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Electric fields near triggered lightning channels measured with Pockels sensors

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[1] Electric field waveforms at horizontal distances from the triggered lightning channel attachment point ranging from 0.1 to 1.6 m have been measured with Pockels sensors at the International Center for Lightning Research and Testing at Camp Blanding, Florida. The measuring system had a dynamic range from 20 kV/m to 5 MV/m and a bandwidth from 50 Hz to 1 MHz. The corresponding currents at the channel base and electric fields at 5, 15, and 30 m from the lightning channel were also measured using a current viewing resistor and flat-plate antennas, respectively. Very close vertical electric fields for 36 strokes in nine triggered lightning flashes were obtained using Pockels sensors. For 8 out of the 36 strokes, horizontal electric fields were also measured using Pockels sensors. Electric field waveforms appear as pulses, with the leading edge of the pulse being due to the leader and the trailing edge due to the return stroke. Of the 36 vertical electric field waveforms, six were more or less V-shaped, while 30 exhibited a considerably slower variation during the return-stroke stage than during the leader stage. Vertical electric field pulse peaks are in the range from 176 kV/m to 1.5 MV/m (the median is 577 kV/m), and horizontal electric field pulse peaks are in the range from 495 kV/m to 1.2 MV/m (the median is 821 kV/m). On-site calibration results show that these electric fields measured using Pockels sensors may be underestimated by 40% or so due to the insufficient upper frequency response of 1 MHz of the measuring system. Additionally, vertical electric fields due to *M* components were measured and compared to electric fields produced by leader/return stroke sequences. For 8 out of 10 *M* components having channel-base peak currents greater than 500 A, vertical electric fields at 0.1 to 1.6 m were below 20 kV/m, the lower measurement limit. For the remaining 2 of 10 *M* components, whose current peaks were between 2.3 and 3.2 kA, vertical electric field peaks were about 100 and 48 kV/m at a distance of 0.1 m from the attachment point, apparently unaffected by the upper frequency response of the measuring system. The vertical electric field measured very close to the lightning channel tends to increase with an increase in the previous no-current interval, that is, in the time elapsed from the cessation of current of the preceding stroke (or of the initial-stage current). *INDEX TERMS:* 3304 Meteorology and Atmospheric Dynamics: Atmospheric electricity; 3324 Meteorology and Atmospheric Dynamics: Lightning; *KEYWORDS:* lightning, electric field, Pockels sensor, leader, return stroke, *M* component

1. Introduction

[2] A knowledge of the electric fields in the immediate vicinity of the lightning channel is needed in studying various aspects of the physics of the lightning discharge and in characterizing the very close lightning electromagnetic environment. The electric field component along the lightning channel, measured very close to (ideally on the surface of) the lightning channel, should not be much different from the longitudinal electric field inside the channel, the tangential component of electric field being continuous across the boundary. Integration of the product of the longitudinal electric field and the channel current over time will yield an estimate of return stroke input energy per unit length. Reliable estimates of the lightning input energy are needed in a number of areas including the determination of the amount of NO produced by lightning and the testing of the validity of proposed thunder generation mechanisms. There is presently no consensus on the energy associated with the lightning return stroke. Various estimates differ by one to two orders of magnitude, as discussed by *Rakov and Uman* [1998].

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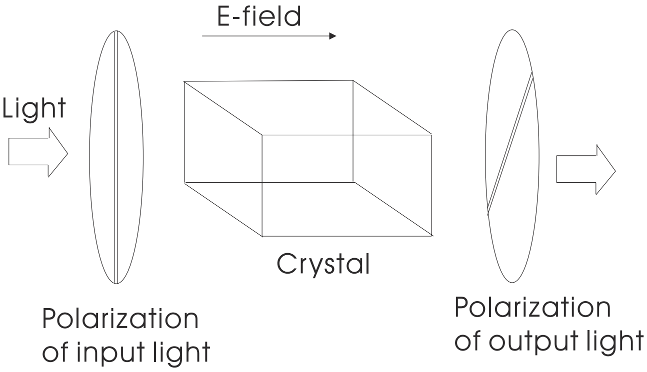

Figure 1. Principle of operation of a Pockels sensor.

[3] The experiments presented here were conducted during summer 2000 at the International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, Florida. Lightning was triggered using the classical rocket-and-wire technique. We present Pockels-sensor measurements of the very close vertical electric fields of 36 strokes and two *M* components, and the very close horizontal fields of eight strokes in nine triggered lightning flashes.

2. Instrumentation

[4] When some types of crystals, for example, quartz, are placed in an external electric field, the polarization of light (direction of the light's electric field intensity vector) passing through the crystal changes as a function of field magnitude and the path length the light traverses, as schematically shown in Figure 1. This is the electro-optic effect discovered by and named after F. Pockels [*Pockels*, 1891]. It follows that electric fields can be measured by transmitting light through such a crystal and comparing the polarization of the output and input light [e.g., *Hidaka*, 1996]. Electric field sensors operating on this principle are referred to as Pockels sensors. Pockels sensors have been used in laboratory spark studies for measurement of the electric field at the tip of leaders and in the leader channels [e.g., *Hidaka and Murooka*, 1985; *Chernov et al.*, 1991]. Pockels sensors have the following advantages for the measurement of electric fields very close to the lightning channel relative to traditional electric dipole sensors:

1. Pockels sensors usually have no conductive parts and are electrically isolated from the ground. Thus, there is relatively little disturbance of the measured field by the sensor, and such sensors can be placed very close to an electrical discharge or even inside the discharge channel.
2. Crystals used in Pockels sensors can respond to changes in the electric field in a wide frequency range from dc to some gigahertz. However, in many cases, including the present experiment, the bandwidth of the Pockels-sensor field measuring system (including, besides the Pockels sensor, a light source, a fiber-optic link, and an optical-to-electrical converter) is limited by other elements of the system.
3. Pockels sensors do not contain electronic circuits or power supplies. Thus, Pockels-sensor measurements are less influenced by the unintended coupling of lightning electric and magnetic fields to the measuring system.

[5] Potential problems in measuring electric fields in the lightning source region related to the distortion of the local electric field by the sensor are discussed by *Baum* [1986]. Since the dielectric constants of the crystal used in a Pockels sensor and of the crystal holder are different from that of the air, the Pockels sensor will cause some distortion of the electric field. This effect can be accounted for (at least in part) by laboratory calibration of the measuring system. *Hidaka* [1996] discusses methods to correct electric fields measured in the source region for the distortion of the field due to the attachment of charged particles to the surface of the Pockels sensor. In this study, we neglect any distortion of the electric field by the Pockels sensors which were installed 0.1 to 1.6 m from the lightning attachment point.

