IN-FLIGHT DIRECT STRIKE LIGHTNING RESEARCH

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EXPANDED ABSTRACT

In future aircraft, the projected use of digital avionic systems, along with composite aircraft structure, compounds lightning related problems. Digital avionic systems are potentially more susceptible to upset by electrical transients than previous generation systems, and the composite structure may not provide electrical shielding equivalent to that provided by metal aircraft. Future design processes will thus require lightning protection assessment techniques for digital avionic systems operating in electromagnetically nonoptimum structures. A necessary requirement of potential assessment techniques (which may range from purely analytical, through simulation, to actual hardware tests) is a refined definition of the lightning electromagnetic hazard. Recent ground-based measurements have indicated that the rise times of lightning electromagnetics are around one order of magnitude faster than is used in current lightning protection criteria.

The NASA Langley Research Center is performing in-flight direct strike lightning research to better define the lightning-generated electromagnetic environment affecting aircraft. The research program uses an NASA F-106B aircraft which operates in a thunderstorm environment and is specially instrumented for lightning electromagnetic measurements. This presentation reviews the instrumentation system and presents typical results recorded by the research instrumentation, during simulated-lightning ground tests performed for a safety survey, along with several examples of direct strike data obtained during the summer of 1980.

INTRODUCTION

The NASA Langley Research Center is performing in-flight direct strike lightning research to better define the lightning-generated electromagnetic environment affecting aircraft. The research program uses an NASA F-106B aircraft which operates in a thunderstorm environment and is specially instrumented for lightning electromagnetic measurements. This presentation reviews the instrumentation system and presents typical results recorded by the research instrumentation, during simulated-lightning ground tests performed for a safety survey, along with several examples of direct strike data obtained during the summer of 1980.

