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Fast electric field waveforms and near-surface electric field images of lightning discharges detected on Mt. Aragats in Armenia

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Abstract. We present the observational data on fast electric waveforms that are detected at 3200 m altitudes above sea level on Mt. Aragats in Armenia during thunderstorms. We analyse the relations of these forms with count rates of particle flux (during Thunderstorm Ground Enhancements -TGEs); to the slow disturbance of the near-surface electrostatic field; and to the lightning location data from the World Wide Lightning Location Network (WWLLN). An observed negative lightning that decreases a negative charge overhead often abruptly terminates TGEs. By analysing the recorded fast electric field waveforms and comparing them with similar classified waveforms reported previously, we could identify the type and polarity of the observed lightnings.

1. INTRODUCTION

The *in situ* observation of the numerous Thunderstorm Ground Enhancements (TGEs, Chilingarian et al., 2010, 2011, Chilingarian 2014), i.e. enhanced fluxes of electrons, gamma rays and neutrons detected by particle detectors located on the Earth's surface and related to the strong thunderstorms above, helped to establish a new scientific topic - high-energy physics in the atmosphere.

During the last 5 years, we experiment with the "beams" of the "electron accelerators" operating in the thunderclouds above the Aragats research station. Thunderstorms are very frequent above Aragats, peaking at May-June and almost all of them are accompanied with enhanced particle fluxes. The station is located on a plateau 3200 m above sea level, by a large lake. Numerous particle detectors and field meters are located in 3 experimental halls and outdoors; the facilities are operated all year round.

The runaway Breakdown (RB) process (Gurevich et al., 1992) which is nowadays mostly referred to as Relativistic Runaway Electron Avalanches (RREA, Babich et al., 2001, Dwyer, 2003) and Modification of the energy Spectra of the electrons (MOS, Chilingarian, Mailyan and Vanyan, 2012) are believed to be a central mechanism of the high-energy processes in the thunderstorm atmospheres. Numerous TGEs observed on Aragats Mt. in Armenia during strong thunderstorms and first simultaneous measurements of TGE electrons and gamma ray energy spectra proved that RREA is a robust and realistic mechanism for electron acceleration. The electrons giving rise to the RREA are accelerated by the electric field formed by the main negatively charged regions in the middle of the cloud and by the transient, lower, positively charged region (LPCR, Chilingarian and Mkrtchyan, 2012) at the bottom. LPCR charge is much less as compared with the thundercloud main charged regions; however, the local influence of LPCR can be essential, for instance LPCR prevents the lightning leader from reaching the ground and usually no −CG lightning occurs when the LPCR is mature (Nag and Rakov, 2009). Only after decaying of the LPCR, the stopped leader makes its path to the ground. Continuous attempts to start the stopped leader produce a large number of low-energy (few eV) electrons by ionizing the air. The low-energy electrons then drift in the thunderstorm electric field, producing discharges and radiofrequency emissions. Bipolar radiofrequency pulses, having possibly originated from these discharges, appear in the early stage of the formation of the conducting channel in the thundercloud (initial breakdown).

The paper is organized as follows. In the second section, we describe the facilities used for the particle-lightning research. In the third section, we review the TGE events abruptly terminated by lightning. In the fourth section, we analyse the fast waveforms of lightnings with an extended data capture length of the digital oscilloscope and in the fifth section, we relate the images of the slow near-surface electrostatic field to the fast electric waveforms. In conclusion, we discuss the preliminary results of our research.

2. INSTRUMENTATION

The data presented in this study were acquired in the fall 2014 and Spring-Summer 2015, at the Aragats Space Environmental Center (ASEC) on Mt. Aragats, Armenia (Chilingarian et al., 2005). Geographical coordinates of the research station are 40°28′N, 44°11′E, and the altitude is 3200 m above sea level. A 52 cm diameter circular flat-plate antenna followed by a passive integrator is used to record the fast electric field waveforms. The decay time constant RC of the integrator is 10 msec. The output of the integrator is directly coupled to a digital oscilloscope. The data presented here are recorded by two types of oscilloscopes: 1) Picoscope 3206 with a 100MS/s sampling rate and data capture length of 5 msec, including 1 msec of pre-trigger time, and 2) Picoscope 5244B with a 25MS/s sampling rate and a data capture length of 500 msec, including 100 msec of pre-trigger time. The amplitude resolution is 8 bit in both cases. The recording system is triggered by a signal from the high-frequency detecting system, which uses a commercial MFJ-1022 active whip antenna that covers a frequency range of 300 KHz to 200MHz. The disturbances of the near-surface electrostatic field are measured with the Boltek EFM-100 electric field mill. The measurements are taken 20 times per second, and the sensitivity range extends up to ~30 km**.** We use also the data of the World Wide Lightning Location Network (WWLLN) to locate the geographical coordinates and to get the estimated stroke energy for the lightnings simultaneously detected by the Network and by our recording system. The estimated stroke energy is the root-mean-square energy of the stroke from 1.3 msec waveform sampling between 7 to 18 kHz

(Hutchins et al., 2012). TGEs analyzed in the present study are detected by an outdoor 3 cm thick scintillator with a sensitive area of 1m^2 operated in the particle counter mode. The detection efficiency is ~98% for electrons and ~5% for gamma rays, the energy threshold is ~2MeV.

