Defense Nuclear Agency
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DNA-TR-90-101

# Comparison of the RF Frequency Spectra of HEMP and Lightning

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March 1991

Technical Report

CONTRACT No. DNA 001-87-C-0180



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| 1 AGENCY USE ONLY (Leave blank) | 2 REPORT DATE | 3 REPORT TYPE AND DATES COVERED |
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|---|---|
| 4 TITLE AND SUBTITLE<br>Comparison of the RF Frequency Spectra of HEMP and Lightning | 5 FUNDING NUMBERS<br>C - DNA 001-87-C-0180<br>PE - 62715H<br>PR - RV<br>TA - RC<br>WU - DH041260 |
| 6 AUTHOR(S)<br>Martin A. Uman | |
| 7 PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>University of Florida<br>Department of Electrical Engineering<br>Gainesville, FL 32611 | 8 PERFORMING ORGANIZATION REPORT NUMBER |
| 9 SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)<br>Defense Nuclear Agency<br>6801 Telegraph Road<br>Alexandria, VA 22310-3398<br>RAAE/Prasad | 10 SPONSORING/MONITORING AGENCY REPORT NUMBER<br>DNA-TR-90-101 |

11 SUPPLEMENTARY NOTES

This work was sponsored by the Defense Nuclear Agency under RDT&E RMC Code B3200874662 RV RC 00000 25904D.

| 12a DISTRIBUTION/AVAILABILITY STATEMENT | 12b DISTRIBUTION CODE |
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13 ABSTRACT *(Maximum 200 words)*

Cloud pulses of the type described by LeVine (1988) and Willett et al. (1989) are much more common than these earlier studies indicate. Our spectra of the largest overhead cloud pulses are nearly parallel to but significantly below the HEMP spectrum from 1 MHz to 50 MHz, while those from Willett et al (1989) obtained from lightning tens of kilometer offshore over salt water show a faster relative decay with increasing frequency, are significantly below ours between 10 and 50 MHz, and are about equal to ours between 3 and 10 MHz. The shortest risetime to initial peak value of overhead lighting pulses are of the order of 0.3 μs. A broader bandwidth system than that used would allow measurement of the rapid field variation occurring throughout the cloud pulses associated with frequencies above about 50 MHz but would observe essentially the same risetime to initial peak. That is, the higher frequency content of the cloud pulses is contained in the rapid field variation throughout the overall waveforms and not in the initial rise to peak value.

| 14 SUBJECT TERMS | 15 NUMBER OF PAGES |
|---|---|
| HEMP Environments | 44 |
| | 16 PRICE CODE |

| 17 SECURITY CLASSIFICATION OF REPORT | 18 SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20 LIMITATION OF ABSTRACT |
|---|---|---|---|
| UNCLASSIFIED | UNCLASSIFIED | UNCLASSIFIED | SAR |

NSN 7540-01-280 5500



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# TABLE OF CONTENTS

# FIGURES

## FIGURES (Concluded)

# SECTION 1

## INTRODUCTION

### 1.1 MOTIVATION FOR THE PRESENT PROGRAM.

Frequently, the question arises as to the degree to which a system's exposure to lightning can be used to infer its vulnerability or lack of vulnerability to high-altitude nuclear EMP (HEMP). As will be discussed in Section 1.2, various limitations in the instrumentation and conduct of past lightning experiments have made comparisons with HEMP difficult. In connection with the development of a time-of-arrival lightning location and characterization system, the University of Florida has evolved a modern, broadband instrumentation system capable of identifying and characterizing all of the important processes in a lightning flash. This instrumentation has been employed on the present program to study fast electric field pulses from cloud lightning flashes occurring directly overhead. The study of overhead lightning avoids the attenuation of high frequency field components resulting from propagation over land and, to a lesser extent, over salt water.

Electric field waveforms from over 1000 flashes were recorded. This report describes the instrumentation, the conduct of the experiments, and discusses the significance of the experimental results with regard to HEMP.

### 1.2 TECHNICAL BACKGROUND.

Several recent studies have addressed the issue of the relationship of the lightning radio frequency (rf) spectrum to the rf spectrum of HEMP (Uman et al., 1982; Gardner et al., 1985; Vance and Uman, 1988; Rustan, 1987; Nanevicz et al., 1988). The HEMP spectrum is well defined in the unclassified literature (Lee, 1986). Most of the problems in comparing lightning and HEMP have arisen because of an inadequate understanding of the various lightning processes and of the electrical current and the rf radiation associated with each.

Wideband electric current measurements of lightning made at the ground strike point have generally suffered from deficiencies in measurement technique which have not allowed the higher frequencies to be properly represented (Uman et al., 1982; Vance and Uman, 1988), while recent aircraft lightning current measurements at the time of a lightning strike that have had the necessary frequency response have been involved in only relative small discharges (e.g., Nanevicz et al., 1988; Rustan, 1987).

Lightning rf measurements fall into two general categories: (1) wideband electric and magnetic field measurements in the frequency range below some tens of MHz, from which spectra are obtained by Fourier analysis; and (2) narrowband electromagnetic measurements from about 10 MHz to about 1 GHz. Wideband field measurements, the first category, have generally been directed at specific lightning processes, most often the return stroke in ground discharges (e.g., Serhan et al., 1980; Preta et al., 1985; Weidman et al., 1981; Weidman and Krider, 1986; Willett et al., 1990), but the spectra of pulses from other lightning processes such as the stepped leader, the preliminary breakdown, and certain types of cloud discharges have also been derived from these wideband measurements (Weidman et al., 1981; Willett et al., 1989; Willett et al., 1990). The second category, narrowband field measurements, generally have not been directed at specific processes and are often suspect regarding knowledge of the distance to the lightning, the type of lightning event, propagation effects, calibration techniques, and assumptions regarding the physical characteristics of the lightning VHF noise (Nanevicz et al., 1987, LeVine, 1987, Boulch and Hamelin, 1985) It is very important to be able to identify and discuss specific individual lightning processes because only these individual processes, well localized in space, can have their radiation fields properly scaled with distance for an adequate comparison with HEMP. Narrowband measurements may potentially receive maximum noise levels from several spatially separated sources radiating at the same time. If, for example, these separate sources are 1 km apart, it is not valid to extrapolate the maximum noise level measured at, say, 10 km, to a distance of, say, 50 m since an observer can only be at that range from one of the several sources (Vance and Uman, 1988). Further, narrowband measurements made with too narrow a bandwidth can suffer from "pulse stacking," leading to erroneously high observed signals assumed to be from single pulses (Nanevicz et al , 1987). The published narrowband data have been compiled in reviews by Oh (1969), Oetzel and Pierce (1969), Pierce (1977), Boulch and Hamelin (1985), LeVine (1987), and others, where questionable assumptions are necessarily made in comparing the data from various investigators.

In comparing lightning and HEMP spectra, it is the region above about 10 MHz which is the most important because it is at these higher frequencies that aircraft resonances occur and that coupling through apertures on the surface of the aircraft is most efficient. Unfortunately, as indicated above, it is in this region above 10 MHz that the lightning data are the least reliable.

Recently, a new in-cloud lightning process has been identified which radiates more strongly than any other lightning process at frequencies from 10 MHz to 50 MHz and perhaps at even higher frequencies (Willett et al , 1989, LeVine, 1980) This process, associated with intracloud flashes, produces isolated pulses whose spectrum at 20 MHz exceeds that of first return strokes in ground discharges, previously viewed as the lightning process with the largest frequency output in that range (Willett et al , 1989) Data taken as part of the present contract work will be presented in this report to add to the existing data on this type of lightning cloud pulse

Our primary conclusion relative to the frequency spectra of various lightning processes including the cloud pulses we have studied, based on all available evidence (Uman, 1987), is that no lightning process has a time-domain risetime to initial peak value much faster than about 0.1 s and hence that lightning-process risetimes to initial peak do not contribute significantly to frequency components above about 10 MHz (as does the 5 to 10 nsec risetime of HEMP, Lee, 1986), but that the lightning time-domain waveforms for many in-cloud processes contain bursts of rapid field variation throughout those waveforms, most evident on electric field derivative records, which serve to enhance the spectrum above 10 MHz.

