GEOPHYSICAL RESEARCH LETTERS, VOL. 14, NO. 11, PAGES 1150-1153, NOVEMBER 1987

THE PROPAGATION SPEED OF A POSITIVE LIGHTNING RETURN STROKE

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Abstract. The first direct determination of the propagation speed of a lightning return stroke lowering positive charge to ground has been made. This stroke was the third of eight otherwise negative strokes in a triggered lightning flash initiated at the Kennedy Space Center, Florida. Two independent optical systems, one photographic and the other photoelectric, yielded common recordings for the third and fourth strokes; the respective two-dimensional return stroke propagation speeds were 1.0 vs. 0.93 x10^8 m/s for the positive (third) stroke and 1.0 vs. 1.0 x10^8 m/s for the fourth stroke. Using fast electric-field data, we estimated the positive stroke peak current to be 21 kA. Photoelectric data only yielded propagation speeds of 1.4, 1.6, 1.2, 1.3, 1.0 and 0.90 x10^8 m/s for the first, second and fifth through eighth return strokes, respectively. All propagation speeds were evaluated over 850 m of channel near ground and have an error estimate of 10-15%. For this positive stroke, we found a return stroke propagation speed typical of negative strokes. Whether positive return strokes, in general, travel at typical negative return stroke speeds must await future measurements.

Introduction

Lightning return strokes typically lower negative charge to ground. Return strokes that lower positive charge to ground were first unequivocally documented in the studies of Hagenguth and Anderson (1952) and Berger (1967) by direct measurement of the lightning current polarity at the channel base. More recent studies have evaluated the polarity of charge lowered in cloud-to-ground flashes through the use of electric field-change measurements of individual strokes (Takeuti et al., 1978; Rust et al., 1981; Brook et al., 1982; Cooray and Lundquist, 1982; Fuquay, 1982). A particularly stringent examination of the occurrence of positive cloud-to-ground lightning in summertime Florida thunderstorms has recently been carried out by Beasley et al. (1983). Using electric field-change measurements coupled with accurately synchronized photoelectric and video recordings, Beasley et al. established beyond a reasonable doubt that positive return strokes do occur naturally to open, flat terrain. Further, using an indirect method, they inferred that positive return stroke propagation speeds are probably similar to those of negative return strokes. However, we are not aware of any published direct evaluation of the propagation speed of a positive return stroke.

In this paper, we report on the first measurements of the return stroke propagation speed of a lightning stroke lowering positive charge to ground. These determinations were made by two independent measurement systems operating simultaneously, which also allows a comparison of the calculated speeds. Unlike the previously cited studies that deal with natural lightning, our observation is of a positive return stroke that occurred within a sequence of negative strokes in a triggered lightning flash initiated by the rocket-trailing wire technique (Newman et al., 1967; Fieux et al., 1978; Hubert et al., 1984).

Paper number 7L6612
0094-8276/87/007L-6612$03.00

Observations

During the summer of 1986, triggered lightning experiments were carried out just north of the Kennedy Space Center (KSC), Florida, on the western bank of Mosquito Lagoon. This locale is well suited for lightning studies because of the high frequency of thunderstorm occurrence. Experimentalists from The Centre d'Etudes Nucleaires Grenoble (CENG), working in cooperation with KSC personnel, were responsible for triggering lightning during thunderstorms and making direct measurements of the lightning currents. Other research groups from various universities and research laboratories participated in the observation of the triggered flashes.

Our recordings were obtained from a position 2.2 km south of the rocket launching site. At this site, two separate experimental systems operated by researchers from The State University of New York at Albany (SUNYA) and the National Severe Storms Laboratory (NSSL) were deployed to gather simultaneously data on the triggered flashes. The primary objective of both systems was to obtain return stroke propagation speed measurements. The SUNYA system consisted of a high-speed streak camera used in conjunction with still and video cameras. This system is essentially identical to that previously described in Idone and Orville (1982) and Idone et al. (1984). The NSSL system included video recordings as well as operation of slow and fast electric-field antennas and a return stroke velocity device (RSVD) recently developed for use in the NSSL mobile laboratory. This device is photoelectric in nature and is similar to the photoelectric systems recently used by Hubert and Mouget (1981) and Nakano et al. (1983). A brief description of the RSVD follows.

