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Atmospheric Gamma-ray Observations at the Telescope Array Detector

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Abstract.

Previously in AtmoHead-2018, we reported joint observations by Telescope Array Surface Detector (TASD), Lightning Mapping Array (LMA), sferic sensor and broadband interferometer of particle showers coincident with lightning. These 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 coincident with high-current processes within the leaders. Scintillator waveform and simulation studies confirmed that these showers must consist primarily of gamma radiation.

On September 11, 2021, atmospheric discharges emitting gamma rays were, for the first time, recorded by a high-speed camera and by lightning detectors on the ground simultaneously. The events were detected by the Telescope Array located in the Utah desert and were filmed by the Phantom v2012 camera, set at an acquisition rate of 40,000 frames per second (fps) in conjunction with the Lightning Mapping Array (LMA), an interferometer, a fast antenna, and the National Lightning Detection Network (NLDN). Results from this study reported the new observation of several events of significantly longer duration and higher fluence, bridging the gap between the TASD and satellite-based detections. These events further demonstrate the similarity between the upward and downward TGF varieties and the likelihood of a common origin for their production.

1. Introduction

Terrestrial Gamma ray Flashes (TGFs) are bursts of gamma rays initiated in the Earth's atmosphere, first reported in 1994 from the Burst and Transient Source Experiment (BATSE) on the Compton Gamma-Ray Observatory satellite [1, 2]. Since then, a number of observations have shown that satellite-detected TGFs are produced by lightning flashes. In particular, the observations indicate that the TGFs are produced by relativistic runaway electron avalanches (RREAs) [3, 4, 5], within the first few milliseconds of upward intracloud (IC) flashes [6, 7, 8, 9]. In normally-electrified storms, intracloud flashes occur between the main mid-level negative and the upper positive charge in the storms, and typically begin with upward-developing negative breakdown. This explains the detection of TGFs by satellites.

As satellite-based observations of upward TGFs have accumulated, the question has been whether lightning produces downward TGFs that could be detected on the ground below or near thunderstorms. In particular, negative-polarity cloud-to-ground (-CG) discharges begin with downward negative breakdown that would be expected to produce TGFs directed earthward. Until recently, only a few TGFs had been detected at ground level in association with overhead lightning [4, 10, 11, 12]. Significant impediments to detecting downward TGFs have been a) the



increasingly strong attenuation of gamma radiation at low altitudes in the atmosphere, and b) the ground-based detectors being either too far below and/or 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) cosmic ray.

The Telescope Array Surface Detector (TASD) cosmic ray observatory is a 700 square kilometer array of plastic scintillator detectors located in Utah's western desert. It consists of 507 three-square-meter detectors on a 1.2 km. The TASD was designed to detect particle showers generated by the interaction of ultra-high energy cosmic rays with the Earth's atmosphere. Several lightning instruments has been installed over the years since 2014 including a high-speed video camera, a Lightning Mapping Array (LMA), a broadband VHF interferometer, and Fast Antenna (FA). Figure 1 shows the layout of all the involved detectors.

The TASD observed numerous thunderstorms and over 25 downward-directed Terrestrial Gamma-ray Flashes (TGFs) within the past 13 years. These observations resulted in enhancing our knowledge in modeling thunderstorms and in understanding downward-directed Terrestrial Gamma-ray Flashes initiation and propagation. In the next sections of this proceeding, I will summarize and discuss some of these observations.

