PROCEEDINGS OF SCIENCE

High-speed Video Camera Observations Associated with a Terrestrial Gamma-ray Flash at the Telescope Array Detector.

Rasha Abbasi [a,*] **and on behalf of the Telescope Array and Lightning Collaboration**

[a] *Loyola University Chicago, Chicago, USA*

E-mail: rabbasi@luc.edu

This work presents observations of the optical emission of a lightning flash in conjunction with a downward-directed Terrestrial Gamma-ray Flash (TGF) at the Telescope Array detector. Previously, we reported joint observations by the Telescope Array Surface Detector (TASD), the Lightning Mapping Array, a sferic sensor, and a broadband interferometer of particle showers in coincidence with lightning. These observations consisted of energetic showers of approximately less than 10-microsecond duration with footprints on the ground of 3-6 kilometers in diameter, originating in the first one to two milliseconds of downward lightning leaders and in coincidence with the initial breakdown pulses stage of negative cloud-to-ground lighting leaders. Scintillator waveform and simulation studies confirmed that these showers must consist primarily of gamma radiations.

In this work, we use the TASD detector, together with a high-speed video camera, in conjunction with multiple lightning instruments at the TASD site, to report on the optical emission associated with a downward-directed terrestrial gamma-ray flash. Results from this study allow us to further the understanding of the initiation and propagation mechanism of terrestrial gamma-ray flashes. It will also further our ability to compare the most recent satellite optical emissions counterpart of upward-directed TGFs to that of downward-directed TGFs.

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

[1](a complete list of authors can be found at the end of the proceedings)
*Speaker

PoS(ICRC2023)250

1. Introduction

Terrestrial gamma-ray flashes (TGFs) are bursts of gamma rays initiated in the Earth's atmosphere. TGFs were first discovered in 1994 by the Burst and Transient Source Experiment (BATSE) at the Compton Gamma Ray Observatory [1, 2]. Since then, satellite-based observations of upward TGFs have accumulated from space using orbiting gamma-ray telescopes. A number of observations have shown that satellite-detected TGFs are produced in association with lightning flashes [3–6]. It was suggested that TGFs should also produce downward TGFs due to the symmetrical charge structure within thunderstorms. Studying TGFs from the ground is highly advantageous due to their proximity to the source. Until recently, only a few TGFs had been detected at ground level in association with overhead lightning [7–12].

Significant impediments to detecting downward TGFs have been due to the strong attenuation of gamma radiation at low altitudes (where high-density lightning is expected), and the ground-based detectors are not widespread enough to detect the forward-beamed radiation. Both issues have been addressed with observations from the large-area Telescope Array Surface Detector (TASD).

The discovery of "burst" events observed by the TASD [13] in correlation with lightning flashes has opened a new window for investigating energetic radiation from the ground. A Lightning Mapping Array (LMA) and electrostatic field change measurements were then installed followed by a VHF interferometer (INTF) and a fast electric field change antenna (FA) 6 km east of the TASD. The TASD "bursts" were found to be typically associated with the first ms of the lightning discharges, and usually lasted a few hundred microseconds [10]. It was also observed that a TGF clearly correlated with fast electric field changes of “initial breakdown pulses” (IBPs) at the beginning of Intra-Cloud (IC) and Cloud-to-Ground (CG) flashes [12].

In recent years, the European Space Agency's Atmosphere-Space Interactions Monitor (ASIM) was mounted on the International Space Station for the purpose of studying TGFs and other related phenomena. Above the atmosphere, ASIM is well-positioned to detect TGFs that occur at a high altitude, and it has observed many since its launch [14–17]. ASIM has revealed, for the first time and, with high timing accuracy, the optical emission timing and strength associated with lightning discharges during the production of TGF observations. In this work, we report on the simultaneous detection of a downward TGF together with the observation of the associated cloud-to-ground lightning flash by a high-speed camera in addition to the low/high radio frequency emission. The camera, operating at 40,000 images per second, allowed us to examine the development stage of the lightning flash during the occurrence of a TGF. The proximity to the source and the utilization of a suite of lightning instruments, along with a high-speed camera, have provided significant advantages in gaining further insights into the characteristics of lightning processes associated with TGF production. Furthermore, this approach has enabled a comparison of the optical emission observations between lightning discharges associated with downward-moving and upward-moving TGFs.

