N73-11658

NASA CONTRACTOR REPORT

NASA CR-2161

NASA CR-2161

CASE FILE COPY

LIGHTNING CRITERIA RELATIVE TO SPACE SHUTTLES: CURRENTS AND ELECTRIC FIELD INTENSITY IN FLORIDA LIGHTNING

by Martin A. Uman and D. Kenneth McLain

Prepared by
WESTINGHOUSE RESEARCH LABORATORIES
Pittsburgh, Pa. 15235
for George C. Marshall Space Flight Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • NOVEMBER 1972

1. REPORT NO.
NASA CR-2161

2. GOVERNMENT ACCESSION NO.

3. RECIPIENT'S CATALOG NO.

4. TITLE AND SUBTITLE
Lightning Criteria Relative to Space Shuttles: Currents and Electric Field Intensity in Florida Lightning.

5. REPORT DATE
November 1972

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
Martin A. Uman and D. Kenneth McLain

8. PERFORMING ORGANIZATION REPORT #
M106

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Westinghouse Research Laboratories
Pittsburg, Pennsylvania 15235

10. WORK UNIT NO.

11. CONTRACT OR GRANT NO.
NAS8-28168

12. SPONSORING AGENCY NAME AND ADDRESS
NASA
Washington, D.C.

13. TYPE OF REPORT & PERIOD COVERED
Contractor Report

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES
Prepared under the technical monitorship of the Aerospace Environment Division, Aero-Astrodynamics Laboratory, NASA-Marshall Space Flight Center.

16. ABSTRACT

The measured electric field intensities of 161 lightning strokes in 39 flashes which occurred between 1 and 35 km from an observation point at Kennedy Space Center, Florida during June and July of 1971 have been analyzed to determine the lightning channel currents which produced the fields. In addition, typical channel currents are derived and from these typical electric fields at distances between 0.5 and 100 km are computed and presented. On the basis of the results recommendations are made for changes in the specification of lighning properties relative to space vehicle design as given in NASA TMX-64589 (Daniels, 1971). The small sample of lightning analyzed yielded several peak currents in the 100 kA range. Several current rise-times from zero to peak of 0.5 μsec or faster were found; and the fastest observed current rate-of-rise was near 200 kA/μsec. The various sources of error are discussed.

17. KEY WORDS
Atmospheric electricity, Lightning, Design criteria, Peak currents, Lightning channel currents, Current rise times.

18. DISTRIBUTION STATEMENT

19. SECURITY CLASSIF. (of this report)
UNCLASSIFIED

20. SECURITY CLASSIF. (of this page)
UNCLASSIFIED

21. NO. OF PAGES
41

22. PRICE
$3.00

* For sale by the National Technical Information Service, Springfield, Virginia 22151

Table of Contents

	Page
Introduction	1
Theory	3
The Experiment	6
Results	8
Errors	15
Discussion	21
Conclusions and Recommendations	24
Acknowledgment	25
References	26
Figures	28

LIGHTNING CRITERIA RELATIVE TO SPACE SHUTTLES: CURRENTS AND ELECTRIC FIELD INTENSITY IN FLORIDA LIGHTNING

by

Martin A. Uman*
and
D. Kenneth McLain
Westinghouse Research Laboratories
Pittsburgh, Pennsylvania 15235

Introduction

Only a few hundred reliable measurements have been made of lightning current vs. time, and all of these represent the current flowing at the base of the lightning channel [Uman, 1969]. Furthermore, most of these measurements involved lightning to tall structures, and it is not clear whether such lightning is similar to strokes to relatively flat ground.

Aircraft and launch vehicles in flight are natural targets for lightning. Thus, it is important to have adequate statistics on current in lightning channels above the ground in order to be able to protect aircraft and vehicles against the deleterious effects of lightning.

Several attempts have been made to derive return-stroke channel current waveforms from measured electric or magnetic fields (e.g., Norinder and Dahle, 1945; Croom, 1964; Srivastava and Tantry, 1966). In none of these studies was the time resolution of the measurement adequate to allow the current risetimes to be properly

---

*Present affiliation: Department of Electrical Engineering, University of Florida, Gainsville, Fla. 32601

calculated. Further, the most extensive work, that of Norinder and co-workers, employed theory which was in error (Uman and McLain, 1969). All previous studies designed to extract current from measured fields have employed the return stroke model of Bruce and Golde [1941].

We have been unable to find in the literature any detailed analysis on a microsecond time-scale of the electric field intensity produced by close (within 10 km) lightning return strokes in cloud-to-ground flashes. A number of calculations of the electric field due to distant (over 100 km) lightning have been made using the moment equation approximation [see McLain and Uman, 1971]; and Morrison [1952], using the same approximation, has computed the electric field at distances between 16 and 100 km for an atypical lightning current rising to peak value in about 50 μsec and decreasing to half of peak value in about 200 μsec.

In the present report we first find a "typical" lightning return-stroke current waveform from measured radiation (distant electric) fields using the technique described by Uman and McLain [1970a], and then, with the derived current, compute the electric field intensity at distances between 0.5 and 100 km using the expression given by McLain and Uman [1971]. The predicted electric field waveforms for close lightning are then compared with measured waveforms. Following this we derive from electric fields measured close to lightning the return stroke currents necessary to produce those fields.

Theory

The electric field intensity E at a distance D from the bottom of a straight vertical channel of height H due to the return stroke current i(z,t) is given by McLain and Uman [1971] as

$$E(D,t) = \frac{2}{4\pi\varepsilon_o}\left[\int_o^H \int_o^t \frac{(2-3\sin^2\theta)}{r^3}\, i(z,\tau - \frac{r}{c})\, d\tau\, dz \right.$$

$$+ \int_o^H \frac{(2-3\sin^2\theta)}{c\, r^2}\, i(z,t - \frac{r}{c})\, dz \qquad (1)$$

$$\left. - \int_o^H \frac{\sin^2}{c^2 r}\, \frac{\partial i(z,t - \frac{r}{c})}{\partial t}\, dz \right]$$

where E is perpendicular to the ground plane, assumed infinitely conducting, and all geometrical parameters are defined in Fig. 1. The first term on the right of (1) is called the electrostatic field, the second the induction or the intermediate field, the third the radiation field. For D>>H (the radiation field dominant) and a constant return-stroke wavefront velocity v, Uman and McLain [1970a] have solved (1) for current in terms of electric field for two return stroke models. In this paper we consider only the transmission line model of Uman and McLain [1969] in which a given current waveshape propagates up the lightning channel at velocity v behind the wavefront: that is, $i(z,t) = i(t-z/v)$. In this case

$$i(t) = \frac{2\pi c^2 \varepsilon_o D}{v}\, E(t + \frac{D}{c}) \qquad (2)$$

as long as $t < H/v$. That is, the current and the electric field have the same waveshape until the return stroke wavefront reaches the top of the channel, a time typically between 20 and 200 μsec.

In order to use the approach described above, we must justify the approximation of a constant return stroke wavefront velocity. According to Schonland [1956], this is the case for return strokes subsequent to the first, with two-dimensional velocities ranging from 2.4×10^7 to 1.1×10^8 m/sec. For first return strokes, the wavefront velocity according to Schonland et al. [1935] is constant between major branches (14 strokes were analyzed). For three first strokes for which detailed data are presented, Schonland et al. [1935] report constant return stroke velocities from ground upward of 1.6×10^8 m/sec for 10 μsec, 5.2×10^7 m/sec for 13 μsec, and 9.2×10^7 m/sec for 17 μsec. Thus for first return strokes it may be reasonable to assume a constant return stroke velocity for about 10 μsec. It follows that calculations for current rise time and peak value are probably valid if, as is usually the case, they occur before about 10 μsec. In this paper we will carry the calculations to 30 μsec and in the absence of other information, will assume that v for first and for subsequent strokes is constant for this time.

As stated, we use a transmission-line model to describe the return-stroke. The most commonly used return stroke model has been that of Bruce and Golde [1941]. In the Bruce-Golde model the channel current is assumed uniform along the channel but time-varying below the return stroke wavefront and zero above. We reject the Bruce-Golde model for several reasons: (1) our computer studies show that it cannot account for the broad initial hump (mostly electrostatic field) observed by us on very close (less than 1 km) electric field waveforms (see Figs. 6 and 8) whereas the transmission line model can; (2) it cannot account for the mirror image effect (Fig. 7 of Fisher and Uman, 1972; Fig. 2c of Taylor, 1963) observed previously and in a number of Florida storms during summer 1971 whereas the transmission line theory can as illustrated by Eqs. (11) and (12) of Uman and McLain,[1970b]; and (3) it is not physically reasonable in that it requires an infinitely fast information transfer along the channel, and even a version of it which is physically reasonable [Dennis and Pierce, 1964] makes less physical "sense" than the transmission line model. Both the Bruce-Golde and the transmission line models are of about equal complexity to use. It is interesting to note that for a linear or concave current-rise to peak, as is observed, both models predict that the peak field and the peak current are attained in the same time. On the other hand, for linearily rising currents and for a given measured electric field value, the Bruce-Golde model yields a peak current 1/2 that found from the transmission line model and for concave rising currents even less (compare Eqs. (6) and (12) of Uman and McLain, 1970a).

The Experiment

The bulk of the electric field measurements on which this report is based were obtained at Kennedy Space Center, Florida during June and July of 1971. Data were also obtained near Pittsburgh, Pennsylvania during the summer of 1970 [Fisher and Uman, 1972] and near Tucson, Arizona during the summer of 1971. Electric field waveforms recorded at these three locations are qualitatively similar. At each location a range of electric field parameters (e.g., risetime, peak value) was observed. The system used to record the electric field waveforms presented in this paper is that described by Fisher and Uman [1972] but modified to have a 2.5 μsec signal delay, a system rise time of slightly less than 0.5 μsec, and a system response to a step function input which decays 30 percent from peak in about 60 μsec.

The antenna was placed on a sandy beach about 10 m from the Atlantic Ocean at Kennedy Space Center, Florida. Distances to the lightning flashes studied were determined from the time separation on strip chart records between the channel light output and thunder arrival for strokes within about 18 km. Several more distant lightning flashes were located from a comparison of visual channel observation with radar maps. Measurements were made on flashes both over land and over water. A total of 98 strokes in 21 flashes at distances less than or equal to 10 km and 63 strokes in 18 flashes at distances between 10 and 32 km were analyzed for return stroke current. Of the latter 18 flashes, 31 strokes in 8 flashes were over water. Of the 98 close strokes, 95 were from a single storm system.

The signs of all measured electric field waveforms presented in this report are indicative of the lowering of negative charge from cloud to ground.

