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AIRBORNE MEASUREMENTS OF TRANSIENT ELECTRIC FIELDS AND INDUCED TRANSIENTS IN AIRCRAFT DUE TO CLOSE LIGHTNING

Electromagnetic Hazards Group
Survivability/Vulnerability Branch
Vehicle Equipment Division

June 1977

Technical Report AFFDL-TR-77-64
Final Report for Period July 1976 - August 1976

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AIR FORCE FLIGHT DYNAMICS LABORATORY
Air Force Wright Aeronautical Laboratories
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio 45433

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Jerome T. Dijak

JEROME T. DIJAK, Captain, USAF
Atmospheric Electricity Project Engr

Philip B. Corn

PHILIP B. CORN, Major, USAF
Chief, Electromagnetic Hazards Group

FOR THE COMMANDER

Ambrose B. Nutt

AMBROSE B. NUTT
Chief, Vehicle Equipment Division

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An Air Force Flight Dynamics Laboratory experiment to measure the electromagnetic environment near lightning and thunderstorms and the induced effects of this environment on aircraft wiring was measured ~~was flown~~ on a NASA Learjet aircraft during July and August 1976 as part of Project Thunderstorm (TRIP-76). Instrumentation consisted of an externally mounted transient electric field sensor, induced transient sensors within the aircraft, a discrete spectrum analyzer, and a computer-based waveform digitizing system for high-resolution, → next page

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high-frequency measurements. The electric field environment near thunderstorms was found to be very active with transients even when no lightning was evident. This environment was also responsible for inducing transients on wiring within the aircraft on an almost continuous basis in the vicinity of storms. The spectral content of pulses observed externally and internally on the aircraft varied widely with time. Comparison between the induced transients due to an accidental direct lightning strike to the aircraft and those due to a nearby strike showed the magnitudes of the effects due to the nearby strike to be nearly half those of the direct strike. The induced transients observed in the Learjet were similar in duration, magnitude, and frequency content to those observed during ground simulated lightning tests on other aircraft.

FOREWORD

This report documents the lightning measurements performed by Air Force Flight Dynamics Laboratory during the NASA Learjet flights of July 1976 at Patrick AFB, Florida. The author gratefully acknowledges the cooperation and efforts of personnel from NASA Johnson Space Center, NASA Kennedy Space Center, NASA Ames Research Center, and Stanford Research Institute in making this program possible on the extremely short notice that was available. The author especially wishes to acknowledge the logistics assistance of Mr. Bob Mason of Ames Research Center and Mr. Cecil Jenkins of the JSC Resident Office at Kennedy Space Center as being especially valuable during the flight program.

TABLE OF CONTENTS

Section	Title	Page
I	Introduction	1
	a. Background	1
	b. Objectives	2
	c. Approach	3
	d. Documentation	4
	e. Fourier Transform Interpretation	5
II	Sensors and Instrumentation	7
	a. Transient Electric Field Sensor (External)	7
	b. Induced Transient Sensors (Internal)	7
	c. Transient Digitizer System	9
	d. Discrete Spectrum Analyzer	15
	e. Electric Field Meters	17
III	Results	19
	a. Transient Electric Field Measurements	19
	1. Graticule Interpretation	20
	2. Transient Digitizer Electric Field Data	21
	b. Spectrum Analyzer Measurements	24
	c. Induced Transient Measurements	28
	1. Aircraft Resonances	29
	2. Typical Sensor Responses	31
	3. Spectral Variability	42
	4. Multiple Event Observations	46
	5. Similarity to Ground Simulation Observations	47
IV	Conclusions	51
V	Recommendations	53
	References	55
	Appendix A: Induced Transient Sensor Configurations	57
	Appendix B: BASIC Language Computer Program Listing	59

LIST OF FIGURES

Number	Title	Page
1	Typical Storm System	4
2	Transient Electric Field Sensor Installation (External)	8
3	Digitizer and Computer Installation	10
4	Cargo Area Equipment Installation	11
5	Digitizing System Configuration	14
6	Spectrum Analyzer Configuration	16
7	Example Transient Electric Field Pulse (1621)	22
8	Example Transient Electric Field Pulses (1609, 1627)	23
9	Example Transient Electric Field Pulses (1703, 1720)	25
10	Learjet NASA 705 External Dimensions	30
11	Sensor 10 Typical Response	33
12	Sensor 8 Typical Response	35
13	Sensor 6 Typical Response	37
14	Sensor 5 Typical Response	38
15	Sensor 9 Typical Response	40
16	Sensor 7 Typical Response	41
17	Transient Spectral Variability, Example 1	43
18	Transient Spectral Variability, Example 2	44
19	Transient Spectral Variability, Example 3	45
20	Multiple Event Observations	47
21	Typical Transient, Ground Lightning Simulation	48
A-1	Induced Transient Sensors -- Schematic Diagrams	57

LIST OF ABBREVIATIONS

AFFDL	Air Force Flight Dynamics Laboratory
FET	Field Effect Transistor
FFT	Fast Fourier Transform (digitally computed)
KHz	Kilohertz
MHz	Megahertz
NASA	National Aeronautics and Space Administration
NS, nS	Nanoseconds (10^{-9} second)
pF	Picofarad (10^{-12} Farad)
SRI	Stanford Research Institute
US, μS	Microseconds (10^{-6} second)

SECTION I

INTRODUCTION

a. Background

The present trend toward use of more sophisticated electronic systems in critical airborne applications has caused a heightened awareness of the threat presented by lightning strikes to aircraft carrying such systems. It has long been known that voltage transients are produced within aircraft electrical wiring when the vehicle is struck by lightning, but in the past these effects have resulted in relatively minor damage to the critical systems onboard.

There are now, however, three important trends in aircraft design which suggest that protection from lightning effects is becoming more important: (1) the flight- and mission-critical subsystems are becoming predominantly electronic rather than mechanical or hydraulic; (2) the electronic systems employ primarily solid-state devices rather than vacuum tubes, which reduces the tolerance of these systems to transients; and (3) composites and other nonmetallic materials are being used increasingly in aircraft construction, which could increase the magnitudes of lightning effects within the aircraft. It is becoming extremely important to understand the lightning-aircraft interaction and to provide efficient and effective protection against the effects of lightning strikes on aircraft.

b. Objectives

This program had several objectives. The first was to obtain high-resolution measurements of the high-frequency electric fields associated with lightning and thunderstorms, while the second was to learn as much as possible about the transients that are induced on wires within the aircraft by nearby lightning activity. Additional goals of this effort were to determine if the sophisticated transient digitizer system could be reliably operated in a harsh airborne environment, and to learn if the transients induced on wires within the aircraft were similar to those observed during ground simulated lightning tests on other aircraft.

c. Approach

It was learned that there was additional payload space available on a National Aeronautics and Space Administration (NASA) Learjet that would be used in thunderstorm research, and Air Force Flight Dynamics Laboratory (AFFDL) was invited by NASA to add equipment to the aircraft and conduct additional lightning measurements while the aircraft was flown in the vicinity of thunderstorms. AFFDL provided most of the equipment and some personnel required for this experimental program, while Stanford Research Institute (SRI) was contracted to provide additional equipment, personnel and technical support. The program was conducted in cooperation with NASA and as a part of the Thunderstorm Research International Program (TRIP-76) at Kennedy Space Center, Florida. Flights were conducted between mid-July and mid-August 1976.

Two different instrumentation payloads were used during this program. The first was a Tektronix transient digitizer system consisting of a PDP-11 minicomputer, one R7912 Transient Digitizer, and associated peripheral devices, provided by AFFDL. This system was used to obtain many measurements on the electric field transients external to the aircraft, and also on the voltage and current transients observed on several induced transient sensors installed inside the aircraft cabin. The second instrumentation payload consisted of a discrete-frequency spectrum analyzer with the capability of recording on magnetic tape the transient signal energy content at eight different frequencies, with simultaneous observation of the external field and internal transients. This equipment was used for low-resolution continuous recordings of lightning events. Due to space limitations on the aircraft, it was not possible to fly both these instrumentation payloads simultaneously.

Electric field measurements were made via a 24-inch-long antenna mounted externally on top of the fuselage, at the approximate center of the aircraft. For observation of induced transients, a wire circuit approximately nine feet long was installed within the aircraft cabin. The configuration of this wire sensor, or antenna, was changed at times from a single wire to a twisted pair, and the terminations at each end of the circuit were varied to determine the effects of the changes in the observed transients.

Flights were made at altitudes between 35,000 and 41,000 feet in and around thunderstorm cells at various locations over southern

Florida. While flights did typically penetrate the thunderstorm clouds themselves, the aircraft's weather radar was used to aid in avoidance of the most severe areas of the cells. Figure 1 shows a typical view of a storm system under investigation (photo taken between penetrations). A typical flight included approximately 20 cloud penetrations of "runs" where measurements were made.

Figure 1 - Typical Storm System

d. Documentation

This report documents in detail only the AFFDL portion of the overall experiment -- that consisting of transient electric field and induced transient measurements performed with the transient digitizer system. Detailed documentation of the SRI portion of the experiment -- that consisting of the spectrum analyzer measurements on nearby and direct lightning strikes to the aircraft -- is contained in the SRI technical report "Airborne Measurement of Electromagnetic Environment Near Thunderstorm Cells (TRIP-76)" (Ref 4) as prepared by SRI under NASA contract NAS9-15101 for AFFDL. Study of both these documents is necessary for an understanding of all the results gained from this program.

e. Discrete Fourier Transform Notes

For those readers not familiar with the applications and limitations of the Discrete Fast Fourier Transform (FFT), a good reference on digital signal processing or communication theory should be consulted to facilitate proper interpretation of the FFT displays in this report. Several other considerations are also applicable. First, the vertical scaling in the FFT displays is linear rather than logrithmic as is common. Second, only the positive half of the Fourier magnitude sequence is displayed, with DC displayed at the left margin of the graticule and maximum frequency displayed at the right margin. Third, it is not, in general, possible to make comparisons of spectral energy content (area under the frequency spectrum curve) between different FFT displays due to the effects of leakage in the FFT computations and differences in time domain and frequency domain sample periods.

SECTION II

SENSORS AND INSTRUMENTATION

a. Transient Electric Field Sensor (External)

Figure 2 shows the external mounting and equivalent circuit for the transient electric field sensor. The sensing element was a 24-inch antenna stub with its output shunted to electrical ground through 200 pF capacitance. The equivalent capacitance of the stub antenna was calculated to be on the order of 7.8 pF. The antenna and its shunting capacitance then formed a capacitive voltage divider where the voltage appearing across the shunting capacitance was directly proportional to the external electric field (as modified by the presence of the aircraft). To measure the voltage, a high input impedance, unity gain FET preamplifier in addition to a stepped capacitive voltage divider attenuator was installed at the antenna. This arrangement allowed measurements to be made at widely varying signal levels without saturation of the preamplifier. The output of the preamplifier was fed into the 50-ohm load presented by the type 7A19 vertical amplifier of the R7912 Transient Digitizer (discussed in detail later) by means of an RG-58 coaxial cable. This sensor was used for all external transient electric field measurements made with the Transient Digitizer measurements throughout the program.

b. Induced Transient Sensors (Internal)

To investigate the induction of transient voltages onto elec-

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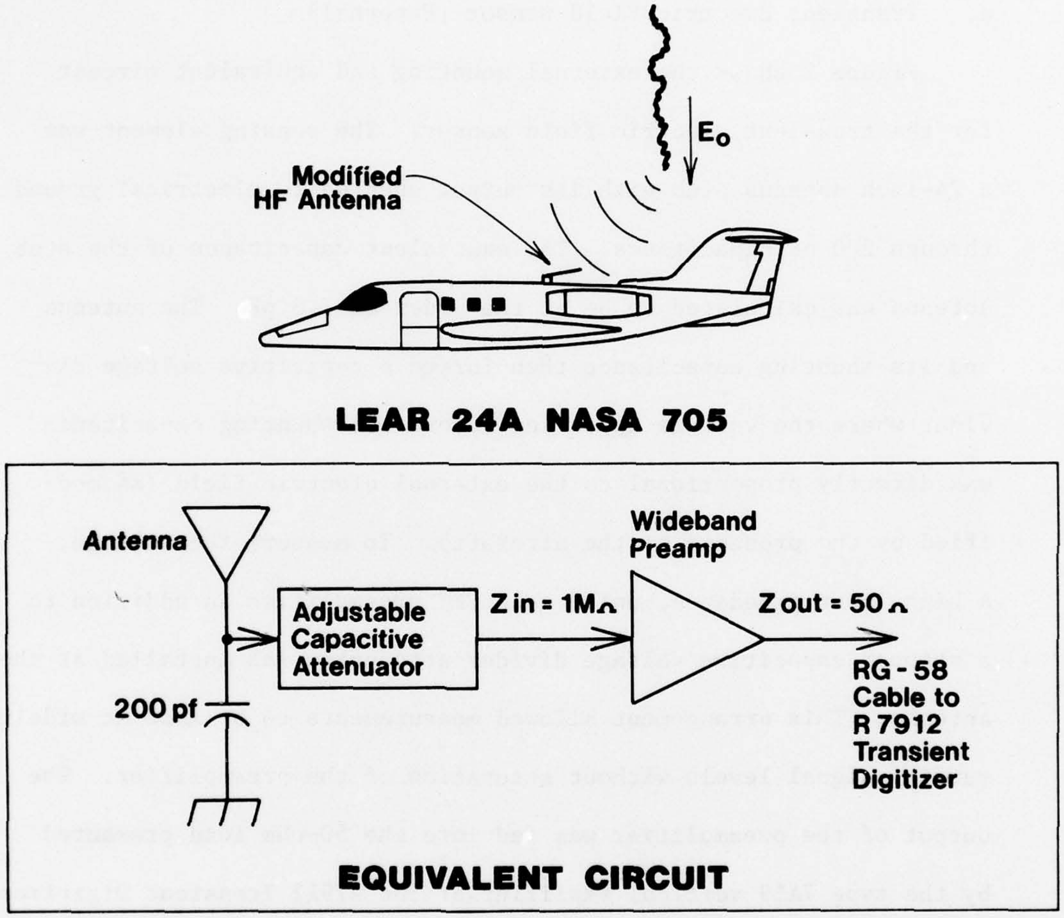


Figure 2 - Transient Electric Field Sensor Installation (External)

trical wiring within the aircraft due to lightning a series of wire sensors were installed within the aircraft cabin. (Due to the limited preparation time that was available, it was not possible to directly monitor existing wiring installed in the aircraft for induced transients.) These sensors consisted of a wire, or pair of wires, strung overhead in the cabin between two shoulder harness mounts. This arrangement provided a sensor that was approximately 111 inches in length and oriented parallel to the longitudinal axis of the aircraft. To investigate the changes in the induced transients that occur in different types of circuits, the endpoint terminations were repeatedly changed on these sensors while the overall length remained the same. The intent of this procedure was to show to what degree overall circuit length and the nature of cable terminating devices affected the characteristics of the transients induced.

Foldout Figure A-1, Appendix A, shows schematically each of the sensors. Each configuration was assigned an arbitrary sensor number for data recording purposes. Although a total of nine different sensor configurations were used, only the six shown in Figure A-1 will be discussed in detail, since no new effects were observed on the other three sensors that could not also be described with the data from these six.

c. Transient Digitizer System

A Tektronix WP2221 Waveform Digitizing system was used throughout this program to perform and record all high-resolution transient measurements. This system is pictured in Figures 3 and 4 as installed in the aircraft, and consists of an R7912 Transient Digitizer, PDP-11/05 minicomputer, magnetic tape drive, graphics terminal, and a printer. Referring to Figure 3, the transient digitizer (bottom of stack), computer, and magnetic tape drive were installed in an equipment rack, while the graphics terminal, its power supply, and the printer were installed in the aircraft cargo compartment as shown in Figure 4.