2. Telescope Array (TA) and the Lightning Instruments at the TA Site

2.1 The Telescope Array Surface Detector

The Telescope Array Surface Detector (TASD) is a 700 km^2 array overlooked by three Fluorescence Detector (FD) sites [18]. The TASD comprises 507 scintillator detectors as shown in Figure 1. Each TASD detector unit consists of upper and lower scintillator planes. Each plane has an area of 3 m^2 and a thickness of 1.2 cm. The upper and lower planes are separated by a 1 mm-thick stainless steel plate, and they are read out by individual photomultiplier tubes (PMTs), which are coupled to the scintillator via an array of wavelength-shifting fibers. The scintillator, fibers, and photomultipliers are contained in a light-tight and electrically grounded stainless steel box (1.5 mm thick on top and 1.2 mm thick on the bottom) under an additional 1.2 mm iron roof, providing protection from extreme temperature variations [18].

The output signals from the PMTs are digitized locally by a 12-bit Fast Analog-to-Digital Converter (FADC) with a 50 MHz sampling rate [19]. The TASD is designed to detect the charged components (primarily electrons, positrons, and muons) of the EAS. An event trigger is recorded when three adjacent SDs observe a time-integrated signal greater than 3 Vertical Equivalent Muons (VEM) within 8 μs. The VEM is a unit of energy deposit, equivalent to the energy deposited in a single TASD scintillator plane by a vertical (and hence perpendicular to the plane) relativistic muon. In more conventional units, a VEM is about 2 MeV per scintillator plane.

When a trigger occurs, the signals from all the SDs within $\pm$ 32 μs that detect an integrated amplitude greater than about 0.3 VEM are also recorded. The trigger efficiency of UHECRs with a zenith angle less than 45° and an energy greater than 10 EeV is approximately 100%, with a corresponding aperture of 1,100 km^{2}sr [18].

2.2 Types of Lightning Detectors

There are four types of lightning detectors operating at the Telescope Array site: the Lightning Mapping Array, Slow/Fast Antenna, INTerFerometer, and a high-speed video camera shown in Figure 1.

The Lightning Mapping Array (LMA) was developed by the Langmuir Laboratory group at New Mexico Tech [20, 21]. The LMA provides us with detailed 3D images of the VHF radiation produced by the lightning inside storms. An eleven-station network of sensors was deployed in 2013 over the 700 km^2 area covered by the TA detector. It detects the peak arrival time of impulsive radio emissions between 60—66 MHz. In radio-quiet areas like the Utah desert, the LMA detects VHF emissions with a time accuracy of 35 ns rms over a wide (>70 dB) dynamic range, from $\leq$10 mW to more than 100 kW peak source power. Cell data modems connect each station to the internet, allowing data to be processed in real-time and posted on the web to be monitored.

In August 2018, a Fast Antenna (FA) and an INTerFerometer (INTF) were deployed at the TA site. The INTF records broadband (20—80 MHz) waveforms at 180 MHz from three flat-plate receiving antennas, and it also determines the two-dimensional azimuth and elevation arrival directions of the VHF radiation with sub-microsecond resolution [22]. This is done on a post-processed basis and defines the radiation centroid in overlapping 0.7 or 1.4 μs windows. Triangular baselines of 121 m were used to maximize the angular resolution over the TASD. The Fast electric

