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Attachment process in rocket-triggered lightning strokes

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Abstract. In order to study the lightning attachment process, we have obtained highly resolved (about 100 ns time resolution and about 3.6 m spatial resolution) optical images, electric field measurements, and channel-base current recordings for two dart leader/return-stroke sequences in two lightning flashes triggered using the rocket-and-wire technique at Camp Blanding, Florida. One of these two sequences exhibited an optically discernible upward-propagating discharge that occurred in response to the approaching downward-moving dart leader and connected to this descending leader. This observation provides the first direct evidence of the occurrence of upward connecting discharges in triggered lightning strokes, these strokes being similar to subsequent strokes in natural lightning. The observed upward connecting discharge had a light intensity one order of magnitude lower than its associated downward dart leader, a length of 7-11 m, and a duration of several hundred nanoseconds. The speed of the upward connecting discharge was estimated to be about 2×10^7 m/s, which is comparable to that of the downward dart leader. In both dart leader/return-stroke sequences studied, the return stroke was inferred to start at the point of junction between the downward dart leader and the upward connecting discharge and to propagate in both upward and downward directions. This latter inference provides indirect evidence of the occurrence of upward connecting discharges in both dart leader/return-stroke sequences even though one of these sequences did not have a discernible optical image of such a discharge. The length of the upward connecting discharges (observed in one case and inferred from the height of the return-stroke starting point in the other case) is greater for the event that is characterized by the larger leader electric field change and the higher return-stroke peak current. For the two dart leader/return-stroke sequences studied, the upward connecting discharge lengths are estimated to be 7-11 m and 4-7 m, with the corresponding return-stroke peak currents being 21 kA and 12 kA, and the corresponding leader electric field changes 30 m from the rocket launcher being 56 kV/m and 43 kV/m. Additionally, we note that the downward dart leader light pulse generally exhibits little variation in its 10-90% risetime and peak value over some tens of meters above the return-stroke starting point, while the following return-stroke light pulse shows an appreciable increase in risetime and a decrease in peak value while traversing the same section of the lightning channel. Our findings regarding (1) the initially bidirectional development of return-stroke process and (2) the relatively strong attenuation of the upward moving return-stroke light (and by inference current) pulse over the first some tens of meters of the channel may have important implications for return-stroke modeling.

1. Introduction

When a downward negative stepped leader in natural lightning approaches within some tens of meters of ground, an upward positive connecting discharge is initiated from the ground or from an object on the ground to meet the downward leader. The upward connecting discharge is part of the transition from leader stage to return stroke stage, this transition being termed the lightning attachment process. Since the latter is important for understanding lightning physics and is also fundamental to methods of lightning protection, it has received considerable attention from the early days of lightning research [e.g., *Uman*, 1987, p. 99]. There exist a number of still and high-speed photographs and video records that can be interpreted as containing evidence of the occurrence of an upward connecting discharge, both in first and subsequent strokes [*Berger*, 1967; *Orville and Idone*, 1982; *Idone*, 1990; *Fisher and Schnetzer*, 1991). However, none of these optical records shows an upward propagating leader making contact with the downward moving leader. The attachment process in altitude-triggered lightning, involving a downward negative stepped leader in virgin air, has been recently studied by *Lalande et al.* [1998], but no optical image of the upward connecting discharge was obtained.

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Using a digital optical system with about 100 ns time resolution, we have imaged the attachment process in two dart leader/return-stroke sequences in "classical" rocket-triggered lightning at Camp Blanding, Florida, during the summer of 1997. We have also obtained simultaneous records of the channel-base current and electric fields at several distances (5-500 m) from the channel. Only fields at 30 m are used here. It is the purpose of this paper to present and discuss these correlated records.