[6] Data presented here were obtained using two identical measuring systems. Each system included a Pockels sensor connected via a fiber-optic link to a light source and an optical-to-electrical (O/E) converter, as shown Figure 2. Each Pockels sensor contained a crystal of KH_2PO_4 (potassium dihydrogen phosphate also referred to as KDP). The dielectric constant of KDP is about 20 along the optical axis and about 50 in the direction perpendicular to the optical axis [*Hidaka*, 1996]. The systems had a relatively large dynamic range, from 20 kV/m to 5 MV/m, but a relatively narrow frequency range, from 50 Hz to 1 MHz. Variation of the sensitivity of the sensor was less than 4% in the temperature range between 0°C and 40°C. In each Pockels sensor, the crystal was installed inside a holder made of a dielectric material (fiberglass reinforced plastic) for protection of the crystal from the humidity. Polarized light from the light source was transmitted through the crystal, passed through an analyzer that converts changes in the light polarization to changes in light intensity (included in the O/E converter in Figure 2), converted to an electrical signal,

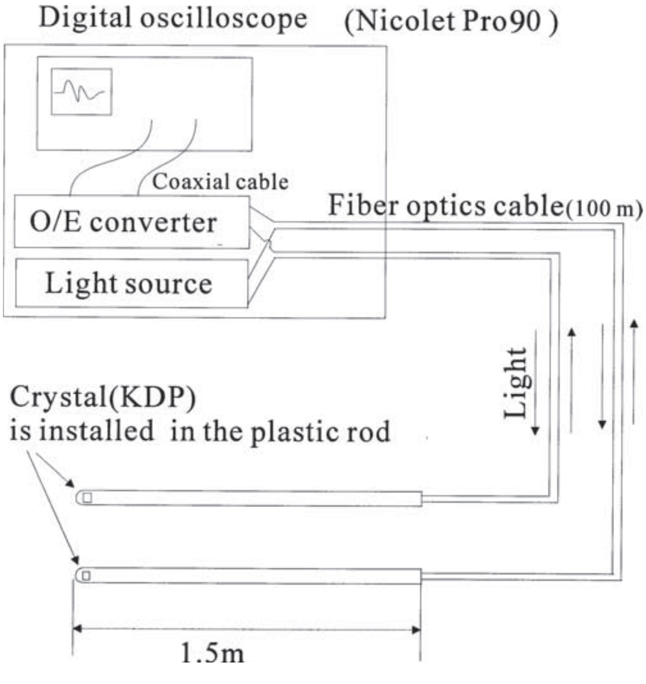

Figure 2. Pockels-sensor measuring system.

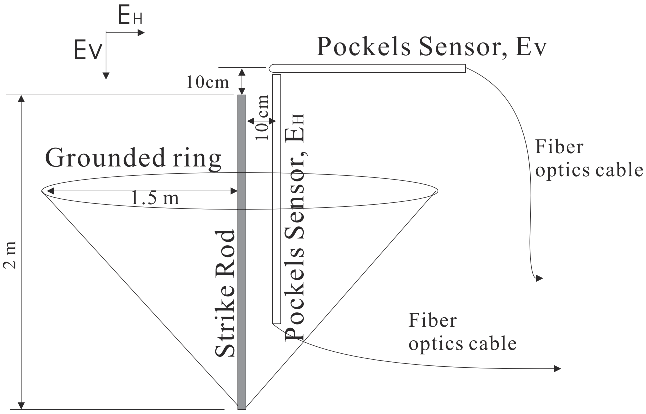

Figure 3. Experimental setup.

and then digitized and recorded by a digitizing oscilloscope (Nicolet Pro 90). The sampling interval was 0.5 μs and the record length was approximately 250 ms.

[7] Pockels sensors were installed on the underground rocket launching facility at the ICLRT [*Rakov et al.*, 2000, 2001; *Crawford et al.*, 2001], as shown in Figure 3 The vertical field sensor was placed at a radial distance of 0.1 m from, and at a height of 0.1 m above the tip of the 2-m vertical strike rod, and the horizontal field sensor was placed directly below it. A metal ring having a radius of 1.5 m was installed around the strike rod. The ring was connected to the base of the strike rod which was grounded. Since lightning channel could attach to either the strike rod or the ring, the horizontal distance between the lightning channel attachment point and the Pockels sensors varied for different events, from 0.1 m to 1.6 m. In one case, stroke 1 in Flash S0026, a branch of the channel was in contact with the vertical field sensor. Additionally, we measured lightning currents with a current viewing resistor (shunt) and electric fields 5, 15, and 30 m from the strike rod with flat-plate antennas.

[8] Field calibration of the Pockels sensors was accomplished by comparing the outputs of the Pockels sensors with that of a flat-plate antenna, both installed 5 m from the lightning channel. Figure 4 shows examples of the two types of observed electric field waveforms, termed slow and fast, measured simultaneously with a Pockels sensor and a flat-plate antenna. The flat-plate antenna was calibrated theoretically [e.g., *Uman*, 1987, Appendix C], and the Pockels sensors were calibrated (up to about 2 MV/m) in plane-plane gaps by CRIEPI personnel. The 2/50 μs voltage waveform produced by a 1-MV impulse generator was used for the laboratory calibration of the Pockels sensors, with the separation between electrodes being 2 or 3 m for creating fields less than 1 MV/m and 0.1 or 0.2 m for creating fields between 1 and 2 MV/m. Figure 5 shows a scatterplot of the magnitude of the vertical electric field due to lightning measured with the Pockels sensor versus that measured with the flat-plate antenna. Figures 4 and 5 show that the magnitudes of slow waveforms are essentially the same for the flat-plate antenna and the Pockels sensor records. However, the magnitudes of the relatively fast waveforms measured with the Pockels sensor are on average about 60% of those measured using the flat-plate antenna. This implies that electric field peaks measured using Pockels sensors may be underestimates by 40% or so,

Figure 3. (continued)