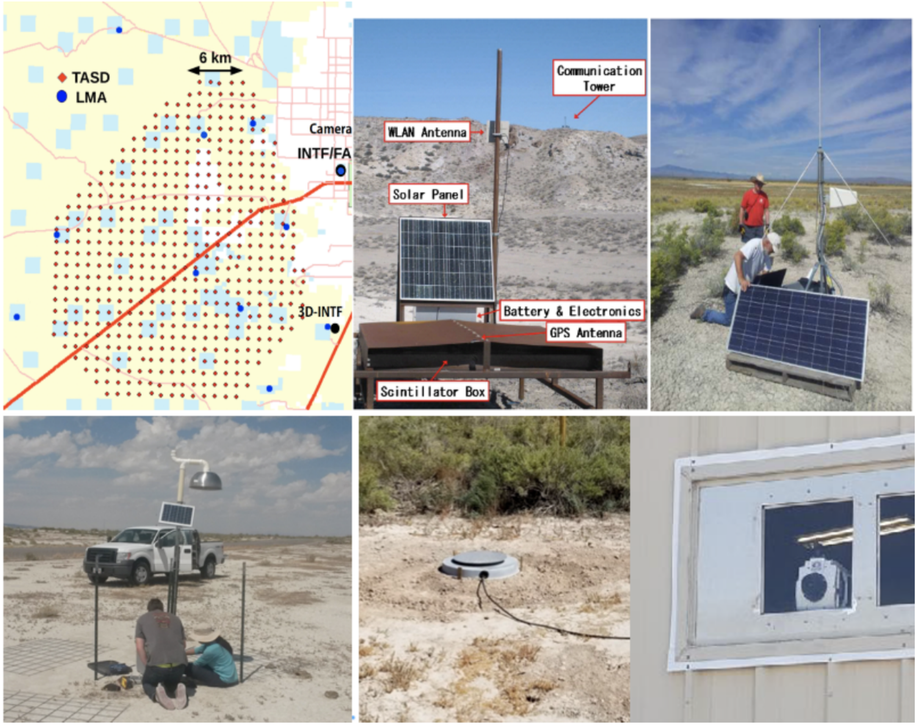

Figure 1: From left to right, the Telescope Array and lightning instruments detectors map, the surface detector, the LMA station, the slow antenna station, the interferometer, and the high-speed-video camera.

field change Antenna (FA) provides high-resolution (180 MHz) measurements of the low frequency and extremely low frequency (LF/ELF) discharge sferics, which are the key to interpreting the INTF and LMA observations. In September 2022, a second INTF was deployed at the west side of the TA site to record Initial Breakdown Pulses (IBPs) covering a larger area of the TA detector and collecting lightning in 3D mode.

In August 2021, a high-speed video camera Phantom V2012 was installed. The camera operating at 40,000 frames per second with a time interval between frames of 25.00 μs and an exposure time of 23.84 μs (at the end of each frame the camera is blind for 1.14 μs due to data transfer). Each frame of the video is time-stamped utilizing a GPS antenna and has a resolution of 1280×448 pixels. The camera is sensitive to the visible and near-infrared spectra (400 nm - 1000 nm). The camera was installed inside a building five kilometers to the east border of the TASD. The 20-mm focal length lens allowed a vertical viewing angle of 35 degrees, and a horizontal angle of 84 degrees covering almost all of the TASD detectors. The camera's position and settings were optimized to observe downward TGF sources that are approximately 30 km from the camera and up to 3 km above ground level. Each video had a recording length of 1.1 seconds and was automatically triggered by changes in luminosity. Data from the camera is saved on a computer at the site and analyzed offline.

3. Observations

On September 11 of 2021, we observed a thunderstorm that produced multiple TGFs within one hour at the Telescope Array site. Figure 2 shows one of the TGFs observed on that day. Figure 2 left shows the height vs. azimuth recorded by a high-speed video camera image of the lightning flash associated with a TGF. This TGF resulted in a burst of three gamma-ray triggers reported by the TASD detector referred to as triggers A, B, and C. The filled triangles in Figure 2 left indicate the source height for each of these triggers. Figure 2 right shows the timing sequence of gamma, electric field change, and INTF detections, together with luminosity observed by the high-speed video camera.

Unlike most of the other TGFs observed at the TA site [23, 24], this energetic downward-directed terrestrial gamma-ray is not only related to the early leader stage. The energetic observed gamma-ray triggers were produced as the leader propagated below the cloud base. The third TGF burst happened when the stepped leader was about halfway to the ground. The energetic observed TGF bursts occurred during the propagation of a fast and bright downward negative leader which resulted in a high peak current return stroke of -154 kA. The TGF presented unique features in terms of energy deposit and duration.

The optical emissions observed by the high-speed video camera were found to start enhancing within 25 microseconds from the onset of the TGF trigger signal and continue to increase 25-75 microseconds after the TGF trigger ceases. ASIM scientists reported that the majority of the TGF detections associated optical pulses are observed to start after a weak increase in the optical emission in the 337 nm and 777.4 nm photometers, and before, or at the onset of, the main ~2 ms long optical pulse [25]. We also observe that the first TGF trigger roughly 200 μs after the onset of the main optical pulse and before the optical luminosity increases and peaks after the first TGF trigger as shown in Figure 2. Note that, the optical emission in this observation includes luminosity peaks that are not associated with TGFs for the same flash. This difference between upward and downward TGF optical emissions could possibly be explained by a number of reasons one of which is the different proximity to the source and the observational geometry.

