Journal of Lightning Research, Volume 1, 2007, pages 80 - 89

Lightning Return Stroke Speed

Vladimir A. Rakov

Department of Electrical and Computer Engineering, University of Florida, Gainesville, Florida, USA

Abstract

The available experimental data on return stroke speed for both negative and positive lightning are reviewed. The often assumed relationship between the return-stroke speed and peak current is shown to be generally not supported by experimental data. Reasons for the return-stroke speed being lower than the speed of light are discussed.

Index Terms

Lightning return stroke, propagation speed, peak current, corona, ohmic losses

1 INTRODUCTION

The optically measured return-stroke speed probably represents the speed of the region of the upward-moving return-stroke tip where power losses are greatest, the power per unit length being the product of the current and the longitudinal electric field in the channel. The peak of the power loss wave likely occurs earlier in time than the peak of the current wave (e.g., Gorin, 1985 [1]; Jayakumar et al., 2006 [2]). Since the shape of the return-stroke light pulse changes significantly with height, there is always some uncertainty in tracking the propagation of such pulses for a speed measurement. For example, if the light pulse peak is tracked, then an increase in pulse risetime translates into a lower speed value than if an earlier part of the light pulse is tracked. It is thought that the error involved in identifying the time of the initial exposure (the time when light intensity first exceeds the background level) on streak photographs, as a basis for the speed measurements, is not large, especially near ground. Techniques for measuring return-stroke speed are discussed, for example, by Idone and Orville (1982) [3].

Lightning return stroke speed is an important parameter in lightning protection studies. Some researchers (e.g., Lundholm, 1957 [4]; Wagner, 1963 [5]) have suggested that the return-stroke speed should increase with increasing peak current. If such relationship indeed existed, it could be used in relating return-stroke peak current to the electric potential of the preceding leader and estimating the lightning striking distance (e.g., Hileman, 1999 [6], pp. 221-222). Further, return-stroke speed is a parameter in the models used in evaluating lightning-induced effects in power and communication lines (e.g., Rachidi et al., 1996 [7]). Finally, an explicit or implicit assumption of the return-stroke speed is involved in inferring lightning currents from remotely measured electric and magnetic fields (e.g., Norinder and Dahle, 1945 [8]; Uman and McLain, 1970b [9]; Uman et al., 1973a, b [10, 11]; Dulzon and Rakov, 1980 [12]; Krider et al., 1996 [13]; Cummins et al., 1998 [14] ; Rakov, 2005 [15]). It is known that the return-stroke speed may vary along the lightning channel. As a result, optical speed measurements along the entire channel are not necessarily representative of the speed within the bottom 100 m or so, that is, at early times when the peaks of the channel-base current and of remote electric and magnetic fields (and of their derivatives) are formed.

In this review, the available experimental data on return-stroke speed for both natural and rocket-triggered negative lightning will be presented. Data for both the entire visible part of the channel and the bottom 100 m or so will be discussed. Limited measurements of return-stroke speed for positive lightning will be considered. It will be shown that the often assumed relationship between the return-stroke speed and peak current is generally not supported by experimental data. Reasons for the return-stroke speed being lower than the speed of light will be discussed.

2. RETURN-STROKE SPEED AVERAGED OVER THE VISIBLE PART OF THE CHANNEL

2.1 Negative lightning

Schonland et al. (1935) [16] found that the first return stroke speed at the channel base was typically near 1 x 10^8 m/s, and at the top of the main channel it was typically near 5 x 10^7 m/s. A summary of more

Submitted: 20/04/2006 Journal of Lightning Research Accepted: 30/10/2006

recently measured return-stroke speeds averaged over the lowest some hundreds of meters of the channel for both natural and rocket-triggered lightning is given in Table 1. In natural lightning, the two-dimensional return-stroke speed (for both first and subsequent strokes combined) was reported by Idone and Orville (1982) [3] from streak-camera measurements to vary from 2.9 x 10^7 to 2.4 x 10^8 m/s, almost an order of magnitude. The sample of Idone and Orville (1982) [3] includes speeds for 17 first and 46 subsequent return strokes, with the mean values within about 1.3 km being 9.6 x 10^7 m/s and 1.2 x 10^8 m/s, respectively. Boyle and Orville (1976) [17] reported return-stroke speeds for 12 strokes varying from 2.0 x 10^7 to 1.2 x 10^8 m/s. A similar wide speed range for natural lightning was found from photoelectric measurements by Mach and Rust (1989a, Fig. 13) [18]. The more recently measured return-stroke speeds presented in Table 1 are generally higher than the earlier results of Schonland et al. (1935) [16], probably due in part to the fact that the recent measurements were made closer to the ground where the return-stroke speed tends to be higher.

In triggered lightning, the return-stroke speed range was found to be 6.7 x 10^7 to 1.7 x 10^8 m/s from streak-camera measurements (three-dimensional speed) (Idone et al. 1984) [20] and 6 x 10^7 to 1.6 x 10^8 m/s from photoelectric measurements in the lowest channel section longer than 500 m ("long-channel" two-dimensional speed) (Mach and Rust, 1989a, Figs. 8 and 14) [18]. Accompanying photoelectric measurements in channel sections less than 500 in length ("short-channel" two-dimensional speed) resulted in a somewhat wider range of speeds of 6 x 10^7 to 2 x 10^8 m/s (see Fig. 8 of Mach and Rust (1989a) [18]). From earlier photoelectric measurements, Hubert and Mouget (1981) [19] reported a three-dimensional return-stroke speed range of 4.5 x 10^7 to 1.7 x 10^8 m/s.

