PROCEEDINGS OF SCIENCE

ONLINE ICRC 2021 THE ASTROPARTICLE PHYSICS CONFERENCE Berlin | Germany 37th International Cosmic Ray Conference 12–23 July 2021

Current status and prospects of surface detector of the TAx4 experiment

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Telescope Array (TA) is the largest observatory in the Northern Hemisphere to detect ultrahigh energy cosmic-rays (UHECRs). A surface detector (SD) array covers approximately 700 km^2, and the SD array is surrounded by three fluorescence detector (FD) stations. TA has found evidence for a cluster of cosmic rays with energies greater than 57 EeV from the TA SD data. In order to confirm this evidence with more data, we started the TAx4 experiment which expands the detection area using new SDs and FDs. We started construction of new SDs which are arranged in a square grid with 2.08 km spacing at the north east and south east of the TA SD array. More than half of the new SDs are already deployed and running. We present the current status of the TAx4 SD, trigger efficiency and exposure prospects for the highest energy part of the cosmic ray spectrum.

37th International Cosmic Ray Conference (ICRC 2021)
July 12th – 23rd, 2021
Online – Berlin, Germany

*Presenter

PoS(ICRC2021)203

1. Introduction

Telescope Array (TA) is the largest observatory in the Northern Hemisphere to detect ultrahigh energy cosmic-rays (UHECRs) [1]. The main purpose of TA is to clarify the source and nature of UHECRs above 10^{18} eV. Full operation of the TA detectors was started on May 11, 2008. The details of the detectors are provided in [2–5]. There are two types of the TA detectors. One is a surface detector (SD), and the other is a fluorescence detector (FD). There are 507 SDs in a square grid with 1.2 km spacing covering approximately 700 km^2. There are 2 layers of 3 m^2 area and 1.2 cm thick plastic scintillators inside of the box of each SD. There are three TA FD stations, two of which have 12 telescopes, while the third has 14. After the construction of the TA detectors, new SDs and FDs were constructed for the TA low energy extension (TALE) experiment [6], and the TAx4 experiment [7]. The sites of the TA, TALE and TAx4 detectors are shown in Fig. 1.

The concentration of the arrival directions (the "hotspot") of cosmic rays was found with 20° oversampling radius using TA SD data collected over five years [8]. The post-trial significance was estimated to be 3.4σ, and the significance was updated to be 2.9σ using the latest data [9]. An implication of declination dependence of cosmic-ray energy spectrum was also reported by the TA experiment [10]. The statistical significance of the difference of the break points of the energy spectra was estimated to be 4.3σ using the latest data [11]. Correlation of arrival directions with energies was shown in [12], and the post-trial significance of the correlation was estimated to be 4.2σ.

In order to examine the evidences of anisotropy which are described above, TAx4 was developed to accelerate the pace of data collection at the highest energies. The SD array of the TAx4 experiment is designed to study cosmic rays with energies greater than 57 EeV. The spacing of the TAx4 SD array is 2.08 km, in contrast to the TA SD's 1.2 km. 500 TAx4 SDs cover approximately three times larger area than the 507 TA SDs; the combined coverage of the TAx4 and TA SDs is approximately 2800 km^2. Two TAx4 FD stations are designed to observe the hybrid events which are detected by both SDs and FDs.

The current status of detectors and performance of the detectors is given in Section 2. The data acquisition system and an implementation of a hybrid trigger is shown in Section 3. Section 4 provides a summary.

2. Current status and performance of the detectors

We finished constructing 257 SDs in February and March 2019. The most of the TAx4 SD scintillator boxes were assembled in Japan, starting in 2015, while 30 units were assembled in Korea in 2018. The boxes were then transported to the USA and the final assembly of the SDs was performed at the Cosmic-Ray Center in Delta City, Utah. We started to take the data of the SDs stably at each communication tower in November 2019. Construction of two TAx4 FD stations was finished. Stable data-taking of the north TAx4 FD station was started from June 2018, and that of the south TAx4 FD station was started from September 2020.

