JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 100, NO. D12, PAGES 25,701–25,710, DECEMBER 20, 1995

Mechanism of the lightning M component

Vladimir A. Rakov, Rajeev Thottappillil, and Martin A. Uman
Department of Electrical Engineering, University of Florida, Gainesville

Philip P. Barker
Power Technologies, Incorporated, Schenectady, New York

Abstract. Analysis of simultaneous measurements of the channel-base current and the vertical electric field 30 m from triggered lightning reveals that the fields associated with M components, although essentially electrostatic, appear to be proportional to the time derivatives of the associated M currents. Based on this finding, coupled with other observations and modeling, a mechanism for the lightning M component is proposed. According to this mechanism an M component involves a downward progressing incident wave (the analog of a leader) followed by an upward progressing reflected wave (the analog of a return stroke). However, as opposed to a leader-return stroke sequence in which the latter removes the charge deposited by the former, both the upward and the downward processes contribute about equally to the total charge flowing from the bottom of the channel at any instant of time. Such a mode of charge transfer to ground, distinctly different from a leader-return stroke sequence, is possible because of the presence of a path capable of supporting the propagation of a traveling wave (facilitated by a continuing current flowing to ground) and the fact that the ground is essentially a short circuit for the downward incident wave, so that the magnitude of the current reflection coefficient at ground is virtually equal to unity. We show that some observed properties of M components can be explained if the lightning channel traversed by an M-current wave is represented as a linear R-C transmission line. In this view, the preferential attenuation of the higher-frequency components on an R-C line is responsible for the lack of frequencies above several kilohertz in both the M-current pulses measured at the channel base and the M-light pulses observed in the bottom 1 km or so of the channel. Further, the relatively high characteristic impedance of the channel, of the order of tens to hundreds of kilohms for frequencies below some kilohertz, inferred from the linear R-C line approximation, is consistent with the observation that even a relatively poor ground is sensed by an incident M wave as essentially a short circuit. However, on a linear R-C transmission line the higher-frequency components travel faster than lower-frequency components (this velocity dispersion implying that the original pulse would spread while propagating along the line), whereas the shape of the M-light pulses does not change much within the bottom 1 km or so, as if the channel were a distortionless transmission line. We speculate, on physical grounds, that the front of the traveling M-current pulse heats the channel so that the pulse tail encounters a lowered resistance and, as a result, accelerates. By virtue of these two opposing effects, velocity dispersion and channel nonlinearity, an M pulse is formed whose more-or-less symmetrical shape is preserved over a relatively large distance, as in the case of a soliton.

1. Introduction

The term "M component" is used to denote the temporary increase in luminosity of the faintly luminous channel observed after some ground return strokes, first described by *Malan and Collens* [1937]. From correlated electric field and photographic observations in South Africa, *Malan and Schonland* [1947] reported that field changes associated with M components, recorded at close range (mostly 6 km or less) with a measurement system having decay time constants of 1 to 21 ms, exhibited a characteristic hooklike shape. They estimated the duration of the hook-shaped M field changes to be typically from 0.2 to 0.8 ms, although values up to 1.6 ms were observed. The most recent review of millisecond-scale characteristics of M field changes is given by *Thottappillil et al.* [1990] who found, in Florida ground flashes, a geometric mean M-change duration of 0.9 ms and a geometric mean time interval between M changes of 2.1 ms. *Rakov et al.* [1992] found that the beginning of the millisecond-scale M field hook is often marked by microsecond-scale pulses whose shape is dissimilar from and whose

Paper number 95JD01924.
0148-0227/95/95JD-01924$05.00

polarity is predominantly opposite to the corresponding features of the preceding return-stroke field pulse. *Fisher et al.* [1993] reported, from their observations of triggered lightning in Florida and Alabama, that M components were associated with current pulses, superimposed on the continuing current of some tens to some hundreds of amperes, at the bottom of the channel. These pulses have amplitudes of typically some hundreds of amperes and risetimes of some hundreds of microseconds; that is, they are distinctly different from the return-stroke current pulses that occur only after the cessation of any preceding current through the channel base and typically exhibit submicrosecond risetimes [*Fisher et al.*, 1993].

Malan and Collens [1937], from their high-speed photographic observations, reported that, out of 9 M components for which they could determine the direction of propagation, 7 progressed downward from the cloud with a speed ranging from 2×10^7 to 4.7×10^7 m/s, while 2 advanced upward from ground with a speed apparently exceeding 10^8 m/s. *Jordan et al.* [this issue], from the displacement between streak-camera images of an M component and the preceding return stroke, inferred that the M component propagated more likely downward than upward. *Rakov et al.* [1992], from the dissimilarity between the microsecond-scale M field pulses and return-stroke field pulses, and from the occurrence of the M pulses at the beginning of the M field hook, deduced that M components are initiated in the cloud, not at ground. *Shao et al.* [1995], from the VHF imaging of lightning channels, reported that M components are typically initiated by fast (10^6-10^7 m/s) negative in-cloud streamers hitting the upper extremity of the conducting channel to ground, with the attachment being associated with microsecond-scale field pulses similar to those studied by *Rakov et al.* [1992]. *Shao et al.* [1995] also observed M components apparently initiated by fast (10^7 m/s) positive streamers developing outward from the upper extremity of the conducting channel to ground, followed by even faster ($>10^7$ m/s) negative recoil processes back into the channel. It is possible that the positive streamer is launched from the pocket of excessive positive charge introduced by the preceding return stroke into the leader source region [see, for instance, *Krehbiel et al.*, 1979] and does not involve the lower sections of the channel to ground. If this be true, the two types of M components reported by *Shao et al.* [1995] may differ only in the manner of connecting the negative charge source to the conducting channel to ground, not in the processes occurring in that channel, these processes being of primary interest in the present study. This difference in supplying negative charges to the channel may potentially influence the amplitude and waveshape of the M-source current but probably not the mechanism of the M component in the conducting channel.

Although M components have been observed for more than half a century, there is no consensus in the literature regarding the mechanism for this lightning process. *Malan and Schonland* [1947, p. 498] claimed that the M process is "a minor form of subsequent stroke," which lowers negative charge to ground but "the charge is usually not large enough, and the other conditions are not always such as, to give rise to a return stroke from the ground." Thus according to *Malan and Schonland* [1947] the M process is similar to a downward leader which is unable to produce a discernible upward return stroke. Later, however, *Schonland* [1956, p. 596], in a review paper, described M components as manifestations of "processes of unknown nature, probably branching inside the cloud." *Kitagawa et al.* [1962] suggested that M components are due to in-cloud K processes that occur at the time when there is a relatively low-level current flowing in the channel to ground and described the M component as "a momentary current increase without involving the leader process." *Uman* [1987, pp. 172-173] also states that "downward-moving leaders have not been observed to precede M-components." The latter view is clearly different from the interpretation of the M component as a leader without a discernible return stroke given by *Malan and Schonland* [1947]. Recent VHF observations of lightning [e.g., *Shao et al.*, 1995] shed some light on the physics of the M process but primarily on its initial development in the cloud before its contact with a conducting channel to ground.

