Lightning Detection at the Telescope Array Cosmic Ray Observatory

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ABSTRACT: It has been known for over a decade that x-ray and gamma radiation (~ 100 keV to 10 MeV) is emitted by lightning strikes. This phenomenon has been observed by ground-and space-based detectors in association with both natural and induced lightning. Recently physicists studying data collected by the 700 km^2 *Telescope Array* (TA) Cosmic Ray Observatory in Western Utah, U.S.A. have observed gamma radiation in coincidence with lightning strikes. Using cosmic ray air shower reconstruction techniques, these gamma ray showers can be pointed back to their origin in the Earth's atmosphere. In response to these observations, a *Lightning Mapping Array* (LMA) consisting of ten autonomous VHF detectors was recently deployed at the Telescope Array site. The LMA detectors record impulsive radiation from lightning with 10 microsecond timing accuracy in order to create 3-dimensional GPS-timed reconstruction of a lightning strike. In addition to contributing to the study of gamma ray generation by lightning, The TA/LMA merger will also be the perfect instrument to search for evidence of a more speculative phenomena: The seeding of lightning strikes by cosmic ray air showers.

INTRODUCTION

There are unknown mechanisms at work in lightning production. For example, macroscopic electric fields inside thunderclouds are typically an order-of-magnitude less than that required for dielectric breakdown[1]. One possible explanation is that lightning is triggered by an avalanche of runaway electrons created by cosmic ray-induced extensive air showers with energy in excess of 10^{16} eV [2].

There have been suggestions that high energy particles may be emitted by natural or triggered lightning interactions in the Earth's atmosphere [3]. Large bursts of such particles may in turn mimic extensive air showers. A direct observation of this effect was recently made using the *Telescope Array* cosmic ray observatory, as described below.

Here, we describe our plan to install a permanent *Lightning Mapping Array* at the Telescope Array site. The combination of TA and LMA detectors will be used in an attempt to understand how lightning strikes produce air shower-like bursts of high energy particles. Also, this detector will be the ideal configuration to search for evidence of cosmic rays triggering lightning strikes. Thus the TA/LMA project has among its scientific objectives the study of a novel known phenomenon in unprecedented detail, and the search for evidence of an as-yet unobserved effect.

TELESCOPE ARRAY OBSERVATIONS

The Telescope Array (TA) in Millard County, Utah, is the largest detector of high-energy cosmic rays in the Northern Hemisphere. It includes a Surface Detector (SD) [4] consisting of 507 scintillation detectors covering approximately 700 km^2, capable of reconstructing cosmic ray induced air showers with primary

