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Development of the TALE Surface Detector Array

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TALE, the Telescope Array Low Energy extension is designed to lower the energy threshold of the Telescope Array to about $10^{16.5}$ eV. The TALE surface detector will include an infill array of 76 scintillation counters (40 with 400 m spacing and 36 with 600 m spacing) and an addition to the Telescope Array surface detector array of 27 counters. We have already deployed 35 counters with 400 m spacing in April 2013. For the additional 68 counters, we will use refurbished scintillation counters used in Akeno Giant Air Shower Array (AGASA). Each of the detector consists of AGASA scintillators, a new PMT and an updated electronics used for the Telescope Array surface detector. Here we report the status of the detectors and simulation.

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1. Telescope Array Low Energy extension (TALE) experiment

The Telescope Array (TA) experiment consists of the surface detector (SD) array of 700 km^2 coverage and 38 fluorescence detectors (FDs), and it continues observations of ultra high energy cosmic rays with energies above 10^{18} eV from 2008. In 2012 we started the Telescope Array Low Energy extension (TALE) experiment additionally installing ten FDs pointing 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 as shown in Figure 1, and the effective threshold energy of the experiment is successfully turned down to lower than 10^{16} eV. We reported the cosmic ray energy spectrum in the wide energy range from $10^{15.9}$ eV above 10^{20} eV[1]. 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} eV and a steepening at around 10^{17} eV. These kinks below 10^{18} eV have been already reported KASCADE-Grande[2], Tunka[3], IceCube[4] and Yakutsk[5].

It has complicated structures showing several kinks and dips rather than a simple power law. In contrast with the ultra high energy region above 10^{18} eV where the extragalactic cosmic rays are dominated, the galactic and the extragalactic components coexist in the lower energy range than 10^{18} eV, and the extragalactic component spectrum has convolved information of source spectra, the spacial distribution of extragalactic sources, integration of energy losses during propagations and the shielding by the galactic magnetic magnetic field. Moreover, the galactic spectrum has a convolution of the physics process limiting the accelerated energy at galactic sources and the confinement of cosmic rays in the Galaxy.

Resolving the convolved information requires an energy spectrum measured with a high statistics and an energy-independent detection efficiency, arrival direction information measured with a constant exposure and a precisely measured chemical composition. For these precise measurements, we will construct the TALE hybrid detector with installing the air shower array of 70 km^2 with 103 SDs in the FOV area of the TALE-FDs as shown in Figure 1. There are three different detector spacing. We plan to install 40 SDs with 400m spacing within the distance range of 3 km from the TALE-FD station, and 36 SDs with 600m spacing in the range from 3 km to 5 km from the TALE-FD station. In the connecting area between the TALE high detector density area and the TA-SD array, 27 detectors will be installed with 1.2 km spacing.

Based on simulation studies, the expected number of events by the SD array is 50,000 per year with the mode energy of $10^{16.5}$ eV, and the expected number of hybrid events is 5,000 per year with the mode energy of $10^{17.3}$ eV. This air shower array has 100 % detection efficiency for energies above 1.4×10^{17} eV, and hybrid observations with FDs provides a remarkable improvement in the Xmax determination achieving the error of 20 g/cm^2 comparing with the monocular FD resolution of 40 g/cm^2.

Comparing with the low energy extension projects in Pierre Auger Observatory, called HEAT and AMIGA, our main advantages are the lower threshold energy (AMIGA has 100 % efficiency for energies above 3×10^{17} eV[6]) and the energy scale indirectly calibrated with an electron accelerator called Electron Light Source (ELS)[7].