2. Instrumentation and Data

Rocket-triggered lightning experiments at Camp Blanding, Florida, have been carried out since 1993, and information on the Camp Blanding lightning research and testing facility is found in papers by *Uman et al.* [1997] and *Rakov et al.* [1998]. The "classical" lightning-triggering technique [e.g., *Rakov et al.*, 1998] involves the use of a small rocket extending a thin grounded wire upward. In the experiments presented here, the triggering wire was made of Kevlar-coated copper with a diameter of 0.2 mm. In the summer of 1997, the high-speed optical imaging system ALPS (Automatic Lightning Progressing Feature Observation System), specifically designed for recording the luminous progression of lightning discharges, was used at Camp Blanding. The initial model of this instrument was designed, constructed, and operated for lightning studies by *Yokoyama et al.* [1990]. The present version of ALPS is similar to the first version, except for an improved image sensor and an improved digitizer that allowed a reduction of the system's size and an increase in its dynamic range. As illustrated in Figure 1, ALPS consists of a conventional camera lens, a pin photodiode array module, amplifiers, a multichannel digitizer, and a personal computer system. A lightning image produced by the lens is first converted to electrical signals by the photodiode array which is mounted in the focal plane of the lens. These signals are then amplified, digitized, and recorded by the personal computer system. The photodiode array module used in the present system consists of 256 (16×16) pin photodiodes, each 1.3×1.3 mm^2 in size, with separation of 1.5 mm between the centers of individual photodiodes. Each of the photodiodes operates at wavelengths from 400 to 1000 nm with a response time of less than 3 ns. The photodiodes are connected, via 256 identical nonlinear amplifiers characterized by amplitude compression of the larger signals, to 256 identical synchronized 8-bit digitizers. The dynamic range of the system is 60 dB and the digitizers are synchronized within better than 10 ns. The ALPS can operate at a time resolution (interframe interval) from 100 ns to 50 ms with either internal or external trigger and can record up to 16,000 frames for each event with up to 16,000 pretrigger frames. The effective exposure time of each frame is much less than the shortest interframe interval of 100 ns. The interframe interval used in this study was 100 ns, and the resulting total recording time per event was 1.6 ms with a 480 μs pretrigger interval. The ALPS was installed 250 m from the rocket launcher and viewed an effective area of 50×50 m^2 in a vertical plane just above the tip of a grounded metallic rod mounted on the rocket launcher, yielding a spatial resolution of about 3.6 m.

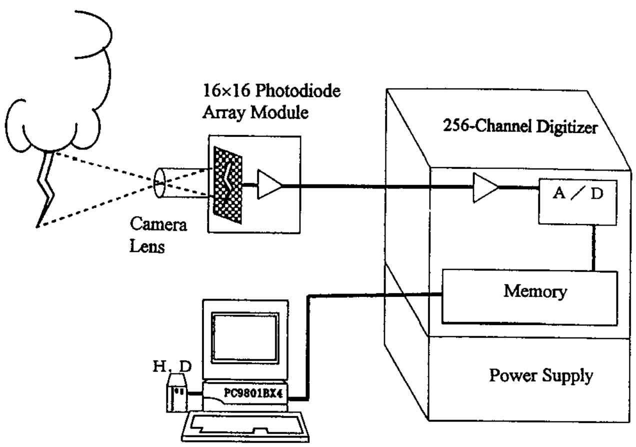


Figure 1. A schematic diagram of the high-speed optical imaging system ALPS.

Using computer graphics software, we were able to view the development of the luminous lightning channels on a computer monitor screen. Generally, this kind of display is sufficient to observe the direction and rate of extension of lightning leader and return stroke channels. For the present detailed study, this data display is insufficient, and therefore the original data from each photodiode were processed as described below. The recorded nonlinear data were first transformed into linear data using the experimental calibration curve (essentially the same for all photodiodes with a difference of less than 1%) for the nonlinear amplifier. Then, the linear data from each photodiode were normalized in amplitude to the luminosity value 30 μs after the return-stroke initial peak. In doing so we assumed, based on the observation of *Jordan and Uman* [1983], that 30 μs after the return-stroke initial peak the entire channel within the field of view of the system (several tens of meters in length) has the same luminosity. At that time, a more or less uniform current should be flowing along the lower part of the channel, although channel shape may cause the luminosity versus height profile to appear nonuniform. The lightning progression was evaluated by comparing the normalized luminosity waveforms from different photodiodes. If extension of a discharge is observed, the measurement of the time differences between the signals from the photodiodes over which the discharge has passed in conjunction with the knowledge of the corresponding channel section lengths allows one to estimate discharge speed. The time differences were measured using the method previously described by *Wang et al.* [1995] who studied lightning progression at the CN (Canadian National) tower in Toronto, Canada, with an 8-channel photodiode system. The error in estimated speed (or perhaps the uncertainty in the definition of speed for a signal whose shape changes with height) depends mainly on the steepness of the light signal front, the length of the channel section observed, and the speed being measured. Errors in the speed estimates made in this study are expected to be less than 30%.

In addition to the ALPS records, we obtained simultaneous measurements of the lightning channel-base current and of the lightning electric field at seven distances from the rocket launcher ranging from 5 to 500 m. For the electric field measurements, flat-plate antennas were used. Their outputs were integrated using passive integrators, transmitted via fiber optic links, and recorded by 8- and 12-bit digitizing oscilloscopes whose sampling intervals were set at 100 ns. Only fields at 30 m are used in this study. For the lightning current measurements, a coaxial current viewing resistor (shunt) was used. Its output was also transmitted through a fiber optic link and recorded using both a digitizing oscilloscope for the relatively high (mostly return-stroke) current and a tape recorder for the relatively low, long-lasting current. Sampling intervals of 40 ns and 2 μs were used for the relatively high current records and the relatively low current records, respectively. All the above instruments were triggered simultaneously by the channel-base current.