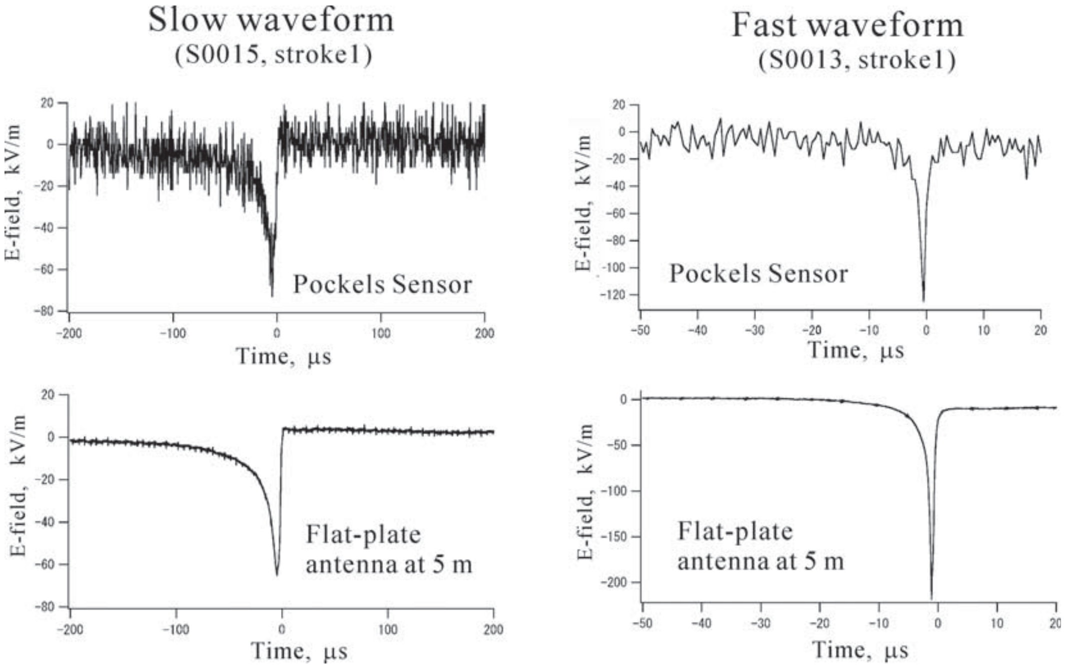

Figure 4. Comparison of the electric field waveforms simultaneously measured with a Pockels sensor and a flat-plate antenna, both at 5 m.

provided that the frequency content of the electric field in the immediate vicinity of the channel is not much different from that of relatively fast waveforms at 5 m. The difference in the response of the Pockels sensors to slow and fast waveforms is presumably caused by the insufficient upper frequency response of 1 MHz of the Pockels sensor measuring system. If the frequency content is higher very close to the channel than at 5 m, the field peaks measured

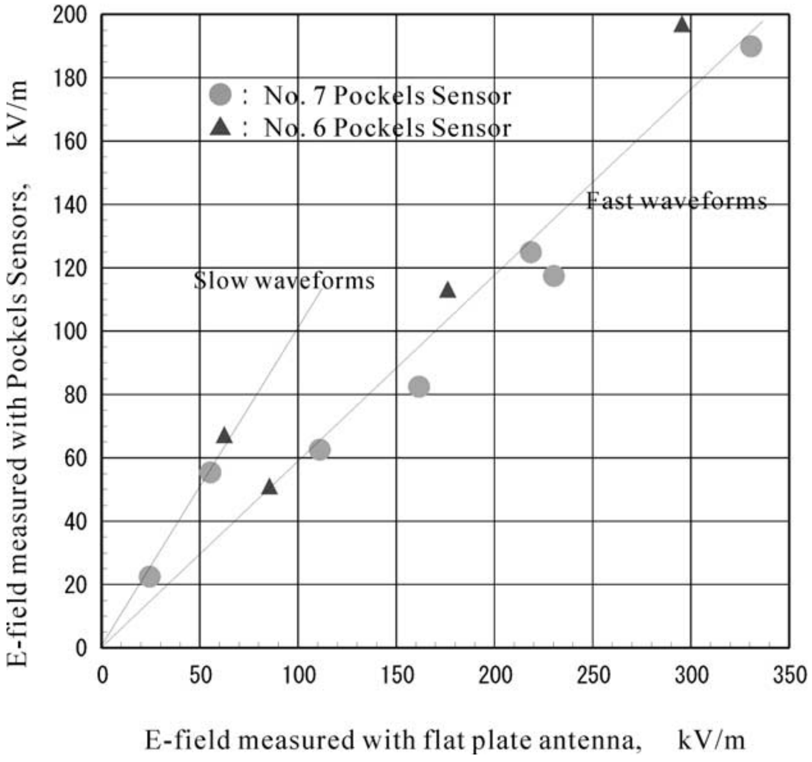

Figure 5. Comparison of magnitudes of the vertical electric field peaks measured with Pockels sensors and a flat-plate antenna, both at 5 m. Pockels sensors No. 6 and No. 7 were subsequently used for measuring the vertical and horizontal electric field components in the immediate vicinity of the lightning channel.

