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Section A

Further development of data acquisition system of the Akeno Giant Air Shower Array

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Abstract

The data acquisition system of the Akeno Giant Air Shower Array (AGASA) is described. The AGASA array covers an area of about 100 km^2 and has been operated since 1990 to study the origin of extremely high energy cosmic rays. In the early stage of our experiment, AGASA was divided into four sub-arrays called branches for topographical reasons so that air showers were observed independently at each branch. In December 1995, we have improved the data acquisition system and unified the four branches into a single detection system. By this unification, the effective detection area of the AGASA increases by about 1.7 times in the early stage.

Keywords: Extremely high energy cosmic rays; Data acquisition; Air shower array

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1. Introduction

We constructed a very large surface array at the Akeno Observatory (35°47′ N, 138°30′ E) to study the origin of extremely high energy cosmic rays. This array, the Akeno Giant Air Shower Array (AGASA), has been operated stably since 1990. The AGASA array covers an area of about 100 km^2 and consists of 111 detectors on the ground (surface detectors) and 27 detectors under absorbers (muon detectors). Each surface detector is placed with a nearest-neighbor separation of about 1 km and the detectors are sequentially connected with a pair of optical fibers as shown in Fig. 1. Since the optical fibers are hung on utility poles of electric and telecommunication companies, the detectors cannot be connected along the shortest distance if no poles are available. In fact, even though the separation of two detectors is only 1 km, some cable lengths between these detectors reach to a few tens of km. This long cable detour makes the triggering method and the data acquisition system of the AGASA complicated. To simplify this, we divided the AGASA array into four sub-arrays called branches. Each of the four branches is referred to as the "Akeno Branch (AB)", the "Sudama Branch (SB)", the "Takane Branch (TB)" and the "Nagasaka Branch (NB)", respectively. Each branch has a data processing and storing station called a "Branch Center", shown in Fig. 1 as a big circle with a dot.

In the early stage of our experiment, the data acquisition system of each branch was operated independently. Then only air showers whose cores hit well within each branch were selected for our analyses.

Recently we have developed a new system with rapid communication of triggering signals among the branches. With this new scheme, we can determine relative time differences between the detectors in the different branches with an accuracy of 40 ns. This accuracy is achieved by a synchronization of all clocks in the whole system and by regular precision measurement of cable length. We can thus include air showers, called "boundary showers", whose cores

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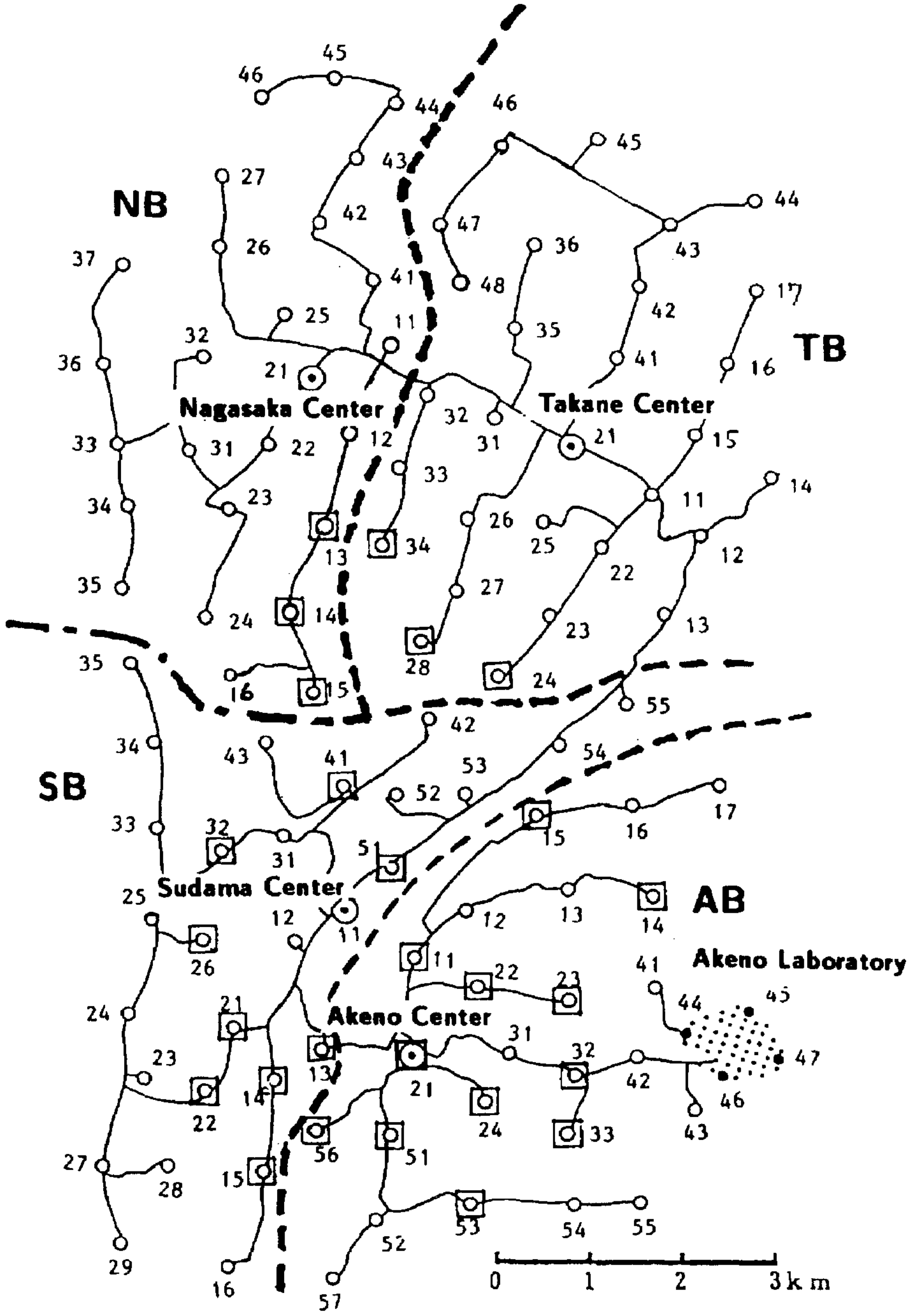