3. Analysis and Results

Two dart leader/return stroke sequences suitable for studying the lightning attachment process were simultaneously recorded by ALPS, by the electric field measuring system, and by the current measuring system during the 1997 triggered-lightning campaign at Camp Blanding, Florida. These two sequences occurred in two different flashes, S9718 at 1930:09 UTC on June 24, 1997, and S9720 at 2026:02 UTC on June 26, 1997. Both events terminated on a vertical metallic rod attached to the rocket launcher with the upper end of the rod being 4 m above ground. Both flashes were triggered when the electrostatic field at ground was approximately -6 kV/m. Judging from the current recordings, these two flashes are typical of negative triggered lightning with a characteristic initial stage (IS) [*Wang et al.*, 1999]. In the first flash, the IS lasted 320 ms with an average current magnitude of about 100 A, and in the second flash it lasted 550 ms with an average current magnitude of about 300 A. Following the IS, one return stroke occurred in the first flash, and two or three return strokes occurred in the second flash. Both dart leader/return-stroke sequences recorded by ALPS correspond to the first strokes within the triggered flashes, these strokes being similar to subsequent, not first, strokes in natural lightning [e.g., *Fisher et al.*, 1993]. The no-current interval between the end of the IS and the following return-stroke current peak are 30 ms and 50 ms for S9718 and S9720, respectively. Since the S9720 sequence (chronologically second) exhibits a more pronounced attachment process, we discuss it first.

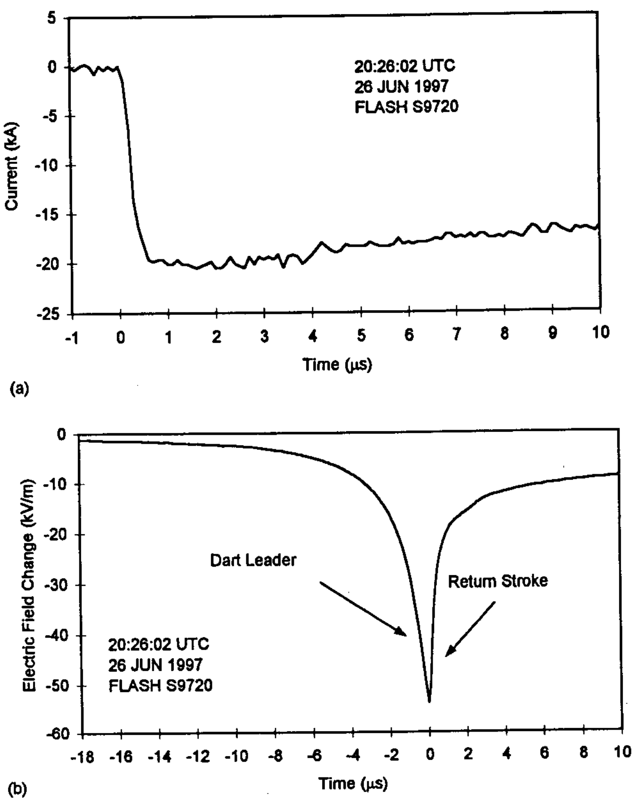


Figure 2. (a) Return-stroke current at channel-base and (b) electric field change due to the dart leader/return-stroke sequence 30 m from rocket launcher of the first dart leader/return-stroke sequence in the flash S9720 triggered at 2026:02 UTC on June 26, 1997, at Camp Blanding, Florida.

