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Telescope Array Low-energy Extension (TALE) hybrid

Shoichi Ogio, for the Telescope Array collaboration[*†]
Graduate School of Science, Osaka City University
E-mail: sogio@sci.osaka-cu.ac.jp

Routine hybrid observations of the surface detectors (SD) in conjunction with the fluorescence detectors (FD) of the Telescope Array Low-energy Extension (TALE) began in November 2018. In this presentation, we will describe the data acquisition system, including the design of the SD array, as well as the FD-to-SD cross-trigger. We will report on the status of operations, and on the preliminary analysis of the TALE hybrid data.

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[*]Speaker.
[†]The other affiliation of S. Ogio: Nambu Yoichiro Institute of Theoretical and Experimental Physics (NITEP), Osaka City University

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1. Introduction

The Telescope Array (TA) experiment consists of a surface detector (SD) array of 700 km^2 in coverage and 38 fluorescence detectors (FDs), and it continues observations of ultra high energy cosmic rays with energies above 10^{18} eV from 2008 [1] [2]. In 2012 we started the Telescope Array Low-energy Extension (TALE) experiment additionally installing ten additional FDs pointing at higher elevation angles, *i.e.*, observing lower energy cosmic rays, than TA FDs. TALE FDs were located just beside the TA FD station at the north corner of the TA SD array, which is called Middle Drum station. The effective threshold energy of the experiment is successfully extended to below to lower than 10^{16} eV. We reported the cosmic ray energy spectrum in the wide energy range from 2 PeV above 10^{20} eV[3]. The energy spectrum for wide energy range has a complicated structure showing several kinks and dips rather than a simple power law. We can see not only the steepening at $10^{19.6}$ eV and the ankle at $10^{18.7}$ eV, but also a flattening at around $10^{16.2}$ eV and a steepening at around $10^{17.0}$ eV. While the highest energy cosmic rays above 10^{19} eV are probably the extragalactic origin, the galactic and the extragalactic components coexist in the lower energy range lower than 10^{18} eV, and the spectrum of the extragalactic component has convolved information of source spectra, the redshift evolution of sources, integration of energy losses during propagations and the shielding by the galactic magnetic magnetic field. In contrast, the spectrum of the galactic component has a convolution of the physics processes limiting the accelerated energy at galactic sources and the confinement of cosmic rays in the Galaxy.

In order to unfold and resolve the convolved information in the galactic and the extragalactic spectra, precise measurements for the chemical composition and for the arrival direction distribution are essentially needed as well as a precisely measured energy spectrum. Moreover, the energy determination and/or the estimation of the acceptance by an experimental apparatus strongly depend on the assumed chemical composition in Monte Carlo calculations. For this reason, the study of the chemical composition is very important.

For these precise measurements, we constructed the TALE SD array covering 40 km^2 with 80 SDs below the observation volume by TALE FDs, and we developed the hybrid observation system for the SD array to be operated with FD-to-SD cross-triggers. Additionally obtained information about the core location and impact timings measured by SDs will improve the event reconstruction accuracy of FD measurements, and as a result, the Xmax determination error will be improved to 20 g/cm^2.

2. Telescope Array Low energy Extension experiment

The TA site is located in the desert at about 1400 m above sea level, centered at 39.3°N and 112.9°W in Millard county, Utah, USA, about 200 km southwest of Salt Lake City. The control center to support operations of the TA, TALE and TA $\times$ 4 instruments is in the city of Delta, which is located near the northeast side of the TA SD array. For hybrid observations the site needed to be located in a semi-desert area with little light pollution from the town. The dry climate allows us to have a high duty cycle for FD-SD hybrid exposure, which is about 10% of real time.

The TA SD array consists of 507 scintillation counter SDs, which were deployed in a square grid with 1.2 km spacing to cover a total area of approximately 700 km^2. The sky above the array

