AD-A114 015 ELECTRO MAGNETIC APPLICATIONS INC DENVER CO F/G 4/1
ATMOSPHERIC ELECTRICITY HAZARDS ANALYTICAL MODEL DEVELOPMENT AN--ETC(U)
AUG 81 M A UMAN, E P KRIDER F33615-79-C-3412
UNCLASSIFIED EMA-81-R-21-VOL-1 AFWAL-TR-81-3084-VOL-1 NL

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AFWAL-TR-81-3084, Volume I

ATMOSPHERIC ELECTRICITY HAZARDS ANALYTICAL MODEL DEVELOPMENT AND APPLICATION

VOLUME I: LIGHTNING ENVIRONMENT MODELING

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August 1981

Final Report for Period August 1979 - June 1981
Approved for public release; distribution unlimited

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER	AFWAL-TR-81-3084, Volume I
2. GOVT ACCESSION NO.	
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle)	ATMOSPHERIC ELECTRICITY HAZARDS ANALYTICAL MODEL DEVELOPMENT AND APPLICATION VOLUME I: LIGHTNING ENVIRONMENT MODELING
5. TYPE OF REPORT & PERIOD COVERED	Technical-Final August 1979-June 1981
6. PERFORMING ORG. REPORT NUMBER	EMA 81-R-21
7. AUTHOR(s)	Martin A. Uman E. Philip Krider
8. CONTRACT OR GRANT NUMBER(s)	F33615-79-C-3412
9. PERFORMING ORGANIZATION NAME AND ADDRESS	Electro Magnetic Applications, Inc. P. O. Box 26263 Denver, Colorado 80226
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS	24020212
11. CONTROLLING OFFICE NAME AND ADDRESS	Flight Dynamics Laboratory (FIESL) Air Force Wright Aeronautical Laboratories Wright Patterson Air Force Base, Ohio 45433
12. REPORT DATE	August 1981
13. NUMBER OF PAGES	172
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	
15. SECURITY CLASS. (of this report)	
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE	

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Lightning
Environment
Modeling
Literature Review
Frequency Spectra

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report is a review of the state of the art of lightning phenomenology and its electromagnetic environment. All aspects and phases are discussed. A model is chosen for each phase which best describes what is currently known and understood. Computer models for predicting the electromagnetic environment for several of the processes are given, along with numerical predictions. A comprehensive bibliography is also provided.

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FOREWORD

This report describes the results of a research effort sponsored by the Atmospheric Electricity Hazards Group of the Air Force Flight Dynamics Laboratory under Contract F33615-79-C-3412. This effort was entitled "Atmospheric Electricity Hazards Analytical Model Development and Application".

The principal investigator was Dr. Rodney A. Perala of Electro Magnetic Applications, Inc. He was assisted in this effort by two subcontractors. Mr. John D. Robb of Lightning and Transient Research Institute, performed the part of the effort having to do with simulation. Drs. Martin A. Uman and E. Philip Krider of Lightning Location and Protection, Inc., performed the effort relating to environment definition.

This volume, Volume I, concerns the lightning environment definition and was prepared by Drs. Uman and Krider under subcontract SC-79-004. The other companion volumes are:

1. Volume II: "Simulation of the Lightning/Aircraft Interaction Event," by J. D. Robb.

2. Volume III. "Electromagnetic Coupling Modeling of the Lightning/Aircraft Interaction Event," by R. A. Perala, F. J. Eriksen,and T. N. Rudolph.

The authors wish to thank the Atmospheric Electricity Hazards Group for their support in this effort.

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Section 1

Introduction

Lightning is a particular hazard to the latest generation of aircraft which uses low-voltage digital electronics for control functions and structural components made of epoxy for strength and weight saving (e.g., Corbin, 1980). The lightning hazard includes (1) the direct lightning current flowing through the aircraft and (2) the electric and magnetic fields generated by either a direct or nearby lightning discharge. To assess the lightning hazard, lightning Location and Protection, Inc. (LLP) has joined with Electromagnetic Applications, Inc. (EMA) and Lightning and Transients Research Institute (LTRI) under Air Force Wright Aeronautical Laboratory (AFWAL) Contract Number F33615-79-C-3412 to study (1) the lightning environment as it relates to aircraft safety, (2) the coupling of lightning currents and fields into aircraft systems and subsystems, and (3) the methods of testing for lightning effects. While LLP has been involved in all three of these efforts, its primary responsibility has been to define the atmospheric electrical environment as it relates to aircraft safety. Here we report on the results of that task.

This report is Volume I of three companion volumes prepared under Contract Number F33615-79-C-3412. The other two volumes are:

1. Volume II: "Simulation of the Lightning/Aircraft Interaction Event," by John Robb.
2. Volume III: "Electromagnetic Coupling Modeling of the Lightning/Aircraft Interaction Event," by R. A. Perala, F. J. Eriksen, and T. N. Rudolph.

This report is divided into four sections: Section 1, you are now reading; Section 2 contains a brief description of lightning including definitions of all lightning-related terms to be used in the remainder of the report; Section 3 details the mathematical approach used in the modeling process; and Section 4 contains both a complete literature survey and some of the results of the modeling to reproduce measured fields and to predict those not yet measured.

Section 1

Bibliography

Corbin, J.C., Protection/Hardening of aircraft electronic systems against the indirect effects of lightning, FAA-FIT Workshop on Grounding and Lightning Technology, March 6-8, 1979, Melbourne, FL, Report No. FAA-RD-79-6, pp. 97-103.

Section 2

Review of Lightning

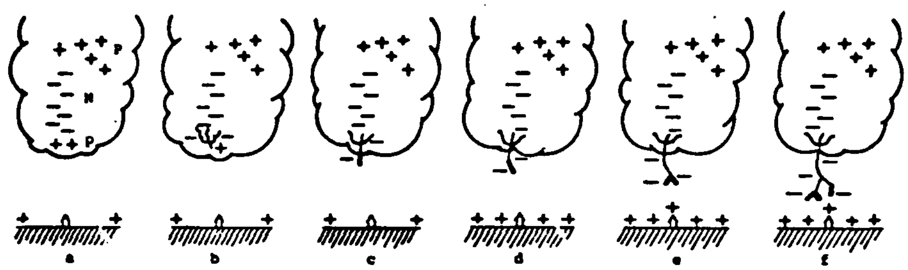
2-1. Introduction

Lightning is a transient, high current electric discharge whose path length is measured in kilometers. The most common source of lightning is the electric charge separated in ordinary thunderstorm clouds (cumulonimbus). Well over half of all lightning discharges occur within the cloud (intracloud discharges). Cloud-to-ground lightning (sometimes called streaked or forked lightning) has been studied more extensively than other forms of lightning because of its practical interest (e.g., as the cause of disturbances in power and communication systems, and the ignition of forest fires) and because it is more easily observed with optical instruments. Cloud-to-cloud and cloud-to-air discharges are less common than intracloud or cloud-to-ground lightning.

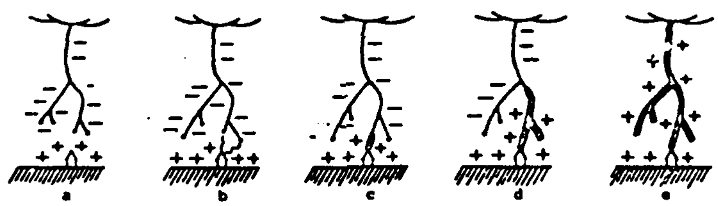
The definition and discussion of discharge components for cloud-to-ground and cloud lightning which follows in the next two sections are adapted from Uman (1969). While our primary interest is in the individual lightning discharge, it is worth noting that the phenomenology of lightning in thunderstorms (e.g., the fraction of the total discharges which are to ground vs. storm phase, the number of lightnings vs. storm duration, the maximum and average flashing rates) is an area of current research interest (see, for example, Livingston and Krider (1978); and the question of whether lightning characteristics are dependent on geographic location, season, or other factors is also being studied. Thomson (1980) reports no significant correlation between the average number of strokes per flash or the interstroke time intervals and the geographic latitude of the measurement. While average lightning discharges at any latitude are probably similar, there are certainly differences within a given region: frontal storms produce a higher flashing rate and more strokes per flash than local convective storms (e.g., Holzer, 1953; Schonland, 1956; Kitterman, 1980), topography affects the channel lengths to ground and other properties (e.g., McEachron, 1939; Winn et al., 1973), and there are seasonal effects such as the positive discharges to ground produced by winter thunderstorms (Takeuti et al., 1973, 1976, 1977, 1978, 1980).

2-2. Cloud-to-Ground Lightning

A typical discharge between cloud and ground is initiated in the cloud and neutralized tens of Coulombs of negative cloud charge in about 0.5 sec. The total discharge is called a flash. Among the various processes comprising a flash are typically 3 or 4 high-current pulses called strokes, each lasting about 1 msec with a separation time of typically 40 to 80 msec. Lightning often appears to "flicker" because the eye resolves the individual light pulses associated with each stroke. In the idealized model of cloud charge shown in Figure 2-1(a), the primary dipole charges P and N are of the order of many tens of Coulombs or more of positive charge and negative charge, respectively, and p is a smaller positive charge. The stepped leader initiates the first stroke in a flash by moving from cloud to ground as sketched in Figures 2-1 and 2-2. The stepped leader is itself initiated by a preliminary breakdown within the cloud, although there is still some disagreement about the exact form and location of this process. In Figure 2-1(b), the preliminary breakdown is shown in the lower part of the cloud between the N and p regions. The preliminary breakdown sets the stage for negative



2.1. Stepped-leader initiation and propagation. (a) cloud charge distribution prior to lightning. (b) discharge called "preliminary breakdown" in lower cloud. (c) - (f) stepped-leader progression toward ground. Scale of drawing is distorted for illustrative purposes. Adapted from Uman (1971).



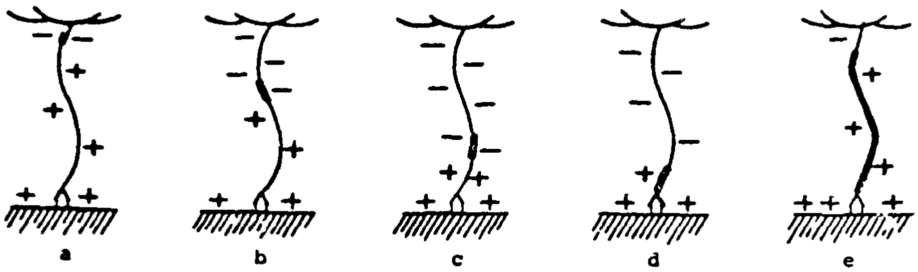
2.2. Return-stroke initiation and propagation. (a) final stage of stepped-leader decent. (b) initiation of upward moving discharges. (c) - (e) return-stroke propagation from ground to cloud. Scale of drawing is distorted for illustrative purposes. Adapted from Uman (1971).

charge (electrons) to be channeled toward ground in a series of luminous steps (hence the name stepped leader). Leader steps are typically 1 μsec in duration and tens of meters in length, with a pause time between steps of about 50 μsec (Figure 2-1(c)-(f), Figure 2-2(a)). A fully developed stepped leader lowers about 5 Coulombs of negative cloud charge toward ground in tens of milliseconds. The average downward velocity is about 2×10^5 m/sec,the average current is of the order of 100 A, and the electric potential of the leader channel with respect to ground is about -1×10^8 V. The intermittent leader steps have pulse currents of the order of 1 kA or more. Associated with the pulse currents are microsecond-scale electric and magnetic field changes. The stepped leader branches in a downward direction during its trip to ground. The preliminary breakdown, the subsequent lowering of negative charge toward ground by the stepped leader, and the resultant depletion of negative charge in the cloud combine to produce a total electric field change with a duration between a few and a few hundred milliseconds.

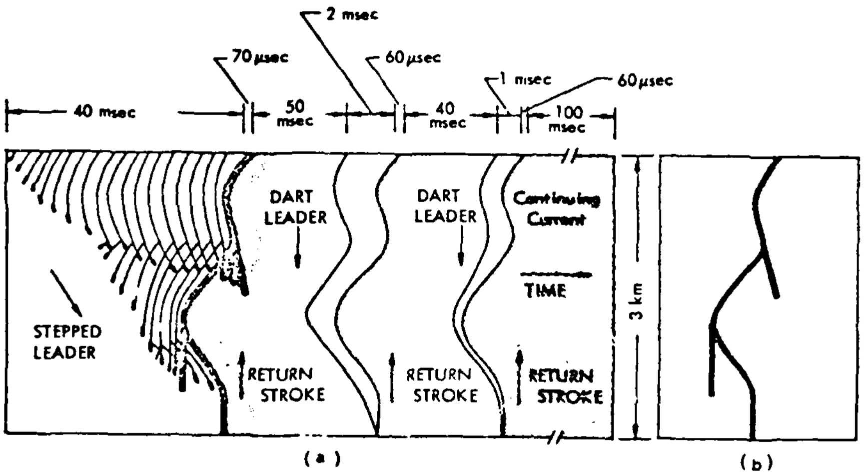
As the stepped leader nears ground, the electric field beneath it becomes very large and causes one or more upward-moving discharges to be initiated at the ground (Figure 2-2(b)), beginning the <u>attachment process</u>. The attachment process at the ground has, as we shall see, common elements with the attachment process for an aircraft in flight. When one of the upward-moving discharges from the ground contacts the downward-moving leader some tens of meters above the ground, the leader tip is connected to ground potential. The leader channel is then discharged by virtue of a ground potential wave, the <u>return stroke</u>, which propagates up the previously ionized path. The upward velocity of a return stroke is typically one-third the speed of light (Figure 2-2(c)-

(e)), and the total transit time from ground to the top of the channel is typically about 100 μsec. The return-stroke, at least its lower portion, carries a peak current of typically 20 kA, with a time from zero to peak of some microseconds. The maximum rate-of-change of the return stroke current is about 75 kA/μsec. or higher. Currents measured at the ground fall to half of peak value in about 50 μsec, and currents of the order of hundreds of Amperes may flow for milliseconds or longer. The rapid return-stroke energy input heats the tortuous leader channel to a temperature near 30,000° K, generating a high-pressure channel which expands and creates the shock waves which eventually become thunder. The return stroke lowers to ground the charge originally deposited on the stepped leader and in doing so produces an electric field change with time variations ranging from sub-microsecond to many milliseconds.

After the return stroke current has ceased to flow, the flash may end. On the other hand, if additional charge is made available to the top of the channel by discharges within the cloud known as K- and J-processes, a continuous or <u>dart leader</u> (Figure 2-3) may propagate down the decaying first return stroke channel at a velocity of about 3×10^6 m/sec. The dart leader lowers a charge of the order of 1 Coulomb by virtue of a typical current of 500 A. The dart leader thus sets the stage for the second (or any subsequent) return stroke. Dart leaders and strokes subsequent to the first are usually not branched. Some leaders begin as dart leaders but end their trips toward ground as stepped leaders. These are known as <u>dart-stepped</u> leaders. Dart-leader electric field changes usually have a duration of about 1 millisecond. Subsequent-stroke electric field changes are similar to, but usually a factor of two or so smaller than, first-stroke field changes. Subsequent strokes have faster



2.3. Dart-leader and subsequent return stroke. (a) - (c) dart leader deposits negative charge on defunct first-stroke channel. (d) - (e) return-stroke propagates from ground to cloud. Scale of drawing is distorted for illustrative purposes. Adapted from Uman (1971).



2.4. (a) The luminous features of a typical lightning flash as would be recorded by a camera with relative motion (horizontal and continuous) between lens and film, a so-called streak camera. Scale of drawing is distorted for illustrative purposes. (b) the same lightning flash as recorded by an ordinary camera. Adapted from Uman (1969).

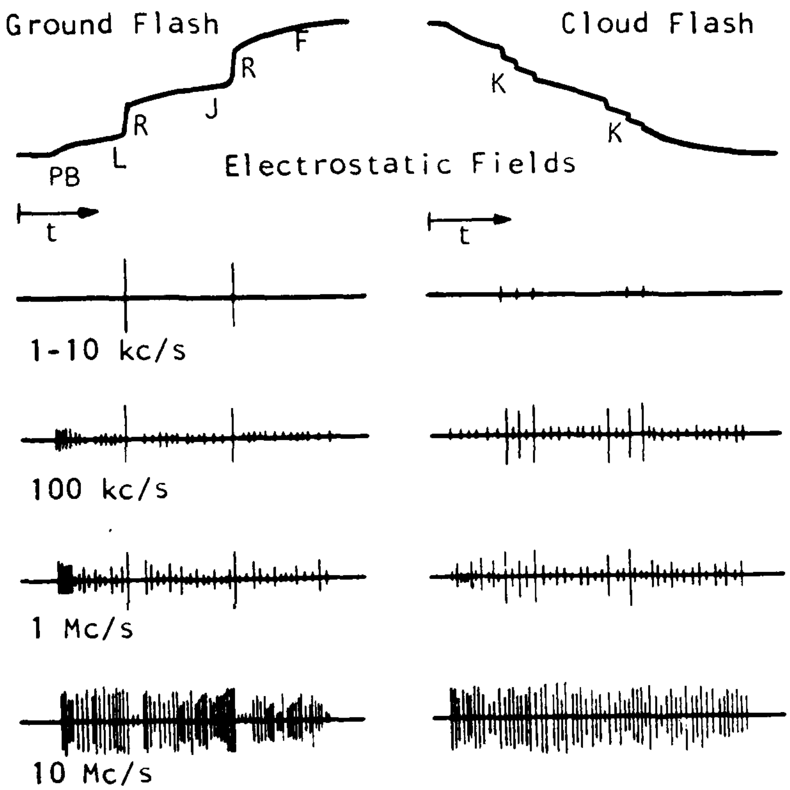
zero-to-peak current risetime than first strokes but a similar maximum rate-of-change of current.

The time between successive return strokes in the same channel is usually 40 to 80 msec but can be tenths of a second if a continuing current flows in the channel. A continuing current can also follow the final stroke in a flash. Continuing currents are of the order of 100 A and represent a direct transfer of charge from cloud to ground. The electric field change produced by a continuing current is linear for roughly 0.1 sec and is consistent with the lowering of about 10 Coulombs of cloud charge to ground. Between one-quarter and one-half of all cloud-to-ground flashes contain a continuing current component.

A drawing of a streak photograph and a still photograph of a typical lightning flash is shown in Figure 2-4. In addition to the usual downward-moving negatively-charged stepped leader shown in Figure 2-4, lightning may also be initiated in the cloud by a positively charged downward-moving stepped leader, but this type of discharge is not common (Berger and Vogelsanger, 1966; Berger 1967, 1972; Takeuti et al., 1973, 1976, 1978, 1980). Furthermore, lightning can be initiated at the ground, usually from tall structures, by upward-going stepped leaders which can be either positively or negatively charged (Berger and Vogelsanger, 1966; Berger, 1967, 1972). The upward-going leaders branch in an upward direction. In this study we will concentrate on the most common form of cloud-to-ground lightning, namely that which lowers negative charge from cloud to ground and is initiated by a downward-moving, negative charged stepped leader.

2-3. Cloud Lightning

Intracloud and intercloud lightning discharges take place between positive and negative cloud charges and have a total duration approximately equal to that of ground discharges, 0.5 seconds. A typical cloud discharge neutralizes roughly 20 to 30 Coulombs of charge over a total path length of 5 to 10 kilometers. The charge transfer process is thought to consist of a continuously propagating leader which generates 5 or 6 weak return strokes called K-changes when the leader contacts pockets of space charge opposite to its own. The K-changes are similar to the K-changes which occur in the cloud during the time between return strokes of ground discharges. Cloud discharges have not been studied nearly as extensively as discharges to ground, and hence much less is known about their detailed physical characteristics. The charge motion in cloud discharges produces electric fields whose frequency spectra have roughly the same amplitude distribution as those of ground discharges for frequencies below about 1 kHz and above about 100 kHz. Within the frequency band from 1 kHz and 100 kHz, the ground discharge is a more efficient radiator because of the very energetic return strokes. Figure 2-5 shows a comparison between ground-flash and cloud-flash electric fields in both the time and frequency domains. The time-domain field changes at close range from both types of discharges are ramp-like with superimposed steps, the ground-stroke steps being much larger than the cloud-flash K-change steps. The outputs of narrow-band tuned receivers centered around the indicated frequencies are drawn below the time domain fields of each flash. Thus, for instance, at 100 kHz the output from the tuned receiver for the ground flash shows a series of pulses corresponding to leader activity, followed by a major pulse at the time of the first return stroke, and so on. The 10 MHz pulses shown in Figure 2-5 for both ground and cloud flashes are of roughly



2.5. Electric field changes in the time domain and the corresponding fields at different frequencies for a typical cloud-to-ground flash and a typical intracloud flash, both at a distance of about 10 to 15 km. PB = preliminary breakdown; L = leader; R = return stroke; J = J-process; F = Final process which may be a continuing current or a cloud discharge; K = K change. Amplitude scales for different frequencies are not the same. Adapted from Malan (1963).

equal magnitude and are thought to be due to relatively small-scale discharges which occur primarily within the cloud. The return-stroke and K-change frequency spectra both have a maximum value in the 5 kHz range, but the return-stroke spectrum has a higher amplitude.

The term "cloud lightning" refers to all lightning which does not reach ground. It is important to keep in mind that cloud-to-ground lightning has a significant in-cloud component and hence probably shares many common features with cloud lightning.

Section 2

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Section 3

Modeling and the Relation of Lightning Currents to Remote Electric and Magnetic Fields

3-1. Modeling

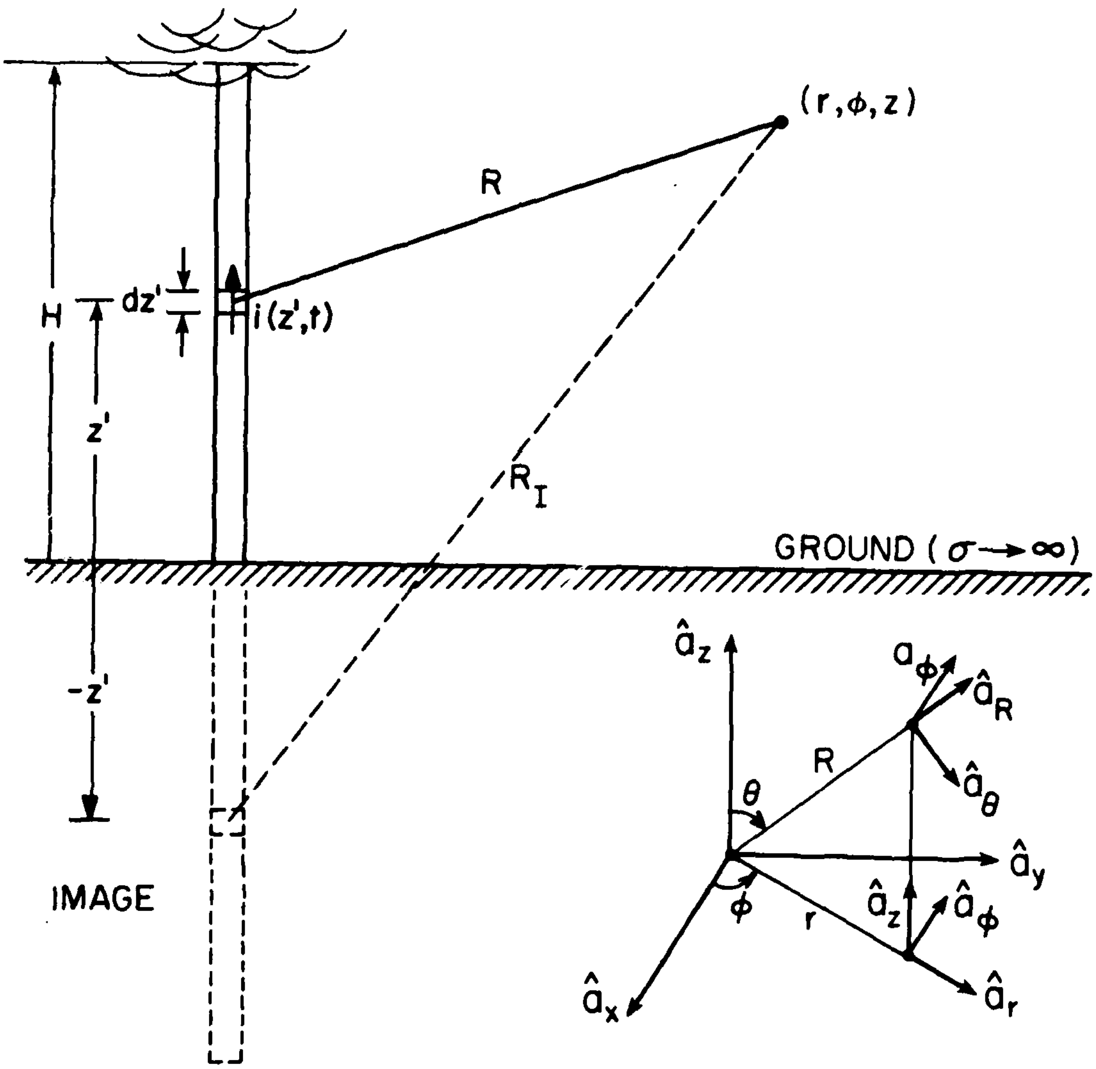
A model can be defined as a physical or mathematical construct which approximates to some degree certain aspects of natural or man-made phenomena. Perhaps the most important aspect of a model is that it can be used for prediction. In this report we will be concerned with the mathematical modeling of lightning processes. The end product of the modeling will be the prediction of the electric and magnetic fields produced by these processes.

There are basically three levels of sophistication in the mathematical modeling of lightning: (1) The most sophisticated model describes the detailed physics of the lightning channel in terms of equations of conservation of mass, momentum, and energy, equations of state, and Maxwell's equations. This type of model requires a detailed knowledge of physical parameters such as the ionization and recombination coefficients and of thermodynamic properties such as the thermal and electrical conductivities. Using this basic approach, one can attempt to predict the channel current as a function of height and time. From a knowledge of the current, the remote electric and magnetic fields can be calculated (e.g., Uman et al., 1975). Modeling of this type has recently been attempted for lightning return strokes by Strawe (1979) and holds considerable promise for providing a better understanding of the return stroke. At present, such modeling does not produce realistic results. (2) A less sophisticated level of modeling involves mathematically describing the lightning channel as a R-L-C transmission line with circuit elements that may vary with height and time. The intent again is to predict a channel current as a function of height and time, and to use this current to calculate the fields. Price and Pierce (1977) and Little (1978, 1979) have used this approach for return strokes. (3) In the least sophisticated approach to modeling, and that which produces the closest approximation to nature, a temporal and spatial form for the channel current is assumed and then used to calculate the remote fields. The assumed current is constrained in its characteristics by the properties of lightning currents measured at ground level and by the available data on the measured electric and magnetic fields. Lin et al. (1980) have reviewed the literature on this last type of modeling for return strokes and have presented a new return stroke model which is superior to previous models.

In the present report, we consider only models of type (3) above: where the channel current is assumed, and then this assumed current is used for detailed calculation of the electric and magnetic fields. The validity of these models can be judged by how well the assumed current agrees with ground-based current measurements, when available, and how well the calculated remote fields compare with measured fields.

3-2. The Relation of Lightning Currents to Remote Electric and Magnetic Fields

We consider all lightning currents to be contained in vertical channels of negligible cross-section above a perfectly conducting ground plane as illustrated in Figure 3-1. Uman et al. (1975) have shown how to compute the remote electric and magnetic fields from Maxwell's equations when the current is specified. The electric and magnetic fields at altitude z and range r from a short length of channel dz' at height z' carrying a



3.1. Definition of all geometrical parameters needed in the calculation of electric and magnetic fields.

time-varying current $i(z',t)$ are

$$d\vec{E}(x,y,z,t) = \frac{dz'}{4\pi\varepsilon_o R} [\{\frac{3r(z - z')}{R^4} \int_o^t i(z',\tau - R/c)d\tau$$

$$+ \frac{3r(z - z')}{cR^3} \cdot i(z',t - R/c) + \frac{r(z - z')}{c^2R^2} \cdot \frac{\partial i(z',t - R/c)}{\partial t} \} \vec{a}_r$$

$$+ \{\frac{2(z - z')^2 - r^2}{R^4} \cdot \int_o^t i(z', \tau - R/c)d\tau + \frac{2(z - z')^2 - r^2}{cR^3} \cdot i(z',t - R/c)$$

$$- \frac{r^2}{c^2R^2} \cdot \frac{\partial i(z',t - R/c)}{\partial t} \}\vec{a}_z] \qquad (1)$$

$$d\vec{B}(x,y,z,t) = \frac{\mu_o dz'}{4\pi R} \{\frac{r}{R^2} \cdot i(z',t - R/c) + \frac{r}{cR} \cdot \frac{\partial i(z',t - R/c)}{\partial t} \} \vec{a}_\phi \qquad (2)$$

where Equations (1) and (2) are in cylindrical coordinates, ε_o is the permittivity and μ_o the permeability of vacuum, and all geometrical factors are defined by Figure 3-1. The effects of the perfectly conducting ground plane are included by postulating an image current beneath the plane as shown in Figure 3-1. The electric and magnetic fields of the image are obtained by substituting R_I for R and z_I' for z' in Equations (1) and (2). Once the expression for the fields of a short channel section are formulated, the fields for the total channel are found by integration over the channel.

An important special case is that of the fields on the ground. For a vertical channel between the heights of H_B and H_T, these are (Uman et al., 1975)

$$E_z(x,y,o,t) = \frac{1}{2\pi\varepsilon_o R} [\int_{H_B}^{H_T} \frac{2z'^2 - r^2}{R^4} \int_o^t i(z',\tau - R/c)d\tau \, dz'$$

$$+\int_{H_B}^{H_T} \frac{2z'^2 - r^2}{cR^3}\, i(z',t-R/c)dz' - \int_{H_B}^{H_T} \frac{r^2}{c^2R^2} \frac{\partial i(z',t-R/c)}{\partial t}\, dz'] \tag{3}$$

$$B_\phi(x,y,z,t) = \frac{\mu_o}{2\pi R} [\int_{H_B}^{H_T} \frac{r}{R^2}\, i(z',t-R/c)dz' + \int_{H_B}^{H_T} \frac{r}{cR} \frac{\partial i(z',t-R/c)}{\partial t}\, dz'] \tag{4}$$

In the remainder of this report we use Equations (1) and (2), along with our best estimate of the channel current for the various lightning processes to calculate the remote electric and magnetic fields generated by those processes. We do these calculations for what we consider to be a typical lightning. To extrapolate these results to the case of a severe lightning, all amplitude values should be multiplied by a factor of ten.