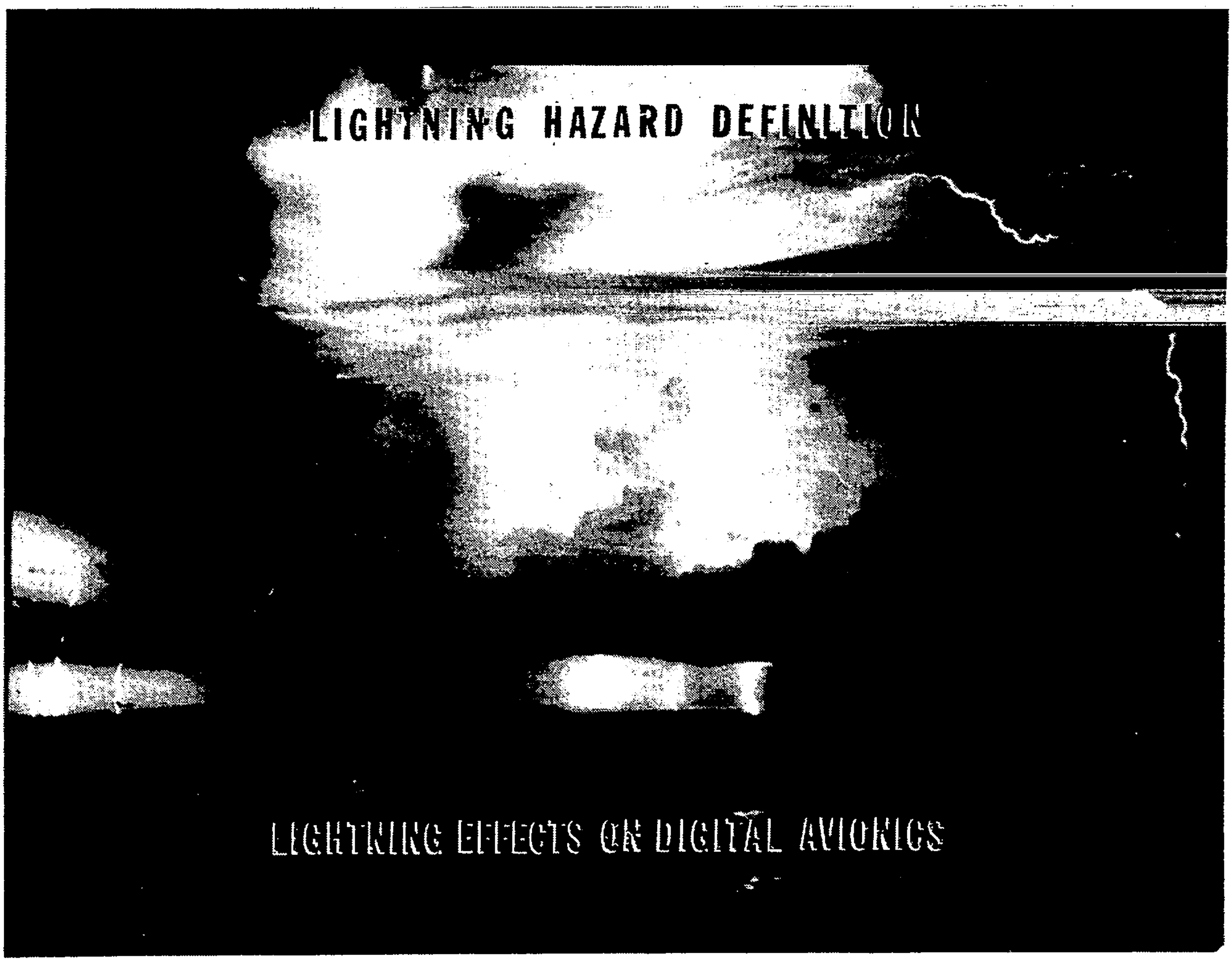


Figure 1

MOTIVATION FOR LIGHTNING RESEARCH

In future aircraft, the projected use of digital avionic systems, along with composite aircraft structure, compounds lightning related problems. Digital avionic systems are potentially more susceptible to upset by electrical transients than previous generation systems, and the composite structure may not provide electrical shielding equivalent to that provided by metal aircraft. Future design processes will thus require lightning protection assessment techniques for digital avionic systems operating in electromagnetically nonoptimum structures. A necessary requirement of potential assessment techniques (which may range from purely analytical, through simulation, to actual hardware tests) is a refined definition of the lightning electromagnetic hazard. Recent ground-based measurements have indicated that the rates of rise of lightning electromagnetics are around one order of magnitude faster than is used in current lightning protection criteria.

LIGHTNING EFFECTS ON DIGITAL SYSTEMS

- COMPOSITE STRUCTURE SHIELDING INEFFECTIVENESS
- DIGITAL SYSTEM SUSCEPTIBILITY TO DISTURBANCE BY ELECTRICAL TRANSIENTS
  - MOMENTARY ANOMALIES - GLITCHES
  - UPSETS - ANOMALIES REQUIRING RESET OR RELOAD
  - PERMANENT DAMAGE - COMPONENT FAILURE
- LIGHTNING CAN SIMULTANEOUSLY AFFECT ALL CHANNELS OF REDUNDANT SYSTEMS

Figure 2

SIMPLIFIED LIGHTNING MODEL

This lightning model illustrates several lightning electromagnetic concepts even though the model is grossly simplified in that it assumes the charge Q is uniformly distributed in a single, straight, vertical, non-tortuous channel. E and B are the electric and magnetic fields, respectively, generated by the lightning current (which is the time rate of change of Q, noted by $\dot{Q}$). H is height of the channel, D is distance from the channel, t is time, c is the speed of light, ε_0 and μ_0 are the permittivity and permeability of free space. The argument (t - D/c) illustrates the traveling wave nature of the radiation. The magnetic field has no static term; the radiation and induction terms are inversely proportional to the first and second power, respectively, of D.

