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R & D Studies for Very High Energy Gamma-Ray Astrophysics at Energies Greater than 10 TeV

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Abstract: In spite of more than 100 discoveries of TeV gamma-ray sources by the current imaging atmospheric Cherenkov telescope (IACT) arrays, Galactic cosmic ray accelerators up to the *knee* energies ($\sim$ PeV) still remain unclear. PeV Explorer (or PeX) is a future project of a relatively small IACT array, optimized to detect gamma rays of energies greater than 10 TeV and aiming to explore Galactic accelerators up to PeV energies. We present the status of our hardware R & D studies for this project and some extension plans.

Keywords: gamma rays — telescopes — instrumentation: detectors — cosmic rays — supernova remnants

1 Introduction

The atmospheric Cherenkov technique for detecting very high energy (VHE) cosmic gamma rays has been developed very quickly and steadily for the last 25 years. During this period, more than 100 gamma-ray sources have been found to be efficient particle accelerators at least up to the TeV energies [1]. Among these, about 10 sources are associated with supernova remnants (SNRs) and may be used to help solve the long-standing mystery of the origin of Galactic cosmic rays. To tackle this mystery, one should obtain evidence at least up to the *knee* energies ($\sim$ PeV) for a hadronic gamma-ray spectrum due to π^0 decays. RX J1713.7$-$3946 is the best studied SNR in the TeV regime because it is one of the brightest TeV sources, clear association with molecular clouds has been seen in the millimeter wave bands [2], and its precisely measured TeV spectrum seemed to be interpreted as of a hadronic origin [3]. However, the *Fermi* LAT team has recently reported their gamma-ray spectrum from this SNR in the GeV regime connecting smoothly to the TeV spectrum, and the overall spectral shape is consistent with a leptonic origin [4]. Moreover, the cutoff energy of 17.9 TeV of the spectrum [5] is too low to explain the primary particle spectrum extending up to PeV even if it is hadronic [6]. Hence, we have had no plausible gamma-ray source for the origin of Galactic cosmic rays up to the *knee*. There are other darker Galactic sources which have hard TeV spectra with no cutoffs and we need to observe them and other Galactic regions more deeply at energies greater than 10 TeV.

The TenTen concept has been proposed to explore the above issue as well as various astrophysical phenomena in the $>$ 10 TeV energy gamma-ray regime [7]. It is a future project for an array of 30–50 imaging atmospheric Cherenkov telescopes (IACTs) of a relatively small aperture (3–5 m diameter) and aims to achieve a 10 km^2 effective area for gamma rays with energies greater than 10 TeV. The concept of this IACT array is based on the simulation study by Plyasheshnikov et al. (2000) [8], which showed that the effective area of the array can cost-effectively be expanded by placing telescopes with larger spacing ($\gtrsim$ 300 m) and equipping imaging cameras of a larger field of view (FoV) such as $\sim$ 8°. This relation is schematically shown in Figure 1. The optimum array configuration must be determined using simulations so that the effective area per cost is maximized as a function of telescope spacing, aperture, and FoV (e.g. [10]). Sea-level sites are ideal for TenTen given the high energy focus. The SST (Small Size Telescope) array of CTA (Cherenkov Telescope Array) [9] is also a similar concept, and may realize the goal of a $>$ 10 TeV array.

We have started our R & D studies for one cell of TenTen consisting of 4 or 5 IACTs, which we call "PeV Explorer" or "PeX". One concern in the above method detecting Cherenkov photons at large core distances is possible degradation of angular and energy resolutions due to the