Results

Typical electric field waveforms from a multiple-stroke lightning flash at a distance between 20 and 40 km are shown in Fig. 2. Distant waveforms from Florida are very similar to the distant waveforms recorded in Pennsylvania (see, for example, Figs. 4-6 of Fisher and Uman, 1972). The waveforms in Fig. 2 are primarily radiation field. The first few tens of microseconds of more distant waveforms (100 km) are essentially pure radiation field, but may suffer propagation distortion as evidenced by a degradation of the risetime and a rounding of the initial peaks and other high frequency components (Fisher and Uman, 1972). We have examined about a thousand waveforms from 16 Florida storms in the distance range 20 to 100 km. The waveforms from the closer part of this range were used to determine typical radiation-field rise-time and behavior around peak while the more distant waveforms were used to obtain data on radiation field fall-time. In this way "typical" radiation field waveforms were derived. "Typical" return-stroke currents were found from these radiation fields using (2). As evident from (2) the current has the shape of the electric field intensity at 100 km (in the absence of propagation distortion). "Typical" currents are shown in Figs. 3-5. Roughly 30 percent of the distant first-stroke fields and 60 percent of the distant subsequent stroke fields could be well approximated by the shape of the 100 km field of Figs. 3a, 4a, and 5a. Roughly 50 percent of the distant first-stroke fields could be well approximated by the shape of the 100 km fields of Figs. 3c, 4c, and 5c. The most common variations from the "typical" were a range of field fall-times, the presence of multiple peaks, and a range of risetimes mostly between 0.5 and 5 μsec.

In Figs. 3-5 is shown the electric field intensity computed from (1) using the transmission-line model for various distances from a typical stroke current for a constant product vI_p (I_p is peak current) and three values of v and I_p. Keeping vI_p constant forces the distant radiation field magnitude to be the same in each drawing via (2). It is assumed that the return stroke wavefront takes more than 30 μsec to reach the channel top, and hence no electric field variation associated with the end of the channel is shown. Figs. 3-5 scale linearly with I_p. For example, if Fig. 3 is to be used for a peak current of 100 kA, the values of electric field given on the ordinate should be multiplied by 5. The field waveshapes at close range are strong functions of v.

We have computed the electric field intensity as a function of distance and return stroke velocity for a range of observed distant waveforms (and currents) and find them all qualitatively similar to the waveforms of Figs. 3-5. The following two results of the calculation are worth comment: First, the distance at which the initial field peak, essentially radiation field, can no longer be discerned is a function of the sharpness (width) of the peak. Sharper peaks can be discerned at closer distances. Second, for a given v, the value to which the close electric field rises at a given time after the initial peak, essentially electrostatic field, depends primarily on the time integral of the current, the charge transferred, to that time. Thus, the slower the distant radiation field falls with time, the higher the close electrostatic field will rise. After the electrostatic field maximum the field decreases slowly with time. When the stroke current has ceased to flow at all points in the channel, the total charge involved in the current waveform has effectively been lowered from the top to the bottom of the channel. The final field value (actually the field change) can be computed from the standard formula (Eq. 3-37, Uman, 1969). For example, for the case given in Fig. 4a and a 5 km high channel, the field at 0.5 km will reach a final value of 58 V/m (its peak is about 1300 V/m), while the field at 10 km will reach a final value of 5.3 V/m.

Figs. 6-11 show measured return-stroke field waveforms from close strokes. All the data shown are from the same storm. The field of the single stroke flash at 0.5 km shown in Fig. 6 could have been produced by a range of return stroke velocities and current waveshapes: For example, a current rising to a peak of 41 kA at 5 μsec and fall-time to half value at 17 μsec in conjunction with a return stroke velocity of 4×10^7 m/sec; or a risetime of 10 μsec to 58 kA and fall-time to half value at 30 μsec in conjunction with a velocity of 1×10^8 m/sec. Figs. 7 and 8 show the fields of close multiple stroke flashes for which no distance ranging was available. From the size of the fields and the time of occurrence during the storm we strongly suspect that the flashes were at about 1 km. The waveforms of Fig. 7 are very similar to the calculated field in Fig. 5a for $v = 1.6 \times 10^8$ m/sec, a distance between 0.5 and 1 km, and peak currents in the 25 to 50 kA range. In Fig. 8 initial radiation field peaks are apparently present on both the first and subsequent strokes. The waveforms are qualitatively similar to those shown in Fig. 4a for a distance slightly greater than 1 km. Some of the late-time decrease in the first-stroke field may be due to system response. Fig. 9 shows fields at 1.1 km. The various stroke fields can be produced by peak currents in the range 20 to 60 kA with return stroke velocities of $1.6 (\pm 0.4) \times 10^8$ m/sec. Velocities outside of this range do not allow the measured wave shape to be adequately reproduced. Fig. 10 shows return stroke field waveforms at 1.5 km. Two of these are analyzed in detail in Fig. 13. Currents which produced the waveforms of Fig. 10 fall in the range 30 to 120 kA with velocities of 1.6 $(\pm 0.4) \times 10^8$ m/sec. Fig. 11 shows return stroke field waveforms at 4.5 km. The first and a subsequent stroke field are analyzed in detail in Figs. 12 and 13. The first stroke peak current is in the range 37 to 75 kA with a velocity of $1.2 (\pm 0.4) \times 10^8$ m/sec. Several of the subsequent stroke fields shown in Fig. 11 required a velocity of $2.4 (\pm 0.4) \times 10^8$ m/sec, remarkably close to the speed of light, in order that the computed waveform match the measured.

While most of the close strokes measured in Florida (the majority from a single storm) have electric field waveshapes indicative of return stroke velocities near or above the upper limit of the range reported by Schonland et al. [1935] and Schonland [1956], most of the electric field waveshapes recorded from close lightning in Pennsylvania (Fisher and Uman, 1972) are indicative of lower return stroke velocities. For example, if it is assumed that the flash whose fields are shown in Fig. 3 of Fisher and Uman [1972] was at 7.5 km, then the best theoretical fit to the waveshape is attained with a velocity of 6×10^7 m/sec and a peak current of 53 kA. The current waveshape is qualitatively similar to that called "typical" in the Florida measurements but with a risetime of 3 μsec and a fall time to half-value at 8 μsec.

For the 98 electric field waveforms due to strokes at distances less than or equal to 10 km (95 of these from the storm system recorded on data rolls 26a,b and 27a,b), both the current waveforms and the return stroke velocities could be determined within limits. Individual return stroke velocities were found to be in the range 0.8 to 2.4×10^8 m/sec for best fits to the electric field data. A typical variation of v for an allowable fit around the best fit value was found to be $\pm 0.4 \times 10^8$ m/sec.

Fig. 12 shows examples of measured electric fields for first strokes at various distances, calculated best fit currents and return stroke velocities, and the calculated electric fields that these yield. Figs. 13 and 14 show similar data for subsequent strokes. For those curves marked "photo", reproductions of the original film records are given in previous figures. Also given on the curves are the data roll number and the GMT time (EDST plus 4 hours) as well as a notation if the stroke was over the Atlantic Ocean.

The computed currents for first return strokes in Fig. 12 are probably valid to a few microseconds after the initial peak at which time it might be expected that a change in velocity due to a major branch would occur. The field dip near 10 μsec and the peak near 20 μsec observed on a number of first stroke waveforms may be due to this change in velocity and the occurrence of a major branch. The field from a first return stroke at 0.5 km which could have been produced by a relatively wide range of currents and velocities is shown in Fig. 6 and discussed previously.

A characteristic of the lightning fields recorded on data rolls 26a,b and 27a,b is the initial double peak. The majority of observed storms (on which we had no good ranging) produced strokes whose fields had single initial peaks, although these strokes were all at distances greater than 10 km.

Calculated peak current statistics are displayed in Fig. 15. For the 98 close strokes, the limits on the peak current are due to the range of return stroke velocities which can be used to fit a given field waveform. For the 63 strokes at $D > 10$ km, velocities could not be determined from field waveshapes so that currents were calculated by assuming $v = 1.7 \times 10^8$ m/sec, the average of the velocities for $D \leq 10$ km. This choice of velocity might be relatively bad since it represents data from primarily one storm system whose lightning could have had an anomalously high v. A lower average v would raise the values of peak current as indicated by (2).

The maximum value of "best-fit" peak current is 106 kA due to a first stroke at 7.7 km. The probable upper limit to this peak current is 150 kA. The highest peak currents recorded in previous studies are near 200 kA [Uman, 1969].

During June and July of 1971 measurements were made by NASA (using magnetic links) of the peak current in several discharges which struck the launch umbilical tower of Apollo 15. The largest of these was reported to be 98 kA.

The maximum value of "best fit" rate-of-change of current averaged from zero to peak is 170 kA/μsec due to a subsequent stroke at 4.5 km with a 0.5 μsec rise-time from zero to peak and a peak value of 85 kA. The probable upper and lower limits to the rate-of-rise are 210 kA/μsec and 140 kA/μsec, respectively. A total of four subsequent strokes were observed with risetimes of 0.5 μsec. Since this is close to the system response time, it is possible that the rise-times were less than 0.5 μsec and hence that the maximum rate-of-rise noted above was even greater than calculated. The highest value of current rate-of-rise previously reported is 80 kA/μsec [Berger and Vogelsanger, 1965] and represents not the average from zero to peak but the maximum value during the current rise to peak. The measurement by Berger and Vogelsanger was of the current produced by a subsequent stroke on a tower top on Mount San Salvatore near Lugano, Switzerland.

Errors

The calculation of currents from measured fields presented in this paper is made assuming (1) that the return stroke velocity is constant, (2) that the return-stroke channel is straight and vertical, (3) that the peak current does not change with height, (4) that the current waveshape does not change with height, and (5) that the return stroke starts at ground level.

(1) The matter of return stroke velocity has been discussed previously. (2) For a straight return stroke channel inclined at some angle to the vertical the calculated current (assuming a vertical channel) can be significantly in error. The worst case occurs if the channel is slanted away from the observer. For example, for a channel slanted away from the observer at 15^{o} from vertical, D = 1.5 km, $v = 8 \times 10^{7}$ m/sec, and a "typical current", the peak electric field is decreased about 15 percent from the vertical-channel case and the maximum value of the electrostatic hump at about 15 μsec is decreased about 30 percent. The field waveshape is changed such that it appears to be due to a vertical channel of higher return stroke velocity. Thus, too high a velocity estimate coupled with too low an electric field measurement would result in a computed current smaller than the actual. For channels slanted toward the observer at about 15^{o} from vertical, D = 1.5 km, $v = 8 \times 10^{7}$ m/sec, and a typical current, the initial field peak is practically the same as in the vertical case due to two effects which tend to cancel: The peak field decreases with

respect to the vertical case because θ from (1) is less than 90° near the channel base, while the peak field increases due to the fact that the time at which signals arrive from higher and higher parts of the channel is less for the slanted channel. For a channel slanted toward the observer, the electrostatic hump is changed such that it appears to be due to a vertical channel of lower return stroke velocity. The net effect would be the computation of a larger current than existed. A channel slanted to the side with respect to the observer at about 15° from the vertical would have exactly the same waveshape as a vertical channel with the same return stroke velocity but would have a magnitude about 4 percent lower. From the above it follows that straight non-vertical channels not more than about 15° from vertical do not produce electric field peaks which are too much different from the vertical channel case. However, relatively large errors in computed return stroke velocity may occur if velocities are determined from electric field waveshapes of non-vertical channels. Currents determined using these velocities will be similarly in error. Clearly, to extract properly the currents from the measured fields, it is necessary to independently measure return stroke velocity and channel shape. Note however that if one wishes to measure and analyze only the first few microseconds of the field waveform (in which the peak generally occurs), only the portion of the channel traversed by the return stroke in that time need be straight and vertical.