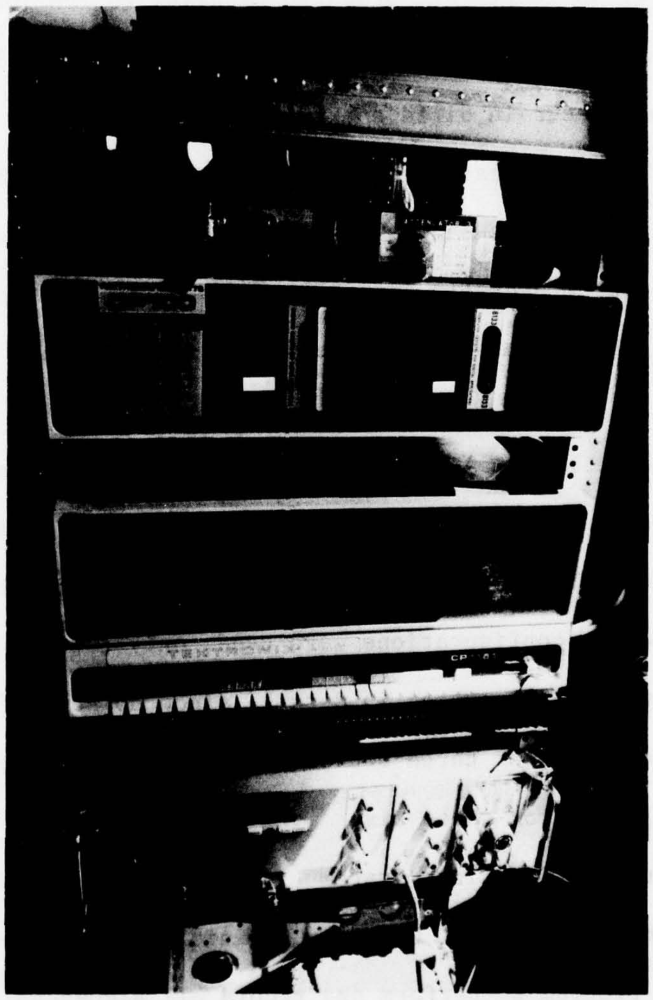


Figure 3 - Digitizer and Computer Installation

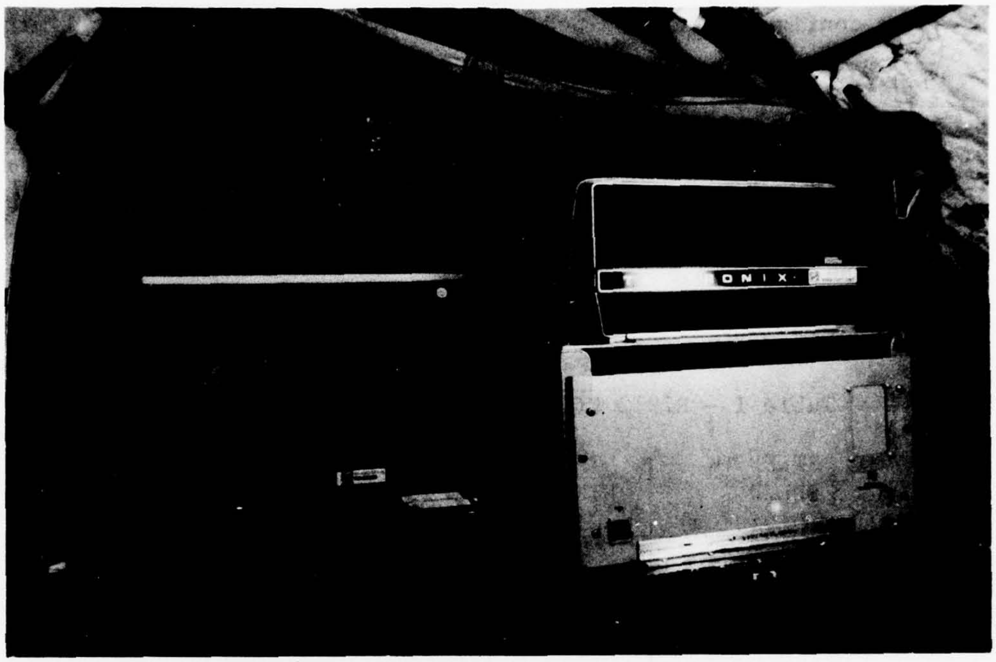


Figure 4 - Cargo Area Equipment Installation

The R7912 Transient Digitizer is essentially a high-speed analog-to-digital converter which can effectively sample at rates of up to 1 GHz. It has the capability of storing data in an array of 512 9-bit digital words with a resolution sufficient to discern 512 distinct vertical levels in each sample. The digitizer is operated much like an oscilloscope, with the exception that its output is directly to the computer where the raw data is converted to a numeric array of 512 elements or samples. Transient waveforms are subsequently processed and stored in this form by the computer.

During this program, the R7912 was operated with a type 7A19 vertical amplifier plug-in and type 7B92A horizontal time base. This configuration resulted in an absolute upper bandwidth limit of 500 MHz for the analog portion of the system. The effective overall system bandwidth, however, is affected by changes in sample rate, and, therefore, changes in R7912 sweep speed. Table I shows the effective system bandwidths based on sample period, sweep speed, and Nyquist frequency.

Table I - R7912 Effective Overall System Bandwidth

SWEEP SPEED (Per Division)	TIME WINDOW WIDTH	SAMPLE PERIOD (51 Samples/Div)	EFFECTIVE SYSTEM BANDWIDTH
100 nS	1 μS	2 nS	250 MHz
500 nS	5 μS	10 nS	50 MHz
1 μS	10 μS	20 nS	25 MHz
10 μS	100 μS	196 nS	2.5 MHz
50 μS	500 μS	980 nS	500 KHz

μS = microseconds nS = nanoseconds

The PDP-11/05 minicomputer forms the hub of the system and makes possible the operation of the various devices as an instrumentation system. When not being used to control the transient digitizer, the computer can also be used (with its BASIC language interpreter) to perform normal computational analysis -- such as Fast Fourier Transforms -- on stored waveforms.

Input/output for the digitizing system is handled by three units. Real-time operator communication with the system is accomplished with the 4010-1 graphics terminal, while the 4610 Hard Copy Unit can provide permanent paper copies of information displayed at the terminal. The CP100 dual cassette drive provides a means of storage and retrieval of programs, data files, and waveform files using magnetic tape cassettes.

Figure 5 shows schematically the operation of the individual units comprising the digitizing instrumentation. The single digitizer channel was connected in turn to each of the various transient sensors, and the measured transient waveforms were stored on magnetic tape by the computer during flight. The stored information was later retrieved for Fast Fourier Transform analysis.

For efficient utilization of the digitizing system, additional BASIC software was developed specifically for this experiment. This software allowed rapid control of the transient digitizer and tape drives, while also enhancing real-time data displays and analysis. Using this software, one transient waveform measurement (including digitizing, some analysis, display, printing, and storage on tape) could be made approximately every 45 seconds. A listing of this software can be found in Appendix B for those familiar with the WDI TEK BASIC language.

With only the single channel of instrumentation, it was not possible to simultaneously observe the transient electric fields external to the aircraft while observing the internal induced transients. This capability would have enhanced the value of the data immensely, and is planned for future programs.

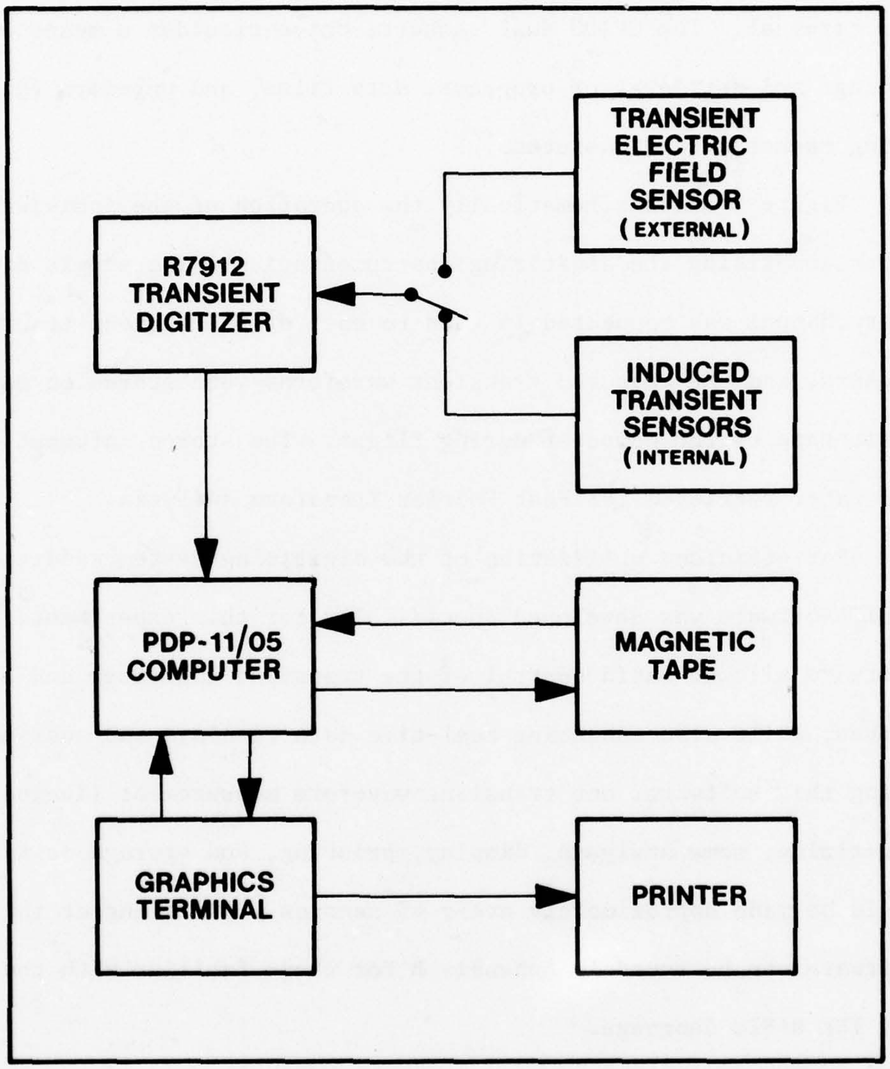


Figure 5 - Digitizing System Configuration

d. Discrete Spectrum Analyzer

For much of the program, a discrete spectrum analyzer was operated in lieu of the transient digitizer system (see Ref 1). This equipment is shown schematically in Figure 6, and consisted of eight discrete bandpass filters and AM detectors simultaneously recording their outputs on a multi-channel 20 KHz magnetic tape recorder.

The signals produced by the external and internal sensors were monitored simultaneously using narrowband (20 KHz) bandpass filters centered at four discrete frequencies -- 1, 3, 10, and 30 MHz. The outputs of these filters were then AM detected and recorded. The recorded data therefore provided a continuous (though low time resolution) measure of the energy within a 20 KHz band centered around each of the filter center frequencies. Two additional data channels were used to monitor signals induced in the external sensor. One of these was used to record the output of the sensor directly; the upper frequency limit of this data was therefore limited by the 20 KHz recorder bandwidth. The other channel contained a 1 KHz bandwidth filter centered at 10 KHz; the output of this filter was recorded directly and gave a good indication of the time of occurrence of lightning events.

Although the results of these measurements will be summarized in Section III, the observations are fully documented in a separate report detailing this portion of the program prepared by Stanford Research Institute (Ref 4).

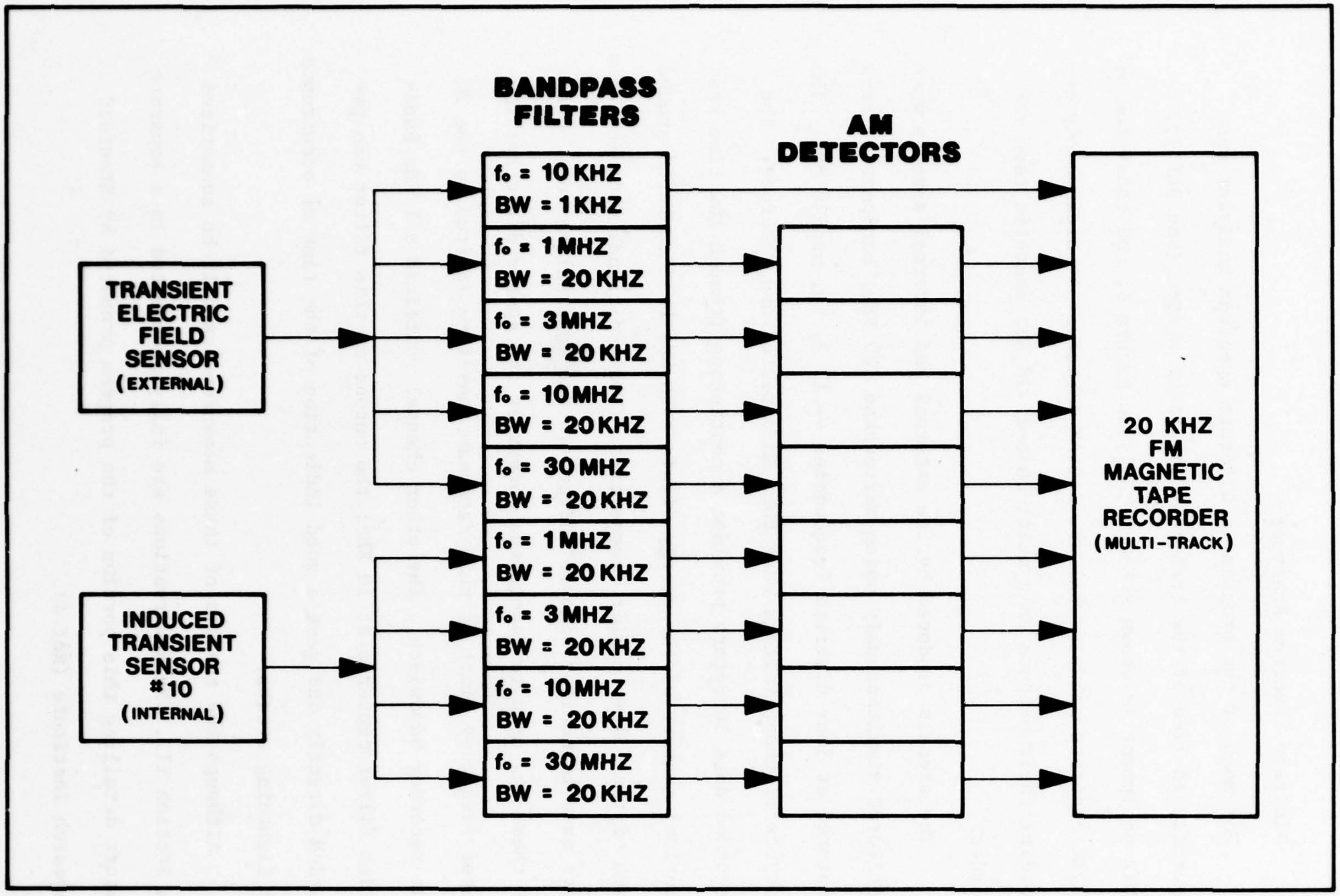


Figure 6 - Spectrum Analyzer Configuration

e. Electric Field Meters

In addition to the previously described instrumentation, the aircraft also carried a system of four electric field meters for recording the static electric fields in the vicinity of the aircraft. These data, however, could not be directly correlated in time with the observations documented in this report, and will therefore not be further discussed. The results of these field meter measurements have been documented in a separate report prepared by NASA/Johnson Space Center (Ref 3).