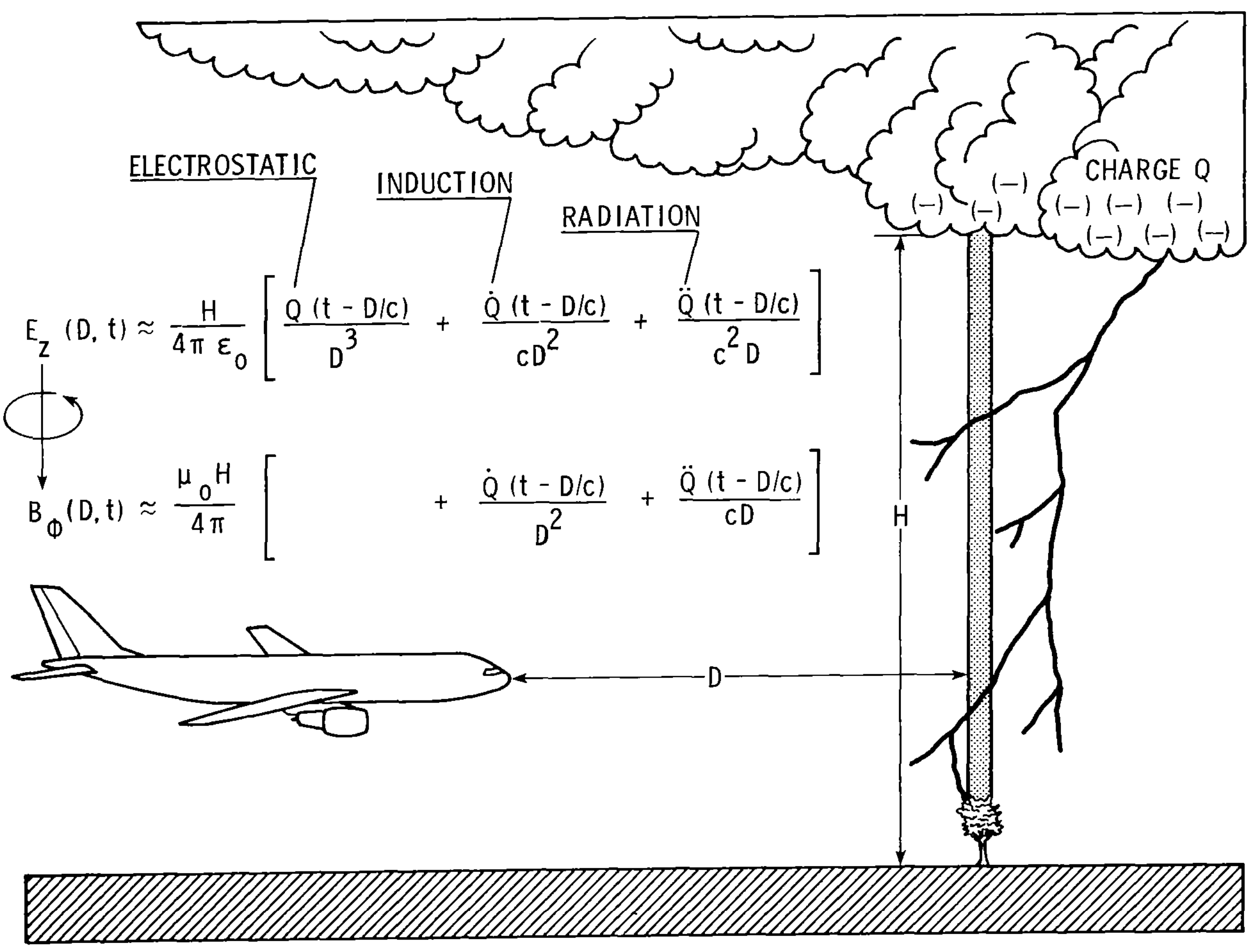


Figure 3

RESEARCH INSTRUMENTATION CONCEPT

The instrumentation concept consists of a number of electromagnetic sensors which measure the electromagnetic fields during the lightning strike to the aircraft. The data are recorded in a shielded, isolated instrumentation enclosure.