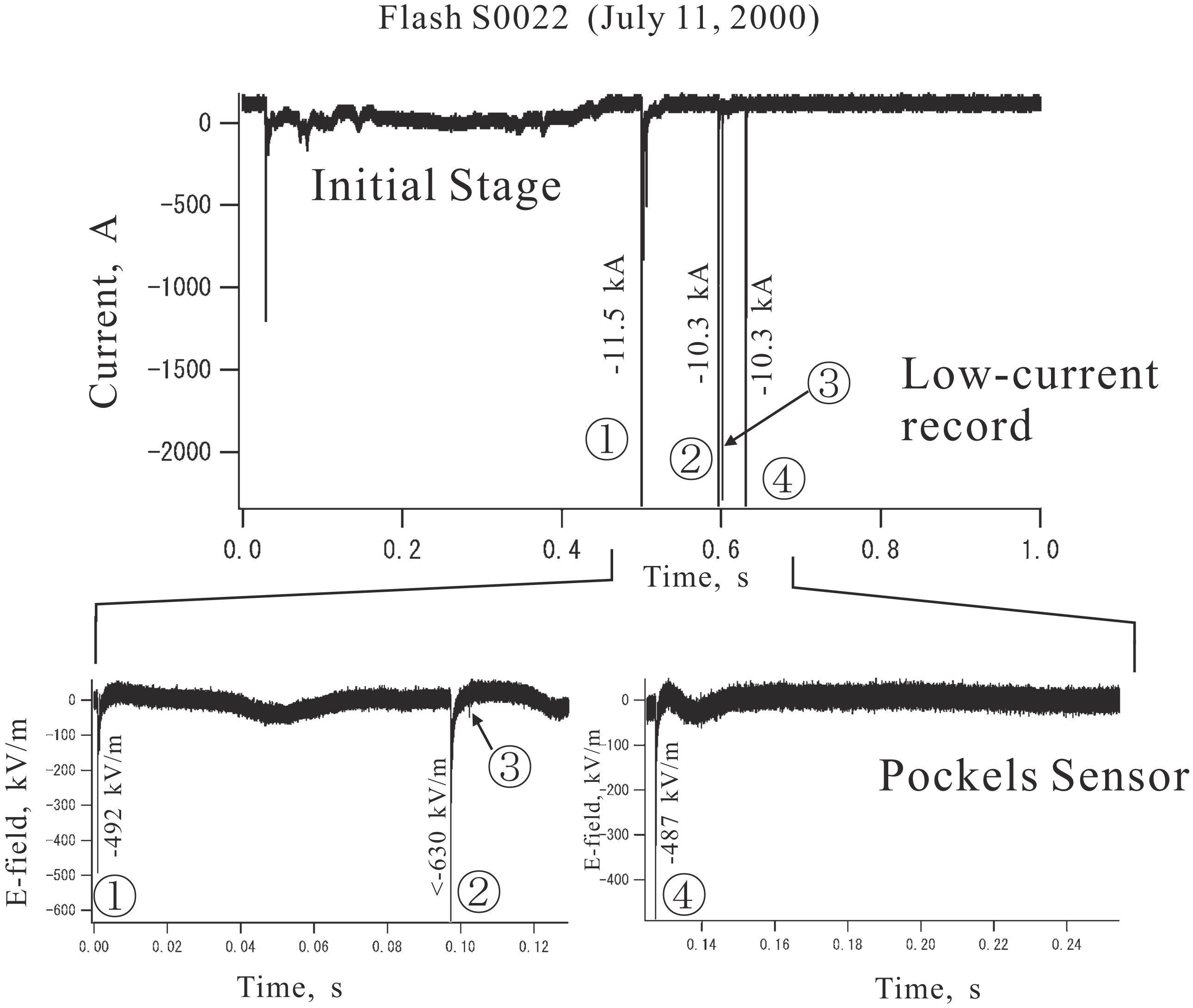

Figure 6. A complete flash low-current record obtained using a current viewing resistor and the corresponding vertical electric field records obtained using a Pockels sensor for Flash S0022, July 11, 2000. The horizontal distance between the lightning channel attachment point and the Pockels sensor was 0.1 m.

by the Pockels sensors may be underestimated by more than 40%.

3. Data Presentation

[9] In the 2000 rocket-triggered-lightning experiments at Camp Blanding, Florida, we obtained very close vertical electric fields for 36 strokes in nine triggered lightning flashes using a Pockels sensor. For 8 out of the 36 strokes, horizontal electric fields were simultaneously measured using a separate Pockels sensor installed near the Pockels sensor that was used to measure vertical electric fields (Figure 3). Data for these 36 strokes (leader/return stroke sequences) are presented in section 3.1. Additionally we obtained electric fields waveforms produced by two *M* components [*Rakov et al.*, 1995, 2001], which are presented in section 3.2.

3.1. Leader/Return Stroke Sequences

[10] For the 36 strokes, measured return-stroke current peaks are in the range from 1.3 to 37 kA (the median is about 12 kA), measured vertical electric field peaks are in the range from 176 kV/m to 1.5 MV/m (the median is 577 kV/m), and measured horizontal electric field peaks are in the range from 495 kV/m to 1.2 MV/m (the median is 821 kV/m). The electric fields were measured at horizontal distances ranging from 0.1 m to 1.6 m from the lightning channel attachment point.

[11] Figure 6 shows overall records of the vertical electric field measured with a Pockels sensor along with the corresponding current waveform for flash S0022. Figure 7 shows, on a 10-ms timescale, waveforms of the vertical electric field and the current for stroke 1 in Flash S0022. Figure 8 shows, on a 50-μs timescale, the current, vertical electric field measured with the Pockels sensor at 10 cm, and the vertical electric field measured with the flat-plate antenna at 15 m. Figure 9 shows the vertical electric field and horizontal electric field measured with Pockels sensors at 10 cm and the vertical electric field measured with the flat-plate antenna at 15 m for stroke 1 in Flash S0033. Note that the Pockels-sensor electric field waveshapes in Figures 8 and 9 are

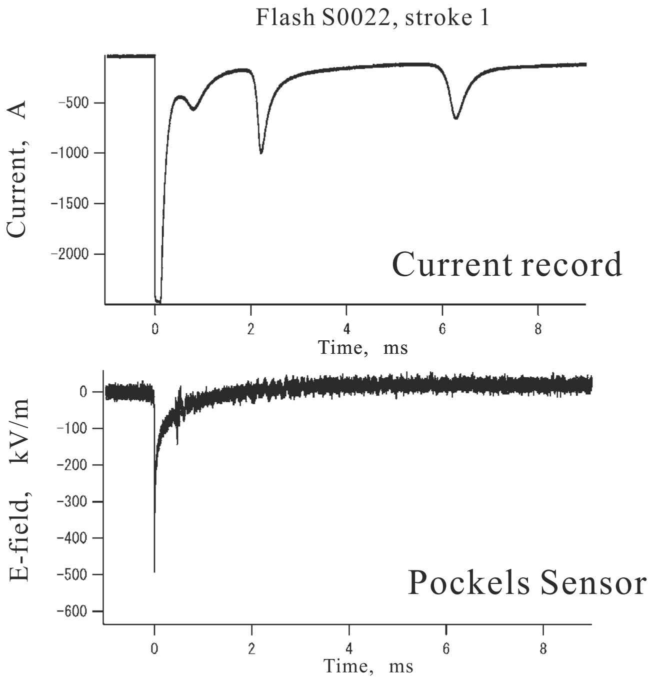

Figure 7. The same as Figure 6, but for the first stroke in the flash. Note three *M* component pulses after the return-stroke pulse in the current record and no corresponding signatures in the electric field record. Ringing starting 400 to 500 μs after the electric field peak is associated with the acoustic shock wave produced by the return stroke.

different. In Figure 8, the risetime of the negative electric field pulse is several microseconds, and the decay time is more than 1 ms. Thus, the electric field waveform at 10 cm does not appear to be V-shaped as is the case at 15 m and at larger distances, up to hundreds of meters or so [*Rubinstein et al.*, 1995; *Rakov et al.*, 1998; *Crawford et al.*, 2001]. However, the electric field waveform at the same distance (10 cm) from the attachment point shown in Figure 9 is V-shaped, with the decay time of the negative electric field pulse being less than 1 μs. Of the 36 vertical electric field waveforms measured with a Pockels sensor, 6 were more or less V-shaped, while 30 exhibited a millisecond-scale decay similar to that seen in Figure 8. Note from Figure 9 that the waveshape of the horizontal electric field is similar to that of the vertical electric field.