2.2. Positive lightning

Mach and Rust (1993) [23], from photoelectric measurements, reported on two-dimensional propagation speeds for 7 positive and 26 negative natural-lightning return strokes. They presented their speed measurements in two groups (similar to speed measurements of Mach and Rust (1989a) [18]

TABLE 1. SUMMARY OF MEASURED RETURN STROKE SPEEDS IN NATURAL AND TRIGGERED NEGATIVE LIGHTNING. ADAPTED FROM RAKOV ET AL. (1992b) [35].

Reference	Min. Speed, m/s	Max. Speed m/s	Mean Speed, m/s	St. Dev. m/s	Sample Size	Comments
Natural Lightning						
Boyle and Orville (1976) [17]	2.0 x 10^7	1.2 x 10^8	0.71 x 10^8	2.6 x 10^7	12	Streak camera, 2-D speed
Idone and Orville (1982) [3]	2.9 x 10^7	2.4 x 10^8	1.1 x 10^8	4.7 x 10^7	63	Streak camera, 2-D speed
Mach and Rust (1989a, Fig. 7) [18]	2.0 x 10^7 8.0 x 10^7	2.6 x 10^8 >2.8 x 10^8	1.3±0.3 x 10^8 1.9±0.7 x 10^8	5 x 10^7 7 x 10^7	54 43	Long channel Short channel (Photoelectric, 2-D)
Triggered Lightning						
Hubert and Mouget (1981) [19]	4.5 x 10^7	1.7 x 10^8	9.9 x 10^7	4.1 x 10^7	13	Photoelectric, 3-D speed
Idone et al. (1984) [20]	6.7 x 10^7	1.7 x 10^8	1.2 x 10^8	2.7 x 10^7	56	Streak camera, 3-D speed
Willett et al. (1988) [21]	1.0 x 10^8	1.5 x 10^8	1.2 x 10^8	1.6 x 10^7	9	Streak camera, 2-D speed
Willett et al. (1989a) [22]	1.2 x 10^8	1.9 x 10^8	1.5 x 10^8	1.7 x 10^7	18	Streak camera, 2-D speed
Mach and Rust (1989a, Fig. 8) [18]	6.0 x 10^7 6.0 x 10^7	1.6 x 10^8 2.0 x 10^8	1.2±0.3 x10^8 1.4±0.4 x10^8	2 x 10^7 4 x 10^7	40 39	Long channel Short channel (Photoelectric, 2-D)

discussed above): one included values averaged over channel segments less than 500 m (four positive flashes were analyzed over segments 332 to 433 m long) and the other included values averaged over channel segments greater than 500 m (seven positive flashes were analyzed over segments 569 m to 2300 m long). For the "short-segment" group, Mach and Rust (1993) [23] found an average speed of 0.8 x 10^8 m/s for positive return strokes and 1.7 x 10^8 m/s for negative return strokes.

Two-dimensional measurements of positive return-stroke speed were also reported by Idone et al. (1987) [24] for one positive return stroke that was part of an eight-stroke rocket-triggered lightning flash in Florida (KSC), the other seven strokes being negative, and by Nakano et al. (1987, 1988) [25, 26] for one natural positive lightning stroke in winter in Japan. Idone et al.'s (1987) [24] measurements yielded a value about 10^8 m/s for the positive stroke and values ranging from 0.9 x 10^8 to 1.6 x 10^8 m/s for the seven negative strokes, all averaged over a channel segment of 850 m in length near ground. Nakano et al. reported a significant speed variation with height, discussed in Section 4.

3. RETURN-STROKE SPEED IN THE LOWEST 100 M OF THE CHANNEL

We now review the optical measurements of lightning return-stroke speed within the bottom 100 m or so of the channel. This channel segment corresponds to the time when the initial peaks of the channel-base current (the typical 10-90% risetime of subsequent return-stroke currents is 0.3 to 0.6 μs (see Fisher et al., 1993, Fig. 6) [27] are formed. It is this value of speed that is needed for estimating the current peak from measured radiation field peak and distance, using simple return-stroke models (e.g., Rakov and Uman, 1998) [28].

Wang et al. (1999c) [29] reported on two-dimensional speed profiles within 400 m of the ground for two return strokes in triggered lightning. These speed profiles, reproduced in Fig. 1, were obtained in 1997 at Camp Blanding, Florida, using the digital optical imaging system ALPS having a time resolution of 100 ns and a spatial resolution of 30 m. The return-stroke speeds within the bottom 60 m of the channel were found to be 1.3 x 10^8 and 1.5 x 10^8 m/s. Wang et al. (1999a) [30], who studied the attachment process in triggered lightning, reported on one value of return-stroke speed near two-thirds of the speed of light and one value near the speed of light. However, these two values, based on ALPS measurements within less than 50 m above the junction point between the descending dart leader and an upward connecting leader, are rough estimates (particularly the latter value estimated within less than 30 m of the attachment point), inferior to the measurements reported by Wang et al. (1999c) [29].

Weidman (1998) [31], from photoelectric measurements in 1996 at Camp Blanding, Florida, and in 1996-1998 in Tucson, Arizona, reported mean return-stroke speeds in the lowest 100 m of the lightning channel of 8.8 x 10^7 and 7.8 x 10^7 m/s for 14 triggered and 9 natural lightning strokes, respectively. Histograms of return-stroke speed measurements reported by Weidman (1998) [31] are reproduced in Fig. 2.

Doug Jordan (personal communication, 1998) [32], used a vertical array of photodiodes at Camp Blanding, Florida, to measure the optical output of the lightning channel at four heights within 50 m of the lightning attachment point. Successful measurements were obtained for one triggered-lightning stroke at a distance of 140 m. At this distance, each photodiode imaged approximately 0.5 m of lightning channel. The speed of the return-stroke optical front averaged over a 12-m height range centered at 30 m above the lightning attachment point was approximately one-third of the speed of light.