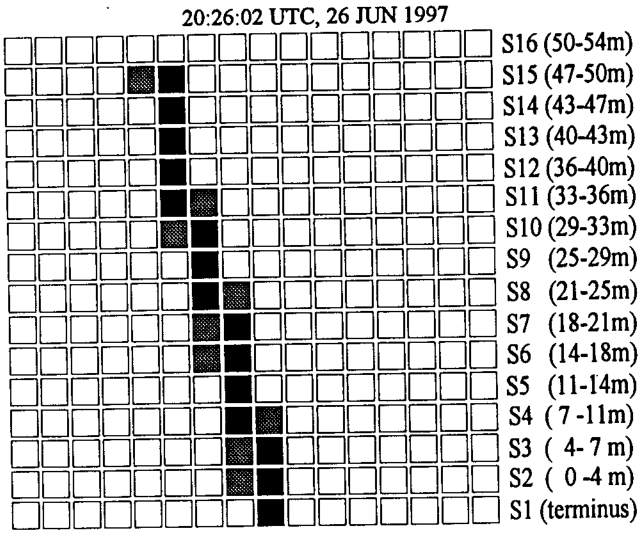


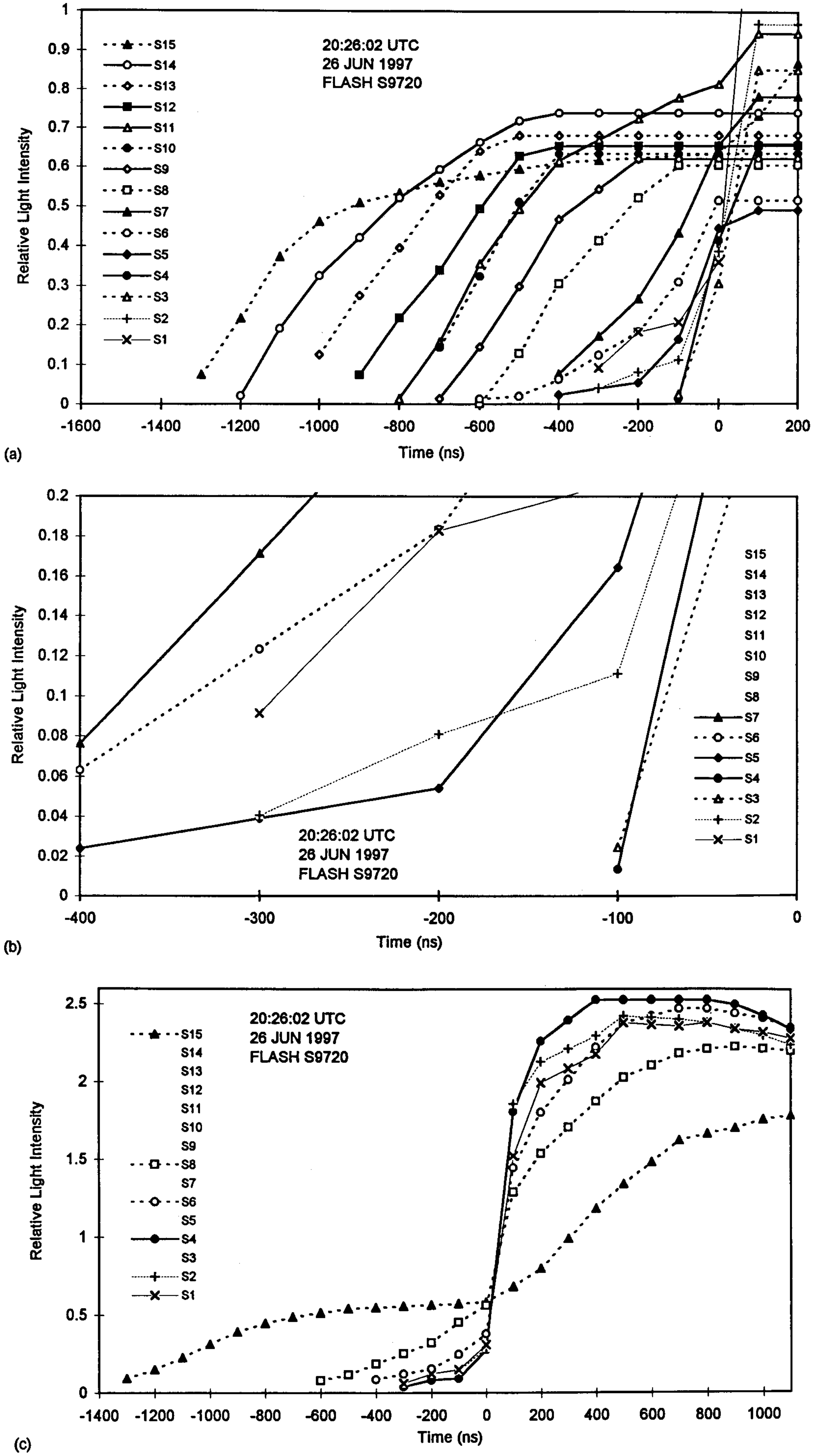
Figure 3. Configuration of the ALPS photodiodes (each shown as a square) which detected pronounced light signals from the S9720 dart leader/return-stroke sequence. Black squares represent photodiodes that detected relatively large light signals (group 1); gray squares represent photodiodes that detected relatively small light signals (group 2); and white squares represent photodiodes that detected essentially no light.

3.1. S9720 Sequence

The channel-base return-stroke current of the S9720 sequence is shown in Figure 2a, and the electric field change due to both dart leader and return stroke at a distance of 30 m in Figure 2b. The return-stroke current has a peak value of about 21 kA and a 10-90% risetime of about 200 ns. The leader electric field change, the leading edge of the pulse in Figure 2b, has a peak value of 56 kV/m.