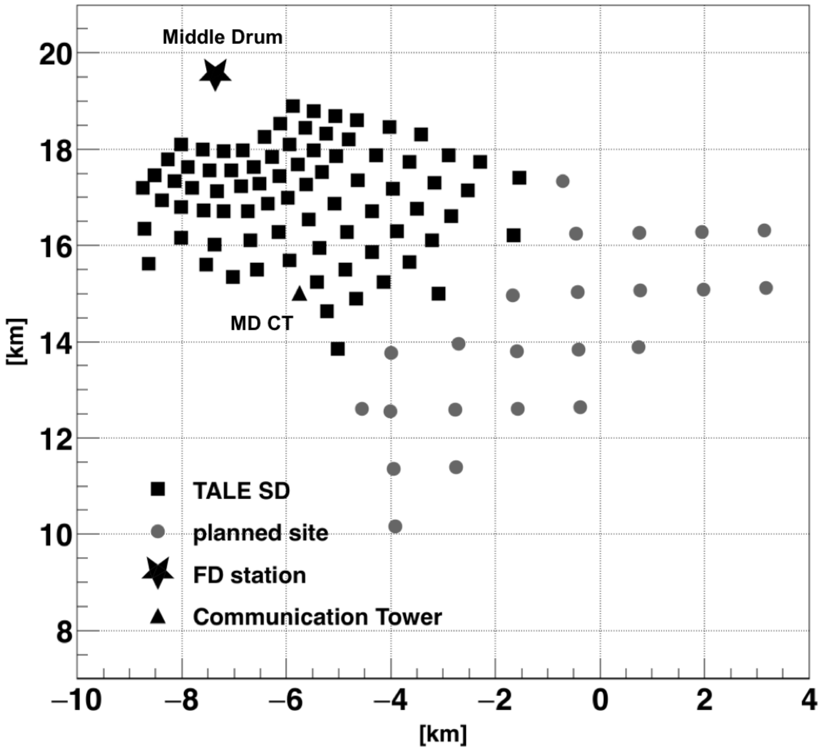

Figure 1: The layout of TALE in Utah, USA. Squares denote 80 SDs and circles are the planned locations of SDs for the connecting region between TA and TALE. The array controlled with a host PC at the communication tower denoted by a triangle and labeled "MD CT". The star symbol denote the Middle Drum station of the TA FDs and the TALE FDs.

is observed by 38 TA FDs, located in three stations.

The TALE SD array consists of 80 detector units, which were deployed to cover a total area of approximately 40 km^2. Fig. 1 shows a layout of the TALE experiment. As shown in this figure the spacing of 40 SDs in the distance range of 3 km from the TALE FD station, which is labeled "Middle Drum" in the figure, is 400 m, and the spacing of the other 40 SDs, which are located in the range from 3 km to 5 km from the TALE-FD station, is 600 m. In the connecting area between the TALE SD array and the TA SD array, 23 planned locations for additional SDs are prepared with 1.2 km spacing for further expansion in the future. Each SD has a plastic scintillation counter of 3 m^2 in size, and transmits SD data via a wireless LAN module. Moreover each detector is powered by a solar panel and a battery.

TALE FD station located at TA Middle Drum (MD) site has ten FD telescopes, which observe $31-59^{\circ}$ in elevation, above the field of view of the original TA FD MD station. The TALE FD station was completed in the fall of 2013, and has been taking data in monocular mode since that time.

2.1 Surface detector

TA SD is designed to be robust and durable for long-term exposure to the desert environment where the detector temperature ranges from -25°C to +50 °C with large diurnal variations. TALE SD holds the same basic design as TA SD based on its satisfactory performance in operation for more than 10 years.

Fig. 2 shows on of the deployed TALE SDs. The communication antenna of a SD with adjustable height is mounted on a 3 meter long steel pole. The deployed SDs communicate with the communication tower called Middle Drum Control Tower (MD CT) shown in Fig. 2. The communication tower has the role of collecting and distributing trigger information from the SDs and the FDs at the Middle Drum station.

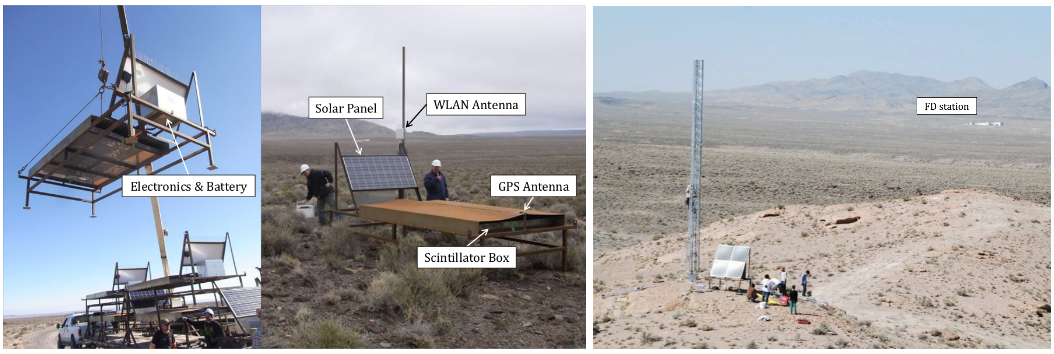

Figure 2: (*left*) A deployed SD in the field. The electronics box and scintillator box are on the steel frame. An electronics unit is installed under the solar panel, and the scintillator box is mounted on the platform under the roof. (*right*) The Middle Drum communication tower for the TALE SD array. There are four solar panels for the power supply, and the stand for the panels contains batteries, host PC and network instruments. The Middle Drum FD station is visible in the distance.