Olsen et al. (2004) [33], using a vertical array of four photodiodes, estimated return-stroke speeds in the bottom 170 m of the channel for five strokes in one flash triggered at Camp Blanding, Florida, in 2003. Light intensity (in millivolts at the input of the oscilloscpoe) waveforms for one of the strokes at four different heights, 7, 63, 117, and 170 m, above the lightning termination point are shown in Fig. 3. Return-stroke speed values estimated tracking the 20% of the peak point on the front of return-stroke light pulse for three different segments of the lightning channel, 7 to 63 m, 63 to 117 m, and 117 to 170 m, are summarized in Table 2. For the lowest channel segment, 7 to 63 m, the speed values are 1.2 to 1.3 x 10^8 m/s. For higher channel segments, speed values are generally higher, varying from 1.6 to 1.8 x 10^8 m/s over the 63 to 117 m segment and from 1.2 to 1.7 x 10^8 m/s over the 117 to 170 m segment. The speed tends to be

Volume 1, 2007, pages 80 - 89. © JOLR 2006 (www.jolr.org)

higher if a point lower than 20% of the peak is tracked. On the other hand, some speed values obtained tracking the 10% point were significantly affected by noise. Speeds over the channel segment from 7 to 117 m estimated using the so-called slope-intercept method, which probably yielded the upper speed bound, ranged from 1.8 to 2.3 x 10^8 m/s. For comparison, the speed range found for the same channel segment but tracking the 20% point was 1.4 to 1.5 x 10^8 m/s.

Thus, based on all the pertinent measurements available to date, the return-stroke speed in the bottom few tens of meters to 100 m of the lightning channel, that is, at the time when the initial peak of the channel-base current is formed is typically one-third to two-thirds of the speed of light.

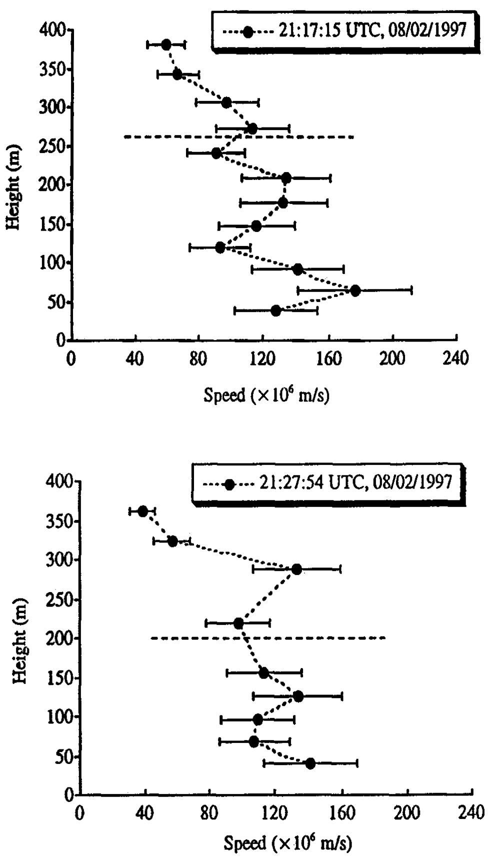

Figure 1. Propagation speed versus height for two return strokes in two different lightning flashes triggered at Camp Blanding, Florida. Each solid circle represents a value of speed averaged over a 60-m section of the channel. For these two events, the return-stroke speeds within the bottom 60 m or so of the channel are 1.3 x 10^8 and 1.5 x10^8 m/s, with a potential error of less than 20%. Adapted from Wang et al. (1999c) [29].

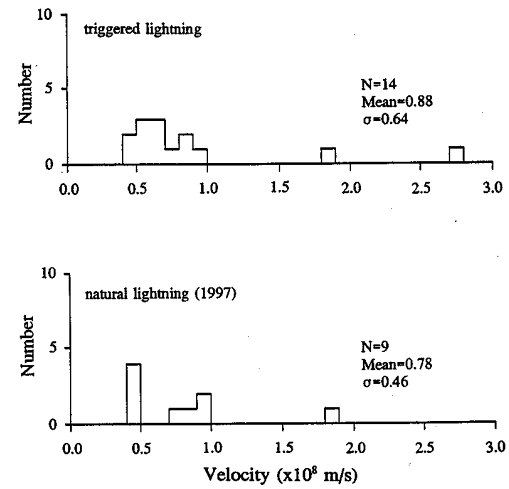

Figure 2. Measurements of triggered and natural lightning return-stroke speeds in the lowest 100 m of lightning channel. Mean values are 8.8×10^7 and 7.8×10^7 m/s for triggered and natural lightning, respectively. Adapted from Weidman (1998) [31].

TABLE 2. RETURN-STROKE SPEEDS (x10^8 M/S) ESTIMATED TRACKING THE 20% POINT ON THE LIGHT-PULSE FRONT FOR TRIGGERED LIGHTNING FLASH F0336 (OLSEN ET AL., 2004) [33].

Height range, m	Stroke order					Estimated error, %
	1	2	4	5	6	
7 – 63	1.3	1.2	1.2	1.2	1.2	10
63 – 117	1.6	1.8	1.8	1.8	1.6	15
117 – 170	1.7	1.2	1.5	1.6	1.5	21

No data are available for stroke 3.

