

AD-A234 306



**Defense Nuclear Agency
Alexandria, VA 22310-3398**



DNA-TR-90-101

Comparison of the RF Frequency Spectra of HEMP and Lightning

**Martin A. Uman
University of Florida
Department of Electrical Engineering
Gainesville, FL 32611**

March 1991

**DTIC
ELECTE
APR 8 1991
S B D**

Technical Report

CONTRACT No. DNA 001-87-C-0180

DTIC FILE COPY

Approved for public release;
distribution is unlimited.

91 4 05 024

Destroy this report when it is no longer needed Do not
return to sender

PLEASE NOTIFY THE DEFENSE NUCLEAR AGENCY,
ATTN: CSTI, 6801 TELEGRAPH ROAD, ALEXANDRIA, VA
22310-3398, IF YOUR ADDRESS IS INCORRECT, IF YOU
WISH IT DELETED FROM THE DISTRIBUTION LIST, OR
IF THE ADDRESSEE IS NO LONGER EMPLOYED BY YOUR
ORGANIZATION.



DISTRIBUTION LIST UPDATE

This mailer is provided to enable DNA to maintain current distribution lists for reports. We would appreciate your providing the requested information.

- ☐ Add the individual listed to your distribution list.
- ☐ Delete the cited organization/individual
- ☐ Change of address

NOTE:
Please return the mailing label from the document so that any additions, changes, corrections or deletions can be made more easily.

NAME _____

ORGANIZATION _____

OLD ADDRESS

CURRENT ADDRESS

TELEPHONE NUMBER () _____

SUBJECT AREA(S) OF INTEREST

DNA OR OTHER GOVERNMENT CONTRACT NUMBER: _____

CERTIFICATION OF NEED TO KNOW BY GOVERNMENT SPONSOR (if other than DNA)

SPONSORING ORGANIZATION: _____

CONTRACTING OFFICER OR REPRESENTATIVE _____

SIGNATURE _____

CUT HERE AND RETURN



Director
Defense Nuclear Agency
ATTN: TITL
Washington, DC 20305-1000

Director
Defense Nuclear Agency
ATTN: TITL
Washington, DC 20305-1000

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1 AGENCY USE ONLY (Leave blank)	2 REPORT DATE 910301	3 REPORT TYPE AND DATES COVERED Technical 870922 - 900710		
4 TITLE AND SUBTITLE Comparison of the RF Frequency Spectra of HEMP and Lightning		5 FUNDING NUMBERS C - DNA 001-87-C-0180 PE - 62715H PR - RV TA - RC WU - DH041260		
6 AUTHOR(S) Martin A. Uman				
7 PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Florida Department of Electrical Engineering Gainesville, FL 32611		8 PERFORMING ORGANIZATION REPORT NUMBER		
9 SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Defense Nuclear Agency 6801 Telegraph Road Alexandria, VA 22310-3398 RAAE/Prasad		10 SPONSORING/MONITORING AGENCY REPORT NUMBER 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 Approved for public release; distribution is unlimited.			12b DISTRIBUTION CODE	
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 lightning pulses are of the order of 0.3 μ s. 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 HEMP Environments		15 NUMBER OF PAGES 44		
		16 PRICE CODE		
17 SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18 SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19 SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20 LIMITATION OF ABSTRACT SAR	

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

CLASSIFIED BY

N/A since Unclassified

DECLASSIFY ON

N/A since Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

CONVERSION TABLE

MULTIPLY TO GET	BY BY	TO GET DIVIDE
foot	3.048 000 x E -1	meter (m)
inch	2.540 000 x E -2	meter (m)
mile (international)	1.609 344 x E +3	meter (m)



Accession For	
NTIS GRA&I	☒
DTIC TAB	☐
Unannounced	☐
Justification	
By _____	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-1	

TABLE OF CONTENTS

Section	Page
CONVERSION TABLE	iii
FIGURES	v
1 INTRODUCTION	1
1.1 MOTIVATION FOR THE PRESENT PROGRAM.	1
1.2 TECHNICAL BACKGROUND	1
2 PREVIOUS LIGHTNING/HEMP COMPARISON	3
3 NEW DATA ACQUIRED FOR PRESENT CONTRACT	4
4 CONCLUSION	6
Appendix	
BIBLIOGRAPHY	7

FIGURES

Figure	Page
1 Frequency spectrum of cloud pulses normalized to a distance of 50 meters and HEMP spectrum	13
2 Frequency spectrum of return strokes normalized to a distance of 50 meters and HEMP spectrum	14
3 Basic recording configuration of the system used during 1989 at the Kennedy Space Center	15
4 Method for generating a composite electric field waveform from the dE/dt and E-field signals	16
5 An electronically integrated E-field waveform recorded on day 269 ..	17
6 dE/dt waveform recorded simultaneously with the E-field waveform shown in Figure 5	18
7 Waveform obtained by numerically integrating the dE/dt waveform shown in Figure 6	19
8 Composite electric field waveform obtained using the method described in Figure 4	20
9 50 MHz VHF radiation recorded simultaneously with the cloud pulse shown in Figures 5 to 8	21
10 225 MHz VHF radiation recorded simultaneously with the cloud pulse shown in Figures 5 to 8	22
11 HEMP time-domain waveform (from Lee [1986])	23
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	24
13 Example of a cloud pulse recorded on day 269	25
14 Example of a cloud pulse recorded on day 269	26
15 Example of a cloud pulse recorded on day 269	27
16 Example of simultaneously recorded waveforms	28
17 Example of simultaneously recorded waveforms	29
18 Example of simultaneously recorded waveforms	30
19 Example of simultaneously recorded waveforms	31
20 Example of simultaneously recorded waveforms	32

FIGURES (Concluded)

Figure		Page
21	Example of simultaneously recorded waveforms	33
22	Comparison of HEMP spectrum (dashed line) with available lightning narrowband spectral data	34

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; Nanavicz et al., 1988). The HEMP spectrum is well de-

fined 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 (c.g., Nanavicz 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 (Nanevitz 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 (Nanevitz 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 in-trailcloud 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; Nanevich 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 μ s were commonly observed. The fastest cloud pulse risetime to initial peak was about 0.3 μ s. 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 μ s. 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 μ s. 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, a time duration of about 10 μ s, 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 us-

ing 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 HEMF 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

BIBLIOGRAPHY

I. Lightning - EMP Comparison

Gardner, R.L., L. Barker, J.L. Gilbert, C.E. Baum, and D.J. Andersh, Comparison of published HEMP and natural lightning on the surface of an aircraft, *Proc. 10th Int. Aerospace Ground Conference Lightning and Static Electricity*, 108 pp., Paris, France, June 10-13, 1985.

Lee, K.S.H., Ed., *EMP Interaction: Principles, Techniques, and Reference Data*, Hemisphere, Washington, DC, 1986.

Nanevich, J.E., E.F. Vance, W. Radsky, M.A. Uman, G.K. Soper, and J.M. Pierre, EMP susceptibility insights from aircraft exposure to lightning, *IEEE Trans. Electromagnetic Comp.*, 30, 463-472, 1988.

Rustan, P.L., Description of an aircraft lightning and simulated nuclear electromagnetic pulse (HEMP) threat based on experimental data, *IEEE Trans. Electromagn. Comp.*, EMC-20, 49-63, 1987.

Tesche, F.M., and P.R. Barnes, A multi-conductor model for determining the response of power transmission and distribution lines to a high altitude electromagnetic pulse (HEMP), *IEEE Trans. Power Del.*, 4, 1989.

Tesche, F.M., and P.R. Barnes, the HEMP response of an overhead power distribution line *IEEE Trans. Power Del.*, 4, 1989.

Uman, M.A., M.J. Master, and E.P. Kridner, A comparison of lightning electromagnetic fields with the nuclear electromagnetic pulse in the frequency range 104 to 107 Hz, *IEEE Trans. EMC*, EMC-24, 410-416, 1982.

Vance, E.F., Electromagnetic-Interference control, *IEEE Trans. Electromagnetic Comp.*, EMC-22, 1980.

Vance, E.F., and M.A. Uman, Differences between lightning and nuclear electromagnetic pulse interactions, *IEEE Trans. Electromagnetic Comp.*, 30, 54-62, 1988.

II. Lightning Frequency Spectra

Alya, S.V.C., Measurements of atmospheric noise interference to broadcasting, *J. Atmos. Terrest. Phys.*, 5, 230, 1954.

Alya, S.V.C., Noise power radiated by tropical thunderstorms, *Proc. IRE*, 43, 966-974, 1955.

Alya, S.V.C., Structure of atmospheric radio noise, *J. Science Ind. Res.*, 21D, 203-220, 1962.

Alya, S.V.C., Spring thunderstorms over Bangalore, *Proc. IEEE*, 51, 1493-1501, 1963.

Alya, S.V.C., A.K.R. Sastri, and A.P. Shriprasad, Atmospheric radio noise measured in India, *Indian J. Rad. Space Phys.*, 1, 1-8, 1972.

Atlas, D., Radar lightning echoes and atmospheric in vertical cross-section, in *Recent Advances in Atmospheric Electricity*, L.G. Smith, Ed., pp. 441-459, Pergamon, Oxford, 1959.

Barlow, J.S., G.W. Frey, Jr., and J.B. Newman, Very low frequency noise power from the lightning discharge, *J. Franklin Inst.*, 27, 145-163, 1954.

Bhattacharya, J., Amplitude and phase spectra of radio atmospheric, *J. Atmos. Terrest. Phys.*, 25, 445, 1963.

Bradley, P.A., The spectra of lightning discharges at very low frequencies, *J. Atmos. Terrest. Phys.*, 26, 1069-1073, 1964.

Bradley, P.A., The VLF energy spectra of first and subsequent return strokes of multiple lightning discharges to ground, *J. Atmos. Terrest. Phys.*, 27, 1045-1053, 1965.

Bradley, P.A., and C. Clarke, Atmospheric radio noise and signal received on directional aerials at high frequencies, *Proc. Inst. Elec. Eng. London*, 111, 1534-1540, 1964.

Brook, M., and N. Kitagawa, Radiation from lightning discharges in frequency the range 400 to 1,000 MC/s, *J. Geophys. Res.*, 69, 2431-2434, 1964.

Chauzy, S., and K. Kably, Electric discharges between hydrometers, *J. Geophys. Res.*, 94, 13,107-13,114, 1989.

Clands, N., Oetzel, G.N., Pierce, E.T., Structure of lightning noise-especially above HF, Lightning and Static Electricity Conference, Wright Patterson AFB, December 1972.

Clarke, C., A study of atmospheric radio noise in a narrow width band at 11 MC/s, *Proc. Inst. of Elec. Eng. London, Pt. B*, pp. 107, 1960.

Clarke, C., Atmospheric radio noise studies based on amplitude probability measurements at Slough, England, during the international geophysical year, *Proc. IEE, London, Pt. B47*, pp. 109, 1962.