Fig. 1. Schematic view of the AGASA. Open circles and squares represent the surface detectors and the shielded detectors, respectively. Solid lines show the routes of the optical fibers for a data communication network. Dotted lines show the boundaries of branches.

hit near the boundaries among the branches, and unify the whole air shower array into a single detection system. We present here details of this new system, which has been in stable operation since December 1995.

2. Data acquisition system

2.1. General

First of all, we describe the basis of the data acquisition system of the AGASA. However, we are not concerned with details of surface detectors and muon detectors because useful descriptions of the old system are found in our previous

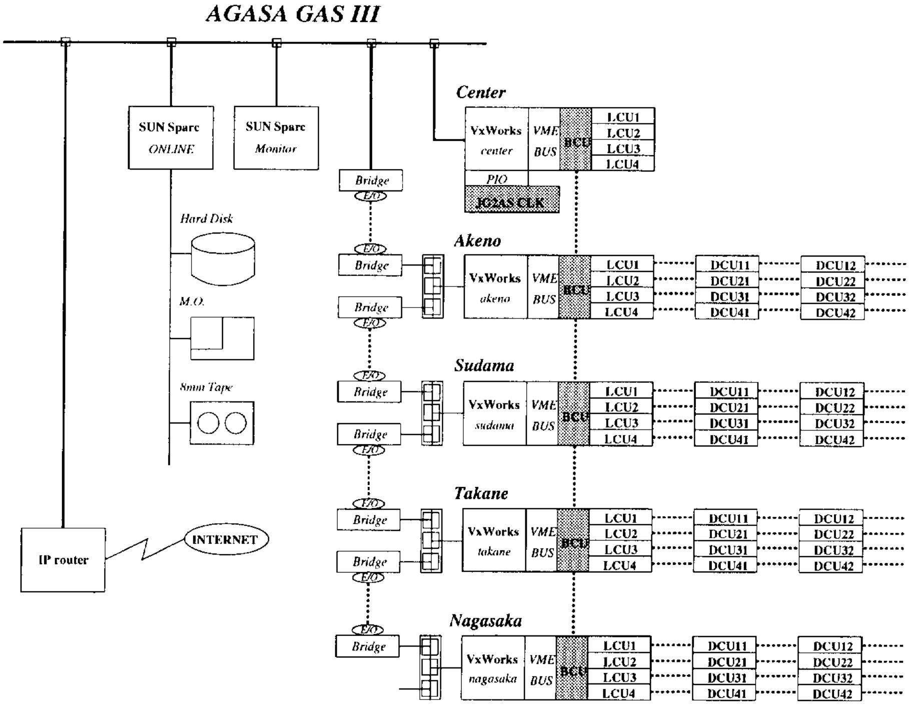

Fig. 2. Block diagram of the AGASA data acquisition system. Each dotted line shows a pair of optical fibers. The BCU network connecting with shaded blocks (BCUs) was installed in this work.