4 VARIATION OF RETURN-STROKE SPEED WITH HEIGHT

Idone and Orville (1982) [3] found that the negative return-stroke speed usually decreases with height, for both first and subsequent strokes, by 25% or more over the visible part of channel relative to the speed near ground. In computing lightning electromagnetic fields, the return-stroke speed is often assumed to be constant (particularly for subsequent strokes) over the radiating channel section (e.g., Rakov and Uman, 1998) [28]. Gorin (1985) [1] suggested a non-monotonic return-stroke speed profile. According to his nonlinear distributed-circuit model for a first stroke, the speed initially increases to its maximum over a channel length of the order of some hundreds of meters and decreases thereafter. The initial speed increase in Gorin's (1985) [1] model is associated with the so-called break-through phase (also called the final jump or switch-closing phase) thought to be responsible for the formation of the initial rising portion of the return-stroke current pulse (see also, Rakov and Dulzon 1991 [34]; Rakov et al. 1992b [35]). Srivastava (1966) [36] proposed, based on the experimental data published by Schonland (1956) [37], a bi-exponential expression for the first return-stroke speed as a function of time, according to which the speed rises from zero to its peak and falls off afterwards. Variation of the return-stroke speed with height for triggered-lightning strokes 2, 4, 5, and 6 in Table 2 suggests that the speed indeed initially increases and then decreases with increasing height. The observed trend for the return stroke speed to initially increase with height (Srivastava, 1966 [36]; Olsen et al., 2004 [33]) apparently argues against some model-based predictions (e.g., Baum, 1990 [38]; Thottappillil et al., 2001 [39]) that the speed may be equal to the speed of light near the channel base. More experimental data on the attachment process and on the early stages of the return-stroke process are needed.

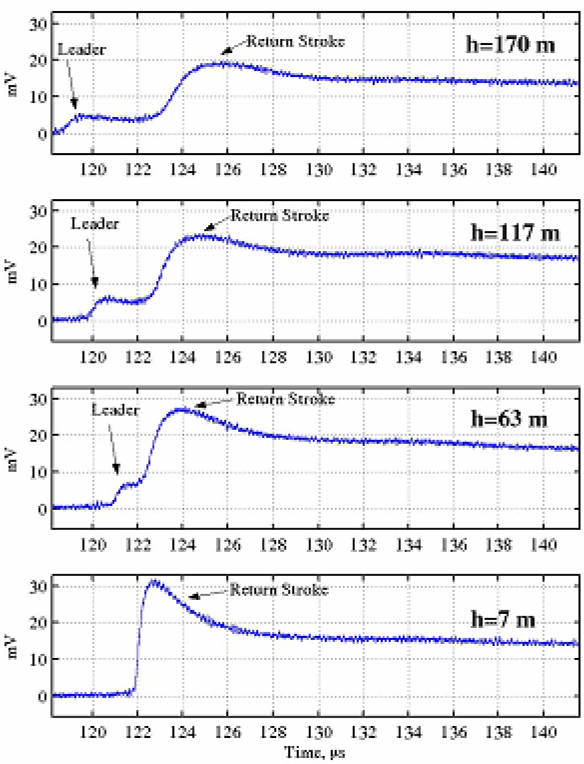

Figure 3. Optical intensity (in millivolts at the input of the oscilloscope) vs. time waveforms at four different heights, 7, 63, 117, and 170 m, above the lightning termination point for stroke 1 in flash F0336. Adapted from Olsen et al. (2004) [33].

We now briefly discuss observed variations of speed with height for return strokes in positive lightning. Nakano et al. (1987, 1988) [25, 26] reported a significant decrease in two-dimensional speed with increasing height over a 180-m section of the channel, from 2 x 10^8 m/s at 310 m to 0.3 x 10^8 m/s at 490 m. On the other hand, Mach and Rust (1993) [23] found no significant speed change with height for positive return strokes. Clearly, more data on positive return-stroke speed are needed.

5 RETURN-STROKE SPEED VS. PEAK CURRENT

Some researchers (e.g., Lundholm 1957 [4]; Wagner 1963 [5]) have suggested that the return-stroke speed should increase with increasing peak current. This suggestion, implying that the return-stroke wave is highly non-linear so that the wave speed is a function of wave amplitude, appears to be not supported by experimental data. In particular, Willett et al. (1989a) [22] and Mach and Rust (1989a) [18] found a lack of correlation between the return-stroke propagation speed and the return-stroke peak current in triggered lightning in Florida. Their data are presented in Fig. 4, where the return-stroke peak current varies from about 6 to 43 kA. Idone et al. (1984) [20] did observe "a nonlinear relationship" between these two parameters in triggered lightning in New Mexico, but it disappears if one excludes the relatively small events that are characterized by return-stroke peak currents less than 6-7 kA in order to make Idone et al.'s (1984) [20] sample similar to those of Willett et al. (1989a) [22] and Mach and Rust (1989a) [18]. If there is a relationship between the return-stroke speed and return-stroke current, as might be expected on physical grounds, it is influenced by many factors and, as a result, characterized by a large scatter. Rakov (1998) [40] inferred, from a comparison of the behavior of traveling waves on a lossy transmission line and the observed characteristics of the lightning return stroke process, that the return stroke is similar to a "classical" (linear) traveling wave. Ionization does occur during the return-stroke process but has a relatively small effect on the wave propagation characteristics, which, according to Rakov (1998) [40], are primarily determined by the transmission-line parameters ahead of the front as opposed to being determined by the wave magnitude. As a result, the return-stroke wave suffers appreciable attenuation and dispersion. Thus, the often assumed relationship (e.g., Chowdhuri et al., 2005, Fig. 4) [41] between the return-stroke speed and peak current is generally not supported by experimental data.

