LIGHTNING ELECTRIC AND MAGNETIC FIELDS

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Abstract: Characteristics of measured electric and magnetic fields generated by various lightning processes are reviewed. Ground flashes of both polarities and cloud flashes are considered. Examples of different types of field waveforms are given.

1. Introduction

Both cloud-to-ground and cloud lightning discharges involve a number of processes that produce characteristic electromagnetic field signatures. In this review, characteristic of measured electric and magnetic fields generated by various lightning processes at distances ranging from tens to hundreds of kilometers will be presented. The emphasis will be put on those processes which produce substantial microsecond- and submicrosecond-scale field variations. The presented characterization of the lightning electromagnetic environment can be useful in the validation of lightning models.

Table 1 summarizes essentially all identifiable lightning radiation field signatures as recorded at ground. Note that apparently there is no characteristic radiation pulse signature associated with lightning K and M processes. Besides return strokes (the first row) and so-called isolated pulses (the last row), the pulses produced by lightning processes represented in Table 1 occur in sequences with submillisecond interpulse intervals. Leader pulses (rows 2 and 3) are presumably emitted by the lower portion of the channel to ground just prior to the initiation of a return stroke, while both initial breakdown pulses (rows 4 and 5) and regular pulse bursts (row 6) are produced by lightning processes occurring inside the cloud. Discussion will concern the overall characteristics of pulse sequences and of individual pulses. Characterization of the fine structure of radiation field waveforms produced by negative return strokes is found, for example, in [1].

2. Negative Ground Flashes

The typical microsecond-scale pulse structure of naturally-occurring negative ground discharges, as observed at ground, includes an initial sequence of pulses (usually called initial or preliminary breakdown pulses) followed, typically some milliseconds to some tens of milliseconds later, by 3 to 5 relatively large return-stroke pulses spaced several tens of milliseconds apart. The duration of the initial sequence of pulses is of the order of 1 ms. The preliminary breakdown pulses (labeled PB) and the first return-stroke pulse (labeled RS) are illustrated in Fig. 1. Individual pulse waveforms characteristic of the preliminary breakdown in negative ground flashes are shown in Fig. 2a. The initial polarity of the preliminary breakdown pulses is usually the same as that of the following return stroke pulse (Fig. 2a should be inverted for direct comparison with Fig. 1). The initial breakdown pulses can have amplitudes comparable to that of the corresponding return-stroke pulses [2], as seen in Fig. 1a. Just prior to the first return-stroke pulse and prior to some subsequent return-stroke pulses there are pulse sequences, in the former case associated with stepped leader process and in the latter case with dart-stepped (regular pulse train) or "chaotic" (irregular pulse train) leader processes. These pulse sequences have been observed to last for some tens to some hundreds of microseconds, and the pulse amplitudes are one to two orders of magnitude smaller than the corresponding return-stroke pulse amplitude. The stepped-leader pulses (labeled SL) are seen just prior to the return-stroke (RS) pulse in Figs. 1a and 1b (less pronounced in Fig. 1a) and also on an expanded time scale (but for a different event) in Fig. 3a, before t = 0. A rather irregular pulse train, indicative of "chaotic" leader, is seen prior to the subsequent return-stroke pulse (before t = 0) in Fig. 3b. Examples of radiation fields due to subsequent return strokes preceded by dart and dart-stepped leaders are found, for example, in [1, Figs. 1c and 1b]. Usually there is a relatively quiet millisecond-scale gap between the end of the preliminary breakdown pulse sequence and the beginning of pronounced stepped-leader pulses (see Fig. 1b). The intervals between the return-stroke pulses, and the time interval of some tens of milliseconds or so following the last return-stroke pulse, contain regular pulse bursts of relatively small amplitude, examples of which are given in [3], and some other, usually irregular (see, for instance, [4]), pulse activity. Pulse peaks in regular pulse bursts are approximately two orders of magnitude smaller than return-stroke initial field peaks in the same flash [3]. As seen in Table 1, the regular pulse bursts are very similar in their characteristics to the pulse sequences associated with dart-stepped leaders. The geometric mean initial electric field peak normalized to 100 km for negative first strokes, 5.9 V/m, is about a factor of two larger than for negative subsequent strokes, 2.9 V/m [5]. The geometric mean time interval between return-stroke pulses is 60 ms.