For the S9720 sequence, a total of 24 photodiodes of the ALPS system detected pronounced optical signals. The positions of those photodiodes are shown in Figure 3, where the lowest row, S1, corresponds to the channel terminus and the remaining rows correspond to various heights above the channel terminus, as indicated on the right of the figure. The height "viewed" above the terminus by S1 is less than 50 cm. As seen in Figure 3, in some rows of the array, two photodiodes responded: one recording a relatively high amplitude signal (solid black square) and the other recording a relatively low amplitude signal (gray square). From our previous experience with ALPS, in the case of an essentially vertical and straight channel section, only one photodiode in a row should detect pronounced signals, since signals due to optical reflection and scattering are usually very weak. Two factors, the channel inclination evident in Figure 3 and the microscale tortuosity reported by *Idone* [1995] may explain why two photodiodes in the same row recorded appreciable signals.

Since two photodiodes in the same row show appreciably different light signal amplitudes, examination of the outputs of these two photodiodes individually can provide additional information, as explained below. We include the photodiodes with the larger output (black squares in Figure 3) into one



(a)
20:26:02 UTC
26 JUN 1997
FLASH S9720
S15
S14
S13
S12
S11
S10
S9
S8
S7
S6
S5
S4
S3
S2
S1
Relative Light Intensity
Time (ns)
-1600 -1400 -1200 -1000 -800 -600 -400 -200 0 200
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
(b)
20:26:02 UTC
26 JUN 1997
FLASH S9720
S15
S14
S13
S12
S11
S10
S9
S8
S7
S6
S5
S4
S3
S2
S1
Relative Light Intensity
Time (ns)
-400 -300 -200 -100 0
0 0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16 0.18 0.2
(c)
20:26:02 UTC
26 JUN 1997
FLASH S9720
S15
S14
S13
S12
S11
S10
S9
S8
S7
S6
S5
S4
S3
S2
S1
Relative Light Intensity
Time (ns)
-1400 -1200 -1000 -800 -600 -400 -200 0 200 400 600 800 1000
0 0.5 1 1.5 2 2.5

group, termed group 1, and the photodiodes with the smaller output (gray squares in Figure 3) into another group, termed group 2. Since most of the data in group 1 are saturated (clipped) in the return-stroke stage and some even in the leader stage, the group 1 data are (in general) only suitable for examination of the leader process. The recorded signals for the dart leader process of the S9720 sequence from all photodiodes in group 1 are shown in Figure 4a. The relative light intensity represents the brightness relative to the value 30 μs after the return-stroke initial peak, as discussed earlier. The initial zero points (points with zero value of light intensity) of all curves are not shown in Figure 4 because they are probably artifacts related to data processing. As evident from Figure 4a, the dart leader propagates downward exhibiting a characteristic light waveform as it approaches the ground to within a height of about 11 m (rows S5 through S15). No leader waveform can be clearly identified in the height range from about 7 to 11 m (row S4) above the channel terminus; however, a relatively weak signal (relative light intensity less than 0.2 or so during the period from t = -300 ns to t = -100 ns or so) preceding the return stroke (which begins at t = 0) is readily seen at heights from 0 to 7 m (rows S1, S2, and S3). An expansion of the relatively weak signal is shown in Figure 4b. As seen in Figure 4b, detectable signals at rows S1 (terminus) and S2 (0-4 m) start at t = -300 ns, 200 ns prior to any appreciable optical signal at row S3 (4-7 m). Also, the S1 signal exceeds the S2 signal at virtually all times prior to return-stroke initiation. These two features are consistent with the interpretation of the weak signal being due to an upward connecting discharge initiated from the terminus and propagating toward the descending dart leader.

The waveforms of the S9720 sequence from all photodiodes in group 2 are shown in Figure 4c. For comparison, the terminus-point signal (row S1) which belongs to group 1 is also included in Figure 4c. Since these waveforms exhibit a very small amplitude relative to the noise level in the leader stage, they are only useful for analyzing the return stroke process. The order of appearance of the rising portions of the curves corresponding to different heights as time increases from t = 0 to t = 400 ns may be interpreted as indicating that the return stroke begins at the S4 level and propagates both upward (see curves S6, S8, and S15) and downward (see curves S2 and S1). This finding is in support of the above interpretation of the relatively weak signal in rows S1, S2, and S3 just prior to the return stroke (see Figures 4a and 4b) being due to an upward connecting discharge. The latter is characterized by light intensity which is about 1 order of magnitude lower than that of the corresponding downward dart leader and has a duration of less than 400 ns. The length of the upward connecting discharge is estimated to be between 7 and 11 m.