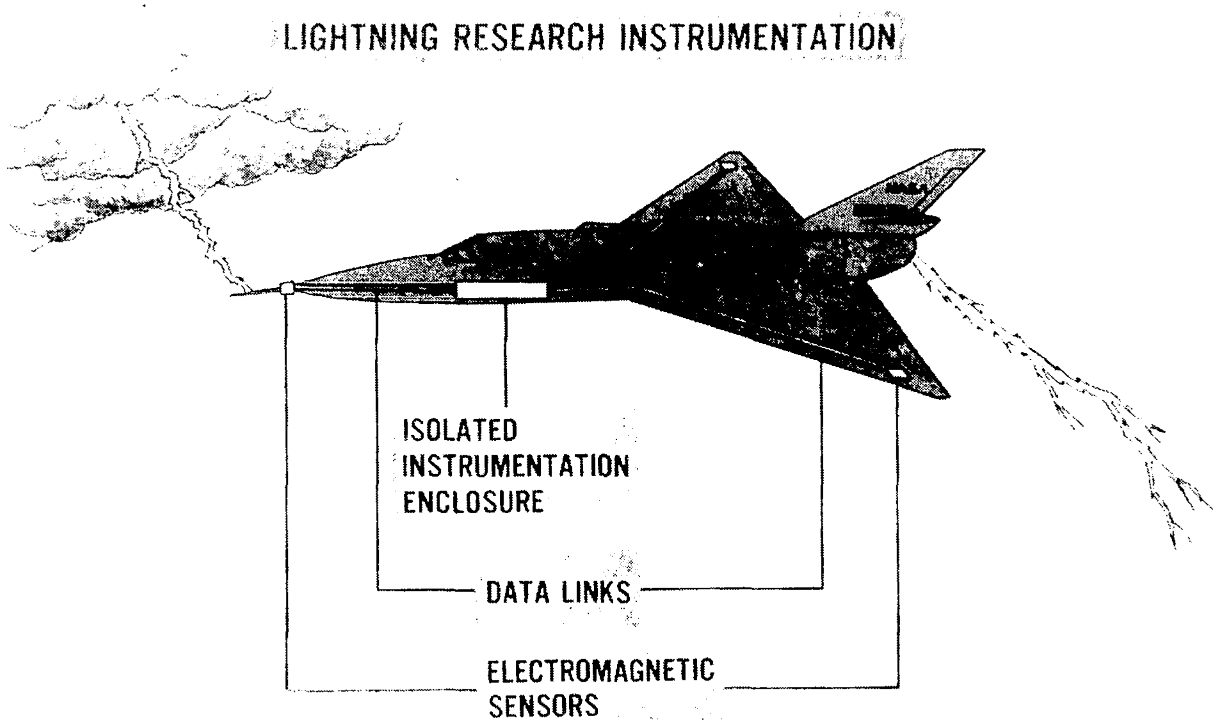


Figure 4

RESEARCH MEASUREMENTS

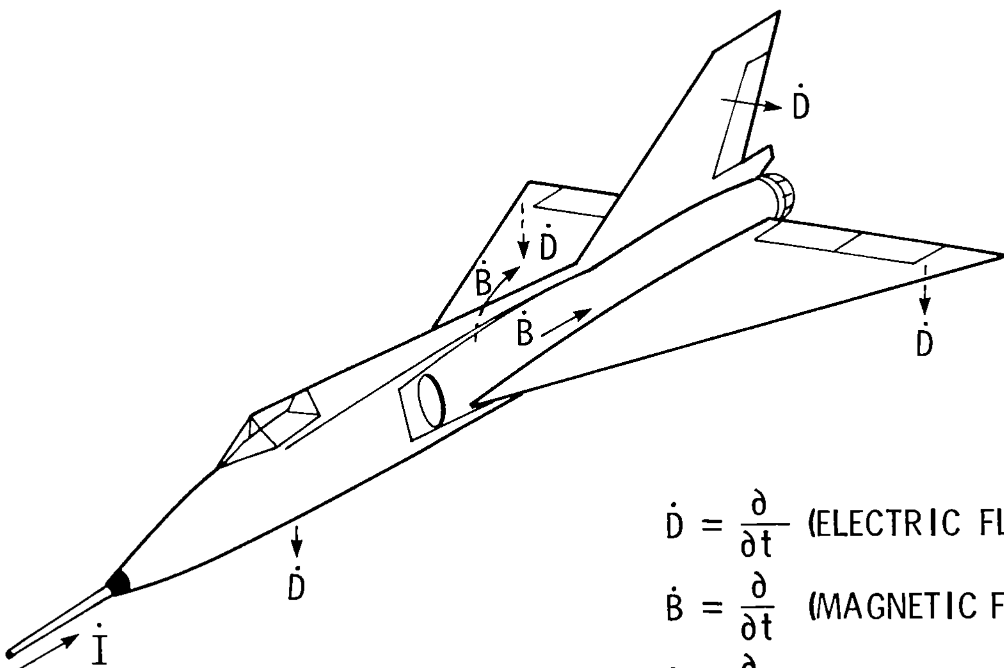
D-Dot, B-Dot, and I-Dot are the measurements of choice as determined by a group of technical experts representing industry, academe, and government. D-Dot is related to rate of change of electric field as $\dot{D} = \varepsilon_0 \dot{E}$, I-Dot is rate of change of strike current to the boom, and B-Dot is rate of change of magnetic flux density. The amplitude ranges are based on a nominal strike with 10 000 amperes and 500 000 volts per meter changes in 0.1 microsecond. The B-Dot range corresponds to that B-Dot generated by the above current at 1-meter radius.

MEASUREMENT	SYMBOL	AMPLITUDE RANGE	SENSOR TYPE
RATE OF CHANGE OF ELECTRIC FLUX DENSITY	$\dot{D}$	50 A/M^2	FLUSH PLATE DIPOLE
RATE OF CHANGE OF MAGNETIC FLUX DENSITY	$\dot{B}$	2×10^4 TESLA/SEC	MULTIGAP LOOP
RATE OF CHANGE OF CURRENT	$\dot{I}$	10^{11} A/SEC	INDUCTIVE CURRENT PROBE

Figure 5

MEASUREMENT LOCATIONS

The electromagnetic sensors are located on the aircraft in regions where the field strengths are greatest. Lightning currents contain frequency components high enough to excite the electromagnetic resonances of the aircraft; thus, the strongest fields occur at the antinode points of the resonances. For the lowest frequency resonances, the charge, and therefore the electric field, antinodes occur at the extremities of the aircraft and the current and magnetic field antinodes occur at the center. Thus, the D-Dot sensors are located near the ends of the nose, tail, and wings, and the B-Dot sensors are located near the center of the fuselage. Practical considerations, such as the location of access panels, dictate the exact sensor locations.



$$\dot{D} = \frac{\partial}{\partial t} \text{ (ELECTRIC FLUX DENSITY)}$$

$$\dot{B} = \frac{\partial}{\partial t} \text{ (MAGNETIC FLUX DENSITY)}$$

$$\dot{I} = \frac{\partial}{\partial t} \text{ (TOTAL CURRENT)}$$

Figure 6

ELECTROMAGNETIC SENSORS

The sensors used in the lightning instrumentation system are derived from designs developed for nuclear electromagnetic pulse measurements. The sensor response to rates of change of the lightning electromagnetic characteristics (as opposed to the current and fields, directly) accentuates the recording of the higher frequency components of the lightning process. Since the magnitudes of induced voltages (and currents) are proportional to rates of change of the lightning electromagnetic characteristics, enhanced definition of the more interesting (from an induced effects viewpoint) portion of the spectrum is obtained. The sensor sensitivity is calculated based on sensor geometry and then checked using a parallel-plate transmission line calibrator. Following are photographs of the I-Dot, B-Dot, and D-Dot sensors, respectively, and a photograph of the flat-plate transmission line calibrator.

