Performance and simulation of the surface detector array of the TAx4 experiment

K. Fujisue[1] on behalf of the Telescope Array Collaboration

[1] Institute for Cosmic Ray Research, the University of Tokyo, Kashiwa City, Chiba 277-8582, Japan

Abstract

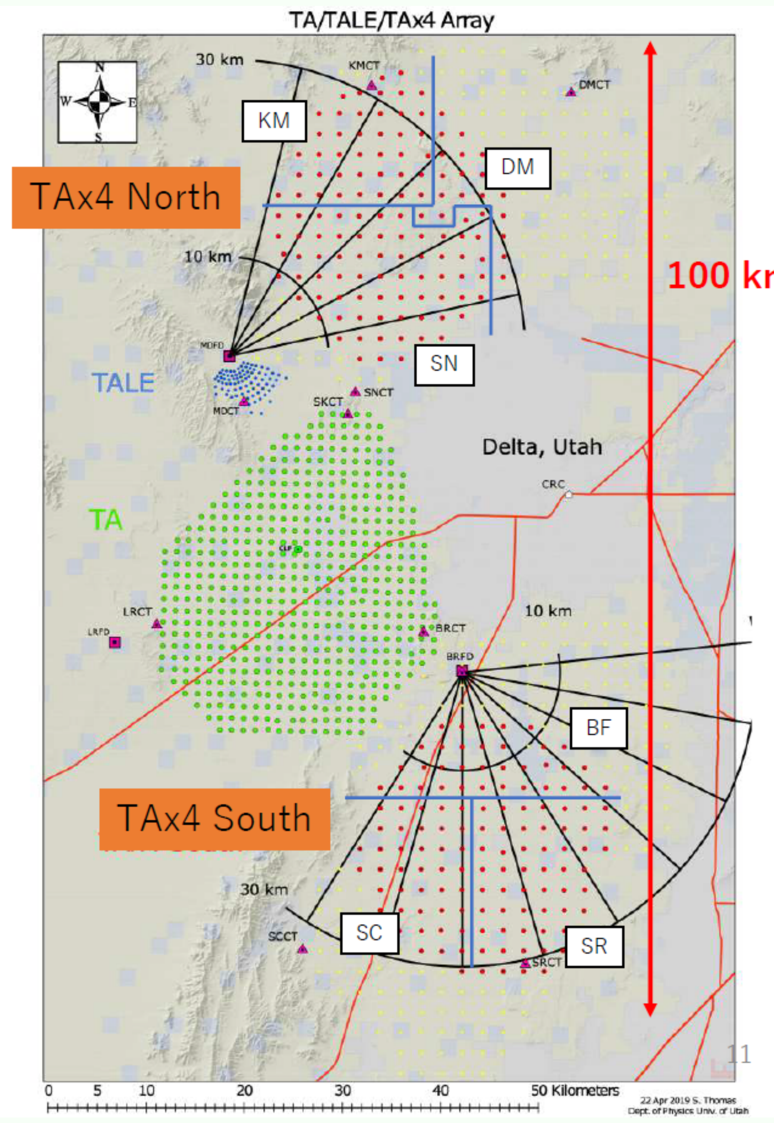
The TAx4 experiment is a project to observe highest energy cosmic rays by expanding the detection area of the Telescope Array (TA) experiment with newly constructed surface detectors (SDs) and fluorescence detectors (FDs). New SDs are arranged in a square grid with 2.08 km spacing at the north east and south east of the TA SD array. We use CORSIKA simulations and implement the calibration data of the new SDs to calculate the performance of the new SDs. We compare the data with the simulation and validate the performance of the SDs. The comparison and the performance will be shown in the presentation.