Clarke, C., and P.A. Bradley, Discussion on 1) atmospheric radio noise and signals received on directional aerials at high frequencies and 2) characteristics of atmospheric radio noise observed at Singapore, *Proc. Inst. Elec. Eng. London*, 113, 752-754, 1966.

Clarke, C., P.A. Bradley, and D.E. Mortimer, Characteristics of Atmospheric radio noise observed at Singapore, *Proc. Inst. Elec. Eng. London*, 112, 849-860, 1965.

Croom, D.L., The spectra of atmospherics and propagation of very low frequency radio waves, Ph.D. Thesis, University of Cambridge, England, 1961.

Croom, D.L., The frequency spectra and attenuation of atmospherics in the range 1-15KC/S, *J. Atmos. Terrest. Phys.*, 24, 1015-1046, 1964.

Dennis, A.S., and E.T. Pierce, The return stroke of the lightning flash to Earth as a source of VLF atmospherics, *Radio Science*, 68D, 779-794, 1964.

Devan, K.R.S., Electric field spectra of lightning return-strokes in the interval from 2 to 500 MHz, *Inst. Elec. & Telecomm. Eng.*, 32, 382-388, Sept.-Oct. 1986.

Galejs, J., Amplitude statistics of lightning discharge currents and ELF and VLF radio noise, *J. Geophys. Res.*, 72, 2943-2953, 1967.

Gardner, R.L., Effect of the propagation path on lightning-induced transient fields, *Radio Science*, 16, 377-384, 1981.

Gardner, R.L., L. Baker, J.L. Gilbert, C.E. Baum, and D.J. Andersh, Comparison of published HEMP and natural lightning on the surface of an aircraft, *Proc. 10th International Aerospace Ground Conference Lightning and Static Electricity*, pp. 108, Paris, France, June 10-13, 1985.

Garg, M.B., K.C. Mathpal, J. Rai, and N.C. Varshneya, Frequency spectra of electric and magnetic fields of different forms of lightning, *Ann. Geophys. T.*, 38, FASC. 2, 177-188, 1982.

Gupta, S.P., VLF spectral characteristics on leader pulses, *IEE Proc. A. Phys. Sci.*

Meas. Instrum. Manage. Educ. Rev. (UK). 134, 789-792, December 1987.

Gupta, S.P., M. Rao, and B.A.P. Tantry. VLF spectra radiated by stepped leaders. *J. Geophys. Res.*, 77, 3924-3927, 1972.

Hallgren, R.E., R.B. McDonald. Atmospherics from lightning from 100 to 600 MHz. Rep. No. 63-538-89, IBM Federal Systems Division, 1963

Harwood, J., and B.N. Harden. The measurement of atmospheric radio noise by an aural comparison method in the range 15-500 KC/s. *Proc. Inst. of Elec. Eng. London*, B107, 53-59, 1960.

Hewitt, F.J., Radar echoes from inter-stroke processes in lightning. *Proc. Phys. Soc. London*, Sect.-B, 70, 961-979, 1957.

Horner, F., Narrowband atmospherics from two local thunderstorms. *J. Atmos. Terrest. Phys.*, 21, 13-15, 1961

Horner, F., Atmospheric of near lightning discharges. in *Radio Noise of Terrestrial Origin*, F. Horner, Ed., pp. 16-17, American Elsevier, New York, 1962.

Horner, F., Radio noise from thunderstorms; in *Advances in Radio Research* 2, J.A. Saxton, Ed., pp. 122-215, Academic Press, New York, 1964.

Horner, F., and C. Clarke, Radio noise from lightning discharges. *Nature*, 181, 688-690, 1958.

Horner, F., and P.A. Bradley, The spectra of atmospherics from near lightning. *J. Atmos. Terrest. Phys.*, 1155-1166, 1964.

Iwata, A., and M. Kanada, On the nature of the frequency spectrum of atmospheric source signal. *Proc. Res. Inst. Atmos.*, 14, 1-6, 1967.

Jones, H.L., R.L. Calkins, and W.L. Hughes, A review of the frequency spectrum of cloud-to-ground and

cloud-to-cloud lightning. *IEEE Trans. Geosci. Elec.*, GE-5, 1, 26-30, 1967.

Kawasaki, Z-I, M. Nakano, T. Takeuchi, M. Nagatani, H. Nakada, Y. Mizuno, and T. Nagai, Fourier spectra of positive lightning fields during winter thunderstorms. *Res. Lett. Atmos. Elec.*, 7, 29-34, 1987.

Kimpura, A., Electromagnetic energy radiated from lightning, in *Problems of Atmospheric and Space Electricity*, S.C. Coroniti, Ed., pp. 352-365, American Elsevier, New York, 1965.

Kosarev, E.L., V.G. Zaitsepin, and A.V. Mitrofanov, Ultrahigh frequency radiation from lightnings. *J. Geophys. Res.*, 75, 7524-7530, 1970.

Labaune, G., P. Richard, and A. Bondiou, Electromagnetic properties of lightning channels formation and propagation. *Electromagnetics*, 7, 361-393, 1987

Lanzertotti, L.J., D.J. Thomson, C.G. MacLennan, K. Rinnert, E.P. Krider, and M.A. Uman, Power spectra at radio frequency of lightning return stroke waveforms. *J. Geophys. Res.*, 94, 13,221-13,227, 1989.

Le Boulch, M., and J. Hamelin, Rayonnement en ondes metriques et decimetriques des orages. *Ann. Telecommun.*, 40, 277-313, 1985.

Le Boulch, M., J. Hamelin, and C. Weidman, UHF-VHF radiation from lightning. *Electromagnetics*, 7, 287-331, 1987.

Lee, K.S., Ed., *EMP Interacting: Principles, Techniques, and Reference Data*, Hemisphere, Washington, DC, 1986.

Leteinturier, C., and J. Hamelin, Experimental study of the electromagnetic characteristics of lightning discharge in the 200 Hz 20 MHz band. *Electromagnetics* 7, 195-204, 1987.

Le Vine, D.M., The effect of pulse interval statistics on the spectrum of radiation

from lightning, *J. Geophys. Res.*, **82**, 1773-1777, 1977.

Le Vine, D.M., Sources of the strongest RF radiation from lightning, *J. Geophys. Res.*, **85**, 4091-4095, 1980.

Le Vine, D.M., Review of measurements of the RF spectrum of radiation from lightning, *Meteorol. Atmos. Phys.*, **37**, 195-204, 1987.

Le Vine, D.M., and E.P. Krider, The temporal structure of HF and VHF radiations during Florida lightning return strokes, *Geophys. Res. Lett.*, **4**, 13-16, 1977.

Le Vine, D.M., J.C. Willett, and J.C. Bailey, Comparison of fast electric field changes from subsequent return strokes of natural and triggered lightning, *J. Geophys. res.*, **94**, 13,259-13,265, 1989.

Le Vine, D.M., The spectrum of radiation from lightning, *International Symposium on Electromagnetic Compatibility*, 249-253, Oct 1980.

Lind, M.A., J.S. Hartman, E.S. Takle, and J.L. Stanford, Radio noise studies of several severe weather events in Iowa in 1971, *J. Atmospheric Sci.*, **29**, 1220-1223, 1972.

Malan, D.J., Radiation from lightning discharges and its relation to discharge processes; in *Recent Advances in Atmospheric Electricity*, L.G. Smith, Ed., pp. 557-563, Pergamon Press, London, 1958.

Marney, G.O., and K. Shanmugam, Effect of channel orientation on the frequency spectrum of lightning discharges, *J. Geophys. Res.*, **76**, 4198-4202, 1971.

Maxwell, E.L., Atmospheric noise from 20 Hz to 30 KHz, *Radio Science*, **2**, 637-644, 1967.

Maxwell, E.L., and D.L. Stone, Natural noise fields from 1 CPS to 100 KC, *IEEE*

Trans. on Antenna and Propagation, AP-11, 339-343, 1963.

Nakai, T., On the time and amplitude properties of electric fields near sources of lightning in the VLF, HF, and LF bands, *Radio Science*, **12**, 389-396, 1977.

Nakai, T., The frequency spectrum of atmospherics, *Proc. Res. Inst. Atmos., Nagoya Univ.*, **3**, 1955.

Nanevich, J.E., E.F. Vance, and J.M. Hamm, Observation of lightning in the frequency and time domains, *Electromagnetics*, **7**, 267-268, 1987.

Nanevich, J.E., E.F. Vance, W. Radsky, M.A. Uman, G.K. Soper, and J.M. Pierre, EMP susceptibility insights from aircraft exposure to lightning, *Electromagnetic Comp.*, **30**, 463-472, Nov. 1988.

Obayashi, T., Measured frequency spectra of VLF atmospherics, *J. Res. National Bureau of Standards*, **64D**, 41-48, 1960.

Oetzel, G.N., and E.T. Pierce, Radio emissions from close lightning; in *Planetary Electrodynamics*, I, S.C. Coroniti and J. Hughes, Eds., pp. 543-570, Gordon and Breach, New York, 1969.

Oh, L.L., Measured and calculated spectral amplitude distribution of lightning sferics, *IEEE Trans. on Electromagnetic Compatibility*, EMC-11, 125-130, 1969.

Pawsey, J.L., Radar observation of lightning on 1.5 meters, *J. Atmos. Terr. Phys.*, **11**, 289-290, 1957.

Pierce, E.T., Atmospherics: their characteristics at the source propagation; in *Radio Science 1963-1966*, Pt. 1, pp. 987-1039, International Scientific Radio Union, Berkeley, Calif., 1967.

Pierce, E.T., The thunderstorm as a source of atmospheric noise at frequencies between 1 and 100 KHz, Stanford Research Institute Technical Report, Project 7045, NASA 2299, June 1969.

Pierce, E.T., Atmospherics and radio noise; in *Lightning*, 1 (Physics of Lightning, R.H. Golde, Ed.), pp. 351-384, Academic Press, New York, 1977.

Pierce, E.T., Spherics (sferics); in *Encyclopedia of Atmospheric Sciences and Astrogeology*, R.W. Fairbridge, Ed., pp. 935-939, Reinhold Publishing, 1967.

Preta, J., M.A. Uman, and D.G. Childers, Comment on "The electric field spectra of first and subsequent lightning return strokes in the 1- to 200-km range" by Serhan et al., *Radio Science*, 20, 143-145, 1985.

Richard, P., A. Delannoy, G. Labaune, and P. Laroche, Results of spatial and temporal characterization of the VHF-UHF radiation of lightning, *J. Geophys. Res.*, 91, 1248-1260, 1986.

Rust, W.D., P.R. Krehbiel, and A. Shlanta, Measurements of radiation from lightning at 2200 MHz, *Geophys. Res. Lett.*, 6, 85-88, 1979.

Rustan, P.L., Description of an aircraft lightning and simulated nuclear electromagnetic pulse (HEMP) threat based on experimental data, *IEEE Trans. Electromagn. Comp.*, EMC-20, 49-63, Feb. 1987.