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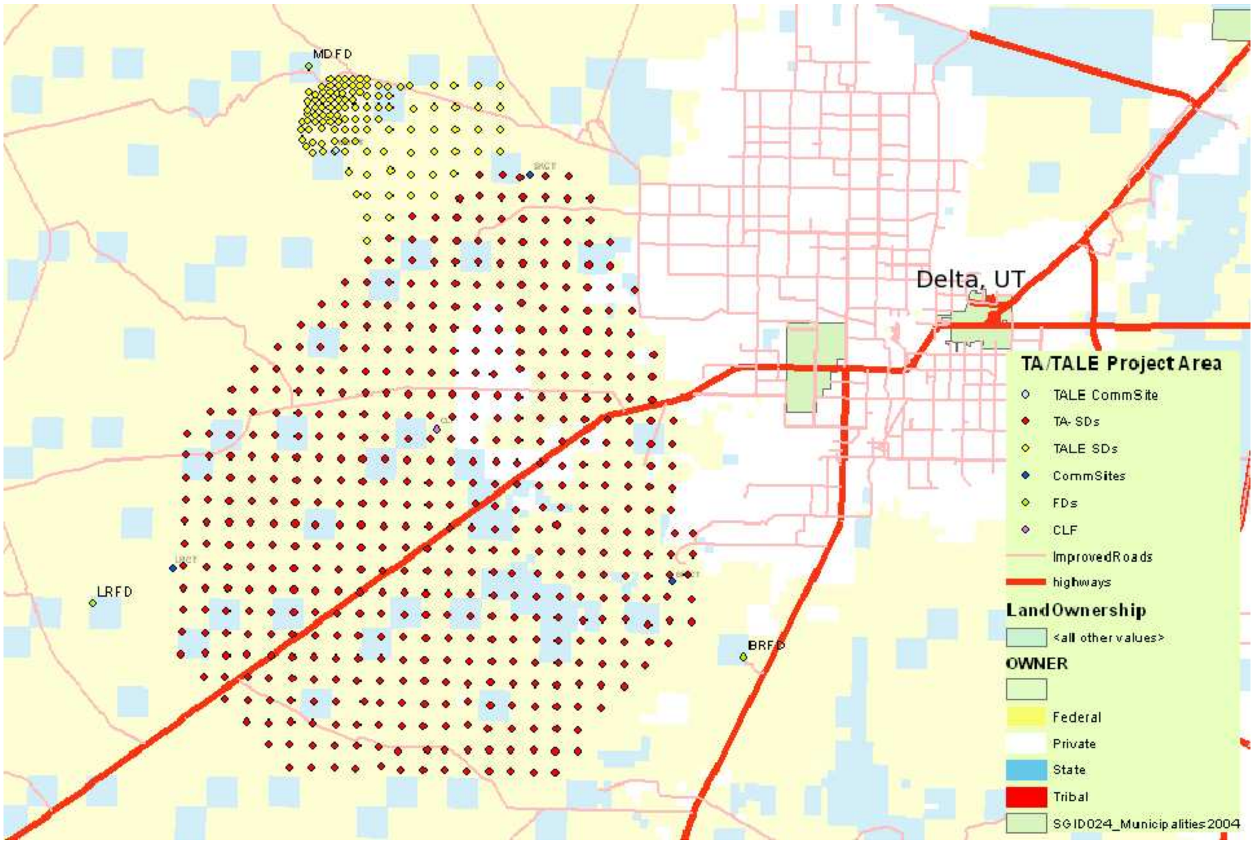

Figure 1: Map of Telescope Array observatory. Gamma ray events reported here were recorded with the surface detector grid, indicated by red diamonds in the figure. Vaisala NLDN data was requested within a 15 mile-radius circle centered at the TA Central Laser Facility (CLF), indicated by the magenta diamond in the figure. (Latitude = 39.29693°, Longitude 112.90875°.)

energies above 10^{18} eV. (Figure 1.) A recently deployed low-energy extension known as TALE will reduce the cosmic ray energy threshold by an order of magnitude.

The TA SD has been used to measure the cosmic ray energy spectrum [5] and to search for anisotropy in high-energy cosmic ray arrival directions [6]. It is also sensitive to atmospheric bursts of particles which are not necessarily directly related to cosmic rays.

Recently, TA SD data air shower events were observed which are hard to explain by conventional cosmic ray production mechanisms. These "trigger bursts" appear to consist of multiple air showers arriving within a very short time interval. In several cases these subshowers are reconstructable, and within uncertainties appear to come from a common vertex several kilometers above ground level. An example of the SD waveforms from such a burst is shown in Figure 2.

These trigger bursts are now known to comprise a subset of TA SD events which are well-correlated in time and space with lightning strikes recorded by the Vaisala [7] National Lightning Detection Network (NLDN). These coincidences are shown in Figure 3. As shown in Figure 4, these events are distinctly different from cosmic ray induced showers of high-energy charged particles and consistent with our expectation for photons in the 100 keV to few MeV energy range.

The interpretation of these anomalous trigger events is that lightning strikes in the vicinity of the