3. TGEs TERMINATED BY LIGHTNING

We will consider six selected TGE events that have been terminated by lightning. The observation data involve 1 sec time series of the count rate of particle flux, 50 msec time series of slow disturbance of near-surface electrostatic field, fast wideband electric field waveforms, and lightning location and stroke energy data from WWLLN.

Three of the selected events, which were observed on the same day, May 11 2015, are shown in Figure 1, where the count rate of particle flux and the disturbances of the near-surface electrostatic field are presented.

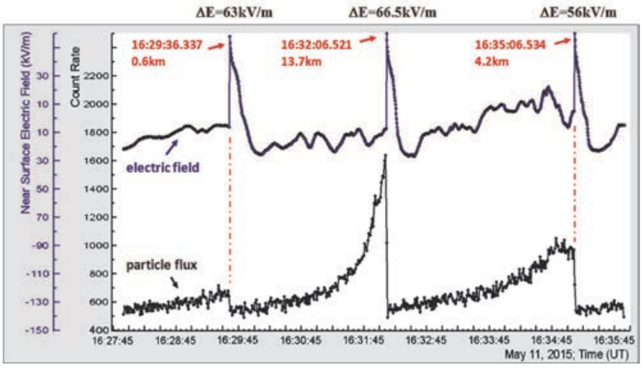

Figure 1. A sequence of three TGEs abruptly terminated by negative lightnings.The lower curve is the 1 sec time series of the count rate of the particle flux detected by the 3 cm thick outdoor scintillator; the upper curve is the 50 msec time series of the electrostatic field disturbances detected by the electric field mill. Lightning detection time and distance to the lightning is according to WWLLN data, and the electric field changes, ΔE, are indicated for each lightning.

As can be seen from Figure 1, all three TGEs are abruptly terminated by lightnings, which are characterized by a strong disturbance of the near-surface electrostatic field measured by the electric field mill. At 16:29:36, the electric field starts its sharp increase, in 100 msec changing from −5.7 kV/m to 57.3 kV/m, and the particle flux count rate is terminated at its rising edge. At 16:32:06, the electric field changes from −6.5kV/m to 60 kV/m, and the termination is observed at the maximum of the count rate. At 16:35:06, the electric field changes from 5.5kV/m to 61.5kV/m, and the termination is observed at the falling edge of the count rate. All three lightnings that terminated the TGEs shown in Figure 1, were detected by WWLLN.

The lightning detection time stamps and distance to lightning are indicated in Figure 1 as well. The distances to the lightning, according to the WWLLN data for the three selected events, are equal to ≈0.6km, ≈13.7km, and 4.2 km. However, the uncertainty in lightning location is rather high, ~5 km.

For all observed TGEs terminated by a lightning the electric field change measured at the ground is positive and it can be attributed to the decrease of negative charge overhead.

The "atmospheric electricity" sign convention (a downward-directed electric field or field change vector is considered positive) is used throughout this paper. Thus, a positive electric field change measured at the ground is produced by a negative lightning, which decreases the negative charge overhead.