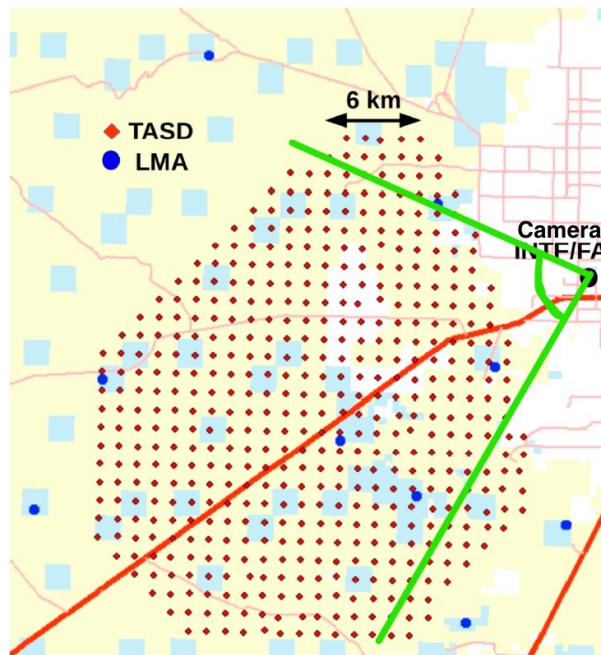


Figure 1. The layout of the TASD detector and the LMA, in addition to the high-speed video camera, the INTF, and the FA. The TASD 507 station, in red diamonds, deployed in the southwestern desert of Utah over a 700 km². While, the Lightning Mapping Array nine stations, in blue circles, deployed throughout the Telescope Array detector. The high-speed video camera, the interferometer and the fast spheric sensor are located ten kilometers to the eastern most edge of the Telescope Array detector. The field of view of the high-speed video camera is demonstrated in the bright green lines with an opening angle of 84 degrees.

2. Observations

In [Abbasi et al., 2017], using data collected between 2008–2013 by the Telescope Array Surface Detector (TASD), a strong correlation between bursts of energetic particle showers and National

Lightning Detection Network (NLDN) lightning activity was established. We then extend those studies by installing local Lightning Mapping Array (LMA) and electrostatic field change measurements in 2013.

Over the next two-years period between 2014 and 2016, a total of ten TGF Bursts of gamma ray showers were observed in coincidence with downward propagating negative leaders in lightning flashes by the T ASD. In these ten TGFs, correlated observations showing the structure and temporal development of three shower-producing flashes were obtained with a 3-D lightning mapping array, and electric field change measurements were obtained for an additional seven flashes, in both cases collocated within the T ASD. National Lightning Detection Network information was also used throughout. The showers arrived in a sequence of 2–5 short-duration ($\leq 10\mu s$) bursts over time intervals of several hundred microseconds and originated at an altitude of approximately 3–5 km above ground level during the first 1–2 ms of downward negative leader breakdown at the beginning of cloud-to-ground lightning flashes as shown in Figure 2. The shower footprints on the ground typical size were found to be up to 3–6 km in diameter. The cores of the energetic showers were observed to be directly below the initial LMA sources as shown in Figure 3. The shower footprints, associated waveforms and the effect of atmospheric propagation indicate that the showers consist primarily of downward-beamed gamma radiation. This has been supported by GEANT simulation studies, which indicate primary source fluxes of $10^{12} - 10^{14}$ photons for 16° half angle beams.

The result that the observations were confined to the first 1-2 ms of the discharges, and usually occurred in a single burst lasting a few hundred microseconds, suggests the TGFs were produced by one or two particularly energetic leader steps at the beginning of the breakdown. From this, we postulated that the TGFs were produced by “initial breakdown pulses” (IBPs) at the beginning of IC and CG flashes. To investigate this postulate further, in 2018, we installed a VHF interferometer (INTF) and a fast electric field change antenna (FA) 6 km east of the T ASD.

Shortly after the installation of the FA and the INTF we observed a TGF clearly correlated with fast electric field changes of an IBPs. The results of this study [16] shows that TGFs are produced during strong initial breakdown pulses (IBPs) in the beginning stages of negative-polarity breakdown. This is shown with a high degree of temporal and spatial resolution provided by a unique combination of the large-area Telescope Array cosmic ray observatory, in conjunction with broadband VHF interferometer and fast electric field change measurements of the parent discharge. The results show that the TGFs occurred during strong initial breakdown pulses (IBPs) in the first few milliseconds of negative cloud-to-ground and low-altitude intracloud flashes. In addition to showing how TGFs are related to IBPs, the observations show that IBPs are produced by a recently identified type of discharge process called fast negative breakdown (FNB) [17]. The fast breakdown propagates at speeds around 1/10 the speed of light as shown in Figure 4.

3. Comparison with Satellite Observations:

The observed downward TGFs are similar to satellite-detected TGFs in that satellite events can be correlated with ground-based sferic observations and are typically found to occur in the beginning stages of negative polarity breakdown (e.g. [6, 8, 13]). In both cases the overall durations are also similar, lasting up to 500 microseconds or longer. However, the observations differ in that the downward TGFs observed by the T ASD consist of a sequence of a few isolated and relatively short-duration bursts ($\leq 10\mu s$), whereas the satellite-detected events are more continuous with time over the full duration of an event ($\geq$ tens of microseconds). In addition, the fluences of the satellite TGFs are substantially larger than those reported by TA, with estimated values of 10^{16} to 10^{18} primary photons [14, 15], two to four orders of magnitude larger than the maximum estimated fluence reported by TA.