In the present paper we propose a mechanism of the M component that both explains the characteristic features (described in section 3.1) of the simultaneously measured channel-base current and vertical electric field at 30 m and allows the reconciliation of the previous, seemingly contradictory, views noted above. The mechanism involves both a downward progressing incident wave (the analog of a leader) and an upward progressing reflected wave (the analog of a return stroke) occurring in a lightning channel that carries a continuing current and is effectively short-circuited to ground.

2. Data

The data analyzed here were acquired during the 1993 triggered-lightning experiments at Camp Blanding, Florida [*Uman et al., 1994*]. There were a total of 5 M components occurring during continuing currents initiated by negative return strokes for which we obtained simultaneous measurements of the current at the bottom of the channel and the vertical electric fields about 30 m from the triggering facility (rocket launcher). Since all five M components exhibited essentially the same behavior, only two will be examined in detail here to substantiate the proposed mechanism of the M component.

The M event whose current and electric field are shown in Figure 1 occurred about 0.6 ms after the first stroke of seven-stroke flash 9320, with the preceding continuing current level being about 120 A. The M event whose current and electric field are shown in Figure 2 occurred about 2 ms after the last stroke of five-stroke flash 9313, with the preceding continuing current level being about 50 A. The M current shown in Figure 1a has a simple, singly peaked waveshape, while the M current shown in Figure 2a exhibits a secondary peak about 300 μs after the first one.

Currents used in this study (see Figures 1a and 2a) were measured at the bottom of the 5-m-high triggering facility using a current-viewing resistor (shunt). Output signals from the shunt were relayed via a 100-m fiber-optic link to a Nicolet Pro 90 digitizing oscilloscope. The signals were digitized at a 2-μs sampling interval, with about 225-ms pretrigger, for the total duration of the flash. The effective system bandwidth was from dc to about 100 kHz.

The electric fields presented for flash 9313 were measured with a flat-plate antenna that had an area of 0.2 m^2 and was placed virtually flush with ground, while the fields of flash 9320 were measured using an elevated flat-plate antenna. Signals from each antenna were integrated using a passive

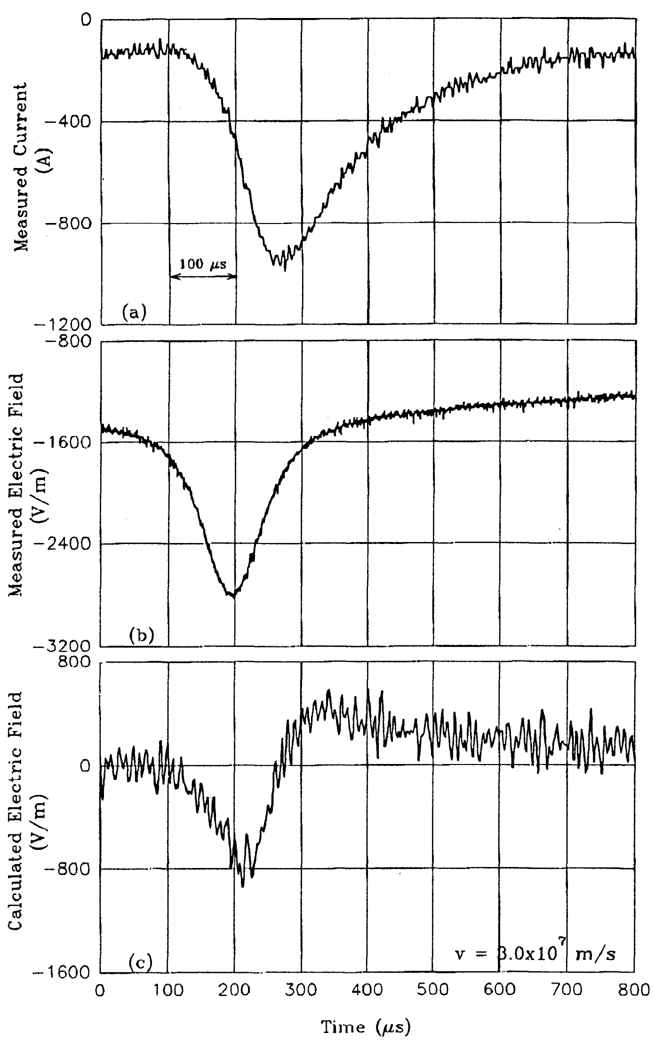

Figure 1. (a) Measured channel-base current, (b) measured 30-m electric field, and (c) calculated 30-m electric field for M component that occurred about 0.6 ms after the first stroke of seven-stroke flash 9320 triggered at Camp Blanding, Florida, 1993.

integrator (a 35-nF capacitor) and relayed via a 100-m fiber-optic link, identical to that used in the current measurements, to another Nicolet Pro 90 digitizing oscilloscope. The decay time-constant of each field-measuring system was about 35 ms. The upper frequency response of the fiber-optic links was about 12 MHz. The signals were digitized at a 10-MHz sampling rate with 12-bit amplitude resolution. No antialiasing filter was used, but this is unlikely to create a problem since the characteristic frequencies of the overall M-component fields are well below 5 MHz [*Thottappillil et al.*, 1990]. For the antenna that was flush with ground we used a theoretically determined field-calibration factor [e.g., *Uman*, 1987, p. 348], while the elevated antenna was experimentally calibrated relative to it. The enhancement factor of the elevated antenna was found to be about 7.5.

The corresponding measured electric field and measured current waveforms shown in Figures 1 and 2 were aligned in time using the characteristic current and field signatures of the preceding return strokes. The alignment is accurate to a few microseconds. In doing this alignment, we are ignoring the delay associated with electric field propagation over 30 m, negligible at about 0.1 μs.

In multiple-station photographic and video records, the lightning channel of flash 9320 appears to be more or less straight and vertical (its inclination does not exceed 20° or so), at least for the bottom hundreds of meters, while the channel shape of flash 9313 below the cloud base resembles a question mark.

