

## MEASURED ENVIRONMENTS WITHIN 20 METERS OF THE STRIKE POINTS OF TRIGGERED LIGHTNING

R.J. Fisher, G.H. Schnetzer, and M.E. Morris  
Electromagnetic Analysis and Testing Department  
Sandia National Laboratories  
Albuquerque, NM 87185, USA  
Telephone (505) 845-8647 FAX (505) 844-7857

### ABSTRACT

Vertical electric fields, azimuthal magnetic fields, and earth voltages developed over 0.5-m radial step distances have been measured at 10 and 20 m from the ground attachment point of triggered lightning. The magnetic fields are found to follow Ampere's law closely. The relationship between maximum vertical electric field change due to a descending dart leader and the peak of its associated return-stroke current is linear. Recorded earth step voltages have the same waveforms as the incident return-stroke currents, and, for distances between 10 and 20 m from the strike point, their amplitudes exhibit a  $1/r$  dependence. Statistics are given for observed radial filamentary arcing from the ground attachment point.

### INTRODUCTION

A detailed knowledge of the electromagnetic environment very close to the ground strike point of lightning is of both general phenomenological interest and considerable importance in designing protection systems and assessing their effectiveness. Using triggered lightning to produce real lightning strikes to designated points on the earth, the electromagnetic environments at ground-level stations located 10 and 20 m from the channel bases were measured. The quantities that were recorded included vertical electric field ( $E_v$ ), horizontal (azimuthal) magnetic field ( $H_a$ ), and earth step potential differences ( $V_s$ ) developed over 0.5-m radial increments. During the summer of 1993, seven flashes were triggered in support of these experiments. Data were acquired on a total of 31 individual return strokes, with a range of peak return-stroke current amplitudes from 3.3 to 30 kA. The experiments were carried out at Ft. McClellan, Alabama at a flat test site that had been freshly cleared of vegetation 45 days prior to the beginning of the testing. The soil composition was heavy red clay, with an average conductivity of  $1.8 \times 10^{-3}$  S/m, the mean value derived from standard four-probe resistivity measurements conducted daily at five different locations throughout the 50-day fielding period. The general site layout is shown in Figure 1. Rocket launching and data recording operations were carried out using the Sandia Transportable Triggered Lightning Instrumentation Facility (SATTLIF), the details of which have been described elsewhere (1).

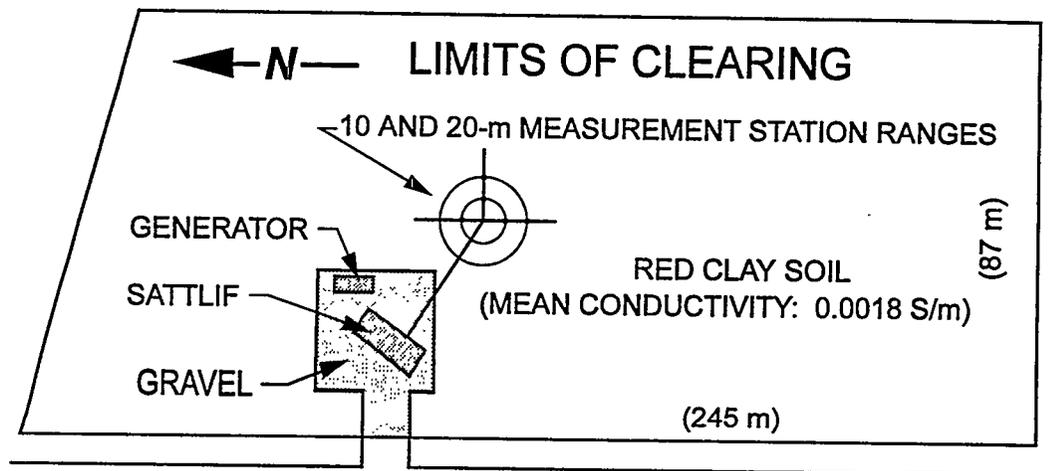


Figure 1. Overview of the 1993 triggered lightning experiment site

## EXPERIMENTAL PROCEDURES

A total of five monitoring stations were arrayed at 10- and 20-m radial distances from the base of the rocket launcher assembly (RLA), which served as the designated strike point for the triggered flashes. It was arranged that flash currents striking the RLA would flow to earth through the coaxial current shunt mounted below the main supporting frame of the launcher. The earthing point consisted of a zinc-coated steel ground rod below the steel instrumentation box that contained the current shunt and its associated fiber optic transmitter electronics. The ground rod depth was intentionally kept to a minimal length to simulate closely a strike to raw earth. Data were acquired during four separate storms. During the first two storms, the ground rod depth was 0.3 m, while for the last two, it was changed to 1.3 m.

