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RF Radiation From Lightning

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National Aeronautics and
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Goddard Space Flight Center
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TM 78095

RF RADIATION FROM LIGHTNING

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GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

RF RADIATION FROM LIGHTNING

ABSTRACT

Radiation from lightning in the RF band from 3-300 MHz has been monitored at the Kennedy Space Center (Florida) during the Thunderstorm Research International Project. Radiation in this frequency range is of interest as a potential vehicle for monitoring severe storms and for studying the lightning itself. Simultaneous measurements have been made of RF radiation and fast and slow field changes. Continuous analogue recordings with a system having 300 kHz of bandwidth have been made together with digital records of selected events (principally return strokes) at greater temporal resolution. The data reveal patterns in the RF radiation for the entire flash which are characteristic of flash type and independent of the frequency of observation. Individual events within the flash also have characteristic RF patterns: Strong radiation occurs during the first return strokes, but delayed about 20 μ sec with respect to the beginning of the return stroke; whereas, RF radiation from subsequent return strokes tends to be associated with cloud processes preceding the flash with comparatively little radiation occurring during the return stroke itself.

PREFACE

Lightning is one of the foremost of weather related hazards: it is responsible for the death of as many people in a typical year as all tornadoes combined, it is a major cause of forest fires, and lightning continually disrupts communications and power distribution systems (White and Haas, 1975). Lightning has also been a subject of relatively long standing concern to NASA, both as a subject of scientific interest relevant to understanding the environment and because of the hazard lightning presents directly to NASA operations.

For example, Lightning hazards are a concern to NASA both during and in preparation for launches. Lightning strikes to launch facilities are not uncommon and even the launch vehicles themselves have been struck. A nearly disastrous example occurred on November 14, 1969, when the manned Apollo 12 was struck by lightning shortly after lift-off. Lightning strikes to launch facilities have resulted in damage during other Apollo and Skylab missions (Apollo 15; Skylab 2, 3 and 4). A testimonial to the extent of this problem is the research the Kennedy Space Center has supported to develop guidelines for electrical safety during launch, including programs in atmospheric electricity to study triggered lightning, to measure parameters of return strokes, and to monitor charge distribution in clouds. The Kennedy Space Center also encouraged the Thunderstorm Research Project to locate at KSC.

Lightning is also a problem of concern to the NASA communications network. Lightning is a source of broadband radiation at RF frequencies and therefor

represents a source of interference in data links. Nearby lightning strikes can also induce error and damage producing transients in cables and instrumentation. The tracking station at Rosman, N.C. has had an unusually severe problem with lightning strikes.

Lightning is also a problem of concern in aircraft. Physical damage is obviously of concern, and commercial aircraft have in fact been downed by lightning (e.g. in 1963 near Elkton, Md.); However, a contemporary problem of increasing importance are transients induced by lightning inside the airplane. Low power digital electronics, increasingly used for guidance and control, are susceptible to transients induced by lightning strikes (e.g. Nanevicz, Bly and Adamo, 1977).

In addition to these several areas of specific concern to NASA operations, lightning is of concern to NASA because of the hazard it presents to human life and environment. For example, in the United States alone, lightning kills between 100 and 200 people each year, as many as tornadoes; is a major cause of forest fires, especially in the remote northwest; and continually disrupts communications and power distribution networks. For example, during a summer period in 1968 when statistics were kept, lightning was responsible for a disruption in power or telephone service on the average of every other day (White and Haas, 1975).

Considering the long history of scientific interest in lightning, surprisingly little is known about the physical processes of the flash or its connection to conventional (non-electrical) meteorology. The parameters of the current pulse as

it propagates up the lightning channel, and even the charging mechanism responsible for lightning are important unresolved questions. Lightning parameters correlate with meteorology of the storm but in ways only partially understood and incompletely studied (Brook and Kitigawa, 1960). The unusual lightning associated with winter thunderstorms in Japan (Pierce, 1976; Takeuti et al., 1973) and the "superbolts" observed from satellite (Turman, 1977) are interesting examples. Unusual lightning is also frequently reported in storms that produce tornadoes (Le Vine, 1976), which has led to several proposals for using the RF radiation from lightning to help monitor tornadoes. (No physical basis for such reports has yet been established; however, because of the incomplete understanding of lightning processes, neither can it positively be established that such claims are unfounded.) Conceivably, when the physics of lightning and its role in weather phenomena are better understood lightning can be controlled (Anon, 1973) and even used to advantage to monitor severe thunderstorms.

The problem of studying lightning is compounded by its transient and remote nature (e.g. return strokes, the source of most physical damage, last only a few hundred microseconds, and most lightning occurs within the cloud hidden from view). However, lightning radiates strongly over a wide range of frequencies from a few hundred hertz to several GHz (Horner, 1964; Kimpara, 1965; Oh, 1969) and modern day electronics are capable of recording this radiation on the time scale of the individual events of which a typical flash is comprised. Progress has been made with wideband, relatively low frequency devices and it is

reasonable to assume that applying modern RF technology, perhaps even space application of the technology, may further improve our understanding of the physical processes of lightning.

Partly in recognition of this potential, a program of research has been instituted at the Goddard Space Flight Center to determine if RF techniques can be brought to bear profitably on the problems of lightning. Specifically, a program has been developed to: 1) assess the potential of RF techniques for monitoring lightning parameters, possibly from space; 2) develop the potential of RF techniques for remotely sensing electrical processes in the cloud, ultimately, by coupling with radar monitoring of the cloud, to investigate the relationship of electrical processes and cloud meteorology; and 3) determine the potential of RF techniques for impacting lightning hazards, for example by identifying potential forest fire hazards in remote areas of the northwest.

The program is relatively small and young with present emphasis focused on item (1) in the preceding list of objectives. The first major ground-based experiment took place during the summer of 1976 at KSC as part of the Thunderstorm Research (International) Project: TRIP-76. A similar experiment was performed during July, 1977, and a small effort is planned in conjunction with TRIP-78. This report is a summary of results from the TRIP-76 experiment, and together with NASA-TM-X-953-77-154 (Le Vine and Meneghini, 1977) also is the text of a paper given at the National Radio Science Meeting (USNC/URSI) at the University of Colorado at Boulder in January, 1978.

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RF RADIATION FROM LIGHTNING

INTRODUCTION

Traditionally lightning flashes are divided into two major categories: Cloud-to-cloud (or intra-cloud) flashes which discharge between charge centers located within the thundercloud, and cloud-to-ground flashes which make electrical contact with the ground. Estimates are that two out of three flashes are of cloud-to-cloud type (Brook and Kitagawa, 1960). On the other hand, cloud-to-ground flashes are the most readily observed since a significant portion of the flash is unobscured by the cloud and as a result are best understood. Photographic observation of the below cloud portion of the flash reveal that rather than a single event a cloud-to-ground flash is actually a sequence of many events. These are illustrated in Figure 1.

Typically, a cloud-to-ground flash begins with a channel forming stage called the stepped leader. The stepped leader establishes an ionized path to ground in a series of discrete steps which advance the channel 50 meters or so, followed by a pause of about 50-100 microseconds before advancing again. The channel advances in an irregular path frequently with branches (false starts which don't reach the ground). When the last step makes contact with the ground a large current pulse, with peak currents on the order of 20kA, propagates up the channel. This event is called a "return stroke." Heating and ionization during the return stroke produces the thunder and bright flash associated with lightning. Typically there are several return strokes in a single lightning flash

to ground. Subsequent return strokes are also preceded by a leader stage, although it is generally not stepped (i. e. a dart leader). Other, less well understood, electrical processes continue in the cloud after the last return stroke is completed. In fact the return stroke phase of the cloud-to-ground flash is often less than half of the total duration. Intra-cloud processes also occur between return strokes.

In this report examples of the electromagnetic fields radiated from lightning will be presented on two time scales. First data will be presented so that patterns associated with the entire flash can be perceived, but by necessity revealing no detail of the structure of individual events. These data reveal a distinct (temporal) pattern in the RF radiation which is essentially independent of frequency, but does depend on the type of lightning flash: Cloud-to-ground flashes are characterized by an abrupt beginning attributable to the stepped leader, whereas cloud-to-cloud flashes begin with a much slower train of noise pulses which is more typical of the end of both types of flash. Secondly, examples will be presented of the radiation associated with individual events, principally return strokes. The data indicate strong RF radiation of characteristic pattern associated with return strokes. In the case of first return strokes, the RF radiation is observed to occur with a delay of about $20 \mu\text{sec}$ with respect to the beginning of the return stroke, independent of frequency in the range of the measurements. In contrast, RF radiation during subsequent return strokes starts an average of about $250 \mu\text{sec}$ before onset of the return stroke and appears

to be associated with cloud processes immediately preceding (and sometimes following) the return stroke, with relatively little radiation occurring during the return stroke itself.

The data were obtained during experiments at the Kennedy Space Center during the Thunderstorm Research Project (Pierce, 1976) during the summer, 1976. Figure 2 is a schematic of the experiment which was performed. Radiation at several RF frequencies between 3 and 300 MHz was received and recorded analogue on magnetic tape. In total, six different receivers were employed consisting of HF receivers at 3 and 30 MHz, which were designed by the Georgia Institute of Technology (Le Vine, et al., 1976), and VHF receivers at 139 and 295 MHz which were manufactured by Watkins-Johnson Inc. (Model WJ-997 at 139 MHz and Model WJ-8730 at 295 MHz). Vertical quarter-wave monopole antennas received vertically polarized signals at each frequency except 3 MHz, where a baseloaded monopole was used because of the long wavelength. Horizontally polarized signals were detected using resonant (half-wave) dipoles at 139 and 295 MHz. Each RF channel had a video bandwidth of 300 kHz, although 3 MHz bandwidth could be obtained in the VHF channels by disconnecting filters. (No significant differences were observed in the temporal structure of the signals between the 300 kHz and 3 MHz bandwidths.)

The six RF outputs were recorded in parallel together with the output from a calibrated electric-field measuring system which consisted of "fast" and "slow" field change detectors. The fast field change system monitored the electric field

changes in the band from a few hundred Hz to a few MHz (i. e. it was a wide band amplifier from about 300 Hz to about 2 MHz; Krider, 1977; Krider, et al., 1977). Since this region includes most of the energy in a typical return stroke, the waveforms out of such a system have the dominant shape of the radiated fields. The slow field change system monitors the quasi-static electric fields at the surface and consequently is an indicator of changes in charge distribution within the cloud. In addition to the continuous recordings made on tape, selected events were recorded at larger bandwidth by means of digital sample and hold devices. Two such devices were operated in parallel, simultaneously recording the signal from the fast field change system and one of the RF channels (Le Vine and Krider, 1977; Krider et al., 1977). The stored waveforms were then displayed on an oscilloscope and photographed. The time resolution of this system was determined by the sampling rate (typically $.5 \mu\text{s}$ per sample) of the waveform recorder and the time base used on the oscilloscope.

With minor modifications, this system existed during the summers of 1976 and 1977. Additional parallel sample and hold devices were added for the 1977 experiments together with a provision for continuous photographing of records. These additions permitted a complete history of return strokes during a single flash to be recorded.

All experiments were performed at the Kennedy Space Center from Universal Camera Site #12 which is located on a slight mound near the beach southeast of launch pad 39 and east of the VAB (Figure 3). The experiment as it existed in

July, 1976 is shown in Figure 4 and as it was arranged in July, 1977 in Figure 5. The school bus belongs to the University of Arizona (E. P. Krider) and housed the sample and hold devices and photographic equipment during the 1977 experiments. The electric field systems were built by the University of Arizona. The truck housed the RF electronics and a parallel electric field system (flat plate antennas on top of the truck). The truck belongs to the Georgia Institute of Technology which provided engineering and field support during the experiments (C. S. Wilson and B. J. Wilson of the Engineering Experiment Station). The large object toward the right in Figure 5 housed a camera and telescope for photographing launches. A view of the electronics and tape recorder from inside the truck is shown in Figure 6 as it existed during July, 1977. An essentially similar, but less compact arrangement was used during July, 1976.

DATA: ENTIRE FLASH

When one views the RF data for an entire flash, for example by displaying the signals recorded with the tape recorder on a strip chart, the flash appears as a sequence of impulses each of which correspond to radiation from individual events within the flash. In this format, cloud-to-ground and cloud-to-cloud flashes have characteristic and distinct patterns which appear independent of frequency in the range of measurements made here. Such a dichotomy was reported at lower frequencies as early as 1960 by Kitigawa and Brook (Kitigawa and Brook, 1960) and has been suggested as the basis for a possible technique for distinguishing flash type (Kitigawa and Brook, 1960; Krielshiemer and Lodge-Osborn, 1972). A schematic of typical patterns is shown in Figure 7.