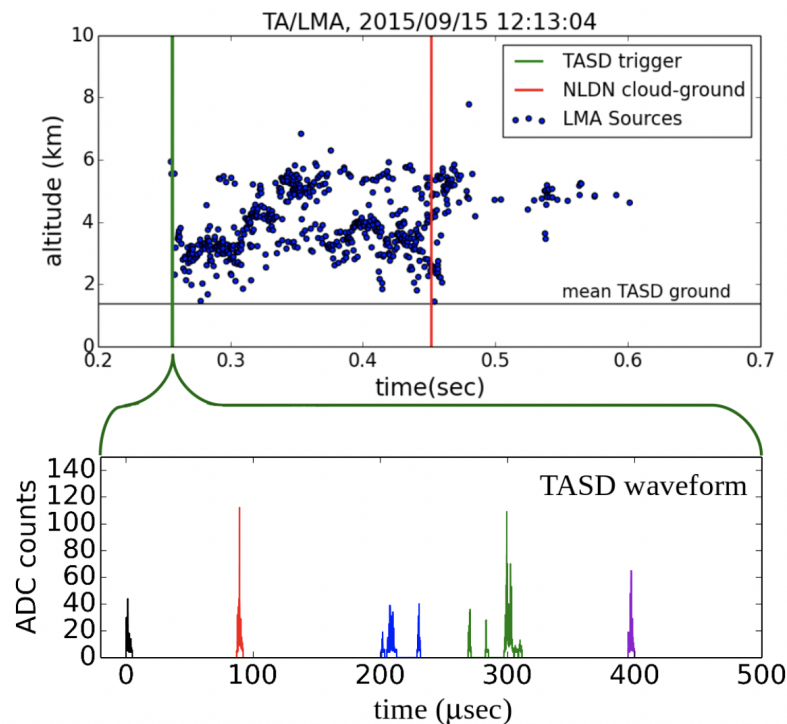


Figure 2. Observations of a TA/LMA-correlated gamma ray shower. Top: altitude versus time for LMA sources over the TASD. The location of mean TASD ground at ~ 1400 m is represented with a horizontal line. Five TASD triggers (vertical green line) occur within 1 ms of the first source, and 200 ms before the NLDN recorded a cloud-to-ground stroke (vertical red line). Bottom: The five-trigger combined waveform for a single TASD which participated in observing this burst event. Time zoomed to 0.5 ms window, approximately the thickness of the vertical green line in the top plot. Individual triggers are distinguished by coloration.

In recent years, a small subset of TGFs has been associated with high-peak current (few hundred kiloampere) IC discharge events, called energetic in-cloud pulses (EIPs) [18]. EIPs are considered to be high-probability producers of at least a class of TGF-generating lightning events [19, 9]. EIPs are energetic versions of what are called preliminary or initial breakdown pulses [20], that are characteristic features of the beginning stages of IC and negative cloud-to-ground flashes. One of the main characteristics of EIPs is the production of extremely energetic events with a high peak current greater than 150 kA [18]. A direct example of downward observed EIP by the Telescope Array detector would be tremendously useful to bridge the differences between the TASD and satellite TGF detections.

The actual correspondence of TGFs with an EIP was observed on September 11 of 2021. On that day nine flashes occurred over the TASD detector. They were all cloud-to-ground flashes with negative polarity. Six of these nine flashes produced TGFs, all of them occurring during a time interval of only 51 minutes. The TGFs were also observed by a state-of-the-art high-speed-video camera that was installed in August of 2021. This allowed us to examine the luminosity of the observed extremely energetic downward-direct terrestrial gamma-ray produced in a cloud-to-ground flash.