Over the course of the summer, data were obtained at each of the monitoring stations indicated in Figure 2. During the first and second storms, identical complements of sensors were deployed at stations 1 through 3. Each consisted of a commercial magnetic field derivative detector (plus in-line active integrator), a flat plate vertical electric field sensor, and an earth step potential sensor with its two 0.3-m long probes separated by a distance of 0.5 m. Stations 1, 2, 4, and 5, comprised of different combinations of sensors as defined in Figure 2, were activated during storms 3 and 4. In this way, data were obtained as functions of radial distance (10 and 20 m) and of azimuth at the multiple monitoring positions around the 10- and 20-m arcs.

With the exception of the earth step potential measurement, the sensors, signal conditioning, data transmission links, and recording instrumentation were all substantially the same as were employed previously during the triggered lightning test of a munitions storage bunker that was conducted during 1991 (2). The technique used in measuring the earth step potentials is described below in the discussion of the experimental results. All of the data presented herein were recorded digitally with a 40-ns sampling interval. The 3-dB upper frequency limit of the incident stroke current measurement was 6 MHz, which was set by the frequency response of the current shunt. The upper frequency limit of the rest of the measurements was 10 MHz.

## **DISCLAIMER**

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

## **DISCLAIMER**

**Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.**

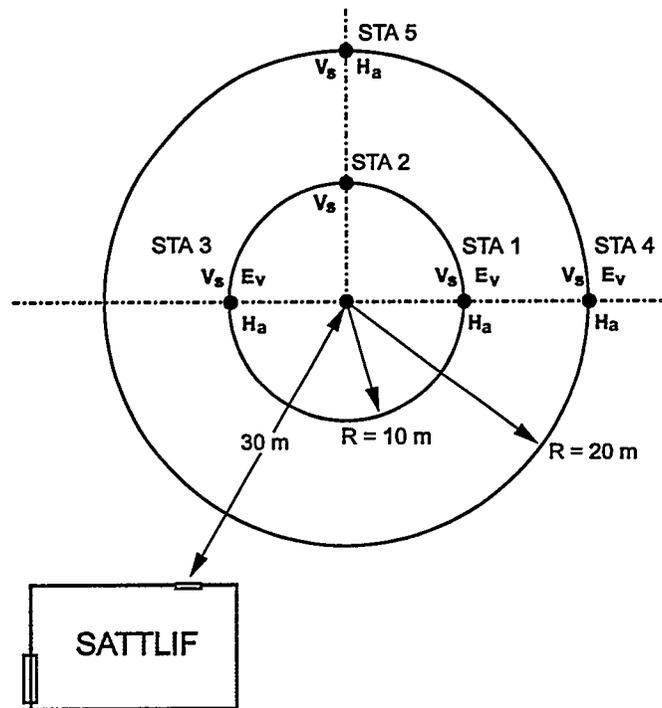


Figure 2. Measurement locations and assigned sensor groups. (Station 2 consisted of  $V_s$  sensor only during Storms 3 and 4; otherwise it was comprised of the full set of sensors.)

## DATA

**MAGNETIC FIELDS**—Plotted in Figure 3 are the peak values of the azimuthal magnetic fields measured at 10.7 and 20.7 m as a function of the peak amplitudes of their associated return-stroke currents. Linear regression lines are displayed for the data set corresponding to each distance. Ampere's law applied to this situation is given by the relationship

$$H(t) = I(t)/(2\pi r) \quad (1)$$

where  $H(t)$  is the magnitude of the azimuthal component of the magnetic field,  $I(t)$  is the current flowing in the channel, and  $r$  is the radial distance from the strike point. In the figure, curves corresponding to Eqn. 1 are plotted as solid lines for each distance. As can be seen, there is very close agreement between this relationship and the experimental data. The correspondence between the waveshapes of the incident stroke currents and their associated magnetic fields is virtually exact in most of the data, although instrumentation effects are evident at times beyond the peaks in some cases.

**VERTICAL ELECTRIC FIELDS**—Figure 4 is a plot of a typical vertical electric field change recorded at 9.3 m from the base of a stroke that was initiated by a dart leader. The V shape of the waveform is characteristic of electric field changes out to well beyond 500 m (3). The rate of change and peak amplitude of the wavefront preceding the bottom of the V is associated with the propagation velocity and linear charge density, respectively, of the descending dart leader. The rapid change following the peak corresponds to neutralization of leader charge as the return-stroke wavefront propagates up the channel from the ground.