SECTION III

RESULTS

a. Transient Electric Field Measurements

The electric field environment around the aircraft when flying in the vicinity of thunderstorms was found to be extremely active. Low amplitude and low frequency field variations were evident every time the aircraft was near a storm. Superimposed on this field environment were less frequent, shorter duration, and higher intensity field variations. These more intense and shorter duration events were of primary interest in this study, since it is this type of event which is most likely to couple inside the aircraft and induce transients on wiring.

A limitation of this data, obtained with the transient digitizer system, is that no simultaneous continuous-time data record was available to aid interpretation of the transient electric field measurements. For this reason, no information is available on the electric field behavior before or after the short time of the observations themselves, and it is difficult to put the observations in their proper context with the overall electromagnetic activity which was occurring. The data obtained with the spectrum analyzer (Sec 3.b) was essentially continuous and did not have this limitation.

Since visual observations of lightning strokes during the flights were very rare (and none of the observations to be presented coincided with sightings) a determination of whether or not a particular observed pulse was due to lightning, and at what range, may only be made by conjecture and study of the waveforms themselves. There were few visual sightings of lightning because much of the flight time was spent in cloud and at altitudes between 35,000 and 41,000 feet, while much of the lightning activity could be expected below these altitudes.

Even with these considerations in mind, the transient electric field observations to be presented represent high-resolution measurements of typical transient electrical activity that can be expected in the vicinity of thunderstorms.

1. Graticule Interpretation

The data displays shown in the figures of this report are of two general types, and some comments on the interpretation of these displays should be helpful. The graticule display of the time-domain data is very similar to that of an oscilloscope. The vertical scaling information in units per division will be located at the upper left corner of the graticule, while the horizontal scaling information (time base) will be located at the upper right corner of the display (usually in microseconds "US" or nanoseconds "NS" per division). Both scales are linear. The zero reference point in the display may change from one figure to the next. The number at the lower right corner of the graticule shows where the zero reference of a particular figure is with respect to the center of the graticule. For instance, the "0 DIV" shown in Figure 7 indicates that the zero reference is at the center of the graticule. The "-3 DIV" shown in Figure 8 indicates that "zero" is three divisions below center. Along the upper left side of the graticule, data logging information is displayed; the date and time are used to uniquely specify or identify each waveform. The maximum and minimum values of each waveform are shown at the upper right corner of the display. For instance, the maximum and minimum values of the waveform in Figure 7 are 3100 and -1425 volts/meter, respectively.

Many of the considerations applying to interpretation of the time domain displays also apply to the frequency domain, or Fourier transform data displays (Figure 11, for example). The vertical axis of these displays will be volts or amperes, while the horizontal axis will be frequency. Only the positive half plane of the Fourier magnitude sequence is displayed, so zero frequency (or DC) is displayed at the left edge of the graticule, while maximum frequency is displayed at the right edge. The zero reference point for these displays will always be three divisions below graticule center.

The vertical units of the FFT displays should rightly be Volt-Seconds or Amp-Seconds to reflect the influence of the discrete frequency sampling in the frequency-domain data. Insufficient time was available, however, to modify the FFT software delivered with the instrumentation system to reflect this.

2. Transient Digitizer Electric Field Data

With the considerations of the above paragraphs in mind, Figures 7 through 9 show several examples of the more interesting electric field pulse waveforms that were observed during this program with the transient digitizer system.

The pulse shown in Figure 7 had one of the highest peak magnitudes of any of the observations.

Notice in Figure 8 that the time base for waveform 1627 is five times longer than that of waveform 1609.

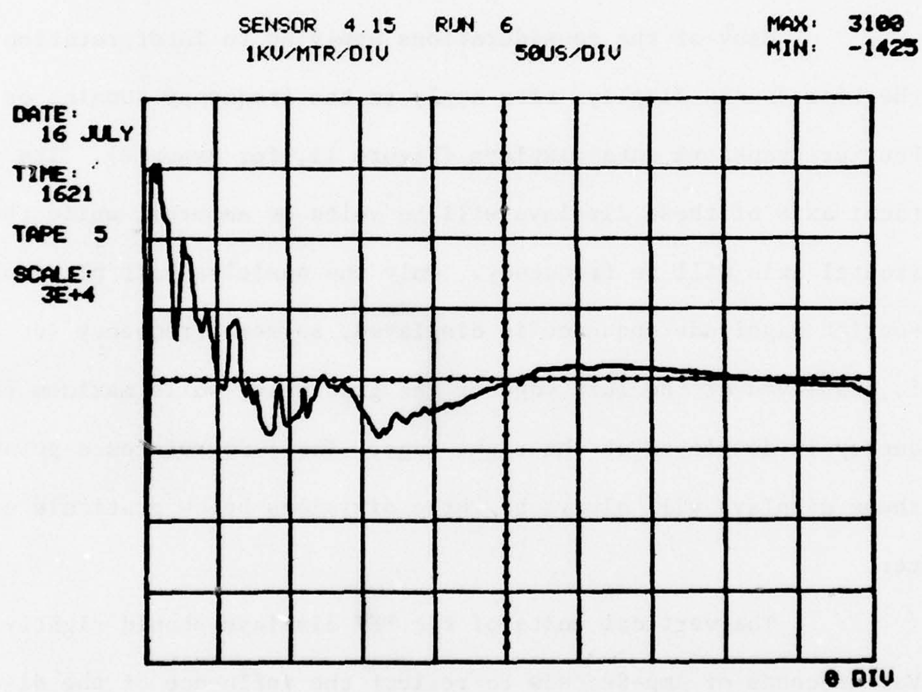


Figure 7 - Example Transient Electric Field Pulse (1621)

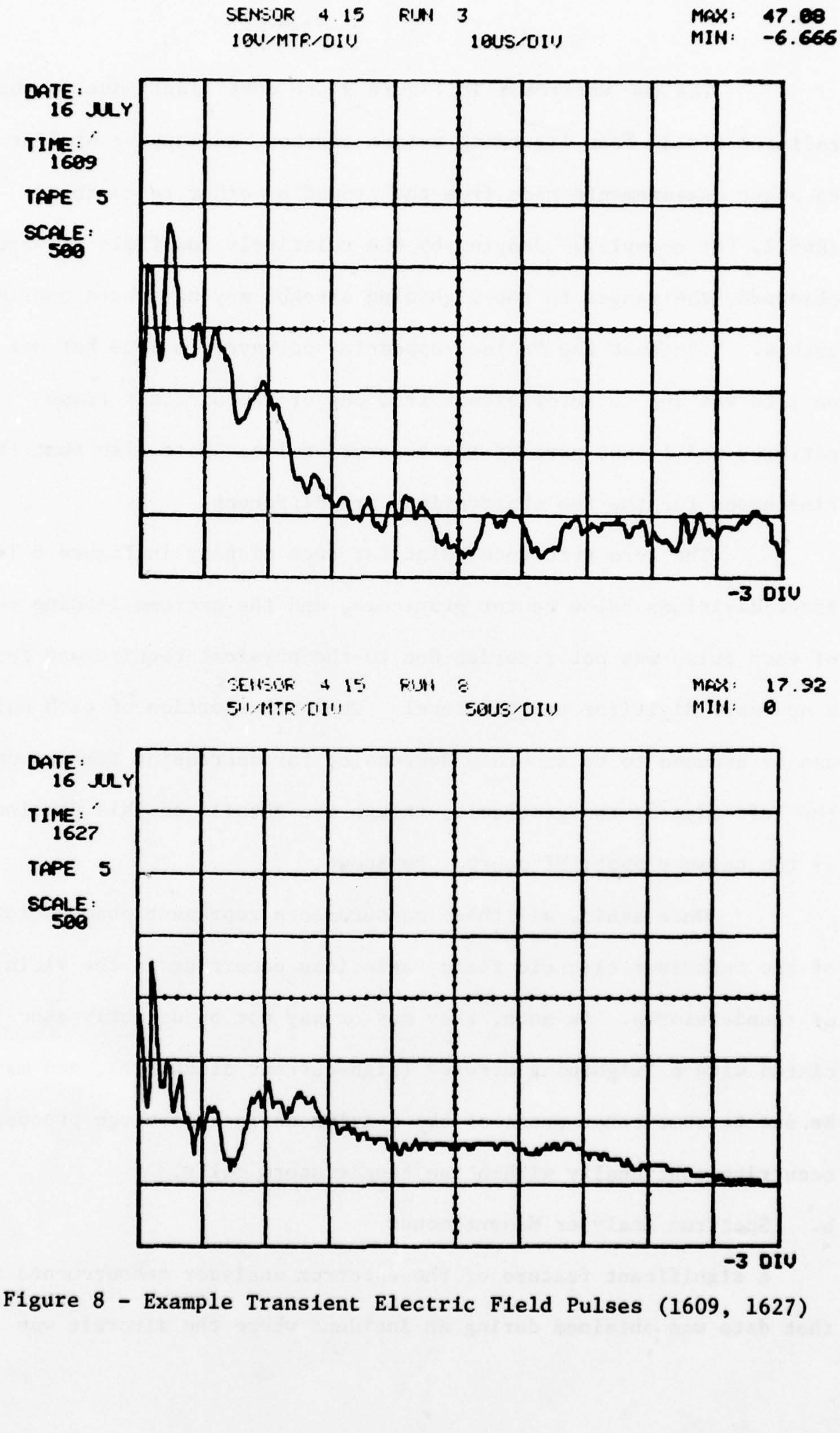


Figure 8 - Example Transient Electric Field Pulses (1609, 1627)

The two waveforms in Figure 9 are most likely due to the radiated fields from lightning return strokes, and appear similar to other measurements made from the ground by other researchers (Ref 2, for example). Judging by the relatively low field strengths observed, the ranges to the lightning strokes may have been considerable. Note that the "noise" appearing on waveform 1703 but not on 1720 was due to interference from one of the aircraft transmitters, and is not part of the observed pulse. Note also that the time bases for the two observations are different.

The zero reference point for each display in Figure 9 is three divisions below center graticule, and the extreme leading edge of each pulse was not recorded due to the physical requirement for a non-zero digitizer trigger level. The early portion of each pulse can be assumed to be smoothly decreasing for decreasing time beyond the left edge of the graticule, though the details of this portion of the pulse cannot, of course, be known.

Once again, all these measurements represent observations of the transient electric field variations occurring in the vicinity of thunderstorms. As such, they may or may not be directly associated with a "lightning stroke" (high-current discharge), and may be due to some other phase of the complex charge-discharge processes occurring continually within the thunderstorm cells.

b. Spectrum Analyzer Measurements

A significant feature of the spectrum analyzer measurements is that data was obtained during an incident where the aircraft was

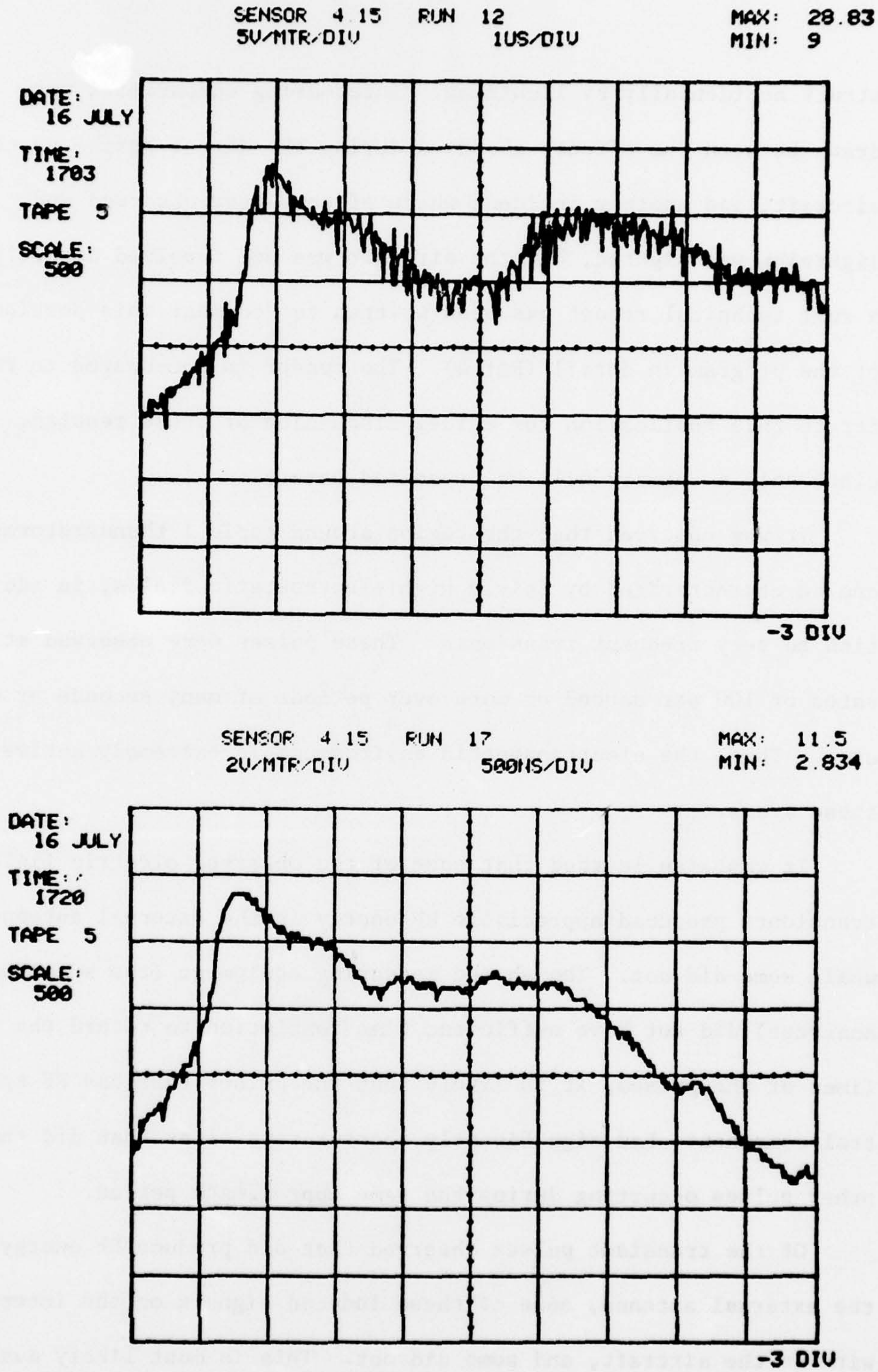


Figure 9 - Example Transient Electric Field Pulses (1703, 1720)

struck accidentally by lightning. Interesting comparisons were drawn between the effects observed during the direct strike to the aircraft, and another incident where effects were observed and lightning was sighted, but the aircraft was not involved directly. A full technical report has been written to document this portion of the program in detail (Ref 4). The reader is encouraged to refer to this publication for a full discussion of these results, since only a summary will be presented here.

It was observed that the region around typical thunderstorms can be characterized by fairly high electrostatic fields, in addition to very frequent transients. These pulses were observed at rates of 100 per second or more over periods of many seconds or minutes. Thus, the electromagnetic environment is extremely active in these areas.

