PROCEEDINGS OF SCIENCE

Effect of optical properties of FDs on reconstruction analysis

Daiki Sato,[a,*] **Takayuki Tomida,**[a] **Ryosuke Hibi,**[a] **Aoi Matuzawa,**[a] **Yuichiro Tameda,**[b] **Daisuke Ikeda**[c] **and Telescope Array Collaboration**

[a] *Academic Assembly School of Science and Technology Institute of Engineering, Shinshu University, Nagano, Nagano, Japan*

[b] *Department of Engineering Science, Faculty of Engineering, Osaka Electro-Communication University, Neyagawa, Osaka, Japan*

[c] *Faculty of Engineering, Kanagawa University, Yokohama, Kanagawa, Japan*

E-mail: 23w2050e@shinshu-u.ac.jp

Abstract. The TA experiment uses fluorescence telescopes to observe cosmic ray air showers. The telescope camera uses PMTs as Pixels. The telescope's PMT pointing direction has an uncertainty of 0.1°, and more precise measurements of the telescope's optical properties are needed to more accurately reconstruct the cosmic ray air showers. We have developed the Opt-copter which is a light source mounted on a drone that can be flown within the telescope's field of view. Observational experiments with the Opt-copter have provided a more accurate analysis of the telescope viewing direction. In this study, we estimate the effect of this measurement of accurate telescope viewing direction on the reconstruction of cosmic ray air showers.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

*Speaker

https://pos.sissa.it/

PoS(ICRC2023)227

1. Introduction

The Telescope Array (TA) experiment, located in Utah, U.S.A., observes ultra-high energy cosmic rays with energies greater than $10^{18.0}$ eV. The TA uses two types of detectors: Fluorescence Detectors (FD) that measures photons emitted from air molecules along the path of the cosmic ray induced air shower, and Surface Detector (SD) that sample of the air shower particles on the ground. It is important that we understand the optical properties of the telescopes to reconstruct observed cosmic ray air showers [1, 2].

The "Opt-copter," an Unmanned Aerial Vehicle (UAV) mounted with a light source and RTK-GPS, was developed to understand and calibrate the optical properties of FDs (Left in Figure 1). This device can be flown within the Field of View (FoV) of the FD and can determine the exact location of the light source mounted on the UAV. It is possible to measure the optical properties of the FD by flying this device into the FD's FoV and observing the light source with the FD (Right in Figure 1)[3]. We performed the observation of the Opt-copter with FD at the Black Rock Mesa(BRM) station in 2018 and 2019. From the observation experiment, the FoV direction of the FD can be analyzed by comparing the actual drone position measured by RTK-GPS with the direction of the light source observed by the FD. Therefore, we analyzed the FoV direction of the FD with an accuracy of 0.03 degrees. Table 1 shows the FoV direction shift of the telescope analyzed using the Opt-copter. This is a shift from the FoV direction based on the star analysis currently used. The uncertainty of the PMT pointing direction based on star analysis is 0.1 degrees. The relationship between the RTK-GPS position and the light-receiving center of gravity depends on the focused image of the camera. We analyzed aberrations that recreate this relationship searching for optimal values through simulation.[4]

In this report, we apply the telescope FoV direction obtained by the "Opt-copter analysis" (hereinafter called the "Copter analysis") to the cosmic ray air shower analysis. We estimate the effect of the reconstruction using the FoV direction obtained by the Copter analysis compared to the reconstruction using the FoV direction obtained by the conventional method of the star analysis.

Figure 1: Left: The appearance of the Opt-copter that has eight arms, all of which are able to be folded. A RTK-GPS antenna is mounted on the top of this device. Right: The image of UV-LED light emission from the Opt-copter to the FD

	FD00	FD01	FD02	FD03	FD04	FD05	FD06	FD07	FD08	FD09	FD10	FD11
ΔAzimuth [deg.]	0.05	0.00	0.04	0.04	0.04	0.02	0.01	-0.04	0.01	-0.05	-0.02	0.01
ΔElevation [deg.]	0.11	-0.04	0.02	-0.03	-0.04	-0.12	-0.05	-0.14	-0.12	-0.19	-0.14	-0.15

Table 1: The FoV direction shift of the telescope at BRM station analyzed using the Opt-copter.The uncertainty of the opt-copter analysis is 0.03 degrees.

