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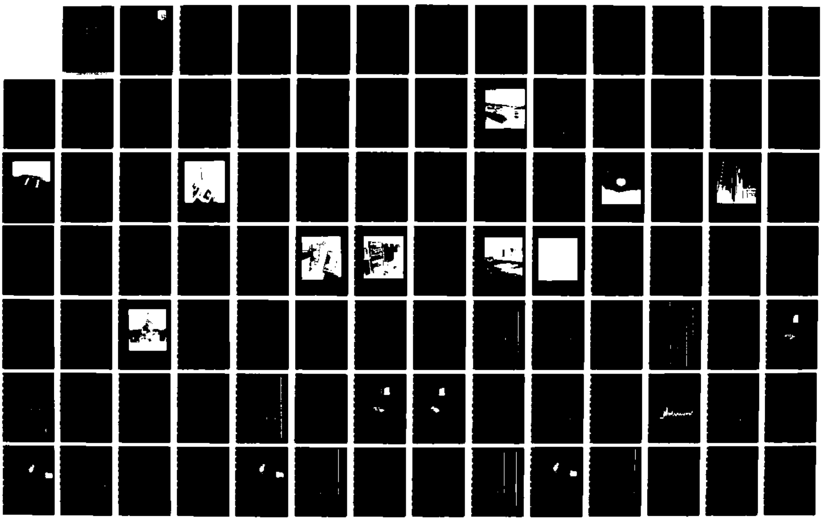

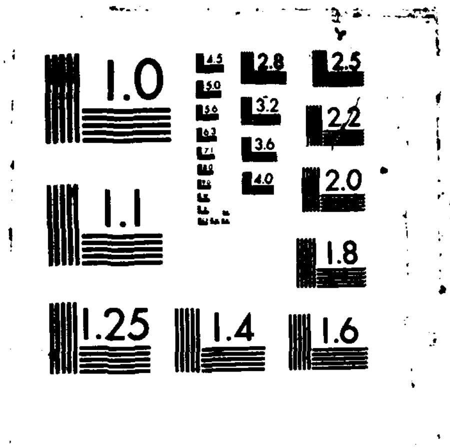

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LOW ALTITUDE LIGHTNING ATTACHMENT TO AN AIRCRAFT

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A CV-580 aircraft was instrumented with external displacement current density sensors, surface current current density sensors, current shunts, and static electric field mill sensors and was flown in the neighborhood of active thunderstorms in central Florida during Summer 1984. Electromagnetic data were collected for 21 direct lightning strikes to the aircraft at altitudes between 2,000 and 18,000 ft. The data consisted DC to 2 MHz analog records and 10.24 microsecond windows of digital samples taken at five nanosecond intervals. The data show the physical mechanism of lightning attachment to the aircraft.

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SUMMARY

This is the first report on a two-year effort to collect direct lightning attachment data using a Federal Aviation Administration (FAA) Convair 580 (CV-580) aircraft. This is a multi-agency program managed by the Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio, with close support from the FAA Technical Center, Atlantic City, New Jersey.

A CV-580 aircraft was instrumented externally with five magnetic field sensors, five electric field sensors, two current shunts, four electric field mills, and two VHF antennas. Internally, three current shunts were used to determine induced transients and a wire loop monitored induced voltages attributable to aperture coupling. The aircraft was stationed at Patrick Air Force Base, Florida and was flown inside or under active thunderstorms. To assess whether a particular lightning interaction with the aircraft was either a natural (intracloud or cloud-to-ground) or a triggered discharge, a field station located on the ground in proximity to the aircraft location was utilized wherein distant electric and magnetic fields were measured and compared to previously acquired data for both types of discharges.

Twenty eight channels of continuous analog data with a 2-megahertz (MHz) bandwidth in the direct channels and a 500 kilohertz (kHz) bandwidth in the FM channels were recorded in the aircraft. Six 7612 Tektronix waveform digitizers with sample rates of 5 nanoseconds (ns) and two windows of 2048 samples per digitizer were used in the aircraft. A variable threshold level between 5×10^9 and 2×10^{10} Amperes/second (A/s) was used to trigger the digital system. Three television cameras were installed to monitor the top of the aircraft and each of the wings. The camera images were stored continuously on separate video cassette recorders. IRIG-B time code available at the

ground site located at the Cape Canaveral Air Force Station was retransmitted to the aircraft and used for time synchronization.

This report presents a description of the aircraft and ground instrumentation used to accomplish the data acquisition during the summer of 1984, and an analysis of the data from the direct lightning attachments recorded in the aircraft. Some of the most important results from the analysis of 1984 data are:

a) The maximum levels of electric and magnetic flux densities measured exceeded 22 Amperes/meter^2 (A/m^2) and 3950 Teslas/sec (T/s), respectively.

b) The three lightning attachments that occurred at altitudes of 4,000 ft and below appeared to be part of cloud-to-ground discharges.

c) For altitudes between 2,000 and 18,000 ft, the probability that an aircraft will be hit by lightning inside or near a thundercloud increases as a function of height and decreasing air temperature.

d) The maximum charge transfer measured during a lightning attachment to the aircraft exceeded 100 Coulombs (C).

e) Twelve of the 21 flashes appeared to have been triggered by the presence of the aircraft in a high intensity electric field.

f) Considerable damage to aircraft nonmetallic surfaces can be expected due to lightning attachment to the aircraft.

FOREWORD

This is the first Air Force Wright Aeronautical Laboratories (AFWAL) Technical Report on the multiagency direct strike lightning measurement program performed by the U.S. Air Force, the Federal Aviation Administration (FAA), and the U.S. Navy. This was an in-house research project for these participating agencies with AFWAL's Flight Dynamics Laboratory managing the entire program as part of its Lightning/Nuclear Electromagnetic Pulse Measurement Program, Work Unit Number 24020243.

This work could never have been accomplished without the dedicated efforts of many individuals within the primary and support agencies cooperating in this effort. Technology/Scientific Services Inc. (T/SSI), the AFWAL in-house contractor, was a key participant in the entire program. T/SSI integrated all Air Force specifications into a comprehensive test program and assisted in collecting and analyzing the data. Special thanks goes to the T/SSI data analysts who developed and operated most of the data acquisition software.

Several dedicated individuals from the FAA were responsible for providing, modifying, and flying the aircraft in order to perform the required missions. Mr Nickolus Rasch was the key FAA participant in the early stages of the program. He was succeeded by Mr Michael Glynn as the FAA Program Manager. Mr Glynn deserves much of credit for making the program possible through his accomplishment of the many tasks required to fly the aircraft. The FAA also provided the pilots who flew these hazardous missions. We are very grateful to all those pilots and especially to Mr Jesse Terry and Navy Capt (Ret) Al Bazer.

We received a great deal of cooperation and support from the Naval Research Lab (NRL) in getting the program started and in performing electric field mill measurements. Dr Lothar Ruhnke and Mr Robert Anderson were the key NRL contributors in this mission.

We are especially grateful for the support provided by numerous individuals from the National Aeronautical and Space Administration (NASA) at Kennedy Space Center and from the Eastern Space and Missile Center (ESMC) at Patrick Air Force Base. Without their help, this program could never have been undertaken.

Finally, we want to thank our colleagues from the Office National d'Etudes et de Recherches Aerospatiales (ONERA) in France who provided additional instrumentation and personnel to perform lightning measurements in the aircraft. In particular, we want to thank Dr Jean-Patrick Moreau, Mr Pierre LaRoche, and Mr Jean-Claude Alliot for their assistance throughout the entire program.

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SECTION I

INTRODUCTION

This program was designed to expand the existing data base on lightning direct strikes to aircraft, to define and validate a lightning characterization model based on airborne aircraft lightning attachment data, and to compare aircraft lightning data with that of simulated nuclear electromagnetic pulse (NEMP) data on the same aircraft.

Only a limited amount of data is presently available on the electromagnetic characteristics of lightning attachment to an aircraft in flight at altitudes from 2,000 to 20,000 ft. There have been only eight experimental programs (References 1 through 8) reported in the open literature which have tried to obtain aircraft lightning research data. The most extensive lightning attachment data has been recorded in a NASA F-106 aircraft at altitudes between 20,000 and 40,000 ft (References 3 and 4). Most of the data reported on the other programs is bandwith-limited by the recording instrumentation. Prior to this program, it appears that there has been no confirmation of data collected in an aircraft during direct attachment by a cloud-to-ground lightning flash.

During this project, an attempt was made to measure some of the parameters that constitute a lightning threat to an aerospace vehicle. About 70% of the total flying hours were spent flying below the cloud base trying to obtain natural cloud-to-ground attachments to the aircraft.

This program was conceived by personnel from the US Air Force, US Navy, and the FAA. These agencies have realized that the aircraft/lightning threat poses a question of flight safety and integrity with the expanded employment of low power microelectronics and advanced structural materials in flight-critical systems. Other organizations joined the initial effort and the result was a large combined program to measure the currents and fields during lightning attachment to an aircraft.

Table 1 shows an organizational block diagram of the various agencies involved in the project. The Air Force Wright Aeronautical Laboratories (AFWAL) and the FAA are the key participants. Electromagnetic Applications (EMA) was under contract with the FAA to develop a program plan and analyze selected data. The Naval Research Laboratory (NRL) provided a field mill system which was used during the summer 1984 to collect static field data on the aircraft. The Air Force Weapons Laboratory (AFWL) provided the six digitizers being used in the aircraft and the two digitizers used in the ground system. AFWL is also overseeing the entire program to determine whether significant results could be obtained by performing simulated NEMP tests in the aircraft. The French organization, Office National d'Etudes et de Recherches Aerospatiales (ONERA), provided two of the sensors mounted on the aircraft wings and the VHF antennas mounted on top of the aircraft. ONERA also provided the instrumentation needed to process and record the data. The Eastern Space and Missile Center (ESMC) provided support for the aircraft and the research crew during the summer program. This support included a dedicated C-band radar used to track the aircraft at all times during flight. ESMC also provided the position of all lightning return strokes measured by the Lightning Location and Protection (LLP) system which covers most of the state of Florida. The National Aeronautics and Space Administration/Kennedy Space Center (NASA/KSC) provided JP-5 fuel to the aircraft and a rocket triggered lightning program to obtain simultaneous data on lightning current measurements at the ground level. Warner Robins Air Logistic Center (WR-ALC) provided support to evaluate the accuracy of the

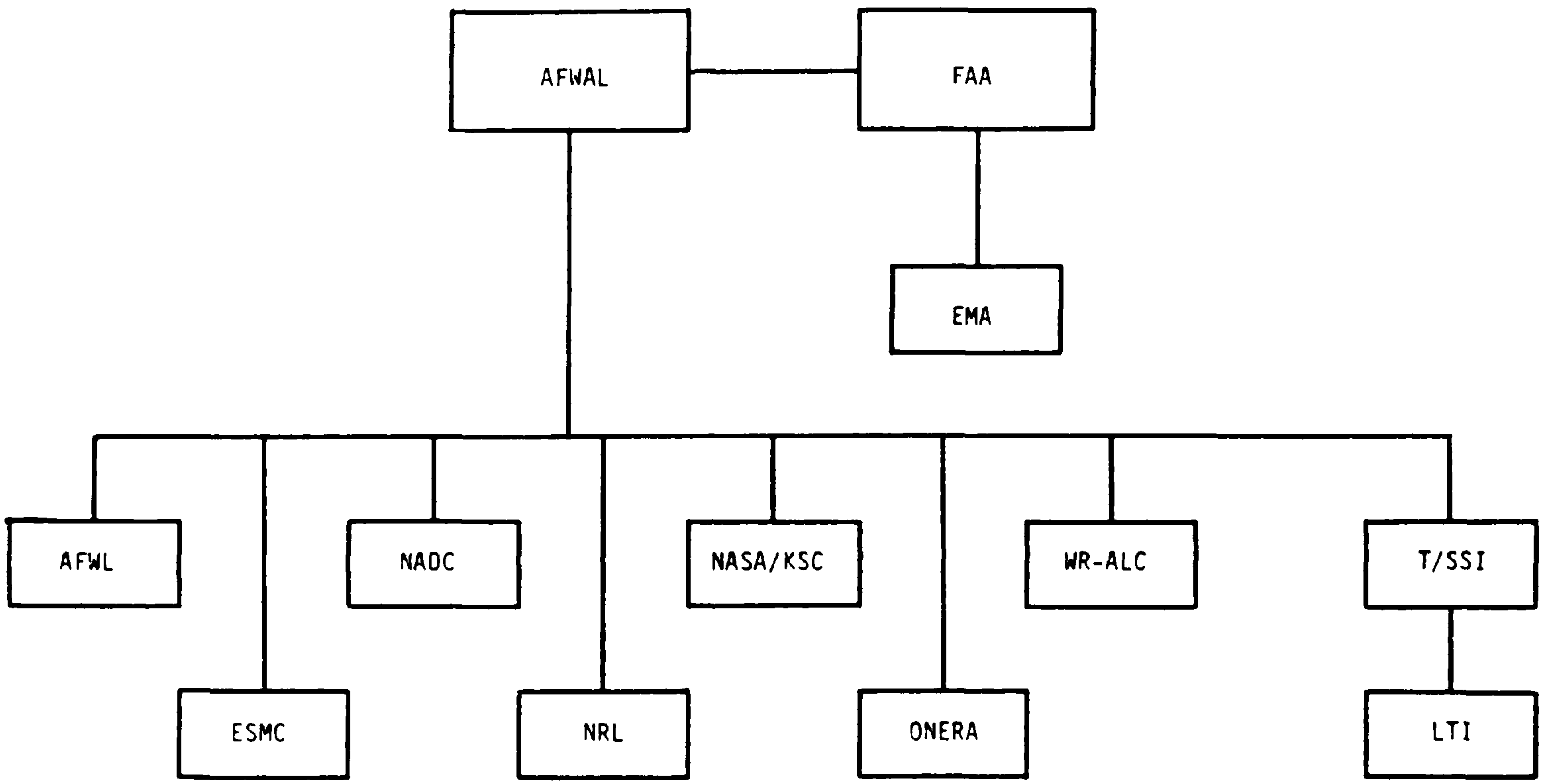


Table 1. Organizational Block Diagram of the Agencies Involved in the Program

UX-11 3M/Ryan Stormscope version designed in 1984. The Naval Air Development Center (NADC) provided some financial support to ensure all the main objectives of the program were accomplished. Technology/Scientific Services, Inc (T/SSI) supported AFWAL in the design of the instrumentation, data collection, and in analysis of the results. Lightning Technologies, Incorporated (LTI) was responsible for the safety of the aircraft. LTI analyzed the aircraft and performed safety tests on the aircraft to ensure the aircraft fuel tank and other vulnerable structures could survive a 100 kiloampere (kA) lightning discharge. LTI also inspected the aircraft after flights to identify the attachment patterns.

The CV-580 aircraft used throughout the program to obtain direct lightning attachment is shown in Figure 1. This is a turbo prop aircraft owned and operated by the FAA Technical Center in Atlantic City, NJ. The aircraft dimensions are shown in Figure 2.

To acquire the required data, the aircraft was flown for a total of 65 hours near active thunderstorms between 11 July and 5 Sept 1984. The flights were performed at altitudes between 2,000 and 18,000 ft in areas of radar reflectivity not to exceed 40 dBZ. The flights were planned to occur in the vicinity of the Kennedy Space Center (KSC) but were extended to the entire central Florida region when active thunderstorms developed.

The CV-580 aircraft was instrumented with five electric and five magnetic field sensors, two current sensors, four electric field mills, and two VHF antennas. These sensors were mounted on or near the skin of the aircraft. Signals from these sensors were transmitted through semi-rigid, solid shield of cables to analog and digital recorders mounted inside the aircraft. The analog recorder used was a 28 channel Honeywell 101 with a frequency response from DC to 500 kHz in the FM channels and 400 Hz to 2 MHz in the direct

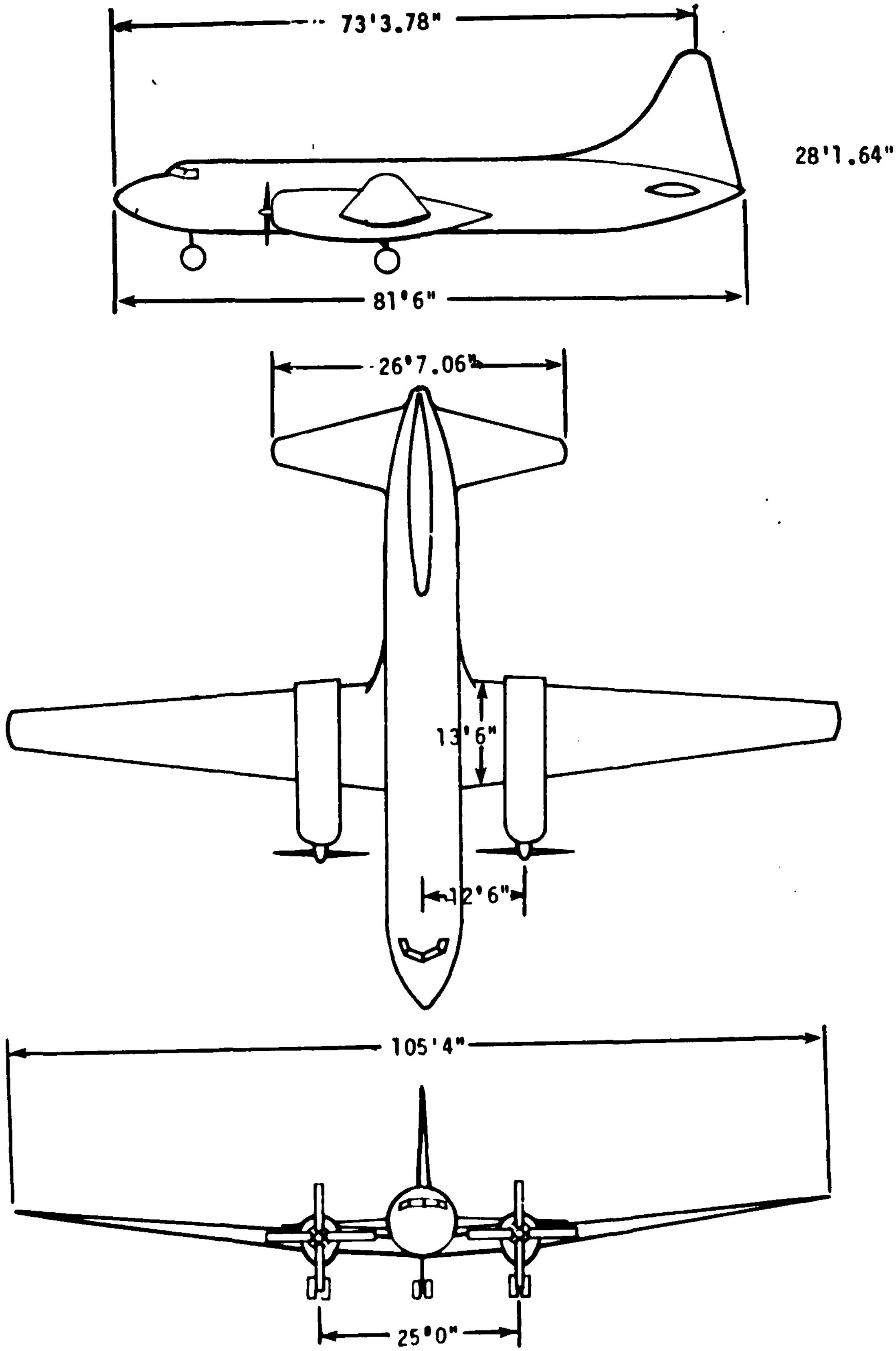


Figure 2. Three View Drawings of CV-580 Aircraft and Overall Dimensions

channels. The aircraft digital data was acquired by using six 7612 Tektronix waveform digitizers with a sampling rate of 5 ns and a sample window of 2048 samples. The data were subsequently recorded on either 9-track tape or 8-inch floppy disks. The digital data acquisition system was set to trigger all digitizers simultaneously whenever a preset threshold level was exceeded. A trigger pulse signal was recorded on one of the channels of the analog recorder whenever a digital trigger had occurred.

The ground station was placed at the eastern tip of the Cape Canaveral Air Force Station to record electric and magnetic fields produced by distant lightning. The primary purpose of this station was to measure the radiated fields produced by flashes that attached to the aircraft.

SECTION II

AIRCRAFT AND GROUND INSTRUMENTATION SYSTEMS

The frequency content of the electromagnetic fields produced by lightning discharges extends from near DC to hundreds of megahertz. A typical flash lasts about 0.5 seconds, but some of the pulses in the flash have risetimes on the order of tens of nanoseconds. Consequently, to measure the characteristics of the individual pulses in the flash and be able to record the entire flash, the instrumentation system must have a frequency response from near DC to about 100 MHz. This wideband frequency response was obtained with a combination of analog and digital recorders in the aircraft and at the ground station. This section provides a detailed description of all the aircraft and ground sensors, recorders, and required interface.

1. AIRCRAFT INSTRUMENTATION

a. External Transient Measurements

Figure 3 shows the location of the transient measurements sensors mounted on the skin of the aircraft. Five surface current rate of change sensors designated as J_S were mounted on the forward upper fuselage (J_{SFUF}), aft upper fuselage (J_{SAUF}), bottom left wing (J_{SBLW}), bottom right wing (J_{SBRW}), and top left wing (J_{STLW}). Five displacement current rate of change sensors designated as J_N were mounted on the left wing tip (J_{NLWT}), right wing tip (J_{NRWT}), top right wing (J_{NTRW}), forward upper fuselage (J_{NFUF}), and vertical stabilizer (J_{NVS}). Current shunts were mounted on the right wing tip (I_{RW}) and on the left wing tip (I_{LW}). Two VHF antennas operating at center frequencies of 63 MHz (VHF_{63}) and 120 MHz (VHF_{120}) were mounted on top of the fuselage.

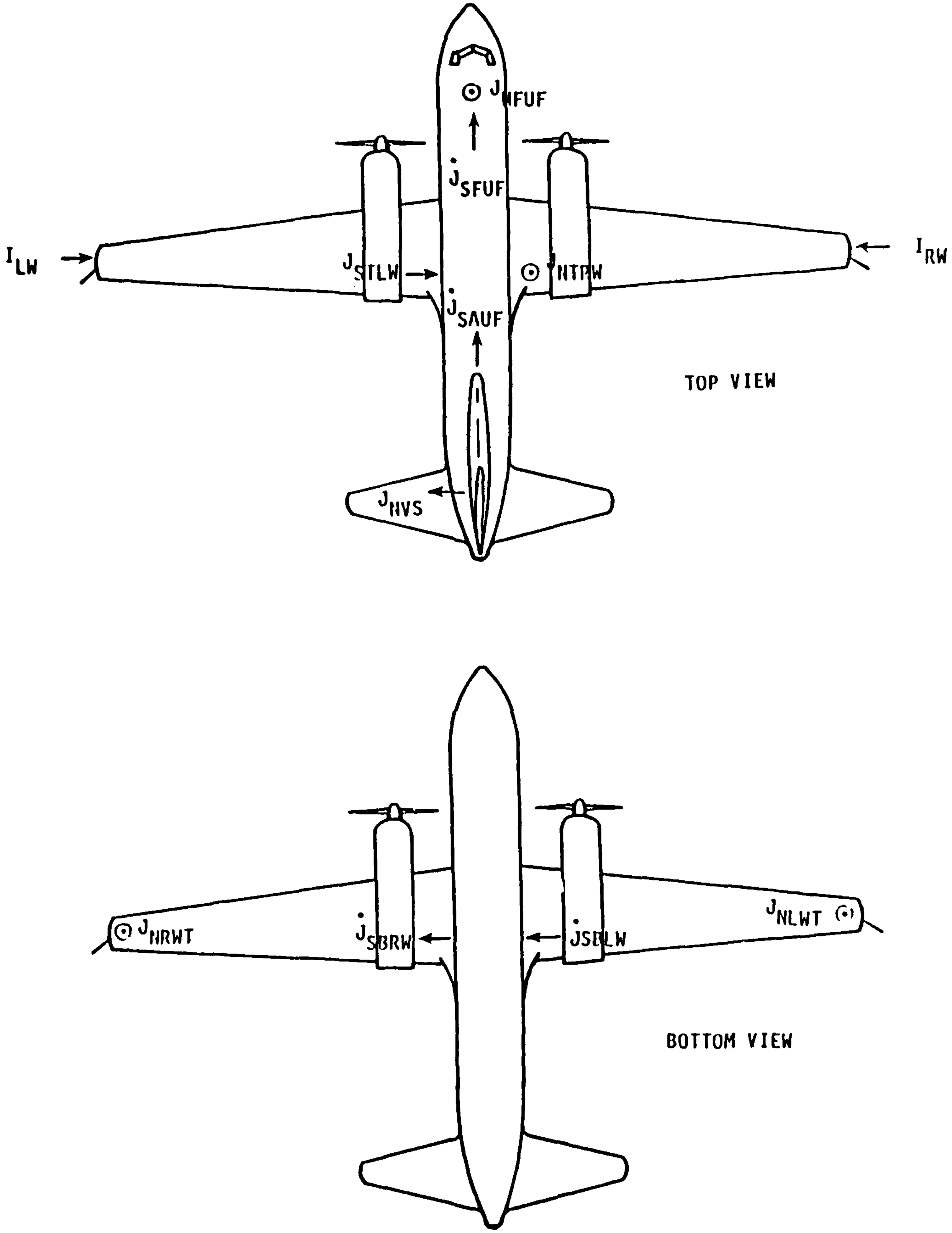


Figure 3. CV-580 Electromagnetic Sensor Locations. Arrows Indicate Direction of Positive Current Flow

All the surface current rate of change sensors except the one mounted on the top left wing (J_{STLW}) were designed by EG&G Electromagnetics (Reference 9). The EG&G sensors were a modified version of the radial Multi-Gap Loop (MGL) ground plane B-dot Model 5 (MGL-5). This type of sensor has an equivalent area of 0.001 m^2, a frequency response in excess of 700 MHz and a risetime of 0.5 ns. Figure 4 shows a picture of the J_{SBRW} sensor as mounted on the CV-580 aircraft. The J_{STRW} sensor was designed in France and provided by ONERA. The physical dimensions and shape of the French sensor are comparable to the MGL-5 sensor. The French sensor sensitivity is between 265 mA/m and 839 A/m, the 3dB bandwidth is from 6 kHz to 130 MHz, and the risetime is 3.5 ns. Figure 5 shows a block diagram of the J_S sensor channels. The sensor output voltage (V_o) in volts is determined from Faraday's law as,

$$V_o = A_{eq} \frac{dB}{dt} \qquad (1)$$

where A_{eq} is the sensor equivalent area of 0.001 m^2 and dB/dt is the rate of rise of the magnetic flux density in T/s.* The sensor was designed to record a differentiated signal level between 50 and 2000 T/s in the digital recorder and an integrated level between 5×10^{-6} and 0.5×10^{-3}T in the direct channel of the analog recorder. The signal splitter, attenuator, and integrator were located in the electronic junction box in the instrumentation rack. The French J_{STLW} output was integrated before the signal splitter; therefore, only integrated signals were recorded for that sensor.

* Although all J_S measurements were scaled to indicate the magnetic flux density rate-of-change expressed in T/s, these measurements are termed as surface current density throughout the text of this report.

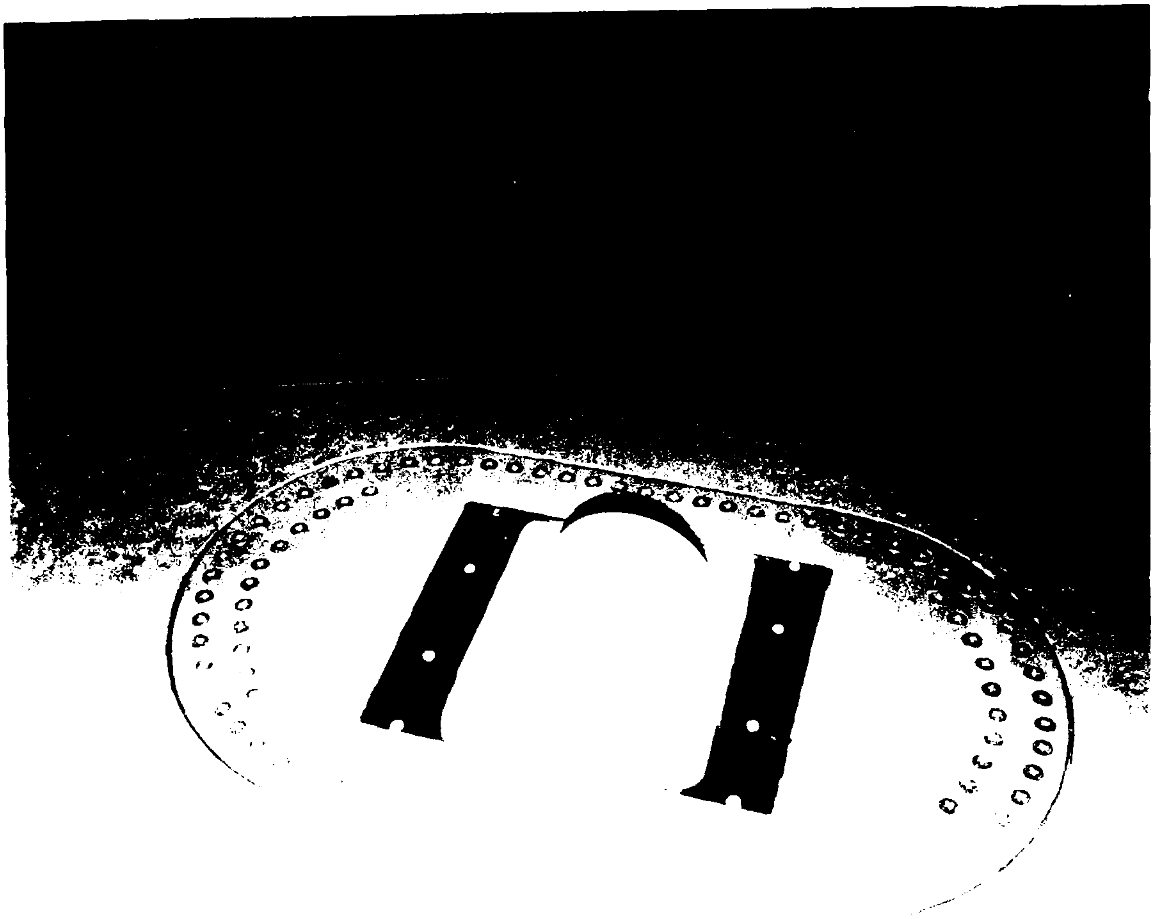


Figure [illegible] Mounted on the [illegible] Aircraft

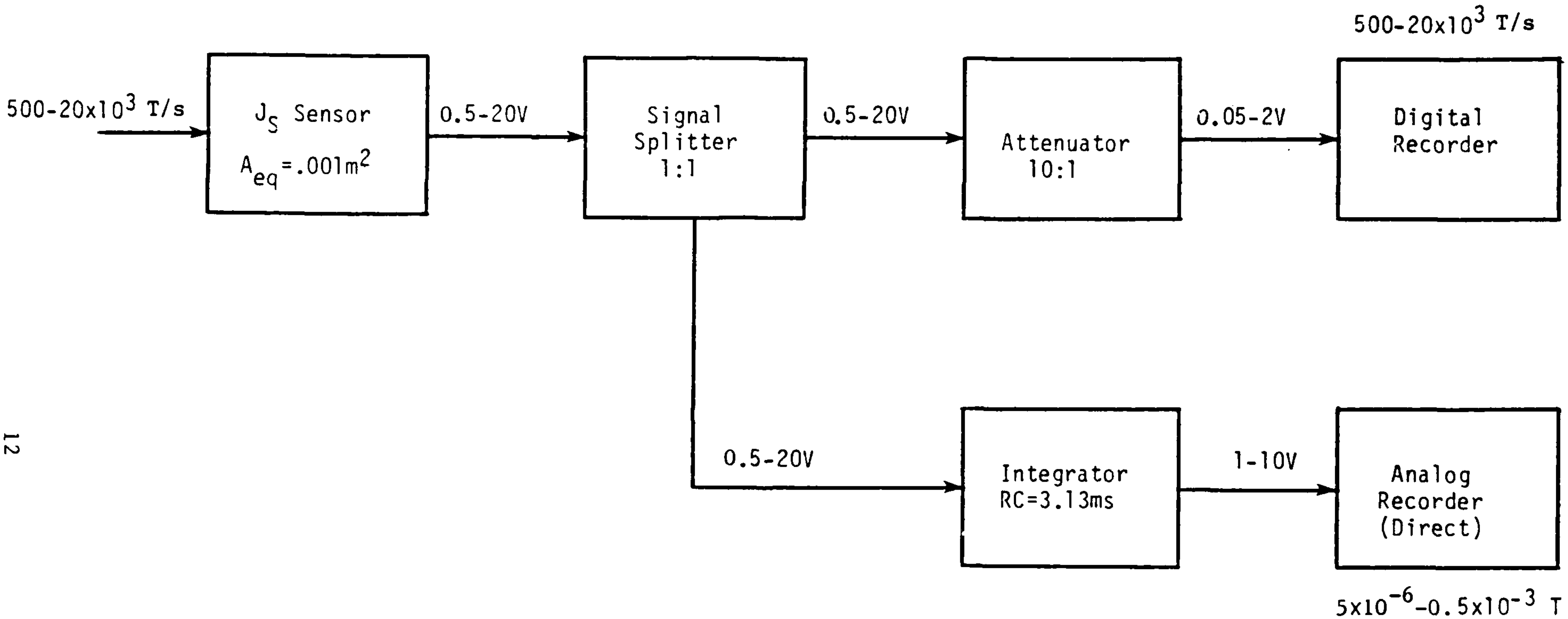


Figure 5. Surface Current Instrumentation Block Diagram

All the displacement current rate of change sensors except the one mounted on the top right wing (J_{NTRW}) were designed by EG&G. The J_{NLWT}, J_{NRWT}, and J_{NVS} were Flush Plate Dipole (FPD) sensors with an equivalent area of 0.01 m^2. The J_{NFUF} is the same design but with an equivalent area of 0.005 m^2. These EG&G sensors have a frequency response in excess of 350 MHz and a risetime of 1 ns. The J_{NTRW} sensor was designed in France and provided by ONERA for this project. This sensor is a Hollow Spherical Dipole (HSD) capable of detecting fields between 100 Volts/meter (V/m) and 316 kV/m with a frequency response from 100 Hz to 130 MHz and a risetime of 3.5 ns. Figure 6 shows a picture of the J_{NLWT} sensor as mounted on the CV-580 aircraft. Figures 7 and 8 show instrumentation block diagrams of the J_N sensors. Figure 7 applies to the J_{NRWT}, J_{NLWT}, and J_{NVS} while Figure 8 applies to the J_{NFUF}. The sensor output voltage (V_o) in volts is determined by applying Gauss' law

$$V_o = R\, A_{eq} \frac{dD}{dt} \qquad (2)$$

where A_{eq} is the sensor equivalent area of 0.01 m^2 or 0.005 m^2 (J_{NFUF}), R is the load resistance of 50 ohms, and dD/dt is the rate of rise of the electric displacement vector in A/m^2. The J_{NLWT}, J_{NRWT}, and J_{NVS} were designed to record a signal between one and 40 A/m^2 in the digital recorder and an integrated level between 35.4×10^{-9} and 8.85×10^{-6} coulombs/m^2 (C/m^2) in the direct channel of the analog recorder. The J_{NFUF} sensor was integrated with a time constant of 220 ms to obtain a low frequency response of 1.5 Hz. The values in Figure 7 have been expressed in V/m by using the assumption that $\varepsilon = \varepsilon_o$. This assumption is not realistic during direct attachment and the real electric field value might be a factor of 2 or 3 lower than the given values. However, this sensor provides a reference waveform to compare the

Figure 6. Picture of the [illegible] Sensor as Mounted on the [illegible] Aircraft

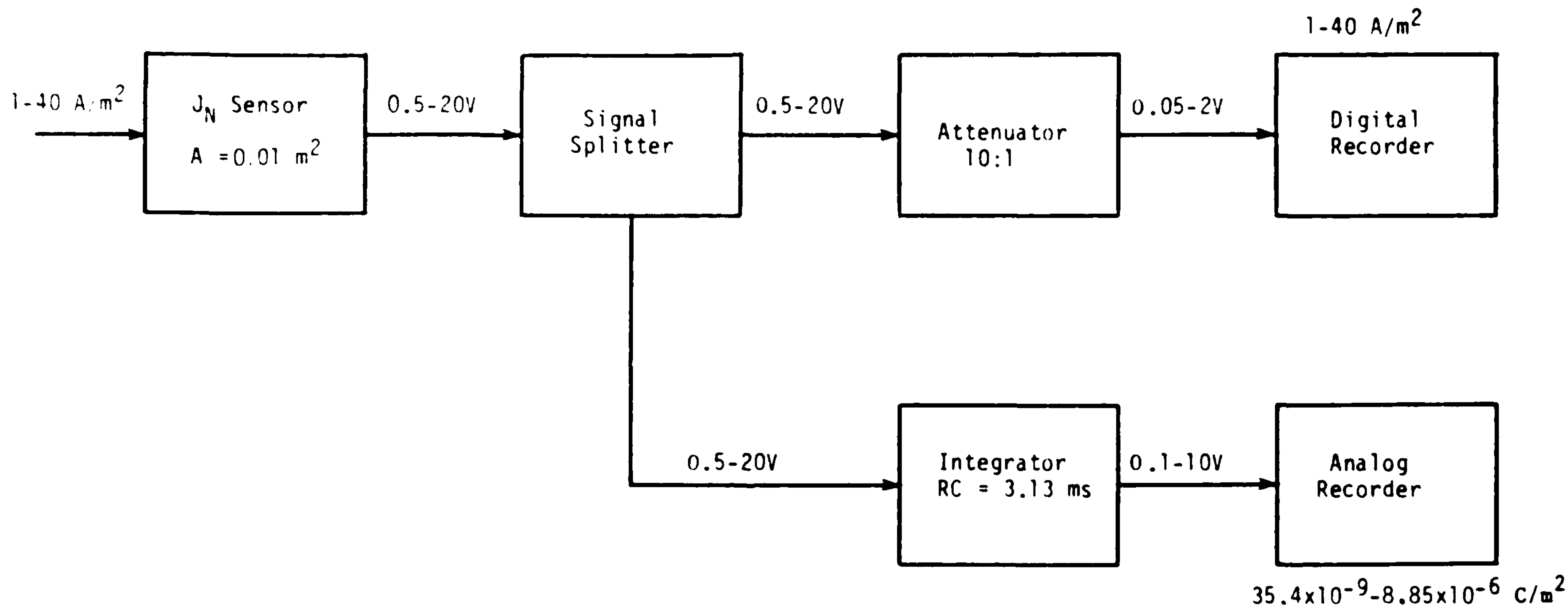


Figure 7. Displacement Current Instrumentation Block Diagram for J_{NRWT}, J_{NLWT}, and J_{NVS} Sensors

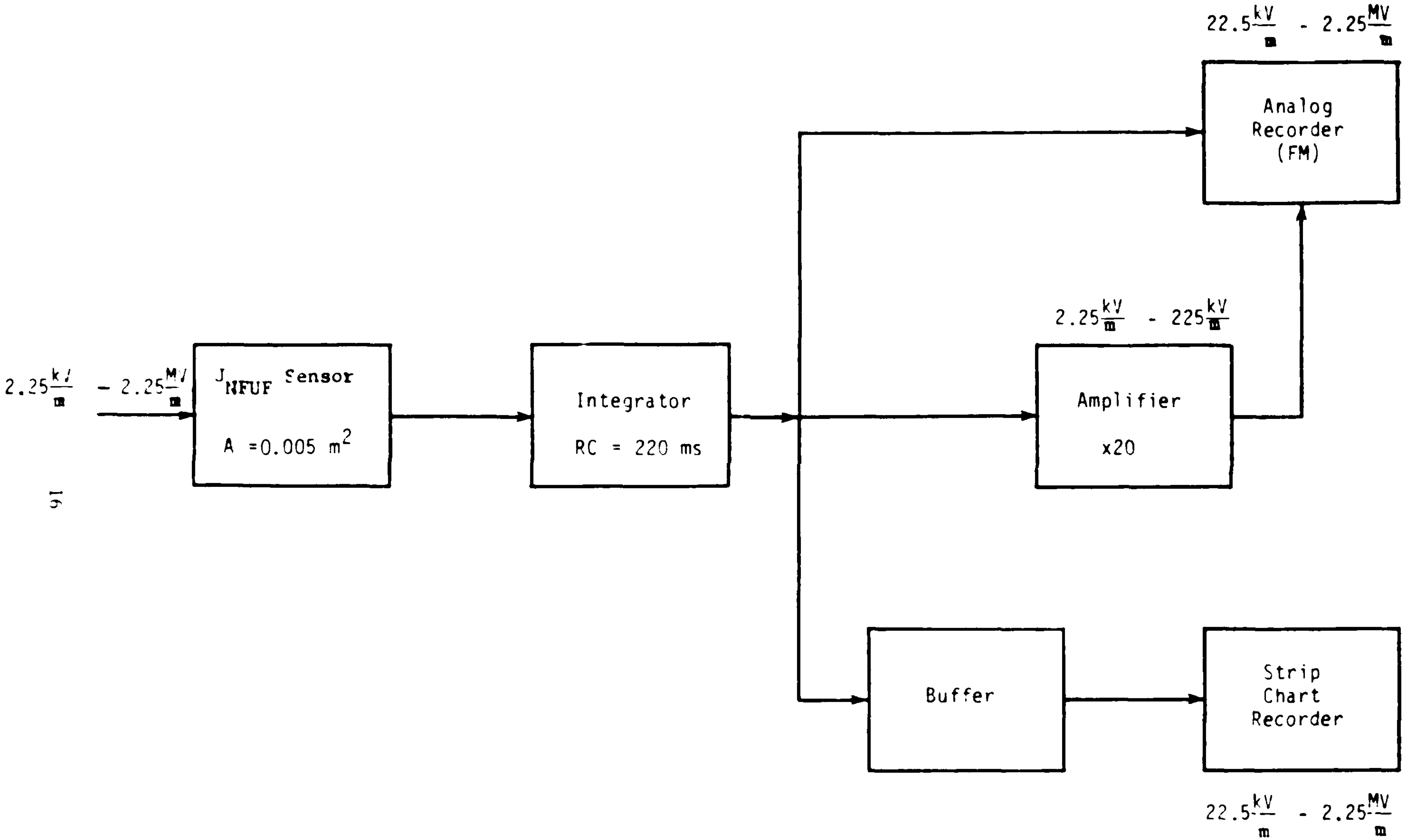


Figure 8. Displacement Current Instrumentation Block Diagram for J_{NFUF} Sensor

magnitude and shape of the field with those of typical electric field measurements at the ground level.

Figure 6 also shows the three foot long boom mounted on each of the wing tips to provide a path for lightning attachment. A current viewing resistor, usually referred to as a current shunt, was mounted on each of the booms. The current shunt consisted of a 5×10^{-3} ohm resistance with a 200-MHz bandwidth and a 2 ns risetime. The shunt, type K-1000-2, was designed by T&M Research Products.

Figure 9 shows the current shunt instrumentation block diagram. The digital recorder was calibrated to record signals between 100 A and 25 kA and the analog recorder was calibrated for values between 10 A and 2 kA. The voltage values in Figure 9 are obtained by using Ohms law for a resistance of 0.005 ohms.

Two VHF antennas were mounted on the fuselage to measure the VHF radiation produced by lightning discharges. The 63-MHz antenna was a Starec type 2204 automatically tuned and designed to be used with transmitters in the VHF/FM band. The antenna output was connected to a bandpass filter centered at 63 MHz with a 6-MHz bandwidth and then to a logarithmic amplifier before being recorded in the analog recorder. The antenna was vertically polarized with a Voltage Standing Wave Ratio (VSWR) less than two. The 120-MHz antenna was a sabre type antenna protected by a fully watertight foam gloss-resin compound radome. The antenna output was connected to a receiver with comparable characteristics to those of the 63-MHz antenna. The 120-MHz antenna was also vertically polarized and had a VSWR less than 2.5.

Table 2 contains a summary of the aircraft exterior transient measurements made with the J_S, J_N, and I sensors, along with the VHF antenna measurement ranges and corresponding frequency responses.

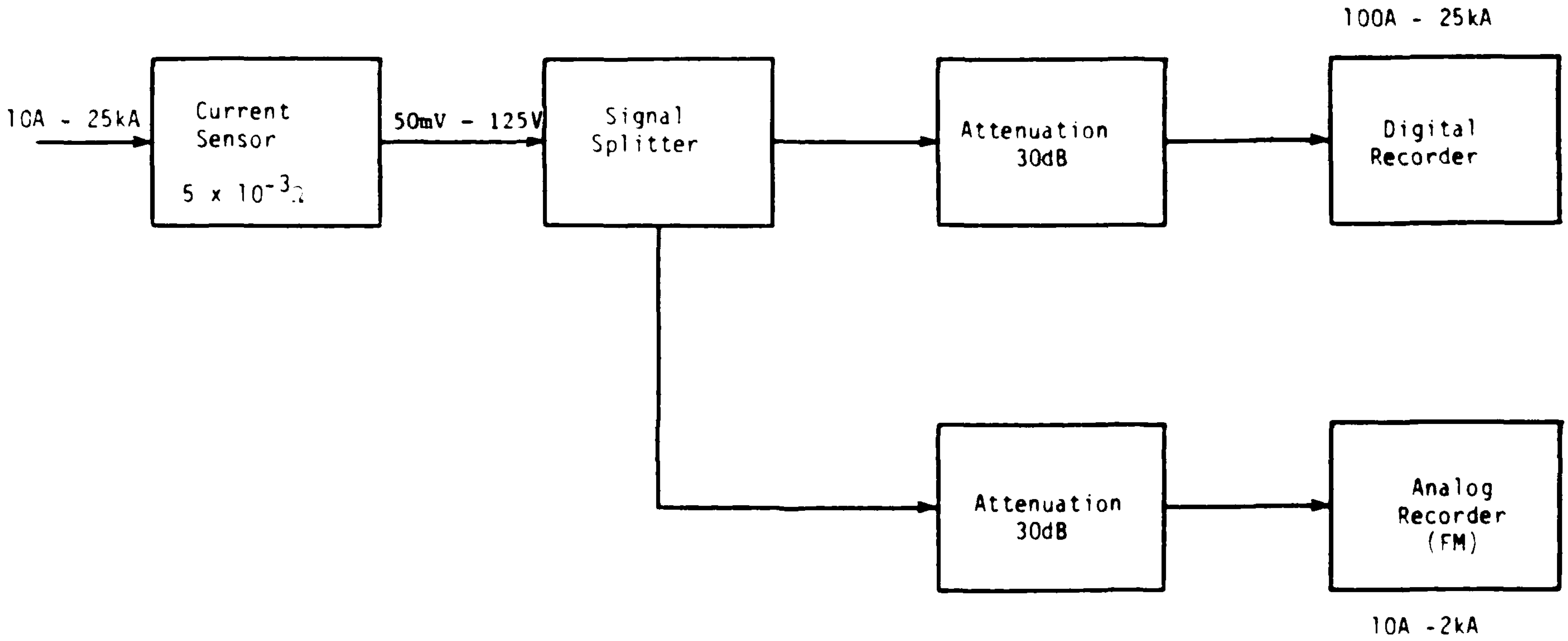


Figure 9. Current Shunt Instrumentation Block Diagram

TABLE 2

AIRCRAFT EXTERIOR TRANSIENT MEASUREMENTS

Sensor	Type	Area/ Sensitivity	Measurement Range	Frequency Range
I_{LW} I_{RW}	Resistive	5mΩ	10 A - 2kA 2kA - 25kA 100A - 25kA	DC - 500KHz(1) 400Hz - 2MHz(2) 40Hz - 80MHz(3)
J_{SBLW} J_{SBRW} J_{SFUF} J_{SAUF}	Multi-Gap Loop	$10^{-3}m^2$	$5x10^{-6}$ - $0.5x10^{-3}$T $5x10^{2}$ - $2x10^{4}$ T/S	400Hz - 2MHz(2) 40Hz - 80MHz(3)
J_{STLW} (ONERA)	Multi-Gap Loop	-	265 mA/m - 839 A/m	400Hz - 2MHz(2) 100Hz - 80MHz(3)
J_{NLWT} J_{NVS} J_{NRWT}	Flush Plate Dipole	$10^{-2}m^2$	$3.54x10^{-8}$ - $8.85x10^{-6}$ C/m^2 1 - 40 A/m^2	400Hz - 2MHz(2) 40Hz - 80MHz(3)
J_{NFUF}	Flush Plate Dipole	$5 \times 10^{-3}m^2$	2.25kV/m - 2.25MV/m	0.5Hz - 500KHz(1)
J_{NTBW} (ONERA)	Hollow Spherical Dipole	-	100V/m - 316 kV/m	400Hz - 2MHz(2) 6kHz - 80MHz(3)
VHF_{63} VHF_{120}	VHF Blade Antenna	-	63MHz, 6MHz B.W. 120MHz	DC - 500kHz(1) 400 - 2MHz(2) 400 - 2MHz(2)

(1) FM Record on Honeywell H101 Instrumentation Recorder
(2) Direct Record on Honeywell H101 Instrumentation Recorder
(3) Recorded on Tektronix 7612D Waveform Digitizer

b. External Static Field Measurements

The NRL designed a static field mill system for the CV-580 aircraft. Figure 10 shows a picture of one of the field mills mounted on the aft lower fuselage. Figure 11 shows the location of the four field mills installed on the aircraft. From the four components of the field mill system, the two horizontal components and the vertical component of the static electric field were determined and recorded on the equipment rack.

c. Internal Transient Measurements

Three clip-on current probes and a wire loop were used to determine internal transient measurements when a lightning discharge attached to the aircraft. The three clip-on current probes were connected to the VOR antenna wire, a 400-Hz aircraft voltage wire, and a signal channel from the autopilot navigation unit. Figure 12 shows one of the clip-on current probes connected to the wire carrying signals from the VOR antenna to the cockpit navigation instruments. To make the wire loop, a wire was extended about 15 feet along the side of the fuselage and looped back across the top of the fuselage. It was terminated across a 50-ohm resistor on the instrumentation box. The induced voltage across the 50-ohm resistor was proportional to the area of the loop and the variation of the magnetic flux density as shown previously in equation (1).

d. Aircraft Internal Instrumentation and Wiring

Figure 13 shows the aircraft instrumentation block diagram. A solid shield semi-rigid 0.25-inch Heliax cable FSJ1-50 was used to carry the signals from the external J_S, J_N, and I sensors to the signal conditioning panels. The corrugated solid copper outer conductors of the heliax cables were grounded at two foot intervals or less throughout the aircraft to prevent any low frequency ground loops from affecting the measurements. RG