The detailed performance of the SDs is written in [7]. Fig. 2 is the expected energy dependence of the trigger efficiency in [7]. 25% energy resolution, 2.2-degree angular resolution and 95%

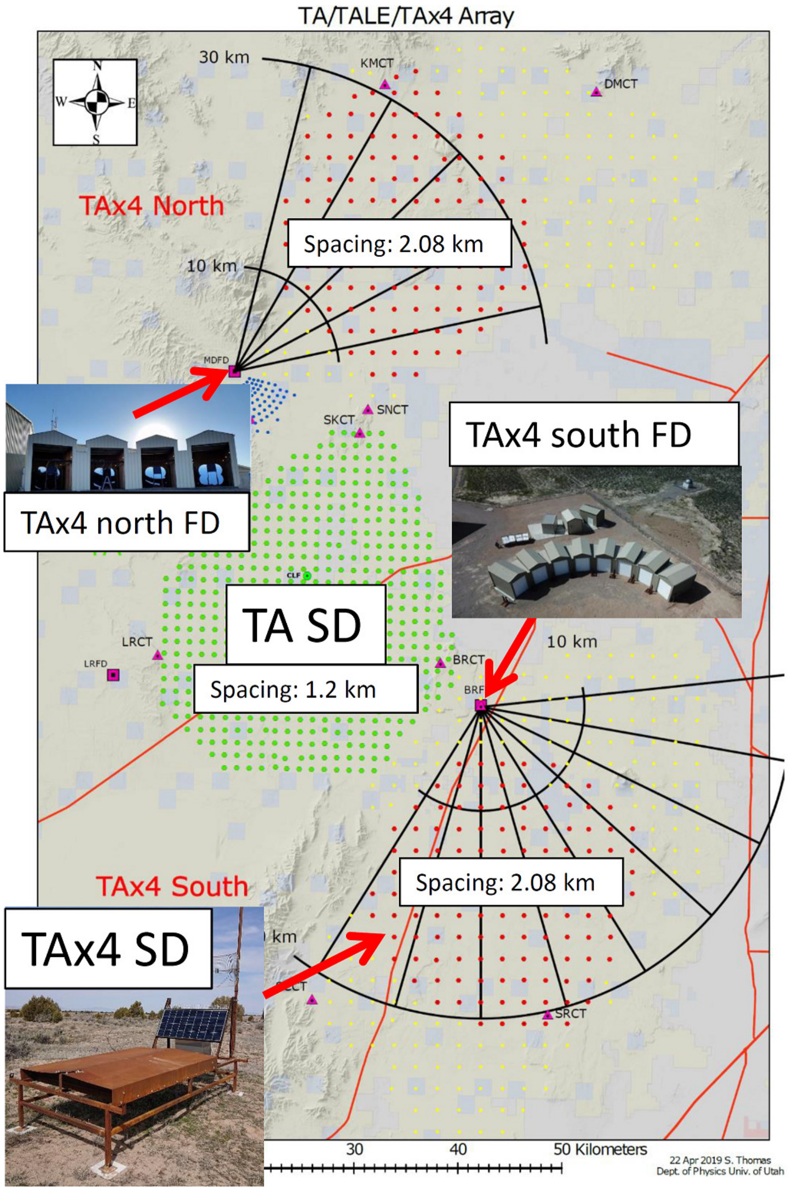

Figure 1: Overview of the Telescope Array (TA) detectors. Each red circle in the north and south shows the site of a deployed TAx4 surface detector (SD). Each yellow circle shows a site for a TAx4 SD where an SD was not deployed yet. Each green circle corresponds to the site of a TA SD. Each blue circle shows the site of an SD of the TALE experiment [6]. The two black fan shapes are the fields of view of the TAx4 fluorescence detectors (FDs). Photographs of a TAx4 SD, the TAx4 north FD station and the TAx4 south FD station are also shown.

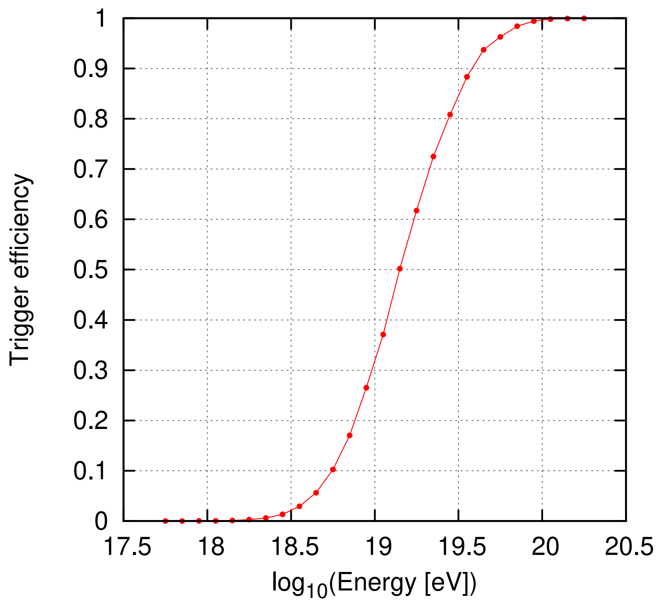

Figure 2: Fig. 4 in [7] is shown here to describe the trigger efficiency of the surface detectors for the TAx4 experiment. Air showers which are induced by cosmic ray protons were simulated to calculate the trigger efficiency.