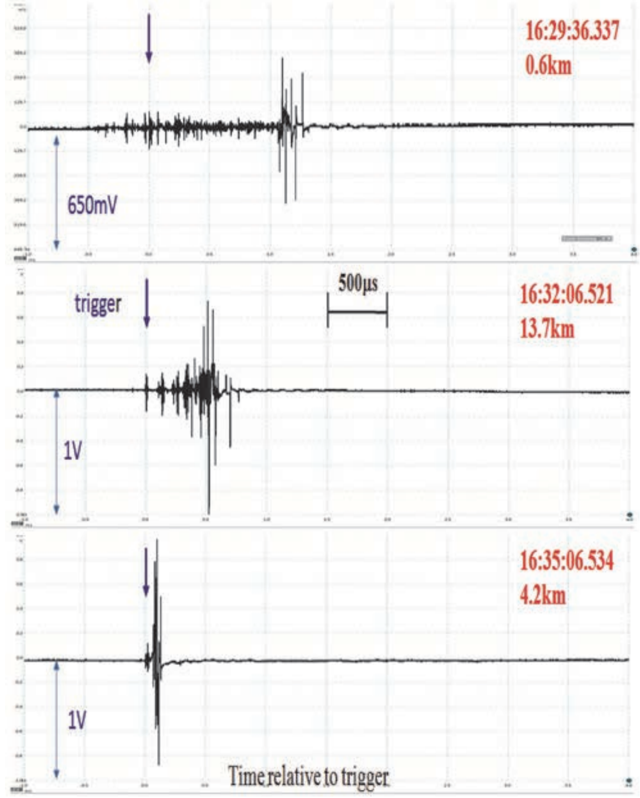

Figure 2. Fast electric field waveforms of three lightnings that terminated the TGEs corresponding to those shown in Figure 1. Data capture length is 5ms, including 1 msec pre-trigger time, sampling frequency is 100Ms/s.

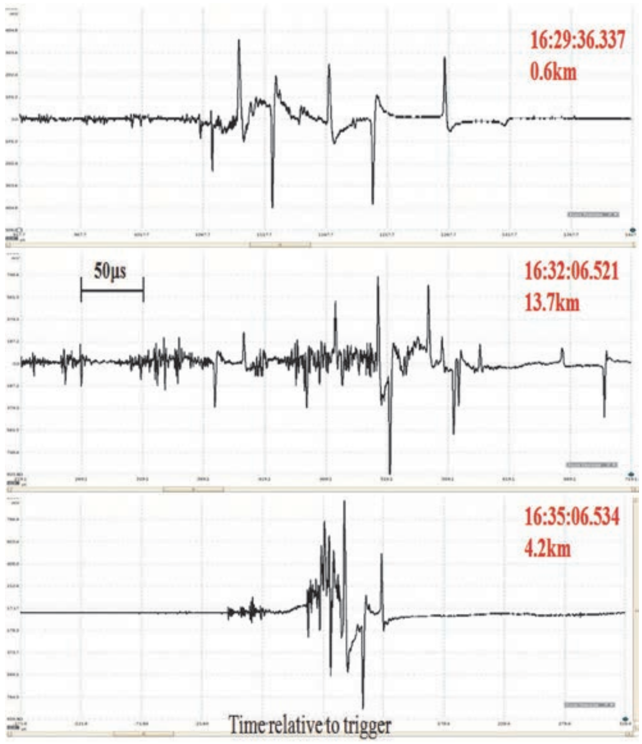

Figure 3. Fast electric field waveforms of Figure 2 are shown here with 10-fold time magnification. All three waveforms show multiple bipolar pulses with typical duration of 1-2 microseconds.

Fast electric field change waveforms for the three selected events are presented in Figures 2 and 3 with different time magnification. All three waveforms show trains of multiple short bipolar pulses of different polarity with typical duration of 1-2 microseconds, and with overall train duration in the range from 150 microseconds to 1 msec. It should be noted, however, that due to short data capture length of 5 msec used in these measurements, the recorded waveforms may show only the preliminary stage of a lightning flash. Therefore, identification of the type of lightning discharge (cloud-to-ground, or intracloud) from the recorded fast electric field is problematic for these measurements.

In Figure 4, we present termination shapes for five selected events. An abrupt termination of the count rate was detected at the rising (c) and falling (b and e) edges of particle flux enhancement, as well as at the maximum of the burst (a and d).

We assume that, most probably, the cloud-to-ground lightning terminates these TGEs. An indirect argument supporting this assumption is that all three lightnings are detected by the WWLLN, which detects only the strongest lightnings with peak currents above 35-40kA with detection efficiency of ~10 %, and vast majority of lightnings detected by the network are cloud-to-ground lightnings. This is primarily because a CG lightning is a much stronger radiator in the frequency range from 3 to 30 kHz used by WWLLN for lightning detection. Nevertheless, we cannot ignore the possibility that a strong intracloud lightning, which can also be recorded by WWLLN, terminates TGE. Another method for the determination of the lightning type is discussed in (Chilingarian et. al., 2016).

The main characteristics of the electrostatic field changes for the six observed TGEs terminated by lightning are summarized in Table 1. Distance to the lightning given in the third column is calculated using latitude and longitude of the lightning determined by the WWLLN data and the coordinates of the Aragats station. The distance is calculated as the great-circle distance between the two points according to the well-known "haversine" formula on the basis of a spherical earth, ignoring the ellipsoidal effects. The estimated stroke energy and its uncertainty according to WWLLN data is given in the last column. All observed lightnings are characterized by very large positive change of the electric field strength. The "amplitude" of lightning as measured by the abrupt disturbances of the near-surface electrostatic field $\Delta E = (E_{Maximum} - E_{start})$ ranges from 42.6 to 84kV/m.