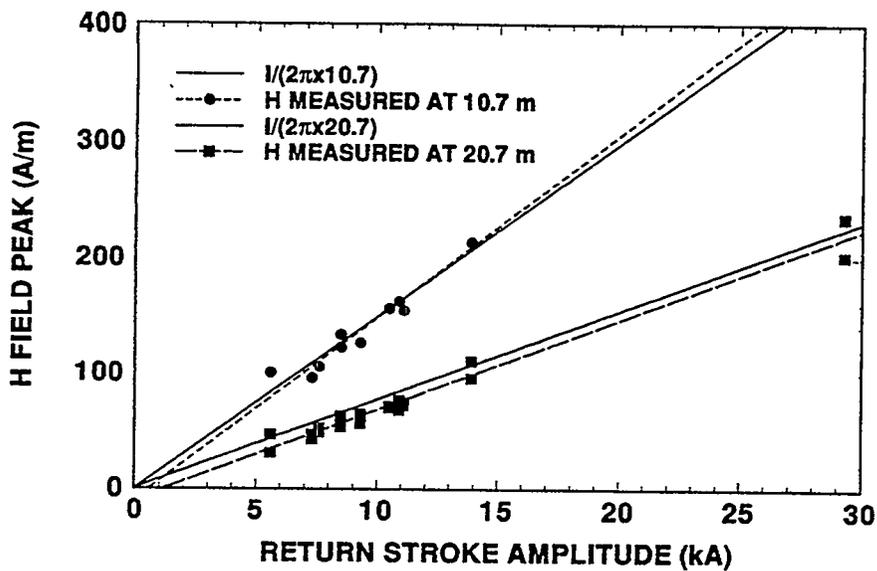


Figure 3. Comparison of Ampere's law with magnetic fields measured at 10.7 and 20.7 m from the strike point

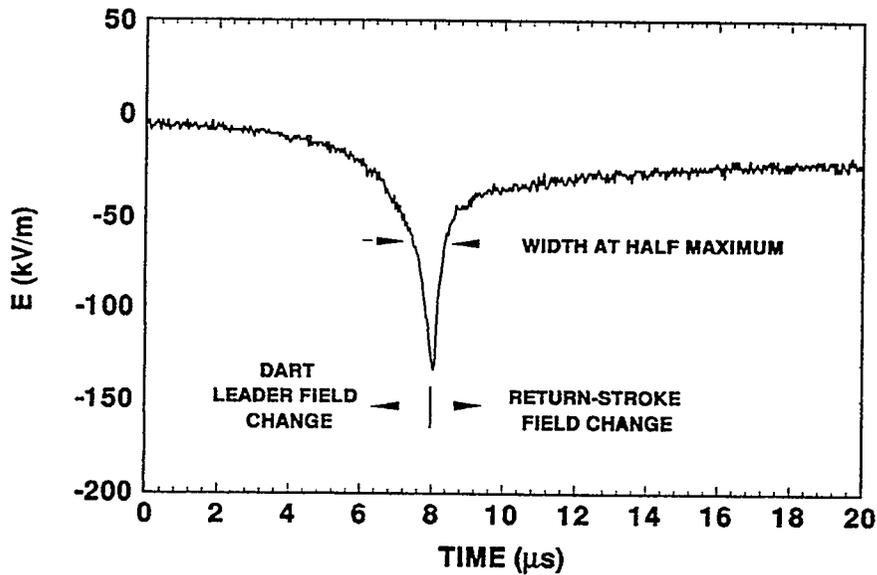


Figure 4. Typical electric field change recorded 9.3 m from the base of a return stroke preceded by a dart leader

Presented in Figure 5 is a plot of recorded peak return-stroke currents against their preceding dart leader electric field changes, as measured at 9.3 and 19.3 m from the channel. The evident linearity (correlation coefficients of 0.7 and 0.95 at the 9.3 and 19.3-m stations respectively) is presumably a consequence of the fact that peak return-stroke current amplitude is proportional to the charge per unit length deposited by the dart leader over the last 100 m or so of its channel. Assuming a linear charge distribution, the proportionality constant is the return-stroke propagation velocity.