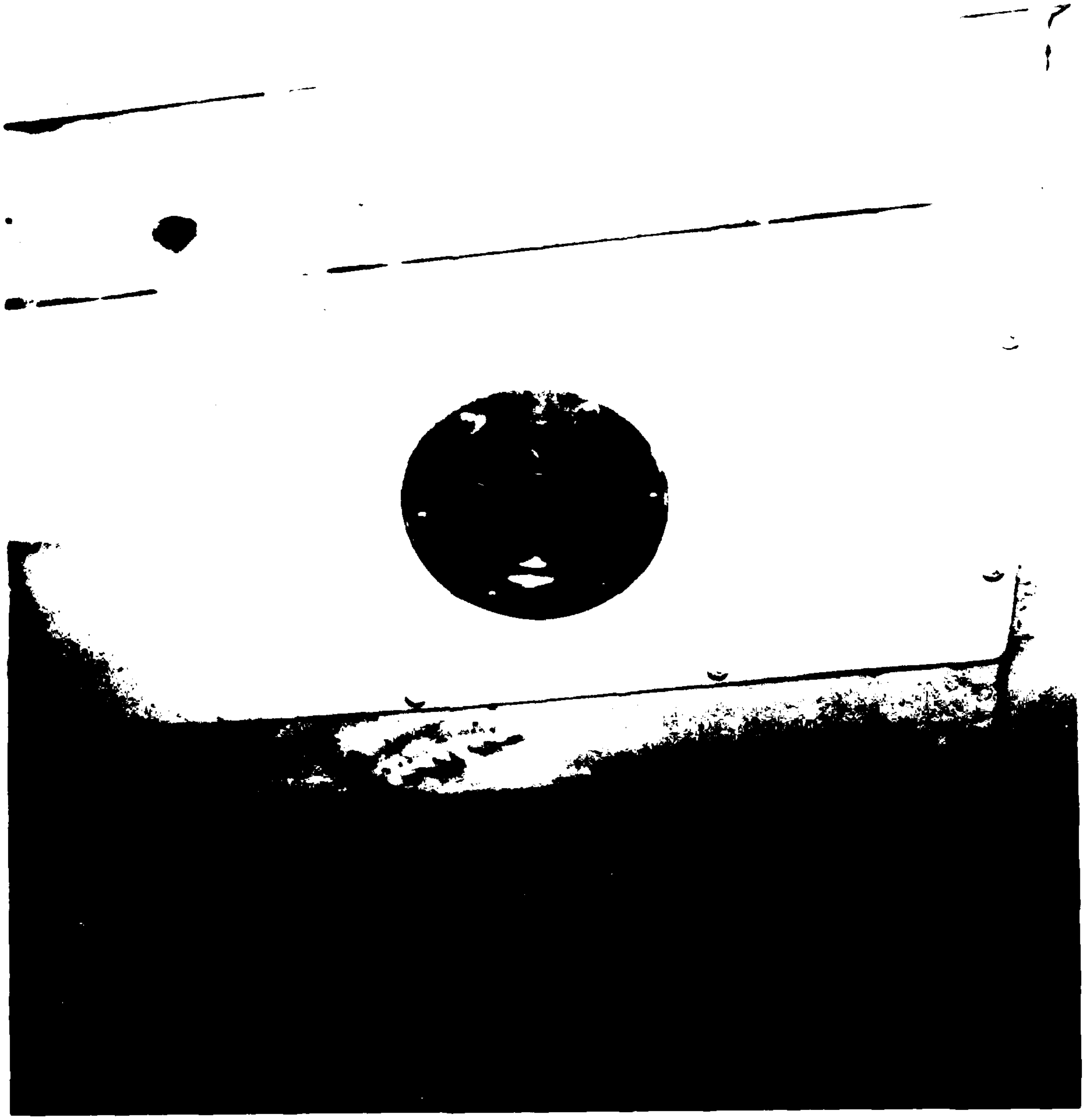


Figure 16. Picture of the Field Mill Installed on the Aft Lower Fuselage

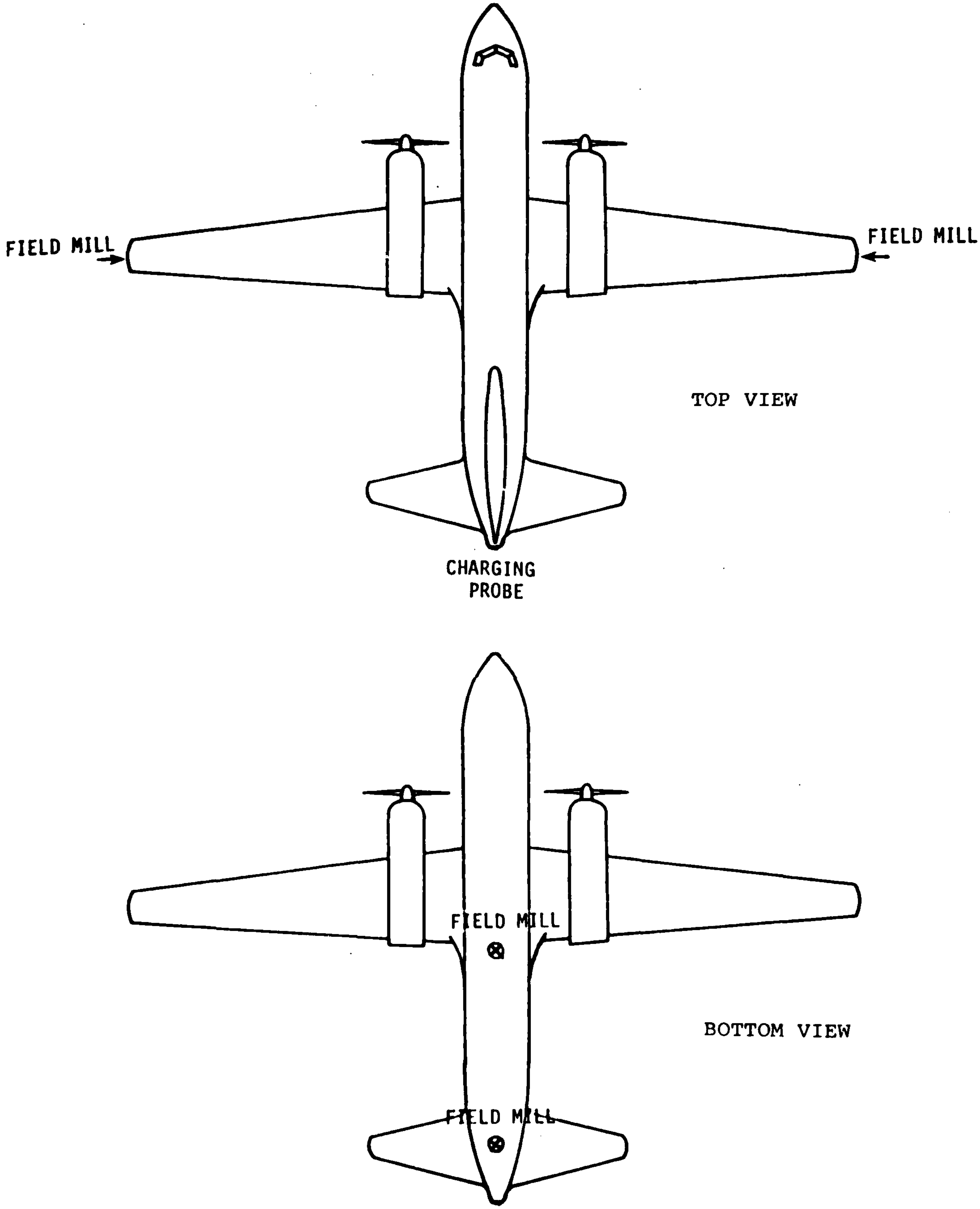


Figure 11. CV-580 Field Mill Locations

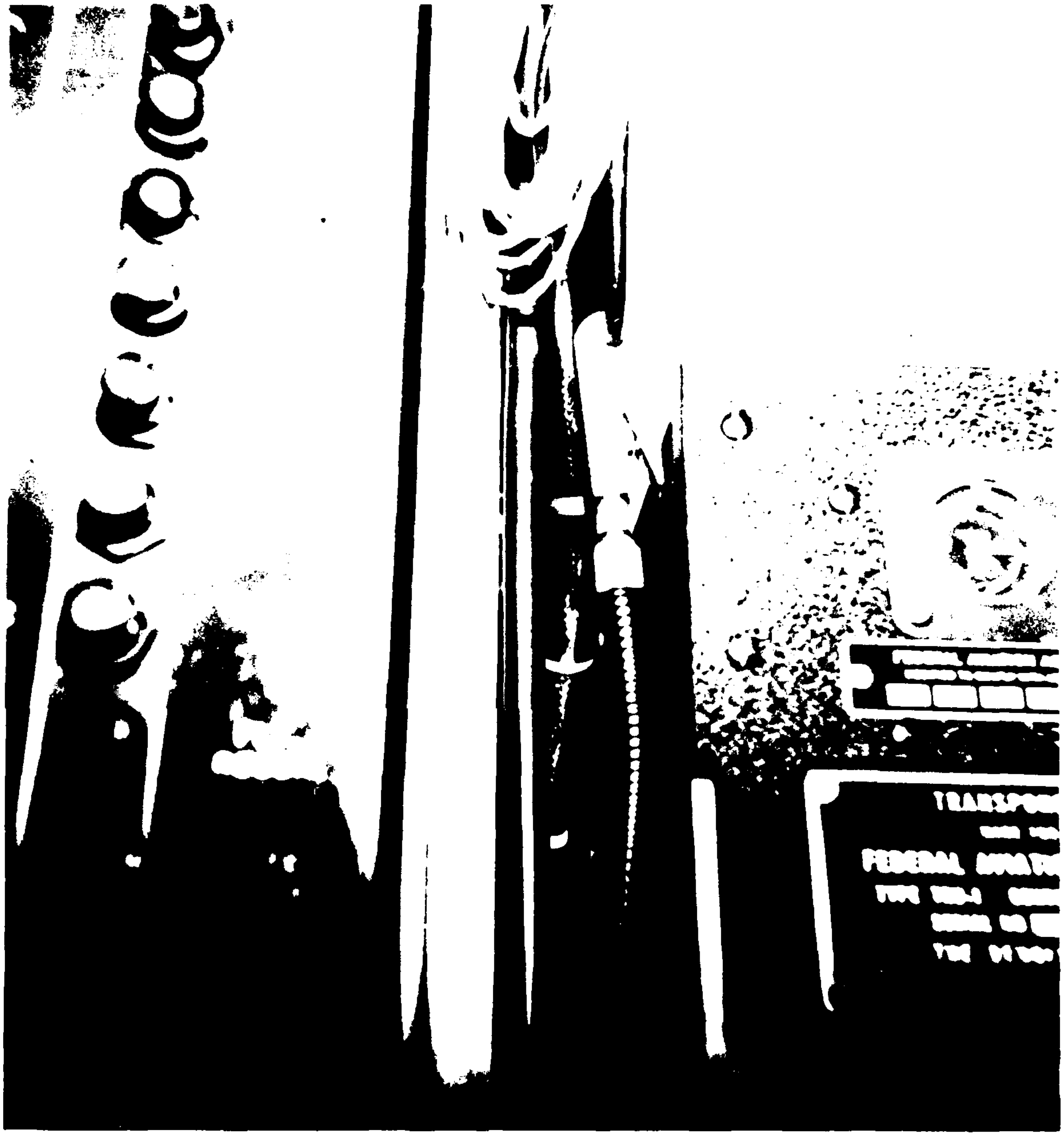


Figure 12. Picture of Clip-On Current Probe Connected to Internal Wire

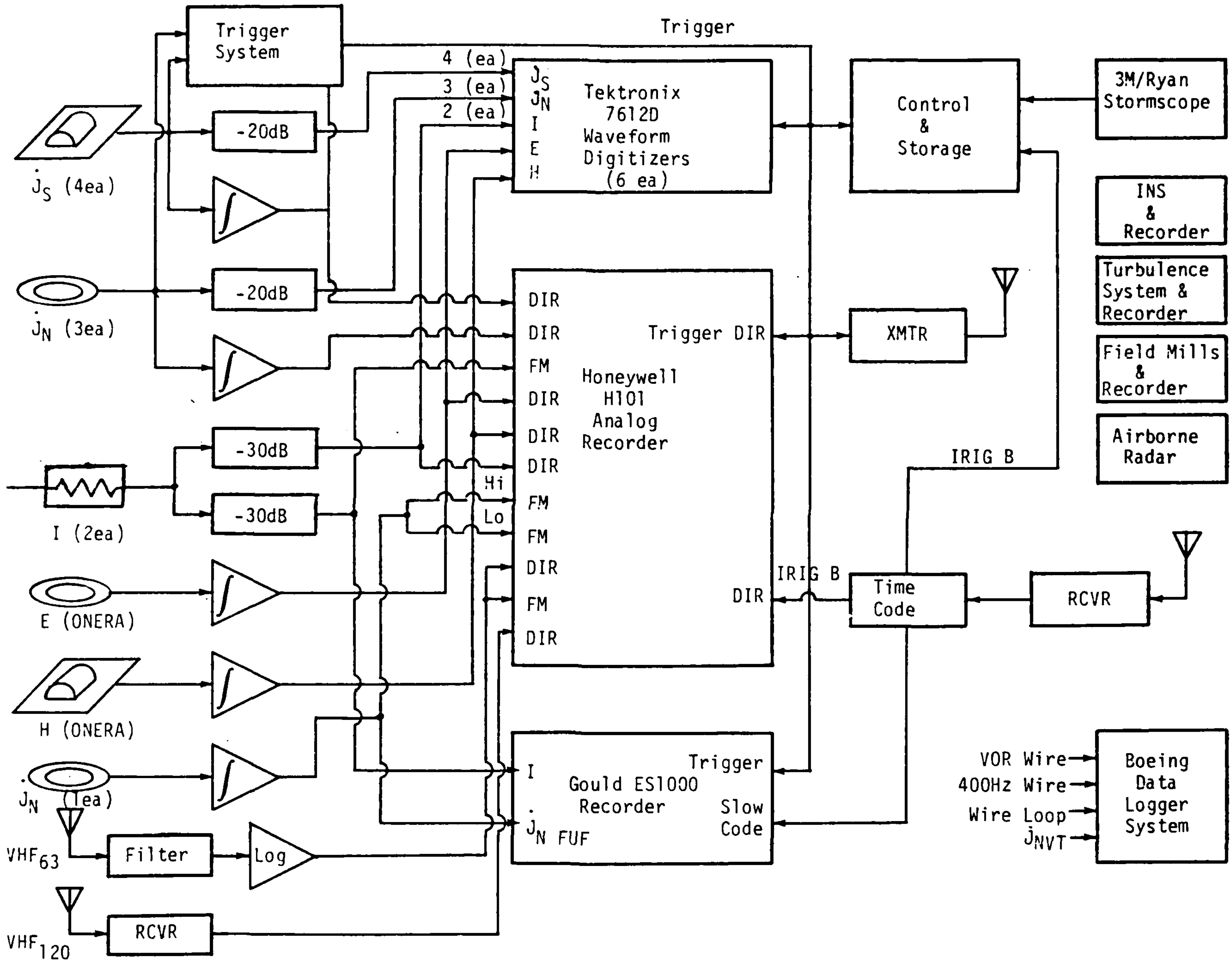


Figure 13. CV-580 Aircraft Instrumentation Block Diagram

8/U 0.405 inch coaxial copper braided cables were used between the VHF antennas and the signal conditioning panel. The splitters, attenuators, amplifiers, buffers, and integrators were located inside the signal conditionering panel. RG 174 0.125 inch braided coaxial cables were used to connect the signals inside the signal conditioning panel. RG 58 cables were used between the signal conditioning panel and the analog and digital recorders. Table 3 shows the specifications of the four type of cables used between the various measurement devices and the recorders. It should be noted that only cables with very low attenuation (Heliax and RG 8/U) were used for the long conductive paths between the sensors and the conditioning panel. The length of the RG 58 and RG 174 cables used in the instrumentation panels did not extend beyond a few feet.

The digital data acquisition system was designed to trigger when any of the signals from the J_S or J_N sensors exceeded preset levels. The trigger system consisted of eight modules, one for each sensor output. Individual modules could be selected as trigger signal sources in any combination and trigger levels on each module could be set independently. When sensor outputs greater than the selected trigger levels were detected, a master trigger signal was sent to all the digitizers through equal length cables to ensure simultaneous triggering.

Six Tektronix 7612D waveform digitizers were used to acquire high frequency data. Each digitizer had two input channels capable of recording 2048 samples with a sampling rate of 5 ns to produce a window of 10.24 μs with an upper bandwidth of 100 MHz. A pretrigger setting of 400 samples was used so that the triggering event occurred at about 2 μs. Inputs from all sensors except the J_{NFUF} went to digitizers, as shown in Figure 13. All the digitizers were programmed and armed by a PDP 11/35 computer. After a set of

TABLE 3

COAXIAL CABLE SPECIFICATIONS

TYPE	ANDREW CORD HELIAX FSJ1-50	RG8/U	RG58C/U	RG174/U
Cutoff Freq, GHz	19	12	25	50
Impedance, Ohms	50	52	50	50
Velocity, % c	78	66	66	66
Atten, dB/100FT @100MHz	1.72	2.0	5.3	8.8
Nominal Size, Inch	0.25	0.405	0.195	0.10
Center Conductor	Copper	Copper	Copper	Copper
	Solid,Corrugated	Copper	Copper	Copper
Outer Conductor	Copper	Braided	Braided	Braided

digital data had been acquired, the time required to store the data and rearm the digitizers was approximately one second. Since the average duration of a flash is about 500 ms, only one digital window per flash was acquired. The data were stored on either a 9-track tape or a floppy disk.

A 28-channel Honeywell 101 analog recorder with a frequency response from 400 Hz to 2 MHz in the direct channels and DC to 500 kHz in the FM channels was used to provide a continuous record of the fields and currents produced by lightning strikes to the aircraft. The measurement ranges in the analog recorder for all the external sensors are shown in Table 2. The signals from the J_S and from J_N external sensors were integrated as shown in Figures 5,7, and 8, then recorded on two analog channels per sensor to cover the entire dynamic range. Fourteen of the sixteen signals from the integrated J_S and J_N channels were recorded by using direct modules. The remaining two integrated signals obtained from the J_{NFUF} sensor in Figure 8 were recorded on FM modules. Two analog signals with different ranges were obtained from each of the two current sensors. To measure the continuing current during direct lightning attachment, all the analog current signals were recorded by using FM channels. The IRIG B time code signal and a trigger pulse to indicate when the digital system had triggered were also recorded in the analog recorder. The IRIG B time code signal was transmitted to the aircraft from the ground station. Therefore, during direct strike lightning acquisition flights, the aircraft and the ground station were synchronized to a resolution better than one millisecond.

A six channel Gould ES1000 electrostatic strip chart recorder was monitored continuously during flight. The two integrated channels from the J_{NFUF}, two current channels, the timing signal from the slow code, and the trigger signal in case of digital data acquisition were monitored on the six channels. The J_{NFUF} integrated signals were sensitive enough to show transient electric fields at the aircraft produced by lightning flashes within a few kilometers.

A turbulence system was mounted on the aircraft by personnel from the FAA to measure and record vertical acceleration. The aircraft location, heading, altitude, and other variables available from the Internal Navigation System (INS) were also recorded by the FAA.

The relative position of any lightning channel within 100 miles of the aircraft was displayed inside the aircraft on a 3M Stormscope display. This information were used during flights to help determine the lightning activity within thunderstorm cells.

The four signal components of the static field obtained by the four field mills mounted on the aircraft skin were carried to the instrumentation rack by Heliax FSJ1-50 coaxial cable. These signal components were fed into an analog computer which was used to determine the two components of the horizontal field, the vertical field, and the charge on the aircraft. The four raw data static field components and the four processed components were displayed in an eight channel strip chart recorder.

A four channel Boeing Data Logger System was activated by the trigger system to obtain four additional simultaneous digital displays. The Data Logger consisted of four time domain windows of 8192 samples with a sample every 16 ns. The data were stored on a digital cassette tape. After any digital, trigger the system was unarmed for about two minutes during which time data was stored on tape. If any trigger occurred by the main aircraft system during the writing period, the data logger would ignore the trigger command and continue on writing the previous data. Three clip-on current probes were connected to single wires in the aircraft interior and the signals were transmitted to the Data Logger System by using the Heliax FSJ1-50 coaxial cable described previously. The three single wire signals monitored were the VOR wire, a wire carrying one of the phases of the 400 Hz power signal, and one of the data signals carrying information between the INS and the autopilot unit. A review of the data after 11 strikes showed that no detectable signal was monitored above the noise level on the autopilot wire. During the last ten strikes, the autopilot signal was replaced by the J_{NVS} signal. The fourth signal in the Boeing Data Logger was used to monitor the induced voltage in an internal wire loop inside the aircraft.

Figure 14 shows a view of the instrumentation layout inside the aircraft. The first rack on the left hand side of Figure 14 contains a video cassette recorder to store the data from one of the cameras, a floppy disk unit used for programming and auxiliary storage of data, and a Cypher 9-track magnetic tape recorder which was used to store the digital data. The second rack contains a TV monitor for the video cameras, the Stormscope display unit, a data display CRT unit, the computer CRT and keyboard used for program and control, and a hard copy machine used to print the digital data stored on the 9-track tape recorder. The third rack contains a power switching unit, the time code unit, and the PDP 11-35 computer main unit. The fourth rack contains three of the 7612D waveform digitizers used to acquire the digital data. Figure 15 shows the fifth, sixth, and seventh racks as mounted on the right hand side. The fifth rack contains the signal conditioning panel, the set of digiswitches used to set the triggering threshold level of the various sensors, and two of the digitizers. The sixth rack contains the Data Logger System with four digitizer and recording capability and a 7612D waveform digitizer. The seventh rack contains the Honeywell 101 28-channel analog recorder with all the reproduce channels. The last rack was used to process

Figure 14. CV-580 Aircraft Rack Layout

Figure 15. Layout of Racks 5, 6, and 7 on the Right Hand Side of the CV-580 Aircraft

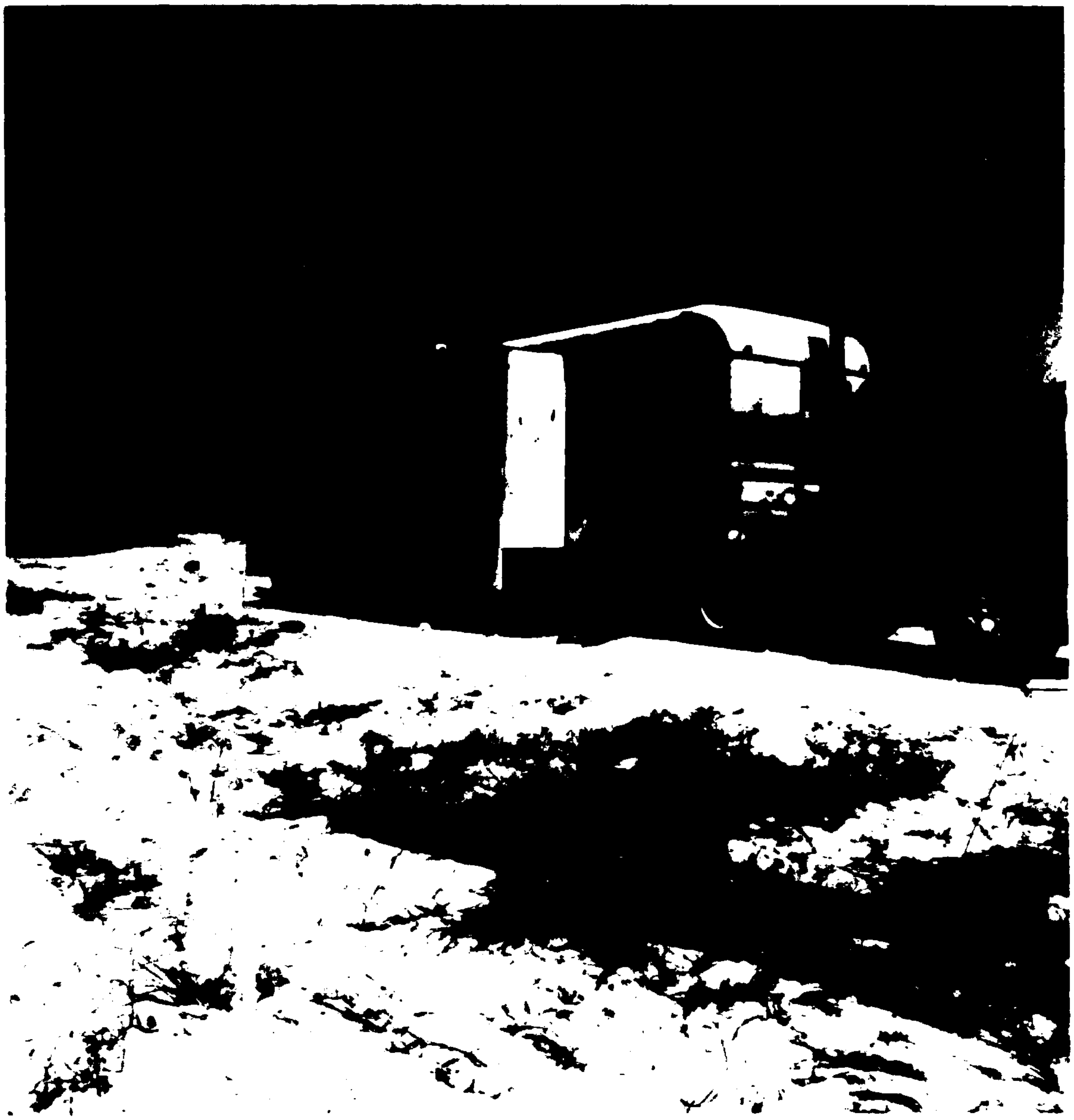
and record the FAA turbulence data. The three racks mounted on the left hand side contain the Gould ES 1000 strip chart recorder, the video cassette recc.ders used to record the video images of two of the cameras, the analog computer, and strip chart recorder used to process and store the field mill data.

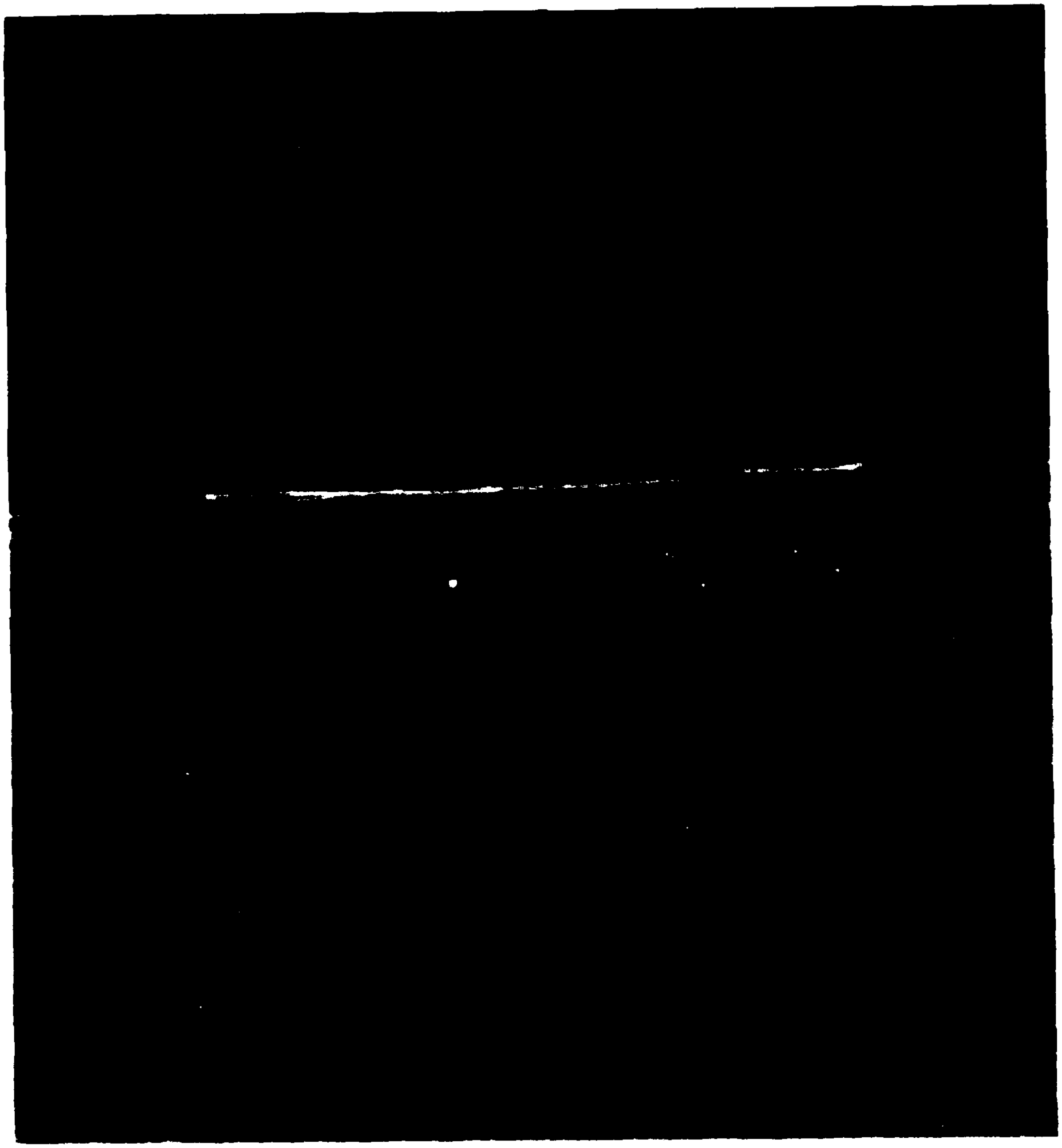
2. GROUND INSTRUMENTATION

A ground station at Cape Canaveral Air Force Station, Florida, recorded electric and magnetic fields produced by distant lightning. The ground station was designed to measure the radiated fields produced by flashes that attached to the aircraft and thus differentiate between cloud-to-cloud and cloud-to-ground flashes and flashes triggered by the aircraft. Since the ground signature of the radiated electric and magnetic fields from cloud-to-ground and intracloud flashes over the entire duration of the flash can be recognized, the type of flash which attached to the aircraft can be determined from the simultaneous radiated fields for the flash received at the ground station and from the aircraft J_N and J_S analog records. These type of characteristics provide an insight for the understanding of the physics of lightning attachment to the aircraft.

Figure 16 shows the US Air Force instrumentation trailer ground site. The trailer was 12 feet high and 36 feet long and was located about 70 feet from the electric and magnetic field antennas. The antennas were mounted on the beach about 30 feet from the high tide level.

Figure 17 shows the four flush plate dipole electric field antennas and the two magnetic field loop antennas which were used to detect the electric and magnetic fields produced by distant lightning. The signals from the antennas were taken through metallic conduits to the instrumentation trailer.





[illegible] Electric and Magnetic Field Antennas Near the Ground Station Trailer

An aluminum wire mesh about 80x20 ft^2 was built to connect the antenna cables and reference to salt water. This ground plane was made to bind the ground reference of the antennas to the mesh and to salt water. Twenty copper rods were driven into the ground and connected to the mesh to ensure a good ground reference.

Figure 18 shows a block diagram of the main instrumentation at the ground station trailer. The signals from three of the four electric field antennas were integrated and recorded in a Bell & Howell 3700 B analog recorder using different gains to increase the dynamic range. The signal from the fourth electric field antenna and the two magnetic field loops were recorded in channels of a 7612 digitizer. Data from the magnetic field loops were also integrated and recorded continuously on the analog recorder. A VHF antenna operating at a center frequency of 63 MHz with a bandwidth of 6 MHz was designed to detect the VHF radiation produced by distant lightning discharges. The VHF radiation data were also recorded in the analog and digital systems. A Gould 260 strip chart recorder was used to monitor some of the sensors during data flights. IRIG B timing data from the Cape Canaveral AFS/Kennedy Space Center complex was recorded at the ground site and transmitted to the aircraft during the first few minutes of flight for synchronization. As a result, aircraft and ground systems were time correlated to the millisecond level during data acquisition flights. A thunder microphone was used at the trailer to estimate the distance from the trailer to the discharge. A Stormscope system was also used at the trailer to estimate the location of distant lightning.

Table 4 shows the measurement range and the frequency response of the four electric field plates, the two magnetic field antennas, and of the VHF

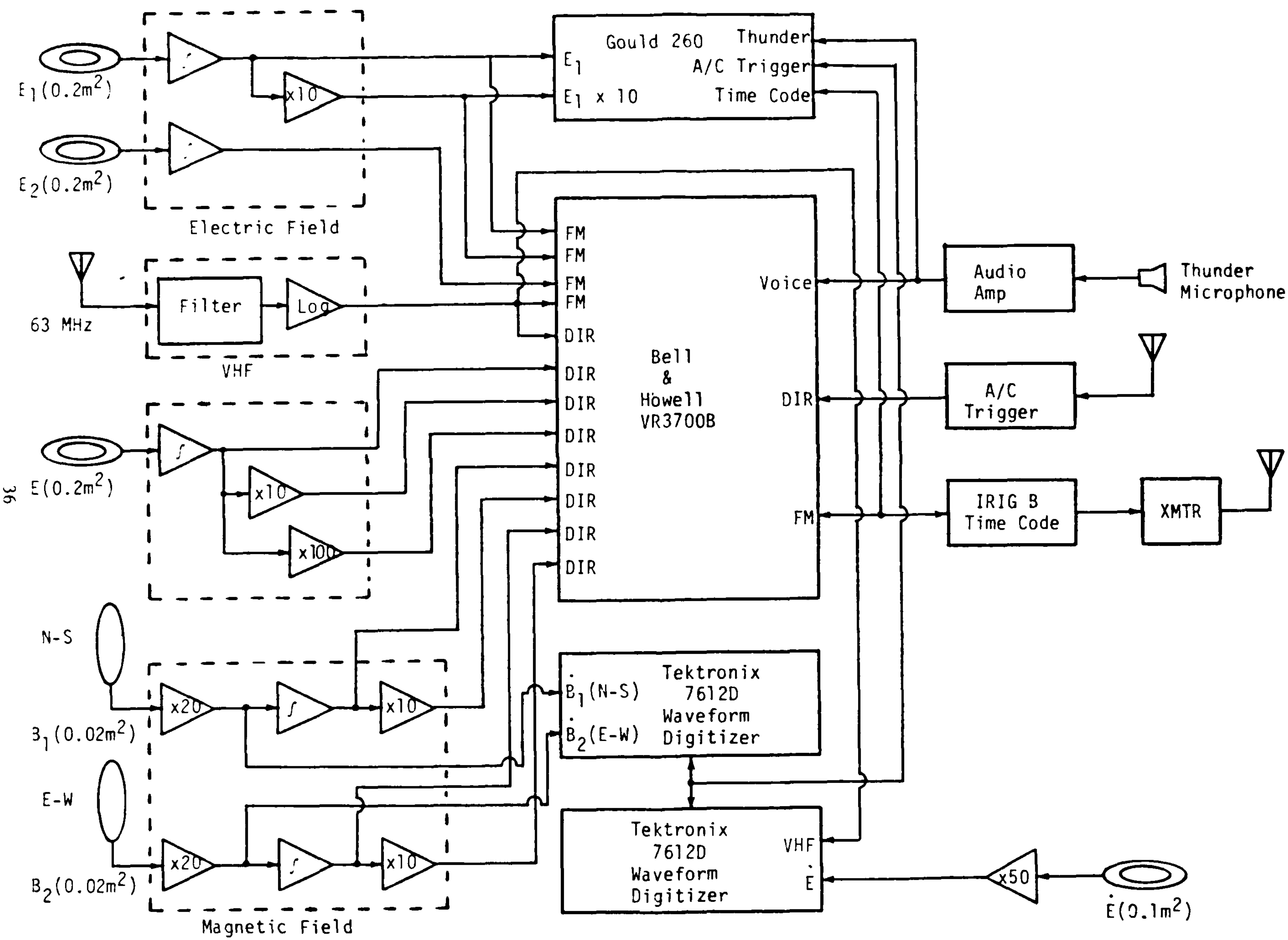


Figure 18. Ground Station Instrumentation Block Diagram

antenna. The measurement range was designed to measure radiated fields from lightning within 60 miles of the trailer.

TABLE 4

GROUND STATION MEASUREMENTS

Sensor	Type	Area	Measurement Range	Frequency Range
E1	Flat Plate	$0.05 m^2$	500 V/m - 100 kV/m	0.1-500 kHz(1)
E2	Flat Plate	$0.2\ m^2$	50 V/m - 1 kV/m	0.1-500 kHz(1)
E3	Flat Plate	$0.1\ m^2$	$2 \times 10^7 - 5 \times 10^9$ V/m/s	50 Hz - 25 mHz(2)
E4	Flat Plate	$0.2\ m^2$	2 V/m - 2 kV/m	50 Hz - 2 mHz(3)
VHF	Flat Plate	$0.06 m^2$	63 mHz, 6 mHz B.W.	50 Hz - 2 mHz(3)
				DC - 500 kHz(1)
				DC - 25 mHz(2)
B1	Cylindrical Moebius Loop	$0.02 m^2$	0.02 - 5 A/m $10^5 - 2.5 \times 10^7$ A/m/s	500 Hz - 2 mHz(3) 500 Hz - 25 mHz(2)
B2	Cylindrical Moebius Loop	$0.02 m^2$	0.02 - 5 A/m $10^5 - 2.5 \times 10^7$ A/m/s	500 Hz - 2 mHz(3) 500 Hz - 25 mHz(2)

(1) FM Record on Honeywell H101 Instrumentation Recorder
(2) Recorded on Tektronix 7612D Waveform Digitizer
(3) Direct Record on Honeywell H101 Instrumentation Recorder

SECTION III

ANALYSIS OF 21 DIRECT LIGHTNING ATTACHMENTS TO THE AIRCRAFT

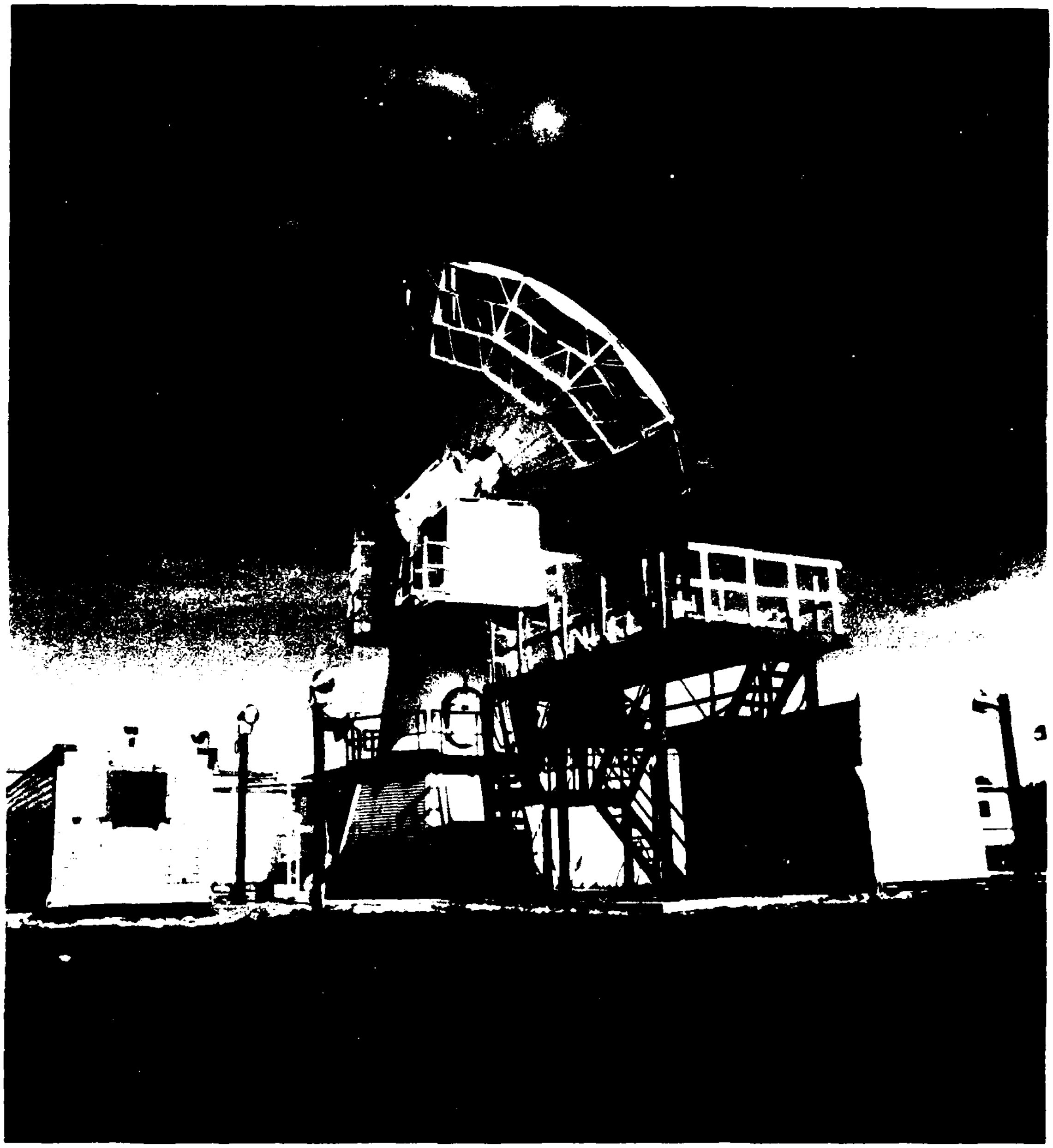
After the aircraft was fully instrumented as shown in Section II and prior to the flight program, lightning simulation tests were conducted on the ground at Wright-Patterson AFB, OH. The purpose of the lightning simulation tests was twofold. First, noise tests on the aircraft had to be performed to detect cable pickup or aperture coupling when the external sensors were not connected. Secondly, all instrumentation had to be checked out completely to ensure that the obtained values of surface and displacement current densities were directly related to lightning simulator current and to further calibrate the data acquisition and recording system.

During the noise tests, all displacement current and surface current density sensors where disconnected with the cables open-circulated and short-circulated, respectively, to approximate the input impedances of the sensors. Peak currents between 5 and 40 kA with risetimes between 200 ns and 2 μs, were injected into the aircraft from nose-to-tail and wing tip-to-wing tip. The aircraft digital system was set to trigger at an appropriate level and the measured signal pickup from the wires going to the sensors was found to be near the noise level of the recording system.

The sensors were then reconnected and displacement and surface current waveforms were recorded and integrated. Though affected by the aircraft response, characterized by a decaying exponential in the data, the current source excitation and the integrated waveforms had similar characteristics.

The CV-580 aircraft was flown to Patrick AFB, FL in late June 1984 and a procedure was developed to determine where and under what conditions to fly the aircraft inside or in proximity to thunderstorms. In accordance with prescribed safety specifications and turbulence limits, the aircraft was restricted from flying in regions that exceeded a precipitation radar return of 40 dBz as measured 20 km away from the storm. To ensure that this condition was met and to guide the aircraft away from high turbulence regions, a system was designed in which an operator continuously observed three CRT displays: the weather radar data, the Lightning Location and Protection (LLP) System (Reference 10) display for the entire area, and the display of the position of the aircraft. The aircraft was tracked by a C-band radar during the entire flight. Figure 19 shows the tracking radar used for this mission. A Vector Control and Display System (VCDS) was programmed to display the position of the aircraft continuously during flight. The LLP system would indicate on a screen where a cloud-to-ground flash had occurred within the monitored region. The aircraft position obtained from the VCDS, the location of the active thunderstorm cells determined from the LLP, and weather radar precipitation maps were used to decide when to fly and how to direct the aircraft during flights.

To study the physics of lightning attachment to aircraft, the CV-580 was flown for over 50 hours at altitudes between 2,000 ft and 18,000 ft from 11 June 84 to 14 Sept 84. Forty-two of these hours were flown inside or in the immediate vicinity of active thunderstorms. Weather permitting, most flights were conducted at altitudes of 2,000, 6,000, 10,000, 14,000, or 18,000 ft. The 42 active thunderstorm hours flown at each altitude were distributed as follows: six hours at 18,000 ft, five hours at 14,000 ft, three hours at 10,000 ft, twelve hours at 6,000 ft, four hours at 4,000 ft, and twelve hours at 2,000 ft. The original intent was to fly within a 60 mile radius of Cape Canaveral Air Force Station. However, as storm conditions developed across central Florida, the operating region was extended



to include most of the entire central Florida region. Figure 20 shows a map of central Florida and the location of the 21 lightning attachments to the aircraft.

A description of each of the 21 lightning flashes is presented next. The attachments are numbered chronologically and correspond to the identification numbers found in Figure 20. For each flash, the following information is presented: a) the known meteorological conditions at the time of the flash, b) the digital data collected if the digital system triggered along with the corresponding threshold level setting, and c) the analog data if recorded during the flash. Aircraft damage and crew impressions are also discussed for some of the events.

1. THE 11 JULY FLASH AT 21:22:10 Z

On 11 July at 21:22:10 Z, a lightning discharge attached to the aircraft while flying near Tampa at an altitude of 14,000 ft. The outside air temperature was 5°C and the aircraft was flying inside the cloud in an area of low turbulence. The location of the aircraft at the time of the flash is shown as (1) in Figure 20.

The digital system was designed to trigger off the J_S sensors and the threshold level for this flight was set at 1500 Teslas/second (T/s). The system did not trigger, indicating that none of the surface current density pulses from this flash exceeded the 1500 T/s level.

Figure 21 displays six of the analog channels during the beginning of the discharge. These six channels were taken from the J_{NFUF}, I_{LW}, J_{NVS}, J_{NLWT}, and J_{NRWT} sensors, and also from the time code. The displacement current density outputs of the J_N sensors were integrated and recorded on the analog recorder. Each integrated output, being proportional to the

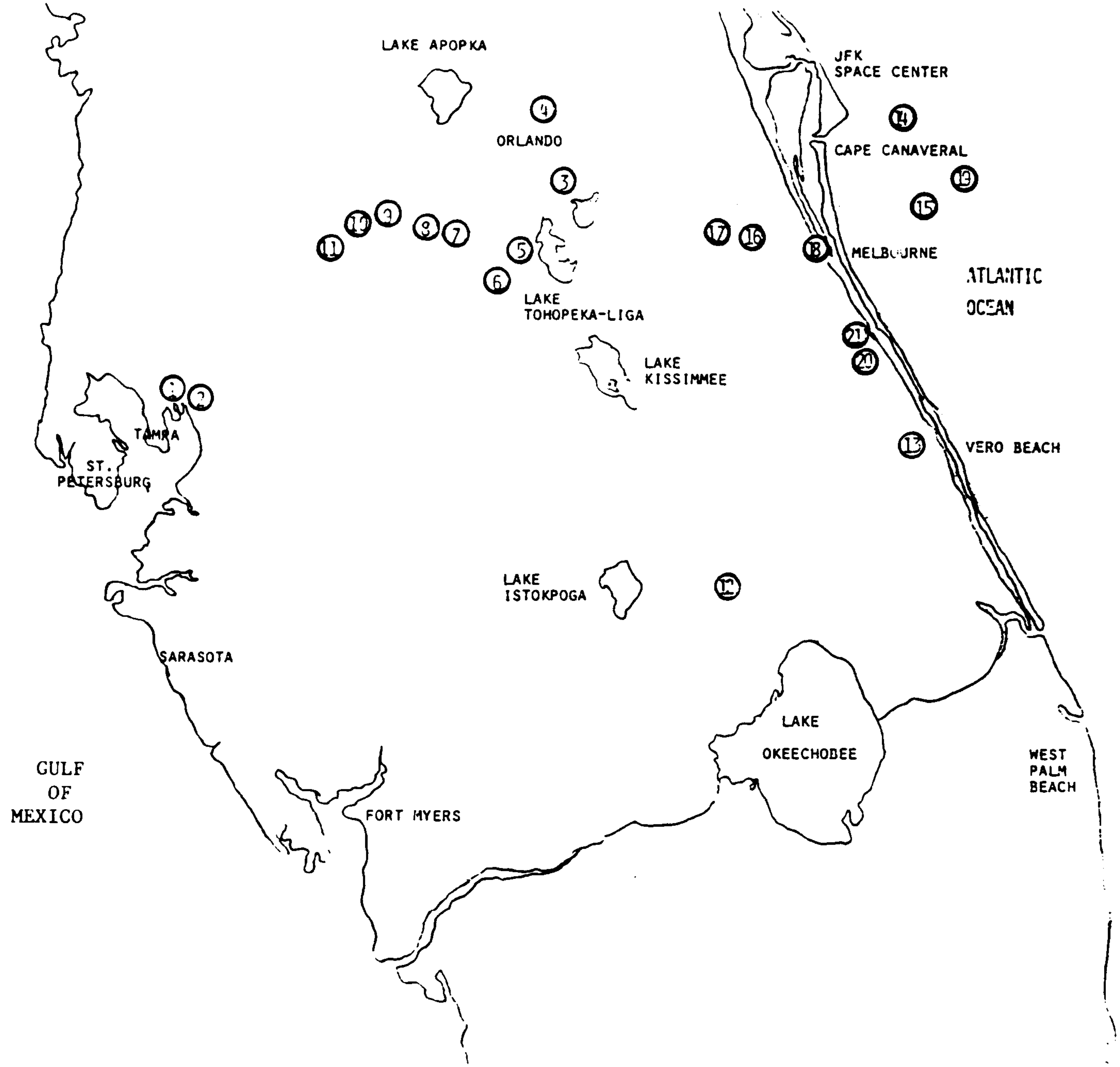


Figure 20. Map Showing Location of 21 Direct Lightning Attachments to CV-580 Aircraft

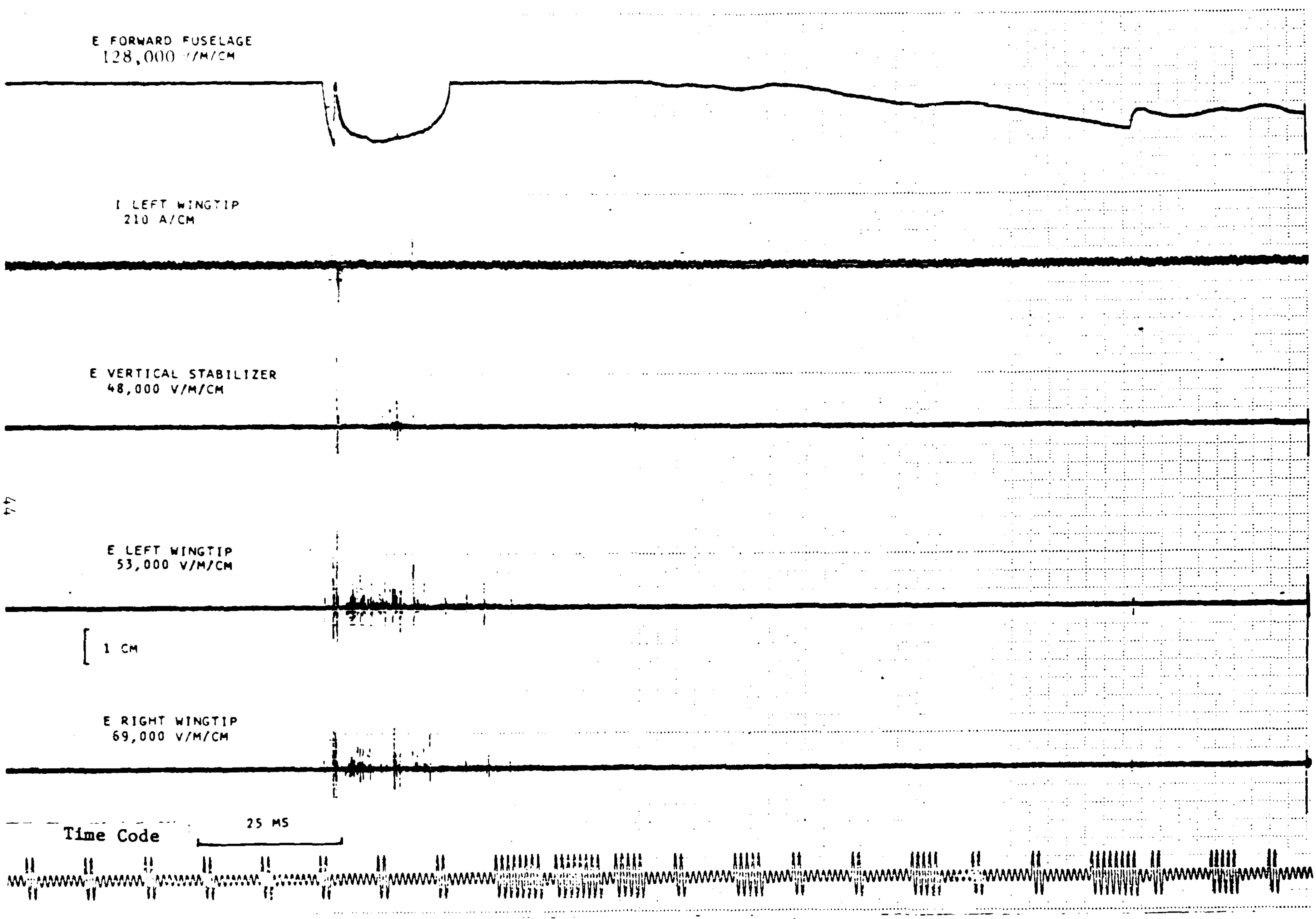


Figure 21. Six Analog Channels Recorded at Beginning of 21:22:10 Flash

electric flux density, was converted to electric field strength using the permittivity of free space. All electric field levels shown in Figure 21 are per unit centimeter. A centimeter scale is included in the figure. The integrator in the J_{NFUF} sensor yielded the E forward fuselage measurement and had a time constant of 220 ms. Therefore, the traces of E forward fuselage for all the flashes in this report have a frequency response near 1 Hz. The E forward fuselage (J_{NFUF}), I left wing tip (I_{LW}), and I right wing tip (I_{RW}) signals were recorded using FM modules with a DC to 500 kHz frequency response. All the remaining channels were recorded in direct modules with a frequency response from 400 Hz to near 2 MHz.

Analysis of the beginning of the discharge on Figure 21 shows that the integrated J_{NFUF} sensor was saturated for at least four seconds prior to the discharge. The positive electric field level indicates that the electric field points away from the aircraft. The initial negative-going slow motion of the E forward *fuselage* suggests a variation on the charge near the aircraft. This indicates that a leader or streamer may have propagated outward from the aircraft surface. The first small transient pulses on the E left wing tip and E right wing tip traces correspond to the beginning of the suspected streamer propagation from the aircraft. Streamer propagation lasted for about 2.1 ms before a fast positive-going pulse appeared on the E forward fuselage trace. Assuming a leader propagation speed of 1.5×10^5 m/s, the channel had to propagate over 300 meters before it contacted a significantly charged region of opposite polarity to produce the fast transient pulse. This discharge is comparable to the return stroke in the case of a cloud-to-ground flash. The relatively short time and length of streamer propagation indicate that the aircraft probably initiated or triggered the discharge. For the next 25 or 30 ms of the flash, a large number of pulses with a maximum pulse repetition rate of 10^4 pulses/sec was observed. Estimates of pulse repetition rates were obtained from analog records reproduced at faster speeds than those shown in this report. During the time of the pulses, it appeared that individual pockets of charge were neutralized through the initial path of the discharge. This initial 25 to 30 ms interval was seen to be the most active part of the discharge. Other isolated pulses can be observed throughout the remainder of the discharge which lasted about 780 ms.

Figure 22 shows the same analog channels for the first 400 ms of the flash. Some of the largest pulses in the flash did not occur during the initial active phase, but in some of the isolated pulses. The largest electric field transients observed in the flash were 165 kV/m and 145 kV/m obtained from the J_{NRWT} and J_{NLWT} sensors, respectively. These occurred during a pulse 180 ms after the beginning of the flash.

2. THE 11 JULY FLASH AT 21:31:01 Z

Nearly nine minutes after the previous flash, the aircraft was again hit by lightning at 21:31:01 Z. The aircraft was still flying at 14,000 ft at a location approximately five miles from the site of the first attachment. The aircraft was flying inside the same cloud in an area of low turbulence where the outside air temperature was again 5°C. The number (2) in Figure 20 indicates the position of the aircraft at the time of this flash.