Table 1. Characterization of radiation field pulses associated with various negative lightning processes. Adapted from Rakov et al. [3]

Type of pulses	Dominant polarity (atmospheric electricity sign convention)	Typical total pulse duration, μs	Typical time interval between pulses, μs	Comments
Return stroke in negative ground flashes	Positive	30-90 (zero-crossing time)	60×10^3	3-5 pulses per flash
Stepped leader in negative ground flashes	Positive	1-2	15-25	Within 200 μs just prior to a return stroke
Dart-stepped leader in negative ground flashes	Positive	1-2	6-8	Within 200 μs just prior to a return stroke
Initial breakdown in negative ground flashes	Positive	20-40	70-130	Some milliseconds to some tens of milliseconds before the first return stroke
Initial breakdown in cloud flashes	Negative	50-80	600-800	The largest pulses in a flash
Regular pulse burst in both cloud and negative ground flashes	Both polarities are about equally probable	1-2	5-7	Occur later in a flash; 20-40 pulses per burst
Isolated pulses (e.g., Willett et al., 1988 [6])	Negative	10-20	-	Not attributed to any known lightning process

Notes: 1. Polarity refers to polarity of the initial half cycle in the case of bipolar pulses.
2. Typical values are based on comprehensive literature search and unpublished experimental data acquired by the University of Florida group.

3. Positive Ground Flashes

Positive flashes usually contain a single return stroke whose microsecond-scale electric or magnetic field waveform is similar to those characteristic of negative first return strokes, except for the initial polarity. An example of positive return stroke electric field waveform is given in Fig. 3c. Small pulses seen before t = 0 in Fig. 3c are indicative of a stepped-leader process. As opposed to negative first strokes, these pulses are detected only in 26 to 30% of field waveforms [7]. The mean initial electric field peak normalized to 100 km for positive first strokes, 11.5 V/m, is about a factor of two larger than for negative first strokes, 5.3 V/m [8]. The microsecond-scale characteristics of initial breakdown pulses associated with positive lightning have been recently studied in [9], [10], and [11].