TAx4 surface detector

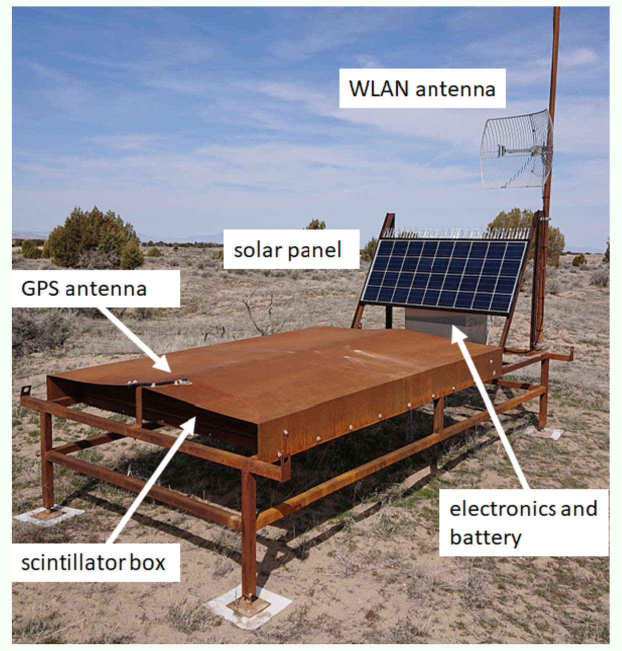
TA found evidence for a cluster of arrival directions of cosmic rays with E > 57 EeV (hotspot). To confirm this hotspot including subsequent TA anisotropy results, we plan to quadruple the TA to accelerate the data collection speed.

The current TA x4 SD array consists of 257 plastic scintillation detectors, deployed on a square grid with 2.08 km spacing, covering an area of approximately 2.5 times TA SD including TA SD.

The basic design of the TAx4 SD is the same as that of the TA SD. Each surface detector consists of two layers of plastic scintillators with PMTs, electronics package consisting of CPU for slow signal processing, CPLD for board control, 50 MHz sampling FADCs, FPGA for fast signal processing, GPS system, ADCs for monitoring, DACs for setting HV of PMTs, and solar power system with charge controller. The host electronics at the corresponding communication tower collects data stored at each SD using 2.4-GHz wireless LAN communication.



Layout of the Telescope Array. The red circles denote deployed TAx4 SDs. The yellow dots denote planned TAx4 SDs. The purple triangles denote the communication towers. The TAx4 SD array is divided into six sub-arrays (KM, DM, SN, BF, SC and SR). The blue lines show the boundaries of TAx4 SD sub-arrays. The green circles denote the TA SDs. The blue circles denote the TALE SDs. The purple squares denote the fluorescence telescope stations.



A photograph of a surface detector

Trigger/DAQ and Monitor

When both PMT signals of a surface detector exceed 0.3 MIP threshold (**level-0 trigger**), waveform information is recorded locally in a buffer with a time stamp by a GPS. When signals exceed 3 MIP threshold (**level-1 trigger**), the level-1 trigger timing information is locally stored in a trigger table, which is transmitted at Hz to the host electronics at the corresponding communication tower. The host electronics decides the final coincidence trigger based on the trigger tables from SDs in the sub-array with the requirement of three adjacent SD hits and a **14-μs** time window (**level-2 trigger**) to collect an air-shower event. For comparison, The **TA** SD uses 8 μs time window. Finally, waveform data from SDs are transmitted to the host electronics.

We have a real-time monitor system that works in the background for SD calibration and maintenance. We have the following monitors from each detector:

(every second)

