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Luminosity characteristics of lightning M components

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Abstract. A high-speed streak photograph of a natural cloud-to-ground lightning return stroke followed by two M components is analyzed. As opposed to the return stroke light pulse whose amplitude and waveshape vary markedly with height, the amplitude and waveshape of one M component light pulse is essentially invariant with height between the cloud base (about 1 km) and ground, while the other M component has a relatively constant light waveshape and a light amplitude that varies somewhat with height. The two M component light pulses, both occurring within about 0.6 ms of the return stroke pulse, exhibit a more or less symmetrical waveshape with a risetime and falltime of the order of many tens of microseconds. For one of the two M components a downward direction of propagation and a corresponding speed of the order of 10^8 m/s are inferred.

1. Introduction

Jordan and Uman [1983] studied relative light intensity as a function of height and time for seven subsequent return strokes in two lightning flashes at ranges of 7.8 and 8.7 km. The observed light signals exhibit a fast rise to peak followed by a slower decrease to a relatively constant value. The amplitude of the initial light peak decreases exponentially with height with a decay constant of about 0.6 to 0.8 km. The 20% to 80% risetime of the light signal is between 1 and 4 μs near ground and increases by an additional 1 to 2 μs by the time the return stroke reaches the cloud base, a height between 1 and 2 km.

In this paper a similar study is performed for M components, defined as the brightening of the lightning channel during continuing luminosity following a return stroke [*Malan and Collens*, 1937]. The term "M component" usually refers to the brightening below the cloud base not associated with channel branches, mostly in subsequent strokes. Channel brightening associated with a branch is termed a "branch component" and is not studied here. Optical M components are accompanied by current pulses at the bottom of the channel, as established by *Fisher et al.* [1993], and characteristic hook-shaped electric field changes at distances of several kilometers or closer, as reported by *Malan and Schonland* [1947] and by *Thottappillil et al.* [1990]. No information on the luminosity waveform of a lightning M component, even at one height, is available in the literature. A single luminosity versus time curve for a heavily branched single-stroke flash, apparently showing three branch components, is presented by *Malan and Collens* [1937, Figure 22]. The curve is hand drawn and is unsuitable for luminosity waveform analysis; it provides only an estimate for the duration and maximum luminosity of the return stroke and of the branch components at one height, not far from the bottom of the channel.

From two-lens streak photography *Malan and Collens* [1937] infer the apparent direction of propagation for nine M components, claiming that seven definitely traveled downward while two appeared to travel upward. They state that many M components, apparently including those with indeterminate directions of movement, have speeds in excess of 10^8 m/s, the limit of their measurements. *Malan and Collens* [1937] also claim that the four slowest M components, all four reportedly showing a downward progression, had speeds ranging from $2x10^7$ to $4.7x10^7$ m/s.

In their propagation analysis, *Malan and Collens* [1937] measure the position on the film of the leading edges of the M component streaked images. However, they state that the leading edges of the M component images are relatively dim and diffuse, as opposed to the brighter, well-defined edges of the return stroke images, and, as a result, the error in determining the position of the leading edges of the M components from the film, according to *Malan and Collens* [1937], can be as large as 20-50 μs. In a few good cases *Malan and Collens* [1937] could determine the position of the M component (or branch component) leading edge to within 5 μs or so. The poorly defined M component leading edge has made the determination of even the direction of propagation of M components uncertain, causing the M process to be one of the least well-understood processes in the optically observable lightning channel.

Malan and Collens [1937, in their Figures 1 and 2], show examples of M component streaked images that follow first and subsequent strokes, respectively. They point out "the lack of curvature" in the M component

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images relative to the preceding return stroke images, apparently implying that the M components have higher speeds than the preceding return strokes. In this paper in addition to the principal objective, an analysis of the luminosity as a function of both time and height for two M components, we attempt to determine the direction of propagation and speed of the brighter M component.