3-3. Computer Calculations

Computer codes which employ Equations (1) and (2) have been written to calculate the electric and magnetic fields and their frequency spectra at any specified point in space with the channel currents as input parameters. We define the frequency spectrum as $20 \log_{10} A(\omega)$ where $A(\omega)$ represents the Fourier transform of either the current $I(t)$ in Amps, the electric field intensity $E(t)$ in V/m, or the magnetic flux density $B(t)$ in Wb/m^2. In Section 4 we give our best estimates of the channel currents for all salient lightning processes and include the results of some sample calculations of electric and magnetic fields and their frequency spectra. As part of the present contract we have provided the AFWAL with annotated computer program listings for the following lightning processes: (1) preliminary breakdown, (2) stepped leader, and (3) return stroke. Due to the relatively short time-duration of this contract, we have not specifically written programs to compute the fields and spectra of the remaining lightning processes, although the necessary channel current values are given in Section 4.

Section 3

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Section 4

Literature Review and Specification of Lightning Models

4-1. Introduction

The brief overview of lightning phenomenology given in Section 2 and the theory presented in Section 3 provide the necessary background for a discussion of the significant literature concerning the modeling of lightning. A bibliography of the most pertinent papers is found at the end of this section. These selected references were derived from a much more extensive bibliography on lightning and related phenomena that was assembled by M.A. Uman and E.P. Krider. Copies of this extensive bibliography are available on request. In our discussion of the literature and the current state of the art in lightning modeling we will consider the following specific topics: cloud charges and static electric fields; the following elements of cloud-to-ground flashes: preliminary breakdown, stepped leader, attachment process, return stroke fields, return stroke frequency spectra, return stroke current, return stroke velocity, return stroke models, dart leader, continuing current, and J and K changes; cloud discharges; and flash frequency spectra for both cloud and ground discharges. The preceeding subjects are given in the bibliography of significant literature in the same order as listed above, and will be considered in that order. Also found in the Bibliography is a list of books on lightning and a list of aircraft/lightning conference proceedings. In the discussion which follows, we will mention explicitly only those references which have directly influenced our view of the modeling process. Nevertheless, an important prerequisite for admission into the field of lightning modeling should be a careful reading of all articles in the bibliography.

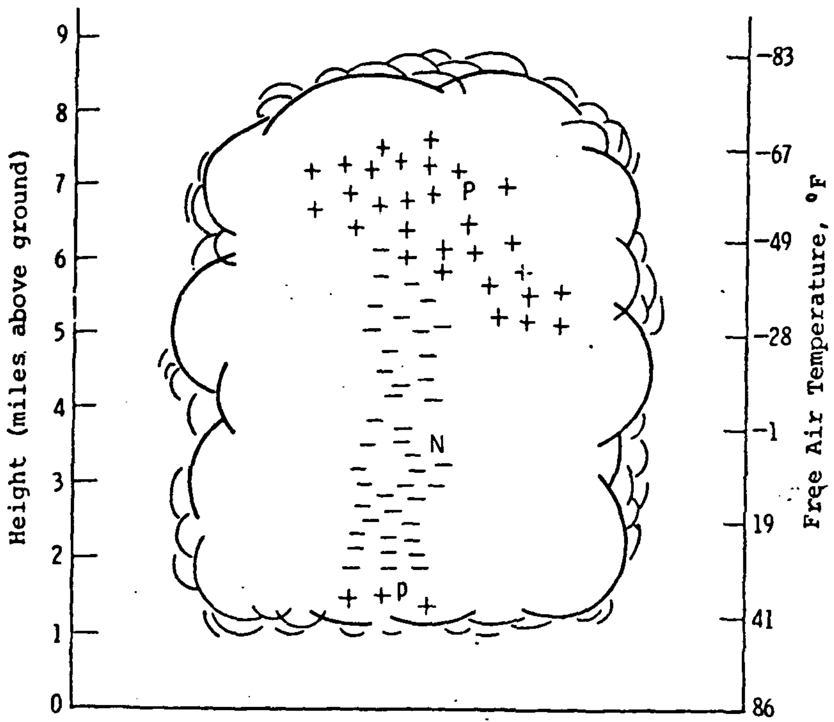
4-2. Cloud Charges and Static Electric Fields

4-2-1. Literature.

The primary generator of lightning is the common thunderstorm or cumulonimbus cloud. Although some measurements have been made of the electrical properties of other types of clouds (Imyanitov et al., 1972; Imyanitov and Chubarina, 1967), we will concentrate on the cumulonimbus because it is the most common lightning generator and because it is the cloud type about which the most is known.

By the early 1930's, a model for the charge structure of a thundercloud had emerged, primarily from ground-based electrostatic field measurements (Wilson, 1916, 1920; Appleton et al., 1920; Schonland and Craib, 1927). In this model the thundercloud charges form a positive electric dipole; that is, there is a positive charge located above a negative as shown in Figure 4-1. From in-cloud measurements Simpson and Scrase (1937) were able to verify this basic dipole structure, and they also found the small concentration of positive charge at the base of the cloud shown in Figure 4-1. More recent measurements have confirmed the general validity of this overall charge structure (e.g., Simpson and Robinson, 1941; Malan, 1952; Huzita and Ogawa, 1976; Winn et al., 1981), although it is now recognized that there can be large horizontal displacements between the positive and the negative charge regions and that the positive charge may be highly diffuse.

Because of the remote (outside the cloud) nature of many of the measurements and the difficulty of interpreting these and the internal measurements in the presence of spatial and time-varying conductivities, the magnitudes and heights of the cloud charge centers are still uncertain (see Kasemir, 1965; Moore and Vonnegut, 1977). For example, space-charge



4.1. Schematic diagram of typical thunderstorm cloud charge distribution in South Africa. Adapted from Malan (1963).

screening layers on the surface of the cloud (Brown et al., 1971; Hoppel and Phillips, 1971; Klett, 1972) can lead to a substantial underestimation of remotely-measured cloud charge magnitudes.

These problems not withstanding, a model such as that shown in Figure 4-1 is generally used. Of more immediate import to the present study is the fact that the overall charge associated with the major charge regions is not uniformly distributed, but rather is found in localized pockets of high space-charge concentration. Evidence for this localized charge structure is to be found (1) in the fact that only occasionally are high values of electric field measured while randomly sampling the internal cloud fields (Winn et al., 1974) whereas, if there were large charge regions, there should be relatively large volumes of high field and (2) in the fact that individual return strokes in a multiple-stroke ground flash may tap different negative charge regions, the localized negative charge regions being displaced primarily horizontally from each other (Krehbiel et al., 1979).

The approach adopted in this study is to use cloud charge distributions consistent with those deduced from ground-based measurements; that is, we assume an idealized cloud with spherical concentrations of charge to represent the p, N, and P regions shown in Figure 4-1. The volumes over which these charges are distributed and their altitudes are chosen so that peak fields predicted by the model are consistent with those reported by investigations in which rockets, ballons, or aircraft were flown directly into clouds.

Typical values given in the literature for the electric charge centers p, N, and P along with their mean observed altitudes above ground level are +4 C at 1.5 km, -24 C at 3 km and +24 C at 6 km in England, ground level being about 1 km above sea level (Simpson and Robinson, 1941); +10 C at 2 km, -40 C at 5 km, and +40 C at 10 km in South Africa, ground level being about 1.8 km above sea level (Malan, 1952); and +24 C at 3 km, -120 C at 6 km and + 120 C at 8.5 km in Japan, ground level being about 1 km above sea level (Huzita and Ogawa, 1976). It is interesting to note that, while the absolute magnitudes of the charges in these models vary considerably, their proportions are relatively constant. Jacobson and Krider (1970) have summarized most available data for the location and size of the N charge neutralized by lightning, their results in Florida (at sea level) being -10 to -40 C at 6 to 9.5 km height.

Since the value for electrical breakdown between plane, parallel electrodes at sea level in dry air is about 3×10^6 V/m, one can assume that inside a particle and aerosol-filled cloud at the reduced pressures characteristic of 4 to 6 km altitude, the fields will probably not exceed 5×10^5 to 1×10^6 V/m. Winn et al. (1974) report having observed a peak of 1×10^6 V/m on one of their rocket flights, though they express reservations about the validity of that measurement. Fitzgerald (1976) also reported a measured peak field of 1.2×10^6 V/m. On the other hand, rocket measurements usually measure only the field component perpendicular to the rocket axis, so that it is possible that the total fields are somewhat larger than those generally reported. Some observed field values are presented in Table 1.

4-2-2. Model.

Based on all of the above data and other data cited in the bibliography we choose to adopt the following model values for the cloud charges: +17 C located in a sphere of radius 0.5 km centered at 4 km, -80 C located in a sphere of radius 2 km centered at 6 km, and +80 C

TABLE 1
THUNDERSTORM ELECTRIC FIELDS
MEASURED IN AIRBORNE EXPERIMENTS

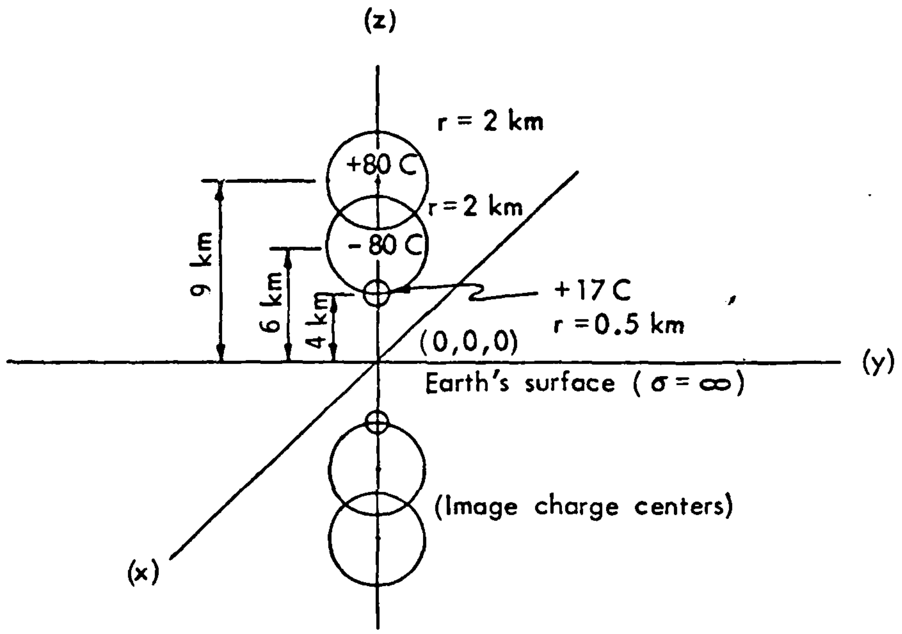
Investigation	Typical (V/m)	High Values Occasionally Observed	Measurement Type
Winn et al. (1974)	$5\text{-}8 \times 10^4$	2×10^5	Rockets
Winn (private comm.)	-	1.4×10^5	Balloons
Rust, Kasemir (private comm.)	1.5×10^4	3.0×10^5	Aircraft
Imyanitov et al. (1972)	1×10^5	2.5×10^5	Aircraft
Evans (1969)		2×10^5	Parachuted Sonde
Fitzgerald (1976)	$2\text{-}4 \times 10^5$	8×10^5	Aircraft

located in a sphere of radius 2 km centered at 9 km, all distances being above sea level. This model for the cloud charge is shown in Figure 4.2.

4-3. Preliminary Breakdown

4-3-1. Literature.

The measured change in the electrostatic field just before the first return stroke in a ground flash has a duration between a few milliseconds and a few hundred milliseconds with a typical value of some tens of milliseconds (e.g., Clarence and Malan, 1957; Kitagawa and Brook, 1960; Takeuti et al., 1960; Harris and Salman, 1972; Thomson, 1980). Since, the stepped leader duration (see Section 4-4) is always shorter than or equal to the duration of the overall pre-stroke field change, some of the observed pre-stroke field change must be attributed to the so-called "preliminary breakdown" within the cloud. Photographic evidence for discharges in the cloud preceeding the stepped leader is given by Malan (1952, 1955) who, using a special streak camera, showed that clouds often produce luminosity for a hundred or more milliseconds before the emergence of the stepped leader from the cloud base. Stepped leaders travel at a typical velocity of about 2×10^5 m/sec and thus should take about 25 msec for the 5 km trip from inside the cloud to ground. It is a matter of some dispute as to whether the relatively long pre-stroke field changes, say over 100 msec (Thomson (1980) in New Guinea found 68 per cent exceeding 100 msec), should be associated with processes which initiate stepped leaders as argued by Clarence and Malan (1957), or whether the long pre-stroke field changes should be treated as relatively independent cloud discharges as argued by Kitagawa and Brook (1960) and by Thomson (1980). Here we define the preliminary breakdown to be those discharge processes which lead directly to the initiation of a stepped leader. In the absence of



4.2. Spherical charge distribution model of cumulonimbus cloud.

a causal relationship, the pre-stroke processes will simply be called a cloud discharge and will be assumed to have the properties of the cloud discharges discussed in Sections 2-3 and 4-10.

Of primary interest to the present study is the location of the preliminary breakdown within the cloud, the nature of the electromagnetic fields generated by it, and the currents which are necessary to produce these fields. The location of the preliminary breakdown has been determined in three ways: (1) from the variation of the initial part of the electrostatic field change with distance for a number of single-station measurements (Clarence and Malan, 1957), (2) from the field change measured simultaneously at eight ground stations (Krehbiel et al., 1979), and (3) from the location of the sources of the initial VHF (30 to 50 MHz) radiation produced within the cloud (Rustan, 1979; Rustan et al., 1980).

Clarence and Malan (1957), assuming that the preliminary breakdown channels were vertical, found that the initial breakdown began between the main negative charge center N and the lower positive charge center p as shown in Figure 2-1(b) and that the discharge was just as likely to start from the positive center and go upward as to start from the negative center and go downward. The measured location for this preliminary breakdown in South African thunderstorms was between 1.4 km and 3.6 km above the ground, ground being about 1.8 km above sea level. Clarence and Malan suggest that, following the breakdown phase which lasts between 2 and 10 msec and is designated B, there is an intermediate stage, designated I, which lasts from zero to hundreds of milliseconds. During the I stage, the breakdown channels become negatively charged to a level at which they can generate a downward-moving stepped leader, the L stage.

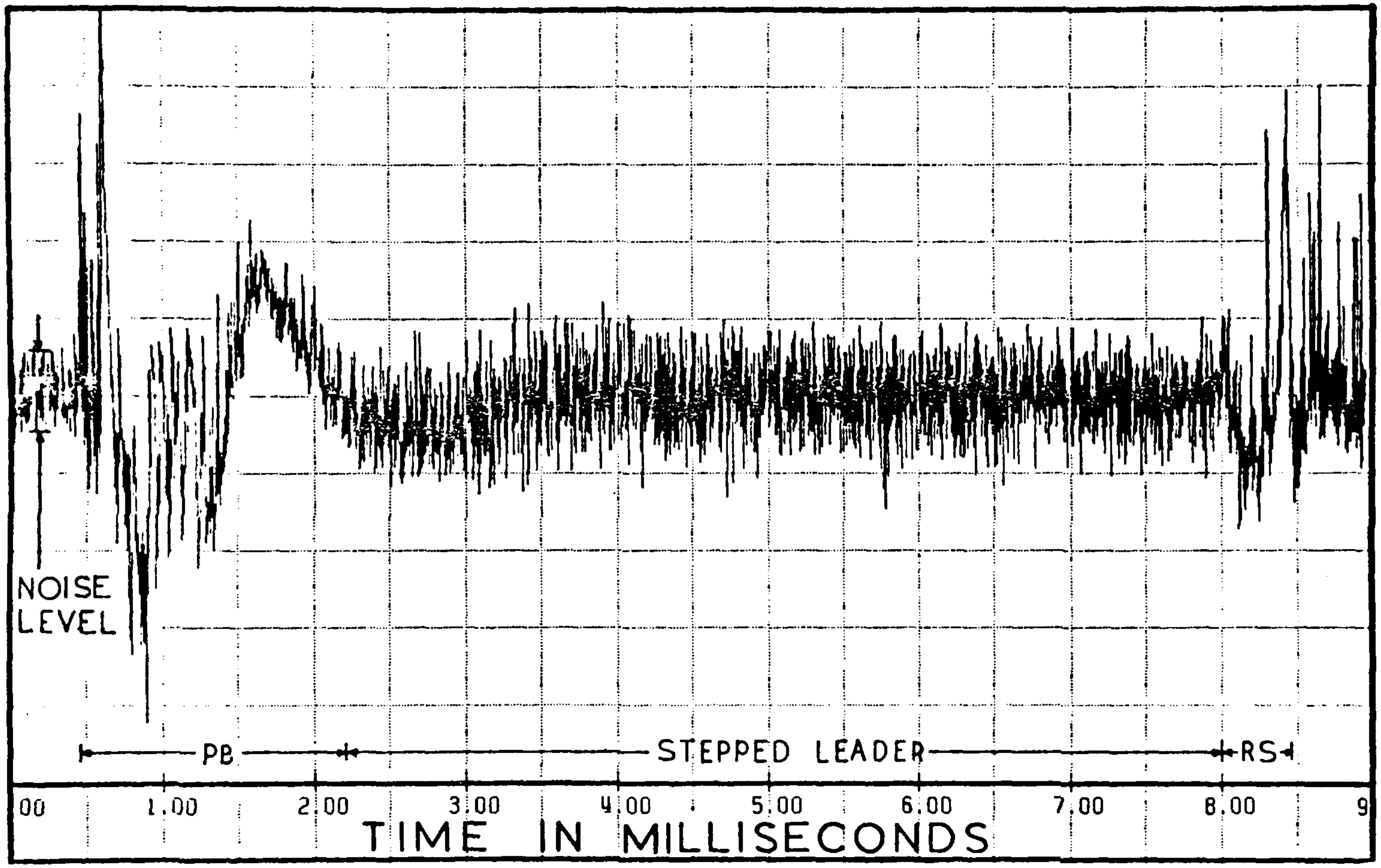
During the B stage, Clarence and Malan (1957) report large VLF pulses, their detailed shapes being unresolved. Investigators following Clarence and Malan (1957) have generally not been able to verify the validity of the BIL scheme (Kitagawa and Brook, 1960; Thomson, 1980; Krehbiel et al.; 1979; Beasley et al., 1981).

Krehbiel et al. (1979) found that, for two flashes with long duration preliminary field changes, the charge motion was initially vertical but soon became horizontal. Negative charge was moved downward and horizontally away from the first stroke charge volume. Finally, one of the succession of these breakdown events launched a leader to ground. Krehbiel et al. (1979) state that the field changes observed by Clarence and Malan (1957) can be interpreted in terms of horizontal channels and hence that the B-I characterization is not justified.

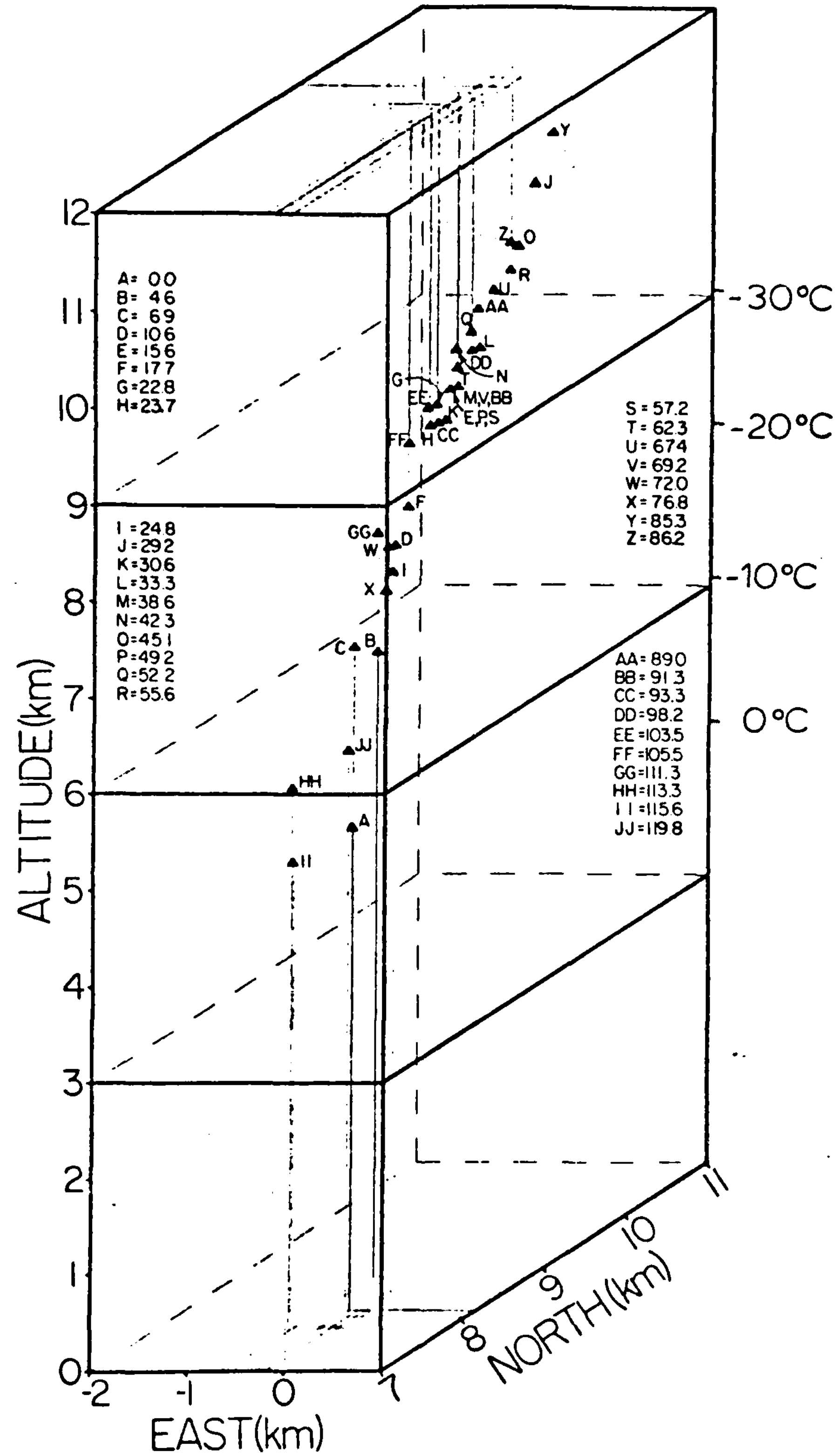
Rustan (1979) and Rustan et al. (1980) located the sources of individual VHF impulses produced by lightning using the difference in the time-of-arrival of the impulses at an array of radio receivers. The preliminary breakdown periods for the flashes that were analysed were of the order of several milliseconds. Contrary to the results of Clarence and Malan (1957), but in agreement with Krehbiel et al. (1979), Rustan (1979) and Rustan et al. (1980) found that the initial sources of VHF in Florida thunderstorms (ground level equals sea level), are roughly vertical between a height of 4 and 10 km and that the appearance of these sources preceeds any significant change in the electrostatic field. The stepped leader emerges from the bottom of this preliminary breakdown column and is characterized by a significant change in the electrostatic field and VHF pulses of much lower amplitude and shorter duration than those of the preceeding preliminary breakdown.

Both the preliminary breakdown and the stepped leader lower negative charge toward ground. Large VLF pulses mark the transition from the preliminary breakdown to the stepped leader, as we shall see in the next paragraph. Figure 4-3 shows an example of the envelope-detected VHF signal during both the preliminary breakdown and stepped leader phases of a cloud to ground flash and Figures 4-4(a) and (b) give examples of source locations determined by the VHF time-of-arrival technique.

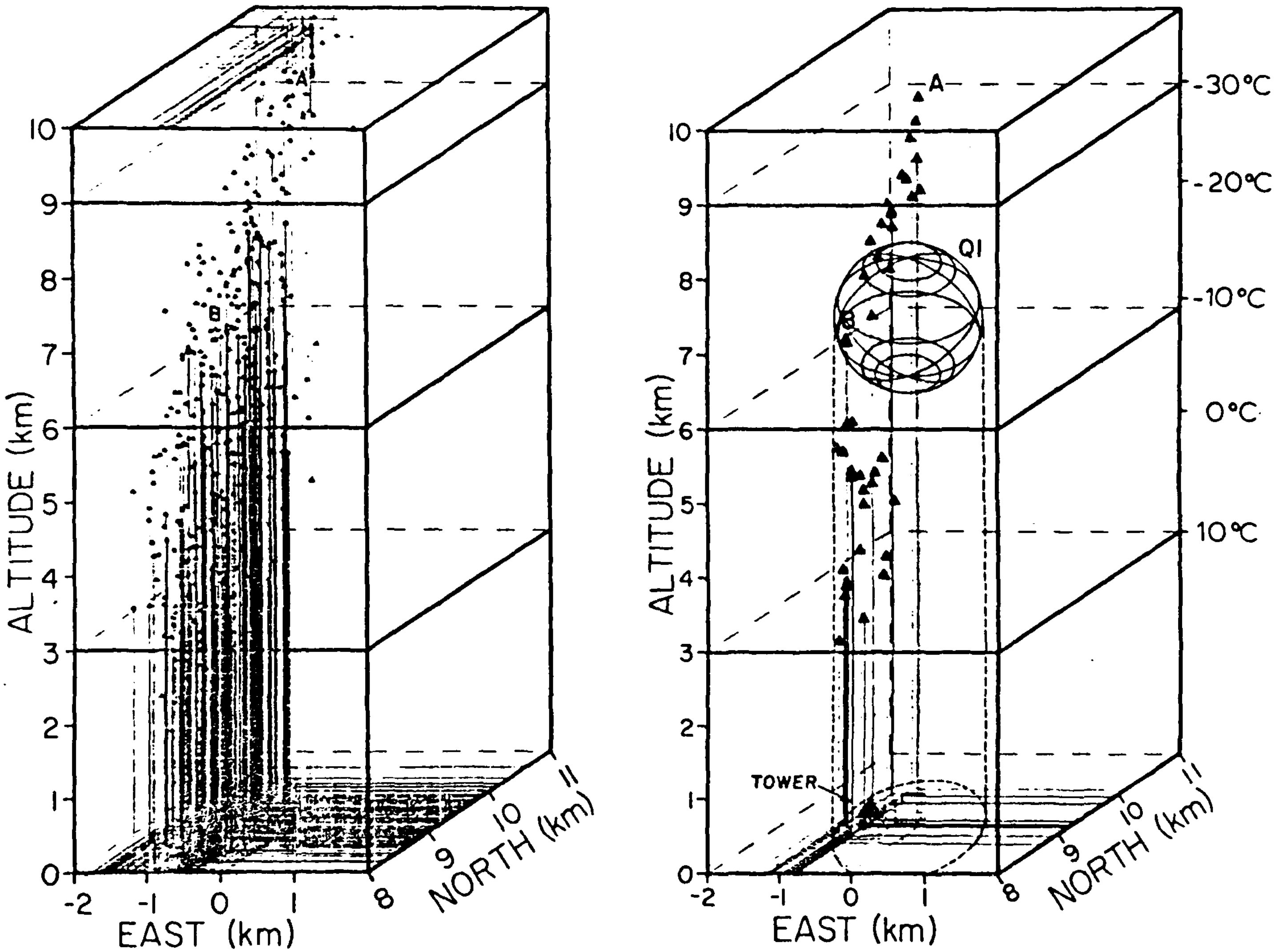
Many investigators (e.g., Kitagawa, 1957; Clarence and Malan, 1957; Kitagawa and Brook, 1960; Krider and Radda, 1975; Weidman and Krider, 1979; Beasley et al., 1981) have presented data which indicate that the beginning of the stepped leader or perhaps the end of the preliminary breakdown is often characterized by a train of relatively large bipolar pulses which can be observed with systems operating at frequencies from VLF to VHF. In much of the literature (e.g., Clarence and Malan, 1957) these pulses are identified as the beginning of a β-leader, as we shall discuss in Section 4-4-1. Examples of these pulses are shown in Figures 4-5(a) and (b) and the frequency spectrum of one of these pulses is shown in Figure 4-6. Beasley et al. (1981) have presented direct evidence that these pulses are produced at the location where the preliminary breakdown of Rustan (1979) and Rustan et al. (1980) ends and the stepped leader begins. Weidman and Krider (1979) have characterized the pulse shapes as follows: The initial polarity is the same as the ground stroke electric field change that follows; the overall shape is bipolar with a 10 μsec rise to peak upon which is superimposed two or three microsecond-width pulses followed by a smooth negative half-cycle and an overall duration of about 50 μsec;



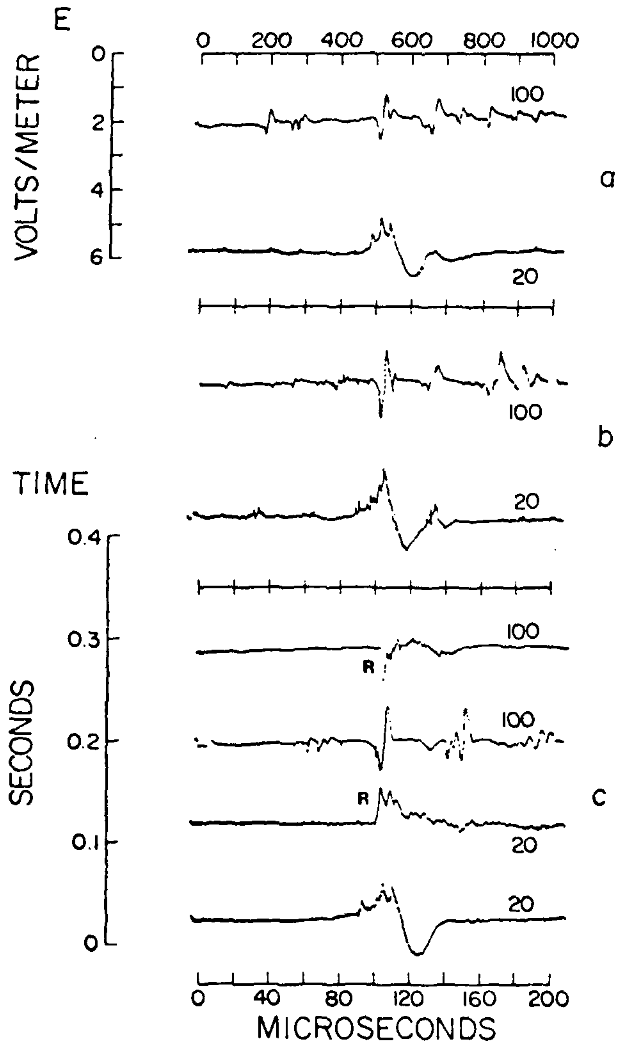
4.3. *Log-amplitude VHF radiation at the beginning of the* 181806 flash on August 8, 1977. PB is the preliminary breakdown and RS the first return stroke.