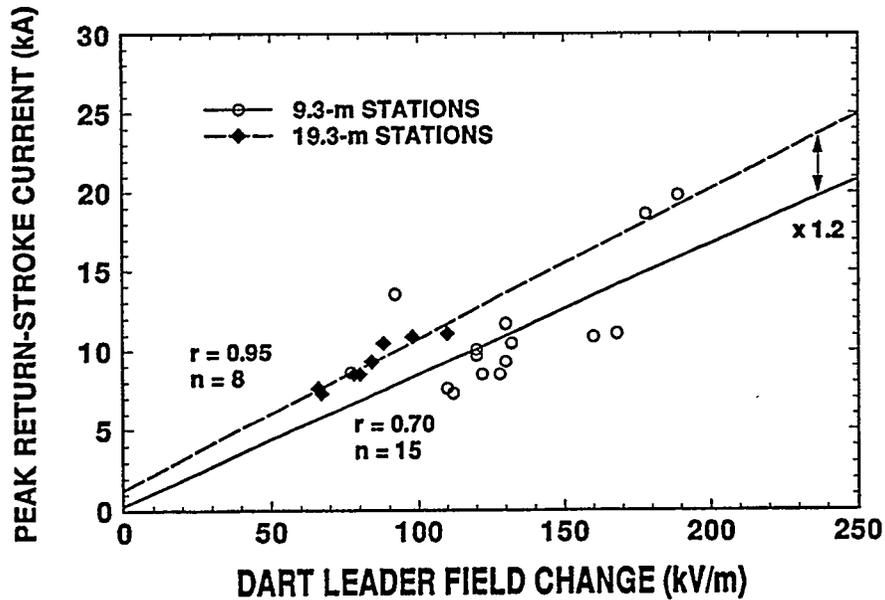


Figure 5. Peak return-stroke current as a function of peak dart leader electric field changes recorded at 9.3 and 19.3 m from the ground strike point

On two occasions, measurements were obtained of electric field changes on strokes preceded by dart-stepped leaders. One example is given in Figure 6. In both instances, the strokes were the final ones in their respective flashes, and both were preceded by extraordinarily long interstroke intervals, namely 345 and 290 ms, respectively. (The median value interstroke interval in triggered flashes in Florida and Alabama is 48 ms(4).) The mean interval between steps in the two examples that were obtained is

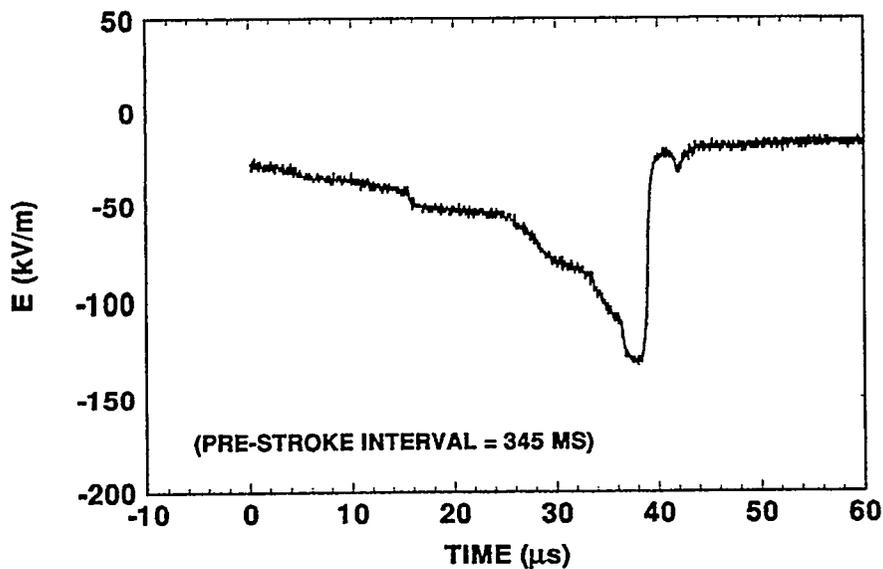


Figure 6. Example of an electric field change recorded 9.3 m from the base of a return stroke preceded by a dart-stepped leader

6.3  $\mu\text{s}$ , a value consistent with data for dart-stepped leaders during the last tens of microseconds prior to return strokes in naturally initiated lightning in Florida, 6.5  $\mu\text{s}$ , and Arizona, 7.8  $\mu\text{s}$ , (5).

**RADIAL EARTH STEP VOLTAGES**—The technique employed in measuring voltages developed by return-stroke currents injected into the earth at the base of the rocket launcher is shown in Figure 7. An adequate equivalent circuit of this measurement is shown in Figure 8. Because the impedance of the instrumentation circuit is so much higher than the source impedance presented by the earth at the probe terminals, the earth voltage is unperturbed by the presence of the measurement circuit. Stray magnetic or electric field coupling into the measurement circuit was not found to be a problem.