4. Summary and Outlook

On September 11 of 2021, we observed a thunderstorm by the TASD. This storm produced multiple TGFs within one hour. In this proceeding, we are presenting the simultaneous detection of one of those downward-directed TGFs together with the observation of the associated cloud-to-ground lightning flash by a high-speed camera, an INTF, and a FA. The energetic detected TGF burst occurred while the leader was propagating below the cloud base. The fast downward negative leader resulted in a high peak current return stroke.

To understand the physics behind the initiation and propagation of TGFs, and to further compare the optical signature correlation between downward-directed and upward-directed TGF emissions [25, 26] we have installed photometers at the TASD site. These photometers share the same field of view as the high-speed video camera and will report, with much higher timing resolution, about the optical emissions from atmospheric electrical discharge processes in three different wavelengths: at 337.0 nm, 391.2 nm, and 777.4 nm.

PoS(ICRC2023)250

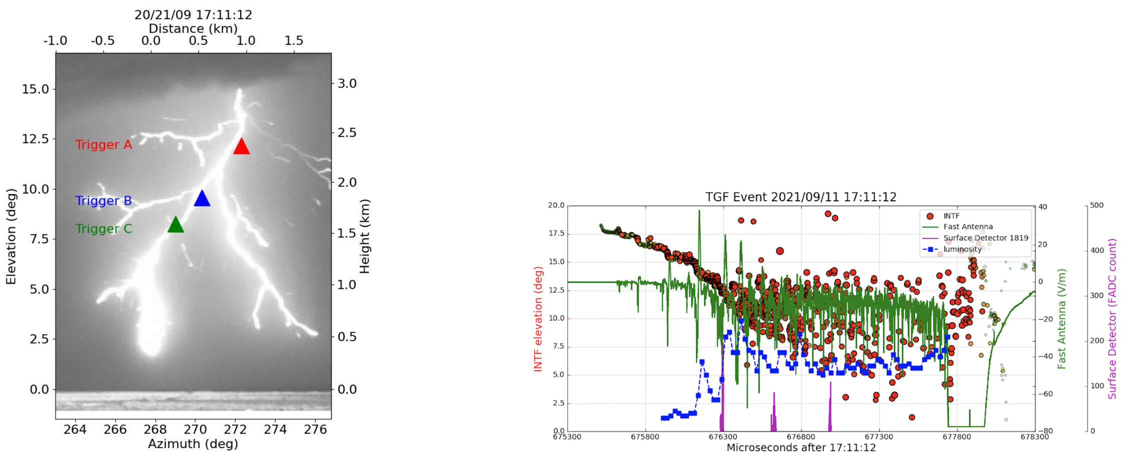

Figure 2: *Left:* This figure shows the elevation vs. azimuth for the whole flash in a frame of the camera. The red, green, and blue triangles are the sources of the TGF for triggers A, B, and C consecutively. *Right:* This figure shows the TASD waveforms for one of the SDs in magenta, the average luminosity in dark blue, the electric-field waveform in green, the INTF elevation in red circles. The flash observed from initiation until the first return stroke within 3 ms duration.

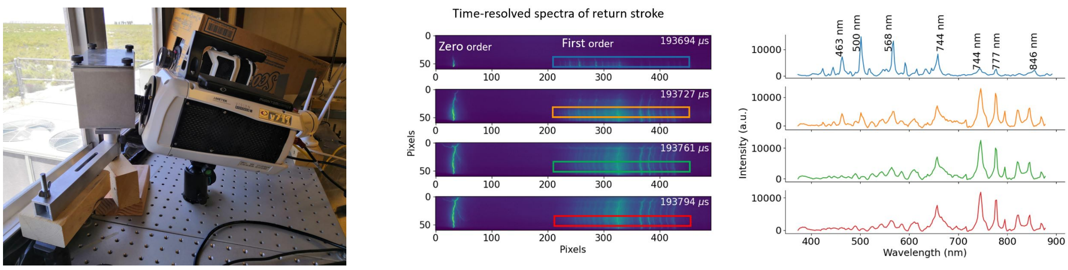

Figure 3: *Left:* The Phantom high-speed video camera v2012 and the v711. *Middle:* A series of the return stroke spectral images which were recorded by our spectroscopic system, at 29,990 frames per second by the Phantom V711. *Right:* From each image in the middle figure, a section of 8×230 pixels was selected of the first order of the dispersion to get the time-resolved spectra of the return strokes.

