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High-Energy Particle Showers in Coincidence with Downward Lightning Leaders at the Telescope Array Cosmic Ray Observatory

John Belz*, **Rasha Abbasi, Ryan LeVon, Jackson Remington**

University of Utah

Paul Krehbiel, William Rison

Langmuir Laboratory, New Mexico Institute of Mining and Technology

Terrestrial Gamma Flashes (TGFs) have been observed in satellite-borne gamma ray detectors for several decades, starting with the BATSE instrument on the Compton Gamma-Ray observatory in 1994. Subsequent observation and simulation efforts have led to a model in which TGFs are produced in relativistic runaway electron avalanches (RREA), during upward negative breakdown at the beginning of intracloud lightning discharges. This model suggests that TGFs should also be produced by the downward negative breakdown that occurs at the beginning of negative cloud-to-ground lightning flashes. Here, we present the first clear evidence for this effect.

The Telescope Array Surface Detector (TASD) is a 700 square kilometer cosmic ray detector, an array of scintillators on a 1.2 km grid. Following the observation of bursts of anomalous TASD triggers correlated with local lightning activity, a Lightning Mapping Array (LMA) and slow electric field antenna were installed at the TASD site in order to study the effect. In data collected with this suite of detectors between 2014 and 2016, we find that the anomalous triggers are clearly produced during the initial breakdown phase of fast, downward propagating, negative lightning leaders. The anomalous bursts are a few hundred microseconds in duration, similar to that seen in satellite observations of TGFs. While the TASD is not optimized for gamma ray detection, we present the results of simulations demonstrating that the fluxes and forward-beaming observed are consistent with production in RREA. We conclude that the anomalous triggers observed by TA are due to high energy radiation produced by the fast downward propagating negative leaders, and are most likely downward-directed Terrestrial Gamma Flashes

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*Speaker.

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1. Introduction

At the previous *International Cosmic Ray Conference* [1], the Telescope Array collaboration reported the observation of "bursts" of Surface Detector (TASD) triggers in coincidence with lightning strikes recorded by the National Lightning Detection Network (NLDN) [2]. In each case two or more TASD triggers occurred within less than a millisecond and were found to be in good temporal and spatial coincidence high-current intracloud lightning.

Motivated by these observations, as well as by recent efforts to understand [3, 4, 5, 6, 7, 8] the *Terrestrial Gamma Flashes* (TGFs) observed by satellite-borne detectors [9, 10], a suite of lightning mapping (LMA) and electric field-measuring instruments were deployed at the Telescope Array detector site in Western Utah, U.S.A. Here, we report on the first joint observations with the TA/LMA instruments. The evidence suggests we are seeing gamma ray showers from downward-propagating negative leaders, consistent with a downward version of the TGF phenomenon. The shower reconstruction capabilities of the TASD therefore holds great promise as a tool for better testing models of TGF, and thus for gaining insight into the origins of the lightning breakdown mechanism.