The digital system was set to trigger at 1500 T/s, but the system did not trigger. As with the previous flash, no J_S pulses exceeded the threshold level. Figure 23 shows six of the analog channels during the beginning of the discharge. These are the same channels given for the previous

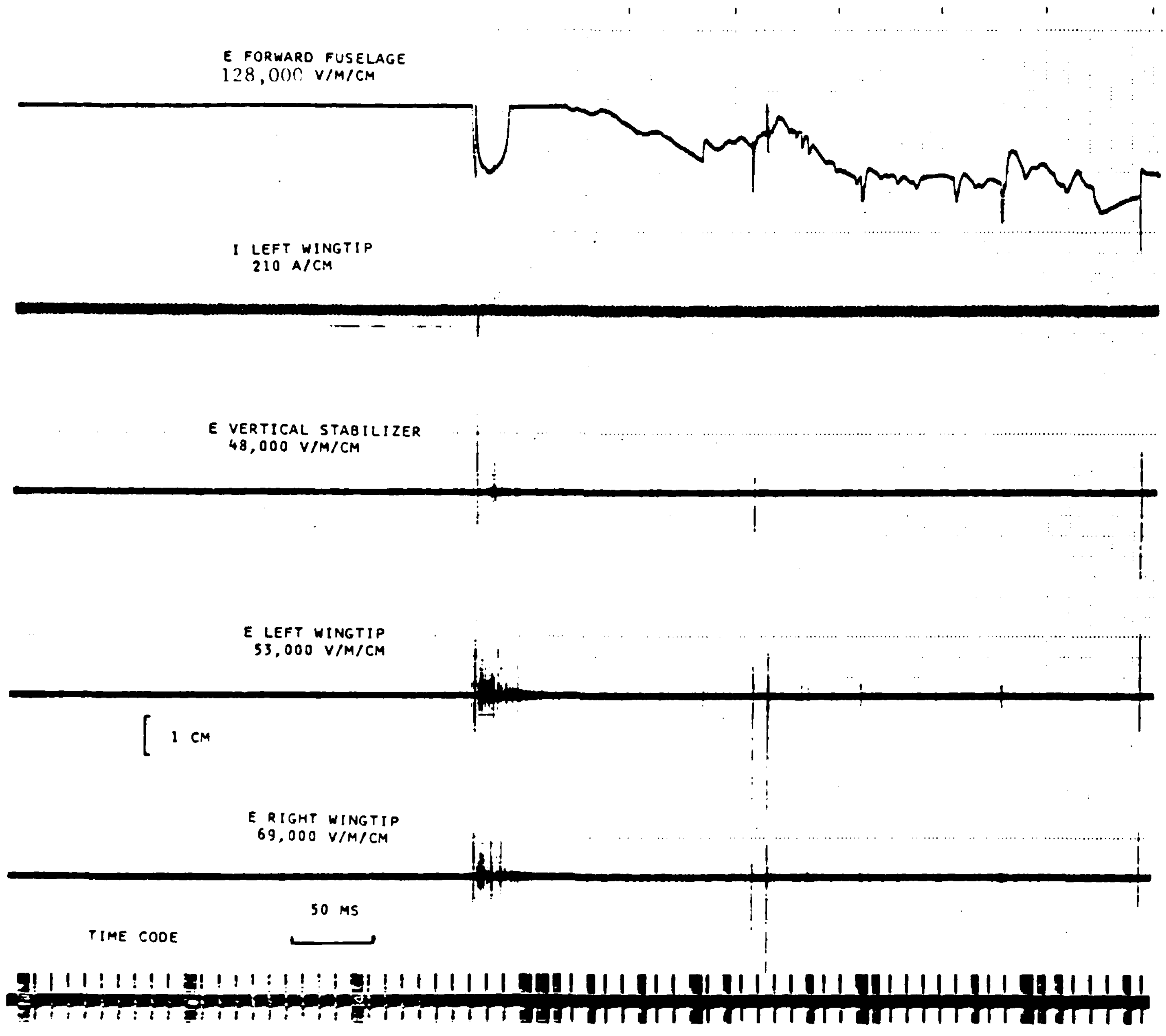


Figure 22. Same Analog Channels for First 400 ms of 21:22:10 Flash

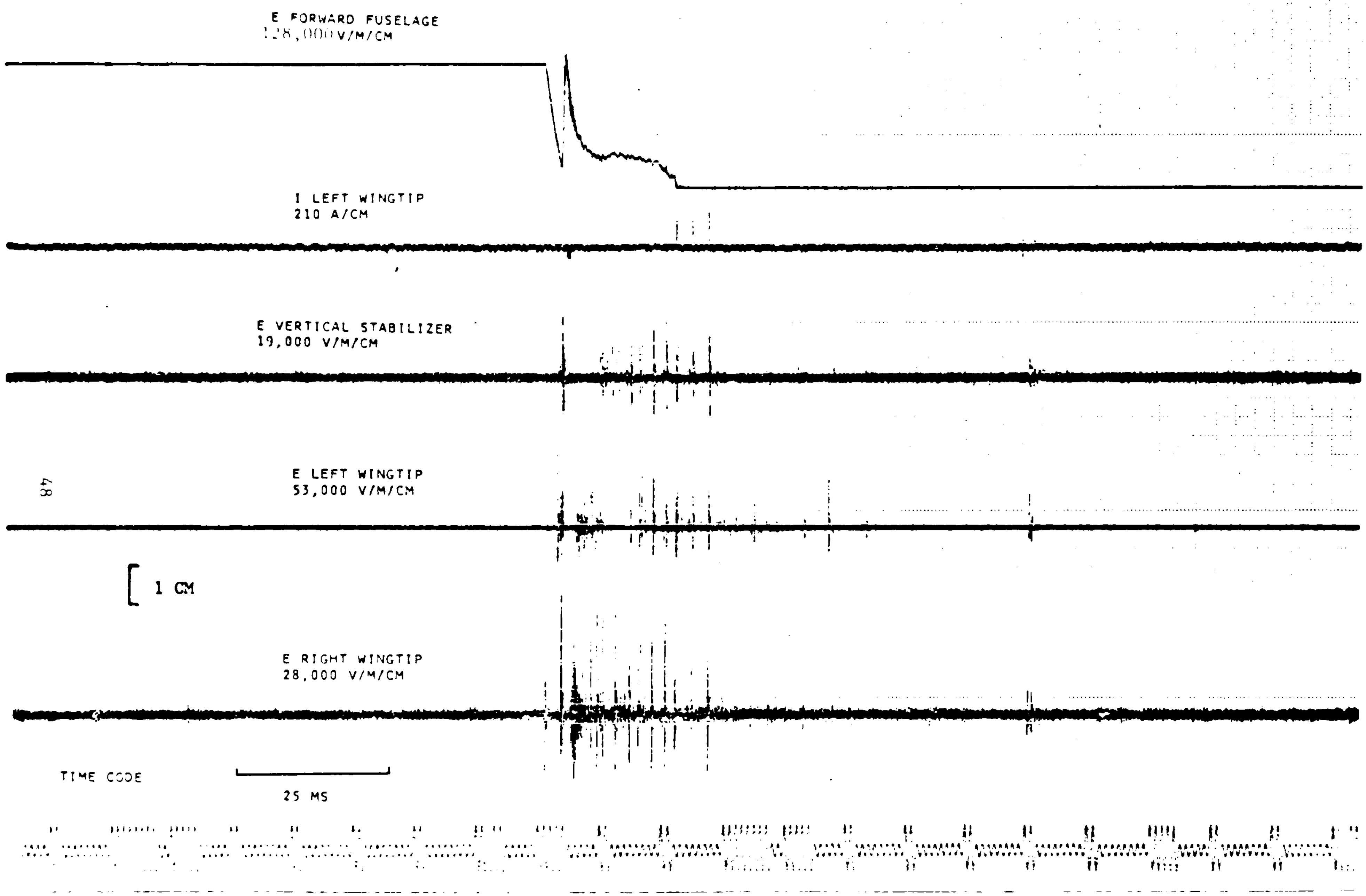


Figure 23. Six Analog Channels Recorded at Beginning of 21:31:01 Flash

flash. The E forward fuselage trace obtained from the J_{NFUF} sensor was initially saturated before showing a slow negative-going transition lasting for 2.7 ms. This indicates a variation of the field near the aircraft. The E right wing tip trace shows a transient pulse of about 42 kV/m corresponding to a leader propagation away from the aircraft. A channel appeared to be completed throughout the aircraft 2.7 ms later producing electric field readings of 132 kV/m near the left wing tip, 91 kV/m near the right wing tip, and 48 kV/m near the vertical stabilizer. Assuming a leader propagation speed of 1.5×10^5 m/s, the channel extended for over 400 m before it was neutralized by a pocket of opposite charge. After the initial 20 ms corresponding to the most active part of the discharge, the aircraft charge polarity reversed and the E forward fuselage saturated in the negative direction. Additional pockets of charge were apparently neutralized about 300 ms after the beginning of the flash as the aircraft charge changed polarity once again. As in the first flash, this discharge seemed to be triggered by the aircraft.

Figure 24 depicts the same six channels of the analog recorder for the entire duration of the discharge. The flash lasted nearly 400 ms and had a maximum pulse repetition rate of about 10^4 pulses/sec during the initial 20 ms.

Upon completion of the 11 July flight, the aircraft was inspected for damage. Pencil-sized holes were observed on the right wing aileron and vertical stabilizer where the skin thickness was about 0.025 inch. Burn marks were found on the horizontal stabilizer and on both wing tips.

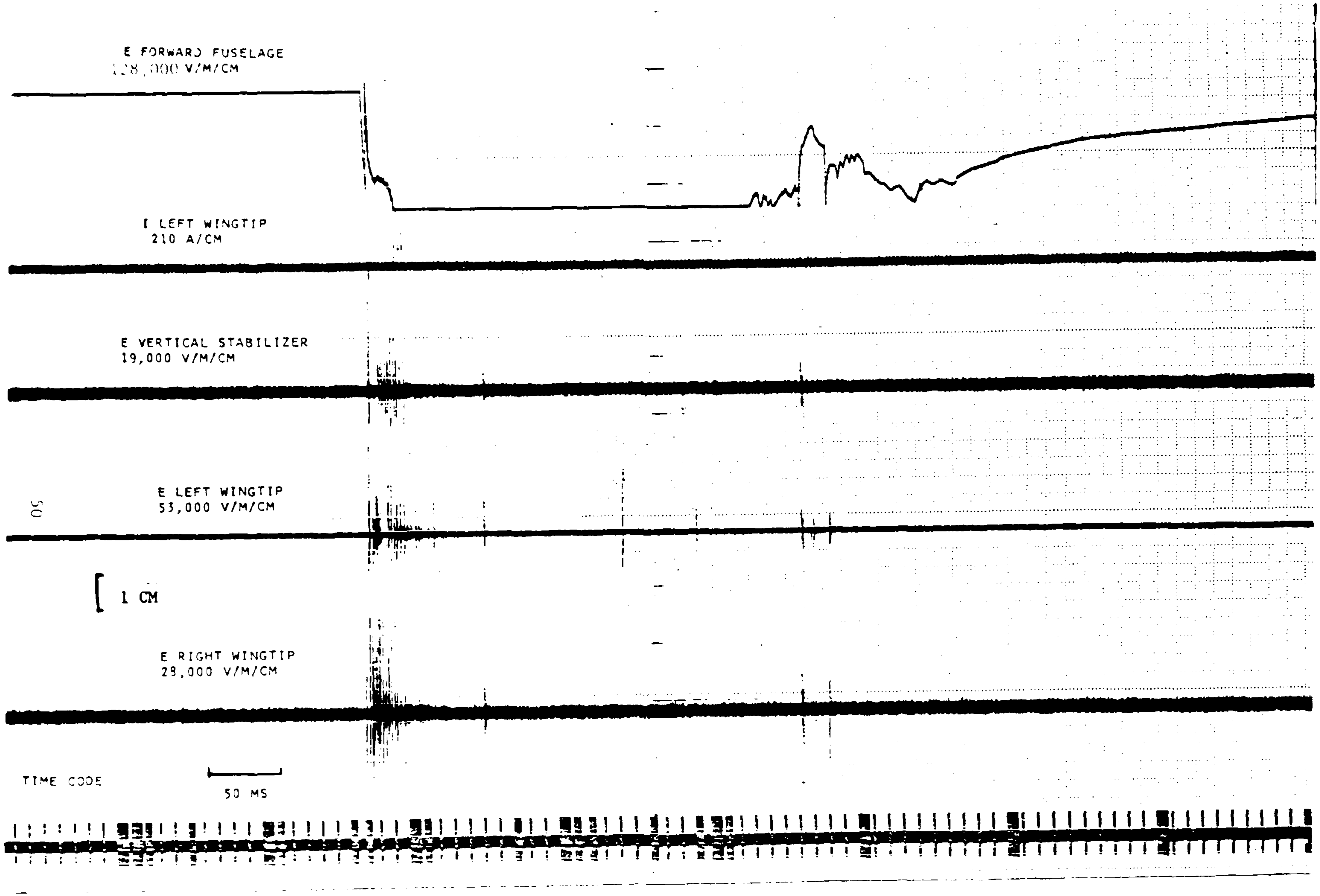


Figure 24. Same Analog Channels for Duration of 21:31:01 Flash

3. THE 13 JULY FLASH AT 20:46:23 Z

On 13 July at 20:46:23 Z, a lightning discharge attached to the aircraft while flying near Orlando, Fl at an altitude of 14,000 ft. The outside air temperature was -3°C and the outside barometric pressure was 8.6 lbs/inch^2. The aircraft was flying at 229 knots inside a low density cloud in an area of low turbulence. The location of the aircraft at the time of the flash is shown as (3) in Figure 20.

Figure 25 shows the radar precipitation return measured by the Tampa Bay, FL weather radar station. The X shows the position of the aircraft at the time of the flash. The dark areas indicate the regions of heavy precipitation returns and the lighter areas show regions of lighter precipitation. The inner circle corresponds to a 25-NM radius. At the time of this flash, the aircraft was located about 15 NM from any considerable precipitation returns.

The threshold level for the digital system was lowered to 400 T/s and the system triggered on the first fast transient as shown by the trigger signal in Figure 26. The top trace in Figure 26 indicates little charge on the aircraft prior to the attachment and shows a negative-going leader pulse for the first 1.7 ms of the discharge. No fast transient pulses were observed prior to this field change indicating that no significant streamers propagated from the aircraft to the charge center that initiated the discharge. Detectable leader motion began about 255 meters away from the aircraft, assuming a uniform leader velocity of 1.5×10^5 m/s. As in the two previous flashes, the aircraft appeared to trigger the discharge. In this case, however, the aircraft was not charged prior to the flash making it unlikely that any significant streamers propagated from the aircraft to intercept the oncoming leader. The very active part of the discharge

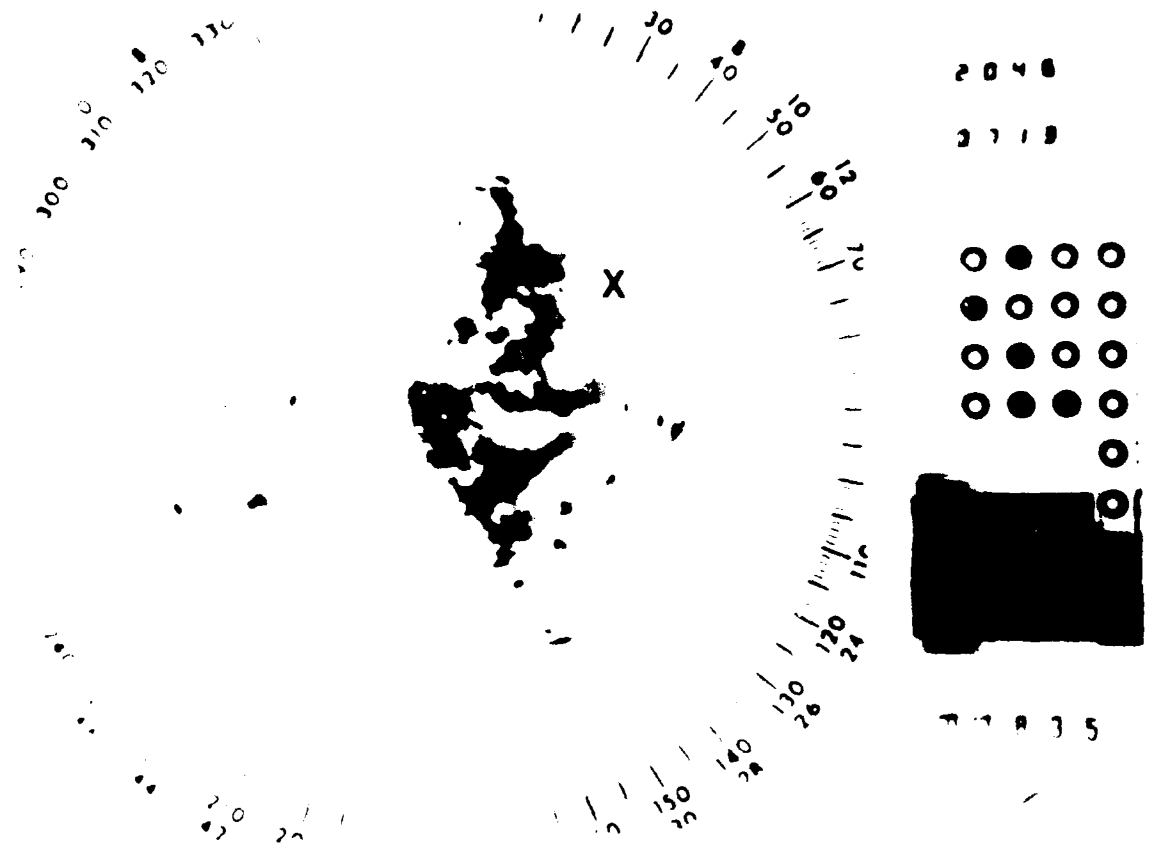


Figure 25. Tampa Bay Precipitation Radar Return Showing Position of CV-580 Aircraft During 20:46:23 Flash

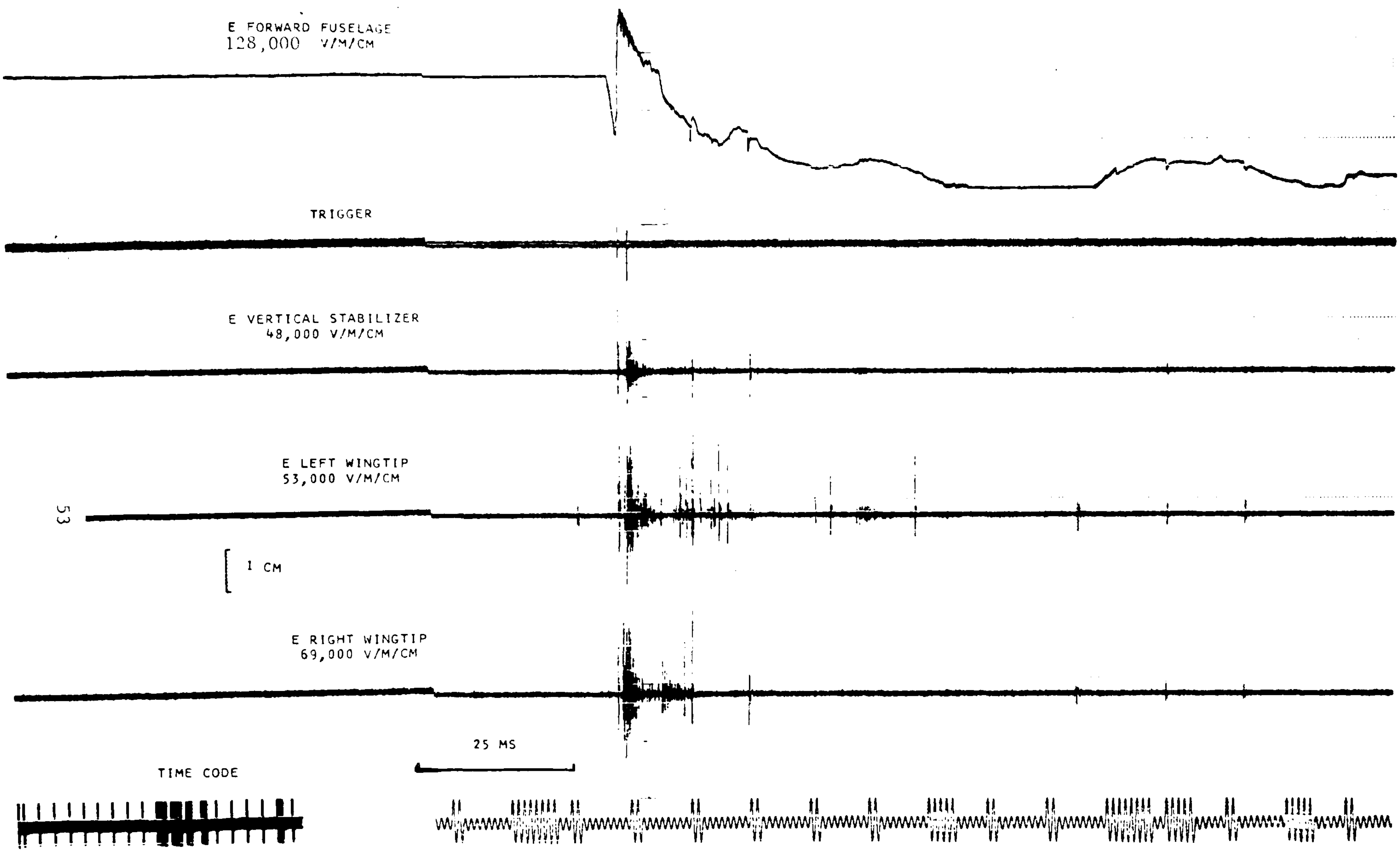


Figure 26. Six Analog Channels Recorded at Beginning of 20:46:23 Flash

lasted 25 ms and the fastest pulse repetition rate during this period exceeded 10^4 pulses/sec.

Figures 27 and 28 show 1.2 μs expansions during the triggered pulse at the beginning of the flash. Figure 27 shows the surface current density at the forward fuselage, aft fuselage, left wing, and right wing J_S sensors. Maximum values of surface current density during triggered pulse were 416 T/s for the forward fuselage, 872 T/s for the aft fuselage, 165 T/s for the left wing, and 127 T/s for the right wing sensors. The damped sinusoidal pattern corresponds to the reflection of the current pulse as it reached the end of the propagation path. Figure 28 shows the displacement current density at the left wing and the vertical stabilizer J_N sensors during the triggered pulse. The maximum values for the displacement current density were 1.2 A/m^2 at the left wing and 3.2 A/m^2 at the vertical stabilizer sensors.

Figure 29 shows the overall characteristics of the flash which lasted about 430 ms. Similarly to the two previous flashes, the attachment process began with a leader followed 1.7 ms later by the fast pulse that triggered the digital system. Most of the transients during the flash occurred during the active 25 ms interval following the initiation of the discharge. Twelve significant transients were measured beyond this initial portion of the flash. These latter transients are referred to as isolated pulses and are probably caused by re-activation of the previous channel, much like subsequent return strokes in cloud-to-ground discharges.

A post-flight inspection of the aircraft revealed a hole the size of a pencil on the vertical tail. Some burn damage was also observed near the tail light on the top of the vertical stabilizer.

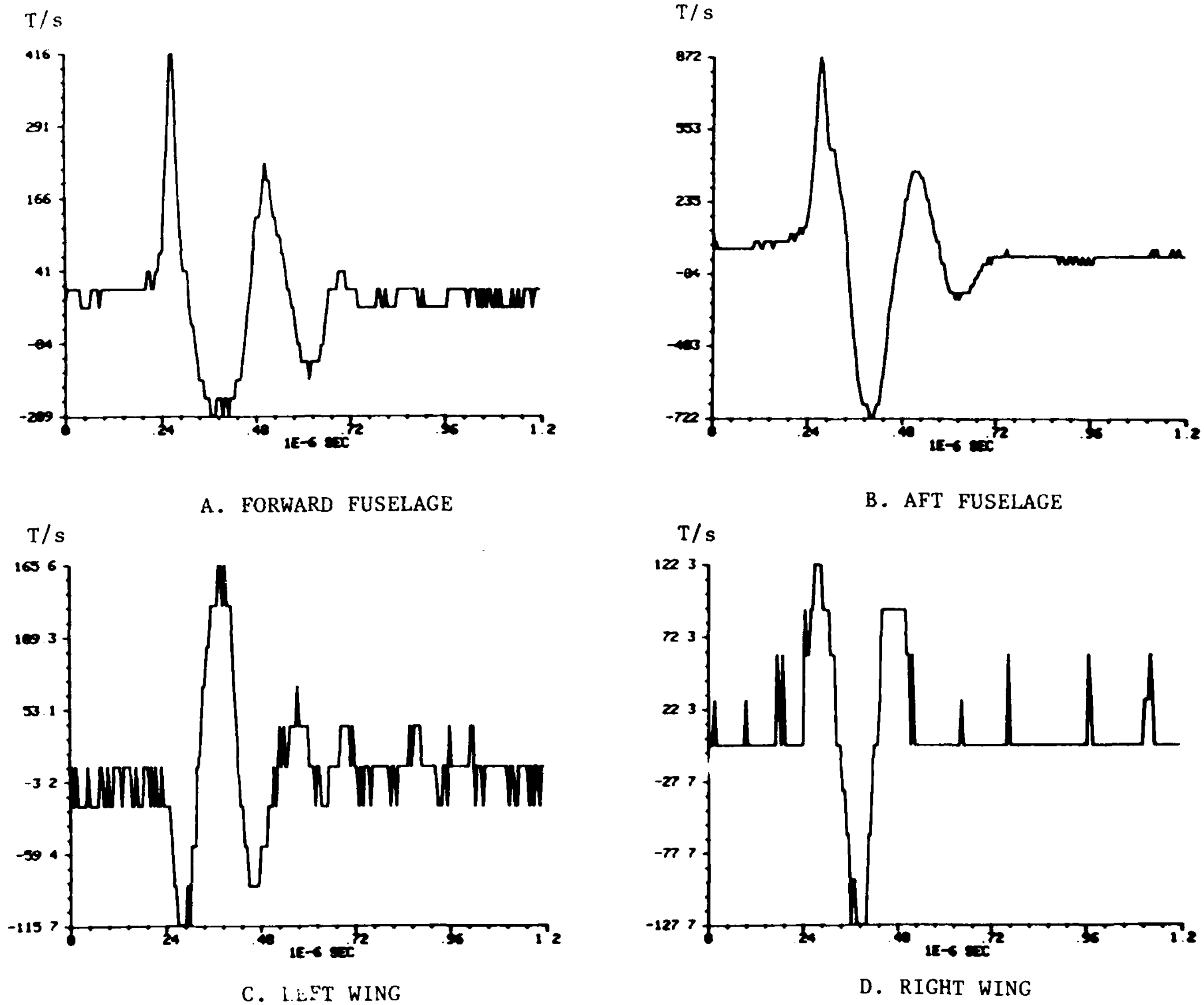


Figure 27. Surface Current Density During Triggered Pulse of 20:46:23 Flash

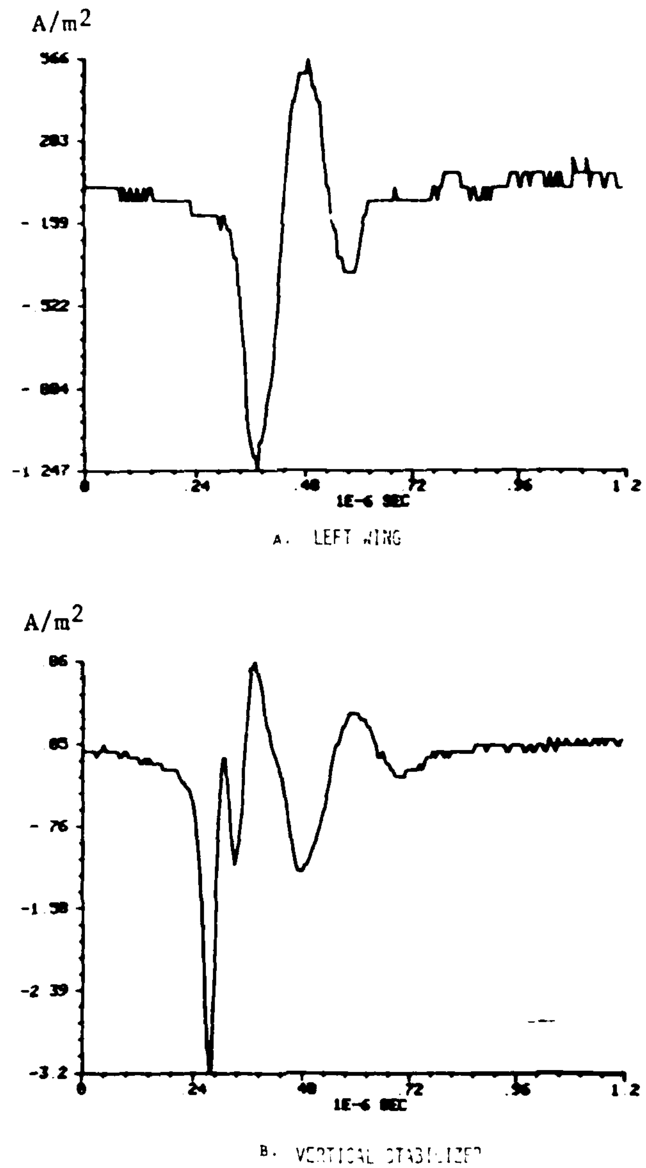


Figure 28. Displacement Current Density During Triggered Pulse of 20:46:23 Flash

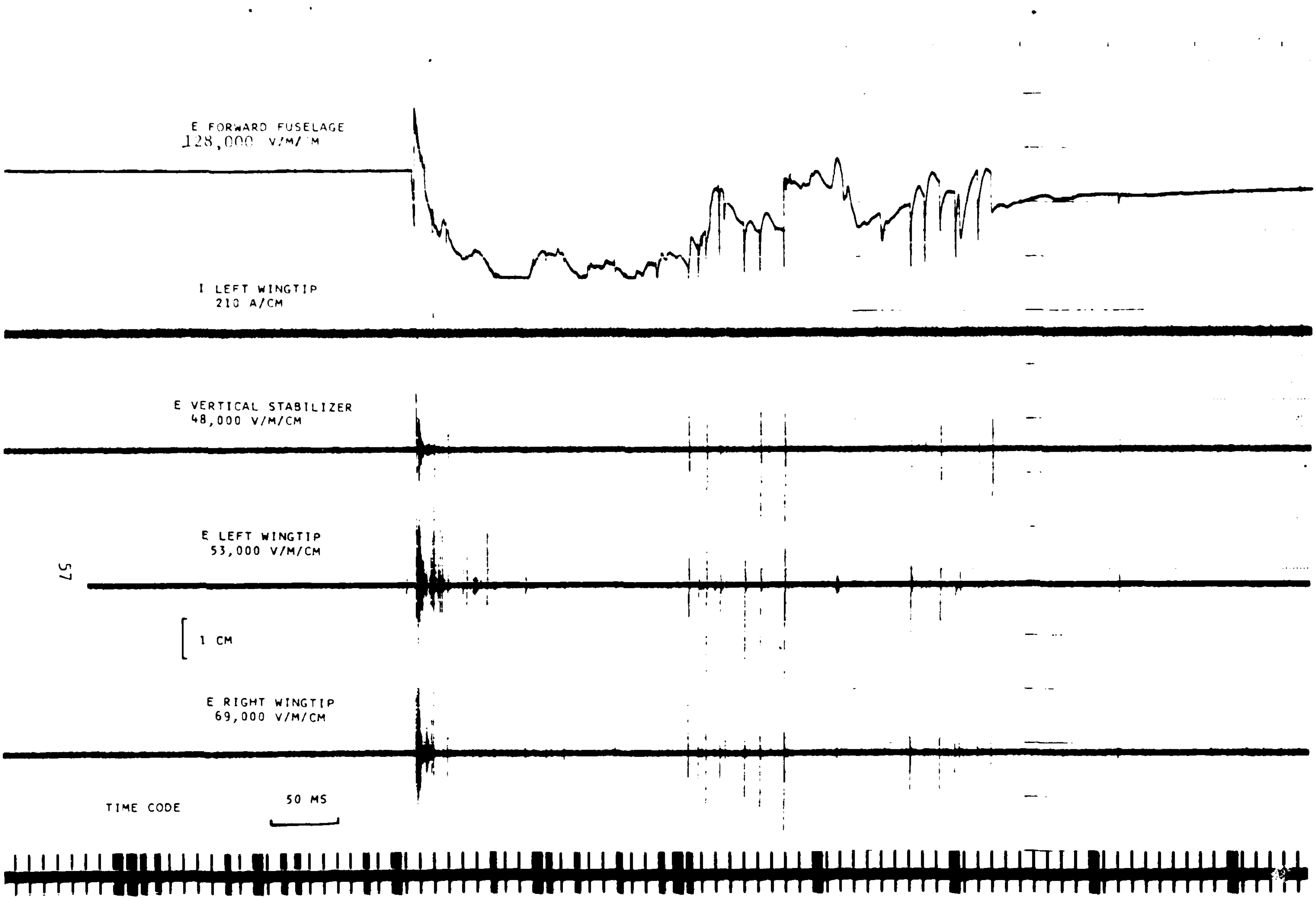


Figure 29. Six Analog Channels for Duration of 20:46:23 Flash

4. THE 6 AUG FLASH AT 21:44:05 Z

The aircraft was hit by lightning on 6 Aug at 21:44:05 Z while flying north of Orlando, Fl at an altitude of 14,000 ft. The aircraft was inside the cloud and its location at the time of the flash is shown as (4) in Figure 20.

Figure 30 shows the Tampa Bay precipitation return three minutes after the lightning attachment. Dark areas indicate regions of heavy precipitation and the inner circle corresponds to a 25-NM radius. The aircraft was approximately 17 NM from any heavy precipitation at the time of the flash.

The threshold level was set at 400 T/s and the digital system triggered on the first transient pulse that exceeded that value. No analog data was recorded because the analog tape was being changed at the time of the discharge. Most of the digital signals recorded for this flash were only ten times larger than the noise level on the digitizers. The largest measured values were 1251 T/s for the J_{SBRW} sensor and 2.53 A/m^2 for the J_{NLWT} sensor. No new damage was found during a thorough inspection of the aircraft.

5. THE 7 AUG FLASH AT 21:20:57 Z

On 7 Aug at 21:20:57 Z, a lightning discharge attached to the aircraft while flying in central Florida. This was the first of seven strikes received during this flight. The aircraft was flying at 18,000 ft with a true air speed of 265 knots. The outside air temperature was -8°C and the barometric pressure was 7.30 lbs/inch^2. The aircraft was flying inside the cloud in an area of low turbulence.

Figure 31 shows the Tampa Bay precipitation return and X marks the position of the aircraft at the time of the flash. The dark areas show the

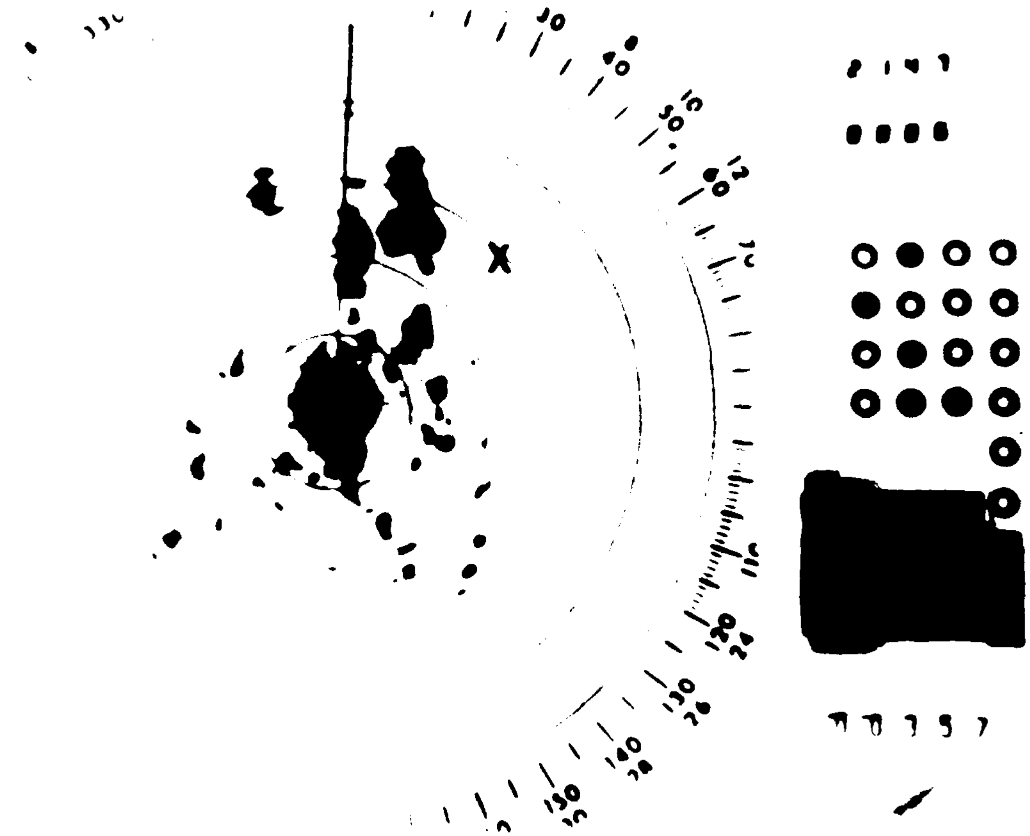


Figure 30. Precipitation Radar Return Showing Position of Aircraft Shortly After 21:44:05 Flash

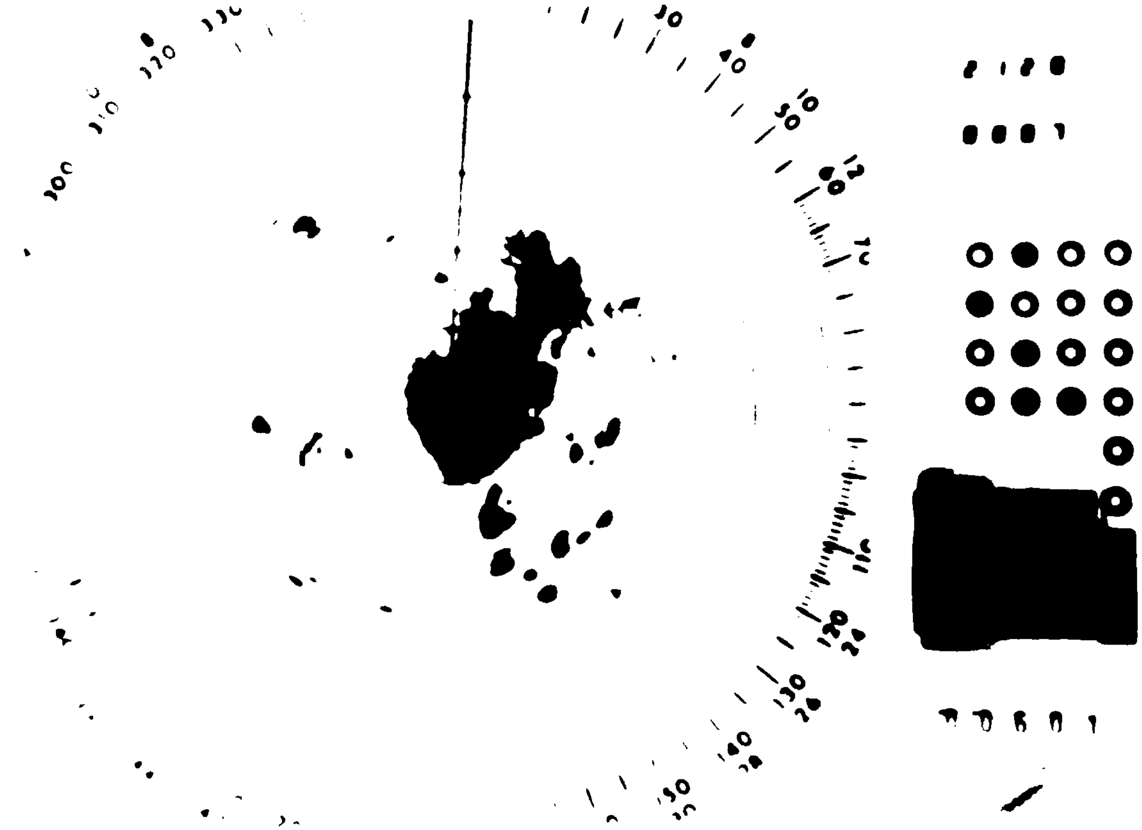


Figure 32 Precipitation Radar Return Showing Position of Aircraft During 21:20:57 Flash

regions of heavy precipitation returns. The display indicates that the aircraft was near the edge of the storm at the time of the flash.

The digital system was set to trigger at 4,000 T/s for any of the J_S sensors but the system did not trigger. The analog records indicate that the flash consisted of several hundred pulses but none of them exceeded this relatively large threshold level.

Figure 32 shows the analog record for five of the channels during the beginning of the discharge. The first trace showing the electric field on the forward upper fuselage reveals a negative-going pulse at the beginning of the discharge. Significant current and electromagnetic fields are observed until the end of the initial negative-going pulse. The pulse lasted 2.1 ms and suggests a steady variation of charge caused by a leader propagating toward the aircraft. Assuming an average velocity of 1.5×10^5 m/s, the leader covered a 315 m path before attaching to the aircraft. The discharge appeared to be triggered by the aircraft and no outward streamer propagation from the aircraft is indicated.

The second trace in Figure 32 shows the actual current flow through the I_{LW} sensor. The current continued to flow for the entire duration of the flash indicating that the leader attached to the left wing tip. Since the current data was recorded using an FM channel with a DC to 500 kHz frequency response, low frequency continuing current pulses can be observed throughout the discharge. As in cloud-to-ground discharges, the current in the lightning flash consisted of unipolar pulses. In lightning attachment to aircraft, however, there are hundreds of pulses per flash instead of a single, isolated current pulse typically observed in a cloud-to-ground discharge. Continuing current flowed on the aircraft for about 400 ms after the initial pulse. Noting the 430 A/cm scale for the I_{LW} trace, the

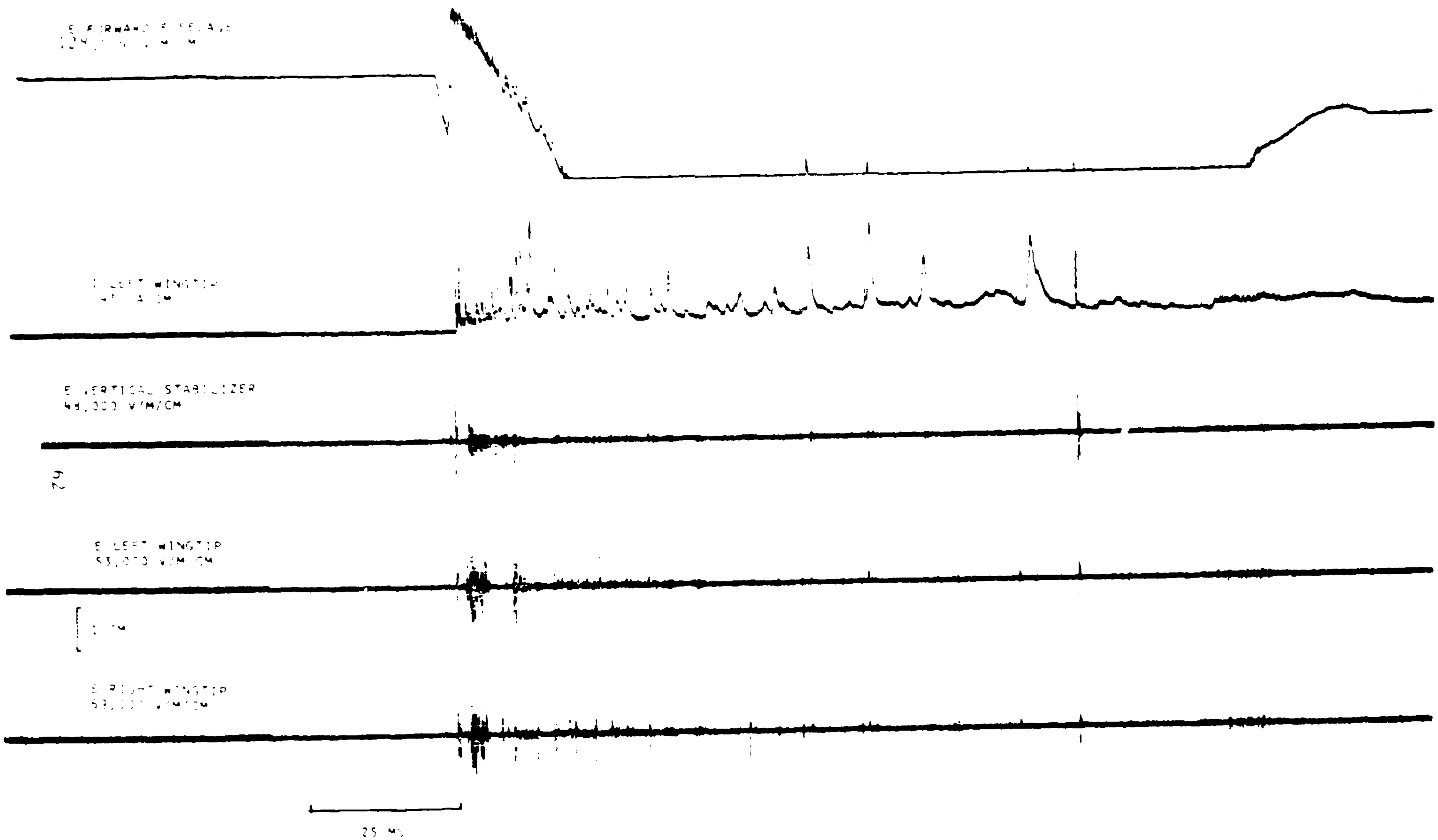


Figure 32. Five Analog Channels Recorded at Beginning of 21:20:57 Flash

average value of the continuing current during the flash was about 200 A. Integration of the current indicates that about 102 C of charge were transferred during the flash. This is an order of magnitude larger than the average charge transfer in intracloud discharges (Reference 11). The current pulses riding on the continuing current vary in magnitude from tens of amperes to a few kiloamperes with risetimes as slow as hundreds of microseconds and as fast as to be bandlimited by the 500-kHz frequency response of the FM channel on the analog recorder. The last pulse on the left wing tip trace of Figure 32 was one of the fastest pulses in the flash that exceeded the frequency response of the channel. Figure 33 shows an expansion of the current flow on the left wing tip during the first 100 ms of the discharge. The average current during this interval was 250 A and the charge transferred was 31 C.

The bottom three traces of Figure 32 show electric fields on the vertical stabilizer, left wing tip, and right wing tip. These traces appear bipolar because they were recorded in direct channels with a lower frequency response of 400 Hz. However, direct channels have an upper frequency response of 2 MHz instead of 500 kHz as in the FM channels. Figure 34 shows the same five channels for the entire 450 ms of the flash. Figures 32, 33, and 34 help demonstrate that the pulse repetition rates decreased significantly after the initial active phase lasting about 75 ms. However, isolated pulses or a small trains of pulses still occurred throughout the duration of the flash. The largest electric field transients measured for the flash were 135 kV/m at the right wing tip, 138 kV/m at the left wing tip, and 100 kV/m at the vertical stabilizer.

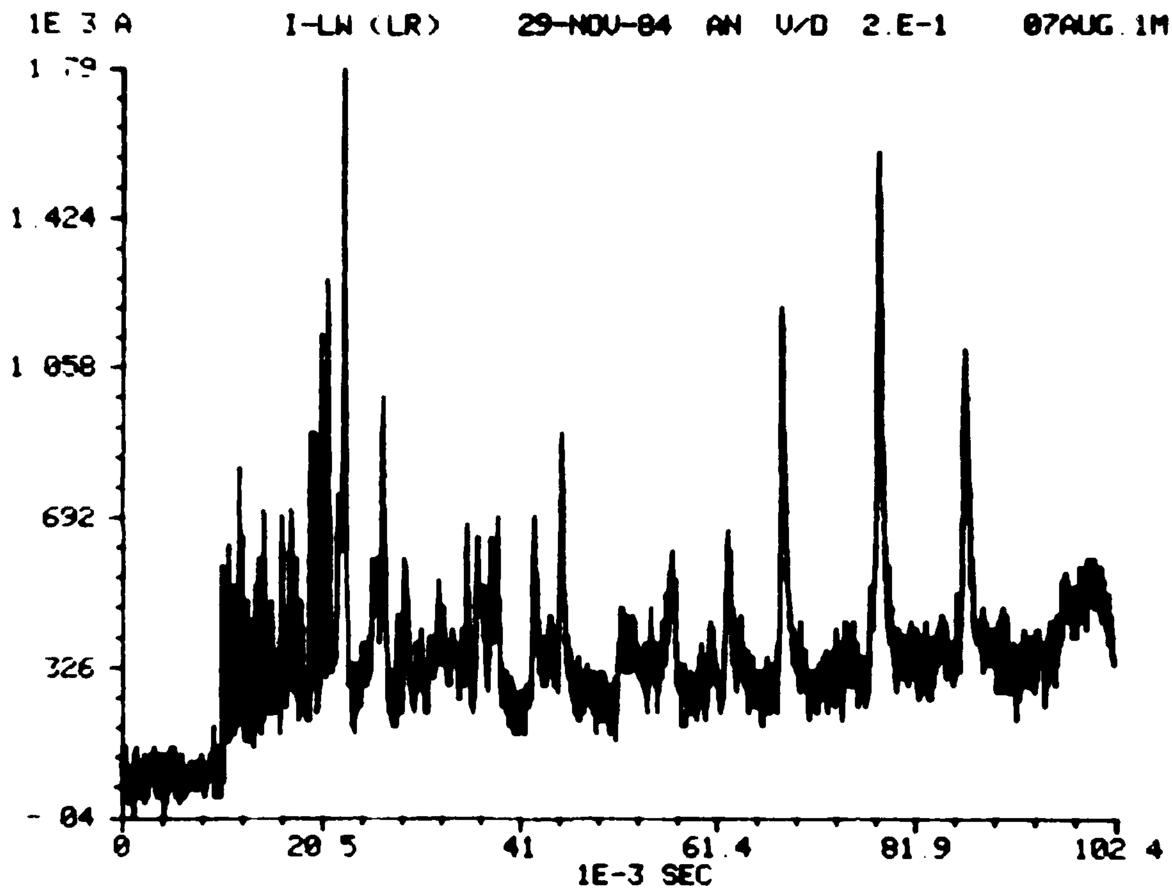


Figure 33. Current Flow on Left Wing Tip During First 100 ms of 21:20:57 Flash

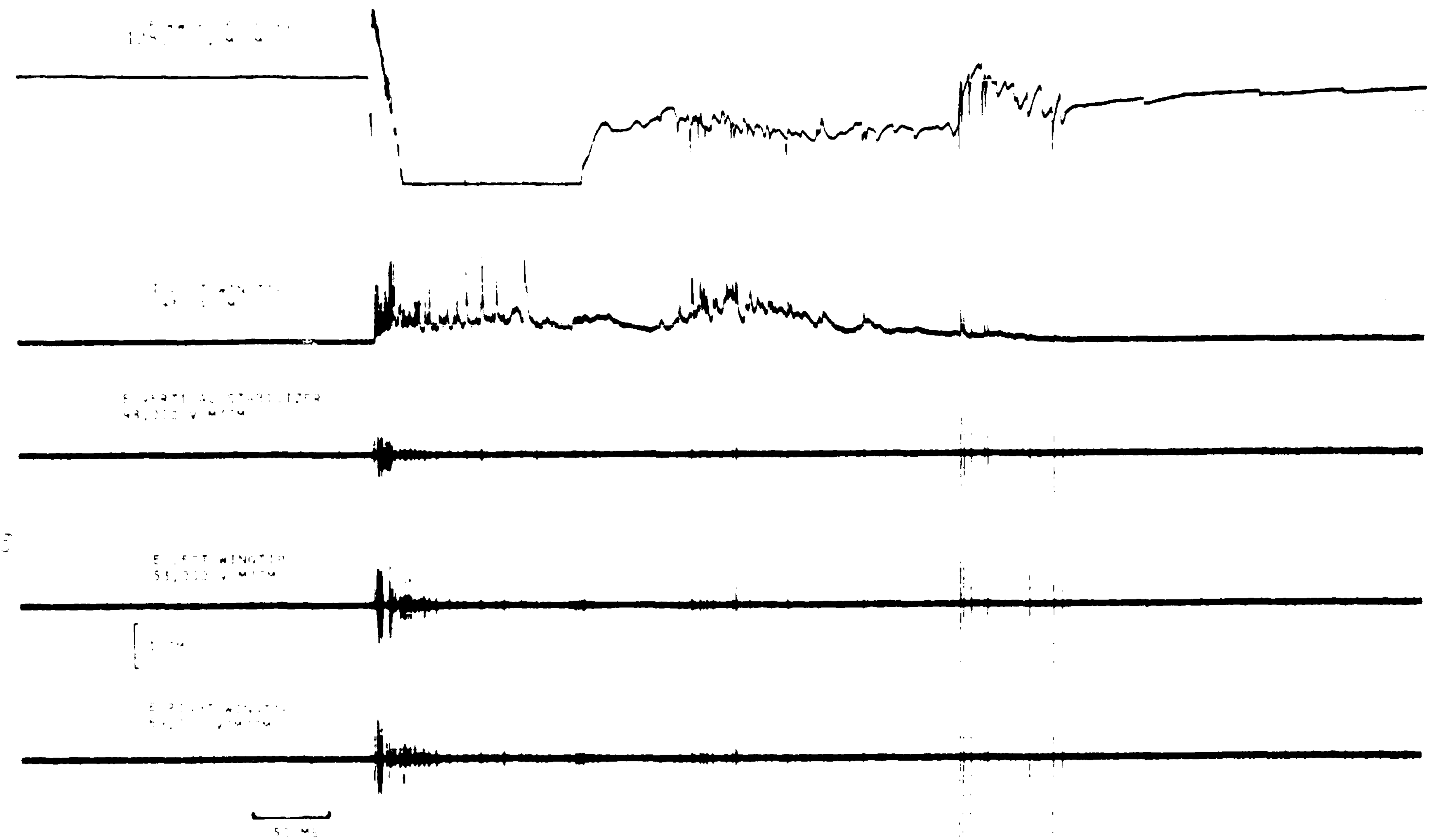


Figure 34. Same Analog Channels for Duration of 21:20:57 Flash

6. THE 7 AUG FLASH AT 21:38:24 Z

The next lightning attachment to the aircraft during this flight occurred at 21:38:24 Z while flying in central Florida. The aircraft was flying at 18,000 ft with a true air speed of 250 knots. The outside air temperature was -6°C and the barometric pressure was 7.25 lbs/inch^2. The aircraft was in clouds in an area of low turbulence. Figure 35 shows the precipitation return which indicates that the aircraft was about 12 NM from any area of heavy precipitation at the time of the strike.