papers [1,2]. A block diagram of this system, including the optical fiber network, is shown in Fig. 2. Each block indicated as DCUxx is a detector control unit (DCU) at each detector site. Each surface detector consists of plastic scintillator of 2.2 m^2 area, which is viewed by a Hamamatsu R1512 photomultiplier tube (PMT) of 125 mm diameter. Each DCU, equipped with a HD64180 microprocessor, sets the high-voltage applied to the PMT, adjusts the amplifier gain, and records information on timing and pulse height of every PMT signal in a ring memory. Furthermore, each DCU sends a signal, which indicates whether the detector was hit by shower particles or not, to the corresponding branch center at every 3.2 μs for trigger judgement. This is termed an ON/OFF signal in the present paper; "ON" indicates that the detector was hit by shower particles. Besides these functions, each DCU accumulates the pulse height of PMT signals continuously and records the temperature inside and outside the DCU and the high-voltage applied to the PMT every 10 min. The DCUs in each branch are divided into several groups and the DCUs in each group are sequentially connected with a communication string which consists of a pair of optical fibers shown by dotted lines in Fig. 2. Each string starts at the corresponding branch center and is managed by a line control unit (LCU) which is also equipped with a HD64180 microprocessor. All the DCUs and the LCUs in a single branch are under the control of a branch control unit (BCU) which contains a V53 microprocessor. One optical fiber of each string from a LCU to the connected DCUs is referred to as a "Command-line (C-line)" and carries commands, clock pulses and timer frames from the BCU. The other, a "Data-line (D-line)", is used to transfer the ON/OFF signals, air shower data and monitor data from the connected DCUs. Since a BCU is designed to execute a series of actions by a single command, a VxWorks operating system (MVME147) manages the flow of the commands issued to that BCU. An interface between each VxWorks and the AGASA operators is provided by a central computer, a SUN SPARC station, through a 10 Mbps ethernet line which consists of a pair of optical fibers.

We now return to our main subject. The following are principally described in this work: 1) a rapid mutual communication system among the BCUs; 2) triggering circuits for the boundary showers; 3) parallel processing on-line software. Detailed accounts of these are given below.

2.2. BCU Network

The main tasks of a BCU are the same as those in the early stage, that is, synchronizing the whole system and generating a trigger signal. For the unification of the four branches, a rapid mutual communication method among all the BCUs must be established and one of these BCUs must synchronize the whole system of the AGASA array and generate a trigger signal. We added such a central BCU, the fifth BCU shown

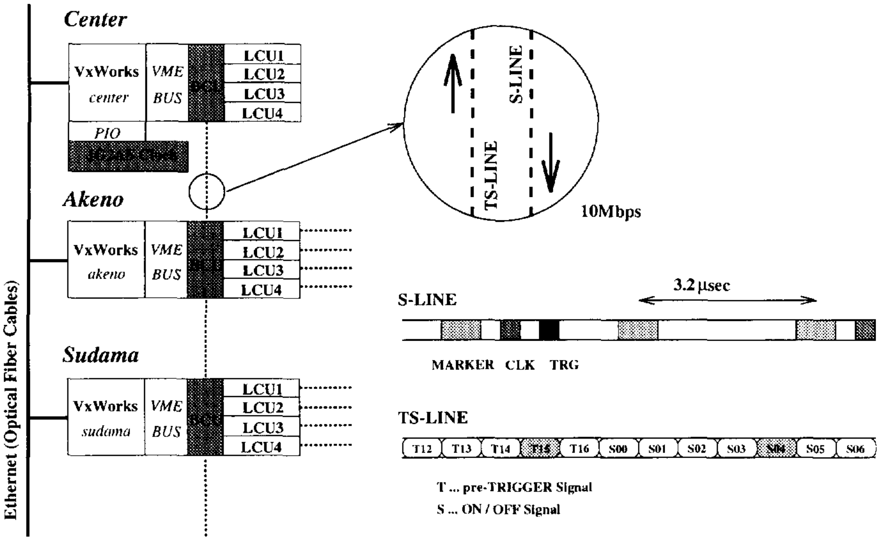

Fig. 3. BCU network (S-line and TS-line).

at the top of Fig. 2, and linked these BCUs with a pair of optical fibers sequentially. This BCU network has the transferring rate of 10 Mbps. We note that the BCU network is independent of the LCU–DCU networks which consist of the D-lines and the C-lines.