Schafer, J.P., and W.M. Goodall, Peak field strengths of atmospherics due to local thunderstorm at 150 megacycles, *Proc. IRE*, 27, 202-207, 1939.

Sen, A.K., and M.K. Das Gupta, Atmospherics in relation to source phenomena and radio wave propagation in the VHF, UHF, microwave and millimeter wave bands, *Ind. J. Radio Space Phys.*, 16, 127-135, February 1987.

Serhan, G.I., M.A. Uman, D.G. Childers, and Y.T. Lin, The RF spectra of first and subsequent lightning return strokes in the 1-200 km range, *Radio Science*, 15, 1089-1094, 1980.

Shumpert, T.H., M.A. Honnell, and G.K. Lott, Jr., Measured spectral amplitude of lightning sferics in the VHF, and UHF bands, *IEEE Trans. on Electromagnetic Compatibility*, EMC-24, 368-372, 1982.

Srivastava, K.M.L., and B.A.P. Tantry, VLF characteristic of electromagnetic radiation from the return stroke of lightning discharge, *Ind. J. Pure and Appl. Phys.*, 4, 272-275, 1966.

Stanford, J.L., M.A. Lind, and G.S. Takle, Electromagnetic noise studies of severe convective storms in Iowa: The 1970 storm season, *J. Atmos. Sci.*, 28, 436-448, 1971.

Steptoe, B.J., Some observations on the spectrum and propagation of atmospherics, Ph.D. Thesis, University of London, England, 1958.

Takagi, M., VHF radiation from ground discharges; in *Planetary Electrodynamics*, S.C. Coroniti and J. Hughes, Eds., pp. 535-538, Gordon and Breach, New York, 1969a.

Takagi, M., VHF radiation from ground discharges, *Proc. Res. Inst. Atmos.*, Nagoya Univ., Japan, 16, 163-168, 1969b.

Takagi, M., and T. Takeuti, Atmospherics radiation from lightning discharge, *Proc. Res. Inst. Atmos.*, Nagoya Univ., 10, P.1, 1963.

Taylor, W.L., Radiation field characteristics of lightning discharges in the band 1 KC/s to 100 KC/s, *J. Res. National Bureau of Standards*, 67D, 539-550, 1963.

Taylor, W.L., Lightning characteristics as derived from spherics; in *Problems of Atmospheric and Space Electricity*, S.C. Coroniti, Ed., pp. 388-404, American Elsevier, New York, 1965.

Taylor, W.L., Electromagnetic radiation from severe storms in Oklahoma during April 29-30, 1970, *J. Geophys. Res.*, 78, 8761-8777, 1973.

Taylor, W.L., and A.G. Jean, Very low frequency radiation spectra of lightning discharges, *J. Res. National Bureau of Standards*, 63D, 199-204, 1959.

Thomas, H.A., and R.E. Burgess, Survey of existing information and data on radio noise over frequency range 1-30 MC/s, *Radio Res. Special Rep.*, 15, 1947.

Uman, M.A., and E.P. Krider, The electromagnetic characteristics of lightning, *J. Defense Research, Special Issue B4-1*, 343-361, 1984.

Uman, M.A., and E.P. Krider, A review of natural lightning: Experimental data and modeling, *IEEE Trans. EMC, EMC-24*, 79-112, 1982.

Uman, M.A., M.J. Master, and E.P. Krider, A comparison of lightning electromagnetic fields with the nuclear electromagnetic pulse in the frequency range 104 to 107 Hz, *IEEE Trans. EMC-24, EMC-24*, 410-416, 1982.

Vance, E.F., and M.A. Uman, Differences between lightning and nuclear electromagnetic pulse interactions, *IEEE Trans. Electromagnetic Comp.*, 30, 54-62, February, 1988.

Watt, A.D., and E.L. Maxwell, Characteristics of atmospheric noise from 1 to 100 KC, *Proc. Inst. Radio Engineers*, 45, 55-62, 1957.

Weidman, C.D., The submicrosecond structure of lightning radiation fields, Ph.D. Thesis, Univ. of Arizona, 1982.

Weidman, C.D., and E.P. Krider, The amplitude spectra of lightning radiation fields in the interval from 1 to 20 MHz, *Radio Science*, 21, 964-970, 1986.

Weidman, C.D., Krider, E.P., and M.A. Uman, Lightning amplitude spectra in the interval 100 KHz to 20 MHz, *Geophys. Res. Lett.*, 8, 931-934, 1981.

Willett, J.C., J.C. Bailey, and E.P. Krider, A class of unusual lightning electric field waveforms with very strong HF radiation, *J. Geophys. Res.*, 94, 16,255-16,267, 1989.

Williams, J.C., Thunderstorms and VLF radio noise, Ph.D. Thesis, Harvard University, Cambridge, Mass., 1959.

Zonge, K.L., and W.H. Evans, Prestroke radiation from thunderclouds, *J. Geophys. Res.*, 71, 1519-1523, 1966.

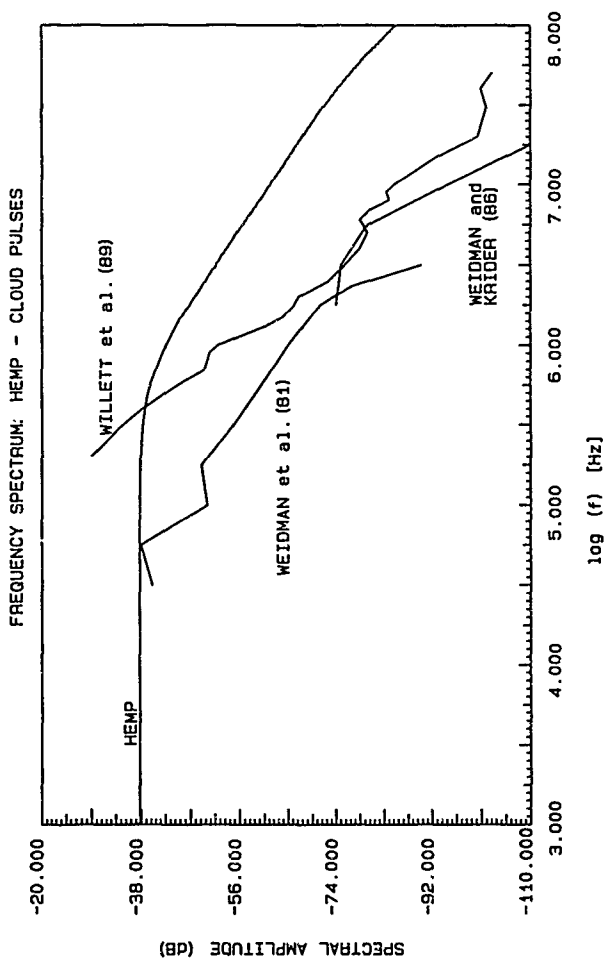


Figure 1. Frequency spectrum of cloud pulses normalized to a distance of 50 meters and HEMP spectrum.

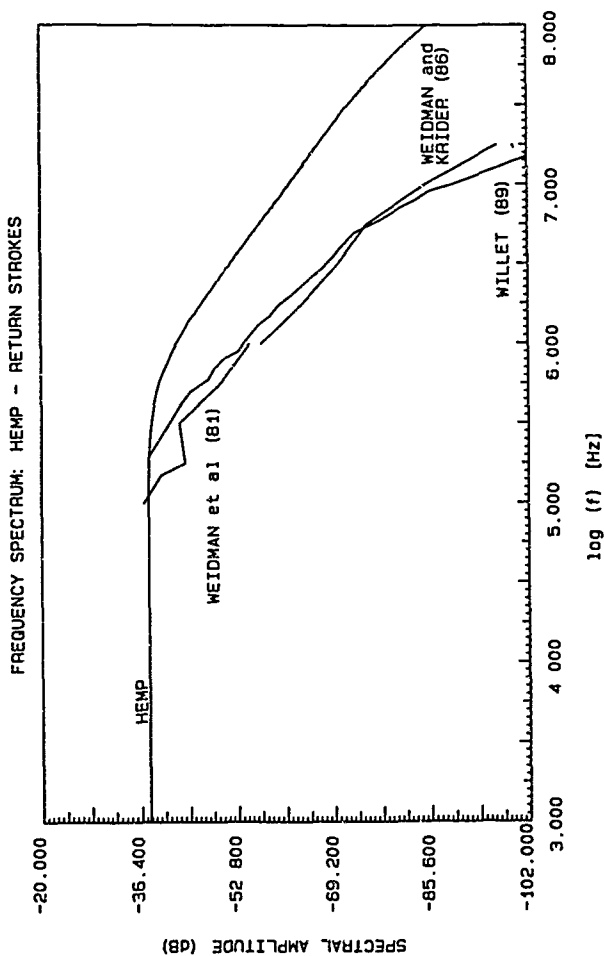
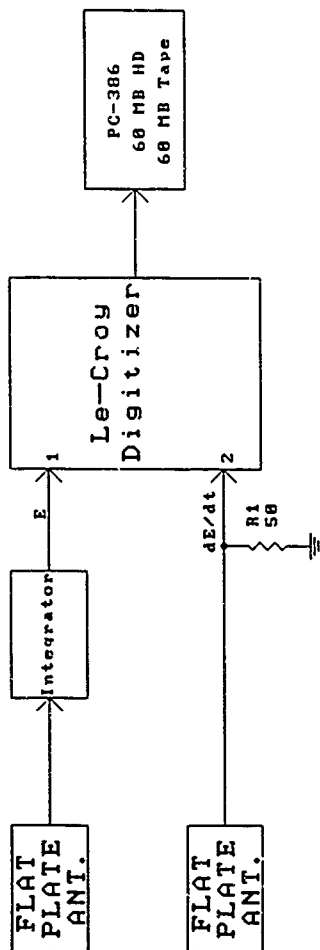
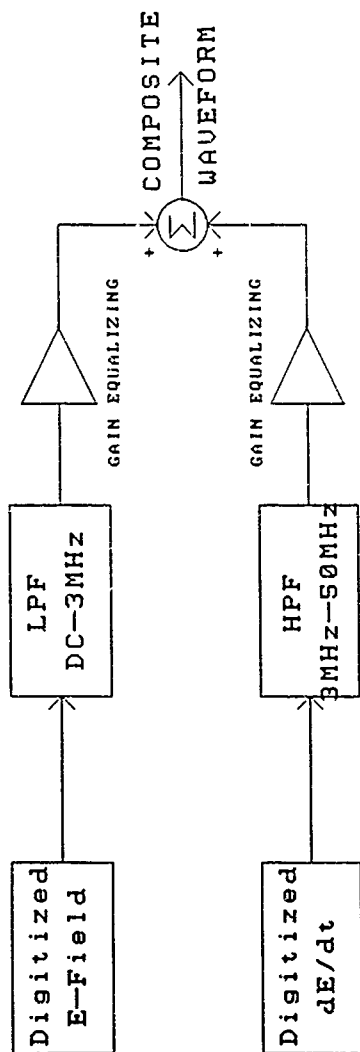


Figure 2. Frequency spectrum of return strokes normalized to a distance of 50 meters and HEMP spectrum.