Typically, a cloud-to-ground flash begins with a sudden crashing of closely spaced pulses which on close examination have characteristics of the stepped leader. This sudden beginning is followed by several large pulses which are generally, but not always, associated with return strokes. Smaller pulses fill the gaps between the large pulses making an early active phase of high pulse density. It is not uncommon in the data to see leader like pulses preceding some of the later large pulses. This may correspond to multiple channel flashes, a hypothesis which the 1977 experiment was designed to test. The flash ends in a stage of gradual decrease both in pulse amplitude and density.

In contrast, a cloud-to-cloud flash begins slowly, builds to an intense stage of closely spaced pulses, but generally not as intense as in the early stages of

the cloud-to-ground flash, and then decays much as it began in a stage of gradually decreasing pulse amplitude and density. The decaying stage of cloud-to-cloud and cloud-to-ground flashes are quite similar.

Typical examples of data are shown in Figures 8 - 10. These examples were obtained by displaying the vertically polarized channels of RF data from the tape recorder on a strip chart. The effective bandwidth of the chart recorder is a few kilohertz, and since the pulses recorded on tape are typically significantly faster (300 kHz bandwidth), each pulse represents the impulse response of the chart recorder at the particular speed employed. Sample data are shown at 3, 30, 139 and 295 MHz together with the slow electric field changes. The amplitude of each trace has been adjusted arbitrarily to make the display clear. Consequently, only relative amplitude information along each trace is correctly displayed and amplitude comparisons between traces can not be made. (For example the signal level at 3 MHz is roughly two orders of magnitude larger than at 295 MHz.) The vertical scale on all traces is linear.

The electric field change in Figure 8 is typical of a distant cloud-to-ground flash with 3 return strokes. The major steps on the slow "slow E" trace indicate return strokes. Notice the characteristic sudden beginning of this flash, the following period of intense activity and then the decay. Notice, also, the frequency independence of this pattern: most events appear at all frequencies. Of course, quantitative statements regarding frequency dependence are complicated by relative sensitivity and bandwidth. (For example, if the gain of one channel

were increased significantly relative to that of others, events would appear at this frequency which did not appear at the others. Similarly, a channel with large bandwidth compared to that of the others can distinguish several events where the other channels could only resolve the sum). However, if one assumes a cause and effect between events in the flash and radiation, then given equivalent bandwidth and sensitivity as in the examples presented here, one would expect frequency independence for a relatively broadband process.

Figure 9 is a typical example of a cloud-to-cloud flash. Notice the absence of an intense beginning. Rather, the flash begins slowly and builds to a period of high pulse density with frequent large pulses, and then decays. The decaying stage is similar to that of the cloud-to-ground flash in Figure 8, but the initial stage is much different. Notice that the pattern is independent of frequency. Notice, also, the distinctly different "slow E" waveform of the cloud-to-cloud flash compared to that of the cloud-to-ground flash. The slow E waveform is also typical of cloud-to-cloud flashes.

Figures 8 and 9 are typical of data observed in Florida; however, all data do not fall into these two categories. An example of one such exception is shown in Figure 10. The RF pattern in Figure 10 from about .4 seconds to the end of the flash is that of a cloud-to-ground flash; however, the beginning at about .1 seconds is much more like that of a cloud-to-cloud flash. It is unlikely that such an example is the result of an overlap (i.e. simultaneously received signal from a cloud-to-cloud and cloud-to-ground flash); The slow E waveform has a

characteristic pattern which, rather than being the sum of those in Figures 8 and 9, begins with a motion initially typically of a cloud flash generally followed by a distinct plateau region of little change and then ending the rapid steps typical of a cloud-to-ground flash. (The slow E record in this example saturated the system. The dashed portion of the curve represents a recreation based on other examples and a few data points near the beginning of the first return stroke.) Two additional examples are shown in Figure 11 in the case of initial upward motion of the slow E trace. In these examples RF radiation at only 30 and 139 MHz is shown to save space, the radiation at the other frequencies being substantially the same. The slow E pattern shown in Figures 10 and 11 is typical of the "breakdown" phase preceding those cloud-to-ground flashes which occur from clouds having a small positive charge at their base (Uman, 1969; Clarence and Malan, 1957). The breakdown phase is assumed to be the result of neutralization of this small positive charge prior to development of the channel to ground. The different initial direction (up or down) of the slow field change (Figures 10 and 11) is what one would expect when comparing observations of close and distant lightning (Uman, 1969). Examples of cloud-to-ground flashes preceded by a breakdown phase were not uncommon in the data surveyed to date, although they were a small percentage of total flashes. In any case, the occurrence of such patterns complicates the choice of an algorithm to distinguish between cloud-to-ground and cloud-to-cloud flashes on the basis of their RF signature.

DATA: INDIVIDUAL EVENTS

In the preceding data the temporal pattern of events in the entire flash was displayed, but no information on the nature of individual events was discernable because events were represented by the impulse response of the system. Examples will now be given of the RF signature and wideband waveforms (fast field changes) of individual events within the flash. These data were obtained by means of the high time resolution circuit (the sample and hold devices and oscilloscope display) shown in Figure 2.

Certain recognizable patterns occur in the waveforms observed on the fast field change system (Krider, 1977; Krider and Radda, 1975; Tiller et al., 1976; Weidman and Krider, 1978). A schematic illustration of several of these patterns is presented in Figure 12. Examples of a first and subsequent return stroke and a cloud process are shown for moderately distant (50 km) lightning. A first return stroke typically begins with a sudden rise followed by a ragged irregular decay toward zero. Typically, the duration is on the order of $100\ \mu\text{s}$ and the radiation is predominantly of a single sign. A subsequent return stroke also begins suddenly, but tends to be much smoother and somewhat shorter in duration (Weidman and Krider, 1978). In contrast, a cloud process tends to be bi-polar, irregular and shorter in duration than the return strokes. Typical examples from data collected in Florida, are shown in Figure 13. Notice, in particular, the leader like pulse preceding the first return stroke and the precursor roughly $200\ \mu\text{s}$ before the subsequent return stroke. The precursor

(presumably a cloud process) before subsequent return strokes is characteristic of the subsequent strokes observed at KSC.

Just as the fast electric field changes associated with these several events are typical of the event, so too is the pattern of radiation at RF frequencies. Figure 14 is an example of RF radiation associated with a sequence of cloud processes. The top trace represents the signal detected at 3 MHz (vertical polarization) and the bottom trace is the fast field change associated with the event. These data were recorded simultaneously using the sample and hold circuitry described in Figure 2. The horizontal scale is 100 μ s per major division and the vertical scale is uncalibrated. (Calibration exists, but has not been included here.) The result is what one might expect of a broadband process: For each event on the lower trace, RF radiation at many frequencies appears on the upper trace. This particular example is typical of the data. In general the cloud events appear to be strong RF radiators.

The situation is more surprising in the case of first return strokes (Figures 15 - 17). The top trace in Figure 15 represents RF radiation at 139 MHz (vertical polarization) and the bottom trace the simultaneously recorded fast electric field change. The horizontal scale is 100 μ s per major division. At first glance the data is what one would expect: simultaneous events on both traces. However, closer examination reveals that the RF radiation (top) doesn't reach its nominal level until some short time after the well defined, abrupt beginning of the return stroke (bottom) has occurred. This is quite clear in

Figure 16 which is the same data but now displayed with a horizontal (time) scale of $20 \mu\text{s}$ per major division. Notice that the RF radiation is delayed some $20 \mu\text{s}$ from the beginning of the event. A second example at 3 MHz is shown in Figure 17 ($20 \mu\text{s}$ per major division). The delay appears to be independent of frequency and is quite characteristically $20 \mu\text{s}$. A summary of observations is given in Figure 18 which shows the magnitude of the delay (horizontal scale) plotted against the relative number of times that particular delay was observed (vertical scale). On the left the results are shown for each RF frequency and on the right the composite of all observations is plotted. Notice that the delay is independent of frequency and that the magnitude of the delay clusters about $20 \mu\text{s}$.

Corroborating evidence for the delay exists. For example, Brook and Kitagawa (1964) in measurements on lightning in New Mexico, reported delays of 60-100 μsec between RF radiation and return strokes, and Takagi (1969) reported a bimodal delay with peaks at 10 and 50 μsec . This corroborating evidence, plus careful temporal calibration of the system indicate that the delay is a real physical phenomena. However, the manner in which it is related to the physics of return strokes is as yet undetermined.

The pattern of RF radiation associated with subsequent strokes is also characteristic, and much different than has just been described for first return strokes. Examples of RF radiation at frequencies of 3 and 139 MHz (vertically polarized) and 295 MHz (horizontally polarized) from subsequent return strokes are shown at the top in Figures 19 - 21, respectively. The time scale is $100 \mu\text{s}$ per major

division. Notice that the significant source of RF radiation is not the return stroke, but the precursor. This is to be compared with first return strokes where the RF radiation was associated with the return stroke itself although not coincident with the beginning of the return stroke. At 3 MHz (Figure 19) one sees that both the cloud phase before and after the return stroke is a more significant source of RF radiation than the return stroke itself. The patterns illustrated in Figures 19 - 21 are typical of data measured during TRIP-76. The nature of the precursor is not certain. An obvious first guess is that it corresponds to the dart leader preceding the subsequent stroke; however, the precursor is closer to the return stroke, by an order of magnitude, than is commonly assumed for the dart leader (Figure 1; Uman, 1969).

CONCLUSIONS

The patterns illustrated above are not selected examples, but are typical of observations made during 1976. The patterns are regular and very distinct for the several events monitored. Why the RF radiation, or for that matter the fast field changes, should have the patterns shown is as yet an open issue, and the subject of contemporary research. However, the very characteristic patterns of the RF radiation offer the hope that once the mechanisms relating them to the lightning flash are understood, the radiation patterns can be recognized and used to monitor the responsible physical process of the flash.

ACKNOWLEDGEMENT

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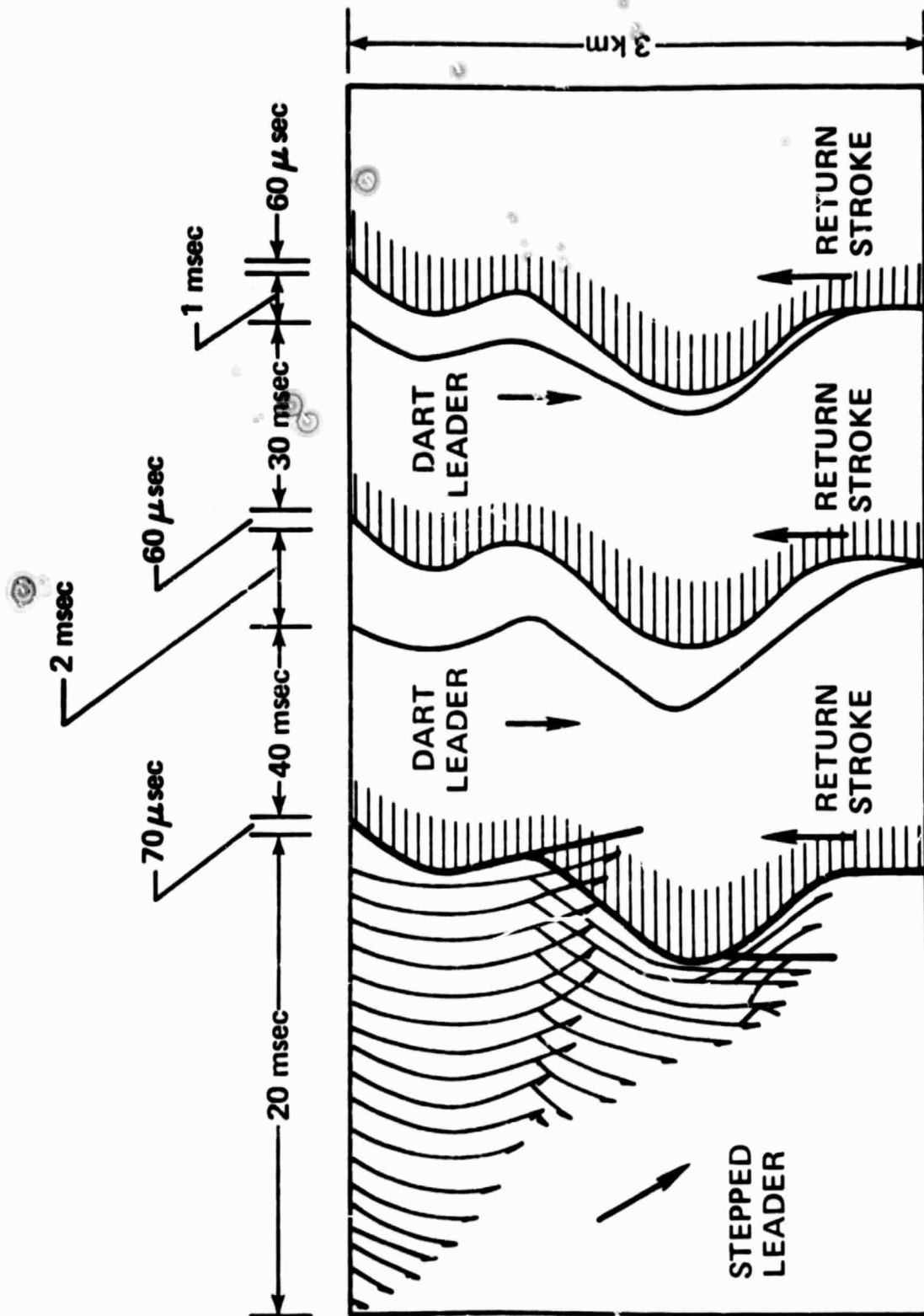


Figure 1. Structure of cloud-to-cloud lightning (after Uman, 1969).