3. Analysis and Discussion

3.1. Observations

The most prominent overall feature of the correlated M currents at the channel base and M electric fields at 30 m (see Figures 1 and 2) is that the field, although essentially electrostatic, appears to vary as the time derivative of the current, as further discussed in section 3.3. Given below are three more detailed observations, each followed by its physical interpretation:

(a) The electric field produced by an M component 30 m from the lightning channel is initially negative-going (using the atmospheric electricity sign convention according to which the removal of negative charge overhead produces a

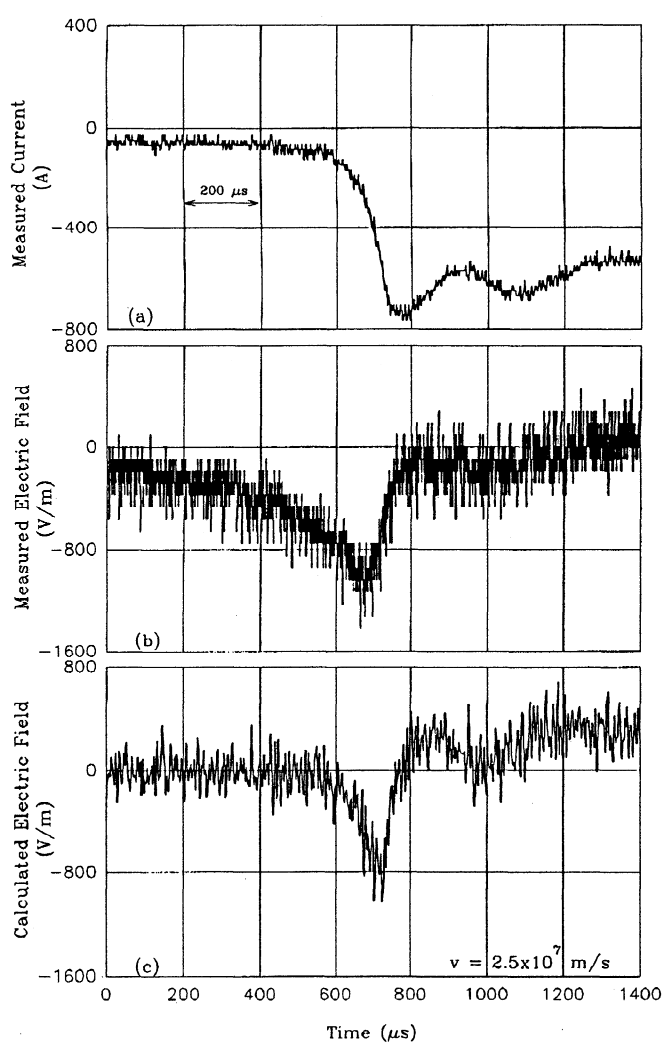

Figure 2. Same as Figure 1 but for M component that occurred about 2 ms after the last stroke of five-stroke flash 9313 triggered at Camp Blanding, Florida, 1993.

positive field change). The field change begins when there is no detectable current above the ambient at the bottom of the channel, consistent with the view of the M component as a leaderlike process transporting negative charge from a cloud charge source toward ground.

(b) The M current at ground emerges from the background negative continuing current when the corresponding electric field at 30 m is still negative-going. This observation implies that initially the negative charge is removed by the current from the lower sections of the channel, while at the same time a larger negative charge is transported downward along the higher channel sections causing the continuing negative field change.

(c) The M-current peak at the channel bottom lags behind the 30-m electric field peak by many tens of microseconds and the waveshapes of current and field pulses are dissimilar (the trailing edge is somewhat slower than the leading edge for the current pulse, whereas the 30-m field pulse is more or less symmetrical or has a trailing edge somewhat faster than a leading edge). This observation implies that charge is being drained from the bottom of the channel faster than it is being supplied there from the upper channel sections, as should be the case if the channel grounding impedance is significantly less than the equivalent impedance of the channel. At such close range, similar values of the grounding impedance and equivalent channel impedance (similar rates of charge supply to and charge removal from the channel base) would result in similar and unshifted waveshapes of the current and electric field, as we will show in section 3.3.

3.2. Mechanism

The three observations listed above can be interpreted within the framework of an M-component mechanism that is based on the following assumptions:

1. There is a channel between cloud and ground that is capable of supporting a traveling current wave. M components occur only in current-carrying channels, as evidenced by the preceding channel luminosity [*Malan and Collens*, 1937] and, additionally, by the preceding continuing currents of some tens to some hundreds of amperes measured at the channel attachment to ground [*Fisher et al.*, 1993]. Such a channel (essentially a grounded quasi-stationary arc) is likely to act as a transmission line (though, perhaps, a nonlinear and nonuniform one) when a current wave is injected into it. A transmission-line representation of the M-component channel was also suggested by *Thottappillil* [1992] and E. M. Bazelyan (personal communication 1993). Assumption 1 is further discussed in section 3.4.

2. The M component is initiated as a current wave launched at the upper extremity of the channel toward ground. This assumption is supported by our observation (a) above.

3. When the M current wave, previously injected at the top of the channel, arrives at ground, the equivalent impedance of the channel is much greater than the channel grounding impedance, so that a reflected wave is produced, as if the channel were terminated in a short circuit. In other words the magnitude of the current reflection coefficient at ground is essentially equal to unity. This assumption is supported by observation (c) above: it will be shown in section 3.3 that the observed overall waveshape of the 30-m M electric field, different from the current waveshape, can be reproduced (within the mechanism being suggested) only if the magnitude of the current reflection coefficient is greater than 0.95 or so. The characteristic shift between the channel-base current peak and the 30-m electric field peak disappears and the waveshape of the field pulse becomes similar to that of the current pulse if the magnitude of the current reflection coefficient is less than 0.5 or so. We will also show, in section 3.4, that a lightning channel carrying a continuing current can be reasonably represented by an R-C transmission line with a characteristic impedance of the order of tens to hundreds of kilohms for frequencies of interest (see Table 1). In that case, a ground impedance as large as some hundred ohms will be sensed by the incident M wave as a short circuit.

4. Both the downward incident current wave and the upward reflected current wave propagate at the same and constant speed. This assumption is arbitrary. However, as discussed later, the M wave speed essentially controls (within the mechanism being suggested) the magnitude of the electric field at 30 m but has relatively little effect either on the field waveform or on the characteristic shift between the channel-base current peak and the 30-m electric field peak.

5. Both the incident and the reflected M current waveforms remain unchanged while propagating along the channel (each wave experiences no distortion and no attenuation). This assumption taken together with assumption 3 implies that in terms of current magnitude the incident and reflected waves are each one half of the current wave measured at ground. This assumption is further discussed in section 3.4.

6. The upward reflected wave does not itself suffer reflection at the cloud charge source. This assumption is arbitrary, but it does not affect the characteristic features of M components described in observations (a) to (c) above, since reflection from the source, even if appreciable, comes into the picture at later times. Perhaps the secondary current peak in Figure 2a, occurring about 300 μs after the first one, is associated with reflection at the source. On the other hand, the secondary peak could be associated with another M component, independently initiated at the channel top. Whatever the origin of the secondary peak, we treat the entire M-current waveform shown in Figure 2a as a single, double-peaked pulse.