BASIC RECORDING CONFIGURATION

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



DIGITAL SIGNAL PROCESSING COMPOSITE WAVEFORMS

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

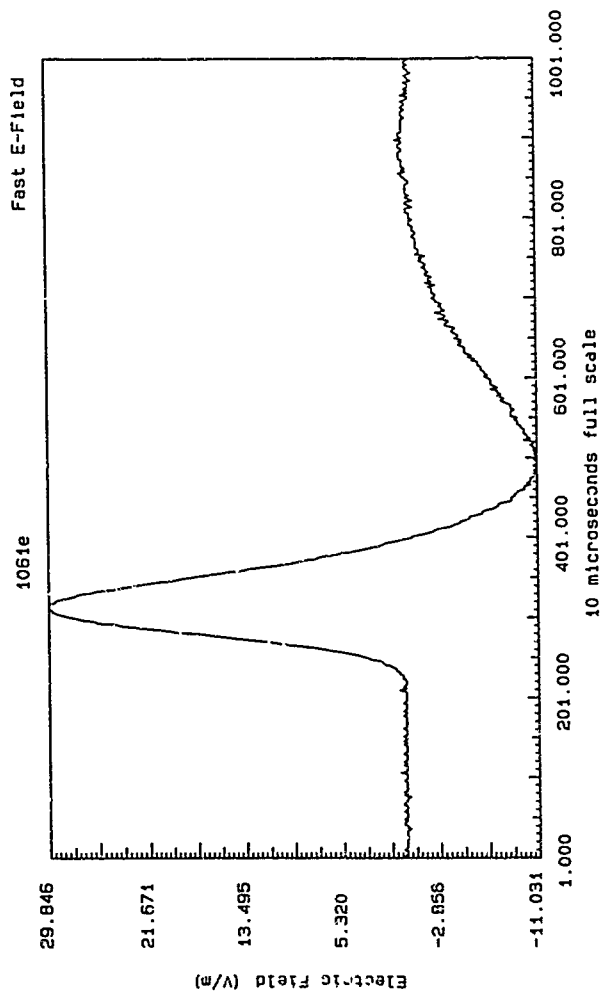


Figure 5. An electronically integrated E-field waveform recorded on day 269.

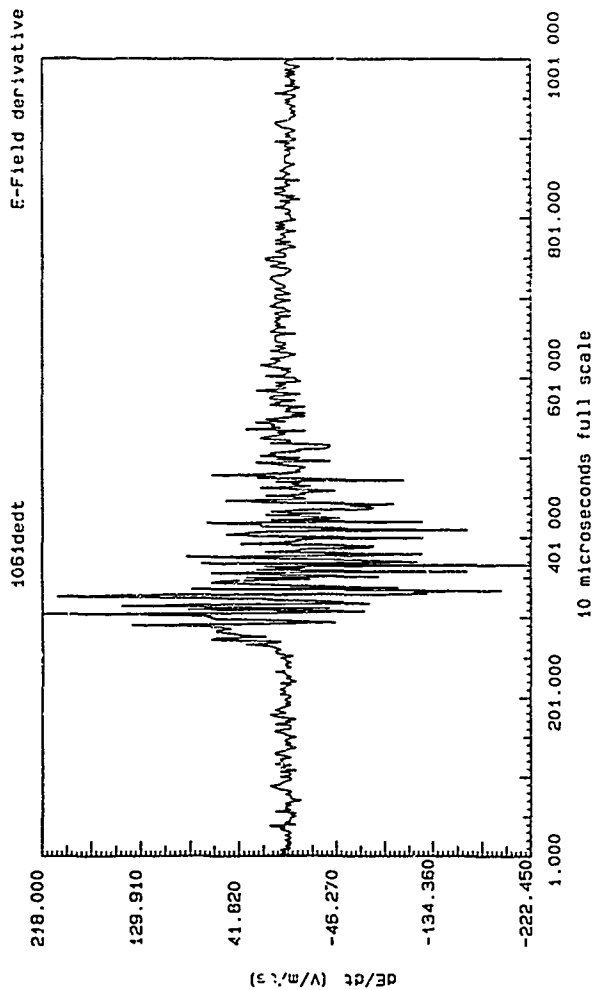


Figure 6. dE/dt waveform recorded simultaneously with the E-field waveform shown in Figure 5.

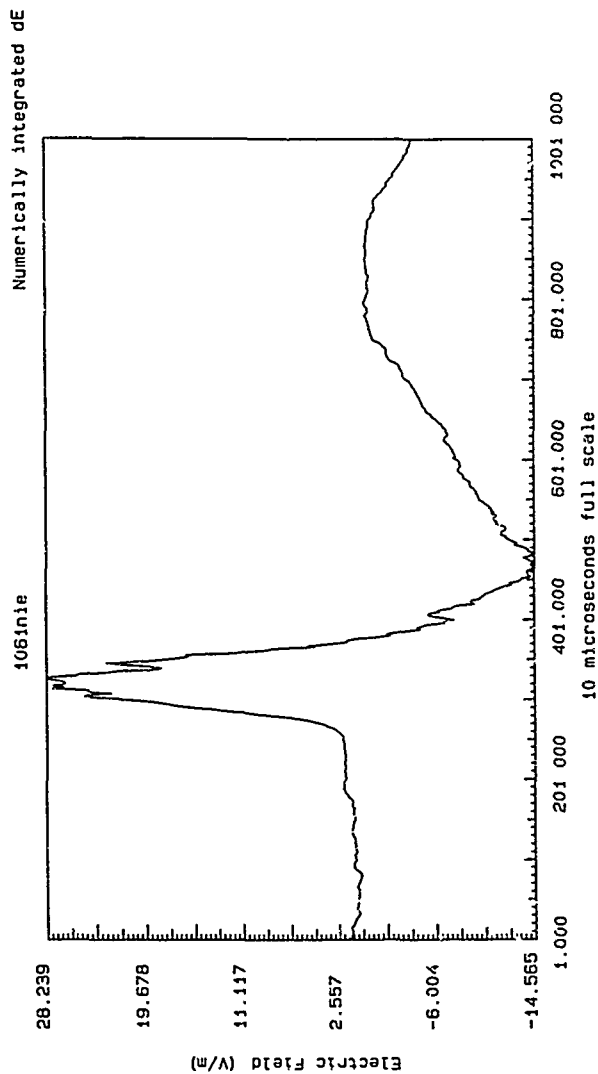


Figure 7. Waveform obtained by numerically integrating the dE/dt waveform shown in Figure 6.

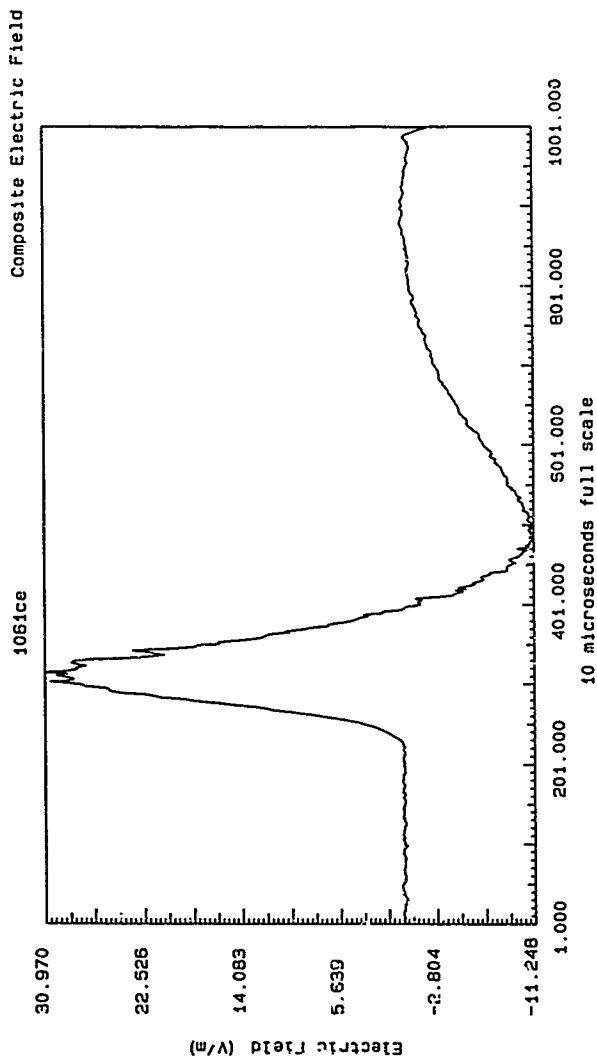


Figure 8. Composite electric field waveform obtained using the method described in Figure 4.

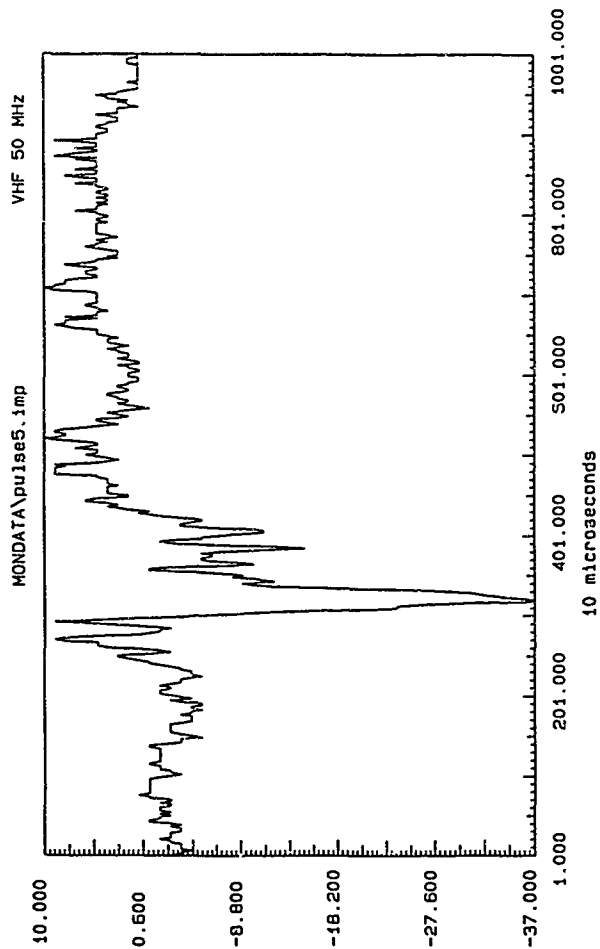


Figure 9. 50 MHz VHF radiation recorded simultaneously with the cloud pulse shown in Figures 5 to 8.