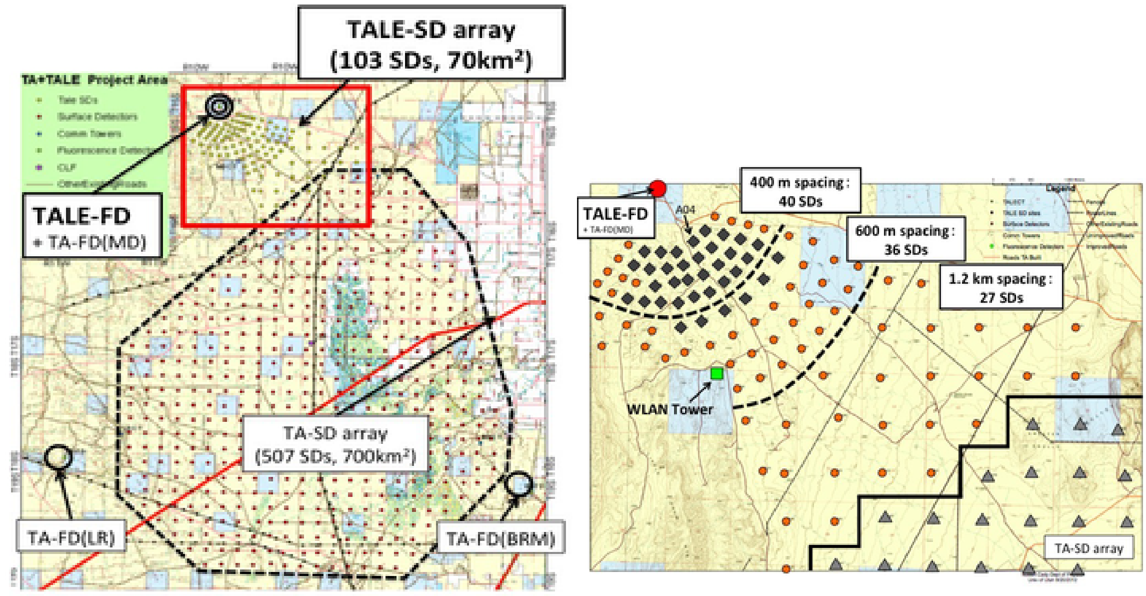

Figure 1: (*Left*)A map of the TA experiment site. The small dots and the open circles indicate the TA-SD locations and the TA-FD stations, respectively. The locations of the TALE-FD station and the TALE-SD array area are also shown. (*Right*)The close up of the TALE-SD array area. The rhombus markers show the installed SD's locations. The arrangement of the small markers are planned arrangement for TALE-SDs. The triangles are TA-SDs. The filled large circle and the open square show the TALE-FD station and the communication tower, respectively.

2. Development of the electronics for TALE-SD

In the 400 m spacing area there are 35 SDs deployed in 2013 as shown in the right panel of Figure 1 with the gray rhombus markers. Among them, 16 SDs operate as the TALE-SD array with the spare electronics for TA-SD.

However, today the wireless LAN modem used in the TA-SD electronics is unavailable, so then the further production of the precise copy of the original is not possible. Then, we have designed a new electronics for TALE-SD consisting of a new, available WLAN module (WiVicom, WVCWB-R-022F) and the other parts which are the precise copy of the original.

A prototype of the new electronics and its block diagram are shown in the left and right pictures of Figure 2, respectively. With the introduction of the new WLAN module, the updates of the firmware for the FPGA and the software for the CPU are needed. We continue to develop new electronics and its software in Osaka City University.

A field test of long distance communication between the new electronics had carried out in the TALE-SD area in Dec. 2014–Jan. 2015. The new electronics were installed at the communication tower and the SD called A-04. We confirmed stable communication and data transfers between the separated electronics.

We continue to carry out another test in the campus of Osaka City University. We have prepared three SDs of 0.25 m^2 area. These detectors are precise copy of the TA-SD except the size of plastic scintillators and the length of wavelength shifter fibers. The three prototype TALE-SD electronics were installed in the detectors, and the other is operated as a communication tower's

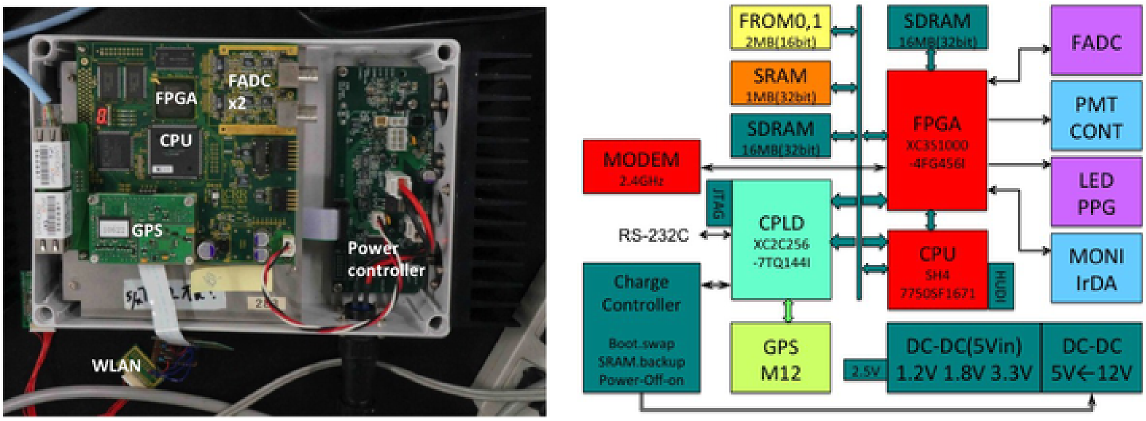

Figure 2: (*Left*)A picture of a prototype electronics for TALE-SD. (*Right*)A block diagram of the prototype electronics.

host electronics, and they are running as an air shower array with the identical operation mode as the TA-SD array. The threshold level of each SD is set at one minimum ionizing particle, and the array DAQ are triggered with three fold coincidence. The SDs are located inside a building as shown in Figure 3, and the spacing is about one meter, the current triggering rate is 10-30 Hz. The communication error rate is about 0.03 %, and this value is consistent with the current error rate in the TA-SD array.

