Space and Power Effective Readout System for Cosmic-Ray Muon Radiography

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***Abstract*– To overcome limitations on power-source availability and observation-site access, a cosmic-ray muon-radiography detection system with an Ethernet port and low power consumption was developed. The system consists of a small solar-power supply and a wireless LAN. It provides a real-time angular distribution of muons in real time as a histogram on a web browser. The developed detection system was used to measure the density profile of a volcano as an angular distribution of cosmic-ray muons penetrating through the volcano. The obtained clear image of the volcano indicates that the performance of the detection system is sufficient for cosmic-ray muon radiography.**

I. Introduction

COSMIC-RAY muon radiography was proposed for volcanic eruption prediction in 1996 [1]. It makes it possible to study an internal structure of a volcano. The internal structure of the volcano is observed as a density profile that is obtained from an angular distribution of cosmic-ray muons penetrating through the volcano. The angular distribution can be obtained from paths of the muons. To determine the paths, a detection system based on plastic scintillation counters is used. The design of its readout system is based on Nuclear Instrumentation Modules (NIMs) [2] and Computer Automated Measurement And Control (CAMAC) [3] modules in the early detection system [1, 4-6]. Since its power consumption is large, commercial power supply is required. However, a commercial power source is not always available and access to the system is limited, because the detection system is located near a volcano. Therefore, location where an observation station can be constructed is limited.

To overcome this limitation, an "emulsion imaging system" using nuclear emulsion films has been developed [7]. This system overcomes the limitation on constructing an observation station because it is small and has no requirement for a power source. As a result, the muon-detection system could be placed near a target pointing toward a topographically prominent feature of interest, i.e., the vent or crater of a volcano. Subsequently, the internal structure of the volume was first revealed by cosmic-ray muon radiography [8,9]. However, these observations are not real-time ones. With real time readings, the method may help in predicting eruptions. Electronics are required for real-time observation. One of the solutions is to employ a small solar-power system and a wireless Local Area Network (LAN). To create such a system, a space and power effective readout system is required. Accordingly, to meet that requirement, we have developed a readout system powered by a small solar-power system.

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II. Detection System

The detection system detects cosmic-ray muons penetrating through a volcano, determines their paths, and generates their angular distribution as a histogram.

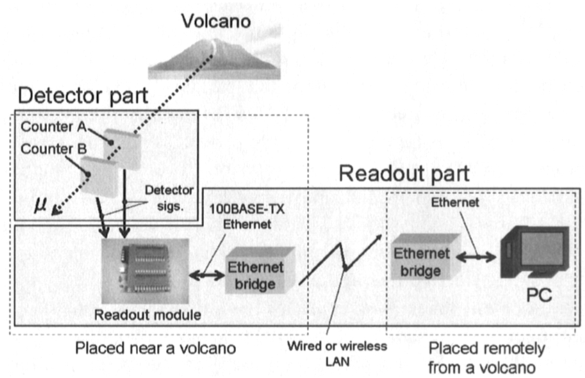

Fig. 1. Detection system for cosmic-ray muon radiography

A block diagram of the detection system is shown in Fig. 1. The system consists of two major parts: a detector and a readout part. The detector part detects the cosmic-ray muons by using two position-sensitive counters. The readout part processes signals from the counters and generates a histogram of angular distribution.

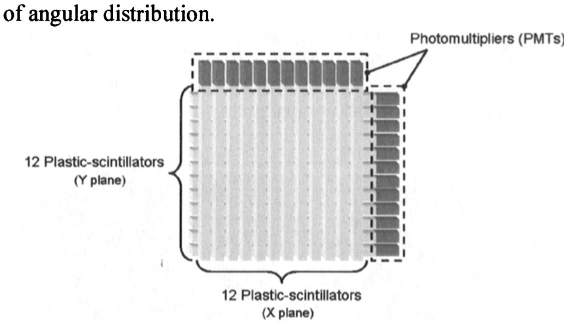

Fig. 2. Schematics of counter

Fig. 2 shows a schematic of the counter, which consists of two plates of plastic-scintillator arrays. The X-plane and Yplane detect horizontal and vertical position of a muon, respectively. One plane consists of 12 scintillators of $15 \times 70 \times 1000$ mm in size. A photomultiplier tube (PMT) is mounted on each scintillator. The total number of signals from PMTs of two counters is 48.

All signals of the PMTs are processed by the readout part. A histogram of an angular distribution of the muons is then generated. The readout system consists of a readout module, Ethernet bridges, and a PC. The readout module processes signals from the detector part, generates a histogram as a web page, and works as a web server. The detector and readout parts are connected through a computer network by the Ethernet bridges. The histogram can be obtained from the PC, which can be located remotely, using a web browser. This module plays a central role in this system. Its details are described from the next section. In addition, all devices without the readout module are commercial products. We can employ a suitable product for our system among various products. A cost-effective and high performance system can thus be easily constructed.