3.2. *M* Components

[12] During the 2000 experiments, we observed many *M* components in the records of the lightning current and the corresponding electric fields measured at distances ranging from 5 to 30 m. However, in most cases, there was no associated electric field signature recorded with Pockels sensors (see, for example, Figure 7). The lower measurement limit of the Pockels sensors was 20 kV/m. Thus, the very close electric fields of the majority of *M* components are inferred to be smaller than 20 kV/m. For eight out of ten *M* components having channel-base peak currents greater than 500 A, vertical electric fields at 0.1 to 1.6 m were below 20 kV/m, the lower measurement limit. (Vertical electric field peaks measured using flat-plate antennas for five of these eight *M* components at 15 m ranged from 1.0 to 2.3 kV/m and for two at 30 m were 0.9 and 1.8 kV/m.) For the remaining two of ten *M* components, whose current peaks were between 2.3 and 3.2 kA, vertical electric field peaks were about 100 and 48 kV/m at a distance of 0.1 m from the attachment point, apparently unaffected by the upper frequency response of the measuring system. (For six *M* component electric fields measured (for another project) at 5 m using a flat-plate antenna, *Rakov et al.* [2001] reported five peak values ranging from 1.2 to 7.5 kV/m and one value of 27 kV/m. The corresponding peak currents ranged from 605 to 3200 A. No electric fields at 0.1 to 1.6 m corresponding to these six events were measured.)

[13] As noted above, the *M* component following stroke 1 in Flash S0036 had a relatively large peak of about 100 kV/m at a distance of 0.1 m from the channel attachment point. The corresponding vertical electric field peaks at 15 and 30 m were about 0.5 and 0.4 kV/m, respectively. The vertical electric field peak at 15 m due to a typical leader/return

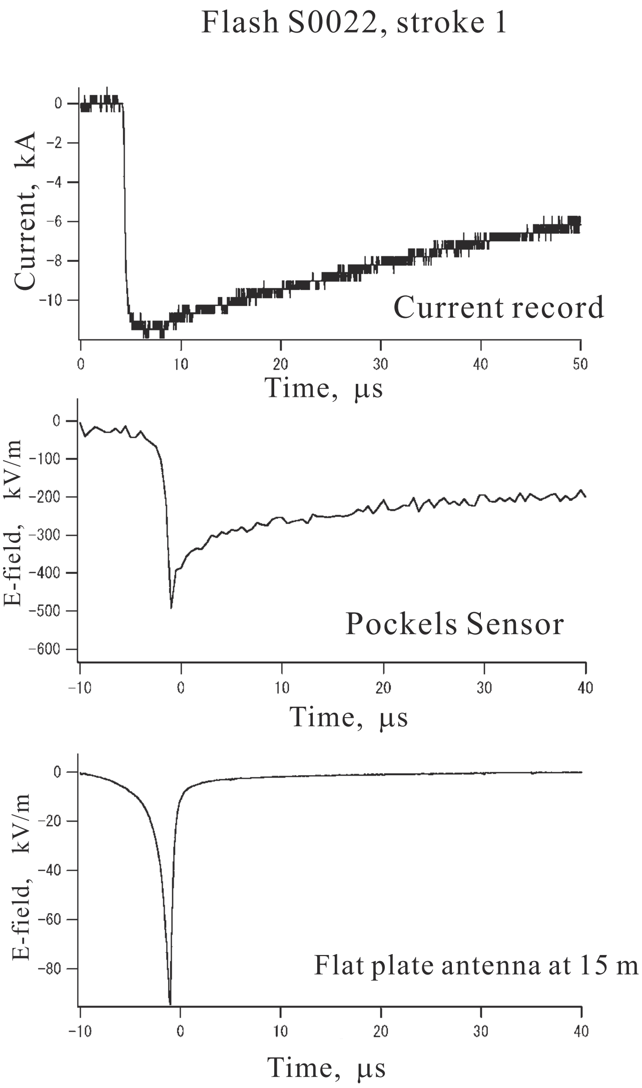

Figure 8. The same as Figure 7, but the high-current record and on an expanded (microsecond) timescale. Also shown is the vertical electric field waveform measured at 15 m with a flat-plate antenna.

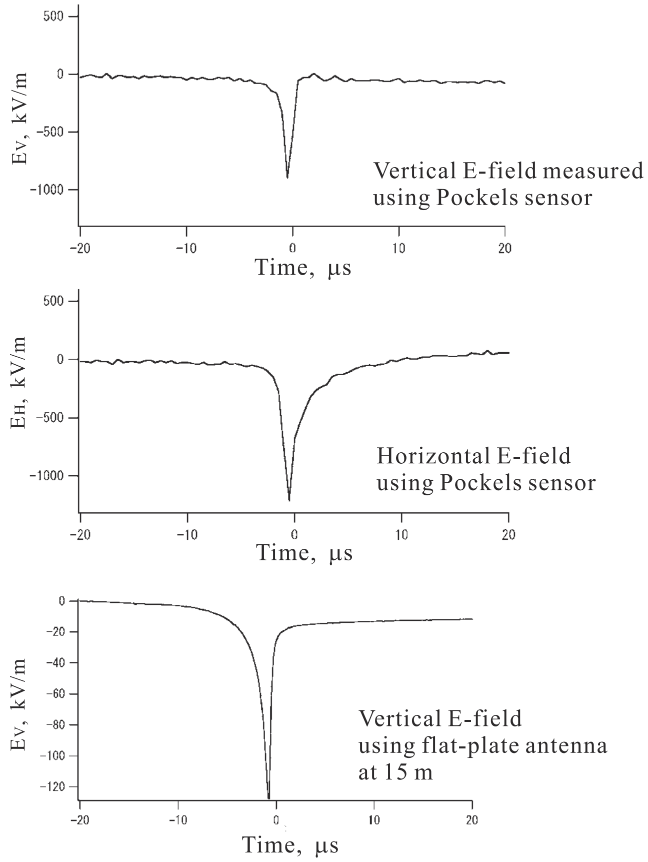

Figure 9. Waveforms of the vertical and horizontal electric fields measured by Pockels sensors 0.1 m from the lightning channel attachment point along with the vertical electric field at 15 m for stroke 1 in Flash S0033.