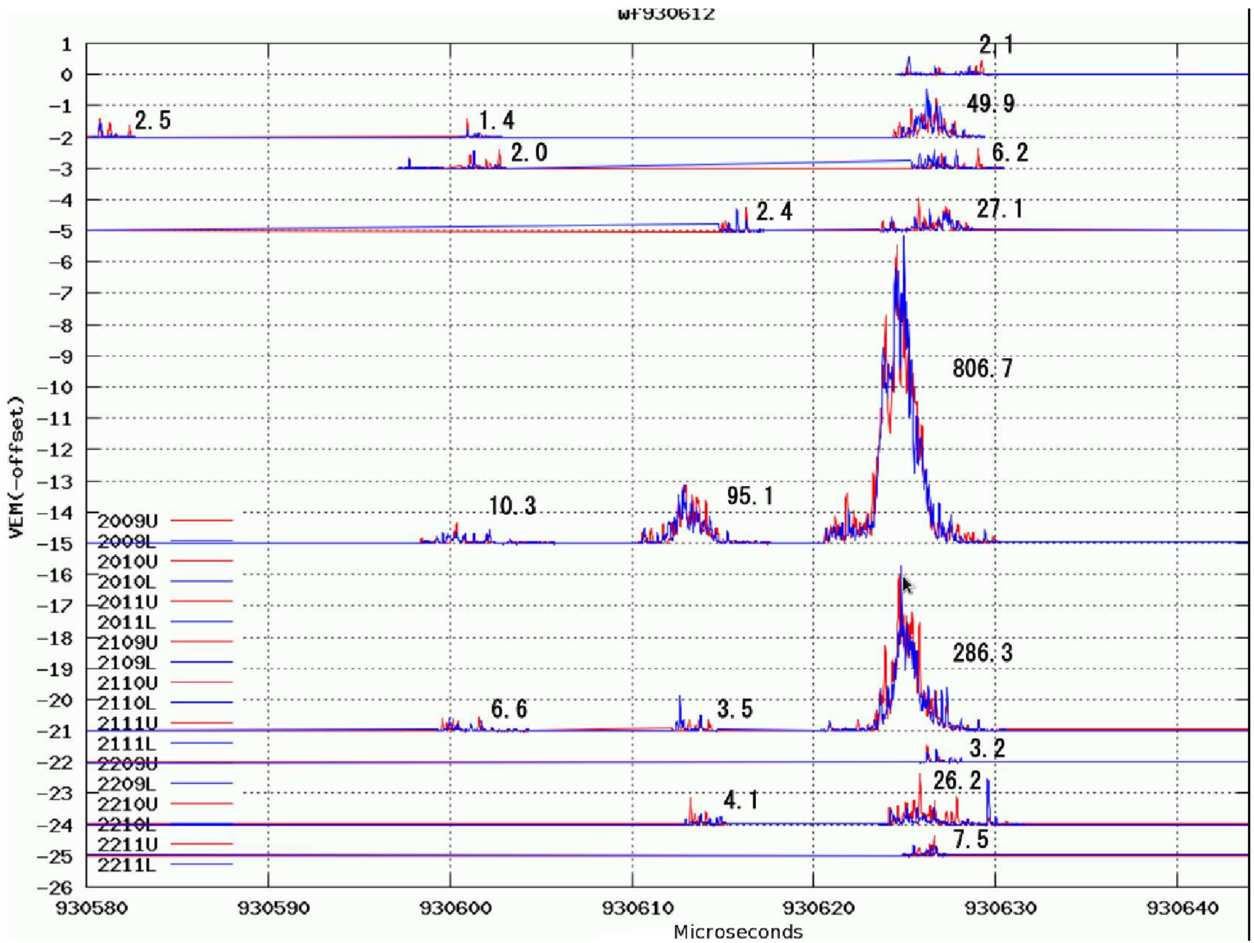

Figure 2: Waveforms captured in a single trigger, part of an 8-trigger "burst" recorded on 2010/10/04. Red and blue waveforms correspond to upper and lower scintillator planes on TA surface detectors. The number given are the total number of particles detected in units of "vertical equivalent muons".

Telescope Array surface detector are emitting showers of high energy particles, most likely gamma rays. While this is a known phenomenon, an important motivator of the present proposal is that in several cases the lightning-correlated gamma showers are *geometrically reconstructable* using techniques similar to that used in cosmic ray air shower reconstruction. See Figure 5. Reconstructable showers have a well defined core (center of energy deposited in the scintillator), and the distribution of hit times in individual SD elements enables reconstruction of the shower arrival direction with a resolution of 1-2 degrees. This cabability — which is unique to large air shower observatories such as Telescope Array — raises the prospect that the gamma radiation may be associated with particular times and features in the lightning profile, provided that the lightning strike itself can be accurately mapped. Such a lightning mapping tool exists and can readily be deployed and utilized in radio-quiet Western Utah, as described below.