It was also learned that some of the observed electric field transients produced appreciable RF energy in the external antenna while some did not. Though the measuring equipment (the spectrum analyzer) did not have sufficient time resolution to record the rise times of the pulses, it is likely that the pulses that had RF spectral components had significantly shorter rise times than did the other pulses occurring during the same approximate period.

Of the transient pulses observed that did produce RF energy in the external antenna, some of these induced signals on the internal wire in the aircraft, and some did not. This is most likely due to different resonances in the aircraft structure being excited by different pulses (i.e., wing-to-wing, fuselage, etc.). It is reasonable to expect that surface currents corresponding to some of these resonant modes would couple energy fairly well onto the internal wire, while others would not.

On at least one occasion a nearby lightning strike was sighted that did not directly contact the aircraft. Data was obtained due to this strike and is well documented in Reference 4. Pulses were observed on the external antenna and the internal wire. It was significant that the magnitude of the RF energy on the internal wire was as much as 20 to 50 per cent as great as was observed with the direct strike. This shows that a very significant transient hazard to onboard avionics systems is encountered merely by flying in the vicinity of lightning activity, while in the past it has been assumed that the effects due to lightning not contacting the aircraft would be minimal compared to the effects of direct strikes.

Another effect was observed on several occasions when the aircraft was flying near a storm (and usually not in cloud). This effect has been tentatively identified as "incipient lightning." Very intense and frequent transients were observed on the external antenna, while many of these also induced signals on the internal wire -- even though no lightning was seen and the aircraft was neither in cloud nor precipitation. The amplitudes of these pulses and induced signals were on the same order as those observed with nearby lightning sightings, and persisted for several minutes. While it was not possible to conclusively establish the origin of these signals with the instrumentation onboard during this experiment, they appeared to be due to either charging and discharging of the aircraft as it flew through a region of high electric field, or perhaps due to spatial variation in the electric field itself in the region, with the variations observed due to the aircraft's speed through the region. Whatever the origin, this phenomenon did induce signals on the external and internal sensors of similar magnitude to those observed with nearby and direct lightning strikes, and thus also presents a threat to onboard electronics.

c. Induced Transient Measurements

Several interesting results were obtained in the investigation of transient induced within the Learjet aircraft. Much to our surprise, transients were found to be induced on an almost continual basis when flying near thunderstorms. It was quite surprising to find such strong transients being induced while merely in the vicinity of lightning rather than being struck directly. It was found that the induced transients experienced by different types of wiring circuits did vary with the physical and electrical characteristics of the circuit itself. The spectral content of the energy exciting the transients was quite variable, and several observations were made where the spectral content changed very dramatically over a period of only a few minutes. There were several occasions where multiple events (up to three) were observed during just one measurement. It was also interesting to note that the observed transients were similar in general waveshape, spectral content, duration, and magnitude to the transients observed during ground simulated lightning tests on other aircraft.

1. Aircraft Resonances

Since the precise coupling mechanism by which lightning energy enters an aircraft to induce transients in internal wiring is not known, it is interesting to first examine the anticipated surface current resonances of the aircraft structure itself. One of the more popular theories is that external field fluctuations set up oscillating surface currents on the aircraft, while these currents then couple inside the structure and induce transients in internal wiring. Before the observed transients are discussed, we will first examine these surface currents.

Figure 10 shows the critical external dimensions (in meters) of the Learjet aircraft that was used during this program. Using these dimensions, and the expression for free-space electrical wavelength (Ref 1:18),

$$\lambda(\text{mtrs}) = \frac{300}{f(\text{MHz})} \tag{1}$$

the resonant frequencies for full-, double-, and half-wave resonance of the fuselage and wings can be computed. These frequencies are shown in Table II.

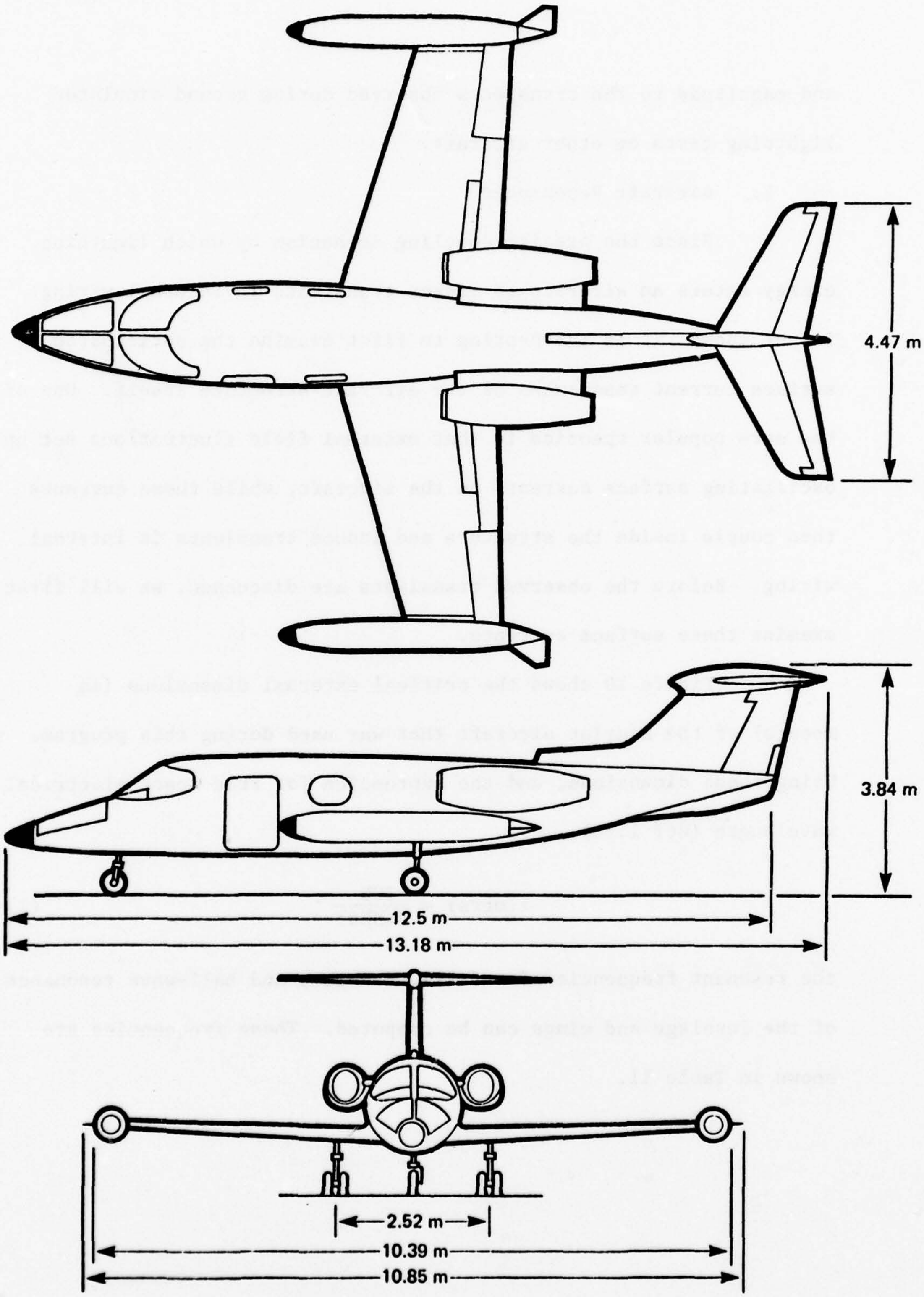


Figure 10 - Learjet NASA 705 External Dimensions
(<u>Learjet Investigators' Handbook</u>, NASA)

Table II - Learjet External Resonances

RESONANCE MODE	DIMENSION (MTRS)	FREQUENCY (MHz) λ	2λ	λ/2
Nose-to-tail	13.18	22.8	45.6	11.4
Wing-to-wing	10.39	28.9	57.8	14.5
Nose-to-wing	11.0	27.3	54.5	13.6
Wing-to-tail	11.0	27.3	54.5	13.6

Since the expression for free-space wavelength does not strictly apply to a geometrically complex conductive body, such as an aircraft fuselage, these computations are very approximate. Allowing for the unknowns in the physical case, the resonant frequency computations can be considered valid only within about ± 20%. The table then gives frequency ranges where if energies are observed inside the aircraft, it is reasonable to hypothesize that the energy was coupled inside the aircraft (through apertures) from fields due to surface currents on the aircraft. Since none of the induced transient observations were made from direct lightning strikes to the aircraft, all effects were due to incident electromagnetic energy intercepting the aircraft, and this environment can be expected to induce surface currents.

2. Typical Sensor Responses

It will be helpful during the following discussions to fold out Figure A-1 (in Appendix A) which shows the schematic diagrams of each of the induced transient sensors. Each of the example waveforms shown for the sensors was chosen from many others to be representative in magnitude and frequency content of most of the observations in each case.

Figure 11 is an example of a typical transient response observed on Sensor 10. The peak magnitude was approximately 80 milliamps, with primary frequency components at 29 and 50 MHz. Figure A-1 shows schematically the physical configuration for Sensor 10. It is important to note that the cabin wall of the aircraft formed an additional conductive path between the forward and aft ends of the wire sensor; this arrangement essentially formed a "loop" approximately 111 inches long and 5-1/2 inches wide at its center.

It is interesting to attempt to explain the appearance of the 29 and 50 MHz components in the signal. The 50 MHz component is most likely due to the half-wave resonance of the wire itself. Using an expression for the electrical half-wave resonance in wire (Ref 1:580),

$$\lambda/2(\mathrm{ft}) = \frac{468}{f(\mathrm{MHz})} \tag{2}$$

the expected half-wave resonance of a 111-inch-long wire is 50.5 MHz. This corresponds very well with the 50 MHz component observed in the signal.

Another reasonable resonance to expect in the sensor would be the half-wave resonance of the loop formed by the combination of the wire and the cabin wall. This "loop" would then have a circumference of approximately 223 inches; using equation (2) again to find

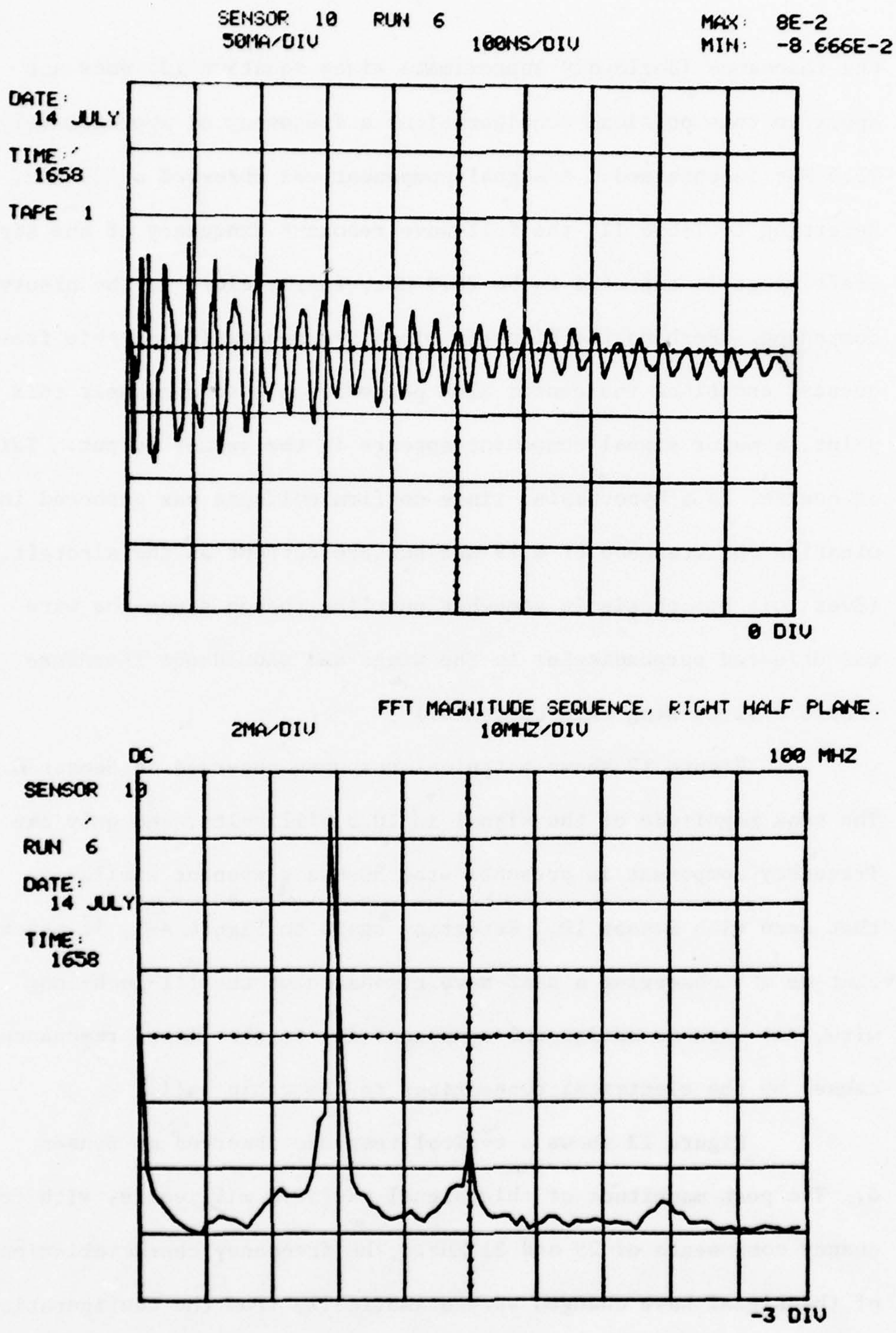


Figure 11 - Sensor 10 Typical Response

the resonance (decidedly approximate since equation (2) does not apply to this physical configuration) a frequency of approximately 25.5 MHz is obtained. A signal component was observed at 29 MHz. Referring to Table II, the full-wave resonant frequency of the aircraft wings is expected to be 28.9 MHz, fairly close to the observed component. Perhaps the aircraft wings are resonating at this frequency, and since the sensor also possesses a resonance near this point, a major signal component appears in the sensor output. This, of course, is a hypothesis, since no firm evidence was gathered indicating the presence of a 29 MHz surface current on the aircraft. (Even this hypothesis is somewhat puzzling though since the wire was oriented perpendicular to the wings and should not therefore couple well to wing skin currents.)

Figure 12 shows a typical response observed on Sensor 8. The peak magnitude of the signal is 10.5 millivolts, and only one frequency component is present: the 50 MHz component similar to that seen with Sensor 10. Referring again to Figure A-1, it appears that we are observing a half-wave resonance of the 111-inch-long wire, but with no additional component due to the "loop" resonance caused by the electrical connections to the cabin wall.