The major results from these measurements are summarized in Figure 9, in which the peak voltages recorded at the 10- and 20-m stations are plotted against peak return-stroke current. As is evident, the voltages are highly linear with respect to the stroke currents that produced them (correlation coefficients of 0.97 at 10 m and 0.98 at 20 m). In those cases for which multiple-station data are available, the voltages from the different stations agree very closely in both amplitude and waveshape. From this it is inferred that the spatial distribution of current density flowing within the earth outward from the injection point must be essentially uniform. Perhaps more precisely stated, there appear to be no significant net effects from any local nonuniformities in that current distribution. This result would, of course, not hold in the presence of any buried

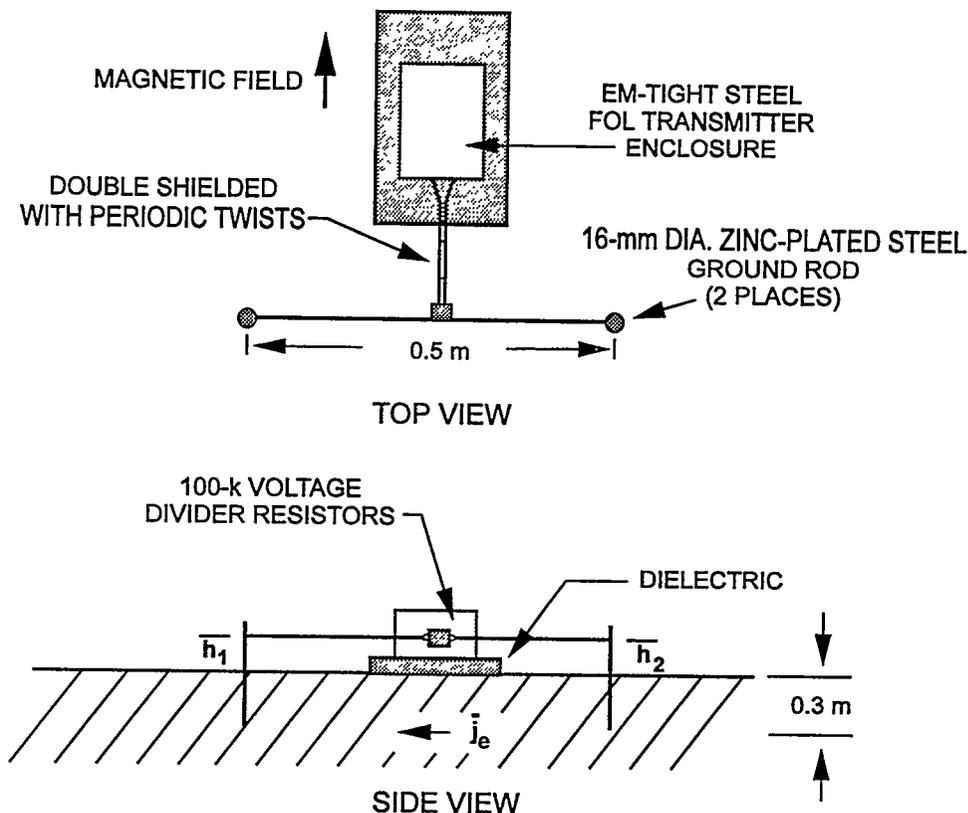


Figure 7. Technique used to measure radial earth step voltages

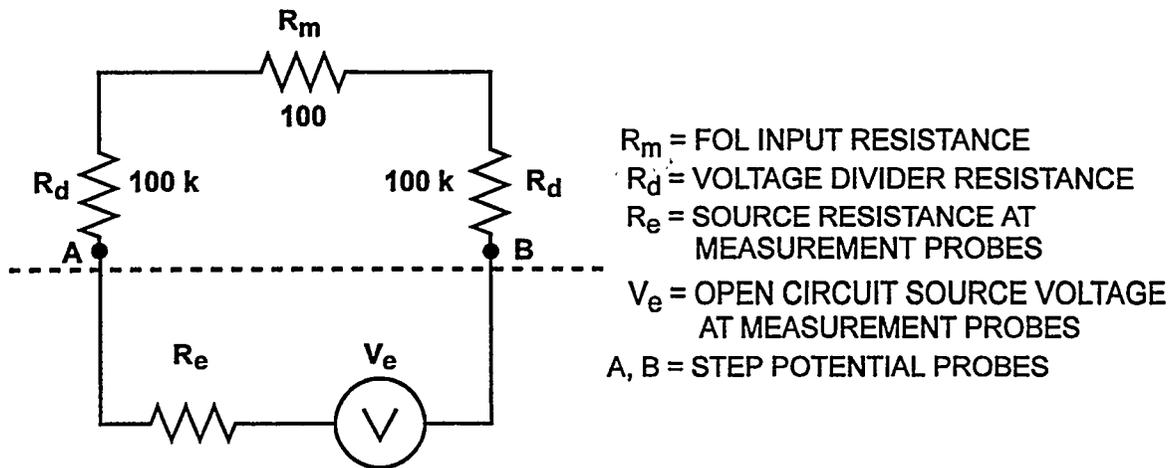


Figure 8. Equivalent circuit model of earth step measurement in Figure 7

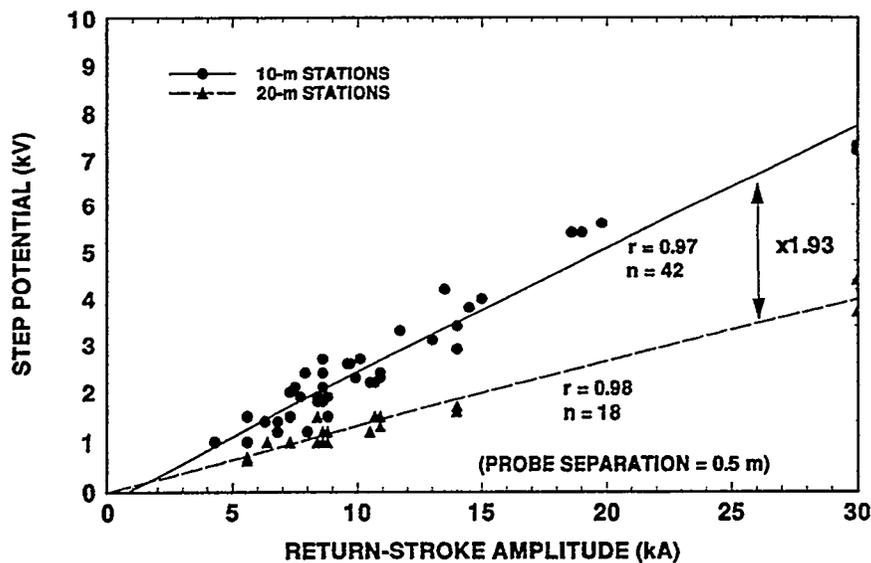


Figure 9. Peak earth voltages developed over 0.5-m step distances measured at 10 and 20 m from triggered lightning strike points plotted against peak return-stroke current

conductors, such as pipes, cables, or even major tree roots; but this situation was intentionally avoided during the present experiments. The waveshapes of the recorded voltages are virtually identical to those of their associated stroke currents.

Perhaps the most interesting feature of the step voltage data is the rate at which they scale with distance from the strike point. Based on the fitted regression line in Figure 10, this dependence is very close to  $1/r$  between the 10 and 20-m stations. This is contrary to the expectation of a  $1/r^2$  functionality that would be predicted by the uniform hemispherical model of current density that is often employed to estimate earth potentials close to a strike point to earth. An alternative model has been proposed that produces very good agreement with the limited present data (7). The model involves