The RSVD consists of eight solid-state silicon detectors mounted behind precision horizontal slits in the focal plane of a 50 mm lens on a 35 mm camera body. In this configuration, each detector has a 0.1 degree vertical by 42 degree horizontal field of view with a 2.8 degree vertical separation between adjacent detectors. The total vertical viewing angle is 21 degrees. At 2.2 km from the flash, each slit isolates 4 m of channel. The light signal from each detector is amplified by circuitry with a 10-90% risetime of 0.6 μs and a decay time of 0.4 ms. The eight light signals, an IRIG-B timing signal, and the electric field waveforms are all recorded on a 14 track analog tape recorder with a measured 10-90% risetime of 0.5 μs and a maximum dynamic timing error jitter between tracks of 0.3 μs. The NSSL

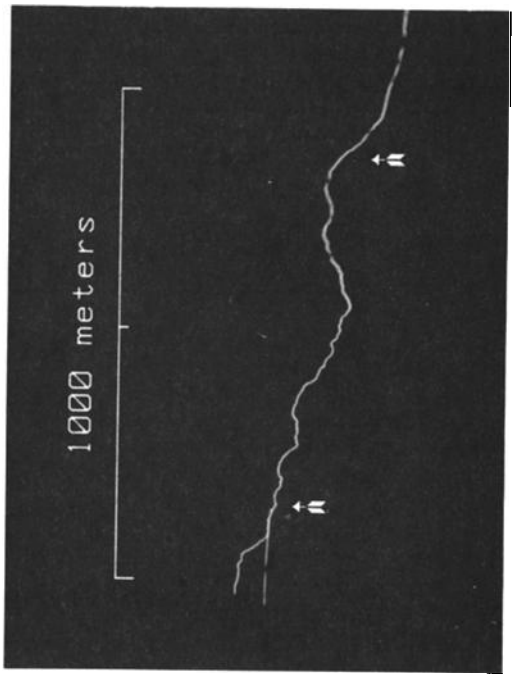

Fig. 1a. Still photograph of the triggered lightning flash of 2138.07 GMT 14 August 1986, taken from a distance of 2.2 km. The arrows correspond to the analysis levels used for the propagation speed determinations.

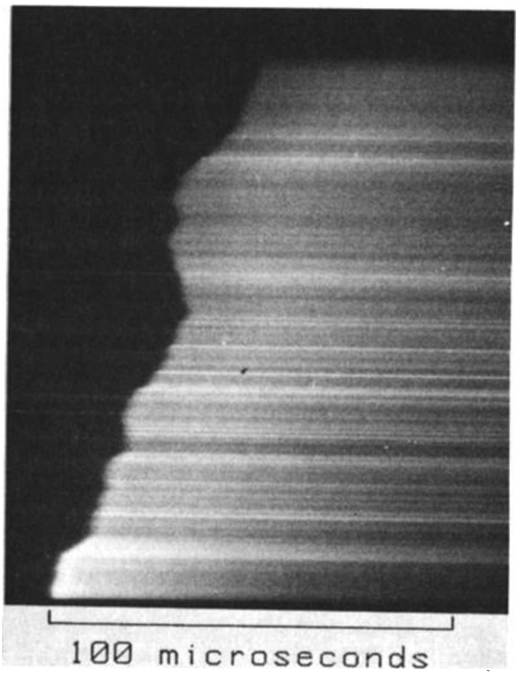

Fig. 1b. Time-resolved streak photograph of the third stroke of the triggered flash shown in Figure 1a. A #29 deep red filter was used during imaging to minimize background exposure.

mobile laboratory was parked adjacent to a trailer that housed the SUNYA system.