Figure 13 shows a typical response observed on Sensor 6. The peak magnitude of this signal was 90.8 millivolts, with frequency components of 29 and 31 MHz. The frequency characteristics of the signal have changed very dramatically from the configuration of Sensor 8, with only the addition of the 10 kilohm resistor at the

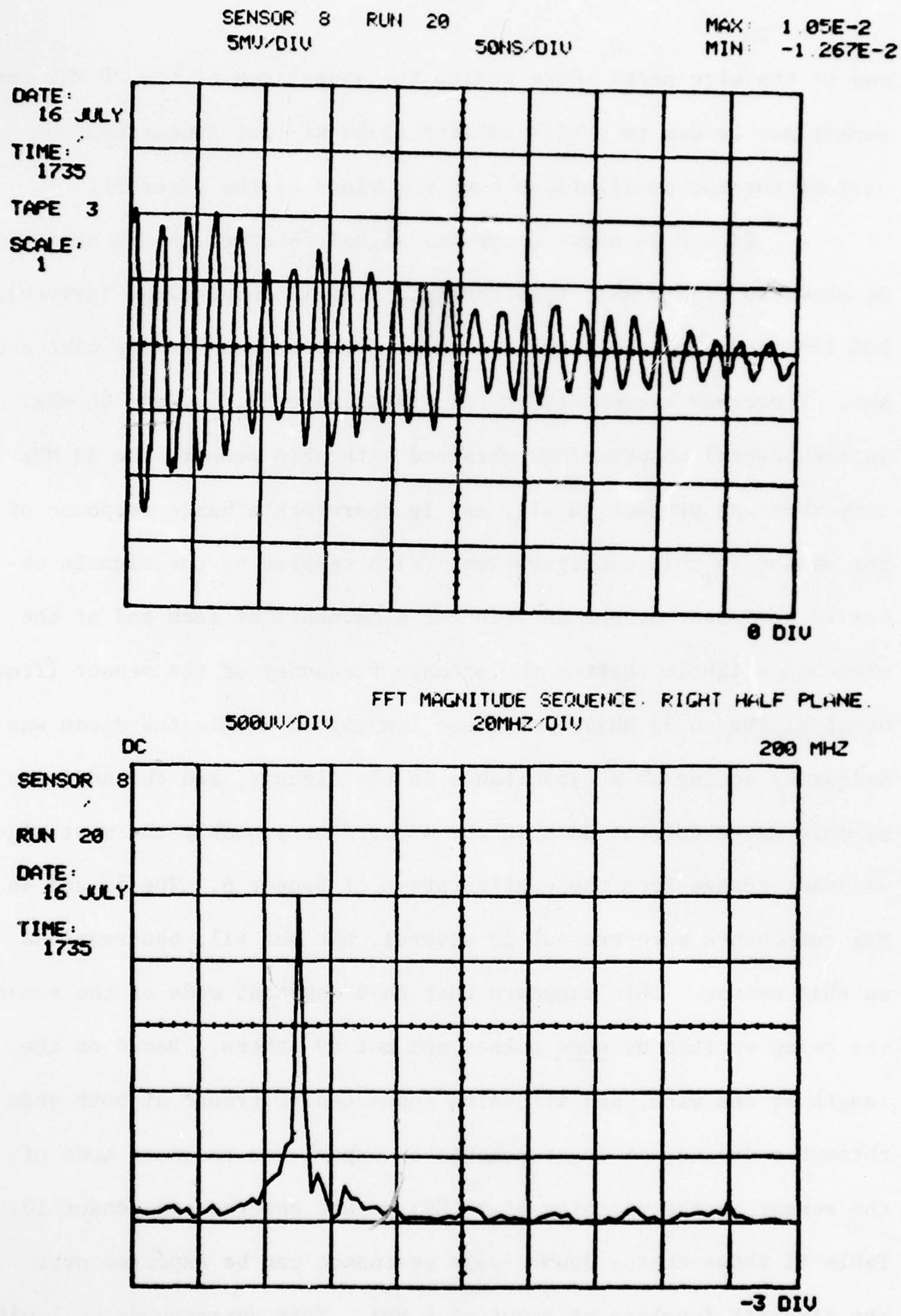


Figure 12 - Sensor 8 Typical Response

end of the wire pair. Once again, the appearance of the 29 MHz component may be due to a high ambient field at that frequency from surface current oscillations over the wings of the aircraft.

Figure 14 shows a typical signal observed on Sensor 5. As shown in Figure A-1, this configuration included diode (sylvania ECG 125) and resistor terminations at opposite ends of the wire sensor. Frequency components in the signal were 33, 52, and 46 MHz. In the several observations obtained with this sensor, the 33 MHz component was present in all, and is therefore a basic response of the sensor in this configuration. With respect to the signals observed on Sensor 6, the addition of components at each end of the wire has slightly shifted the primary frequency of the sensor (from about 31 MHz to 33 MHz). At these low signal levels the diode was primarily acting as a capacitance in the circuit, and the addition of this extra current path in the sensor was probably the most significant change from the configuration of Sensor 6. The 52 and 46 MHz components were present in several, but not all, observations on this sensor. This suggests that this resonant mode of the sensor was being excited by some pulses and not by others. Based on the length of the wire, and its being connected to ground at both ends through a device, it is reasonable to expect one resonant mode of the sensor in the vicinity of 50 MHz as was observed on Sensor 10. Table II shows that a double-wave resonance can be expected over the aircraft fuselage at about 45.6 MHz. This corresponds well with the 46 MHz component which was observed several times in the signal.

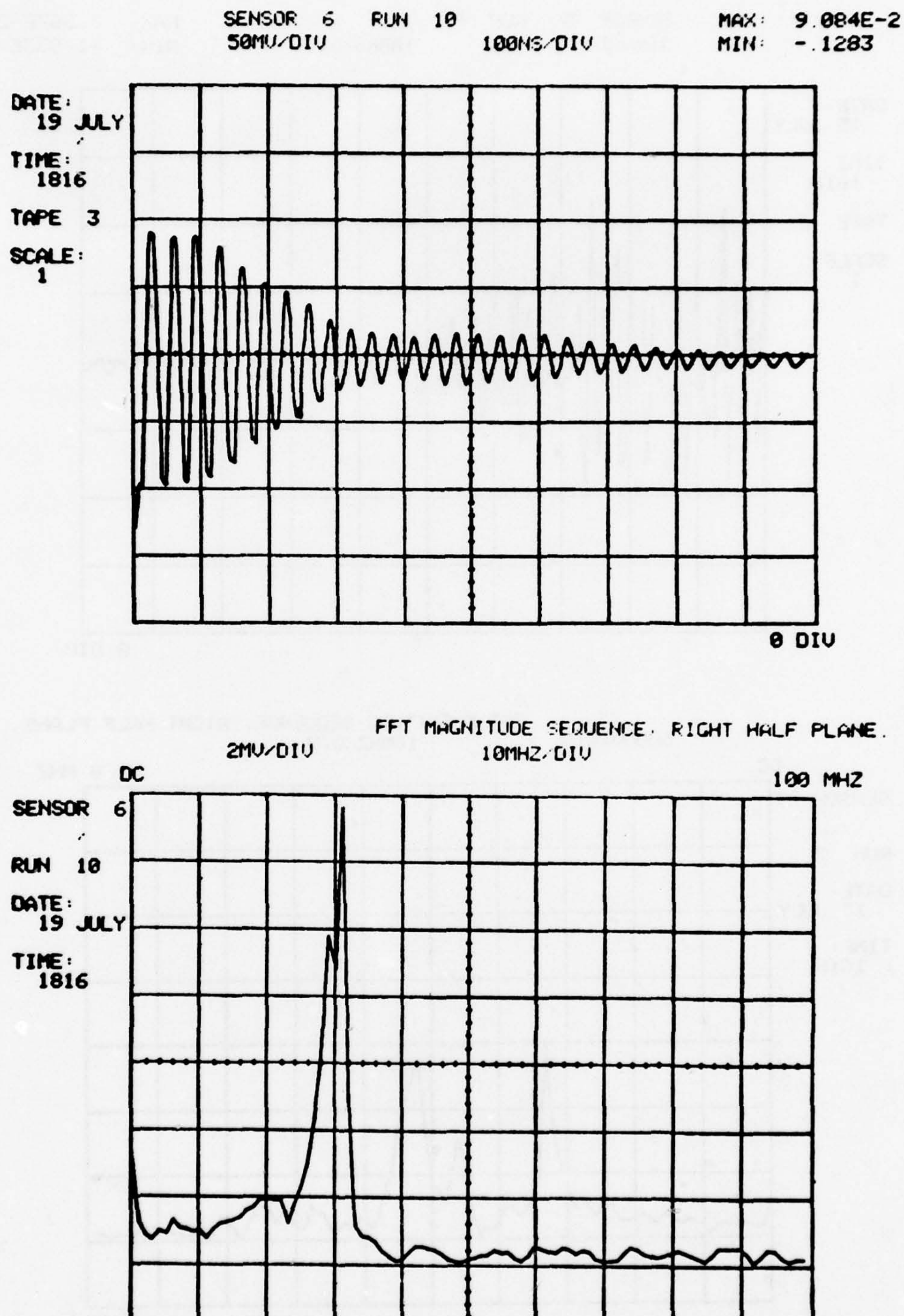
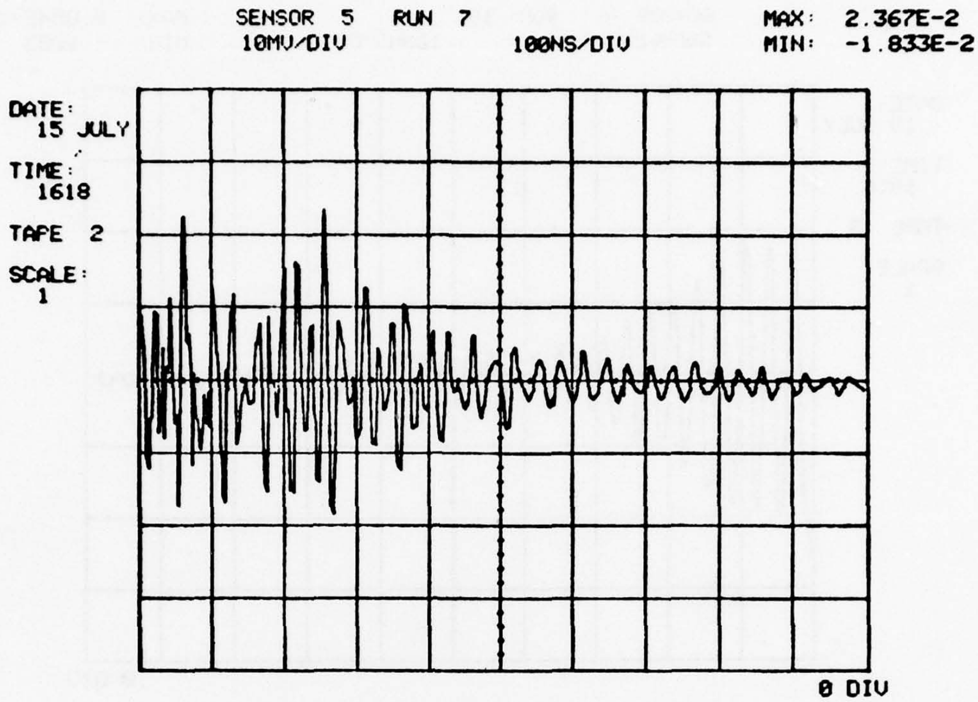


Figure 13 - Sensor 6 Typical Response



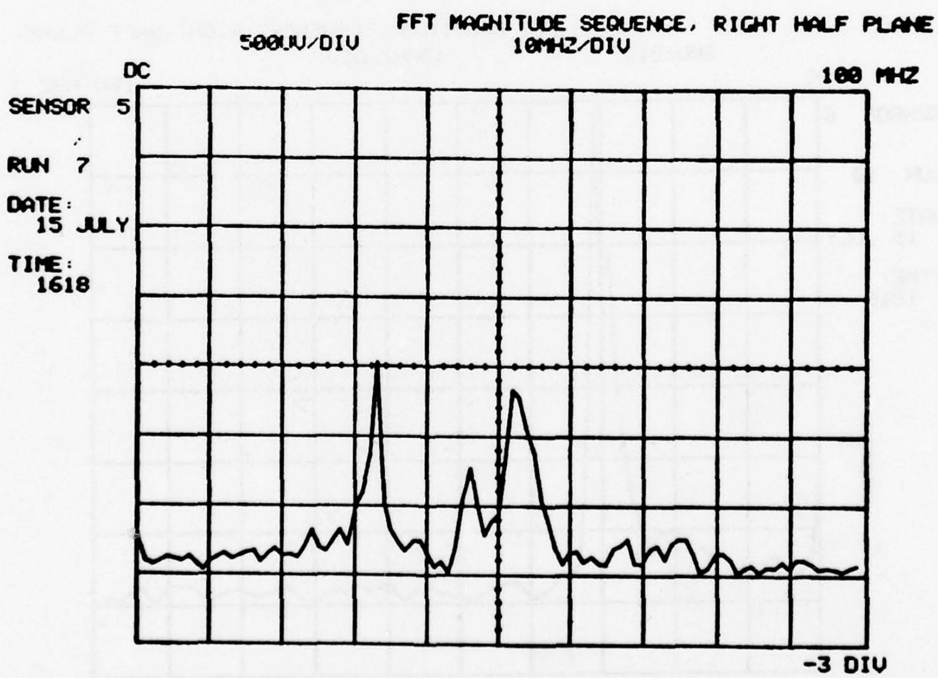


Figure 14 - Sensor 5 Typical Response

Perhaps the 46 MHz energy was also exciting a 52 MHz resonance in the sensor itself, causing both components to appear in the output.

Sensors 9 and 7 employed a Tektronix P6046 high input impedance voltage probe to isolate the sensor from the coaxial cable to the instrumentation. Figure 15 is an example of an observed transient on Sensor 9. Since the 22 and 24 MHz components appeared in all observations on this sensor, they appear to be the primary response of the sensor. The 14 and 18 MHz components visible in this particular measurement were not present in all other observations on this sensor, and are therefore possibly due to some oscillations in the aircraft structure that did not occur with every pulse. Further evidence of these spectral variations will be presented in the following section. The primary change made with this sensor configuration was the removal of the ground connection at one end of the wire. It is this change which is most likely responsible for the shift in the primary frequency component from 33 to 24 MHz.

Figure 16 is an example of an observed transient on Sensor 7. This sensor was very similar to Sensor 9, and the observed signal is also very similar. The 58 MHz frequency component evident in the FFT display of Figure 16 was not present in most of the observations on this sensor, and is therefore most likely due to the spectral variability of the exciting pulses or the aircraft response. There was little difference in the observed transient signals between a direct short termination (Sensor 9) and a 47-ohm termination (Sensor 7) on the sensor.