An M-component mechanism based on these assumptions is illustrated in Figures 3a and 3b showing, respectively, current (incident, reflected, and total) distributions along the channel at different times and current waveforms (incident, reflected, and total) at different heights along the channel. The M-current waveform at ground level that we used in Figures 3a and 3b (also Figure 3c) is shown in Figures 4a and 4b. Note that from Figure 3b both the amplitude and the waveshape of the total M current pulse do not vary appreciably within heights typically observable with optical techniques, 0 to 1-2 km, a behavior very similar to that of the M luminosity pulses in different channel sections reported by *Jordan et al.* [this issue]. Further, Figure 3b clearly shows why the incident and reflected M waves have never been observed using streak photography (except, perhaps, one case reported by *Jurenka et al.* [1992] in which a severe M component apparently exhibited a downward progression followed by an upward progression). The front duration of the M-current wave, typically hundreds of microseconds [*Fisher et al.*, 1993], is usually longer than the time required for an M-wave round-trip between the cloud base and the ground; that is, when the reflected wave arrives at the cloud

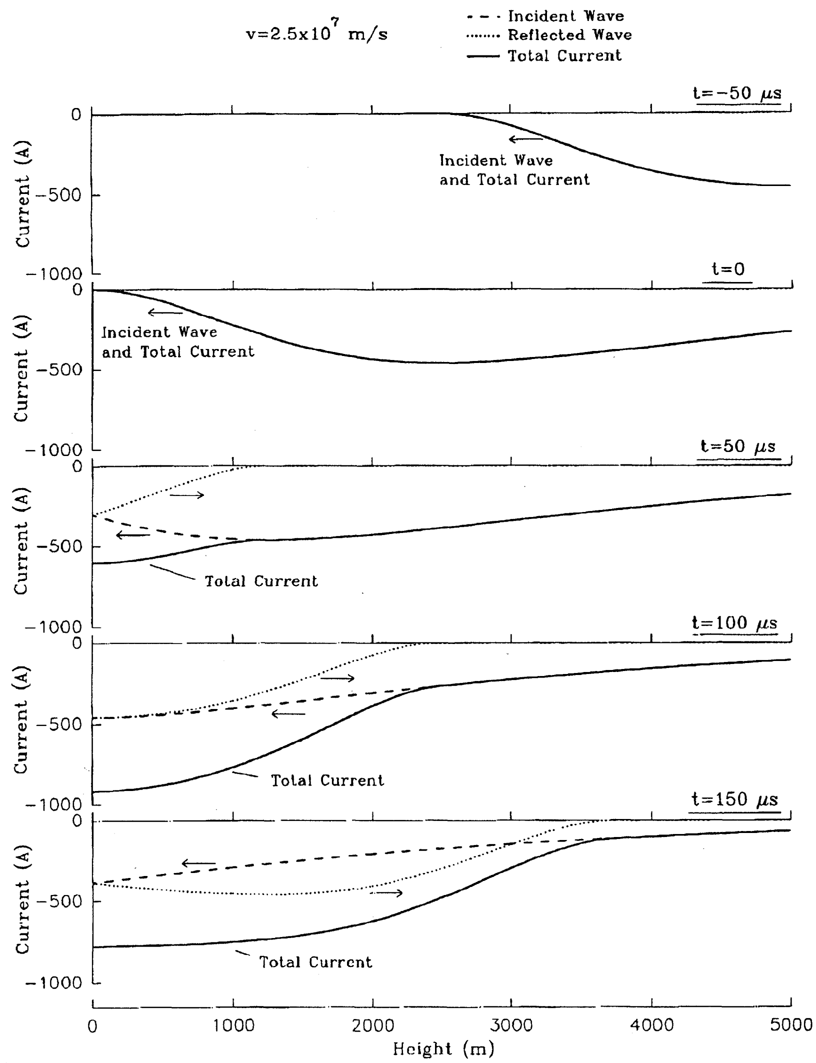

Figure 3a. M-current distributions along the channel at different times. At t = 0, the incident wave front arrives at ground. See text for details.

base, the incident wave is still rising to its maximum, or has just attained the maximum, as seen in Figure 3b for a height of 1000 m. Therefore the incident and reflected wave peaks are likely to separate in time, if at all, inside the cloud. The likelihood of such a separation decreases as the M-wave speed (represented by the slope of the two slanted lines in Figure 3b) increases and/or the risetime of the M-current pulse becomes longer. It is important to note from Figure 3b (see also Figure 3c that shows the superposition of the total current waveforms at different heights, except for ground level, from Figure 3b) that within the bottom 1000 m or so the initial portion of the total current wave front is determined by the descending incident wave and hence appears to be propagating downward, whereas the final portion of the total current wave front is dominated by the ascending reflected wave and hence appears to be propagating upward. Note also that the middle part of the total current wave front appears almost simultaneous in all channel sections between ground and about 1000 m height, implying a much higher propagation speed than for either earlier or later parts of the front. Thus different parts of the total M current wave front appear to travel at different speeds and even in different directions. As a result, depending on the point on the M current front that is associated with maximum luminosity and on such factors as film type, exposure, and film processing, very different speeds and either upward or downward propagation directions can be optically observed, consistent with the experimental data reported by *Malan and Collens* [1937].

Assumptions 1 to 3 were inferred from observations (a) to (c) above and are the key assumptions of the M-component mechanism being proposed. According to this mechanism an M component involves both a downward progressing incident wave (the analog of a leader) and an upward progressing reflected wave (the analog of a return stroke). However, as opposed to a leader-return stroke sequence in which the latter removes the charge deposited by the former, both the upward and the downward processes contribute about equally to the total charge flowing from the bottom of the channel to ground at any instant of time. In this view, the M "return stroke" starts ascending from ground, while the main M "leader" charge is still descending along the higher channel sections. It appears to us that assumptions 1 to 3 is the only way to a self-consistent explanation of our observations (a) to (c).