A complete listing of journal papers in the reviewed literature concerning lightning rf spectra and a separate listing of those papers containing a comparison of those spectra with the HEMP spectrum are found in the Appendix.

# SECTION 2

## PREVIOUS LIGHTNING/HEMP COMPARISON

Lightning/HEMP rf spectra comparisons have been made using both theoretical analyses with model currents and fields (e.g., Uman et al., 1982; Gardner et al., 1985; Vance and Uman, 1988) and actual experimental data from lightning strikes to aircraft that were also subjected to an EMP simulator or other EMP calibration (e.g., Rustan, 1987, Nanevicz et al., 1988). In Figure 1 we summarize the results of some of these comparisons for cloud pulses including the results of Willett et al. (1989) on the rf spectrum of the newly discovered type of cloud pulses referred to in the Introduction, and in Figure 2 we present similar data for return strokes in ground flashes. The lightning spectra in Figures 1 and 2 are all normalized to a distance of 50 m using an inverse distance relationship.

# SECTION 3

## NEW DATA ACQUIRED FOR PRESENT CONTRACT

Measurements of wideband electric field and narrowband VHF radiation from overhead cloud pulses were made during the summer and fall of 1989 at the Kennedy Space Center. The wideband electric field recordings consisted of an electronically integrated "slow-decay" E-field sensor with a bandwidth of 6 Hz to 7 MHz, a "fast-decay" E-field sensor with a bandwidth of 16 kHz to 7 Mhz, and a dE/dt sensor with an upper frequency response of 100 MHz. The narrowband VHF receivers were centered at 50 and 225 MHz. Each of these VHF receivers had a bandwidth of 10 MHz. All systems were simultaneously triggered by either the 225 MHz radiation alone or by a combination of that radiation, electric field derivative, and electric field signals.

The frequency spectra of the wideband electric field waveforms have been calculated for the range of a few Hz to 50 MHz. The electric field signals used for the spectrum calculations are generated from both the direct field waveforms and the numerically integrated dE/dt waveforms. The basic recording configuration is presented in Figure 3. The sensors were on the ground at a distance of about 130 m from the closest structure, and were connected to the recording station by means of fiber optics. The fiber optics had a bandwidth to 150 MHz. The output of a flat plate antenna was integrated using an electronic integrator and subsequently digitized. The electronic integrators used in our experiment have an upper -3dB frequency of about 7 MHz. The output of the other flat plate antenna, which is proportional to the derivative of the electric field, was simultaneously digitized along with both VHF receiver outputs. The digitized signals were transferred to a 80386-based computer and stored on a hard disk. When the hard disk capacity was reached, the information was transferred to magnetic tapes for permanent storage.

A composite electric field waveform was generated digitally using the scheme shown in Figure 4. The digitized E-field waveform was passed through a 3 MHz digital low-pass filter, thus removing frequency components above that frequency. The digitized dE/dt waveform was numerically integrated and then passed through a 3 MHz high-pass filter, thus removing frequency components below this frequency. The filtered waveforms were then added together to create the composite electric field waveform. The actual frequency and phase response of the filters were tested by applying a square wave at the input of each filter and adding the outputs of the filters to produce a composite waveform. The composite waveform was a square wave of exactly the same amplitude as the input waveform.

The following sequence of figures illustrates the procedure described in the previous paragraph. An electronically-integrated E-field waveform is shown in Figure 5. A simultaneously recorded dE/dt figure is presented in Figure 6. After performing a numerical integration on the dE/dt signal, we obtain the waveform shown in Figure 7. The composite signal, obtained after scaling, filtering, and adding together both E-field waveforms is presented in Figure 8. Recordings of the envelope of the narrowband VHF radiation at 50 and 225 MHz for the same cloud pulse whose wideband fields are found in Figures 5 to 8 are presented in Figures 9 and 10, respectively.

The power frequency spectrum of the wideband E-field waveforms was obtained using FFT techniques The waveforms were properly windowed to prevent introduction of high frequency components in the spectrum A HEMP waveform from Lee (1986) is presented in Figure 11. Figure 12 compares the HEMP spectrum with the average spectra of the largest ten cloud pulses, out of a total of 250 cloud pulses analyzed to date, with the cloud pulse fields normalized to 50 meters assuming the sources to be directly overhead and at an altitude of 5 km.

A wide variety of pulses were recorded during the 1989 measurements. Pulses with 10 to 90 percent risetimes faster than 0.5 μs were commonly observed. The fastest cloud pulse risetime to initial peak was about 0.3 μs. Since the sources of at least some of the cloud pulses could be more or less horizontally oriented, the magnitude of the radiation detected at the horizontal flat plate sensor, the vertical field component, would, in those cases, be reduced from the source value. Additionally, since the cloud sources are assumed to be at the closest possible distance, 5 km, the field values normalized to 50 m are smaller than if the actual sources were somewhat farther away, as is likely the case. The sum of these two effects might cause the actual field observed at 50 m for large pulses to be an underestimate, perhaps of a factor of 2 or 3, from the values plotted in Figure 12. Such a change would be hardly noticeable on the logarithmic scale.

Figures 13 through 15 show calibrated records of 3 additional cloud pulses Figures 16 through 21 are an uncalibrated collection of different types of cloud pulses with their associated VHF radiation and E-field records Each figure shows from top to bottom:

- Fast electric field integrator
- VHF radiation at 50 MHz
- dE/dt record
- VHF radiation at 225 MHz
- Slow electric field integrator

It is important to note that some trains of cloud pulses have a duration greater than 100 μs. Also, some records show significant radiation at 225 MHz while exhibiting little at 50 MHz.

We have not as yet calibrated the VHF channels at 50 MHz and 225 MHz. When that is done, we will be able to present a comparison of HEMP and the cloud pulse spectrum to 225 MHz along with narrowband lightning data from previous investigators. In lieu of that comparison, we show in Figure 22 the available narrowband lightning data taken from Oh (1969) along with the same HEMP spectrum shown in Figures 1 and 2 All lightning data and the HEMP spectrum have been normalized to a bandwidth of 1 kHz. The lightning data are normalized to a distance of 1 mile. The reliability of the narrowband lightning data has been discussed in Section 1.2.

# SECTION 4

## CONCLUSION

The shortest risetime to initial peak value of overhead lightning pulses are of the order of 0.3 μs. A broader bandwidth system than that used would allow measurement of the rapid field variation occurring throughout the cloud pulses associated with frequencies above about 50 MHz but would observe essentially the same risetime to initial peak. That is, the higher frequence content of the cloud pulses is contained in the rapid field variation throughout the overall waveforms, a time duration of about 10 μs, and not in the initial rise to peak value.

Cloud pulses of the type described by LeVine (1988) and Willett et al. (1989), which we have analyzed in this report, are much more common than these earlier studies indicate, probably because their technique of triggering involved using a narrowband signal in the 3 to 18 MHz range while we employed a 225 MHz trigger, often in combination with electric field and electric field derivative signals. Different portions of the cloud pulse spectrum (i.e., 50 MHz vs 225 MHz) may occur at different times and presumably originate from different (although not much different) spatial locations during the ten microseconds or so of the cloud pulse duration. Our spectra of the largest overhead cloud pulses are nearly parallel to but significantly below the HEMP spectrum from 1 MHz to 50 MHz, as shown in Figure 12, while those from Willett et al. (1989) obtained from lightning tens of kilometer offshore over salt water and plotted in Figure 1 show a faster relative decay with increasing frequency, are significantly below ours between 10 and 50 MHz, and are about equal to ours between 3 and 10 MHz.