the assumption of a thin surface layer of much higher conductivity than that of the bulk of the earth below it. The high conductivity layer is ascribed to standing rain water, which existed more or less uniformly over the test site during the triggering sessions. Unfortunately, with the limited amount of presently available data, it is not yet possible to validate definitively this or any other model for explaining the observed behavior.

**RADIAL SURFACE ARCING**—In addition to the active electrical measurements described above, numerous video records were taken from various angles and with different fields of coverage. Sixteen-millimeter high speed movies with 5-ms time resolution were also obtained on 5 of the 7 triggered flashes. These records revealed the frequent occurrence of substantial radial surface arcing outward from the ground attachment point. As indicated in Figure 10, significant arcing was detected on 100 percent of all strokes with peak currents of 15 kA or greater, as well as on a significant fraction of strokes with currents below that level. The arcing appeared to be random in direction. Not every stroke in the same flash produced a detectable arc, and during some flashes, arcs occurred in one direction on one stroke and in another direction on some other stroke. Following each storm the area around the base of the RLA was carefully examined for residual evidence of arcing. With the exception of localized occurrences of splintering of pieces of plywood, which were placed on the ground to avoid standing in mud when working around the launcher, no such evidence was observed. Nor were any fulgurites found when the earthing rod was either removed or changed. What was observed, however, was distinct evidence of discrete, concentrated current exit points at several spots along the length of the steel ground rods after they were removed from the earth.