stroke sequence is of the order of 100 kV/m and is about 50 kV/m at 30 m [*Crawford et al.*, 2001]. The horizontal electric field of the *M* component at 0.1 m was below 20 kV/m, the lower measurement limit of the sensor. The bottom 3 m or so of the *M* component channel was predominantly horizontal, so that the measured vertical electric field 0.1 m away and 0.1 m above the channel attachment point was apparently dominated by the vertically directed electric field perpendicular (radial) to the horizontal channel segment. The continuing current before and after the *M* component was about 790 A. The time interval between the *M* component current peak and the preceding return-stroke current peak was about 4 ms. The polarity of the vertical electric field waveform at 0.1 m was opposite to that of the corresponding vertical electric field waveforms at 15 and 30 m, confirming that the 0.1-m field was essentially the radial electric field measured just above the lowest, horizontal channel segment while the 15-m and 30-m vertical electric fields at ground level were dominated by contributions from the higher, vertical part of the lightning channel. (For a charged L-shaped channel above ground, the direction of the electric field vector just above the horizontal element of the L is opposite to that of the electric field vector on the ground at a distance much greater than the length of the horizontal element of the L.) For all other events presented in this paper the polarity of vertical electric field waveforms at 0.1 to 1.6 m was the same as that at 15 and 30 m (see, for example, Figures 8 and 9).

[14] We now present measurements for the second *M* component that occurred after stroke 2 in Flash S0022 and whose channel was more vertical than for the *M* component after stroke 1 in Flash S0036 discussed above. Figure 10 shows, on a 100-μs timescale, the vertical electric field of this latter *M* component along with the corresponding current waveform (no electric fields at 5, 15, or 30 m were measured for this event). The background continuing current was less than several amperes and the time interval between the *M* component current peak and the preceding return-stroke current peak was about 5 ms. It is worth noting that typical *M* components occur when the background continuing current is of the order of tens to hundreds of amperes and are characterized by risetimes and peak currents of the order of hundreds of microseconds and hundreds of amperes, respectively [*Thottappillil et al.*, 1995]. The *M* component peak electric field was 48 kV/m at a distance of 0.1 m. This field value is much smaller than that of a typical leader/return stroke sequence at similar or even larger distances. Figure 11 shows, for comparison, the electric field waveform of a leader/return stroke sequence for which the return-stroke peak current was between 2.3 and 3.2 kA, similar to the peak current of the *M* component discussed above. For this leader/return stroke sequence, the horizontal distance between the Pockels sensor and the lightning channel attachment point was between 1.4 m and 1.6 m. The electric field peak of the leader/return stroke

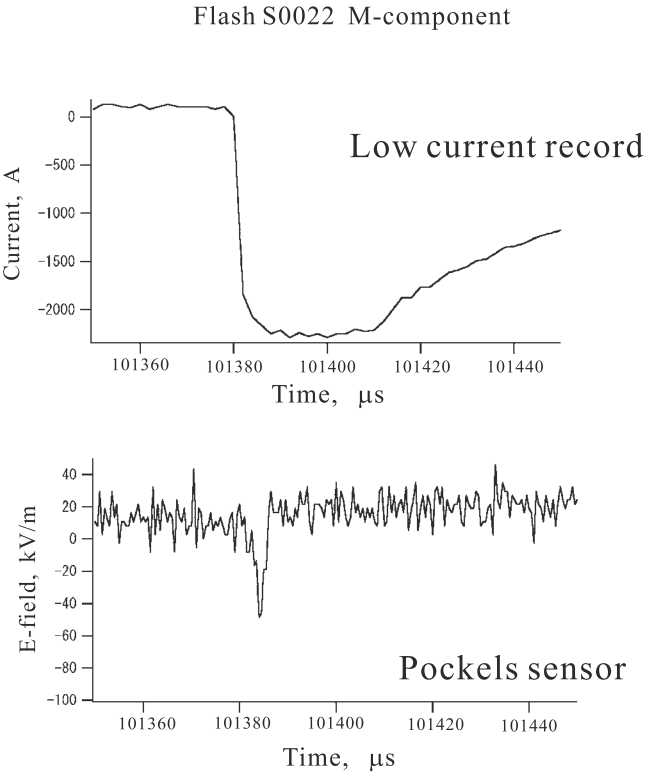

Figure 10. Channel-base current and corresponding 0.1-m vertical electric field of an *M* component that occurred after stroke 2 in Flash S0022, July 11, 2000. The current waveform is saturated at about 2300 A, with the peak value being between 2.3 and 3.2 kA.

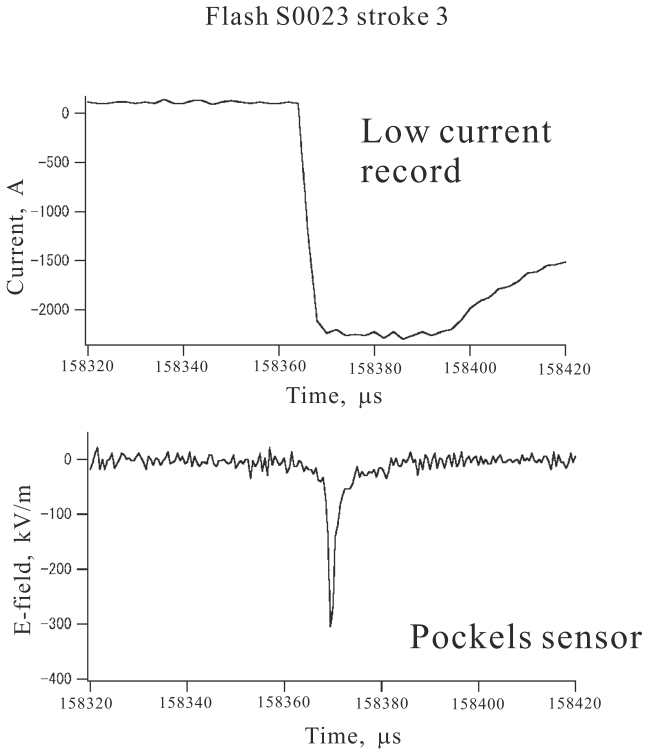

Figure 11. Same as Figure 10, but for a leader/return stroke sequence in Flash S0023, July 11, 2000, and for a horizontal distance of 1.4 to 1.6 m. The current waveform is saturated at about 2300 A, with the peak value being between 2.3 and 3.2 kA.

sequence was 305 kV/m. While the peak current of the return stroke was similar to that of the *M* component, the electric field peak of the leader/return stroke sequence 1.4 to 1.6 m from the attachment point is 6 times larger than that of the *M* component 0.1 m from the attachment point, consistent with the guided-wave mechanism of the *M* component [*Rakov et al.*, 2001].