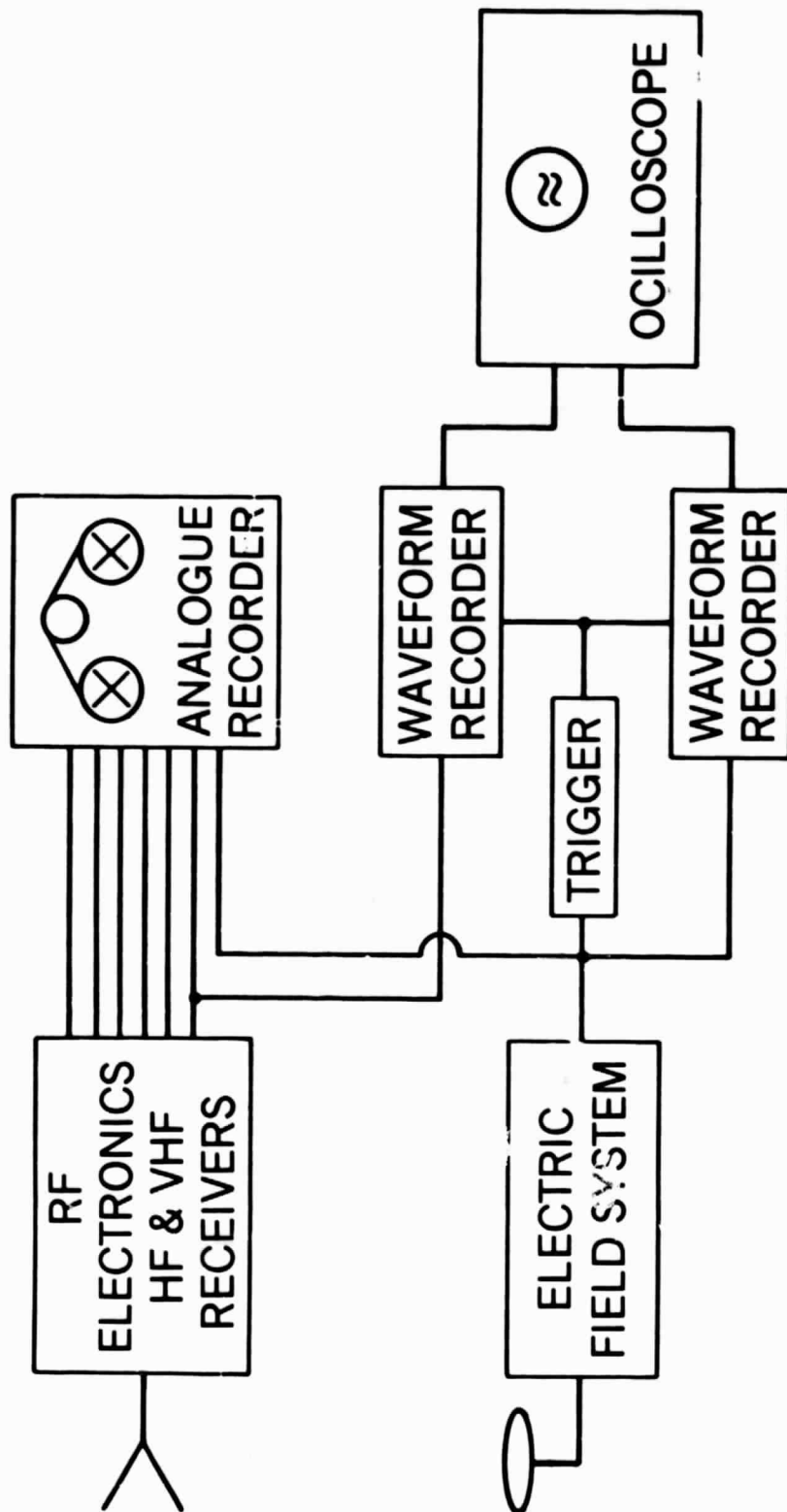


Figure 2. Block diagram of the experiment as performed during the summer, 1976.

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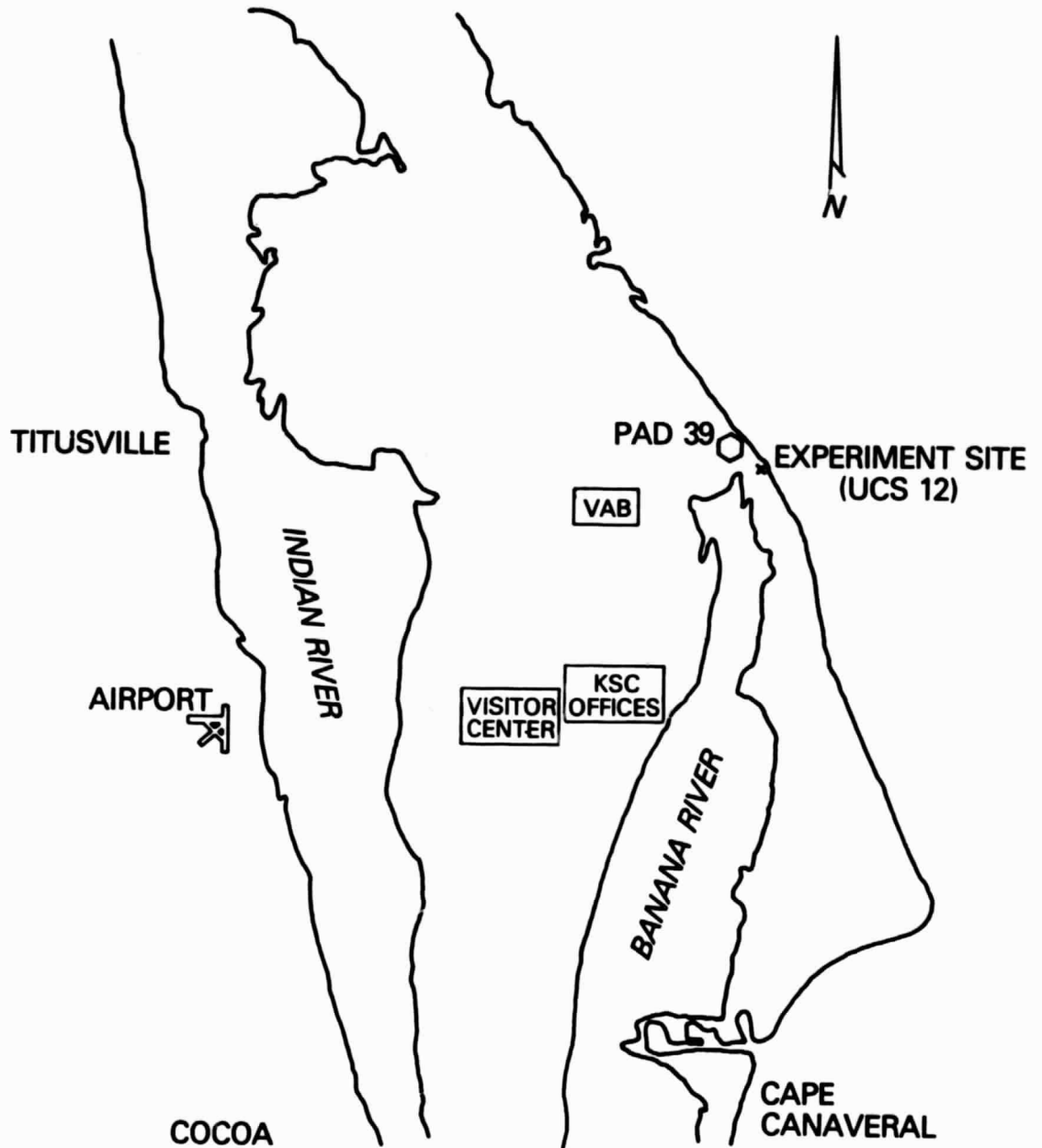


Figure 3. Location of the experiment. The site was Universal Camera Site #12 at the Kennedy Space Center.

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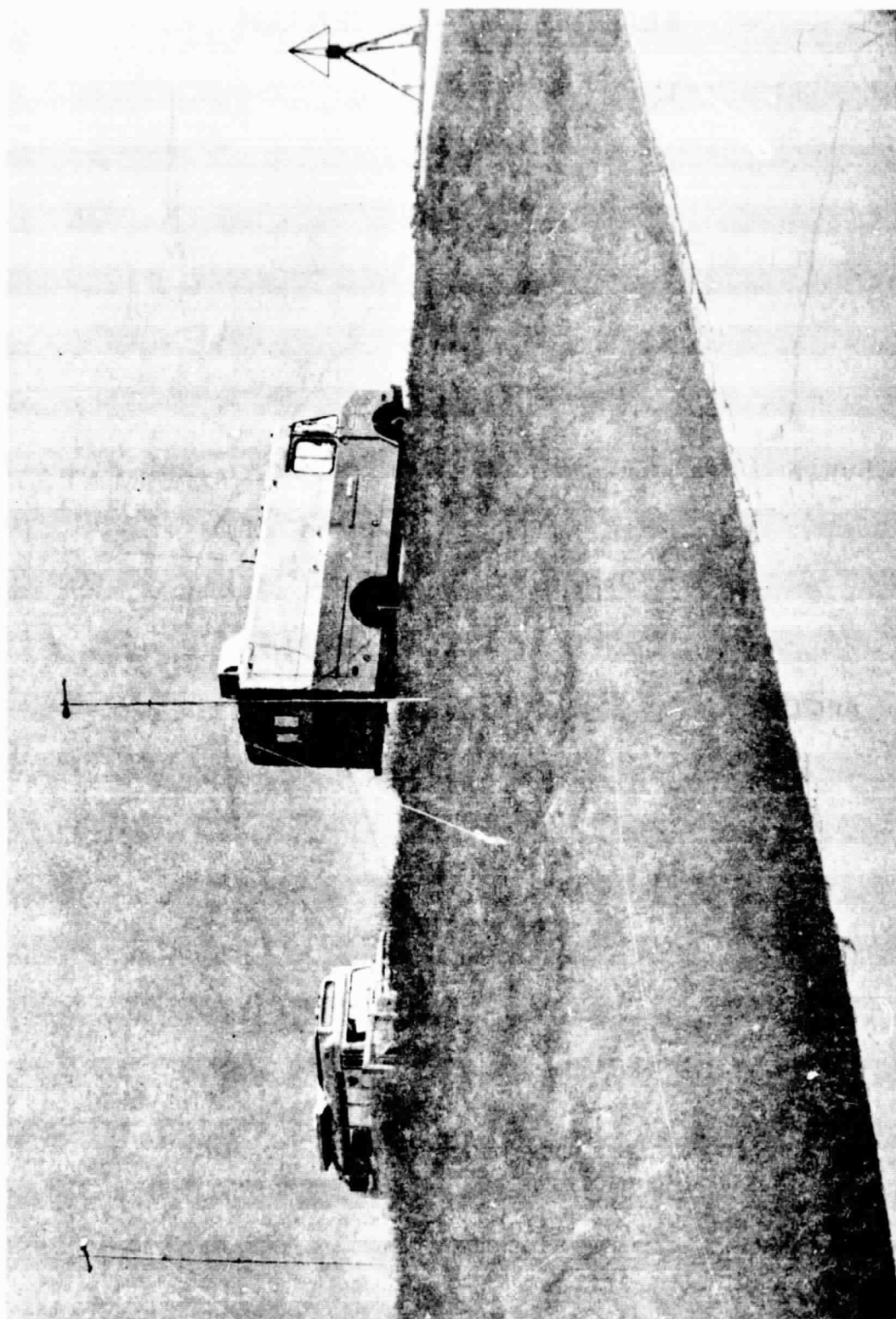


Figure 4. The experiment site, July, 1976.