Additional assumptions 4 to 6 are not dictated by the data and serve to simplify significantly the model based on the suggested mechanism. These assumptions control the

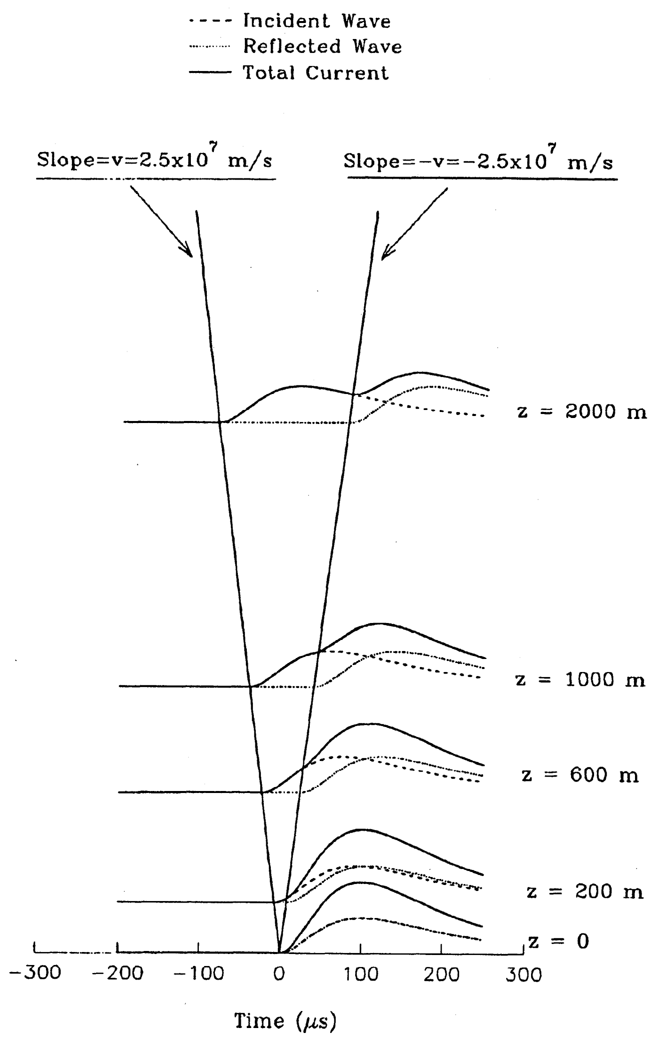

Figure 3b. M-current waveforms at different heights along the channel. At t = 0, the incident wave front arrives at ground. At z = 0, the incident and reflected waves coincide with each other. See text for details. Note that the current waveforms have been inverted for illustrative purposes relative to the preceding and following figures.

distribution of current (and charge) along the channel and hence are best tested using multiple-station electric and magnetic field measurements (not further discussed here).

3.3. Modeling

Based on assumptions 1 to 6, we can express the M current i(z,t) at any height z along a straight vertical channel of height H at time t as follows:

$$i(z,t) = i(H, t-(H-z)/v) \quad \text{if } t<H/v \tag{1}$$

$$i(z,t) = i(H, t-(H-z)/v) + i(H, t-(H+z)/v) \quad \text{if } t\geq H/v \tag{2}$$

where v is the M-wave propagation speed and i(H,t) is the current injected at the top of the channel (at height H), equal to one half of the total current measured at the channel base according to assumptions 3 and 5. The incident-wave charge per unit length and reflected-wave charge per unit length are determined, from the continuity equation relating charge density and current, as the corresponding currents divided by v (downward progression) and by -v (upward progression), respectively. The corresponding M electric field at ground level above a perfectly conducting Earth is

$$E_z(d,t) = \frac{1}{2\pi\varepsilon_0}\int_0^H\left[\frac{2z^2-d^2}{R^5}\int_0^t i\left(z,\tau-\frac{R}{c}\right)d\tau + \frac{2z^2-d^2}{cR^4}\, i\left(z,t-\frac{R}{c}\right) - \frac{d^2}{c^2R^3}\,\frac{\partial i\left(z,t-\frac{R}{c}\right)}{\partial t}\right]dz \tag{3}$$

where d is the horizontal distance between the lightning channel and the observation point, $R = \sqrt{d^2+z^2}$, and i(z,t) is given by (1) and (2) with appropriate retardation [e.g., *Uman*, 1987]. Channel height H was assumed to be 5 km, more than sufficient to take into account virtually all channel sections contributing to electric field at 30 m. The electric fields at 30 m calculated using (3) and the measured currents shown in Figures 1a and 2a are essentially electrostatic, the first field component in (3). Calculations also show that the propagation speed, an adjustable parameter in our M-component model represented by (1) and (2), essentially controls the M electric field magnitude and has relatively little effect on the field waveshape. The model-predicted fields along with the speed providing the best field magnitude match with the measurements are presented in Figures 1c and 2c. It is important to note that the overall shape of the field waveforms can be reproduced only if the magnitude of the current reflection coefficient is greater than 0.95 or so.

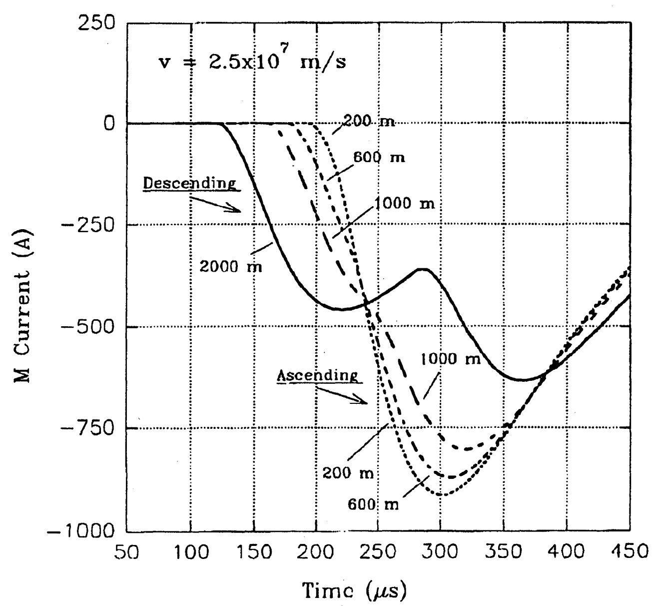

Figure 3c. Superposition of the total M-current waveforms at different heights (except for z = 0) from Figure 3b. The incident wave front arrives at ground at t = 200 μs. See text for details.