4. Analysis and Discussion

4.1. Electric Field Waveforms

[15] The slower decaying electric field waveform at 0.1 m for stroke 1 in Flash S0033, shown in Figure 8, is possibly indicative of appreciable leader charge near the lightning attachment point that is not neutralized by the rapidly propagating return stroke but rather by another, slower (millisecond-scale) process. Note that the bulk of the leader charge is thought to be stored in the radial corona sheath surrounding the leader channel core. The effect of the leader charge left unneutralized by the return stroke is not seen at 15 m, possibly because this unneutralized charge remained only near the attachment point with the higher channel sections being discharged normally.

[16] As noted earlier, both the magnitudes and waveshapes of the horizontal electric fields are similar to those of the vertical electric fields, as illustrated in Figure 9. One explanation of this observation is that Pockels sensors installed to measure either longitudinal (vertical) or radial (horizontal) electric field component each actually measured a mix of those two components. The observed similarity of the magnitudes of the vertical and horizontal electric field waveforms suggests that a total electric field vector makes, on average, an angle of approximately 45° with respect to a vertical.

4.2. Relationship Between Electric Field Peak and Peak Current

[17] Figure 12 shows the relationship between the peak current and the magnitude of the electric field measured at 0.1 m and 1.4 to 1.6 m with Pockels sensors and at 5 and 15 m with flat-plate antennas. Data for the electric field at 30 m are not included in Figure 12 to avoid overcrowding, but the sample size and the correlation coefficient for this data set do appear in Table 1. Solid circles represent the vertical electric field measured with the Pockels sensor 0.1 m from the attachment point, hollow circles represent the vertical electric field measured with the Pockels sensor 1.4 to 1.6 m from the attachment point, and diamonds represent the horizontal electric field measured with the Pockels sensor 0.1 m from the attachment point. Solid and hollow triangles represent leader electric fields (not much different from return-stroke electric fields at distances ranging from 5 to 500 m and therefore used here as proxies for peak electric fields) measured by flat-plate antennas at 5 and 15 m, respectively. Sample sizes and linear correlation coefficients are summarized in Table 1. Similar information available in the literature for distances ranging from 9.3 to 500 m is also included in Table 1.

[18] As seen in Figure 12, there exists a relatively strong correlation between the vertical leader electric field at 5 or 15 m and the peak current. The correlation coefficients are

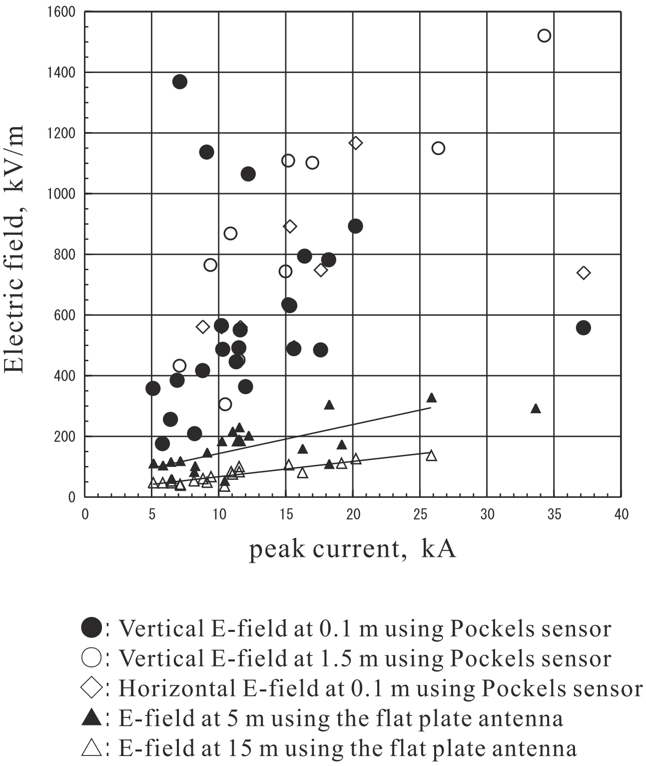

Figure 12. Relationship between close electric field and peak current.

Table 1. Relationship Between the Peak Current and the Magnitude of the Close Electric Fields[a]

Electric Field Component	Plot Symbol in Figure 12 or Reference	Sample Size	Correlation Coefficient
Vertical, 0.1 m	solid circle	22	0.16
Horizontal, 0.1 m	diamond	8	0.36
Vertical, 1.4–1.6 m	hollow circle	11	0.83
Vertical, 5 m	solid triangle	22	0.72
Vertical, 9.3 m	*Rakov et al.* [1998]	15	0.70
Vertical, 15 m	hollow triangle	20	0.91
Vertical, 19.3 m	*Rakov et al.* [1998]	8	0.95
Vertical, 30 m	this study	16	0.92
Vertical, 30 m	*Rakov et al.* [1998]	16	0.98
Vertical, 50 m	*Rakov et al.* [1998]	16	0.98
Vertical, 110 m	*Rakov et al.* [1998]	20	0.87
Vertical, 500 m	*Rubinstein et al.* [1995]	17	0.80

[a] See also Figure 12.

0.72 and 0.91 at 5 and 15 m, respectively. According to *Rakov et al.* [1998] and *Rubinstein et al.* [1995], at distances ranging from 9.3 to 500 m, the correlation coefficients are from 0.70 to 0.98 (see Table 1). There is also a relatively strong correlation between the vertical electric field peak at 1.4 to 1.6 m and the peak current (correlation coefficient 0.83). In contrast, there is essentially no correlation between the peak current and the vertical and horizontal electric field peak at 0.1 m, with the correlation coefficients being 0.16 and 0.36, respectively. For the total electric field peak, the correlation coefficient is 0.32. The lack of correlation observed at the closest distance, 0.1 m, is possibly related to the largest field-waveform distortion, since the fastest field waveforms are expected at this range. Note that the correlation coefficient between the peak current and the vertical electric field measured by Pockels sensor at 5 m is 0.69 (sample size 21), similar to that between peak current and electric field measured with the flat-plate antenna at the same distance (0.72; see Table 1).