A square solar panel (Kyocera KD145SX-UFU, 1500 × 668 mm^2) is mounted on the platform to supply power to the electronics. Front-end electronics and a battery are in contained in a box made with 1.2 mm thick stainless steel, is mounted behind the solar panel. A larger box which contains scintillators and PMTs is mounted under a 1.2 mm thick iron roof to protect the scintillation detector from large temperature variations induced by direct sunlight.

The design and the components for 35 scintillation detectors of the 80 TALE SDs are entirely identical to those of TA SDs. The scintillation detector for the other 45 TALE SDs is newly designed and having common specifications with the scintillation detectors for the TAx4 SD experiment[4]. Fig. 3 shows a schematic of the inside of the box of the newly designed scintillation detector. Each SD consists of two layers of plastic scintillator, each of which has an area of 3 m^2 and a thickness of 1.2 cm. A stainless steel plate which has 1 mm in thickness is inserted between the layers. As show in Fig. 3, each scintillator layer consists of two segments. The size of one segment is 1.5 m × 1.0 m. On the top side of the scintillator segment, there are grooves in parallel along the length of the segment. The span of grooves and the total number of grooves are 4.0 cm and 56 per layer, respectively, and the depth of a groove is 1.5 mm. Scintillation light is collected through wavelength-shifting fibers (WLSF) (Y-11, Kuraray Co. Ltd.). The length of a WLSF is 6.1m. One WLSF is wrapped around one turn on the surface and laid along two grooves. Therefore, the total number of WLSFs is 28 per layer. The averaged signal strength on the photo-cathode for one minimum ionizing particle (MIP) is 23.3 ± 2.3 p.e..

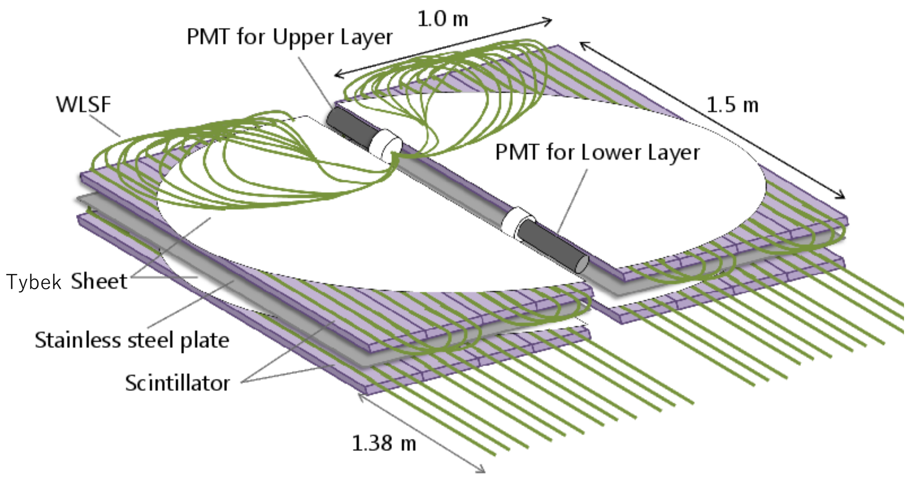

Figure 3: Inside of a scintillator box with scintillator plates, WLSFs and PMTs. A total of 28 WLSFs are laid on each layer and transmit scintillation light to a PMT.

Both ends of the WLSFs from a layer are bundled together and connected to a PMT (HAMAMATSU R8619). All the PMTs are calibrated to obtain the relation between high voltage and gain, and they are operated to keep the typical gain at 5×10^6. Under this condition, the linearity of the SD is kept to better than 7% up to the FADC maximum limit.

3. Detector Electronics

Almost all the design and specifications except the wireless LAN module and the related firmware are identical with those for TA SDs. The output signals from PMTs are digitized by a 12 bit FADC with a 50 MHz sampling rate on the CPU board. Signal greater than approximately 0.3 MIPs are stored in a memory buffer on the CPU board as Level-0 trigger data. The stored waveform is 2.56 μs long (128 FADC bins). Signals greater than 3.0 MIPs are stored as a Level-1 trigger data, which are sent to a single-board computer, called "host PC", which controls trigger decision and data acquisition processes at the MD CT, via a wireless LAN module (WVCWB-R-022(05), WiViCom Co., Ltd.) using UDP protocol. The local trigger rates are about 750 Hz for Level-0 and about 20 Hz for Level-1.