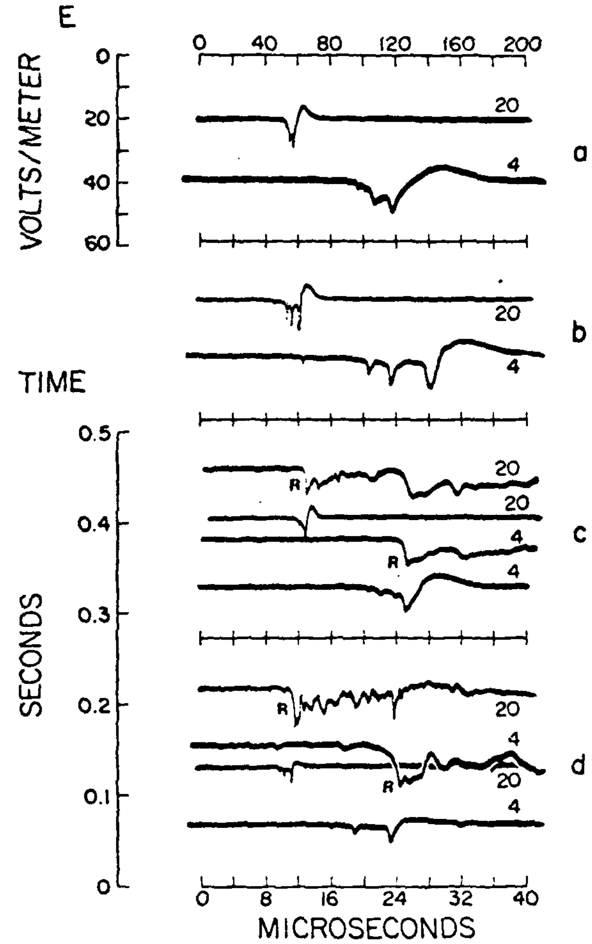
4.4(a). VHF source locations for the initial 120 μsec of the lightning to ground whose VHF radiation is shown in Fig. 4.3.



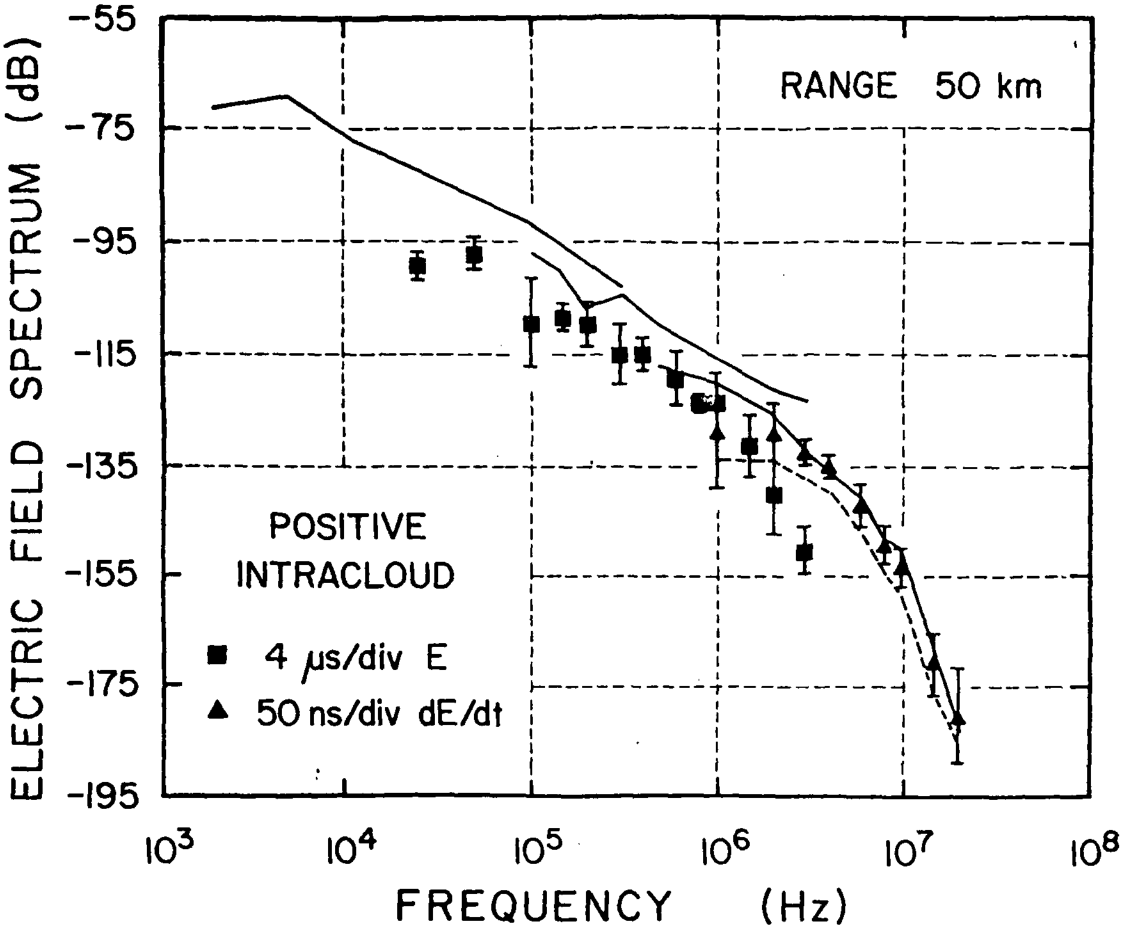
4.4(b). VHF source locations for the preliminary breakdown (AB) and stepped leader (below B) for the lightning to ground whose VHF radiation is shown in Fig. 4.3. On left are all locations, on right only the average locations determined each 94 μsec.



4.5(a). Large bipolar electric fields radiated by lightning discharges at end of preliminary breakdown or beginning of stepped leader at distances of 100 to 200 km. Each waveform is shown on both a slow (100 μs/div) and a fast (20 μsec/div) time scale, the latter inverted with respect to the former. The fast trace has been positioned so that the centers of each trace coincide in time. A positive field is shown as a downward deflection on the slow trace. The time interval between the return stroke R and the discharge preceding it in (c) is shown on the scale at left. Adapted from Weidman and Krider (1979).



4.5(b). Large bipolar electric fields radiated by lightning discharges at end of preliminary breakdown or beginning of stepped leader at distances of 30 to 50 km. Each wave form is shown on both a slow and fast time scale, the latter indented with respect to the former. A positive field is shown as a downward deflection on all records. The time interval between the return stroke R and the discharge preceding it in (c) and (d) is shown on the scale at left. Adapted from Weidman and Krider (1979).



4.6. Frequency spectra of the electric fields of 5 large bipolar pulses between 15 and 45 km normalized to 50 km. Solid lines represent the first return stroke frequency spectra given in Fig. 4.16. Time-domain waveforms of bipolar pulses are shown in Figs. 4.5(a) and (b).

the amplitude approaches that of the return stroke; and several pulses separated by about 100 μsec is a characteristic pattern. Since the detailed shapes of the β pulses of Clarence and Malan (1957) were not resolved by their experimental apparatus, it is not known whether their pulses were similar to those shown in Figures 4-5(a) and (b), but it is likely they were in view of the fact that Weidman and Krider (1979) found that the shapes of the pulses in cloud discharges which did not precede return strokes were similar to the shapes of the pulses which did precede return strokes. The polarities of the two types of pulses, however, were opposite. Since the cloud pulses and the preliminary breakdown pulses are apparently generated in part by an intermittent or stepped process, it is natural to expect that the literature regarding the differences between these pulses and pulses associated with the photographed stepped leader would be confused, as is apparently the case.

Prior to the occurrence of pulses of the type shown in Figures 4-5(a) and (b), there is appreciable VHF radiation from the cloud (Malan, 1958; Brook and Kitagawa, 1964; Iwata and Kenada, 1967; Rustan, 1979), presumably due to localized breakdown processes involving relatively small charge transfers.

The detailed physics of the preliminary breakdown is not understood; however, there have been a number of suggestions as to how breakdown could start in the cloud, continue to grow, and eventually produce a stepped leader (e.g., Loeb, 1966, 1970; Dawson and Duff, 1970; Phelps, 1974; Griffiths and Phelps, 1976 a,b; Diachuk and Muchnik, 1979).

4-3-2. Model.

We will adopt the view that the large pulses shown in Figures 4-5(a) and (b) are associated with the final part of the preliminary breakdown. A plausible description of the physical processes necessary to produce a pulse of this type is the following (Weidman and Krider, 1979): Each of the fast electric field pulses riding on the slower overall pulse is generated by a breakdown process that elongates or radially spreads the channel. Each fast current pulse has a submicrosecond risetime, a duration of about a microsecond, and a peak current of about one kA as determined from electric field measurements. When the overall channel is formed, a slower current flows with a peak value of several kA and a total duration of about 80 μsec, and it is this slower current that generates the overall bipolar field shape.

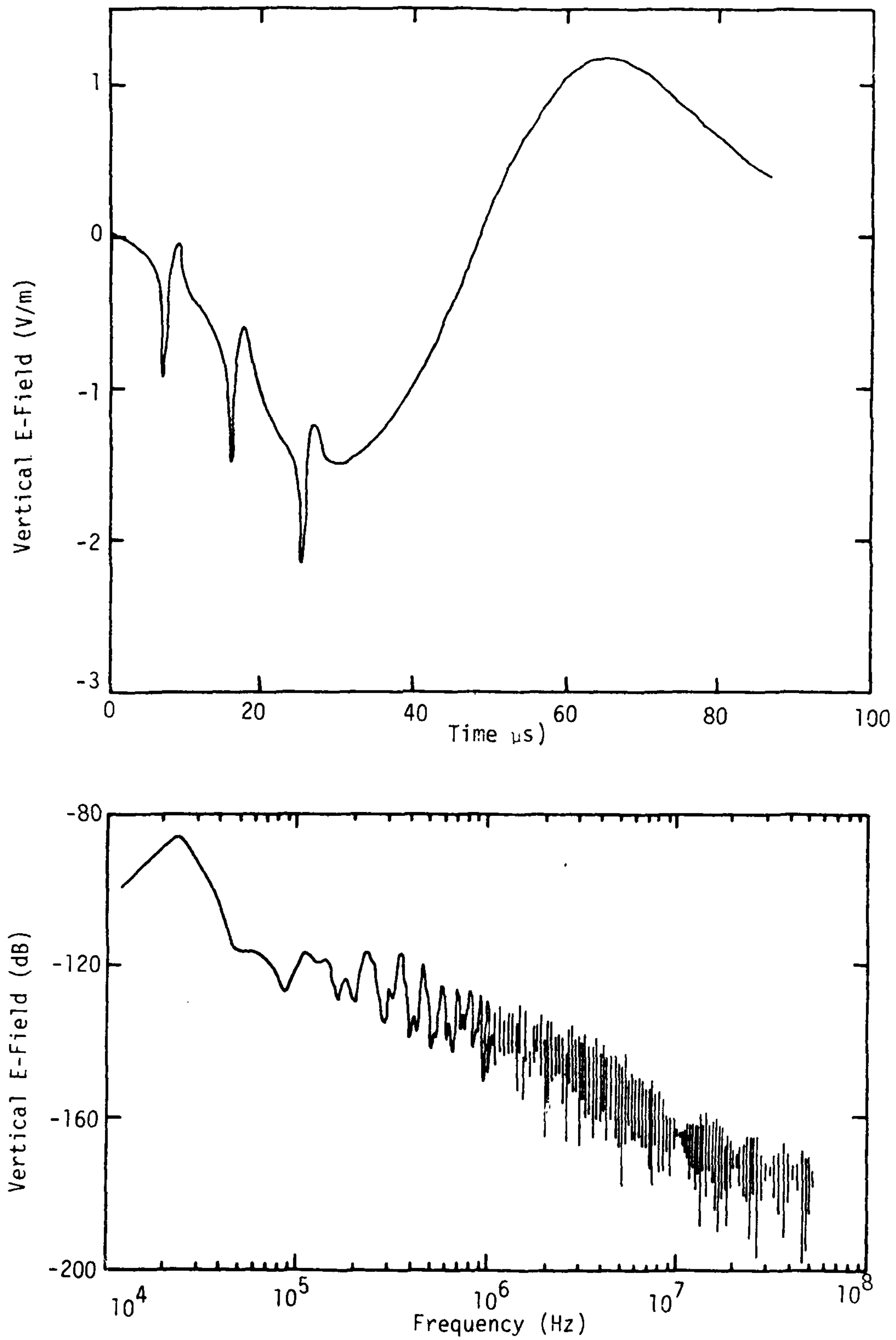
We model each of the overall pulses as a current having a Gaussian shape, $I_o e^{-t^2/T^2}$, with I_o = 10 kA, T = 25 μsec, with t = 0 occuring 20 μsec after the final sharp current pulse, which propagates down a vertical channel section 1050 m in length at a velocity of 5×10^7 m/sec. The current is uniform along the channel down to the propagating front.

Superimposed on the downward propagating current are fast current pulses due to three breakdown steps, each 350 m long. Each fast pulse has a triangular shape current of rise-time 0.1 μsec and decay to zero at 2 μsec. Each fast current pulse propagates vertically upward at a velocity of 10^8 m/sec as it attenuates as $I_p = I_{po}\, e^{-z/\Theta}$ where I_{po} = 2 kA, Θ = 75 m and z has its origin at 350 m, 700 m, and 1050 m from the top of the 1050 m channel section at times separated by 7 μsec. Calculated electric and magnetic fields for this model at the ground and in the air are shown in Figure 4-7. Note the good correspondence with the ground-based measurements shown in Figures 4-5(a) and (b).

4-4. Stepped Leader

4-4-1. Literature.

A significant fraction of what is known today about stepped leaders



4.7. Calculated bipolar pulse of the type shown in Figs. 4.5(a) and (b) and its frequency spectrum at 50 km. Compare with experimental data shown in Fig. 4.6.

was determined photographically by Schonland and his coworkers (Schonland et al., 1938 a,b; Schonland, 1956) in South Africa using streak cameras. The photographic measurements were also supplemented by slow (millisecond scale) electrostatic field measurements at close range (e.g., Schonland et al., 1938; Malan and Schonland, 1947; Schonland, 1956). Recently measurements have been made with microsecond resolution of the electromagnetic fields due to individual leader steps (e.g., Weidman and Krider, 1980; Krider et al., 1977; Krider and Radda, 1975).

We now list some of the more important characteristics of stepped leaders that will be needed in the modeling process:

(1) On the basis of step length and average earthward velocity, Schonland (1938) and Schonland et al. (1938 a,b) have divided leaders into two classes, α and β. The type α leaders have a uniform earthward velocity of the order of 10^5 m/sec, have steps that are shorter and much less luminous than the β steps, and do not vary appreciably in length or brightness. Type β leaders begin with long, bright steps and a high average earthward velocity, of the order of 10^6 m/sec, exhibit extensive branching near the cloud base, and, as they approach the earth, they assume the characteristics of α leaders. Schonland (1956) states that the majority of photographed leaders are type α, whereas the majority of electrical measurements indicate type-β. This fact and the fact that the non-α characteristics of β's are photographed at high altitude suggests that the initial β characteristics are probably associated with the preliminary breakdown process. As noted in the previous section, we will adopt this interpretation and consider all stepped leaders to have only α characteristics. The step lengths of type α leaders are typically 50 meters when the leader is relatively far above the ground, with a pause

time between steps ranging from 40 to 100 μsec (Schonland, 1956). Longer pause times are followed by longer step lengths. From time-resolved photographic records, Schonland (1956) states that average two-dimensional stepped leader velocities are between 0.08 and 2.4 x 10^6 m/sec, the most often measured value being close to 2 x 10^5 m/sec. These values are not consistent with the value obtained by dividing the 50 m step length by pause times between 40 and 100 μs, 5 x 10^5 to 1 x 10^6 m/s. From electric field records Kitagawa (1957) observed a mean pause time of 50 μsec for steps far above the ground, decreasing to 13 μsec as the leader tip approached the ground. Recent work has verified that leader pulses on electric field records just before the return stroke occur at about 15 μsec intervals (Krider and Radda, 1975; Krider et al., 1977). However, this may be due to the fact that there are steps in several branches radiating simultaneously, making the apparent time between leader pulses shorter than the time in any one branch.

(2) The luminosity of the step rises to its peak in about 1 μsec and falls to half this value in roughly the same time (Schonland et al., 1935; Schonland, 1956; Orville, 1968; Krider, 1974). Thus, for a 50 meter step the velocity of propagation of the light along the step must exceed 5 x 10^7 m/sec. Negatively charged leaders are photographically dark between steps, but positively charged leaders emit some light and have less distinct steps (Schonland, 1956; Berger and Vogelsanger, 1966).

(3) Photographs (Schonland et al., 1935; Berger and Vogelsanger, 1966) show a faint corona discharge extending for about one step length in front of the bright leader step. The luminosity of this advance corona does not appear to develop between steps but rather occurs simultaneously with the creation of the bright step behind it. Luminous stepped leader diameters

have been measured photographically to be between 1 and 10 meters with no central core apparent (Schonland, 1953). The expectation that there is a central current-carrying core follows from the spectral measurements of Orville (1968) and the fact that, for an arc of several hundred Amperes in air, the average current needed to lower 5 Coulombs of charge in 10 msec or so flows in a narrow channel some centimeters in diameter.

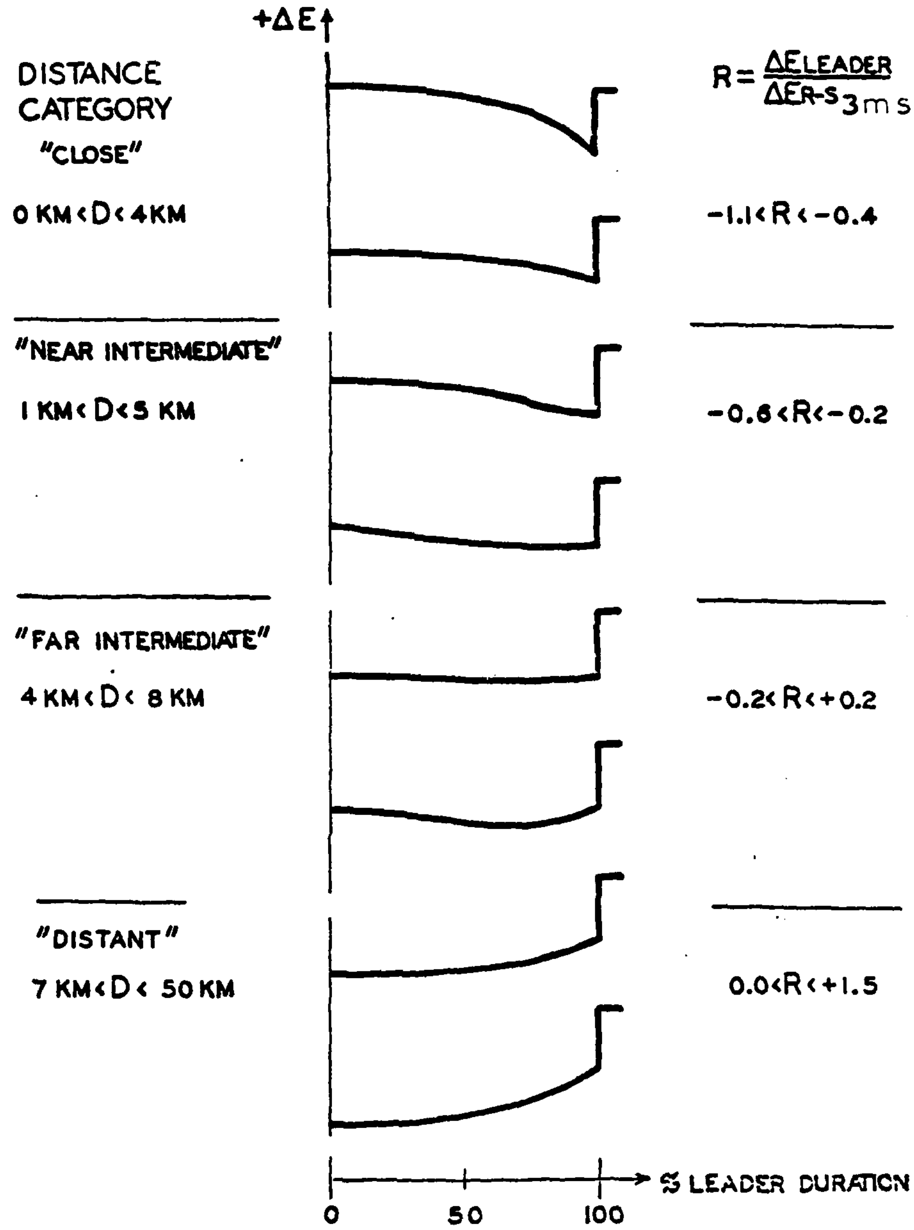
(4) The time-varying electrostatic fields for the stepped leader are reasonably well understood (Malan and Schonland, 1947) and hence easily modeled by the lowering of negative charge along a vertical line. The field change is relatively smooth which implies that the leader lowers charge continuously between steps and that the step process itself does not lower appreciable charge (Schonland, 1953; Krider et al., 1977). Typical electrostatic fields measured on the ground at various distances from the stepped leader are shown in Figure 4-8 (Beasley et al., 1981).

(5) Using measurements of the fields radiated by leader steps near the ground (see Figures 4-9(a), (b), and (c)), Krider et al., (1977) and Weidman and Krider (1980) infer that step currents are in the kA range or larger with submicrosecond rise times. The frequency spectrum of the field due to one step is shown in Figure 4-10.

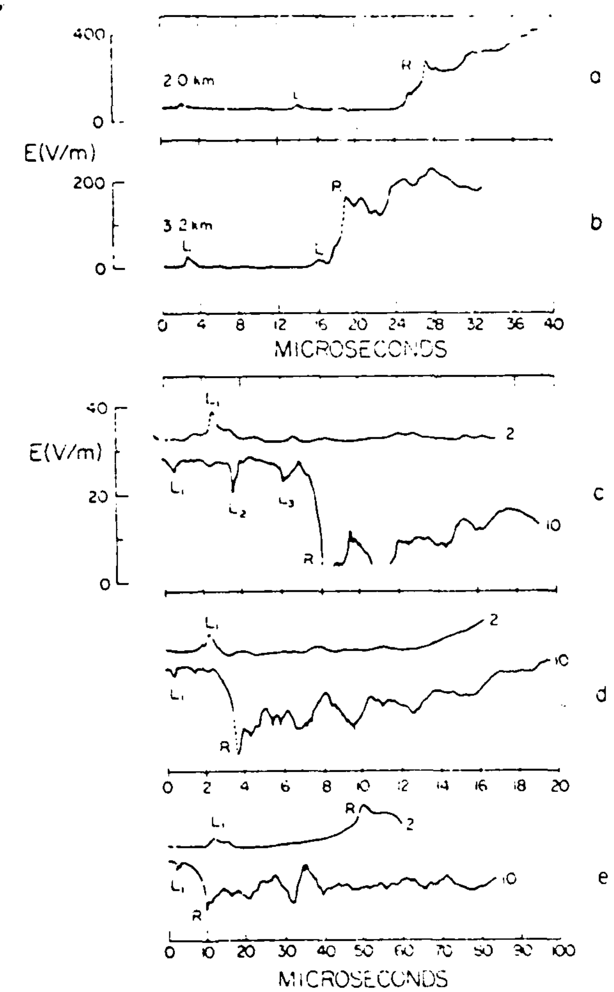
There is considerable theory, primarily qualitative, on the formation and propagation of the stepped leader (e.g., Schonland, 1956, 1953, 1938; Bruce, 1941, 1944; Loeb, 1966, 1968; Klingbeil and Tidman, 1974 a,b; Szpor, 1970, 1977; Wagner and Hileman, 1958, 1961). Very little of this theory, however, has a direct bearing on the modeling process.

4-4-2. Model.

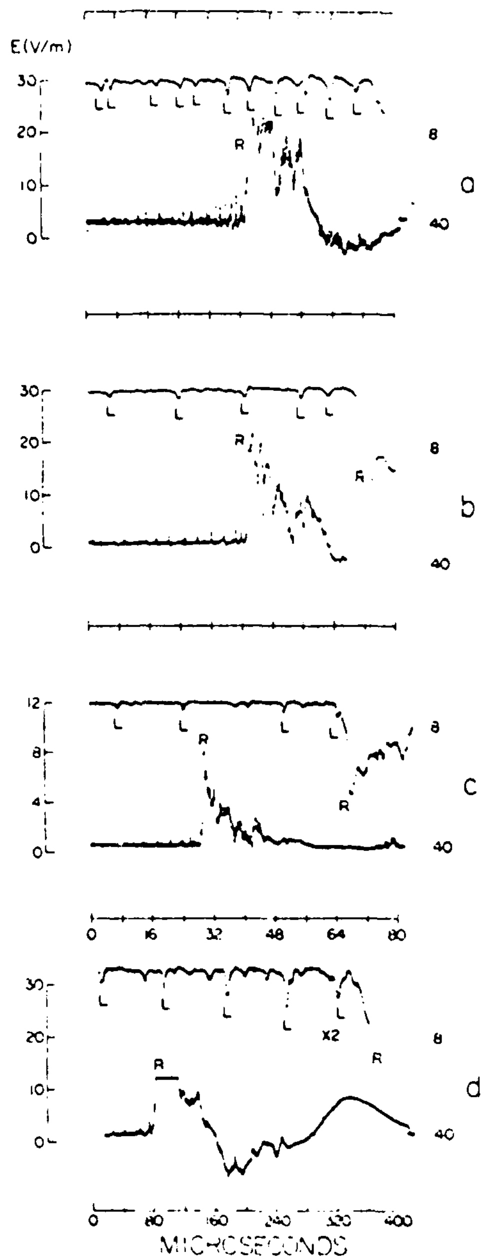
On the basis of the above experimental data, we propose the following model of the current in the stepped leader: A spherical charge exists



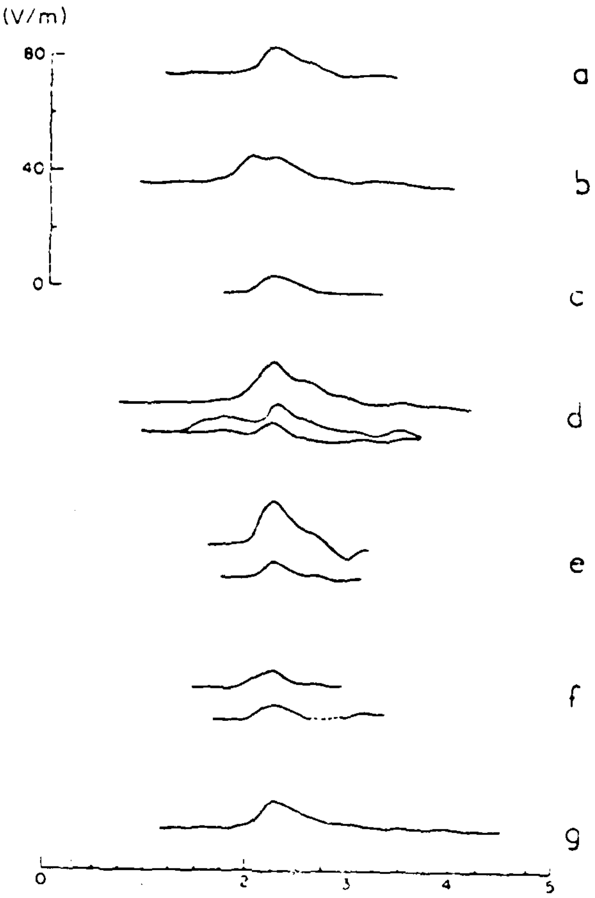
4.8. Measured stepped leader electric fields vs. time at ground for various distances to the leader. Adapted from Beasley et al. (1981).



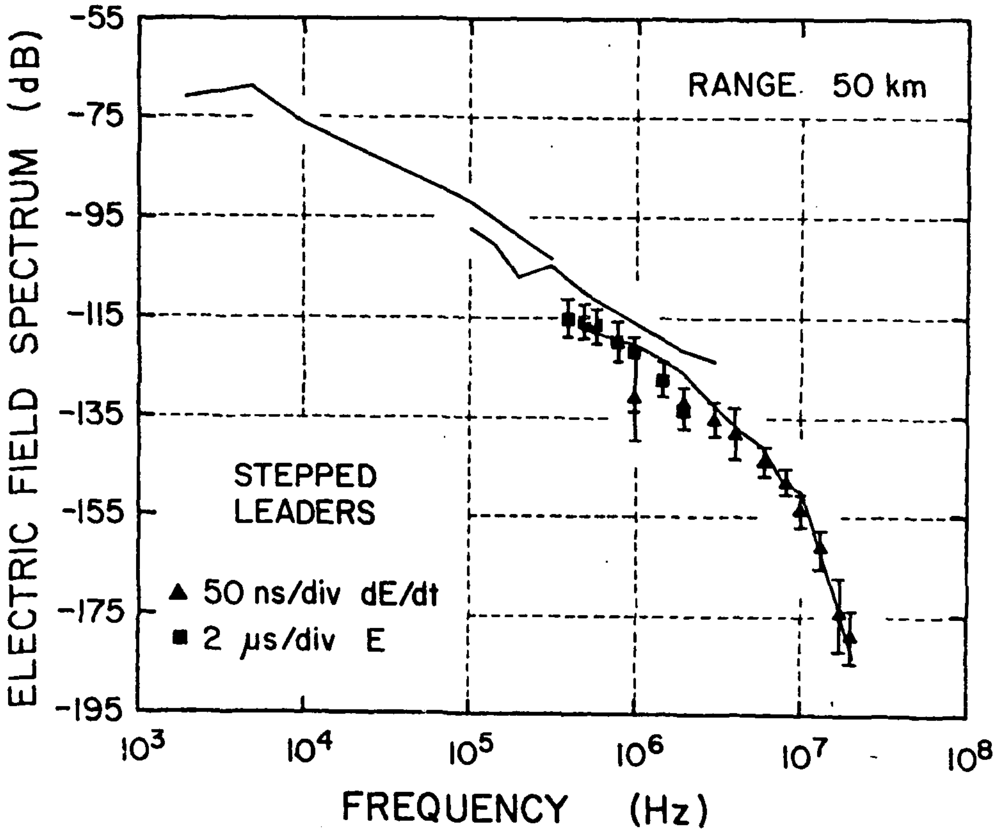
4.9(a). Electric fields produced by close leader steps and return strokes in Florida. (a,b) Oscilloscope records from discharges at 2 and 3.2 km. (c-e) Records from discharges at 15-30 km over water and inverted with respect to (a,b). The initial portion of the lower (10 μs/div.) trace in (c-e) is shown inverted and on a 2 μs/division time base on the upper trace. Adapted from Krider et al. (1977).



