

Update on the large-scale cosmic-ray anisotropy search at the highest energies by the Telescope Array Experiment

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The study of large-scale anisotropy at the highest energies is essential for understanding the transition from cosmic rays of galactic origin to those of extra-galactic origin, along with the magnetic fields in the galaxy and those beyond. Motivated by a significant detection of the large-scale anisotropy above 8 EeV by the Pierre Auger Observatory (Auger), we had previously reported, using 11 years of Telescope Array (TA) surface array data, a result compatible both with that of Auger, and with an isotropic source distribution [1]. In this contribution, we will show the preliminary updated results using 12 years TA SD data to search for the large-scale anisotropy at the highest energies.

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

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1. Introduction

Over 100 years after the discovery of cosmic rays, there are still many open questions concerning the origin and nature of ultrahigh-energy cosmic rays (UHECRs) [2, 3]. With small deflections of UHECRs by galactic and intergalactic magnetic fields, $\sim 5^\circ Z(E/50 \text{ EeV})^{-1}$, (where Z is the charge of nuclei [4]), a small-intermediate scale anisotropy¹ is predicted at the highest energies. On the other hand, the distance to sources and deflections by magnetic fields are increased at lower energies around 10 EeV, but still allowing for the possibility of a large-scale anisotropy, such as one that might be approximated as a dipole [5–7].

1.1 Telescope Array experiment

The Telescope Array experiment (TA) is the largest cosmic-ray detector in the Northern hemisphere, located near the city of Delta, Utah, USA (39.30° North and 112.91° West, and at ~ 1400 m above sea level) [8]. The surface detector array (SD) consists of 507 plastic scintillators of 3 m^2 area deployed in a square grid with a 1.2 km spacing. The total acceptance is about 700 km^2 . Additional surface detectors, designed to provide a fourfold increase in observation area, collectively referred to a TA $\times 4$, have begun operation [9]. Fluorescence detector (FD) view the air space above the SD. The FD measures directly the calorimetric energy of an air shower from the energy deposited by particles in the shower during its longitudinal development [10].

The arrival direction of an UHECR is inferred as measured by the TA SD is evaluated from the relative difference in arrival time of the shower front at each surface detector (which are time-synchronized using GPS modules). The energy estimator of the TA SD is the particle density measured at a distance of 800 m from the air shower axis, called S_{800} . The S_{800} parameter is converted to the primary energy as a function of zenith angle based on a Monte Carlo simulation using the CORSIKA software package [11]. The obtained energy is calibrated to the calorimetric energy measured by the fluorescence detectors using a scaling factor of $1/1.27$ [12]. The typical resolution of the TA SD is $1.0^\circ \sim 1.5^\circ$ in arrival direction and $10\% \sim 15\%$ in primary energy [12], and the systematic uncertainty in the energy scale is quoted at 21% [13].

1.2 Large-scale anisotropy search

Recently, the Pierre Auger Collaboration reported the observation of a significant large-scale anisotropy in the arrival directions of cosmic rays above 8 EeV, indicating an obvious dipole structure of 4.7% amplitude in a projection of the right ascension with a 5.2σ significance [14]. An enhancement of the dipole amplitude above 4 EeV and results down to 0.03 EeV are also reported [15, 16]. These results are consistent with an extragalactic origin of UHECRs. In the Northern hemisphere, the Telescope Array Collaboration reported a result consistent both with an isotropic source distribution, and with the dipole structure reported by Auger using 11 years TA SD data[1].

In this proceedings, we report the large-scale cosmic-ray anisotropy search at the highest energies and its energy dependences using 12 years TA SD data.

¹In this research field, we define a small angular scale anisotropy as less than 5° , intermediate scale as 10° to 35° and large scale as $> 40^\circ$.