2. Instrumentation, Data, and Data Processing Techniques

In 1978, researchers from the State University of New York at Albany (SUNYA) working at the NASA Kennedy Space Center, Florida made high-speed photographic measurements of natural lightning with a Beckman and Whitley streak camera. The film used was Kodak 5474 Shellburst with a gray base. The camera was operated with two collimating lenses covered by number 92 filters. The filters blocked almost all sunlight, reducing the fogging of film due to background light, while passing the bright hydrogen line (H_α) at 656.3 nm emitted by lightning. The atomic hydrogen is present in the hot lightning channel due to the breakup of atmospheric water vapor (H_2O). H_α is not present in sunlight because it is absorbed in the outer regions of the Sun.

Analyzed here are the two M components following one of the two subsequent return strokes in a cloud-to-ground flash that occurred at 4.9 km at 2041:00 UT on July 29, 1978. A streak camera image of the return stroke followed by the two M components is shown in Figure 1. The image was digitized by the University of Florida group using an Optronics Photomation microdensitometer capable of digitizing a 23x23 cm image at a spatial resolution of 12.5 μm. To the best of the authors' knowledge, the streak camera image analyzed here is the only one presently available for M component luminosity profile analysis.

All light intensity profiles presented in this study are in relative light units, while the microdensitometer measures "specular" film density. Film calibration from which the measured (specular) film density could be related to the incident relative light intensity (in relative light units) was performed by SUNYA. The film showed little sensitivity below 10 relative light units, but the relation between the specular film density and relative light intensity was approximately linear from 10 to 1000 relative light units. Any inaccuracies in the film calibration are unlikely to influence the main results of the present study, since these results are concerned with the relative evolution of the M light pulses along the channel and, additionally, the propagation characteristics of one of those pulses. The alignment and calibration of the microdensitometer as well as the custom software used to control the microdensitometer are described by *Jordan* [1990].