The synchronization of electronics of the SDs is done by PPS signals received by GPS units(IL-GPS-0030-B, i-Lotus). Time stamps are produced with a precision of 9.4 ns. Each SD unit described above is powered by one solar panel and one deep cycle battery (DC100, C&D Technology Inc.). Please see Section 3.2 in reference [1] for details of common design and specification of the electronics for TA/TALE SDs.

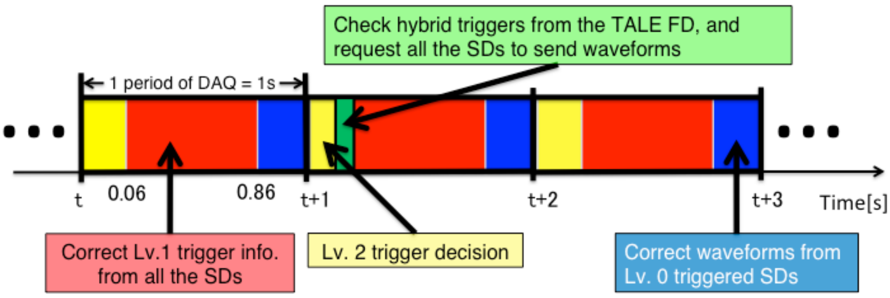

Figure 4: This is a time chart of the DAQ cycle of the TALE SD array. For each period the start-point is synchronized with the GPS PPS signal. The single DAQ cycle to recored an air shower event data continues in the following steps. (1, *Red*) The host PC requests/receives the most recent Level-1 trigger information including a Level-1 trigger time table. (2, *Yellow in the next period*) Event trigger, called Level-2 trigger, decision. (3, *Green*) Check hybrid trigger signals. With the Level-2 or the hybrid trigger trigger the host PC requests each SD to transfer waveform data. (4, *Blue, in the following periods*) The host PC corrects waveforms.

4. Data communication and air shower triggers

There is a single-board computer, called "host PC", (Raspberry Pi 2 model B) at the MD CT for controlling trigger decision and data acquisition processes. Fig. 4 shows a time chart of the DAQ cycle switching processes running on the host PC. The DAQ cycle is synchronized with the PPS signals. In one DAQ cycle, the host PC requests each SD to send the most recent (one second before) Level-1 trigger information including a time table in the previous one second period, and it receives the data immediately. The data size of the information and the time required for transfer depend on the Level-1 triggering frequency, and the averages are 160 bytes and 5.9 ms, respectively. From the Level-1 trigger time tables of all the SDs, an air shower event trigger is generated when any five SDs are coincident with in 8 μs. We call this trigger the Level-2 trigger, and the current Level-2 triggering rate is 0.002 Hz. The host PC checks hybrid trigger signals from the TALE FD followed by the Level-2 trigger decision process. The hybrid trigger condition on the TALE FD DAQ system is very simple, which is the number of hit PMTs > 5 and the event duration > 500 ns. The hybrid triggering rate is about 0.05 Hz. With the Level-2 or the hybrid trigger trigger the host PC requests each SD to transfer waveform data within $\pm$ 32 μs from the trigger timing, and the host PC corrects waveform data in the next periods.

For stable observation and calibration in later analysis, the status, the environment and the responses of SDs need to be monitored continuously. For it is purpose, a monitoring process runs on each SD in a 10 min cycle. The size of monitoring data for 10 min is 9600 bytes, and the data are divided into 600 subsets. Each subset is sent along with a Level-1 trigger time table.