While the Telescope Array detector has observed over 25 TGFs in the last 13 years, this

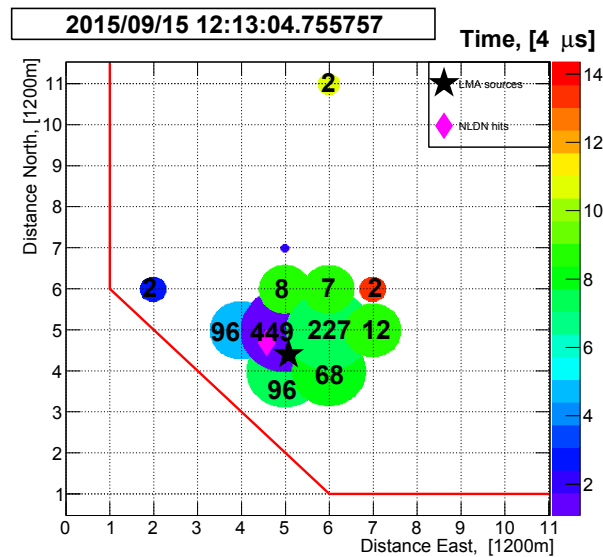


Figure 3. Footprint of TASD triggers for the event, with the numbers indicating the Vertical Equivalent Muon (VEM) counts, and the color indicating the relative arrival times. Initial LMA and NLDN events are indicated by stars and diamonds respectively. The red line indicates the southwestern boundary of the TASD array.

weakly convective, hail producing (as reported by scientists from the site) storm, in particular, has been found to be special in many ways. At first, all the TGFs observed on that day were produced by cloud-to-ground flashes with return stroke peak currents that ranged in magnitude from 53 kA all the way to 223 kA. In addition, the maximum energy deposit on one of the surface detectors had reached energies of up to 33,913 VEM (74 GeV). Also, the duration of one of the TGF bursts have lasted up to 40 μs . Note that all of the previously detected TGFs by the TASD detector, except for flash three in [21], were produced by flashes with an average peak current of 52 kA and maximum peak current of 139 kA, a deposited maximum energy on a single surface detector of no more than 997 VEM (2 GeV) and a duration of a burst of less than 10 μs . Most importantly, while the average rate of TGF observations by the TASD detector has varied from one to two events per year, this storm resulted in six TGF observations within one hour (25% of all TGF observed in the past 13 years). This makes it the highest rate of TGF observations in both one thunderstorm and in all thunderstorm seasons, observed by the TASD detector in the southwestern desert of Utah.

The energetic observed gamma ray bursts were produced as the leader clearly formed below the cloud base, in some bursts more than half-way to the ground as shown in Figure 5. The downward atmospheric gamma ray consisted of isolated bursts that are clearly correlated with initial breakdown (IB) pulses as shown in Figure 6. The optical luminosity observed for these TGFs start to increase within 25 μs from the onset of the IBP and the TGF signal and continues to increase 25-50 μs after TGF and IBP signal ceases. In total, the intensity of the entire optical emission duration lasts between 50-100 μs .

It is interesting to note that the TGF sources, produced in this rare thunderstorm, are found to correlate with an initial breakdown pulse and an extremely energetic thunderstorm that corresponds in peak current magnitude to EIPs. It is also interesting to note that the fluence of this flash was found to be 3×10^{15} which is also comparable to the lower limit fluence estimates for TGF satellite observations. Moreover, the duration of the TGF bursts observed on the same

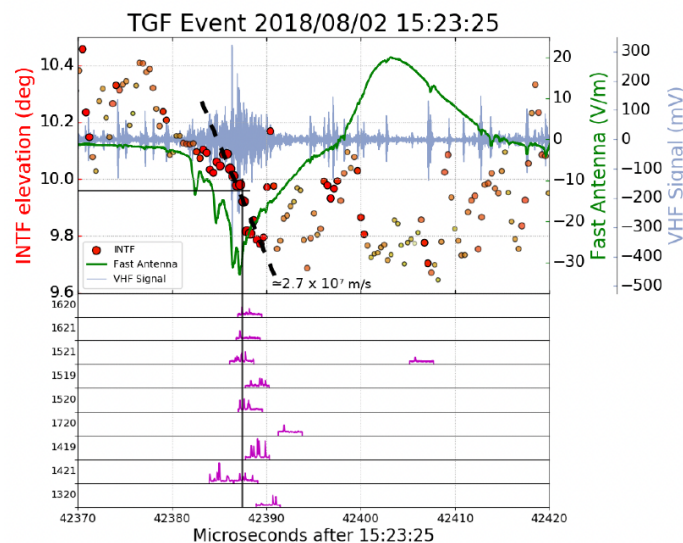


Figure 4. Detailed comparative observations. Time-shifted surface detector data for the primary gamma-ray event during each a TGF-producing flash, showing how the TASF detections (lower axes) compared to each other, and their relation to the VHF radiation sources and fast electric field sferics (upper axis) of the developing discharges. Black vertical and horizontal line show the median onset time of the gamma burst(s) during the downward FNB. FNB propagation speed are indicated by the dashed line and associated value.