2. Effect of FoV on reconstruction analysis

The field of view direction is an important parameter in the reconstruction of cosmic rays, and the field of view direction of telescope in BRM station analyzed by the Opt-copter is more accurate than conventional methods. The FoV direction analyzed has an overall downward shift and the elevation angle shift is larger than the azimuth angle. The Star analysis, conventional method, observes stars in FDs and determines the FoV direction from the star catalogs. In order to apply the FoV direction of the Copter analysis to cosmic ray air shower analysis, it is important to estimate the effect of the reconstruction using the FoV direction obtained by the Copter analysis compared to the reconstruction using the FoV direction obtained by the conventional method of the the star analysis.

2.1 Analysis Method

The FoV direction of the telescope from the Copter analysis is different from the FoV direction of the telescope by the star analysis used in the conventional reconstruction. It is assumed that the Copter analysis is able to recreate the actual FoV direction of the telescope, then the FoV direction that should be used in the reconstruction is the FoV direction by the Copter analysis. We evaluate the effect of changing the FoV direction used for cosmic ray reconstruction from the FoV direction of the star analysis to the FoV direction of the Copter analysis. This analysis is performed as follows.

1. Simulates the observation of an air shower using the FoV direction by the Copter analysis.
2. It performs two reconstructions for one simulation data.
   - Reconstruction using FoV direction by the Copter analysis.
   - Reconstruction using FoV direction by the Star analysis.
3. Compare the results of the two reconstructions.

The FoV direction in the simulation uses the Copter analysis, which is presumed to be the actual telescope FoV direction. Therefore, this analysis estimates to determine the effect of changing the FoV direction of the reconstruction with the actual observation. The FoV direction by the star analysis is the standard FoV direction used in TA experiments.

2.2 Data set

The simulations and reconstructions use the data set in Table 2. This analysis uses the monocular reconstruction analysis to estimate the effect of the telescope's FoV direction only. The quality cuts summarized in Table 3 are applied to all reconstructed events.

Primary Composition	Proton, Iron
Interaction model	QGSJET II-04
Log(E/eV)	Proton: 18.5, 19.0, 19.5, 20.0
	Iron: 18.5, 19.0, 19.5
Zenith angle	0 - 65 degrees
Azimuth angle	0 - 360 degrees
Number of event	100000 for each event
Reconstruction mode	Monocular mode

Table 2: Simulation data set

Track length	> 10 degrees
Time extent	> 2 μs
Number of PMTs	> 10
Zenith angle	< 55 degrees
$\chi^2_{geom}/n.d.f.$	< 100
Xmax in the FoV of FDs.	
The geometrical and the longitudinal fittings are converged.	
Could be reconstructed in both FoV direciton	

Table 3: Quality Cut

As shown in Table 1, the FoV direction shift of the FD analyzed by the Opt-copter is a bit different for each telescope. In order to perform this analysis, it is necessary to change the FoV direction of each telescope in the analysis software.

2.3 Result and Discussion

Figure 2 shows the Xmax distributions at $10^{19.0}$ eV for proton reconstructed by each FoV direction. The left figure shows the result for events reconstructed using FoV direction by the Copter analysis, and the right figure shows for events reconstructed using FoV direction by the star analysis. Reconstructed Xmax mean and standard error are 781.6 ± 1.0 g/cm^2 for the FoV direction using the Copter analysis and 774.8 ± 1.0 g/cm^2 for the FoV direction using the star analysis. Using the FoV direction of the Copter analysis in the reconstruction, Xmax is deeper than using the FoV direction of the star analysis. The analysis was performed for each particle and energy, and the means are summarized the Figure 3 Left. For all particles and energies used in this analysis, Xmax is deeper when using the FOV direction determined by the Copter analysis. Each effect is checked by taking the difference between the average of $\mathrm{Xmax}_{\mathrm{Copter}}$ and $\mathrm{Xmax}_{\mathrm{Star}}$. Figure 3 Right shows the difference between the $\mathrm{Xmax}_{\mathrm{Copter}}$ mean value and the $\mathrm{Xmax}_{\mathrm{Star}}$ mean value. As energy increases, the difference between the means of each Xmax increases. We infer the effect increases with energy because the observable distance from the FD increases with energy.

We analyze the differences per event to evaluate the effect on a single event. The following is performed in the reconstruction.