(3) According to Schonland [1956] the luminosity of subsequent strokes tends to decrease as the return stroke propagates upward, but the decrease is not pronounced. Thus one might expect the current not to decrease much with height. For first strokes, luminosity decreases abruptly at each major branch [Schonland, 1956], but is apparently roughly constant between major branches. The primary effect of the magnitude of the current waveform decreasing slowly with height is to cause the field after the initial peak to decrease more rapidly. For example, for the typical current shown in Fig. 3a but decreasing linearly to half-magnitude at a 5 km channel top, the field at 100 km would pass through zero and go negative at about 20 μsec.

(4) The leader channel is an imperfect conductor and hence there will be different propagation velocities and attenuation coefficients for the various frequency components of the current waveshape. (Strictly speaking, this statement is only valid for a linear system, which the lightning channel, its currents, and fields may not well approximate). One therefore would expect some distortion in the waveshape with height. The fact that "mirror image" waveforms exist indicates that in some cases at least this distortion is not too great.

(5) When the stepped leader nears ground, the electric field at ground will probably become large enough to initiate from ground one or more upward-going leaders (connecting discharges) which, from the meager observational evidence available, are of 10 to 50 m length above flat ground [Uman, 1969]. Perhaps a reasonable upper limit

would be 100 m in view of the fact that Berger and Vogelsanger [1965] found connecting discharges of 20 to 70 m length above a 55 m tower on Mount San Salvatore near Lugano, Switzerland. If the return-stroke current starts to flow at the connection of the upward and downward-moving leaders and propagates components both upward and downward, the total measured electric field will be due to both components. Any significant current wave $i(t+(z-h)/v)$, where h is the length of the connecting discharge, which propagates down the connecting discharge will cause an increase in the measured field while it is propagating. For the upper limit length of 100 m and $v = 1 \times 10^8$ m/sec, the propagation time down the connecting discharge would be 1 μsec. Thus, it is conceivable that the field due to current traversing the connecting discharge may contribute to the initial field peak for first strokes. The result would be that too large a channel current would be calculated during the time of the downward propagation. After the downward propagation front (voltage discontinuity and resultant current wave) reflects from the ground, the resultant upward propagating front and the main front ahead of it may be treated as one system with an overall channel current $i(t - z/v)$ which would probably have two peaks. It is not known whether subsequent strokes have connecting discharges. Not infrequently electric field waveforms are observed which have a very sharp pulse occurring during the waveform rise to peak. This pulse might be due to the field from the connecting discharge. High-speed photographs time-correlated with the electric field traces will be necessary to settle these questions.

It is difficult to assess properly the errors in computed current due to differences between the model and actual return strokes. In view of the fact that most return stroke velocities as determined from electric field wave shapes were relatively high compared to the ranges reported by Schonland et al. (1935) and Schonland (1956), it would appear that most channels were either vertical or leaning away from the observer. Since it is more reasonable to expect the channels to have been randomly oriented, it follows that most were probably more or less vertical. On the other hand, much of the close data were taken on a single storm while it was moving toward the observation point. It is possible that the meteorological conditions were such as to slant these channels away from the observation point. If there is an error in calculated current due to this effect, it is probably in the direction of too small a computed current.

The uncertainty in current magnitude due to drift and calibration errors in the electric field measuring system and errors in extracting the field data from the 35 mm film on which the waveforms were recorded is estimated to be ± 15 percent.

Thunder ranging generally results in a slight underestimation of the distance to the main-current channel since sound is heard first from the nearest branches or in-cloud channels. This error becomes larger as the strokes become closer. Assuming that the initial thunder clap comes from the vertical main channel, we were sometimes able to differentiate between the initial thunder and that due to the main channel. If this approach is correct, the underestimation of distance for the closest strokes probably does not exceed 20 percent. Any distance underestimate leads to an underestimate of the current magnitude.

Discussion

The available statistics on lightning peak current, current risetime, and time to half of peak current value have been summarized by Uman [1969]. The most reliable data on current waveshapes come from the Empire State Building study (Hagenguth and Anderson, 1952), the Mount San Salvatore study (Berger and Vogelsanger, 1965; Berger, 1967), and the study by McCann [1944]. The total number of strokes analyzed in these studies was about 300 although not all salient properties of the current were published for all 300 strokes. (For example, there are only 115 published risetime measurements). Information on peak currents is more plentiful (about 3000 measurements) primarily due to the magnetic link data reported by Lewis and Foust [1945]. All of the above data refer to the currents flowing at the base of the lightning channel, generally in structures which project high above the normal terrain.

The peak current statistics of Figure 15 are in reasonable agreement with previous measurements. The 98 close strokes have a median peak current about twice that indicated by previous work. The 63 strokes for which $D > 10$ km have a peak current distribution very close to that reported by Lewis and Foust [1945]. Our measured current risetimes, generally in the range 0.5 to 5.0 μsec, are in good agreement with the literature which shows median risetimes in the range 1 to 3 μsec.

The primary discrepancy between the current waveshapes reported in this paper and those measured directly due to current flow in tall structure is the current waveshape around peak and its fall-time.

We generally find sharply peaked currents with a time to half of peak value of about 10 μsec. The waveforms from direct current measurement generally show no sharp peak and a time to half of peak value of 30 to 40 μsec. If an initial peak were superimposed on these data, the resultant currents would be very similar to those derived from our field measurements. Three possible explanations for the discrepancy are: (1) The current in a structure at the base of the lightning may not have the same waveshape as the current propagating up the channel due to the effects of the connecting discharge and since the structure has different impedance characteristics from the channel; (2) The measurement techniques used on structures may have failed to detect sharp peaks which did exist; (3) The return stroke model is deficient and field peaks do not translate into current peaks.

The current waveshapes for first strokes given in Fig. 12 are remarkably similar to the first stroke currents of Berger and Vogelsanger [1965] and Berger [1967]. In particular both sets of data usually show a broad second field-peak near 20 μsec. Berger [1967] attributes the second peak to branch currents. The similarity between our data and his is probably fortuitous since the model calculations do not take into account the effects of branches or of expected changes in the return stroke velocity.

Kalakowsky and Lewis [1967] have presented data on stroke location and electric field intensities for very large strokes in New England. The study lasted for 30 months. From these data and assumed return stroke velocities we can compute peak currents for the New England strokes. The largest of half a million waveforms is indicative of a peak current of about 110 kA if $v = 2 \times 10^8$ m/sec, 220 kA if $v = 1 \times 10^8$ m/sec, and proportionally higher if v is lower. Twenty seven of the half million waveforms (or about 0.005 percent) were indicative of a current over about 38 kA if $v = 2 \times 10^8$ m/sec or over about 76 kA if $v = 1 \times 10^8$ m/sec.

As noted in "The Experiment" section, 31 strokes in eight flashes were observed over the Atlantic Ocean. Neither this "water" sample nor the sample of strokes over land is large enough to draw any conclusions relative to the possible difference between lightning over water and over land. The primary apparent difference in the samples is that over-water currents have smaller peak values than the over-land currents.

The risetimes of the over-water fields (which cannot be significantly affected by propagation losses) and the currents calculated from them were between 1.0 and 9.0 μsec. Eight subsequent strokes had rise-times of about 1.0 μsec. The six first-strokes on which measurements could be made had risetimes between 4.0 and 9.0 μsec, somewhat greater than typical over-land risetimes.

Conclusions and Recommendations

A small sample of Florida lightning has yielded several peak currents in the 100 kA range or above. Several current risetimes of 0.5 μsec or faster were found; and the fastest observed current rate-of-rise was near 200 kA/μsec. In Section 9.2.2 of NASA TM-64589 it is stated that 2 percent of currents can be expected to be over 100 kA, that these current peaks will be reached in 10 μsec, and that the maximum rate-of-rise of current will be 10 kA/μsec. On the basis of the data presented in this report relative to channel currents in lightning to normal terrain, we feel the specification on current risetime and rate-of-rise of current should be changed: risetimes are generally 1 μsec to a few microseconds with a minimum of tenths of a microsecond and a maximum of 10 μsec; rates-of-rise of current may occasionally be expected to exceed 200 kA/μsec.

The original objective of this research was to obtain a meaningful statistical distribution of peak currents and current risetimes. It is clear that additional measurements will be necessary in order to achieve this goal. Further, as indicated by the discussion in the "Errors" section, return stroke velocity must be photoelectrically or photographically measured and channel shape must be determined photographically in coordination with the electric-field and stroke-distance measurements if accurate return-stroke currents are to be derived. This set of coordinated experiments would also allow further verification of the return-stroke model used. We therefore recommend that additional research in this direction be supported.

Acknowledgment

The research results in this report were obtained with support from the National Aeronautics and Space Administration (NAS8-28168 and NAS9-11629), from the Atmospheric Sciences Program of the Office of Naval Research (N00014-71-C-0005 and N00014-68-A-0173-0018) and from the National Science Foundation (GA-31976).

The experimental data presented was obtained under NASA Contract No. NAS9-11629 by M. A. Uman, R. J. Fisher, and E. P. Krider. We would like to thank Mr. A. J. Carraway and his group at the NASA Kennedy Space Center, Florida, the personnel of the KSC Weather Station, and the personnel of the Air Force Weather Station on the Cape for help which greatly aided in the data taking.

REFERENCES

1. Berger, K., Novel Observations on Lightning Discharges: Results of Research on Mount San Salvatore, J. Frank. Inst., 283, 478-525, 1967.

2. Berger, K., and E. Vogensanger, Messungen und Resultate der Blitzforshung der Jahre 1955-1963 auf dem Monte San Salvatore, Bull. Swiss Electroteck. Verein, 56, 2-22, 1965.

3. Bruce, C. E. R., and R. H. Golde, The Lightning Discharge, J. IEE, London, 88 (pt. 2), 487-524, 1941.

4. Croom, D.L., The Frequency Spectra and Attenuation of Atmospherics in the Range 1-15 kc/s, J. Atmosph. Terr. Phys., 26, 1015-1046, 1964.

5. Daniels, Glenn E., Terrestrial Environment (Climatic) Criteria Guidelines for Use in Space Vehicle Development, 1971 Revision, NASA TM X-64589, George C. Marshall Space Flight Center, Marshall Space Flight Center, Alabama 35812.

6. Dennis, A.S., and E. T. Pierce, The Return Stroke of a Lightning Flash to Earth as a Source of VLF atmospherics, Radio Sci., 68D, 777-794, 1964.

7. Fisher, R.J., and M. A. Uman, Measured Electric Field Risetimes for First and Subsequent Lightning Return Strokes, J. Geophys. Res., 77, 399-406, 1972.

8. McLain, D. K., and M. A. Uman, Exact Expression and Moment Approximation for the Electric Field Intensity of the Lightning Return Stroke, J. Geophys. Res., 76, 2101-2105, 1971.

9. Hagenguth, J.H., and J. G. Anderson, Lightning to the Empire State Building, pt. 3, Trans. AIEE, 71(pt.3), 641-649, 1952.