day have lasted of up to $40 \mu\text{s}$ which is comparable to the TGF satellite observations. Similarly, the optical observations at the TASF detector, were the optical observations peaks after the onset of TGFs, are consistent with the satellite ASIM observations [22]. The satellite ASIM have revealed in the past two years, a consistent feature of TGF's optical emission observations is that the TGFs were observed one to two ms after the beginning of a weak increase in the optical emission in the 337 nm and 777.4 nm photometers, and before the onset of the main optical pulse. Our data indicate a substantial increase in the visible light in correlation with the TGF production. From this result it seems reasonable to conclude that our result indicates that the optical emission from downward and the upward observed TGFs have the same source.

4. Conclusion and Outlook

The Telescope Array Surface Detector together with a suit of lightning instruments are contributing in a unique way, to solving decades of mysteries related to lightning initiation, lightning propagation, and the origin of Terrestrial Gamma-ray Flashes. With the most recent event observed on September 2021 we were able to show that the fluence, time duration, and optical emission of the pulses from the observed downward-going TGF event by the TASF supports the fact that downward-directed and upward-directed TGFs are variants of the same phenomenon.

To further compare the optical signature of downward and upward-directed TGF emission [22] with higher timing resolution in both desired wavelengths, we are currently developing photometers to install at the TASF site sharing the same field of view as the high-speed video camera and will report on the optical emissions from atmospheric electrical discharge processes that peak at 337 nm (associated with the streamer development) and 777 nm (associated with

the stable leader propagation). In addition, in July 2021, we installed a split-less spectroscopic system at the T ASD. The system includes a high-speed camera, Phantom v711, and a grism placed in front of the camera. The grism can diverse the light from 600 nm to 1050 nm. The split-less spectra from this system will be recorded simultaneously with the recording from Lightning Mapping Array, high-resolution Interferometer, Fast Antenna, and another high-speed camera. This will allow us to investigate the lightning spectra and channel temperature of a Terrestrial Gamma ray Flash in conjunction with the changing of their luminosity, energy deposit, and peak current, which will enable us to better understand the TGFs initiation and propagation phenomenon.