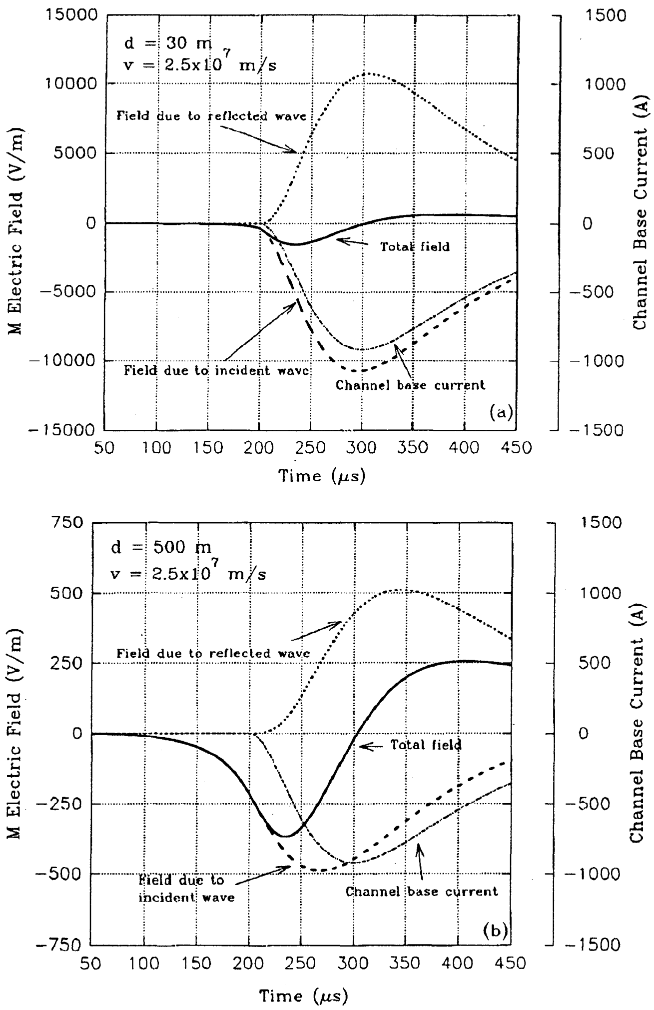

Figure 4. Formation of M-electric field waveform at (a) 30 m and (b) 500 m from the channel. Also shown is the corresponding channel-base current which begins at t = 200 μs, when the incident current wave front arrives at ground. See text for details.

Further, if the magnitude of the reflection coefficient is less than 0.5 or so, our calculations show that there is essentially no shift between the current and the field peaks and the field pulse looks similar to the current pulse (trailing edge slower than leading edge). Good agreement between the calculated (Figures 1c and 2c) and the measured (Figures 1b and 2b) fields is evident in terms of the overall waveshape, magnitude (note that the measured M fields do not start from zero level), and time shift between the field and the current peaks. The speeds that provided the correct field magnitudes are in the range of measured speeds for M components [*Malan and Collens*, 1937; *Shao et al.*, 1995], although at the lower end. Note that within the suggested M-component mechanism, an increase in propagation speed results in a significant reduction of the field magnitude, so that higher-speed M components are less likely to be detected in electric field records [see also *Thottappillil*, 1992].

In the model presented, the total electric field due to an M component is the superposition of the field associated with the incident current (or charge) wave and the field associated with the reflected wave. This is illustrated in Figure 4a for an M component similar to that presented in Figure 1. The M-current waveshape was approximated by an analytical expression to avoid the instrumental and numerical noise apparent in the traces shown in Figures 1 and 2. The amplitude of that M-current pulse (see Figures 4a and 4b) at ground was set at about 900 A. It is this pulse that was used to illustrate the proposed M-component mechanism in Figure 3. It is clear from Figure 4a that the M field is the difference between the two field waves that are similar in both magnitude and waveshape but are opposite in polarity and slightly shifted in time with respect to each other. In fact, the total M field appears to vary as the time derivative of the 30-m field due to the incident wave, and the total M-field magnitude is a relatively small fraction of the magnitude of either of the two field component waves. Figure 4a also illustrates that for a matched channel termination, i.e., no reflected wave, the current (also shown in Figure 4a) and 30-m field have similar waveshapes. It follows that the M-field waveshape is approximately the time derivative of the channel-base current waveshape with appropriate constants.

Figure 4b shows the calculated field for the same M component as it would be observed at 500 m. As distance increases to 500 m, the time shift between the incident-wave field and the reflected-wave field appears to be larger, and the M-field magnitude becomes a significant fraction of the incident-wave field component. The disparity between the M-field signatures at 30 m and 500 m is related to the difference between the lengths of the channel contributing to the field at ground level: a few hundred meters at a distance of 30 m versus some kilometers at 500 m [*Rubinstein et al.*, 1995]. At 500 m the contributing length is comparable to the length of the M wave front (about 2 km in Figure 3a; see the trace for t = 0), so that appreciable contributions to the field at 500 m are produced even before the incident M wave arrives at ground (see Figure 4b). At 30 m the contributing length is much smaller than the length of the M wave front, so that only a small contribution to the 30-m field is produced by the time the incident M wave arrives at ground (see Figure 4a).

It is interesting to note from Figures 4a and 4b that the M field is relatively insensitive to the change in distance: about 1.5 kV/m at 30 m and about 0.4 kV/m at 500 m, a threefold to fourfold difference in field for a more than 15-fold difference in distance. Typical measured leader fields at 30 m (16 measurements: this study and [*Rubinstein et al.*, 1995]) and at 500 m (40 measurements [*Rubinstein et al.*, 1995]) are some tens of kilovolts per meter and about 1 kV/m, respectively (a more than tenfold variation). The dissimilarity between the M fields and leader fields as a function of distance is due to the difference in the distribution of charge along the channel. The leader charge is often assumed [e.g., *Rubinstein et al.*, 1995] to be uniformly distributed along the channel, and it is possible that this charge is more concentrated at the bottom of the downward moving leader in order to facilitate breakdown processes in front of the leader tip and allow further leader propagation. On the other hand, M charge at the bottom of the channel tends to decrease toward ground, partly due to reflection at ground, as can be inferred from Figure 3a, keeping in mind that the incident-wave charge per unit length and reflected-wave charge per unit length are determined as the corresponding currents divided by v (downward progression) and by -v (upward progression), respectively. As an observer moves away from the channel, the electric field due to either leader or M component (1) tends to decrease because of an increase in distance to the source and (2) is determined to a greater extent by the charge in the higher channel sections. In the case of an M component the higher channel sections have larger charge than lower channel sections and, as a result, the decrease in the field due to a larger distance to the channel is diminished. In the case of a leader the higher channel sections are equally or less charged and, as a result, the decrease in field due to a larger distance to the channel is unaffected or enhanced. A relative insensitivity of the M electric field to the change in distance was also suggested by E. M. Bazelyan (personal communication, 1993) from his consideration of the M component as a transient process initiated by impressing a voltage at one end of an R-L-C transmission line short-circuited at the other end, with L and C taken as constants and R assumed to vary as a function of current.