A wired and wireless Local Area Network (LAN) can be employed for the network. If wireless bridges and a small solar-power system are used, a remote observation station can be constructed near a volcano; that is an advantage for this observation. However, to employ a small solar power system, low power consumption is required. This is the main issue concerning this system development. The power supply capability of a small solar-power system that can be applied for an observation station located at near a volcano is about 400W. With the ratio of shining taken into consideration, however, effective average power is about 40W. This system development faces another issue. It is difficult to construct a large or heavy station at near a volcano, where access is, naturally, limited. To reduce construction cost of the station, small size and light weight are vital. To resolve these issues, we have developed the readout module. The power-consumption target of the module was set several watts, which is sufficiently low compared to the effective average power. The size and weight targets were set to single module and several hundred grams, respectively.

III. Readout Module

The module processes all signals from the detector part and generates a histogram. The PC can obtain the histogram from the readout module by using a web browser.

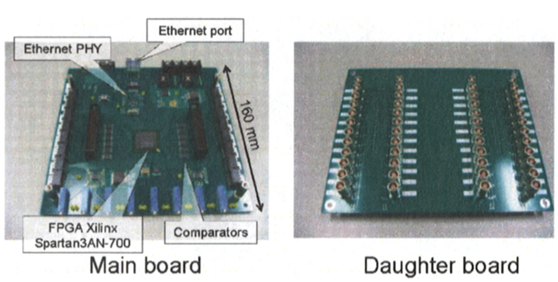

Fig. 3. Photographs of main and daughter boards.

The readout module is $35 \times 160 \times 160$ mm in size and 420 g in weight. It consists of a main and a daughter board. Photographs of these boards are shown in Fig. 3. The daughter board is a connector changer so that various types of connectors can be used mounted on the main board. Signals are processed by the main board. The main parts are comparators, a Field-Programmable Gate Arrays (FPGA, Xilinx Spartan3AN-700) [10], and an Ethernet physical-layer device (PHY, SMSC LAN8700i) [11].

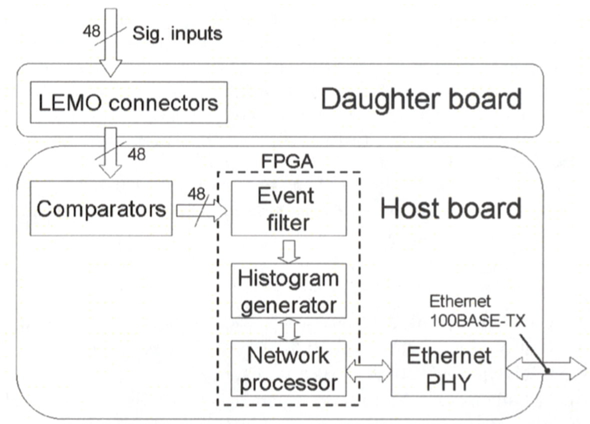

Fig. 4. Block diagram of the readout module.

Fig. 4 shows a block diagram of the readout module, which consists of LEMO connectors, comparators, an event filter, a histogram generator, a network processor, and an Ethernet PHY. The FPGA works on 50-MHz system clock. The event filter, the histogram generator, and the network processor are implemented on the single FPGA.

The detector signals are received and are digitized by the comparators. The event filter selects events that can construct muon paths and generates "information data" for the paths. The information data consists of detection times and detection positions of the two counters. A histogram as an angular distribution of the selected events is generated by the histogram generator from the path information. The network processor deals with the follows network protocols [12] to access the histogram from a remote PC using a web browser. The network protocols used for this purpose are Ethernet, Internet Protocol (IP), Transmission Control Protocol (TCP), Hyper Text Transfer Protocol (HTTP), and Hyper Text Markup Language (HTML). The Ethernet PHY converts signals between the FPGA and Ethernet. The details of the circuits on the FPGA are described in the following sections.

A. Event filter

The event filter selects events that can construct the muon paths and generates its path information.