1. Select the same event that were reconstructed in both FoV.
2. $\Delta\mathrm{Xmax(n)} = \mathrm{Xmax}_{\mathrm{Coptere}}(\mathrm{n}) - \mathrm{Xmax}_{\mathrm{Star}}(\mathrm{n})$

Figure 4 Left shows the ΔXmax distributions at $10^{19.0}$ eV for Proton and Figure 4 Right shows the mean and standard error of the same analysis for each energy and particle type. Each air shower event tends to be deeper. As shown in Table 1, the FoV direction by the Copter analysis tends to be lower compared to the FoV direction by the star analysis. This shows that the shift in FoV direction results in a deeper Xmax. Additionally, there is a difference in ΔXmax between protons and iron. We speculate that this is due to the different telescopes triggered by the depth of shower development

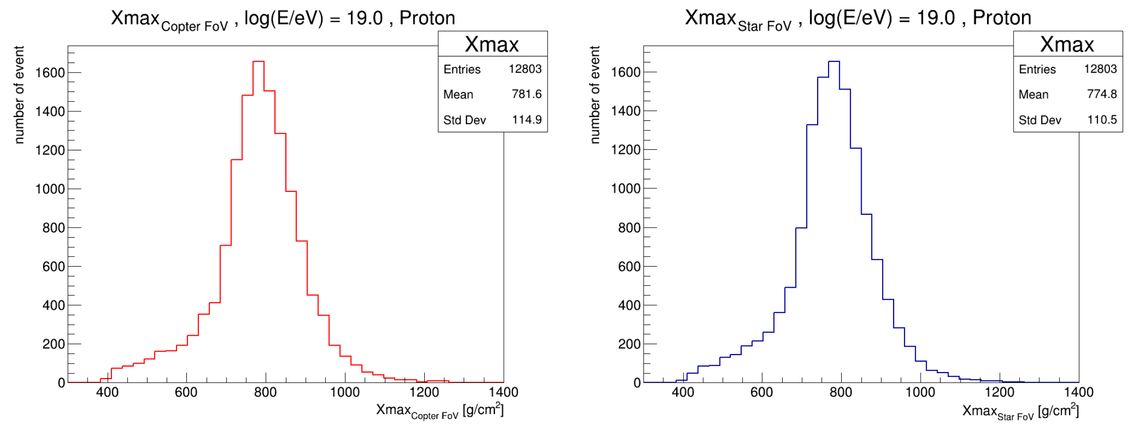

Figure 2: Left: Reconstructed Xmax distribution using the FoV direction by the Copter analysis for a Proton at $10^{19.0}$ eV, Right: Reconstructed Xmax distribution using the FoV direction by the star analysis for a Proton at $10^{19.0}$ eV

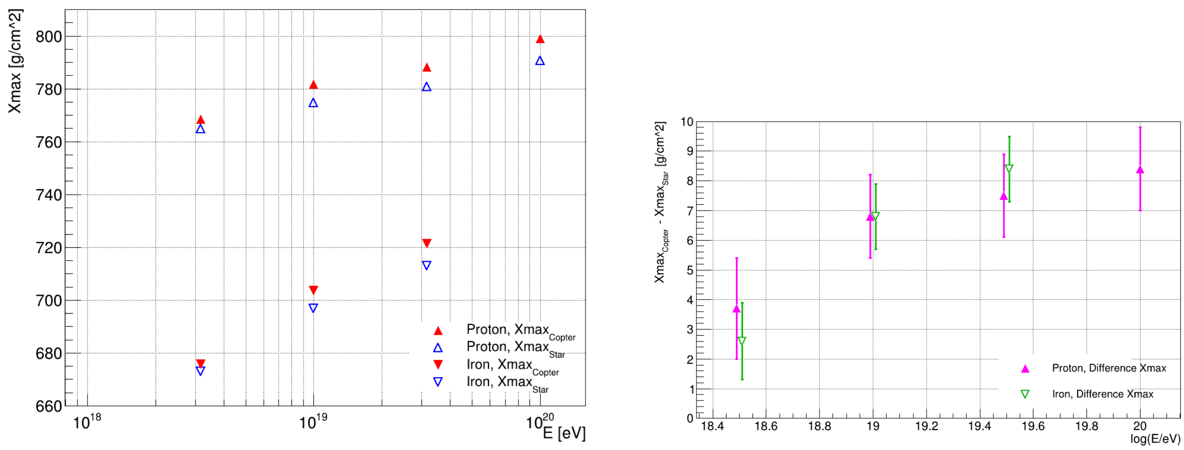

Figure 3: left: Reconstructed Xmax value for proton and iron primary cosmic rays at various energies in this study. (Red: Using FoV direction by the Coper analysis, blue: Using FoV direction by the star analysis.) Right: Differences between $\mathrm{Xmax}_{\mathrm{Copter}}$ and $\mathrm{Xmax}_{\mathrm{Star}}$ at various energies. As energy increases, the difference also increases.