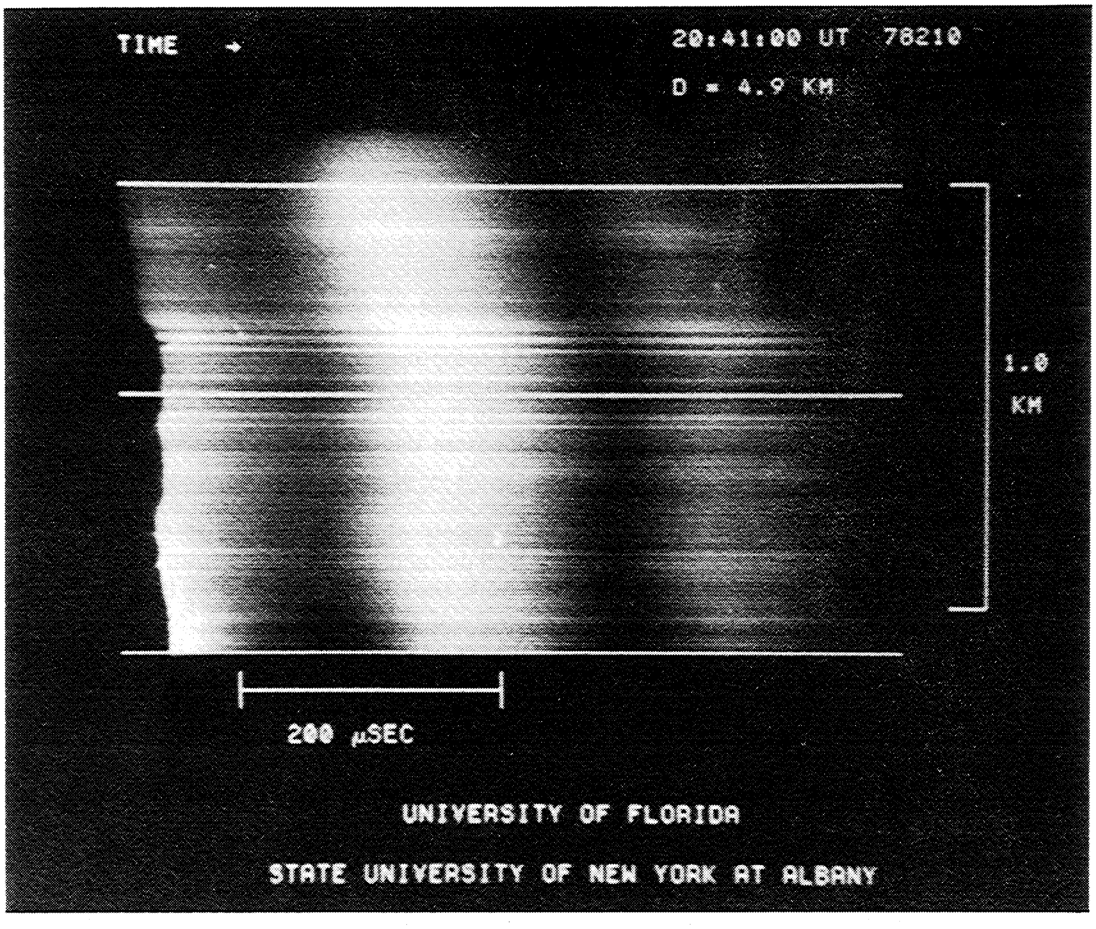

Figure 1. Digitized streak-camera images of a return stroke and two associated M components from a flash that occurred at 2041:00 UT on July 29, 1978. Heights indicated by the three horizontal lines correspond to the relative light intensity profiles shown in Figures 2a to 2c.

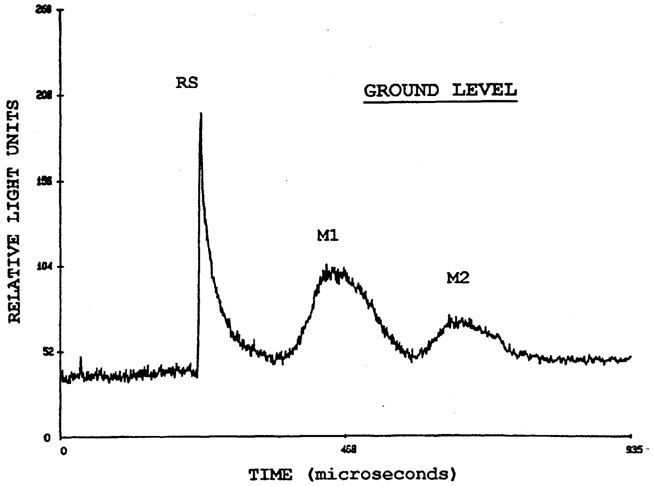

Figure 2a. Relative light intensity profile at ground level showing a return stroke light pulse (RS) and two M component light pulses (M1 and M2). The corresponding streak camera images are shown in Figure 1.

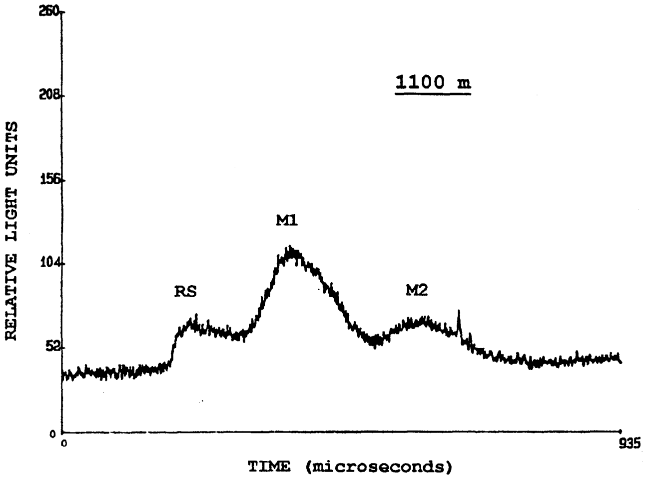

Figure 2c. Same as Figure 2a, but at 1100 m above ground.