Fig. 3 illustrates the BCU network. One optical fiber which carries information from the central BCU to the local BCUs is a "Synchronization-line (S-line)" while the other is a "Trigger-Signal-line (TS-line)". Through both of the S-line and the TS-line, data are continuously transmitted in periodic frames, which are 3.2 μs long for the S-line and 12.8 μs long for the TS-line. The S-line carries the synchronization signal, timer frames and a trigger signal. Using the S-line's periodic frames, the central BCU synchronizes four local BCUs, that is, synchronizes the whole system. A clock in each DCU is phase locked with the clock in the central BCU. The TS-line is used to transfer the ON/OFF signals with pre-trigger signals which are taken up in Section 2.3 below. The length of a TS-line's frame, 12.8 μs, is determined to minimize the gate width for trigger judgement. Of the 128 bits in each TS-line's frame, 16 bits are shared for pre-trigger signals, 72 bits for the ON/OFF signals received from the DCUs and the remainder for data flow headers. However, 72 bits are not sufficient to transmit the ON/OFF signals received from all the DCUs, and the length of TS-line's frames, 12.8 μs, is too long for the BCUs to transmit the ON/OFF signals in every 3.2 μs. The first problem is solved with rearrangement of the ON/OFF signals in each TS-line's frame: each BCU removes unnecessary ON/OFF signals for the subsequent BCUs to generate (pre-)trigger signals and assigns new ON/OFF signals received from the local DCUs instead of removed ones. For the second problem, each BCU assigns the logical sum signal of four consecutive ON/OFF signals received from a DCU to one ON/OFF signal in each TS-line's frame.

2.3. Triggering method and timing adjustment

A trigger signal is generated whenever five (or more) fold coincidence occurs among neighboring detectors within a time window of 25.6 μs. However when neighboring detectors are spread over plural branches, a BCU extends the gate width to 38.4 μs by adding 12.8 μs due to the length of a TS-line's frame. To reduce accidental coincidences, triggering is performed through comparison with the patterns of hit-detectors and those patterns which were selected from simulated patterns of hit-detectors and are stored beforehand in the BCUs. To select anticipated patterns of hit-detectors, we generated artificial air showers with energies of 10^{18} eV and directions sampled from an isotropic distribution over the whole area of the AGASA. The gate width, 25.6 μs, required for the coincidence judgement depends only on the geometrical detector arrangement. This minimum value is realized in such a way that the propagation time through optical fibers and modules from all the DCUs to the central BCU are adjusted to be the same. This is also helpful in reducing accidental coincidences, and the rate of accidental coincidences is now ~0.3 Hz.

Triggering of the new system is not performed by the central BCU alone but shared among all the BCUs. Each BCU generates two kinds of pre-trigger signals. One is a "local pre-trigger" signal, which is based on a combination pattern

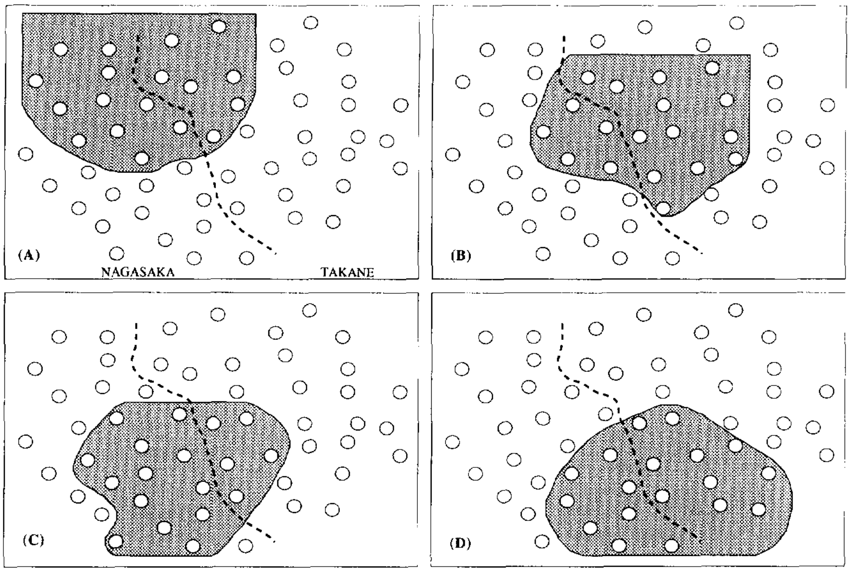

Fig. 4. Input assignment of four MATRIX18 circuits on the Takane BCU.

of hit-detectors in a single branch. The other is a "boundary pre-trigger" signal for boundary showers. Accepting these pre-trigger signals and the ON/OFF signals, the central BCU generates a trigger signal and broadcasts it to the whole system.