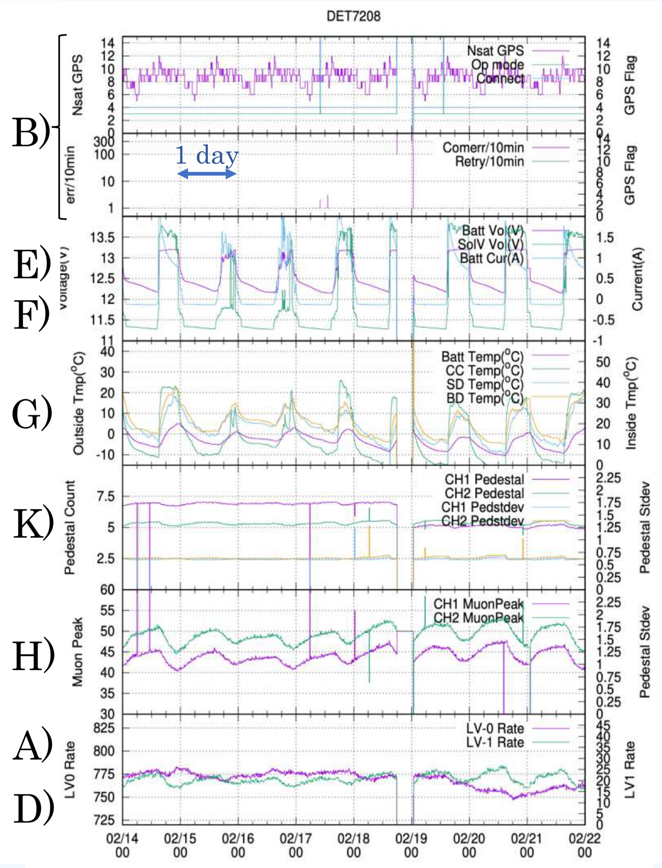
A) No. of events with >3 MIP coincidence (for the level-1 trigger rate)
B) GPS time stamps (GPS status)
C) Max. clock count between 1 PPS

(every minute)

D) No. of events with >0.3 MIP coincidence (for the level-0 trigger rate)
E) Battery voltage, current
F) Voltage of solar panel,
G) Temperature at several positions and humidity inside the detector

(every 10 minutes)

H) Charge histogram (for gain calibration)
I) Pulse height histogram (for linearity check)
J) Charge histogram (for linearity check)
K) Pedestal histogram
L) GPS condition flag
No. of detected satellites
the condition of GPS antenna connection



Example of monitor of a detector

MC simulation

We use an analysis method same as the TA SD with Monte Carlo (MC) simulation data [1] to understand the performance of the TAx4 SD, and check the quality of the real data. We use a library of showers generated by the **CORSIKA** program using **QGSJET-II-04** to model high-energy hadronic interactions (*), FLUKA to model low-energy hadronic interactions, an EGS4 to model electromagnetic interactions. We use a dethinning algorithm that enables us to reconstruct the information lost using the CORSIKA thinning option in the same way as the MC simulation of the TA SD. For this study, proton showers were used.

(STEP1)

A shower library was created with 6200 dethinning CORSIKA showers with **primary energies** distributed in $\Delta\log_{10}E = 0.1$ bins between $10^{17.5}$ and $10^{20.5}$ **eV**. The number of showers in each bin is 200. These showers are simulated with **zenith angles** θ from 0° to 60° assuming an isotropic distribution ($\sin\theta\cos\theta$ distribution at the detector level).

(STEP2)

For each simulated event, all shower particles that strike the ground are divided spatially by their landing spots into **6x6 m² "tiles"** on the ground and into 20 ns wide bins by their arrival time.

(STEP3)

The total energy deposited by all particles that arrived in a particular tile, and into a virtual TAx4 SD counter located at its center, is calculated using the GEANT4 simulation package. The energy deposited as a function of time is stored in the shower library. In the final step of the shower library generation, each titled shower is sampled about 600 times through a detailed simulation of the detector, including Poisson fluctuation of energy deposit in the detector and electronics response and so on. The shower core positions, the azimuth of the shower axis, and event times are varied in this process. The detector simulation utilizes **real-time calibration** data from the TAx4 SD.

[1] B. T. Stokes, D. Ivanov, J.N. Matthews, G.B. Thomson, Astropart. Phys. 35 (2012) pp. 759-766.

(*) For the TA SD analysis, QGSJET-II-03 is used.

Reconstruction

Two fits are used to reconstruct the properties of the cosmic rays measured with the TAx4 SD in the same way as the TA SD.

(Geometry fit)

The fit to the times when detectors were struck, using the modified Linsley shower-shape function, is made to determine the arrival direction and the core position of the event.