Figure 5. The experiment site, July, 1977.

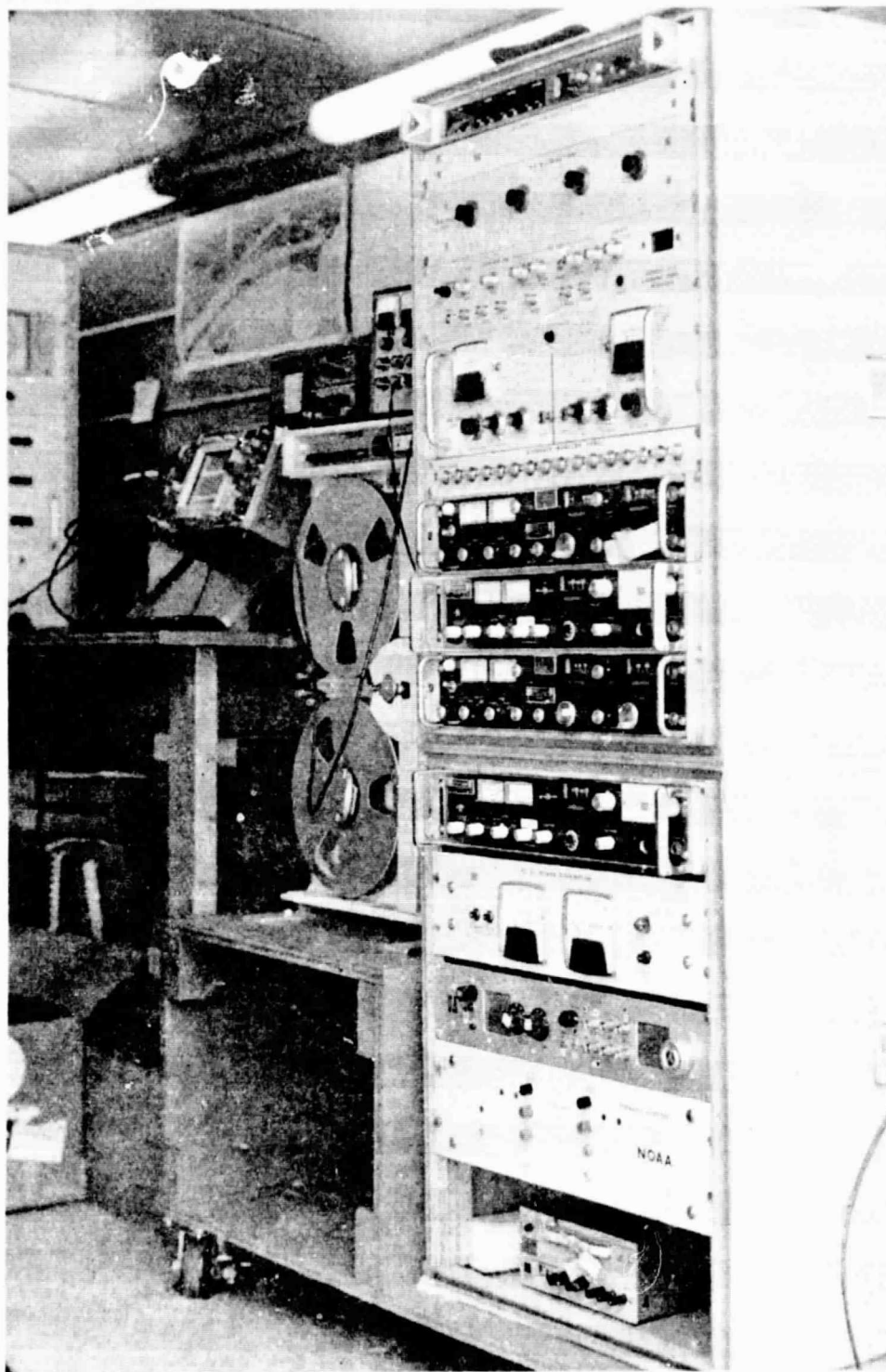
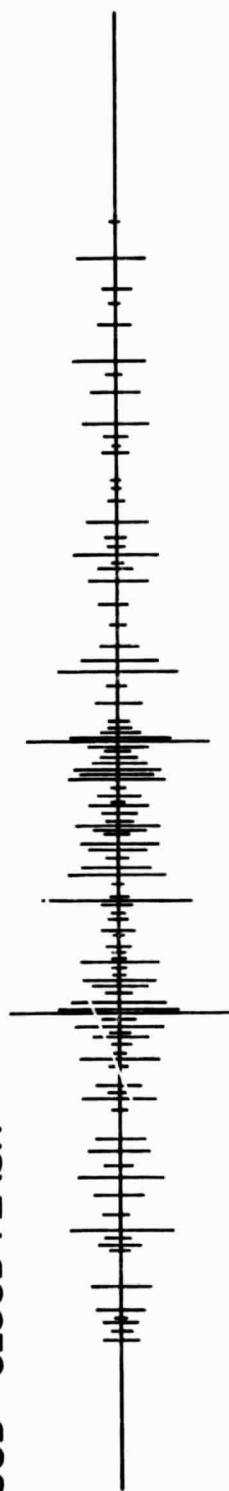


Figure 6. A view of the RF electronics and tape recorder as seen from the rear of the truck (July, 1977).

CLOUD—CLOUD FLASH



CLOUD—GROUND FLASH

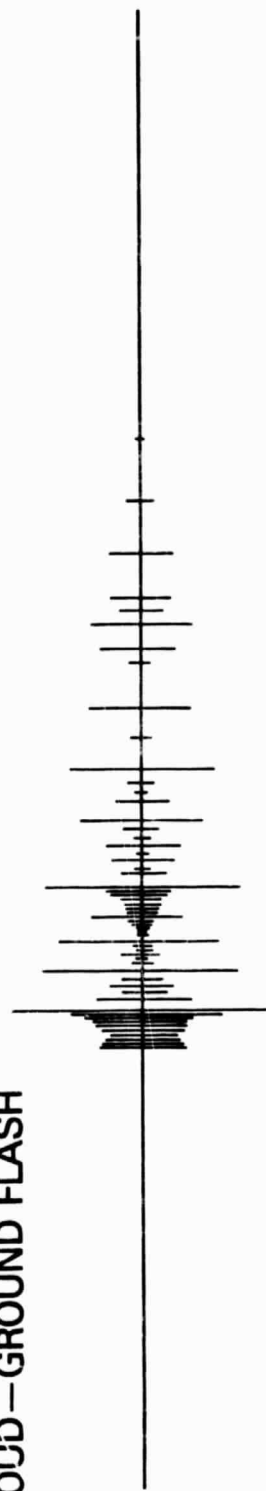


Figure 7. Typical structure of RF radiation from lightning.

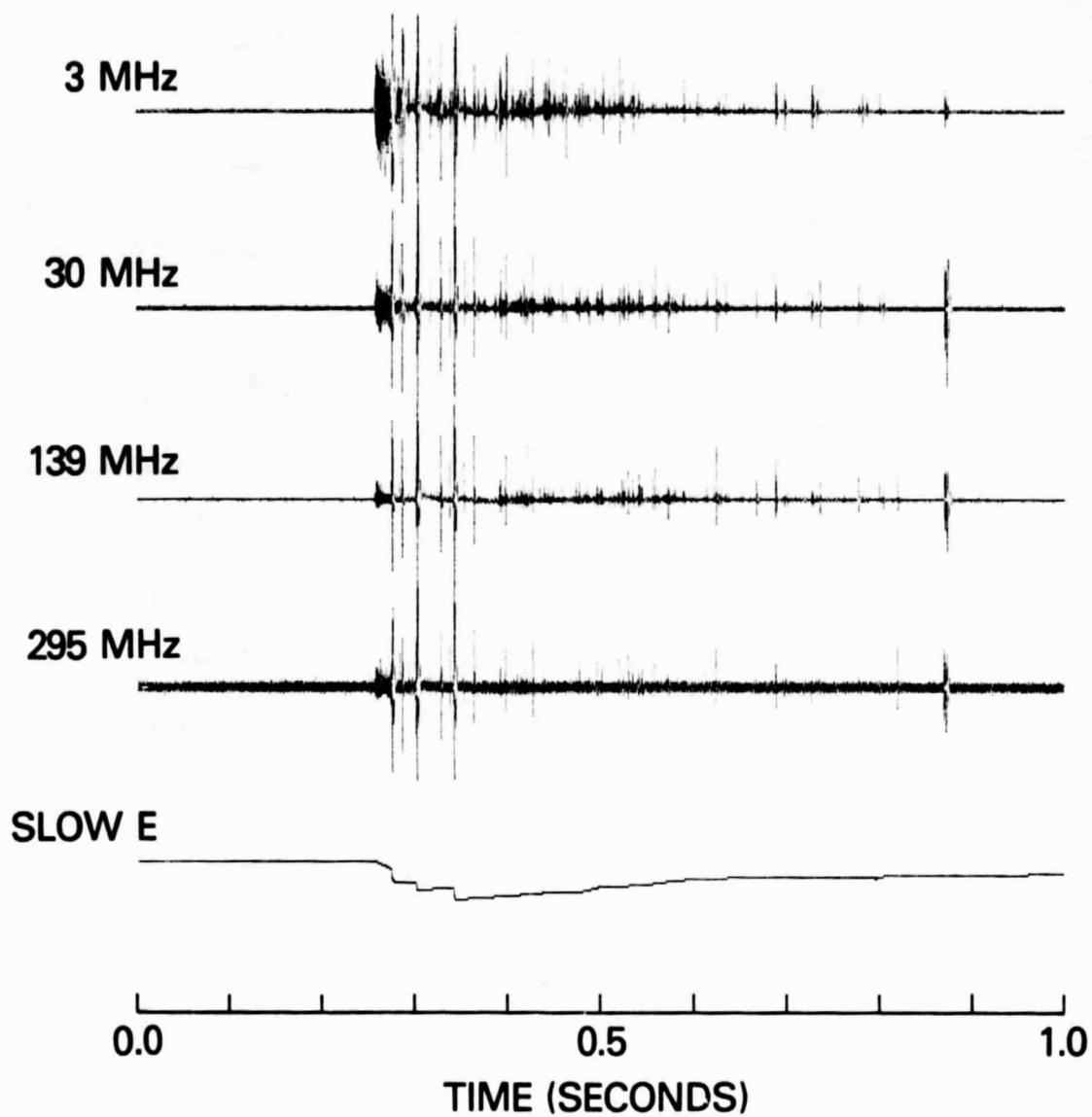


Figure 8. Example of RF radiation from a cloud-to-ground flash.
All RF data is vertically polarized.