THE LIGHTNING MAPPING ARRAY

The *Lightning Mapping Array* (LMA) technology developed at the Langmuir Institute for Atmospheric Research is an ideal instrument for studying electrical discharges — including those which accompany high-energy particle emission — in the Earth's atmosphere.

The Langmuir LMA [8] utilizes low-VHF (60-66 MHz) radio emissions in order to create 3-dimensional reconstruction of lightning strikes. It is most sensitive when deployed in radio-quiet, rural areas. An LMA detector unit is shown in Figure 6. It consists of a solar panel, electronics box, RF receiver antenna and a directional cellphone antenna for intersite communications.

The LMA makes use of a time-of-arrival technique, in which an array of typically 10-12 antennas spaced over an area of order 60 km diameter, detects impulsive RF radiation from lightning. Each impulse, occurring at space-time coordinates x, y, z and t, will be recorded in LMA detector i at a time t_i given by

$$t_i = t + \frac{\sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2}}{c} \tag{1}$$

where x_i, y_i, z_i are the detector coordinates and c is the speed of light. For five or more detectors, a meaningful fit may be performed to reconstruct the time and position of the impulse's origin. Better fits are obtained with more detectors. The result is a detailed map, with time development, of a lightning strike such as that shown in Figure 7.

We have recently deployed a temporary LMA at the TA site, and we are seeking support for a permanent installation.

CONCLUSION

Physicists in the Telescope Array collaboration have recently discovered that lightning-induced showers of high-energy particles may be reconstructed by a state-of-the-art cosmic ray observatory. Motivated by this discovery, we propose to install a permanent Lightning Mapping Array at the TA site in Millard County, Utah. This detector — a rare synergy between astrophysics and atmospheric science — will enable the study of particle acceleration mechanisms within atmospheric electrical storms in a unique fashion. Secondly, it will be the perfect detector configuration to investigate the long-hypothesized connection between cosmic rays and lightning.

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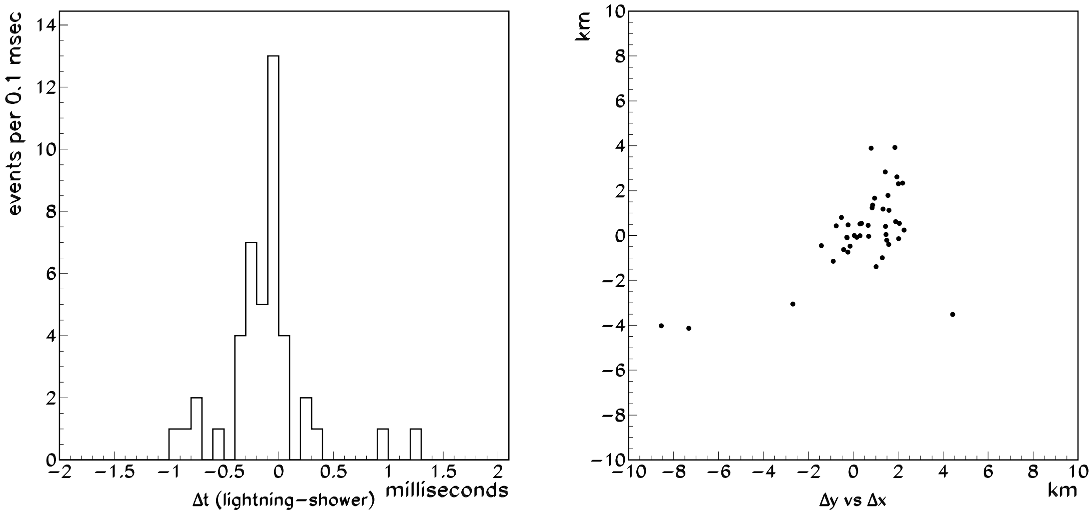