2. Lightning Detection at Telescope Array

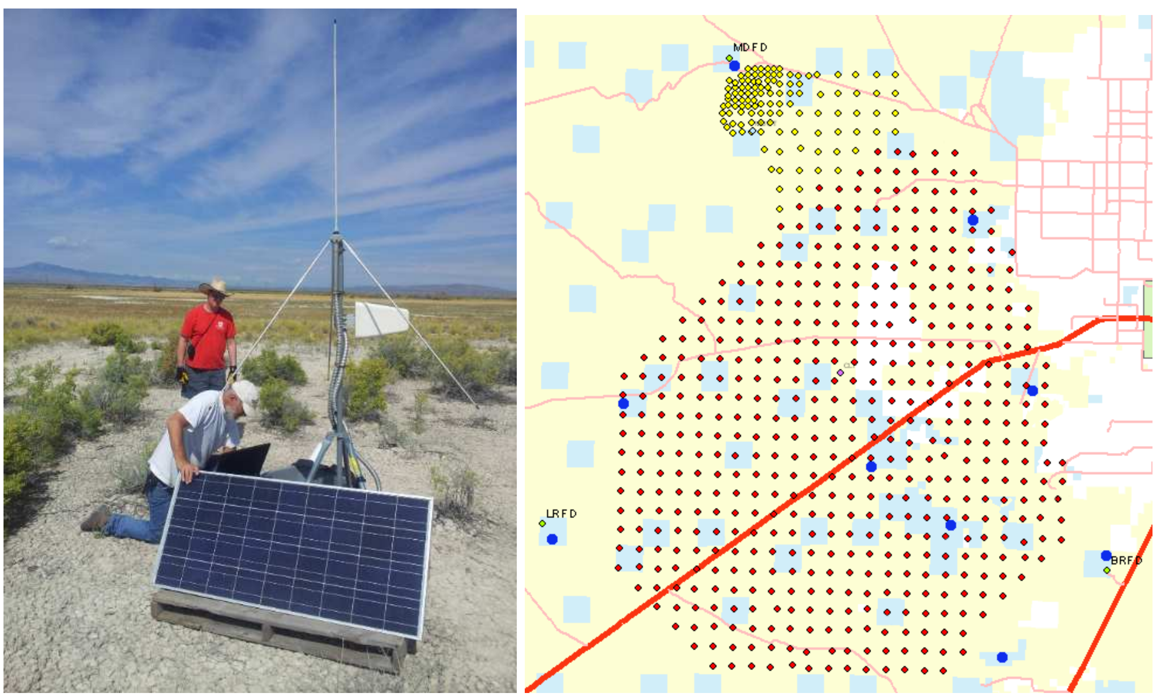

Figure 1: *Left:* W. Hanlon (Utah) and W. Rison (New Mexico Tech) installing VHF Lightning Mapping Array detector at TA site. *Right:* Map of Telescope Array observatory, showing 1.2 km grid of surface detectors (red circles), TALE surface detectors (yellow circles), fluorescence detector locations (green circles) and LMA detectors (blue circles).

The TASD is comprised of 507 scintillator detectors on a 1.2 km square grid. Each detector unit consists of two 3 m^2 scintillator planes, each plane is 1.2 cm thick. The two planes are sep-

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arated by a 1 mm thick steel plate, and 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 stainless steel box. Output signals from the PMTs are digitized locally by a 12 bit Fast Analog-to-Digital Converter (FADC) with a 50 MHz sampling rate [12].

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 signal greater than 3 Vertical Equivalent Muons (VEM) within 8 μs. When a trigger occurs the signals from all the SDs within $\pm$ 32 μs and amplitude greater than 0.3 VEM are also recorded. The typical SD trigger rate for cosmic ray showers is less than 0.01 Hz [13].

To understand the response of the TASD to photons and low-energy electrons we performed a detailed Geant4 [14, 15] simulation of the individual scintillator response [16]. The detector steel and scintillators were included in the simulation, along with supporting structure, as was the earth under the detector which could contribute to signal via backscatter. Energy deposited in the upper and lower planes of scintillator is recorded as a function of incident particle energy for a large number of primary particles incident on the virtual scintillation detector. Mean energy deposit was recorded in the upper and lower scintillator as a function of incident particle energy. The results of this simulation are summarized later (Figure 6). Electrons above 10 MeV (20 MeV) are expected to deposit the same energy as minimum ionizing particles in the upper (lower) scintillator. High-energy photons on average will deposit about one fifth of the energy of a minimum ionizing particle, due to inefficient conversion via Compton scattering and pair production in the detector steel and scintillator.

In October of 2013, a Lightning Mapping Array [17, 18] (LMA) was installed at the TASD site (Figure 1). This array consisted of nine autonomous VHF receivers spaced throughout the TASD. The performance of this array was unstable prior to August of 2015, and only decimated data was available for most detectors. A field trip to upgrade the LMA was undertaken in August of 2015, and since then the system has been operating in optimal condition [19].

A lightning mapping detector operates by recording impulsive radiation from lightning "sources" in the 60–66 MHz VHF band. Signals above a threshold are digitized after passing through a front end consisting of an analog Channel 3 filter. These signals are stored locally, with GPS time stamps, and uploaded for interesting time periods via a wireless communication uplink. Offline, information from multiple detector stations is combined and fits are performed which determine the three-dimensional spatial location and timing of each source. Trains of sources can then be displayed together in order to provide a complete image of the lightning flash as shown in Figure 2.