3.4. Evolution of an M-Current Wave Traveling Along the Lightning Channel

We now discuss in more detail assumption 5 regarding the lack of distortion and attenuation of the M-current waves when they travel along the channel. If we represent a lightning channel carrying a continuing current as a lossy transmission line characterized by its resistance R, capacitance C, and inductance L, all per unit length, the propagation constant of such a channel in the frequency domain will be [e.g., *Sadiku*, 1994]

$$\gamma = \sqrt{j\omega C(R+j\omega L)} \tag{4}$$

where ω is the angular frequency; $\omega=2\pi f$ with f the frequency in Hertz. Further, as a first approximation, we assume that the traveling M-current waves do not significantly affect R, C, and L and that none of these three parameters varies with height; that is, the transmission line is assumed to be linear (possible nonlinearities are discussed later in this section) and uniform. Then, C and L can be estimated [e.g., *Gorin*, 1985] as those of a straight vertical conductor and are about 4 pF/m and 3 μH/m, respectively, for a channel of 1-cm radius at a height of the order of a few kilometers above ground. Note that both L and C are relatively insensitive to changes in height h above ground or channel radius r since they vary as the logarithm and the inverse of the logarithm, respectively, of the ratio of 2h to r [e.g., Gorin 1985]. *King* [1961], from his experiments with free-burning arcs in air and nitrogen, found that the longitudinal electric field E in the arc channel decreases when current I increases up to 50 A or so and remains about constant, at 1000 V/m, for larger currents. *Latham* [1980], based on his model of an air arc, showed that the reason for this shape of the E-I relation is the change from a thermal-conduction-dominated channel at low currents to a radiation-dominated channel at high currents. *Latham* [1986] calculated E as a function of I to be lower "by a factor of 2 or so" than that experimentally obtained by *King* [1961]. Based on King's data, we estimate that the resistance R = E/I for arcs carrying currents of 50 and 100 A should be 20 and 10 Ω/m, respectively. We assume for the following analysis that R is 20 Ω/m (the main conclusions from this analysis are essentially the same for R = 10 Ω/m). Using the above estimates of R, C, and L, we find that for f«1 MHz it follows that ωL«R, and (4) reduces to

$$\gamma = \alpha + j\beta \approx \sqrt{j\omega RC} \tag{5}$$

where α and β are, respectively, the attenuation constant and phase constant of the channel; that is, the channel is effectively an R-C transmission line for f«1 MHz. The attenuation and phase constants are equal in magnitude and can be expressed as

$$\alpha = \beta = \sqrt{\frac{\omega RC}{2}} \tag{6}$$

The phase velocity V and the characteristic impedance Z_0 of an R-C transmission line in the frequency domain are

$$V = \frac{\omega}{\beta} = \sqrt{\frac{2\omega}{RC}} \tag{7}$$

$$Z_0 = \sqrt{\frac{R}{j\omega C}} = \sqrt{\frac{R}{\omega C}}\angle -45^\circ \tag{8}$$

The current reflection coefficient at ground is

$$r_g = \frac{Z_0 - Z_g}{Z_0 + Z_g} \tag{9}$$

where Z_g is the channel grounding impedance. All parameters given by (5) to (9) are functions of frequency. Table 1 gives values of $|Z_0|$, r_g (for assumed Z_g = 500 Ω, purely resistive), V, α, and the attenuation distance 1/α (the distance along the channel over which the e-fold attenuation occurs) for three frequency components, all three being significantly lower than 1 MHz, the condition of validity of expressions (5) through (8). Note that the frequency spectra of both the M-current pulses at the bottom of the channel [*Fisher et al.*, 1993] and the M-light pulses in the bottom 1 km or so of the channel [*Jordan et al.*, this issue] are essentially determined by frequency components in the range from 0 to less than 10 kHz (risetimes from tens of microseconds to milliseconds).

Values of V for f = 1 kHz and f = 100 kHz are similar to the optically determined speeds of M components [*Malan and Collens*, 1937]. However, the speeds in the table should not necessarily correspond to the optically measured speeds (see discussion of Figures 3b and 3c above).

It follows from Table 1 that the higher frequencies travel at higher speeds and are attenuated faster than the lower frequencies. For instance, a 100-kHz wave is attenuated 20-fold after traveling only 420 m at about one third of the speed of light, while a 1-kHz wave propagates an order of magnitude slower and is attenuated only 2-3 times over 1.4 km, the maximum distance between the cloud base and the ground observed in the streak-photography experiments in Florida [*Jordan et al.*, 1992]. Thus, if frequencies of the order of 100 kHz were present in the incident M-current wave at its origin (upper extremities of the lightning channel), they would have negligible magnitude compared to the frequencies of the order of 1 kHz and lower when the incident wave is about to emerge from the cloud base. It follows that the preferential attenuation of the higher-frequency components on an R-C line is probably responsible for the lack of frequencies above several kilohertz in the M-current pulses measured at the channel base [*Fisher et al.*, 1993] and in the M-light pulses observed in the bottom 1 km or so of the

Table 1. Characteristics of Lightning Channel Represented by an R-C Transmission Line Having R = 20 Ω/m, C = 4 pF/m, and Terminated in a 500-Ω Resistance

f, kHz	$\|Z_0\|$, kΩ	r_g (for Z_g = 500 Ω)	V, m/s	α, Np/km	1/α, km
0.01	282	1.00 ∠-0.1°	9×10^5	0.07	14
1	28	0.98 ∠-1.4°	9×10^6	0.7	1.4
100	2.8	0.78 ∠-15°	9×10^7	7	0.14

Attenuation of 1 Np denotes a reduction to 1/e = 0.368 (about 37%) of the original value; 1 Np = 20 $\log_{10}e$ = 8.686 dB.

channel [*Jordan et al.*, this issue]. The presence of relatively high frequencies at the source, that are not observed in the channel-base currents, is suggested by the observations [*Rakov et al.*, 1992; *Shao et al.*, 1995] of microsecond-scale electric field pulses at the beginning of the M process. The relatively high characteristic impedance of the channel, of the order of tens to hundreds of kilohms for frequencies below some kilohertz, calculated on the basis of the linear R-C line approximation, is consistent with our inference from observation (c) (see section 3.1) that even a relatively poor ground, as existed at Camp Blanding, is sensed by an incident M wave as essentially a short circuit. For an assumed grounding impedance as high as 500 Ω and for frequencies below some kilohertz the current reflection coefficient at ground is almost purely real and its magnitude is close to unity (see Table 1).

In the previous discussion we assumed that R, C, and L were constants. We now discuss potential nonlinearities of the lightning channel. On physical grounds the M waves guided along the lightning channel are expected to cause additional atomic excitation and ionization (otherwise M components would not be luminous), radial expansion of the channel, and charging and discharging not only of the channel core carrying the longitudinal current to ground but also of the radial-corona sheath surrounding that core, whose size depends on the electric potential associated with the M component. As a result, the values of R, C, and L of the continuing-current channel that we used earlier in this section will be altered to some degree by the propagating M waves (a nonlinear transmission line). Inductance L is influenced only by an increase in the channel core radius. A change in the channel core radius from the 1 cm assumed above to 10 cm (the maximum expected value) results in less than a 15% decrease in L. The capacitance C of the channel, including the corona sheath, is larger than that for the channel core only. For an equivalent channel radius of 10 m or so (channel core plus the largest expected corona sheath) it is about 2 times greater than the capacitance (used earlier in this section) of a 1-cm channel core. Resistance R of the channel can be estimated as the ratio of the longitudinal electric field intensity in the channel to the corresponding channel current. For currents in excess of some tens of amperes the field intensity is more or less constant, at 1000 V/m [*King*, 1961]. Therefore if, for instance, the current increases from 50 A (the continuing current level in Figure 2) to 750 A (the M-current level in Figure 2), the channel resistance R should decrease 15-fold. Similarly, the expected decrease in R associated with the M component illustrated in Figure 1 is about sevenfold. Thus of the three channel parameters, R, C, and L, the largest variation during the M-component process should be expected for R, although the dynamics of transition from a relatively high to a relatively low channel resistance and back is unknown. If R decreases an order of magnitude, from 20 to 2 Ω/m, then the linear R-C transmission line approximation is only valid for frequencies below 10 kHz (versus below 100 kHz for 20 Ω/m), a range still covering the spectra of observed M-current [*Fisher et al.*, 1993] and M-light [*Jordan et al.*, this issue] pulses.