On the basis of inferences from Figures 4a, 4b, and 4c, a schematic time-resolved picture of the attachment process of the S9720 sequence is shown in Figure 5. Figure 5 is quite similar to *Idone*'s [1990] Figure 1, which presents idealized leader and

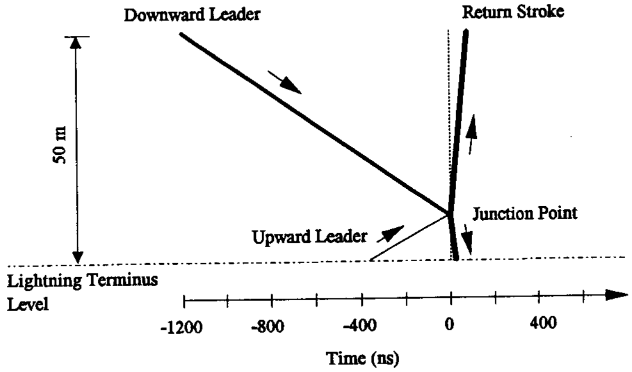


Figure 5. A streaked image sketch of the attachment process of the S9720 dart leader/return-stroke sequence. Time advances from left to right. Times and heights correspond to those in Figures 4a and 4b.

return-stroke streaked images based on his time-resolved photograph of a lightning stroke presumably containing an upward connecting discharge, except that an observed upward connecting discharge is additionally depicted in our Figure 5. Knowing the heights covered by the different photodiodes along the discharge channel and the time difference between the corresponding light signals, we estimate the average speeds of the downward dart leader and of the upward connecting leader to be 4×10^7 m/s and 2×10^7 m/s, respectively.

It is important to note that the most intense light signal during the return-stroke process is observed at its starting location, S4, which is apparently the junction point between the descending dart leader and the upward connecting discharge. We estimate from Figure 4c that the risetime of the return-stroke light signal increased from 200 to 700 ns and its peak decreased from 2.5 to 1.6 relative light units as the return stroke propagated upward about 40 m. For a comparison, we also examined the corresponding downward dart leader waveforms at different heights and found that these waveforms do not vary much with height in terms of either 10-90% risetime or peak value, consistent with findings of *Jordan et al.* [1997] for natural dart leaders within some hundreds of meters of the ground.

3.2. S9718 Sequence

The channel-base current of the S9718 sequence is shown in Figure 6a, and the electric field change 30 m from the rocket launcher is shown in Figure 6b. The return-stroke current exhibits a peak value of 12 kA with a 10-90% risetime of 600 ns. The dart leader peak electric field change is 43 kV/m.

Similar to the S9720 sequence, the ALPS data are organized in two groups. Figure 7a, the relatively high light intensity data (group 1), will be used for the analysis of the dart leader stage, and Figure 7b, the relatively low light intensity data (group 2), will be used for the analysis of the return-stroke stage. In this

Figure 4. Normalized light signals of the S9720 dart leader/return-stroke sequence versus time at different heights above the channel terminus (a) relatively large light signal photodiodes (group 1) data, (b) an expanded portion of Figure 4a for a better view of the upward connecting discharge, and (c) selected relatively small light signal photodiodes (group 2) data. Additionally shown in Figure 4c is the terminus (S1) data that belong to group 1. In Figure 4c, data for t<0 are inaccurate (inferior to the data for t<0 in Figures 4a and 4b). The flat portions of signals in Figure 4a after t = 0 are due to saturation of ALPS. The normalization process makes the flat portions of the light signals from different photodiodes appear at different levels. Relative light intensity represents the brightness relative to the value 30 μs after the return-stroke initial peak (see text for details). Heights corresponding to different photodiode rows are given in Figure 3.

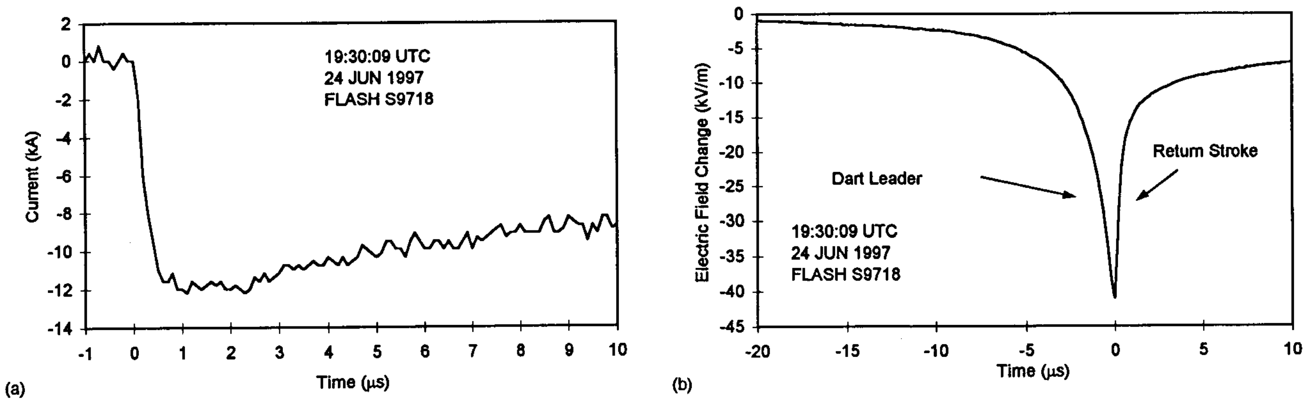


Figure 6. Same as Figure 2, but for the first dart leader/return-stroke sequence in the flash S9718 triggered at 1930:09 UTC on June 24, 1997, at Camp Blanding, Florida.