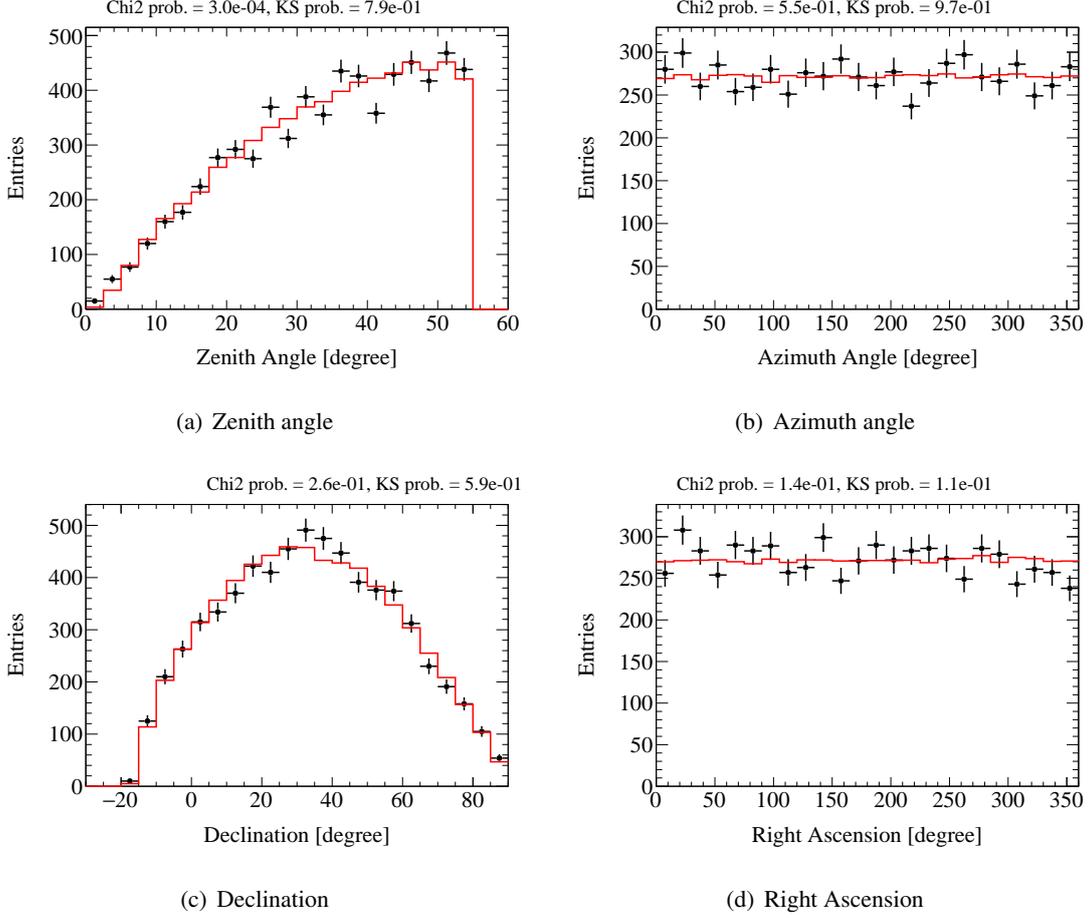


Figure 1: Parameter comparisons between the measured distribution and expectation evaluated from the MC simulations. Probabilities of the statistical tests using χ^2 test and Kolmogorov-Smirnov test are described on the top of the figures.

2. Data-set and methodology

The TA SD data recorded over 12 years from May 2008 to May 2020 were used for a study of the large-scale anisotropy. To apply the same cut with our earlier publication, we use an *a priori* energy threshold of 8.8 EeV, equivalent to 8 EeV used by Auger, accounting for 10% energy scale difference between the two experiments [17].

There were 6518 events above 8.8 EeV, with zenith angles less than 55° and passing the same quality cuts used in the TA spectrum analysis [12]. In this data-set, TA SD is capable of measuring UHECRs were injected in a declination band from -15° to 90° . As the trigger efficiency of the TA SD below 10 EeV is less than 100%, the obtained right ascension distribution is compared with the expected distribution produced an isotropic UHECR sky, and from a time-dependent Monte Carlo (MC) simulation including actual calibration constants, live time and dead time of each surface detector station, and TA SD trigger efficiencies.

Before investigating large-scale cosmic-ray anisotropy, consistencies of the parameter distribu-