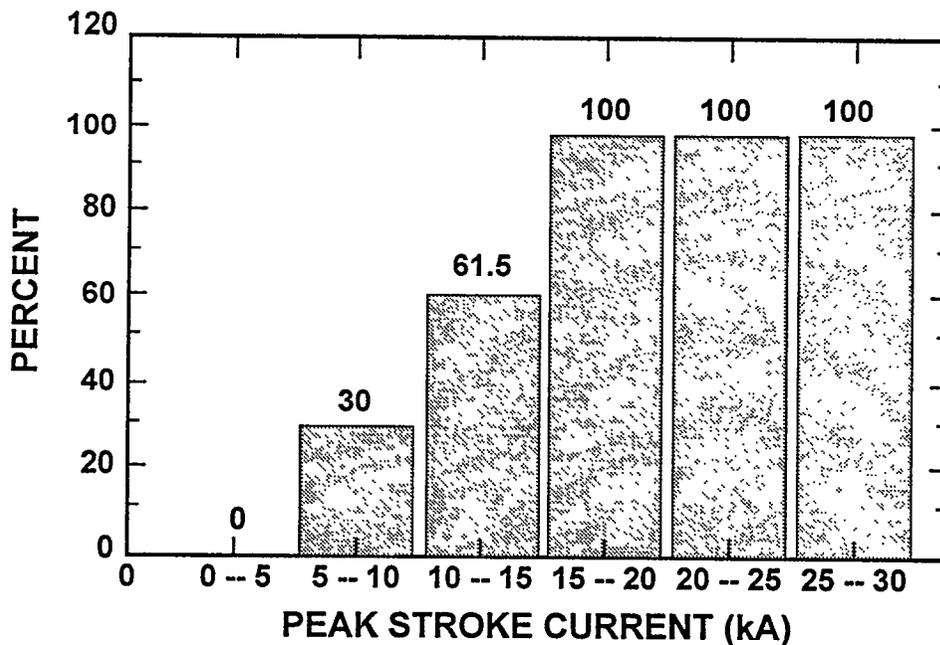


Figure 10. Frequency of detected surface arcing from the base of a poorly grounded triggered lightning termination mast as a function of peak return-stroke current amplitude

During one particular stroke of 20-kA peak amplitude, the Station 1 instrumentation was contacted by one branch of a surface arc. Analysis of the behavior of the various sensors at that station indicated that the arc carried approximately 1 kA, or about 5 percent of the peak current of that stroke. The most impressive photograph of this arcing phenomenon that was obtained is shown in Figure 11. The right edge of the photograph represents a distance of 10 m from the strike point under the RLA. The horizontal branch of the arc can be seen to have reached this range. As deduced from excursions in the signals recorded at one or more of the 20-m station sensors on two other occasions, a range of at least 20 m was attained by some of the arcs. Whether this distance was ever exceeded cannot be determined with certainty from the present data.