3. Results and Discussion

3.1. Relative Light Intensity Versus Height

Relative light intensity profiles at three heights along the channel of both the return stroke and two M components are presented in Figures 2a through 2c. It is evident from these figures that M component light intensity has a very different character than return stroke light intensity. The return stroke light pulse exhibits a relatively fast rise to peak at ground level, appreciably degrading with height (a typical behavior for return strokes as discussed in the introduction). Figures 3 and 4 show the peak relative light intensity versus height for M1 and M2, respectively, obtained by measuring the amplitude of the light pulses at different heights along the channel. The first M component light pulse is almost invariant with height, at least below the cloud base of about 1 km (see Figure 3). The second M component pulse (see Figure 4) does exhibit some decrease in amplitude (note the different amplitude scale compared to Figure 3) with increasing height. Interestingly, the second M component pulse peaks at ground level and at 1100 m are about equal if measured with respect to the following, instead of preceding, background light level. The first M component pulse peak is approximately the same when measured at either the leading or the trailing side of the pulse, at each height. The return stroke pulse has maximum amplitude at ground level, whereas in the upper half of the visible channel section (see Figures 2b and 2c) the M component pulses are dominant. The M component light pulses are more or less symmetrical with a risetime and falltime of the order of many tens of microseconds. Similar symmetrical waveshapes were reported by *Fisher et al.* [1993, Figure 4b] for M current pulses measured at the bottom of triggered-lightning channels. The typical M current risetimes observed by *Fisher et al.* [1993] are somewhat longer than for our M light pulses, some hundreds of microseconds, perhaps

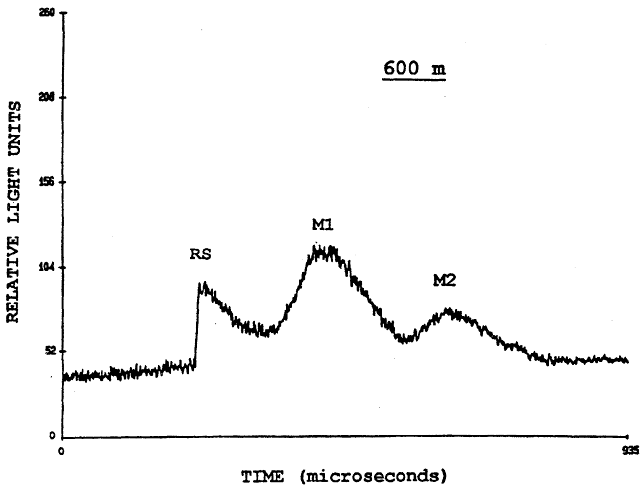

Figure 2b. Same as Figure 2a, but at 600 m above ground.

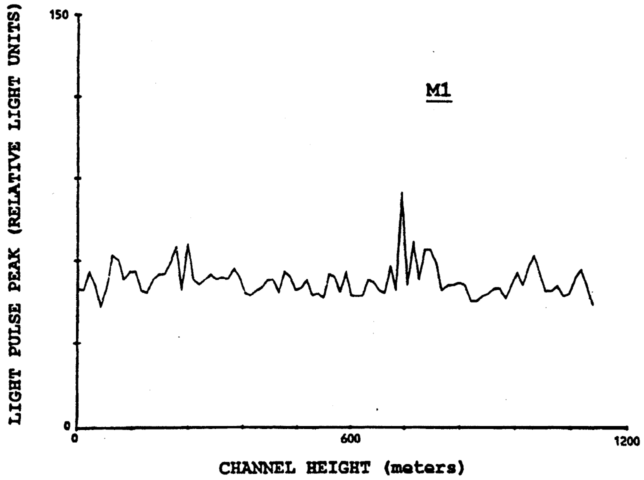

Figure 3. Peak relative light intensity versus height for the first M component (M1).

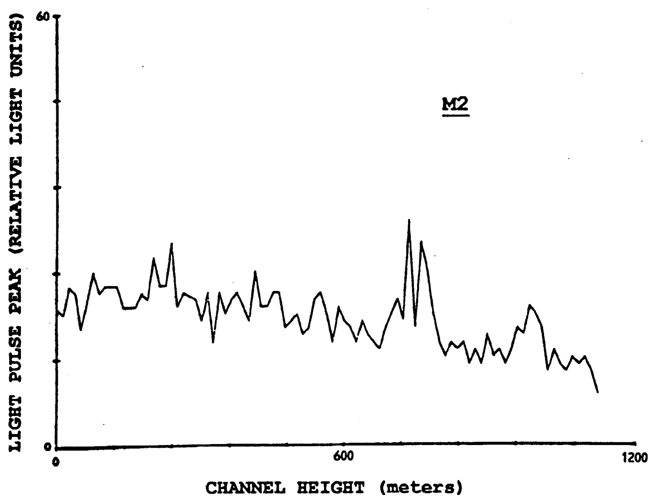

Figure 4. Peak relative light intensity versus height for the second M component (M2).

because Fisher et al.'s M components occur later after the return stroke than the M components studied here.