Figure 3: ***Left:*** **Time difference $\Delta t = t_{NLDN} - t_{SD}$ between NLDN lightning strikes over the TA surface detector and SD trigger times. This histogram was compiled for data collected between 2008 and 2013. A total of 26 NLDN strikes are represented in this histogram, each NLDN strike has between one and six entries depending on the number of coincident showers within the ± 2 millisecond time window.** ***Right:*** **Scatter plot showing spatial difference Δx (East-West) and Δy (North-South) between the NLDN hits and TA SD shower core locations within ± 2 millisecond time coincidence.**

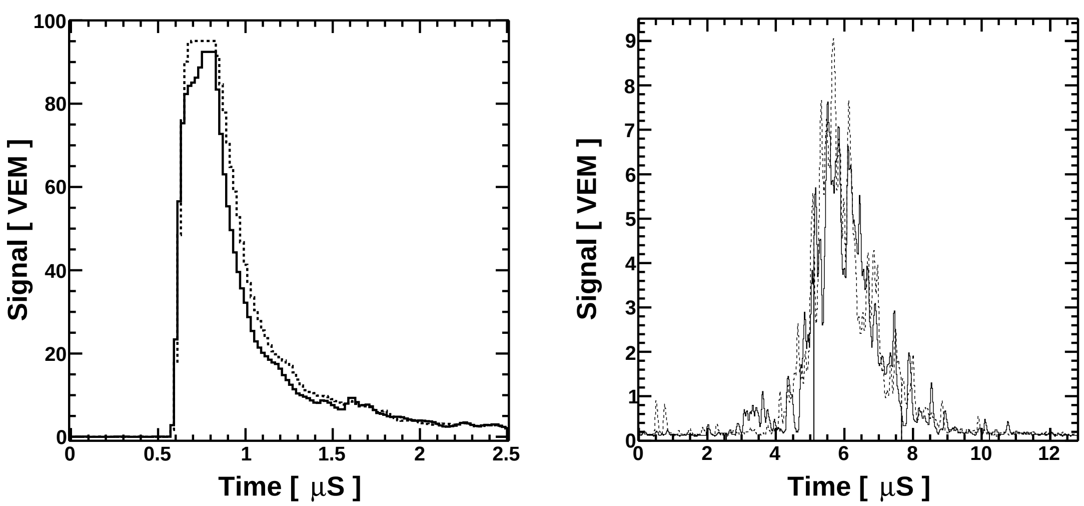

Figure 4: ***Left:*** **Upper (solid histogram) and lower (dashed histogram) scintillator waveforms for SD array element near the core of a cosmic ray-induced air shower. The vertical axis represents the signal in units of vertical equivalent muons (VEM). Upper and lower waveforms are typically similar in shape for cosmic ray events, and the saturation (“flat top”) observed in the lower scintillator is also typical for detectors near the air shower core.** ***Right:*** **Waveforms for SD element near core of lightning-correlated gamma ray shower. The magnitude of the energy deposit is less, and clearly different in the upper and lower scintillator due to fluctuations in the gamma conversion process.**