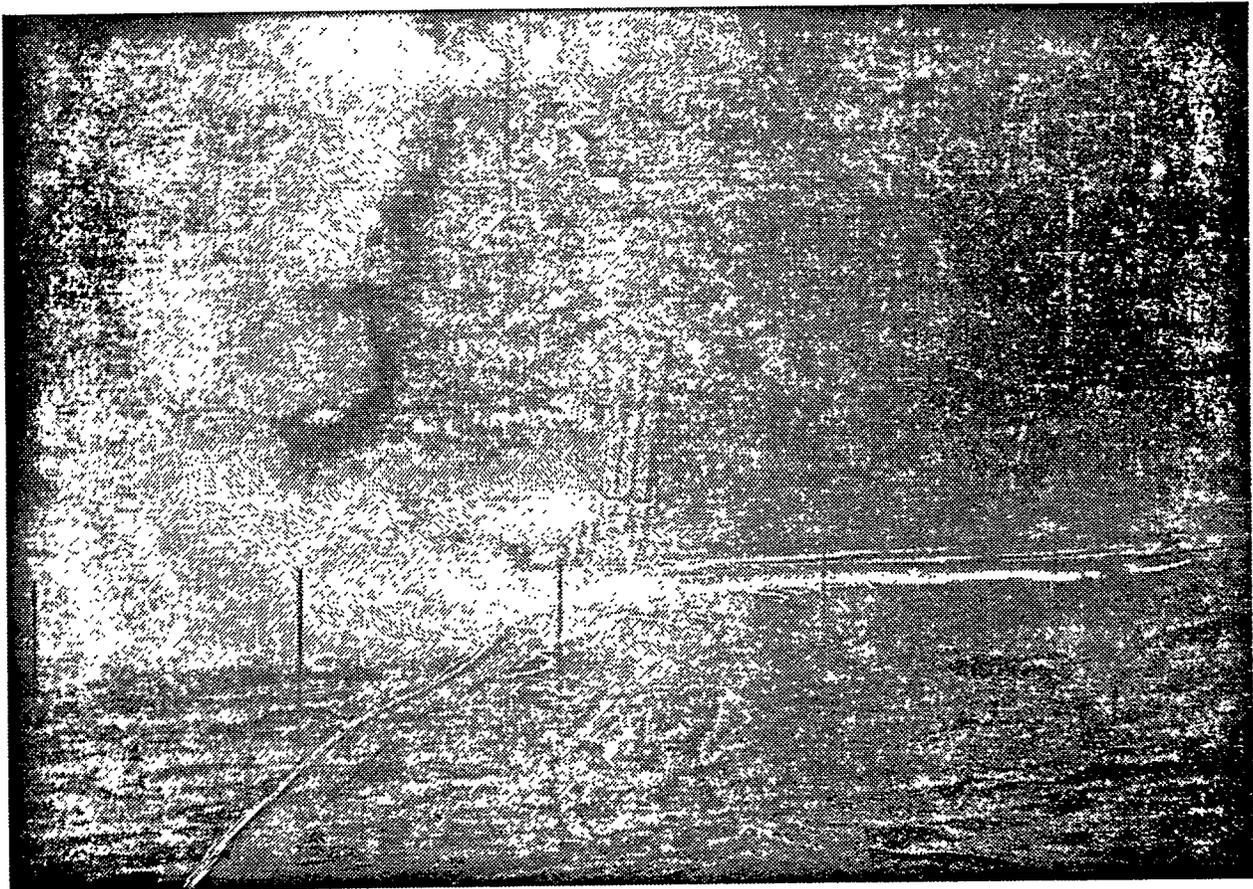


Figure 11. Still photograph of radial branched surface arcing from the base of a triggered lightning channel; the observed arcing occurred on the second stroke (peak current of 29.4 kA) of Flash 93-12. (Attachment of the return stroke to the top of the strike rod is outside the field of view.)

## CONCLUSIONS

Analysis of the data performed to date has resulted in the following conclusions:

1. The magnetic field at ground level out to a range of at least 20 m from the base of a lightning channel is well described by Ampere's law.
2. Subsequent return-stroke current amplitudes are linear with respect to the peak electric field changes produced by the dart leaders that initiate them.
3. Vertical electric field change amplitudes as high as 300 kV/m, occurring with rise times of the order of a few microseconds, can be experienced at a range of 20 m from a lightning channel, which is carrying a return-stroke current of 30 kA.
4. Earth step potentials measured at 10 and 20 m from the strike point are linear with return-stroke current and have the same waveshape as their associated return-stroke currents. Over the range of 10 to 20 m, their peak magnitudes fall off as  $1/r$ .
5. The likelihood of significant radial surface arcing out to ranges well in excess of 20 m must be considered to be part of the hazardous environment close to the base of a lightning channel, even in areas of relatively high earth conductivities. Individual branches of such arcs can carry appreciable fractions of the peak value of return-stroke current.

## ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy under Contract DE-AC04-94AL85000 and by the U.S. Department of the Army, Armament Research, Development and Engineering Center, Picatinny Arsenal.

## REFERENCES

1. Schnetzer and R.J. Fisher, "The Sandia Transportable Triggered Lightning Instrumentation Facility," Int. Aerospace and Ground Conf. on Lightning and Static Electricity, Cocoa Beach, April 16-19, 1991.
2. Schnetzer and R.J. Fisher, "Rocket-Triggered Lightning Test of an Earth-Covered Munitions Bunker," Int. Aerospace and Ground Conf. on Lightning and Static Electricity, Atlantic City, October 2-5, 1992.
3. Uman, V.A. Rakov, R. Thottappillil, T. Vesaggi, A. Eybert-Berard, L. Barret, P.P. Barker, and S.P. Hnat, "Multiple-Station Measurements of Close Electric and Magnetic Fields Produced by Triggered Lightning," Fall Meeting of the American Geophysical Union, San Francisco, December 1993.
4. Fisher, G.H. Schnetzer, R. Thottappillil, V.A. Rakov, M.A. Uman, and J.D. Goldberg, "Parameters of Triggered Lightning in Florida and Alabama," *J. Geophys. Res.* 98, 22,887-22,902, 1993.
5. Krider, C.D. Weidman, and C.R. Noggle, "The Electric Fields Produced by Lightning Stepped Leaders," *J. Geophys. Res.* 82, 951-960, 1977.
6. Fisher, G.H. Schnetzer, and M.E. Morris, "Measured Fields and Earth Potentials at 10 and 20 m from the Base of Triggered Lightning Channels," 22nd Int. Conf. on Lightning Protection, Budapest, September 19-23, 1994.