No digital data was collected for this flash because the threshold level was being changed at the time. However, Figure 36 shows six analog traces for the beginning of the discharge. The flash began with a negative-going leader pulse shown on the E forward fuselage trace lasting for 2.2 ms. This corresponds to a leader propagation 330 m in length, assuming a 1.5×10^5 m/s leader velocity. No electric field or current transients were observed prior to the leader process indicating that no streamer propagated from the aircraft. The 63-MHz VHF radiation measured on top of the fuselage patterns the leader pulse. The VHF envelope detector apparently detected the oncoming leader and a corresponding increase in VHF radiation is indicated. The most active part of the flash lasted about 30 ms between the time of the first transient pulse on the E right wing tip, E vertical stabilizer, and E left wing tip traces and the end of the active pulse train. As in other flashes, there were several isolated pulses after the initial pulse train. The E forward fuselage trace saturated in the negative direction about 20 ms after the beginning of the flash.

The same six traces are shown in Figure 37 for the duration of the flash which lasted about 940 ms. It began with an initial 30 ms pulse train with a maximum pulse repetition rate near 10^4 pulses/sec followed by

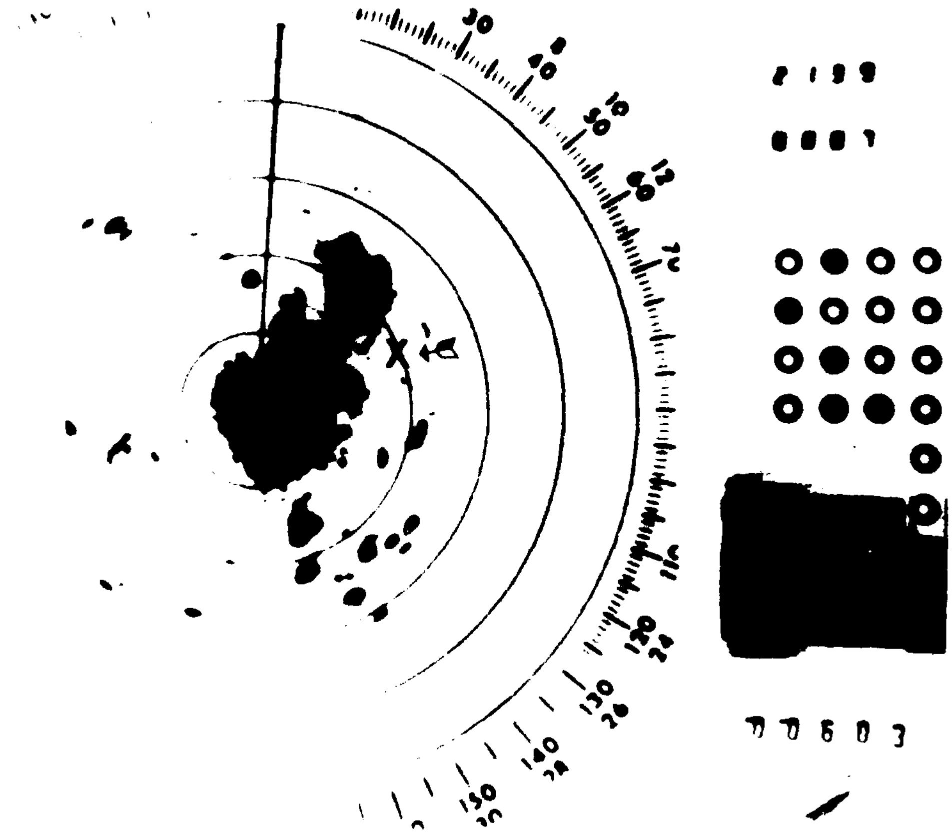


Figure 35. Precipitation Radar Return Showing Posi..on of Aircraft During 21:38:24 Flash

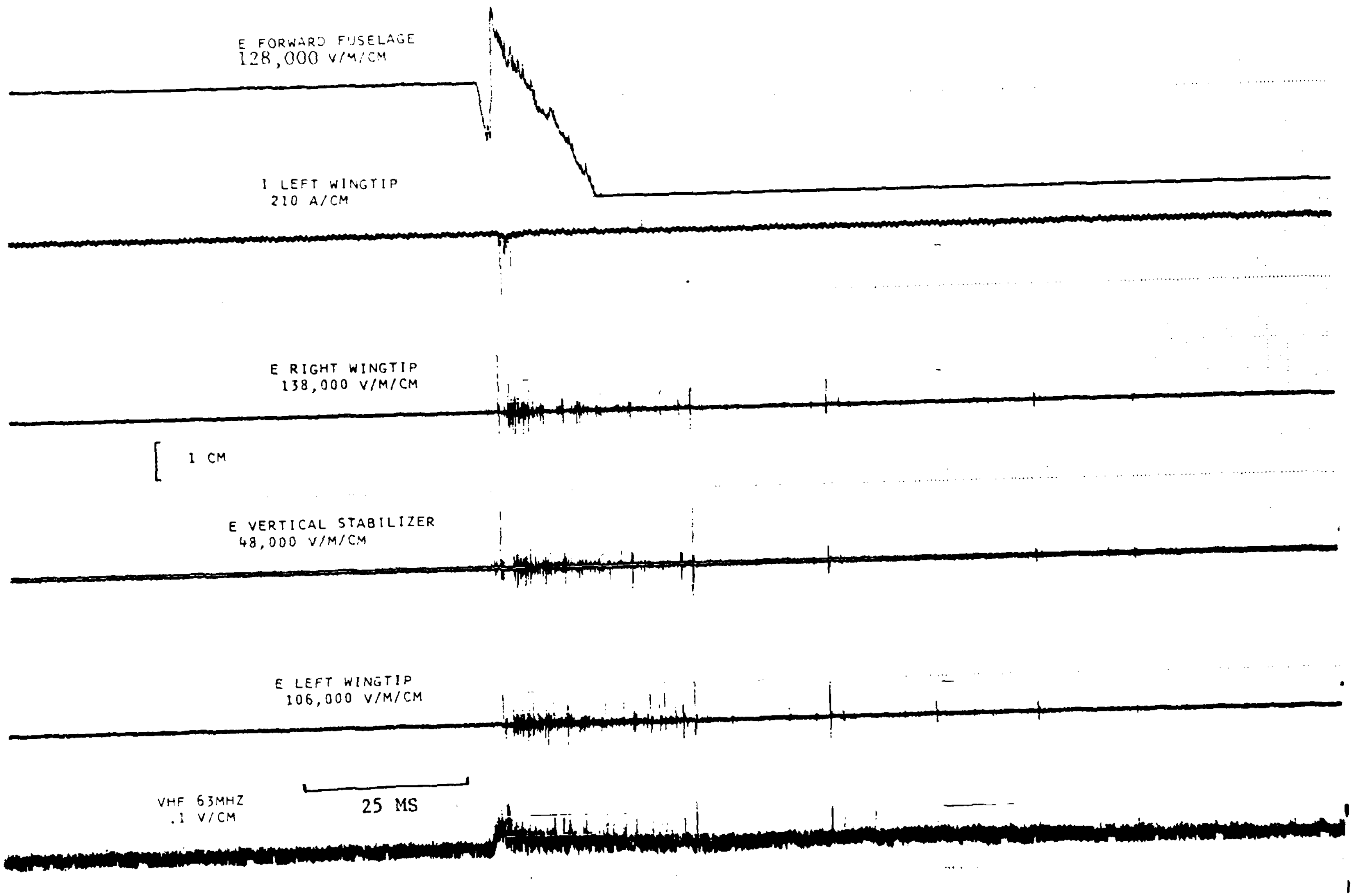


Figure 36. Six Analog Channels Recorded at Beginning of 21:38:24 Flash

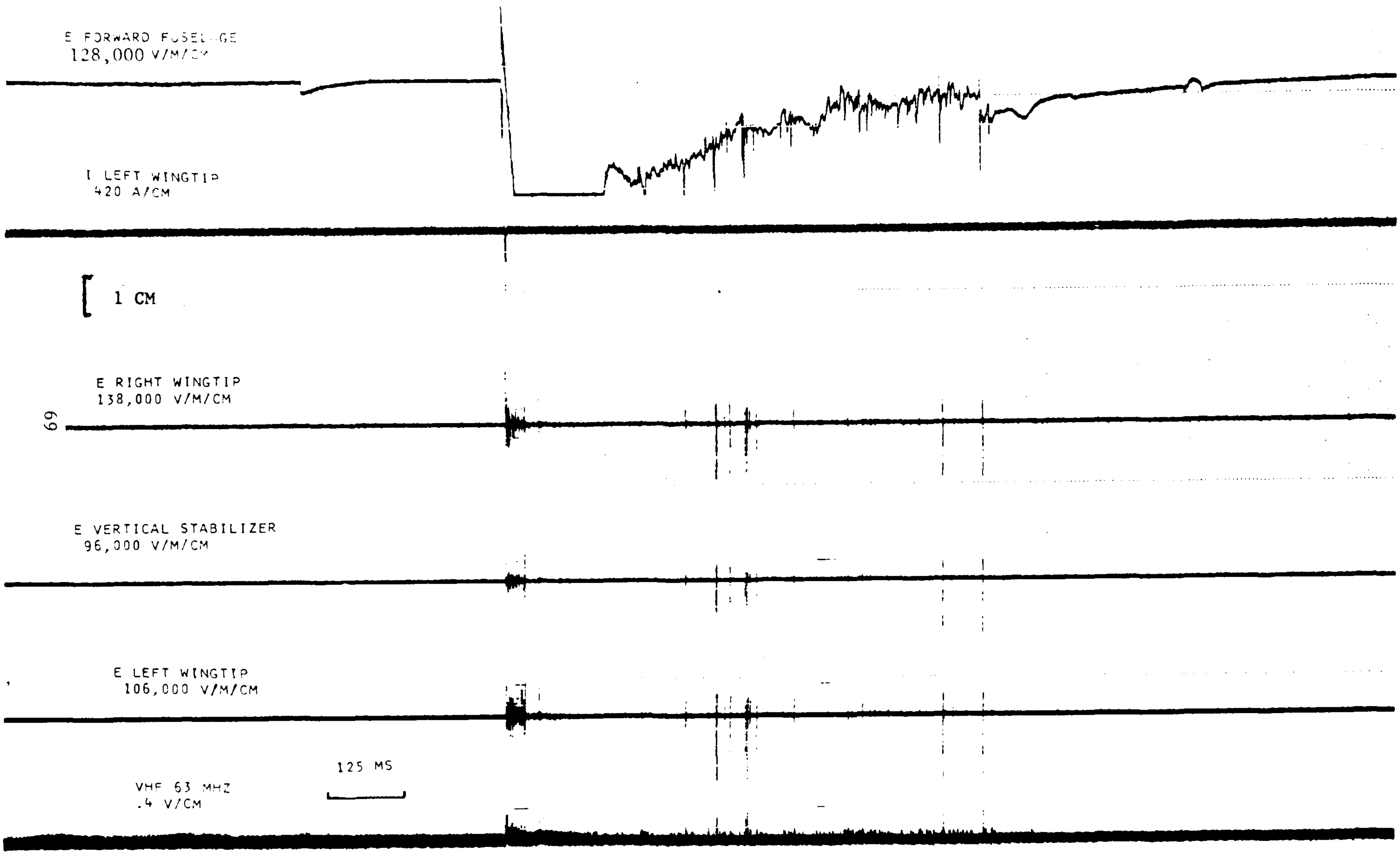


Figure 37. Same Analog Channels for Duration of 21:38:24 Flash

a few isolated pulses. The highest electric field transients measured during the flash were about 207 kV/m on the right wing tip, 130 kV/m on the vertical stabilizer, and 170 kV/m on the left wing tip. The largest transients occurred during some of the isolated pulses near the end of the flash.

7. THE 7 AUG FLASH AT 21:41:24 Z

A few minutes later, a lightning discharge attached to the aircraft at 21:41:24 Z. Flight altitude and atmospheric conditions were the same as for the previous flash. Figure 20 gives the location of the aircraft at the time and Figure 38 shows the Tampa Bay precipitation return shortly before the lightning attachment. The aircraft was just inside a region of heavy precipitation.

The digital threshold level was set to 400 T/s and the system triggered during one of the first transient pulses. The trigger signal is shown in the second trace of Figure 39. The only significant pulse measured during the triggered event was the displacement current density at the J_{NRWT} sensor. This pulse is shown in Figure 40 and reached 22.52 A/m^2 in 10 ns. The J_{NLWT} and J_{NVS} sensors recorded values of 0.908 and 0.942 A/m^2, respectively. Surface current densities at the J_{SBRW}, J_{SFUF}, and J_{SAUF} sensors measured 618 T/s, 469 T/s, and 683 T/s, respectively.

The top trace in Figure 39 shows the negative-going leader pulse that lasted for about 2.1 ms at the beginning of the discharge corresponding to a 315-m propagation path. No significant streamers were detected propagating from the aircraft though the event was probably triggered by the CV-580 as it flew near the charge center. The most active part of the discharge lasted for about 15 ms and the fastest pulse repetition rate was near 10^3 pulses/sec. Maximum electric field values measured during the flash were

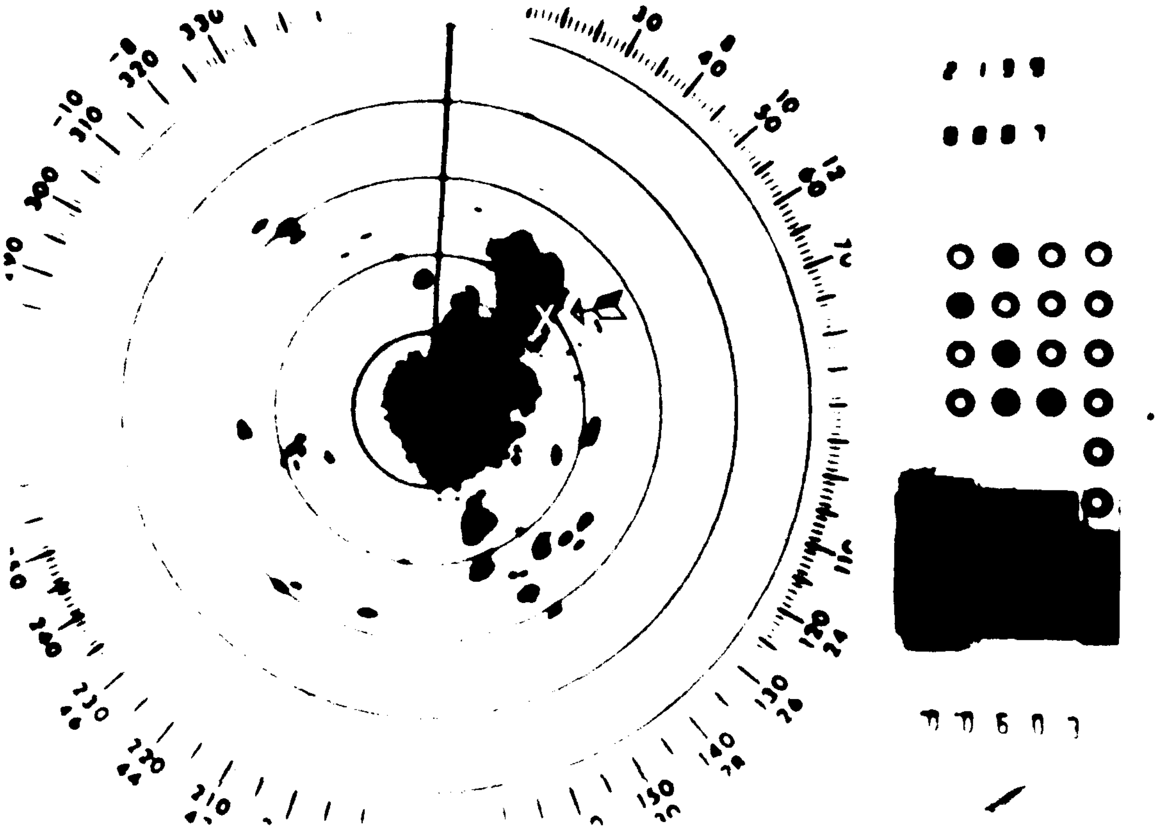


Figure 38. Precipitation Radar Return Showing Position of Aircraft Shortly Before 21:41:24 Flash

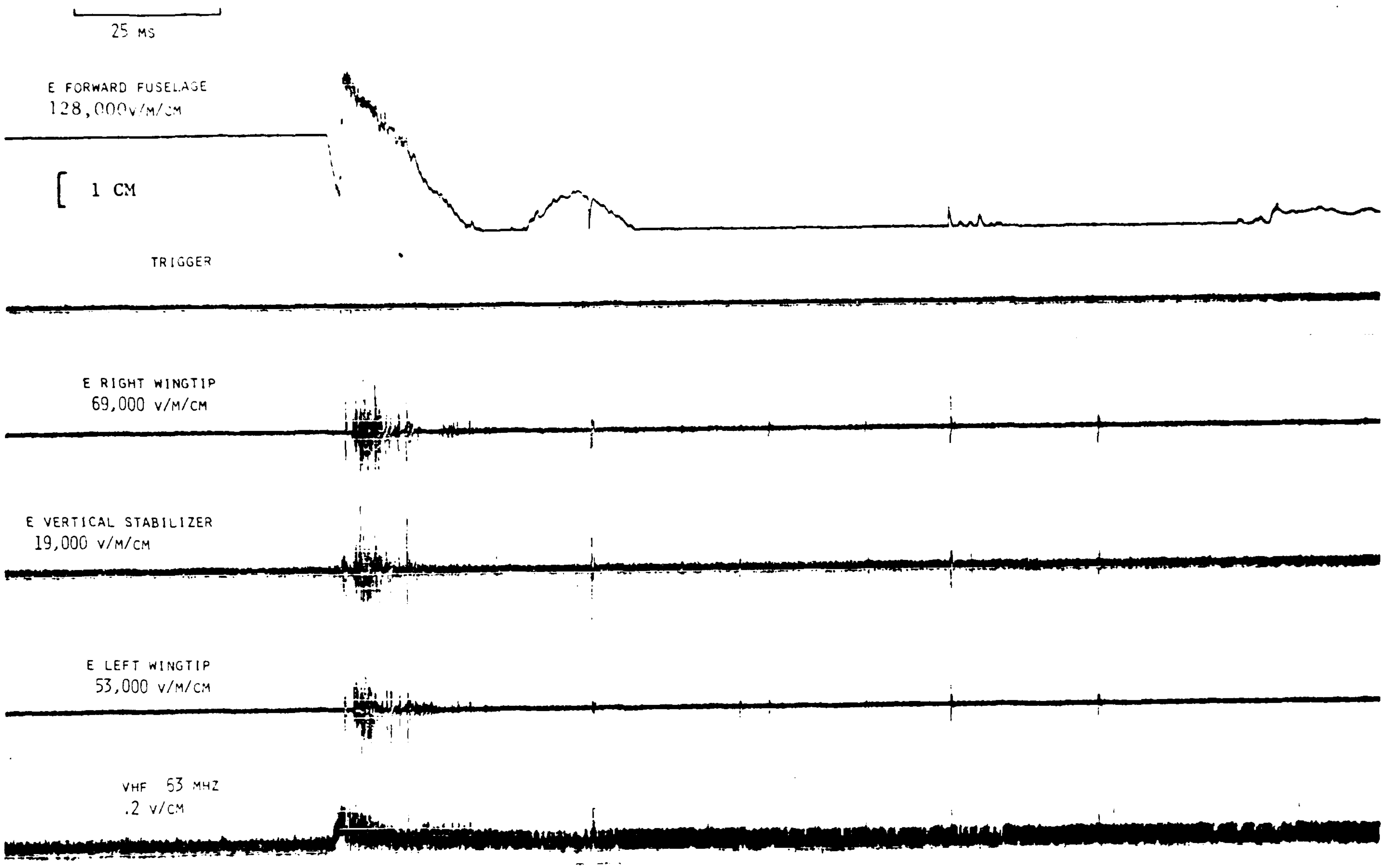


Figure 39. Six Analog Channels Recorded at Beginning of 21:41:24 Flash

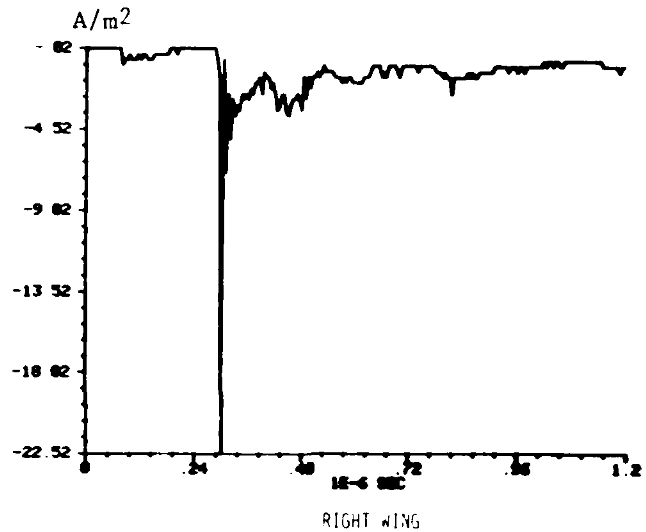


Figure 40. Displacement Current Density on Right Wing Tip During 21:41:24 Flash

about 170 kV/m on the right wing tip, 95 kV/m on the left wing tip, and 37 kV/m on the vertical stabilizer.

Figure 41 shows the the same analog channels for the duration of the flash which lasted about 780 ms. Following the initial leader and active phase region, about 12 large isolated pulses occurred during the remainder of the flash. The top trace indicates that the electric field measurement from the J_{NFUF} sensor had saturated in the negative direction for about 120 ms after the onset of the discharge.

8. THE 7 AUG FLASH AT 21:41:59 Z

The next attachment to the aircraft occurred 35 seconds later at 21:41:59 Z while flying at 18,000 ft. The outside air temperature was -6°C and the barometric pressure was 7.32 lbs/inch^2. The aircraft was flying in low turbulence just inside a region of heavy precipitation, as shown in Figure 42.

The threshold level was set at 400 T/s and the system triggered on the first transient pulse after the initial electric field transition. The top trace in Figure 43 shows an apparent leader propagation that lasted about 2.1 ms. Most of the charge in the region that initiated the leader was probably neutralized during the initial active phase that lasted about 17 ms. The maximum pulse repetition rate in this phase was less than 10^3 pulses/sec, a lower rate than in most other flashes. The maximum electric field transients measured during the flash were about 127 kV/m at the vertical stabilizer, 118 kV/m at the right wing tip, and 138 kV/m at the left wing tip.

Figure 44 shows the surface current density on the forward and aft fuselage during the triggered pulse. The largest value of surface current

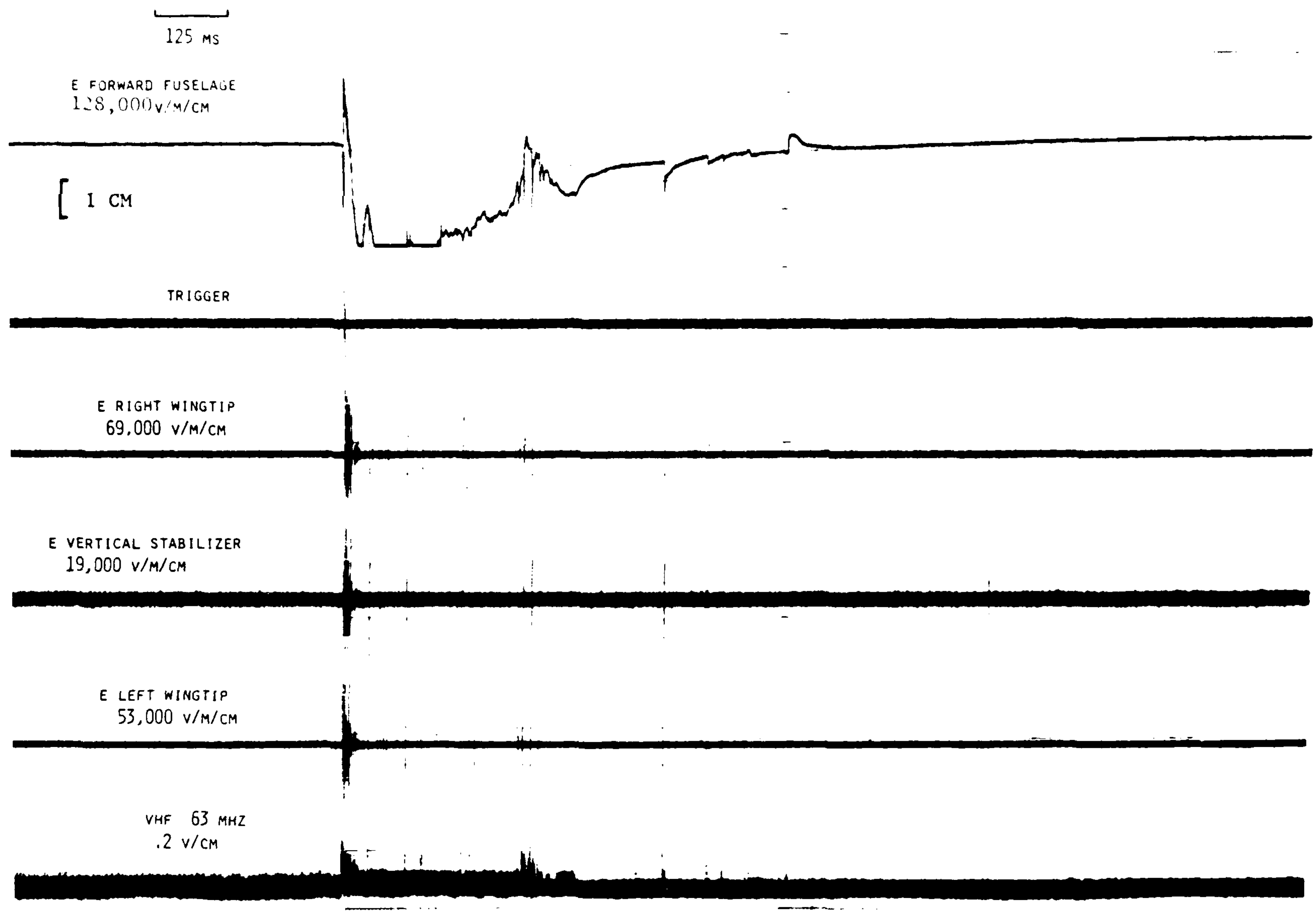


Figure 41. Same Anolog Channels for Duration of 21:41:24 Flash

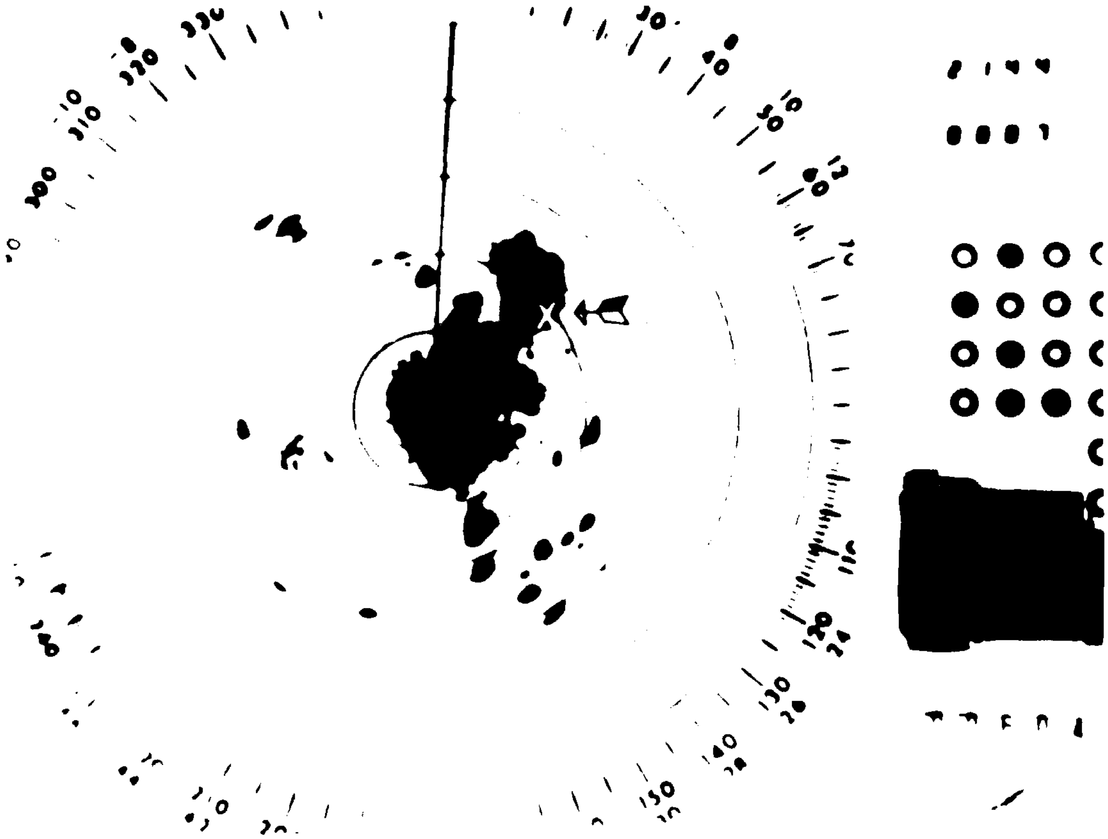


Figure [illegible]. Tampa Bay Precipitation Radar Return Showing Position of Aircraft Shorlty After 21:41:59 Flash

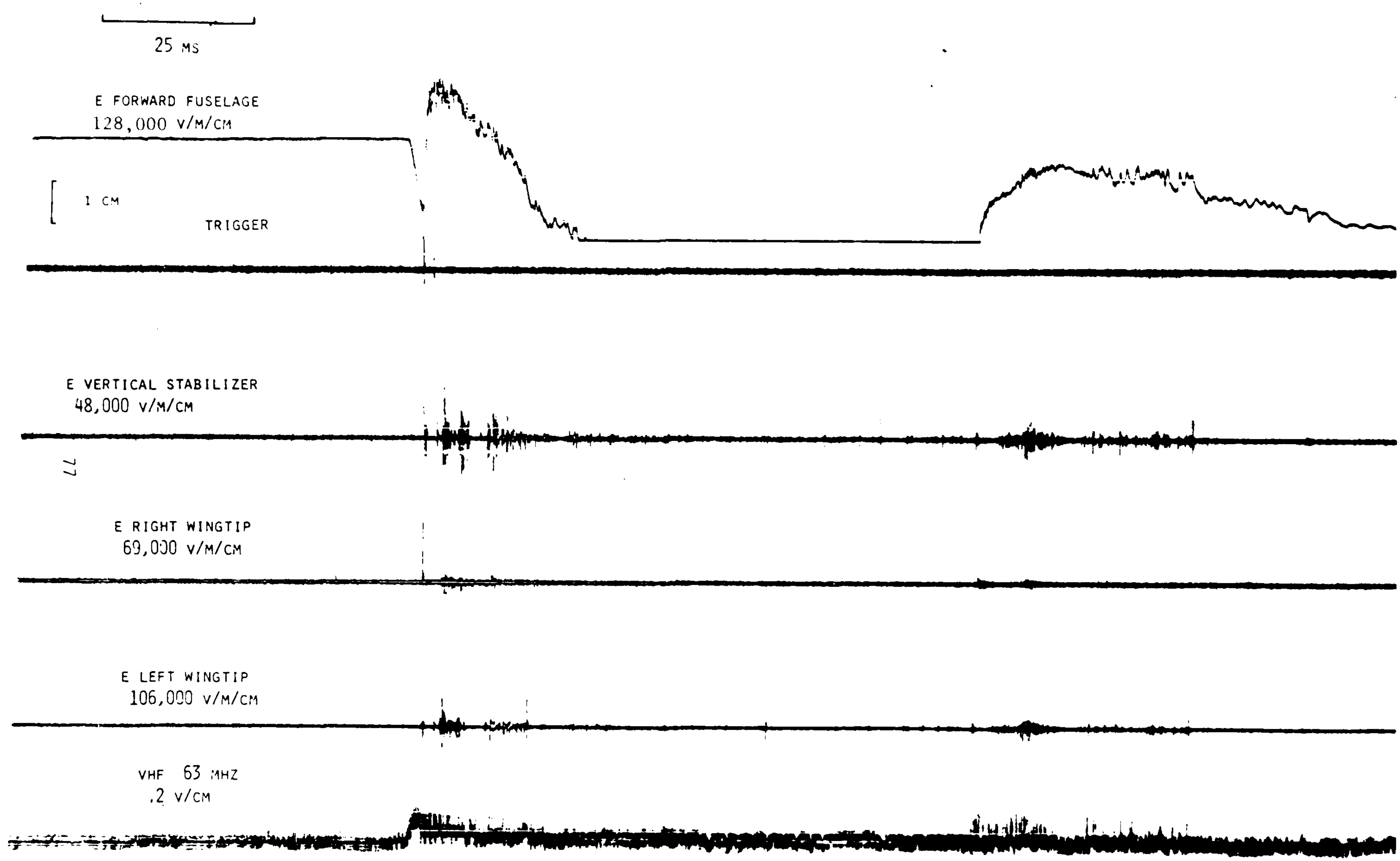


Figure 43. Six Analog Channels Recorded at Beginning of 21:41:59 Flash

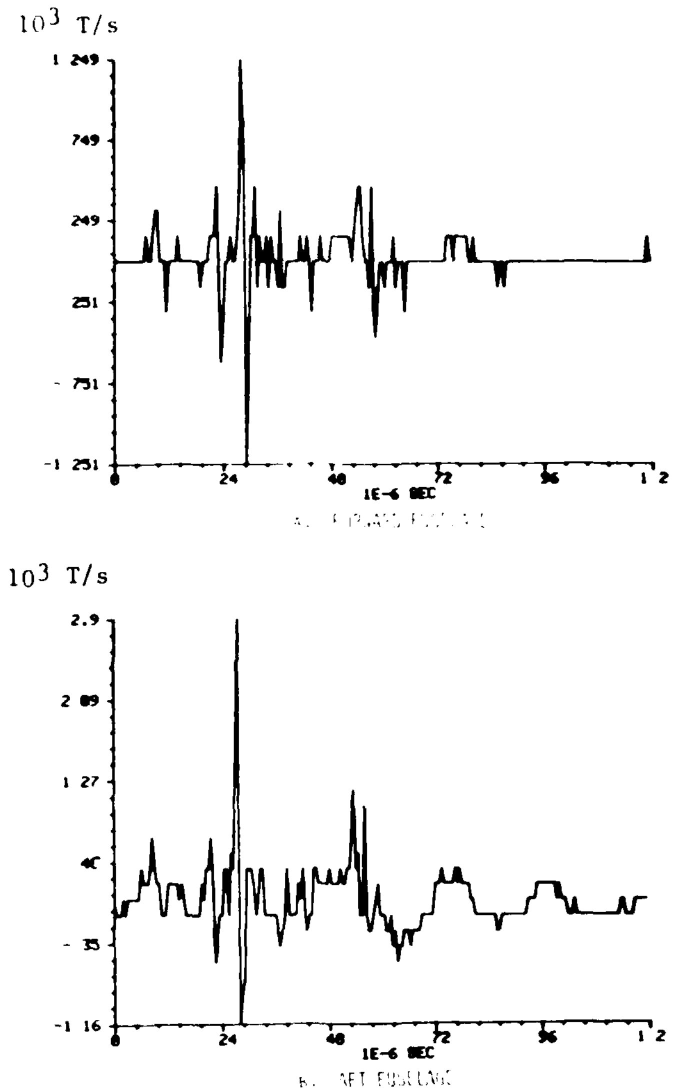


Figure 44. Surface Current Density on Forward and Aft Fuselage During 21:41:59 Flash

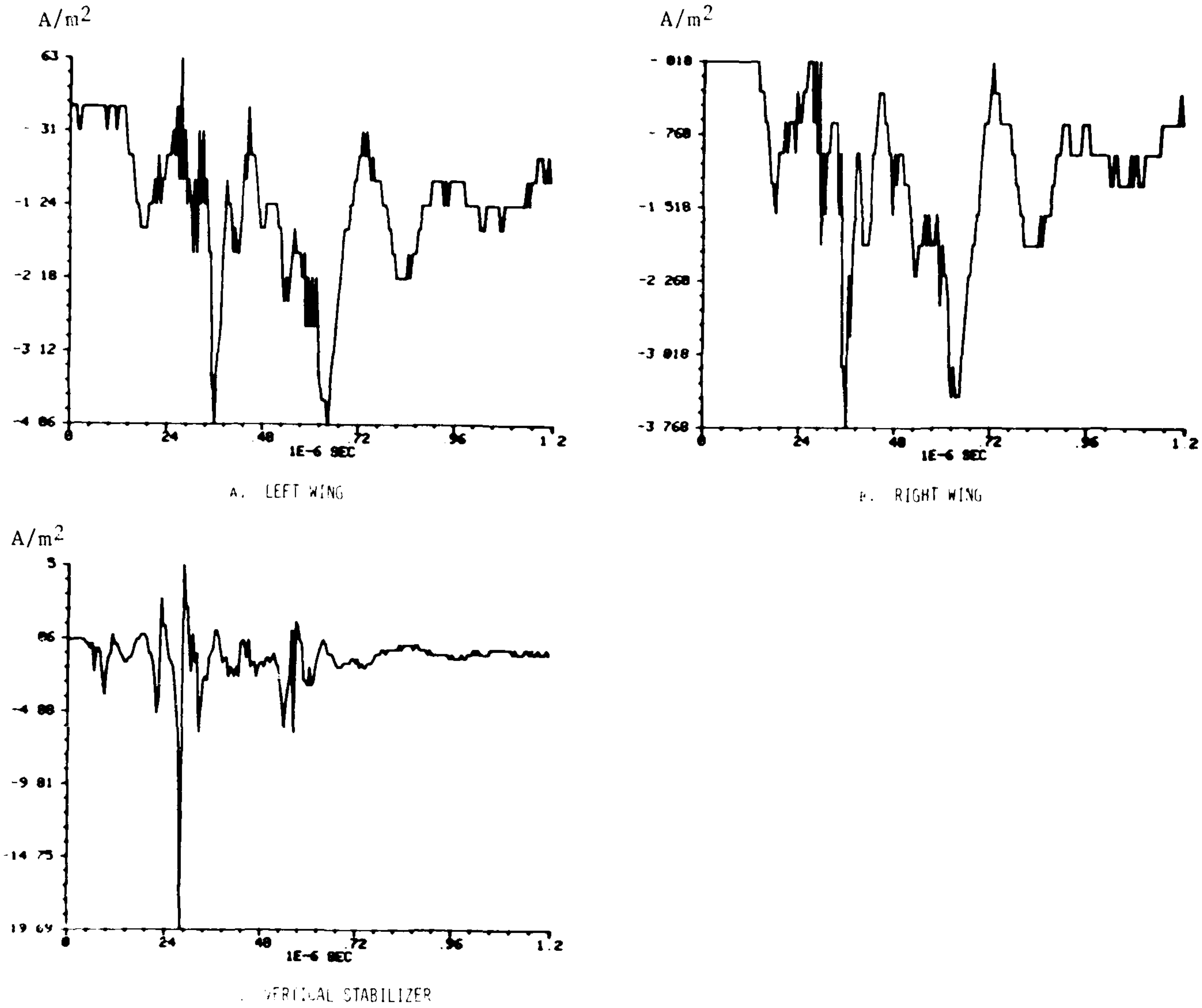
density reached 2900 T/s at the aft fuselage. Figure 45 shows the displacement current density on the left wing, right wing, and vertical stabilizer. The largest displacement current density pulse was 19.69 A/m^2 at the vertical stabilizer. These peak values, along with pictures from the top VCR camera, indicate that the lightning flash attached to the vertical stabilizer of the aircraft.

Figure 46 shows the same channels of analog data for the entire duration of the flash which lasted 680 ms. Even though the 17-ms initial active phase did not produce a pulse repetition rate as large as in some of the other flashes, there were more isolated pulses in this flash than in most of the other strikes.

9. THE 7 AUG FLASH AT 21:43:26 Z

The fifth strike to the aircraft during this flight occurred at 21:43:26 Z. The altitude and atmospheric conditions remained the same and the location of the aircraft is shown as (9) in Figure 20. Figure 47 shows that the CV-580 was located inside a region of heavy precipitation at the time of the flash.

Figure 48 shows traces of the E forward fuselage, trigger pulse, E right wing tip, E vertical stabilizer, E left wing tip, and VHF radiation during the beginning of the discharge. The E forward fuselage trace saturated in the negative direction before and after the discharge. The time interval from the initiation of the negative-going pulse on the forward fuselage to the triggered pulse was about 2.2 ms. This corresponds to streamer propagation toward the aircraft for a distance of approximately 330 m. The aircraft was not charged prior to the discharge and there appeared to be no significant streamers propagating outward from the



Displacement Current Density on Left Wing, Right Wing, and Vertical Stabilizer During 21:41:59 Flash

AD-A183 290 LOW ALTITUDE LIGHTNING ATTACHMENT TO AN AIRCRAFT(U) AIR FORCE WRIGHT AERONAUTICAL LABS WRIGHT-PATTERSON AFB OH P L RUSTAN ET AL MAY 87 AFWAL-TR-86-3009 2/2

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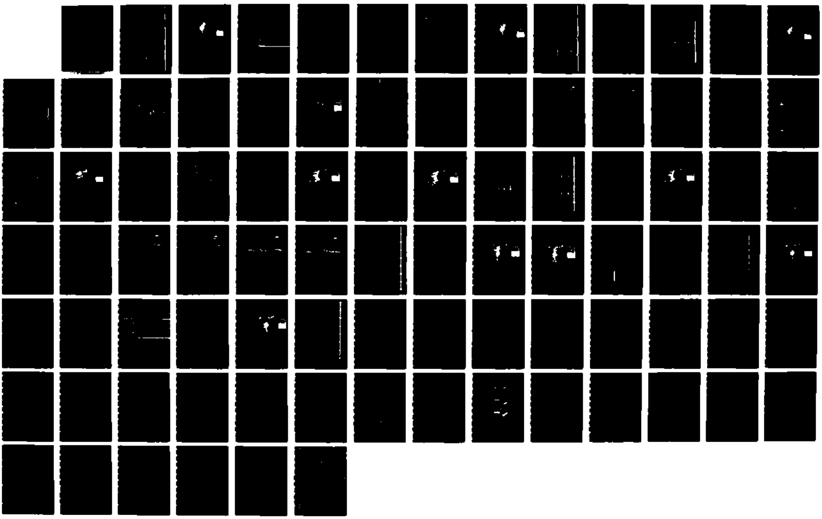
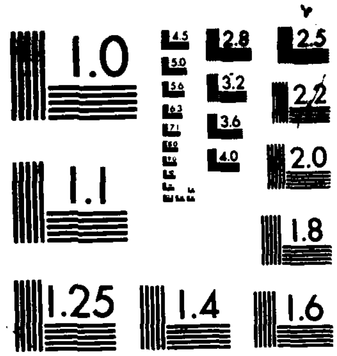




MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

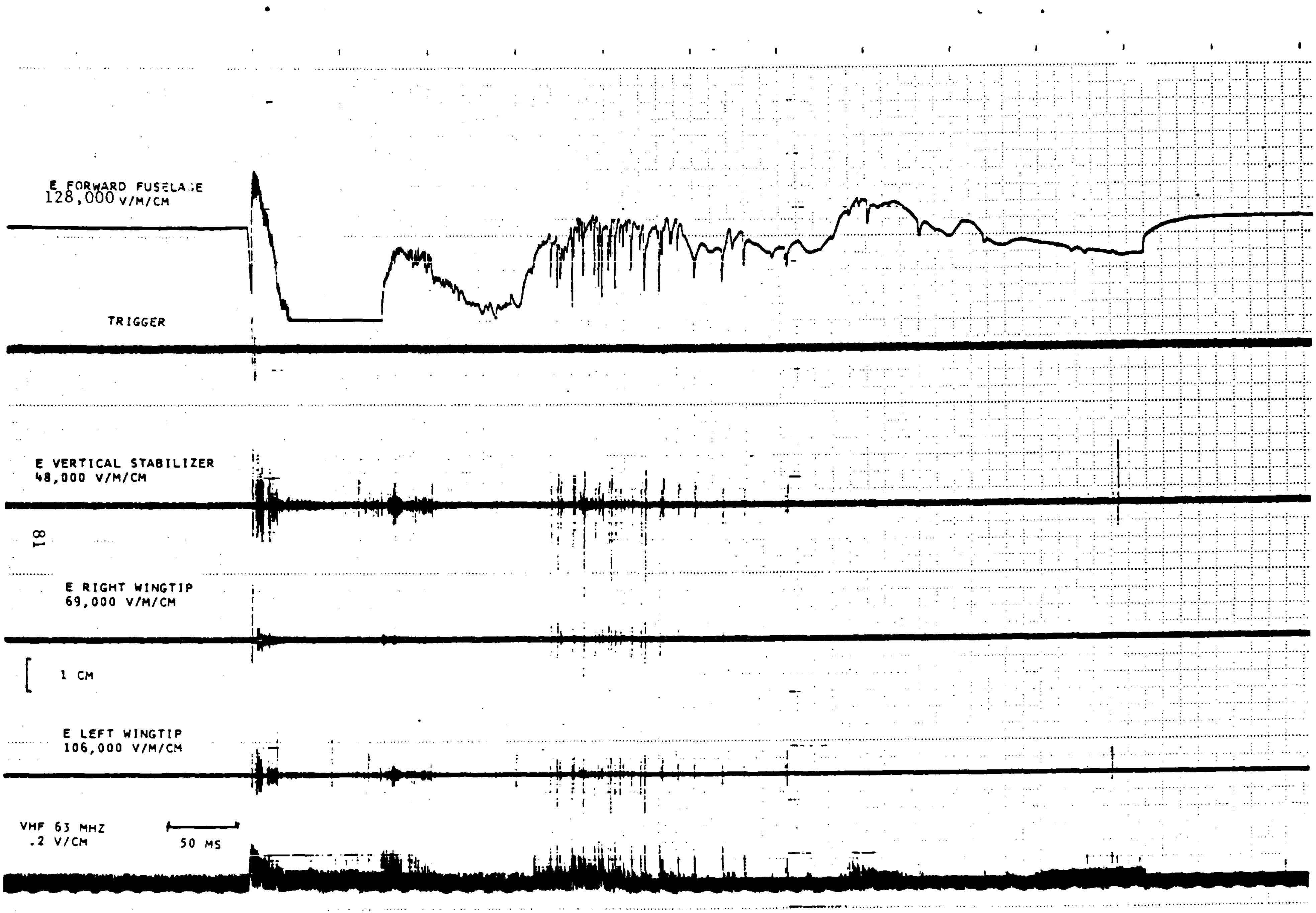


Figure 46. Same Analog Channels for Duration of 21:41:59 Flash

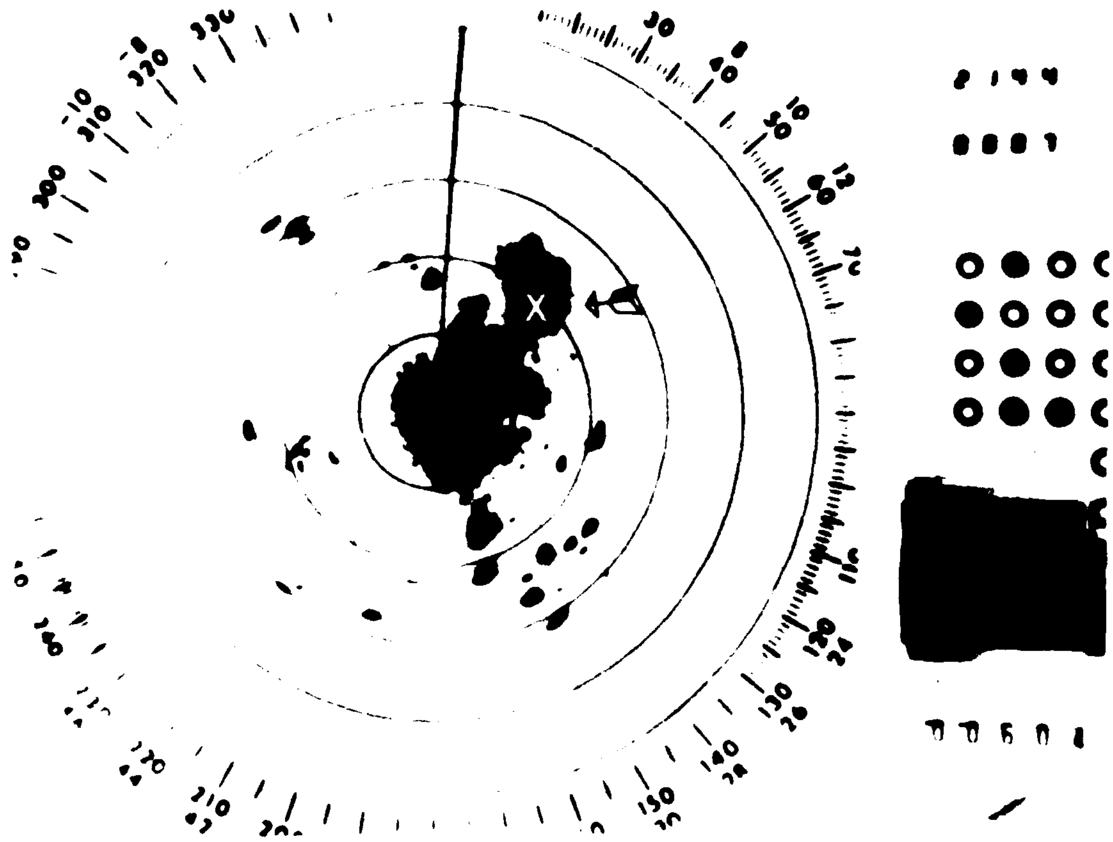


Figure 47. Precipitation Radar Return Showing Position of Aircraft During 21:43:26 Flash

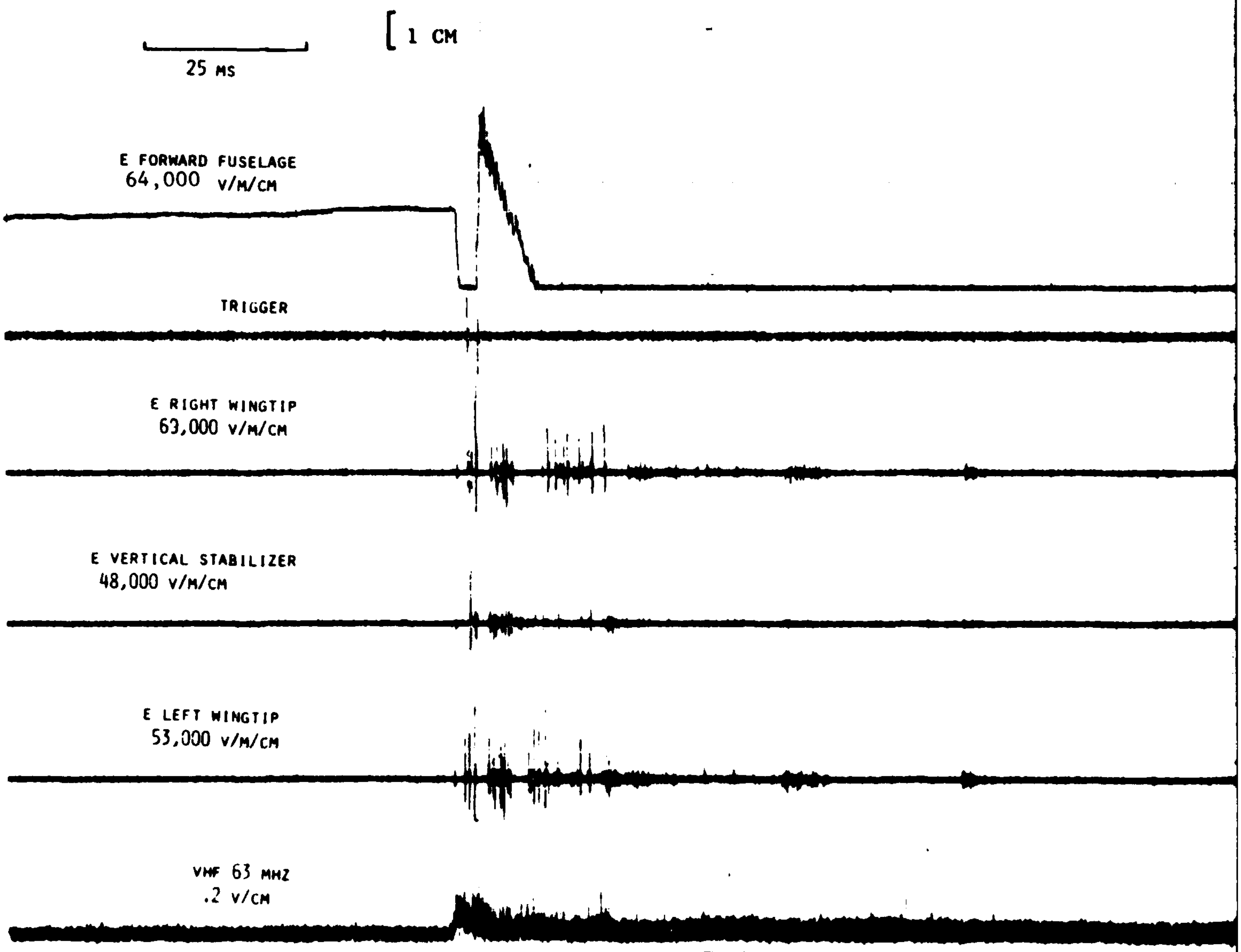


Figure 48. Six Analog Channels Recorded at Beginning of 21:43:26 Flash

aircraft. The pulse repetition rate during the initial 23 ms was about 10^3 pulses/sec.