During the 2014 thunderstorm season, the TASD was also instrumented by a "slow antenna", sensitive to changes in the electric field at the Earth's surface [20]. This instrument is essentially an open-air capacitor read out with a 4 second time constant. The recorded voltages were converted to electric field changes, and analyzed offline during periods of interest. Unfortunately, the slow antenna was not operating during the times the LMA was operating at full capacity, so only the NLDN was available for secondary lightning information.

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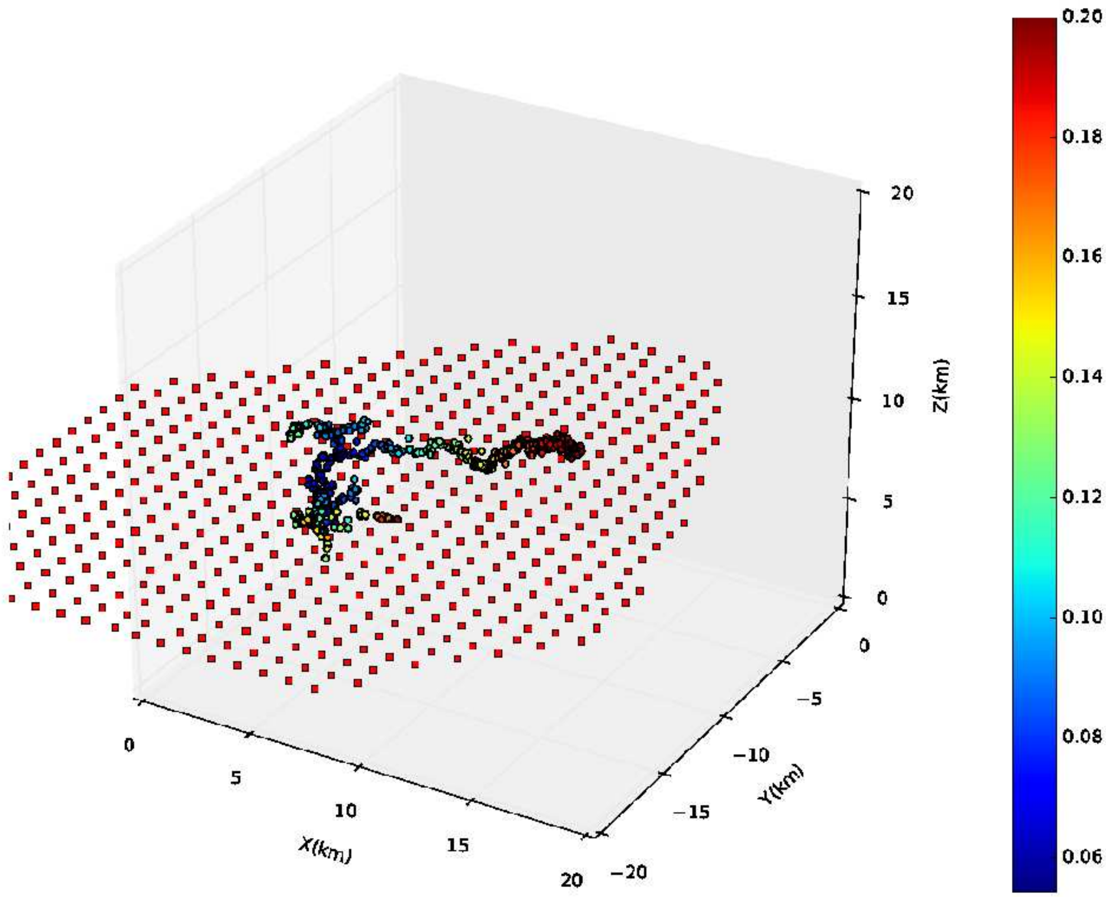

Figure 2: Three-dimensional image of intracloud lightning flash, with color representing time in seconds, for a lightning event which occurred over the TASD on 10 August, 2015. The surface detector locations are represented by red squares.