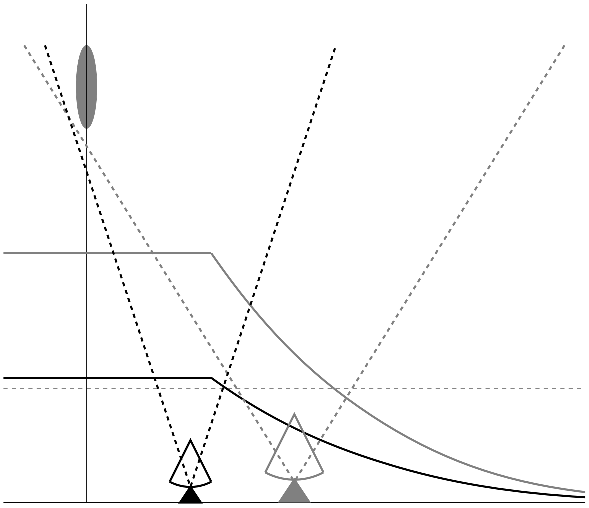

Figure 1: Schematic view showing a new concept of a sparse IACT array. Cherenkov photons emitted from the gamma-ray shower (upper-left ellipse) make a light pool on the ground (thick solid black line), which has a plateau area up to a radius of $\sim$ 100 m surrounded by a wider skirt area. In the existing IACT arrays, telescopes have been placed within the plateau area and triggered when the number of Cherenkov photons collected by the telescope exceeds the virtual threshold level (thin dashed line). The effective area can be expanded by detecting photons in the skirt area, requiring larger aperture and FoV (thick gray lines).

rapid drop of the Cherenkov photon density there. A new analysis method compensating this degradation has been developed utilizing the time gradient of a Cherenkov light image along its major axis [11]. The larger the distance between the gamma-ray source position and the centroid of the Cherenkov image in the FoV, the larger the time gradient is. Thus, the time gradient is a good distance estimator and can effectively be used to improve angular resolution with the so-called Algorithm 3 for reconstruction of the arrival direction [12]. The improved angular resolution does not only give a better sensitivity but also makes possible more precise morphological comparison of gamma-ray source distributions with molecular clouds which is very important in the discussion of emission mechanisms.

The optimum array telescope spacing of TenTen/PeV Explorer depends on the physics target of interest, which may demand a wide range of telescope spacings. We can avoid this risk in array optimization by constructing the array with movable telescopes like ALMA [13]. An example demonstrating flexibility of this “Mobile Telescope Array” is shown in Figure 2. We can get a better sensitivity with a sparse IACT array especially at high energies (this is based on the TenTen concept). In contrast, a dense IACT array gives better angular and energy resolutions as well as a lower energy threshold. In this paper, we present the status of our R & D studies of hardware for PeX, also focusing on the Mobile Telescope Array considered as an extension plan in the future.

2 Hardware R & D

2.1 Low Power Consumption Electronics System

To realize mobile IACTs for the future project described above, it is desirable to make movable telescopes run on their own local power supply, independent of cumbersome cables. High capacity batteries have very actively been developed for use in many companies and we can expect some batteries fulfilling our requirements being available in the future. Therefore, there is a need to reduce power consumption of the IACT system. We first started with developing a low power consumption electronics system with an application-specific integrated circuit (ASIC) implementing analog memory cell (AMC) circuits which sample voltages of a Cherenkov signal pulse with a speed of $\sim$ 1 GHz. We plan to optimize the system performance in terms of power consumption and cost by developing our own ASIC. Since there are no cables between the telescopes, observed data should be transferred via a wireless network on site.

2.1.1 Analog Memory Cell

The AMC circuit is a parallel circuit of capacitors and sampling switches. Each capacitor holds a signal voltage when its paired sampling switch is turned off. The sampling switches are sequentially turned off controlled by a delay line and an input pulse shape is recorded and read out by an ADC later. The specifications of the AMC circuit have been determined as follows. A sampling speed faster than 500 MHz and the analog bandwidth up to 500 MHz are necessary for the time gradient analysis. The sampling depth of 64–128 cells, corresponding to the 64–128 ns time window in the case of 1 GHz sampling speed, is sufficient considering the time dispersion of Cherenkov photons at large core distances [14]. The voltage resolution greater than 10 bits is selected to achieve a dynamic range of Cherenkov light amplitude measurements better than three orders of magnitude. The circuit diagram has been developed on the basis of previous work on readout of hybrid avalanche photo detectors (HAPDs) [15].