4.9(b). Electric field wave forms produced by four lightning discharges in Florida at distances of 20 to 100 km. Each record contains an abrupt return stroke transition R preceded by small pulses characteristic of leader steps. The polarities of all wave forms reproduced are in the sense of negative charge being lowered to ground. The same wave form is shown on both a slow (40 μs/div) and an inverted fast (8 μs/div) time scale. The vertical gain of the fast trace for d has been magnified by a factor of 2 in relation to the lower trace. Adapted from Krider et al. (1977).



4.9(c). Fast time-resolved records of stepped leader pulses produced by lightning discharges over seawater at distances of 20 to 30 km or less. Adapted from Krider et al. (1977).

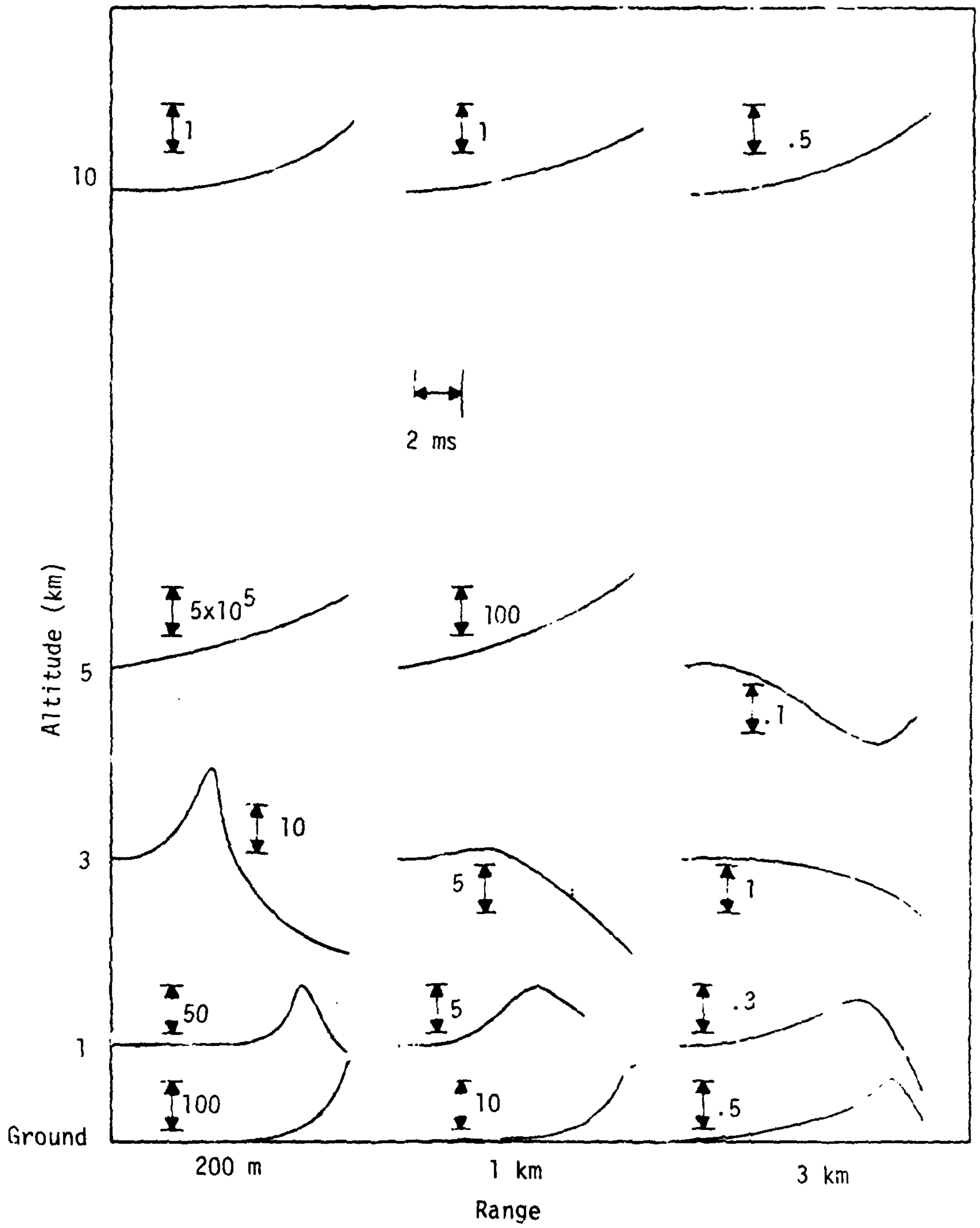


4.10. Frequency spectra of the electric fields of 9 leader steps between 20 and 50 km normalized to 50 km. Solid lines represent the first return stroke frequency spectra given in Fig. 4.16.

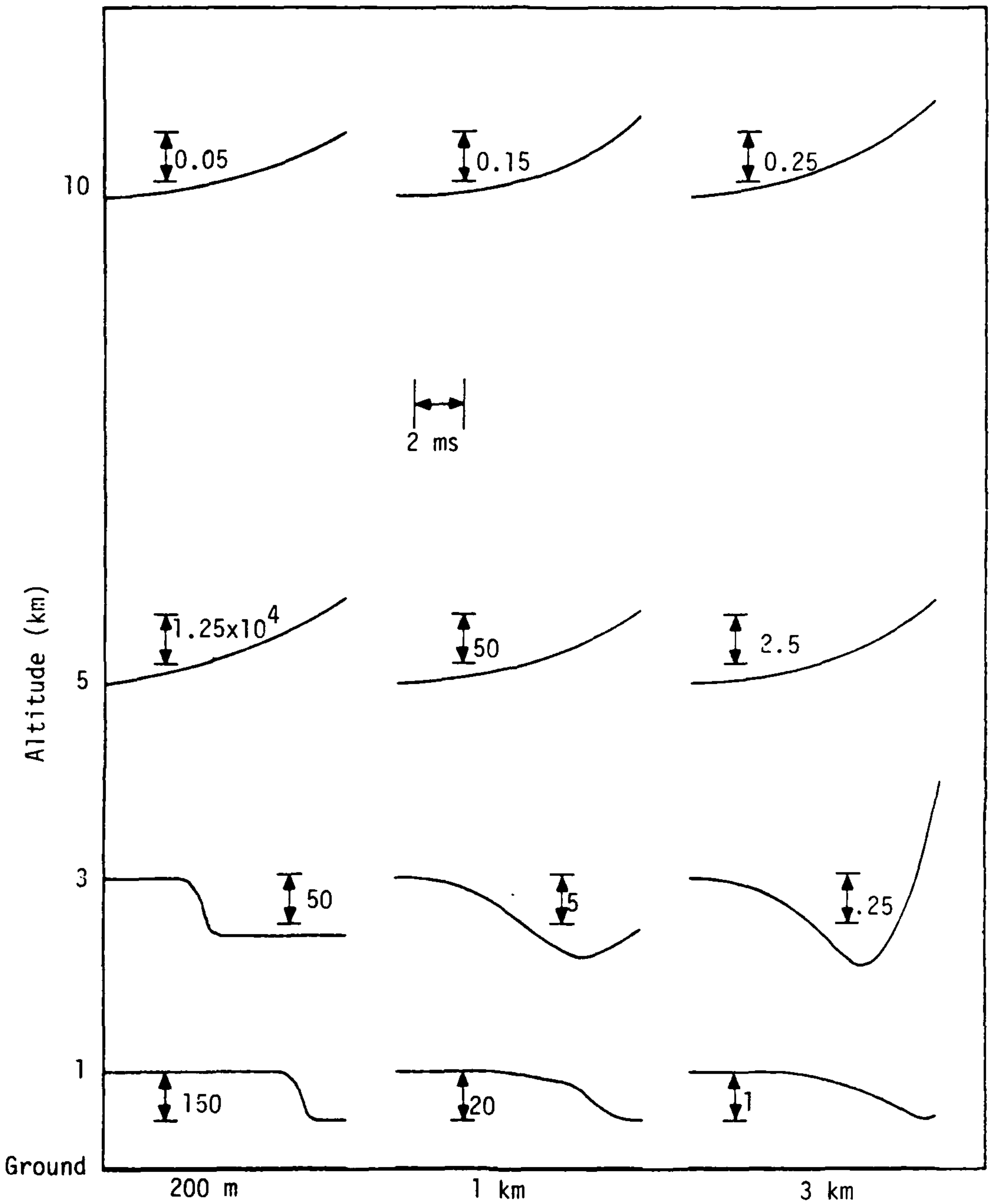
in the cloud at 5 km height which allows a slowly increasing current $I(t) = I_o e^{+\gamma t}$ to flow into the channel. The channel containing this current propagates downward at a constant velocity v with the current I(t) uniform throughout the channel length. The charge deposited on each channel section is $\int I(t)dt$ where the integral is over the time taken to form the section. The current I(t) is chosen so as to (1) produce a final charge distribution of the form $\rho = \rho_o e^{-z/\lambda}$ C/m on the leader necessary to provide the proper initial conditions for the generation of the return stroke fields discussed later, and (2) produce the slow electric field changes observed at ground level for a typical stepped leader. The values of the leader parameters are $\rho_o = -2.7 \times 10^{-3}$ C/m, $\lambda = 2$ km, $v = 5 \times 10^5$ m/s, $\gamma = 264$ sec^{-1}. The current I(t) starts at $I_o = 100$ Amps and increases exponentially to a final value of 1400 Amps when the leader touches the ground 10 msec later. The leader stores a total charge of -5.0 C.

Superimposed on the roughly steady current are fast breakdown pulses produced by the individual leader steps. These pulses occur every 80 μsec and each succeeding pulse is initiated at a height 40 m lower than the previous one so as to produce an average downward velocity of 5×10^5 m/s. Each fast current pulse is assumed to have a triangular shape, with a maximum value of 1 kA, a rise-time to peak of 0.1 μsec, and a fall to zero in 2 μsec. Each fast current pulse propagates upward at a constant velocity of 10^8 m/sec while it attenuates as $e^{-z/\Theta}$, where $\Theta = 50$ m and z has its origin at the bottom of each succeeding step.

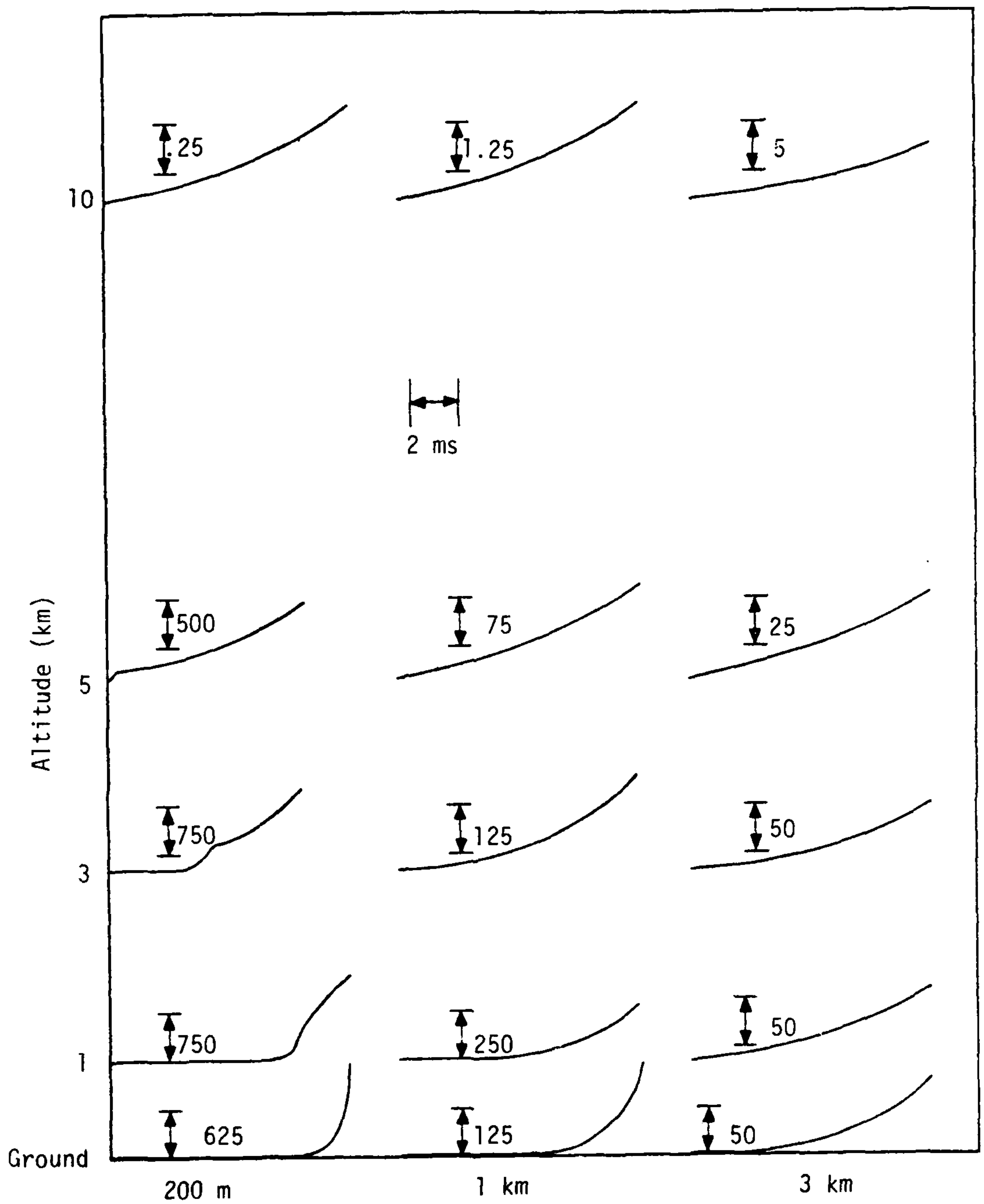
The leader fields computed using the above model are shown in Figures 4-11(a), (b), and (c) for the slow current, and Figures 4-11(d), (e), and



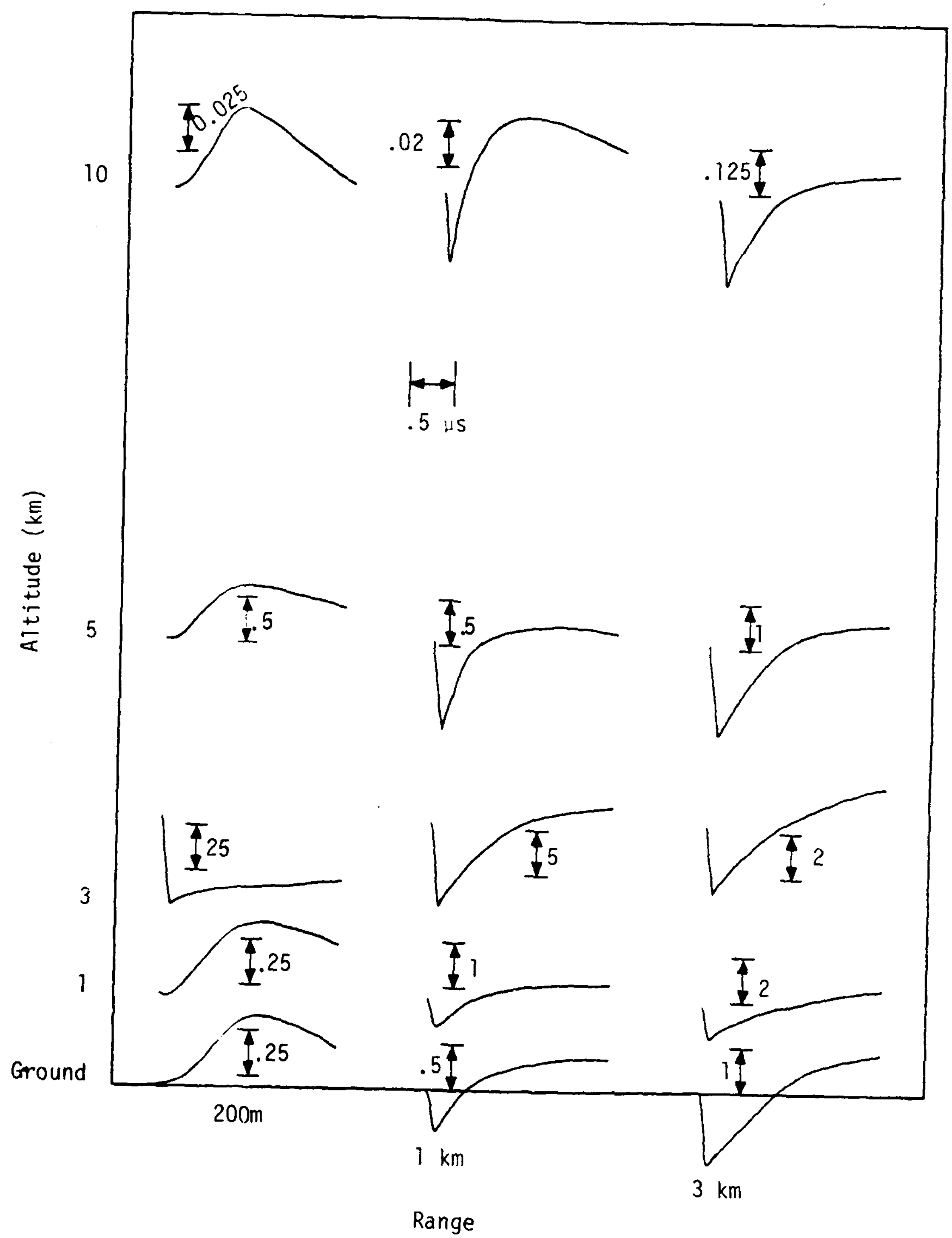
4.11(a). Calculated vertical electric fields for the slow stepped leader current. Scales in kV/m.



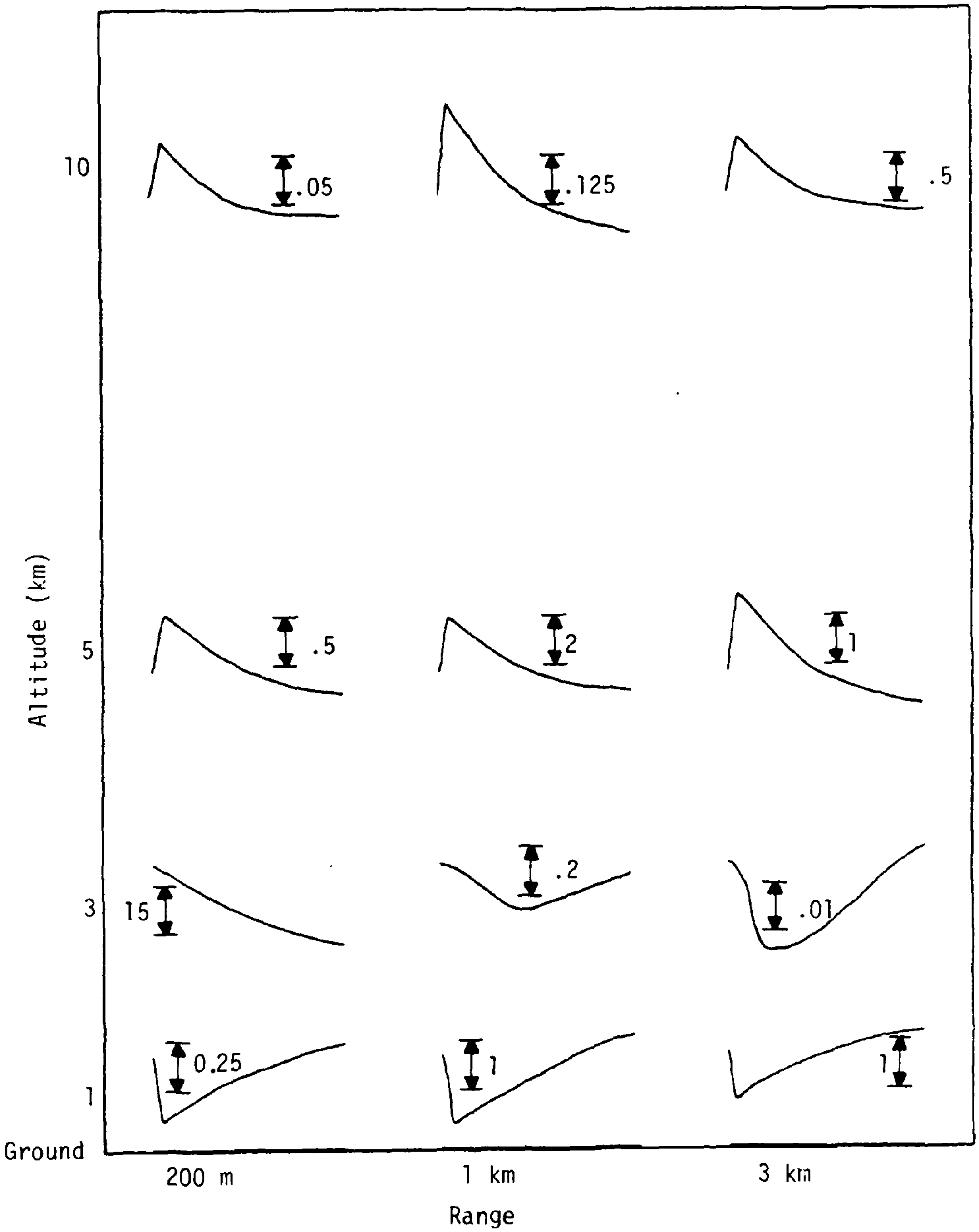
4.11(b). **Calculated horizontal electric fields for the slow stepped leader current. Scales in kV/m.**



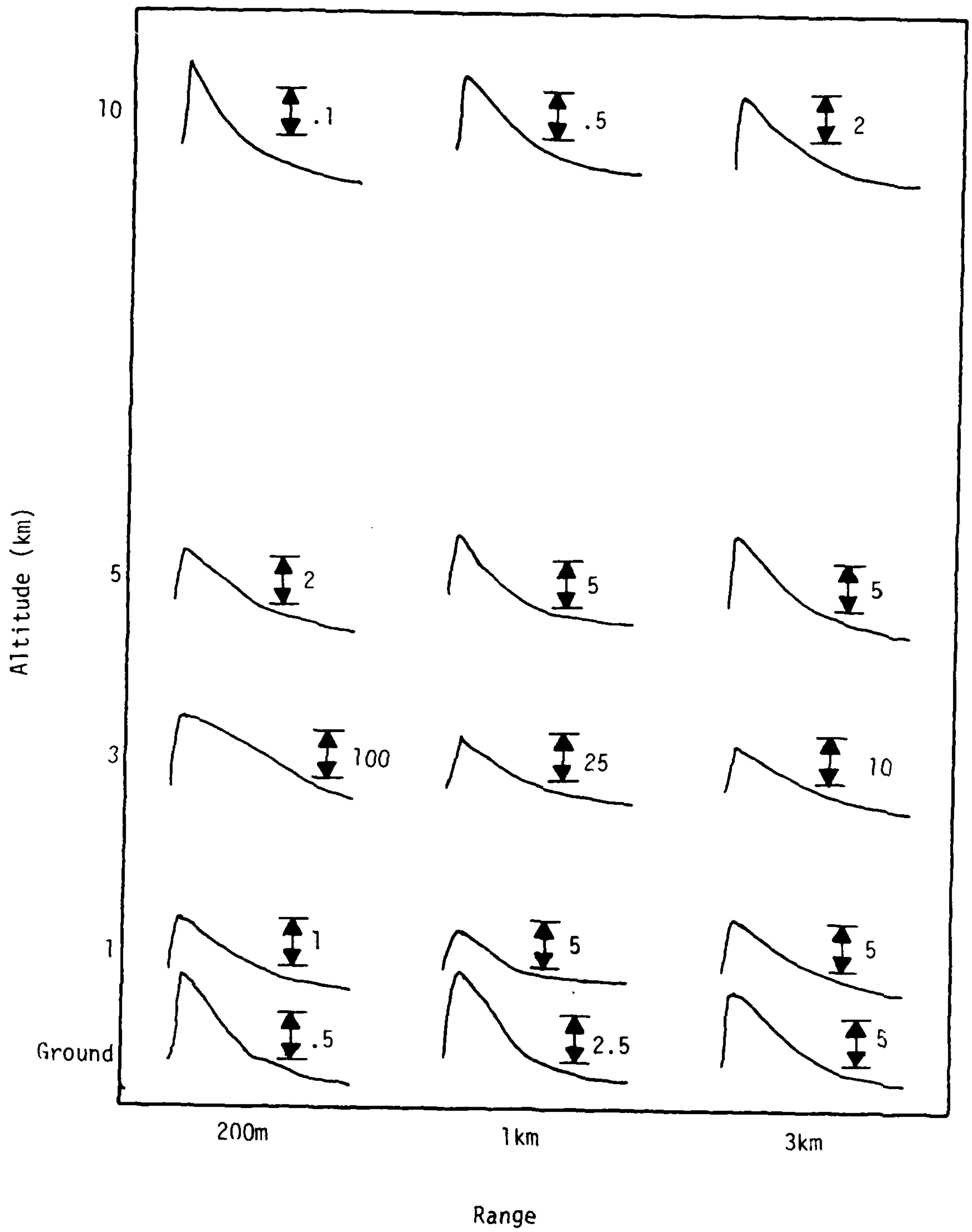
4.11(c). Calculated magnetic fields for the slow stepped leader current. Scales in nT.



4.11(d). Calculated vertical electric fields for a leader step current at a height of 3 km. Scales in V/m.



4.11(e) Calculated horizontal electric fields for a leader step current at a height of 3 km. Scales in V/m.



4.11(f) Calculated magnetic fields for a leader step current at a height of 3 km. Scales in nT.

(f) for the leader step current, both on the ground and in the air.

4-5. Attachment Process

4-5-1. Literature.

When the stepped leader approaches any conducting object such as an aircraft or a transmission-line tower, the electric field produced by the charge on the leader can be enhanced by the object to the point where discharges (called leaders, connecting leaders, or, sometimes, streamers) are emitted from the object. The characteristics of these discharges are not well understood, but have been the subject of considerable discussion in the context of modeling lightning strikes to power lines where the attachment process plays a significant role in the design of overhead ground wire protection.

An important parameter in lightning protection is the "striking distance": the distance between the object to be struck and the downward-moving leader tip at the instant that the connecting leader is initiated from the object. It is assumed that at this instant of time the point of strike is determined. It follows that the actual junction point is somewhere between the object and the tip of the last leader step. Often, it is assumed to be midway between.