and the different distances from the telescope that are likely to be observed by different particle types. In the future, we will analyze the effect of individual differences in the shift of the telescope's field of view direction and its effect at the distance observed. And we estimate the effect of FoV direction on cosmic ray reconstruction using the hybrid mode(Reconstruction method using FD and SD data). In order to apply the FoV direction of the Copter analysis to the TA experiment and to perform a more accurate cosmic ray air shower analysis, it is necessary to conduct a measurement experiment of optical properties at all stations at the TA site (Long Ridge station and Middle Drum station).

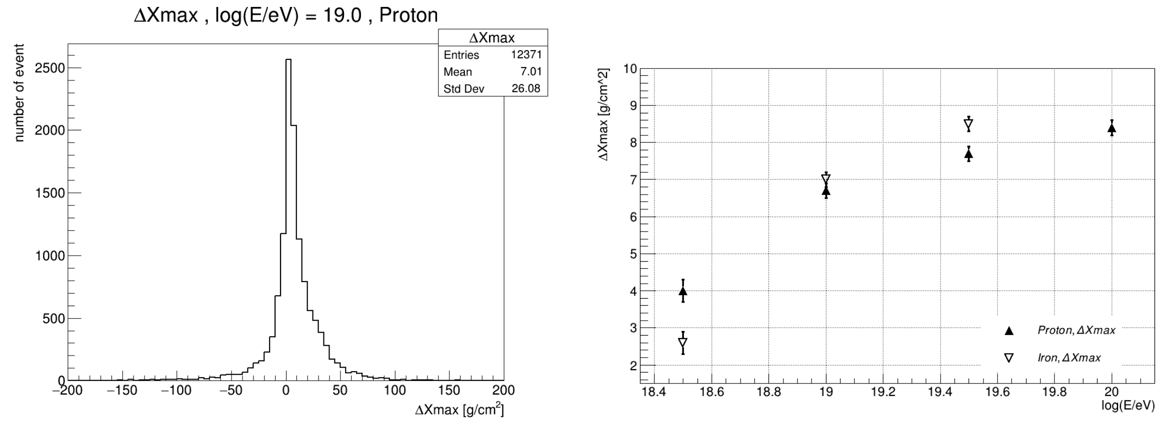

Figure 4: Left: Distribution of ΔXmax for proton at $10^{19.0}$ eV. Right: Mean ΔXmax values with standard errors at various energies.

3. Conclusion

We estimated the effect of changing the FoV direction to the more accurate FoV direction analyzed by the Opt-copter on the cosmic ray analysis. We have found that the reconstructed Xmax is deeper when using the FoV direction from the Copter analysis than when using the conventional FoV direction. Reconstructed Xmax mean and standard error are 781.6 ± 1.0 g/cm^2 for the FoV direction using the Copter analysis and 774.8 ± 1.0 g/cm^2 for the FoV direction using the star analysis. The Xmax increases as the energy of cosmic rays in the simulation is increased. In the future, we will estimate the effect of FoV direction on cosmic ray reconstruction using hybrid mode. In order to apply the FoV direction of the Copter analysis to the TA experiment, it is necessary to conduct a measurement experiment of optical properties at all stations at the TA site (Long Ridge station and Middle Drum station).

References

[1] H. Tokuno et al. New air fluorescence detectors employed in the telescope array experiment. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 676:54–65, 2012.

[2] T. Abu-Zayyad et al. The surface detector array of the telescope array experiment. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 689:87–97, 2012.

[3] Takayuki Tomida, Taichi Inadomi, Terutsugu Seki, Yuichiro Tameda, Yuya Oku, and Kengo Sano. Development of the calibration device using UAV mounted UV-LED light source for the fluorescence detector. In *EPJ Web of Conferences*, volume 210, page 05015. EDP Sciences, 2019.