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3. Observations

Following Okuda [1], we looked for bursts in which two or more TASD triggers occurred within 1 millisecond. During the 2015 and 2016 thunderstorm seasons, three such triggers were found for which full LMA and NLDN information is available. These events are summarized in Table 1, and illustrated in Figures 3 and 4. The timing of the TASD triggers are clearly associated with the preliminary breakdown or "stepped leader" [21] phase of the lightning, prior to the first return stroke to ground.

During 2014, a total of seven TASD trigger bursts were recorded for which slow antenna data was available. One typical event is shown in Figure 5. These plots show electric field changes in addition to TASD trigger times and NLDN cloud-to-ground hits. In the zoomed view close to the time of the first two TASD triggers (middle panel), two time regimes of the flash are clearly apparent: (1) The more shallowly-sloped stepped-leader stage, and (2) the more steeply-sloped return stroke which is confirmed by an NLDN cloud-to-ground event. The TASD events are clearly occuring during the leader stage, consistent with the LMA observations in Figure 4. The third panel

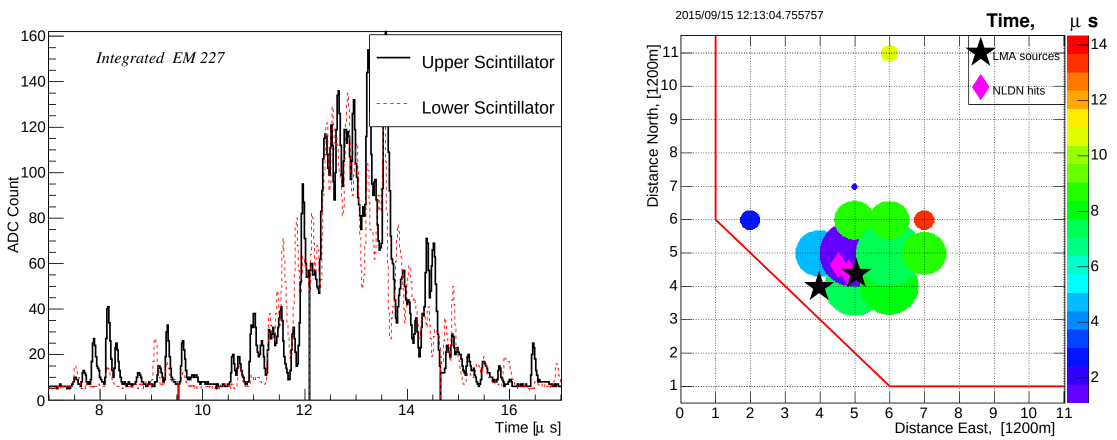

Figure 3: Left: Upper and lower scintillator waveforms for the LMA-correlated TASD burst at 12:13:04 on 15 Sept. 2015. Right: Footprint of TASD triggers for the event, with the numbers indicating the Vertical Equivalent Muon (VEM) counts, and the color indicating the relative arrival times. Initial LMA and NLDN events are indicated by stars and diamonds respectively. The red line indicates the southwestern boundary of the TASD array.

Table 1: TASD "trigger burst" events during 2015-2016 thunderstorm seasons. In addition to date and time, the number of triggers in the burst and the peak energy deposit (VEM units) are provided.

Date	Time (UT)	N_{trig}	VEM_{max}
2015/09/15	12:13:04	5	30, 499, 37, 142, 39
2015/09/15	19:37:01	4	72, 75, 47, 25
2016/05/10	02:41:50	5	105, 109, 4,162, 22,118

in Figure 5 shows that a third TASD trigger is likely occuring during the "dart leader" (secondary breakdown along an established current channel) stage of a subsequent return stroke, making this particular event somewhat unique among the Telescope Array observations.

4. Discussion

The timing of the TASD bursts with respect to the lightning activity recorded in the LMA and slow antenna data streams clearly indicates that the surface detector activity is occurring during the stepped-leader stage of the flash. In the case of the LMA activity, the locations of the stepped leader stage of the flashes are also known, and are in close proximity to the TASD bursts. All this is consistent with the expectation from downward TGFs which is gleaned from the satellite observations.