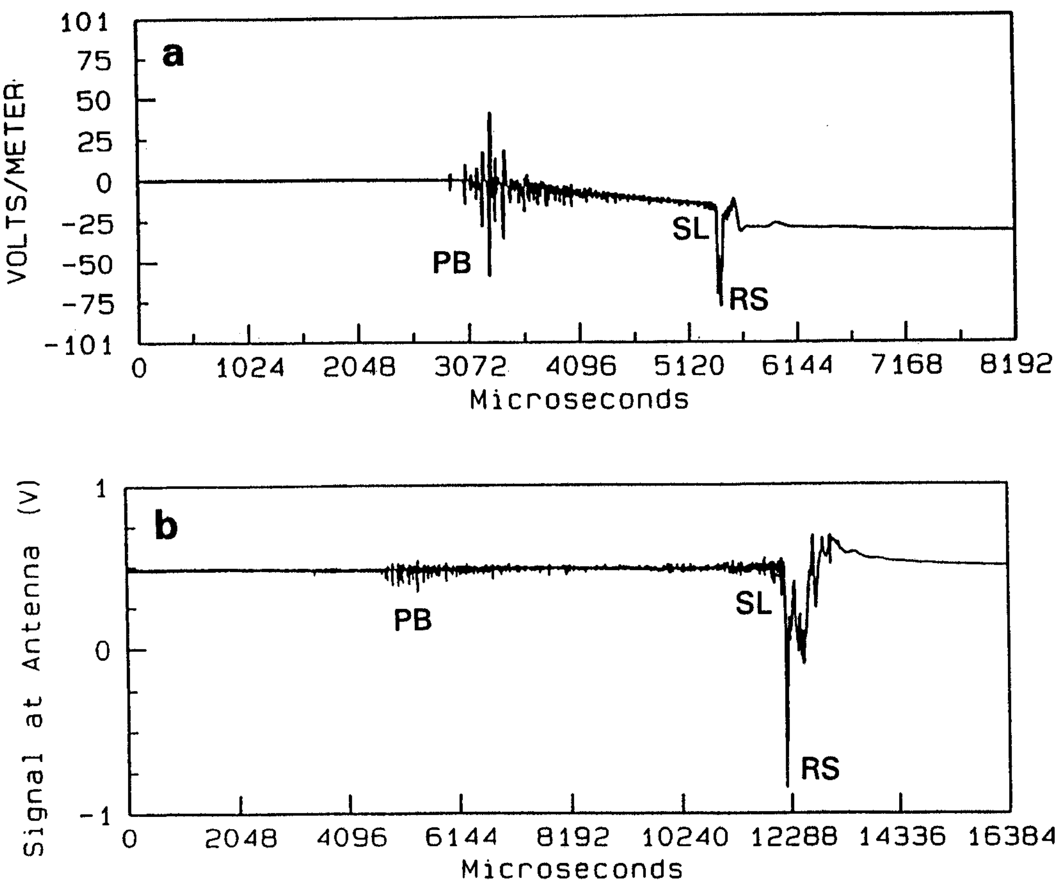


Fig. 1. Examples of electric fields due to negative first strokes in cloud to ground lightning: (a) winter lightning at about 25 km, (b) summer lightning at unknown distance. PB stands for preliminary breakdown, SL for stepped leader (just prior to its attachment to ground), and RS for return stroke. Time scales in Figs. 1a and 1b, are about 8.2 and 16.4 ms, respectively. Note that the separation between PB and RS, the duration of the stepped leader, is smaller than usual, particularly in Fig. 1a. Positive electric field change (atmospheric electricity sign convention) deflects downward. Adapted from Brook [2].

4. Cloud Flashes

The typical pulse structure that is observed in naturally-occurring cloud discharges (see, for example, [12]) includes an initial sequence (or sequences) of pulses of relatively large amplitude, spaced some hundreds of microseconds apart and occurring within the first several to a few tens of milliseconds, followed by a number of regular pulse bursts of significantly smaller amplitude. Pulses within the burst are several microseconds apart with each burst lasting for some hundreds of micro-seconds. The occurrence of larger pulses in cloud flashes is illustrated in Fig. 4, with the individual pulse waveforms characteristic of the initial breakdown in cloud flashes being shown in Fig. 2b. The initial polarity of these pulses tends to be opposite to that of the initial breakdown pulses in negative ground flashes. Note that Fig. 2b should be inverted for direct comparison with Fig. 4. Examples of regular pulse bursts in cloud discharges are found, for instance, in [3]. There are also microsecond-scale pulses with amplitudes appreciably lower than those of the initial breakdown pulses which are dispersed, as opposed to clustering in bursts, throughout the flash [12]. Some of these smaller and often irregular pulses are associated with step-like K field changes. K changes typically occur in the latter part of the cloud flash and are separated by many tens of milliseconds.

An example of isolated pulses (also called narrow bipolar pulses) is given in Fig. 2c. These pulses have peaks and peak time derivatives comparable to those of return strokes in ground flashes. Spectral analysis indicates that the sources of isolated pulses radiate much more strongly than first return strokes at frequencies from 10 MHz to at least 50 MHz [6]. Induced effects of the isolated pulses might represent the greatest lightning-related threat to an aircraft in flight.

Acknowledgment: The author wish to thank M.A. Uman for his comments on this review and D.E. Crawford for providing Figs. 2 and 3.

