

The Telescope Array Low-energy Extension

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The Telescope Array Low-energy Extension (TALE) experiment is a hybrid air shower detector for observation of air showers produced by very high energy cosmic rays above $10^{16.5}$ eV. TALE is located at the Telescope Array (TA) experiment site in the western desert of Utah, USA. TALE has a Surface Detector (SD) array made up of 103 scintillation counters (40 with 400 m spacing, 36 with 600 m spacing and 27 with 1.2 km spacing) and a Fluorescence Detector (FD) station consisting of 10 FD telescopes located at the Telescope Array Middle Drum FD station, which is made up of 14 telescopes. TALE-FD full operation started in 2013. The deployment of the 103 SDs was completed in March 2017, and to date about 70 % of the array is in operation with a full triggering and DAQ system. Here we report an overview of the experiment, its capabilities and the technical details of the TALE SD trigger and DAQ system from 4 month's operation.

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1. Introduction

The Telescope Array (TA) experiment consists of the Surface Detector (SD) array of 700 km² coverage and 38 fluorescence detectors (FDs), and it continues observations of ultra high energy cosmic rays with energies above 10¹⁸ eV from 2008. In 2012 we started the Telescope Array Low Energy extension (TALE) experiment additionally installing 103 FDs pointing higher elevation angles, *i.e.*, observing lower energy cosmic rays, than TA FDs. TALE FDs were located just beside the TA SD array at the north corner of the TA SD array, and the effective threshold energy of the experiment is successfully turned down to lower than 10^{16.5} eV. We report the cosmic ray energy spectrum in the wide energy range from 10^{15.9} eV above 10²⁰ eV [1]. It has complicated structures 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 10¹⁶ eV and a steepening at around 10¹⁷ eV.

In contrast with the ultra high energy region above 10¹⁸ eV where the extragalactic cosmic rays are dominated, the galactic and the extragalactic components coexist in the lower energy range than 10¹⁸ eV. And the spectrum of extragalactic component 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 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.

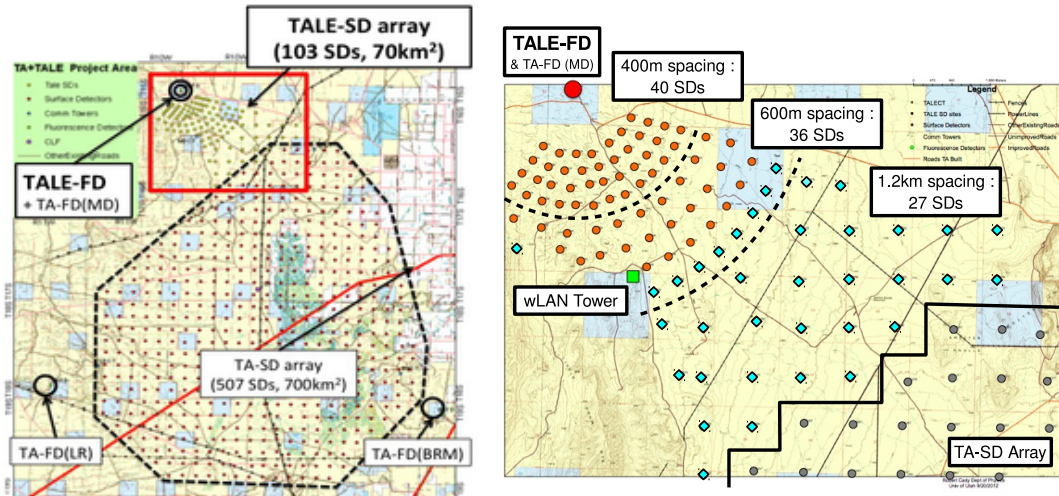


Figure 1: Left panel shows a map of the TA experiment site including TALE site. The small dots and the open circles indicate the TA SD counters and the TA FD stations, respectively. The close up of TALE site is shown in Right panel. All 103 counters were deployed, the circles show the SD counters including DAQ electronics. Other counters (rhombus) were deployed without electronics.

In order to resolve the convolved information the pressing issues are 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 km² with 103 SDs in the FOV area of the TALE FDs as shown in Fig. 1.

The TALE FD station is located next to TA Middle Drum (MD) station, and these stations are watching almost same field of view in azimuthal angle. However, the TALE FD telescopes are watching higher in elevation than TA FDs, so that it can observe lower energy showers. The number of telescopes for TALE is 10, and they are looking 31 degree to 59 degree in elevation.

Fig. 1 shows a arrangement of the TALE SD array which has three different detector spacing. We deployed 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 high density area of TALE SD and the TA SD array, 27 detectors were deployed 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/cm² comparing with the monocular FD resolution of 40 g/cm².

2. The current status of the operation and the data analysis

TALE FD telescopes had been installed in November 2012, and we continue operating since September 2013. We already reported the energy spectrum from 10^{15.9} eV to 10²⁰ eV [?].

On the other hand, for the TALE SD array, the communication tower for the DAQ host was installed in Oct. 2012, and 35 SDs had been deployed at in the 400m spacing area. Among these, 16 detectors with the DAQ electronics which were originally manufactured as spares for TA SDs. The set of 16 SDs is making up an air shower array and the test DAQ system is continued with 100 % efficiency from May 2013.