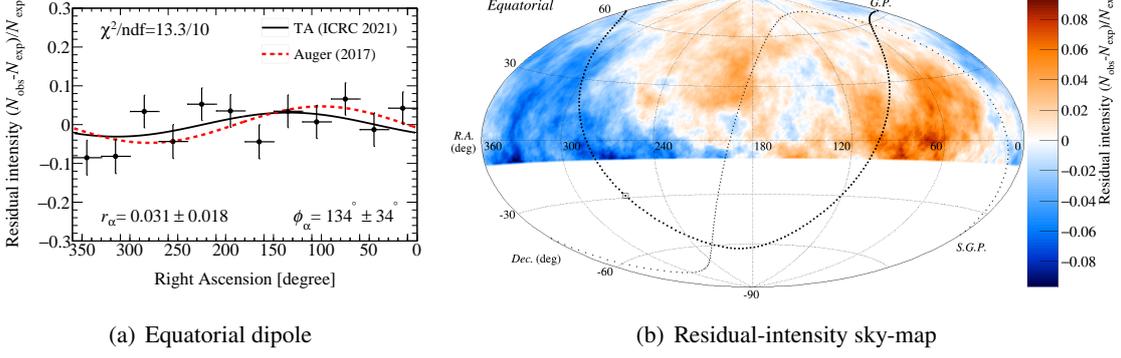


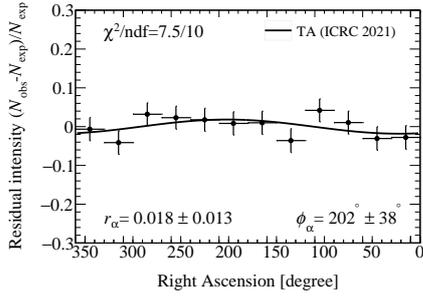
Figure 2: (a) Residual intensities of UHECRs with energies above 8.8 EeV observed with 12 years of TA data as a function of the right ascension. The black curve shows the TA fitted dipole result and the red dashed curve represents the dipole reported by Auger. (b) Sky map of residual intensities between TA data and an isotropic distribution shown in the Equatorial and the Galactic coordinates. The arrival directions are oversampled with a 45° radius cylindrical function. The galactic plane (G.P.) and the super-galactic plane (S.G.P.) are shown as thick and thin dotted curves, respectively. The galactic center (G.C.) is indicated by the open square.

tions between observed data and MC simulation are first verified. Figure 1 shows distributions of zenith angle, azimuth angle, declination and right ascension for the 12 years TA SD data compared with expectations evaluated from the time-dependent MC simulation. In all four cases the data and MC are in good agreement.

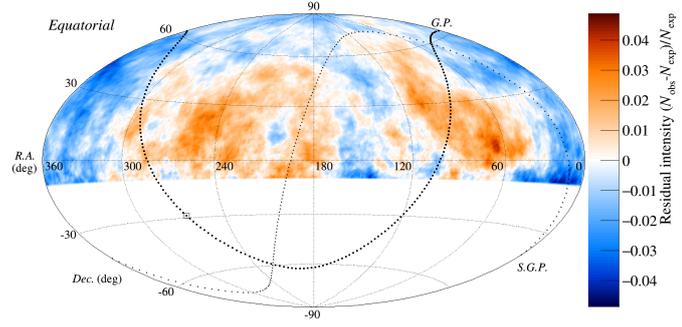
3. Result

Figure 2(a) shows the residual intensity as a function of right ascension between 12 years of TA SD data and the isotropic expectation calculated from the time-dependent MC simulation. The residuals are fitted to the form $r_\alpha \cos(x - \phi_\alpha)$, where r_α is the amplitude of the dipole and ϕ_α is the phase. The obtained dipole structure has an amplitude r_α of $3.1 \pm 1.8\%$ and a phase ϕ_α of $134^\circ \pm 34^\circ$. The TA SD data points are also compared with (a) an isotropic distribution and (b) the dipole structure reported by Auger. The latter has a 4.7% amplitude and a phase of 100° . With current statistics, the obtained TA SD result is consistent with an isotropic distribution. Since there is no significant dipole structure, an upper limit is evaluated for a chance probability of 1% that a fluctuation of an isotropic source distribution would yield an amplitude greater than the reference limit. The obtained 99% confidence-level upper-limit on amplitude is 7.6% for TA data above 8.8 EeV.

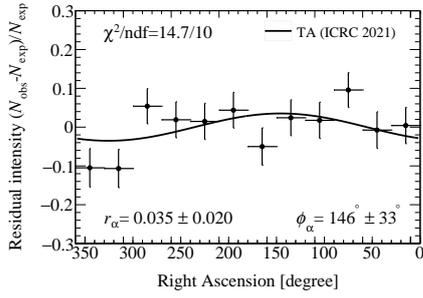
Figure 2(b) shows the sky map of residual intensities with oversampling of 45° top-hat function to discern the structure of the dipole components. Although no significant amplitude is found, the direction of the limited dipole enhancement is far away from the Galactic center. This result would be more indicative of an extragalactic source distribution than a galactic one. Furthermore, we search for an energy dependence of the dipole components in four energy ranges above 4 EeV as shown in Figure 3. There is no significant component of dipole structure in all energy ranges.