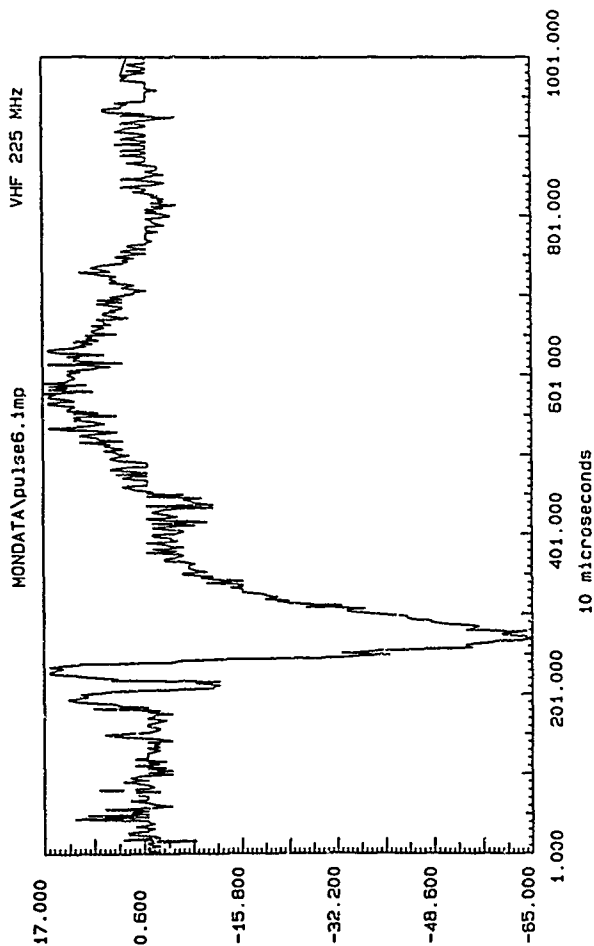


Figure 10. 225 MHz VHF radiation recorded simultaneously with the cloud pulse shown in Figures 5 to 8.

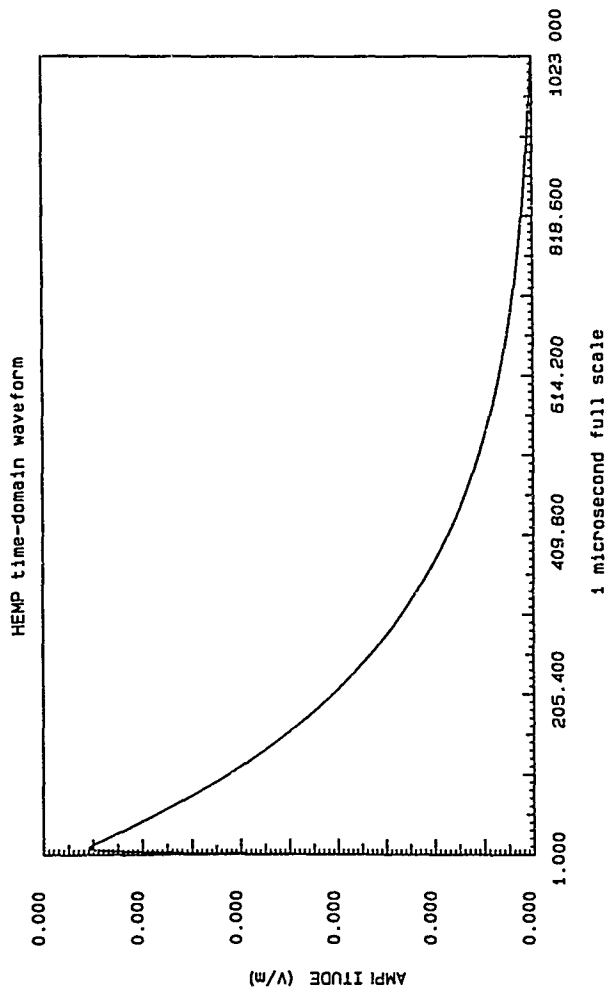


Figure 11. HEMP time-domain waveform (from Lee [1986]).

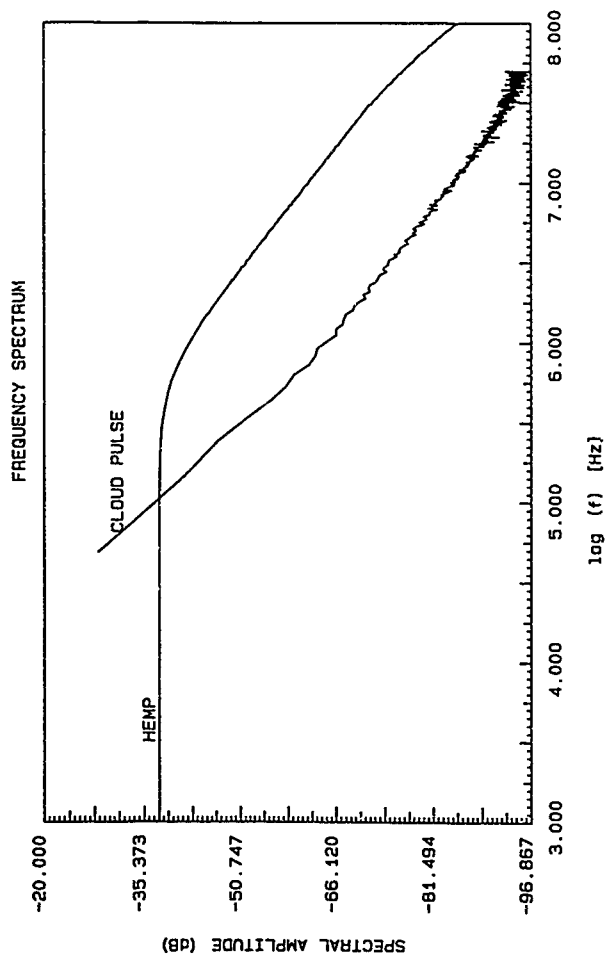


Figure 12. Comparison of the average power spectrum of the ten largest cloud pulses recorded at KSC during the 1989 experiment, normalized to 50 meters, and HEMP spectrum.

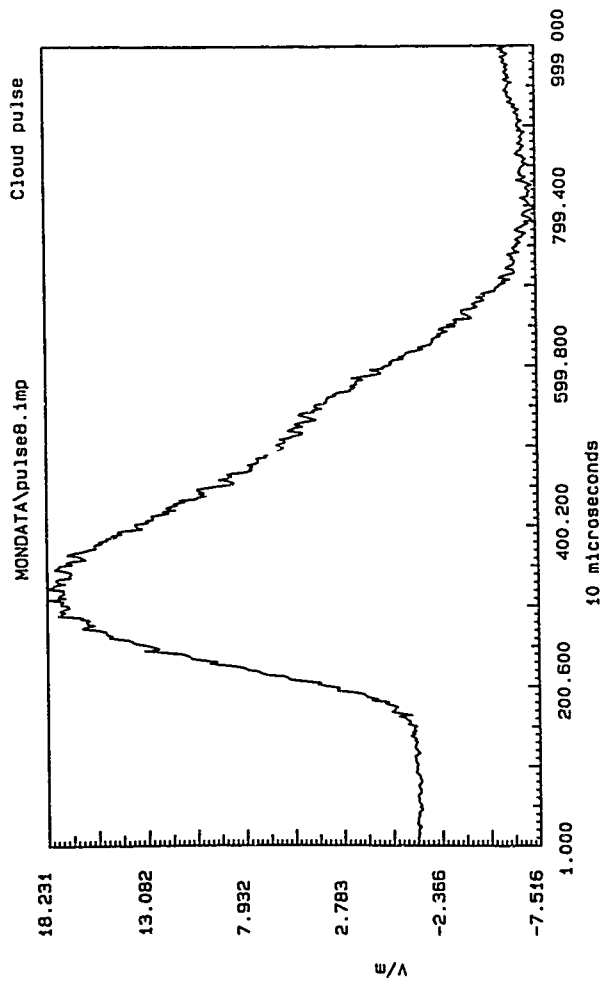


Figure 13. Example of a cloud pulse recorded on day 269.

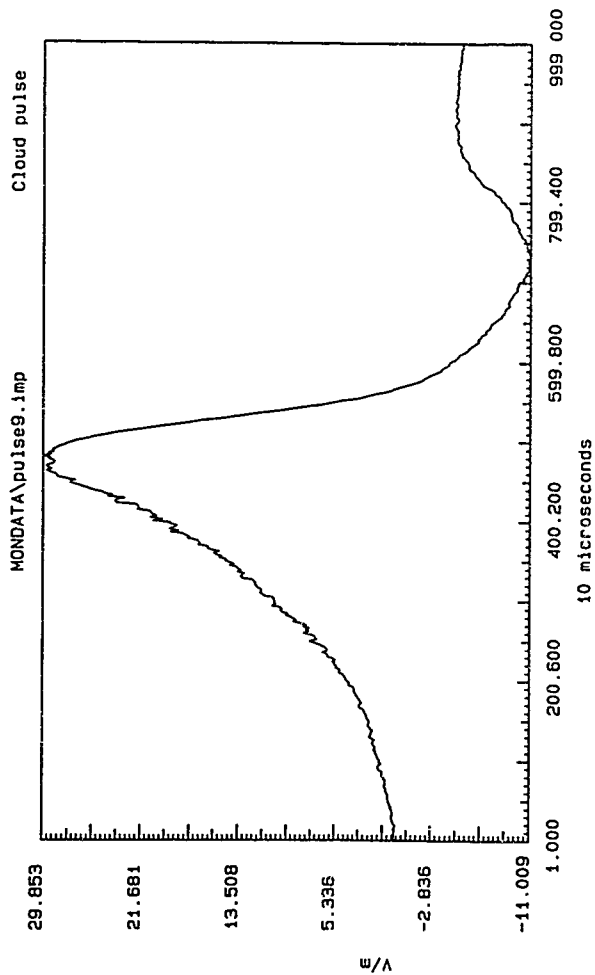


Figure 14. Example of a cloud pulse recorded on day 269.