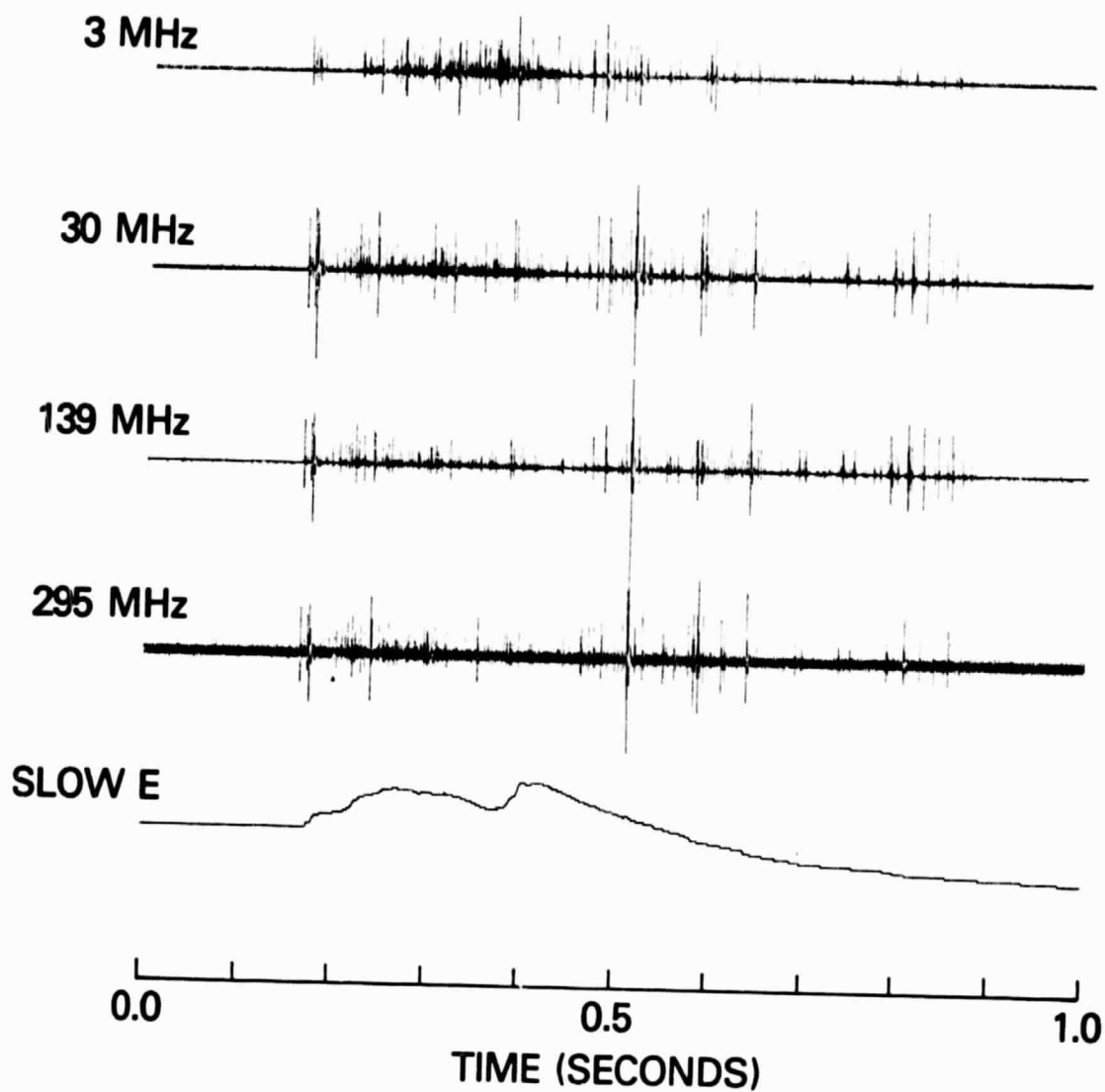


Figure 9. Example of RF radiation from a cloud-to-cloud flash.
All RF data is vertically polarized.

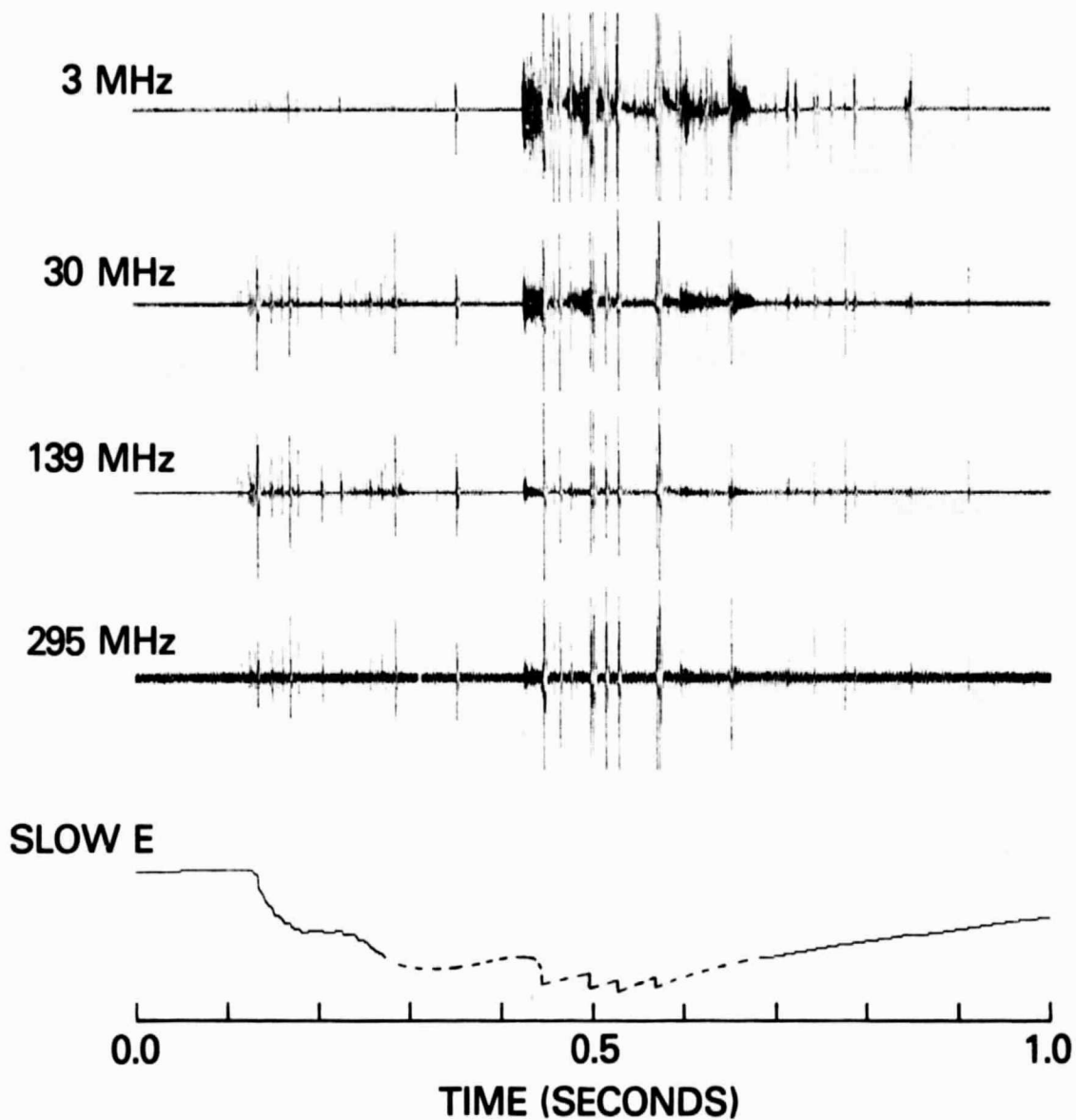
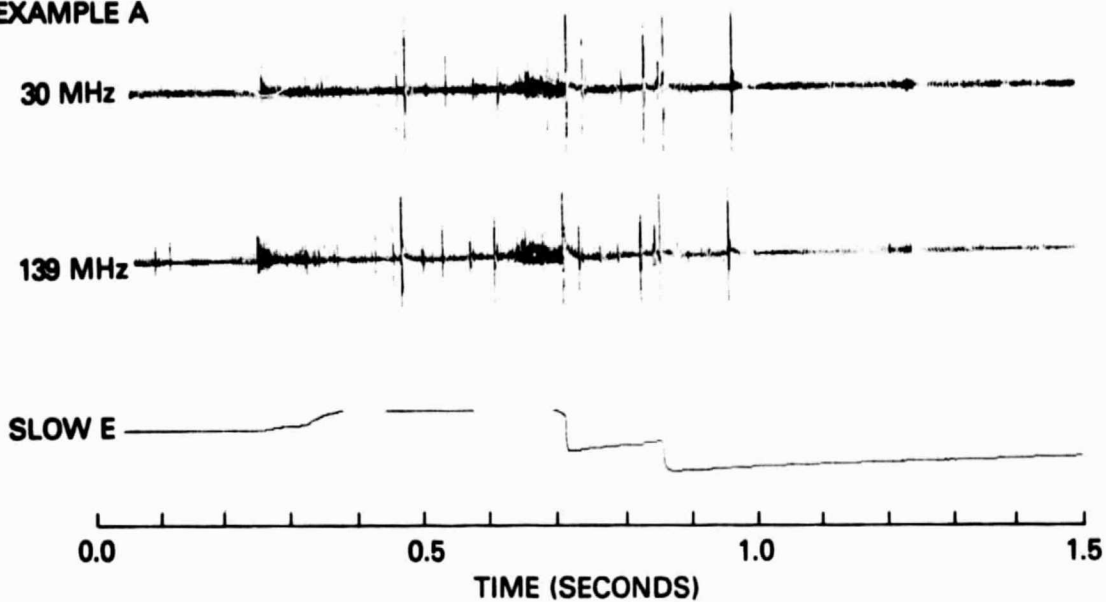


Figure 10. Example of a mixed flash. The early cloud-like radiation may be due to neutralization of positive charge at the cloud base ("breakdown" phase of the flash) preceding development of the cloud-to-ground flash.

EXAMPLE A



EXAMPLE B

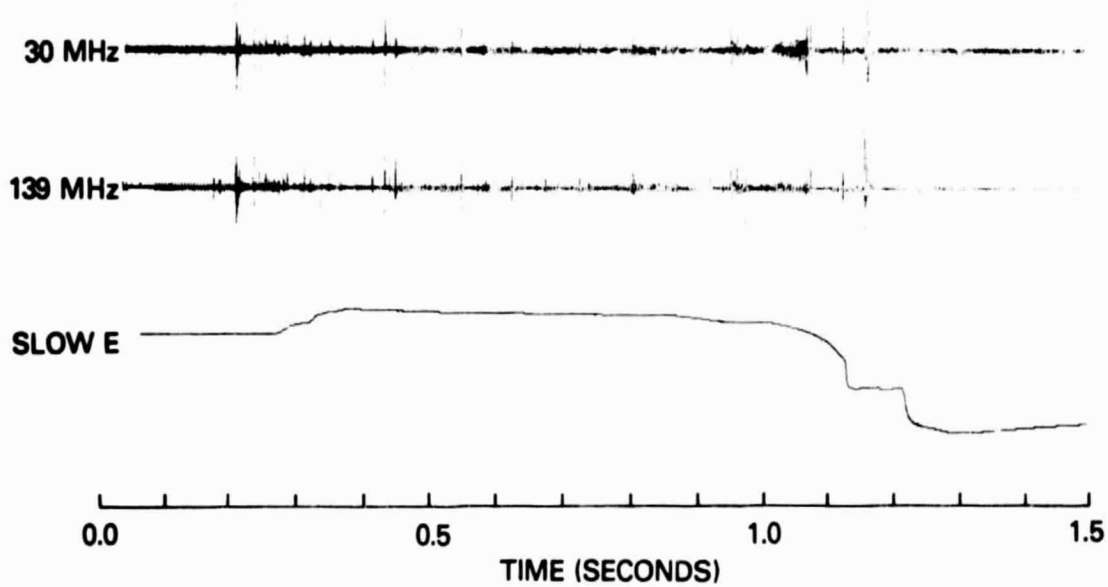
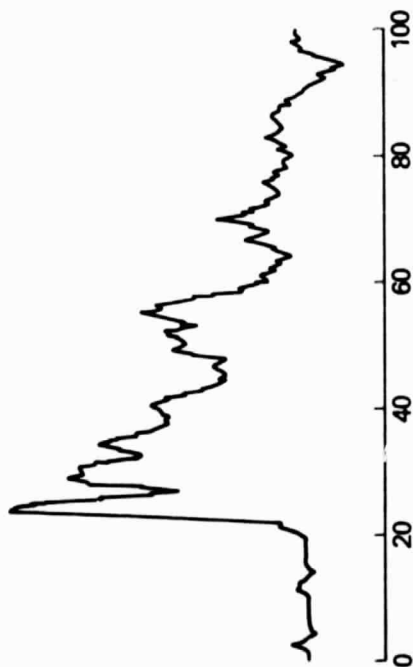
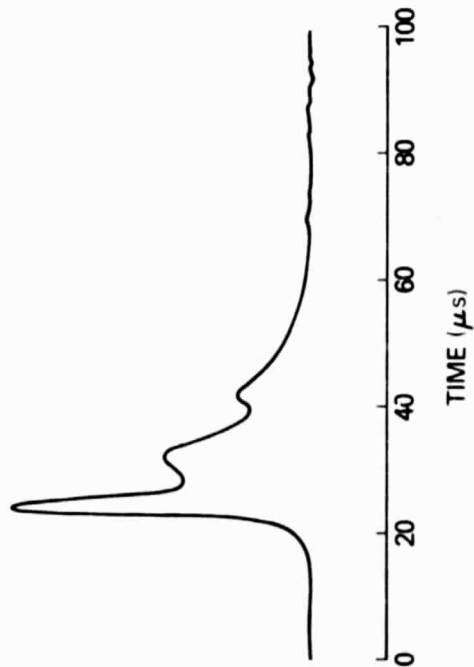


Figure 11. Examples of cloud-to-ground flashes with preceding breakdown phase.