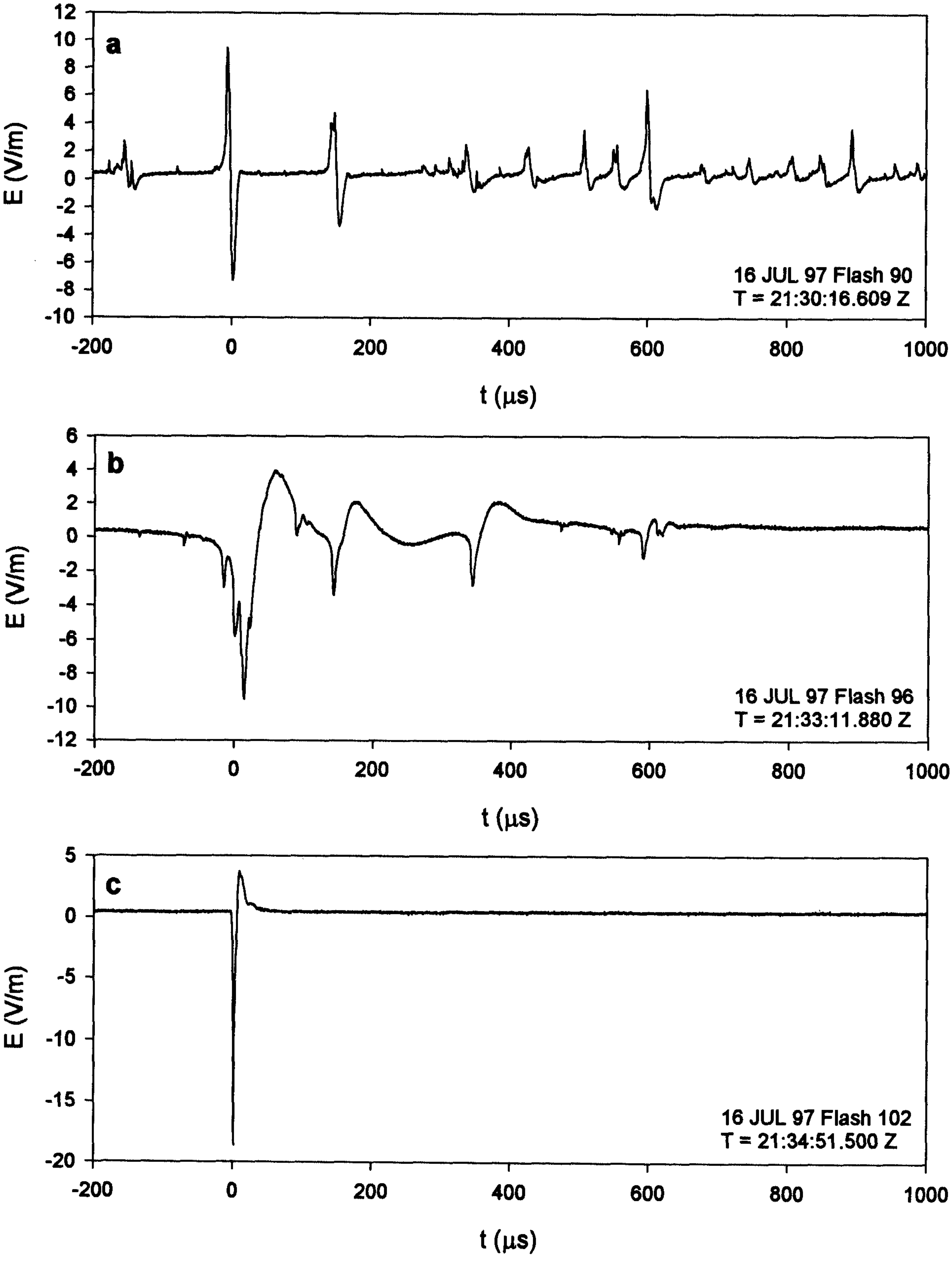


Fig. 2. Examples of electric field pulse waveforms characteristic of (a) the initial breakdown in negative ground flashes, (b) the initial breakdown in cloud flashes, and (c) the isolated pulses presumably not related to any known lightning discharge process. The waveforms have been recorded, from a distant storm, at Camp Blanding, Florida. Positive electric field (atmospheric electricity sign convention) deflects upward.