However, the electric field strength at the start of its abrupt change is quite different for the six selected events, ranging from -25.5kV/m to +5.5kV/m. All six discussed lightnings occurred near the Aragats research station: the distance to the lightning according to the WWLLN data is in the range 0.6-13.7km.

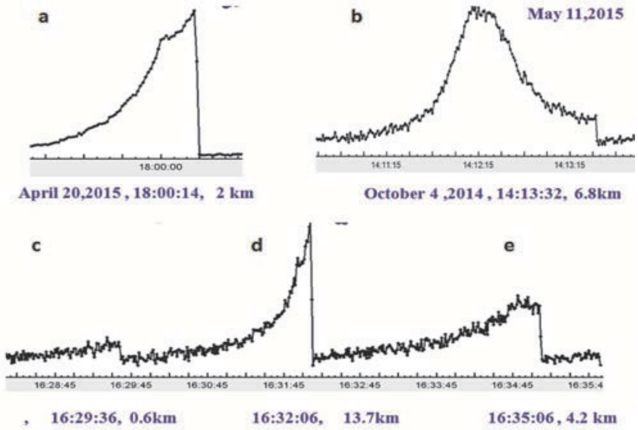

Figure 4. Various shapes of TGE termination observed for five selected events: at the maximum of particle flux (a, d); at the falling edge (b, e), at the rising edge(c).

We examined the time coincidences of the abrupt changes of the electrostatic field measured by EFM-100 field mills installed at the Aragats station and the time stamps of lightning detection by the WWLLN. The statistics for 137 event is presented in Figure 5, where the histogram shows the number of events as a function of time difference between WWLLN time stamps and corresponding maxima of electrostatic field disturbances.

As can be seen from Figure 5, the standard deviation of the distribution is ~350 msec. The shift of the center of the distribution towards negative values of the time difference by about 250 msec is due to the fact that the maximum of the electrostatic field change caused by lightning and measured by the field mill is achieved later than the time stamp WWLLN which detects the maximum of the electromagnetic emission pulse from the lightning.

Table 1. Parameters of electrostatic field change, distance to lightning, and estimated stroke energy observed for TGEs terminated by lightning.

ate	Time (UT)	Distance km	Start electric field E_{start}, kV/m	Max electric field E_{max}, kV/m	$\Delta E = E_{max} - E_{start}$ kV/m	FWHM of field change	Stroke Energy (J)
20-Apr-15	18:00:14	2	1.2	49.2	48	1.1sec	23513±14259
20-Apr-15	18:02:01	8	-3.41	39.2	42.6	1.2s	N/A
4-Oct-14	14:13:32	6.8	-25.5	58.5	84	5sec	N/A
11-May-15	16:29:36	0.6	-5.7	57.3	63	8sec	56516±40695
11-May-15	16:32:06	13.7	-6.5	60	66.5	6sec	N/A
11-May-15	16:35:06	4.2	5.5	61.5	56	5sec	5295±1660

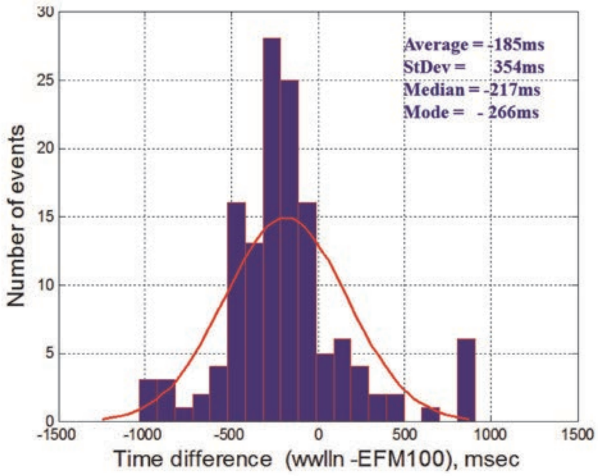

Figure 5. Histogram of time coincidences between WWLLN detection time stamps and the time stamps of electric field maximum measured by field mill EFM-100.

4. CLASSIFICATION OF LIGHTNINGS BY TYPE AND POLARITY

After installing a digital oscilloscope with an extended data capture length of 500 msec, we investigate the relations of the fast electric field waveforms and the disturbances of the near-surface electrostatic field. The waveforms of the selected lightnings recorded with a capture length of 500 msec have some typical features, which allow us to identify the type and polarity of a lightning flash.