FIRST RETURN STROKE



SUBSEQUENT RETURN STROKE



CLOUD PROCESS

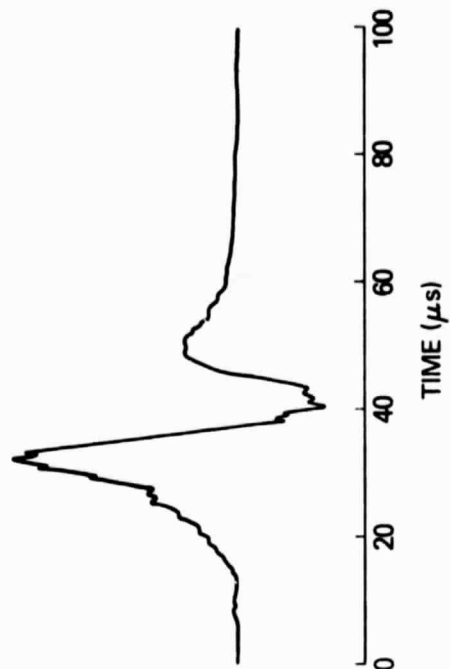
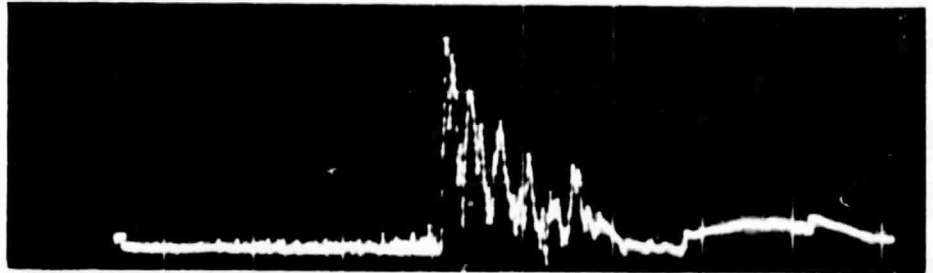
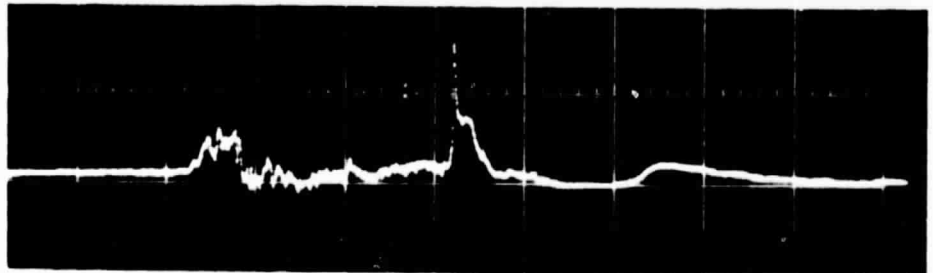


Figure 12. Typical radiation fields as measured with a fast field change system.

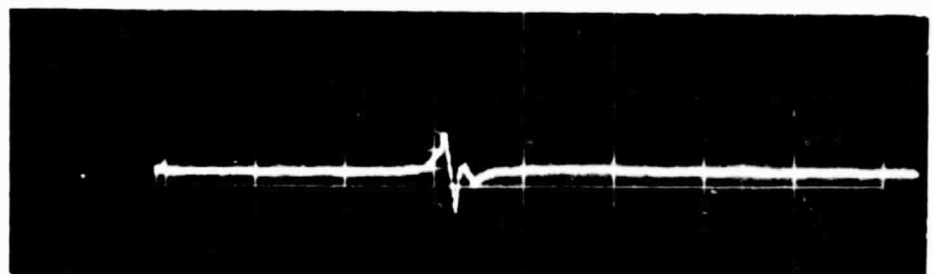
FIRST RETURN STROKE



SUBSEQUENT RETURN STROKE



INTRA CLOUD PROCESS



-400 -200 0 200 400

TIME (μ s)

Figure 13. Example of radiated fields measured at KSC during the summer, 1976, using a fast field change system.

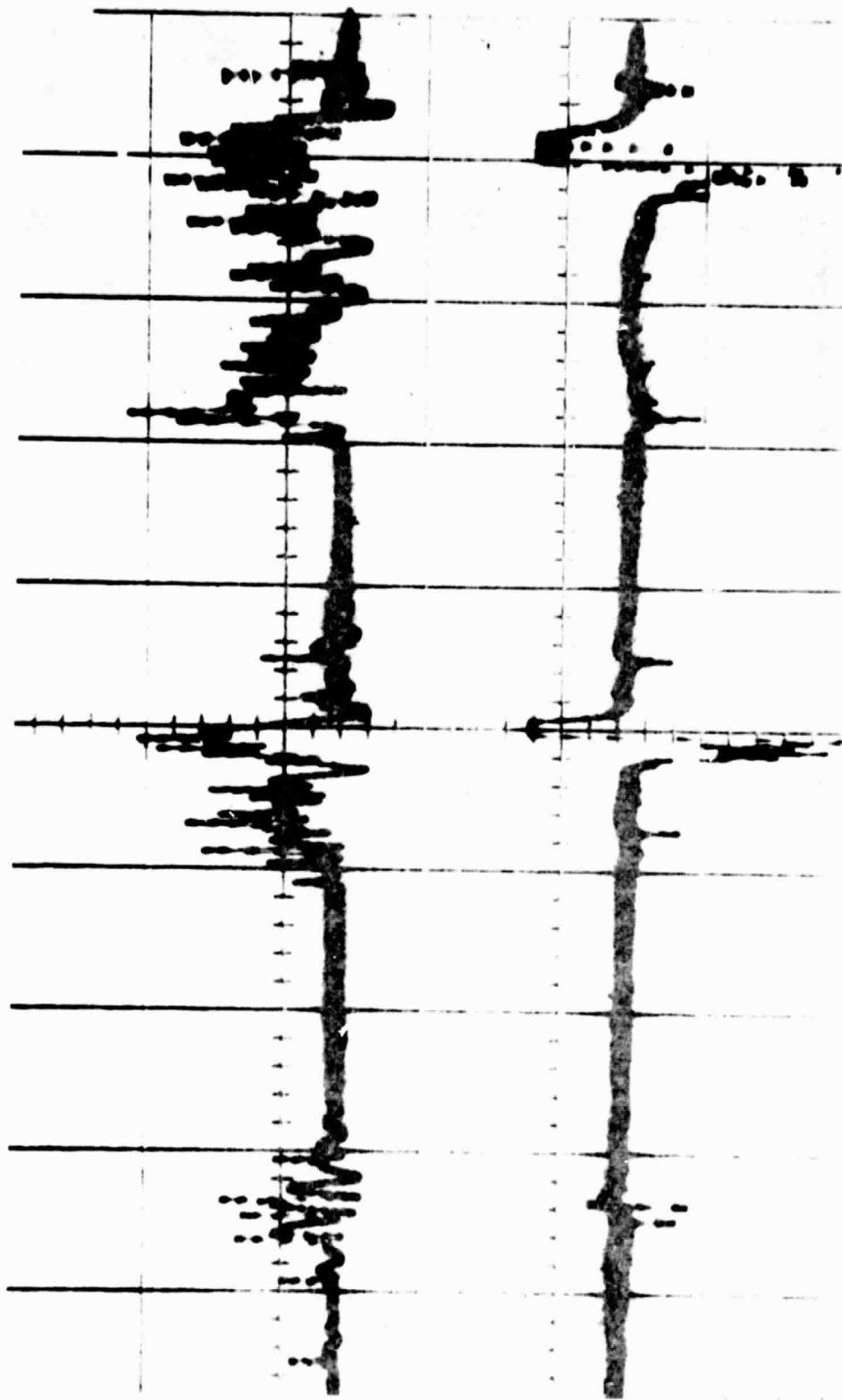


Figure 14. RF radiation at 3 MHz (top) and fast field change (bottom) due to an intra-cloud event.
Time scale is 100 μ s per major division. Vertical polarization.

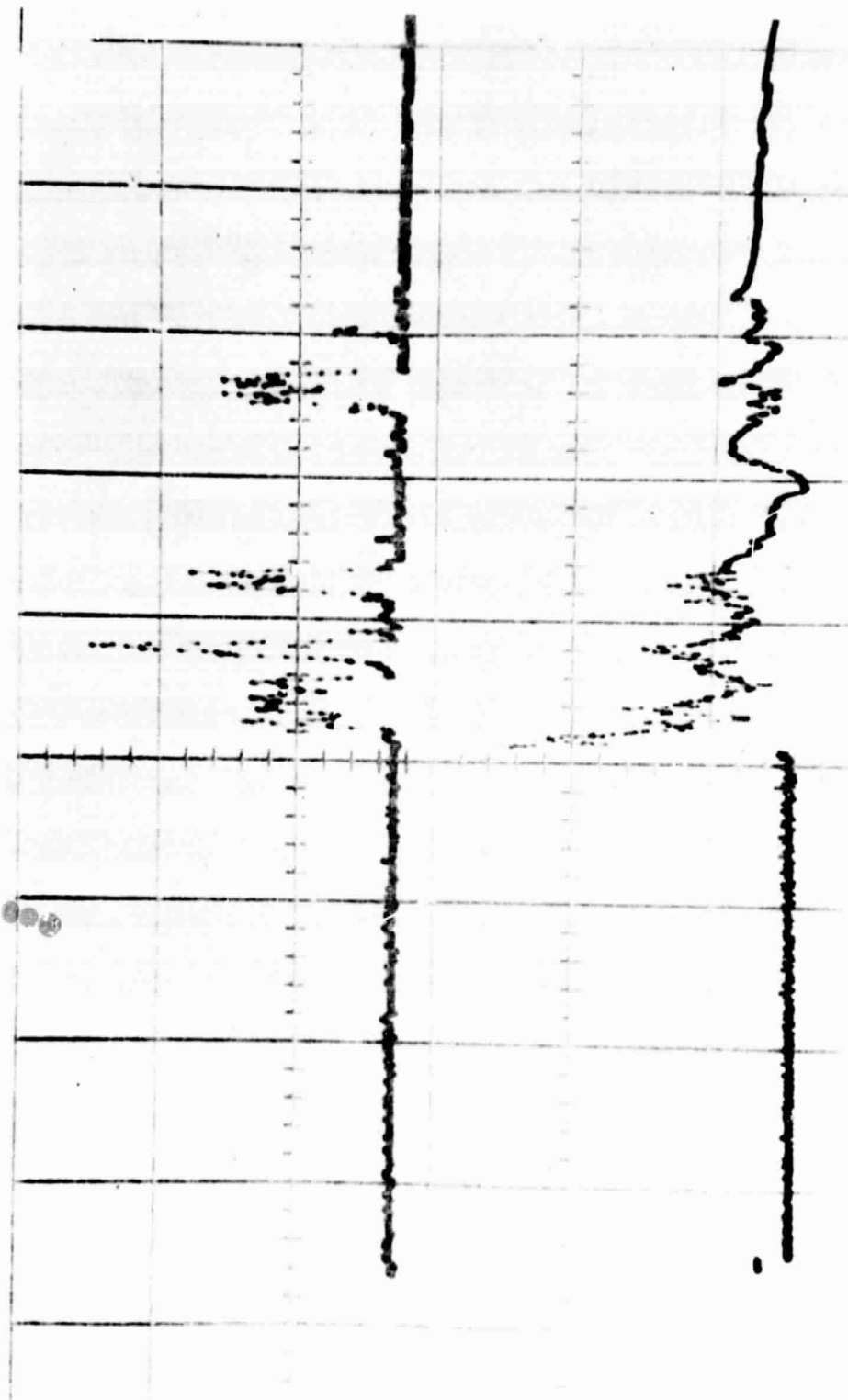


Figure 15. RF radiation at 139 MHz (top) and fast field change (bottom) due to a first return stroke. The time base is 100 μ s per major division. Horizontal polarization.