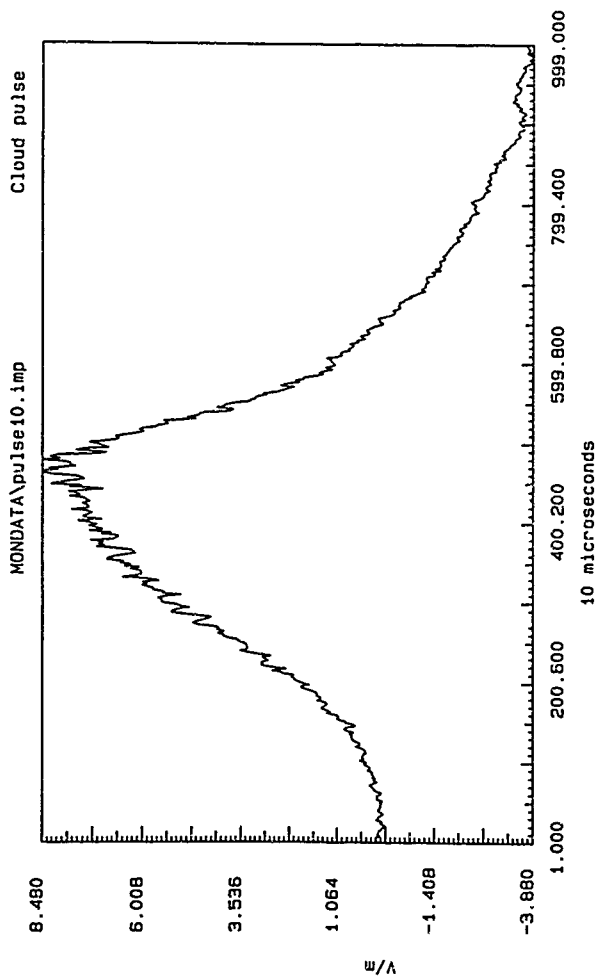


Figure 15. Example of a cloud pulse recorded on day 269.

FILE 26800911.P89

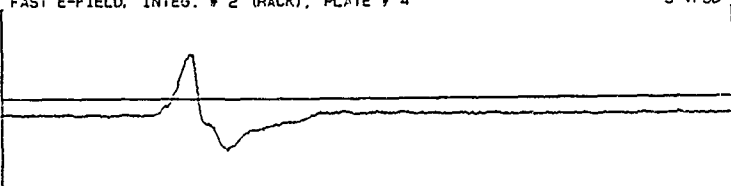
TIME 21.17:48.126857

POINTS: 16384

163.84 lsecs

FAST E-FIELD, INTEG. # 2 (RACK), PLATE # 4

5 VFSO



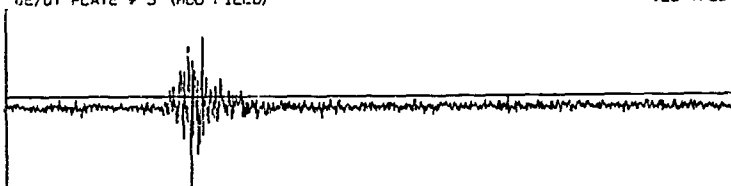
50 MHz VHF

25 VFSO



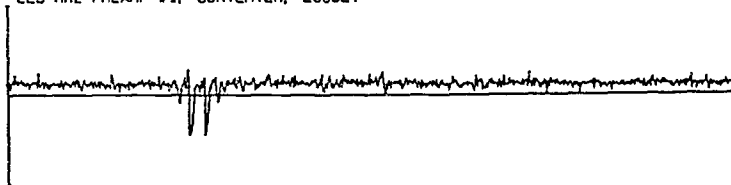
dE/dT PLATE # 3 (MOD FIELD)

.25 VFSO



225 MHz PREAMP #1, CONVERTER, LOGDET

5 VFSO



SLOW E-FIELD, INTEG. # 3 (RACK), PLATE # 5

.25 VFSO

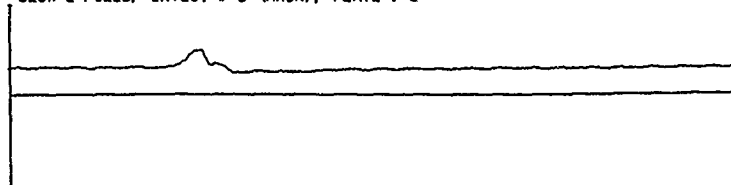


Figure 16. Example of simultaneously recorded waveforms.

FILE 26801141.P89

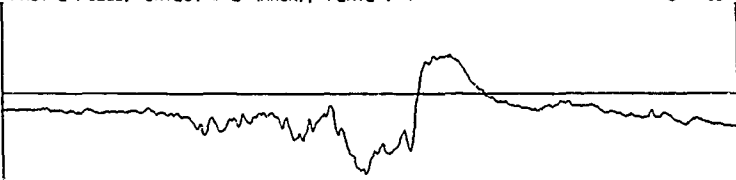
TIME 21. 24. 24.907670

POINTS: 16384

163.84 lsecs

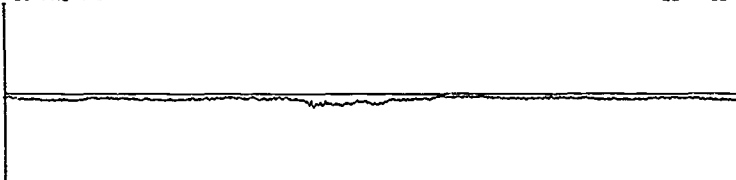
FAST E-FIELD, INTEG. # 2 (RACK), PLATE # 4

5 VFSD



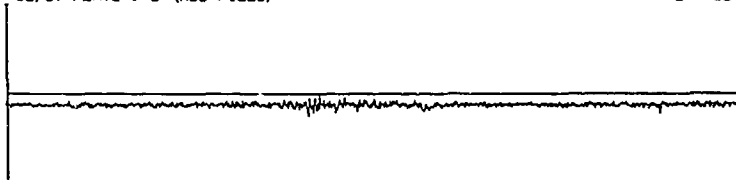
50 MHz VHF

25 VFSD



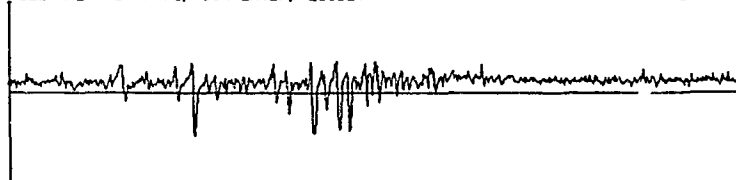
dE/dt PLATE # 3 (MDD FIELD)

5 VFSD



225 MHz PREAMP #1, CONVERTER, LOGDET

5 VFSD



SLOW E-FIELD, INTEG. # 3 (RACK), PLATE # 5

.25 VFSD

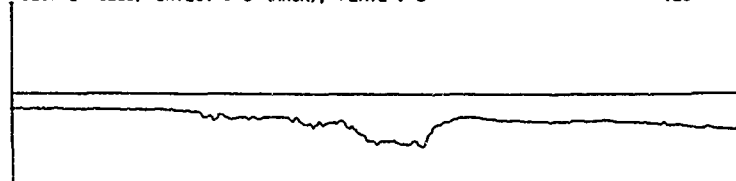


Figure 17. Example of simultaneously recorded waveforms.

FILE 26801083.P89

TIME 21: 22: 49.858734

POINTS: 16384

163.84 lsecs

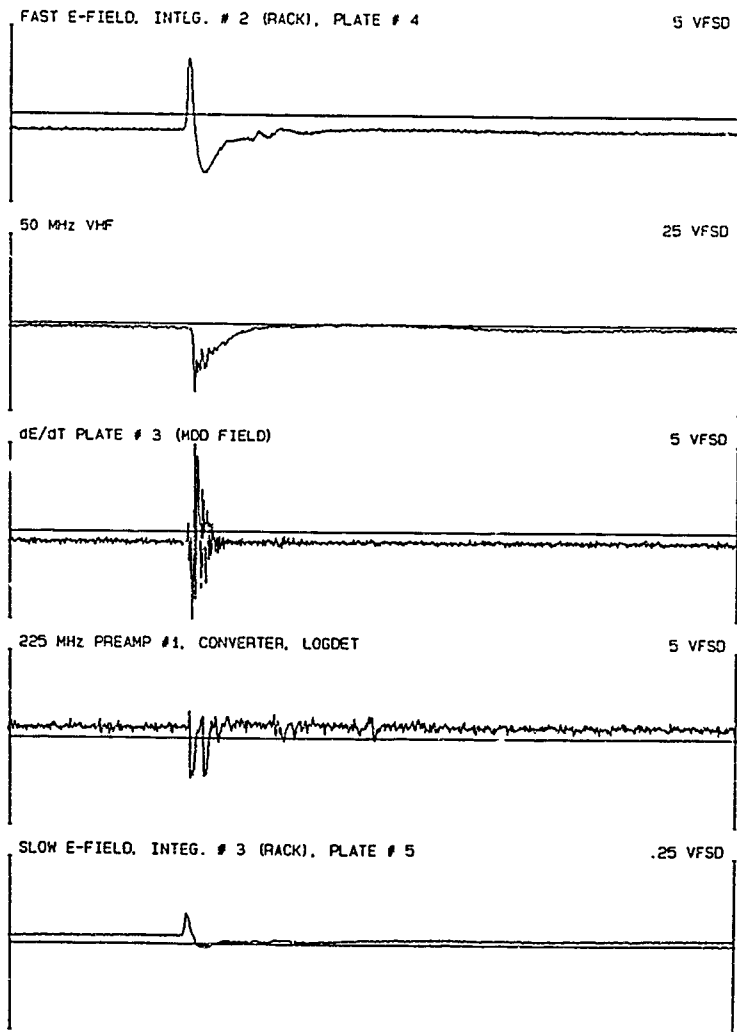


Figure 18. Example of simultaneously recorded waveforms.

FILE 26801058.P89

TIME 21. 21: 57.957315

POINTS: 16384

163.84 lsecs

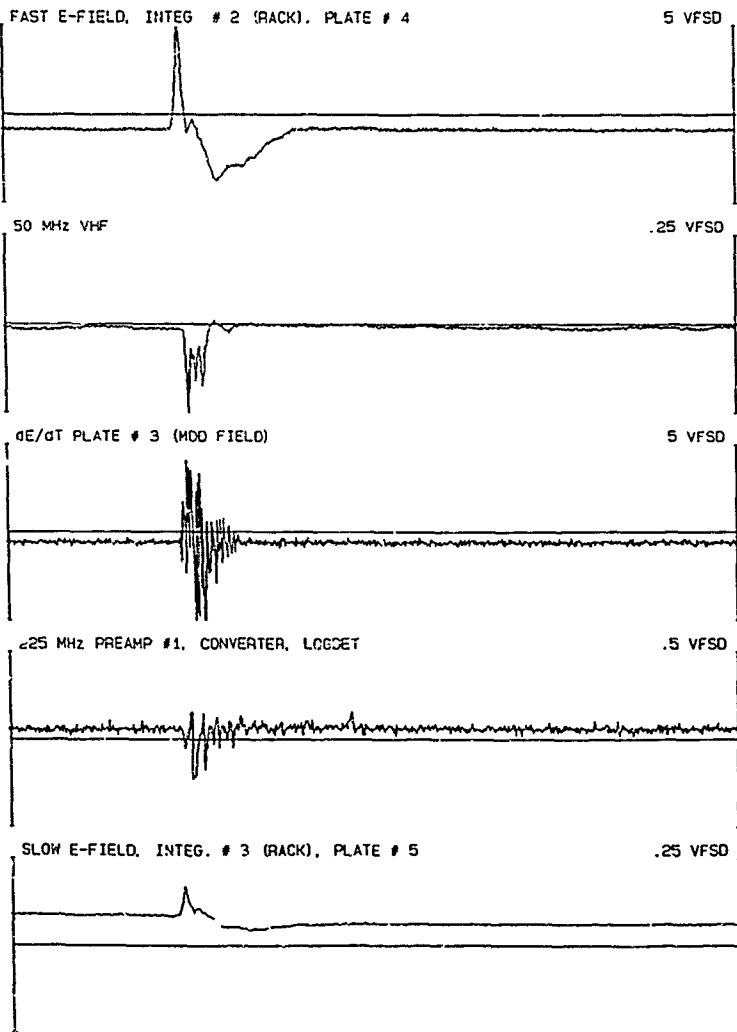


Figure 19. Example of simultaneously recorded waveforms.