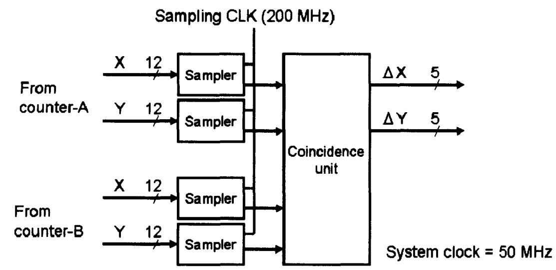

Fig. 5. Block diagram of the event filter

Fig. 5 shows a block diagram of the event filter, which consists of samplers and a coincidence unit. Input signals from the comparators are sampled at 200 MHz (5-ns period). To reduce sampling errors and influence of characteristic variations of the detectors, a pulse of a sampled signal is stretched to 40 ns when the pulse width is shorter than 40 ns. The coincidence unit selects events from the sampled signals and generates their path information. The selection criteria are as the follows. There is one signal from each scintillator-array plane, so the two signals of the same counter are detected simultaneously, and the all signals are within a coincidence window. The window size can be set from 0 to 2 us by a 20 ns unit. An angle of an incident muon is calculated with a difference between the detection positions of the two counters. The path information consists of two 5-bit-width data of detection position differences in both the horizontal, ΔX, and vertical planes, ΔY.

B. Histogram generator

The histogram is generated in a 32 bit-width internal memory of the FPGA. The path information, which has 10-bit width, generated by the coincidence unit is used as the address for access to the internal memory. The data corresponding to the address are counted up when an event is detected. These data are read by the network processor, described in the next section, when a remote PC access to this histogram.

C. Network processor

The network processor deals with network protocols to access the histogram from a remote PC by using a web browser. The PC can execute instructions as the follows: histogram data are obtained and cleared. In addition, this block has event counters for monitoring of the detectors. Their data are also obtained and cleared by using a web browser.

The feature of this block is that those network protocols are processed by a hardware circuit specialized for a web page. There is no CPU and no other programmable sequencers in this block. This design has an advantage in terms of power consumption and failure rate in running. Generally, the protocols are processed by a system employing an embedded CPU with an operating system (OS). The system requires an external memory device because the size of the internal memories is too small to store a program. Increasing the number of devices increases power consumption and failures during manufacturing and running. Accordingly, decreasing the number of devices also reduces power consumption and the failure rate during manufacturing and running.

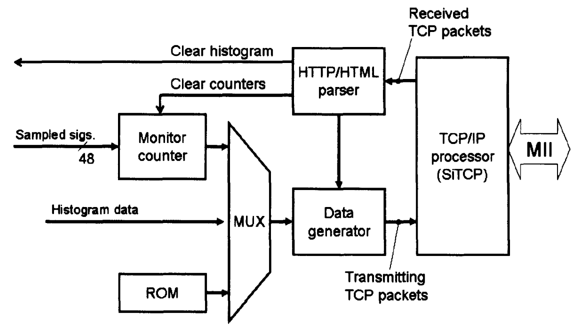

Fig. 6. Block diagram of the network processor.

Fig. 6 shows a block diagram of the network processor, which consists of a TCP/IP processor (SiTCP) [13, 14], a HTTP/HTML parser, event counters, a read only memory (ROM), a multiplexer (MUX), and a data generator. This module works as a web server. The network protocols processed by this block are HTML, HTTP, TCP, IP, and Ethernet. The SiTCP processes TCP, IP, and Ethernet. The SiTCP is a hardware based TCP/IP processor, which can be implemented on a FPGA with no other external devices, for example, memory devices [13, 14]. The parser analyzes HTML and HTTP data extracted from TCP packets by the SiTCP and executes commands from the remote PC. There are three commands: "clear histogram data," "clear event counters," and "obtain histogram data". There are clear buttons for the histogram data and event counters on a web page (as shown in Fig. 7). A command packet to clear histogram data or event counters is transmitted from the PC when the clear button is clicked. Acknowledge packets for the commands are sent by this block when the histogram data or the event counters are cleared. The event counters count up according to detector signals for one second after the clear command received.