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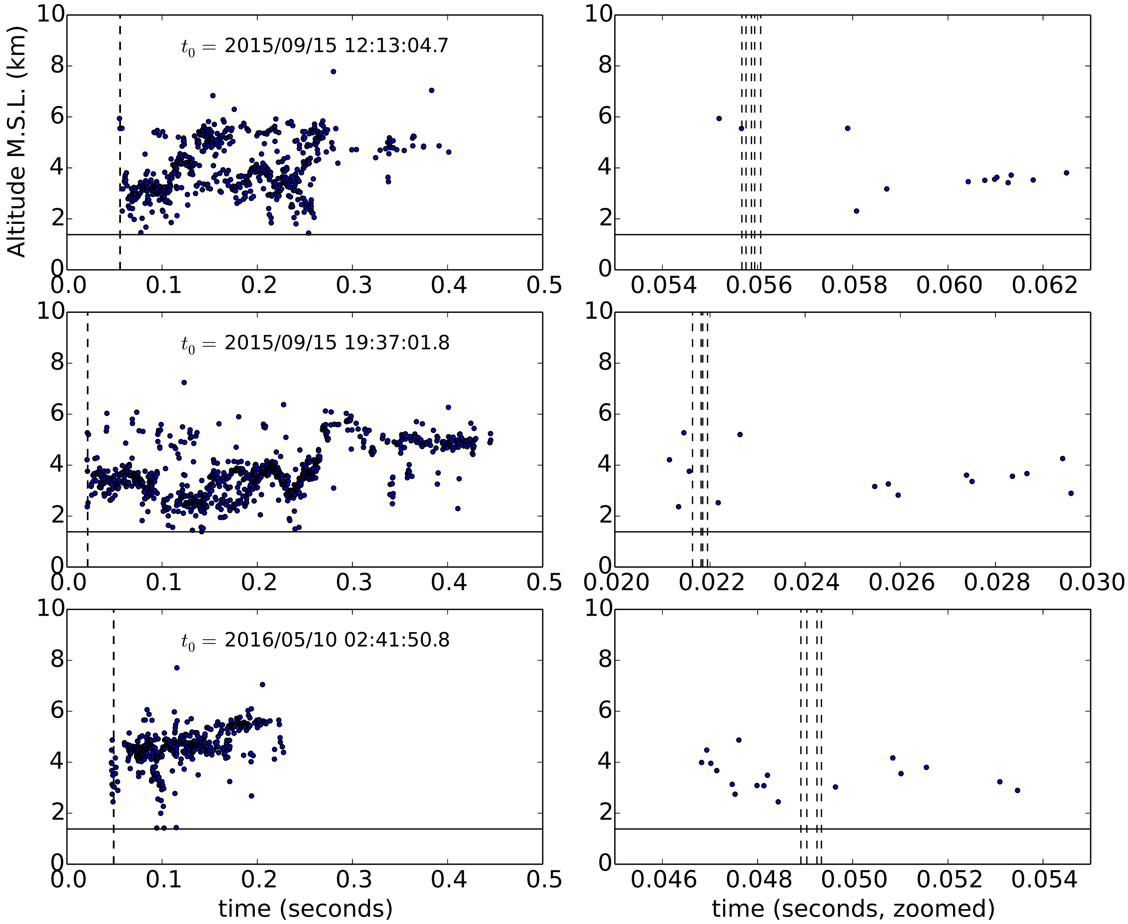

Figure 4: LMA altitude versus time plots for three TASD trigger bursts recorded in coincidence with LMA activity. The horizontal solid line represents mean Telescope Array ground, while the vertical dashed lines represent the timing of the TASD triggers. The left column shows all flashes on a 0.5 second time scale, while the right column is zoomed to illustrate the details of the TASD trigger timing. TASD triggers are clearly associated with the stepped leader phase of the lightning, prior to the return stroke(s) to ground indicated by the “descent” of the LMA sources from the cloud towards TA ground.