The flash of interest was initiated at 2138:07 GMT 14 August 1987. The surface electric field at launch of the triggering rocket was +5.5 kV/m, indicating net negative charge overhead (physics sign convention). A photograph of the flash is shown in Figure 1a. Note that there were two ground terminations. Video recordings of this flash show that the first two return strokes followed the trigger wire to ground (the right fork); the next six strokes followed the termination on the left. The time sequence and polarity of strokes for this flash are listed in Table 1. (The stroke polarity is defined by the charge brought to ground.) Direct measurement of the current for the first and second strokes indicated negative peak currents of 28 and 25 kA, respectively. Since the later strokes did not terminate on the current measuring shunt, no direct current measurements are available for these strokes. However, fast electric field-change measurements made with the NSSL mobile lab as well as measurements made by researchers from the University of Florida (E. Thompson, private communication), indicated that the third stroke in this flash, and only this stroke, lowered positive charge to ground. The NSSL fast antenna electric field records for the second and third strokes in this flash are shown in Figure 2, clearly indicating the polarity reversal between strokes. Hence, the third stroke in this flash, which established a new path to ground, lowered positive charge to ground.

The SUNYA streak camera imaged only two strokes of this flash. Normally the sequence of stroke imaging is not known. However, we are certain these images correspond to the third and fourth strokes of this flash and can be individually identified as such because: 1) the geometry of the streak images near ground is that of the second termination, 2) the timing of the second and third strokes places them within the half-second exposure window starting 320 ms after triggering by the first return stroke (note: an intentional shutter tripping delay of 320 ms was used after optical triggering by the first light pulse to avoid photography of the uninteresting initial continuing current phase of the flash; in this case, however, optical triggering occurred with the first return stroke as evident from the video record), 3) a luminosity increase seen approximately 250 μs after the third stroke on the photoelectric record is also seen in the photographic record for the presumed third stroke, and, most critically, 4) the separation of the stroke images on film accurately corresponds to the known interstroke interval (368.49 ms) and the known writing rate of the film.

It should be noted that neither system recorded a leader to the third stroke of this flash although, presumably, a stepped leader was necessary to establish the new channel to ground. Further, the light signal recorded by the RSVD as well as the streak camera image showed nothing extraordinary with

Table 1. Return stroke times (GMT), polarity, directly measured peak currents (I_p in kA) and propagation speeds (10^8 m/s) for the flash of 2138:07 14 August 1986. The error estimate for all propagation speeds is 10-15%.

Stroke Time	Polarity	I_p	Speed RSVD	Speed Streak
2138:07.265	neg	28	1.4	-
07.347	neg	25	1.6	-
07.721	pos	-	0.93	1.0
08.090	neg	-	1.0	1.0
08.189	neg	-	1.2	-
08.273	neg	-	1.3	-
08.374	neg	-	1.0	-
08.413	neg	-	0.90	-

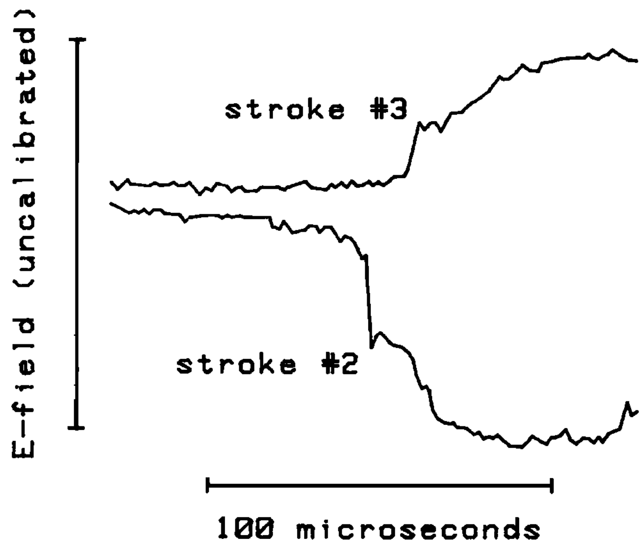

Fig. 2. NSSL fast antenna recording system electric-field waveforms (uncalibrated) of the second and third strokes in the triggered flash of Figure 1. The 10-90% risetime of the fast antenna was 0.5 μs with a decay time of 1 ms.

regard to the optical characteristics of this stroke. The streak image of the third stroke is shown in Figure 1b.