Some prototype AMC chips have been made with the 0.25 μm process of United Microelectronics Corporation (UMC). We selected 75 fF and 400 fF capacitors in order to control various parameters within acceptable levels and to compare with the previous work [16]. Performance of the prototype chips has been investigated with a test board shown in Figure 3. Noise levels of their pedestals were measured to be smaller than the amount corresponding to 1 bit of the external ADC and the requirement for the dynamic range was confirmed to be fulfilled. The analog bandwidth was also checked with sinusoidal input signals. The cutoff frequency is a factor of 2 or 3 smaller than of our 500 MHz specification even in the case of the best result

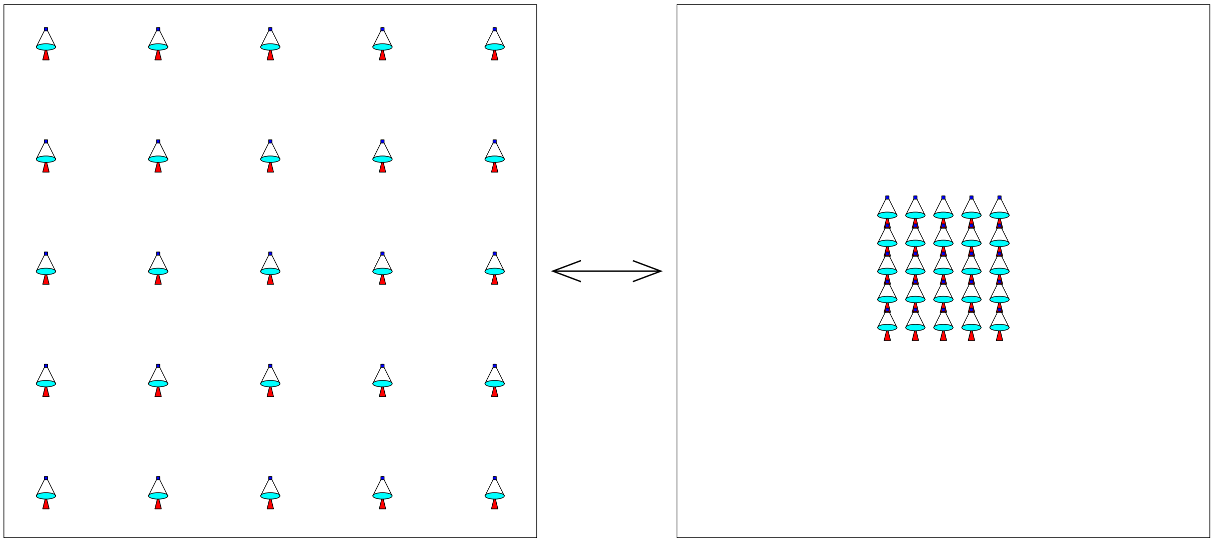

Figure 2: Two major configurations of the "Mobile Telescope Array" considered as an extension plan of TenTen. The sparse IACT array (left) has a larger effective area and hence gives a better sensitivity especially at high energies. In contrast, the dense IACT array (right) gives better angular and energy resolutions as well as a lower energy threshold. The Mobile Telescope Array gives us more flexibility by changing array configuration.