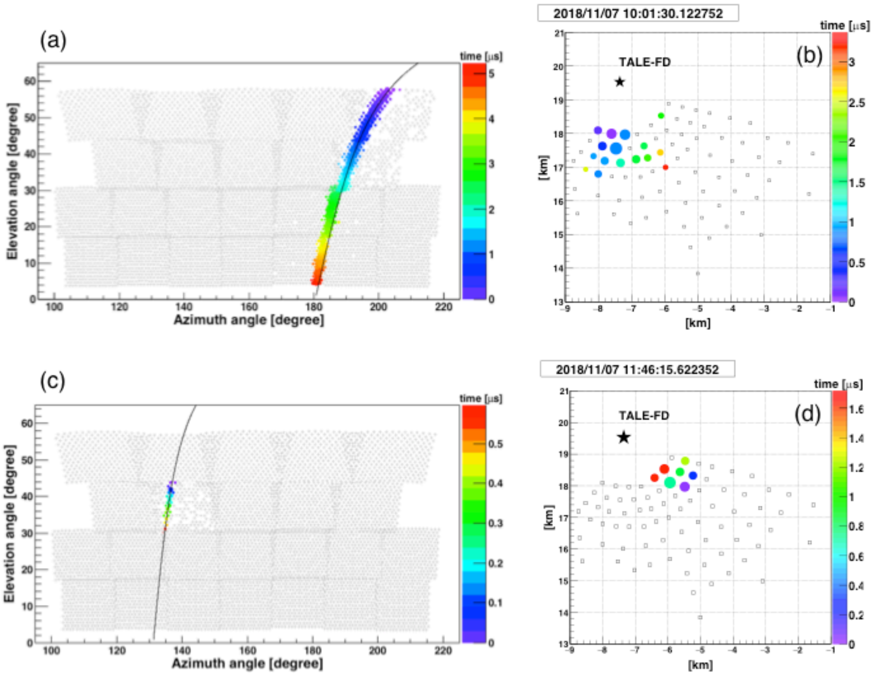

Figure 5: Two hybrid events observed in Nov. 7, 2018. (a) and (c) are observed images taken by TALE FDs (above 30°) and TA MD FDs (below 30°).Hit PMTs are indicated with colors indicating relative arrival time. (b) and (d) are event displays on the TALE SD array. The size and color of each marker shows the relative signal strength and arrival time. The hybrid event shown by (a) and (b) is a relatively high energy event, and the energy and Xmax are determined by our hybrid analysis programs as $\log E = 17.94$ and Xmax $= 823$ g/cm^2. The event shown by (c) and (d) is a relatively low energy event, which energy is lower than 10^{17} eV.

5. The hybrid observation and data analysis

The total of 80 SDs were deployed by the end of February 2018 and the TALE SD array started operation in March 2018. The extended hybrid trigger observation started in November 2018. Fig. 5 shows real hybrid event samples taken in November 2018. Currently, we are developing the hybrid Monte Carlo/analysis programs and tuning the programs. In principle, the hybrid analysis method reduces the number of the fitting parameters and improved the determination accuracy of the shower geometry, as shown in Fig. 6.

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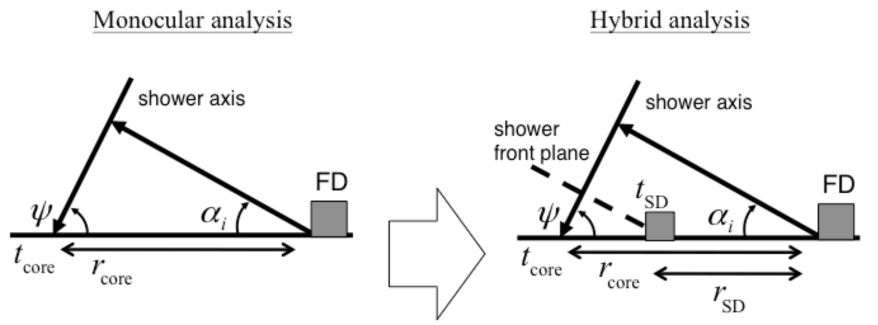

$$t_i = t_{\text{core}} + \frac{1}{c}\frac{\sin\psi - \sin\alpha_i}{\sin(\psi+\alpha_i)} r_{\text{core}}$$

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$$t_{\text{core}} = t_{\text{SD}} + \frac{1}{c}(r_{\text{core}} - r_{\text{SD}})\cos\psi$$

Figure 6: The schematics of the monocular and the hybrid analysis for the shower geometry reconstruction. Moreover the relations between the measured values, which are t_i, α_i and the fitting parameters, which are t_{core}, r_{core} and ψ. In the hybrid analysis the two observable, t_{SD} and r_{SD}, are added to the relation of the monocular analysis, and as a result the number of the fitting parameter is reduced to two and the geometry determination accuracy is improved.

University of Tokyo. The experimental site became available through the cooperation of the Utah School and Institutional Trust Lands Administration (SITLA), U.S. Bureau of Land Management (BLM), and the U.S. Air Force. We appreciate the assistance of the State of Utah and Fillmore offices of the BLM in crafting the Plan of Development for the site.The people and the officials of Millard County, Utah have been a source of steadfast and warm support for our work which we greatly appreciate. We gratefully acknowledge the contribution from the technical staffs of our home institutions. The full acknowledgements are found in the contribution paper for the highlights of the Telescope Array experiments in this conference proceedings.

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