# APPENDIX

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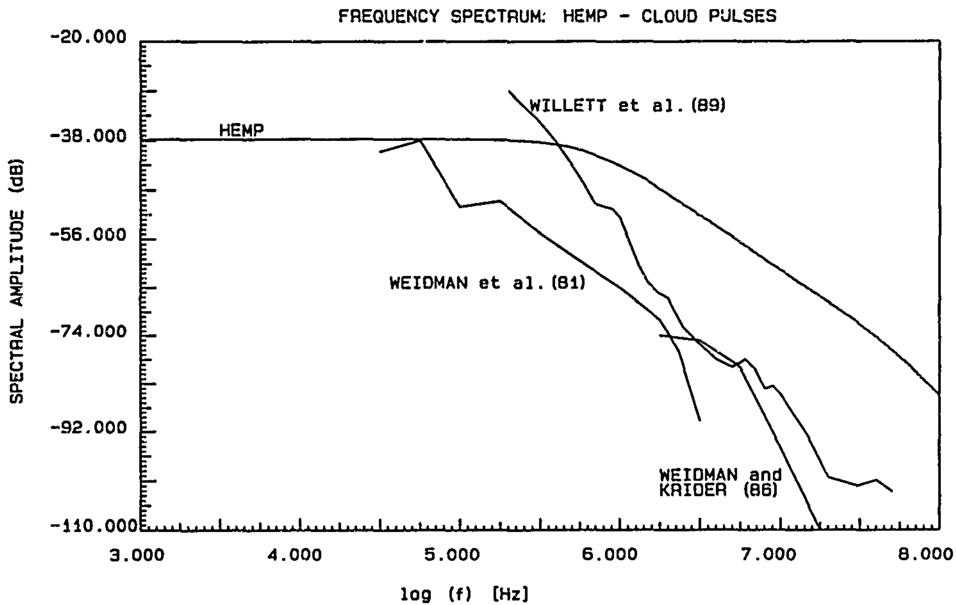



Figure 1. Frequency spectrum of cloud pulses normalized to a distance of 50 meters and *HEMP* spectrum.

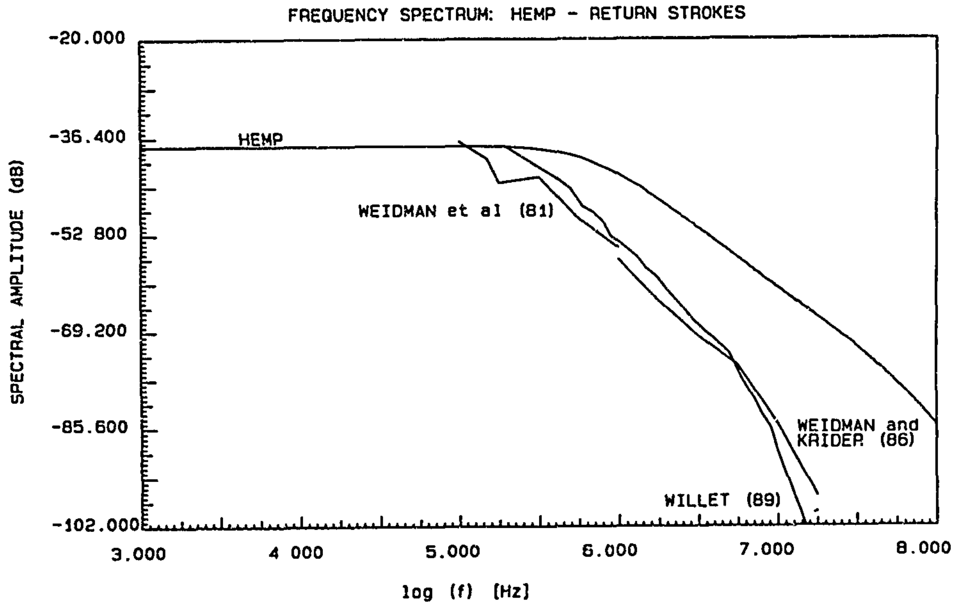
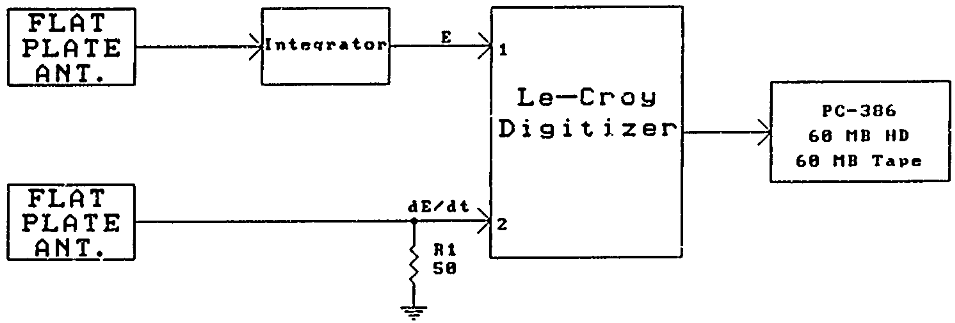



Figure 2. Frequency spectrum of return strokes normalized to a distance of 50 meters and HEMP spectrum.




BASIC RECORDING CONFIGURATION

Figure 3. Basic recording configuration of the system used during 1989 at the Kennedy Space Center.

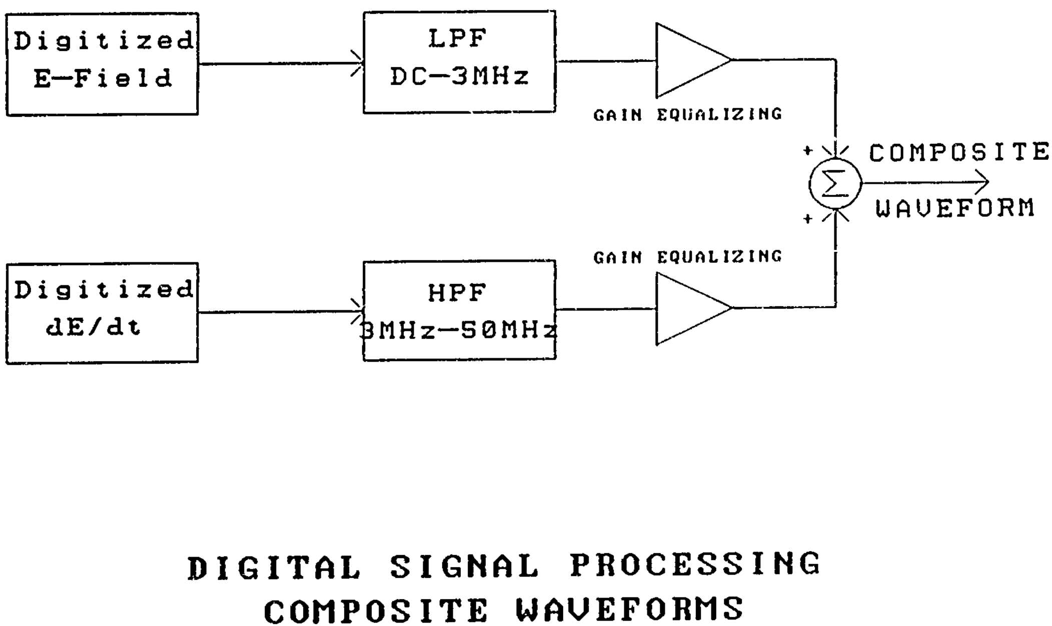



Figure 4. Method for generating a composite electric field waveform from the dE/dt and E-field signals.

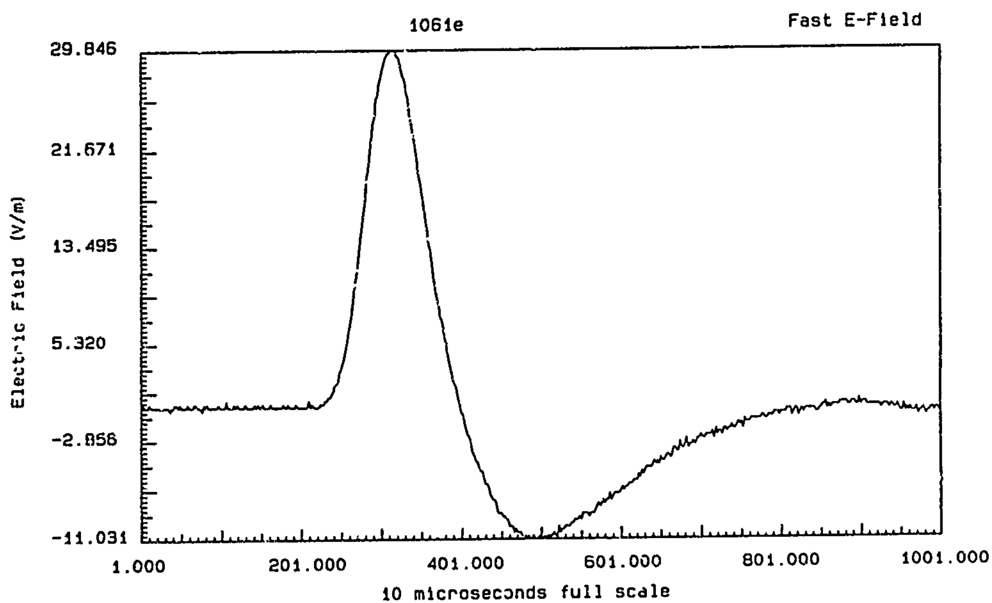



Figure 5. An electronically integrated E-field waveform recorded on day 269.