4.3. Relationship Between Electric Field Peak and Previous No-Current Interval

[19] Figure 13 shows the relationship between the vertical electric field at distances ranging from 0.1 to 1.6 m and the previous no-current interval, that is, the time elapsed from the cessation of current of the preceding stroke (or of the initial-stage current). Some correlation exists between these two parameters: correlation coefficients are 0.75 and 0.79 for events with peak current below (16 values) and above (10 values) 12 kA, respectively. The electric field increases with an increase in the previous no-current interval. *Uman and Voshall* [1968] and *Picone et al.* [1981] theoretically showed how the temperature of the lightning channel decreases with elapsed time from the end of the return stroke. A decrease in channel temperature is accompanied by a decrease in channel conductivity [*Yos*, 1963]. Perhaps the correlation between the electric field peak and the previous no-current interval seen in Figure 13 implies that

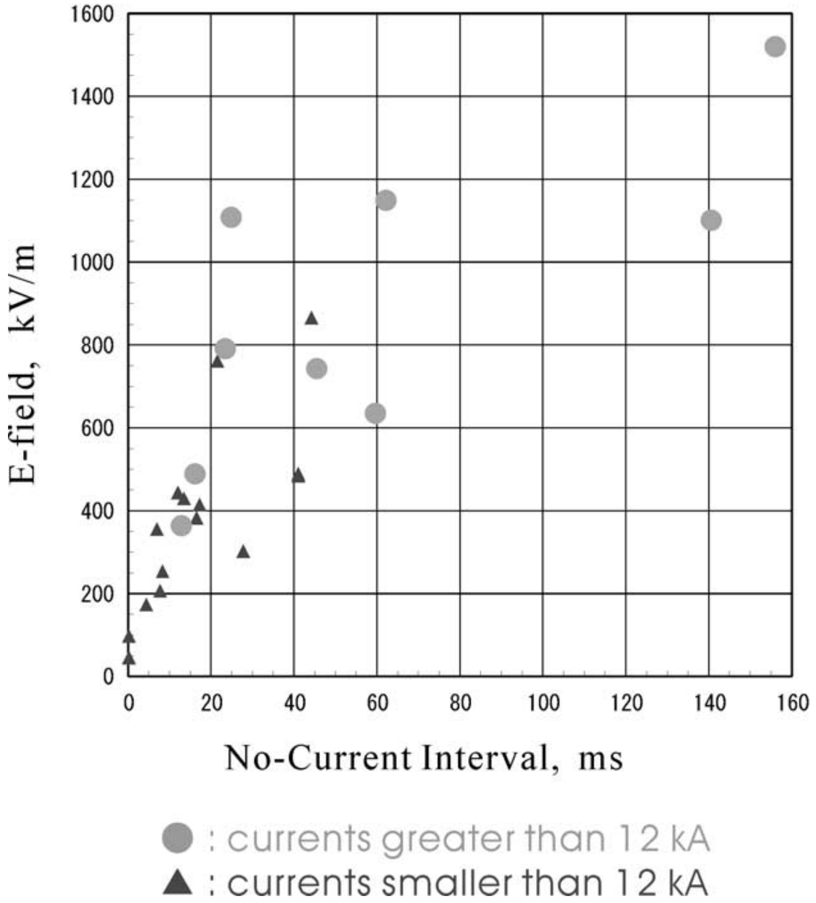

Figure 13. Relationship between vertical electric field at 0.1 to 1.6 m and previous no-current interval. Two data points on the vertical axis (zero no-current interval) correspond to *M* components.

the dart leader needs to establish a larger electric field across its front in order to be able to propagate along a channel of lower conductivity. Interestingly, the dart leader speed exhibits a stronger correlation with the return-stroke peak current than with the previous interstroke interval [*Jordan et al.*, 1992]. The speed increases with an increase in the peak current and tends to decrease (with a large scatter) with an increase in the interstroke interval. Thus, it appears that higher-front-field and slower dart leaders tend to propagate in the channels that have had more time to decay to lower electrical conductivity.

4.4. Maximum Measured Electric Field

[20] The maximum value of the measured electric field in this experiment was 1.5 MV/m (vertical electric field of stroke 1 in flash S0026). This value is similar to that expected to exist across the moving dart leader front [*Rakov*, 1998]. The channel of stroke 1 in flash S0026 branched and one of the branches contacted the Pockels sensor. Thus, the distance between the Pockels sensor and the lightning channel corresponding to the maximum measured field value was minimal, and the measured vertical electric field was radial with respect to the channel. As noted above, the peak electric fields measured using Pockels sensors may be underestimated by 40% or so (or more if electric field waveforms in the immediate vicinity of the lightning channel are appreciably faster than the fast 5-m electric field waveform shown in Figure 4) due to the insufficient upper frequency response of 1 MHz of the measuring system. If we apply a correction factor of 1.67 to the measured value of 1.5 MV/m to account for this 40% measurement error, we obtain a maximum value of electric field of 2.5 MV/m, which is close to the value of the breakdown field of 3 MV/m in a uniform air gap at sea level. As noted in section 2, we neglected any electric field distortion by Pockels sensors located 0.1 to 1.6 m from the lightning attachment point.

5. Summary

[21] We have conducted an experiment to measure the electric fields in the immediate vicinity of the lightning channel. Vertical electric fields for 36 strokes (leader/return stroke sequences) in nine triggered lightning flashes were obtained using a Pockels sensor. Both V-shaped and non-V-shaped electric field signatures were observed. For 8 out of the 36 strokes, horizontal electric fields were also measured using another Pockels sensor. Vertical electric field peaks were in the range from 176 kV/m to 1.5 MV/m (a median of 577 kV/m), and horizontal electric field peaks were in the range from 495 kV/m to 1.2 MV/m (a median of 821 kV/m). The electric fields were measured at distances ranging from 0.1 to 1.6 m from the channel attachment point. A maximum electric field value of 1.5 MV/m was measured for a stroke whose channel was branched with one of the branches contacting the Pockels sensor. This value is similar to that expected to exist across the propagating dart leader front, although it was for the radial field component with respect to the lightning channel. We additionally measured vertical electric field waveforms at 0.1 m due to two *M* components. For one of these *M* components, the electric field was a factor of 6 smaller than the electric field at 1.4 to 1.6 m due to a leader/return stroke sequence, while the peak currents of the *M* component and return stroke were similar, 2 to 3 kA. At a distance of 0.1 m there is essentially no correlation between the peak current and either the vertical or the horizontal electric field peak (or the total electric field peak) in contrast with a relatively strong correlation observed between the peak current and the peak electric field at horizontal distances ranging from 1.4 to 500 m from the channel attachment point. This lack of correlation for vertical or horizontal electric field at 0.1 m may be real or may be due to errors in measuring the field peak associated with the insufficient upper frequency response of the Pockels sensor measuring system. The electric field tends to increase with an increase in the previous no-current interval. This latter observation suggests that the electric field very close to the lightning channel is influenced by the age of the channel ahead of the dart leader tip.

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