Fast electric field waveforms for three selected lightnings are shown in Figures 6, 7 and 8. In all three waveforms, multiple weak microsecond-scale bipolar pulses are followed by a strong bipolar pulse, the amplitude of which is by an order of magnitude higher than that of the weak pulses. Typical amplitude is 10-20mV for weak pulses, and 200-300mV for the strong ones. Time interval between the beginning of weak pulses and start of the strong pulse is 160 msec, 74 msec, and 28 msec for the lightnings shown in Figures 6, 7, and 8, respectively. In order to identify the type and polarity of lightnings, we compare the waveforms shown in Figures 6-8 with the waveform of the negative cloud-to-ground (CG) lightning recorded at Lightning Observatory in Gainesville Florida, USA (Zhu et al 2014), shown in Figure 9. Multiple weak bipolar pulses around 4-5 msec are identified by as preliminary breakdown (PB) pulses, and the strong bipolar pulse at 21.5 msec with positive polarity of initial half cycle is identified as negative return stroke (RS). The typical duration of PB process is a few milliseconds; the time interval between PB pulses and strong bipolar pulse considered as stepped-leader duration (Zhu et al., 2014). We believe that fast electric field waveforms of lightning flashes detected on Aragats and shown in Figures 6-8 can be interpreted in a similar way.

Thus, weak bipolar pulses followed by a strong bipolar pulse in the waveforms of Figures 6-8 we identify as preliminary breakdown (PB) pulses (and stepped leader pulses in Figures 7 and 8) followed by the return stroke pulse. In waveforms of Figures 6 and7, the PB pulses are followed by a positive return stroke at 162 msec and 74 msec after trigger, respectively. In both cases the return stroke is positive, because the polarity of the initial half cycle of the strong bipolar pulse is negative. In the waveform of Figure 8, the PB pulses are followed by a negative return stroke at 28.7 msec after trigger.

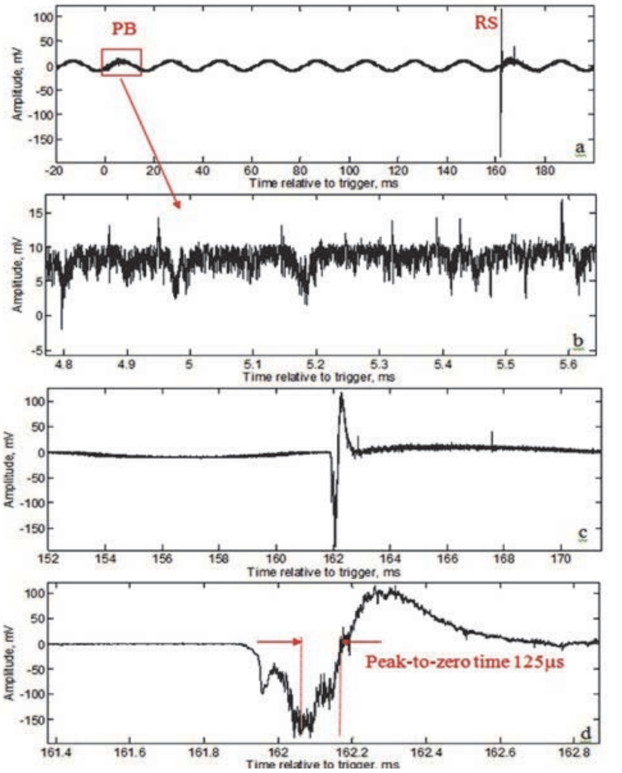

Figure 6. Fast electric field waveform detected at 15:51:21.446, August 6 2015. WWLLN data: distance to lightning 3.7 km, stroke energy (4586 ±1160) J.

Preliminary breakdown (PB) pulses are followed by the return stroke (RS) pulse. Frame b) shows expansion of PB pulses, frames c) and d) show expansion of RS. Classification: positive cloud-to-ground lightning (+CG).