3.2. Direction and Speed of M Component Propagation

For the events studied here neither the second (from the twin lens streak camera) streaked image nor a still image of the channel (see, for instance *Idone and Orville*, [1982, Figure 2]) is available. Thus the determination of the M component propagation direction is not straightforward. Nevertheless, with some reasonable assumptions, we can attempt to infer the direction and speed of propagation for the first (brightest) M component from the displacement of the M component image relative to the return stroke image. In doing so, we express the displacement on the film in terms of time by dividing the streaked image spatial displacement on the film by the film writing rate. Naturally, the analysis is performed only in a plane perpendicular to the line of sight of the camera. As has been observed by several investigators (e.g., Malan and Collens) the return stroke and the M component follow the same channel.

If we overlay the first M component and the return stroke images in Figure 1 so that the leading edges of the two coincide at ground (see Figure 5), the M component edge above ground is to the left of the return stroke edge. Note that using the digitized streaked images makes the determination of the leading edges of the light pulses at different heights a relatively simple and straightforward procedure (see Figure 2) as compared to the procedure necessarily used by *Malan and Collens* [1937] who examined the original negatives with a transparent glass scale graduated in tenths of a millimeter. Potential errors in the analysis to follow are discussed in section 3.3.

The relative position of the two streaked images shown in both Figures 5a and 5b would be sufficient to conclude that the M component must propagate downward and the return stroke upward if the position of the still channel image were known to be between the M component and return stroke streaked images, as shown in Figure 5a. Unfortunately, no still image is available. If this still image were to the left of both the M component and return stroke streaked images, as shown in Figure 5b, then, for the same relative position of the two streaked images, the M component and the return stroke would both propagate upward. A still channel position to the right of the return stroke streaked image is unrealistic since it would correspond to a return stroke propagating downward.

We measured the displacement $T = 20$ μs between the leading edges of the two streaked images (aligned at ground) at height $H = 1000$ m. Based on this information and assuming that the channel is straight and inclined, we determine that, if the return stroke one-dimensional upward speed were 5×10^7 m/s, the still channel image would coincide with the streaked M component image and no propagation analysis of the M component would be possible. Further, if the return stroke speed were less than 5×10^7 m/s, the still channel image would be to the left of the M component image (see Figure 5b) and the M component would propagate upward. Finally, if the upward return stroke speed were greater than 5×10^7 m/s, the still channel image would be between the two streaked images (see Figure 5a) and the M component would propagate downward. In the limit of an infinite return stroke speed, the still channel image would coincide with the streaked return stroke image, as expected. All the situations described above can be inferred from the formula relating the one-dimensional M component speed V_M to the assumed one-dimensional return stroke speed V_{RS} through the observed values of T and H:

$$V_M = \frac{1}{1/V_{RS} - T/H} \tag{1}$$

This formula follows from the geometries shown in Figures 5a and 5b. For the M component in question $T/H = (5 \times 10^7 \text{ m/s})^{-1}$. Thus, we find $V_M > 0$ (upward progression) if $V_{RS} < 5 \times 10^7$m/s, and $V_M < 0$ (downward progression) if $V_{RS} > 5 \times 10^7$ m/s.

Idone and Orville [1982] presented statistics for 17 first-stroke and 46 subsequent-stroke two-dimensional speeds. The speed range was from 2.9×10^7 to 2.4×10^8 m/s with a mean value of 1.1×10^8 m/s. The distribution of return stroke speeds shows that only 6 of 63 strokes, both first and subsequent, have speeds less than 6×10^7 m/s. The two-dimensional speed is higher than the one-dimensional speed in the above expression. If we assume that the difference does not exceed 20% or so, then the odds are approximately 10 to 1 that the M component M1 in Figures 1, 2, and 3 traveled downward rather than upward. In support of this result, the initiation of M components in the cloud, implying a following downward propagation, was inferred by *Rakov et al.* [1992] from their analysis of M electric fields and by *Shao et al.* [1994] from the VHF imaging of lightning channels. The M component downward one-dimensional speed for M1 calculated using the above formula and assumed values of V_{RS} in the range from 0.8×10^8 to 2×10^8 m/s is given in Table 1.