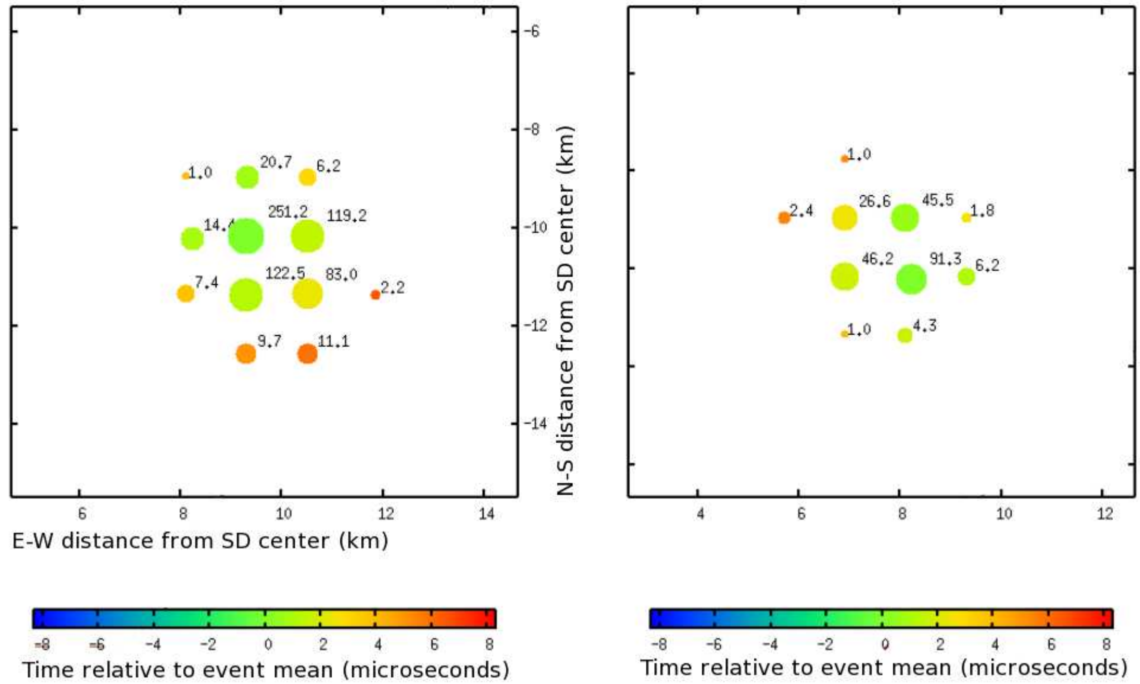

Figure 5: Location of Surface Detector hits recorded in two distinct gamma ray showers, which hit the detector 126 microseconds apart. An NLDN intracloud lightning strike was recorded within a millisecond of these showers. The position of the circle indicates the location of the hit counter relative to the array center. Numbers indicate the size of the waveform detected in units of Vertical Equivalent Muons (VEM). The color represents the time relative to the event mean of the hits, information which may be used to reconstruct the geometry of the gamma ray shower.

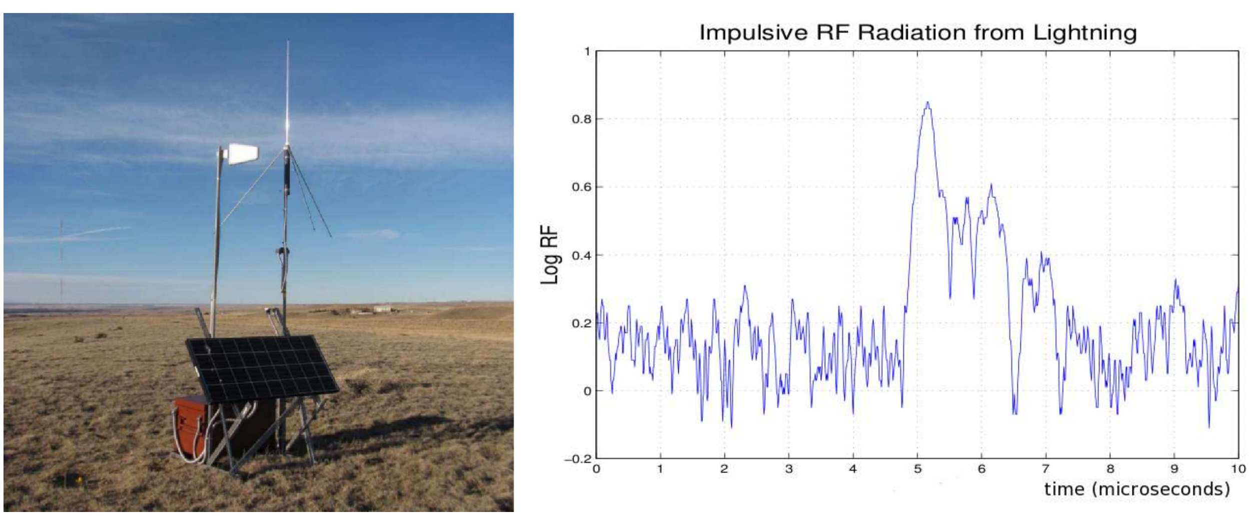

Figure 6: *Left:* Single lightning mapping array unit. Solar panel, box holding electronics, receiver antenna and cellphone communications antenna. *Right:* Impulsive 60 MHz radiation from lightning. Each LMA unit records time and amplitude of impulses above trigger threshold. With times from five or more LMA units, the source of this impulse may be reconstructed in space and time.