The digital system triggered on the first transient pulse exceeding 400 T/s and triggered pulse is also shown in Figure 48. Figure 49 shows the displacement current density on the left wing, right wing, and the vertical stabilizer. The most significant pulse was on the right wing and reached a maximum of 20.4 A/m^2. The pulse on the left wing had similar waveform characteristics but its magnitude was only a fourth of the magnitude on the right wing. The vertical stabilizer pulse was much smaller than either wing pulse.

Figure 50 shows the surface current density on the forward fuselage, aft fuselage, and the right wing. Again, the largest pulse of 1,254 T/s occurred on the right wing. The largest pulses on the forward and aft fuselage were 477 and 799 T/s, respectively. The largest electric field pulses measured for the entire discharge were 165 kV/m on the right wing, 67 kV/m on the vertical stabilizer, and 108 kV/m on the left wing.

10. THE 7 AUG FLASH AT 22:02:01 Z

The next strike occurred at 20:02:01 Z at the position shown as (10) in Figure 20. The aircraft was flying at 18,000 ft in an area with some turbulence. Precipitation returns taken one minute before the discharge, as shown Figure 51, indicate that the aircraft was located at the edge of a region of heavy precipitation.

Figure 52 shows six traces from the analog recorder during the beginning of the flash. The top trace gave the first indication of the flash as a negative-going pulse was observed on the E forward fuselage. A small transient pulse was detected before the large positive-going pulse

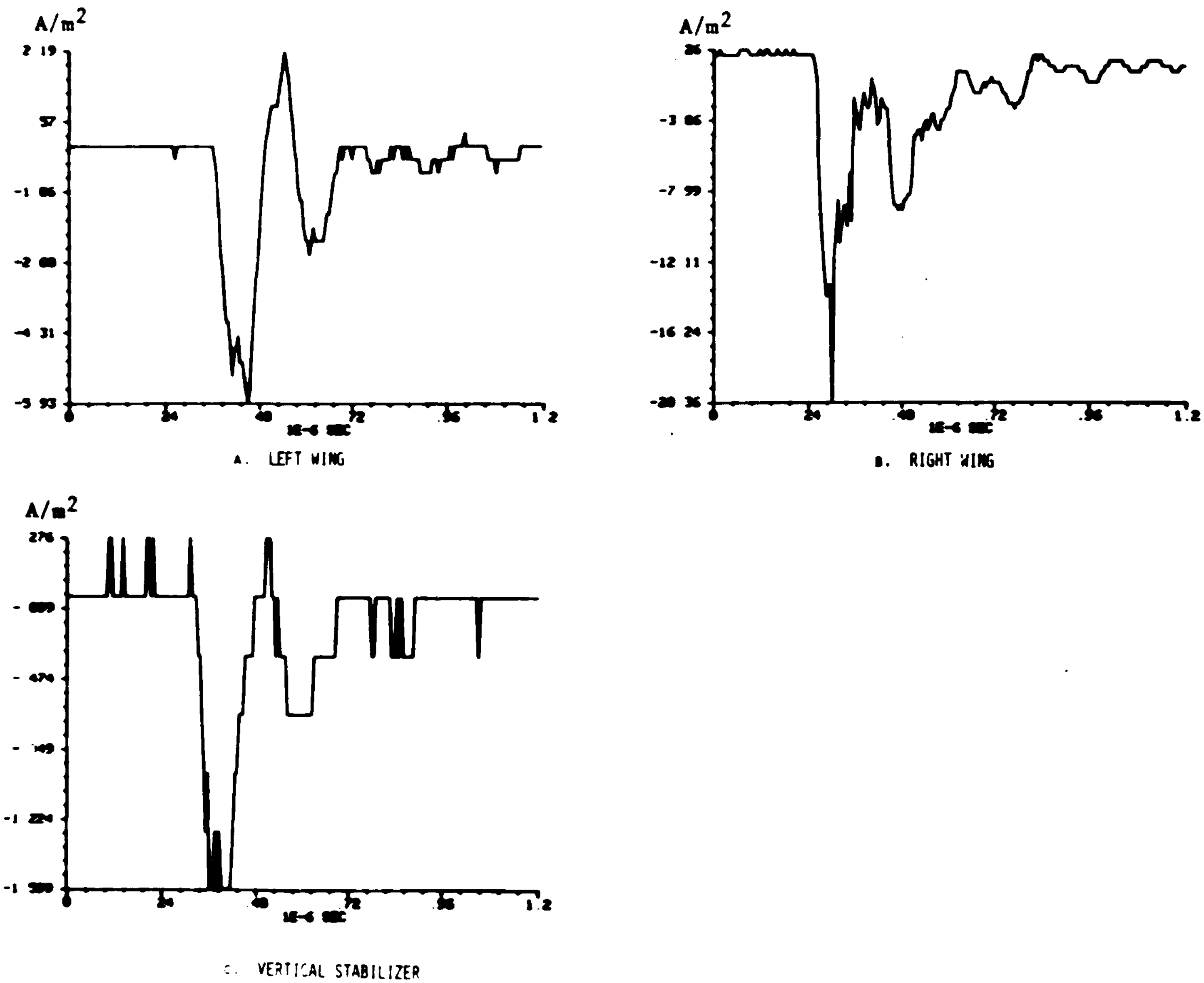


Figure 49. Displacement Current Density During Triggered Pulse of 21:43:26 Flash

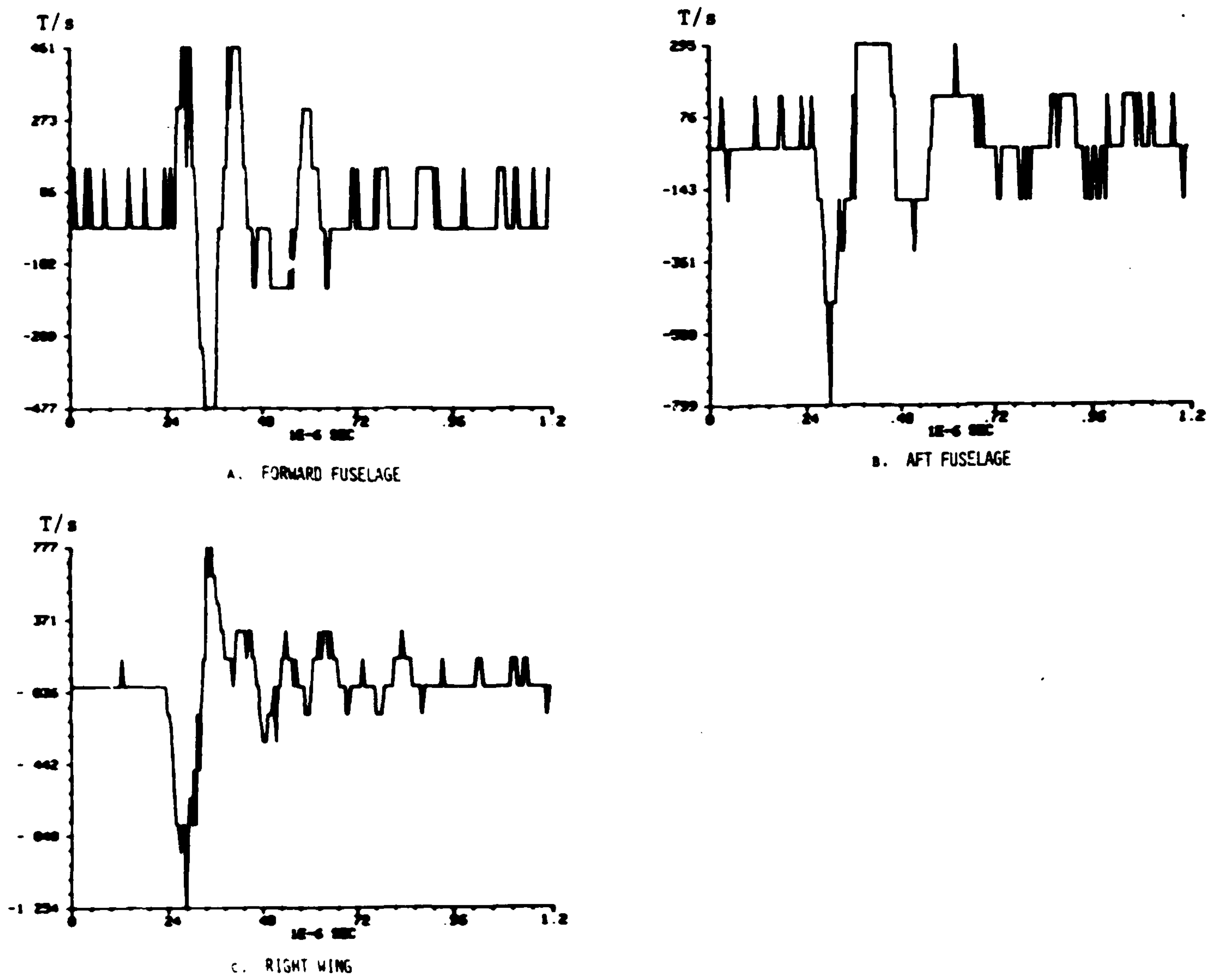


Figure 50. Surface Current Density During Triggered Pulse of 21:43:26 Flash

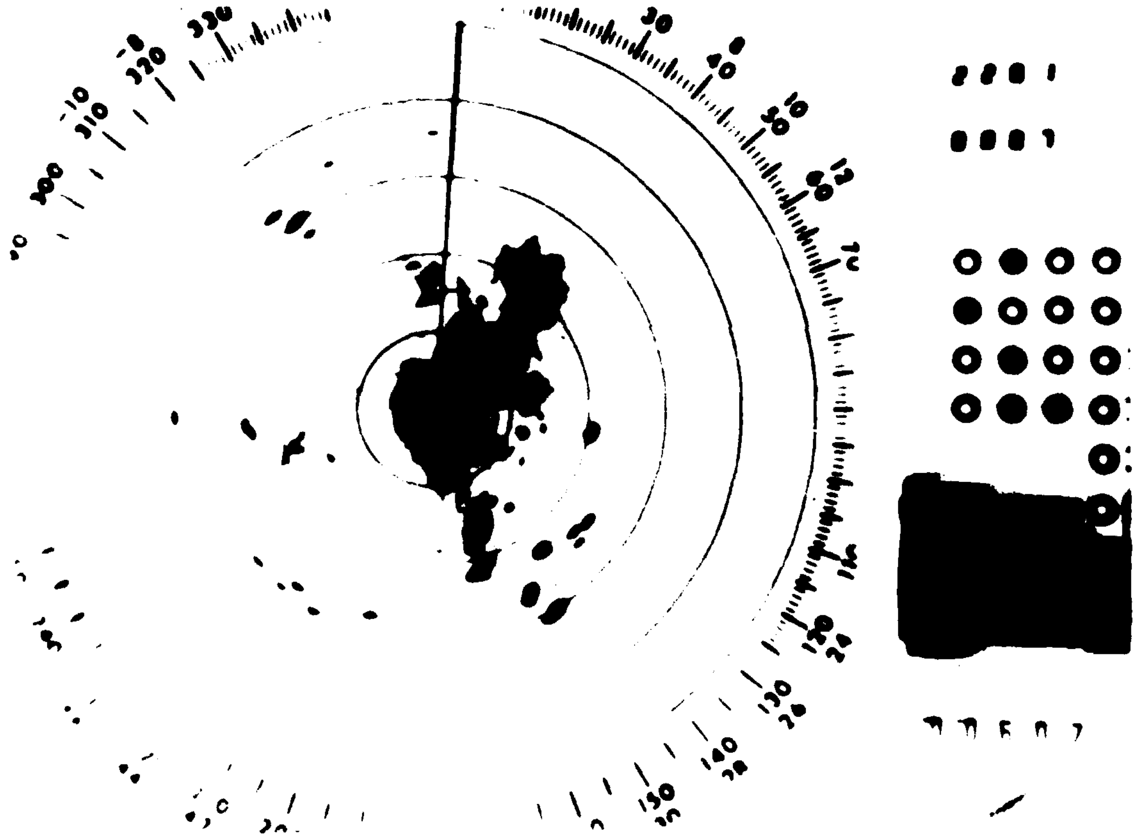


Figure 51. Precipitation Radar Return Showing Position of Aircraft During 22:02:01 Flash

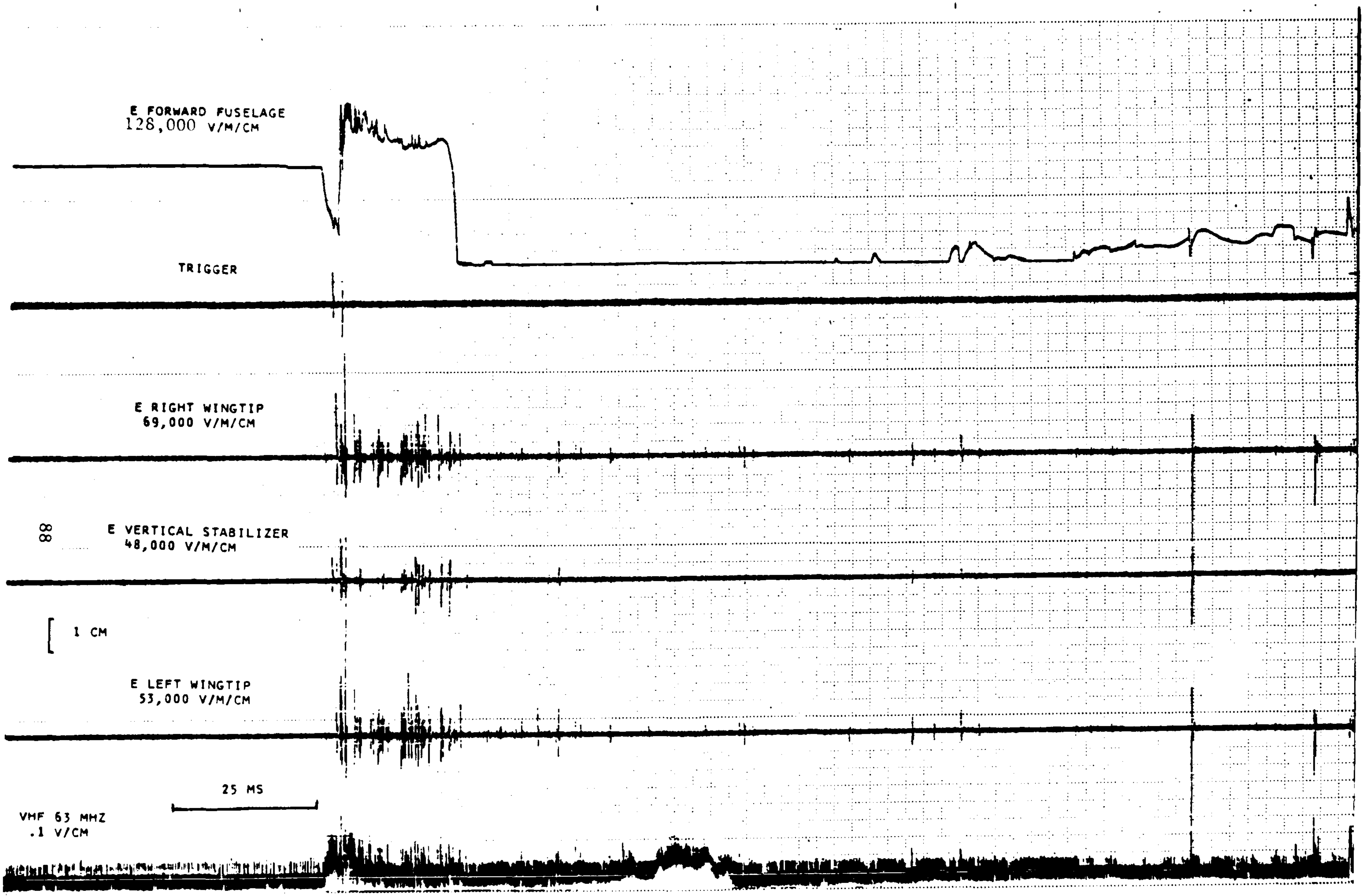


Figure 52. Six Analog Channels Recorded at Beginning of 22:02:01 Flash

indicating probable charge neutralization throughout the aircraft. The digital system was set to trigger at 400 T/s and the field produced by the first small positive pulse exceeded that threshold level. Consequently, the system triggered before the largest transient pulse occurred. Digital data for this flash is not shown because the peak values during the sampled interval reached only a few quantized levels. The surface current density levels on the forward fuselage and right wing were estimated for the first large positive transient shown in the top trace. The peak forward fuselage current was at least 5.5 kA, but only about 2.5 kA appeared to propagate through the right wing. However, near the end of the initial active period of the flash which lasted 22 ms, a transient current pulse of about 5.5 kA propagated through the right wing. The electric field trace on the right wing tip shows a transient pulse of 207 kV/m and is one of the largest transients seen in this study. The largest electric field pulse on the vertical stabilizer was only 70 kV/m. The leader for this flash lasted 2.1 or 2.5 ms depending on whether the leader ended at the time of the first small transient that triggered the digital system or at the time of the large transient pulse. Assuming a leader velocity of 1.5×10^5 m/s, these times correspond to a leader distance of 315 or 375 m.

Figure 53 shows the same analog channels for the duration of the flash. The E left wing tip trace shows a transient pulse of about 180 kV/m at the beginning of the discharge. In Figure 53, the initial active period corresponds to a high positive level on the E forward fuselage indicating an electric field pointing away from the aircraft. As negative charge was transferred to the aircraft, the electric field reversed polarity 22 ms after the first large transient. The pulse repetition rate decreased

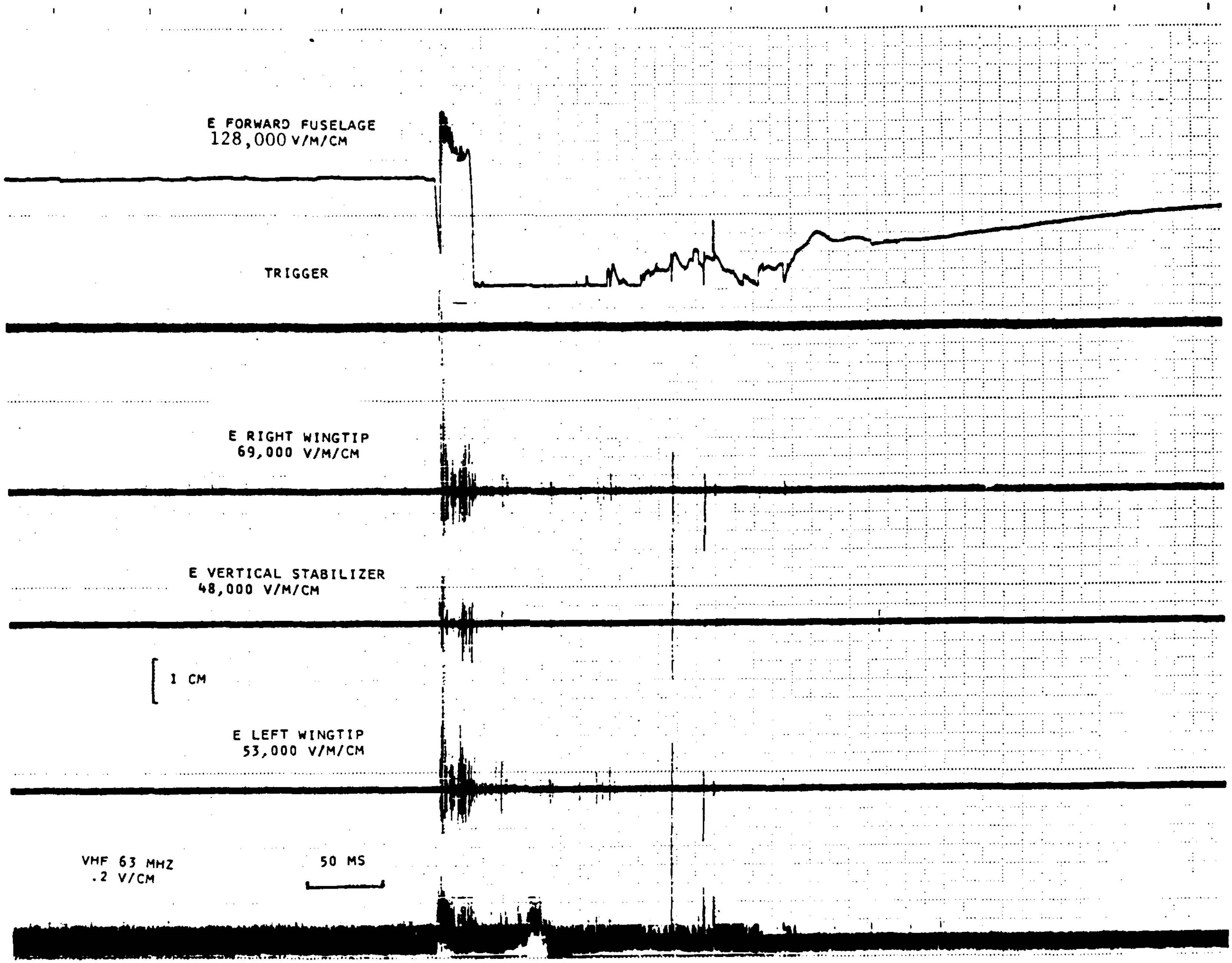


Figure 53. Same Analog Channels for Duration of 22:02:01 Flash

considerably and only a few isolated transient pulses occurred during the remainder of the discharge. The entire flash lasted approximately 240 ms.

This flash apparently struck the VOR antenna on the front forward fuselage because fragments from the antenna fell inside the cockpit at the time of the flash and neither the VOR nor ILS antenna functioned afterwards. Following the flight, over 20 pit marks were found on top of the fuselage suggesting that the flash swept back towards to tail of the aircraft.

11. THE 7 AUG FLASH AT 22:12:40 Z

The seventh and last attachment to the aircraft during this flight occurred at 22:12:40 Z. The aircraft was flying inside the cloud in an area of low turbulence. Figure 54 shows that the aircraft was on the edge of a region of heavy precipitation at the time of the flash.

Figure 55 shows analog traces of the E forward fuselage, the trigger pulse, the current on the left wing tip, the E left wing tip, the E right wing tip, and the VHF radiation during the beginning of the discharge. The E forward fuselage shows a pattern somewhat different than that seen in the ten previous flashes. The E forward fuselage trace shows a slow negative-going pulse lasting for nearly 20 ms before transient pulses were detected on aircraft sensors. Assuming a leader velocity of 1.5×10^5 m/s, the leader propagated about 3 km before contacting the aircraft. Streamers appeared to propagate twice from aircraft extremities during the last 5 ms of this 20 ms interval. The second of these streamers triggered the digital system set to trigger at 400 T/s.

This flash did not have the typical leader process nor an initial active phase with a high pulse repetition rate as seen in most other

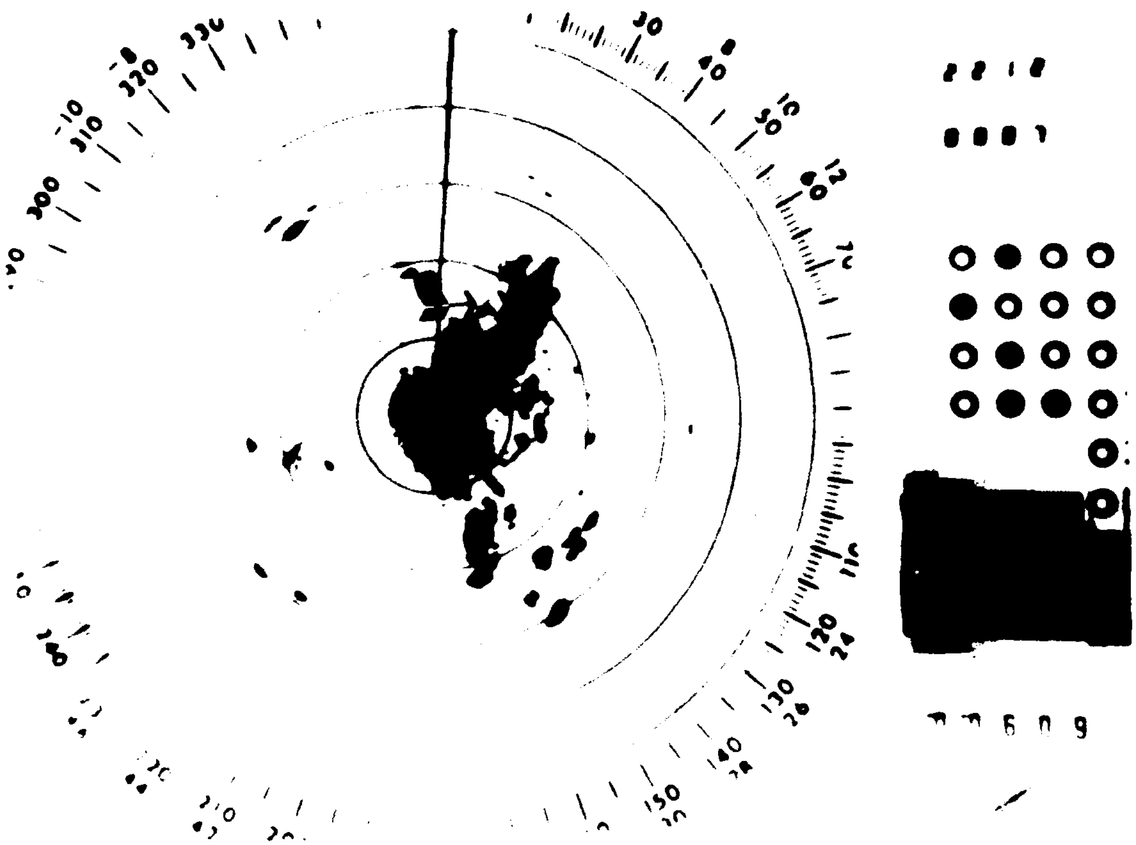


Figure 54. Precipitation Radar Return Showing Position of Aircraft During 22:12:40 Flash

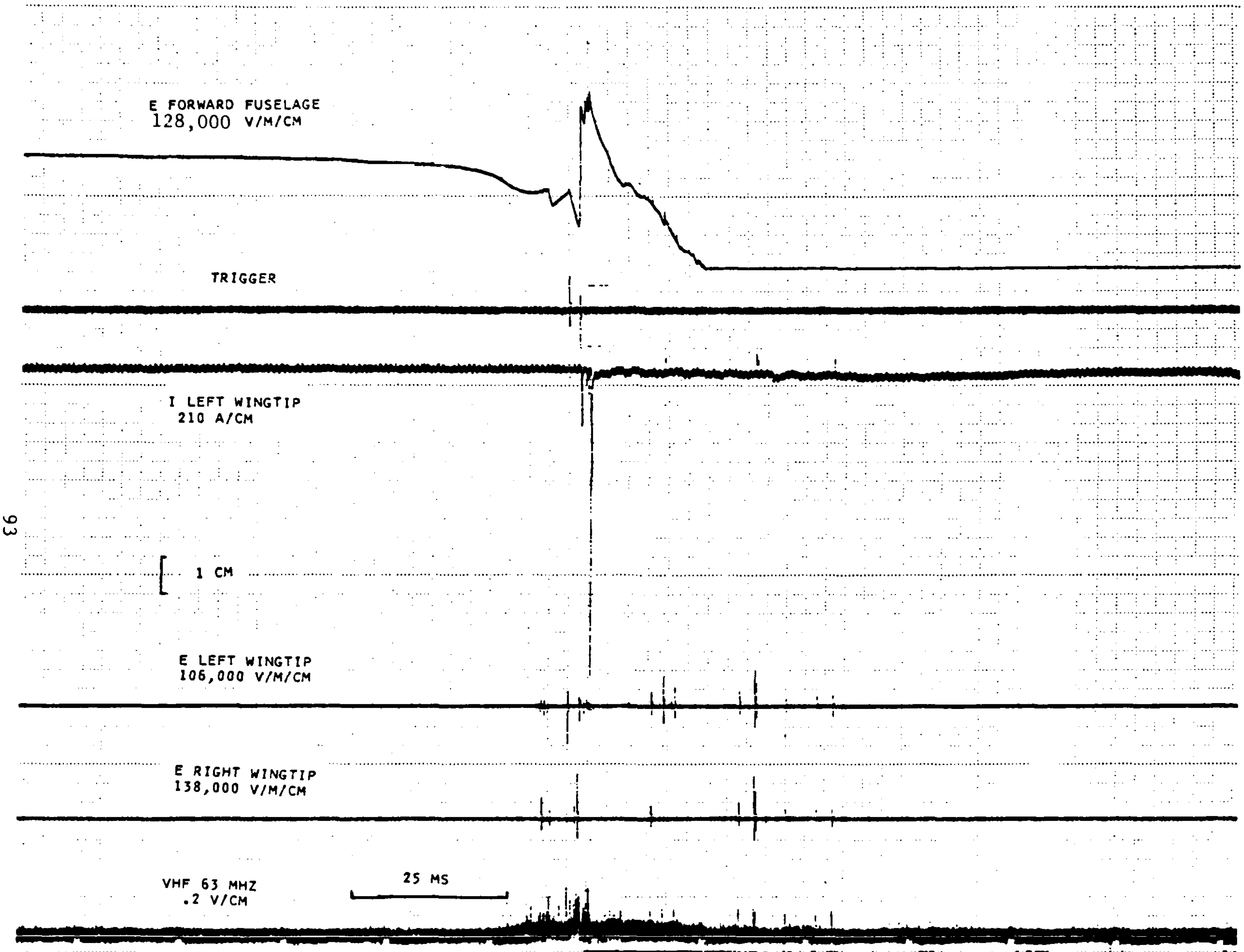


Figure 55. Six Analog Channels Recorded at Beginning of 22:12:40 Flash

flashes. Following the large positive-going pulse on the E forward fuselage, there were only a few isolated pulses in the flash. A current pulse of about 1.7 kA propagated through the left wing tip 2 ms after the discharge channel attached to the aircraft. The relatively long time and distance of leader propagation suggests that the discharge was not triggered but that the aircraft intercepted one of the channels of a natural intracloud discharge.

Figure 56 shows the left wing displacement current density from the digital data collected at the time the system triggered. The maximum value of displacement current density on the left wing was nearly 1.6 A/m^2. The largest value of the surface current density measured at that time was only 465 T/s.

Figure 57 shows six analog traces for the duration of the discharge. The flash lasted approximately 500 ms and contained only about 35 transient pulses during the entire discharge. The largest electric field transients measured during the discharge were about 125 kV/m on the left wing tip, 165 kV/m at the right wing tip, and 84 kV/m on the vertical stabilizer.

A total of seven lightning flashes attached to the CV-580 during the 7 Aug flight. In addition to any damages mentioned earlier, a post flight inspection revealed numerous other holes and burn marks in the skin of the aircraft. Burn spots were found on the left wing current boom leading to a finger-sized hole in the aileron two feet away. Fourteen pit marks were observed on the right wing directed over the fuel tank. Burn marks and a pencil-sized hole were found over the right flap. Burn spots were also found on top of the vertical stabilizer and near both wing tips. Some damage was incurred on one of the right wing propeller blades and the

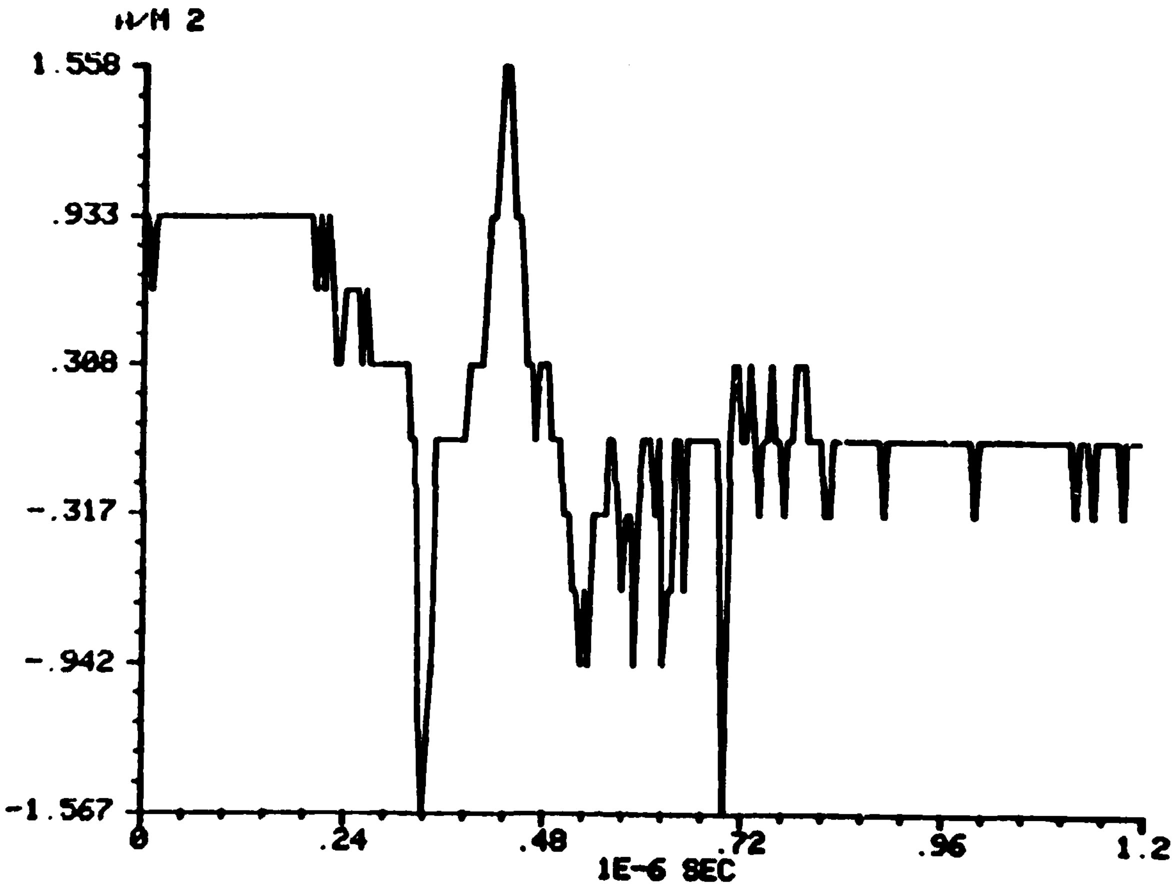


Figure 56. Displacement Current Density on Left Wing During Triggered Pulse of 22:12:40 Flash

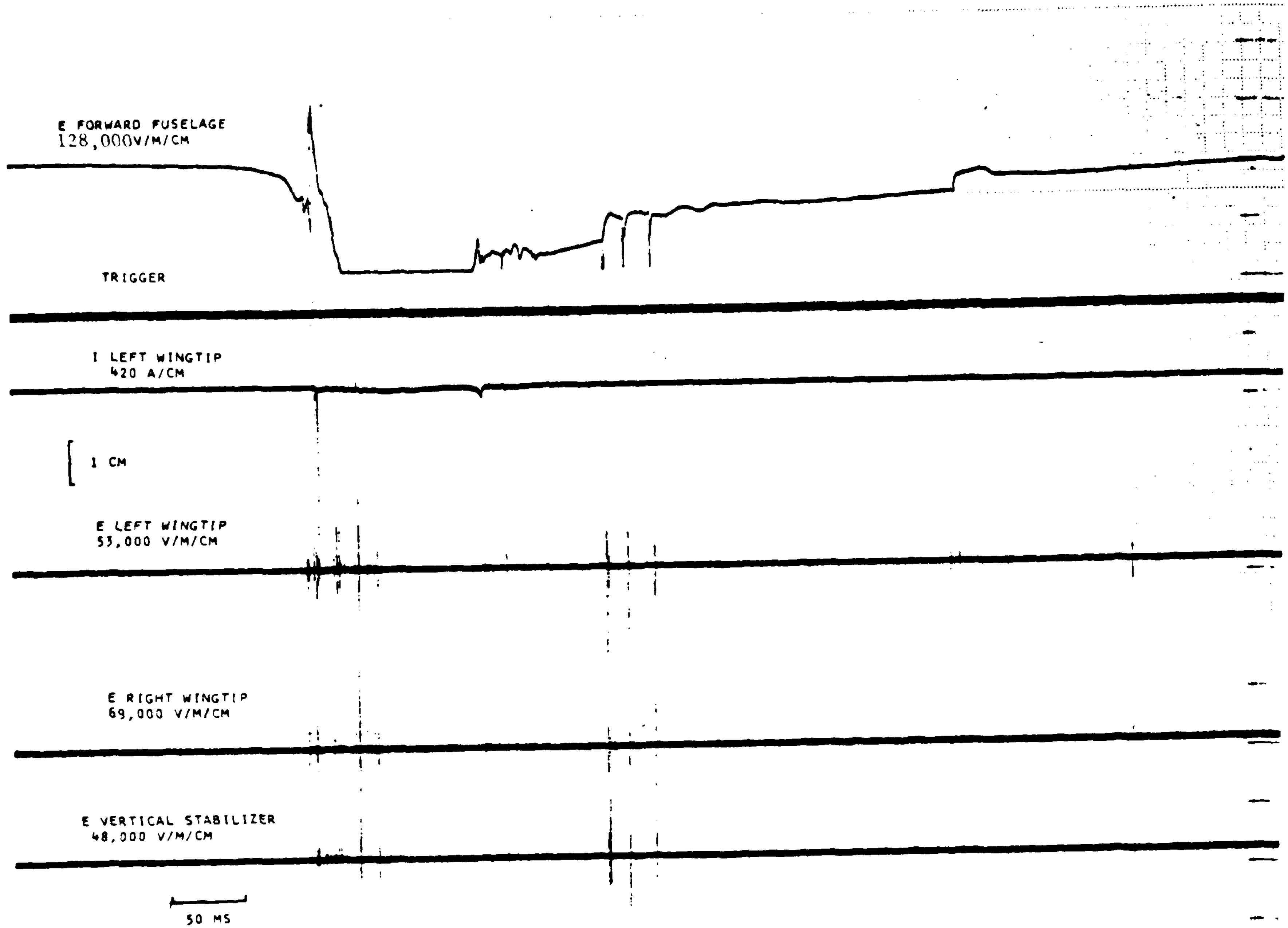


Figure 37. Six Analog Channels for Duration of 22:12:40 Flash

weather radar failed for three sweeps following the last strike of the day but recovered to operate normally afterwards.

12. THE 17 AUG FLASH AT 21:36:01 Z

A lightning discharge attached to the aircraft on 17 Aug at 21:36:01 Z while flying at an altitude of 4,000 ft just north of Lake Okeechobee as initiated by position (12) in Figure 20. The aircraft was flying in a region of turbulence near the bottom of the cloud base. The precipitation return in Figure 58 shows that the aircraft was in clouds but about 20 NM away from any area of heavy precipitation.

Figure 59 shows six channels of analog data recorded at the time of the flash. The E forward fuselage trace shows a negative-going pulse for about 4.7 ms prior to the first transient pulse. A leader may have propagated for a much longer time but there was not sufficient resolution in this channel to detect streamer motion farther than 1 km away from the aircraft. The strike did not appear to be triggered by the aircraft. Following the first transient pulse, two other pulses occurred about 3 ms apart. The largest electric field transients measured during the flash were 57 kV/m on the right wing tip, 120 kV/m on the vertical stabilizer, and 159 kV/m on the left wing tip. The flash lasted 140 ms but consisted primarily of three large transient pulses at the beginning of the discharge and an isolated transient pulse near the end.

The digital threshold level was set at 800 T/s and the system triggered on the first of the three large transient pulses at the beginning of the discharge. Figure 60 shows the surface current density on the forward fuselage, aft fuselage, left wing, and right wing. The forward fuselage

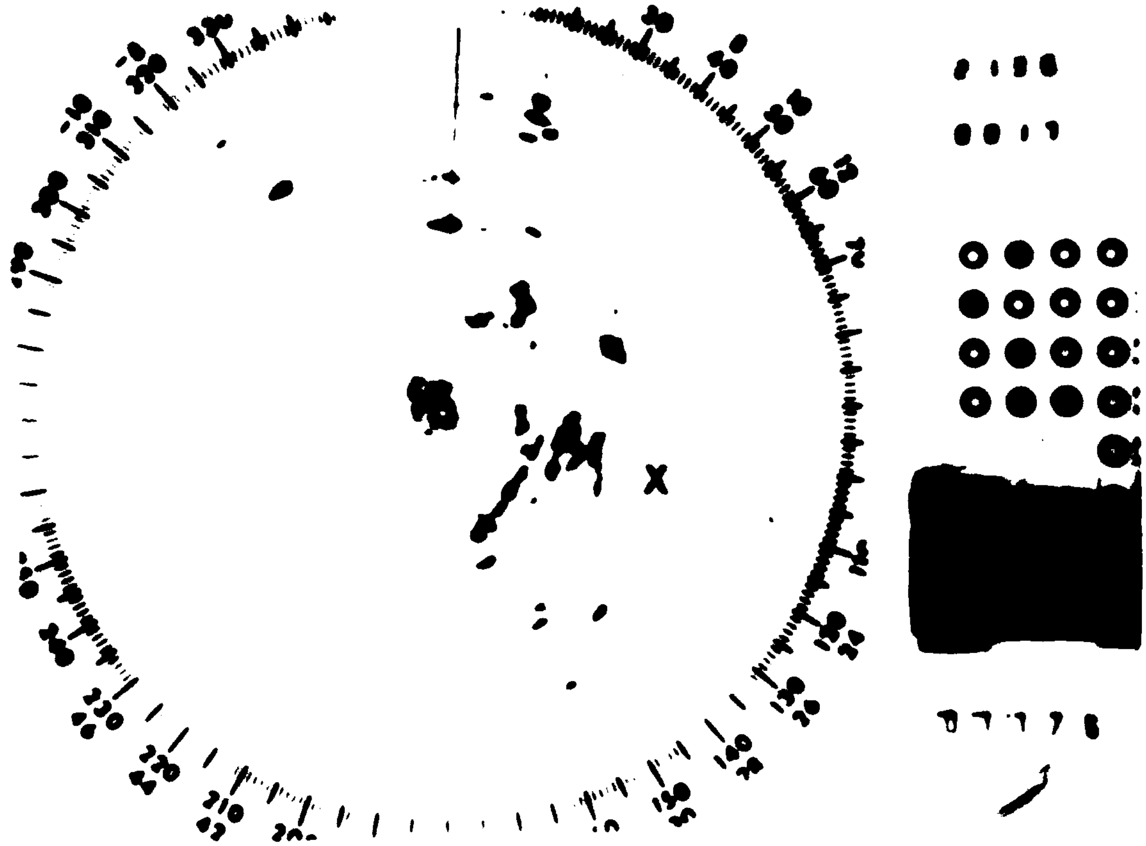


Figure 58. Precipitation Radar Return Shown Position of Aircraft During 21:36:01 Flash

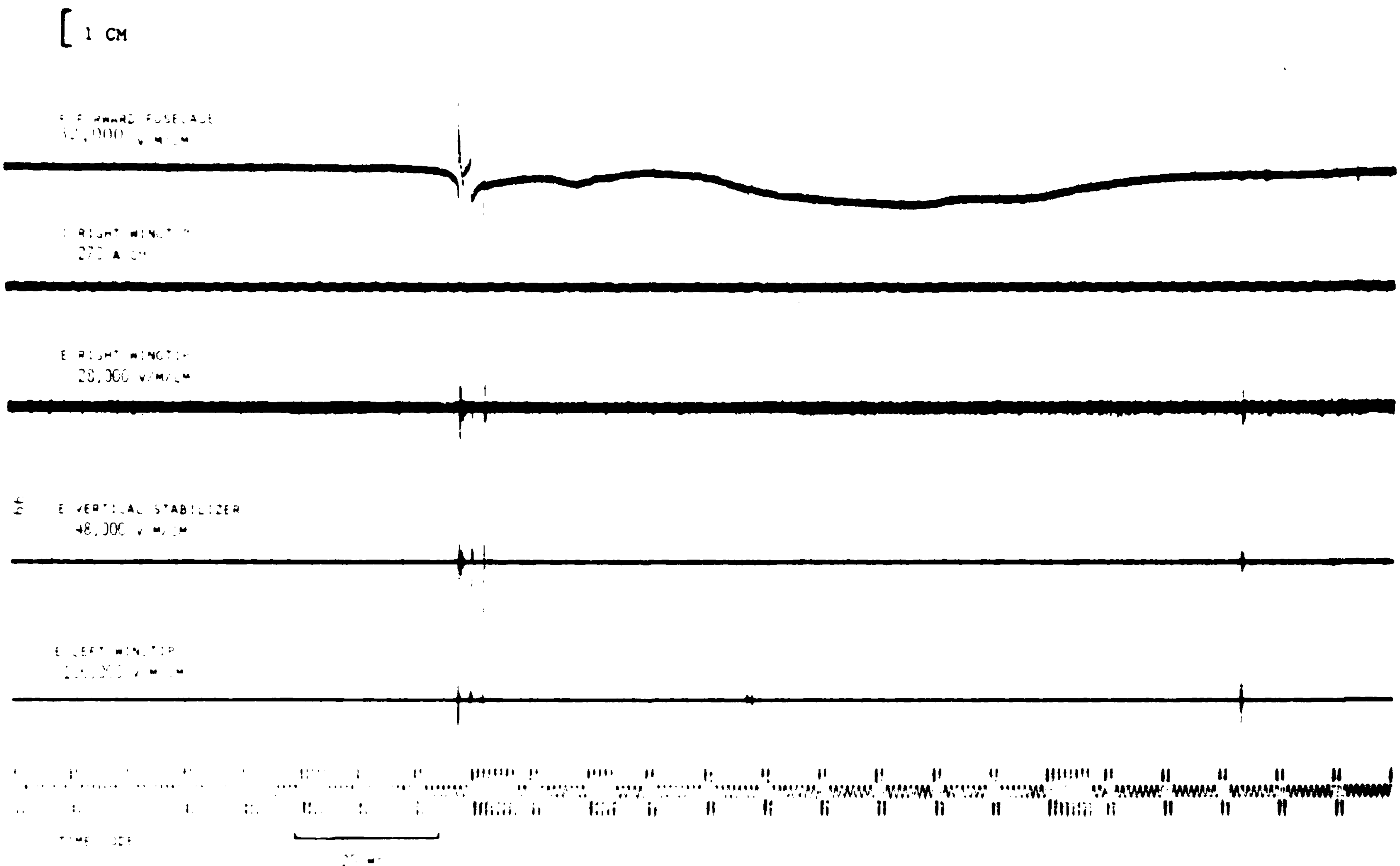


Figure 59. Six Analog Channels Recorded During 21:36:01 Flash

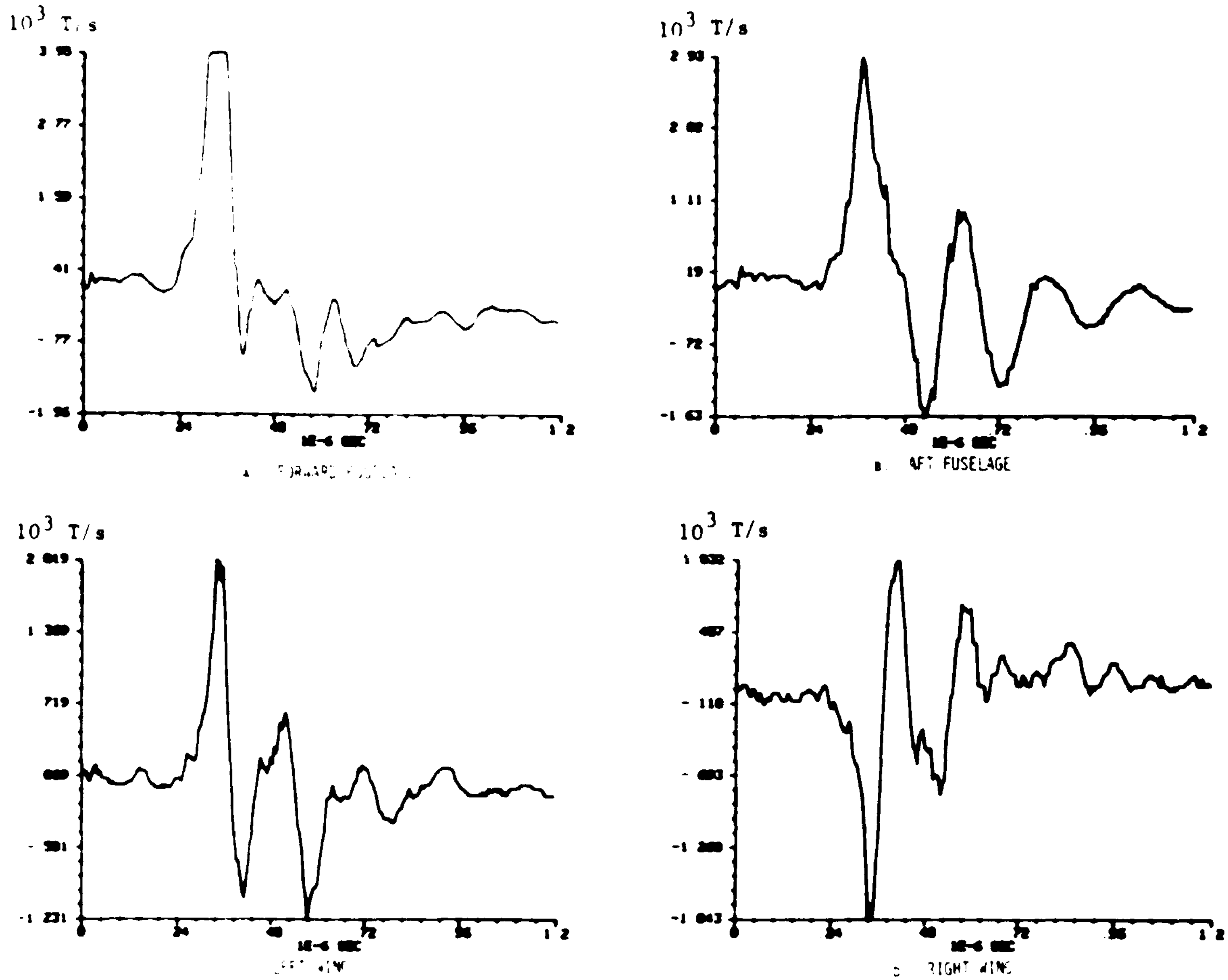


Figure 60 Surface Current Density During Triggered Pulse of 21:36:01 Flash

waveform saturated at 3950 T/s and had the largest magnitude measured for any discharge during the entire summer program.

Figure 61 was obtained by overlaying the forward and aft surface current density waveforms after accounting for cable delays. The physical time shift corresponds to the propagation of the current pulse from the nose to the the rear of the fuselage. Figure 62 was obtained by overlaying the surface current density waveforms for the right and left wings once all cable delays had been removed. The waveforms overlayed perfectly indicating that as the current propagated from the attachment point near the nose toward the rear of the aircraft, some of the current propagated into the wings. Since the wing J_S sensor locations were symmetrical, the current arrived at both sensors simultaneously.

Figure 63 shows the displacement current density waveforms recorded during the sampled interval on the left wing, right wing, and vertical stabilizer. The left and right wing waveforms saturated at 8.77 and 7.74 A/m^2, respectively. The displacement current density at the vertical stabilizer reached a maximum value of 8.08 A/m^2.

This flash struck the radome of the CV-580 and propagated toward the rear of the fuselage and to both wings. A burn mark found in the interior of the radome was the only apparent damage to the aircraft. The attachment was also seen on the top video camera as it swept to the rear of the fuselage.