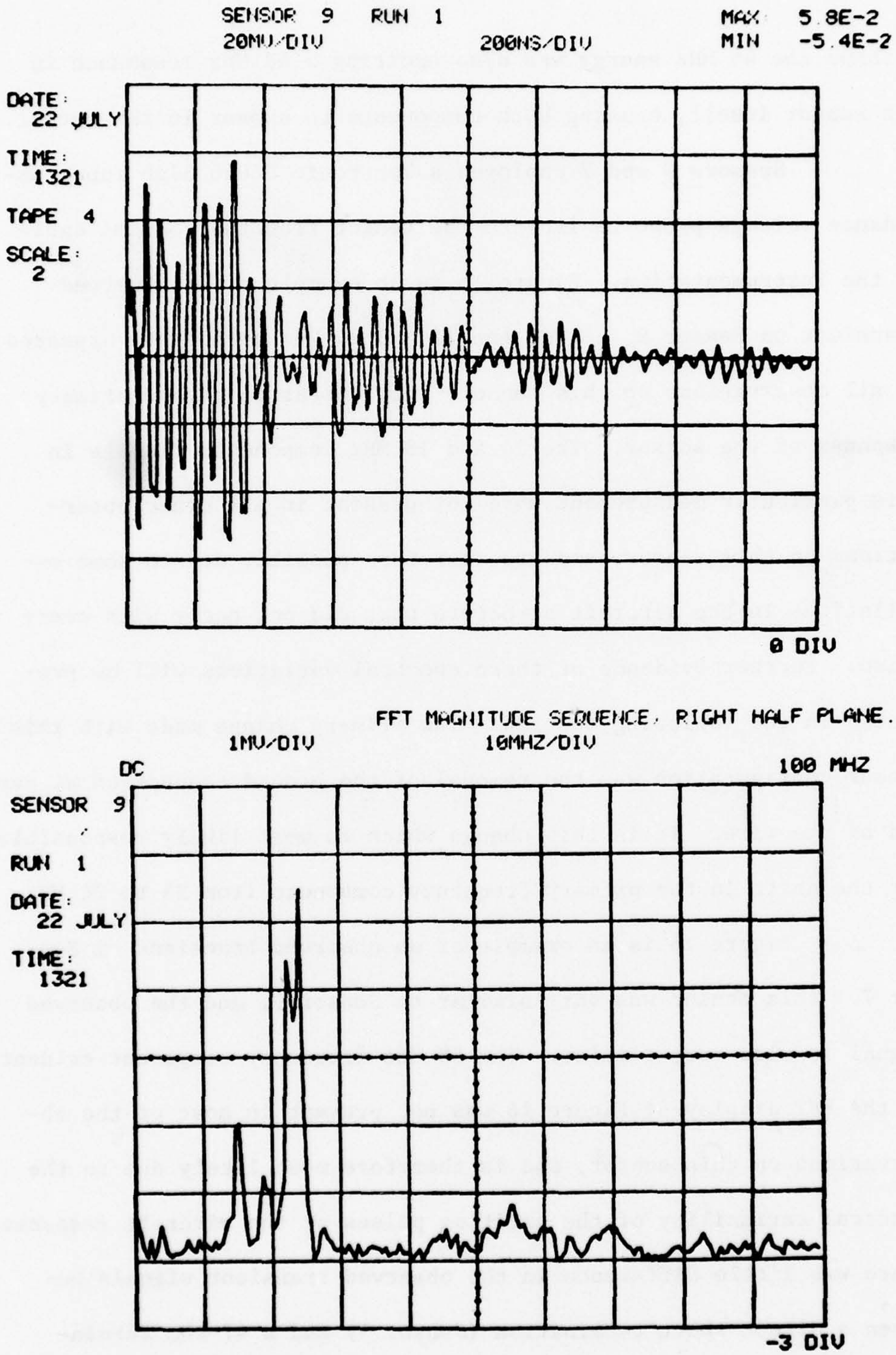


Figure 15 - Sensor 9 Typical Response

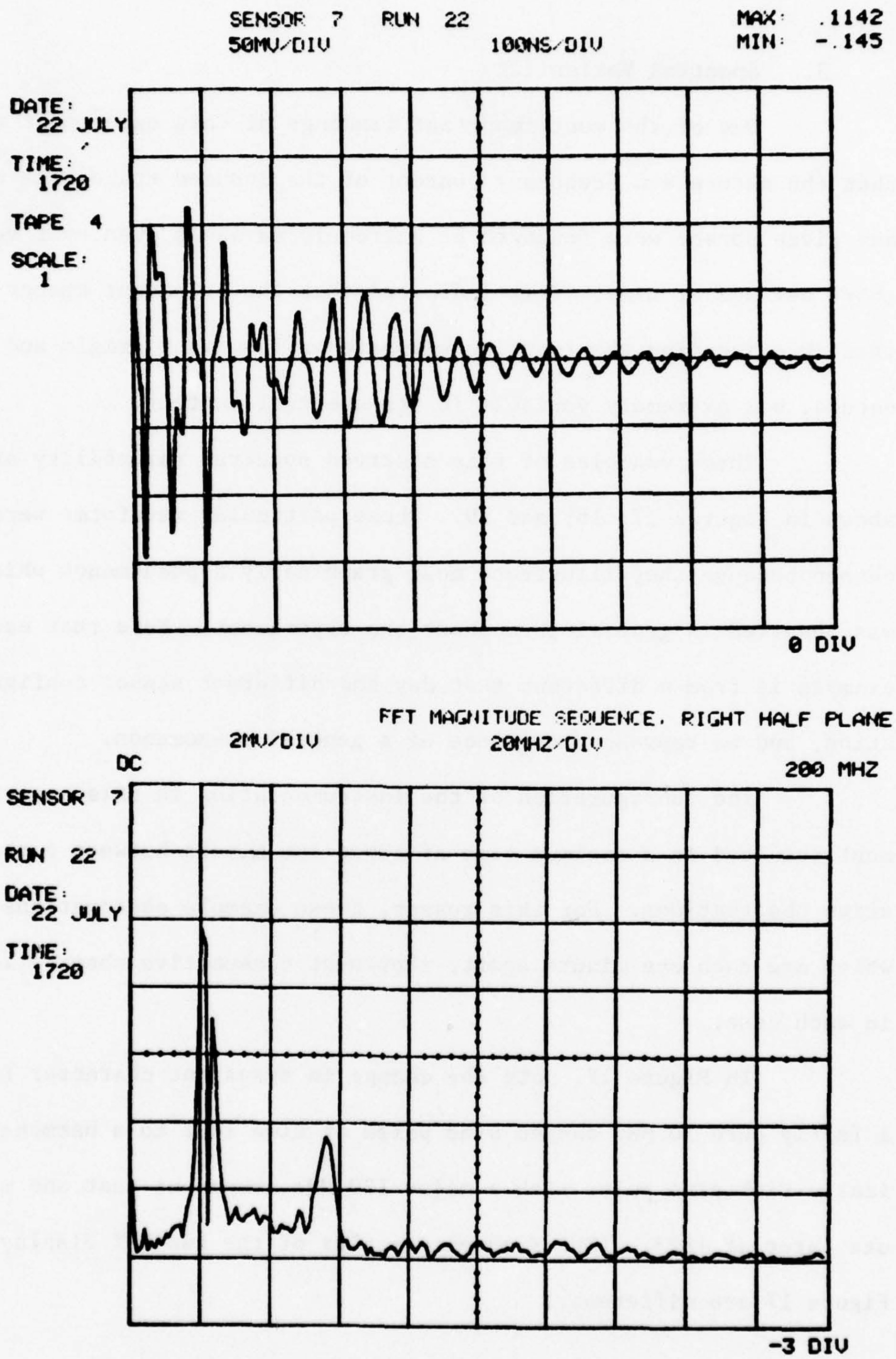


Figure 16 - Sensor 7 Typical Response

3. Spectral Variability

One of the most important findings of this experiment was that the nature and frequency content of the induced transients on any given sensor were found to be extremely variable even over very short periods of time. This indicated that the transient energy which was inducing the transients, whatever its exact origin and nature, was extremely variable in its spectral content.

Three examples of this observed spectral variability are shown in Figures 17, 18, and 19. These particular waveforms were chosen because they illustrate most graphically a phenomenon which was observed in general throughout the experiment. Note that each example is from a different test day and different sensor configuration, and so represent evidence of a general phenomenon.

The configuration of the instrumentation in this experiment resulted in a minimum time of about one minute between consecutive observations. For this reason, these example observations, which are each one minute apart, represent consecutive observations in each case.

In Figure 17, note the change in transient character from a fairly pure 30 MHz damped sine pulse at time 1822 to a harmonically-rich sine pulse with a major 120 MHz component just one minute later at 1823. (The frequency scales of the two FFT displays in Figure 17 are different.)

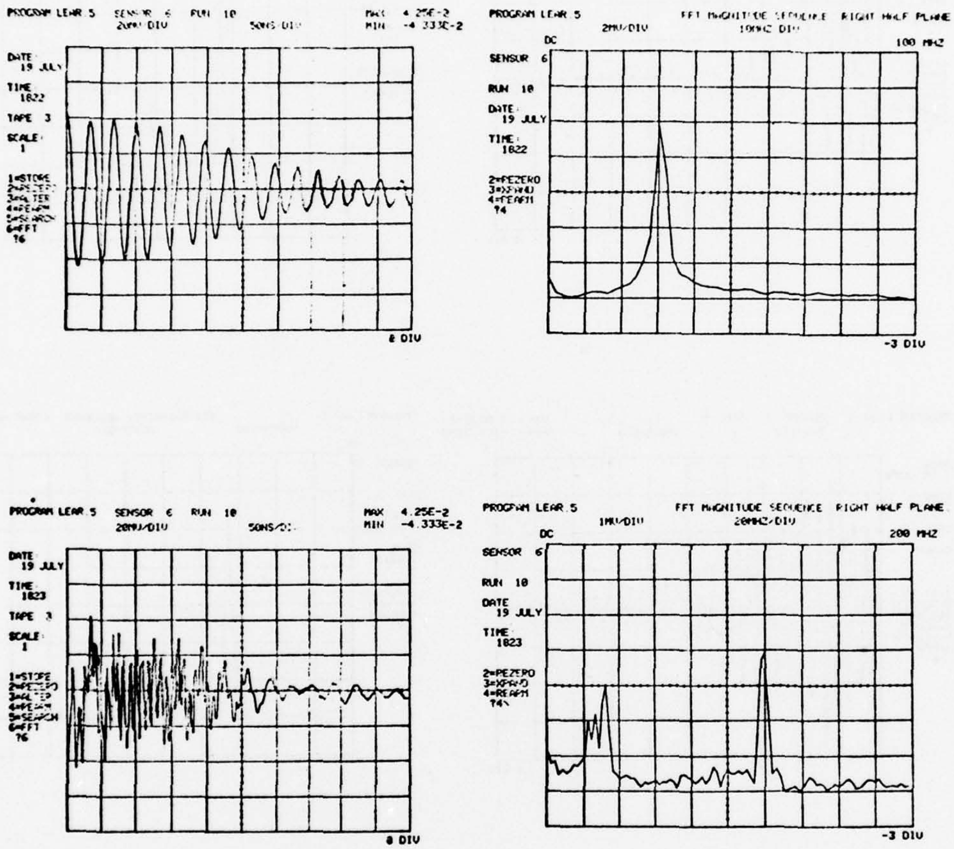


Figure 17 - Transient Spectral Variability, Example 1

In Figure 18, note the change in the pulse from a combination of 33 and 52 MHz components at time 1611 to a pure sine pulse of 33 MHz only at 1612.

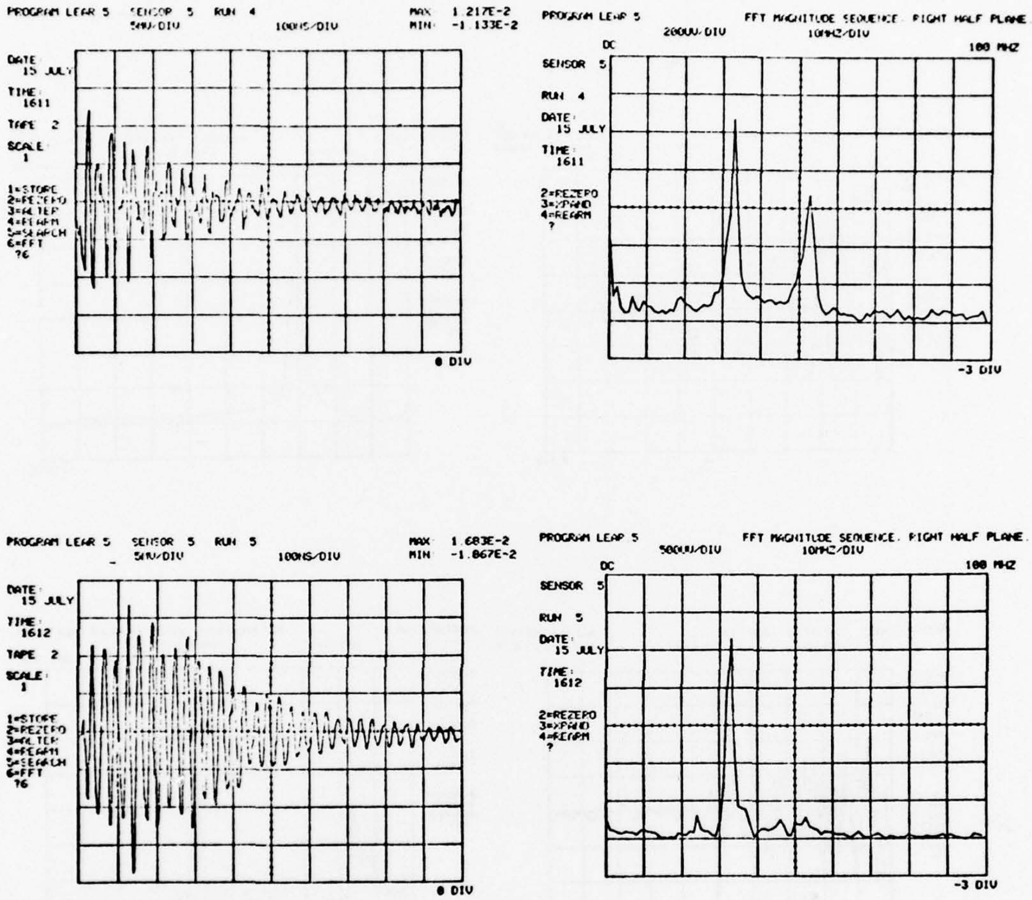


Figure 18 - Transient Spectral Variability, Example 2

In Figure 19 note the change in the transient from a pulse rich in several frequency components (primarily around 23 and 120 MHz) at 1337 to one with only a 23 MHz component at 1338, and then back to a pulse with major frequency components at 23 and 120 MHz at 1339. Note also that 50 MHz component is significant in the observation at 1337, but not in the others.