10. Kalakowsky, C. B., and E. A. Lewis, VLF Sferics of Very Large Virtual Source Strength, MF, LF, and VLF Radio Propagation Conference, Publication No. 36, IEE, London, Nov. 1967, pp 228-245.

11. Lewis, W. W., and C. M. Foust, Lightning Investigation on Transmission Lines, pt. 7, Trans. AIEE, 64, 107-115, 1945.

12. McCann, G. D., The Measurement of Lightning Currents in Direct Strokes, Trans. AIEE, 63, 1157-1164, 1944.

13. Morrison, R.B., The Variation with Distance in the Range 0-100 km of Atmospheric Wave-Forms, Phil. Mag., 44, 980-992, 1953.

14. Norinder, H., and Ö. Dahle, Measurements by Frame Aerials of Current. Variations in Lightning Discharges, Arkiv Mat. Astron. Fysik, 32A 1-70, 1945.

15. Schonland, B. F. J., The Lightning Discharge, Handbuch der Physik, 22, 576-628, 1956.

16. Schonland, B. F. J., Malan, D. J., and H. Collens, Progressive Lightning II, Proc. Roy. Soc., 152, 595-625, 1935.

17. Taylor, W. L., Radiation Field Characteristics of Lightning Discharges in the Band 1 kc/s to 10 kc/s, J. Res. NBS Radio Propagat., 67D, 539-550, 1963.

18. Srivastava, K. M. L., and B. A. P. Tantry, VLF Characteristics of Electromagnetic Radiation from the Return Stroke of Lightning Discharge, Indian J. of Pure and Appl. Phys., 4, 272-275, 1966.

19. Uman, M. A., Lightning, McGraw-Hill, New York, 1969.

20. Uman, M. A., and D. K. McLain, Magnetic Field of Lightning Return Stroke, J. Geophys. Res., 74, 6899-6910, 1969.

21. Uman, M.A., and D. K. McLain, Lightning Return Stroke Current from Magnetic and Radiation Field Measurements, J. Geophys. Res., 75, 5143-5147, 1970a.

22. Uman, M. A., and D. K. McLain, Radiation Field and Current of the Lightning Stepped Leader, J. Geophys. Res., 75, 1058-1066, 1970b.

PERMANENT RECORD BOOK ENTRIES: 204479, p. 25, 29, 30

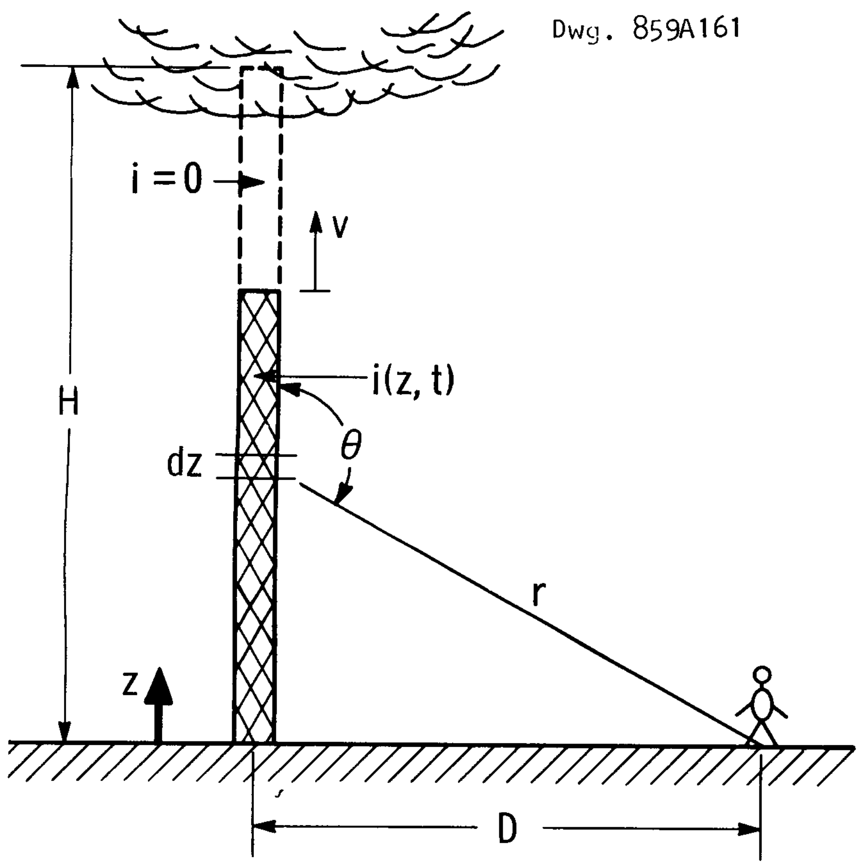

Fig. 1. Drawing defining the pertinent geometrical factors used in computing the electric field intensity of the lightning return stroke.

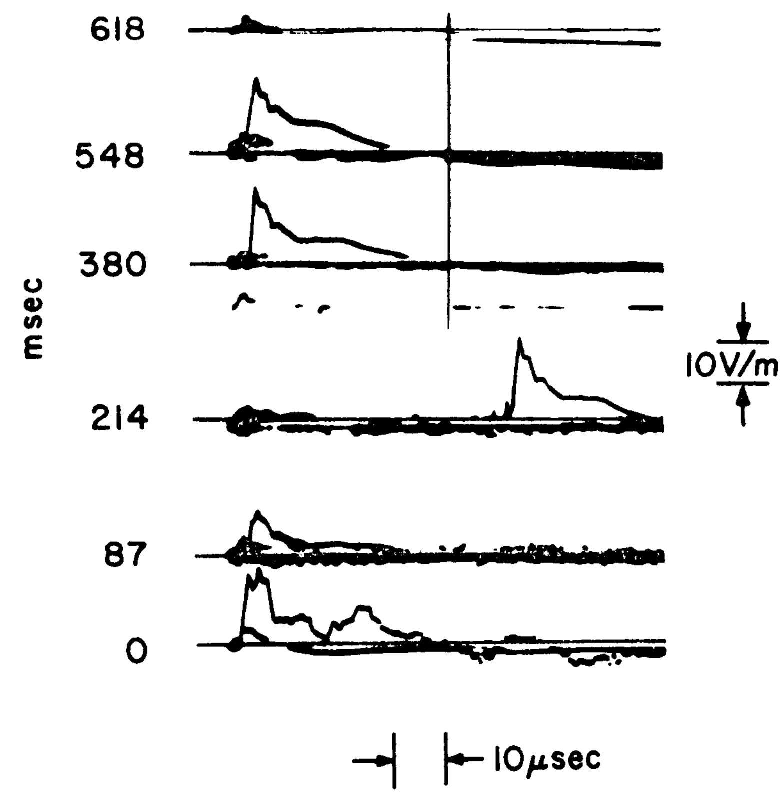

Fig. 2. Electric field waveforms for the various return strokes in a typical Florida lightning flash at a distance between 20 and 40 km.

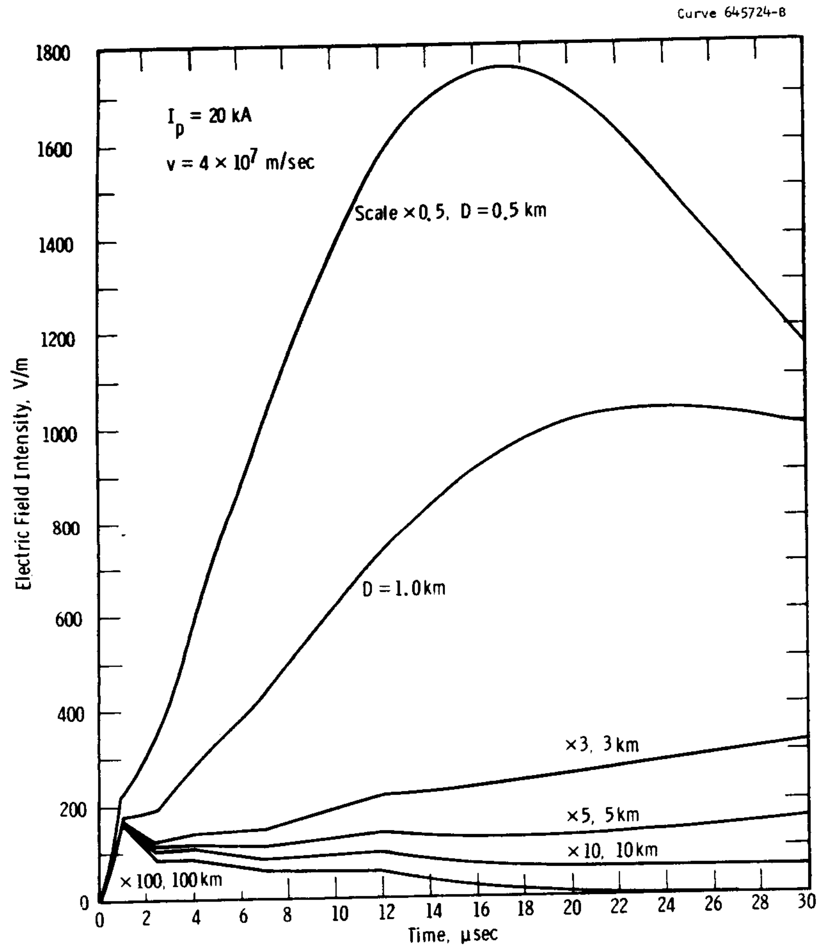

Fig. 3a. Calculated electric field intensity for $v = 4 \times 10^7$ m/sec and various distances for typical currents whose waveshapes are that of the electric field at 100 km. The ordinate scales with I_p.

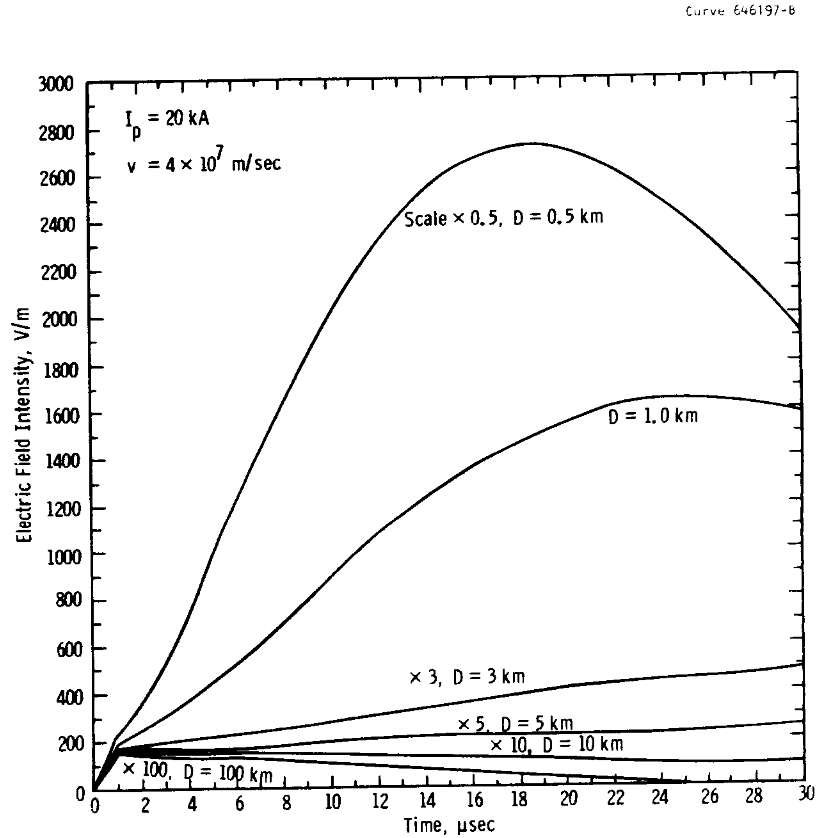

Fig. 3b. Calculated electric field intensity for $v = 4 \times 10^7$ m/sec and various distances for typical currents whose waveshapes are that of the electric field at 100 km. The ordinate scales with I_p.