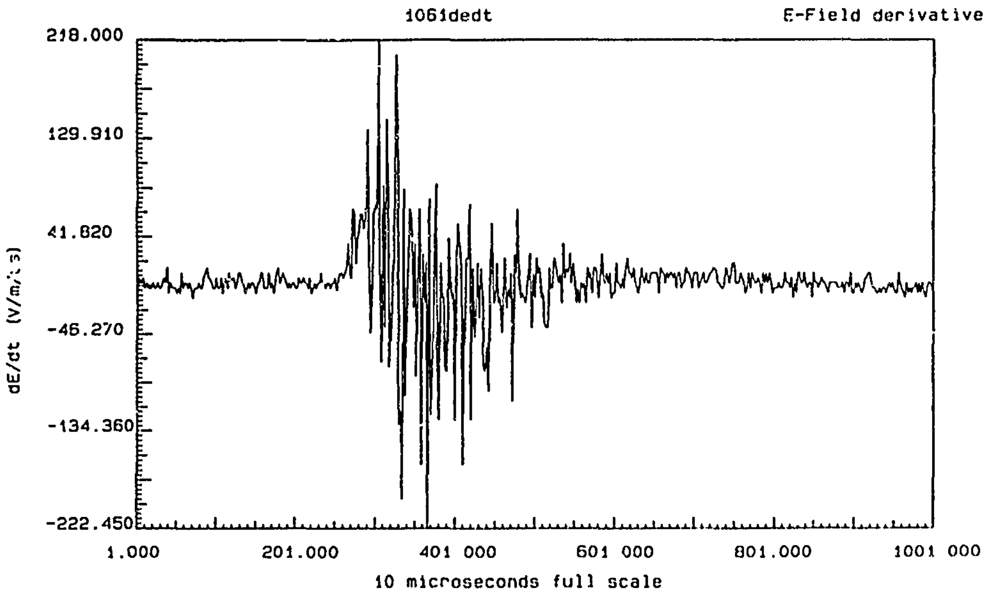



Figure 6. dE/dt waveform recorded simultaneously with the E-field waveform shown in Figure 5.

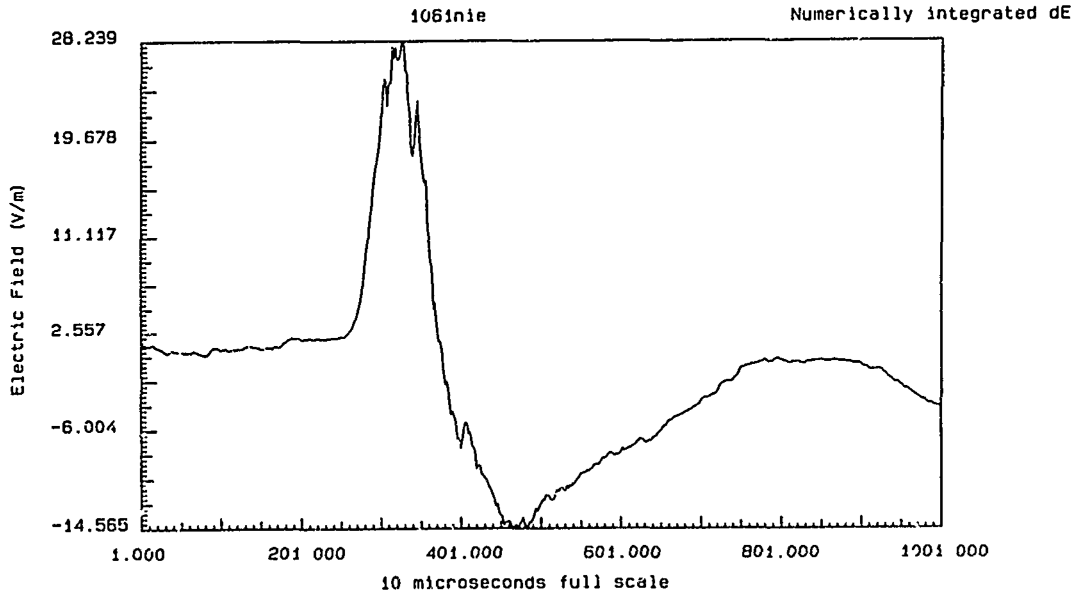



Figure 7. Waveform obtained by numerically integrating the dE/dt waveform shown in Figure 6.

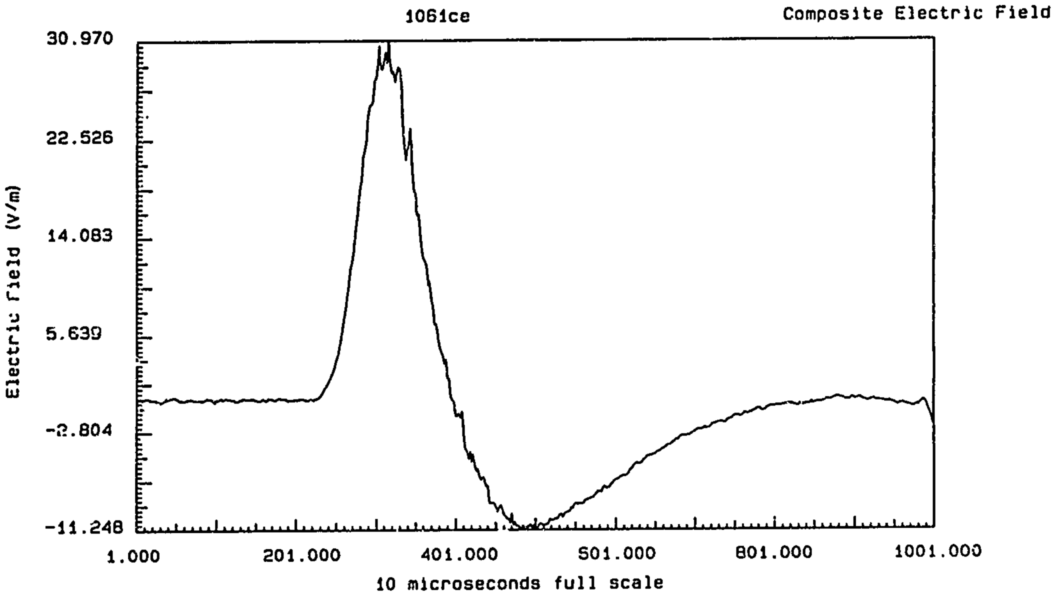



Figure 8. Composite electric field waveform obtained using the method described in Figure 4.