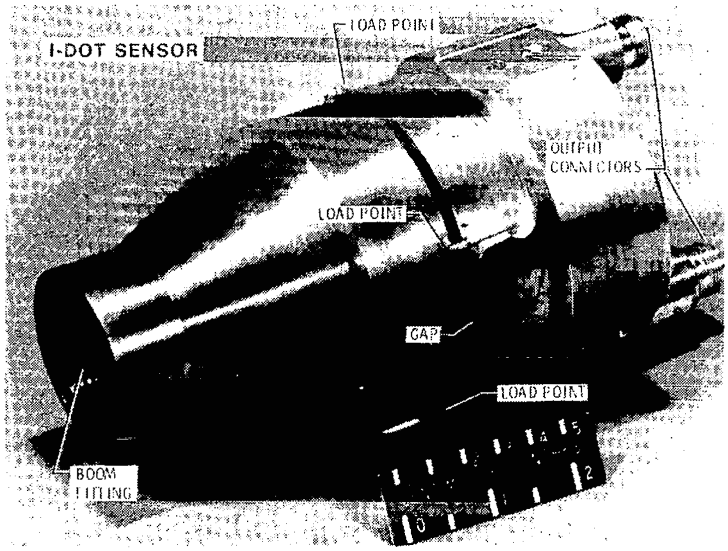


Figure 7

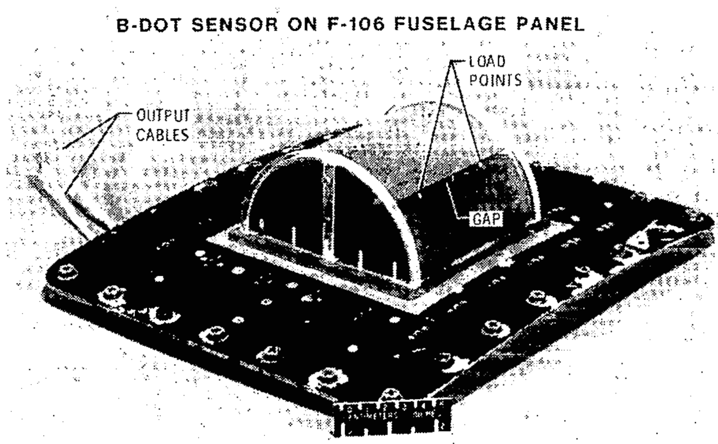


Figure 8

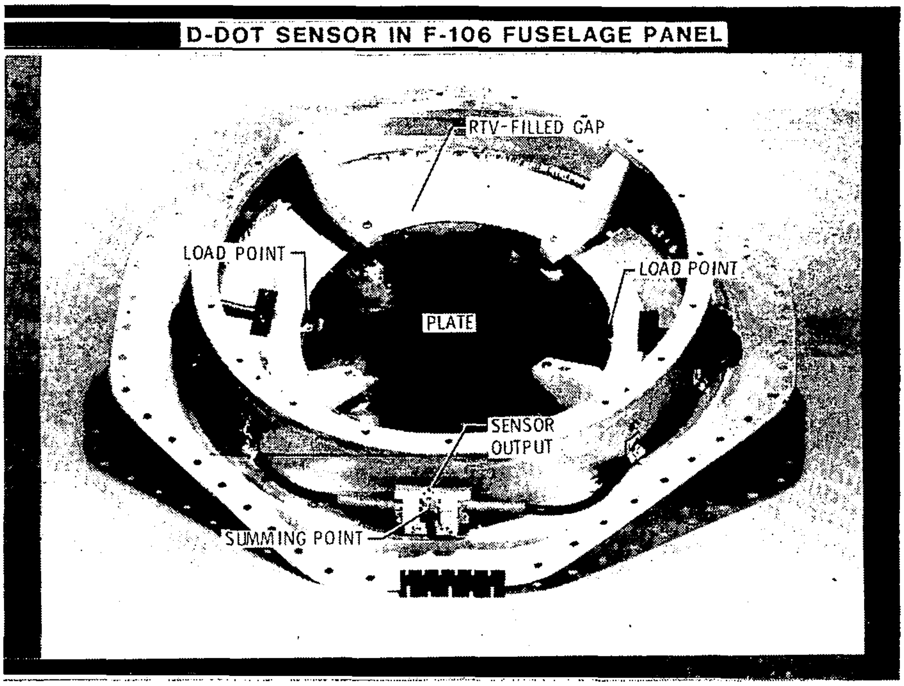


Figure 9

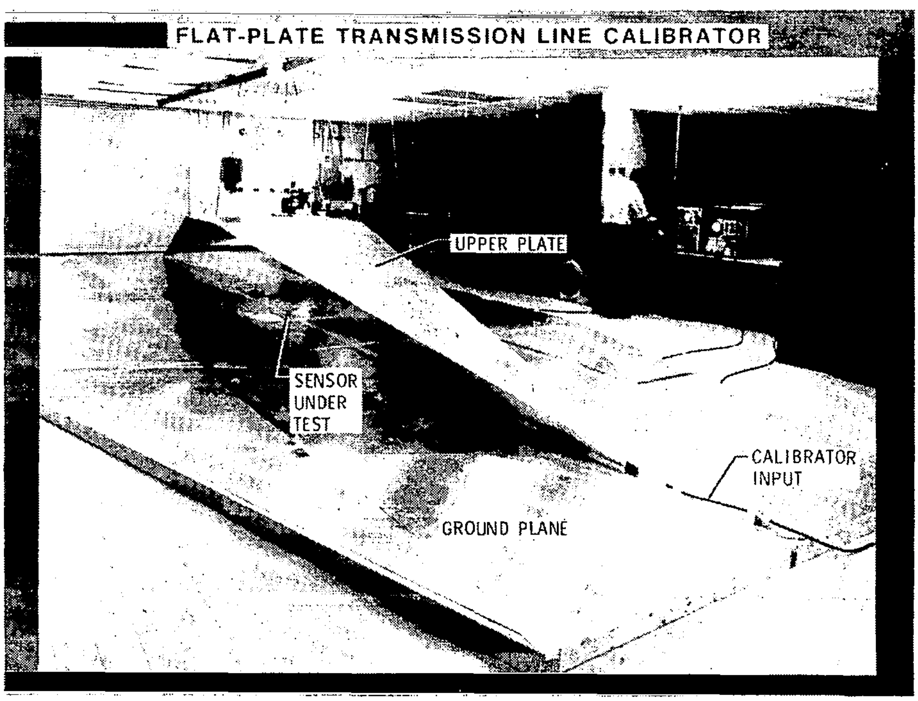


Figure 10

INSTRUMENTATION SYSTEM

This is the instrumentation system with the cover removed. The system is approximately 2-1/4 m x 1-1/2 m x 1/2 m and weighs about 450 kg (1000 pounds).

Specially expanded Biomation transient waveform recorders provide a unique capability for recording lightning electromagnetic transients. The transient recorders have solid-state memories which are continually updated with 6-bit data samples each 10 nanoseconds. Upon occurrence of a lightning strike, an internally generated trigger signal causes the recording to momentarily stop, temporarily storing the acquired lightning waveform in the memory. The memory contents are then formatted and recorded in the instrumentation tape recorder for permanent storage. The system then automatically resets for the next strike. The basic Biomation Model 6500 recorder memory was increased in an in-house development by over two orders of magnitude to allow a significant data window recording of 1300 microseconds of data at 10 nanoseconds resolution.