((Energy Estimation)

The primary energy estimation of events is established by measuring the charge density at 800 meters in lateral distance from the shower axis (S800). The measured particle densities from the detectors are fit to the modified AGASA lateral distribution function (LDF). The energy is firstly estimated from the table of S800 vs. sec(θ) for the true MC energy.

For the TA SD, the energies obtained from the energy estimation table are calibrated against the TA fluorescence detector using events that are observed simultaneously by both TA SD and FD. Comparing the energy scale 1.27 of the TA SD MC using QGSJET II-03 hadronic interaction model, we use the energy scale factor of 1.20 for the final energy estimation from the TAx4 SD MC using **QGSJET II-04** hadronic interaction model here in this conference.

(Performance of TAx4 SD from MC)

We obtained 28% energy resolution, 2.4-degree angular resolution of cosmic rays with E > 57 EeV under the condition described in "Data and MC comparison" section.

(Example of the reconstruction of a real data)

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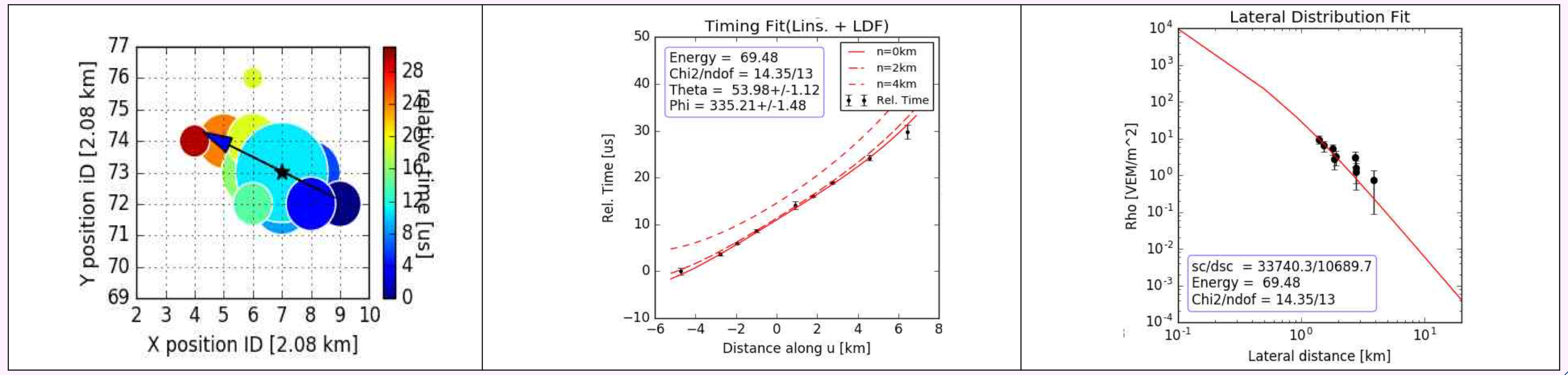

Data and MC comparison

The real collected by KM sub-array (about 1/8 of the total added) for 1 year (Oct. 8, 2019 to Oct. 7, 2020) are used here. The data and MC comparison is performed after the quality cuts of (i) N_{SD}>=4, (ii) zenith angle θ < 55 degrees, (iii) χ^2/ndof < 4 and (iv) directional error δ_{dir} < 8 degrees , (v) fractional error of S800 < 0.50, and (vi) reconstructed core position of at least 400 m away from the edge of the array. In each histogram, the real data are represented by blue crosses and MC simulation data are represented by solid red lines. The first two histograms show the distributions of reconstructed core positions on the (a) east-west and (b) north-south axes. The third histogram (c) shows the number of spatially and temporally contiguous counters per event. The fourth and fifth histograms show the total signal per detector (d) and per event (e). In the sixth histogram (f), we see the χ^2 per degree of freedom for the combined fit (simultaneous geometry and lateral density fit). The next two histograms show the distribution of θ (g) and azimuth angle. The last two histograms show the distribution of S800 (i) and estimated primary energy (j) values. The real data and the MC simulation agree within statistical errors.