A remaining question is whether bursts of gamma rays produced at an altitude of several kilometers would produce the signal observed in the surface detectors. The TASD is an inefficent detector of photons, as it relies on Compton conversion in the detector steel or scintillator for a detection to occur. Simulation studies (Figure 6, left) show that at the highest energies photons will deposit on average about one fifth of the energy of a minimum ionizing charged particle per scintillator plane. Further, there will be substantial attenuation of photons in the atmosphere, which will have a photon attenuation length of order 100 meters at typical Telescope Array elevations [22].

To understand the effects of detector inefficiency and atmospheric attenuation, we performed a Geant4 [14, 15] simulation of photon showers originating in the atmosphere. These showers were thrown according a Relativistic Runaway Electron Avalanche (RREA) spectrum [23], and taken to have a pointlike origin a kilometer or more above Telescope Array ground. Based on the observed

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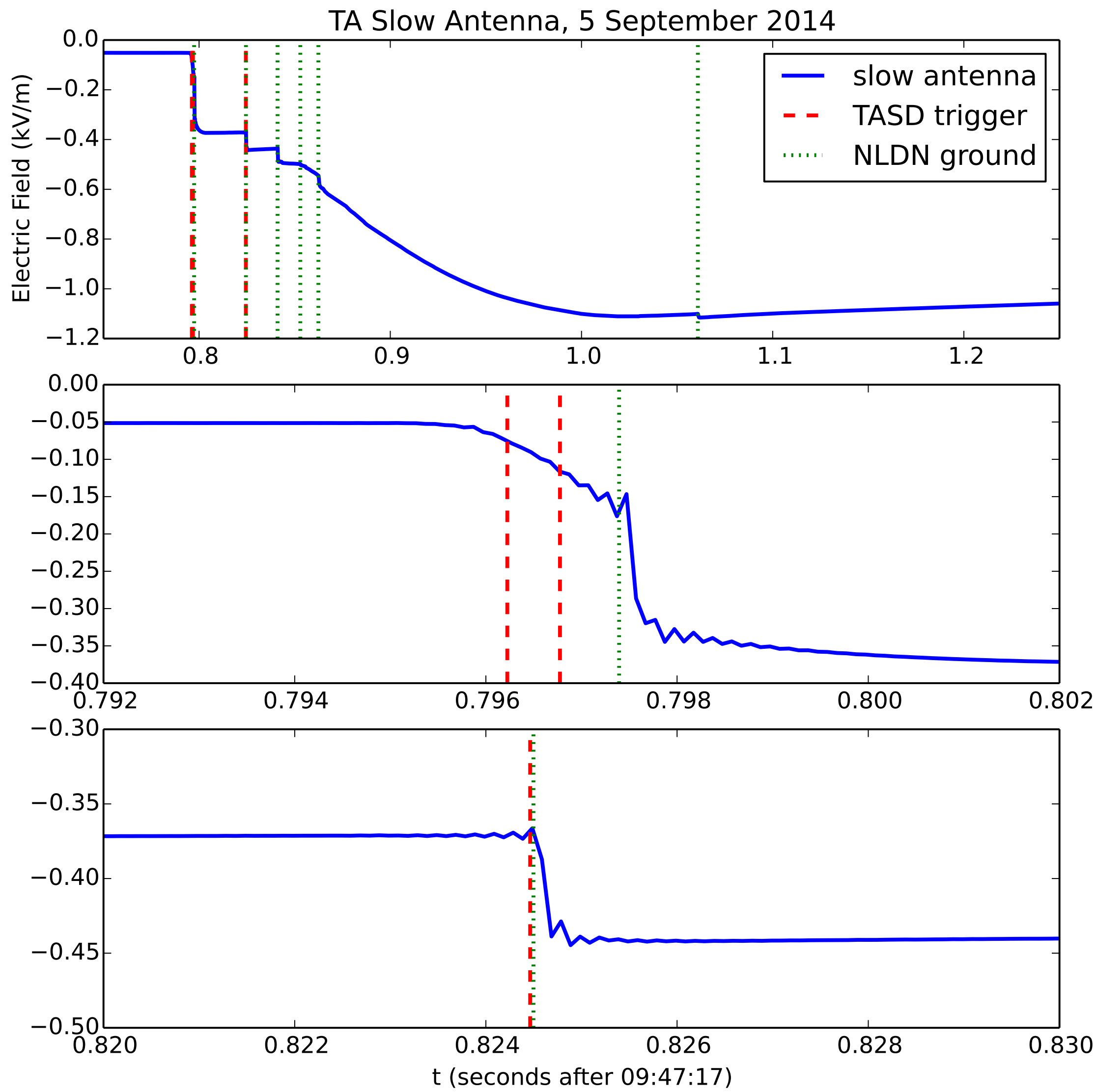