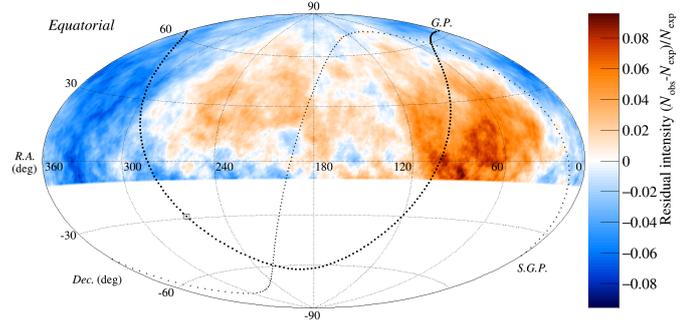
(a) $4 \text{ EeV} \leq E < 8 \text{ EeV}$



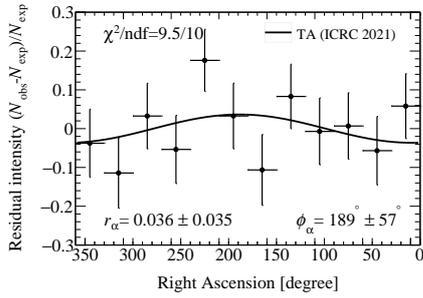
(b) $4 \text{ EeV} \leq E < 8 \text{ EeV}$



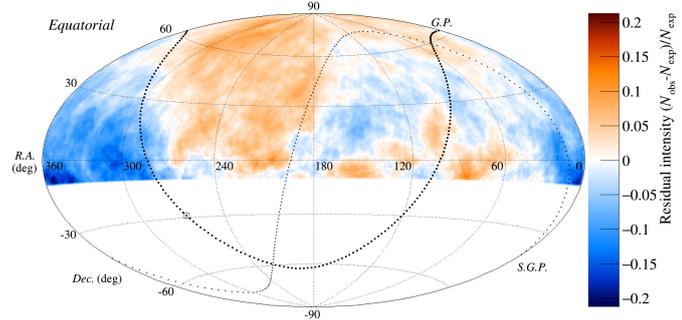
(c) $8 \text{ EeV} \leq E < 16 \text{ EeV}$



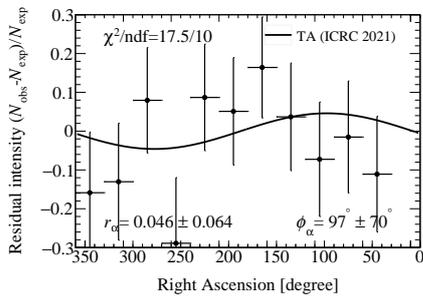
(d) $8 \text{ EeV} \leq E < 16 \text{ EeV}$



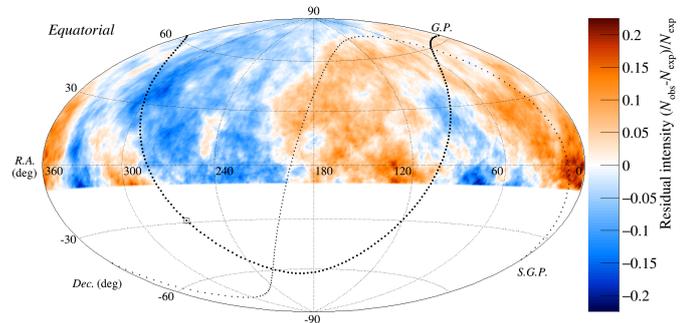
(e) $16 \text{ EeV} \leq E < 32 \text{ EeV}$



(f) $16 \text{ EeV} \leq E < 32 \text{ EeV}$



(g) $32 \text{ EeV} \leq E$



(h) $32 \text{ EeV} \leq E$

Figure 3: Preliminary results from 12 years of TA SD data of residual intensities vs right ascension (left) and skymap (right) in four energy ranges; (a,b) $4 \text{ EeV} \leq E < 8 \text{ EeV}$, (c,d) $8 \text{ EeV} \leq E < 16 \text{ EeV}$, (e,f) $16 \text{ EeV} \leq E < 32 \text{ EeV}$ and (g,h) $32 \text{ EeV} \leq E$.