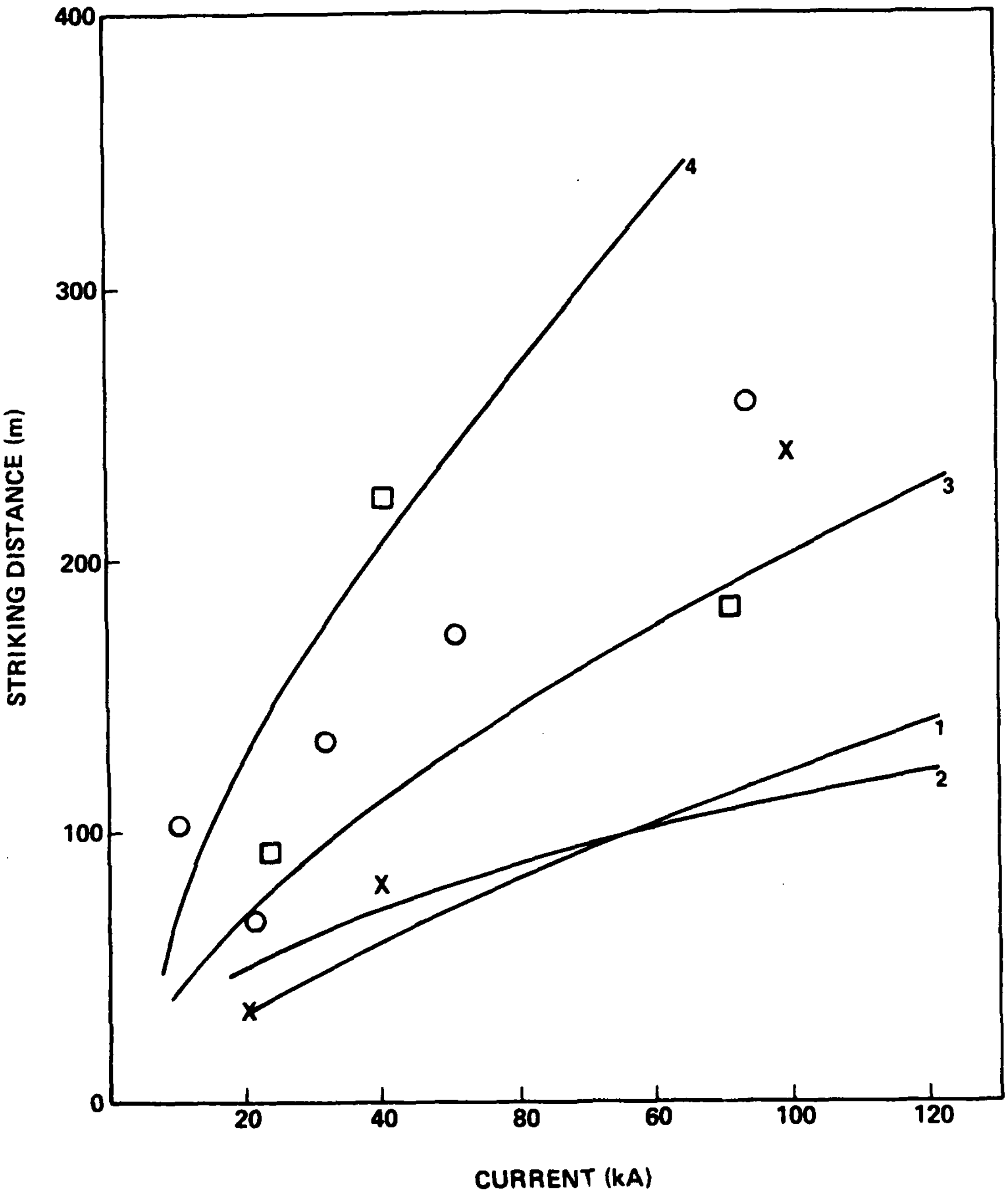
We now examine the attachment process as it relates to lightning strikes to ground or to objects attached to the ground. General reviews of this phenomena have been given by Golde (1967, 1977) who outlines the following analytical approach: a reasonable charge distribution is assumed to be present on the leader channel, and the resultant fields on remote objects are calculated. The leader is assumed to be at the striking distance when the field at some point exceeds a critical breakdown value that is determined by laboratory tests. Various authors have derived relations between the striking distance and the leader charge (e.g., Golde, 1945). The relationship of more practical value in power line design, however, is that of striking distance to the peak current of the following return stroke. To make this connection, the peak current must be related to the leader charge distribution. It has not been proven that these two quantities are actually related, since the leader charge may be spread over a rather large volume in various leader branches, whereas the peak stroke current is determined in a few microseconds in a short channel section that is attached to ground. On the other hand, Berger (1972) shows that there is a correlation between the measured return stroke peak current at ground and the total charge transfer to ground in the first 1 msec or so. The best fit relating peak current I to charge transfer Q for 89 negative strokes is

$$I = 10.6\ Q^{0.7}$$

with I measured in kA and Q in Coulombs. According to this expression, a typical peak current of 25 kA corresponds to a total leader charge of 3.3 C. When this expression is combined with the relation between charge and breakdown field, a relation for striking distance d_s can be found in terms of peak current. For example, one of several theoretical analyses reviewed by Golde (1977) yields

$$d_s = 10\ I^{0.65}$$

where d_s is in meters and I in kA. In Figure 4-12, several theoretical curves discussed by Golde (1977) are shown along with experimental data from Eriksson (1978). From the available experimental data and theory it is possible to conclude that striking distances are generally between a few tens and a few hundred meters.



4.12. Striking distance vs. return stroke peak current for objects attached to ground. [curve 1: Golde (1945); Curve 2: Wagner (1963); curve 3: Love (1973); curve 4: Rühling (1972); X: Davis (1962); O: estimates from 2-D photographs by Eriksson (1978); □: estimates from 3-D photography by Eriksson (1978)]. Adapted from Golde (1977) and Eriksson (1978).

An aircraft in flight can become attached to a lightning channel by initiating discharges which connect to the stepped leader or to any of the other phases of lightning in which there is a propagating channel (e.g., the J-process discussed in Section 4-9). Further, an aircraft can trigger lightning which otherwise would not have occurred had the aircraft not been there. Triggering is made possible by virtue of the field enhancement caused by the presence of the plane in a region where the field is already high and the resultant generation and propagation of leaders in two directions away from the plane toward regions of opposite charge. The charge on the aircraft due to precipitation interactions and the resultant field at the plane surface may increase the probability of a lightning strike. Further, the charge deposited in the wake of the aircraft (which is opposite in polarity to that on the plane) due to precipitation charging may serve either to guide the lightning to the plane or to shield the plane from it. A discussion of these and other effects is given by Vonnegut (1965).

Experimental data on 52 lightning events measured with an instrumented F-100F aircraft are given by Petterson and Wood (1968). It is not known in which phases of the various lightning discharges the plane was involved. Since positive charge was usually transferred into the nose boom, Petterson and Wood (1968) infer that most of the strikes were intracloud discharges between the upper positive and lower negative cloud charge regions (Figures 4-1 and 4-2). Most peak currents were several thousand Amperes, apparently taking milliseconds to reach these values. There were also a number of fast current pulses with zero to peak rise-times of about 1 μsec. The maximum current was 22 kA for which the rise-time was not recorded. Of some interest is the fact that once a lightning channel became attached to the F-100F, the motion of the plane did not detach the channel, but rather stretched it. Recent, and as yet unanalyzed, data on airplane strikes have been reported by Pitts (1981) and by Pitts and Thomas (1981).

4-5-2. Model.

The attachment of typical lightning to an aircraft in flight can be modeled as follows: A leader with a charge density of 10^{-3} C/m, typical of the stepped leader, approaches the aircraft from an arbitrary direction at a velocity of 10^5 to 10^6 m/sec. If the aircraft geometry is known, the electrostatic field at various points on the aircraft surface can be calculated. When the fields on the wings, nose, tail, and other extremities exceed a critical value, corona will begin and outward-going discharges will be initiated. These discharges will decrease the electric field at the surfaces of the plane because of shielding. The "striking distance" is determined by the distance to the incoming leader at the time when the aircraft emits the outward-going leaders. The time taken for the leaders to join is probably of the order of 10 μsec and the striking distance is probably of the order of the plane length. When contact between the leaders takes place, the aircraft, originally at the ambient potential of the environment, is raised to the potential of the lightning channel in a characteristic charging time determined by the channel impedence, roughly 1000 Ohms, and the aircraft capacitance, 10^{-9} to 10^{-10} F. Thus the expected charging time is 10^{-7} to 10^{-6} sec, and, for a channel potential of 10^8 to 10^9 volts, the rate of change of aircraft voltage will be 10^8 to 10^{10} V/μsec. Lightning contact will cause the electric field at the plane surface to reverse direction, and the aircraft may produce additional corona and leaders. In any event, the primary channel will propagate through the aircraft in the form of a relatively steady current on which may be superimposed fast pulses due to leaders steps, K-changes, return strokes, or any other impulsive lightning processes which might occur in the channel.

4-6. Return Strokes

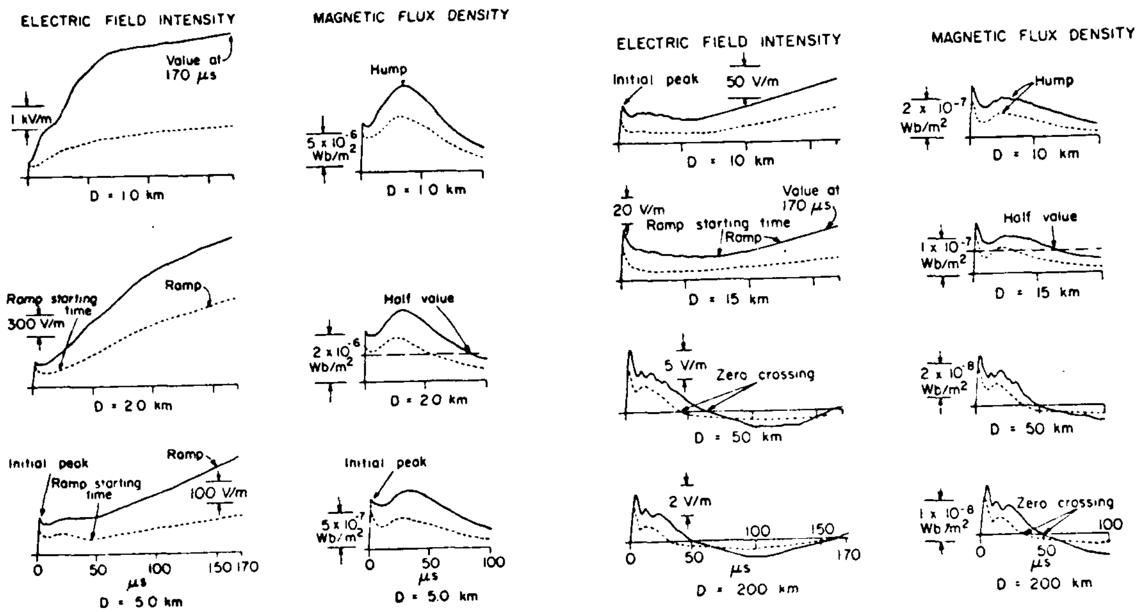
4-6-1. Literature.

The return stroke is the most studied and best understood lightning process. This research has been motivated both by practical considerations (e.g., the need to reduce lightning damage and lightning caused outages on overhead power lines) and by the fact that, of all the phases of lightning, the return stroke lends itself most easily to measurement.

Several types of experimental data are available which relate to modeling of the return stroke currents and fields: (1) Wideband (dc to some MHz) electric and magnetic fields at ground level (e.g., Tiller et al., 1976; Weidman and Krider, 1978; Lin et al., 1979; Weidman and Krider, 1980) and, to a very limited extent, above ground level (Baum, 1980; Nanevicz and Vance, 1980; Pitts, 1981; Pitts and Thomas, 1981); (2) measured electric field frequency spectra (e.g., Taylor, 1963; Serhan et al., 1980); (3) current waveforms at ground level (e.g., Berger et al., 1975; Garbagnati et al., 1975) and, to a very limited extent, above ground (Petterson and Wood, 1968; Pitts, 1981; Pitts and Thomas, 1981); and (4) return stroke velocities (e.g., Schonland et al., 1935, Boyle and Orville, 1976; Saint-Privat D'Allier Research Group, 1979; Hubert and Mouget, 1980). In order for any model of the return stroke to be valid, it must be capable of describing in a self-consistent way the above independently measurable fields, currents, and velocities. We now consider the above four types of experimental data in detail.

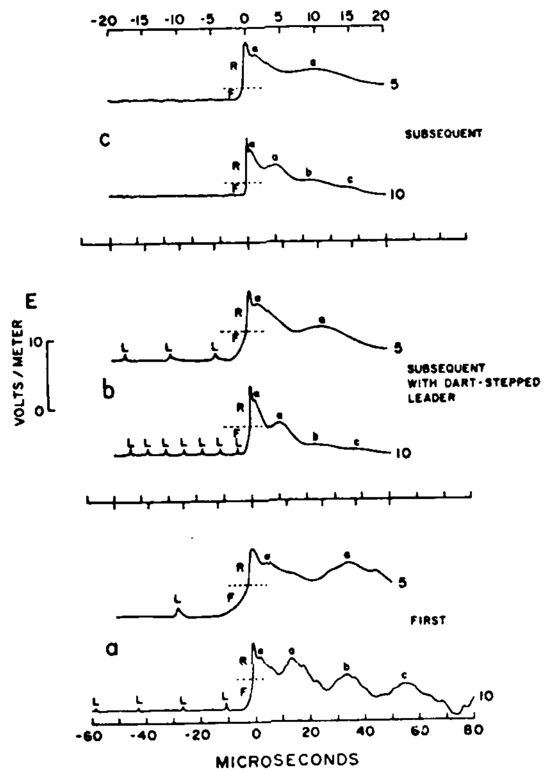
(1) The most complete description of return stroke electric and magnetic fields is given by Lin et al. (1979). The bandwidths of the electric field recording systems extended from near dc to over 1 MHz and for the magnetic field systems from 1 kHz to over 1 MHz. For both electric and magnetic fields, the system zero to peak rise times were about 0.3 μsec. Measurements were made simultaneously at two Florida stations separated by either 50 or 200 km with the result that fields were obtained over a distance range from 0.2 to 200 km. Lin et al. (1979) present typical first and subsequent stroke waveform as shown in Figures 4-13(a) and (b) and statistical data on the salient characteristics of the waveforms. While Lin et al. (1979) and previous studies in the same experimental program (e.g., Fisher and Uman, 1972; Tiller et al., 1976; Uman et al., 1976a) focused primarily on the overall characteristics of the field waveforms, Weidman and Krider (1978; 1980) have examined the microsecond and submicrosecond structure of the waveforms. They find that the initial return stroke in a cloud-to-ground flash produces an electric field "front" which rises in 2 to 8 μsec to about half of the peak field amplitude and is followed by a fast transition to peak whose 10 to 90 percent risetime is about 90 nsec. Subsequent stroke fields have fast transitions very similar to first strokes but fronts which last only 0.5 to 1 μsec and which rise to only about 20% of the peak field. The fine structure of typical first and subsequent stroke electric fields are shown in Figure 4-14.

To measure lightning field changes on a 10 nsec time scale accurately, it is essential that the field propagation from the lightning



(a) (b)

4.13. (a) Typical electric field intensity (left column) and magnetic flux density (right column) for first (solid line) and subsequent (dotted line) return strokes at distances of 1, 2, and 5 km. The following characteristic features of the wave forms are identified: for electric field, initial peak, ramp-starting time, ramp, and 170 μs value; for magnetic field, initial peak, hump, and half-value. (b) Typical fields as described in Figure 4.13(a) for distances of 10, 15, 50, and 200 km. Characteristic waveform features identified in addition to those noted in Figure 4.13(a) are electric and magnetic field zero crossings. Adapted from Lin et al. (1979).

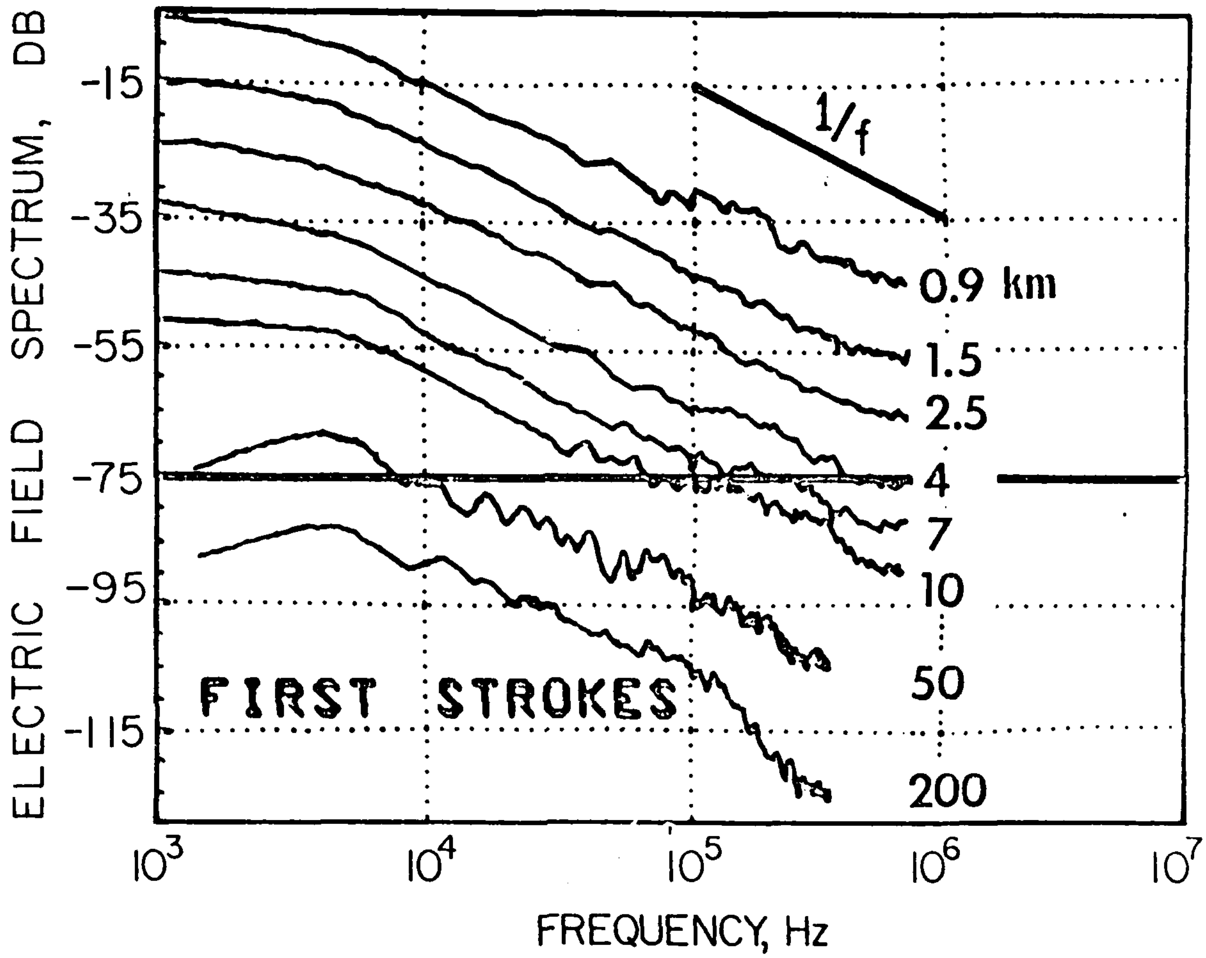


4.14. Sketches of the detailed shapes of the radiation fields produced by (a) the first return stroke, (b) a subsequent return stroke preceded by a dart-stepped leader, and (c) a subsequent stroke preceded by a dart leader in lightning discharges to ground. The field amplitudes are normalized to a distance of 100 km. The small pulses characteristic of leader steps L are followed by a slow front F and an abrupt, fast transition to peak R. Following the fast transition, there is a small secondary peak or shoulder α and large subsidiary peaks, a, b, c, etc. The lower trace in each case shows the field on a time scale of 20 μs/div, and the upper trace is at 5 μs/div. The origin of the time axis is chosen at the peak field in each trace. Adapted from Weidman and Krider (1978).

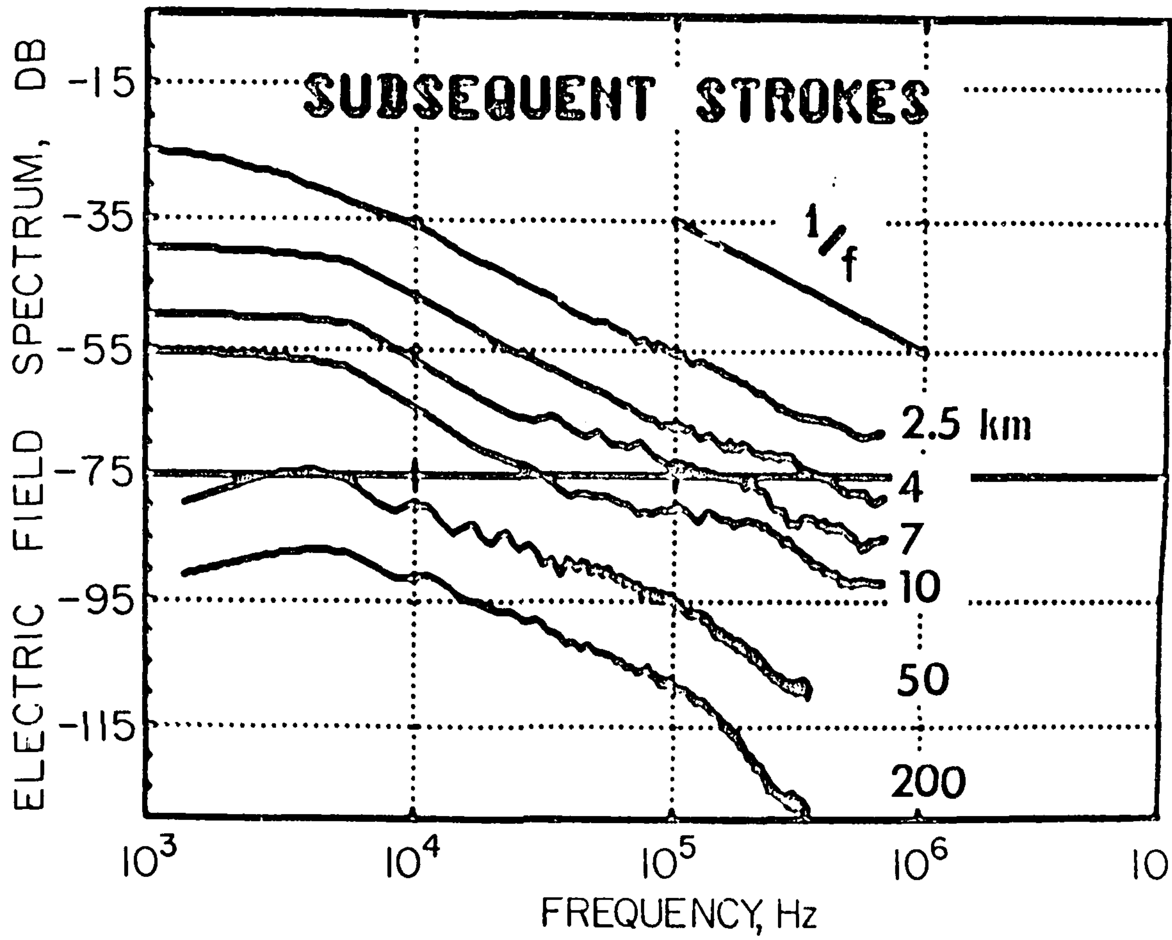
to the receiving antenna be over salt water; otherwise there will be a degradation in the high frequency content of the fields due to propagation over the relatively poorly conducting earth (e.g., Uman et al., 1976b; Weidman and Krider, 1980). On the other hand, it is possible that lightning striking salt water could produce inherently faster risetimes than lighting striking ground. Weidman and Krider (1978) argue that this is probably not the case.

(2) The most complete data on return stroke frequency spectra below 1 MHz are given by Serhan et al. (1980) and were obtained by Fourier analyzing the time-domain electric field waveforms of Lin et al. (1979) and Tiller et al. (1976). These spectra extend over a frequency range from 1 kHz to 700 kHz for lightning at distances between 1 km and 200 km and are reproduced in Figures 4-15(a) and (b). To obtain the frequency spectra for strokes within 10 km, Serhan et al. (1980) had to truncate the electric field values which end with an appreciable offset value (see Fig. 4.13) thus artifically introducing a high frequency content to the waveforms which does not exist in nature. The extent of this high frequency enhancement is presently under study. All of the other return stroke frequency spectra data in the literature (e.g., Taylor, 1963; eleven measurements discussed by Dennis and Pierce, 1964), with the exception of the narrow band measurements of Horner and Bradley (1964), are of distant lightning, and all have an upper frequency cutoff below 100 kHz.

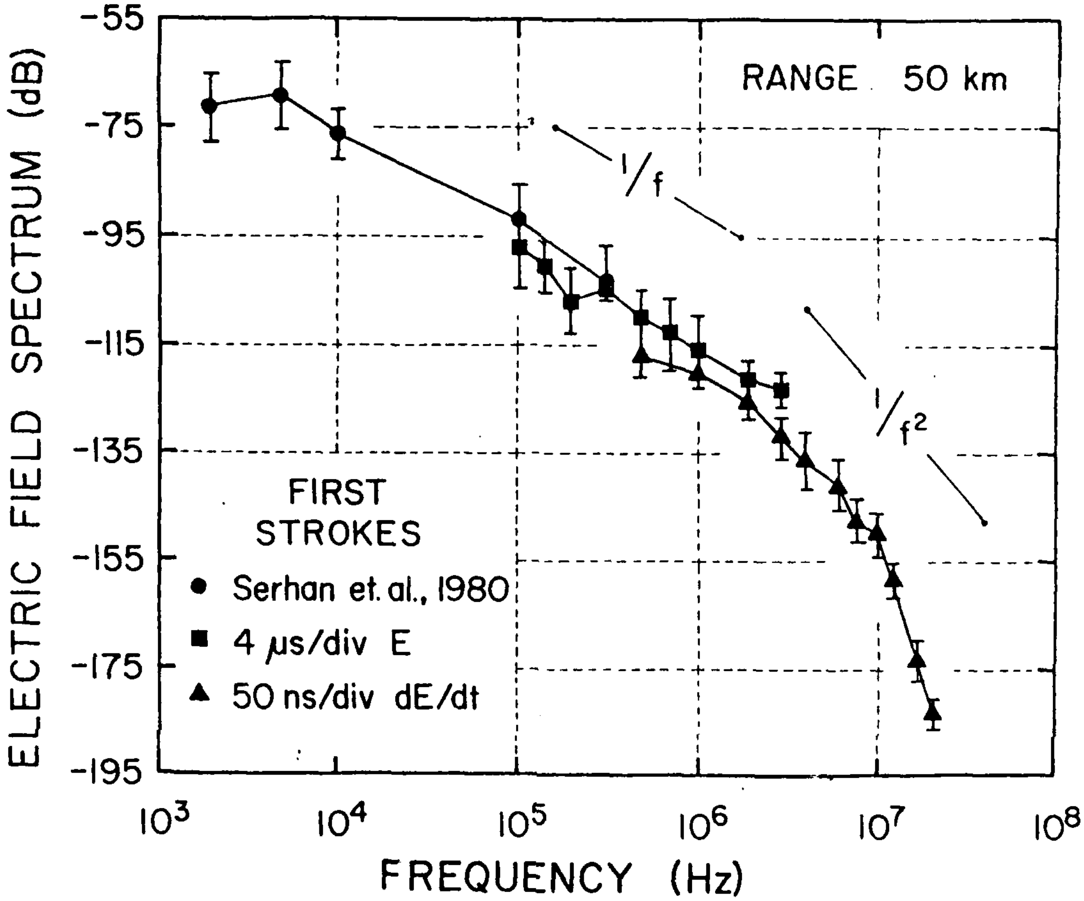
Some first return stroke frequency spectra up to 20 MHz due to Krider and coworkers are shown in Figure 4-16 for lightning at 50 km over salt water. These were obtained by Fourier analyzing wideband electric fields from five return strokes. Since the lightning flashes and the propagation path were over salt water, there should have been



4.15(a). Frequency spectra for first return strokes at various distances. Adapted from Serhan et al. (1980).



4.15(b). Frequency spectra for subsequent return strokes at various distances. Adapted from Serhan et al. (1980).

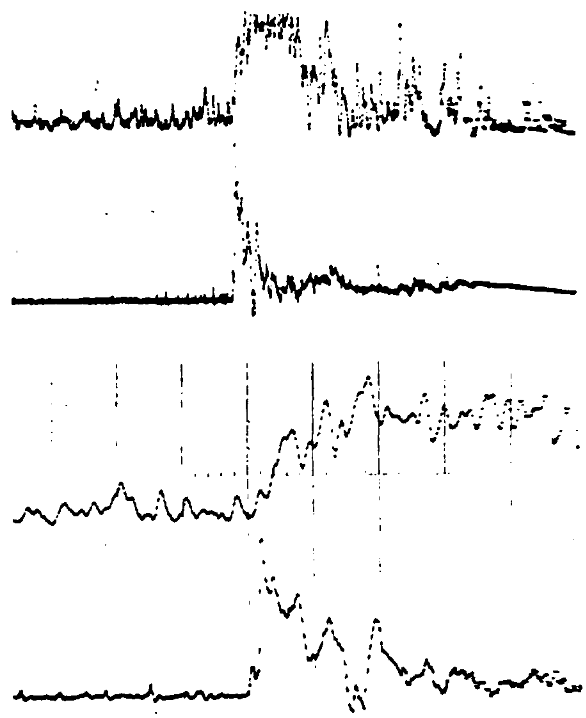


4.16. Frequency spectra for 5 first return strokes over salt water at a distance of 43 to 47 km normalized to 50 km.

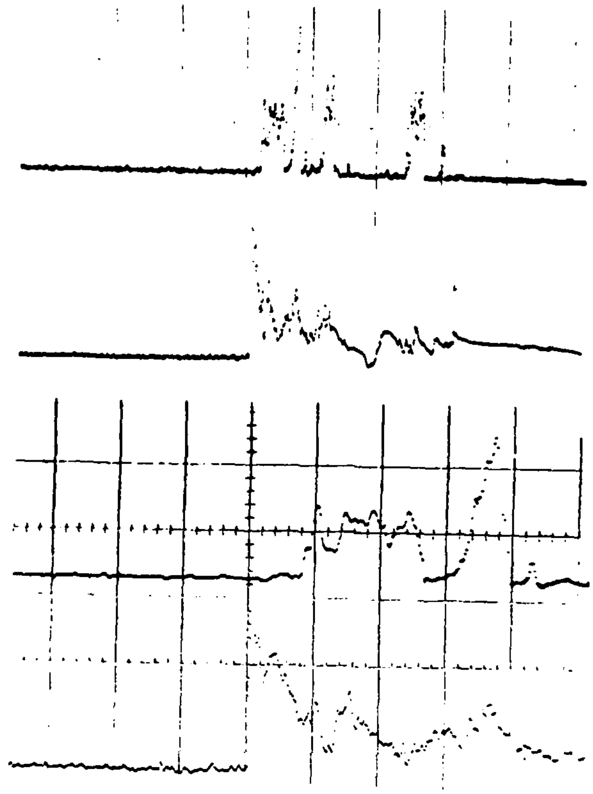
negligible ground wave attenuation. Such attenuation is evident in the 50 and 200 km spectra of Serhan et al. (1980) shown in Figures 4-15(a) and (b) for lightning over land.

LeVine and Krider (1977) have made narrow band RF measurements at 3, 30, 139, and 295 MHz correlated with wideband electric field measurements. They show that first strokes have strong radiation at all of these frequencies, but that the radiation does not start until 10 to 30 μsec after the start of the wideband waveform, suggesting that the RF radiation is due to the effects of first stroke branches and cloud processes. Supporting this suggestion is the observation that subsequent strokes, which generally have no branches, generate little HF or VHF radiation. Examples of the LeVine and Krider (1977) data are given in Figures 4-17(a) and (b), and 4-18(a), (b), and (c).