Figure 5: One of seven "burst" events recorded during 2014 in which slow-antenna activity was available. In each of the three panels, electric field (kilovolts per meter) is recorded as a function of time (blue curve). Also included are the TASD trigger times (red dashed lines) and NLDN cloud-to-ground hits (green dotted lines). The second and third panels are "zoomed" views of the top panel, close to the time of the TASD hits.

footprints of the actual showers, the simulated photons were randomly distributed in a vertical cone with a half-angle of 16°. Photons and their shower products were propagated through a realistic model of the atmosphere, then through simulated surface detectors in which the scintillator energy deposit was recorded. The energy deposit, in VEM units, was normalized to the expectation for a shower consisting of 10^{14} RREA photons with energy above 10 keV at altitude. Results are plotted in the right panel of Figure 6.

The first observation that we draw from our simulation is that is that no photons of energy less than 100 keV deposited any detectable energy in the surface detectors from altitudes greater than

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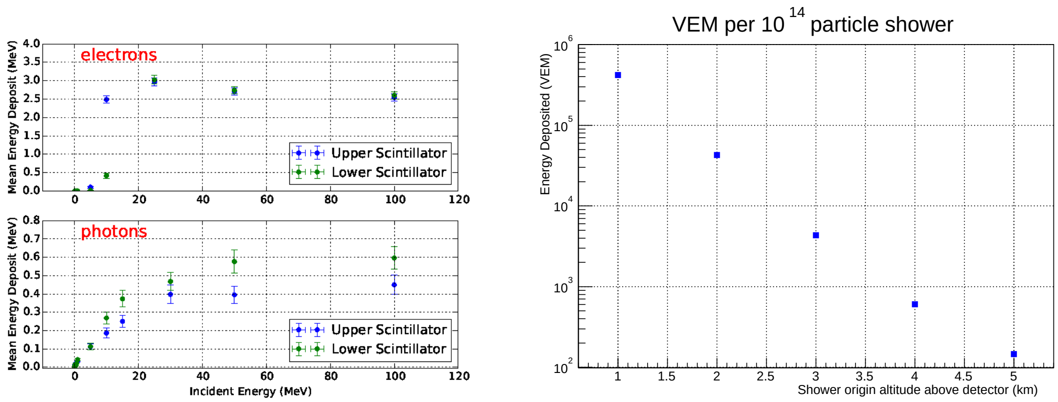

Figure 6: *Left:* Results of Geant4 simulation of mean TASD energy deposit for incident electrons and photons. *Right:* Energy deposit (VEM units) in a TASD scintillator at the shower core of a 10^{14}-photon Relativistic Runaway Electron Avalanche (RREA) shower, as a function of shower altitude, with energy and angular distributions as described in the text.

one kilometer above ground level. This indicates that the TASD bursts cannot be caused by lower energy *x*-ray photons. Further, the predicted energy deposits are consistent with the observations as recorded in the burst events. In future work, we will utilize TASD timing information to reconstruct the photon showers more accurately and attempt to more tightly constrain this phenomenon.

5. Conclusion

Altogether the Telescope Array observatory has detected approximately 20 burst events in eight years of observation. In about half of these events, the surface detector observations are supplemented with lightning detector data. Measurements to date appear to be consistent with these bursts arising from downward TGFs originating in negative downward lightning leaders. In this case, these events comprise the majority of the world's downward TGF sample and establish the TA/LMA combination as a major emergent facility for high-energy atmospheric research.

6. Acknowledgements

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