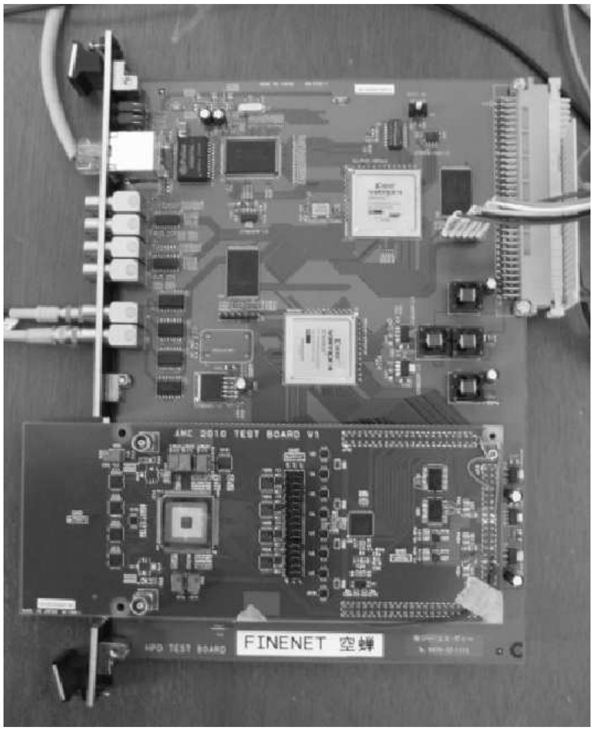

Figure 3: Test setup of the prototype AMC board. The AMC board at the bottom is connected to the module for readout. The AMC ASIC chip is located in the left-hand side of the AMC board.

of 75 fF and will be improved in the next prototype. The power consumption was measured to be about 180 mW for 64 cells including that of the external ADC and suppressed to a reasonable level. This ASIC chip can be compared to others under development (e.g. [17]).

2.2 Automatic Calibration System of Telescope Pointing

The pointing of each mobile telescope (or the directions of rotation axes) has to be calibrated every time after moving. This work can be a time-consuming burden if done manually, especially in an array of 30–50 telescopes. Therefore, some automatic calibration system must be prepared at least for rough measurements of axis directions (fine tuning can be done with a CCD camera taking pictures of bright stars). We have tested a GPS compass board (Hemisphere Crescent Vector OEM) with two GPS antennas (Novatel GPS-701-GG), which can measure the direction of the line connecting the two antennas using the real time kinematic (RTK) technique. We suppose that two GPS antennas are set on the optical axis of each telescope with some distance (< 4.5 m in this compass board). The elevation and azimuthal directions are measured and read out from the compass board every 100 ms and their accuracy can be improved by averaging accumulated data. Some long-time continuous measurements for 24 hr have been done to check the direction accuracy [18]. We confirmed that the accuracy better than 1 arcmin is achieved by accumulating data for 100 minutes in the case that the distance between the antennas is 4.5 m and this compass system can be used in rough measurements before fine tuning with a CCD camera. We also tried to measure directions of a CANGAROO-III telescope with this system equipped near the imaging camera but found that the system became unstable proba-

Figure 4: 3 m diameter Cherenkov telescope installed at the Akeno Observatory of ICRR.

bly owing to the multipath effect[1]. The calibration system must be carefully designed considering this effect for the future telescopes.

3 Summary and Future Plan

We are developing instruments for the future projects of VHE gamma-ray astrophysics at energies $\gtrsim 10$ TeV. The prototypes of the AMC ASIC chips for a low power consumption electronics system and the GPS compass system automatically calibrating telescope pointing have been made and tested. These are necessary for the mobile telescopes but can also be utilized effectively in the smaller array of PeV Explorer. A lithium-ion battery for a solar car was also obtained and is currently being tested for future use.

We have obtained a used Cherenkov telescope with 3 m aperture, which was already repaired except the mirrors (we plan to recoat them within a year), and installed at the Akeno Observatory of the Institute for Cosmic Ray Research (ICRR), University of Tokyo (Figure 4). This telescope can be utilized as a test bench for any future IACT array project including CTA. The electronics system under development will be installed in this telescope together with an imaging camera of ~ 32 photomultiplier tubes and a simple triggering system. We plan to do some test observations with this system, at least a part of which will be powered by the lithium-ion battery and demonstrated as the first battery-powered IACT system.

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