The wideband RCA Adviser video recorder has 6-MHz bandwidth and is capable of recording continuously for 24 minutes. This continuous recorder provides information on the overall lightning scenario to supplement the data "snapshots" recorded by the transient waveform recorders.

Power system isolation for the instrumentation is obtained using a motor-generator set. A 3-phase, 208-V, 400-Hz, 13-kVA electric motor external to the enclosure drives a nonconducting flexible coupler to a 12.5-kVA, 120/208-V, 3-phase, 400-Hz AC generator located within the enclosure to power the system.

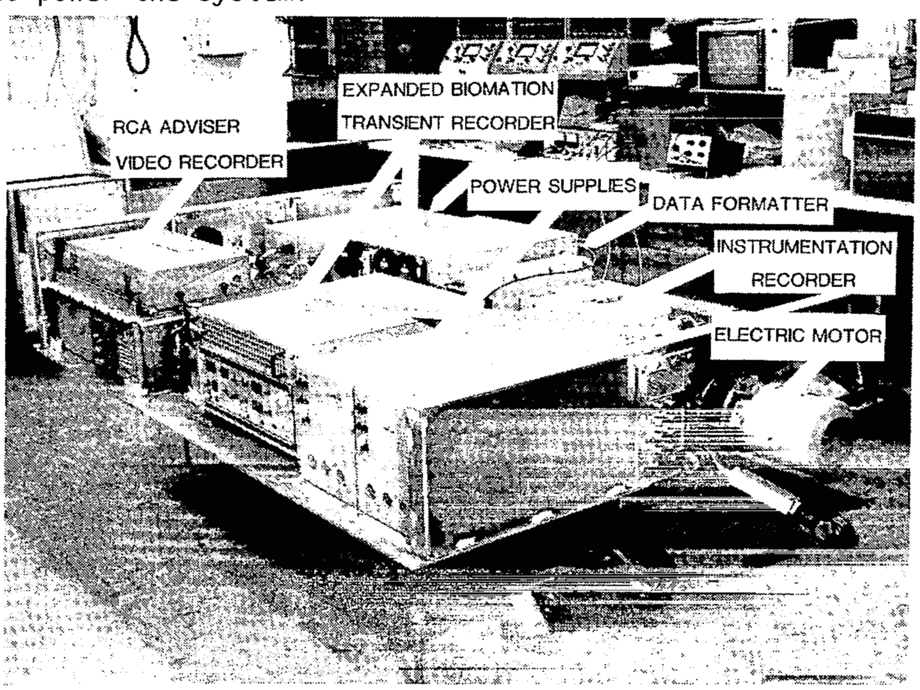


Figure 11

TRANSIENT RECORDER BLOCK DIAGRAM

The key feature of the transient recorder is the expanded memory which provides 131 072 data samples at 10 nanosecond sample intervals. The memory uses an interleaved architecture to achieve this speed with Intel 2147-3 RAM integrated circuits with a 55 nanosecond write-cycle period.