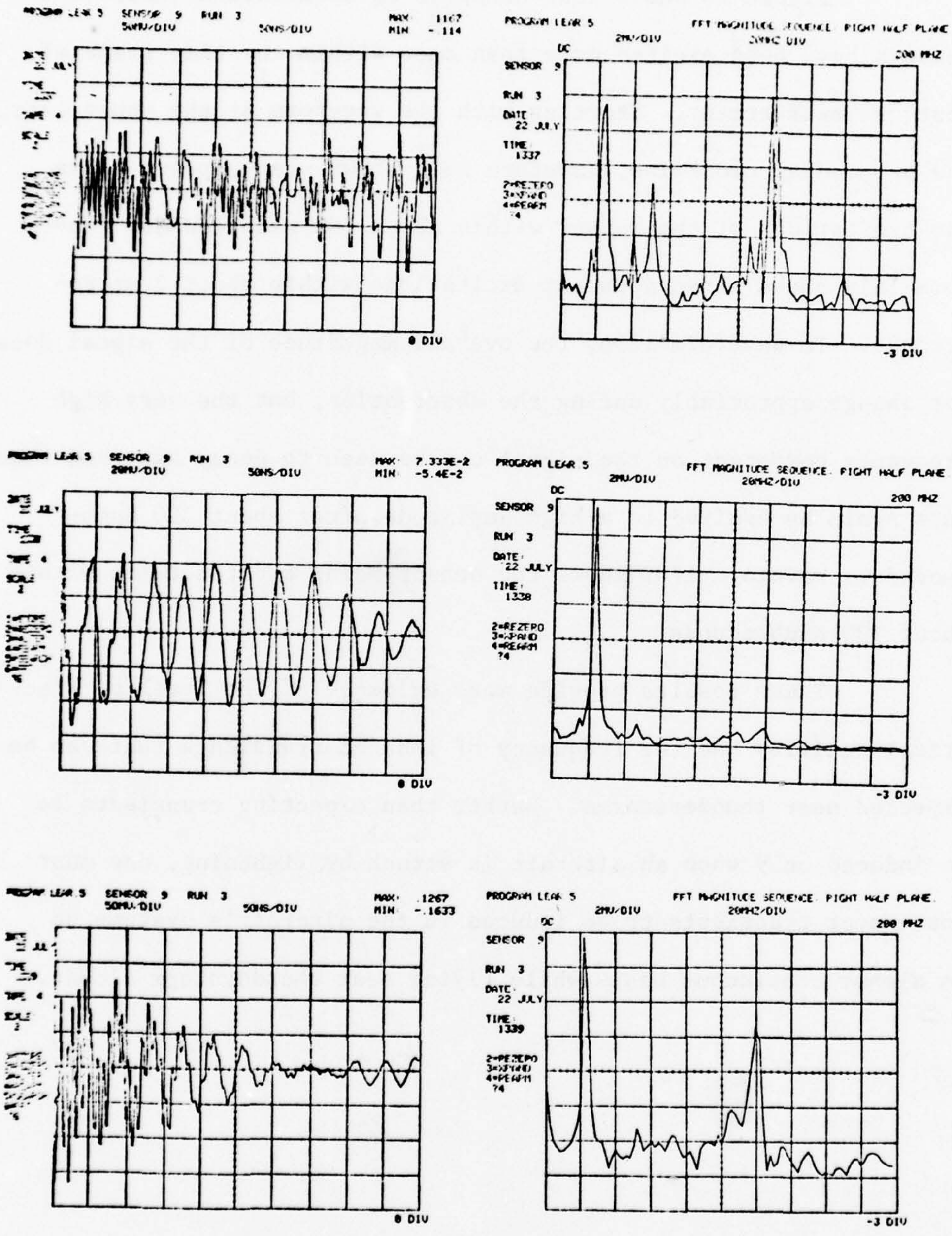


Figure 19 - Transient Spectral Variability, Example 3

4. Multiple Event Observations

Figure 20 shows four examples of observations where the sensors have been excited more than once within the time frame of just one measurement. Starting with the waveform at the upper left, and proceeding clockwise, waveform 1815 shows what appears to be two excitations of the sensor within about 700 nanoseconds. Waveform 1819 shows three apparent excitations within about 2 microseconds. In waveform 1336, the overall magnitude of the signal does not change appreciably during the observation, but the very high frequency component on the signal can be seen to decay away and then once again be excited to a high amplitude after about 350 nanoseconds. Waveform 1709 shows the sensor being excited twice within about 700 nanoseconds.

These results provide more evidence of the level of electrical activity and the frequency of induced transients that can be expected near thunderstorms. Rather than expecting transients to be induced only when an aircraft is struck by lightning, one must now expect transients to be induced in the aircraft's systems on an almost continuous basis while flying near thunderstorm clouds.

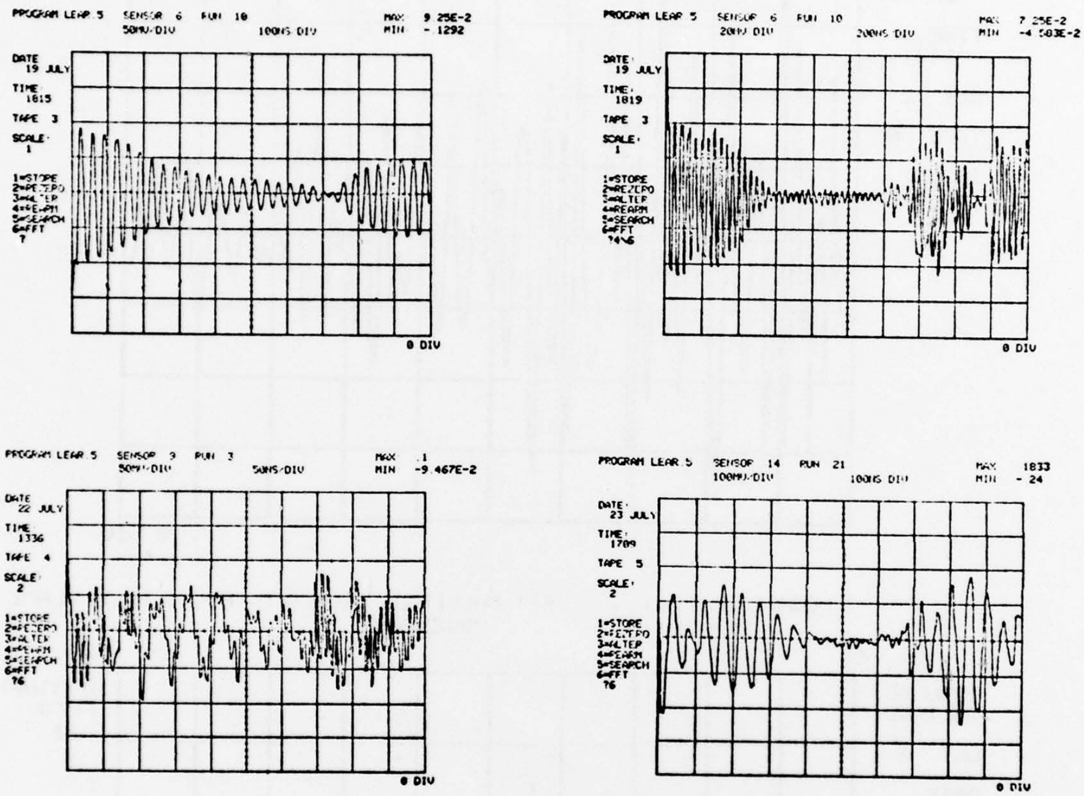


Figure 20 - Multiple Event Observations

5. Similarity to Ground Simulation Observation

The induced transients observed during this program while flying in the vicinity of natural lightning were similar to the induced transients observed during ground simulated lightning tests on other aircraft. Figure 21 is an example of a typical transient observed during a ground simulated lightning test on an A-7 aircraft,

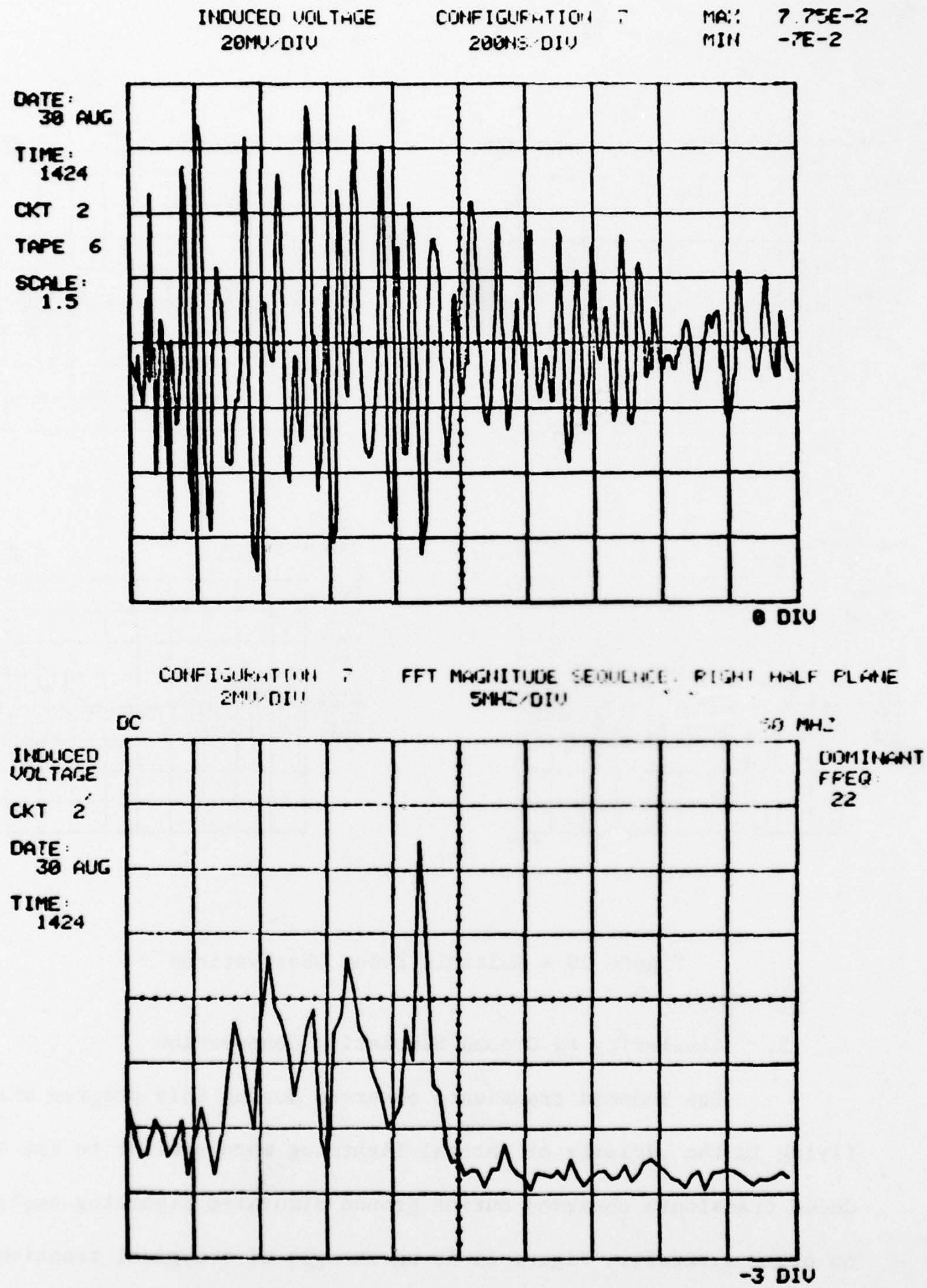


Figure 21 - Typical Transient, Ground Lightning Simulation

and this transient is indeed similar to the transients experienced by the Learjet in magnitude (78 millivolts peak), overall duration (2 to 40 microseconds estimated), and frequency content (major components between 10 and 25 MHz). Additional examples of similar signals could also have been presented from tests on F-111, F-16, and F-4 aircraft.

The observation shown in Figure 21 was made during a test of the Navy A-7 Airborne Light Optical Fiber Technology (ALOFT) aircraft. The specific measurement point was within the Navigation and Weapons Delivery Computer, on the data line "Data Output to FLR (Forward Looking Radar) Signal Generator." The lightning simulation consisted of a 1.6 x 50 microsecond double-exponential current pulse with a peak current of 2000 amperes which was applied nose-to-tail through the aircraft.

This circuit was considerably longer than the 9-foot wire sensor used in the Learjet, and much more complex. These factors could easily account for the lower frequencies (compared to the Learjet data) apparent in the signal. The lower frequencies may also be due to the fact that measurements were made during this simulation via a fiber optics analog data link which had an upper frequency limit of approximately 25 MHz, and so, had there been frequency components above 25 MHz in the signals, they would not have been observed. (Since the Learjet measurements did not involve this bandwidth limitation, frequencies above 25 MHz were observed on many occasions.)

It is also possible that the ground simulation was not exciting the same high-frequency (greater than 25 MHz) effects in the aircraft that the natural lightning had, though this cannot be determined from these measurements.

With these considerations in mind, the similarities between the ground and airborne observations are important because they suggest that the present ground lightning simulation techniques may indeed be simulating some aspects of the aircraft-lightning interaction even though sufficient evidence is not yet available to show this conclusively. This is the first evidence, however, to suggest similarity between the effects produced in ground lightning simulations and those produced by natural lightning.

SECTION IV

CONCLUSIONS

The region in and near active thunderstorm cells was found to be electrically extremely active, with transient pulse signals being observed with repetition rates in excess of 100 per second for extended periods. It was found that a few per cent of the electric field pulses observed contained appreciable RF energy (in the 1 to 30 MHz range), and that only some of these pulses coupled sufficient energy inside the aircraft to induce transient signals on a wire sensor installed in the cabin. Nevertheless, several observations were obtained where a transient sensor was excited more than once within periods of less than one microsecond. It was found that it can be assumed that when an aircraft is flying near a thunderstorm transients are being induced on the aircraft's electrical systems on an almost continuous basis -- even with no direct lightning strike to the aircraft, nor apparent lightning nearby.

Investigations into the induced transients observed on different wire sensor configurations showed that the nature and frequency content of the signals does indeed depend upon the overall length and configuration of the circuit in question, in addition to the terminating impedance at each end of the wire circuit.

Often the observations showed that the spectral content of the pulses exciting the transient sensors was highly unpredictable and variable, with wide variations in frequency content being evident in consecutive observations on particular sensors. This phenomenon is most likely due to variations in spectral content from one external-field pulse to the next, in addition to variations in the type of surface current oscillations set up over the skin of the aircraft from one pulse to the next.

Comparison between the transient magnitudes experienced with an accidental strike to the aircraft and an observed nearby lightning strike showed the transients from the nearby strike to be 20 to 50 per cent as intense as those from the direct strike. This indicates that merely being in the vicinity of lightning presents a significant hazard to the onboard electronics in an aircraft, while it has been previously assumed that only a direct strike posed a real threat.

The induced transients observed on the wire sensors in the Learjet were similar in magnitude, duration, and frequency content to other observations made during ground simulated lightning tests on other type aircraft (such as F-4, F-111, F-16, and A-7). Though these similarities are insufficient to conclusively prove the validity of the present ground lightning simulation techniques for aircraft testing, these results do suggest that some aspects of the aircraft-lightning interaction are being simulated during ground tests.

SECTION V

RECOMMENDATIONS

Based on the results of this experiment, several recommendations can be made for future research into the lightning phenomenon and its effect in aircraft. (As this report is being written, an experiment is being assembled which will embody many of these recommendations.)

Much more work needs to be done in characterizing the lightning threat in the radio frequency region. An understanding of the lightning spectrum in the region between 1 and 75 MHz, where most aircraft resonances occur, is especially critical to predicting and devising protective schemes for the lightning transient effects in aircraft.

To establish the credibility of ground simulated lightning test techniques, observations of transient effects while in flight near lightning and during ground lightning tests needs to be made with the same sensor and recording instrumentation. A comparison of these data should show the validity of the simulations.

Airborne measurements of the lightning environment should be made with several channels of transient digitizers to allow direct comparison between external field activity, induced transients, and skin currents on the aircraft through simultaneous multi-channel measurements.

External field measurements should be made with a wide-bandwidth (DC to 100 MHz) magnetic field probe rather than an electric field sensor as was used in this program. Magnetic field measurements should be less affected by the presence of static charge carried by the aircraft.

An experiment should be flown which combines the transient digitizer (high time resolution, but not continuous recording) and spectrum analyzer (low time resolution, but continuous recording) instrumentation into one payload so that the high resolution transient digitizer observations could be interpreted in the context of the overall electrical activity.

REFERENCES

1. The Radio Amateur's Handbook (Forty-ninth Edition). American Radio Relay League: Newington, CT, 1972.

2. Berger, K. "Development and Properties of Positive Lightning Flashes at Mount S. Salvatore with a Short View to the Problem of Aviation Protection." Paper presented at Lightning and Static Electricity Conference, Culham Laboratory, England, April 1975.