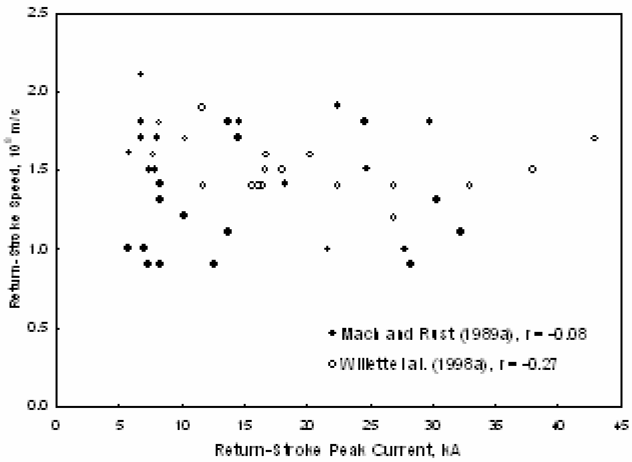

Figure 4. Return-stroke speed vs. peak current for 29 triggered-lightning strokes observed at the Kennedy Space Center (KSC), Florida, in 1986 and reported by Mach and Rust (1989a) [18] and 18 triggered-lightning strokes from the 1987 KSC experiments reported by Willett et al. (1989a) [22]. Peak current shown in the scatter plot as 38 kA may be an underestimate. Note that the linear correlation coefficients (r) for both data sets are low and negative, not in support of the often assumed relationship between these two lightning parameters.

6 WHY IS THE RETURN STROKE SPEED LOWER THAN THE SPEED OF LIGHT?

It is well known that the propagation speed of waves on a uniform, linear, and lossless transmission line surrounded by air is equal to the speed of light, $c = (LC)^{-1/2} = (\mu_0\varepsilon_0)^{-1/2}$. However, a vertical lightning channel (leaving aside the general validity of its transmission-line approximation, discussed, for example, by Rakov and Uman (1998) [28]) is a non-uniform, nonlinear, and lossy transmission line. Indeed, its inductance and capacitance per unit length vary with height above ground, so that its characteristic impedance, $(L/C)^{1/2}$, increases with height. Thus, a return-stroke wave will suffer dispersion even in the absence of losses. Further, charge cannot be confined within the narrow channel core carrying the longitudinal current; it is pushed outward via radial electrical breakdown forming the so-called corona sheath. Finally, channel resistance per unit length ahead of the return-stroke front is relatively high (causing wave attenuation and additional dispersion) and decreases by two orders of magnitude or so behind the front.

Two primary reasons for the lightning return-stroke speed, v, being lower than the speed of light are: (1) the effect of radial corona surrounding the narrow channel core (the radius of the charge-containing corona sheath is considerably larger than the radius of the core carrying the longitudinal channel current, so that $(LC)^{-1/2} < (\mu_0\varepsilon_0)^{-1/2} = c$, and hence $v < c$), and (2) the ohmic losses in the channel core that are sometimes represented in lightning models by the distributed constant or current-dependent series resistance of the channel.

The corona effect explanation is based on the following assumptions:

(a) The longitudinal channel current flows only in the channel core, because the core conductivity, of the order of 10^4 S/m, is much higher than the corona sheath conductivity, of the order of 10^{-6}–10^{-5} S/m (Maslowski and Rakov, 2006) [42]. The longitudinal resistance of channel core is expected to be about 3.5 Ω/m (Rakov, 1998) [40], while that of a 2-m radius corona sheath should be of the order of kiloohms to tens of kiloohms per meter. The corona current is radial (transverse) and hence cannot influence the inductance of the channel.

(b) The radial voltage drop across the corona sheath is negligible compared to the potential of the lightning channel. According to Gorin (1985) [1], the average radial electric field within the corona sheath is about 0.5–1.0 MV/m, which results in a radial voltage drop of 1–2 MV across a 2-m radius corona sheath (expected for subsequent return strokes). The typical channel potential (relative to reference ground) is about 10–15 MV for subsequent strokes (Rakov, 1998 [40]; Kodali et al., 2005 [43]). For first strokes, both the corona sheath radius and channel potential are expected to be larger, so that about an order of magnitude difference between the corona sheath voltage drop and channel potential found for subsequent strokes should hold also for first strokes.

(c) The magnetic field due to the longitudinal current in channel core is not significantly influenced by the corona sheath. For corona sheath conductivity of 10^{-6} –10^{-5} S/m and frequency of 1 MHz, the field penetration depth is 160 to 500 m (and more for lower frequencies), which is much larger than expected radii of corona sheath of a few meters.

In summary, the corona sheath conductivity is low enough to neglect both the longitudinal current through the sheath and shielding effect of the sheath, but high enough to disregard the radial voltage drop across the sheath.

Theethayi and Cooray (2005) [44], using a linear distributed-circuit model of the lightning return stroke, examined the influence of constant shunt conductance on characteristics of waves propagating along the lightning channel. It follows from results of their analysis that either neglecting the weakly conducting corona sheath (ignoring the radial breakdown on the lateral surface of channel core) or extending it to infinity (allowing the radial breakdown to occupy the entire upper half space), results in a propagation speed for the highest frequency components that is essentially equal to the speed of light. Predictions of more realistic non-linear distributed-circuit models are discussed below.