Figure 3: The setup for the array test of the prototype electronics.

3. Test of AGASA surface detector

There are two options for the design of the TALE-SDs. One option is precise copy of the

TA-SD. The other option is reusing of the scintillators and the detector boxes used in the Akeno Giant Air Shower Array (AGASA) experiment[8].

One TA-SD consists of two layers of 3 m^2 area and 1.2 cm thick plastic scintillators, 208 wavelength shifter fibers of 5 m length, and two one–inch PMTs. The measured uniformity for a vertically incident muon is 5-10 %. On the other hand, one AGASA detector has nine 50 cm $\times$ 50 cm $\times$ 5 cm plastic scintillator and one five–inch PMT. The total area is 2.2 m^2. The dimension of the AGASA detector is shown in Figure 4.

Today, about 900 AGASA scintillators are stored in the Akeno Observatory[9] of Institute for Cosmic Ray Research, University of Tokyo. Among these scintillators, 15 scintillators were randomly sampled, and for each sample its scintillation yield and the position dependence of the yield were measured. The fluctuation (the sample standard deviation) of the scintillation yield among different samples is 7 %, and the fluctuation among different positions is 2 %.

The uniformity of an AGASA detector for a vertically incident muon is calculated with Geant 4 simulations. The uniformity depends on the reflectivity of box's surface and the photocathode location. When the reflectivity is 95 % and the photocathode is located on the same level of the scintillators' surface, the difference between the detected number of photoelectrons for a vertical muon at the distance of 20 cm from the PMT center and that of 100 cm is 10 %.

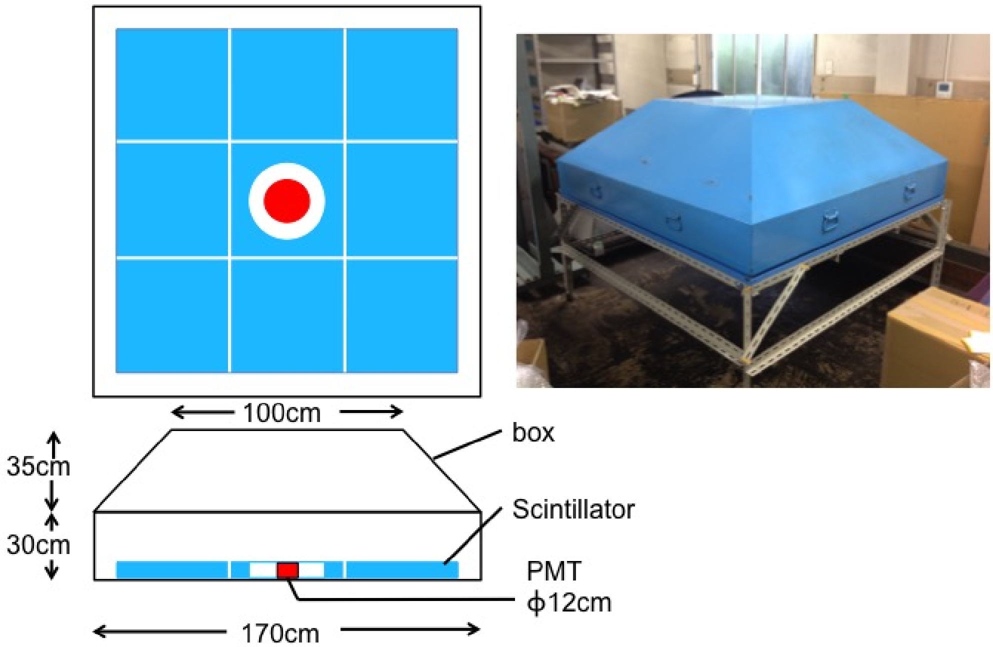

Figure 4: (*Left*)A section view of an AGASA detector. (*Right*) A picture of the detector.

4. Summary

TALE is an extension project of the TA experiment to lower the energy threshold down to $10^{16.5}$ eV. We plan to construct the hybrid detector with installing ten FD telescopes and an air shower array of 67 km^2 with 103 SDs. The FDs and 16 SDs have already installed and their operations are continued from 2013. Moreover, we obtained funds (Grant-in-Aid for Scientific Research(S) from Japan Society for the Promotion of Science) to construct other 70 SDs and to continue the TALE experiment. The constructions and installations of the TALE-SD array are scheduled to be finished in 2017 JFY and to start its full operation.

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