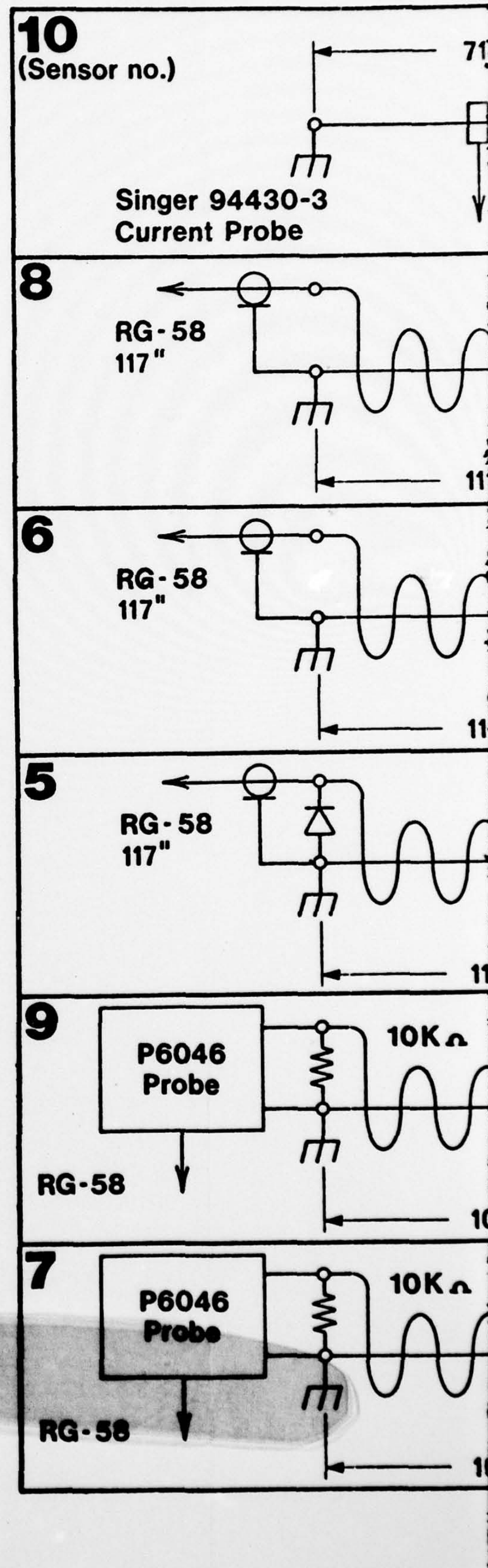
3. "JSC Thunderstorm Experiment Results." NASA Technical Report JSC-12509, prepared by Program Operations Office, NASA Johnson Space Center, Houston, TX, March 1977.

4. Nanevicz, Adamo, and Bly. "Airborne Measurement of Electromagnetic Environment Near Thunderstorm Cells (TRIP-76)." Stanford Research Institute technical report prepared for NASA and Air Force Flight Dynamics Laboratory under contract NAS9-15101, March 1977. SRI project 5536.

APPENDIX A

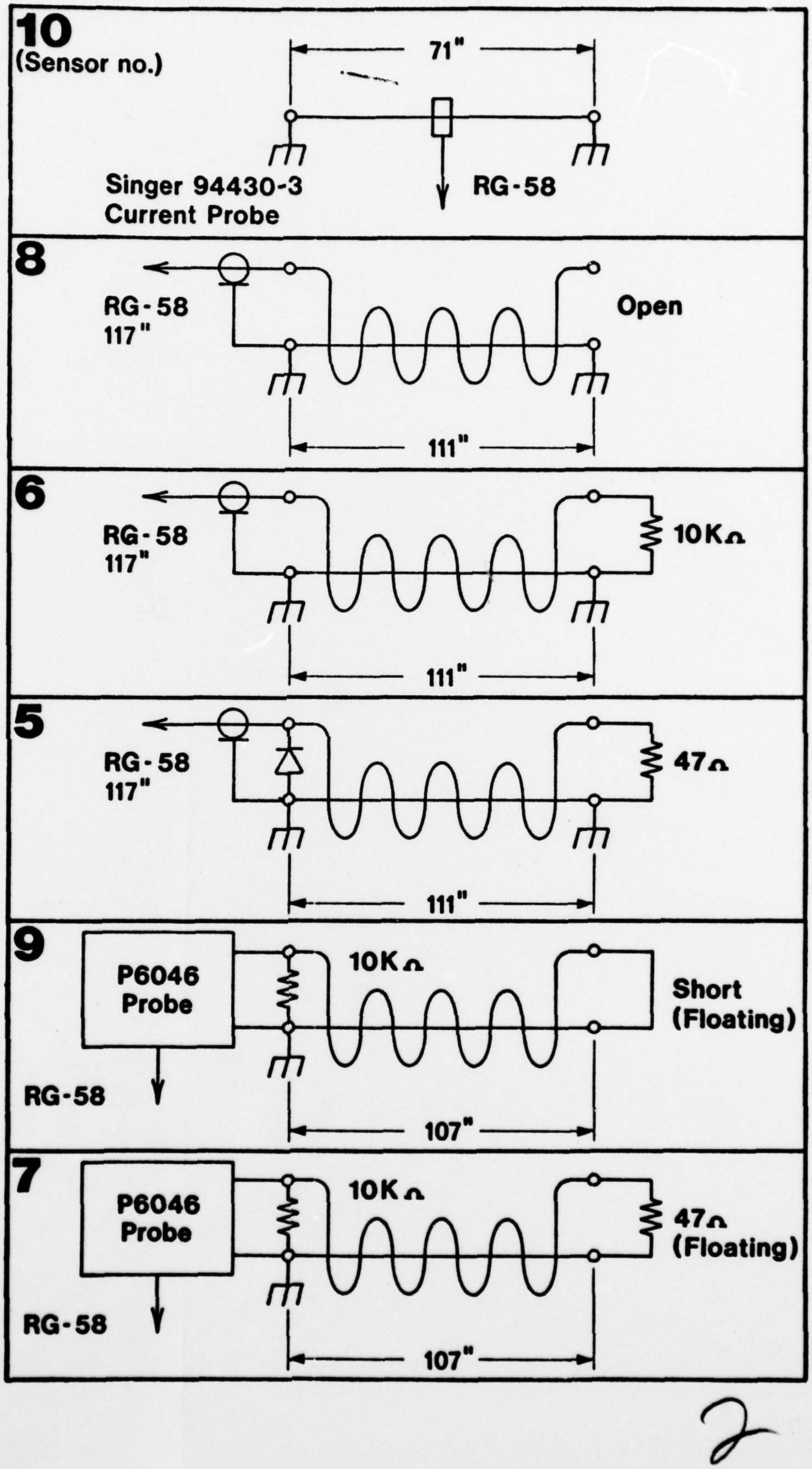
INDUCED TRANSIENT SENSOR CONFIGURATIONS

Induced Transien



IFIGURATIONS

Induced Transient Sensors



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APPENDIX B

BASIC LANGUAGE COMPUTER PROGRAM LISTING

The BASIC program shown below and on the following pages was used for data acquisition and processing during this experiment. It is included for reference purposes only for those familiar with the WDI TEK BASIC language. No further documentation, such as flow-charts or narrative description, are available.

```
8000 PRINT "^C^L":PRINT "PROGRAM LEAR.9     CAPT J. DIJAK     24 JAN 77"
8005 GOSUB 9350:REMARK COMPUTE HANNING WINDOW.
8010 PRINT " ":LET HA$="S/DIV":LET HB$="S/DIV":LET HC$="S/DIV":LET VC=0:
LET ZC=0
8015 LET R7=7:PRINT "DATE:  JULY";:INPUT DT:PRINT " "
8017 PRINT "SENSOR, SCALE:";:INPUT S,S1:PRINT " "
8018 PRINT "DATA TAPE NUMBER ";:INPUT TP:PRINT " "
8020 PRINT "ACQUIRE ZERO:  1-YES  2-NO  ";:INPUT X
8025 REMARK SENSOR 1 IS E-FIELD ANTENNA.  SENSORS 2 AND ABOVE ARE INDUCE
D CIRCUITS.
8030 IF X=2 THEN 8050
8040 ACQUIRE ZERO
8050 PRINT " ":PRINT "WAITING TO ARM.":WAIT
8070 DIGITIZE :ACQUIRE :PRINT "^G"
8080 PRINT "1=GRAPH RAW  2=REZERO  4=REARM  ";:INPUT X1
8090 IF X1=2 THEN 8040
8100 IF X1=4 THEN 6070
8110 PRINT " ":PRINT "TIME (EDT, 24 HR CLOCK), RUN:":INPUT T,R
8120 PRINT "^C^L":GRAPH RAW
8130 PLOT 0,0,730:PRINT "^_PROGRAM LEAR 5   SENSOR";S;"   RUN";R
8140 PLOT 0,0,670:PRINT "^_DATE ":PRINT ;DT;" JULY":PRINT " "
8150 PRINT "TIME:":PRINT ;T:PRINT " "
8155 PRINT "TAPE";TP:PRINT " "
8160 PRINT "SCALE ":PRINT ;S1:PRINT " ":PRINT " "
8170 PRINT "2=REZERO":PRINT "3=NOR":PRINT "4=REARM":INPUT X1
8180 IF X1=2 THEN 8040
8190 IF X1=4 THEN 8070
8410 NORMALIZE B:LET B=B*S1
8420 LET HB=0:LET TB=0:LET VB=0:LET ZB=0
8425 LET HB$="S/DIV"
8430 IF S<10 LET VB$="V/DIV"
8437 IF S>=10 LET VB$="A/DIV"
8438 IF S>14 LET VB$="V/MTR/DIV"
8439 IF S=13 LET VB$="V/DIV"
```

```
8440 LET P3=MAX(B):LET P4=MIN(B)
8442 IF S=14 LET VB$="V/DIV"
8445 CWRITE 0,LEAR,DT,T,R,S,P3,P4,B,SB,S1,Y
8450 PRINT "^C^L":GRAPH B
8460 PLOT 0,0,780:PRINT "^_   SENSOR";S;"   RUN";R
8464 PLOT 0,800,780:PRINT "^_MAX:",[P3] P3
8466 PLOT 0,800,740:PRINT "^_MIN:",[P4] P4
8470 PLOT 0,0,670:PRINT "^_DATE:":PRINT ;DT;" JULY":PRINT " "
8480 PRINT "TIME:":PRINT ;T:PRINT " "
8487 IF X1=7 23 THEN 9300
8490 PRINT " ":PRINT " "
8500 INPUT X1
8510 IF X1=2 THEN 8040
8520 IF X1=4 CREAD F,1,LEAR,DT,T,R,S,P3,P4,B,SB,S1,TP:GOTO 9060
8530 IF X1=5 THEN 9010
8540 IF X1=3 THEN 9070
8550 IF X1=6 THEN 8590
8570 CWRITE 1,LEAR,DT,T,R,S,P3,P4,B,SB,S1,TP:GOTO 8500
8590 LET C=B*A*2.5:LET SC=SA
8592 REMARK WINDOWED WAVEFORM IN ARRAY C.
8594 FFT C,C,D,POLAR
8595 GOSUB 9600:REMARK CHANGE DISPLAY UNITS.
8600 LET VC=0:LET TC=256
8610 LET HC$="HZ/DIV"
8630 PRINT "^C^L":GRAPH C
8650 PLOT 0,410,780:PRINT "^_FFT MAGNITUDE SEQUENCE, RIGHT HALF PLANE."
8660 PLOT 0,120,710:PRINT "^_DC":PLOT 0,830,710:PRINT "^_",HC/1E+5;" MHZ
"
8670 PLOT 0,0,670:PRINT "^_SENSOR";S:PRINT " "
8680 PRINT " ":PRINT "RUN";R:PRINT " "
8690 PRINT "DATE:":PRINT ;DT;" JULY":PRINT " "
8700 PRINT "TIME:":PRINT ;T:PRINT " ":PRINT " "
8705 GOSUB 9700:REMARK COMPUTE DOMINANT FREQUENCY.
8710 PRINT " ":PRINT " "
8720 IF X1=2 THEN 8040
```

```
8730 IF X1=4 CREAD F,1,LEAR,DT,T,R,S,P3,P4,B,SB,S1,TP:GOTO 9060
8740 PRINT " ":PRINT "EXPAND BY ";:INPUT X:LET HC=HC/X:GOTO 8630
9010 PRINT " ":PRINT "FILE SEARCH ON DRIVE 1 ":PRINT " "
9012 PRINT "TAPE NUMBER:"; INPUT TP:PRINT " "
9015 PRINT "DATE, TIME, RUN ": INPUT D2,T2,R2
9020 CREAD F,1,LEAR,DT,T,R
9030 IF DT<>D2 THEN 9020
9040 IF T<>T2 THEN 9020
9045 IF R<>R2 THEN 9020
9050 IF TP=1 CREAD R,1,LEAR,DT,T,R,S,P3,P4,B,SB
9055 IF TP<>1 CREAD R,1,LEAR,DT,T,R,S,P3,P4,B,SB,S1,TP
9060 IF S<>4 THEN 8425
9062 IF S1=1 LET B=B*500:LET S1=500
9064 IF S1=8.4 LET B=B*4400/8.4:LET S1=4400
9066 IF S1=84 LET B=B*(3E+4)/84 LET S1=3E+4
9068 LET S=4.15:LET VB$="V/MTR/DIV":LET Y=6
9069 GOTO 8440
9070 PRINT " ":PRINT "HB,TB,VB,ZB ";:INPUT HB,TB,VB,ZB:GOTO 8450
9200 REMARK PRINT-A-DATA TAPE ROUTINE.  14 JULY 76
9210 PRINT "^E^LPRINT-A-TAPE ROUTINE." PRINT " "
9215 PRINT "TAPE NUMBER:"; INPUT TP:PRINT " "
9217 IF TP=1 LET S1=0
9220 PRINT "VIEW OPTION   1-YES  2-NO  ";:INPUT X
9223 PRINT " ":PRINT "HARD COPY OPTION   1-YES  2-NO ";:INPUT X2
9225 LET X1=7.23:REMARK FLAG
9230 IF TP=1 CREAD F,1,LEAR,DT,T,R,S,P3,P4,B,SB
9235 IF TP<>1 CREAD F,1,LEAR,DT,T,R,S,P3,P4,B,SB,S1,TP
9240 GOTO 8420
9300 IF X2=1 THEN PRINT "^E^W"
9310 IF X=1 WAIT
9320 IF TP=1 CREAD F,1,LEAR,DT,T,R,S,P3,P4,B,SB:GOTO 8420
9330 CREAD F,1,LEAR,DT,T,R,S,P3,P4,B,SB,S1,TP:GOTO 8420
9350 LET B=.6283 INTEGRATE B,B
9355 LET B=0.5*(1-COS(B)):LET B=B/MAX(B)
9365 RETURN
```

```
9600 IF SC=1.024E+8 LET HC=5E+7
9605 IF SC=5.12E+7 LET HC=2E+7
9610 IF SC=2.56E+7 LET HC=1E+7
9615 IF SC=1.28E+7 LET HC=5E+6
9620 IF SC=1.024E+7 LET HC=5E+6
9625 IF SC=5.12E+6 LET HC=2E+6
9630 IF SC=2.56E+6 LET HC=1E+6
9635 IF SC=1.28E+6 LET HC=5E+5
9640 IF SC=1.024E+6 LET HC=5E+5
9645 IF SC=5.12E+5 LET HC=2E+5
9648 RETURN
9700 LET M=0
9705 FOR J=256 TO 350
9710 IF M<C(J) LET M=C(J):LET FM=J
9715 NEXT J
9720 LET FM=(FM-256)*SC/(51.2*1E+6)
9730 PLOT 0,925,670:PRINT "^_DOMINANT"
9735 PLOT 0,925,645:PRINT "^_FREQ:"
9740 PLOT 0,910,620:PRINT "^_";FM
9745 PLOT 0,0,400:PRINT "^_"
9750 RETURN
READY
*
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