Ohmic losses in the channel cannot be neglected at frequencies, 100 kHz – 1 MHz, expected in the return-stroke front near ground. Indeed, the expected resistance per unit length of the dart-leader channel which is traversed by a subsequent return stroke is about 3.5 Ω/m, which is comparable to the inductive reactance per unit channel length at frequencies ranging from 100 kHz to 1 MHz (Rakov, 1998) [40]. As seen in Table 3, for these frequencies, the characteristic impedance of the dart-leader channel is about 0.5–1 kΩ, and the propagation speed is 2–2.5 x 10^8 m/s. As the return-stroke wave propagates upward, the dominant frequency of the wavefront decreases, with the lower frequencies being characterized by lower propagation speeds.

TABLE 3. CHARACTERISTICS OF PRE-RETURN–STROKE CHANNEL THAT IS FORMED BY DART LEADER AND HAS R = 3.5 Ω/M, L = 2.3 μH/M, AND C = 7 PF/M, AS A FUNCTION OF FREQUENCY, f. ADAPTED FROM RAKOV (1998) [40].

f, kHz	Z_o, kΩ	v_p, m/s	v_g, m/s	v_g^*, m/s	δ, km
0.01	89π-45°	2.3 x 10^6	4.5 x 10^6	2.3 x 10^6	36
0.1	28π-45°	7.2 x 10^6	1.4 x 10^7	7.2 x 10^6	11
1	8.9π-45°	2.3 x 10^7	4.5 x 10^7	2.3 x 10^7	3.6
10	2.8π-44°	7.0 x 10^7	1.3 x 10^8	7.6 x 10^7	1.2
100	0.93π-34°	1.9 x 10^8	2.7 x 10^8	2.5 x 10^8	0.44
10^3	0.58π-6.8°	2.5 x 10^8	2.5 x 10^8	2.5 x 10^8	0.33
10^4	0.57π-0.69°	2.5 x 10^8	2.5 x 10^8	2.5 x 10^8	0.33

Z_o is the characteristic impedance, v_p is the phase velocity, v_g and v_g^* are two estimates of group velocity, and δ is the attenuation distance.

Higher-frequency current components are expected to propagate at speeds close to $(LC)^{-1/2}$, while lower-frequency components should be significantly affected by the distributed resistance. As a result, the return-stroke current waveform will suffer dispersion. In distributed-circuit models with non-linear resistance per unit length, the "running away" higher-frequency components should be attenuated more significantly than slower propagating lower-frequency components. As a result, the overall current waveform will be composed of a weak "precursor" and a "main disturbance" propagating at different speeds. Indeed, such a "precursor" current propagating at $(LC)^{-1/2}$ was observed by Gorin and Markin (1975) [45], Bazelyan et al. (1978) [46], Gorin (1985) [1], and Bazelyan and Raizer (2000) [47], who used nonlinear distributed circuit models with resistance per unit length varying as a function of charge (time integral of current) transferred through a given channel section. However, this "precursor" was dwarfed by the "main disturbance" propagating at a speed considerably lower than $(LC)^{-1/2}$. The magnitude of the "precursor" current computed by Bazelyan et al. (1978) [46] was a few amperes versus tens of kilamperes for the "main disturbance". It is this "main disturbance", as opposed to the "precursor", that serves to both (1) transform the relatively high resistance leader channel to relatively low resistance return-stroke channel and (2) neutralize leader charge on the channel. Therefore, the "main disturbance" constitutes the return stroke proper.

Reasons for the return-stroke speed being necessarily lower than the speed of light given above are based on the assumptions that the associated electromagnetic field structure is TEM. There are, however, lightning return stroke models of electromagnetic type (see Baba and Rakov (2006) [48] for a recent review) that are based on Maxwell's equations and do not require the TEM assumption. Such models predict (e.g., Baba and Rakov, 2005 [49]) that waves on vertical conductors above ground suffer dispersion and appear to propagate (at least near ground surface) at a speed that is slightly lower than the speed of light, even in the absence of corona (and ohmic losses). This effect can be explained considering such a conductor as a non-uniform transmission line whose characteristic impedance increases with height, particularly near the ground surface. As a result, the distributed impedance discontinuity will cause distributed reflections that will influence the effective wave propagation speed.

Interestingly, in electromagnetic models, which represent lightning channel as a vertical monople antenna, the distributed (constant) resistance, typically 1 Ω/m or less, apparently has little effect on propagation speed compared to either changing parameters of surrounding medium (Moini et al., 2000) [50] or introducing reactive loading of the channel (Baba and Ishii, 2001, 2003) [51, 52]. Further, Visacro and Silveira (2004) [53], who used a hybrid model that employs both antenna and circuit theory concepts, found that the wave propagation speed is influenced more by the simulated corona sheath than by distributed (constant) resistance ranging from 0.035 to 1 Ω/m. On the other hand, Gorin and Markin (1975) [45], Bazelyan et al. (1978) [46], Gorin (1985) [1], and Bazelyan and Raizer (2000) [47] reported that, in their uniform, nonlinear distributed-circuit models, the return-stroke speed was significantly influenced by both the corona effect and nonlinear distributed resistance. The initial value of the latter was 10 Ω/m or more, considerably larger than the constant resistance values employed in the electromagnetic or hybrid models discussed above.

7 SUMMARY

The average propagation speed of a negative return stroke (first or subsequent) below the lower cloud boundary is typically between one-third and one-half of the speed of light. For positive return strokes, the speed is of the order of 10^8 m/s, although data are very limited. The negative return-stroke speed within the bottom 100 m or so is expected to be between one-third and two-thirds of the speed of light. The negative return stroke speed usually decreases with height for both first and subsequent strokes. There exists some experimental evidence that the negative return stroke speed may vary non-monotonically along the lightning channel, initially increasing and then decreasing with increasing height. There are contradicting data regarding the variation of positive return stroke speed with height. The often assumed relationship between the return-stroke speed and peak current is generally not supported by experimental data.