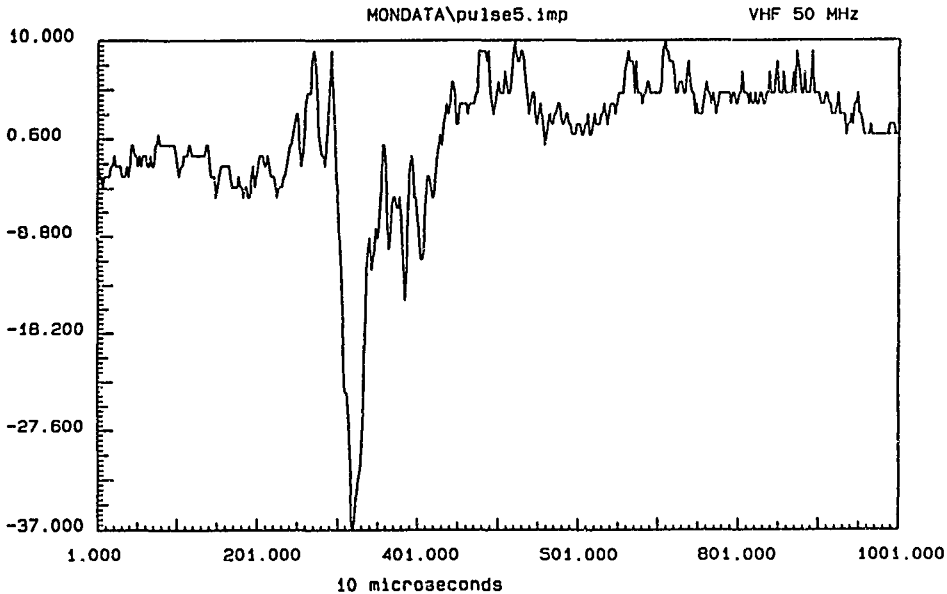



Figure 9. 50 MHz VHF radiation recorded simultaneously with the cloud pulse shown in Figures 5 to 8.

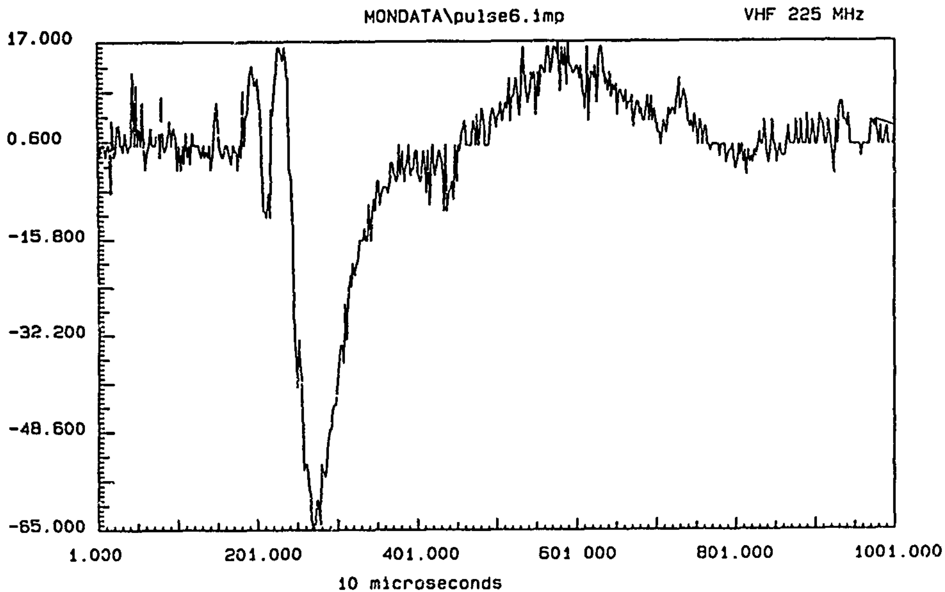



Figure 10. 225 MHz VHF radiation recorded simultaneously with the cloud pulse shown in Figures 5 to 8.

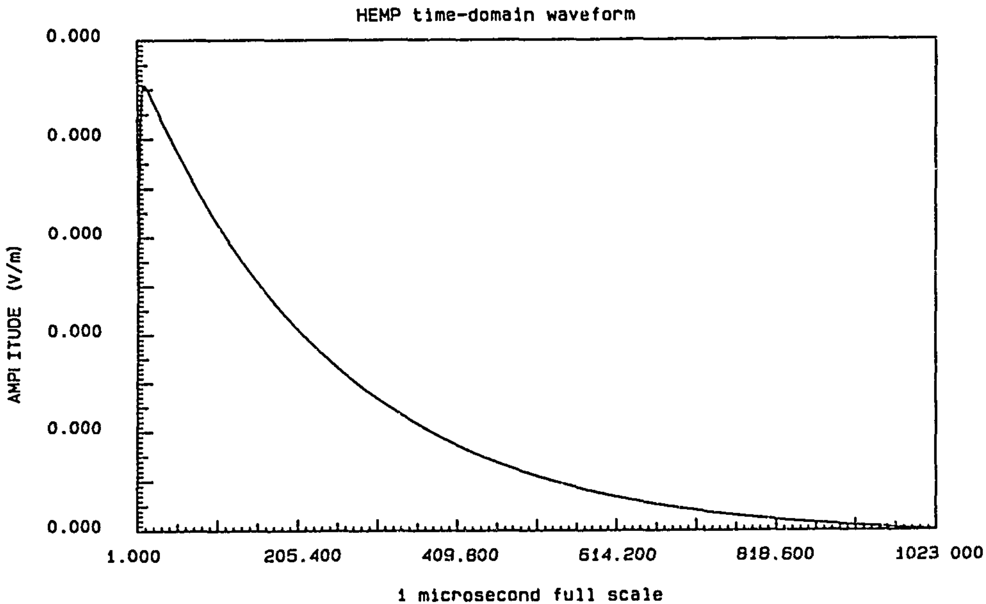



Figure 11. HEMP time-domain waveform (from Lee [1986]).

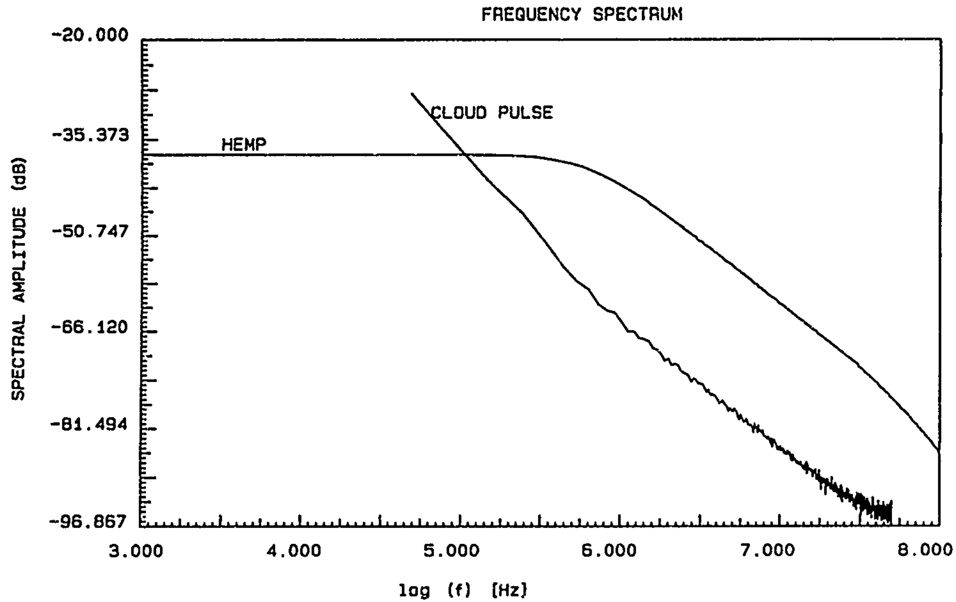



Figure 12. Comparison of the average power spectrum of the ten largest cloud pulses recorded at KSC during the 1989 experiment, normalized to 50 meters, and HEMP spectrum.