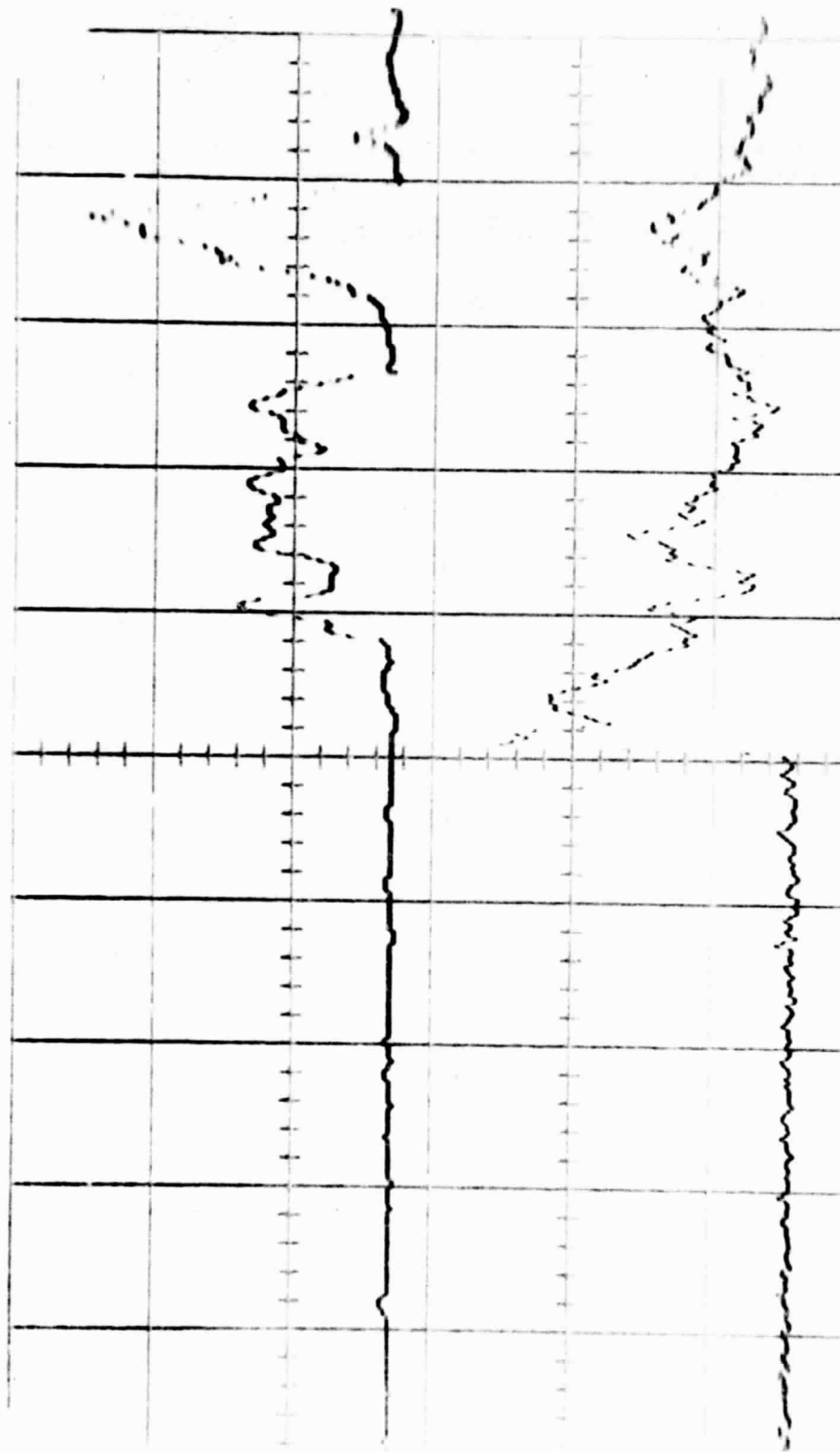


Figure 16. The same data as shown in Figure 15, but with the time base expanded to $20\mu s$ per major division.

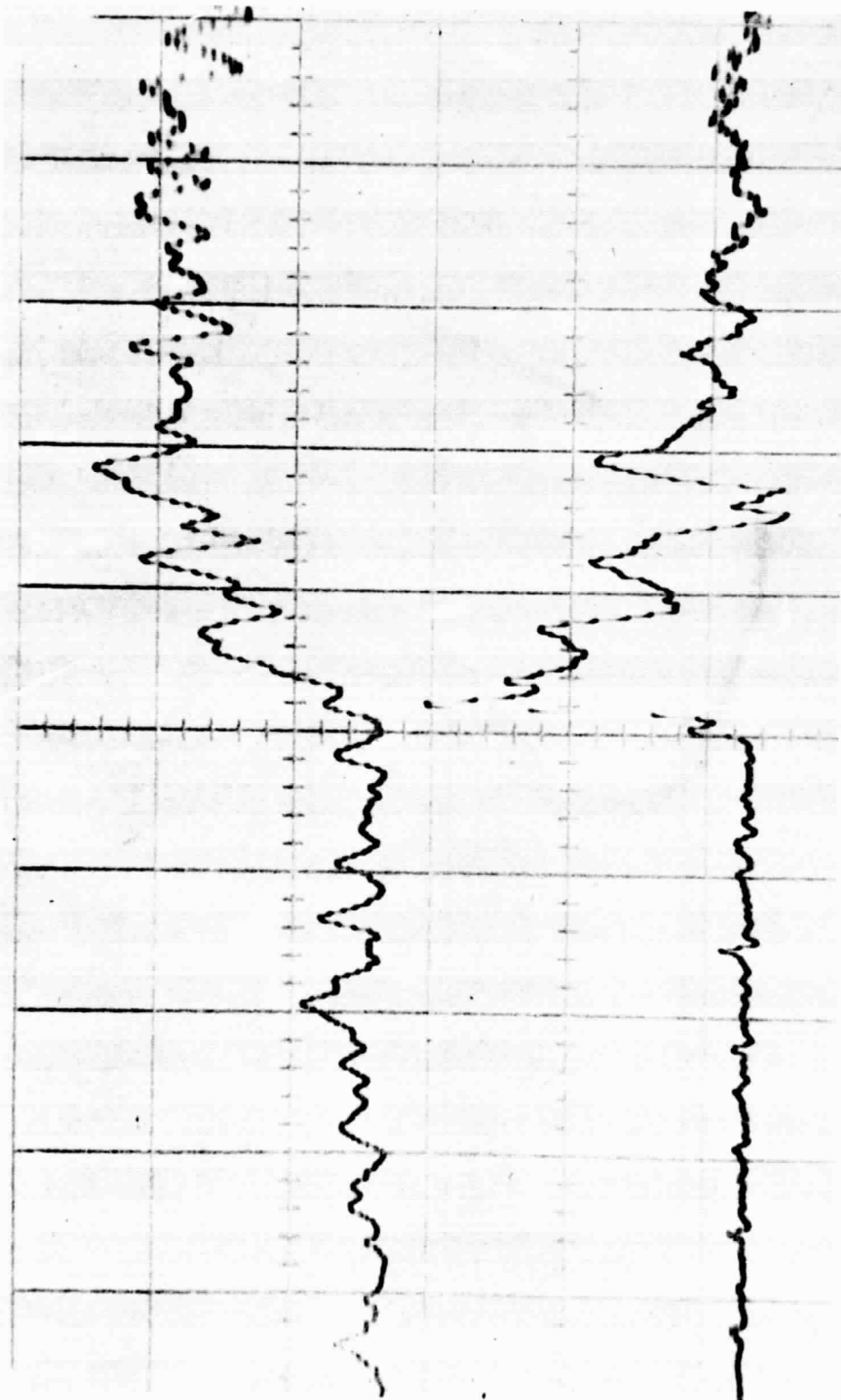


Figure 17. RF radiation at 3 MHz (top) and fast field change (bottom) due to a first return stroke.
The time base is 20 μ s per major division. Vertical polarization.

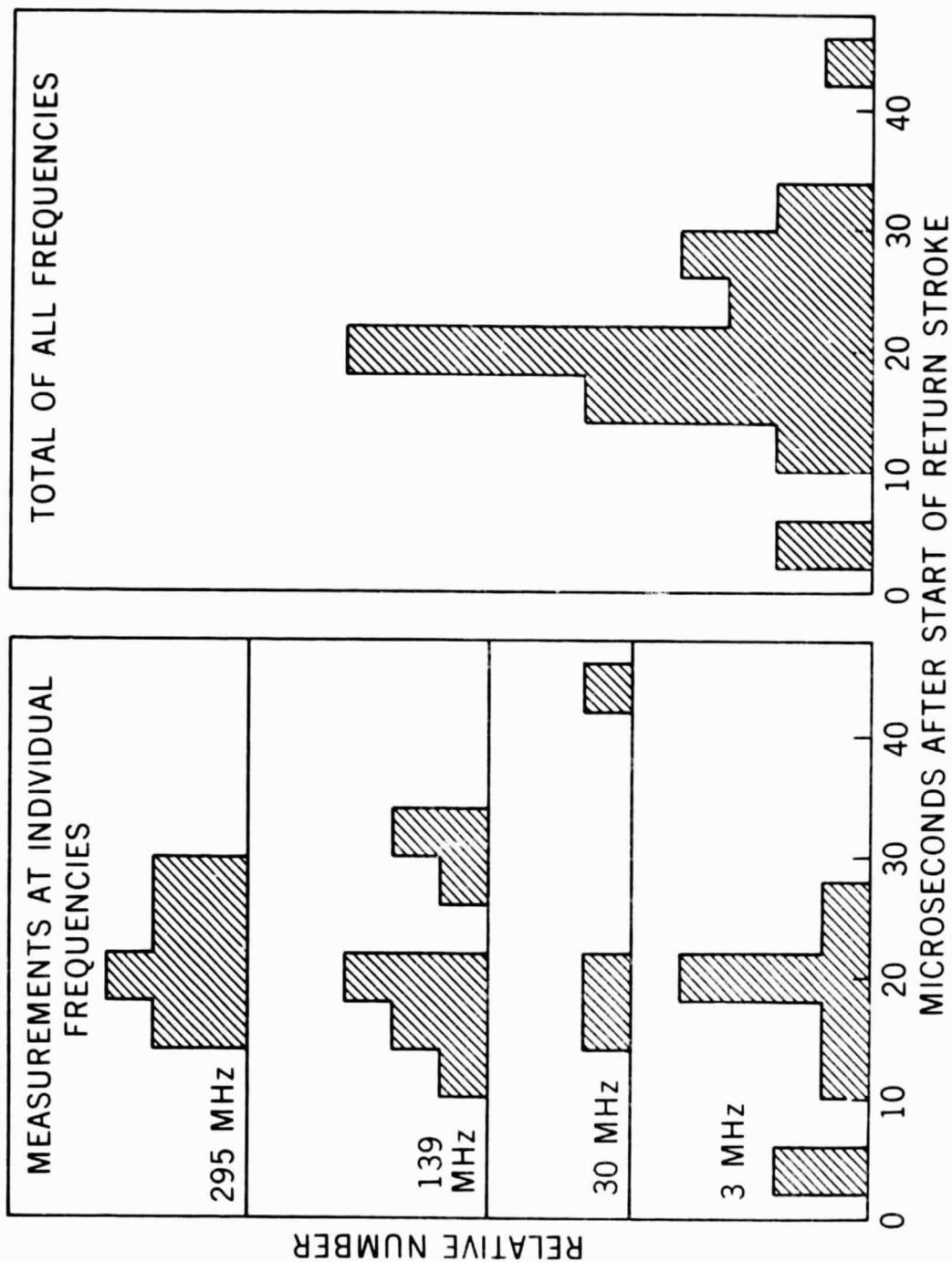


Figure 18. Summary of measured delay. The delay is plotted on the abscissa and the number of times that delay was observed is plotted on the ordinate.