In addition to observing the optical emission of lightning events using the phantom-V2012 and the photometers, we have started observing the spectroscopy of TGFs via a split-less spectroscopic system transferred from Dr. Saba's lab in Brazil to Utah and installed next to the V2012 at the TA site as shown in Figure 3. The main goal of this study is to quantify the chemical components, temperature, and electron density of the lightning flashes producing and non-producing TGFs. The split-less spectroscopic system includes an additional high-speed camera v711 and a grism (grating prism) placed in front of the camera. The grism can diverse light from 400 nm to 900 nm. An example of the time-resolved optical spectra of a lightning flash that was observed in 2022 is shown in Figure 3. The optical emission studies of lightning at the Telescope Array detector will allow us to build further conclusions that support the model responsible for the TGF initiation and verify if downward-directed TGFs are a variant of the same phenomenon that causes upward-directed TGFs.

References

[1] G. J. Fishman *et al.*, "Discovery of intense gamma-ray flashes of atmospheric origin," *Science*, vol. 264, p. 1313, 1994.

[2] C. Kouveliotou, "BATSE results on observational properties of gamma-ray bursts," *The Astrophysical Journal Supplement*, vol. 92, pp. 637–642, 1994.

[3] S. A. Cummer *et al.*, "The lightning-tgf relationship on microsecond timescales," *Geophys. Res. Lett.*, vol. 38, p. L14810, 2011.

[4] S. A. Cummer *et al.*, "Lightning leader altitude progression in terrestrial gamma-ray flashes," *Geophys. Res. Lett.*, vol. 42, p. 7792–7798, 2015.

[5] F. Lyu *et al.*, "Ground detection of terrestrial gamma ray flashes from distant radio signals," *Geophysical Research Letters*, vol. 43, no. 16, pp. 8728–8734, 2016.

[6] X. Shao *et al.*, "A closer examination of terrestrial gamma ray flash related lightning processes," *J. Geophys. Res.*, vol. 115, p. A00E30, 2010.

[7] M. D. Tran *et al.*, "A terrestrial gamma-ray flash recorded at the Lightning Observatory in Gainesville, Florida," *Journal of Atmospheric and Solar-Terrestrial Physics*, vol. 136, pp. 86–93, 2015.

[8] B. M. Hare *et al.*, "Ground-level observation of a terrestrial gamma ray flash initiated by a triggered lightning," *Journal of Geophysical Research: Atmospheres*, vol. 121, no. 11, pp. 6511–6533, 2016.

[9] T. Enoto *et al.*, "Photonuclear reactions triggered by lightning discharge," *Nature*, vol. 551, no. 7681, pp. 481–484., 2017.

[10] R. Abbasi, T. Abu-Zayyad, M. Allen, E. Barcikowski, J. Belz, D. Bergman, S. Blake, M. Byrne, R. Cady, B. Cheon, *et al.*, "Gamma ray showers observed at ground level in coincidence with downward lightning leaders," *Journal of Geophysical Research: Atmospheres*, vol. 123, no. 13, pp. 6864–6879, 2018.

[11] D. J. Pleshinger *et al.*, "Gamma ray flashes produced by lightning observed at ground level by TETRA-II," *Journal of Geophysical Research: Space Physics*, vol. 124, no. 11, pp. 9229–9238, 2019.

[12] J. Belz, P. Krehbiel, J. Remington, M. Stanley, R. Abbasi, R. LeVon, W. Rison, D. Rodeheffer, T. Abu-Zayyad, M. Allen, *et al.*, "Observations of the origin of downward terrestrial gamma-ray flashes," *Journal of Geophysical Research: Atmospheres*, vol. 125, no. 23, p. e2019JD031940, 2020.

[13] R. Abbasi, M. Abe, T. Abu-Zayyad, M. Allen, R. Anderson, R. Azuma, E. Barcikowski, J. Belz, D. Bergman, S. Blake, *et al.*, "The bursts of high energy events observed by the telescope array surface detector," *Physics Letters A*, vol. 381, no. 32, pp. 2565–2572, 2017.

[14] T. Neubert, N. Ostgaard, V. Reglero, E. Blanc, O. Chanrion, C. Oxborrow, A. Orr, M. Tacconi, O. Hartnack, and D. Bhanderi, “The asim mission on the international space station,” *Space Science Reviews*, vol. 215, 2019.