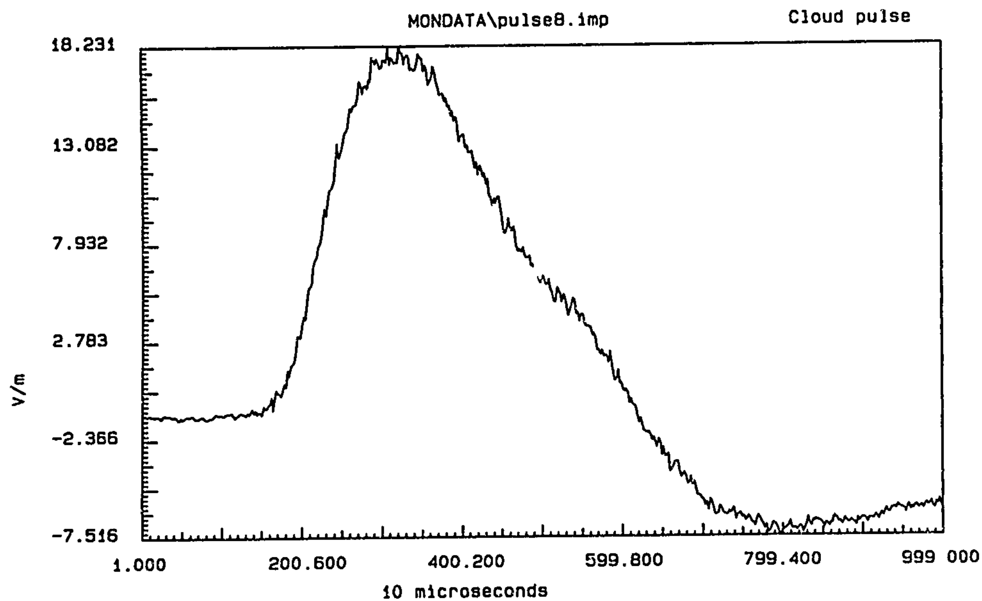



Figure 13. Example of a cloud pulse recorded on day 269.

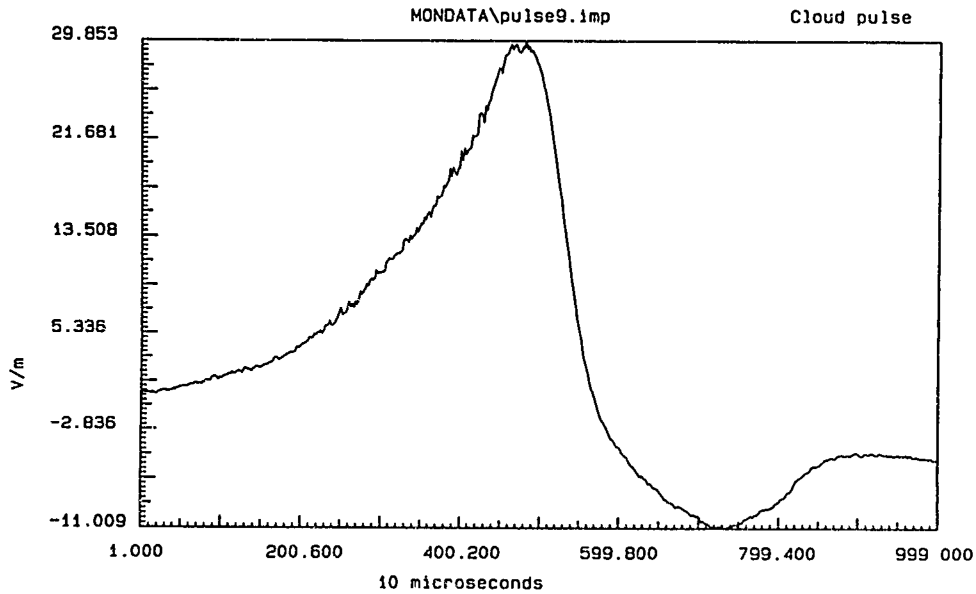



Figure 14. Example of a cloud pulse recorded on day 269.

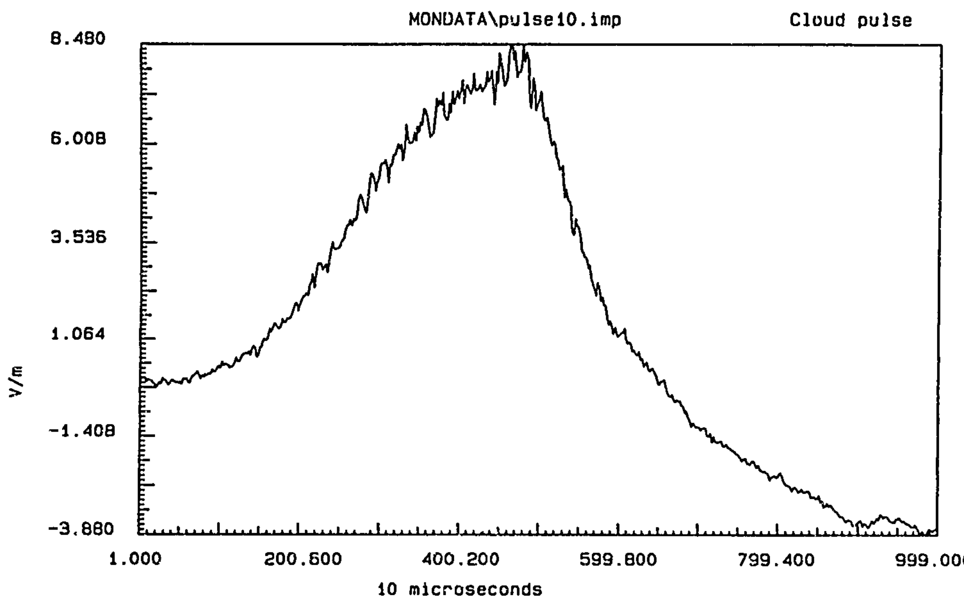



Figure 15. Example of a cloud pulse recorded on day 269.

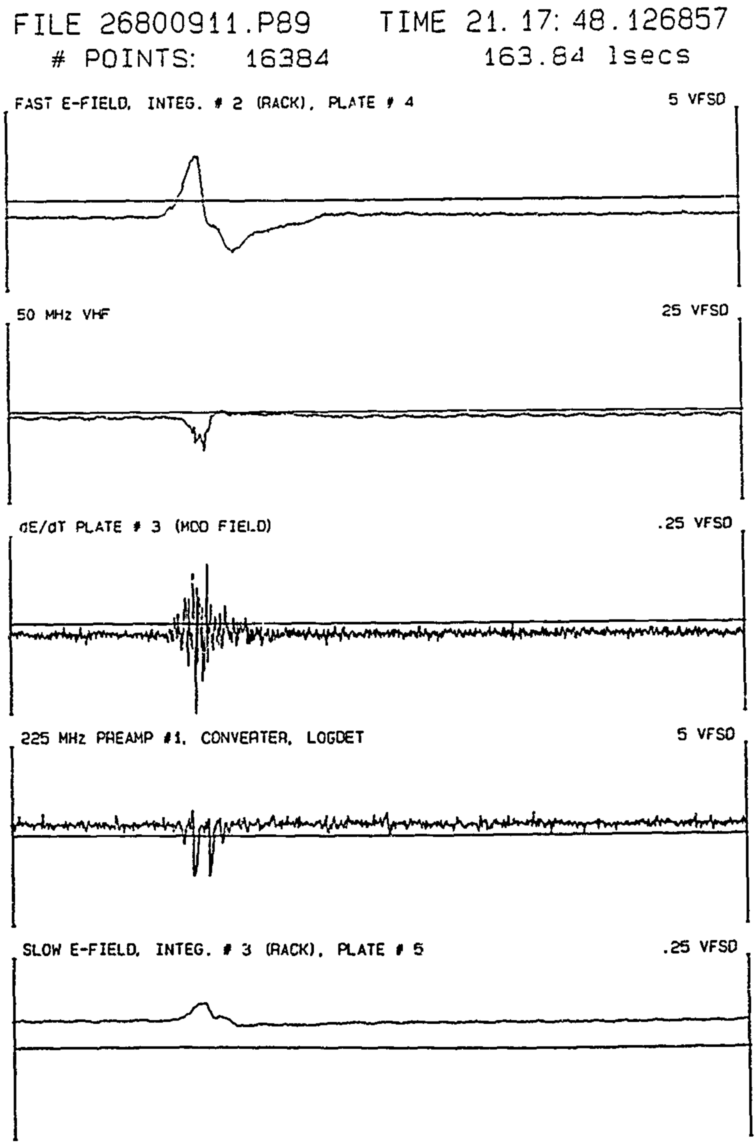



Figure 16. Example of simultaneously recorded waveforms.