[4] Arata Nakazawa et al. FOV direction and image size calibration of Fluorescence Detector using light source on UAV. In *Proceedings of 37th International Cosmic Ray Conference — PoS(ICRC2021)*, volume 395, 2022.

Full Authors List: the TelescopeArray Collaboration

R.U. Abbasi[1], Y. Abe[2], T. Abu-Zayyad[1,3], M. Allen[3], Y. Arai[4], R. Arimura[4], E. Barcikowski[3], J.W. Belz[3], D.R. Bergman[3], S.A. Blake[3], I. Buckland[3], B.G. Cheon[5], M. Chikawa[6], A. Fedynitch[6,7], T. Fujii[4,8], K. Fujisue[6], K. Fujita[6], R. Fujiwara[4], M. Fukushima[6], G. Furlich[3], Z. Gerber[3], N. Globus[9*], W. Hanlon[3], N. Hayashida[10], H. He[9], R. Hibi[2], K. Hibino[10], R. Higuchi[9], K. Honda[11], D. Ikeda[10], N. Inoue[12], T. Ishii[11], H. Ito[9], D. Ivanov[3], A. Iwasaki[4], H.M. Jeong[13], S. Jeong[13], C.C.H. Jui[3], K. Kadota[14], F. Kakimoto[10], O. Kalashev[15], K. Kasahara[16], S. Kasami[17], S. Kawakami[4], K. Kawata[6], I. Kharuk[15], E. Kido[9], H.B. Kim[5], J.H. Kim[3], J.H. Kim[3†], S.W. Kim[13], Y. Kimura[4], I. Komae[4], K. Komori[17], Y. Kusumori[17], M. Kuznetsov[15,18], Y.J. Kwon[19], K.H. Lee[5], M.J. Lee[13], B. Lubsandorzhiev[15], J.P. Lundquist[3,20], T. Matsuyama[4], J.A. Matthews[3], J.N. Matthews[3], R. Mayta[4], K. Miyashita[2], K. Mizuno[2], M. Mori[17], M. Murakami[17], I. Myers[3], S. Nagataki[9], K. Nakai[4], T. Nakamura[21], E. Nishio[17], T. Nonaka[6], S. Ogio[6], H. Ohoka[6], N. Okazaki[6], Y. Oku[17], T. Okuda[22], Y. Omura[4], M. Onishi[6], M. Ono[9], A. Oshima[23], H. Oshima[6], S. Ozawa[24], I.H. Park[13], K.Y. Park[5], M. Potts[3‡], M.S. Pshirkov[15,25], J. Remington[3], D.C. Rodriguez[3], C. Rott[3,13], G.I. Rubtsov[15], D. Ryu[26], H. Sagawa[6], R. Saito[2], N. Sakaki[6], T. Sako[6], N. Sakurai[4], D. Sato[2], K. Sato[4], S. Sato[17], K. Sekino[6], P.D. Shah[3], N. Shibata[17], T. Shibata[6], J. Shikita[4], H. Shimodaira[6], B.K. Shin[26], H.S. Shin[6], D. Shinto[17], J.D. Smith[3], P. Sokolsky[3], B.T. Stokes[3], T.A. Stroman[3], Y. Takagi[17], K. Takahashi[6], M. Takamura[27], M. Takeda[6], R. Takeishi[6], A. Taketa[28], M. Takita[6], Y. Tameda[17], K. Tanaka[29], M. Tanaka[30], S.B. Thomas[3], G.B. Thomson[3], P. Tinyakov[15,18], I. Tkachev[15], H. Tokuno[31], T. Tomida[2], S. Troitsky[15], R. Tsuda[4], Y. Tsunesada[4,8], S. Udo[10], F. Urban[32], I.A. Vaiman[15], D. Warren[9], T. Wong[3], K. Yamazaki[23], K. Yashiro[27], F. Yoshida[17], Y. Zhezher[6,15], and Z. Zundel[3]