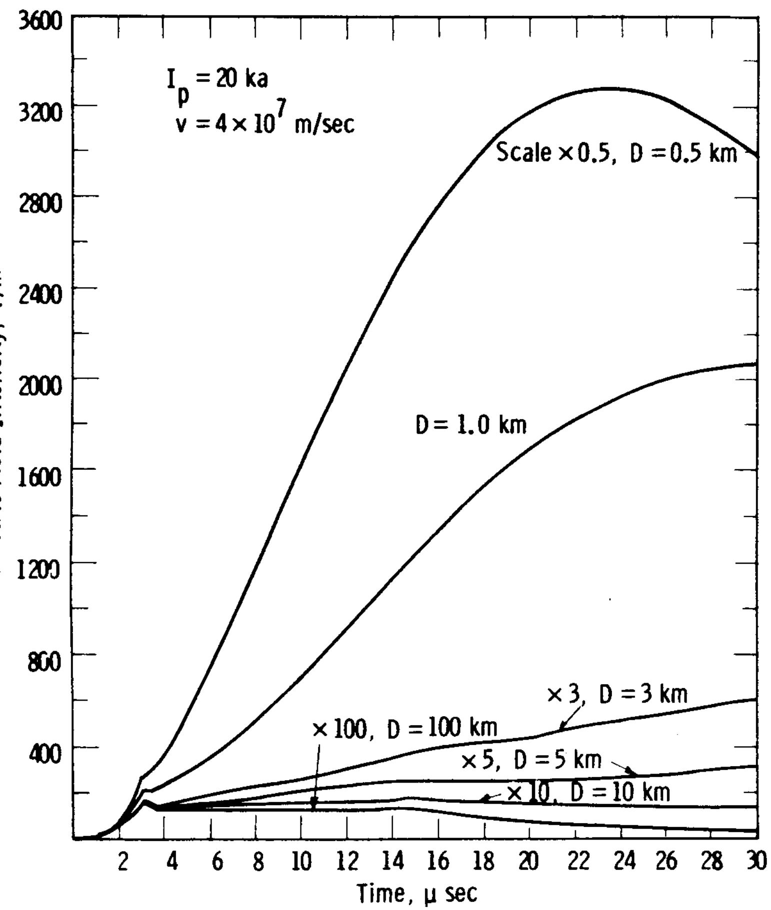

Fig. 3c. Calculated electric field intensity for $v = 4 \times 10^7$ m/sec and various distances for typical currents whose waveshapes are that of the electric field at 100 km. The ordinate scales with I_p.

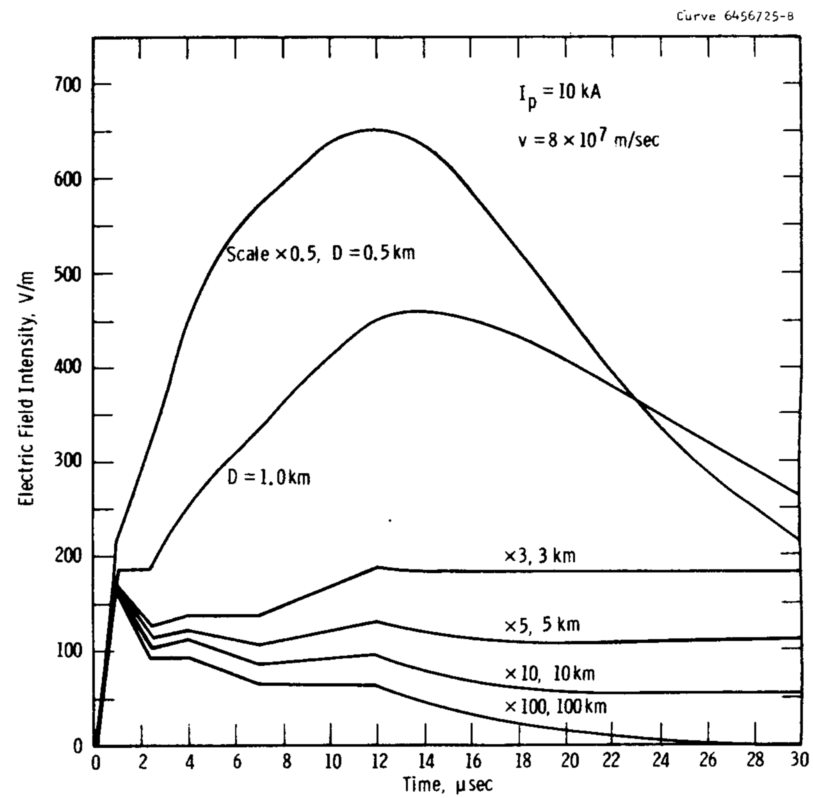

Fig. 4a. Calculated electric field intensity for $v = 8 \times 10^7$ m/sec and various distances for typical currents whose waveshapes are that of the electric field at 100 km. The ordinate scales with I_p.

Curve 646195-A

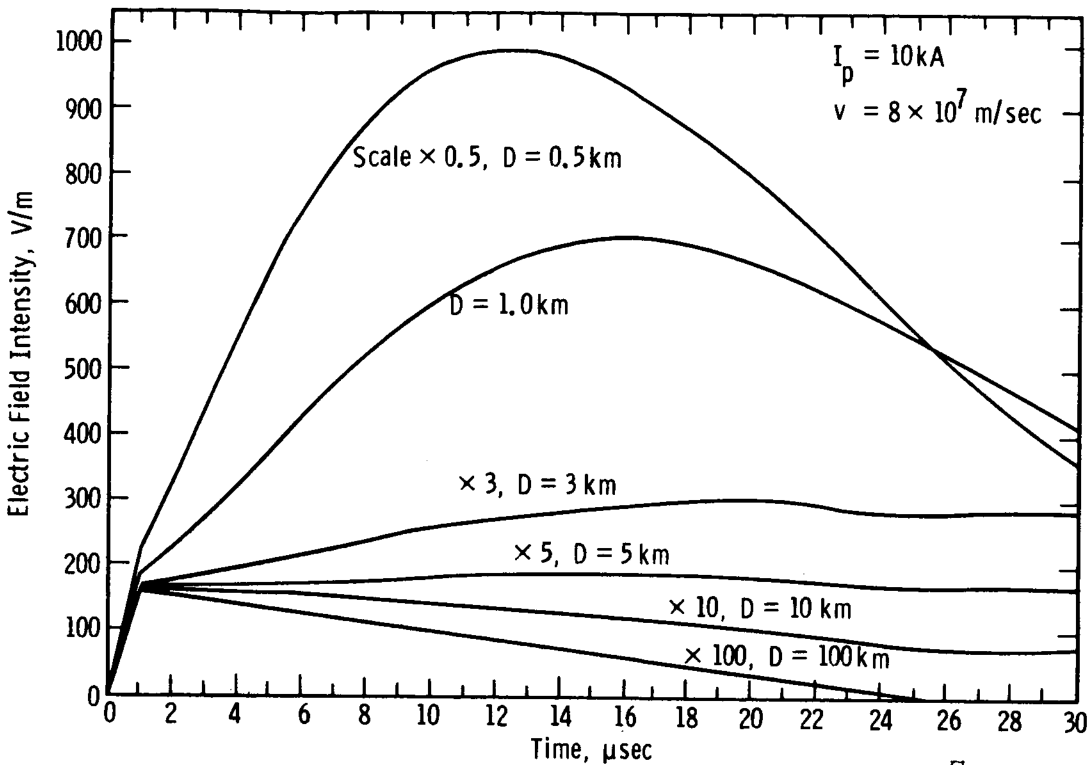

Fig. 4b. Calculated electric field intensity for v = 8 x 10^7 m/sec and various distances for typical currents whose waveshapes are that of the electric field at 100 km. The ordinate scales with I_p.

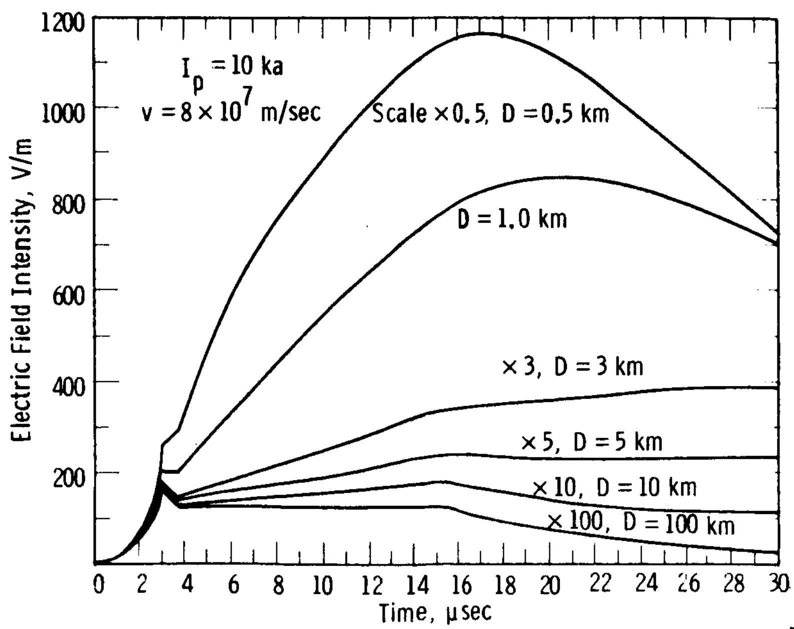

Fig. 4c. Calculated electric field intensity for v = 8 x 10^7 m/sec and various distances for typical currents whose waveshapes are that of the electric field at 100 km. The ordinate scales with I_p.