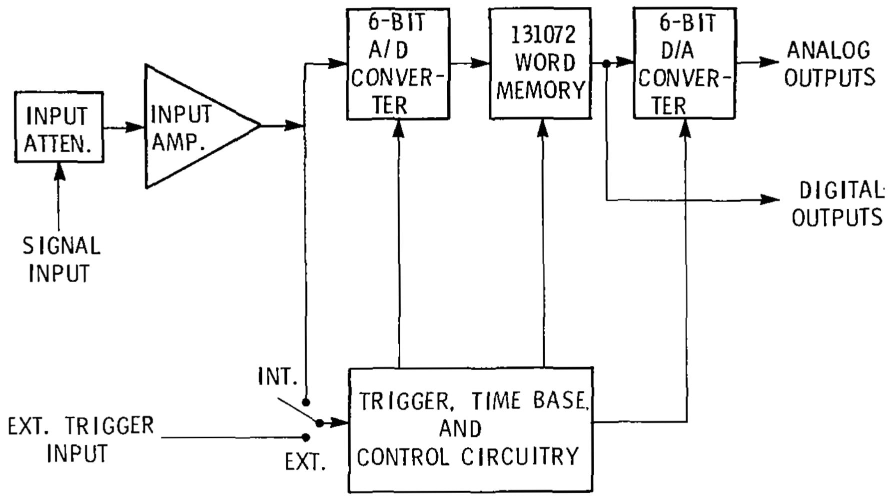


Figure 12

EXPANDED TRANSIENT WAVEFORM RECORDER FEATURES

- 6-BIT AMPLITUDE RESOLUTION (1.56%)
- FREQUENCY RESPONSE - DC TO 50 MHz
- 131072 (2^{17}) DATA WORD CAPACITY
- SAMPLE RATES UP TO 100 MHz
- DATA WINDOW LENGTH OF 1310 MICROSECONDS AT 100 MHz
- INTERNAL OR EXTERNAL TRIGGERING
- DATA WINDOW SELECTION WHICH IS BEFORE, DURING, OR AFTER TRIGGER EVENT