[1] *Department of Physics, Loyola University Chicago, Chicago, Illinois 60660, USA*
[2] *Academic Assembly School of Science and Technology Institute of Engineering, Shinshu University, Nagano, Nagano 380-8554, Japan*
[3] *High Energy Astrophysics Institute and Department of Physics and Astronomy, University of Utah, Salt Lake City, Utah 84112-0830, USA*
[4] *Graduate School of Science, Osaka Metropolitan University, Sugimoto, Sumiyoshi, Osaka 558-8585, Japan*
[5] *Department of Physics and The Research Institute of Natural Science, Hanyang University, Seongdong-gu, Seoul 426-791, Korea*
[6] *Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba 277-8582, Japan*
[7] *Institute of Physics, Academia Sinica, Taipei City 115201, Taiwan*
[8] *Nambu Yoichiro Institute of Theoretical and Experimental Physics, Osaka Metropolitan University, Sugimoto, Sumiyoshi, Osaka 558-8585, Japan*
[9] *Astrophysical Big Bang Laboratory, RIKEN, Wako, Saitama 351-0198, Japan*
[10] *Faculty of Engineering, Kanagawa University, Yokohama, Kanagawa 221-8686, Japan*
[11] *Interdisciplinary Graduate School of Medicine and Engineering, University of Yamanashi, Kofu, Yamanashi 400-8511, Japan*
[12] *The Graduate School of Science and Engineering, Saitama University, Saitama, Saitama 338-8570, Japan*
[13] *Department of Physics, SungKyunKwan University, Jang-an-gu, Suwon 16419, Korea*
[14] *Department of Physics, Tokyo City University, Setagaya-ku, Tokyo 158-8557, Japan*
[15] *Institute for Nuclear Research of the Russian Academy of Sciences, Moscow 117312, Russia*
[16] *Faculty of Systems Engineering and Science, Shibaura Institute of Technology, Minato-ku, Tokyo 337-8570, Japan*
[17] *Graduate School of Engineering, Osaka Electro-Communication University, Neyagawa-shi, Osaka 572-8530, Japan*
[18] *Service de Physique Théorique, Université Libre de Bruxelles, Brussels, Belgium*
[19] *Department of Physics, Yonsei University, Seodaemun-gu, Seoul 120-749, Korea*
[20] *Center for Astrophysics and Cosmology, University of Nova Gorica, Nova Gorica 5297, Slovenia*
[21] *Faculty of Science, Kochi University, Kochi, Kochi 780-8520, Japan*
[22] *Department of Physical Sciences, Ritsumeikan University, Kusatsu, Shiga 525-8577, Japan*
[23] *College of Science and Engineering, Chubu University, Kasugai, Aichi 487-8501, Japan*
[24] *Quantum ICT Advanced Development Center, National Institute for Information and Communications Technology, Koganei, Tokyo 184-8795, Japan*
[25] *Sternberg Astronomical Institute, Moscow M.V. Lomonosov State University, Moscow 119991, Russia*
[26] *Department of Physics, School of Natural Sciences, Ulsan National Institute of Science and Technology, UNIST-gil, Ulsan 689-798, Korea*
[27] *Department of Physics, Tokyo University of Science, Noda, Chiba 162-8601, Japan*
[28] *Earthquake Research Institute, University of Tokyo, Bunkyo-ku, Tokyo 277-8582, Japan*
[29] *Graduate School of Information Sciences, Hiroshima City University, Hiroshima, Hiroshima 731-3194, Japan*
[30] *Institute of Particle and Nuclear Studies, KEK, Tsukuba, Ibaraki 305-0801, Japan*
[31] *Graduate School of Science and Engineering, Tokyo Institute of Technology, Meguro, Tokyo 152-8550, Japan*
[32] *CEICO, Institute of Physics, Czech Academy of Sciences, Prague 182 21, Czech Republic*

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) JP19H05607, for Scientific Research (S) JP15H05741, for Science Research (A) JP18H03705, for Young Scientists (A) JPH26707011, and for Fostering Joint

∗ Presently at: University of California - Santa Cruz
† Presently at: Argonne National Laboratory, Physics Division, Lemont, Illinois 60439,USA
‡ Presently at: Georgia Institute of Technology, Physics Department, Atlanta, Geogia 30332,USA

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-1806797, PHY-2012934, PHY-2112904, PHY-2209583, and PHY-2209584 as well as AGS-1613260, AGS-1844306, and AGS-2112709; 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, IISN project No. 4.4501.18, by the Belgian Science Policy under IUAP VII/37 (ULB), by National Science Centre in Poland grant 2020/37/B/ST9/01821. 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. We thank Patrick A. Shea who assisted the collaboration with much valuable advice and provided support for 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 computing resources from the Center for High Performance Computing at the University of Utah as well as the Academia Sinica Grid Computing Center (ASGC) is gratefully acknowledged.