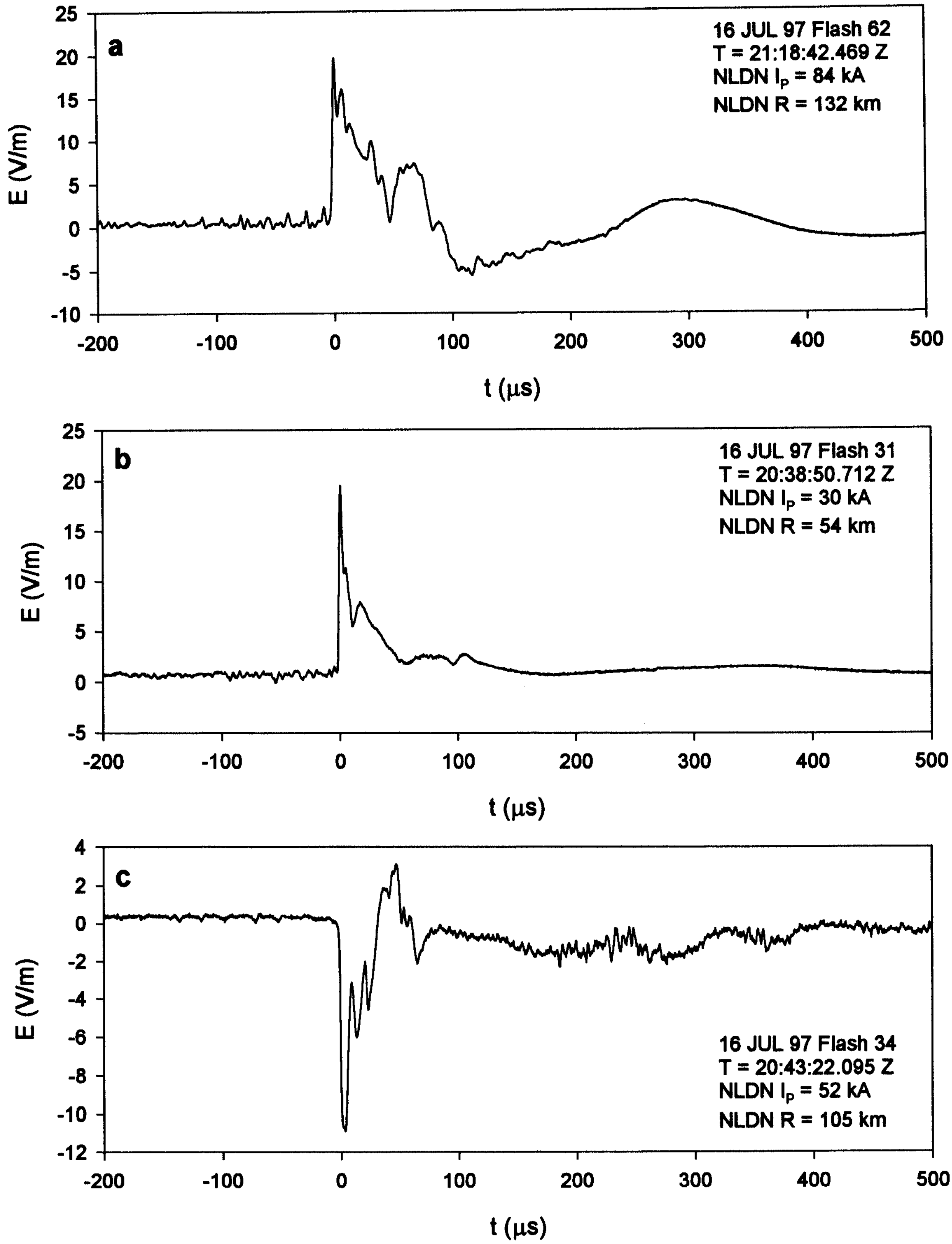
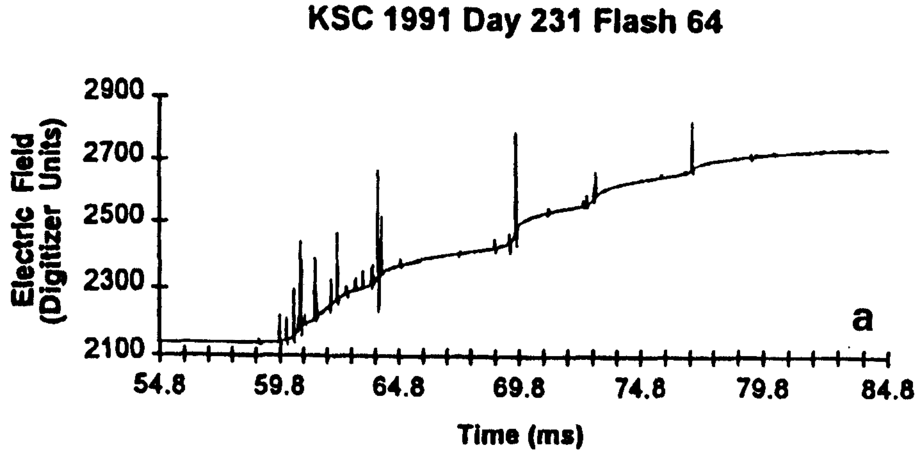


Fig. 3. Examples of electric field pulse waveforms for (a) the negative first stroke, (b) the negative subsequent stroke, and (c) the positive first stroke. All three events have been detected by the U.S. National Lightning Detection Network (NLDN), and their NLDN reported characteristic (estimated peak current I_p and distance R) are given on the plots. See also caption of Fig. 2.



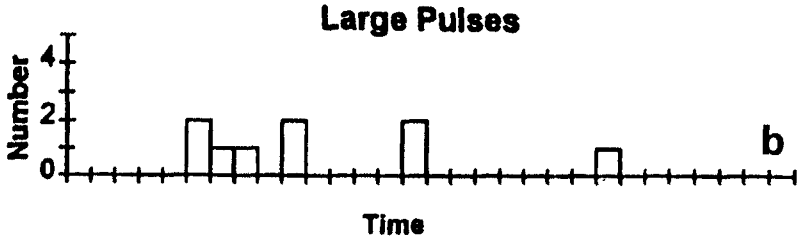


Fig. 4. Typical pulse structure of the first 25 ms of a cloud flash: (a) electric field change, (b) histogram of the occurrence of large microsecond-scale pulses. No large pulses occurred during the following 500 ms of the flash. The large pulses were defined as having peak-to-peak amplitudes equal or greater than 50% of the average amplitude of the five largest pulses in the flash. The electric field change and the histogram are displayed on the same time scale. Positive field change (atmospheric electricity sign convention) deflects downward. Adapted from Villanueva et al. [12].

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