FILE 26800380.P89

TIME 20:21:48.885808b

POINTS: 16384

163.84 lsecs

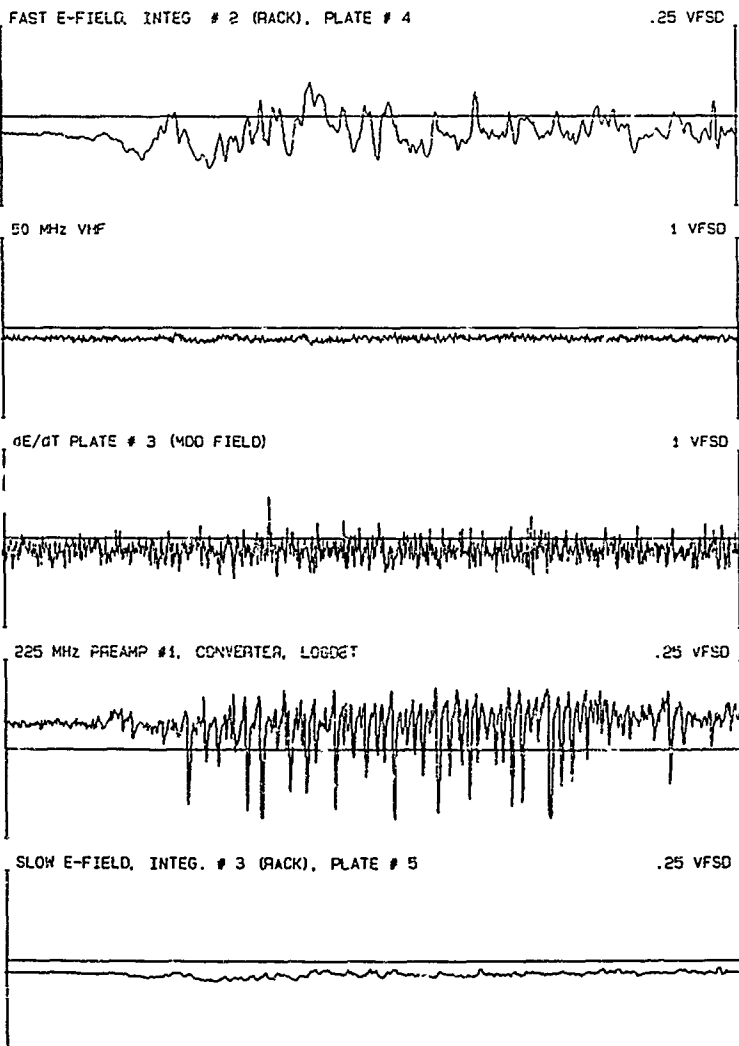


Figure 20. Example of simultaneously recorded waveforms.

FILE 26800881.P89 TIME 21:16.57.766252

POINTS: 16384

163.84 lsecs

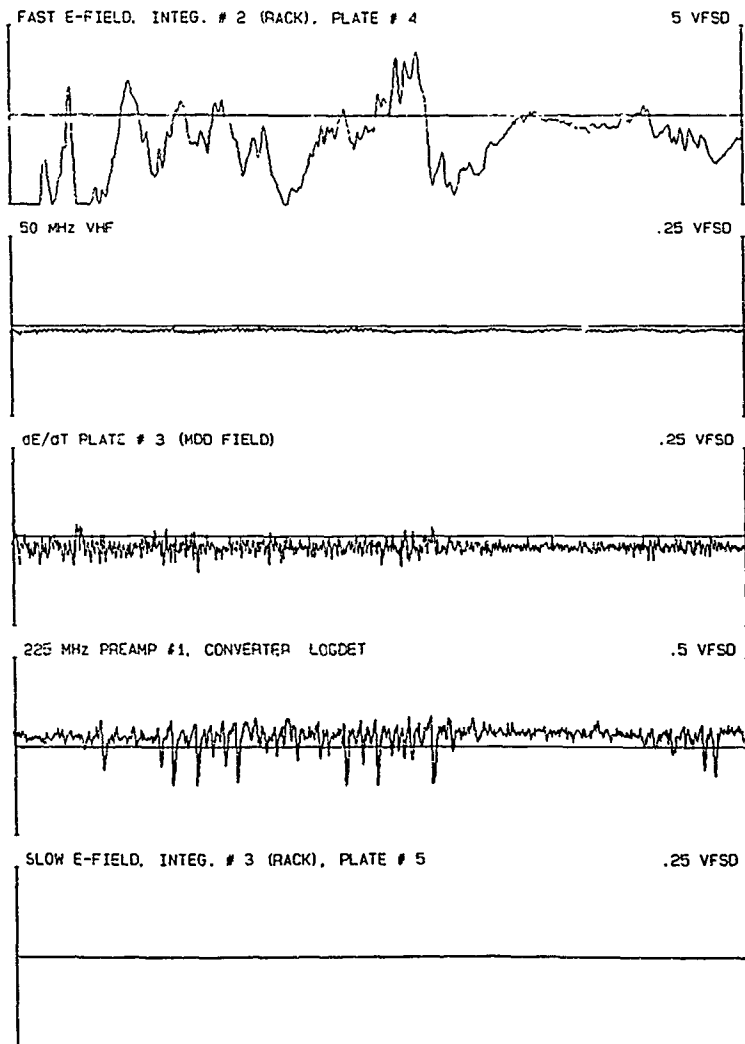


Figure 21. Example of simultaneously recorded waveforms.

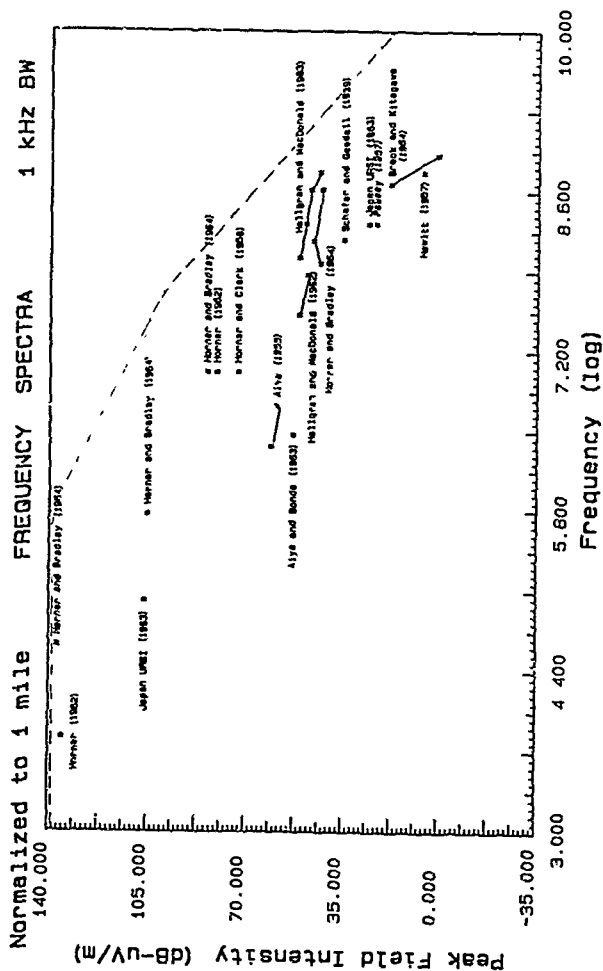


Figure 22. Comparison of HEMP spectrum (dashed line) with available lightning narrowband spectral data.

DISTRIBUTION LIST

DNA-TR-90-101

DEPARTMENT OF DEFENSE

ARMED FORCES RADIOBIOLOGY RESEARCH INSTITUTE

ATTN: DR M R LANDAUER/BHS

ASSISTANT TO THE SECRETARY OF DEFENSE

ATTN: EXECUTIVE ASSISTANT

DEFENSE COMMUNICATIONS AGENCY

ATTN: CODE DTJ (B410) DEANE PARKER

DEFENSE COMMUNICATIONS AGENCY

ATTN: COMMANDER

DEFENSE COMMUNICATIONS ENGINEER CENTER

ATTN: CODE R410

DEFENSE INTELLIGENCE AGENCY

ATTN: DT-5A (R BURGER)

ATTN: RTS-2B

ATTN: VP-TPO

DEFENSE NUCLEAR AGENCY

ATTN: DTRA

ATTN: OPNA

ATTN: OPNS

ATTN: RAAE

ATTN: RAE

ATTN: RAEV

2 CYS ATTN: TITL

DEFENSE NUCLEAR AGENCY

2 CYS ATTN: NMRS (MSGT YOAS)

2 CYS ATTN: TDTT

2 CYS ATTN: TST E RINEHART

DEFENSE TECHNICAL INFORMATION CENTER

2 CYS ATTN: DTIC/FDAB

DNA PACOM LIAISON OFFICE

ATTN: DNALO

NATIONAL DEFENSE UNIVERSITY

ATTN: NWCO

NET ASSESSMENT

ATTN: DOCUMENT CONTROL

STRATEGIC AND THEATER NUCLEAR FORCES

ATTN: DR E SEVIN

THE JOINT STAFF

ATTN: JKA

ATTN: JKC (ATTN: DNA REP)

ATTN: JKCS

ATTN: JLWT (THREAT ANALYSIS)

ATTN: JPEM

THE JOINT STAFF

ATTN: J-3/NUC OPS BR, STRAT OPS BR

ATTN: J-5 NUCLEAR & CHEMICAL DIV

ATTN: J-6F D BUTTS

ATTN: J-8/CAD

DEPARTMENT OF THE ARMY

ABERDEEN PROVING GROUND

ATTN: AMSLC-VL-DE, R REITZ

DEPARTMENT OF STAFF FOR OPS & PLANS

ATTN: DAWO-ODW

HARRY DIAMOND LABORATORIES

ATTN: SLCHD NW

2 CYS ATTN: SLCHD-NW-E

ATTN: SLCHD-NW-E L PATRICK

ATTN: SLCHD-NW-EP

ATTN: SLCHD-NW-RC

ATTN: SLCHD-NW-TN

ATTN: SLCHD-NW-TN (G MERKEL)