A linear R-C transmission line is dispersive, with the higher-frequency components traveling faster than lower-frequency components (see (7) above). As a result of this velocity dispersion, one would expect an M pulse to spread while propagating along the channel. However, because of the ionization produced by the M-pulse front, the pulse tail encounters a lowered resistance and hence accelerates, as follows from (7). The latter effect, associated with channel nonlinearity, may act to compensate for pulse spreading due to the velocity dispersion inherent to a linear R-C transmission line. A dynamic balance between these two opposing effects might well create conditions for the formation of an M-pulse that maintains its more-or-less symmetrical shape over a relatively large distance along the channel, as if it were a soliton [e.g., *Hasegawa*, 1989].

Acknowledgements. This research was supported in part by NSF grant ATM9014085 (Program Director R. C. Taylor). The experimental part of the study took place at the lightning triggering facility at Camp Blanding, Florida, the Florida Army National Guard Base. The facility was designed, constructed, and operated in 1993 by the Electric Power Research Institute (Project EPRI RP3326, Project Manager R. Bernstein). Lightning triggering was performed by A. Eybert-Berard and colleagues of the Centre d'Etudes Nucleaires de Grenoble, France. W. Jafferis supported the experiment with NASA equipment. The authors wish to thank S.P. Hnat of Power Technologies, Inc., and J. A. Versaggi of the University of Florida who participated in setting up and operating the current and field measuring systems.

References

Fisher, R.J., G.H. Schnetzer, R. Thottappillil, V.A. Rakov, M.A. Uman, and J.D. Goldberg, Parameters of triggered-lightning flashes in Florida and Alabama, *J. Geophys. Res.*, *98*, 22,887-22,902, 1993.

Gorin, B. N. Mathematical modeling of lightning return stroke, *Elektrichestvo*, *4*, 10-16, 1985.

Hasegawa, A., Optical solitons in fibers, in *Springer Tracts in*

Modern Physics, vol. 116, 75 pp., Springer-Verlag, New York, 1989.

Jordan, D. M., V. P. Idone, V. A. Rakov, M. A. Uman, W. H. Beasley, and H. Jurenka, Observed dart leader speed in natural and triggered lightning, *J. Geophys. Res.*, *97*, 9951-9957, 1992.

Jordan, D. M., V. P. Idone, R. E. Orville, V. A. Rakov, and M. A. Uman, Luminosity characteristics of lightning M components, *J. Geophys. Res.*, this issue.

Jurenka, H., V. P. Idone, and M. Brook, The characteristics of M-components as observed in Florida triggered lightning (abstract), *Eos Trans. AGU*, *73*, 104, 1992.

King, L.A., *The Voltage Gradient of the Free-Burning Arc in Air or Nitrogen*, reference G/XT172, British Electrical and Allied Industries Research Association, Leatherhead, Surrey, England, 1961.

Kitagawa, N., M. Brook, and E.J. Workman, Continuing currents in cloud-to-ground lightning discharges, *J. Geophys. Res.*, *67*, 637-647, 1962.

Krehbiel, P.R., M. Brook, and R. McCrory, An analysis of the charge structure of lightning discharges to the ground, *J. Geophys. Res.*, *84*, 2432-2456, 1979.

Latham, D.J., A channel model for long arcs in air, *Phys. Fluids*, *23*(8), 1710-1715, 1980.

Latham, D.J., Anode column behavior of long vertical air arcs at atmospheric pressure, *IEEE Trans. Plasma Sci.*, *PS-14*, 220-227, 1986.

Malan, D.J., and H. Collens, Progressive lightning III — The fine structure of return lightning strokes, *Proc. R. Soc. London A*, *162*, 175-203, 1937.

Malan, D.J., and B.F.J. Schonland, Progressive lightning, 7, Directly correlated photographic and electrical studies of lightning from near thunderstorms, *Proc. R. Soc. London A*, *191*, 485-503, 1947.

Rakov, V.A., R. Thottappillil, and M.A. Uman, Electric field pulses in K and M changes of lightning ground flashes, J. Geophys. Res., *97*, 9935-9950, 1992.

Rubinstein, M., F. Rachidi, M. A. Uman, R. Thottappillil, V.A. Rakov, and C.A. Nucci, Characterization of vertical electric fields 500 m and 30 m from triggered lightning, *J. Geophys. Res.*, *100*, 8863-8872 1995.

Sadiku, M. N. O., *Elements of Electromagnetics*, 821 pp., Sounders College, Orlando, Fla., 1994.

Schonland, B.F.J., The lightning discharge, in *Handbuch der Physik*, vol. 22, pp. 576-628, Springer-Verlag, New York, 1956.

Shao, X. M., P. R. Krehbiel, R. J. Thomas, and W. Rison, Radio interferometric observations of cloud-to-ground lightning phenomena in Florida, *J. Geophys. Res.*, *100*, 2749-2783, 1995.

Thottappillil, R., A study of cloud-to-ground lightning processes with emphasis on data analysis and modeling of the return stroke, Ph.D. dissertation, Univ. of Florida, Gainesville, 1992.

Thottappillil, R., V. A. Rakov, and M. A. Uman, K and M changes in close lightning ground flashes in Florida, *J. Geophys. Res.*, *95*, 18,631-18,640, 1990.

Uman, M.A., *The Lightning Discharge*, Academic, San Diego, Calif., 1987.

Uman, M. A., et al., Electric fields close to triggered lightning, paper presented at the International Symposium on Electromagnetic Compatibility, pp. 33-37, Univ. of Rome "La Sapienza," Rome, September 13-16, 1994.

P. P. Barker, Power Technologies, Inc., Schenectady, NY 12301-1058.

V. A. Rakov (corresponding author), R. Thottappillil, and M. A. Uman, Department of Electrical Engineering, University of Florida, Gainesville, FL 32611-6200.

(Received December 19, 1994; revised June 5, 1995; accepted June 5, 1995.)