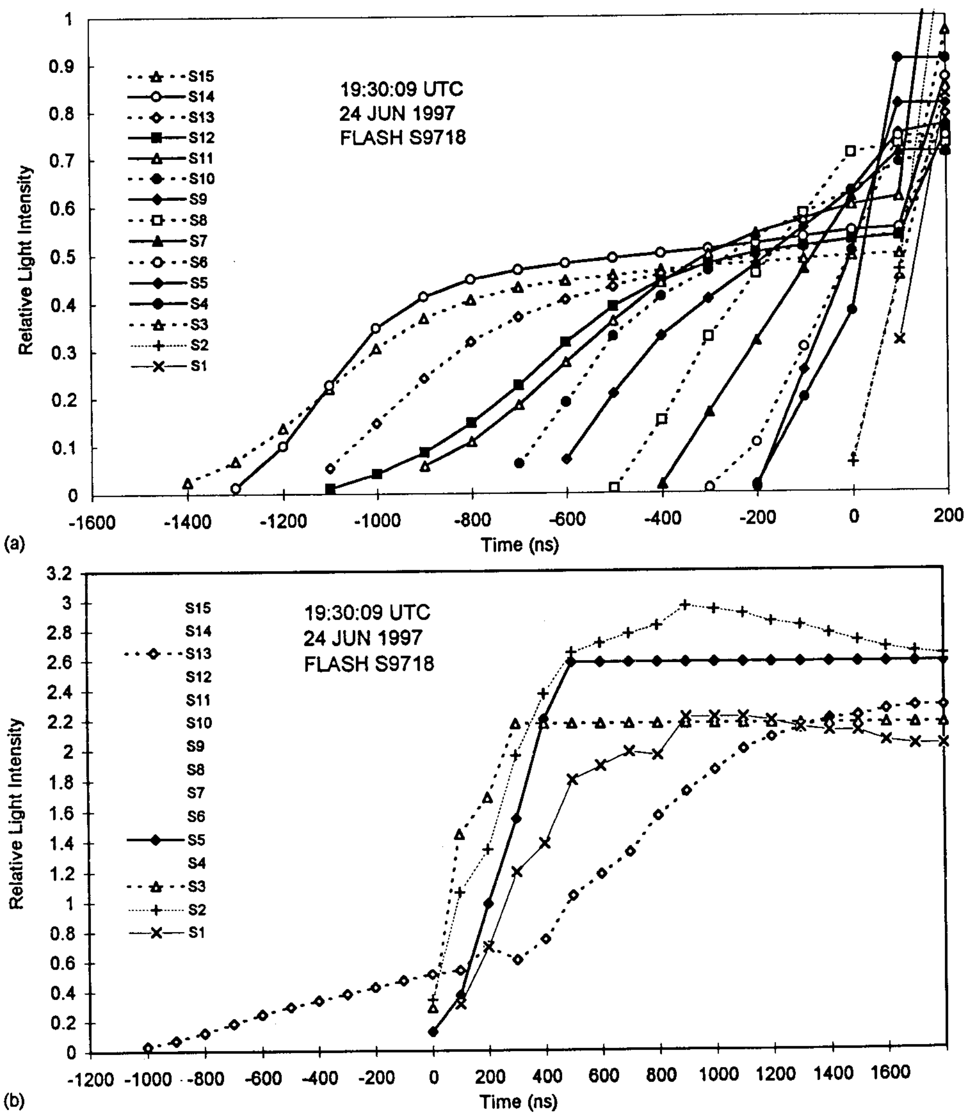


Figure 7. Normalized light signals of the S9718 dart leader/return-stroke sequence versus time at different heights above the channel terminus (a) for analysis of the dart leader process based on group 1 data and (b) for analysis of the return-stroke process based on group 2 data. In the original data for this event, zero output occurred at t = -100 ns for all photodiodes due to an unknown problem; the data points shown here for that time are inferred by interpolation between the neighbor points (at t = 0 and t = -200 ns). Relative light intensity represents the brightness relative to the value 30 μs after the return-stroke initial peak (see text for details). Heights corresponding to different photodiode rows are given in Figure 3.