Curve 645723-A

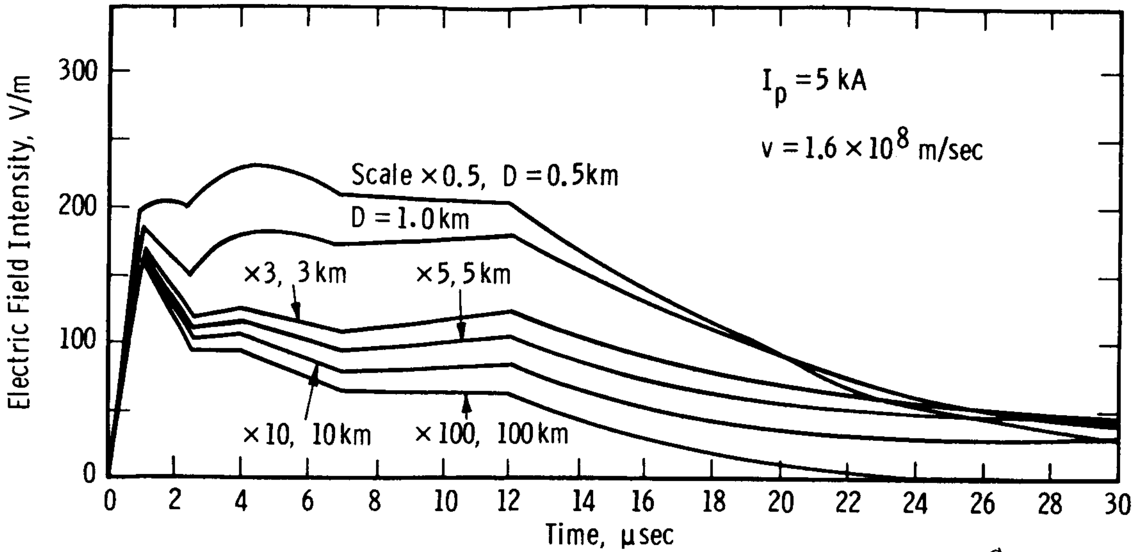

Fig. 5a. Calculated electric field intensity for v = 1.6 x 10^8 m/sec a and various distances for typical currents whose waveshapes are that of the electric field at 100 km. The ordinate scales with I_p.

Curve 646196-A

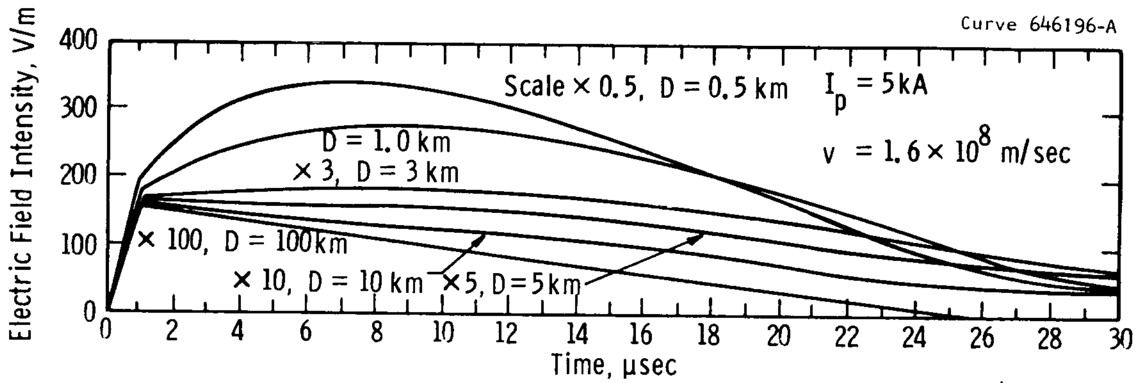

Fig. 5b. Calculated electric field intensity for v = 1.6 x 10^8 m/sec and various distances for typical currents whose waveshapes are that of the electric field at 100 km. The ordinate scales with I_p.

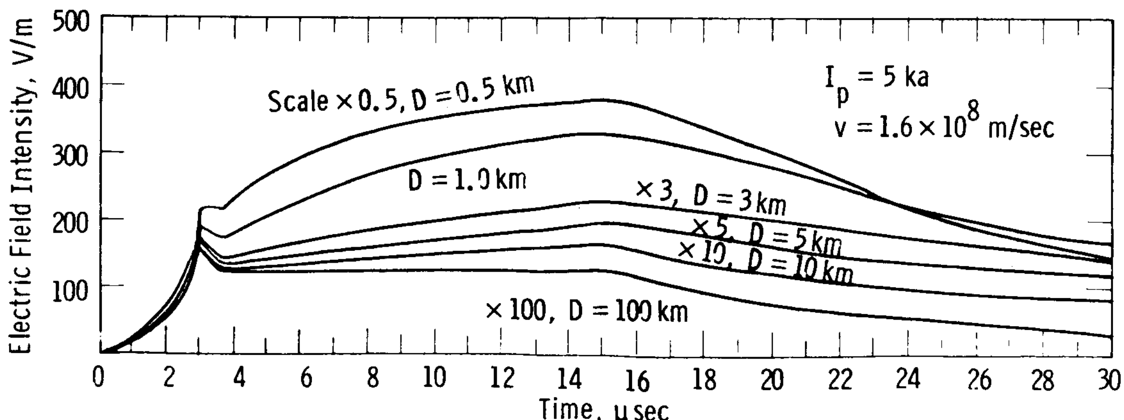

Fig. 5c. Calculated electric field intensity for v = 1.6 x 10^8 m/sec and various distances for typical currents whose waveshapes are that of the electric field at 100 km. The ordinate scales with I_p.

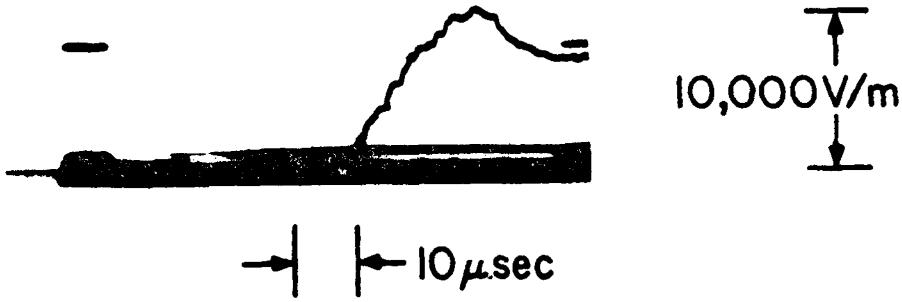

Fig. 6. The return-stroke electric field intensity for a single stroke flash at 0.5 km.

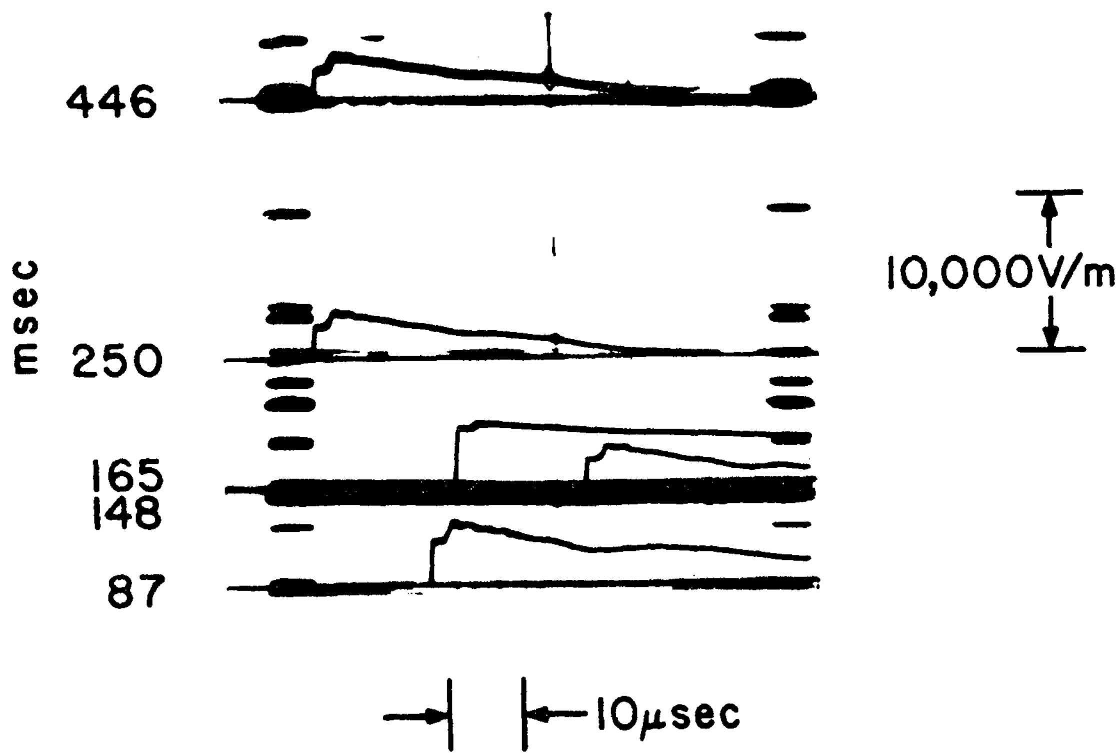

Fig. 7. The electric fields of subsequent strokes in a multiple stroke flash at a distance probably near 1 km.

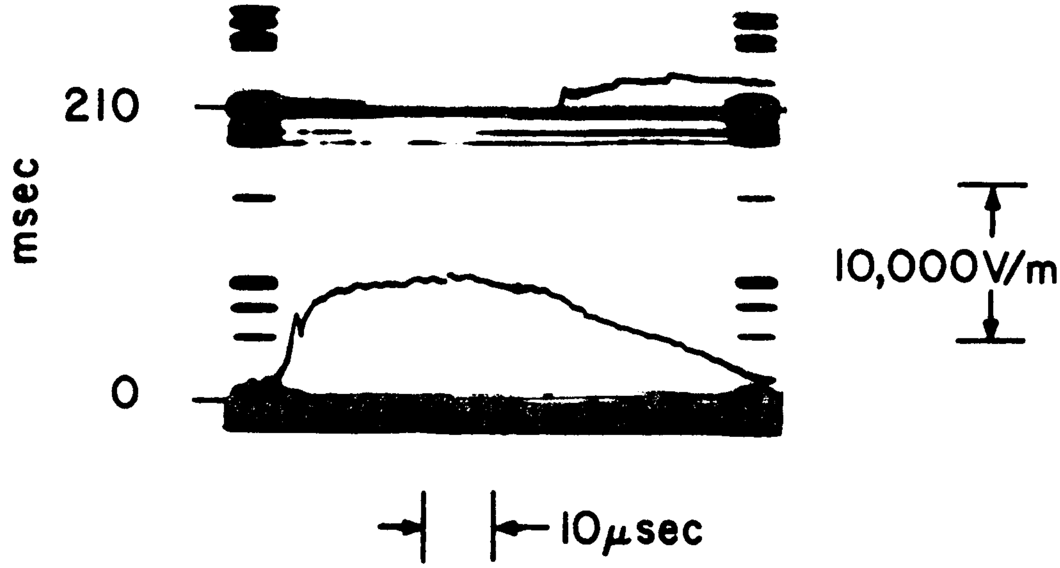

Fig. 8. The electric fields of the first and subsequent strokes in a 2-stroke flash at a distance probably near 1 km.

