Telescope Array observatory for the high energy radiation induced by lightning

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Abstract. The Telescope Array (TA) experiment detects air-showers induced by ultra high energy cosmic rays. The TA ground Surface particle Detector array (TASD) observed some short-duration bursts of air-shower like events. These events are evidently correlated with lightning. Therefore, we have deployed lightning detectors in the vicinity of the TASD. We report the feature of these air-shower like events and the current study combined with these lightning detectors.

1. Introduction
The Telescope Array (TA) experiment detects air-showers induced by ultra high energy cosmic rays, located in midwest in Utah, USA (Figure 1). Some high energy radiation bursts of air-shower like events were observed by the Telescope Array Surface Detector (TASD), and correlated with lightning discharge detected by National Lightning Detection Network (NLDN) [1][2].

Figure 1. Telescope Array Experiment. Left: 507 ground surface particle detectors (tiny dots above) are surrounded by 3 atmospheric fluorescence telescope stations. Right: Particle detecting part of TASD consists of 2 layers of 3 m² plastic scintillators. Each scintillation layer has 1.2 cm thickness and provides information respectively via wavelength-shifting fibers [3].
There are some precedent observations for the relation between high energy radiation and identified lightning discharge. Their coverage area is several km$^2$ at most, whereas TASD is deployed 680 km$^2$. The precedent observations measure the energy of radiation and TASD measures spatial distribution of radiation. Therefore, TASD is unique and complementary to observe high energy radiation from lightning. In addition, TASD is the largest radiation detector with high sensitivity for electromagnetic component in the northern hemisphere. Near future, there is no promising plan to deploy radiation detectors in such a large area for radiation from lightning. Therefore, we deployed lightning detectors in the vicinity of the TASD to get coincidences with lightning discharge as many as possible.

2. Observed Burst Events
We searched for the burst of air shower events. The criteria of this search is more than 3 events within 1 ms, and we found 10 bursts of events in 5 years data [2]. In this search, we did not use position information. However, all these events for each bursts are very localized within ~1 km radius. Considering the events which could not generate shower trigger but are found in waveforms, the time gaps of events in a burst are distributed from several to a hundred microseconds. Some events of 5 bursts in 10 bursts were reconstructed.

An example comparison views of burst event with normal event are shown in Figure 2. All reconstructed burst shower fronts are much more curved than usual cosmic ray air showers (Figure 2 Middle). This means that these burst showers seem to start developing at lower altitudes in the sky than normal cosmic ray air showers. Waveforms of many burst events do not have sharp rising edges (less muonic) for which SDs are located at the nearest shower cores (Figure 2 Bottom). However, the time integrated energy deposit to SD is similar to the cosmic ray air shower (Figure 2 Top).

3. Correlation with Lightning
Our check of correlation between shower bursts and lightning shows that observed shower bursts are clearly synchronized ($\pm$1ms) with negative intracloud lightning. And the absolute peak current of synchronized lightning is much higher than other lightning. Therefore, these bursts are very rare phenomena. A geometrical example of reconstructed burst events and correlated lightning information is shown in Figure 3 Left. Two reconstructed shower axis tend to point small region at low sky, where is the intracloud lightning discharge. We also checked the correlation between lightning and all SD events, regardless of burst. The time difference between all SD events and lightning is shown in Figure 3 Right. Therefore, SD events correlated with lightning are associated with the initial processes of the flash. And the time gaps of events in a burst correspond to the stepped leader process of lightning.

4. Deployed lightning detectors and Future
We deployed different types of lightning detectors in the vicinity of the TASD. 4 lightning discharge antennas of LF band were deployed surrounding TASD, measuring timing, direction and amplitude of discharge. Time Of Arrival (TOA) and Magnetic Direction Finder (MDF) method can determine the position of the lightning discharge [4] (Figure 4). Another VHF band antennas were also deployed, which can measure the height of sferics. In addition to measure the pulse from lightning discharge, we deployed continuous atmospheric electric field antenna too. This result also shows the high energy radiation from lightning associates with the initial part of the lightning process [5] (Figure 5).

We will observe more high energy radiation bursts induced by lightning, with various lightning detectors.
Figure 2.
Left: An event in a burst. Right: A normal air-shower event. This normal air-shower event has almost same zenith angle and shower size of burst event shown in left. Top: Lateral number of detected particle distribution. Middle: Lateral arrival timing distribution. Bottom: Signal waveforms from SDs in the vicinity of shower core. Red and Blue correspond two PMT channels for two layers of scintillator. Each horizontal level corresponds to individual SD. Vertical value has shifted to avoid superposition of waveforms from different SDs.
Figure 3. Left: Color shows the height from ground up to 3000 m. Red point shows shower core hit position. Circle shows lightning position with 300 m radius (NLDN position error). Synchronized (intracloud) lightning is set at z=3000 m. Right: Time difference between lightning and all SD events, not only burst. The synchronized lightning is at center bin.

Figure 4. Left: Lightning location determination for a 4-fold coincidence event. Black dots show the locations of lightning detector. Red lines show hyperbolae by TOA on the basis of LDA. Blue arrows show the directions to the lightning discharge from detector by MDF. Right: Waveform of LDC for the left event. Black shows electric field. Red shows east-west magnetic field. Blue shows north-south magnetic field.

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Figure 5. Left: Electric field slow antenna profile with TASD and NLDN event timing. Right: Enlarged initial part of left.

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