2.3.1. Local pre-trigger

A local pre-trigger signal is generated with the same trigger logic that we used in the old system. In each branch, each DCU sends an ON/OFF signal to the corresponding LCU through the D-line at every 3.2 μs. The LCUs pass the received ON/OFF signals to the BCU with their logical products on the basis of the simulated patterns for a local pre-trigger signal. Then the BCU generates a local pre-trigger signal and transmits it to the central BCU through the TS-line. To reduce accidental coincidences, about 900 patterns are registered for each branch, and all the DCUs in one branch send their ON/OFF signals to the corresponding BCU after adjusting the propagation time to be the same. These adjustment values $T_{\mathrm{DCU}}^{\mathrm{corr}}$ of all the DCUs are determined with results of cable delay time measurement in that branch as

$$T_{\mathrm{DCU}}^{\mathrm{corr}}(i) = \max_{j \in \mathrm{branch}} \{T_{\mathrm{DCU}}(j)\} - T_{\mathrm{DCU}}(i), \qquad (1)$$

where $T_{\mathrm{DCU}}(i)$ is cable delay time from the local BCU to the ith DCU in that branch. At the start of a RUN, each local BCU measures the cable delay time T_{DCU} by counting the turn-around frequency of signals on two optical fibers from the local BCU to the ith DCU till a measurement accuracy reaches to 1 ns. This means that time for measurement increases with the cable length since the turn-around frequency decreases with the cable length. In this way the adjustment values $T_{\mathrm{DCU}}^{\mathrm{corr}}$ can be determined with an accuracy of 1 ns for all the DCUs.

2.3.2. Boundary pre-trigger

We have newly attached four RAMs (Hitachi HM620 HLJP-45) to each BCU for boundary pre-trigger decisions. This RAM is called a "MATRIX18" circuit; "18" is the number of inputs designating an address of that RAM (2^{18} bits). The input signals of a MATRIX18 circuit are selected out of the ON/OFF signals which are received from the local DCUs and through the TS-line. Fig. 4 illustrates this assignment for boundary showers between the Takane Branch and the Nagasaka Branch. In the Takane BCU, the ON/OFF signals received from eighteen DCUs in each shaded area are assigned to the inputs of each MATRIX18 circuit. Each MATRIX18 circuit judges whether or not the patterns of hit-detectors assigned to its inputs agree with those simulated patterns which were selected for boundary showers, and generates a boundary pre-trigger signal. Then the BCU transmits the logical sum signal of these four pre-trigger signals to the central BCU through the TS-line. A schematic view of these procedures for boundary pre-trigger judgement among three branches is shown in Fig. 5. In this figure, three ON/OFF signals received from the detectors of NB15, TB28 and SB42 are assigned to the inputs of one MATRIX18 circuit mounted on the Sudama BCU. In this way other detectors near the boundaries among the three branches are assigned to eighteen inputs of each MATRIX18 circuit mounted on the Sudama BCU.

For real coincidence among the detectors in the different branches, each BCU adds a common delay to the ON/OFF signals received from the local DCUs before assigning them to the MATRIX18 circuits. This delay $T_{\mathrm{BCU}}^{\mathrm{corr}}$ is determined