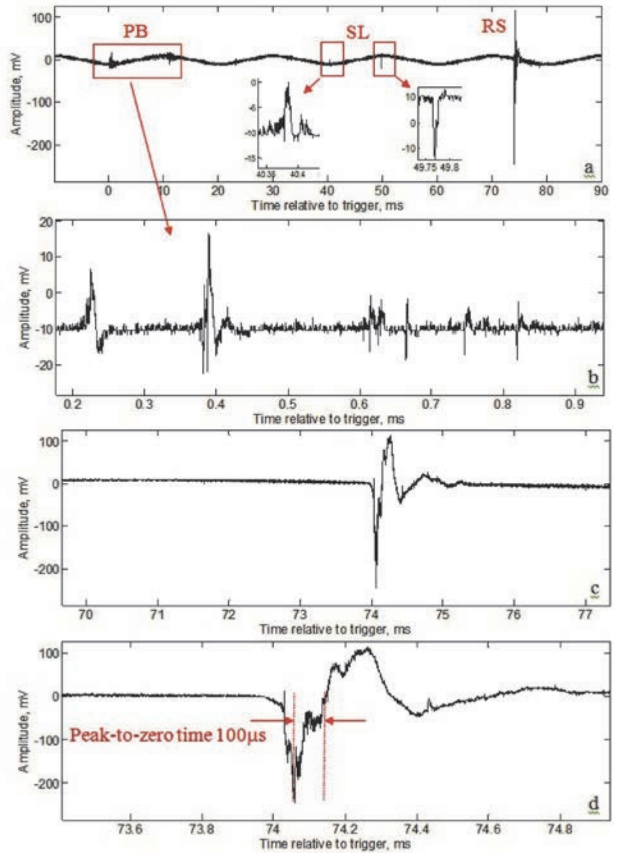

Figure 7. Fast electric field waveform detected at 02:58:49.244, August 2, 2015, WWLLN data: distance to lightning 5.9 km, stroke energy (3071 ±802) J. The pulses between the PB and RS shown in the insets of frame a) are presumably the stepped leader (SL) pulses. Classification: positive cloud-to-ground lightning (+CG).

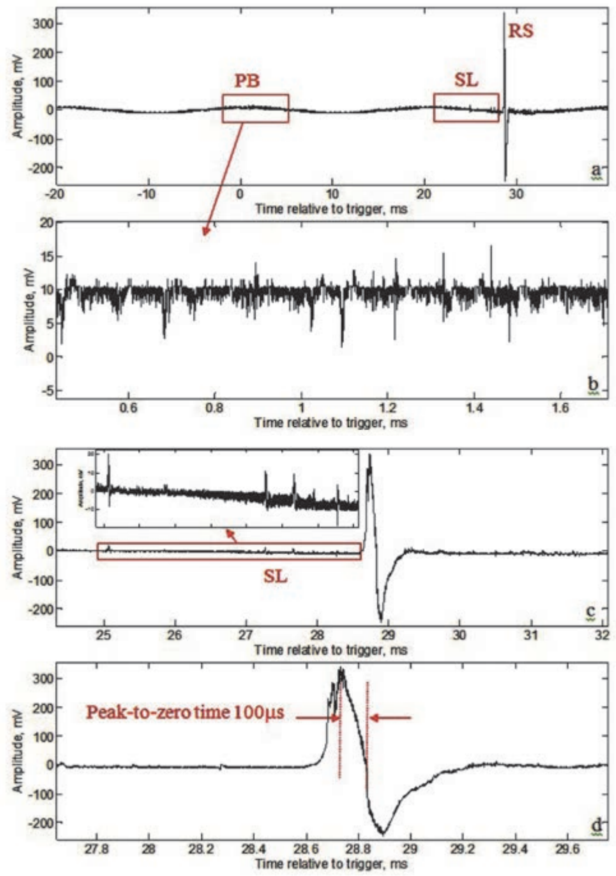

Figure 8. Fast electric field waveform detected at 15:42:31, August 6, 2015, distance to lightning estimated by EFM-100 field mill is in the range 6-28 km. Bipolar pulses in the inset of frame c) are presumably the stepped leader (SL) pulses. Classification: negative cloud-to-ground lightning (-CG).

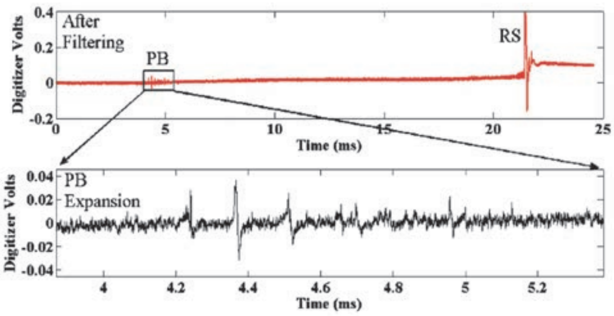

Figure 9. Fast electric field waveform of negative CG lightning recorded at Lightning Observatory in Gainesville Florida, USA (Zhu et al 2014)

Here, the return stroke is negative because the polarity of the initial half cycle of the strong bipolar pulse is positive (as mentioned above, we use the "atmospheric electricity" sign convention for electric fields, in which a positive electric field change corresponds to negative return stroke). In the waveforms of Figure 7 and 8, some bipolar pulses are observed also in the time interval between PB pulses and the return stroke pulse. We assume that they can be interpreted as leader pulses.