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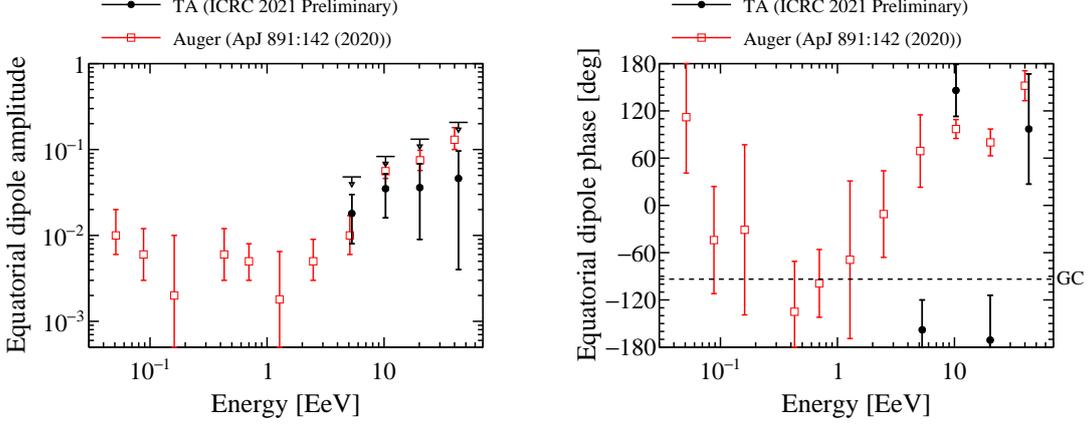


Figure 4: Preliminary result of equatorial dipole amplitude and phase measured with Telescope Array experiment from 12 years of data (black filled circles), compared to Auger reported result (red open squares) [16]. The phase toward the Galactic center (GC) is indicated as a dashed line.

Figure 4 shows the obtained preliminary result of amplitude and phase using 12 years TA SD data compared to the Auger reported result [16].

None of the measured TA data amplitudes are significantly different from zero, but their best-fit values appear to increase with energy, while the corresponding phases are all far from the Galactic center. Table 1 is the summary of preliminary results and their corresponding upper limit on amplitude with 99% confidence level.

E [EeV]	E_{med} [EeV]	N	r_{α} [%]	ϕ_{α} [°]	r_{α}^{UL} [%]
$8.8 \leq E$	13.0	6518	$3.1^{+1.6}_{-1.6}$	134 ± 34	7.6
$4 \leq E < 8$	5.3	13361	$1.8^{+1.2}_{-1.0}$	202 ± 38	4.8
$8 \leq E < 16$	10.3	5446	$3.5^{+1.7}_{-1.9}$	146 ± 33	8.3
$16 \leq E < 32$	20.2	1623	$3.6^{+3.2}_{-2.7}$	189 ± 57	13.2
$32 \leq E$	43.2	595	$4.6^{+5.0}_{-4.2}$	97 ± 70	20.7

Table 1: Summary of preliminary dipole search result of 12 years TA SD data. The energy range, median energy, number of events, best-fit dipole amplitudes and phase angles, and 99% confidence upper limits of r_{α}^{UL} are tabulated.

4. Conclusion

We report the results of the search for dipole structure in the arrival direction of UHECR using 12 years of TA SD data from the Northern sky and for possible energy dependence of the amplitudes. There are no significant large-scale anisotropies with the current limited statistics. We have evaluated a 99% confidence-level upper limit of $r_{\alpha}^{\text{UL}} = 7.6\%$ above 8.8 EeV on the amplitude of a dipole structure in a projection of the right ascension. Although the tendency of amplitude and phase of the dipole structure shows a similar one reported from Auger, much greater statistics from

TA are required to distinguish the two hypotheses. Future data collection by TA and the on-going upgrade of TA×4 will be essential for further studies.

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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 and JP19H05607, 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 the Evolution of Matter in the Universe (r-EMU); by the U.S. National Science Foundation awards PHY-1404495, PHY-1404502, PHY-1607727, PHY-1712517, PHY-1806797 and PHY-2012934; 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). This work was partially supported by the grants of The joint research program of the Institute for Space-Earth Environmental Research, Nagoya University and Inter-University Research Program of the Institute for Cosmic Ray Research of University of Tokyo. 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 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.