Fig. 2 is an example of a hybrid event taken by the TA-Middle Drum and TALE FDs together with the TALE SD array. On the left panel of Fig. 3 we show an energy distribution of the TALE FD events detected in 1080 hour observation time from June 2014 to March 2016. The right panel is a Monte Carlo calculated aperture. We also currently proceed with evaluations of our monocular event reconstruction accuracy comparing monocular analysis results with FD-SD hybrid analysis results for time matched events.

Mar. 2017, remaining SD counters were deployed and all of 103 counters had installed. 67 counters among them have new electronics and 16 old electronics were replaced with new one at the same time. Except some SDs because of initial failure (for example network trouble), renewed DAQ system with new electronics has stably running with 55 SD counters.

3. Development of New electronics for TALE/TAx4 SD

We adopted a common design of new TALE SD and the TALE SD DAQ system with TAx4 SD in order to reduce development and production costs. We obtained funds (Grant-in-Aid for Scientific Research(S) from Japan Society for the Promotion of Science) to construct other 70

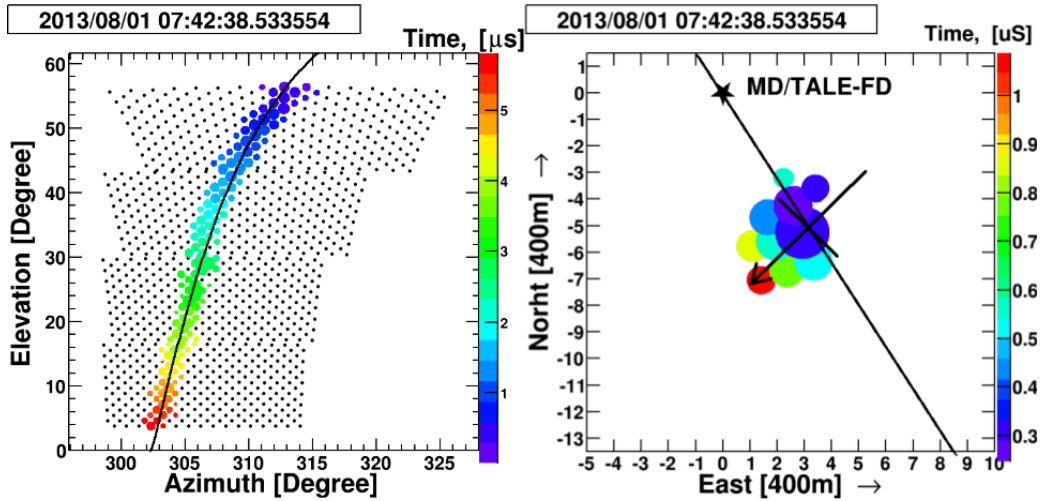


Figure 2: A hybrid event taken by the TA-Middle Drum and TALE FDs (*Left*) together with the TALE SD array (*Right*).

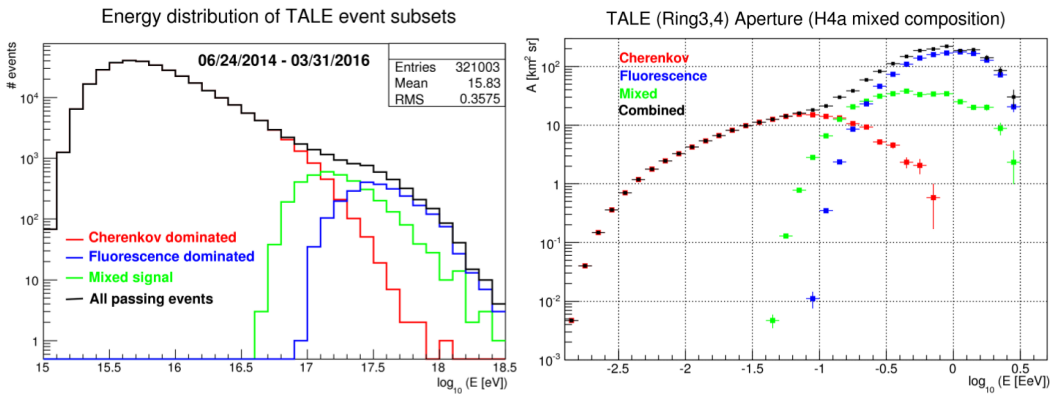


Figure 3: (*Left*) An energy distribution of the TALE FD events detected in 1080 hour observation time from June 2014 to March 2016. (*Right*) A Monte Carlo calculated aperture.

SDs and to continue the TALE experiment. The constructions and installations of the TALE SD array are scheduled to be finished in 2017 Japanese Fiscal Year and to start its full operation. The expected specifications of the TALE hybrid detector are as follows: the threshold energy is about $10^{16.5}$ eV; the expected event rate is about 5,000 hybrid events per year; the angular resolution reaches 1.0 degree; the Xmax resolution is 20 g/cm^2 .