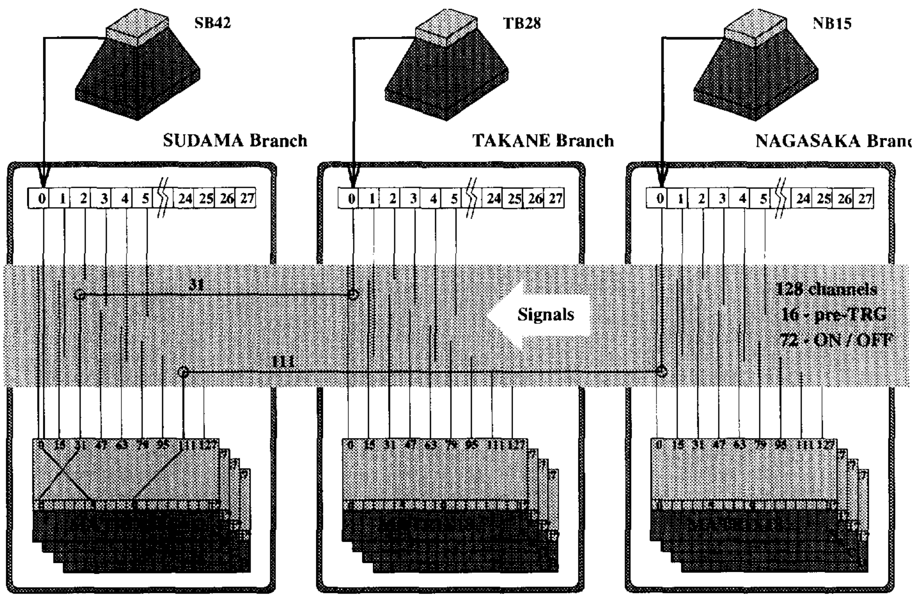

Fig. 5. Schematic view of boundary pre-trigger judgement.

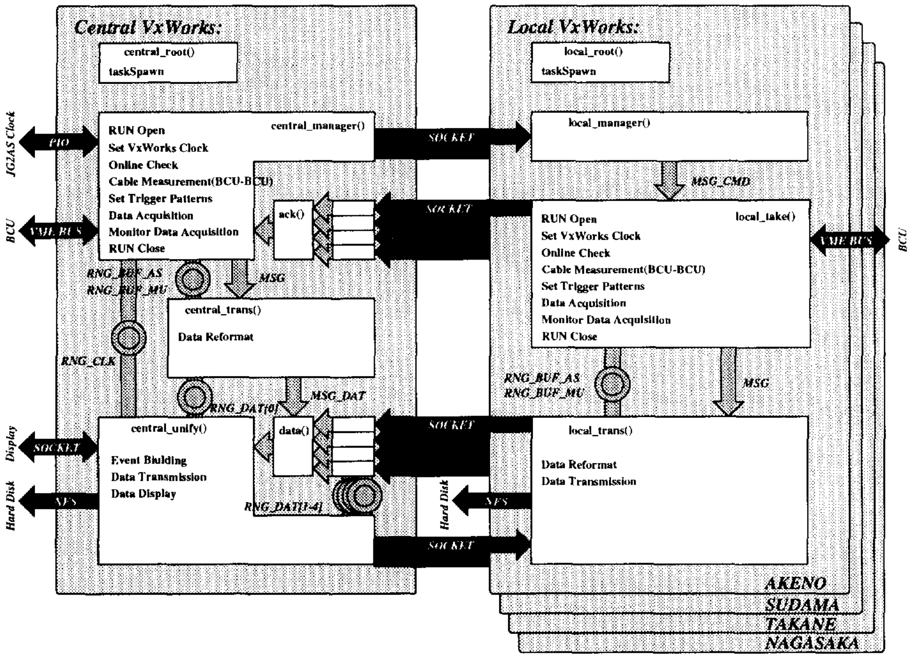

Fig. 6. Block diagram of the on-line software.

as follows:

$$T^{\rm corr}_{\rm BCU}(i) = \max_{j\in{\rm array}} \{T_{\rm BCU}(j) + T^{\rm max}_{\rm DCU}(j)\} - \{T_{\rm BCU}(i) + T^{\rm max}_{\rm DCU}(i)\} \qquad (2)$$

$$T^{\rm max}_{\rm DCU}(i) \equiv \max_{k\in{\rm branch}(i)} \{T_{\rm DCU}(k)\},$$

where $T_{\rm BCU}(i)$ is the cable delay time from the central BCU ($i = 0$) to the ith BCU ($i = 1,2,3$, and 4 represent the Akeno, the Sudama, the Takane and the Nagasaka BCU, respectively). After $T_{\rm DCU}$ measurement, the cable delay time $T_{\rm BCU}$ are measured and then each BCU sets its delay $T^{\rm corr}_{\rm BCU}$ with an accuracy of 1 ns. Under this scheme, all the DCUs in the AGASA array turn out to be equidistant from the central