13. THE 19 AUG FLASH AT 00:55:26 Z

On 19 August at 00:55:26 Z, a lightning discharge attached to the aircraft while flying west of Vero Beach at an altitude of 4,000 ft. The location of the aircraft at the time of the flash is shown as (13) in

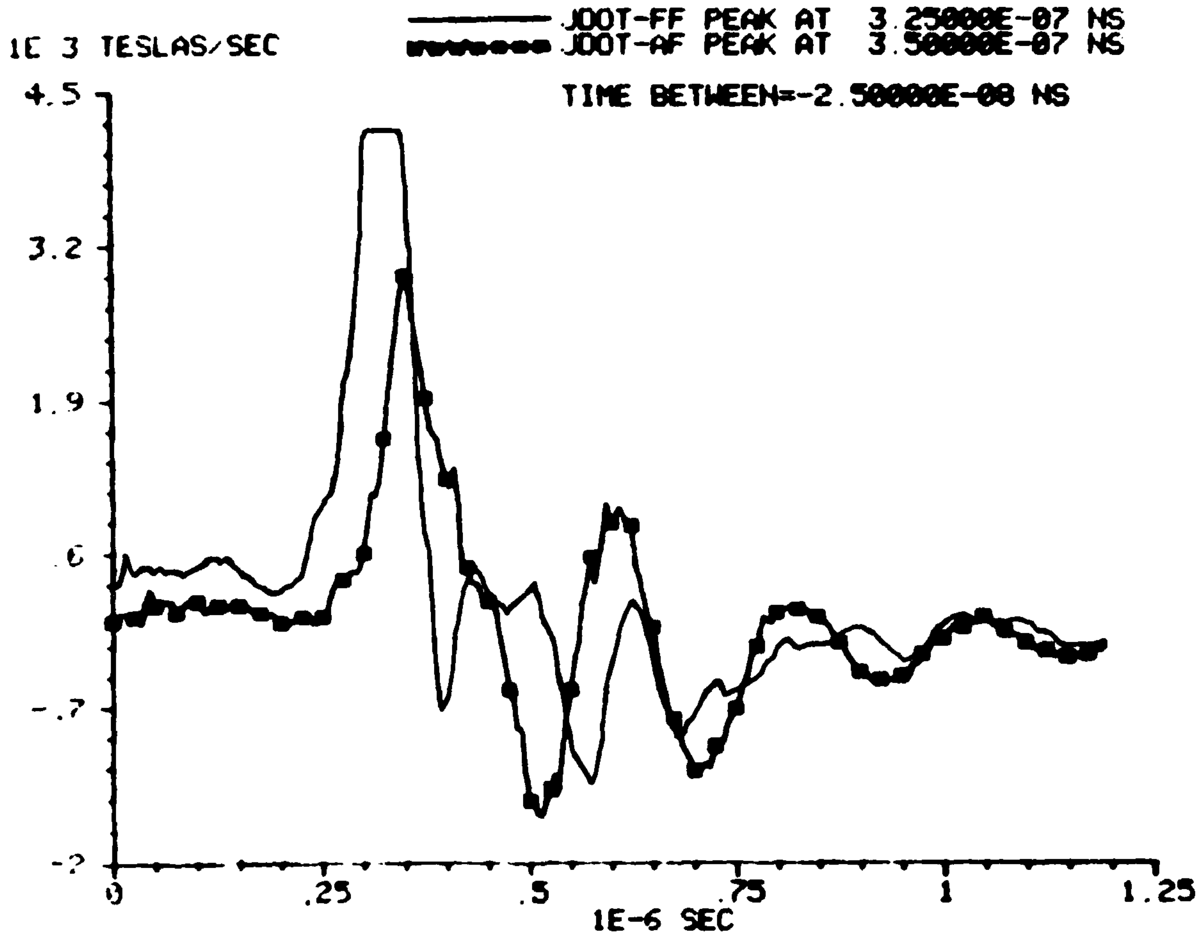


Figure 61. Overlay of Surface Current Density on Forward and Aft Fuselage During 21:36:01 Flash

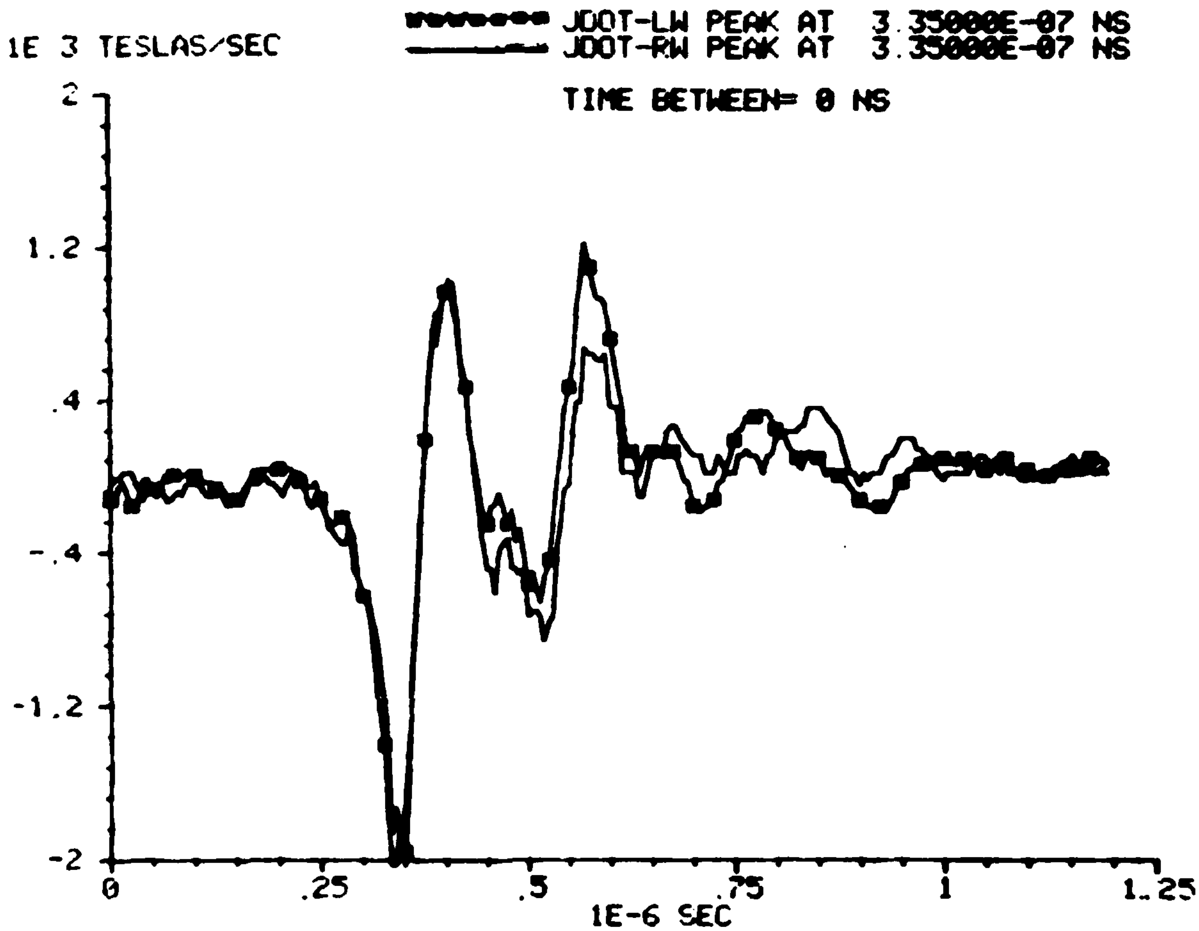


Figure 62. Overlay of Surface Current Density on Left and Right Wings During 21:36:01 Flash

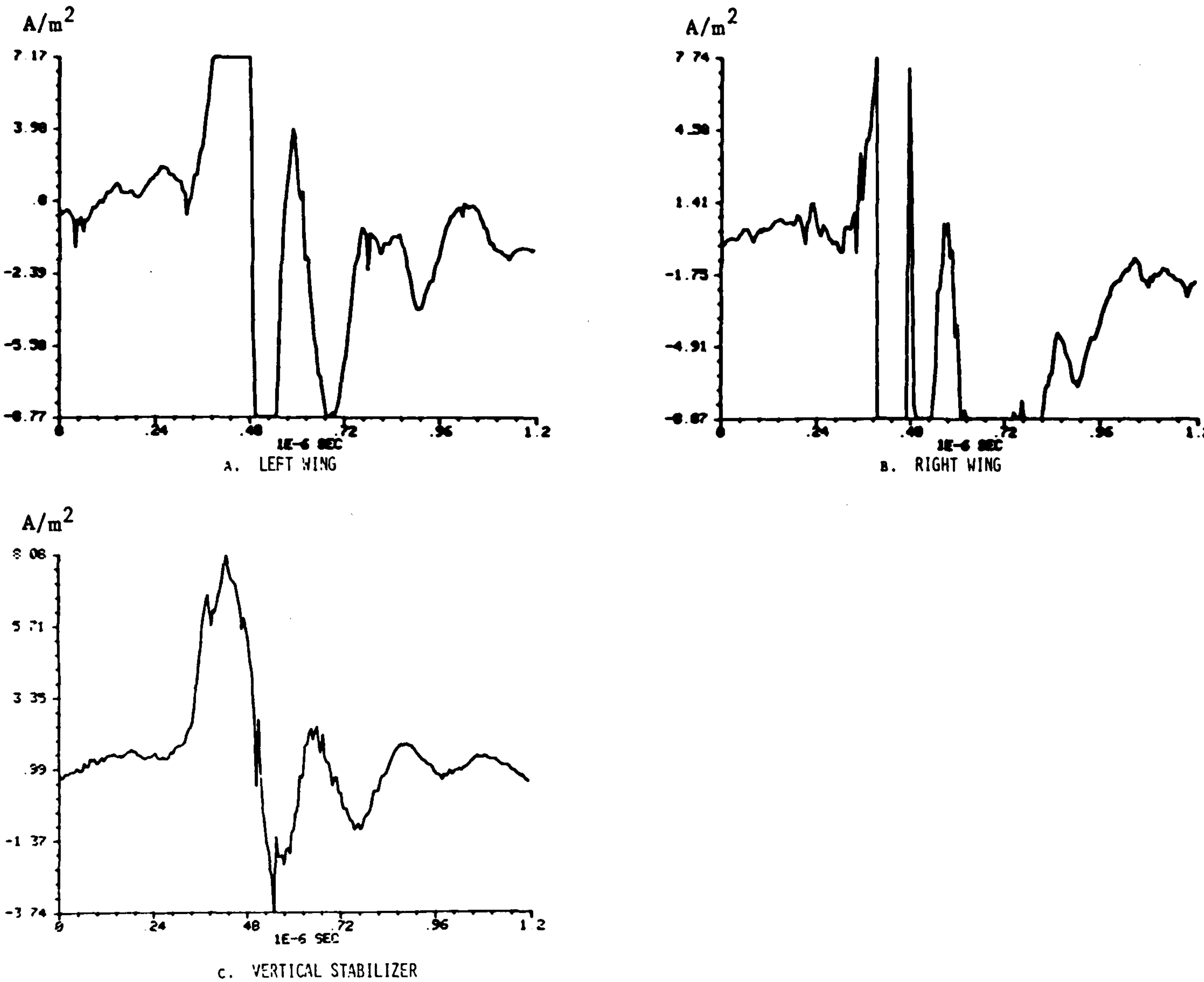


Figure 63. Displacement Current Density During Triggered Pulse of 21:36:01 Flash

Figure 20. The aircraft was flying inside the cloud in an area of no turbulence.

The threshold level was set at 1200 T/s and the system triggered during one of the pulses in the flash. No analog data was recorded because the tape was being replaced at the time. Figures 64 and 65 show displacement current density and surface current density measurements taken during the sampled interval. The largest displacement current density value recorded was 1.5 A/m^2 on the vertical stabilizer and the peak surface current density level was 2,560 T/s on the right wing. No damage was found on the aircraft that could be attributed to this flash.

14. THE 20 AUG FLASH AT 17:36:00 Z

Another low altitude attachment to the aircraft occurred on 20 Aug at 17:36:00 Z while flying at 2,000 ft over the ocean east of Cocoa Beach. The outside temperature was 17°C and the outside barometric pressure was 13.6 lbs/in^2. The aircraft was flying at 195.5 knots just below the cloud base estimated to be at 3,500 ft and was in an area of low turbulerce. The location of the aircraft at the time of the flash is shown as (14) in Figure 20.

Figure 66 shows the precipitation return from the Daytona Beach weather radar station eight minutes after the lightning discharge. At the time of the flash, the aircraft was about five miles from a region of heavy precipitation.

The system was set to trigger at 1,200 T/s and it triggered on the first fast transient in the discharge. No analog data was recorded during of the flash. Figures 67 and 68 show displacement current density and surface current density levels measured at the time of the triggered pulse.

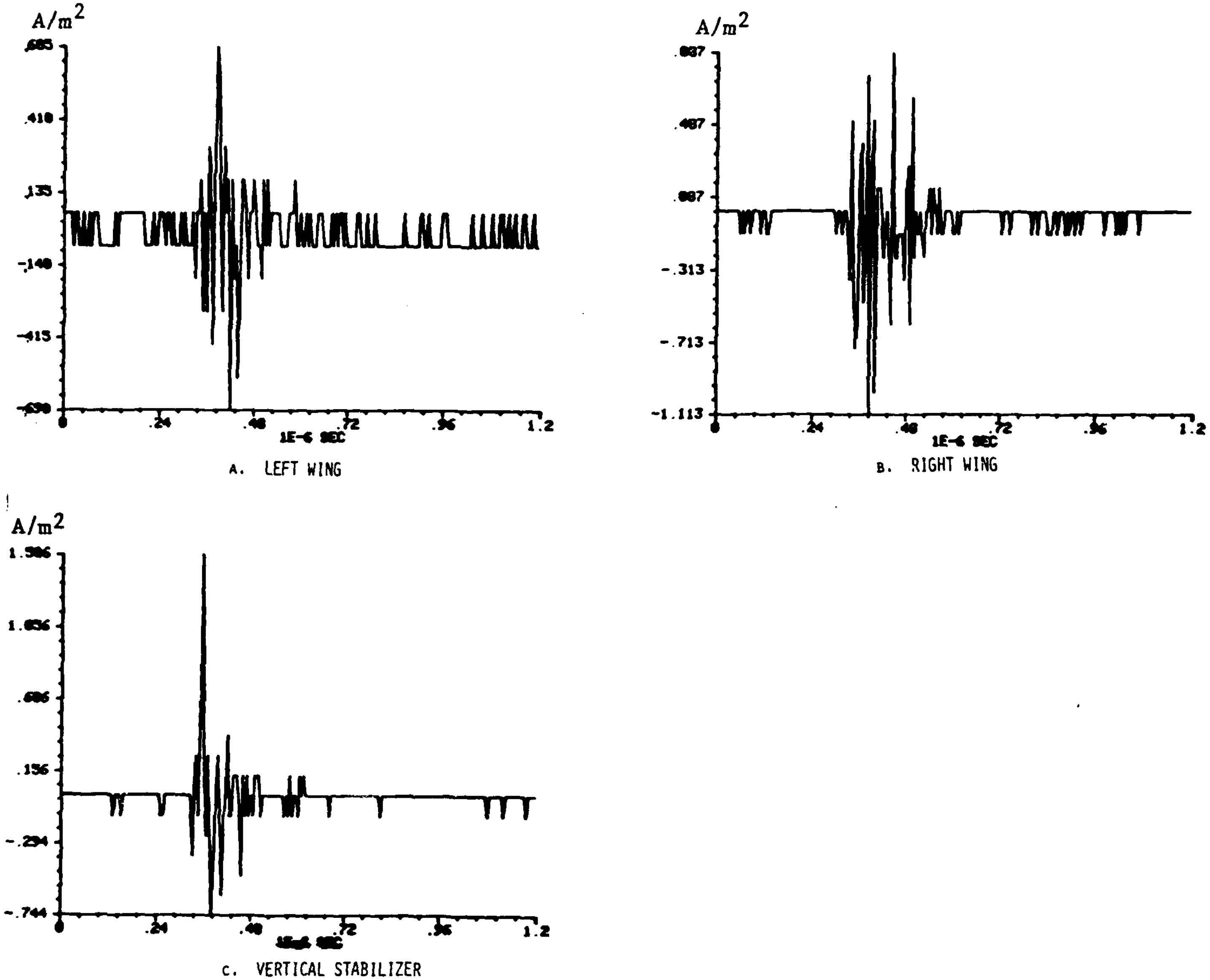


Figure 64. Displacement Current Density During Triggered Pulse of 00:55:26 Flash

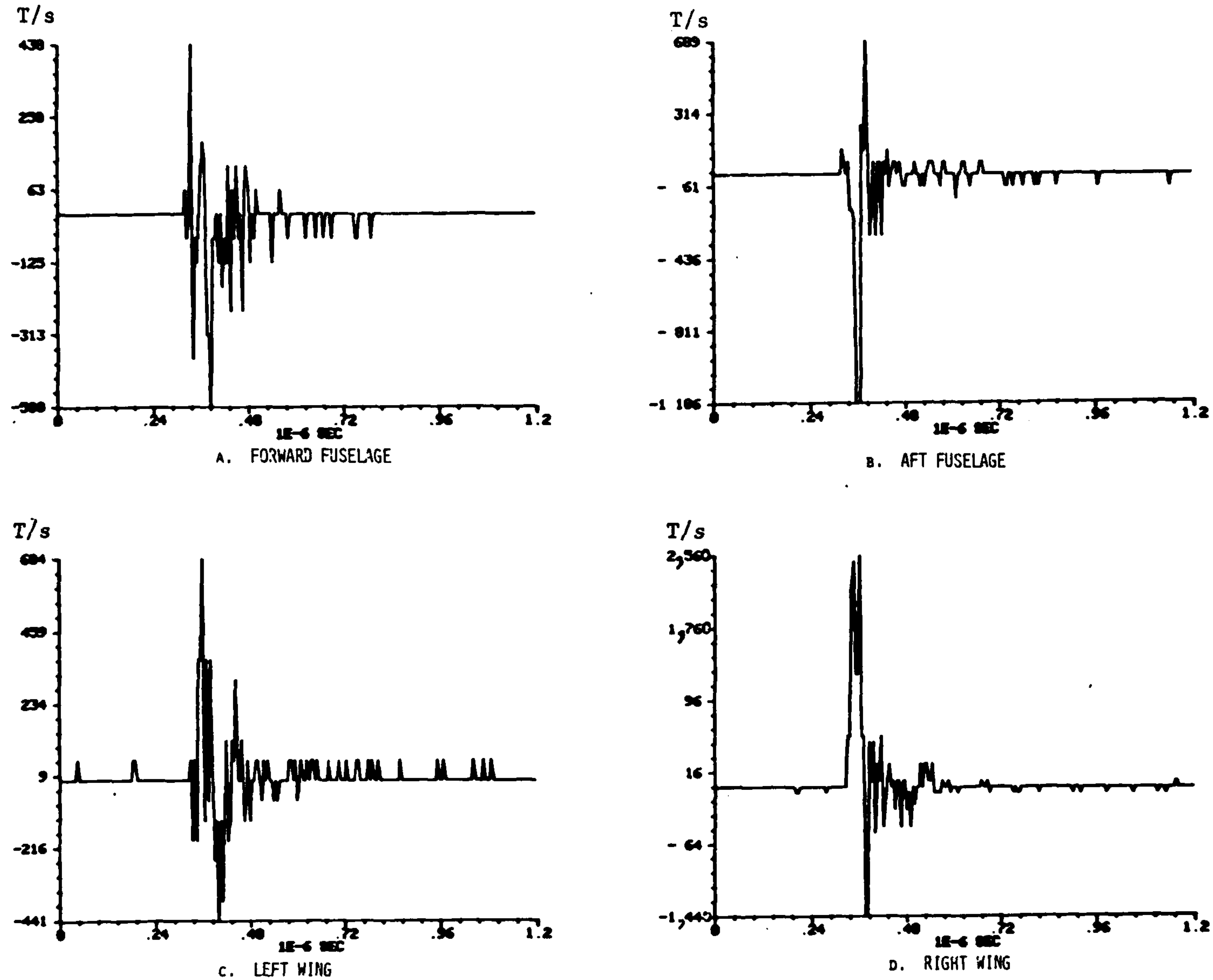


Figure 65. Surface Current Density During Triggered Pulse of 00:55:26 Flash

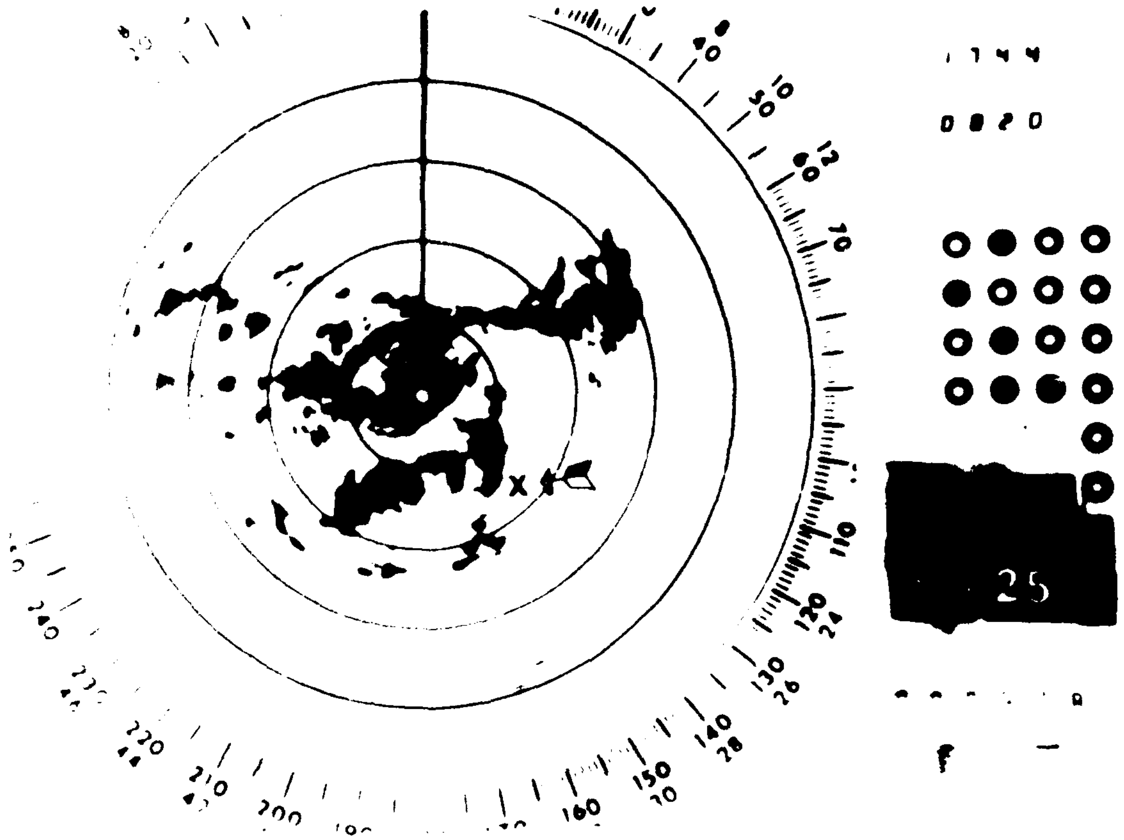


Figure 66. Daytona Beach Precipitation Radar Return
Eight Minutes Before 17:36:00 Flash

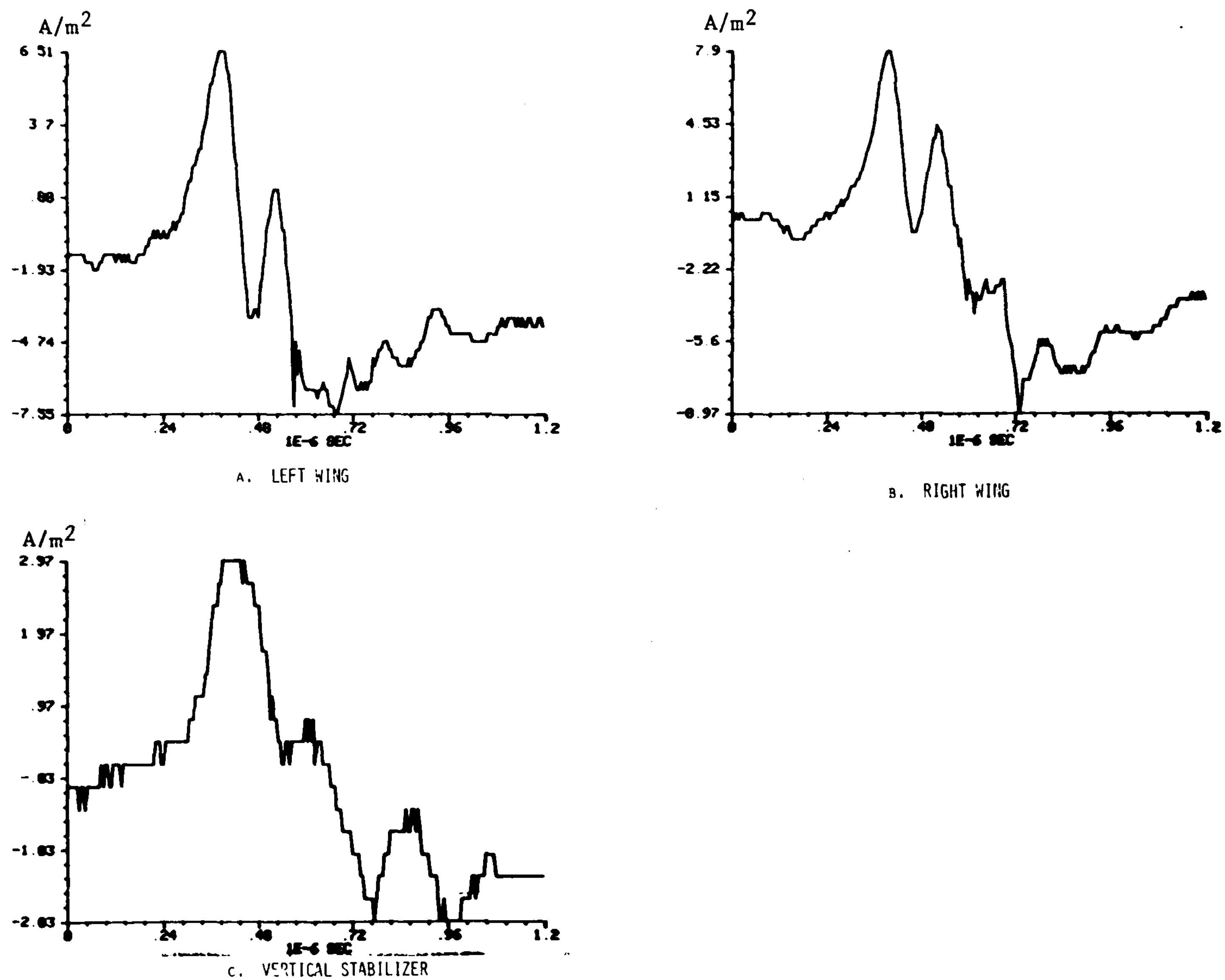


Figure 67. Displacement Current Density During Triggered Pulse of 17:36:00 Flash

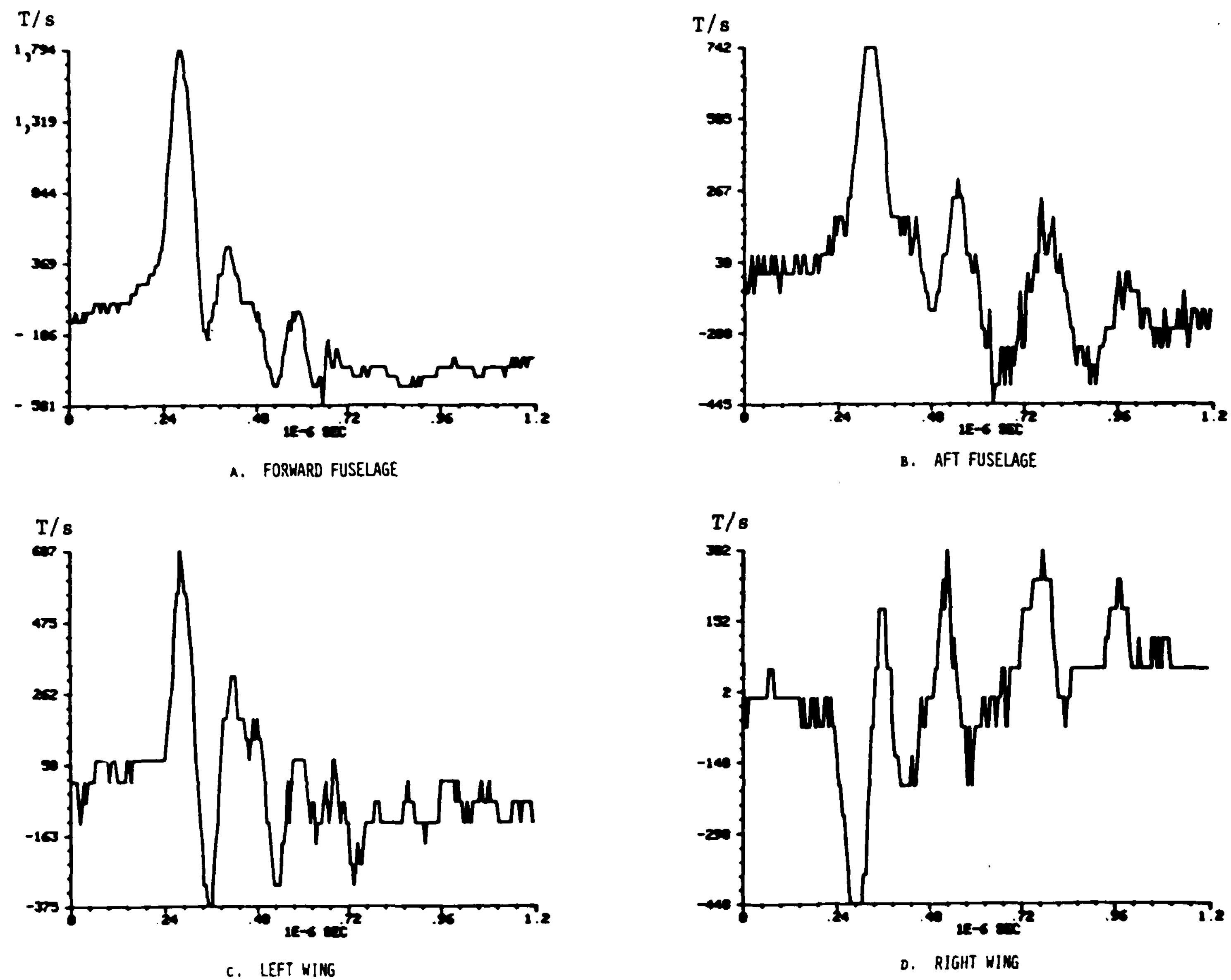


Figure 68. Surface Current Density During Triggered Pulse of 17:36:00 Flash

The largest displacement current density value was on the right wing and it reached 9.0 A/m^2. The largest surface current density was on the forward fuselage and reached 1,794 T/s.

Video data indicates that the flash may have contained five return strokes and the copilot reported that he saw the channel make contact with the water. The aircraft was apparently struck by a small branch of the flash rather than by the main channel. No damage was found during a post-flight inspection of the aircraft.

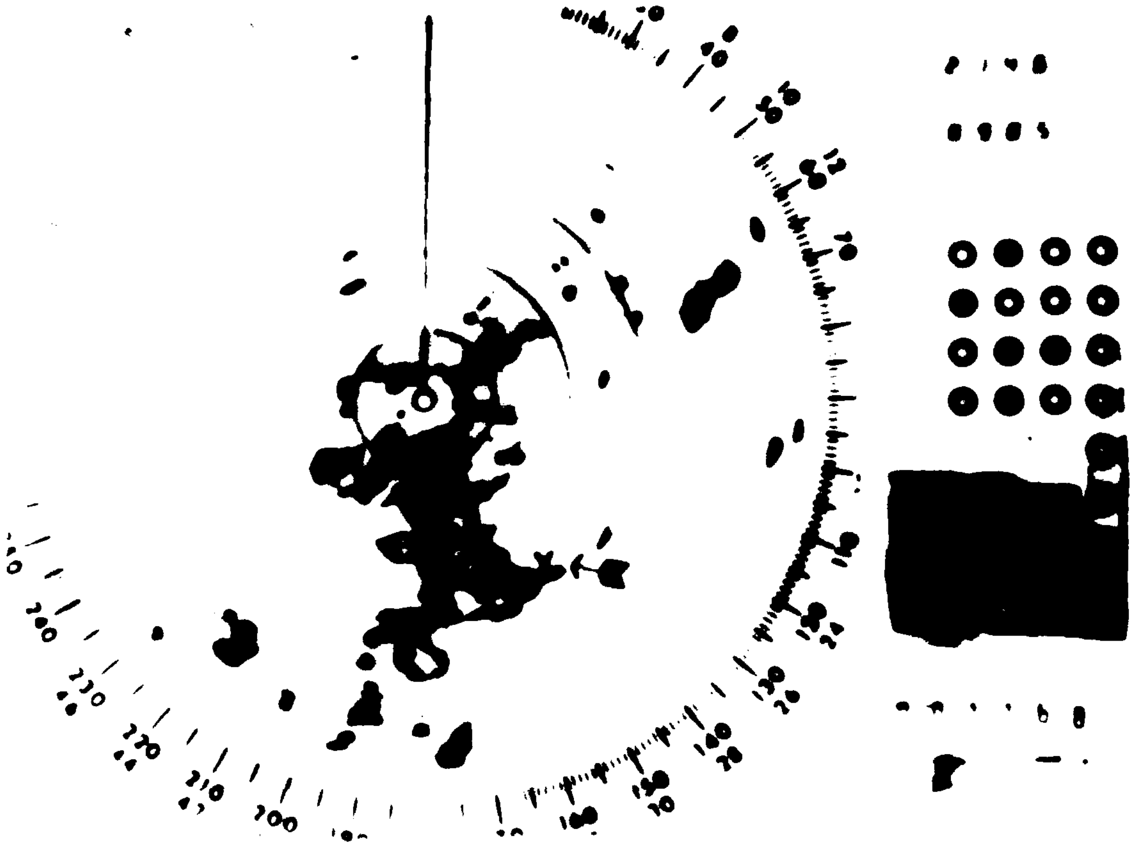
15. THE 5 SEPT FLASH AT 21:44:12 Z

On 5 Sept at 21:44:12 Z, a lightning discharge attached to the aircraft while flying near Melbourne at an altitude of 18,000 ft. The outside air temperature was -5°C and the outside barometric pressure was 7.2 lbs/in^2. The aircraft was flying inside the cloud in an area of low turbulence at the location shown as (15) in Figure 20. Figure 69 shows the Daytona Beach precipitation return two minutes after the lightning discharge. At the time of the flash, the aircraft was located at the edge of a region of heavy precipitation. This was the first of seven attachments during this flight.

The digital system was set to trigger at 1,500 T/s but did not trigger. No analog data was recorded for this flash either.

16. THE 5 SEPT FLASH AT 21:52:15 Z

The next attachment occurred at 21:52:15 Z while flying south of the NASA Kennedy Space Center, as indicated by (16) in Figure 20. The aircraft was flying at 18,000 ft and the outside air temperature and barometric pressure were -4°C and 7.27 lbs/in^2, respectively. Figure 70 shows the



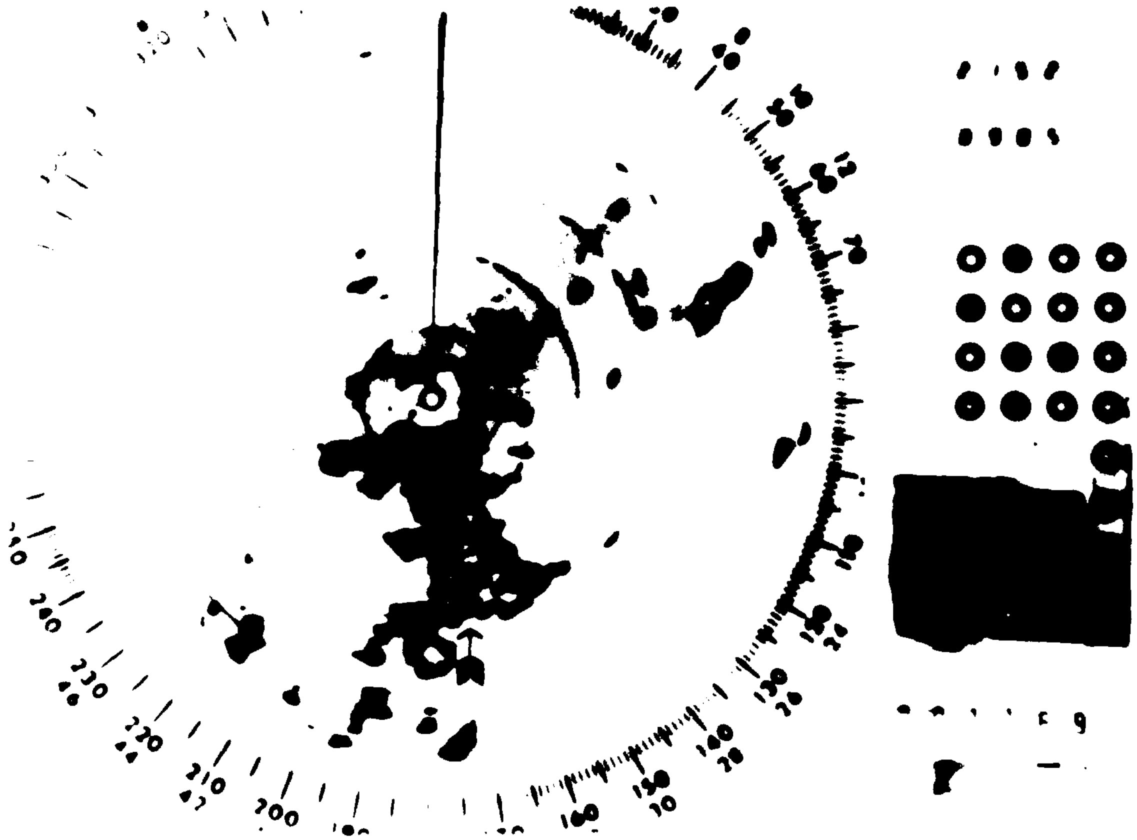
precipitation return from Daytona Beach and indicates that the aircraft was flying near regions of heavy precipitation.

The digital system did not trigger at the 1,500 T/s threshold level. Figure 71 shows five traces of the analog data recorded at the beginning of the flash. The polarity of the E forward fuselage trace appears inverted when compared with previous flashes. The dynamic range of the J_{NFUF} sensor had been increased to prevent the saturation observed on some of the previous traces. Subsequently, a positive electric field change corresponded to a field change pointing toward the aircraft. A slow moving leader pulse was detected during the first 1.6 ms of the discharge. This corresponds to 240 m of detectable leader motion. There seemed to be no significant streamer propagation from the aircraft to the charge center that initiated the flash. The very active part of the flash lasted 35 ms and the fastest pulse repetition rate during this period was near 10^3 pulses/sec.

Figure 72 shows the electric field on the forward fuselage, vertical stabilizer, right wing tip, and left wing tip for the entire 360 ms of the discharge. The largest electric field transients detected were 80 kV/m on the vertical stabilizer, 162 kV/m on the right wing tip, and 106 kV/m on the left wing tip.

17. THE 5 SEPT FLASH AT 21:53:05 Z

About one minute later at 21:53:05 Z, a lightning discharge attached to the aircraft while flying 20 miles northwest of Melbourne, as indicated by (17) in Figure 20. The aircraft was flying inside the cloud in an area of low turbulence at the same altitude as the previous flash. Figure 73


240
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160
150
140

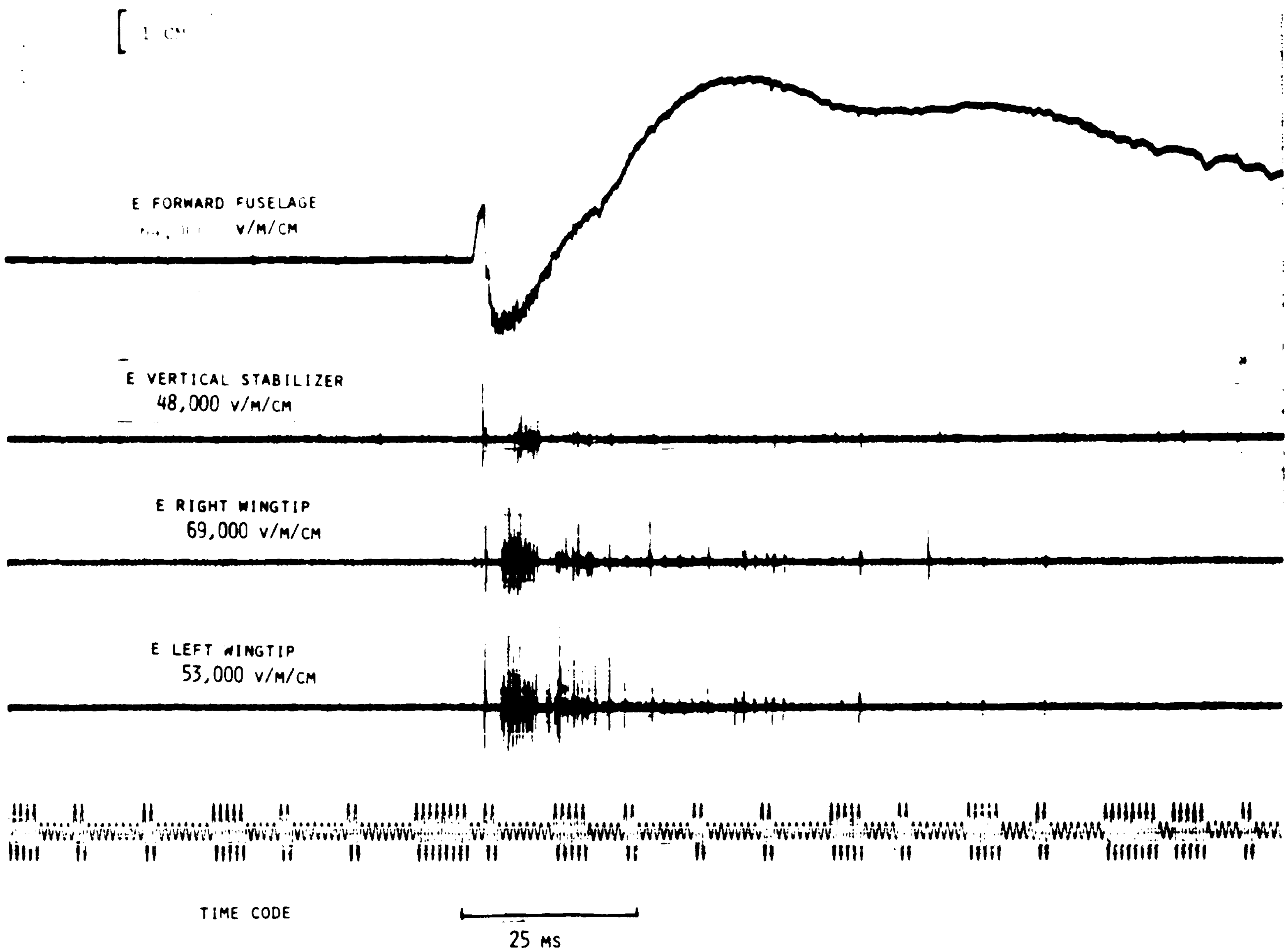

Figure 71. Five Analog Channels Recorded at Beginning of 21:52:15 Flash. Forward Fuselage Trace Inverted

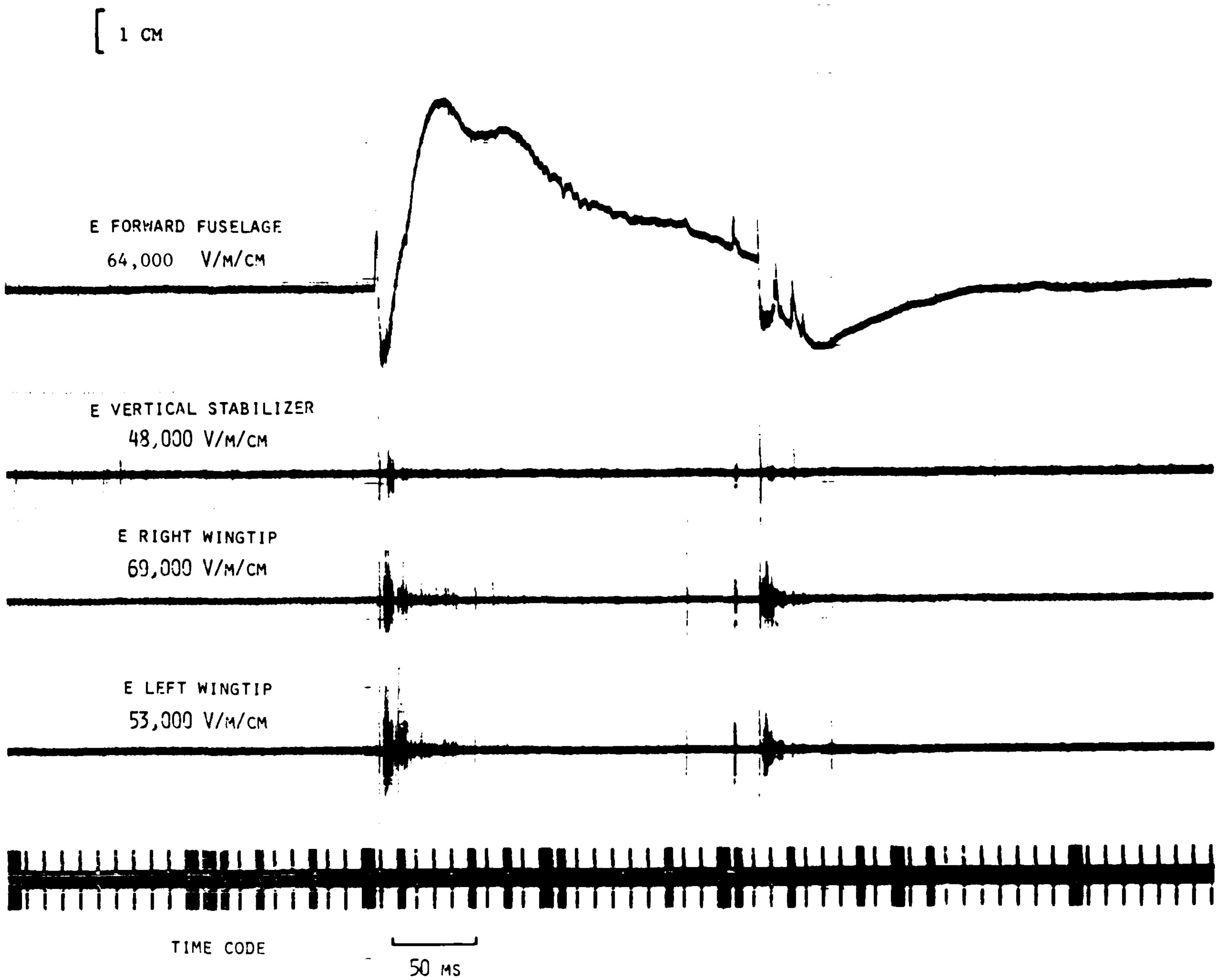

Figure 72. Same Analog Channels for Duration of 21:52:15 Flash. Forward Fuselage Trace Inverted

shows that the aircraft was flying in an area of heavy precipitation at the time of the strike.

The system was triggered at 1500 T/s during a fast transient pulse near the middle of the flash. Figure 74 shows six analog traces at the beginning of the flash. The E forward fuselage field increased to about 30 kV/m prior to the faster negative discharge. This relatively small increase in field strength was somewhat slower and smaller than most of the field charges observed in other flashes. The first transient pulse occurred on the E right wing tip trace. Current propagation through the right wing tip current shunt is shown 1 ms later on the second trace. The right wing tip appeared to be the only part of the aircraft interacting with the lightning channel during the first 15 ms of the attachment. The pulse marked (1) in the E right wing tip trace of Figure 74 was the pulse that triggered the digital system. By that time, the channel had propagated to the left wing tip and vertical stabilizer. Some transient pulses after the trigger indicate current flow through the right wing tip boom of magnitude between one or two kiloamperes.

Figure 75 and 76 show the surface current density and displacement current density expansions for the time of the trigger. The maximum values of surface current density in Figure 75 are 1,045 T/s on the forward fuselage, 1,403 T/s on the aft fuselage, 1,081 T/s on the left wing, and 2,065 T/s on the right wing. Maximum displacement current density values in Figure 76 are 8.83 A/m^2 on the left wing, 21.69 A/m^2 on the right wing, and 5.11 A/m^2 on the vertical stabilizer. The data shown in Figures 75 and 76 are consistent with the analog records which indicate that the flash probably attached to the right wing and propagated throughout the aircraft.