(3) The most complete description of lightning return stroke currents at the base of the channel is due to the work of Berger and coworkers in Switzerland and is reviewed by Berger et al. (1975). These measurements were obtained at the top of a tower on a mountain as were all other current waveforms of statistical significance. Because of this, the published waveforms of the currents measured at towers may well be different from those of strikes to low objects or the ground. Of particular interest is the early portion of the first stroke waveform, since this may partially be due to an upward-going leader (see Section 4-5) and thus might be different for a tall structure than for normal ground or low objects. Also, first stroke currents striking tall objects are expected to be larger, on the average, than those to normal ground (Sargent, 1972). In any event, the measurements of Berger et al. (1975) are summarized in Figure 4-19 and Table 2. Other

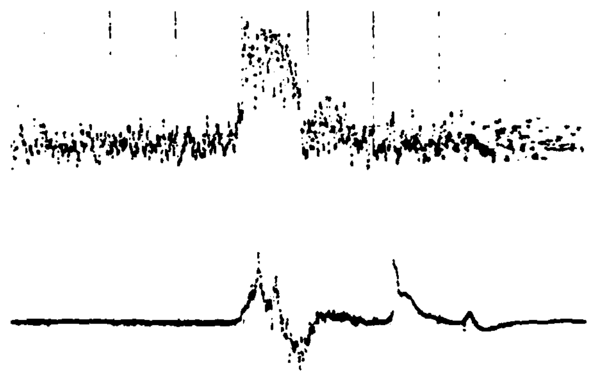


4.17(a). Simultaneous oscilloscope records of the 3 MHz RF signal (top trace) and the electric field (lower trace) due to a first return stroke. The time base is 100 μsec/large division for the top two traces and 20 μsec/large division for the bottom two traces. Adapted from LeVine and Krider (1977).

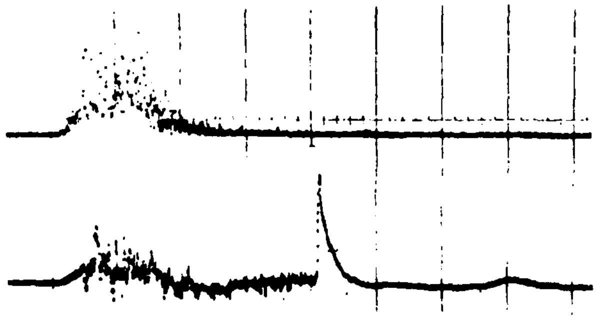


4.17(b). Simultaneous records of the 139 MHz RF with horizontal polarization (top trace) and the electric field (lower trace) due to a first return stroke. The time base is 100 μsec/large division for the top two traces and 20 μsec/large division for the bottom two traces. Adapted from LeVine and Krider (1977).

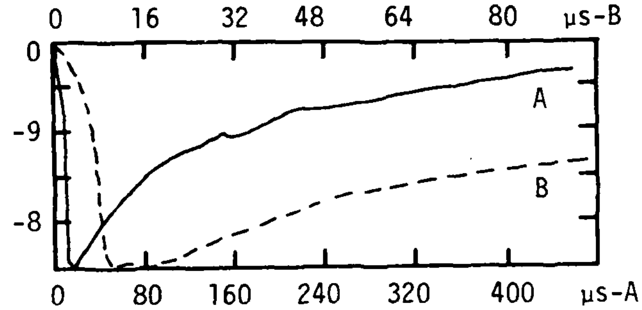
4.18(a). Simultaneous records of the 3 MHz RF signal (top) and the electric field (bottom) due to a subsequent return stroke. The time base is 100 μsec/large division. Adapted from LeVine and Krider (1977).



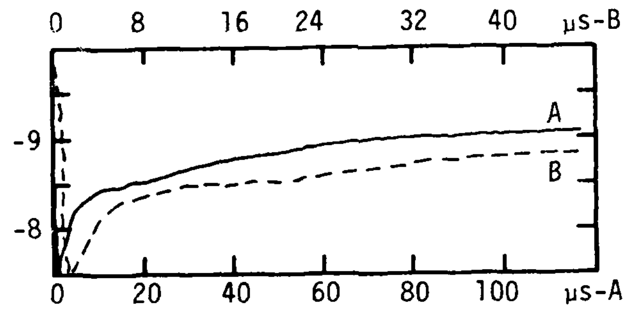
4.18(b). Simultaneous records of the 295 MHz RF with horizontal polarization (top) and the electric field (bottom) due to a subsequent return stroke. The continuous pulses on the RF channel prior to any electric field activity are due to receiver noise. The time base is 100 μsec/large division. Adapted from LeVine and Krider (1977).



4.18(c). Simultaneous records of the 139 MHz RF with vertical polarization (top) and the electric field (bottom) due to a subsequent return stroke. The time base is 100 μsec/large division. Adapted from LeVine and Krider (1977).



Negative First Strokes



Negative Subsequent Strokes

4.19. Average return stroke currents measured by Berger and coworkers as reported by Berger at al. (1975).

TABLE 2

Lightning Current Parameters.

Adapted from Berger et al. (1975)

Number of Events	Parameters	Unit	Percent of cases exceeding tabulated value		
			95%	50%	5%
	Peak current (minimum 2 kA)				
101	negative first strokes	kA	14	30	80
135	negative subsequent strokes	kA	4.6	12	30
26	positive first strokes (no positive subsequent strokes recorded)	kA	4.6	35	250
	Charge				
93	negative first strokes	C	1.1	5.2	24
122	negative subsequent strokes	C	0.2	1.4	11
94	negative flashes	C	1.3	7.5	40
26	positive flashes	C	20	80	350
	Impulse charge				
90	negative first strokes	C	1.1	4.5	20
117	negative subsequent strokes	C	0.22	0.95	4.0
25	positive first strokes	C	2.0	16	150
	Front duration				
89	negative first strokes	μsec	1.8	5.5	18
118	negative subsequent strokes	μsec	0.22	1.1	4.5
19	positive first strokes	μsec	3.5	22	200
	Maximum di/dt				
92	negative first strokes	kA/μsec	5.5	12	32
122	negative subsequent strokes	kA/μsec	12	40	120
21	positive first strokes	kA/μsec	0.20	2.4	32
	Stroke duration				
90	negative first strokes	μsec	30	75	200
115	negative subsequent strokes	μsec	6.5	32	140
16	positive first strokes	μsec	25	230	2000

TABLE 2 (continued)

Number of Events	Parameters	Unit	Percent of cases exceeding tabulated value		
			95%	50%	5%
	Integral (i^2dt)				
91	negative first strokes	A^2 sec	$6.0x10^3$	$5.5x10^4$	$5.5x10^5$
88	negative subsequent strokes	A^2 sec	$5.5x10^2$	$6.0x10^3$	$5.2x10^4$
26	positive first strokes	A^2 sec	$2.5x10^4$	$6.5x10^5$	$1.5x10^7$
	Time				
133	between negative strokes	msec	7	33	150
	Flash duration				
94	negative (including single stroke flashes)	msec	0.15	13	1100
39	negative (excluding single stroke flashes)	msec	31	180	900
24	positive (only single stroke flashes)	msec	14	85	500

tower measurements of current (e.g., Garbagnati et al., 1975, 1978; Eriksson, 1978) are, in general, consistent with those of Berger.

The long first stroke risetimes shown in Figure 4-19 may be indicative of an upward-going leader. Subsequent strokes have risetimes for which the median value from 2 kA to peak is reported to be 1 μsec. Berger et al. (1975) state that 5% of the 120 front times measured were less than 0.2 μsec and 5% of the maximum rates-of-rise of current exceeded 120 kA/μsec. Fieux et al. (1978) report that their 10 to 90% subsequent strokes risetime was less than 1 μsec in 70 percent of 63 measurements. Weidman and Krider (1980) have derived maximum rates of rise of current from first and subsequent stroke fields and find a mean of about 90 kA/μsec with maximum values about twice the mean. Peak currents for first strokes are generally thought to be in the 20 to 40 kA range with 200 kA occuring at about the 1% level although there is some argument about the exact statistics (Szpor, 1969; Sargent, 1972). Lightning currents passing through an aircraft in flight have been measured by Petterson and Wood (1968), Pitts (1981), and Pitts and Thomas (1981). The aircraft was apparently involved with few if any return strokes, but rather primarily with other portions of ground discharges or with cloud discharges.

(4) Return stroke velocities are difficult to measure accurately because the luminosity of the return stroke wavefront has a shape which varies with height (Hubert and Mouget, 1980; Jordan and Uman, 1980; Weidman and Krider, 1980). First stroke velocities decrease with height as each major branch is passed; but subsequent stroke velocities are fairly constant with height (Schonland et al., 1934, 1935). All measurements obviously refer to the out-of-cloud portion of the lightning. Reviews of

the relatively meager velocity data which are available (Boyle and Orville, 1976; Lin et al., 1979) show values which range from 2×10^7 to 2×10^8 m/sec. Typical velocities near ground for both first and subsequent strokes are probably close to 1×10^8 m/sec.

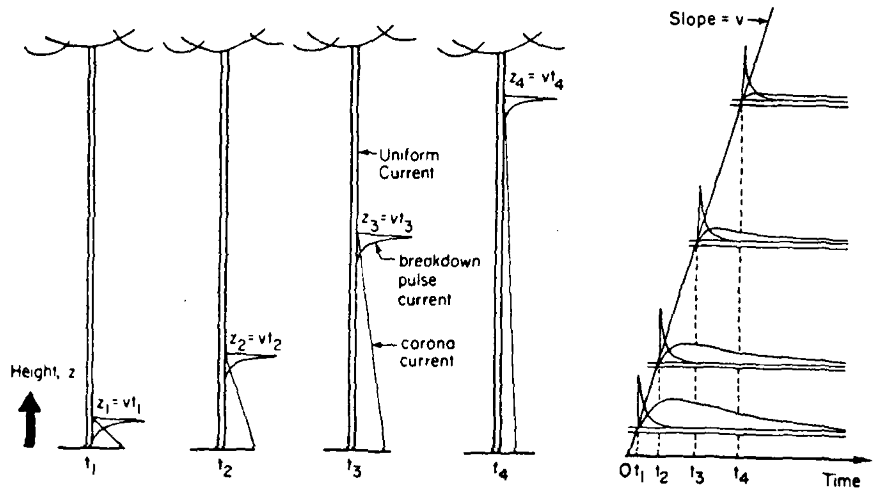
4-6-2. Model.

Given the above experimental data on which to base modeling we are prepared to discuss available models. As discussed in Section 3, we choose not to consider models which attempt to calculate the return stroke current from more or less fundamental considerations (e.g., Papet-Lepine, 1961; Price and Pierce, 1977; Little, 1978; Strawe, 1979), but rather we consider only models in which appropriate channel currents are chosen to conform with measured channel base currents and measurements of the remote electric and magnetic fields produced by actual currents (e.g., Bruce and Golde, 1941; Dennis and Pierce, 1964; Lin et al, 1980).

Lin et al. (1980) have summarized the present state of return stroke modeling, and have shown that previous models do not accurately predict the fields measured simultaneously at two separated stations. Lin et al. (1980) have proposed a new model which does predict the observed fields. This model has been tested primarily on subsequent strokes because these have relatively constant return stroke velocities and no branches. The model reproduces reasonably well the electric and magnetic fields measured at two ground stations, separated by either 50 or 200 km, using a reasonable current waveform at ground level. The modeling of first strokes using the same technique produces reasonable fields but the inferred ground level currents do not look like the waveforms measured during strikes to towers.

Inclusion of the upward-going leader in the modeling (e.g., Weidman and Krider, 1978) does not provide a solution to the problem since currents of the order of 10 kA would have to flow in the upward-going leader to produce the measured fields, and it is generally thought that these leader currents are much smaller.

We choose to model both first and subsequent strokes using the Lin et al. (1980) approach and a modification of it since this does produce measured field waveforms for both first and subsequent strokes and since it is the best that is presently available. The assumed current distribution is shown in Figure 4-20. The current is divided into three components: (1) a short-duration upward propagating pulse of current associated with the upward propagating breakdown at the return-stroke wavefront; (2) a uniform current that may already be flowing (e.g., the steady leader arc current) or may start to flow soon after the return stroke begins; and (3) a current we call the "corona current" which is caused by a radially inward and then downward movement of the charge initially stored in the corona envelope surrounding the leader arc. Statistics on the magnitude and waveshape of these three current components are given by Lin et al. (1980) from analysis of the two-station electric and magnetic field measurements for an assumed return stroke velocity of 10^8 m/sec. Lin et al. (1980) have assumed that the upward-propagating breakdown current pulse does not decay with height, an assumption that may well be reasonable for subsequent strokes. We have modified the Lin et al. (1980) model to allow the breakdown current pulse to decay with height so as to better simulate first strokes and perhaps subsequent strokes for channel portions within the cloud where the velocities are not known.



4.20. Current distribution for the model of Lin et al. (1980).

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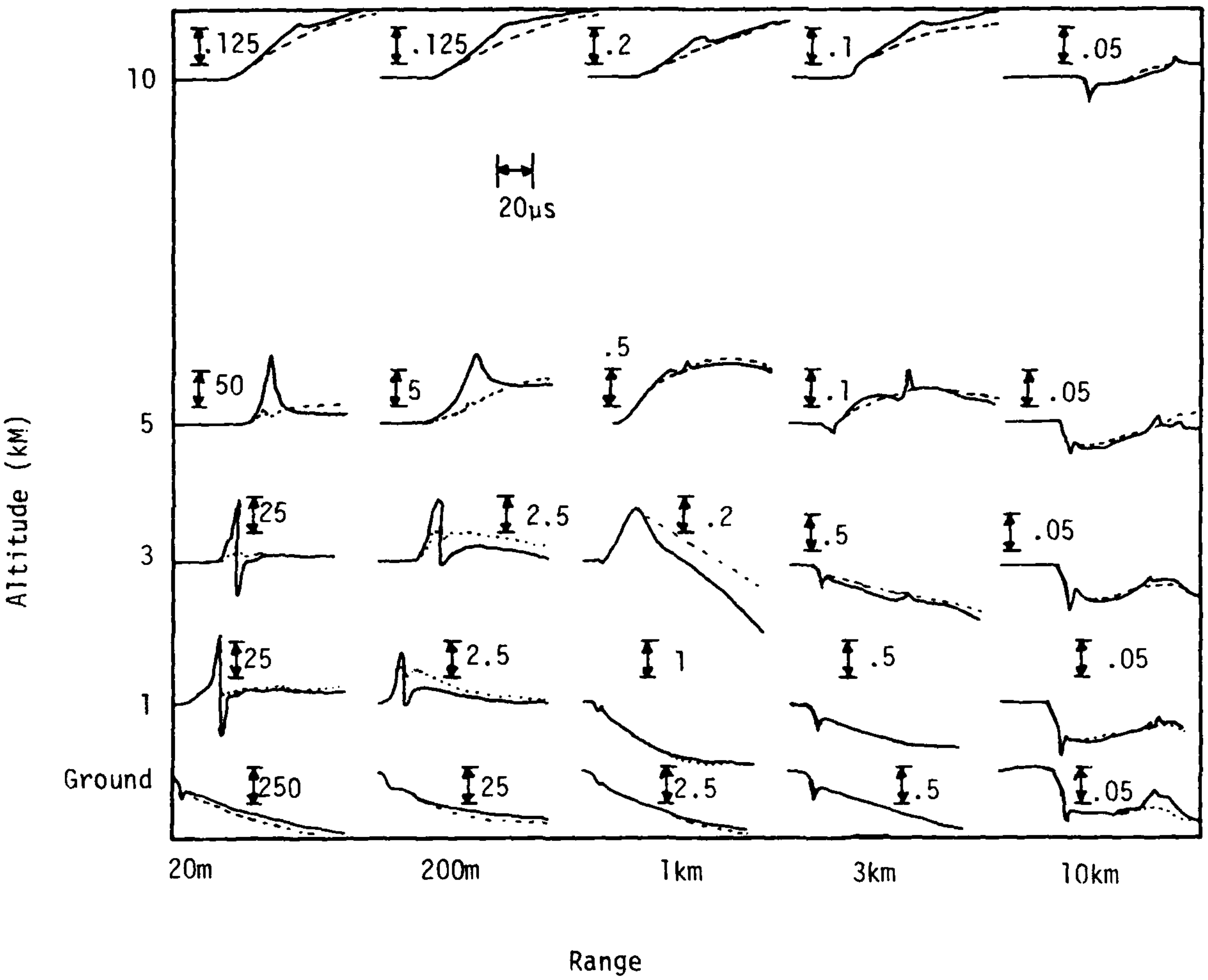
Fields calculated both on the ground and in the air (Uman et al., 1980) using the Lin et al. (1980) model and the model with the modified breakdown pulse current are shown in Figures 4-21(a), (b), (c), (d), (e), and (f) for the various current parameters that are listed in Tables 3(a) and (b). Examples of frequency spectra for these fields are shown in Figures 4-22(a) and (b). Figure 4-22(a) gives the computed spectrum which would be observed on the ground 50 km distant from a first return stroke. This computed spectrum should be compared to the experimental data given in Figure 4-16. Figure 4-22(b) gives the spectrum predicted to occur 200 m from the return stroke channel. The time-domain fields at the ground and far away from the lightning are not much affected much by the decay of the breakdown pulse with height, whereas the fields near the channel are strongly affected, as is evident in the figures. The breakdown current for the first stroke is chosen to have a pulse shape which reproduces the measured fields. As a result a precursor current of about 0.5 km length is required to proceed up the channel ahead of the fast current pulse. It is questionable whether such a precursor current actually exists. Strawe (1980) has argued that such a precursor is to be expected.

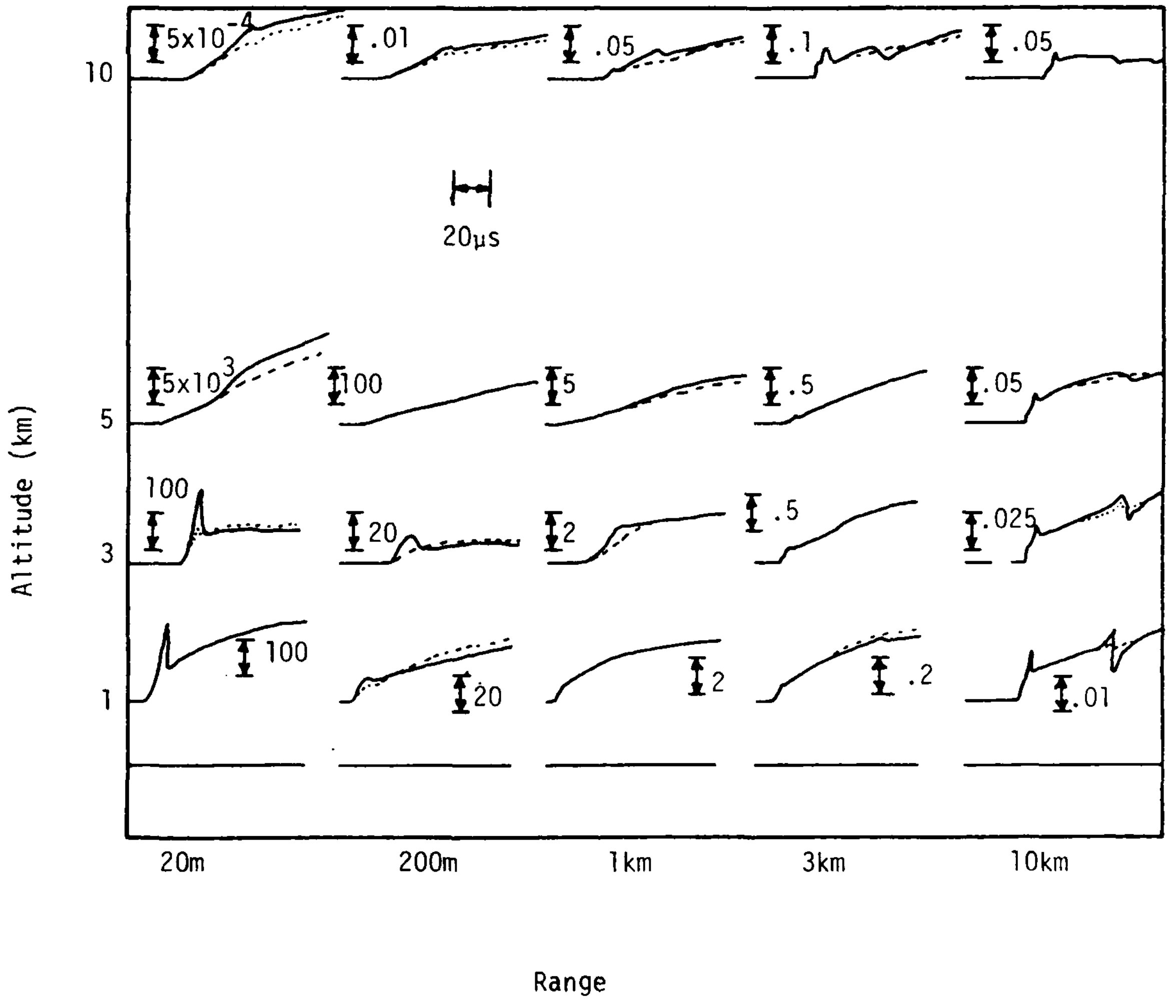
4-7. Dart Leaders

4-7-1. Literature.

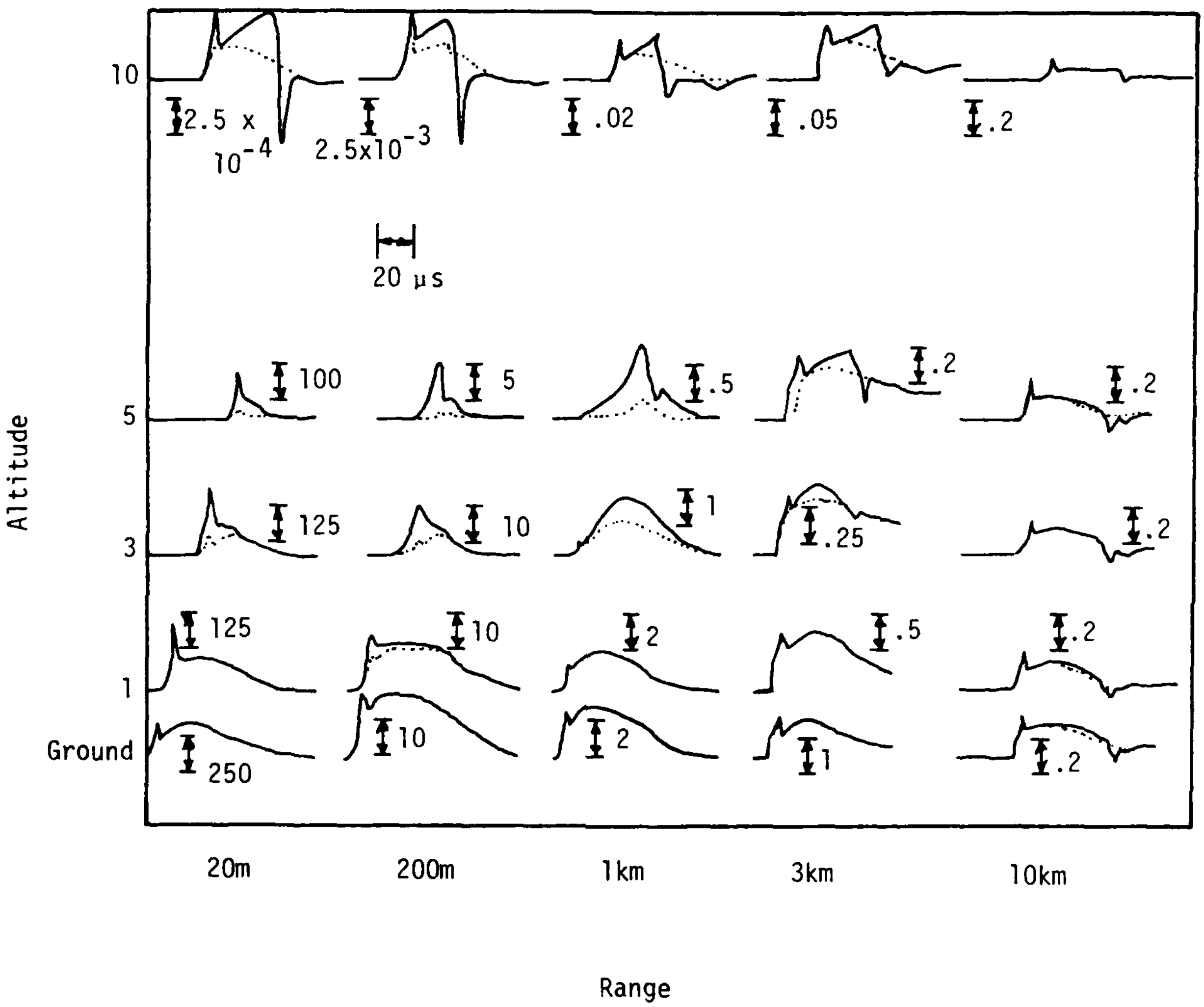
Return strokes subsequent to the first in a flash to ground are usually initiated by dart leaders. Dart leaders are so named because they appear on streak camera photographs to be a 50 m long dart of light propagating toward earth. Dart leaders carry cloud potential earthward via an ionizing wave of potential gradient (Loeb, 1966) and lower about 1 C of negative charge (Brook et al., 1962) in about 1



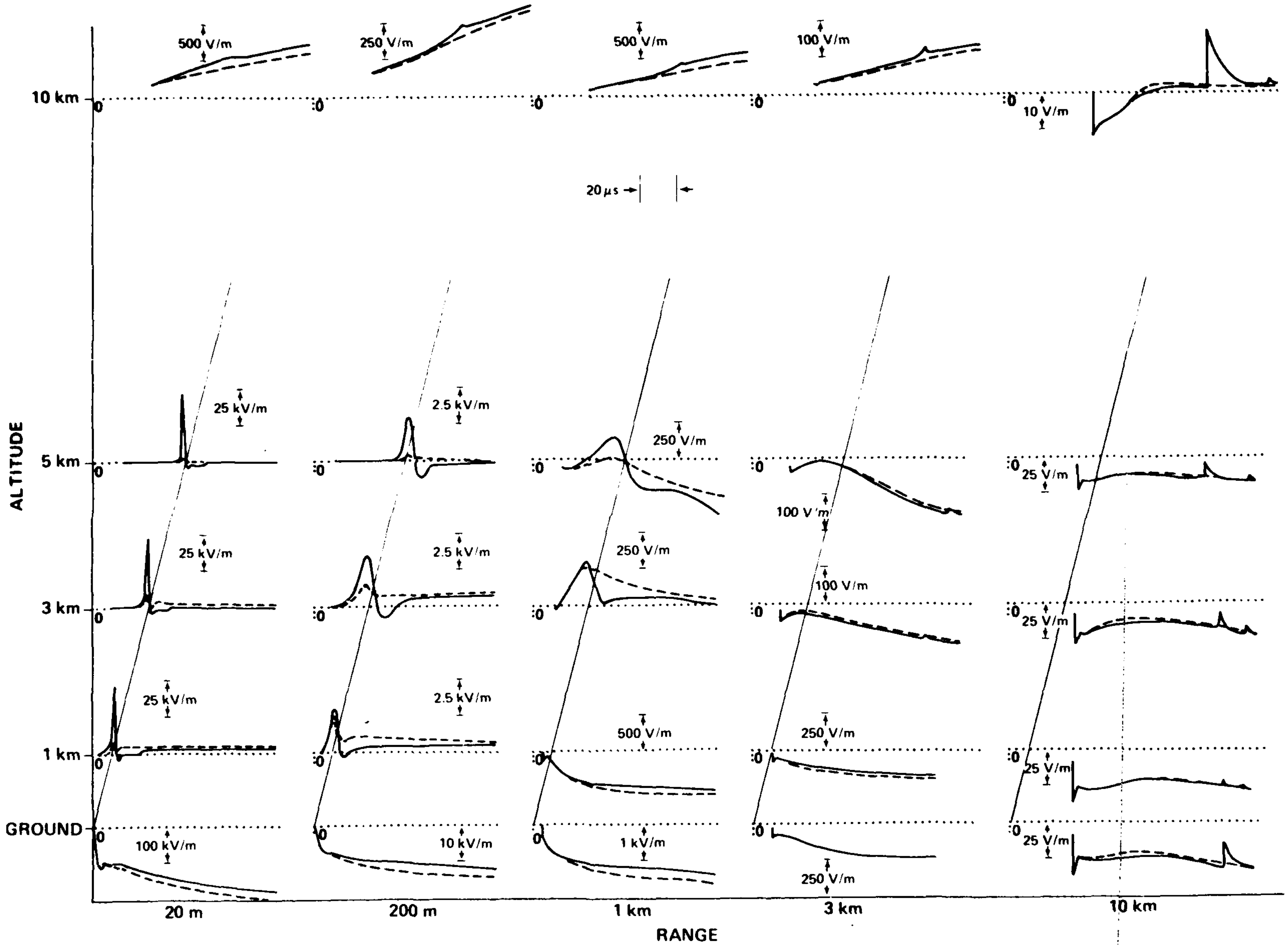
4.21(a). Calculated first return stroke vertical electric field intensity. Solid curves represent original model of Lin et al. (1980); dotted curves the modified model. Scale in kV/m.