8 ACKNOWLEDGEMENT

This work was supported in part by NSF grant ATM-0346164. The author would like to thank V. Cooray, G. Maslowski, and N. Theethayi for helpful discussions.

9 REFERENCES

1. Gorin, B.N. 1985. Mathematical modeling of the lightning return stroke. Elektrichestvo, 4,10-16.
2. Jayakumar, V., Rakov, V.A., Miki, M., Uman, M.A., Schnetzer, G.H., and Rambo, K.J. 2006. Estimation of input energy in rocket-triggered lightning, Geophys. Res. Lett., 33, L05702, doi:10.1029/2005GL025141.
3. Idone, V.P., and Orville, R.E. 1982. Lightning return stroke velocities in the Thunderstorm Research International Program (TRIP). J. Geophys. Res. 87: 4903-15.
4. Lundholm, R. 1957. Induced overvoltage-surges on transmission lines and their bearing on the lightning performance at medium voltage networks. Trans. Chalmers Univ. Technol. No. 120, 117 p.
5. Wagner, C.F. 1963. Relation between stroke current and velocity of the return stroke. AIEE Trans. Power Appar. Syst. 82: 609-17.
6. Hileman, A.R. 1999. Insulation coordination for power systems, 767 p., New York: Marcel Dekker.
7. Rachidi, F., Nucci, C.A. Ianoz, M., and Mazzetti, C. 1996. Influence of a lossy ground on lightning-induced voltages on overhead lines. IEEE Trans. Electromagn. Compat. 38: 250-64.
8. Norinder, H., and Dahle, O. 1945. Measurements by frame aerials of current variations in lightning discharges. Arkiv. Mat. Astron. Fysik 32A: 1-70.
9. Uman, M.A., and McLain, D.K. 1970b. Lightning return stroke current from magnetic and radiation field measurements. J. Geophys. Res. 75: 5143-7.
10. Uman, M.A., McLain, D.K., Fisher, R.J., and Krider, E.P. 1973a. Electric field intensity of lightning return stroke. J. Geophys. Res. 78: 3523-9.
11. Uman, M.A., McLain, D.K., Fisher, R.J., and Krider, E.P. 1973b. Currents in Florida lightning return strokes. J. Geophys. Res. 78: 3530-7.
12. Dulzon, A.A., and Rakov, V.A. 1980. Estimation of errors in lightning peak current measurements by frame aerials (in Russian). Izv. VUZov SSSR, ser. Energetika 11: 101-4.
13. Krider, E.P., Leteinturier, C., Willett, J.C. 1996. Submicrosecond fields radiated during the onset of first return strokes in cloud-to-ground lightning. J. Geophys. Res. 101: 1589-97.
14. Cummins, K.L., Krider, E.P., and Malone, M.D. 1998b. The U.S. National Lightning Detection Network and applications of cloud-to-ground lightning data by electric power utilities. IEEE Trans. on Electromagn. Compat. 40 (II): 465-80.

15. Rakov, V.A. 2005. Evaluation of the performance characteristics of lightning locating systems using rocket-triggered lightning, in Proc. of Int. Symp. on Lightning Protection (VIII SIPDA), Sao Paulo, Brazil, Nov. 21-25, 2005, 697-715.
16. Schonland, B.F.J., Malan, D.J., and Collens, H. 1935. Progressive Lightning II. Proc. Roy. Soc. (London) A152: 595-625.
17. Boyle, J.S., and Orville, R.E. 1976. Return stroke velocity measurements in multistroke lightning flashes. J. Geophys. Res. 81: 4461-6.
18. Mach, D.M., and Rust, W.D. 1989a. Photoelectric return-stroke velocity and peak current estimates in natural and triggered lightning. J. Geophys. Res. 94: 13,237-47.
19. Hubert, P., and Mouget, G. 1981. Return stroke velocity measurements in two triggered lightning flashes. J. Geophys. Res. 86: 5253-61.
20. Idone, V.P., Orville, R.E., Hubert, P., Barret, L., and Eybert-Berard, A. 1984. Correlated observations of three triggered lightning flashes. J. Geophys. Res. 89: 1385-94.
21. Willett, J.C., Idone, V.P., Orville, R.E., Leteinturier, C., Eybert-Berard, A., Barret, L., and Krider, E.P. 1988. An experimental test of the "transmission-line model" of electromagnetic radiation from triggered lightning return strokes. J. Geophys. Res. 93: 3867-78.
22. Willett, J.C., Bailey, J.C., Idone, V.P., Eybert-Berard, A., and Barret, L. 1989a. Submicrosecond intercomparison of radiation fields and currents in triggered lightning return strokes based on the transmission-line model. J. Geophys. Res. 94: 13,275-86.
23. Mach, D.M, and Rust, W.D. 1993. Two-dimensional velocity, optical risetime, and peak current estimates for natural positive lightning return strokes. J. Geophys. Res. 98: 2635-8.
24. Idone, V.P., Orville, R.E., Mach, D.M., and Rust, W.D. 1987. The propagation speed of a positive lightning return stroke. Geophys. Res. Lett. 14: 1150-3.
25. Nakano, M., Nagatani, M., Nakada, H., Takeuti, T., and Kawasaki, Z. 1987. Measurements of the velocity change of a lightning return stroke with height. Res. Lett. Atmos. Electr. 7: 25-8.
26. Nakano, M., Nagatani, M., Nakada, H., Takeuti, T., and Kawasaki, Z. 1988. Measurements of the velocity change of a lightning return stroke with height. In Proc. 1988 Int. Aerospace and Ground Conf. on Lightning and Static Electricity, Oklahoma City, Oklahoma, pp. 84-86.
27. Fisher, R.J., Schnetzer, G.H., Thottappillil, R., Rakov, V.A., Uman, M.A., and Goldberg, J.D. 1993. Parameters of triggered-lightning flashes in Florida and Alabama. J. Geophys. Res. 98: 22,887-902.
28. Rakov, V.A., and Uman, M.A. 1998. Review and evaluation of lightning return stroke models including some aspects of their application. IEEE Trans. on Electromagn. Compat. 40: 403-26.
29. Wang, D., Takagi, N., Watanabe, T., Rakov, V.A., and Uman, M.A. 1999c. Observed leader and return-stroke propagation characteristics in the bottom 400 m of the rocket triggered lightning channel. J. Geophys. Res. 104: 14,369-76.
30. Wang, D., Rakov, V.A., Uman, M.A., Takagi, N., Watanabe, T., Crawford, D.E., Rambo, K.J., Schnetzer, G.H., Fisher, R.J., and Kawasaki, Z.-I. 1999a. Attachment process in rocket-triggered lightning strokes. J. Geophys. Res. 104: 2143-50.
31. Weidman, C.D. 1998. Lightning return stroke velocities near channel base. In Proc. 1998 Int. Lightning Detection Conf., GAI, Tucson, Arizona, 25 p.
32. Jordan, D.M. 1998. Personal communication.
33. Olsen, R.C., Jordan, D.M., Rakov, V.A., Uman, M.A., and Grimes, N. 2004. Observed two-dimensional return stroke propagation speeds in the bottom 170 m of a rocket-triggered lightning channel. Geophys. Res. Lett., 31, L16107, doi: 10.1029/2004GL020187.
34. Rakov, V.A., and Dulzon, A.A. 1991. A modified transmission line model for lightning return stroke field calculations. In Proc. 9th Int. Zurich. Symp. on Electromagnetic Compatibility, Zurich, Switzerland, pp. 229-35.
35. Rakov, V.A., Thottappillil, R., and Uman, M.A. 1992b. On the empirical formula of Willett et al. relating lightning return-stroke peak current and peak electric field. J. Geophys. Res. 97: 11,527-33.
36. Srivastava, K.M.L. 1966. Return stroke velocity of a lightning discharge. J. Geophys. Res. 71: 1283-6.
37. Schonland, B.F.J. 1956. The lightning discharge. In Handbuch der Physik 22: 576-628, Berlin, Springer-Verlag.
38. Baum, C.E. 1990. Return-stroke initiation. In Lightning Electromagnetics, pp. 101-14, New York: Hemisphere Publishing Corp.