Analysis

The return stroke propagation speeds derived from each optical system are listed in Table 1. The RSVD recorded signals from all eight strokes. For simplicity, only speeds determined between the first and eighth RSVD slit levels are presented. The arrows of Figure 1a identify these slit levels; the two-dimensional channel length between these levels is 850 m. Analysis of the streak images was carried out between these same levels though other levels were used with essentially the same result. The analysis technique and resulting error estimate for the streak camera speeds are identical to that discussed in Idone and Orville (1982). Analysis of RSVD data is done by calculating the time difference between the beginning of the most rapidly varying portion of the light signal at the different slit levels, after systematic errors due to tape skew were measured and removed. A complete description of the RSVD and the analysis technique can be found in Mach (1987).

Discussion

The agreement between the two sets of propagation speed measurements for the third and fourth return strokes is very good. There can be little doubt that the propagation speed of this positive return stroke is close to the typical speed of 10^8 m/s found for negative return strokes in several recent studies (Hubert and Mouget, 1981; Idone and Orville, 1982; Nakano et al., 1983; Idone et al., 1984). However, it must be remembered that this positive stroke did occur during a triggered flash with otherwise negative current pulses. Current polarity reversals within a flash have been observed, but are apparently rare. Hagenguth and Anderson (1952) reported only five instances of positive impulsive current peaks within otherwise negative flashes. This suggests that the positive stroke described here may not be typical of positive return strokes that occur in natural flashes.

Knowledge of the peak current magnitude for this stroke would help assess its similarity to natural lightning positive strokes. Although the new channel termination prevented direct current measurement, we can estimate the magnitude of the positive peak current for the third stroke using the available information. According to the transmission line model of the lightning return stroke (Uman et al., 1975), the initial electric field peak is proportional to the product of the peak current and the return stroke propagation speed. Thus, the peak current of the third stroke can be estimated as

$$I_3 = (E_3/E_2)\ (V_2/V_3)\ I_2$$

where I_2 is the magnitude of the peak current of the second stroke, E_3/E_2 is the ratio of magnitude of fast electric field change for the second and third strokes, and V_2/V_3 is the ratio of the return stroke propagation speeds. Here, $I_2 = 25$ kA, E_3/E_2 is very close to 0.5 as evident from Fig. 2, and V_2/V_3 is chosen as (1.6/.96) with 0.96 x 10^8 m/s being an average of the two listed speeds for the third stroke. The resulting estimate for I_3 is 21 kA; an identical analysis using values from the first stroke yields a peak current of 20 kA. Hence this positive stroke peak current is roughly half the median value of 35 kA reported by Berger et al. (1977) for the peak currents of triggered strokes lowering positive charge.

Conclusions

The first direct measurement of the return stroke propagation speed of a positive lightning return stroke was found to be close to 10^8 m/s just above ground as determined by two different optical systems. This value is comparable to that typical of negative strokes and is consistent with the belief that return stroke speeds probably do not depend on polarity. However, a single observation clearly cannot justify this belief, especially since this stroke may not be typical of naturally occurring positive strokes to open ground. Additional direct measurements of positive return stroke propagation speeds in natural flashes are necessary to investigate adequately the possible dependence of propagation speed on stroke polarity.

Acknowledgments. We are indebted to A. Eybert-Berard and L. Barrett of CENG for graciously providing us with the current measurements used here. We thank W. Jafferis for his support and organization of the triggered lightning studies at KSC. Special thanks are due C. D. Weidman and L. Scudder for operating the NSSL equipment. Implementation of the RSVD for studying lightning in severe storms was supported in part by the Severe Storms and Local Weather Research Office of NASA under order H-39299B. This research was funded in part by the National Science Foundation (ATM8400207).

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(Received June 22, 1987;
revised October 9, 1987;
accepted October 14, 1987.)