reconstruction efficiency of cosmic rays with energies greater than 57 EeV are expected. We expect that the resolution is good enough for the studies of anisotropy.

3. Data acquisition and an implementation of a hybrid trigger

The Level-0, Level-1, and Level-2 triggers are implemented in the TAx4 data-acquisition systems as TA. The detailed description on the data-acquisition systems is written in the Section 5 in [7]. The Level-2 trigger is the trigger to select the events to collect waveforms from each SD. The Level-2 triggers are judged in each sub-array independently now. The inter-tower triggers are being tested. TAx4 SD trigger efficiency is about 30% at around 10 EeV, so a hybrid trigger was implemented from 2020 June for higher efficiency. FDs send trigger timings to the communication towers in order to get waveforms within ± 128 μs around the timings. As a result, three times larger than the TA SD-FD equivalent hybrid events in total for the energies greater than 10 EeV.

4. Summary

Implications of anisotropy were obtained by the TA experiment. Declination dependence of the energy spectrum was claimed at 4.3σ in the energy spectrum using TASD 11 years data. 2.9σ hotspot was obtained using TASD 11 years data.

500 new SDs with 2.08 km spacing and two new FD stations were designed for the TAx4 experiment. More than half of the TAx4 SDs (257 SDs) were deployed in 2019. Construction of the TAx4 FDs was finished. Stable run of the data acquisition of the new detectors was started.

The stable run of the TAx4 SDs was started from November 2019, the stable run of the north TAx4 FDs was started from June 2018, and the stable run of the FDs was started from September 2020. A hybrid trigger started to run from June 2020.

We calculated the expectation of the significance of the hotspot in the next five years in the following way. If we continue to run the TA and TAx4 SDs and assume the efficiency of the TAx4 SDs which is obtained in Section. 2, approximately 384 events above 57 EeV will be obtained in total in 2025. If we extrapolate the pace of the data collection within the same oversampling radius as the hotspot, we will obtain approximately 88 events within the radius out of 384 events. The post-trial significance of the hotspot analysis is expected to be approximately 6σ in 2025 using the number of events.

Acknowledgements

The Telescope Array experiment is supported by the Japan Society for the Promotion of Science(JSPS) through Grants-in-Aid for Priority Area 431, for Specially Promoted Research JP21000002, for Scientific Research (S) JP19104006, for Specially Promoted Research JP15H05693, for Scientific Research (S) JP15H05741, for Science Research (A) JP18H03705, for Young Scientists (A) JPH26707011, and for Fostering Joint International Research (B) JP19KK0074, by the joint research program of the Institute for Cosmic Ray Research (ICRR), The University of Tokyo; by the Pioneering Program of RIKEN for Evolution of Matter in the Universe (r-EMU); by the U.S. National Science Foundation awards PHY-1404495, PHY-1404502, PHY-1607727, PHY-1712517, and PHY-1806797; by the National Research Foundation of Korea (2017K1A4A3015188, 2020R1A2C1008230, & 2020R1A2C2102800) ; by the Ministry of Science and Higher Education of the Russian Federation under the contract 075-15-2020-778, RFBR grant 20-02-00625a (INR), IISN project No. 4.4501.18, and Belgian Science Policy under IUAP VII/37 (ULB). The foundations of Dr. Ezekiel R. and Edna Wattis Dumke, Willard L. Eccles, and George S. and Dolores Doré Eccles all helped with generous donations. The State of Utah supported the project through its Economic Development Board, and the University of Utah through the Office of the Vice President for Research. 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. Patrick A. Shea assisted the collaboration with valuable advice and supported the collaboration's efforts. 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 are indebted to the Millard County Road Department for their efforts to maintain and clear the roads which get us to our sites. We gratefully acknowledge the contribution from the technical staffs of our home institutions. An allocation of computer time from the Center for High Performance Computing at the University of Utah is gratefully acknowledged.

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