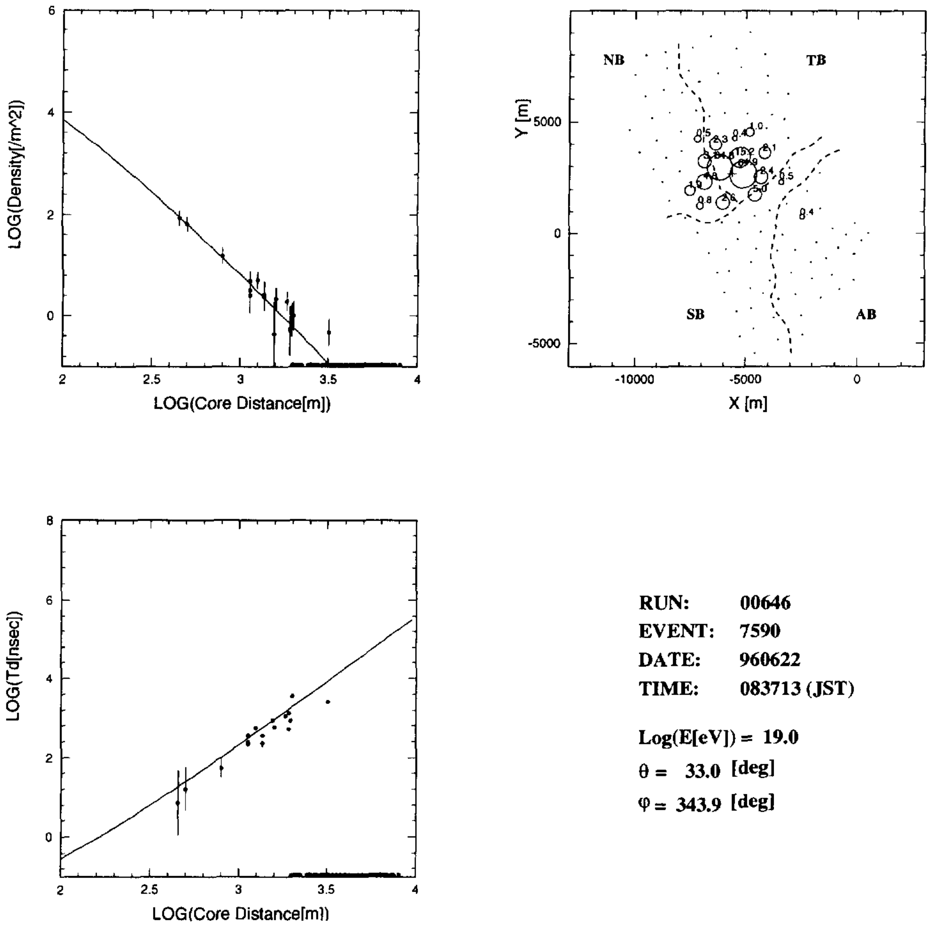

Fig. 7. Event example. (a) Lateral distribution of charged particles. (b) Particle density map. Radius of each circle corresponds the logarithm of the particle density [m^{-2}]. (c) Shower front structure. "Td" is the delay time of the charged particles from the shower plane without its cone structure.

BCU, and the ith BCU recognizes that all the DCUs in the $(j \geq i)$th branches turn to be equidistant from that BCU.

2.4. On-line software

A VxWorks operating system manages a series of commands issued to each BCU as mentioned in Section 2.1 above. We developed parallel processing on-line software to control all the VxWorks's. Fig. 6 shows a block diagram of this software. The left part is installed on the central VxWorks and the right part is on each of four local VxWorks's. To reduce system dead time, each part is divided into two groups, processes requiring real time operation and processes which can be delayed.

The main task of this software is "central_manager( )" on the central VxWorks. This task issues a series of commands both to the central BCU and to four local BCUs. The tasks of "local_manager( )" and "local_take( )" relay commands received from the main task to each local BCU. In addition, the main task gets an absolute time (JST) through a JG2AS clock (40.0 kHz) within 1 ms accuracy. The above tasks compose the real time part. Data accumulated from the BCUs by the tasks of "central_manager( )" and "local_take( )" are transferred to the task of "central_unify( )" through the tasks of "central_trans( )" and "local_trans( )", respectively. Finally, the task of "central_unify( )" rearranges received data and stores them on a hard disk of the central computer via the Network File System (NFS).

Those procedures are carried out in the following steps of data acquisition:

(i) a RUN number is set for all the VxWorks;
(ii) each VxWorks clock is set by the JG2AS clock;
(iii) status of the LCU-DCU networks are checked;
(iv) the high-voltage and the other parameters of each detector are set;
(v) each BCU measures T_{DCU} and makes all the DCUs in that branch set their adjustment time $T^{\mathrm{corr}}_{\mathrm{DCU}}$;
(vi) the central BCU measures T_{BCU} and makes the local BCUs set their offset $T^{\mathrm{corr}}_{\mathrm{BCU}}$;
(vii) trigger patterns for the local and boundary pre-triggers

are registered on all the BCUs;
- (viii) data acquisition starts;
- (ix) after 9999 events have been collected, data acquisition is stopped;
- (x) monitor data for each detector are accumulated;
- (xi) a RUN is closed.