ATTN: SLCHD-IM-TL (TECH LIB)

ATTN: W PATTERSON

NUCLEAR EFFECTS DIVISION

ATTN: STEWS-NE J MEASON

OFFICE OF ASSISTANT SECRETARY OF ARMY

RESEARCH, DEVELOPMENT & ACQ

ATTN: SARD-ZCA

U S ARMY ATMOSPHERIC SCIENCES LAB

ATTN: SLCAS-AS

U S ARMY BALLISTIC RESEARCH LAB

ATTN: SLCBR-SS-T (TECH LIB)

ATTN: SLCBR-TB B (G BULMASH)

ATTN: SLCBR-VL

U S ARMY ENGINEER DIV HUNTSVILLE

ATTN: CEHND-SY J LOYD

ATTN: HNDED-SY

U S ARMY MISSILE COMMAND/AMSMI RD-CS-R

ATTN: AMSMI-RD-CS-R (DOCS)

U S ARMY NUCLEAR & CHEMICAL AGENCY

ATTN: MONA NU (D BASH)

U S ARMY STRATEGIC DEFENSE CMD

ATTN: CSSD-H-SAV

U S ARMY STRATEGIC DEFENSE COMMAND

ATTN: CSSD-SL

U S ARMY TEST & EVALUATION COMMAND

ATTN: TECHNICAL LIBRARY

U S ARMY WAR COLLEGE

ATTN: LIBRARY

U S ARMY MATERIEL SYS ANALYSIS ACTVY

ATTN: AMXSY-CR

USA SURVIVABILITY MANAGEMENT OFFICE

ATTN: SLCSM-SE J BRAND

DNA-TR-90-101 (DL CONTINUED)

USACACDA
ATTN: ATZL CAD-N

DEPARTMENT OF THE NAVY

NAVAL AIR SYSTEMS COMMAND
ATTN: AIR 5161

NAVAL AIR TEST CENTER
ATTN: ROTARY WING TEST DIRECTORATE
ATTN: SY84

NAVAL POSTGRADUATE SCHOOL
ATTN: CODE 1424 LIBRARY

NAVAL RESEARCH LABORATORY
ATTN: CODE 2627 (TECH LIB)

NAVAL SURFACE WARFARE CENTER
ATTN: CODE H25 G BRACKETT
ATTN: CODE R41
ATTN: CODE 425

NAVAL SURFACE WARFARE CENTER
ATTN: CODE H-21

OFFICE OF CHIEF OF NAVAL OPERATIONS
ATTN: NOP 098 (OFC RES-DEV-TEST & EVAL)
ATTN: NOP 503
ATTN: NOP 551
ATTN: NOP 541F
ATTN: OP 654

THEATER NUCLEAR WARFARE PROGRAM OFC
ATTN: PMS 423

DEPARTMENT OF THE AIR FORCE

AERONAUTICAL SYSTEMS DIVISION
ATTN: ASD/ENACE

AFIA/INIS
ATTN: AFIA/INKS

AIR FORCE CTR FOR STUDIES & ANALYSIS
ATTN: AFCSA/SAMI (R GRIFFIN)

AIR FORCE SPACE COMMAND
ATTN: DEES/D C DE MIO

AIR FORCE TECHNICAL APPLICATIONS CTR
ATTN: TXR

AIR UNIVERSITY LIBRARY
ATTN: AUL-LSE

OKLAHOMA CITY AIR LOGISTICS CTR
ATTN: MMETS/H R DVORAK
ATTN: MMETT MAJ HANSEN

SACRAMENTO AIR LOGISTICS CTR
ATTN: GEORGE DUGAN

SPACE DIVISION/IN
ATTN: IND

SPACE DIVISION/YA
ATTN: YAR

SPACE SYSTEMS DIVISION
ATTN: SSD/MSG, CAPT D ROBBINS

USAF/LEEEU
ATTN: LEEU

WEAPONS LABORATORY
ATTN: J FISHER
ATTN: NTAA
ATTN: WL/SUL

DEPARTMENT OF ENERGY

LAWRENCE LIVERMORE NATIONAL LAB
ATTN: L-86 H CABAYAN

LOS ALAMOS NATIONAL LABORATORY
ATTN: REPORT LIBRARY

SANDIA NATIONAL LABORATORIES
ATTN: ORG 1230
ATTN: TECH LIB 3141

OTHER GOVERNMENT

CENTRAL INTELLIGENCE AGENCY
ATTN: OSWR/NED
ATTN: OSWR/STD/MTB

FEDERAL EMERGENCY MANAGEMENT AGENCY
ATTN: R GATES, EMP PROGRAM
ATTN: SL-CD-MP

DEPARTMENT OF DEFENSE CONTRACTORS

ALLIED-SIGNAL, INC
ATTN: DOCUMENT CONTROL

BDM INTERNATIONAL INC
ATTN: E DORCHAK

BDM INTERNATIONAL INC
ATTN: B TORRES,
ATTN: L O HOEFT
ATTN: B PLUMMER

BOEING CO
ATTN: D EGEKROUT
ATTN: D CHAPMAN

BOEING TECHNICAL & MANAGEMENT SVCS, INC
ATTN: ARNOLD D BAKER

BOOZ ALLEN & HAMILTON, INC
ATTN: TECHNICAL LIBRARY

BOOZ-ALLEN & HAMILTON, INC
ATTN: D VINCENT
ATTN: L ALBRIGHT
ATTN: THOMAS J ZWOLINSKI

COMPUTER SCIENCES CORP
ATTN: A SCHIFF

E-SYSTEMS, INC
ATTN: TECH INFO CTR

EG&G SPECIAL PROJECTS INC
ATTN: J GILES

ELECTRO MAGNETIC APPLICATIONS, INC
ATTN: D MEREWETHER

FAIRCHILD SPACE COMPANY
ATTN: R CARPENTER

FLORIDA UNIVERSITY OF
2 CYS ATTN: M A UMAN

GENERAL ELECTRIC CO
ATTN: DAREN NERAD

GENERAL ELECTRIC CO
ATTN: P HEILAND

GENERAL RESEARCH CORP
ATTN: W NAUMANN

GRUMMAN AEROSPACE CORP
ATTN: H SMITH, TECH INFO CNTR

GTE GOVERNMENT SYSTEMS CORP
ATTN: TECH LIBRARY

HERCULES DEFENSE ELECTRONICS SYSTEMS, INC
ATTN: SECURITY (J TETI)

HONEYWELL SYSTEMS & RESEARCH CENTER
ATTN: SR&C LIBRARY/T CLARKIN

IIT RESEARCH INSTITUTE
ATTN: I MINDEL

INSTITUTE FOR DEFENSE ANALYSES
ATTN: CLASSIFIED LIBRARY
ATTN: TECH INFO SERVICES

JAYCOR
ATTN: E WENAAS

JAYCOR
ATTN: E WENAAS
ATTN: M SCHULTZ, JR

KAMAN SCIENCES CORP
ATTN: LIBRARY/B KINSLOW

KAMAN SCIENCES CORP
ATTN: DASAC
ATTN: E CONRAD

KAMAN SCIENCES CORPORATION
ATTN: TECHNICAL LIBRARY

KAMAN SCIENCES CORPORATION
ATTN: DASAC
ATTN: R RUTHERFORD

KEARFOTT GUIDANCE AND NAVIGATION CORP
ATTN: J D BRINKMAN

LITTON SYSTEMS, INC
ATTN: J SKAGGS

LOCKHEED MISSILES & SPACE CO, INC
ATTN: TECH INFO CTR D/COLL

LOCKHEED SANDERS, INC
ATTN: BRIAN G CARRIGG

LTV AEROSPACE & DEFENSE COMPANY
2 CYS ATTN: LIBRARY

METATECH CORP
ATTN: C JONES

METATECH CORPORATION
ATTN: W RADASKY

MISSION RESEARCH CORP
ATTN: C LONGMIRE
ATTN: EMP GROUP
ATTN: N CARRON
ATTN: TECH INFO CENTER
ATTN: W CREVIER

MISSION RESEARCH CORP
ATTN: J LUBELL
ATTN: J R CURRY
ATTN: W BEREUTER

MISSION RESEARCH CORP, SAN DIEGO
ATTN: V VAN LINT

MITRE CORPORATION
ATTN: M FITZGERALD

MITRE CORPORATION
ATTN: DIRECTOR

NICHOLS RESEARCH CORP, INC
ATTN: HUGO HARDT

PACIFIC-SIERRA RESEARCH CORP
ATTN: H BRODE

R & D ASSOCIATES
ATTN: C MO (NUCLEAR EFFECTS DIV)
ATTN: DOCUMENT CONTROL
ATTN: G K SCHLEGEL

R & D ASSOCIATES
ATTN: J P CASTILLO
ATTN: W S KEHRER

RAND CORP
ATTN: ENGR & APPLIED SCIENCES DEPT

DNA-TR-90-101 (DL CONTINUED)

RAYTHEON CO
ATTN: H FLESCHER

RCA CORPORATION
ATTN: G BRUCKER

RESEARCH TRIANGLE INSTITUTE
ATTN: M SIMONS

ROCKWELL INTERNATIONAL CORP
ATTN: P BELL

ROCKWELL INTERNATIONAL CORP
ATTN: B-1 DIV TIC (BAOB)

ROCKWELL INTERNATIONAL CORP
ATTN: J C ERB, OA13

ROCKWELL INTERNATIONAL CORP
ATTN: G SMITH

S-CUBED
ATTN: J KNIGHTEN
ATTN: LLOYD DUNCAN

SCIENCE & ENGRG ASSOCIATES, INC
ATTN: R M SMITH

SCIENCE APPLICATIONS INTL CORP
ATTN: W ADAMS
ATTN: W CHADSEY
ATTN: W LAYSON

SCIENCE APPLICATIONS INTL CORP
ATTN: P J DOWLING

SRI INTERNATIONAL
ATTN: E VANCE
ATTN: J PREWITT
ATTN: W GRAF

TELEDYNE BROWN ENGINEERING
ATTN: LEWIS T SMITH

TRW
ATTN: M J TAYLOR

TRW INC
ATTN: A R CARLSON
ATTN: G E MORGAN

TRW INC
ATTN: LIBRARIAN

TRW SPACE & DEFENSE SECTOR
ATTN: J D PENAR

TRW SPACE & DEFENSE SECTOR SPACE &
ATTN: HL DEPT/LIBRARY

UNISYS CORPORATION DEFENSE SYSTEMS
ATTN: TECHNICAL LIBRARY

UNITED TECHNOLOGIES CORP
ATTN: ATTN M A ZILLER

FOREIGN

DEFENCE RESEARCH ESTABLISHMENT OTTAWA
ATTN: S KASHYAP

FOA 2
ATTN: B SJOHOLM

FOA 3
ATTN: T KARLSSON