[15] M. Heumesser *et al.*, “Spectral observations of optical emissions associated with terrestrial gamma-ray flashes,” *Geophysical Research Letters*, vol. 48, no. 4, p. 2020GL090700, 2021.

[16] A. Lindanger *et al.*, “Production of terrestrial gamma-ray flashes during the early stages of lightning flashes,” *Journal of Geophysical Research: Atmospheres*, vol. 127, no. 8, p. e2021JD036305, 2022.

[17] I. Bjørge-Engeland *et al.*, “Terrestrial gamma-ray flashes with accompanying elves detected by asim,” *Journal of Geophysical Research: Atmospheres*, vol. 127, no. 11, p. e2021JD036368, 2022.

[18] T. Abu-Zayyad *et al.*, “The surface detector array of the Telescope Array experiment,” *Nucl. Instrum. Meth.*, vol. A689, pp. 87–97, 2013.

[19] T. Nonaka *et al.*, “Performance of the Surface Detector of the Telescope Array experiment,” in *Proceedings, 32nd International Cosmic Ray Conference (ICRC 2011): Beijing, China, August 11-18, 2011*, vol. 2, p. 170, 2009.

[20] W. Rison *et al.*, “A gps-based three-dimensional lightning mapping system: Initial observations in central new mexico,” *Geophysical Research Letters*, vol. 26, no. 23, pp. 3573–3576, 1999.

[21] T. J. Ronald *et al.*, “Accuracy of the lightning mapping array,” *Journal of Geophysical Research: Atmospheres*, vol. 109, no. D14, 2004. D14207.

[22] M. G. Stock *et al.*, “Continuous broadband digital interferometry of lightning using a generalized cross-correlation algorithm,” *Journal of Geophysical Research: Atmospheres*, vol. 119, no. 6, pp. 3134–3165, 2014.

[23] R. U. Abbasi *et al.*, “Gamma ray showers observed at ground level in coincidence with downward lightning leaders,” *Journal of Geophysical Research: Atmospheres*, vol. 123, no. 13, pp. 6864–6879, 2018.

[24] J. W. Belz *et al.*, “Observations of the origin of downward terrestrial gamma-ray flashes,” Accepted for publication by the Journal of Geophysical Research: Atmospheres and is now "in print". arXiv:2009.14327.

[25] N. Ostgaard *et al.*, “First 10 months of tgf observations by asim,” *Journal of Geophysical Research: Atmospheres*, vol. 124, no. 24, pp. 14024–14036, 2019.

[26] C. A. Skeie, N. Østgaard, A. Mezentsev, I. Bjørge-Engeland, M. Marisaldi, N. Lehtinen, V. Reglero, and T. Neubert, “The temporal relationship between terrestrial gamma-ray flashes and associated optical pulses from lightning,” *Journal of Geophysical Research: Atmospheres*, vol. 127, no. 17, p. e2022JD037128, 2022.

Full Authors List: Telescope Array and Lightning 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], Z. Zundel[3], M. M. F. Saba[33], P. R. Krehbiel[34], W. Rison[34], N. Kieu[1], D. R. da Silva[33], M. A. Stanley[34], Dan Rodeheffer[34], J. Mazich[1], R. LeVon[2], K. Smout[2], and A. Petrizze [2].

[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 1050, 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
[33]National Institute for Space Research (INPE), Sao Jose dos Campos, Brazil.
[34]Langmuir Laboratory for Atmospheric Research, New Mexico Institute of Mining and Technology, Socorro, NM, USA.

Acknowledgements

Operation and analyses of this study have been supported by NSF grants AGS-2112709, AGS-1844306, AGS-1613260, AGS-1205727, and AGS-1720600. 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 U.S. National Science Foundation awards PHY-0601915, PHY-1404495, PHY-1404502, and PHY-1607727; by the National Research Foundation of Korea (2016R1A2B4014967, 2016R1A5A1013277, 2017K1A4A3015188, 2017R1A2A1A05071429) ; by the Russian Academy of Sciences, RFBR grant 20-02-00625a (INR), IISN project No. 4.4502.13, 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 Shea assisted the collaboration with valuable advice on a variety of topics. 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. We thank Ryan Said and W. A. Brooks of Vaisala Inc. for providing quality NLDN data lightning discharges over and around the TASD under their academic research use policy.

* 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