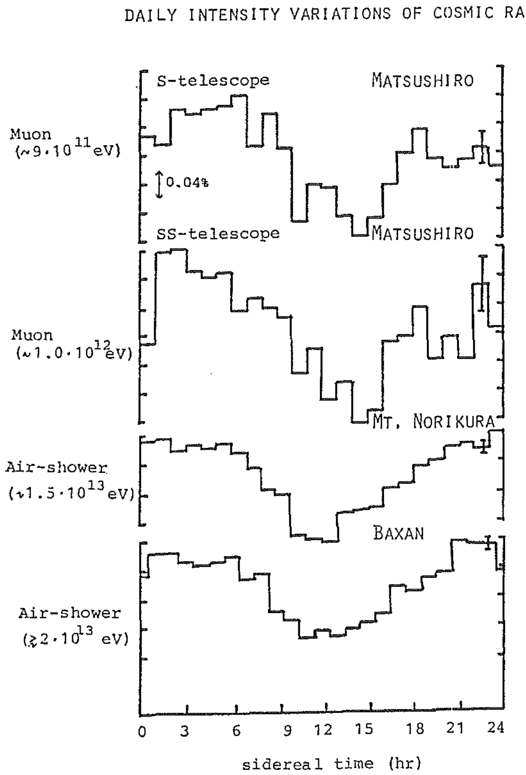


Figure 35
The observed daily intensity variations in sidereal time for S- and SS-telescopes at Matsushiro, and air-shower measurements at Mt. Norikura and Baxan.

observed semi-diurnal vectors at Matsushiro are shown together with those from other underground and air-shower measurements; the phases in the upper part and the amplitude in the lower part in the figure (ELLIOT, 1979; FUJII et al., 1984). It seems highly likely that the existence of the semi-diurnal term in the sidereal daily wave may be definite at around 6~7 hr LST (and 18~19 hr LST) in a wide range of energies 10^{11}~10^{14} eV.

Figure 35 shows the observed sideresl daily variations in sidereal time at the three observation stations and compares with each other; from S- and SS-telescopes at Matsushiro underground station (220 m.w.e. depth; ~10^{12} eV), from air-shower measurements at Mt. Norikura (>2 · 10^{13} eV), and at Baxan (≳2 · 10^{12} eV) (NAGASHIMA et al., 1989). We can see in the figure that both air-shower measurements show very similar time-profile, characterized with rather flat nature during 19 hr to 8 hr and rather V-shape form with a minimum around 12 hr (NAGASHIMA et al., 1989). The daily variations of S- and SS-telescopes at Matsushiro, on one hand, show a similar time-profile to the above two, and on the other hand, somewhat deformed in such that the intensities may be a little bit higher than those in around 19-0 hr interval, which may be very similar to that of SS-telescope at Sakashita (UENO, personal communication, 1988). As emphasized by NAGASHIMA et al. (1989), such a shape of the daily intensity variation may indicate that the anisotropy or anisotropies responsible for the observations would contain more than two anisotropies instead of a single in free-space.

From the above descriptions of the underground observatory and some of the observed results with the multi-directional muon telescope at the effective vertical depth of 220 m.w.e. at Matsushiro for a full five-year period 1984 through 1989, we can summarize that;

(1) The underground cosmic-ray observatory was completed at Matsushiro, Nagano City, Nagano Pref., Japan, in the year 1983, and the multi-directional muon telescope has been installed at the effective vertical depth of 220 m.w.e. underground.

(2) The cosmic ray muon detectors used are plastic scintillator (1×1 m in area and 10 cm thick slab) detectors, and arranged in two layers spaced by 150 cm vertically. In the detectors we have adopted a 'double photomultipliers system', and succeeded in obtaining better S/N-ratio and quite improved high-volatage characteristics of the detectors. By taking two-fold coincidence between the detectors in two layers of 25 detectors each, we have constructed the 17 directional component-telescopes. We started the observations on March 22, 1984, and have continued them since that date upto the present with high operation time-rate (complete days/total days in operation) of ~95%.

(3) We have observed some of the characteristic atmospheric effects at the deep underground; large barometric coefficients and also the semi-annual intensity variations of muons. Those effects may have been well explained by considering the atmospheric temperature effect in addition to the usual barometric effect on the observing muons.

(4) We have observed the solar diurnal variations of cosmic rays significantly during 1984-1985, and determined the anisotropy responsible for them as having the amplitude ~0.35% in ~18 hr LT with high cut-off ~300 GeV, which is in accordance with that obtained in the lower energy regions ($\lesssim 3 \cdot 10^{11}$ eV).

(5) We have also observed significant and persistent sidereal diurnal variations of cosmic rays with median primary energies of detection $6 \cdot 10^{11} \sim 1.3 \cdot 10^{12}$ eV for a full five-year period 1984-1989. The multi-directional observation has shown definitely that the observed vectors are originated from some sidereal anisotropies in free-space. Less possibility of the contribution of atmospheric origin may be proved with the multi-channel observation. The following observed facts may support the above conclusion that smaller amplitudes are ob-

served by the three north-pointing telescopes (N-, N2-, and N3-telescope), whose asymptotic orbits are almost parallel to the Earth's spin axis, and also the anti-sidereal diurnal vectors for all component-telescopes are small and insignificant.

(6) The present observed sidereal diurnal vectors show a good coincidence with those obtained at the other underground stations and by air showr measurements (≈0.06% in amplitude with higher energies of detection) (Nagashima et al., 1989).

(7) Rather larger amplitudes have been obtained by the south-pointing telescopes, in particular the vectors of ~0.12% or more in amplitude in ~2 hr LST direction by S3-telescope. This may be consistent with the negatively decreasing spectrum of the sidereal diurnal variations obtained by long-running air-shower observations at Mt. Norikura (Nagashima et al., 1989).

(8) The observed sidereal semi-diurnal variations may also be significant, showing its phase at around 7 hr. These are in good agreement with other observed results in a wide energy range $10^{11} \sim 10^{14}$ eV (Fujii et al., 1984).

(9) The daily intensity variations of cosmic rays in sidereal time of S- and SS-telescopes at Matsushiro show a similar time-profile to those observed by air-shower measurements at Mt. Norikura and at Baxan with higher energies ($>10^{13}$ eV), characterized by a plateau during 19 hr to 8 hr and a V-shaped sink with a bottom at around 12 hr in the variations (Nagashima et al., 1989).

(10) We have tentatively examined 'toward-away' field dependent sidereal diurnal variations, and obtained the T-A vectors in ~21 hr LST, being somewhat deviated from Swinson's of ~18 hr LST in the lower energy regions.

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