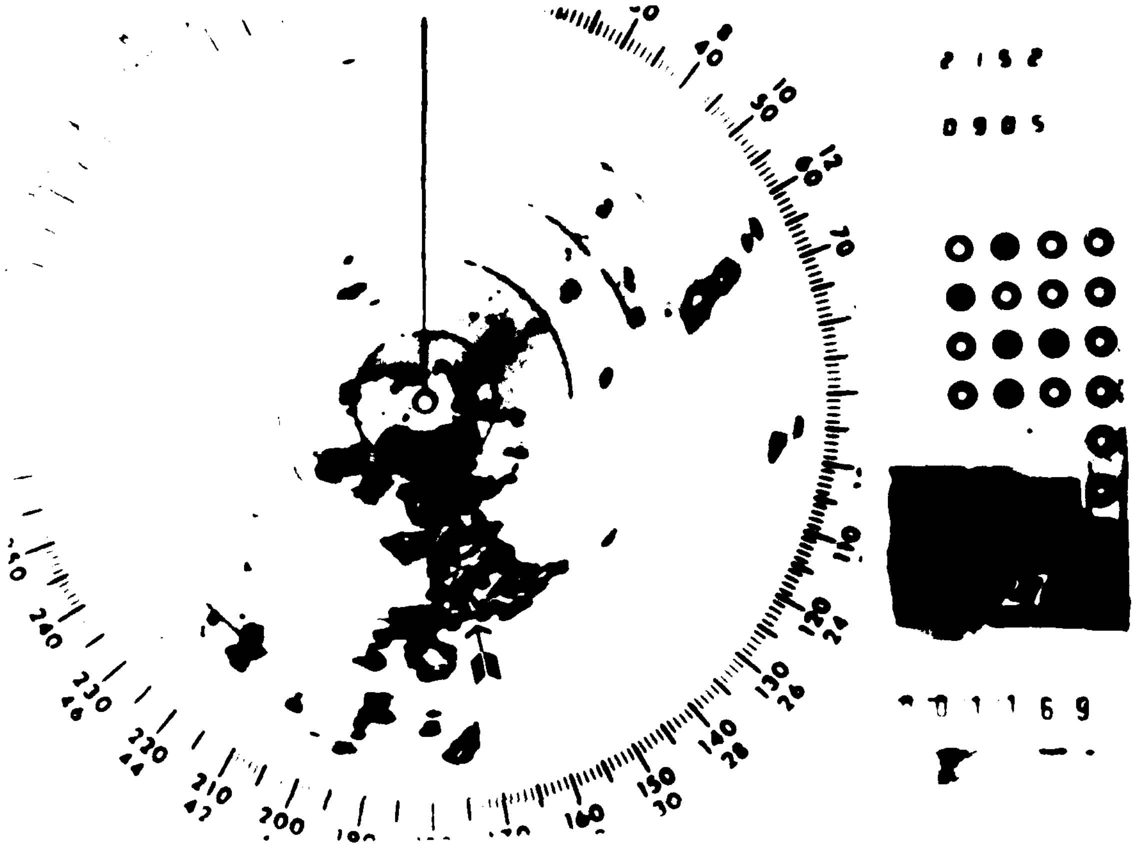

Figure 73. Precipitation Radar Return Showing Position of Aircraft During 21:53:05 Flash

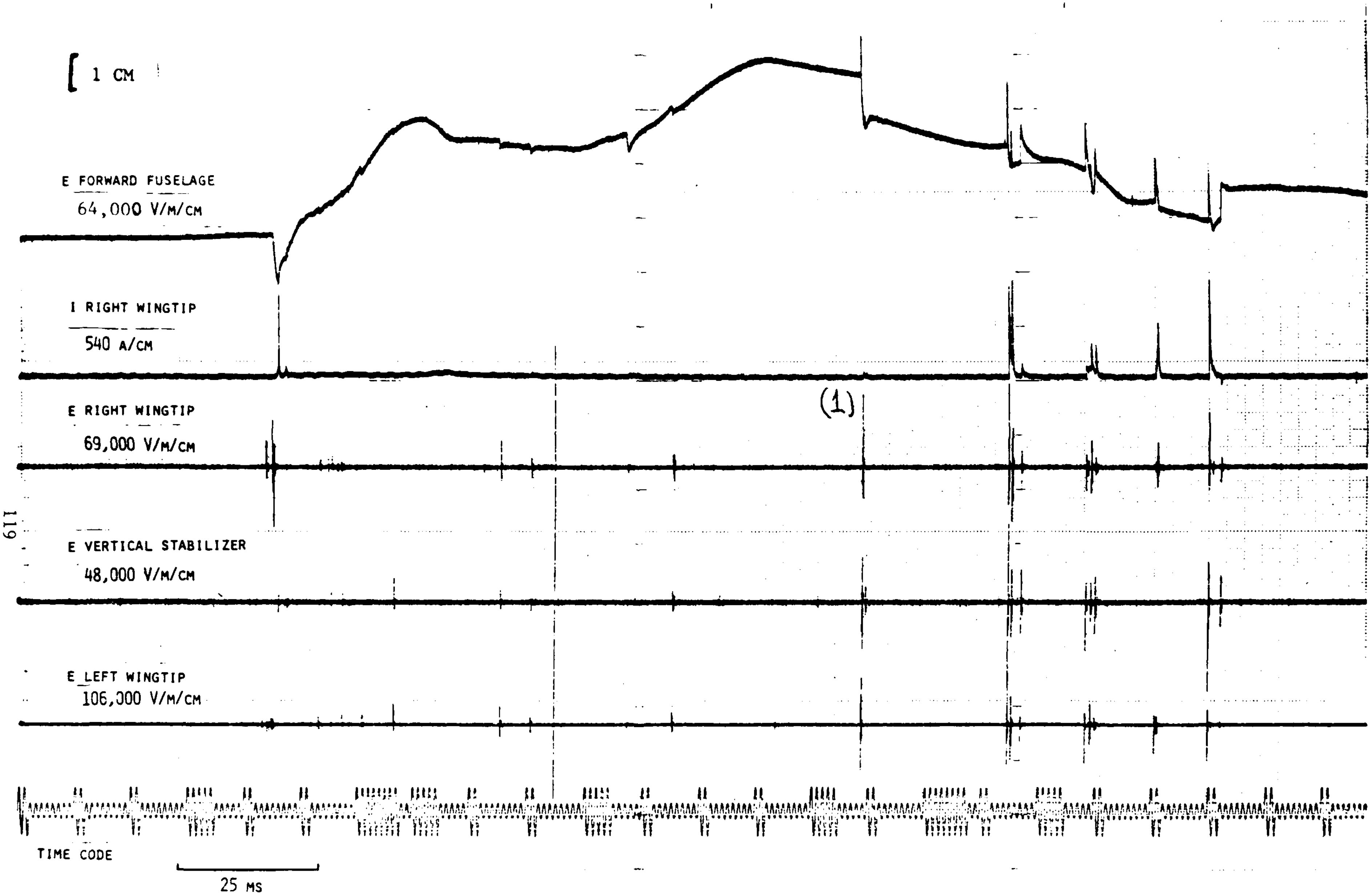

Figure 74. Six Analog Channels Recorded at Beginning of 21:53:05 Flash. Forward Fuselage Trace Inverted

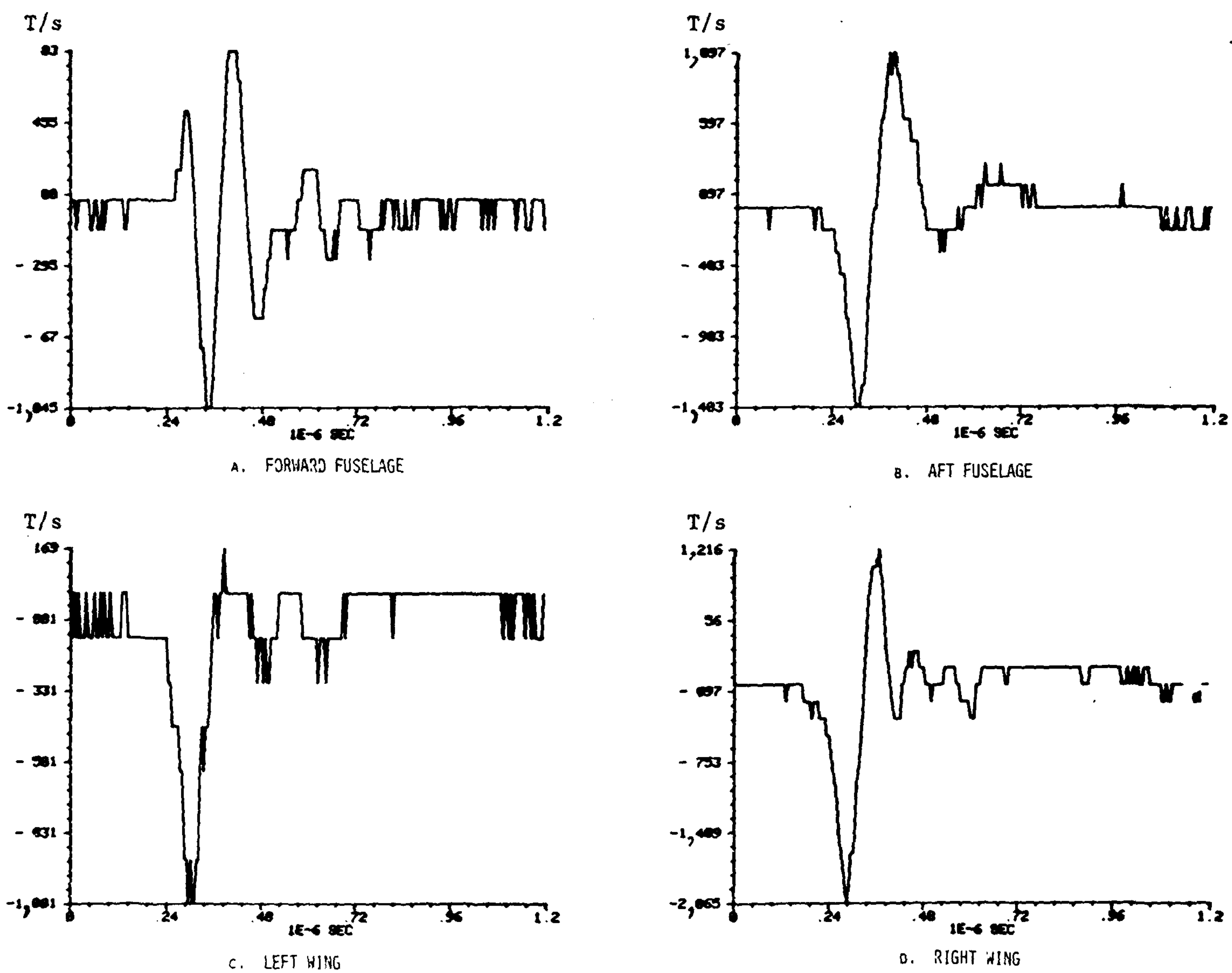

Figure 75. Surface Current Density During Triggered Pulse of 21:53:05 Flash

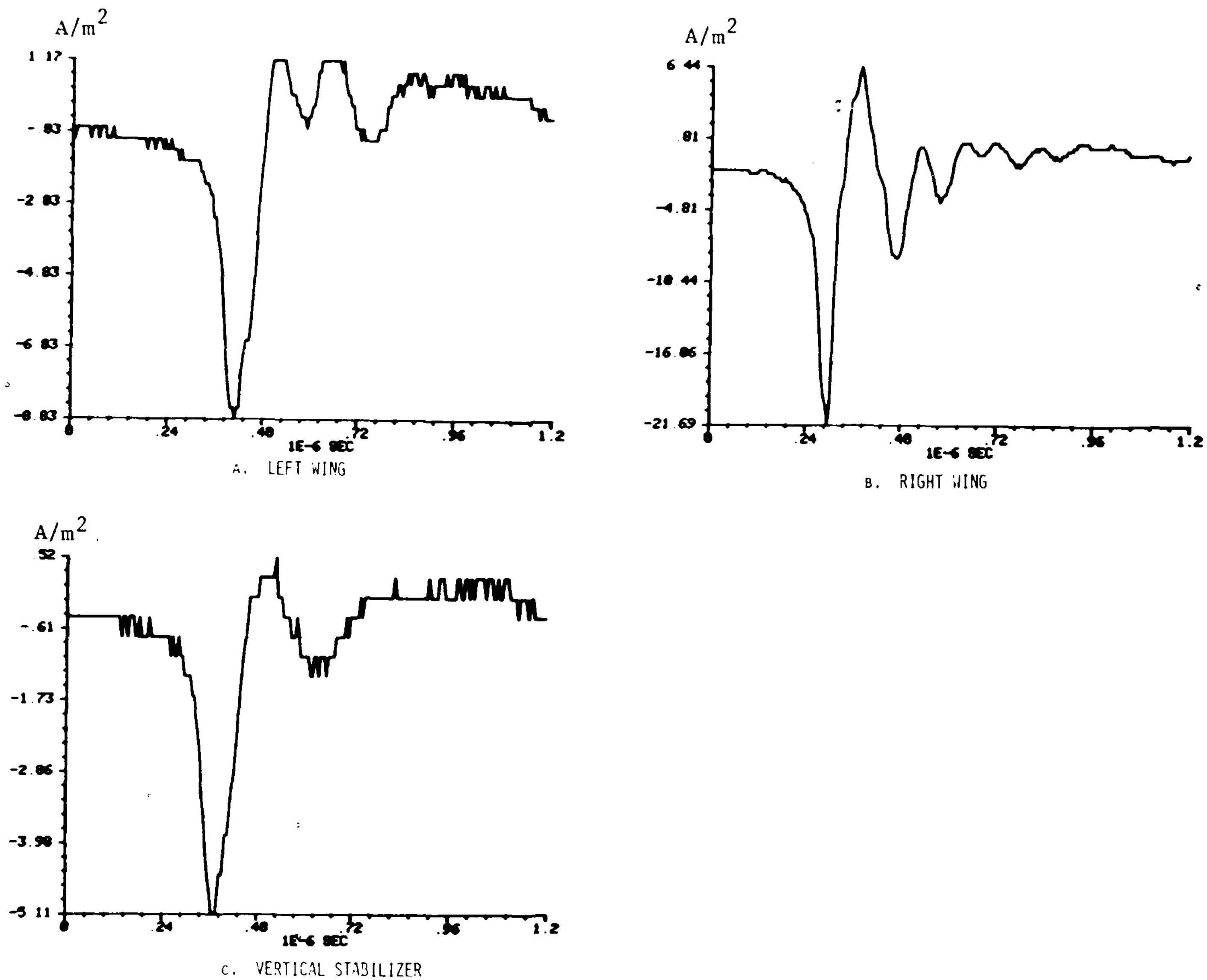

Figure 76. Displacement Current Density During Triggered Pulse of 21:53:05 Flash

Figure 77 overlays the displacement current density on the right and left wing after the cable propagation delays were removed. The time required for the displacement current density pulse to propagate from the right wing tip to the left wing tip was 100 ns. The distance from the J_{NRWT} to the J_{NLWT} sensor was approximately 100 ft and the 100 ns delay corresponded to a propagation velocity equal to the speed of light. Figure 78 shows the displacement current density on the right wing and the vertical stabilizer. The peak value on the vertical stabilizer occurred 75 ns after the largest pulse on the right wing. The distance over the conducting surface of the aircraft from the right wing to the vertical stabilizer was approximately 80 ft. The time delay over this distance also corresponded to a propagation speed near the speed of light. Figure 79 shows overlays of the surface current density on the right and left wings. These J_S sensors were mounted on the wings between the engine and the fuselage and were roughly 15 ft apart. The time delay between peak magnitudes was about 15 ns and again corresponded to a speed of light propagation. Finally, Figure 80 shows the surface current density on the forward and aft J_S sensors mounted on the top of the fuselage. No time delay was observed between the arrival of the pulse to both sensors. Since these sensors were at equal distances from the wings, a wave propagation from the right wing splitting at the fuselage probably reached both sensors at about the same time.

Figure 81 shows the same analog channels for the duration of the flash that lasted about 310 ms. The largest electric field transients recorded were about 162 kV/m on the right wing tip, 265 kV/m on the left wing tip, and 110 kV/m on the vertical stabilizer. The measured current through the right wing tip sensor was 1.5 kA.

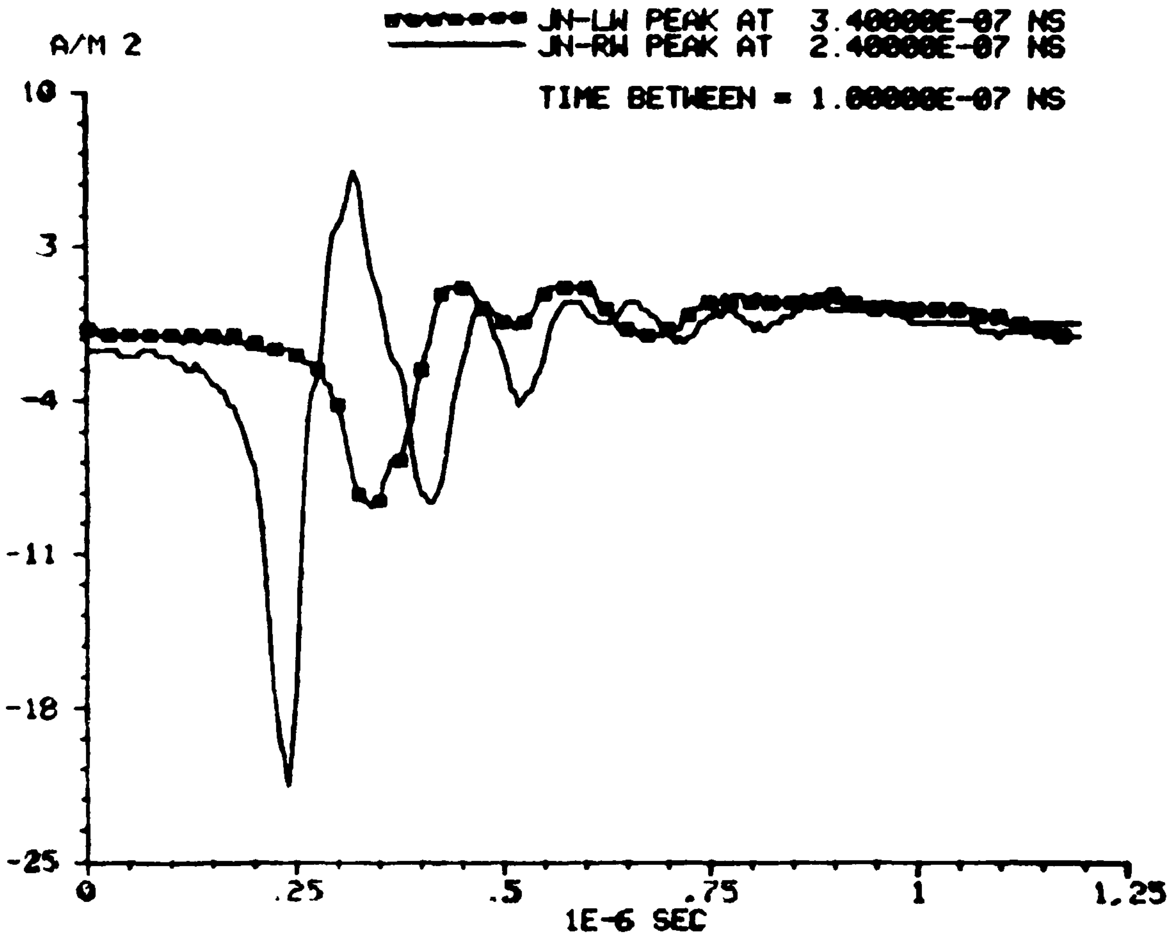

Figure 77. Overlay of Displacement Current Density on Right and Left Wings During 21:53:05 Flash

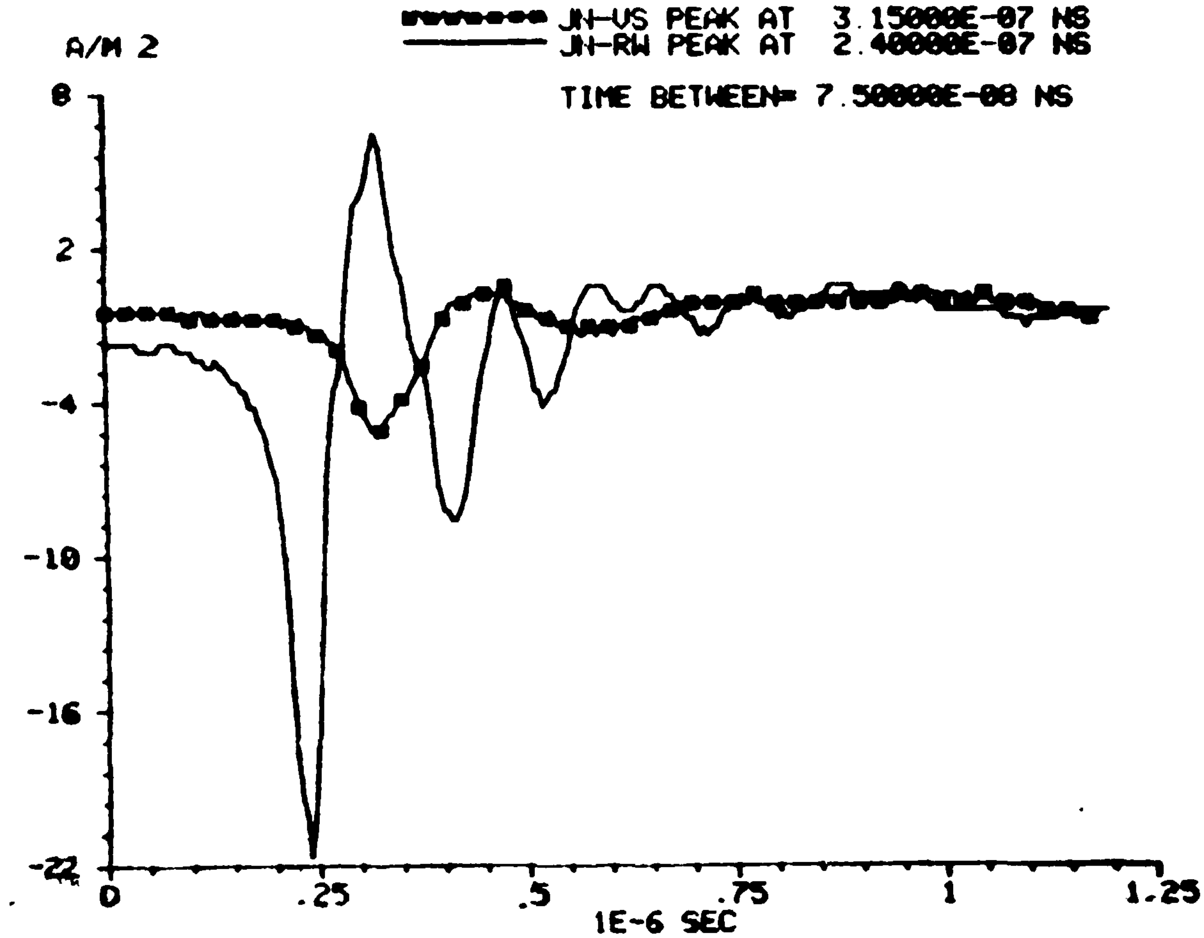

Figure 78. Overlay of Displacement Current Density on Right Wing and Vertical Stabilizer During 21:53:05 Flash

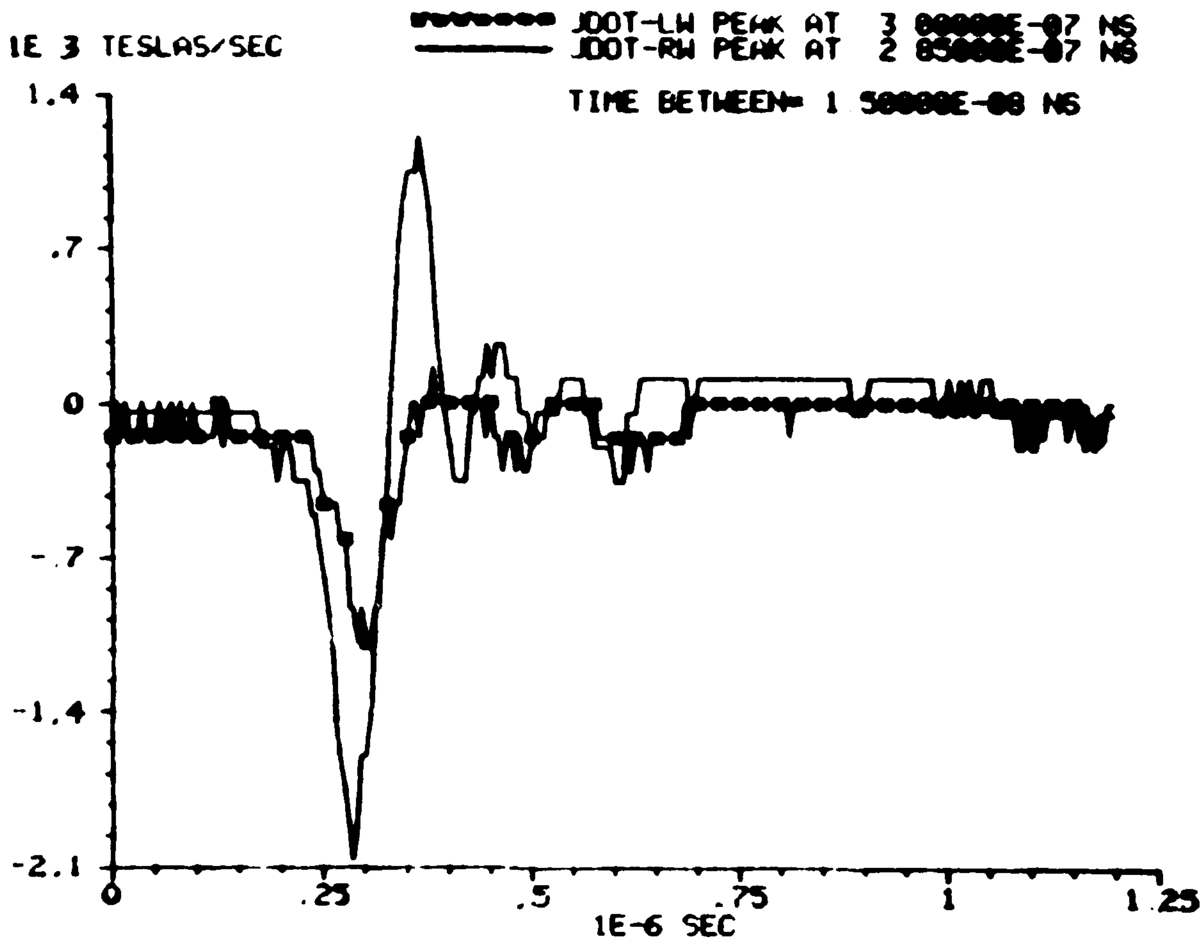

Figure 79. Overlay of Surface Current Density on Left and Right Wings During 21:53:05 Flash

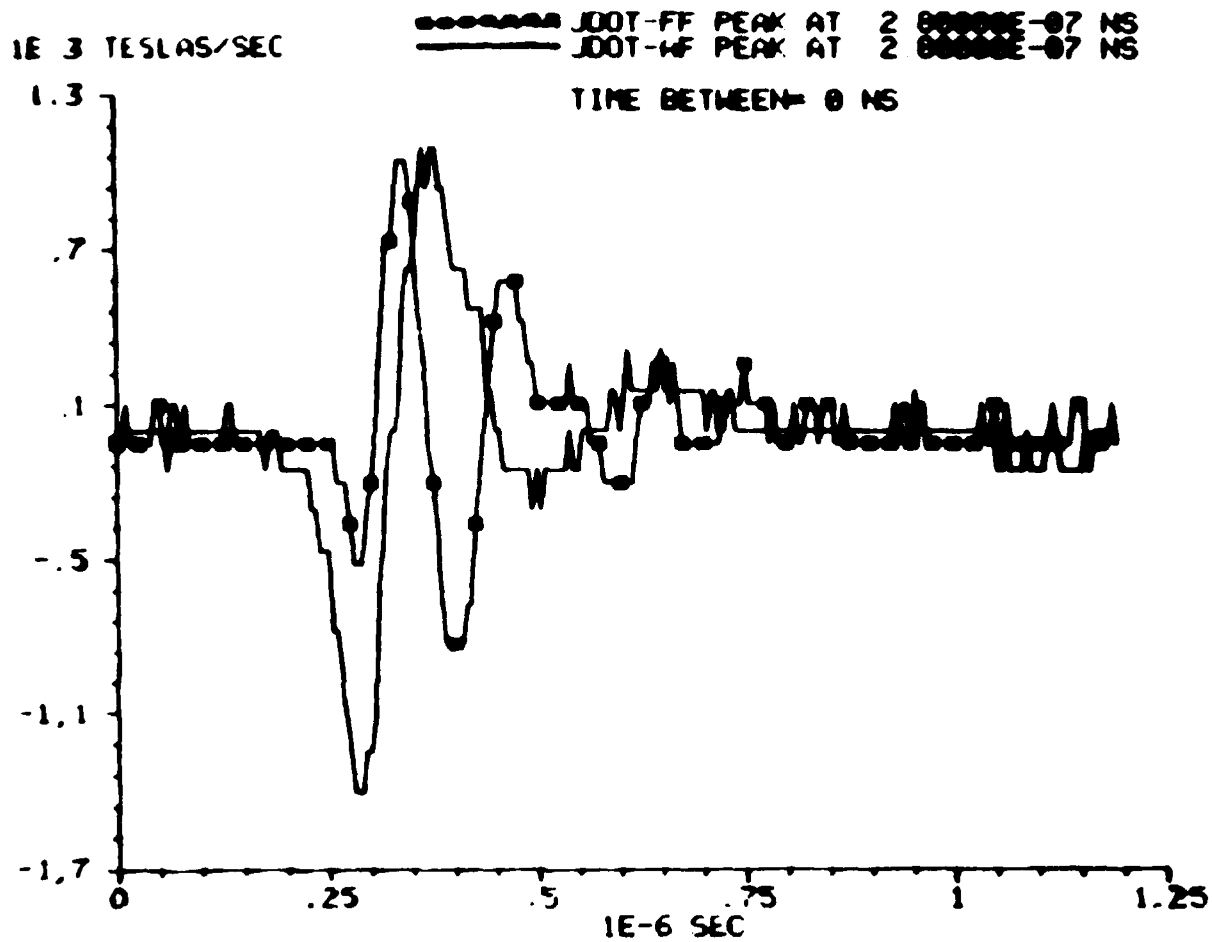

Figure 80. Overlay of Surface Current Density on Forward and Aft Fuselage During 21:53:05 Flash

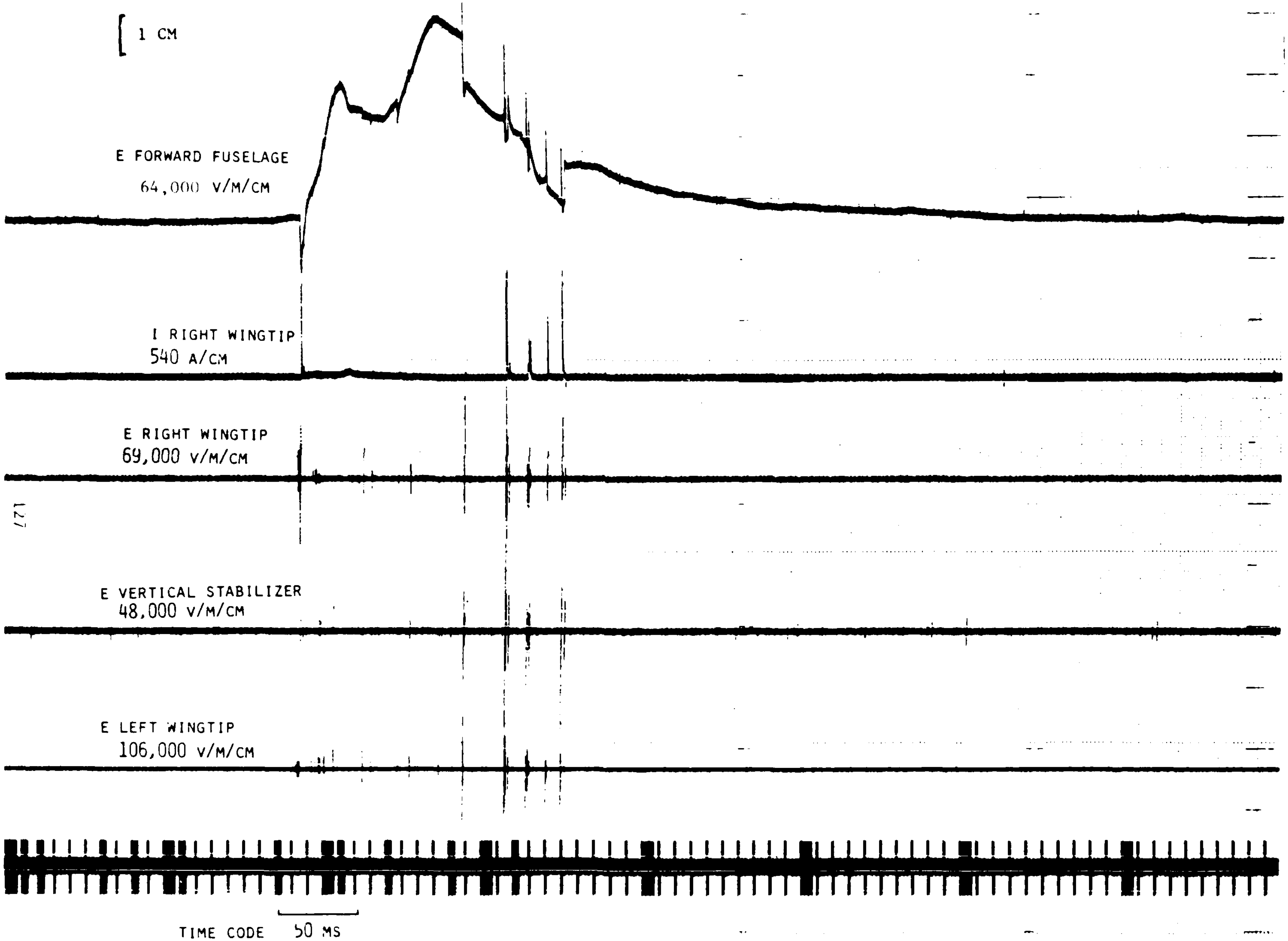

Figure 81. Same Analog Channels for Duration of 21:53:05 Flash, Forward Fuselage Trace Inverted

18. THE 5 SEPT FLASH AT 22:34:42 Z

The next lightning attachment occurred at 22:34:42 Z while flying near Melbourne as shown by (19) in Figure 20. The aircraft was still flying at 18,000 ft and the outside air temperature and barometric pressure were -5°C and 7.13 lbs/inch^2, respectively. The aircraft was flying inside the cloud in an area of low turbulence. Figure 82 shows the Daytona Beach precipitation return and indicates that the aircraft was at the edge of an area of heavy precipitation at the time of the flash.

The digital system did not trigger at the threshold level of 1,500 T/s. No analog data was recorded at the time of the flash.

19. THE 5 SEPT FLASH AT 23:06:08 Z

About one-half hour later, the aircraft was struck by lightning at 23:06:08 Z while flying over the ocean east of Cape Canaveral AFS as indicated by (19) in Figure 20. The aircraft was flying at the same altitude as before and was in an area of low turbulence but outside any region of significant cloud structure. Figure 83 shows that at the time of the flash, the aircraft was on the edge of an area of heavy precipitation.

The digital threshold level was set at 1500 T/s but the system did not trigger during this flash. Figure 84 shows six analog channels recorded during the beginning of the flash. The top trace of the E forward fuselage shows a slow steady electric field change for about 21 ms prior to any fast transients. This corresponds to a long leader indicating that the flash probably developed and propagated a few kilometers before being affected by the presence of the aircraft. Streamers appeared to propagate from the aircraft to intercept the oncoming leader. The streamers generated fast

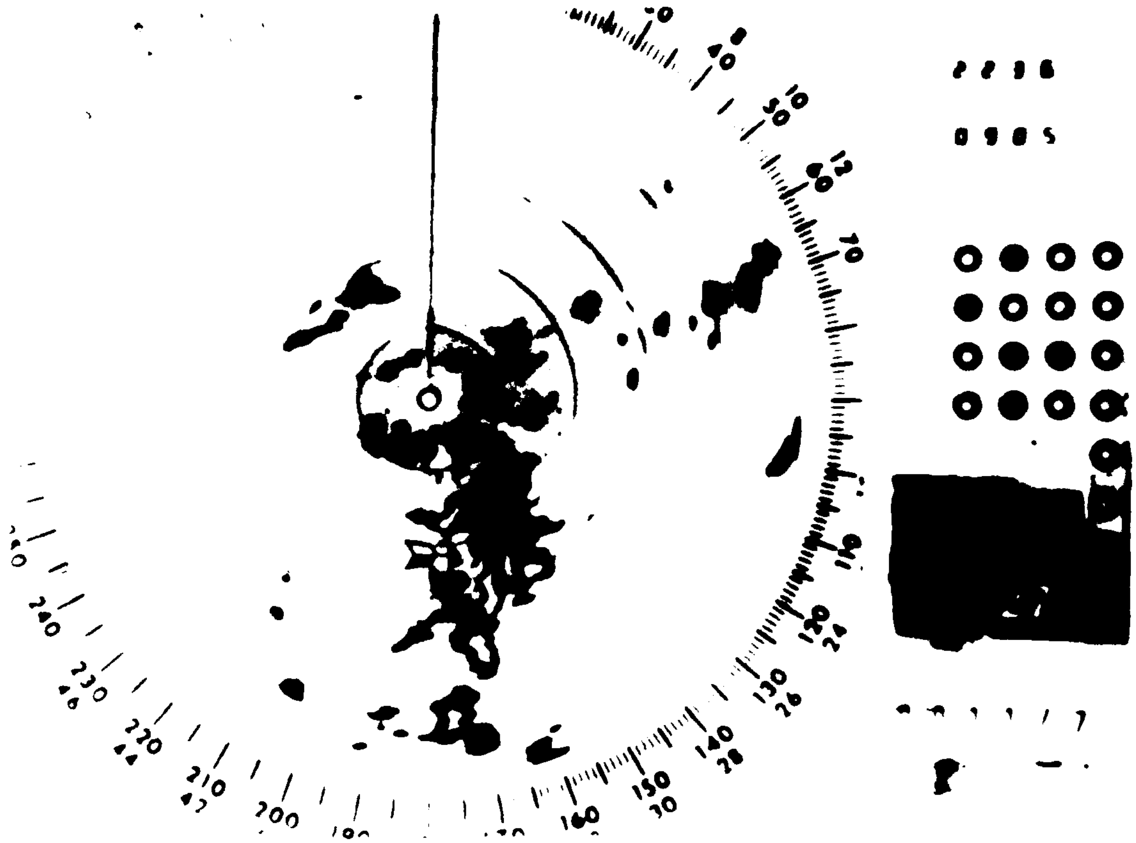

Figure 82. Precipitation Radar Return Showing Position of Aircraft During 22:34:42 Flash

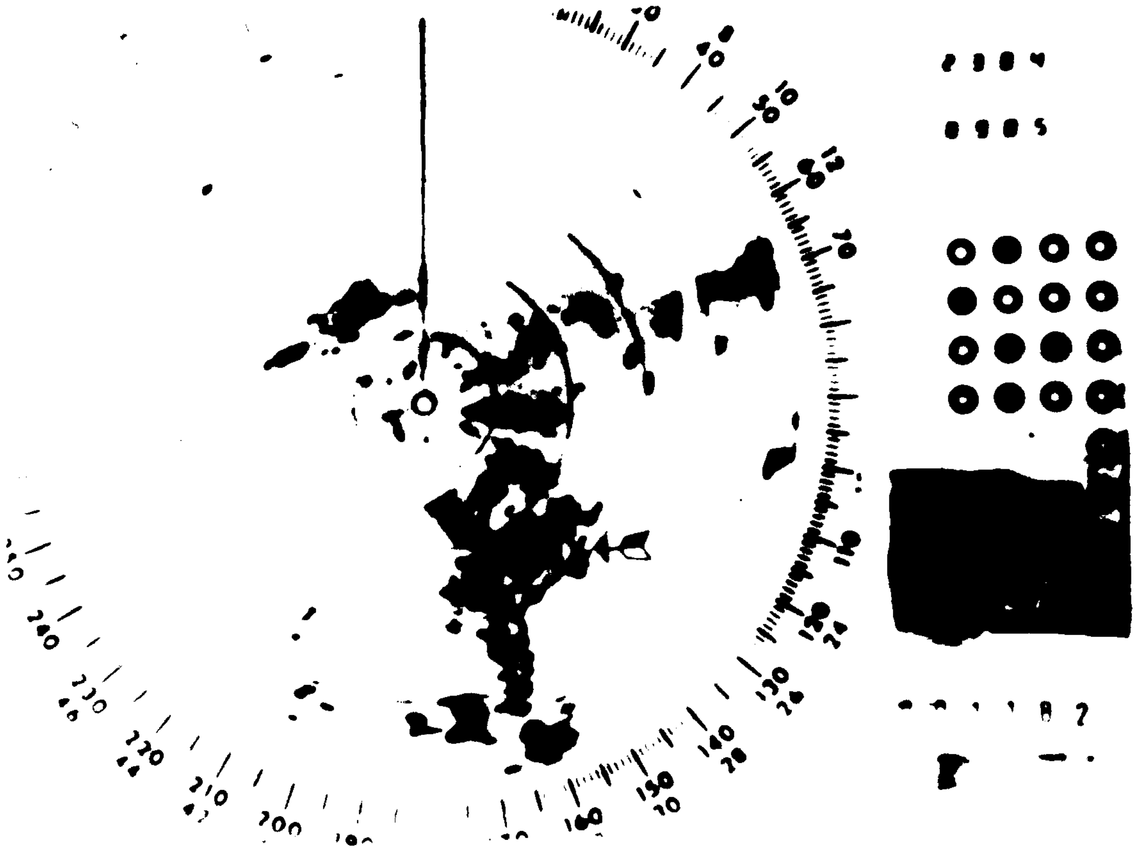

Figure 83. Precipitation Radar Return Showing Position of Aircraft During 23:06:08 Flash

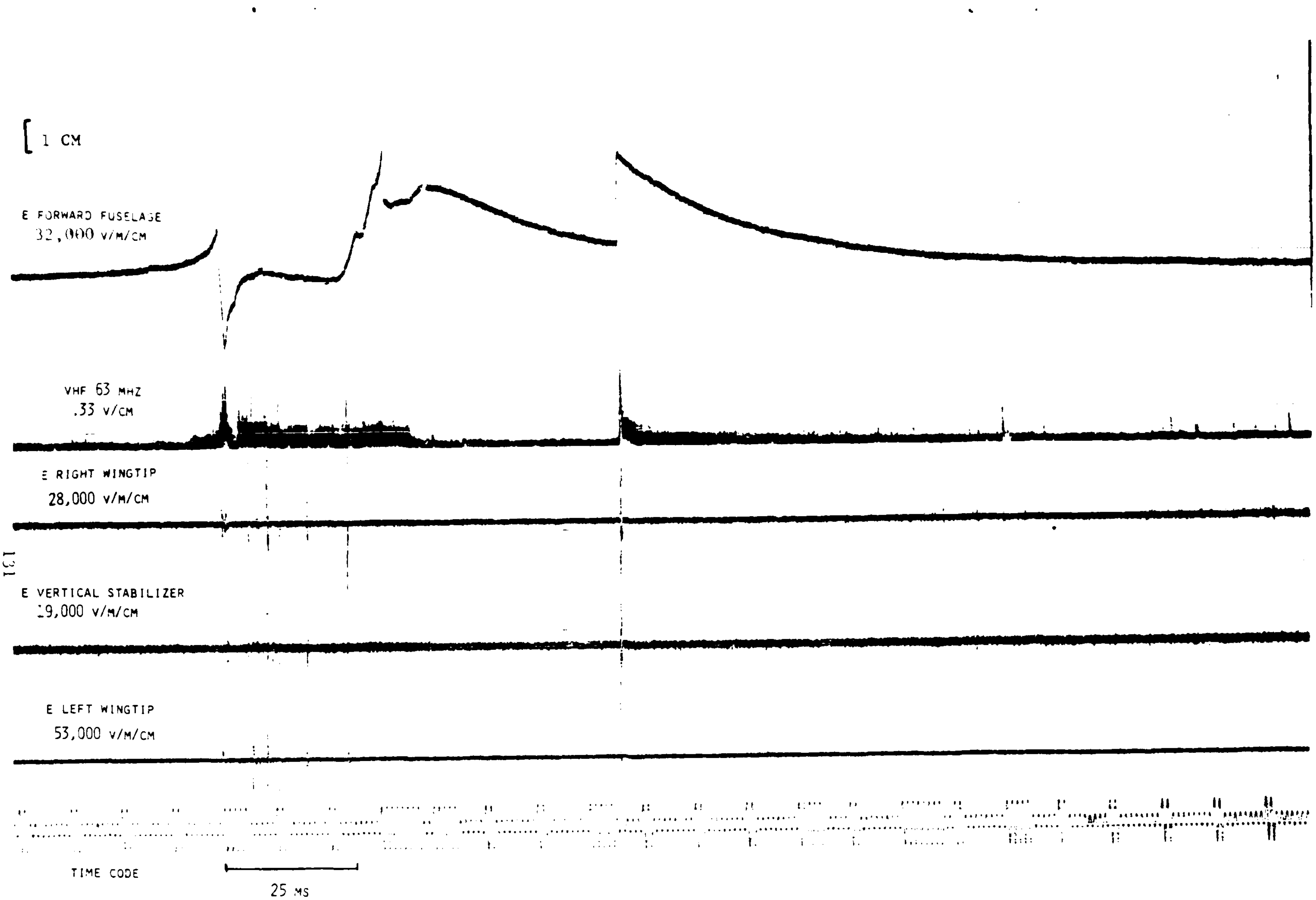

Figure 84. Six Analog Channels Recorded at Beginning of 23:06:08 Flash. Forward Fuselage Trace Inverted

transients on the aircraft wing tips and an even faster field change on the forward fuselage.

The aircraft then became part of an apparent intracloud discharge for a period of about 100 ms. Near the end of the flash, a very fast transient pulse approaching the bandwidth limit of the analog recorder was measured. This pulse is larger than the other pulses in the flash and resembled a return stroke in a cloud-to-ground discharge. The Kennedy Space Center LLP system detected a single return stroke cloud-to-ground flash at 23:06:08:16 at a range of 19.2 NM and a bearing of 120.1° from the weather office. Our estimate of the position of the aircraft obtained from the VCDS at the time of the flash showed a 21.4-NM range at a 123.3° heading from the same location. These small differences in range and bearing corresponded to a 3- to 4-mile discrepancy and could be explained by small errors in the detection systems and/or by horizontal propagation of the flash. The data suggests that the aircraft intercepted a natural intracloud discharge that was followed by a cloud-to-ground discharge with one return strike.

Figure 85 shows six analog channels for the entire duration of the flash which lasted about 130 ms. The largest electric field transients during the flash were 70 kV/m on the right wing tip, 40 kV/m on the vertical stabilizer, and 80 kV/m on the left wing tip.

20. THE 5 SEPT FLASH AT 23:20:36 Z

Another lightning discharge attached to the aircraft while flying about 30 miles south of Melbourne at 23:20:36 Z. This location is shown as (20) in Figure 20. The aircraft was flying inside the cloud at 18,000 ft in an area of low turbulence. Figure 86 shows that the aircraft was in a region of heavy precipitation at the time of the flash.

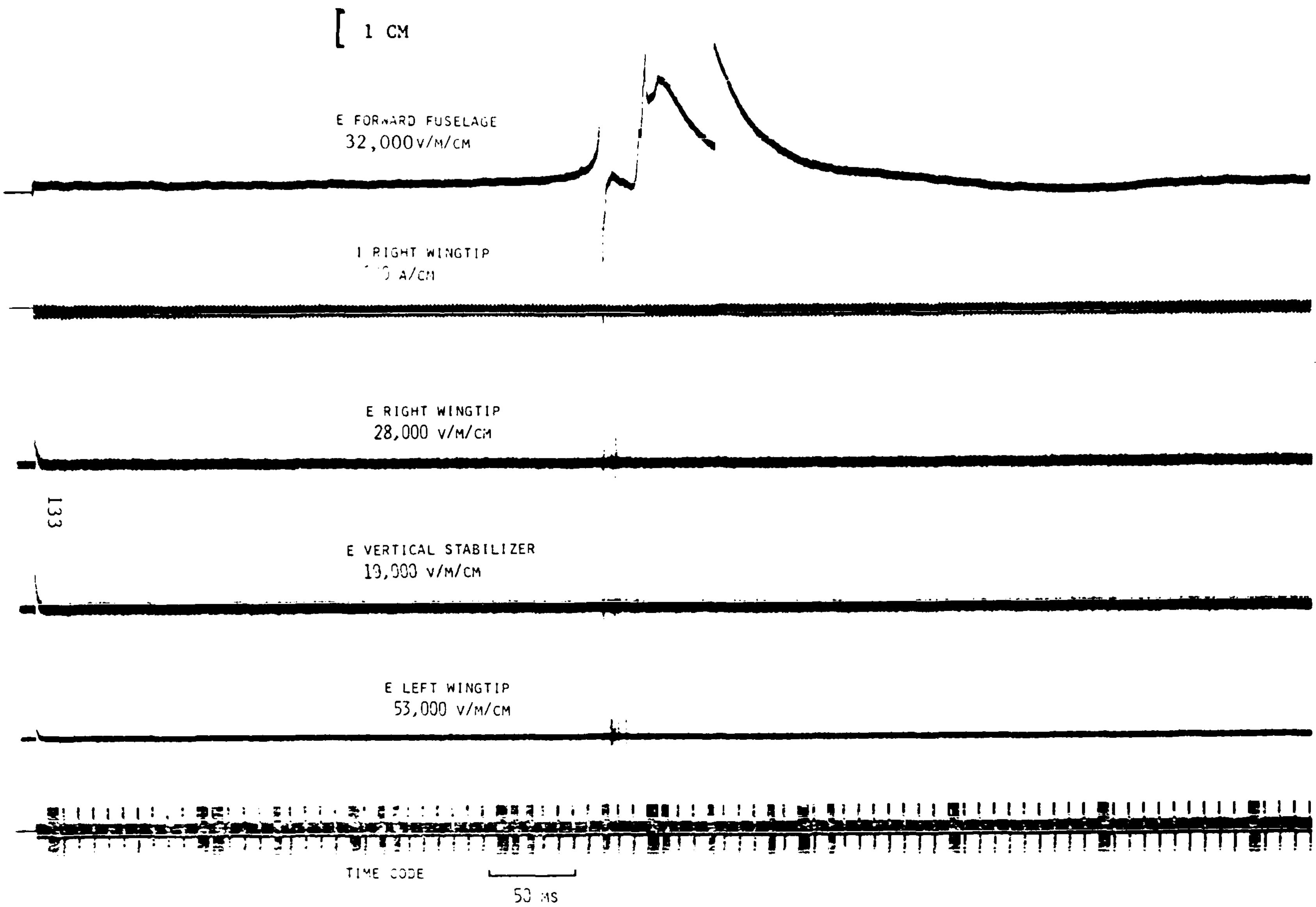

Figure 85. Six Analog Channels for Duration of 23:06:08 Flash. Forward Fuselage Trace Inverted

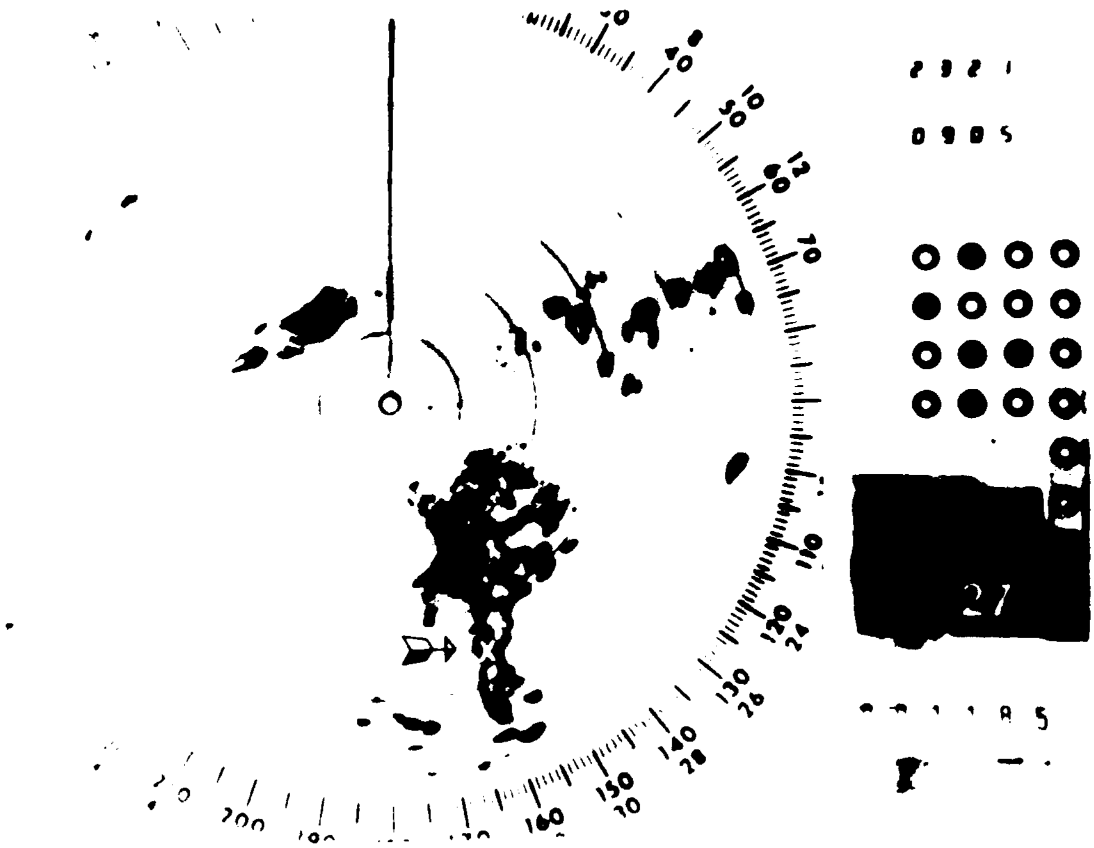

Figure 86. Precipitation Radar Return Showing Position of Aircraft During 23:20:36 Flash

The digital system triggered at 1500 T/s but the digital data was not able to be stored because some of the equipment had overheated. As a result, only analog data is available for this flash. Figure 87 shows six channels of analog data recorded during the beginning of the flash. The E forward fuselage trace shows field changes for about 1.6 ms prior to the first transient pulse of the flash. Assuming a leader velocity of 1.5×10^5 m/s, the leader propagated about 240 m before attaching to the aircraft. No significant electric field transient were observed during the beginning of the leader pulse and no streamers propagated from the aircraft to intercept the oncoming leader. It appeared that the discharge was triggered by the presence of the aircrart. Most of the pulse activity occurred on the wings with the left wing tip trace showing of largest magnitudes. The traces show hundreds of pulses during the first 35 ms of the discharge with only a few isolated pulses afterwards. The largest field magnitudes observed were during these isolated pulses.

Figure 88 shows the same analog channels for the duration of the flash which lasted about 750 ms. The largest electric field transients found during some of the isolated pulses were 115 kV/m on the left wing tip, 103 kV/m on the vertical stabilizer, and 80 kV/m on the right wing tip.

21. THE 5 SEPT FLASH AT 23:26:53 Z

The last lightning attachment for this flight and for the summer program occurred at 23:26:53 Z while flying about 20 miles south of Melbourne. This is shown as (21) in Figure 20. The outside air temperature was -2°C and the outside barometric pressure was 7.8 lbs/inch^2. The aircraft was flying inside the cloud at 18,000 ft in an area of low

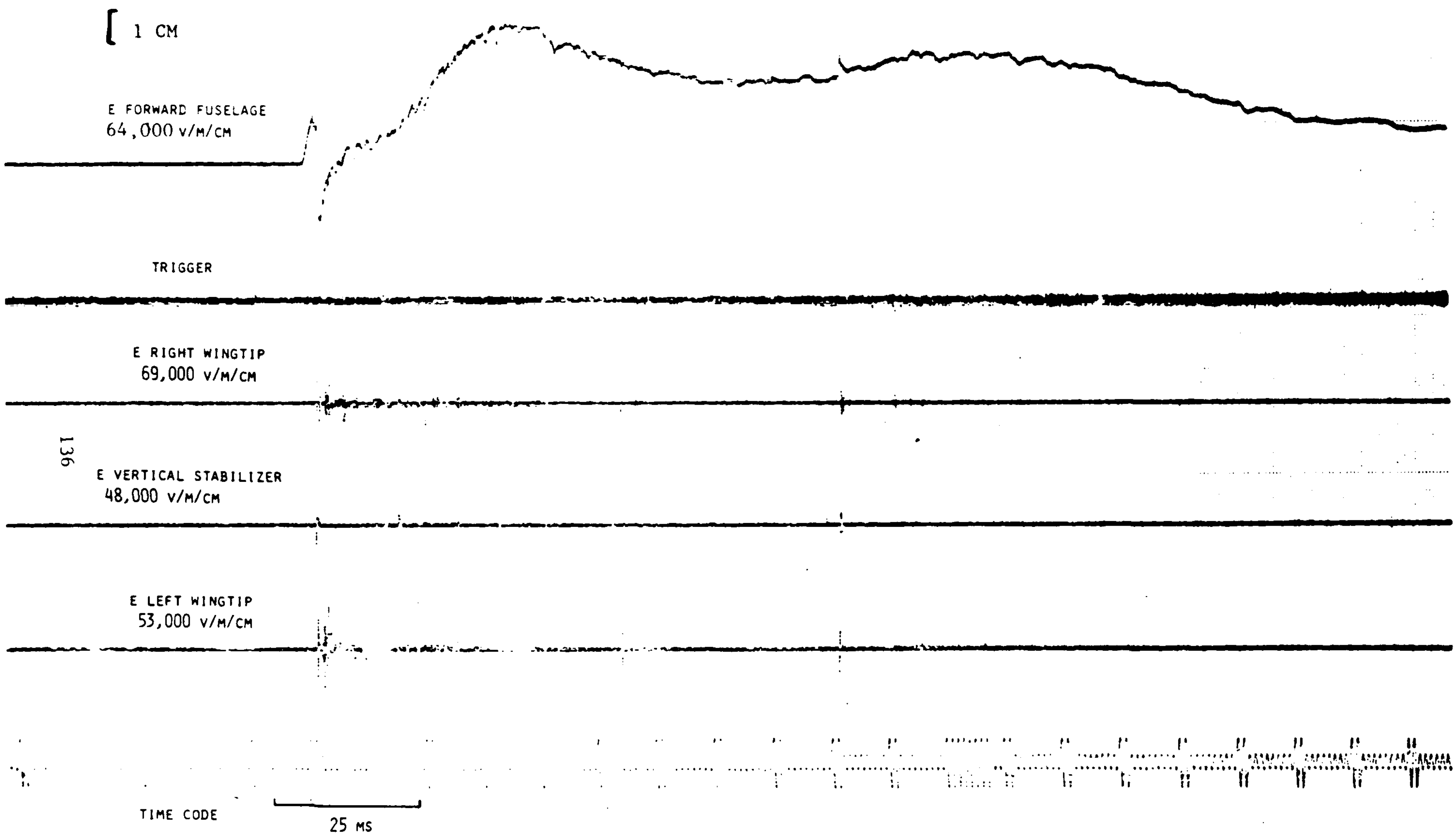

Figure 87. Six Analog Channels Recorded at Beginning of 23:20:36 Flash. Forward Fuselage Trace Inverted

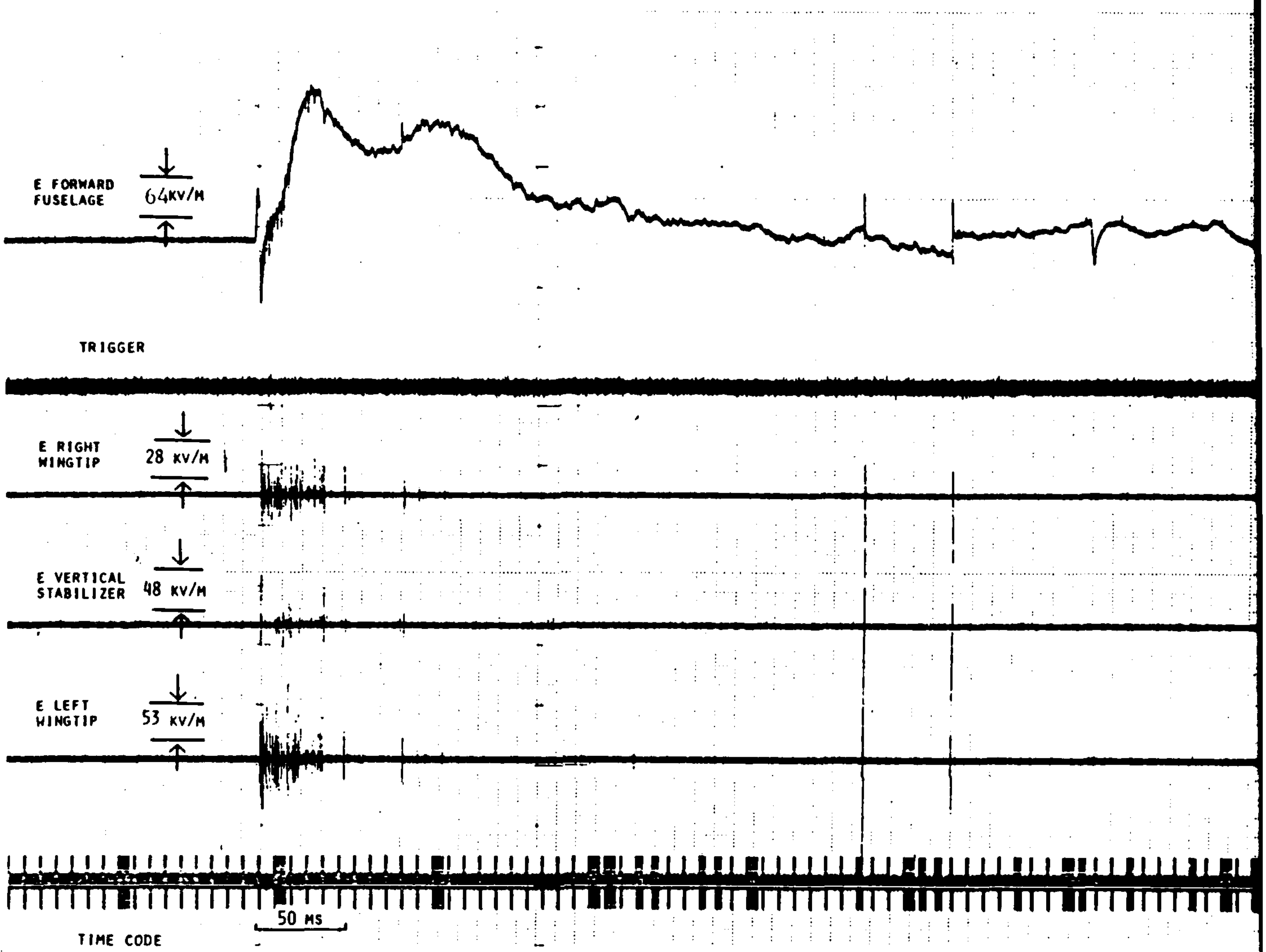

Figure 88. Same Analog Channels for Duration of 23:20:36 Flash. Forward Fuselage Trace Inverted

turbulence. Figure 89 shows that the aircraft was about 5 miles from any region of heavy precipitation returns.