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 as a result the protocol for the wireless LAN communications between the DAQ host and SDs has been changed from a specially designed one for the TA SD array to TCP/IP. With the introduction of the new protocol we can use a general-purpose personal computer as the DAQ host and an access point for broadcasting. In contrast to the new system, the existing system for TA SD

array uses an SD electronics as the DAQ host consisting of a specially designed firmware.

The new electronics and its block diagram are shown in Fig. 4 and Fig. 5, respectively. With the introduction of the new WLAN module, the updates of the firmware for the FPGA and the software for the CPU were needed. Almost all of the development items for the new electronics and the DAQ system had been finished. Several field tests of the new electronics and the DAQ system had carried out in the TALE SD area. We have already confirmed the stability of the continuous run of the DAQ cycle for existing TALE SDs and the stability of long distance (max. 18 km) communications.

One of the remaining major development items is the speeding up of the data transfer in SD electronics. The maximum number of SDs which a DAQ host can process is now 70. For example, adopting SPI instead of UART for the protocol between the wireless LAN module and the FPGA in the electronics, we expect 35 % increase of the data transfer speed.

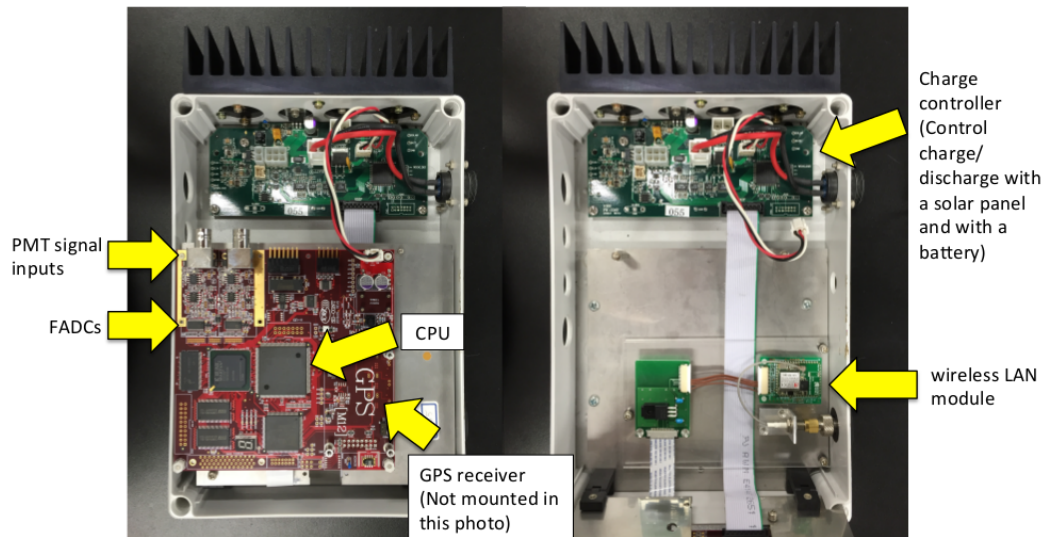


Figure 4: A picture of the new SD electronics for the TALE and TAx4 experiments.

4. Summary

TALE is an extension project of the TA experiment to lower the energy threshold down to $10^{16.5}$ eV. Construction of the hybrid detector with 10 FD telescopes and an air shower array of 67 km^2 with 103 SDs has mostly finished. The FDs and 16 SDs already installed were operated from 2013, a preliminary results of FD mono energy spectrum was reported in this conference. SD array data analysis has been also developing, therefore hybrid analysis will be started soon.

The new SD electronics and new DAQ system for TALE and TAx4 have been developed. The production of 100 sets and installation of 70 sets of new electronics have already finished. Although some more improvements of DAQ system are required for the TALE SD array of 103 SDs, also TAx4 SD array, new DAQ system is stably running with 55 SDs.

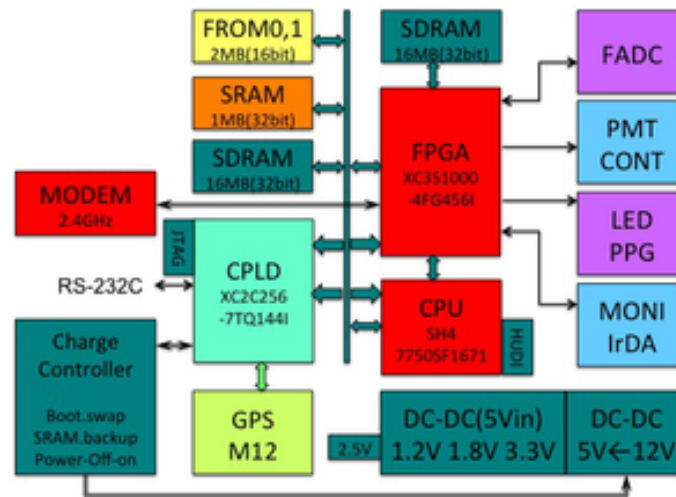


Figure 5: A block diagram of the new SD electronics.

5. Acknowledgements

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References

- [1] T. AbuZayyad et. al, in this conference