3.3. Potential Errors in the Analysis of Direction and Speed of M Component Propagation

The main source of error in our analysis of the propagation of the M component in section 3.2 is the assump-

Figure 5a.

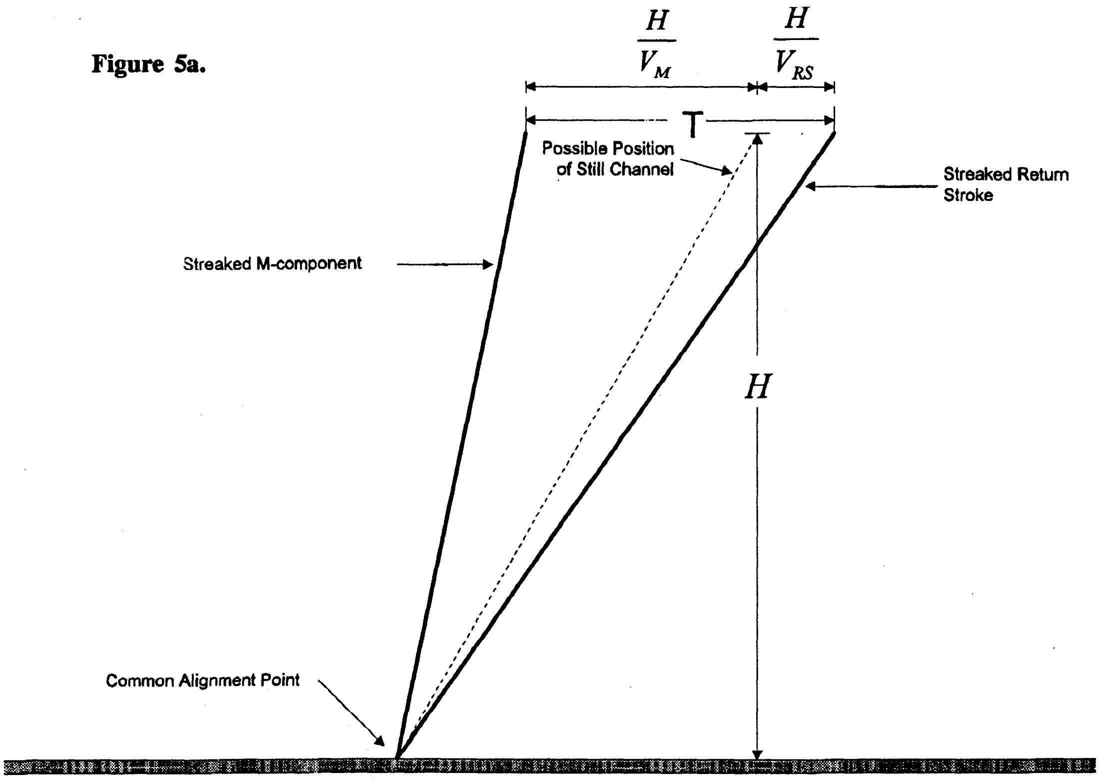

Figure 5b.