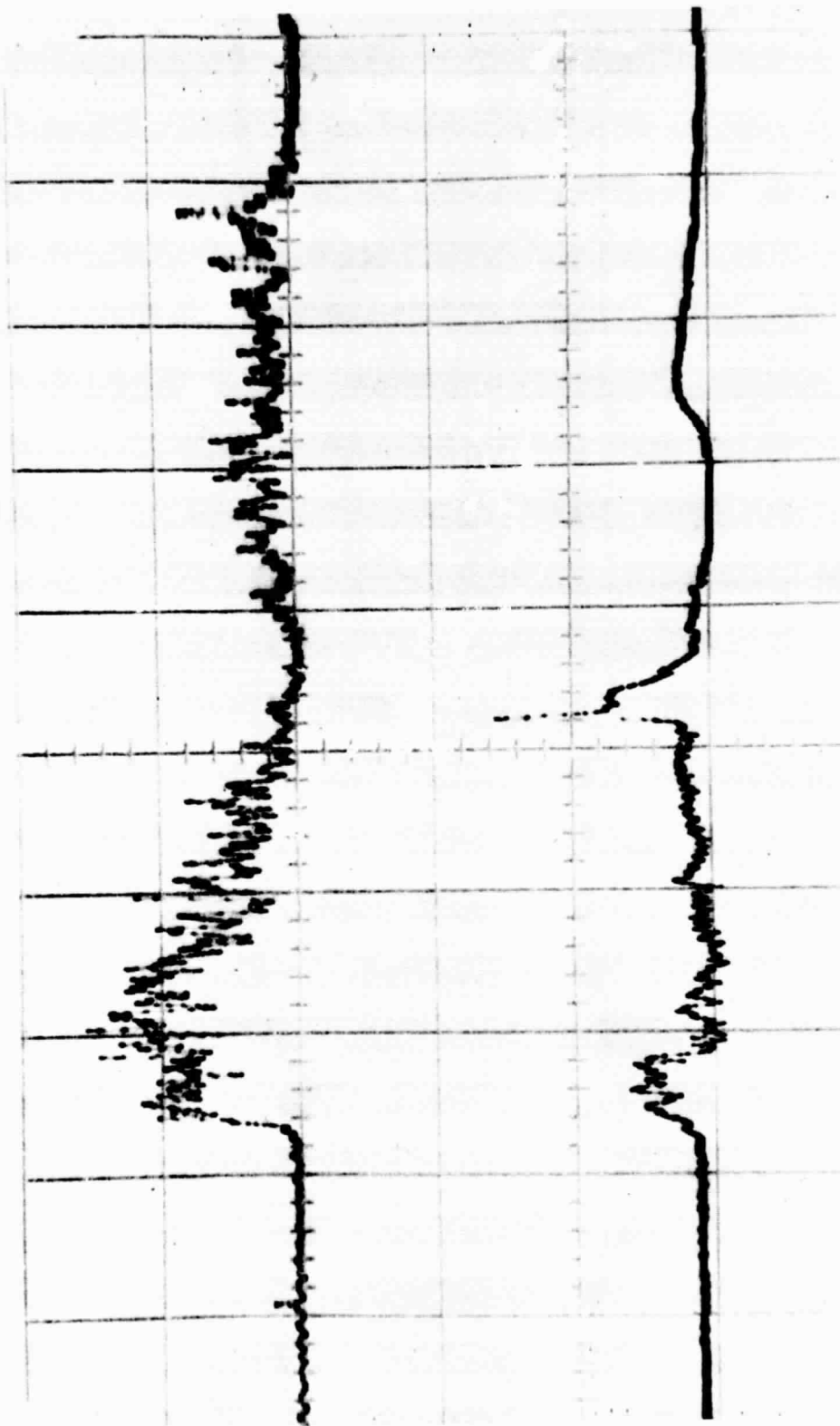


Figure 19. RF radiation at 3 MHz (top) and fast field change (bottom) from a subsequent return stroke. The return stroke is the sharply peaked event at the center of the bottom trace. The time base is 100 μ s per major division. Vertical polarization.

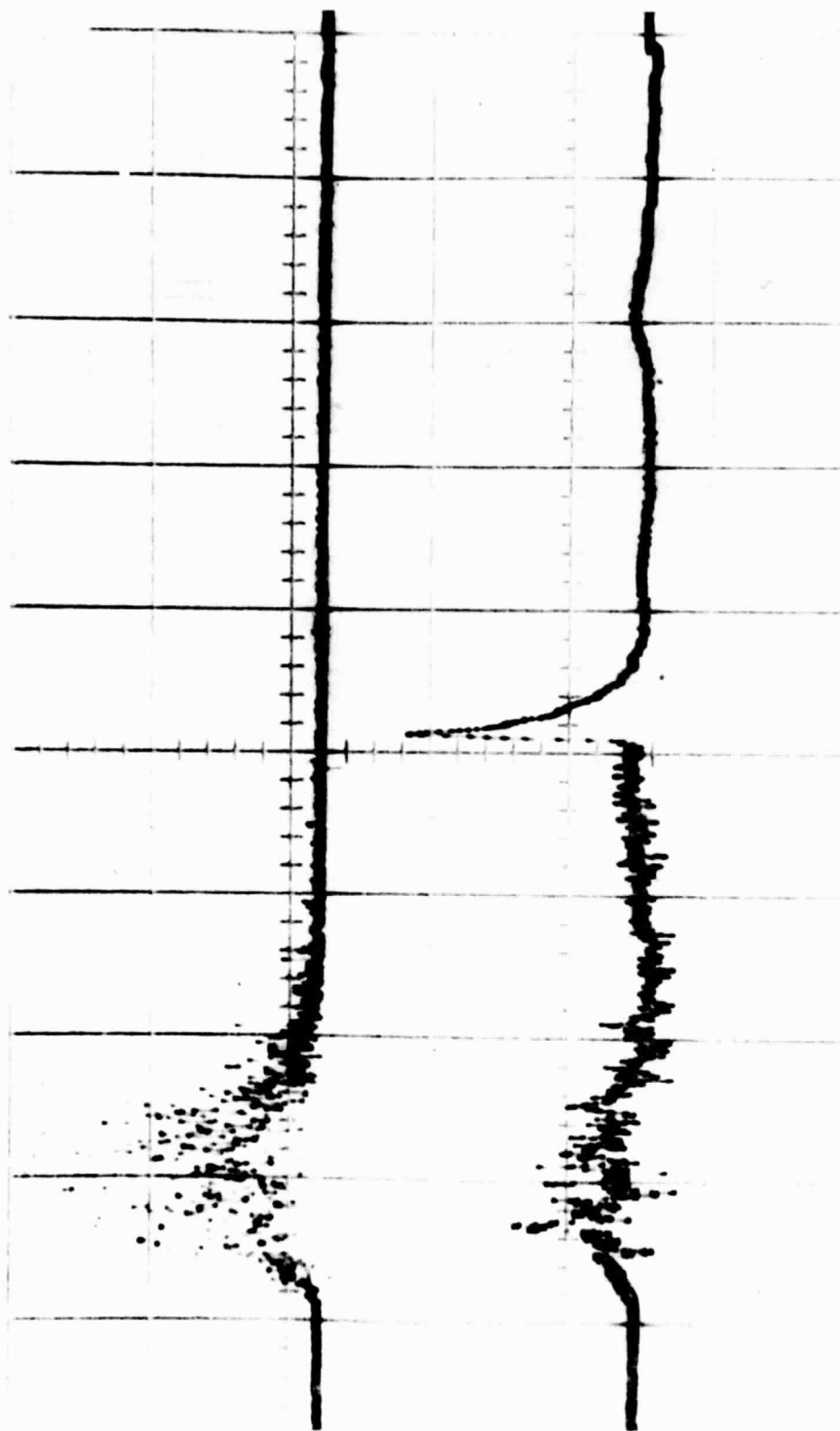


Figure 20. RF radiation at 139 MHz (top) and fast field change (bottom) from a subsequent return stroke.
The time base is 100 μ s per major division. Vertical polarization.

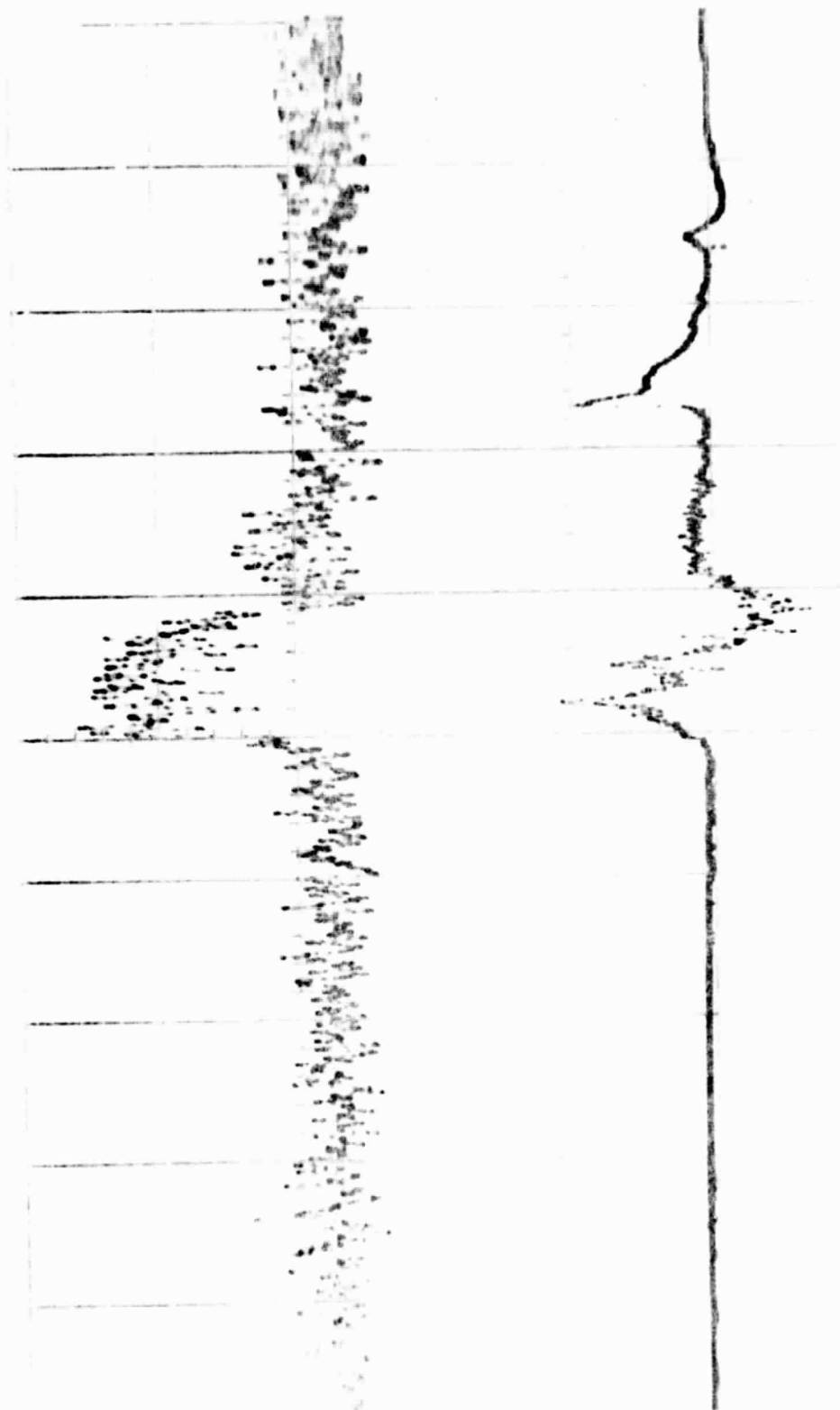


Figure 21. RF radiation at 295 MHz (top) and fast field change (bottom) from a subsequent return stroke.
The time base is 100 μ s per major division. Horizontal polarization.

BIBLIOGRAPHIC DATA SHEET

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16. Abstract Radiation from lightning in the RF band from 3-300 MHz has been monitored at the Kennedy Space Center (Florida) during the Thunderstorm Research International Project. Radiation in this frequency range is of interest as a potential vehicle for monitoring severe storms and for studying the lightning itself. Simultaneous measurements have been made of RF radiation and fast and slow field changes. Continuous analogue recordings with a system having 300 kHz of bandwidth have been made together with digital records of selected events (principally return strokes) at greater temporal resolution. The data reveal patterns in the RF radiation for the entire flash which are characteristic of flash type and independent of the frequency of observation. Individual events within the flash also have characteristic RF patterns: Strong radiation occurs during the first return strokes, but delayed about 20 μsec with respect to the beginning of the return stroke; whereas, RF radiation from subsequent return strokes tends to be associated with cloud processes preceding the flash with comparatively little radiation occurring during the return stroke itself.			
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