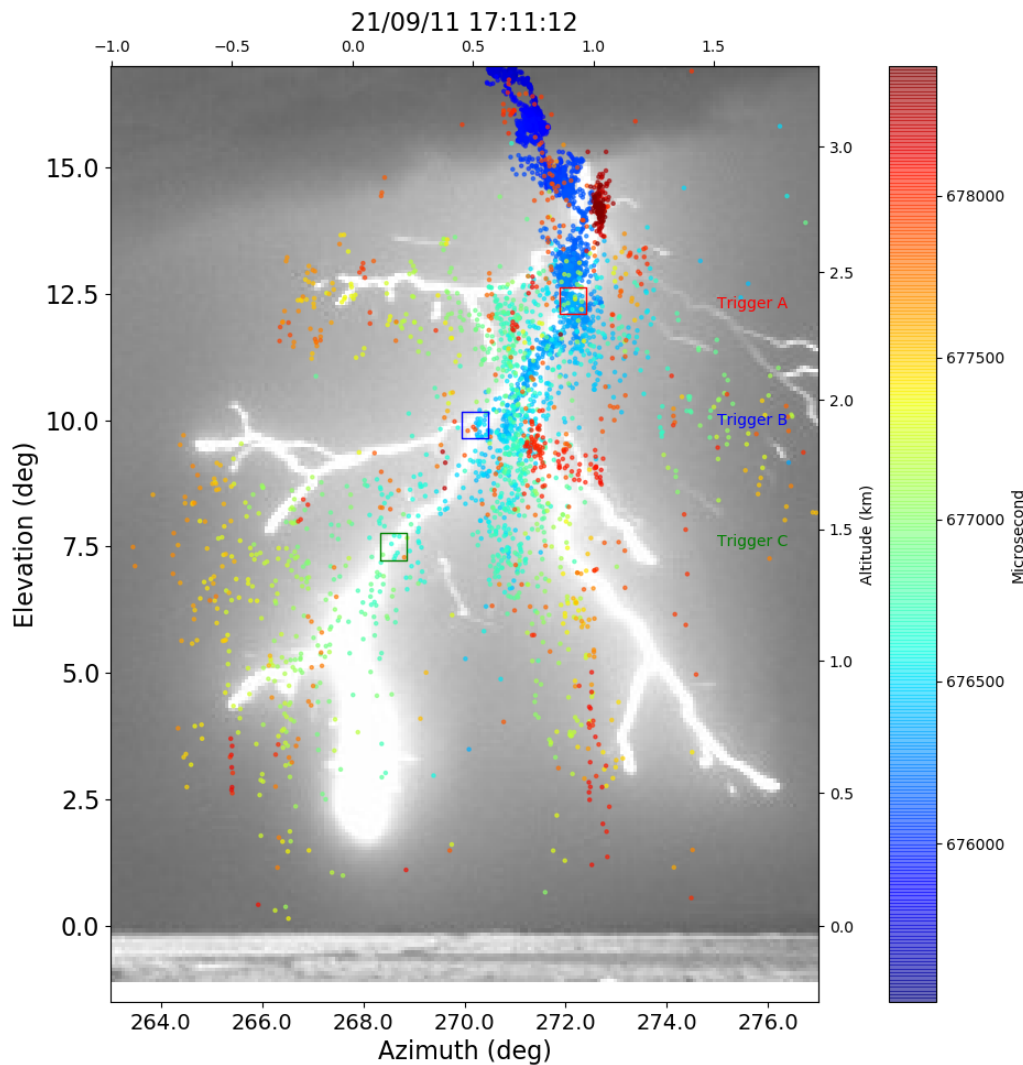


Figure 5. The elevation vs. azimuth for the whole flash in a still image using the high-speed video camera in addition to the INTF point sources.

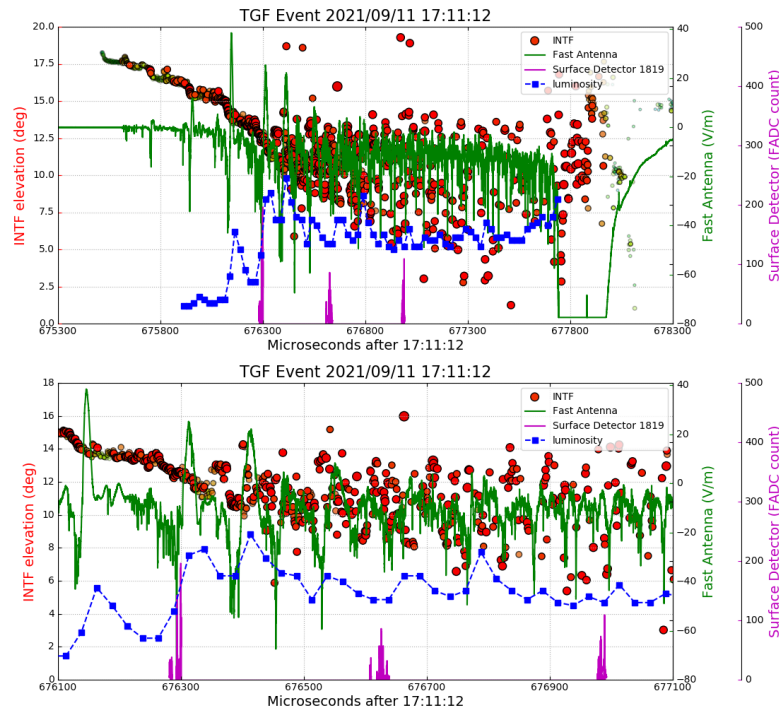


Figure 6. The TASF waveforms in pink, the average luminosity vs. time in dark blue, the fast antenna waveform in green, the INTF elevation vs. time in red circles (size and color are proportional to the power of the radio signal). Top: The flash observed from initiation until the first return stroke within 3 ms duration. Bottom: a zoomed in version of the top plot within 1 ms. It shows a clear sequence of the radio, gamma, and optical emission.

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