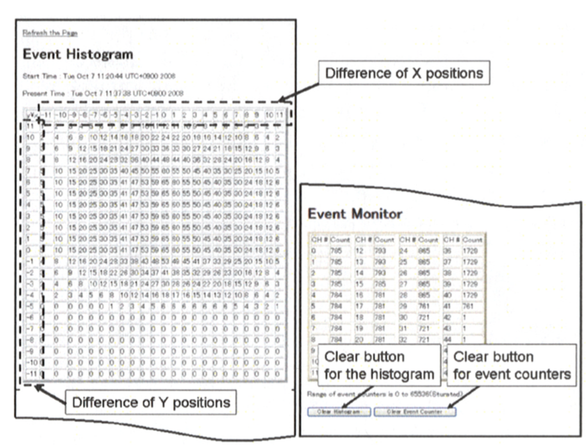

Fig. 7. Web page showing the histogram

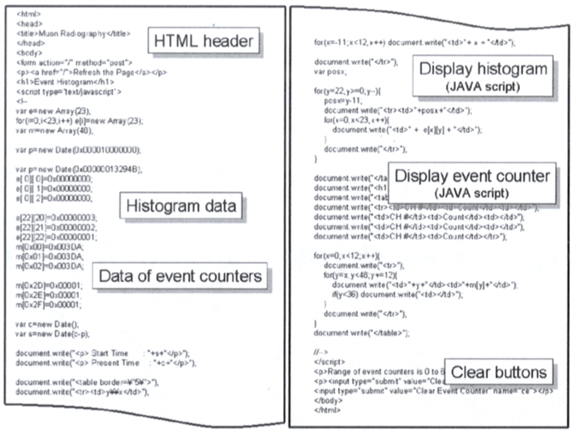

Fig 8. HTML source for a web page showing the histogram

Fig. 8 shows a HTML source file of the web page, which consist of three parts: fixed data, histogram data, and values of event counters. The fixed data are a HTML header, HTML codes, and Java scripts. The Java scripts are used to reduce load on this block. The fixed data are read from the ROM. The histogram data and values of event counters are read from the histogram memory and event counters, respectively. These data sources are selected by the data generator with the MUX when data for the web page are generated. The SiTCP transmits these data to the PC. The histogram is displayed on the web page on the remote PC.

IV. Test and Results

The power consumption of the readout module was measured, and a volcano was observed with the developed readout system.

The measured power consumption of the readout module is 2.5W. This power consumption is low enough to be supplied by a small solar-power system.

The readout system has been used to observe a volcano, namely, Mt. Iodake (main peak: 703 m in height) on Satsuma-Iojima island, located about 1000 km southwest of Tokyo, Japan, from July 2008. A small, prefabricated observation station was constructed near the foot of Mt. Iodake – at a distance from the peak of about 1.2 km. A photograph of the observation station is shown in Fig. 9 (a); the mountain behind the station is Mt. Iodake. The photograph on the right of Fig. 9 (b) shows the counter and readout module of the detection system used in this station. The other counter of the detectors is not shown. Since commercial power is supplied to this station, a solar power system was not used for the observation.

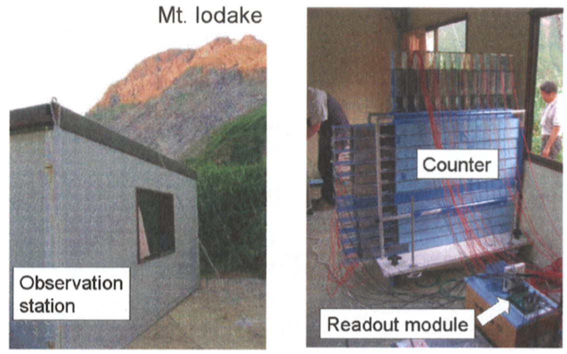

Fig. 9. Photograph of the observation station and detection system. (a) Observation station with Mt. Iodake in the background. (b) Detection system installed in the station (other counter not shown).

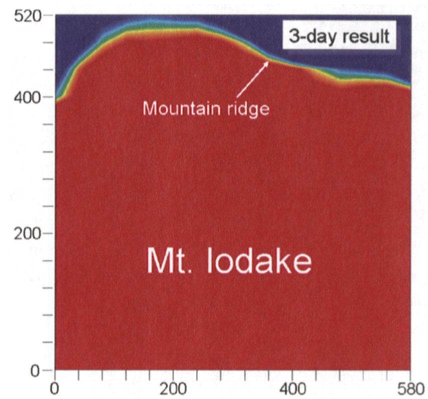

Fig. 10. A radiographic image of Mt. Iodake. The red and blue areas represent relatively high and low density, respectively.

Fig. 10 shows the first result obtained with this detection system, namely, radiographic image of Mt. Iodake. The red area represents relatively high density, namely, the count of detected muons is relatively low. The blue area represents relatively low density, namely, the count of detected muons is relatively high. This result was obtained from measurements over three days. The analysis process is as follows: correct efficiencies of detectors, remove high-frequency components of the image, and normalize by the value of the sky (i.e., blue area). The line of the mountain ridge is shown clearly. This result shows that the performance of the readout system is sufficient for cosmic-ray muon radiography experiments.

V. Summary

To meet the requirements of small size and low power consumption, a special readout module was developed for this system. The module processes detector signals and generates a histogram for the angular distribution of muons. The module size is 35×160×160 mm, its weight is 420 g, and its low power consumption is low, i.e., 2.5W. It is operated by remote PC using a web browser. The readout system makes it possible to employ a small solar-power system and a wireless Local Area Network (LAN). A detection system can therefore be constructed near a volcano, where there is no commercial power and access to an observation station is limited. Accordingly, a detection system incorporating the readout system was used for observing a volcano, namely, Mt. Iodake, in July 2008. This three-day-observation succeeded in obtaining the first clear, cosmic-ray muon radiography image of the volcano. This result shows that performance of the readout system is sufficient for future observations of other volcanoes by cosmic-ray muon radiography.

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