We note that the peak-to-zero time of the initial half cycle is 125µs for the waveform of Figure 6, and about 100µs for the waveforms of Figures 7 and 8. This long fall time, or return from the minimum (or maximum) to zero supports the classification of the observed events as CG lightnings. According to the criterion used by (Heavener et al.,2003) at the Space and Atmospheric Science Group, Los Alamos National Lab, the classification of CG events is based solely on the relatively slow (greater than 30µs) fall time.

5. IMAGES OF THE CORRESPONDING NEAR-SURFACE ELECTROSTATIC FIELD

In Figure 10 we show the disturbances of the near-surface electrostatic field for three lightnings discussed in the previous section and measured by EFM-100 electric field mill.

The main characteristics of the electrostatic field changes, the distance to lightning and estimated stroke energy, are summarized in Table 2. The difference $\Delta E = (E_{max}-E_{start})$ between the electrostatic field at the maximum and at the start of its abrupt change is -64.6kV/m and -41.5kV/m for lightnings occurred on August 6. For the lightning that occurred on August 2, the electrostatic field abruptly rises from 11 kV/m to 39 kV/m during 100 msec and then drops down to -23 kVm in 50 msec with a subsequent long recovery time of (FWHM=30sec). These parameters of the slow electric field measured by the field mills fulfill the conditions for CG lightnings introduced in (Chilingarian et al., 2015, Tab. 1). Thus, we have the same classification of lightning type made by fast waveforms and "slow" near-surface electric field patterns.

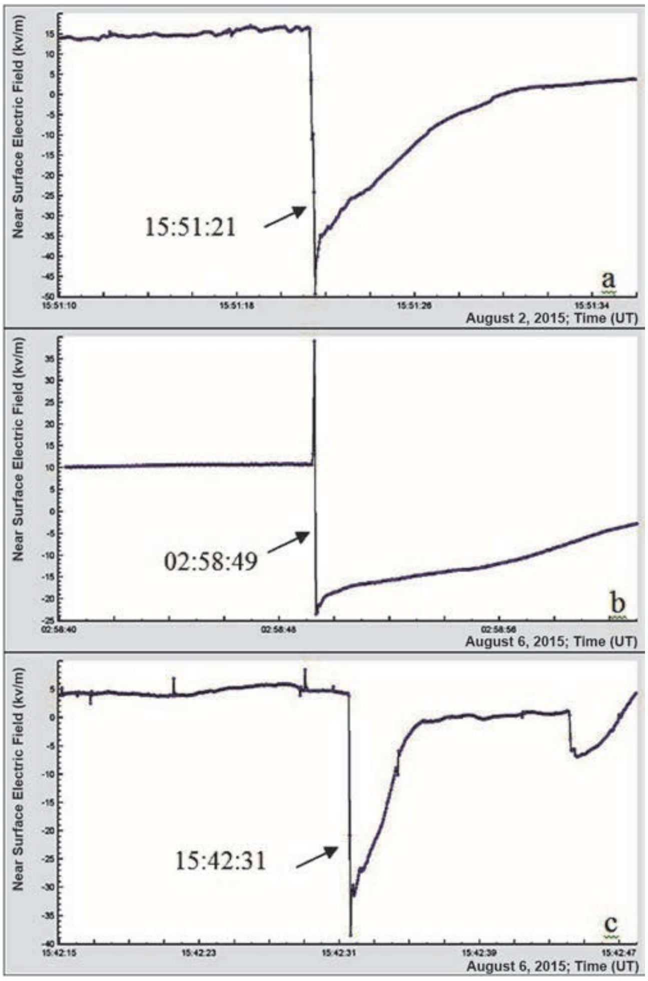

Figure 10. 50 msec time series of near-surface electrostatic field for three selected lightnings. a) 15:51:21 August 6,2015; b) 02:58:49 August 2,2015; c) 15:42:31 August 6,2015. Distance to lightning for a) and b) which were detected also by WWLLN is 3.7km and 5.9km, respectively. Distance to lightning for c) estimated by EFM-100 field mill is about 6km.

It is interesting to compare the disturbances of the electrostatic field and fast electric field waveforms for the three lightnings. For the lightning that occurred on August 6 at 15:51:21, the electrostatic field change is negative and hence, it is produced by a positive lightning, which neutralizes the positive charge overhead.

Table 2. Parameters of electrostatic field change, distance to lightning, and estimated stroke energy for three observed lightnings.