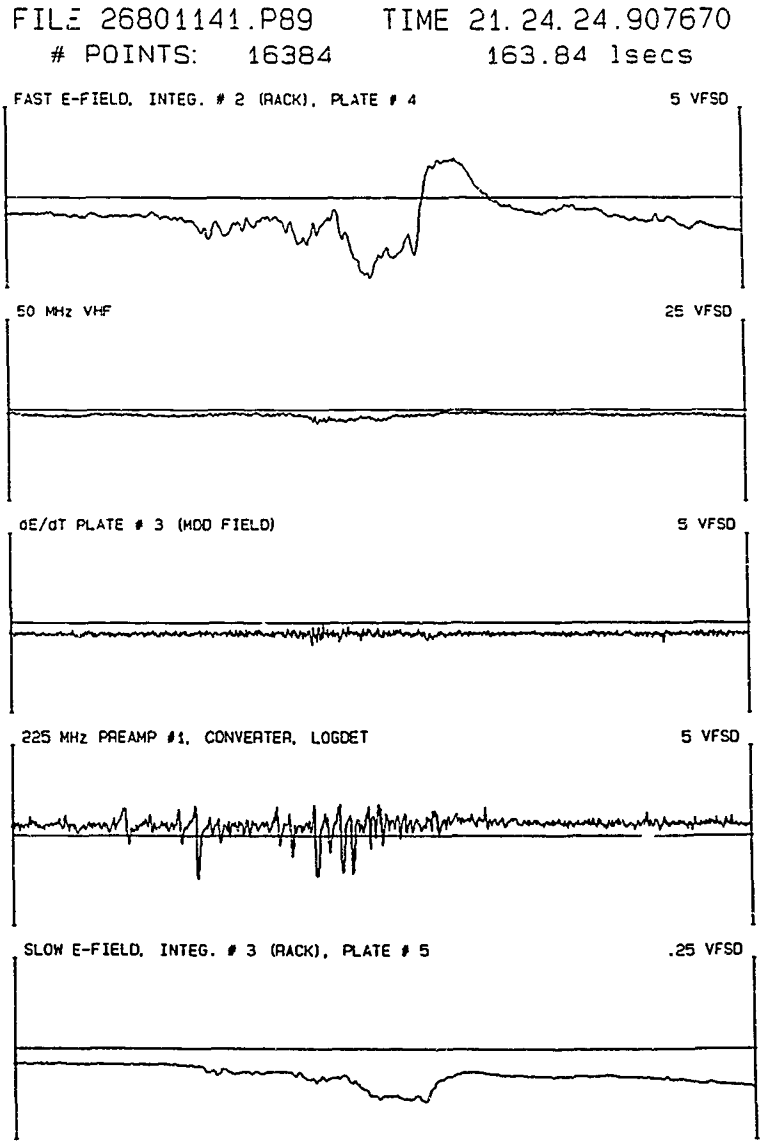



Figure 17. Example of simultaneously recorded waveforms.

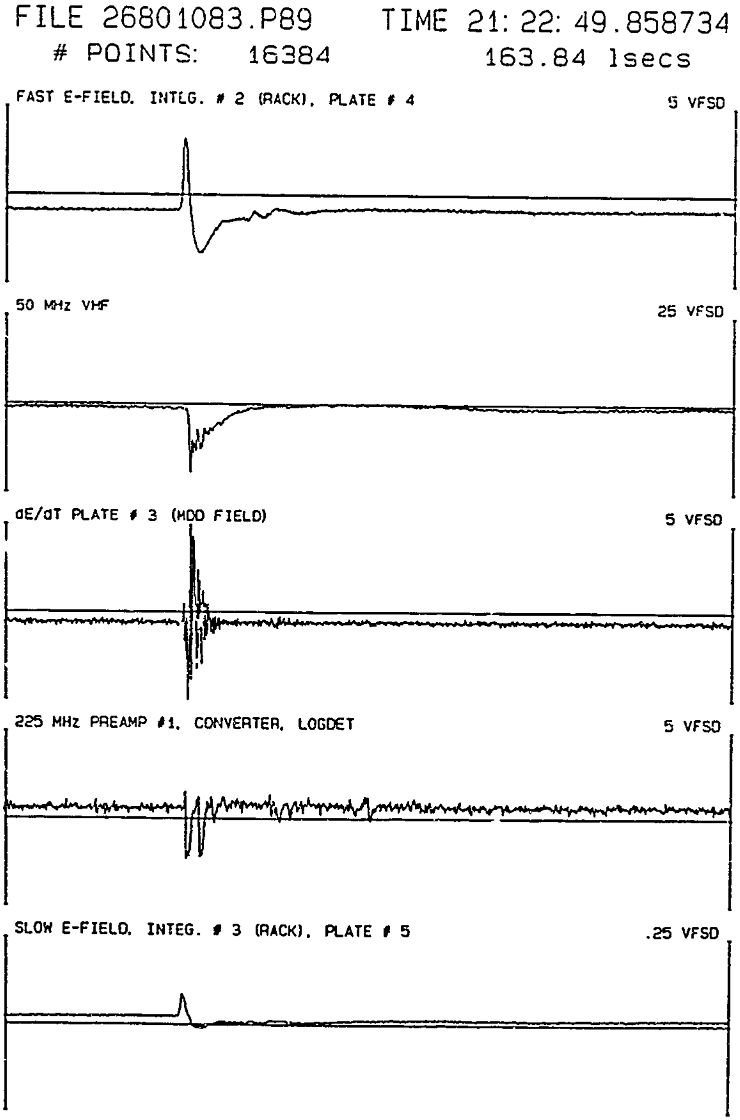



**Figure 18. Example of simultaneously recorded waveforms.**

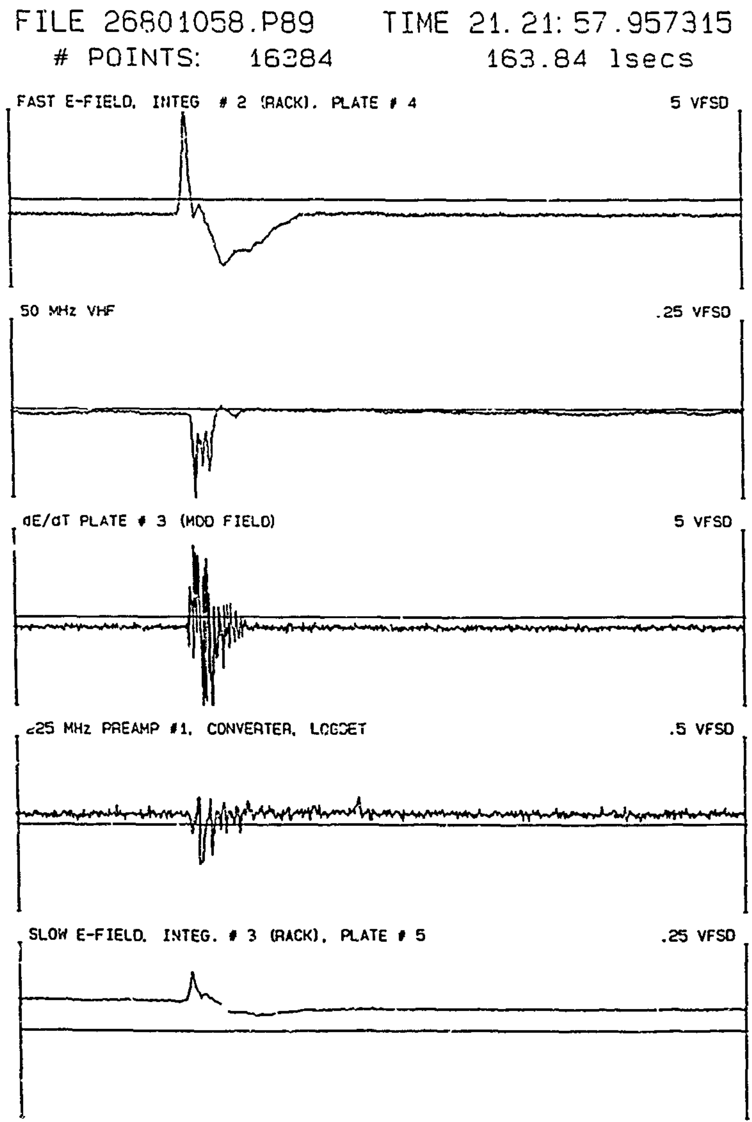



Figure 19. Example of simultaneously recorded waveforms.