The new system has flexibility in selecting branch combination to be unified. Normally this system is operated with all branches. However any VxWorks-BCU pair may serve as the central pair and any number of the local pairs can be unified, Therefore if any branch needs to be stopped for any reason, the AGASA array is able to continue data acquisition without that branch or to be divided into two parts according to circumstances.

3. Effective detection area for the AGASA

Fig. 7 shows an example of an air shower observed by the unified system of the AGASA array: (a) shows the lateral distribution of charged particles; (b) is the particle density map; and (c) shows the shower front structure. Before the four branches were unified into a single detection system, such an event would have been excluded from the analyses of the energy spectrum and the anisotropy of extremely high energy cosmic rays because its core hit near the boundary region between the branches.

To examine the timing accuracy attained by the unified system, we introduced a ξ^2 parameter as a measure of goodness of fitting on the arrival direction fit. This ξ^2 value differs from the normal χ^2 value in the sense that the thickness of the shower front does not follow a Gaussian distribution. In Fig. 8, we compare a normalized ξ^2 distribution of arrival direction fit for showers whose cores hit well inside branches (white histogram) and that for boundary showers (shaded one). Thus we see that the ξ^2 distribution for boundary showers coincides with that for inner showers, and that the relative time differences among the detectors in the different branches are determined within the expected accuracy.

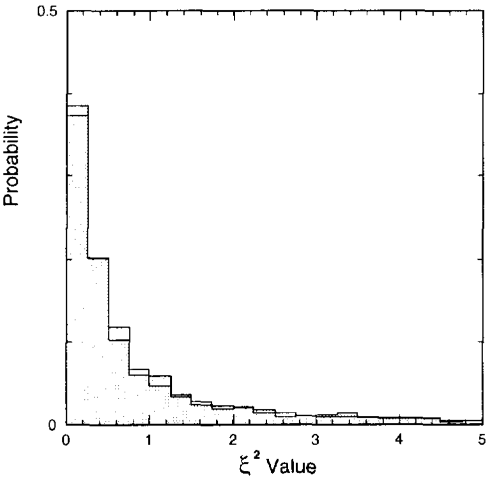

Fig. 8. Normalized ξ^2 distributions of arrival direction fit (white histogram: for air showers well inside branches, shaded histogram: for boundary showers).

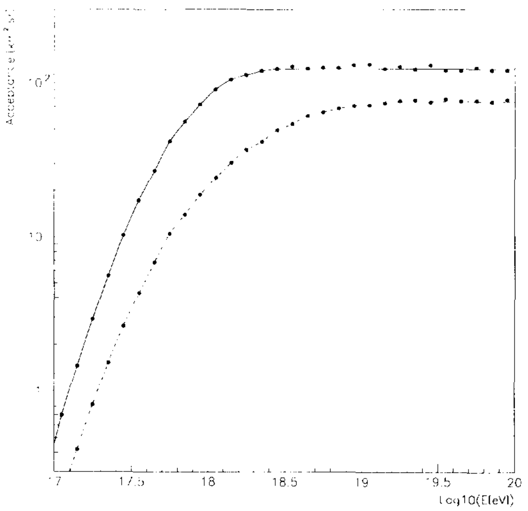

Fig. 9. A plot of the effective detection area of the AGASA as a function of the primary energy (solid line: for the AGASA, broken line: for the sum of the four independent branches).

Fig. 9 shows the effective detection area of the AGASA array as a function of the primary energy. To calculate this effective detection area, we simulate a large number of artificial air showers over a larger area than that of the AGASA with directions sampled from an isotropic distribution. In Fig. 9, the solid line represents the effective detection area for air showers with zenith angles less than 45°, and the broken line shows the area before branch unification. The effective detection area of the AGASA and that of the sum of the four branches are independent of the primary energy above $\sim 10^{18.5}$ eV and $\sim 10^{19}$ eV, respectively. In this energy range, the effective detection area of the AGASA array is 125 $\mathrm{km}^2\mathrm{sr}$, while it is 76 $\mathrm{km}^2\mathrm{sr}$ for the four independent branches.

4. Conclusions

Operation with the unified data acquisition system of the AGASA array began on 13 December 1995. With this system, the effective detection area of the AGASA array is 125 $\mathrm{km}^2\mathrm{sr}$ and it is 1.7 times as large as that of the sum of the four independent branches.

In the following three years, the number of events observed by the AGASA will be equivalent to that observed in the last five years. We thus expect that the studies of the energy spectrum and the anisotropy of extremely high energy cosmic rays will make further progress.

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