N	Date	Time (UT)	Distance km	Start electric field E_{start}, kV/m	Max electric field E_{max}, kV/m	ΔE= E_{max} E_{start} kV/m	FWHM of field change	Stroke Energy (J)
1	6-Aug-15	15:51:21	3.7	15.8	-48.8	-64.6	4sec	4586±1160
2	2Aug-15	02:58:49	5.9	11 39	39 -23	28 -62	35 msec 30sec	3071±802
3	6-Aug-15	15:42:31	6	3.5	-38	-41.5	2sec	N/A

This is consistent with the polarity of the lightning determined from the fast electric field waveform shown in Figure 6. For the lightning that occurred at 02:58:49, there are two changes of the electrostatic field having opposite polarity: a large positive change is immediately, within 100 msec, followed by a huge negative change. This negative change is produced by a positive lightning, which neutralizes the positive charge overhead, and this is again consistent with the polarity of the lightning determined from the fast electric field waveform shown in Figure 7. A question arises: what is the origin of the positive change of the electrostatic field in the beginning? The fast field waveform of Figure 7 shows that the positive return stroke is preceded by a long stage (about 50 msec) of multiple weak bipolar pulses, which can be identified as preliminary breakdown and stepped leader pulses, as it was already mentioned above. Even though these pulses are weak, the total charge neutralized by these multiple discharges can be quite large, and the electric field mill can detect the electrostatic field change produced by charge neutralization prior to the return stroke.

We also note that the lightning occurred on August 2 at 02:58:49.244 has the strongest PB pulses among the selected three, and only for this event (among the three) the electrostatic field change is not typical, showing a large positive change followed by an even larger negative one. If we assume that the positive change of the electrostatic field observed in the beginning of the lightning is related to the stage of preliminary breakdown and negative change then - to the stepped leader, we come to the conclusion, that prior to the positive return stroke which neutralizes positive charge overhead, the discharges of the preliminary stage neutralize the negative charge overhead.

For the lightning on August 6 at 15:42:31, the electrostatic field change is negative and hence, we can expect that a positive lightning, which neutralizes a positive charge overhead, could produce it. However, this conclusion is in contradiction with the lightning polarity determined from the fast electric field waveform shown in Figure 8, where the positive polarity of the initial half cycle (Figure 8 c, d) clearly indicates a negative lightning, which neutralizes a negative charge overhead.

We can suppose that a possible reason for this contradiction could be the sign reversal of the electrostatic field with distance (e.g., Rakov and Uman, 2003, p. 71.), and that the true polarity (negative) of this lightning is determined from fast field waveform, since the polarity of radiation field does not change with distance. However, no polarity reversal of electrostatic field has been detected by our three field mills for this lightning, so an unambiguous identification of the type and polarity is not possible.

6. CONCLUSION

The TGE events copiously measured on Aragats during thunderstorms are represented by the 50 ms, one-second and one-minute time series of the gamma ray and electron count rates as well as by gamma-ray energy spectra, meteorological conditions, fast and slow disturbances of the near-surface electric field, which allowed us to investigate their causal relation to lightning initiation (Chilingarian et al., 2015).

We monitor the particle fluxes from thunderclouds and atmospheric discharges by networks of near-surface electric field sensors and fast electric field waveforms. TGE slowly discharge the lower dipole allowing smooth decaying of the large negative electrostatic field on the ground. In contrast, lightnings “kill” the TGE immediately; the abrupt change of the near surface electric field by the negative cloud-to-ground lightning is accompanied by the abrupt termination of the TGE. Thus, investigation of the lightning-TGE relations can shed new light on the long-standing problem of lightning initiation.

Extended data capture length of digital oscilloscope allows investigating relations of the fast electric field waveforms and disturbances of near-surface electrostatic field. Weak bipolar pulses followed by strong bipolar pulse in the waveforms can be identified as preliminary breakdown (PB) pulses followed by stepped leader pulses and by the large return stroke pulse. Long fall time of the return stroke pulse supports the classification of observed events as CG lightnings.

For the lightning of August 6 at 15:51:21, the electrostatic field change is negative and hence, it is produced by a positive lightning, which neutralizes a positive charge overhead. This is consistent with the polarity of lightning determined from the fast electric field waveform.

The lightning of August 2 at 02:58:49.244 has the strongest PB pulses among the three selected, and only for this event (among the three analyzed) the electrostatic field change is not typical, showing a large positive change followed by an even larger negative one. We can speculate that the positive change of the electrostatic field observed in the beginning of the lightning of August 2 is related to the stage of the preliminary breakdown and negative change then - to the stepped leader. Thus, we conclude that prior to the positive return stroke, which neutralizes the positive charge overhead the discharges of the preliminary stage neutralize the negative charge overhead.

For the lightning of August 6 at 15:42:31, the electrostatic field change is negative and hence, we can expect that a positive lightning, which neutralizes a positive charge overhead, produce it. However, this conclusion is in a contradiction with the polarity of lightning determined from the fast electric field waveform. The question of an unambiguous identification of the type and polarity of this lightning remains open.

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