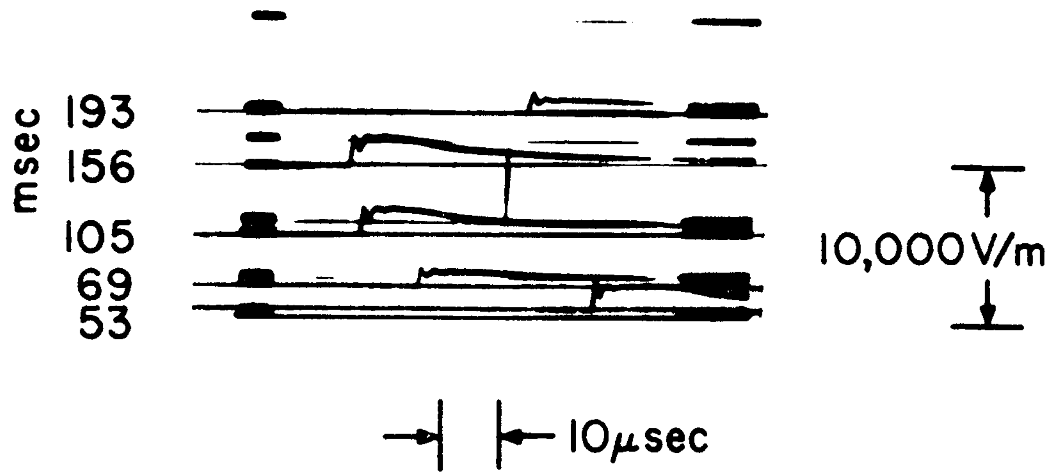

Fig. 9. The electric fields of subsequent strokes in a multiple stroke flash at 1.1 km.

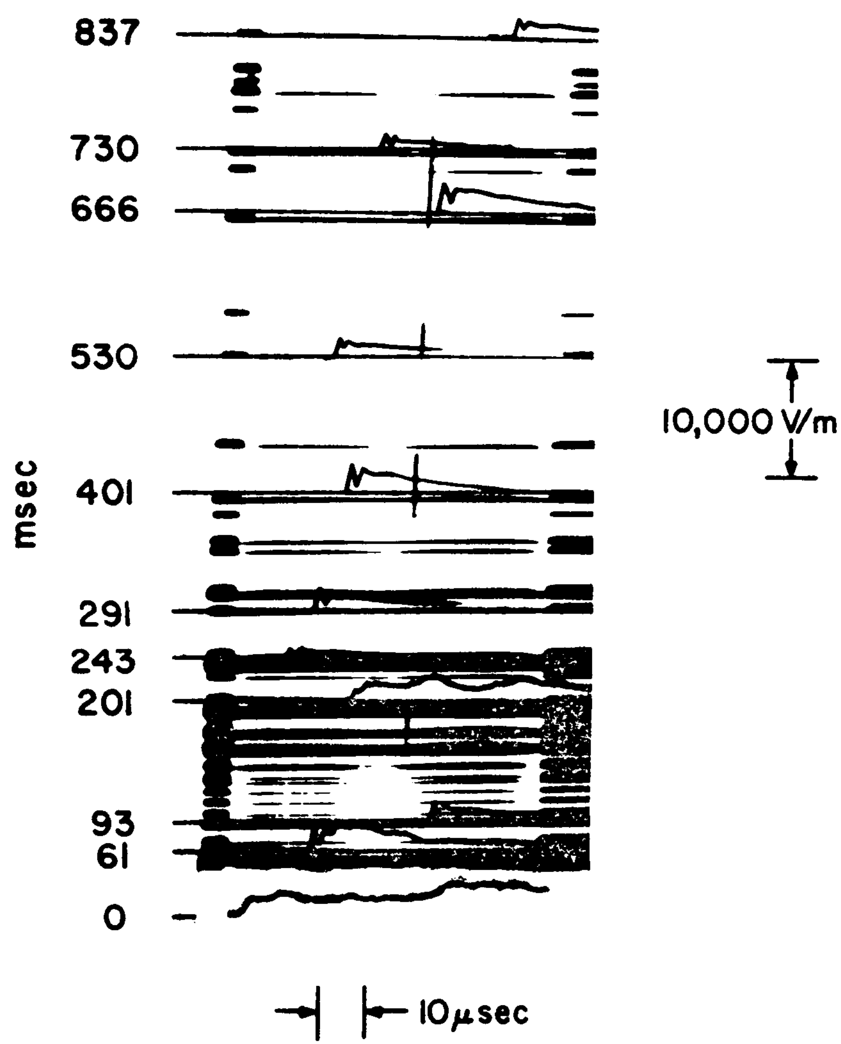

Fig. 10. The electric fields of a multiple stroke flash at 1.5 km. Two waveforms are analyzed in detail in Fig. 13.

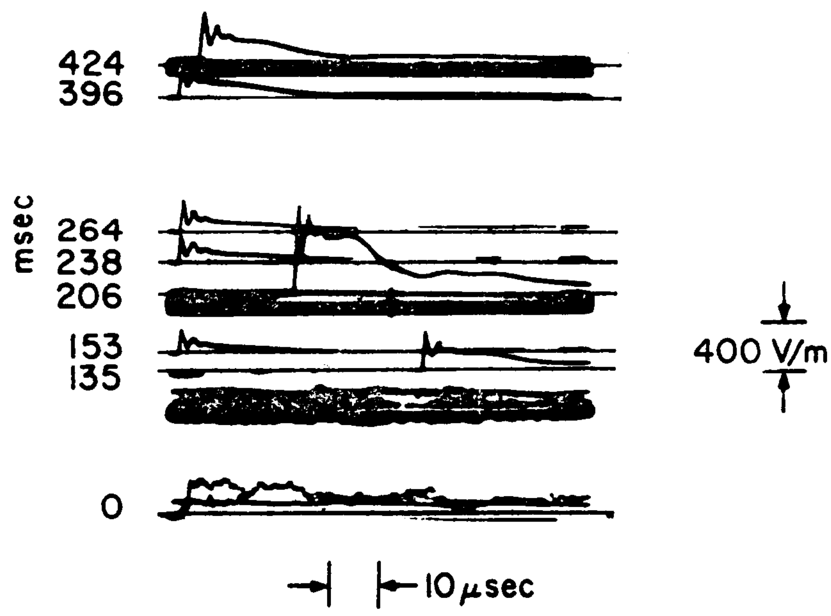

Fig. 11. The electric fields of a multiple stroke flash at 4.5 km. Two waveforms are analyzed in detail in Figs. 12 and 13.

Curve 647686-B

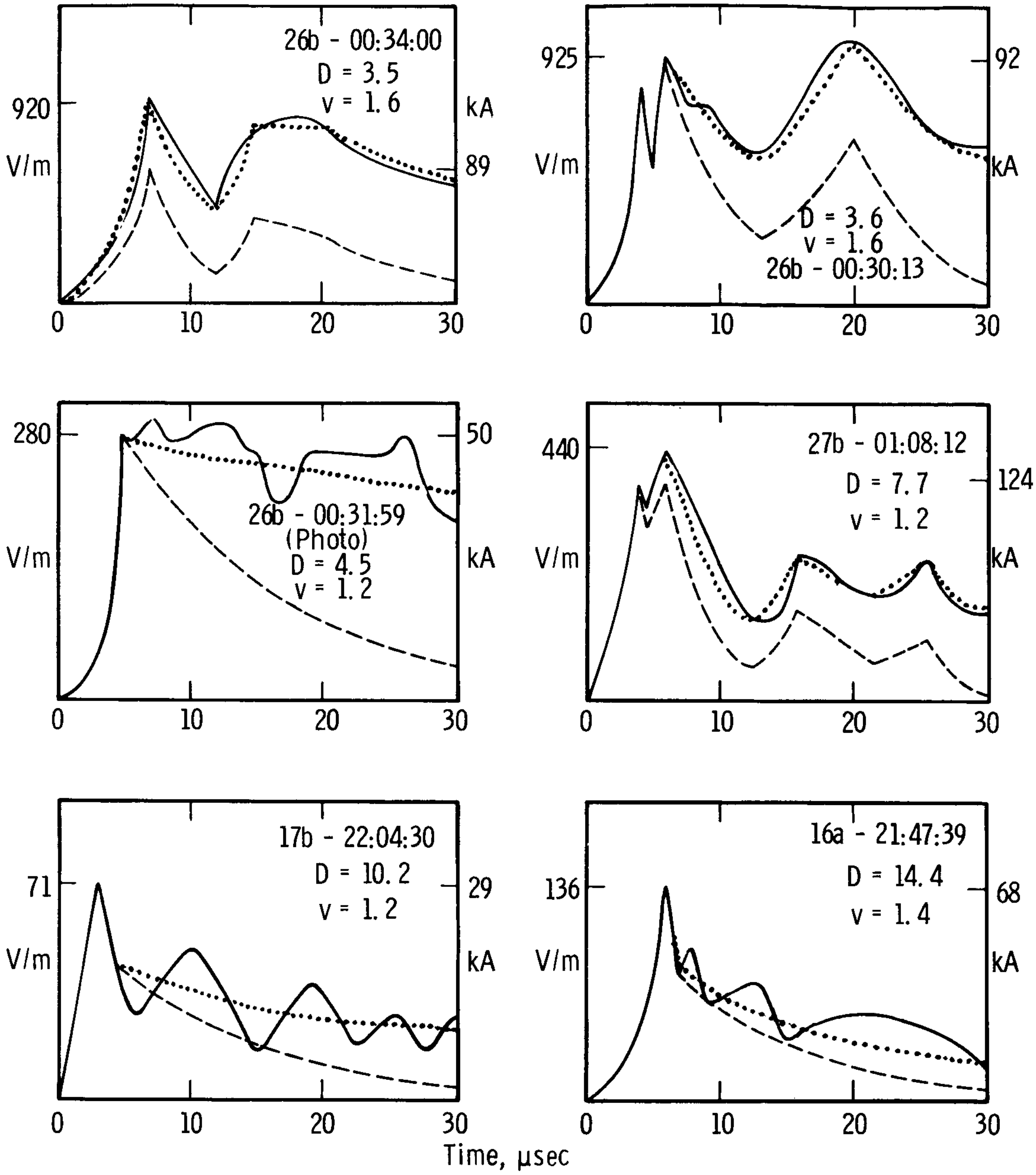

Fig. 12. Electric fields and currents of 6 first return strokes at distances between 3.5 and 14.4 km. The calculated current waveforms (dashed lines) and return stroke velocities are of those which give calculated electric fields (dotted lines) closely matching the measured fields (solid lines). Stroke distance D is in km; return stroke velocity v in 10^8 m/sec.