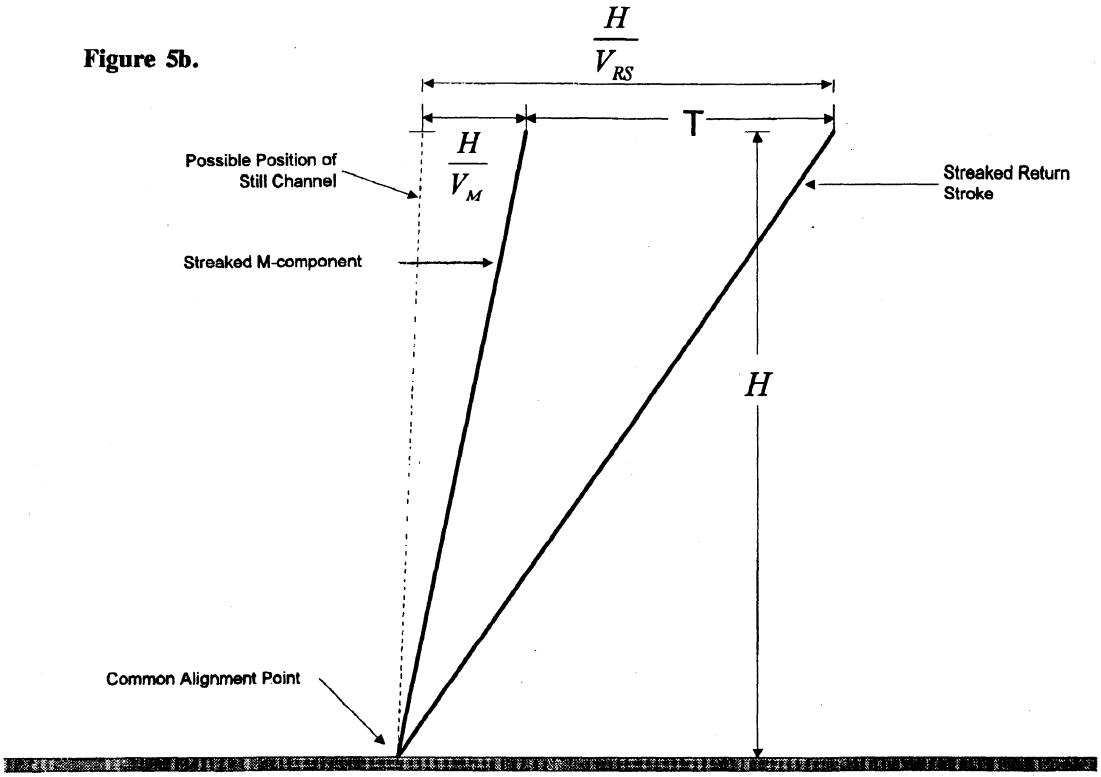

Figure 5. Sketches illustrating the determination of the direction of propagation and speed for the first M component (M1). See text for details.

tion necessarily made regarding the beginning of the M light pulse. As seen in Figure 2, the three light pulses appear overlapping; that is, the front of each pulse seems to emerge from the tail of the preceding pulse (or from the superposition of the tails of the preceding pulses). In the case of M1, the return stroke tail varies significantly with height, from a very fast exponential-type falloff at ground level to a slower, approximately linear decay at 1100 m. As a result, it is possible that a progressively larger portion of the front of the M pulse is "buried"

Table 1. One-Dimensional Downward Speed Inferred for M1 Using Equation (1) and Different Assumed Values of V_{RS}

Parameter	Values			
V_{RS} , m/s	0.8×10^8	0.9×10^8	1×10^8	2×10^8
V_M , m/s	1.3×10^8	1.1×10^8	1×10^8	0.7×10^8

under the preceding return stroke pulse tail as height increases. It is even possible that at some height the return stroke pulse rides on the slowly rising front of the M component that had started before the upward moving return stroke front arrived at that height. In any event, there is likely a tendency to underestimate the separation between the leading edges of the return stroke and M component streaked images at a given height when these images are aligned at ground; that is, to move the upper end of the M component image in Figure 5 to the right. If this be the case, then the odds that the M component propagates downward are even greater than 10 to 1, and the M component speed values are somewhat lower than those inferred in section 3.2.

4. Summary

The luminosity characteristics of return strokes and of M components are distinctly different as a function of height above ground. M component light pulses exhibit very little variation in both shape and amplitude within the bottom 1 km or so of the channel, as compared to return stroke light pulses which significantly decrease in amplitude and lose their sharp leading edge while propagating from ground to the cloud base. As a result, at heights of some hundreds of meters and above, the amplitude of M light pulses may exceed that of the preceding return stroke pulse. The M light pulses appear to be more or less symmetrical with a risetime and falltime of the order of many tens of microseconds. For one of the two M components analyzed it is inferred that the M process originated in the cloud and propagated downward at a speed of the order of 10^8 m/s.

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