Table 1. Observed Characteristics of Rocket-Triggered Lightning Strokes Including Attachment Process

Parameter	Event ID	
	S9718	S9720
Return-stroke current peak, kA	12	21
Dart leader electric field at 30 m, kV/m	43	56
Downward dart leader speed, m/s	3×10^7	4×10^7
Upward return-stroke speed, m/s	2×10^8	$\sim 3 \times 10^8$
Upward connecting leader length, m	4-7	7-11
Upward connecting leader speed, m/s	?	$\sim 2 \times 10^7$
Upward connecting leader duration, ns	?	< 400
Dart leader light 10-90% risetime, ns	700	600
Return-stroke light 10-90% risetime at junction, ns	600	200
Return-stroke light 10-90% risetime at 50 m above terminus, ns	1200	700
Return-stroke light peak value at junction, relative units	3	2.5
Return-stroke light peak value at 50 m above terminus, relative units	2	1.6

sequence, as seen in Figure 7a, we can clearly identify the characteristic light waveforms due to the descending dart leader at heights greater than 7 m above the channel terminus (row S4 through row S15) but not in the lower channel section (row S1 through row S3). As seen in Figure 7b, the following return stroke starts at the channel section between 4 and 7 m (row S3) and then travels in both upward (rows S3, S4, S10, and S13) and downward (rows S1, S2, and S3) directions. An upward connecting discharge must have occurred and met the downward dart leader at the channel section between 4 and 7 m and hence we infer that the length of the upward connecting discharge of sequence S9718 is between 4 and 7 m. In this sequence, only the speeds of the downward dart leader and the upward return stroke wave could be reasonably estimated, 3×10^7 m/s and 2×10^8 m/s, respectively. The risetime of the return-stroke light signal increased from 600 to 1200 ns, and its peak decreased from 3 to 2 relative light units as the return stroke propagated upward about 45 m. A summary of the results for dart leaders/return-stroke sequences S9718 and S9720 is given in Table 1.

4. Discussion and Concluding Remarks

As argued by *Idone* [1990], there is no reason to believe that upward propagating discharges making contact with descending leaders should not occur in response to approaching downward dart leaders in subsequent strokes. Our results provide the first direct evidence of the occurrence of such upward propagating and connecting discharges. In the two dart leader/return-stroke sequences we studied, the observed or inferred upward connecting discharges appear to have a duration less than 400 ns, which is shorter than the best time resolution of streak cameras used to date in lightning studies. Apparently, this is the primary reason why *Idone* [1990] failed to find direct evidence of the upward connecting discharges in his streak-camera recordings of nine subsequent strokes in four triggered flashes, although he inferred the upper limit for their lengths. The lengths of the upward connecting discharges of the two triggered-lightning events analyzed here are basically in agreement with his "absolute" upper bound of 12 to 27 m with a mean of 19 m. Further, our results, although based on a small sample of two strokes, suggest that the larger the dart leader electric field change and the higher the following return-stroke current peak, the longer the upward connecting discharge, as would be expected on physical grounds.

The upward connecting discharge appears to be much weaker in light intensity than its associated downward dart leader, probably indicating that the upward connecting discharge is associated with much smaller current than the downward dart leader. This is possibly due to the relatively short time for the formation of the upward leader. Alternately, the relatively low light intensity could be due to the fact that the upward discharge is of positive polarity, whereas the downward dart leader is negatively charged. Neither of our current recording systems (one for relatively high current, the other for relatively low current) was capable of detecting the current of the upward connecting discharge for the following reasons. The high-current system has an amplitude resolution of about 1 kA, which is of the same order of magnitude as the mean value 1.7 kA of the current of downward dart leader inferred by *Idone and Orville* [1985] and probably much larger than the maximum expected current of the upward connecting discharge (tens to hundreds of amperes as inferred from the measured currents of upward positive leaders in the initial stage of classical triggered lightning). The relatively low current system has an amplitude resolution of about 20 A but its sampling interval is 2 μs, considerably longer than the duration of the upward connecting discharge studied here (some hundreds of nanoseconds).

Obtaining ALPS data in conjunction with the measurement of the current of the upward connecting discharge in triggered lightning will be one of our future goals.

Our finding that return strokes start at a junction point elevated above ground and initially propagate both upward and downward has been previously hypothesized by a number of researchers [e.g., *Uman et al.*, 1973; *Willett et al.*, 1988, 1989]. The present study provides the first experimental support for such a scenario in strokes initiated by dart leaders. Further, we note that the light signal peak of a return stroke attenuates about 30% within the lowest tens of meters of the lightning channel. This is a much stronger attenuation than can be inferred from *Jordan and Uman* [1983, Figure 6], which presents the peak relative light intensity versus height for natural subsequent return strokes, although the bottom 50 m or so of the channels they observed were likely obscured by trees. Our findings regarding (1) the initially bidirectional development of return-stroke process and (2) relatively strong attenuation of the upward moving return-stroke light (and by inference current) pulse over the first some tens of meters of the channel may have important implications for return stroke modeling.

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