Volume 1, 2007, pages 80 - 89. © JOLR 2006 (www.jolr.org)

39. Thottappillil, R., Schoene, J., and Uman, M. A. 2001. Return stroke transmission line model for stroke speed near and equal that of light, Geophys. Res. Lett., Vol.28, No.18, pp. 3593-3596.
40. Rakov, V.A. 1998. Some inferences on the propagation mechanisms of dart leaders and return strokes. J. Geophys. Res. 103: 1879-87.
41. Chowdhuri, P., et al. 2005. Parameters of lightning strokes: a review. IEEE Trans. on Power Delivery, Vol. 20, No. 1, pp. 346-358.
42. Maslowski, G., and Rakov, V.A. 2006. A study of the lightning-channel corona sheath, J. Geophys. Res., 111, D14110, doi:10.1029/2005JD006858.
43. Kodali, V., Rakov, V.A., Uman, M.A., Rambo, K.J., Schnetzer, G.H., Schoene, J., and Jerauld, J. 2005. Triggered-lightning properties inferred from measured currents and very close electric fields, Atmos. Res., vol. 76, issue 1-4, pp. 355-376.
44. Theethayi, N. and Cooray, V. 2005. On the representation of the lightning return stroke process as a current pulse propagating along a transmission line. IEEE Trans. on Power Delivery, Vol. 20, No. 2, pp. 823-837.
45. Gorin, B.N., and Markin, V.I. 1975. Lightning return stroke as a transient process in a distributed system. Trudy ENIN, 43, 114-130.
46. Bazelyan, E.M., Gorin, B.N., and Levitov, V.I. 1978. Physical and Engineering Foundations of Lightning Protection. Gidrometeoizdat, Leningrad, 223 p.
47. Bazelyan, E.M., and Raizer, Yu. P. 2000. Lightning Physics and Lightning Protection, 325 p., Bristol: IOP.
48. Baba, Y., and Rakov, V.A. 2006. Electromagnetic models of the lightning return stroke. J. Geophys. Res., in press.
49. Baba, Y., and Rakov, V.A. 2005. On the mechanism of attenuation of current waves propagating along a vertical perfectly conducting wire above ground: application to lightning, IEEE Trans. on EMC, Vol. 47, No. 3, pp. 521-532.
50. Moini, R., Kordi, B., Rafi, G.Z., and Rakov, V.A. 2000. A new lightning return stroke model based on antenna theory. J. Geophys. Res., 105, 29,693-29,702.
51. Baba, Y. and Ishii, M. 2001. Numerical electromagnetic field analysis of lightning current in tall structures. IEEE Trans. on Power Delivery, Vol. 61, No. 2, pp. 324-328.
52. Baba, Y. and Ishii, M. 2003. Characteristics of electromagnetic return-stroke models, IEEE Trans. Electromagn. Compat., Vol. 45, No. 1, pp. 129-135.
53. Visacro, S., and Silveira, F.H. 2004. Evaluation of current distribution along the lightning discharge channel by a hybrid electromagnetic model. J. Electrostatics, 60, 111-120.