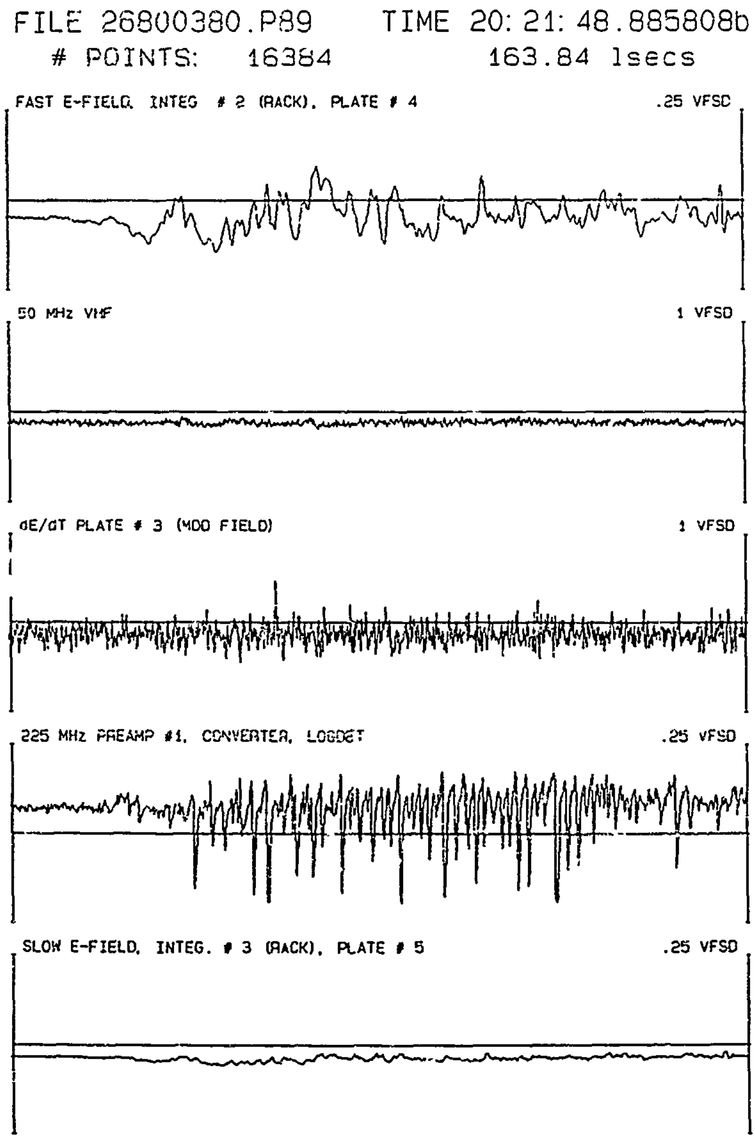



Figure 20. Example of simultaneously recorded waveforms.

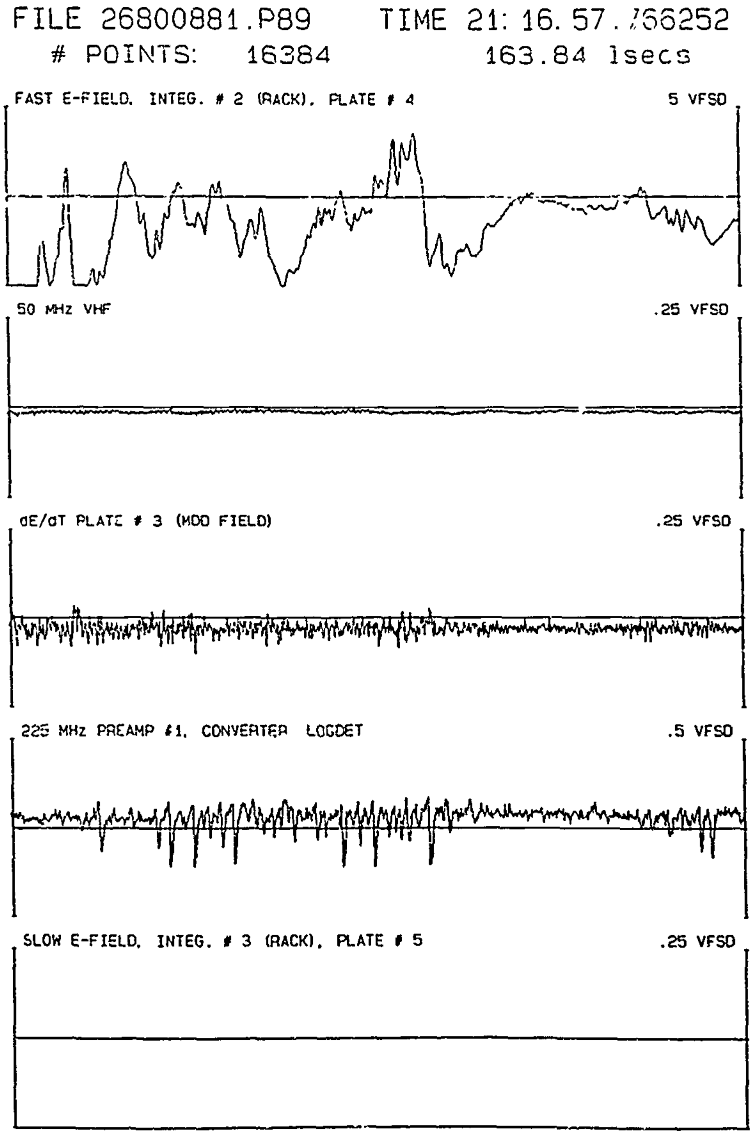



**Figure 21. Example of simultaneously recorded waveforms.**

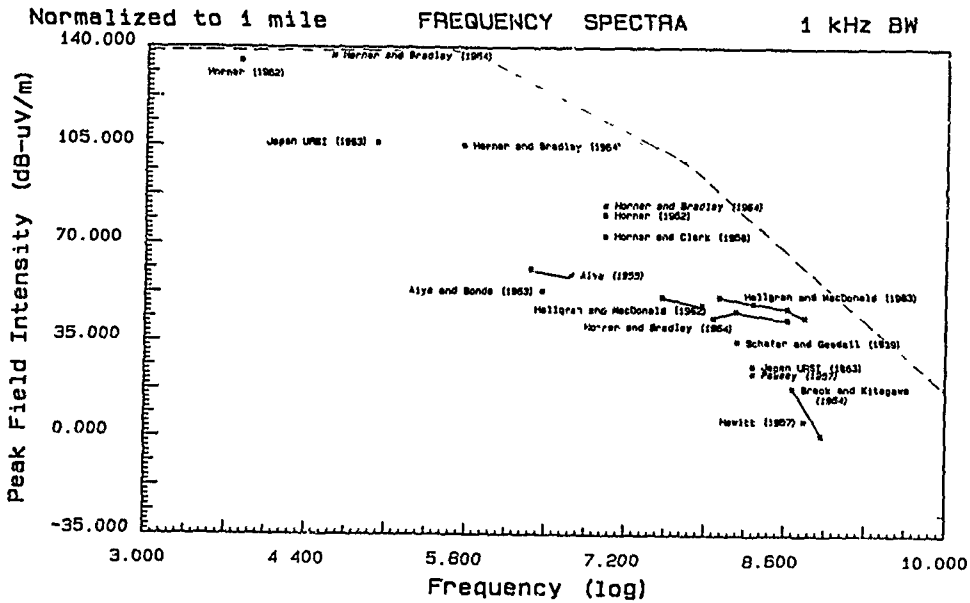



Figure 22. Comparison of HEMP spectrum (dashed line) with available lightning narrowband spectral data.

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