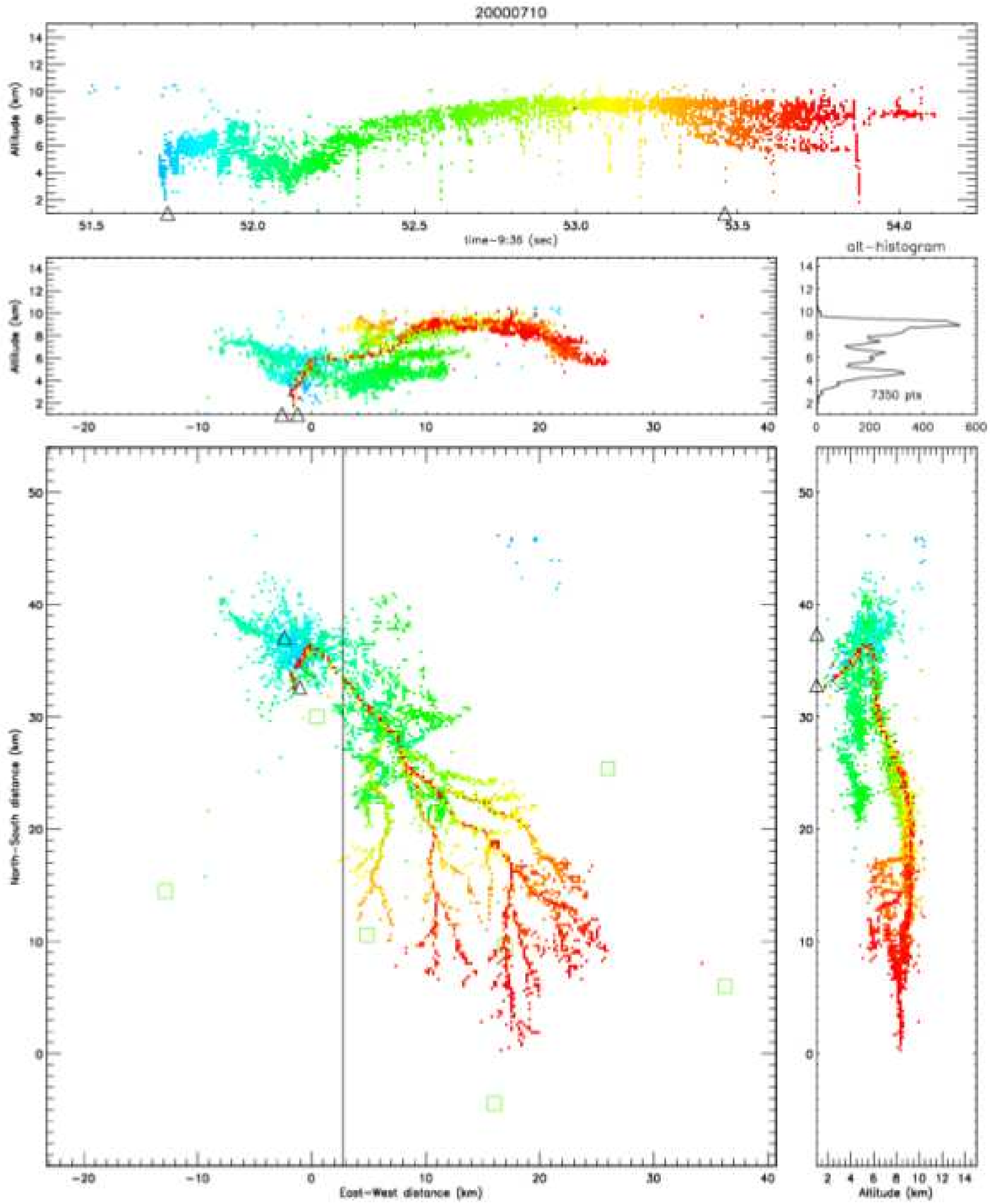

Figure 7: LMA Event display for cloud-to-ground lightning strike.