Curve 647688-B

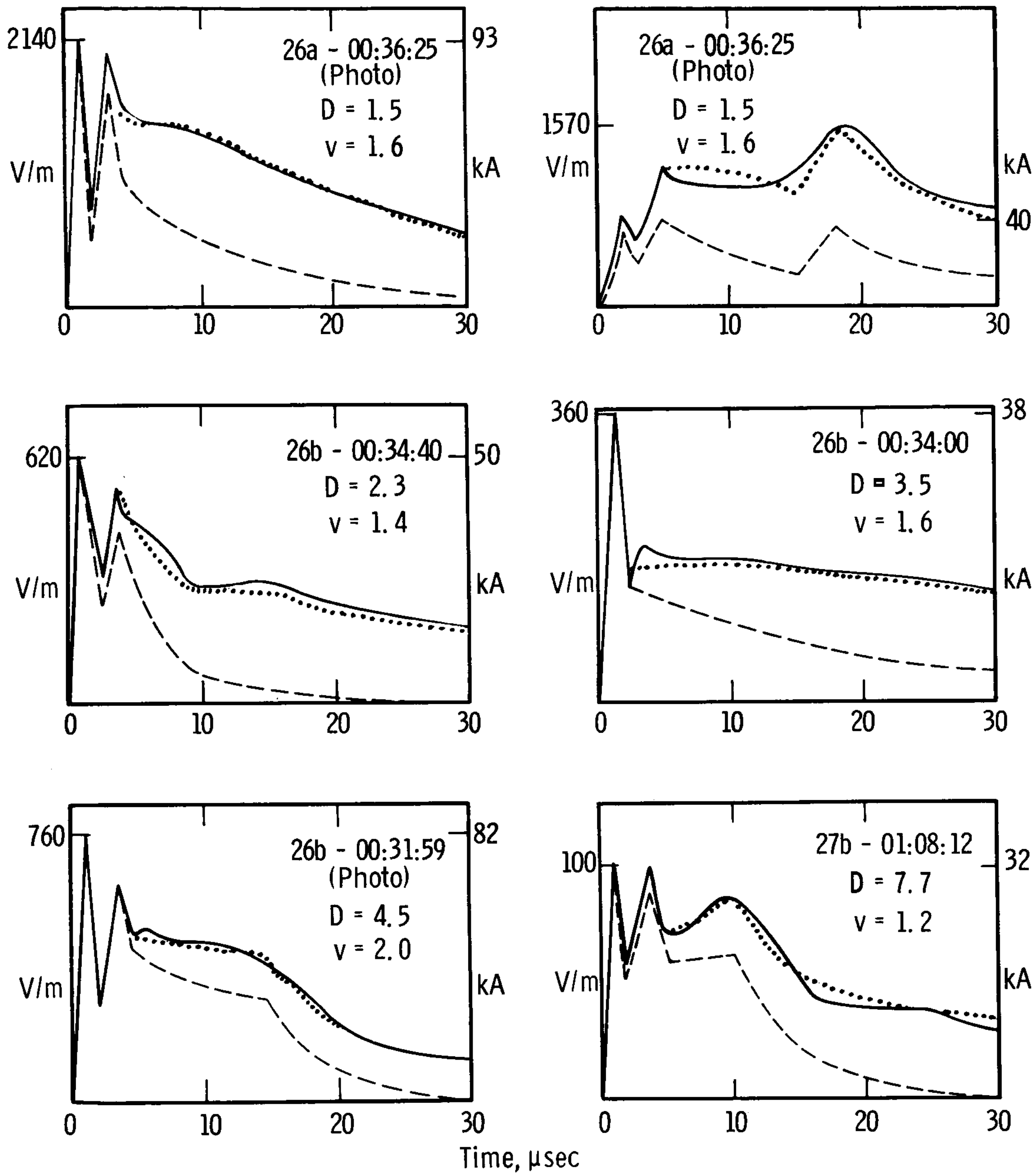

Fig. 13. Electric fields and currents of 6 subsequent return strokes at distances between 1.5 and 7.7 km.

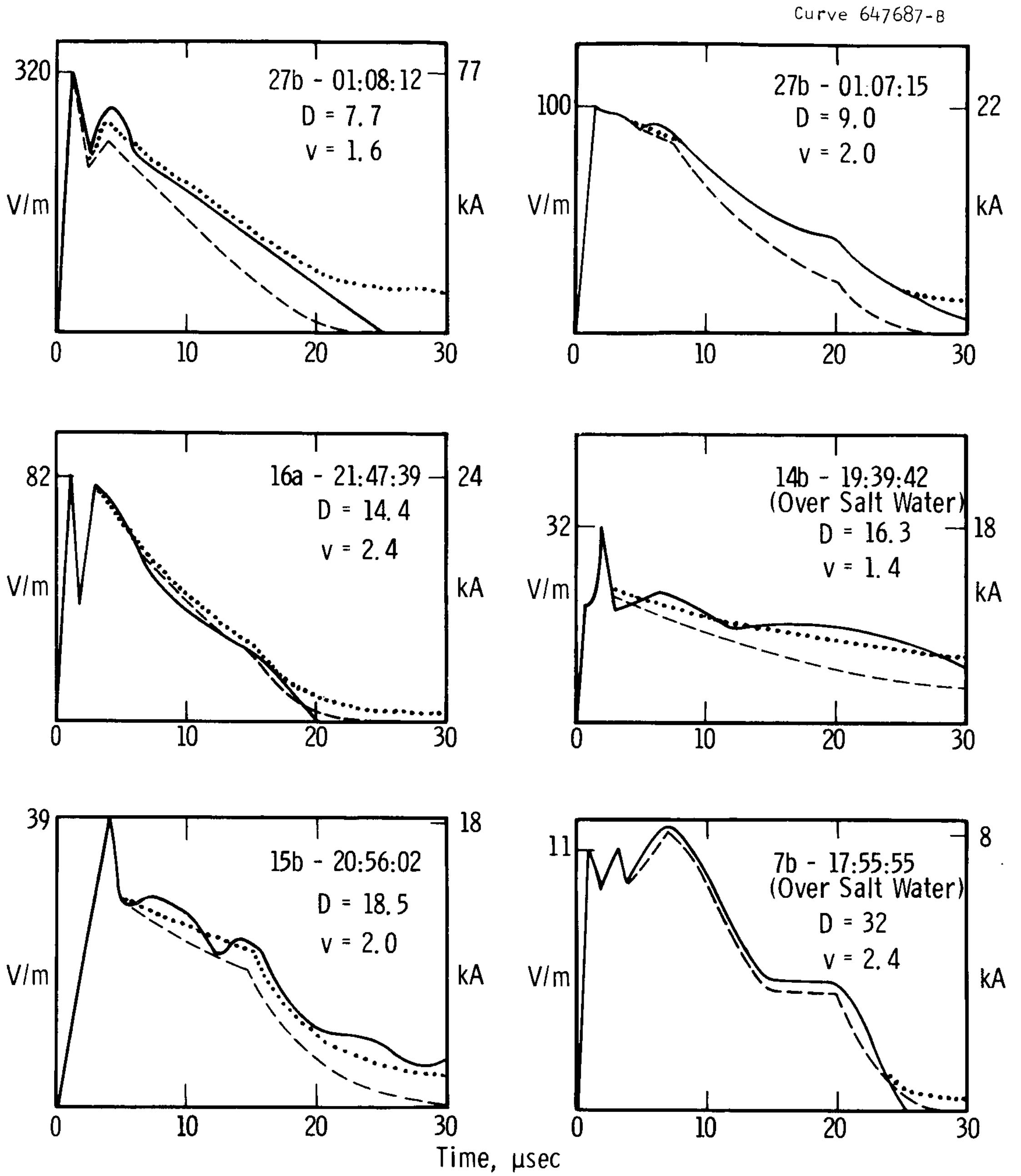

Fig. 14. Electric fields and currents of 6 subsequent return strokes at distances between 7.7 and 32 km. Two waveforms due to strokes over the Atlantic Ocean are shown.

Curve 647622-A

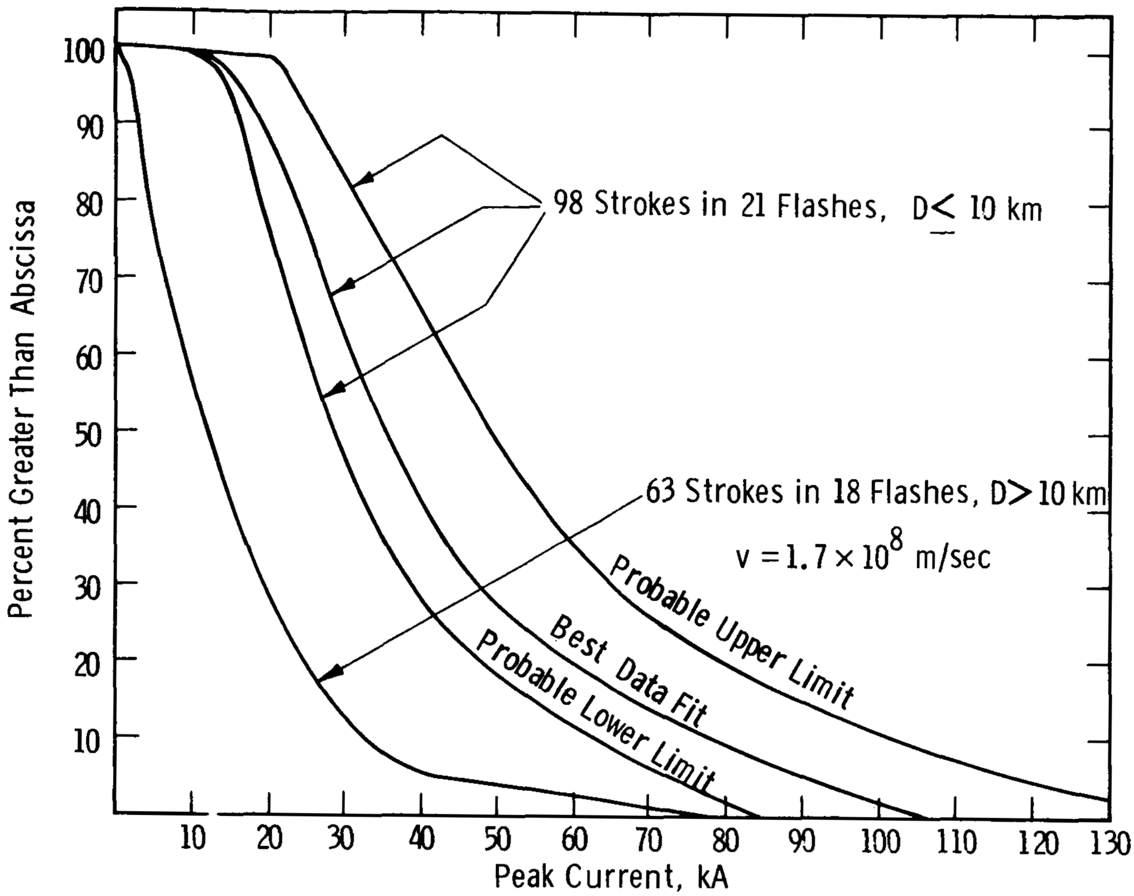

Fig. 15. Statistical distribution of peak currents. For the 98 close strokes, the probably upper and lower limits are due to the range of return stroke velocities for which reasonable fits to the measured fields can be obtained. This spread in peak values does not include the effect of measurement errors and errors due to possible deficiencies in the model. These are discussed in the Errors section.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE $300

SPECIAL FOURTH-CLASS RATE
BOOK

POSTAGE AND FEES PAID
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION
451

U.S.MAIL

POSTMASTER: If Undeliverable (Section 158 Postal Manual) Do Not Return

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons. Also includes conference proceedings with either limited or unlimited distribution.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include final reports of major projects, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION OFFICE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546