The digital system had become overheated about 10 minutes prior to the flash so the system was not armed. Consequently, we were unable to determine whether this flash would have triggered the digital system.

Figure 90 shows six analog channels recorded for the entire duration of flash. The E forward fuselage trace shows a slow steady positive change in the electric field for about 21 ms prior to the flash. A faster. negative-going transient was then observed. An expansion of this trace showed that fast electric field transients occurred on the right and left wing tips during the positive leader pulse about 0.7 ms prior to the negative transient. It appeared that a leader pulse propagated towards the aircraft for about 21 ms and that one of the leader branches got close enough to produce streamer propagation from the aircraft. The flash lasted about 200 ms and the largest current pulse measured during this time was about 1.8 kA on the right wing tip at the beginning of the attachment. The largest electric field transient measured during the flash was 140 kV/m on the right wing tip.

A post-flight inspection of the aircraft revealed significant damage to the deicing foam near the center of the right wing propeller. Burn spots typical of lightning attachments were found on the tip of one of the propeller blades. Burn marks were also found on the right wing tip boom and on the vertical stabilizer.

In conclusion, this section presented a brief description of the data recorded during the 21 direct lightning strike to the CV-580 during the summer 1984 program. The next section will summarize this data, present relevant facts concerning the data, and give an interpretation of the results.

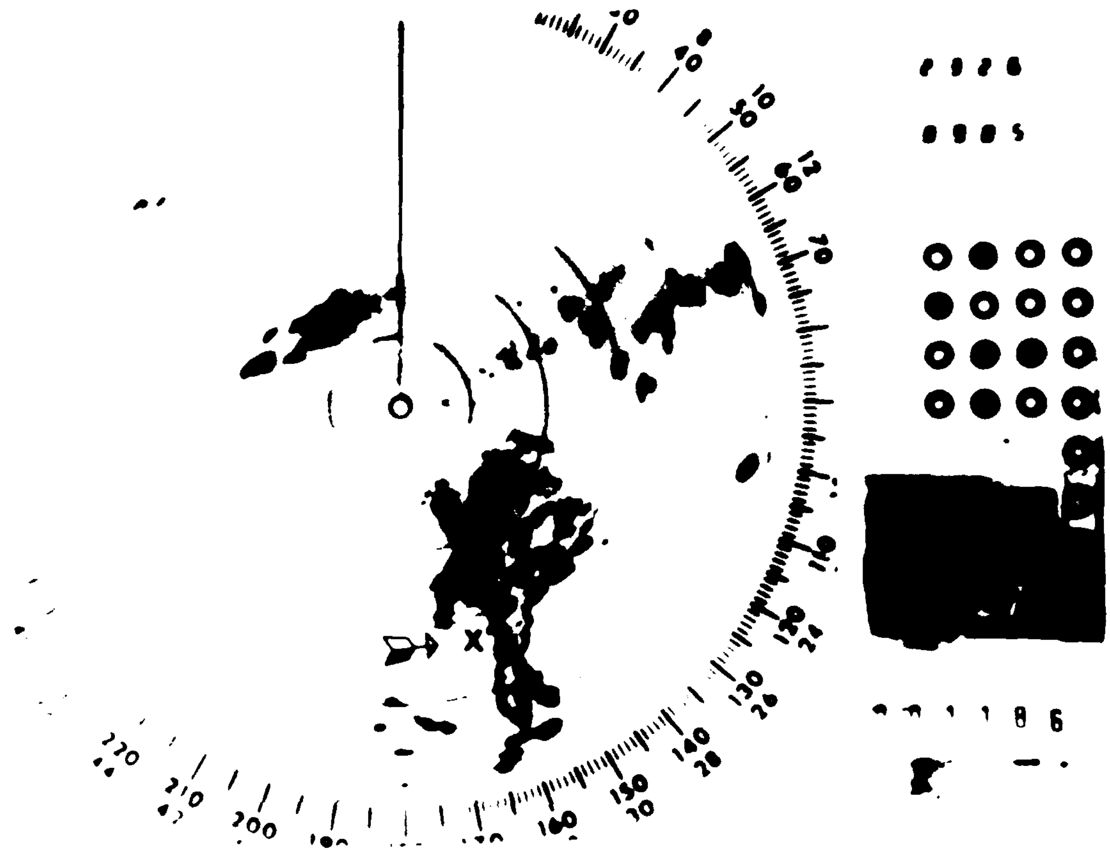

Figure 89. Precipitation Radar Return Showing Position of Aircraft During 23:26:53 Flash

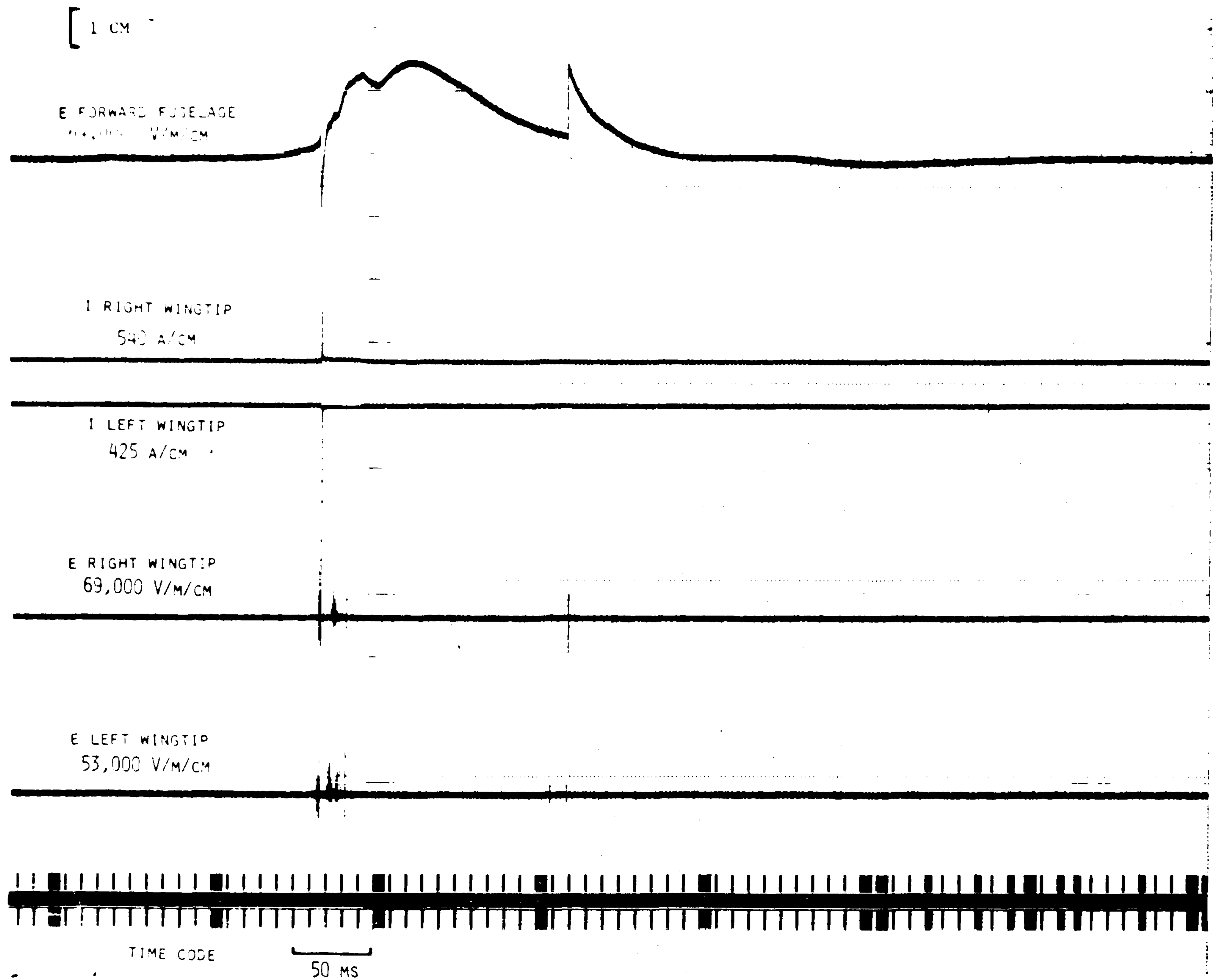

Figure 90. Six Analog Channels for Duration of 23:26:53 Flash. Forward Fuselage Trace Inverted

SECTION IV

SUMMARY OF THE CHARACTERISTICS OF AIRCRAFT LIGHTNING ATTACHMENTS

The purpose of this section is to summarize the results by identifying common patterns of the recorded strikes. Several areas will be addressed: (1) aircraft lightning attachment as a function of altitude, temperature, and turbulence; (2) initiation of the discharges and overall structure of the flashes; (3) correlation of aircraft and ground lightning data; (4) analysis of the 5 ns sampling; and (5) physics of the lightning attachments.

1. AIRCRAFT LIGHTNING ATTACHMENT AS A FUNCTION OF ALTITUDE, TEMPERATURE, AND TURBULENCE

Table 5 summarizes these parameters at the time of each attachment to the aircraft. The turbulence data used in this table was qualitative as reported by the aircraft operators. The letters N, L, M, and S represent levels of none, light, moderate, and severe turbulence. The "in-clouds" column was also based on qualitative observations. If the aircraft was flying inside any cloud at the time of the strike, the column was marked yes (Y). The no (N) description was used only if the aircraft was flying in clear sky at the time. No consideration was given to the distance between the aircraft and the nearest thunderstorm cell. The "charging" and "duration" columns refer to significant charging on the aircraft as indicated by the VHF radio noise or by multiple spots on the Stormscope just prior to each strike. Table 6 lists latitude, longitude, range, and bearing of the aircraft obtained from the VCDS at the time of each strike along with airspeed and air pressure.

TABLE 5

Lightning Attachment Correlated with Altitude, Temperature, and Turbulence

STRIKE	DATE	TIME	OAT(°F)	ALT(Ft)	TURB.	IN-CLOUDS	CHARGING	DURATION(Sec)
1	7/11	21:22:10	27	14,000	L	Y	Y	4
2	7/11	21:31:01	26	14,000	L	Y	Y	4
3	7/13	20:46:23	26	14,000	L	Y	N	-
4	8/6	21:44:05	26	14,000	L	Y	N	-
5	8/7	21:20:57	18	18,000	L	Y	N	-
6	8/7	21:38:24	21	18,000	L	Y	N	-
7	8/7	21:41:24	21	18,000	L	Y	N	-
8	8/7	21:41:59	21	18,000	L	Y	Y	3
9	8/7	21:43:26	19	18,000	L	Y	N	-
10	8/7	22:02:01	20	18,000	L	Y	N	-
11	8/7	22:12:40	20	18,000	L	Y	N	-
12	8/17	21:36;01	55	4,000	N	Y	N	-
13	8/19	00:55:26	57	4,000	N	N	-	-
14	8/20	17:36:00	62	2,000	N	N	N	-
15	9/5	21:44:12	23	18,000	N	N	-	-
16	9/5	21:52:15	24	18,000	L	N	N	-
17	9/5	21:53:05	24	18,000	M	Y	N	-
18	9/5	22:34:42	24	18,000	L	Y	N	-
19	9/5	23:06:08	21	18,000	L	N	N	-
20	9/5	23:20:36	22	18,000	L	N	N	-
21	9/5	23:26:53	28	18,000	L	Y	N	-

TABLE 6

Lightning Attachment Correlated with
Latitude, Longitude, Range, Bearing, Speed, and Pressure

STRIKE	LAT/LONG	BEARING(°)	RANGE(Naut. Miles)	TAS(Knots)	PRESS(Lbs/Inch^2)
1	27:57/82:26	255	107	---	---
2	27:55/82:24	254	105	---	---
3	28:55/81:20	267	44	229	8.6
4	28:33/81:22	277	44	---	---
5	28:13/81:28	252	46	265	7.3
6	28:09/81:33	252	57	250	7.2
7	28:16/81:44	260	64	268	7.3
8	28:17/81:46	262	66	274	7.3
9	28:20/81:52	265	70	252	7.3
10	28:20/81:57	264	74	253	7.3
11	28:16/81:59	263	77	252	7.2
12	27:20/81:01	202	73	---	---
13	--------	---	--	---	---
14	28:21/80.10	120	28	---	---
15	28:13/80:18	---	--	195	13.6
16	28:10/80:50	222	24	266	7.3
17	28:10/80:53	227	26	278	7.3
18	28:10/80:39	200	19	290	7.1
19	28:17/80:12	123	21	273	7.0
20	--------	---	--	---	---
21	27:51/80:36	188	35	269	7.8

Figure 91 shows the percentage of hours flown at each altitude and Figure 92 gives the percentage of lightning strikes received there. Even though the aircraft was flown at altitudes at or below 10,000 ft about 70% of the time, only three strikes occurred at these lower altitudes. These strikes occurred on 17, 19, and 20 August 1984. The 20 August strike occurred while the aircraft was flying below the cloud base at an altitude of 2,000 ft. There was visual confirmation of a cloud-to-ground discharge. The other two strikes occurred at 4,000 ft inside the lower base of the cloud but confirmation that the aircraft was involved in a cloud-to-ground discharge could not be obtained. The LLP system, however, indicated a cloud-to-ground discharge within five miles of the aircraft at the time of the 17 August flash.

Figures 93-95 show histograms of precipitation returns, turbulence, and outside air temperature at the times of the lightning strikes to the aircraft. Before generalizing these results, the reader should remember that aircraft penetration inside thunderstorms was limited to areas of precipitation returns less than 40 dBz. Most often, pilots flew the aircraft on the edge of the thunderstorms and avoided penetration inside the middle of the storms. Penetrations inside storm centers only occurred during decaying stages of the storms when radar precipitation returns were considerably less than 40 dBz.

[illegible]. THE INITIATION OF THE DISCHARGES AND OVERALL STRUCTURE OF THE FLASHES

Table [illegible] summarizes some of the electromagnetic data collected during the [illegible] lightning strikes to the aircraft. A determination of whether or not the aircraft triggered a lightning discharge is based on detailed expansions of

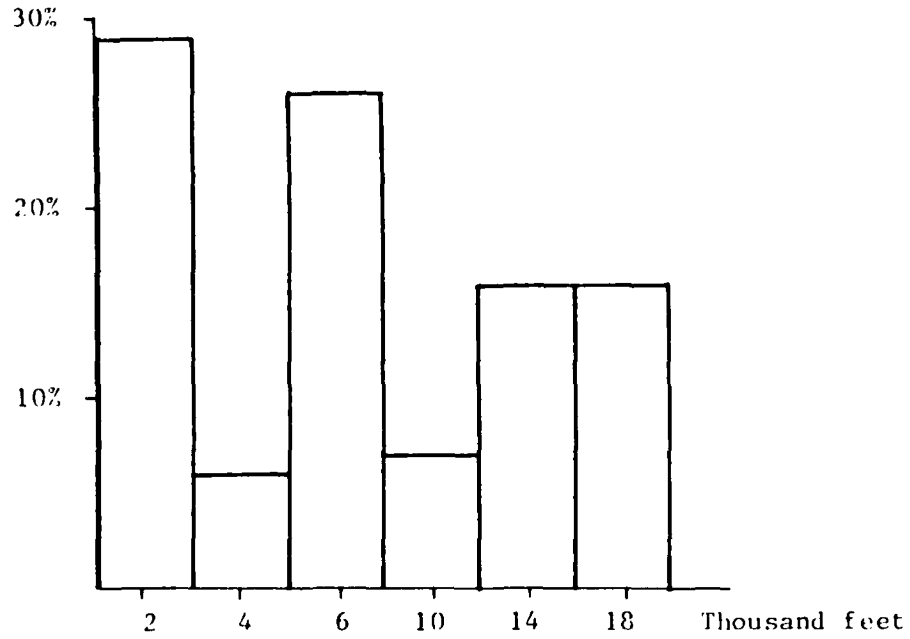

Figure 91. Histogram Showing the Percentage of Hours Flown at Different Altitudes

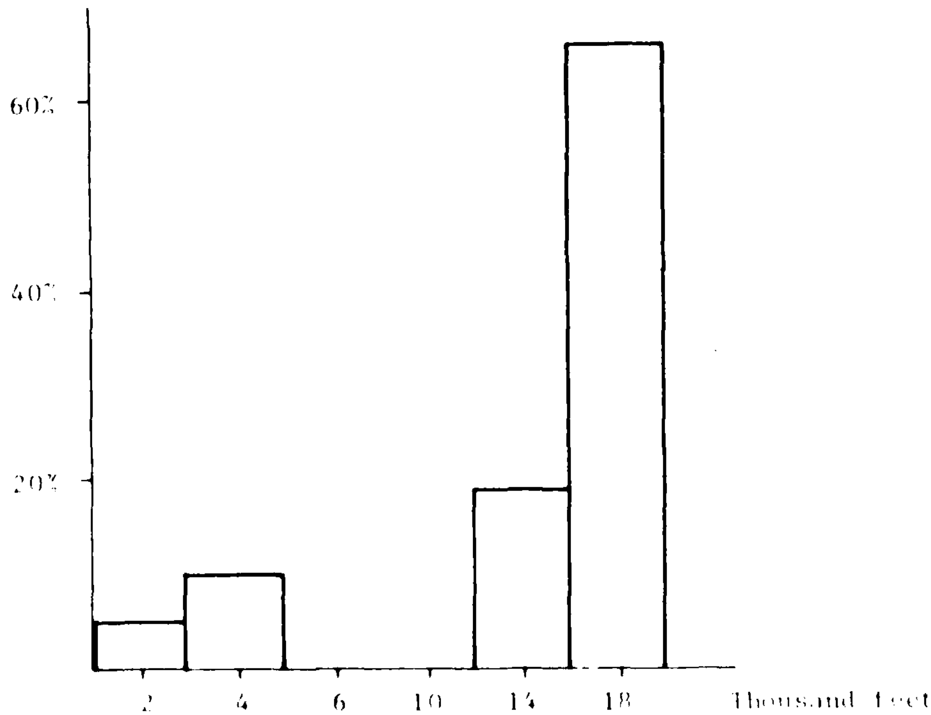

Figure 92. Histogram Showing the Percentage of Lightning Strikes at Different Altitudes

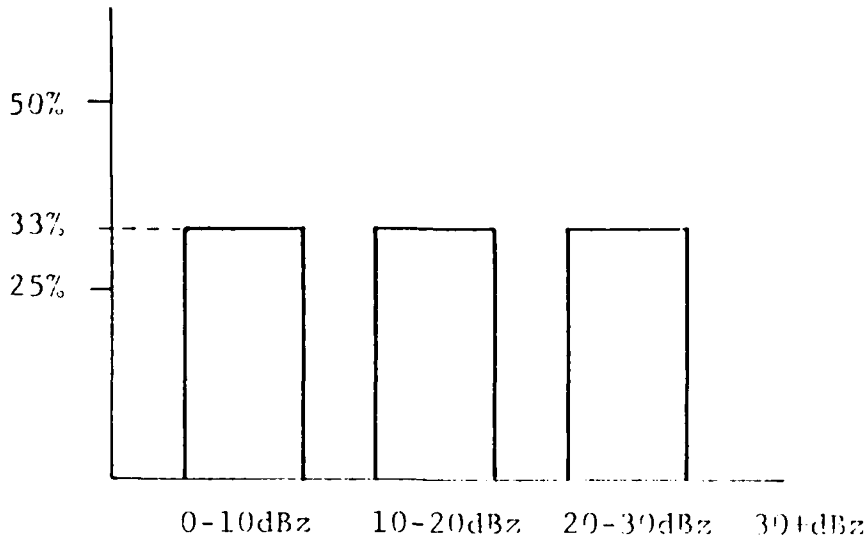

Figure 93. Histogram Showing Percentage of Lightning Strikes for Various Levels of Precipitation Returns

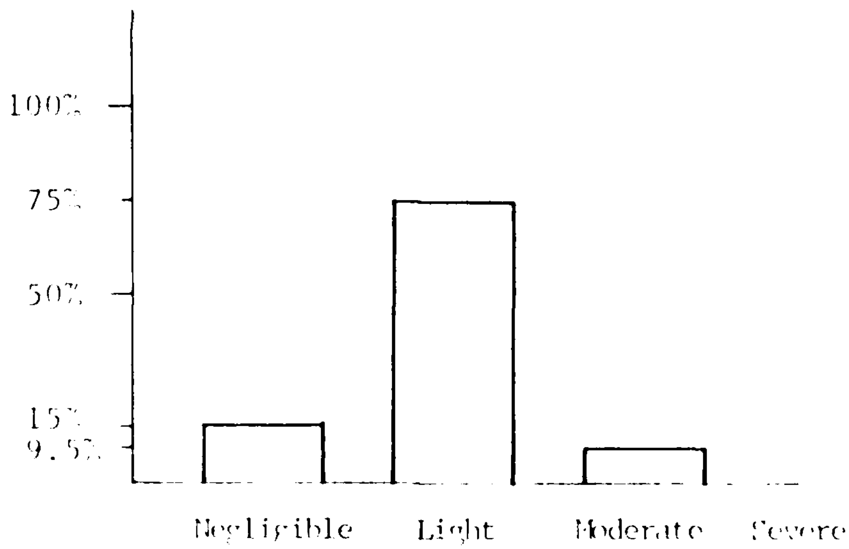

Figure 94. Histogram Showing the Percentage of Lightning Strikes at Different Levels of Turbulence

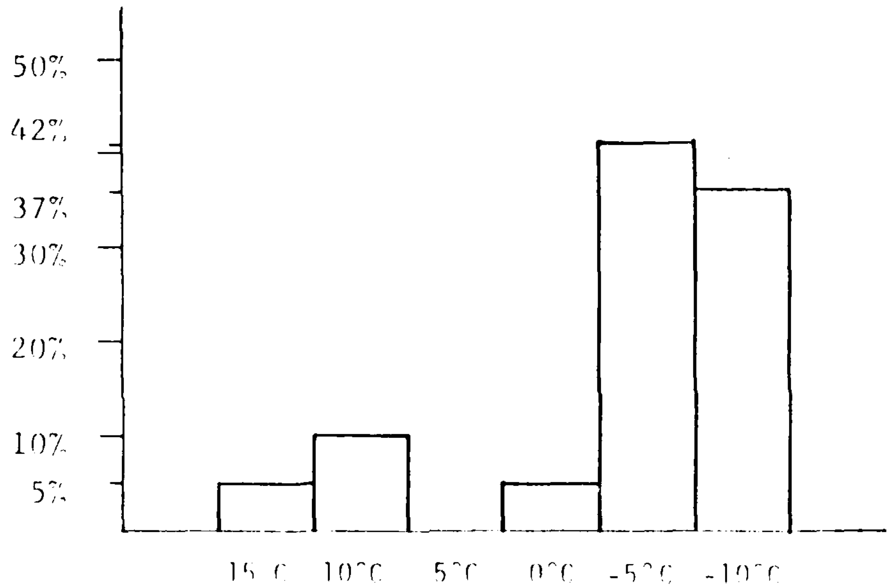

Figure 95. Histogram Showing the Percentage of Lightning Strikes at Different Ambient Temperatures

TABLE 7

Summary of Lightning Flash Characteristics

Flash No	Height (ft)	Triggered Discharge	Leader Duration (ms)	Distance to Charged Region (m)	Streamers Propagated from Aircraft
1	14,000	Yes	2.1	315	Yes
2	14,000	Yes	2.7	405	Yes
3	14,000	Yes	1.7		No
4	14,000	Yes	-	-	-
5	18,000	Yes	2.1	315	No
6	18,000	Yes	2.2	330	No
7	18,000	Yes	2.1	315	No
8	18,000	Yes	2.1	315	No
9	18,000	Yes	2.2	310	No
10	18,000	Yes	2.1	315	No
11	18,000	No	20.0	3000	No
12	4,000	No	4.7	705	No
13	4,000	No	-	-	No
14	2,000	No	-	-	No
15	18,000	-	-	-	-
16	18,000	Yes	1.6	240	No
17	18,000	INT*	5.0/1.0	750/150	Yes
18	18,000	-	-	-	-
19	18,000	INT*	21.0/1.8	3150/270	No
20	18,000	Yes	1.6	240	No
21	18,000	INT*	21/0.7	3150/105	Yes

INT* - The discharge was not triggered by the presence of the aircraft but its path was affected by the aircraft.

the analog data at the beginning of each flash. These data were presented in the previous section, when available.

When the electric field detected on the forward fuselage showed a slow steady variation from zero for a two millisecond or less period prior to any fast electric field change, it was assumed that the aircraft triggered the discharge. It was also assumed that the first fast electric field change indicated actual attachment of a propagating lightning channel to the aircraft. With average leader velocities being approximately 1.5×10^5 m/s, a two millisecond electric field change corresponds to about 300 meters of channel propagation. Within this distance, aircraft enhancement of the field should be sufficient to trigger a discharge. Discharges could occur from the surrounding region to the aircraft or from the aircraft to the region.

None of the flashes categorized as triggered show slow field changes for more than 2.7 ms before the first fast transient. It was assumed that each discharge began with propagation of a leader. Twelve of the 21 discharges have the characteristics of a triggered flash. Three of the remaining flashes, those at low altitudes, appear to be part of cloud-to-ground discharges. In addition, flash (11) on Table 7 shows a slow steady field change for about 20 ms prior to the first fast field change. This is not characteristic of a triggered discharge.

Flashes (17), (19), and (21) show slow field changes of 5, 21, and 21 ms, respectively, before somewhat faster field changes more characteristic of triggered flashes are observed. For these flashes, two numbers are listed in the "leader duration" column, the first number being the length of slower field change. These discharges apparently propagated for several milliseconds (5, 21, and 21, respectively) before one of the channels of the flash came close enough to be attracted to the aircraft because of the field enhancement. This type of discharge was marked as INT because the flash appeared to be intercepted by the aircraft.

The remaining three of the 21 total flashes could not be categorized because analog data was not recorded. The "distance to the charge region" column in Table 7 corresponds to a multiplication of the leader duration by the 1.5×10^5 m/s average leader velocity.

Figure 96 shows expansions of the forward fuselage electric field records during the beginning of 10 triggered discharges. Each of these flashes started with a slow negative-going electric field change followed by a fast positive field change. Figure 97 shows the electric field record for one of the flashes not described as being triggered by the presence of the aircraft. The slow negative electric field change lasted over 20 ms before the sharp positive field change occurs, indicating the time of the actual lightning attachment.

Table 8 summarizes some of the characteristics of the analog and digital data collected for the 21 strikes. The last two columns were obtained from analog records. The duration of the flashes ranged from 130 ms to 1.3 sec, an order of magnitude difference. Following the initial active period and first field change, all triggered discharges had active pulse repetition rates usually lasting between 20 and 50 ms. Maximum pulse repetition rates during this phase sometimes reached 10^4 pulses/sec.

These initial active trains of pulses were usually followed by short trains of pulses with durations of a few milliseconds or by a few isolated pulses. About 80% of all the pulses in each flash occurred during the first 50 ms. However, isolated pulses near the end of a discharge were often the largest pulse transients measured during the entire event. Overall, the

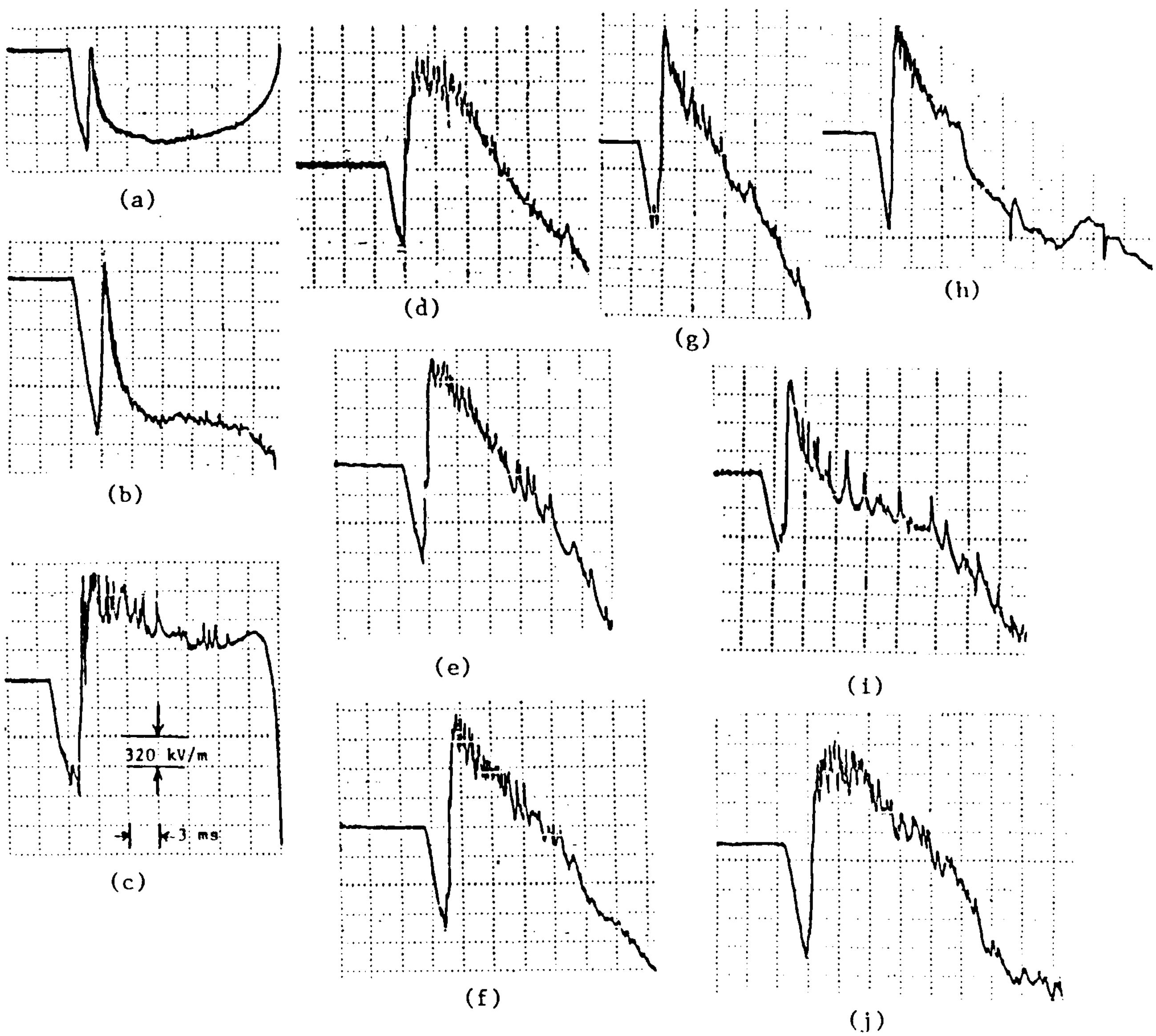

Figure 96. Forward Fuselage Electric Field Measurements During the Initiation of 10 Different Lightning Discharges. Horizontal Scales Are 3 ms Per Division. Vertical Scales Are 320 kV/m Per Division.

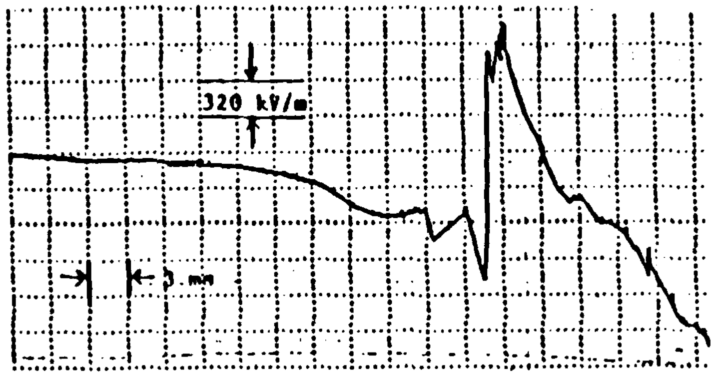

Figure 97. Forward Fuselage Electric Field Trace During One of the Flashes Intercepted by the Aircraft

TABLE 8

Peak Surface and Displacement Current Densities
Measured During 21 Lightning Attachments

Flash No	Digital System Threshold Level (T/s)	Digital System Triggered	DIGITIZER DATA: Largest Surface Current Density Pulse (T/s)	DIGITIZER DATA: Largest Displacement Current Density Pulse (A/m^2)	ANALOG DATA: Largest E Field Transient (kV/m)	Duration of Flash (ms)
1	1500	No	-	-	165	780
2	1500	No	-	-	132	400
3	400	Yes	872	3.2	160	430
4	400	Yes	1251	2.5	-	-
5	4000	No	-	-	135	450
6	4000	No	-	-	207	940
7	400	Yes	683	22.5	170	780
8	400	Yes	2900	19.7	138	680
9	400	Yes	1254	20.4	165	1300
10	400	Yes	415	0.8	207	240
11	400	Yes	465	1.6	165	500
12	800	Yes	3950(Sat)	8.77(Sat)	159	140
13	1200	Yes	2560	1.5	-	-
14	1200	Yes	1794	9.0	-	-
15	1500	No	-	-	-	-
16	1500	No	-	-	162	360
17	1500	Yes	2065	21.7	265	310
18	1500	No	-	-	-	-
19	1500	No	-	-	80	130
20	1500	Yes	-	-	115	750
21	1500	No	-	-	140	200

total durations of the attachments are comparable to those of cloud-to-ground and intracloud discharges which last an average of about 0.5 sec (Reference 11).

The largest electric field transients were obtained from displays of analog electric field measurements having a frequency response from 400 Hz to near 2 MHz. All the flashes had electric field transients higher than 100 kV/m and the largest field change was about 200 kV/m.

The digital system triggered whenever any surface current density measurement exceeded a preset threshold level. The selected level ranged from 400 T/s to 4000 T/s for the different flights. The digital system did not trigger during the two strikes for which the trigger level was set at 4000 T/s. Digital triggering occurred for two of nine strikes where the trigger level was set at 1500 T/s. The system always triggered whenever the threshold level was set at 1200, 800, or 400 T/s, as was done for 10 of the 21 events. Peak surface and displacement current densities measured during the triggered events are also shown in Table 8. The largest surface current density exceeded the saturation level of 3950 T/s for one of the low altitude flashes and the maximum displacement current density was 22.5 A/m^2 during one of the flashes at 18,000 ft.

3. CORRELATION OF AIRCRAFT AND GROUND LIGHTNING DATA

During the 5 Sept strike at 23:20:36 Z, the CV-580 aircraft was flying 68 km south of the ground station. The aircraft was flying inside the clouds in an area of low turbulence at an altitude of 18,000 ft with an outside air temperature of -3°C.

Figure 98 shows some of the analog data recorded in the aircraft and on the ground during the beginning of the discharge. The top six traces were

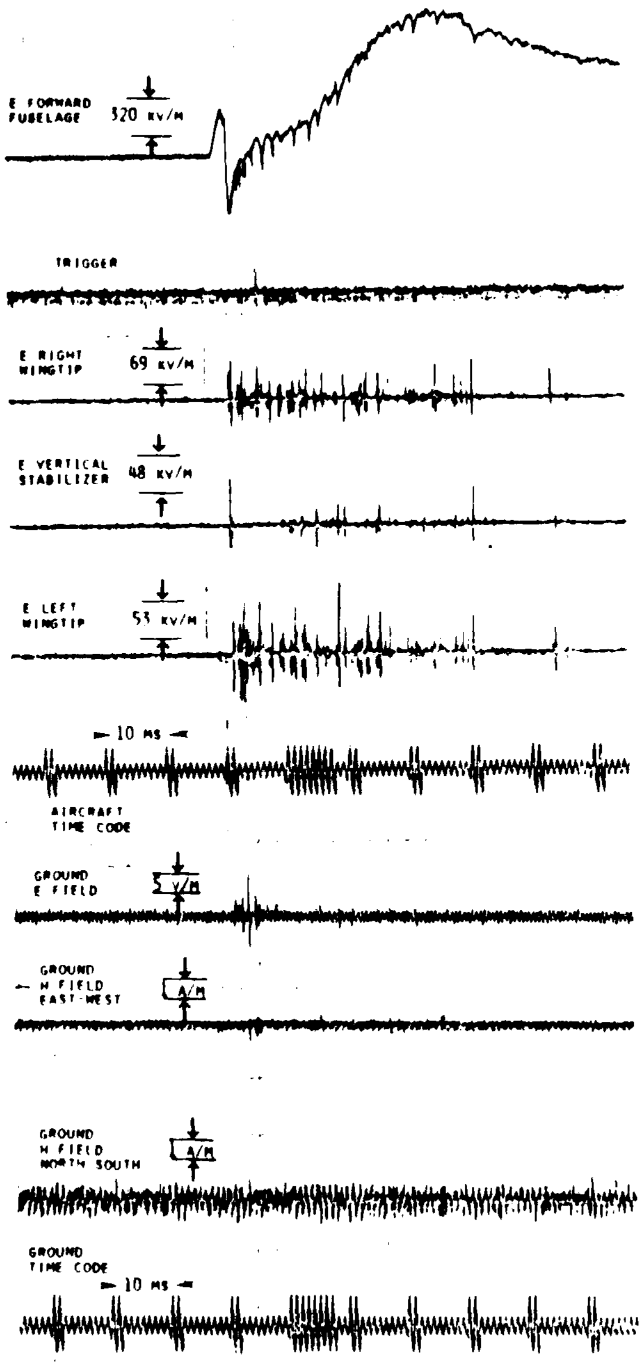

Figure 98. Simultaneous Displays of Analog Records During Beginning of 23:20:36 Flash. Top Six Traces Were Recorded in the Aircraft and Bottom Four Traces Were Recorded at the Ground Site.

played back from the analog recorder on the aircraft and the bottom four traces show simultaneous far field data at the ground station 68 km away. The first six traces in Figure 98 are identical to those in Figure 87 for the beginning of the discharge. The bottom four signals are, from top to bottom, the vertical electric field, two perpendicular components of the magnetic field, and the ground time code. The time correlation between the aircraft and the ground station was about 1 ms.

The top trace corresponding to the electric field on the forward fuselage appears inverted when compared to the traces in Figures 96 and 97. This is the result of changes made to the signal conditioning box, as noted earlier. This flash fits our characterization of a triggered discharge with the lightning channel attachment to the aircraft occurring at the time of the fast negative-going transition on the forward fuselage electric field. Large ground electric and magnetic field pulses were measured about 3 ms after the initial lightning attachment to the aircraft. It appears that the lightning discharge propagated several kilometers after striking the aircraft sending additional charge through the channel.

Two important observations can be made by comparing the aircraft and ground data. First, the lightning attachment to the aircraft was a full blown lightning discharge of intensity comparable to those of intracloud flashes. If the strike consisted of only small discharges within the region surrounding the aircraft, the electromagnetic fields created by the discharge could not be measured 68 km away. This point can be further illustrated by considering the expansion of the ground electromagnetic field data shown in Figure 99. The shape and relative magnitude of these pulses are comparable to those measured by Weidman and Krider (Reference 12) about 30 or 40 miles from intracloud discharges. Secondly, at the time of the

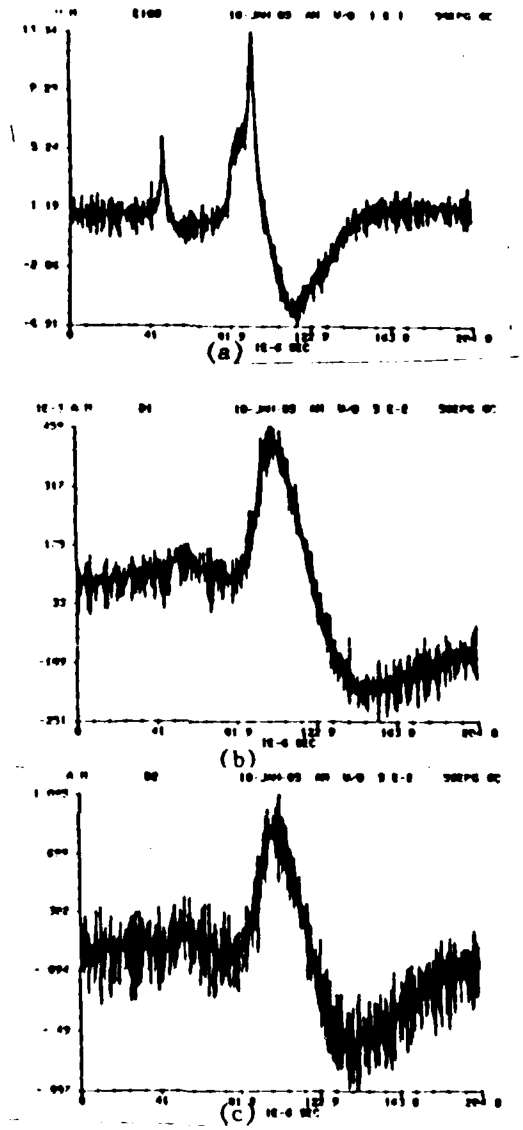

Figure 99. Simultaneous Records of (a) Vertical Electric Field and (b) and (c) Two Magnetic Fields Measured at the Ground Site During the Intracloud Discharge

initial aircraft attachment which occurred about 2 ms after the beginning of the slow electric field change, the lightning discharge was still in its beginning stages of propagation. The main lightning channel which neutralized most of the charge involved in the discharge was not formed until about 3 ms later. The aircraft became part of the discharge channel but was not a main source of charge. The channel had to propagate beyond the aircraft to find sufficient charge to neutralize the discharge. For this specific case, several point charge models could be made to estimate the amount of charge needed for an intracloud discharge to measure nearly 15 V/m 68 km away. In any case, the result would likely require a charge of about 10^4 times the charge on the aircraft.

4. ANALYSIS OF THE 5 NS SAMPLING

Twelve of the 21 lightning strikes triggered the digital system while set at threshold levels of 400, 800, 1200, or 1500 T/s. Digital data for one of these strikes were lost during acquisition due to extreme heating of the 7612D transient recorders. For the other 11 triggering events, 12 simultaneous signatures of surface or displacement current densities and the currents were collected. These data were shown in Section III for the respective events.

Most of the collected data were from the surface and displacement current density sensors located throughout the aircraft. Two important points can be derived from these results. First, only two out of nine events triggered the system at a threshold setting of 1500 T/s and zero out of two events triggered at a threshold setting of 4000 T/s. However, the system always triggered at threshold levels of 400, 800, and 1200 T/s. From this limited statistical sample, an attempt can be made to estimate the rate of rise of the current during the many pulses of an aircraft lightning attachment. Assuming a uniform current distribution during individual current pulses on the aircraft, the rate of rise of the current during about half of the strikes did not exceed 4×10^{10} A/s. For events that triggered the digital system, the corresponding maximum rate of rise of the current was about 7×10^{10} A/s. These values are well below the accepted MIL-STD-1757 of 1×10^{11} A/s. However, a nonuniform distribution of the current flow throughout the aircraft could produce a significant increase in these levels. The second point to be made is that by studying the propagation of the lightning channels in Figures 62 and 79, it was clear that lightning propagated over the entire surface of the aircraft and reflected back from all the aircraft extremities.

Figure 61 showed the attenuation and reflection of the current pulses on the aircraft as the pulse propagated from the attachment point near the nose of the aircraft to the tail and wings. The peak surface current density pulse was attenuated by half as it propagated about 10 meters from the forward toward the aft fuselage. The most significant reflections of the current pulses occurred between main aircraft extremities such as from nose-to-tail or from wing tip-to-wing tip. However, some reflections can be measured whenever there is a discontinuity in the aircraft resistance looking from the direction of the propagating lightning channel.

Figure 79 showed a similar case for which the current pulse propagated from the right wing tip attachment point to the rest of the aircraft. For that case, the most significant reflection occurred at the opposite wing tip but reflections were also measured between the fuselage and the engines. Interestingly, attenuation per meter of electromagnetic propagation during lightning attachments to the wings appears to be smaller than during lightning attachments to the fuselage.

5. PHYSICS OF THE LIGHTNING ATTACHMENTS

Several important implications regarding the physics of lightning discharges have been discussed in this report. Data obtained during 21 lightning strikes showed sufficient similarities to improve significantly our understanding of the lightning discharge. This section provides a summary of some of the most important characteristics of the data and their implications on the physics of lightning discharges.

a. Meteorological conditions at the time of the discharges. The average amount of time between lightning strikes to the CV-580 aircraft flying at 18,000 ft was about 20 minutes. The time increased to about 30 minutes at 14,000 ft and become several hours between 2000 and 10,000 ft. When compared to the results from the NASA F-106 aircraft which flies primarily above 20,000 ft (References 3 and 4), it becomes apparent that the average time between lightning strikes is a function of the cloud charge density surrounding the aircraft. The F-106 aircraft has experienced lightning strike rates much higher than the CV-580 aircraft at altitudes between 20,000 and 35,000 ft. The same F-106 aircraft, while flying between 10,000 and 20,000 ft, obtained much lower lightning strike rates than the CV-580.

In most Florida thunderstorms, the main negative charge center is located between 16,000 and 30,000 ft and this is the region having the highest charge density. The F-106 has experienced high lightning strike rates above 30,000 ft probably due to the high positive charge density near the top of a thunderstorm. However, the charge density becomes quite small between the bottom of the cloud and about 10,000 ft. This accounts for the difficulty of obtaining lightning strikes to the aircraft at these lower altitudes.

b. Types of lightning discharges to aircraft. As was discussed in this report, 12 of the 21 lightning attachments appeared to be triggered by the presence of the aircraft within about 300 meters of a charged region. When the aircraft flew near one of these charged regions, there was an enhancement of the electromagnetic field near aircraft extremities such as the wing tips, nose, and the vertical tail producing a breakdown between the charge region and the aircraft. Streamer propagation in this region would start at either the aircraft, the surrounding charge region, or both. When the channel formed through the aircraft, it probably propagated for several kilometers until it neutralized the original charge region near the aircraft. The aircraft could not accumulate sufficient charge to be one of the charge centers in the discharge. Consequently, the discharge continued as a regular intracloud discharge with the only difference being that it was initiated by the presence of the aircraft near the charged region.

This rationale is supported by several aspects of the data. Since there is a small volume of charge density below 10,000 ft, the aircraft cannot trigger a discharge at those altitudes and the probability of receiving a lightning strike is reduced to the mere possibility of the aircraft intercepting an already propagating intracloud or cloud-to-ground flash. Additionally, all the aircraft lightning strikes were comparable in total length and characteristics to intracloud or cloud-to-ground discharges as indicated by correlation of aircraft and ground station data.

c. Structure of the lightning discharges. The types of pulse structures observed during aircraft lightning strikes have characteristics similar to those reported in the literature for intracloud flashes. Without considering the initial few milliseconds apparently affected by the presence of the aircraft, the discharges show two distinct phases. The first phase lasts between 20 and 60 ms and is characterized by high pulse repetition rates in the neighborhood of 10^3 or 10^4 pulses/sec. This phase is followed by isolated pulses or short trains of pulses separated by tens or hundreds of milliseconds. These two phases can be compared with the description of intracloud discharges given by Kitagawa and Brook (Reference 13). Instead of recognizing three phases (initial, active, and junction), our data basically shows the active and junction phases. During the active phase, there is continuing channel propagation and discharging of new pockets of charges throughout the semi-established channel. As the channel propagates and approaches a new pocket of charge, that region will discharge through the existing channel and produce a fast pulse in the data. When the main region is discharged, taking the amount of time corresponding to the length of the active region, the channel remains semi-active for hundreds of milliseconds and few additional pockets of charges are discharged during this period. This process is similar to a cloud-to-ground discharge with hundreds or thousands of mini return strokes.

d. Individual pulses in the discharges. The individual pulses in aircraft lightning discharges can have very different characteristics. Current and field pulses may have risetimes ranging from tens of nanoseconds to several microseconds. However, the magnitudes of the current pulses are much lower than those measured on the ground during cloud-to-ground discharges. All current pulses which were measured or inferred by the field pulses did not exceed 4 or 5 kA. The main subject of concern is the pulse repetition rates of these pulses. While an isolated 2 or 4 kA pulse with a risetime of about 100 ns does not exceed the MIL-STD-1757, a fast pulse repetition rate involving hundreds or thousands of pulses could have a detrimental effect on aircraft instrumentation. There should be an intense effort to understand the potential vulnerability of aircraft electronics to the effects of high pulse repetition rates.

e. Continuing current during the lightning discharges. Previous data reported in the literature (Reference 11) estimate charge transfers of about 10 C during intracloud discharges. However, for one aircraft strike where the entire lightning discharge propagated through one of the wing tips, the charge transfer exceeded 100 C. This strike occurred on 7 Aug 85 and is listed as strike (6) in Table 5. Even though this was the only discharge that propagated through one of the current booms during the entire duration of the discharge, measurements performed during portions of other discharges also showed rather large charge transfers. Since the aircraft was located near charge centers during the triggered discharges, apparently much larger charge transfers occur than those that can be estimated by ground measurements. Presently, MIL-STD-1757 provides for a maximum charge transfer of 200 C. Our data does not rule out the possibility of maximum charge transfers in excess of 200 C.

SECTION V

CONCLUSIONS

This interim report highlights the progress made during the first year of a two year in-flight program to investigate direct lightning attachments to aircraft and to compare the measured responses with those of simulated NEMP. A cursory look at the 1984 efforts reveals several noteworthy findings.

The sensors and instrumentation described in Sections II and III formed an elaborate data acquisition system capable of recording aircraft responses over a wide range of frequencies. The system performed extremely well despite the often turbulent and excessively warm operating conditions. Based on this performance, 12 additional digital channels were added to the 1985 system.

Twenty-one direct lightning strikes to the CV-580 were recorded. Twelve of the strikes appeared to be triggered by the presence of the aircraft while three attachments may have occurred in branches of cloud-to-ground discharges. Peak electric and magnetic flux densities measured 22 A/m^2 and 3950 T/s, respectively. The maximum charge transfer during one lightning attachment was estimated to be over 100 C.

The probability that an aircraft will be struck by lightning appears to increase as a function of height within the altitude ranges of the CV-580. Accordingly, most of the strikes occurred at ambient temperatures below the 0°C. These trends account for the relative difficulty in obtaining low altitude attachments below 10,000 ft.

None of the recorded measurements exceeded threat levels defined in MIL-STD-1757. However, pulse repetition rates on the order of 10^4 pulses/sec were often observed. The effects of such high pulse repetition rates on aircraft microelectronics should be investigated and addressed in existing lightning protection specifications.

The aircraft incurred numerous pin holes and burn marks as a result of direct lightning attachments. Considerable damage to nonmetallic surfaces was also observed.

The results noted here are based on a minimal amount of analysis of the recorded data. An in-depth study is continuing and major results will be reported in future reports.

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