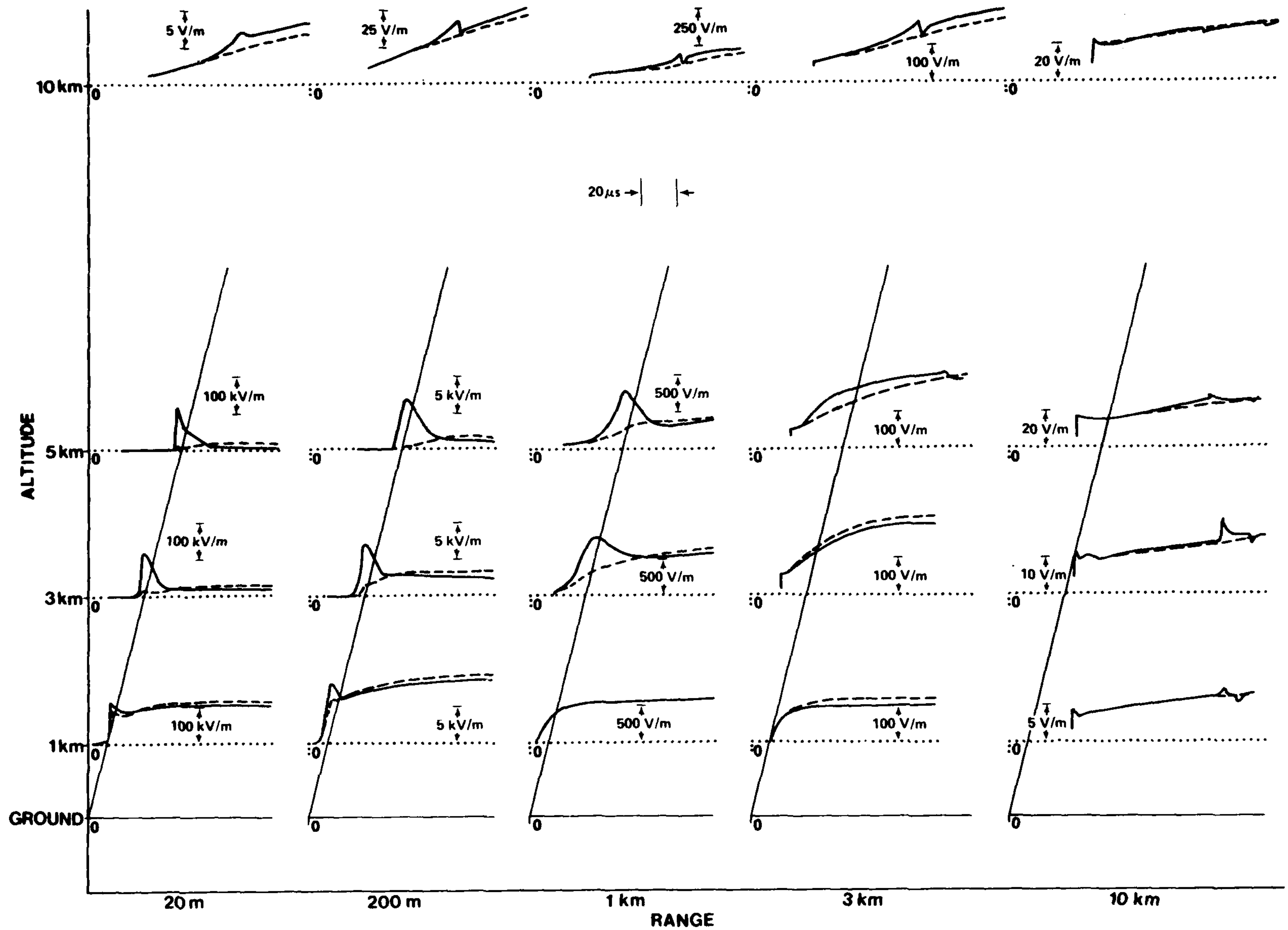
4.21(b). **Calculated first return stroke horizontal electric field intensity. See caption on Fig. 4.21(a). Scale in kV/m.**



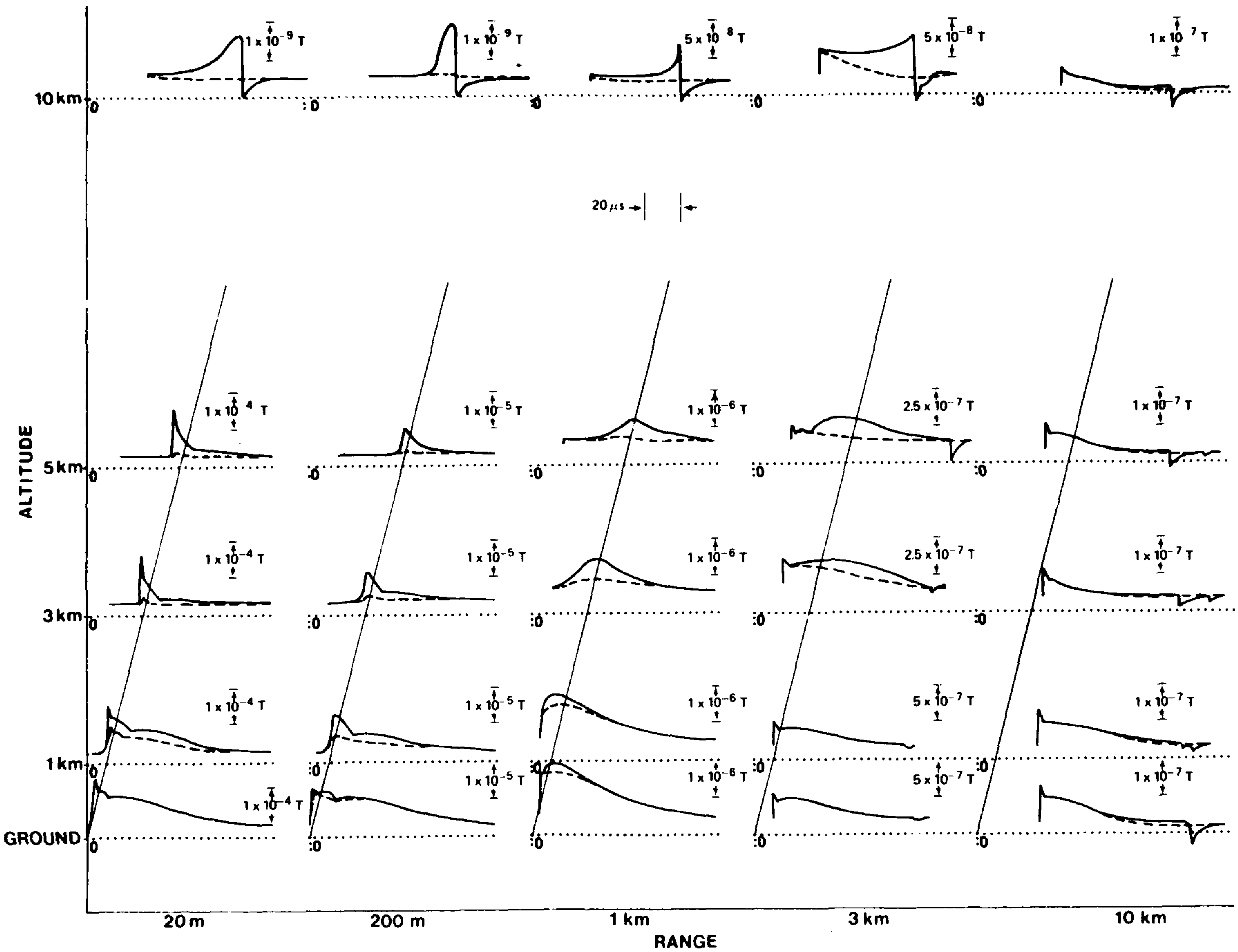
4.21(c). **Calculated first return stroke magnetic flux density. See caption on Fig. 4.21(a). Scale in μT.**



4.21(d). Calculated subsequent return stroke vertical electric field intensity. See caption on Fig. 4.21(a).



4.21(e). Calculated subsequent return stroke horizontal electric field intensity. See caption on Fig. 4.21(a).



4.21(f). Calculated subsequent return stroke magnetic flux density. See caption on Fig. 4.21(a).

TABLE 3(a) FIRST RETURN STROKE PARAMETERS

$$L = 5.0 \times 10^3 \text{ m}$$

$$v = 1 \times 10^8 \text{ m/sec}$$

(1) Breakdown pulse piecewise linear segments:

t(μsec)	I_p(kA)
0.0	0.0
5.0	15.0
5.1	30.0
7.0	8.0
15.0	2.0
40.0	0.0

The pulse may decay exponentially with height above the ground with a decay constant

$$\lambda_p = 2.0 \times 10^3 \text{ m}$$

(2) Uniform current

$$I_u = 5.0 \text{ kA}$$

time duration = 0.3 msec

(3) Corona current per unit length is

$$I_c = I_{co}\, e^{-z'/\lambda}\,(e^{-\alpha t} - c^{-\beta t}) \qquad \text{A/m}$$

where, I_{co} = 50.0 A/m

λ = 2.0×10^3 m

α = 1×10^5 sec^{-1}

β = 3×10^6 sec^{-1}

TABLE 3(b) SUBSEQUENT RETURN STROKE PARAMETERS

$$L = 7.5 \times 10^3 \text{ m}$$

$$v = 1.0 \times 10^8 \text{ m/sec}$$

(1) Breakdown pulse piecewise linear segments

t(μsec)	I_p(kA)
0.0	0.0
1.0	3.0
1.1	14.9
3.7	7.4
11.0	1.4
40.0	0.0

The pulse may decay exponentially with height above the ground with a decay constant

$$\lambda_p = 1.5 \times 10^3 \text{ m}$$

(2) Uniform current:

$$I_u = 3.1 \text{ kA}$$

time duration = 0.3 msec

(3) Corona current per unit length is

$$I_c = i_{co}\, e^{-z'/\lambda}\, (e^{-\alpha t} - e^{-\beta t}) \qquad \text{A/m}$$

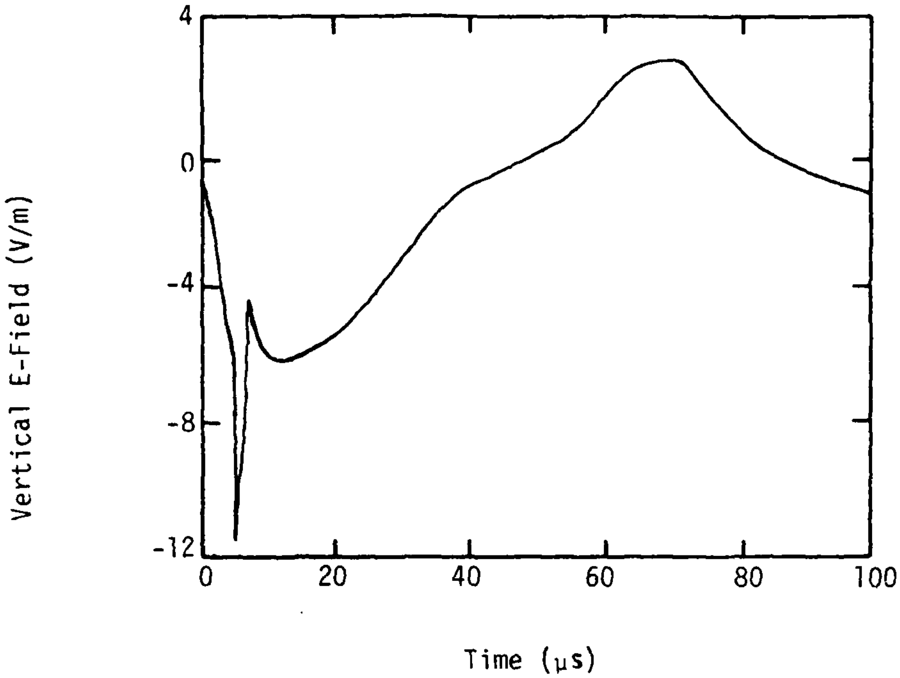
where

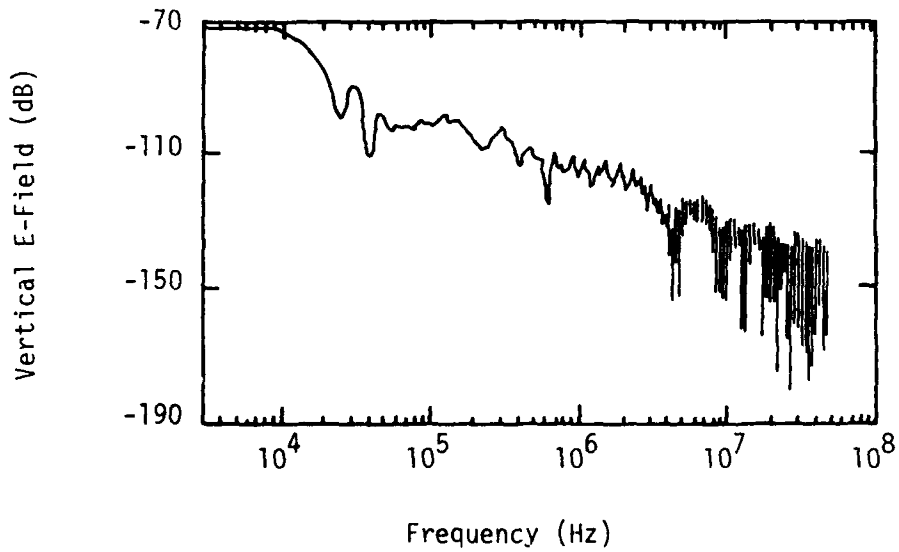
I_{co} = 21.0 A/m

$\lambda = 1.5 \times 10^3$ m

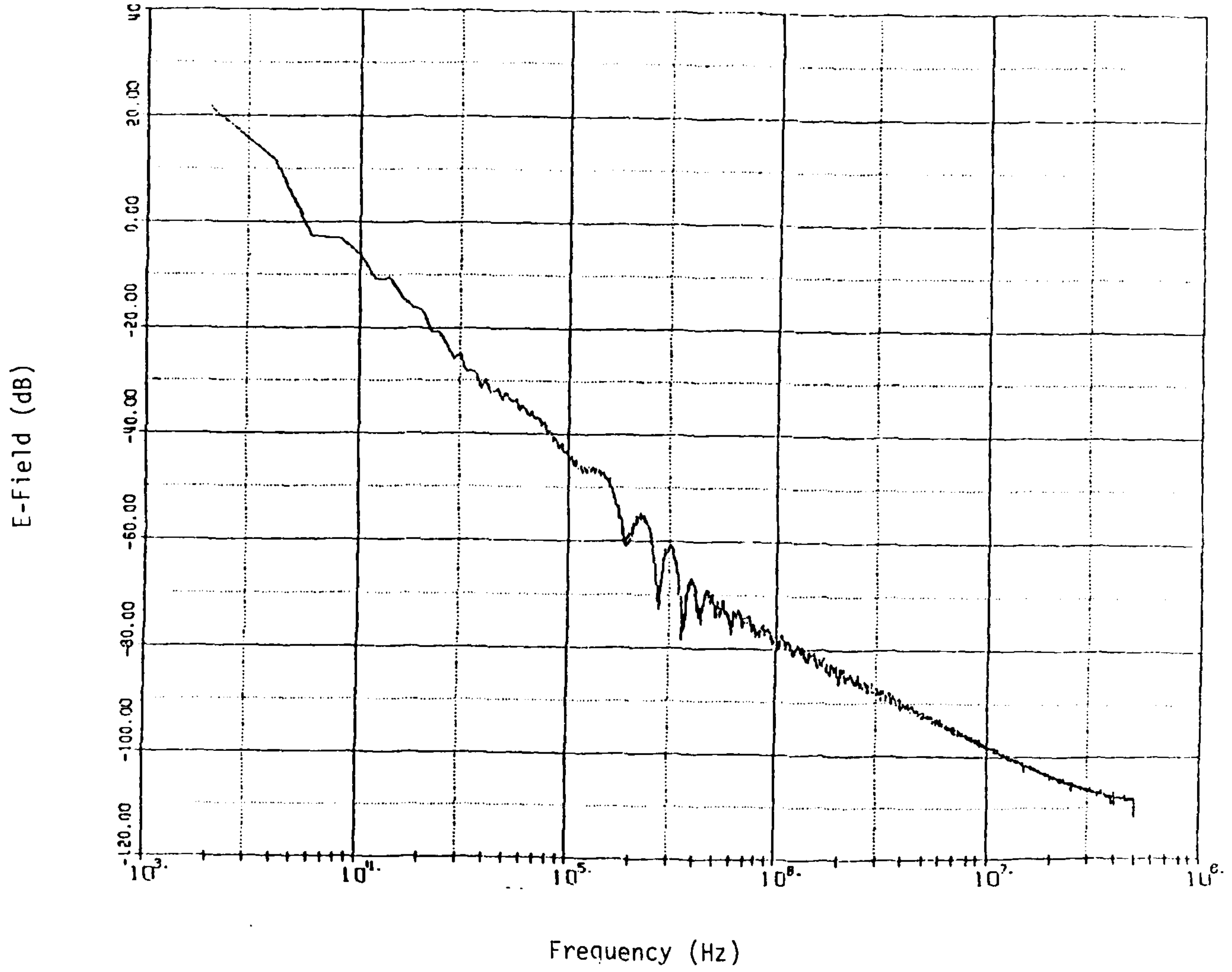
$\alpha = 1 \times 10^5$ sec^{-1}

$\beta = 3 \times 10^6$ sec^{-1}





4.22(a). **Calculated frequency spectra for first return stroke vertical electric field intensity at 50 km on the ground.**



4.22(b). Calculated frequency spectra for first return stroke horizontal electric field intensity 200 m from the channel at a height of 1 km.

msec. It follows that these leaders must have a current of the order of 1 kA. Dart leader velocities range from about 1 to 27 x 10^6 m/sec, with the higher velocities being related to shorter interstrokes intervals and the lower velocities to longer intervals (Winn, 1965; Schonland et al., 1935; Schonland, 1956).

The electric field changes produced by dart leaders have been described by Malan and Schonland (1951). At a range of 5 to 8 km, the first dart leaders in multistroke flashes produce positive field changes and later ones have hook-shaped field changes which begin with a negative polarity. The implication is that succeeding leaders originate from charge volumes higher in the cloud, the typical increase in height between successive leaders being about 0.7 km according to Malan and Schonland (1951) and about 0.3 km according to Brook et al., (1962). Apparent leader heights varied between 2 and 13 km (Brook et al., 1962). Schonland et al. (1938) have inferred from the field ratios of 46 dart leaders and return-strokes that the dart leader channels tend to be uniformly charged, although, as we have seen in Section 4-6, the charge removed by subsequent return strokes is apparently not uniform.

If the time interval between strokes is long, the dart leader may change from a continuously moving leader to a stepped leader, a so-called dart-stepped leader. The stepped portion has a relatively high downward velocity (about 10^6 m/sec), short step lengths (about 10 m), and short time intervals between steps (about 10 μsec) (Schonland, 1956; Krider et al., 1977).

The in-cloud portion of the dart leader produces considerable radiation at VHF frequencies (Takagi, 1969 a,b; LeVine and Krider, 1977; Rustan, 1979; Rustan et al., 1980) and in the microwave region from 400 to 1000 MHz (Brook and Kitagawa, 1964). This radiation eminates primarily from the cloud rather than from the channel to ground (Proctor, 1976; Rustan, 1979; Rustan et al., 1980). The RF associated with the dart leader starts about 250 μsec before the return stroke (LeVine and Krider, 1977) and, at frequencies above about 100 MHz, ceases about 100 μsec prior to the return stroke (LeVine and Krider, 1977; Brook and Kitagawa, 1964). At 3 MHz the dart leader radiation often continues up to and during the return stroke (LeVine and Krider, 1977). These effects are illustrated in Figures 4-18(a), (b) and (c).

4-7-2. Model.

We model the dart leader in exactly the same way that we model the continuously-moving portion of the stepped leader (see Section 4-4). The parameters used are $\rho_0 = -2.0 \times 10^{-4}$ C/m, $\gamma = 3.5 \times 10^3$ sec^{-1}, $\lambda =$ 1.5 km, $v = 4 \times 10^6$ m/sec. The leader starts at a height of 7.5 km with a current of 1 Amp and exhibits a current of 800 Amps when it touches ground about 2 msec later. Computed fields are not shown but are similar to those of Figures 4-11(a), (b), and (c).

4-8. Continuing Current

Return stroke currents can last up to a millisecond or so, the "intermediate" currents during the final millisecond decreasing from a few kA to zero (Hagenguth and Anderson, 1952). Following the current associated with the return stroke proper there may also be a low level continuing current to ground whose charge source is distributed horizontally in the cloud (Krehbiel et al., 1979). Continuing currents have been measured directly in strikes to towers (Berger and Vogelsanger, 1965) and have been inferred from remote measurements of interstroke electric and magnetic fields. Brook et al (1962) and Kitagawa et al. (1962) have made correlated photographic and electric field observations in New Mexico. So-called "long" continuing currents durations, defined by the New Mexico group as those lasting longer than a typical 40 msec interstroke interval, were found to have durations up to 500 msec, the average being 150 msec. The charges lowered by continuing currents were between 3.4 and 29.2 C, the average being about 12 C. Current values were between 38 and 130 Amperes. Williams and Brook (1963), also in New Mexico, used a magnetometer to measure magnetic field from which continuing current was derived. They found an average current of 184 Amps, an average charge transfer of 31 C, and an average duration of 184 msec. Krehbiel et al. (1979) using multiple electric field measuring systems in New Mexico found continuing currents between 50 and 580 A for three discharges. The initial continuing current values were 580, 185, and 150 A, and all three continuing currents decreased with time. Livingston and Krider (1978) have reviewed the literature on the occurance of continuing current as well as presenting their own finding that 29 to 46% of the flashes in individual storms studied at the Kennedy Space Center had continuing current. About half of the 200 flashes observed by Brook et al. (1962) and Kitagawa et al. (1962) in New Mexico had a long continuing current interval and about 1/4 of all the interstroke intervals had one. Schonland (1956) states that about 20% of all flashes in South Africa contain a continuing current; Thomson (1980) gives a figure of 48% for New Guinea.

The continuing currents measured by Berger and Vogelsanger (1965) following strikes to an instrumented tower in Switzerland were found to be of the order of 100 to 300 Amperes. Half the flashes containing continuing current intervals lowered over 25 C, with a maximum charge lowered of 80 C.

The "long" continuing currents referred to in the preceding paragraphs are apparently the source of lightning-associated burning effects (e.g., forest fires (Fuqua et al., 1967), burned-through overhead ground wires on power systems, metal damage on airplanes). Brook et al. (1962) and Kitagawa et al. (1962) also discuss "short" continuing currents, those that last less than 40 msec. In either case, after the continuing current ends, a normal interstroke interval, presumably containing a J-change, follows if there is to be another return stroke to ground. Continuing currents, as far as is known, do not produce appreciable radiation above a few kilohertz and hence will not be included in our modeling for close electromagnetic effects. Actually, the continuing current fields should not be much different from the fields of the slow component of the stepped leaders current.

4-9. J and K Changes in Discharges to Ground

4-9-1. Literature.

During the time interval between successive strokes in a flash to ground, of the order of 50 msec, there is usually a slow, relatively steady change in the electric field due to charge motion within the cloud. This change is called a J-change, the J standing for "Junction." Impulsive discharges termed K-changes are usually superimposed on the J-change at intervals of 5 to 10 msec (Kitagawa and Brook, 1960; Kitagawa et al., 1958). Kitagawa and Brook (1960) and Kitagawa (1965) suggest that the slow J-process is actually due to the instrumentally-smoothed sum of the field changes due to the rapid K-processes, each of which lasts less than 1 msec. Kitagawa and Brook (1960) show that the distribution of time intervals between K-changes in the interstroke intervals of discharges to ground is essentially the same as the distribution of K-change intervals in the final portion, the so-called J-portion, of an intracloud discharge, although the polarity of the K-changes may be different in cloud and ground discharge. Ogawa and Brook (1964) state that K-changes in cloud discharge are an order of magnitude larger than K-changes in ground discharges while others (e.g., Ishikawa, 1961; Wadhera and Tantry, 1967, a,b) claim they are of the same magnitude. We will discuss the J and K changes of cloud discharges in Section 4-10.

The J-field change in ground discharges is almost always negative for flashes within a few kilometers and can be positive or negative for discharges beyond about 5 km (Malan and Schonland, 1951a,b; Malan, 1955, 1963). During the J-change there is no appreciable luminosity in the channel between cloud base and ground. Further, Malan and Schonland (1951b) report that for flashes in the 5 to 12 km range, J field changes occuring early in the flash are positive while later ones are negative. If all distant J changes were positive instead of a mixture of positive and negative, that would be clear evidence for J-changes being due to a vertical motion of either negative charge downward or positive charge upward. It is likely that all distant J-changes are not positive because (1) many of the J-processes are more horizontal than vertical and (2) some of the apparent negative field change that occurs during the interstroke period is due to the rearrangement of charge in the atmosphere between the measurement point and the source rather than at the source (Illingsworth, 1971). Evidence for non-vertical J-processes has recently been reported by Ogawa and Brook (1969) and Krehbiel et al. (1979). Rustan (1979) found vertical J-processes in some flashes and horizontal ones in others. The exact orientation of the J-process is undoubtedly related to the structure of the thunderstorm cloud.

Schonland (1938) suggested that, during the time interval between strokes, J-discharges progress downward from previously untapped negative charge centers in the cloud to the top of the previous return stroke channel. Apparent confirmation of this view of the J-process is given by Rustan et al. (1980) for one flash and by Rustan (1979) for 3 more flashes. They found VHF source locations moving downward from high in the cloud at a velocity of about 2×10^5 m/sec while the J electric field change indicated either a raising of positive charge or a lowering of negative charge, the latter being the choice in since the VHF sources were descending. On the other hand, Bruce and Golde (1941), and Malan and Schonland (1951b), argue that the J-change represents a raising of positive charge from the top of the previous return stroke channel into new regions of negative charge. Further, visual observations (Brook and Vonnegut, 1960) tend to confirm this view. Krehbiel et al. (1979) have deduced from multiple-station electric field measurements that J-processes in New Mexico usually move negative charge horizontally toward the top of a previous stroke, but that this is not necessarily the same negative charge that is involved in the next stroke to ground.

The K-processes are generally thought to be "recoil streamers" or small return strokes which occur when a propagating channel encounters a pocket of opposite charge within the cloud. In this view, the J-changes are not necessarily the sum of their K-changes. The detailed characteristics of the K-change currents are very much in doubt, although there is evidence that the duration is generally between about 500 μsec and 750 μsec (Brook and Kitagawa 1964; Rustan, 1979; Rustan et al., 1980). Arnold and Pierce (1964) give a median value of 0.1 for the ratio of the peak K-electric field to the return stroke electric field peak which implies that K-processes exhibit peak currents of the order of several thousand Amperes, since the K-processes have velocities several times lower than return strokes (Rustan, 1979, Rustan et al., 1980, Arnold and Pierce, 1964). Steptoe (1958) and Muller-Hillebrand (1968) have proposed expressions for the K-process current. Both investigators suggest that the K-process current rises to peak in 9 μsec. The actual rise is probably faster, since the equipment used to measure the K-electric field waveforms had a relatively poor upper frequency response. The K current falls to half value in tens of microseconds and then remains at a low level until a significant fraction of a Coulomb of charge is transferred.

If an intermediate or a continuing current is flowing to ground when a K-change occurs, the K-change will brighten the channel to ground and the luminous event below cloud is called an M-component (Kitagawa et al., 1962; Malan and Schonland, 1947). The implication of this observation is that the continuing current discharge is propagating away from the top of the return stroke channel when it contacts a region of negative charge, and that the resulting K-change propagates downward to ground, perhaps in a manner similar to that of a dart leader.

4-9-2. Model.

We model the J-process as a descending negative discharge, with a maximum channel length of several kilometers, which carries a steady current of 50 Amps for about 50 ms and hence transfers a total charge of the 2.5 C. We model the several K-processes which occur during the J-process in the same way that we model the return strokes in ground discharges (see Section 4-6) and use the current parameters listed in Table 4.

4-10. Cloud Discharges

4-10-1. Literature.

The words "cloud discharge" may well refer to a variety of different phenomena. The cloud discharge which sometimes precedes a ground discharge by more than 100 msec (see Section 4-3) may be different from the typical isolated cloud flash, and there may be several types of isolated cloud flashes, the distinction between intracloud lightning, intercloud lightning, and cloud-to-air lightning being hardly discussed in the literature. Since relatively little is known about cloud discharges, we shall concentrate on the type about which the most is known, the typical isolated intracloud flash.

The average durations of cloud discharges have been given by a number of investigators, for example, 245 msec by Pierce (1955), 490 msec by Mackerras (1968), 300 msec by Takagi (1961) 420 msec by Ishikawa (1961), and 500 msec by Ogawa and Brook (1964). The bulk of the available ground-based electric field data suggests that a typical intracloud flash contains an initial downward moving discharge which propagates at a velocity of about 10^4 m/sec and which lowers positive charge from the upper cloud region toward the lower negative charge (see Figures 4-1 and 4-2). When contact occurs several upward-moving K-changes are initiated. Electrostatic field measurements by Ogawa and Brook (1964), Takagi (1961), Takeuti (1965), and Ishikawa and Takeuchi (1966) show that 60 to 75% of the cloud discharge field changes are consistent with

TABLE 4. K-PROCESS PARAMETERS FOR GROUND DISCHARGES

$L = 1$ km

$v = 4 \times 10^7$ m/sec

(1) Breakdown pulse piecewise linear segments:

$t(\mu sec)$	$I_F(kA)$
0.0	0.0
1.0	0.5
1.1	3.0
3.7	1.5
11.0	0.3
40.0	0.0

(2) Uniform current:

$I_u = 0.05$ kA

time duration = 0.3 msec

(3) Corona current per unit length is

$$I_c = I_{co}\, e^{-z'/\lambda}\, (e^{-\alpha t} - e^{-\beta t}) \qquad \text{A/m}$$

where

$I_{co} = 5.0$ A/m

$\lambda = 0.5$ km

$\alpha = 1 \times 10^5\ \text{sec}^{-1}$

$\beta = 3 \times 10^6\ \text{sec}^{-1}$

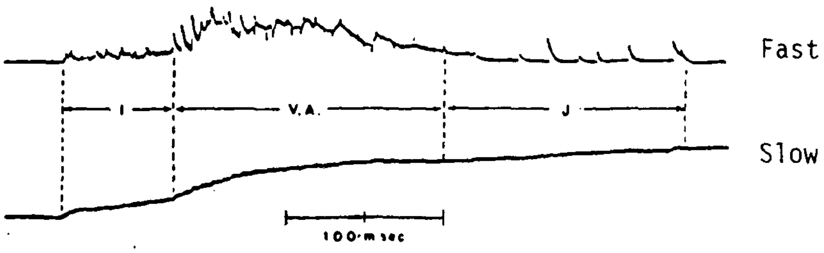
the downward movement of a positive charge. On the other hand, Smith (1957) working in Florida found that 56 percent of the cloud discharges were initiated by negative discharges moving upward from the lower part of the thundercloud, and only 17 percent were of the downward positive type. Smith described the remaining cloud discharges as the neutralization of a dipole cloud charge where the negative charge was above the positive. The luminosity variation of an intracloud event is usually composed of a continuous, slowly-varying background on which is superimposed a series of rapid pulses (Takagi, 1961; Malan, 1955; Brook and Kitagawa, 1960).

The average change in the total electric moment produced by cloud discharges have been found to be 80 C-km (Pierce, 1955), 150 C-km (Mackerras, 1968), and 200 C-km (Takagi, 1960; Wang; 1963). Since the path lengths between charge centers are roughly about 5 km, charge transfers are probably in the range of 15 to 40 C, values which are similar to ground flashes.

There have been few accurate determinations of the total length of cloud discharges. Rustan (1979) using a VHF source location technique found a total channel length of about 10 km for each of three vertically oriented cloud discharges. To find the charge locations from ground-based electrostatic field measurements, a minimum of seven ground stations are needed if the discharge is not vertical and a minimum of five stations if it is vertical. The seven stations provide information to solve for seven variables, the charge and the x,y,z coordinates of each endpoint. The five stations provide data to determine the charge, the x,y coordinates, and height of each end of the channel. Analyses of multiple station electric field records by Workman et al. (1942) and Reynolds and

Neill (1955) show that cloud discharges in New Mexico are primarily horizontal: vertical charge separations are typically 0.6 km, with the positive charge generally above the negative, and the horizontal charge separations are typically 1 to 10 km. The moment changes are of the order of 10 C-km, an order of magnitude smaller than the more recent measurements referenced above, probably due to the small vertical charge separation, but the charge transfers are similar, typically 10 to 20 C. Smith (1957) used only two ground stations in Florida and hence could not find accurate charge locations. Takeuti (1965) used only three stations, but was able to estimate total path lengths in Japan of 2 to 8 km. It should be noted that multiple simultaneous measurements of electric fields are difficult to obtain and that data from different sets of stations in the same experiment can give quite different results presumably because of errors in measurement and difficulty in identifying a unique portion of the discharge at all stations (Krehbiel et al., 1979).

The electric field change produced by a typical intracloud discharge on a millisecond scale is shown in Figure 4-23. Kitagawa and Brook (1960) have divided this overall field change into three portions, as shown: (1) an initial portion having a duration of 50 to 300 msec and characterized by small pulses with a mean pulse interval of 680 μsec. According to Kitagawa and Brook (1960), this initial process is quite different from the more rapid pulsations that characterize the beginning of a discharge to ground; (2) a very active portion lasting of the order of 100 msec and characterized by large VLF pulses and a relatively rapid electrostatic field change; and (3) the final or J-type portion which is similar to the J-change in ground discharge and is characterized by impulsive K-changes which occur at intervals ranging from 2 to 20 msec.



4.23. Diagram of the typical field change of a cloud discharge. The upper and lower traces are recorded simultaneously by the fast and slow antennas, respectively. Adapted from Kitagawa and Brook (1960).

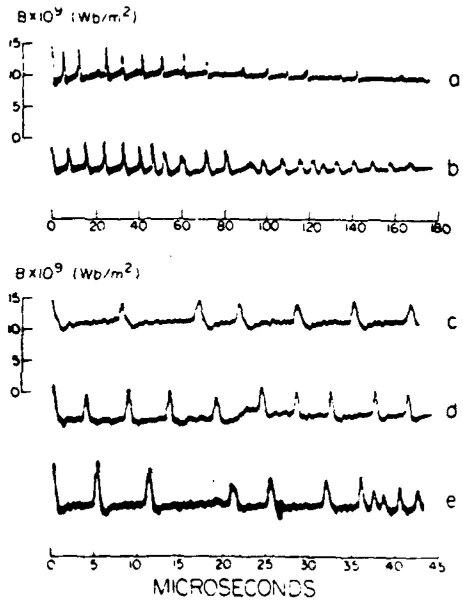
Kitagawa and Brook report that 50 percent of 1400 cloud discharge field changes contained all three of the above phases, 40 per cent were missing the initial portion, and 10 per cent contained just the initial portion or the very active portion or both.

The characteristics of the individual pulses superimposed on the slow electrostatic field change are of primary importance in the present study. The larger pulses are generally called K-changes; the smaller ones do not have a name. Ogawa and Brook (1964) state that K-changes do not occur during the initial or very active portions and interpret K changes as being due to upward-propagating negative recoil streamers that are initiated by a downward-moving positive discharge. Apparently the cloud discharge K-changes are similar to those which occur during the period between return strokes in flashes to ground (see Section 4-9) and hence the discussion in Section 4-9 is also valid for the present case. On the other hand, cloud and ground discharge K-changes are usually of opposite polarity and, according to Ogawa and Brook (1964), the mean moment change of cloud K-changes, 8 C-km, is considerably larger than the largest moment change, 2 C-km, found for ground K-changes. Ogawa and Brook (1964) suggest that the negative cloud K-changes (or recoil streamers) have the following properties: time duration 1 to 3 msec, channel length 1 to 3 km, velocity 2×10^6 m/sec, charge neutralized 3.5 C, average current 1 to 4 kA. They also report that during the J-period there were most frequently six of these processes. Rustan (1979) and Rustan et al. (1980) have used a VHF source location technique to follow the propagation of several cloud K-changes. These had a velocity of 1 to 4 x 10^7 m/sec and propagated upward from a height of 5 to 8 km to a height of about

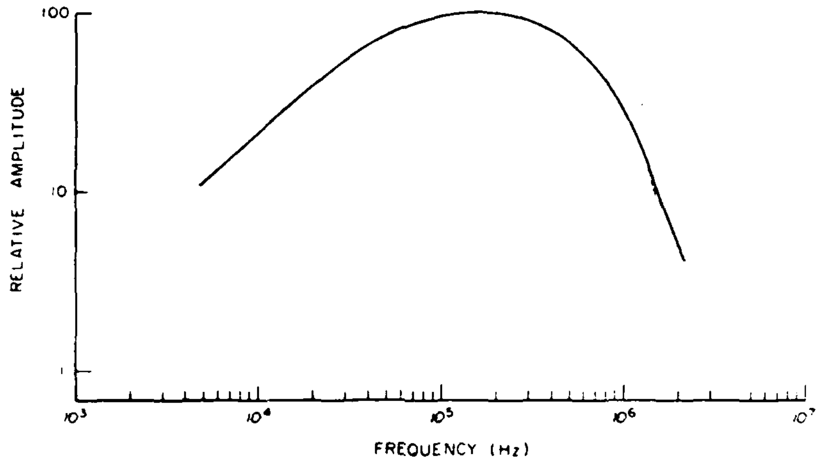
13 km. Although K-changes are reported by Ogawa and Brook (1964) to occur only in the final portion of a cloud discharge, it is difficult to see how their occurrence could be ruled out in the very active portion, particularly in view of the multitude of electric field pulses occuring during that time.

Krider et al. (1975), Weidman and Krider (1979), and Krider et al. (1979) have examined the detailed shapes of individual pulses generated by cloud discharges. Two types of pulses were found: (1) regular sequences of primarily unipolar pulses which occur at 5 μsec intervals and have a total sequence duration of 100 to 400 μsec. (2) large amplitude, bipolar pulses similar to those we have associated with the preliminary breakdown (see Section 4-3) but with opposite polarity and larger pulse intervals.

(1) The unipolar pulses have risetimes of 0.2 μsec or less and a full width at half maximum of about 0.75 μsec. Examples of these pulses are given in Figure 4-24(a) and the frequency spectrum of one pulse sequence is given in Figure 4-24(b). Krider et al. (1975) note the similarity of these pulse sequences to those radiated by the dart-stepped leaders which sometimes preceed subsequent strokes in ground discharges (see Section 4-7) and suggest that a similar dart-stepping process may occur in the cloud discharge. If each of 20 to 80 pulses occuring at 5 μsec intervals has a length of 20 m (a value similar to dart-stepped leaders) the total channel length would be 200 to 800 m and the propagation velocity would be 2×10^6 m/sec. These values are similar to the Ogawa and Brook (1964) description of a K-change. Krider et al. (1975) find that the sequences of regular pulses occur throughout the cloud discharge but state that there is a tendency for the sequences to occur at the end of the discharge.



4.24(a). Trains of unipolar magnetic field pulses produced by five different intracloud lightning discharges within 50 km in Arizona. Adapted from Krider et al. (1975).



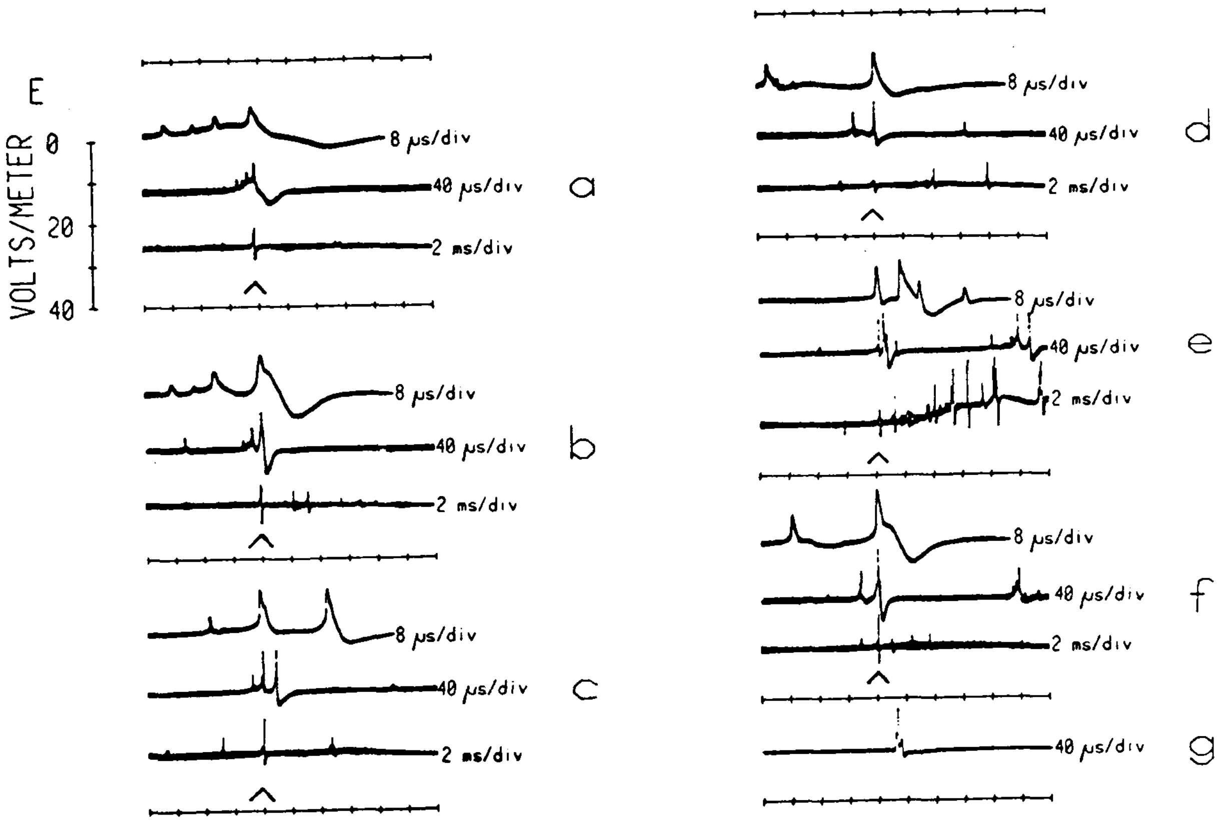
4.24(b). The relative Fourier amplitude as a function of frequency for a typical intracloud pulse sequence as shown in Fig. 4.24(a). Adapted from Krider et al. (1975).

This implies that some may well be associated with K-changes.

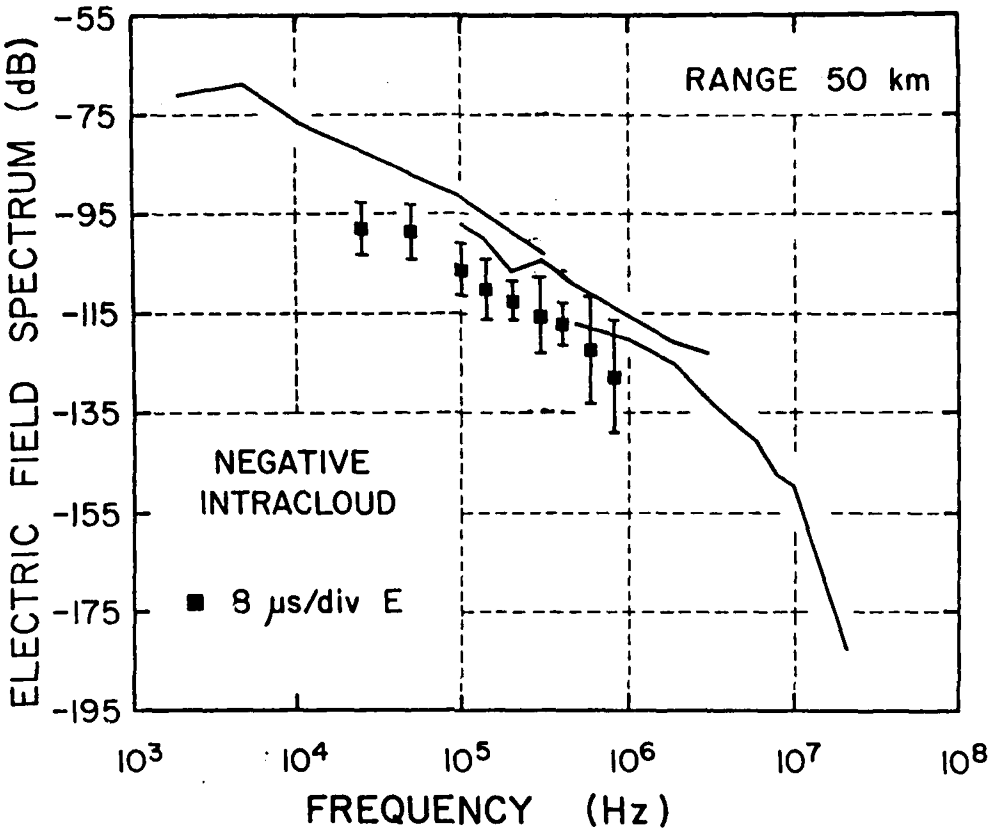
(2) Examples of the large bipolar waveforms are shown in Figure 4-25(a) and the frequency spectrum of one pulse is shown in Figure 4-25(b). Weidman and Krider (1979) have found that these large pulses often have several fast unipolar pulses superimposed on the initial rise to peak. The shape of the fast impulses is similar to individual pulses in the regular sequences just discussed. The large pulses have a mean full width of 63 μsec and a mean pulse interval of 780 μsec, a value which is similar to the 680 μsec mean pulse interval reported by Kitagawa and Brook (1960) for the initial portion of the discharge. On the other hand, the bipolar pulses are among the largest events in the cloud discharge and these perhaps should be associated with the very active portion of the discharge. Weidman and Krider (1979) suggest that the fast pulses on the initial rise are due to a step-like breakdown current and that the subsequent large bipolar field is due to a slower current surge flowing in the channel established by the steps. Krider et al. (1979) have shown that RF radiation at frequencies between 3 and 295 MHz is coincident with each bipolar pulse, as illustrated in Figures 4-26(a), (b), (c), and (d), which in turn implies that the process generating the pulse probably involves the breakdown of virgin air rather than propagation along an already existing channel.

4-10-2. Model.

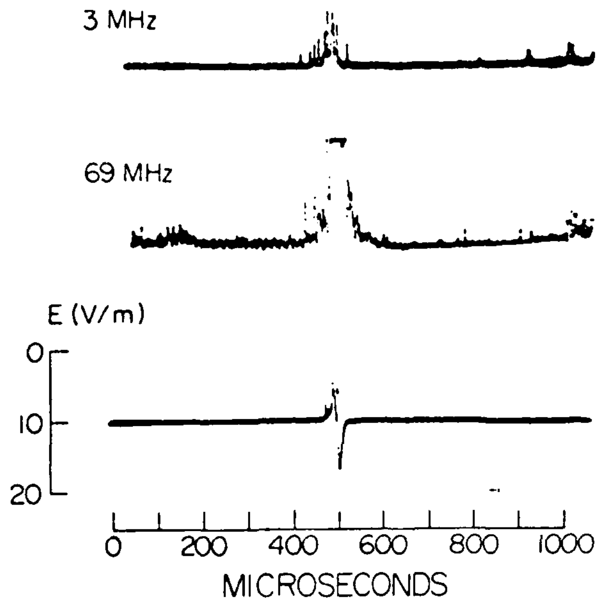
In view of the above, we will model the various portions of a cloud discharge as follows: (1) The initial stage will be modeled in a fashion similar to the stepped leader (see Section 4-4-2) except that we use a time between steps of 700 μsec instead of 80 μsec. The various other parameters are $I_o = 80$ A, $\gamma = 3.2$ sec^{-1}, $\lambda = 7 \times 10^3$ m, $v = 2.3 \times 10^4$



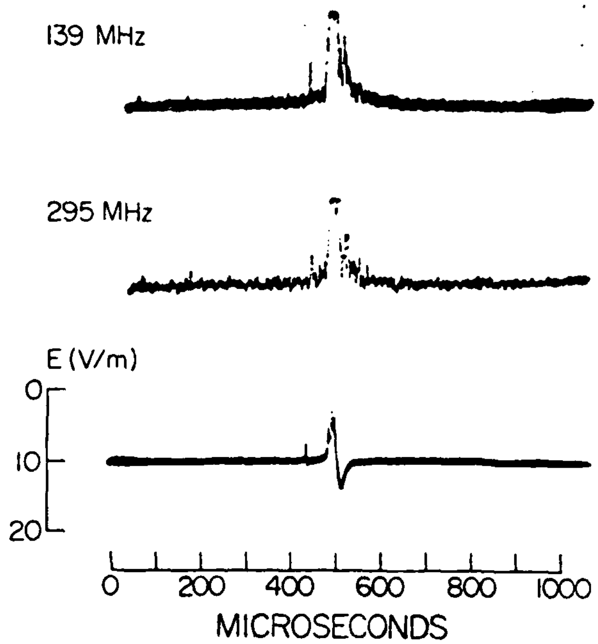
4.25(a). Large bipolar electric fields radiated by intracloud discharges at distances of 15 to 30 km. Each event is shown on time scales of 2 μs/ div, 40 μs/div, and 8 μs/div. The points on each trace directly above the caret coincide in time. A positive field is shown as a downward deflection on all records. Adapted from Weidman and Krider (1979).



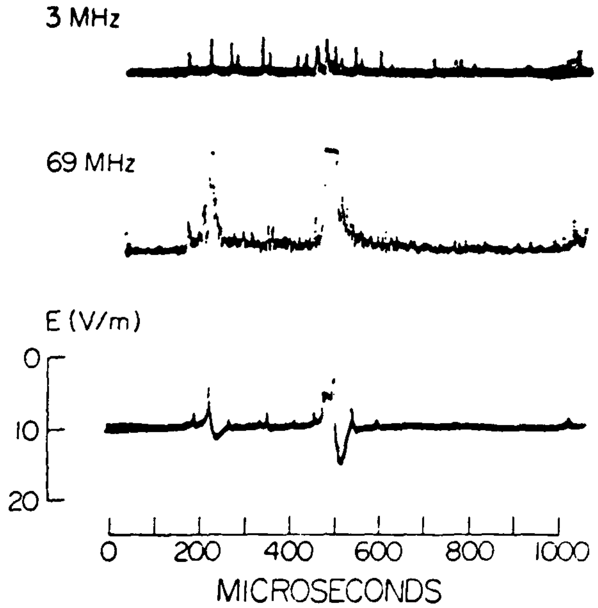
4.25(b). Frequency spectra of 6 large bipolar electric fields from intracloud discharges as shown in Fig. 4.25(a). Lightning between 15 and 30 km, normalized to 50 km. The solid lines represent the first return stroke frequency spectra given in Fig. 4.16.



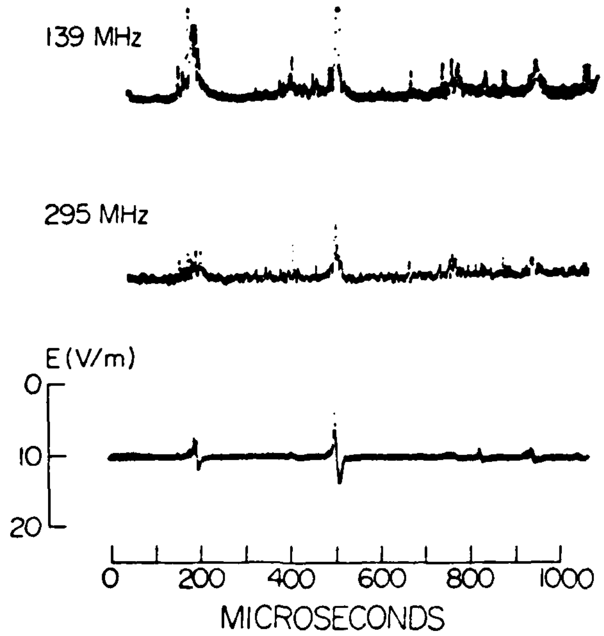
4.26(a). A large bipolar electric field and associated RF emissions at 3 and 69 MHz produced by an intracloud lightning discharge on July 28, 1977. The polarity of the electric field is such that a negative potential gradient is displaced upward. Adapted from Krider et al. (1979).



4.26(b). A large bipolar electric field and associated RF emissions at 139 and 295 MHz. See also caption for Figure 4.26(a). Adapted from Krider et al. (1979).



4.26(c). A sequence of large bipolar electric fields and associated RF emissions at 3 and 69 MHz. See also caption for Fig. 4.26(a). Adapted from Krider et al. (1979).



4.26(d). A sequence of large bipolar electric fields and associated RF emissions at 139 and 295 MHz. See also caption for Figure 4.26(a). Adapted from Krider et al. (1979).

m/sec, $\rho = 4.8 \times 10^{-3}$, and Q = 9.4 C. The step length is found by multiplying the velocity by the pause time between steps and hence is 16 meters. The duration of the initial portion is 100 msec during which time the leader moves downward from 10.0 km to 7.7 km and the current increases from 80 to 110A. Superimposed on the roughly steady current are the fast breakdown step pulses whose parameters are the same as those given in Section 4-4-2 except θ = 32 m and the polarity is opposite. (2) The very active stage is treated in a fashion similar to the preliminary breakdown of Section 4-3-2. The current pulses are similar to those described in Section 4-3-2, but they are of opposite polarity to the preliminary breakdown pulses that preceed stepped leaders in ground discharges. We use three preliminary breakdown pulses, each covering a vertical height of about 900 m. Each breakdown pulse in turn is initiated by three leader-like steps each beginning 300 meters below the previous one and separated by a time of 10 μsec. Each breakdown step has a triangular current with a 0.1 μsec linear rise-time and a 2 μsec linear fall to zero. Other parameters describing the step current pulses are θ = 75 m and I_o = 2 kA. The current in each of the larger 900 meter sections forms by propagating down the vertical channel section at a velocity of 5×10^7 m/sec and is uniform along the channel. The shape of the current is of the form $I_o e^{-t^2/T^2}$, with I_o = 5 kA, T = 25 μsec, where t = 0 starts 20 μsec after the last step pulse. The three breakdown pulses during the very active stage extend the channel from an altitude of 7.7 km to 5.0 km. (3) The final or J-stage is modeled as a series of four K-changes each of which is similar to the return stroke of Section 4-6-2. The various parameters used are listed in Table 5. The K-changes begin at heights of 5.0, 5.5, 6.0, and 6.5 km, respectively, and propagate upward at a velocity of 2×10^7 m/sec.

TABLE 5. K-PROCESS PARAMETERS FOR CLOUD DISCHARGES

$L = 3$ km

$v = 2 \times 10^7$ m/sec

(1) Breakdown pulse piecewise linear sections

t(μsec)	I_p(kA)
0.0	0.0
1.0	1.0
1.1	6.0
3.7	3.0
11.0	0.6
40.0	0.0

(2) Uniform current

$I_u = 0.2$ kA

time duration = 0.3 msec

(3) Corona current per unit length is

$$I_c = I_{co}\, e^{-z'/\lambda} \left(e^{-\alpha t} - e^{-\beta t}\right) \quad \text{A/m}$$

where

$I_{co} = 10.0$ A/m

$\lambda = 1.0$ km

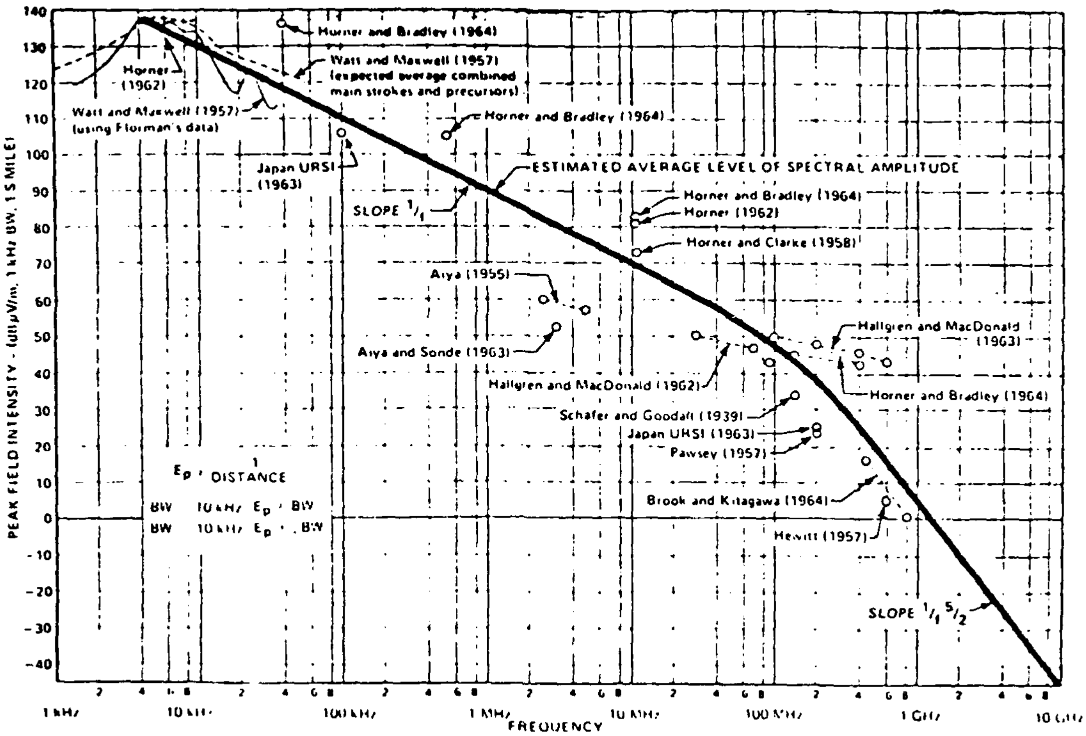
$\alpha = 1 \times 10^5$ sec^{-1}

$\beta = 3 \times 10^6$ sec^{-1}

4-11. Flash Frequency Spectra

A number of investigators have used narrow band receivers at a variety of frequencies to sample portions of the lightning frequency spectrum. As we have seen in this report, spectra are best determined by Fourier analysing time domain waveforms, although the effects of ground-wave propagation must be considered at the higher frequencies. A composite view of the flash integrated frequency spectrum which incorporates essentially all published measurements is shown in Figure 4-27. Similar composite spectra have been published by Kimpara (1965), Oh (1969), Oetzel and Pierce (1969), Pierce (1977), and others. The measurements generally represent the maximum amplitude of the flash frequency spectra which occur during the flash at each of the sampled frequencies. For many applications the total energy associated with each sampled frequency, a parameter proportional to the square of the amplitude of the frequency spectrum at that frequency integrated over time, is more useful.

Since most measurements have been made for lightning at distances greater than 10 km, the frequency content above about 1 MHz in Figure 4-27 must be considered a lower limit to the actual value since the higher frequencies are strongly attenuated by ground wave propagation (see Section 4-6 and Figures 4-15(a) and (b)). Further, from the integrated spectrum, it is not possible to determine which lightning process produces a particular spectral emission. Thus the integrated spectra are useful in the present study only as a rough guide to the frequency content of any given process by assuming, conservatively, that the particular process generates essentially all of the spectral content that was measured.



Investigators	Observation Frequency	Antenna Polarization	Receiver Bandwidth	Average Sferic Distance (miles)	Normalized Peak Field Strength, Median Value (dB μV/m, 1 kHz, 1 s mi)
Watt and Maxwell (1957)*	1 kHz–40 kHz			20–30	See composite curves, Fig. 1
Horner and Bradley (1964)	40 kHz	Vertical	250 Hz†	4–10	136
	550 kHz	Vertical	250 Hz†	4–10	105
	11 MHz	Vertical	250 Hz†	4–10	82
	200 MHz	Vertical	250 Hz†	4–10	48
	400 MHz	Vertical	250 Hz†	4–10	43
Aiya (1955)	2.9 MHz	Vertical	6 kHz	400–2500	60
	4.7 MHz	Vertical	6 kHz	400–2500	58
Aiya and Sonde (1963)	3 MHz	Vertical	6 kHz	1–15	52.4
Horner and Clarke (1958)	11 MHz	Vertical	300 Hz	1–4	73
Horner (1962)	6 kHz	Vertical	300 Hz	6.25‡	134.6
	11 MHz	Vertical	300 Hz	6.25	81
Hallgren and MacDonald (1962)	30 MHz	Vertical	50 kHz	1‡	50
	75 MHz	Vertical	50 kHz	1‡	47.5
	90 MHz	Vertical	50 kHz	1‡	42
	150 MHz	Vertical	50 kHz	1‡	45
	400 MHz	Vertical	50 kHz	1‡	43
Hallgren and MacDonald (1963)	100 MHz	Vertical	50 kHz	1‡	50
	200 MHz	Vertical	50 kHz	1‡	48
	400 MHz	Vertical	50 kHz	1‡	45
	600 MHz	Vertical	50 kHz	1‡	42
Schafer and Goodall (1939)	150 MHz	Vertical	1.5 MHz	2–20	33.25
Pawsey (1957)	200 MHz	Horizontal	100 kHz	100–175	24.4
Hewitt (1957)	600 MHz	Unknown (Parabola)	1 MHz	4–12	5.8
Brook and Kitagawa (1964)	420 MHz	Circular	1.5 MHz	6–20	17
	850 MHz	Circular	1.5 MHz	6–20	0.2
Japan URSI (1963)	100 kHz	Vertical	10 kHz	18.7	105.4
	200 MHz	Vertical	10 kHz	18.7	25.4

* Calculated from data of E. F. Florman, NBS Rept. 3558, November 10, 1955.
† Normalized by author; actual bandwidth of receiver not given.
‡ Normalized by author; actual distance not given.

4.27. Spectrum of total lightning flash normalized to a bandwidth of 1kHz and a distance of 1 statute mile. Adapted from Oh (1969).

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