Figure 13

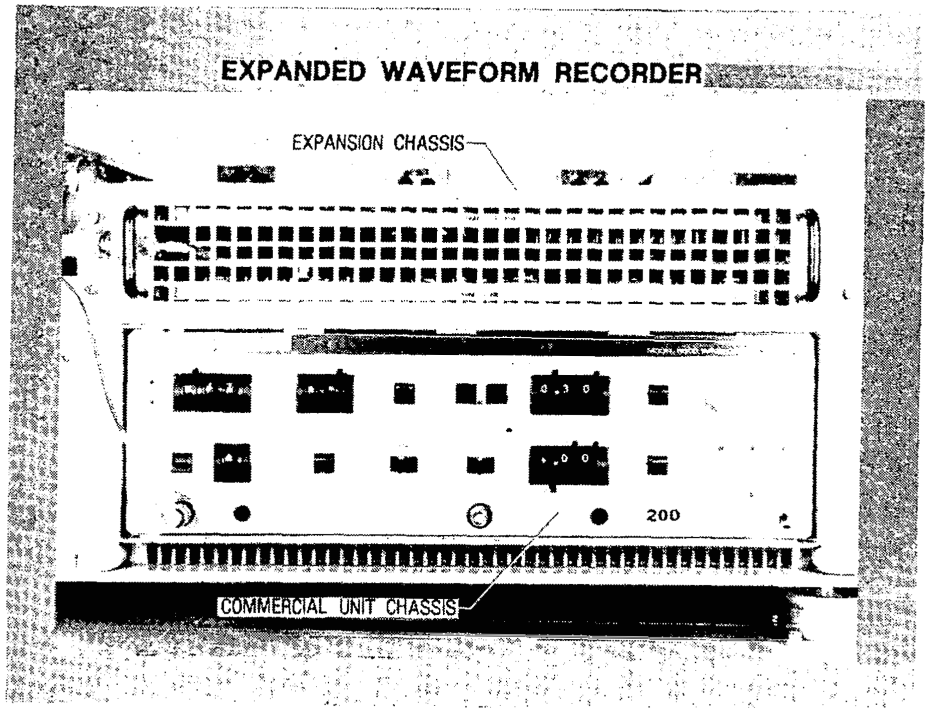


Figure 14

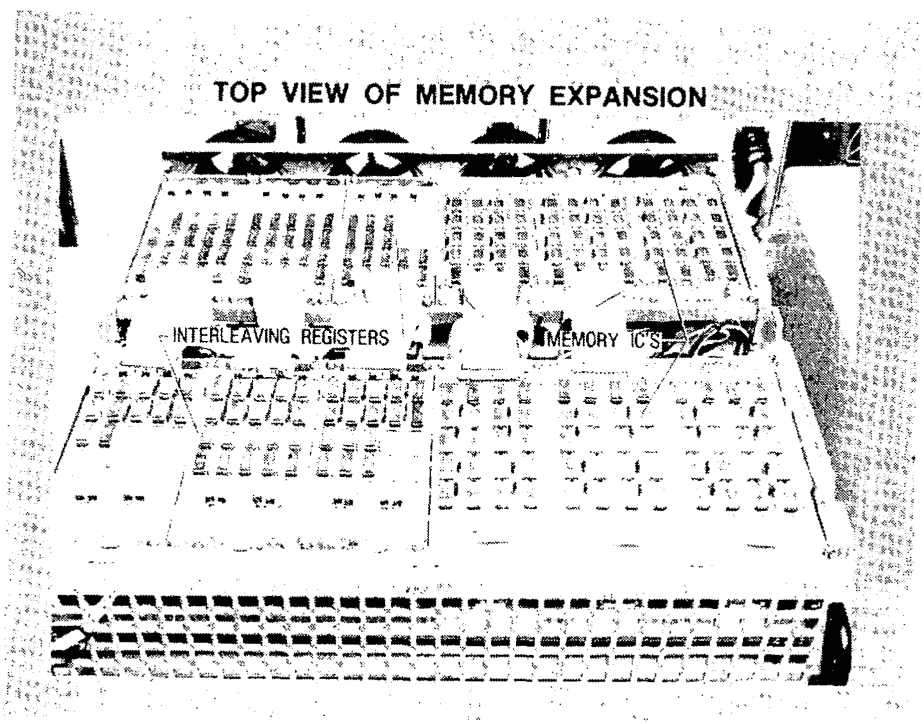


Figure 15

INSTRUMENTATION SYSTEM WITH COVER

This is the instrumentation system ready for mounting in the aircraft missile bay.

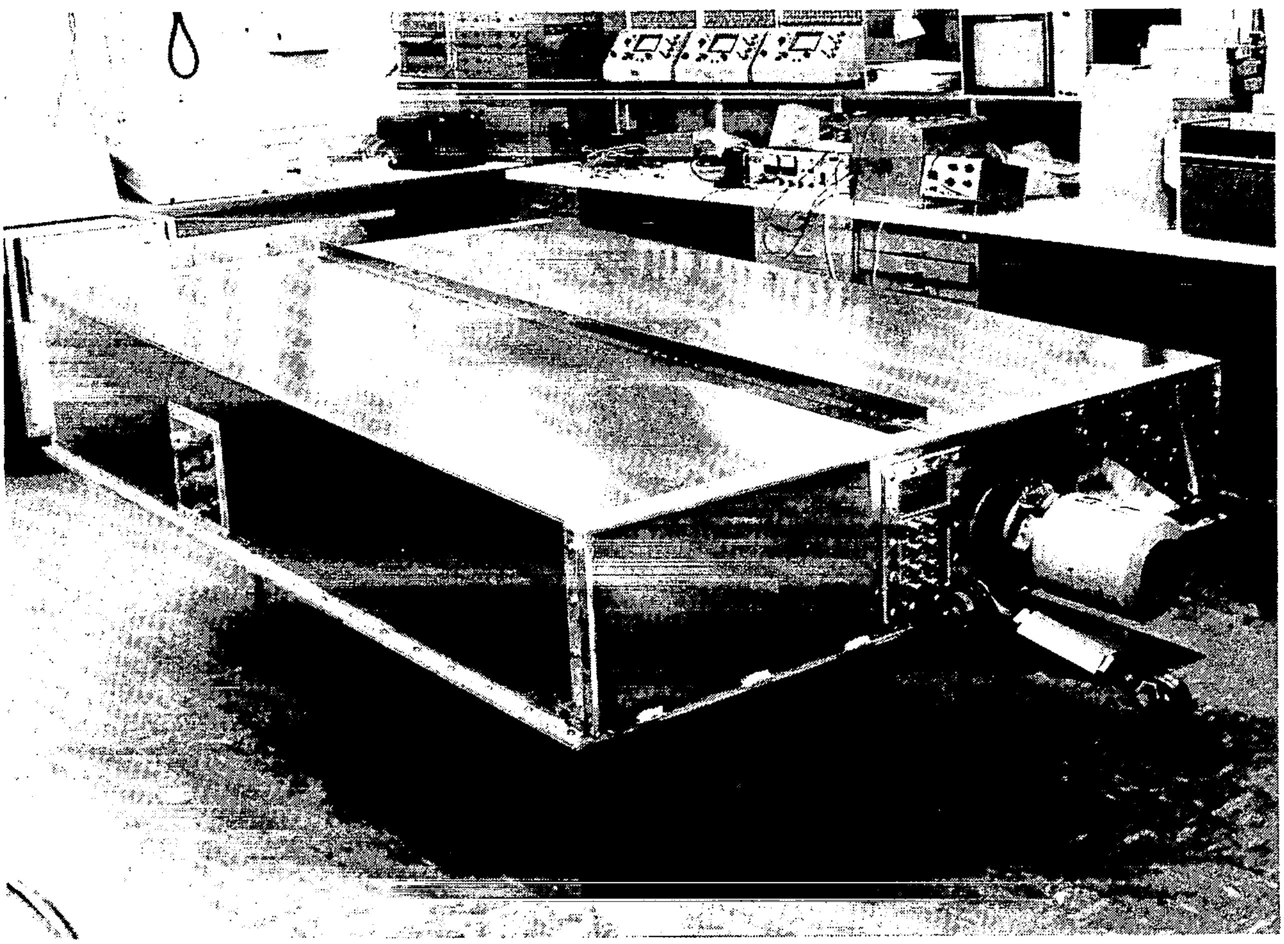


Figure 16

D-DOT SENSOR MOUNTED UNDER AIRCRAFT CHIN

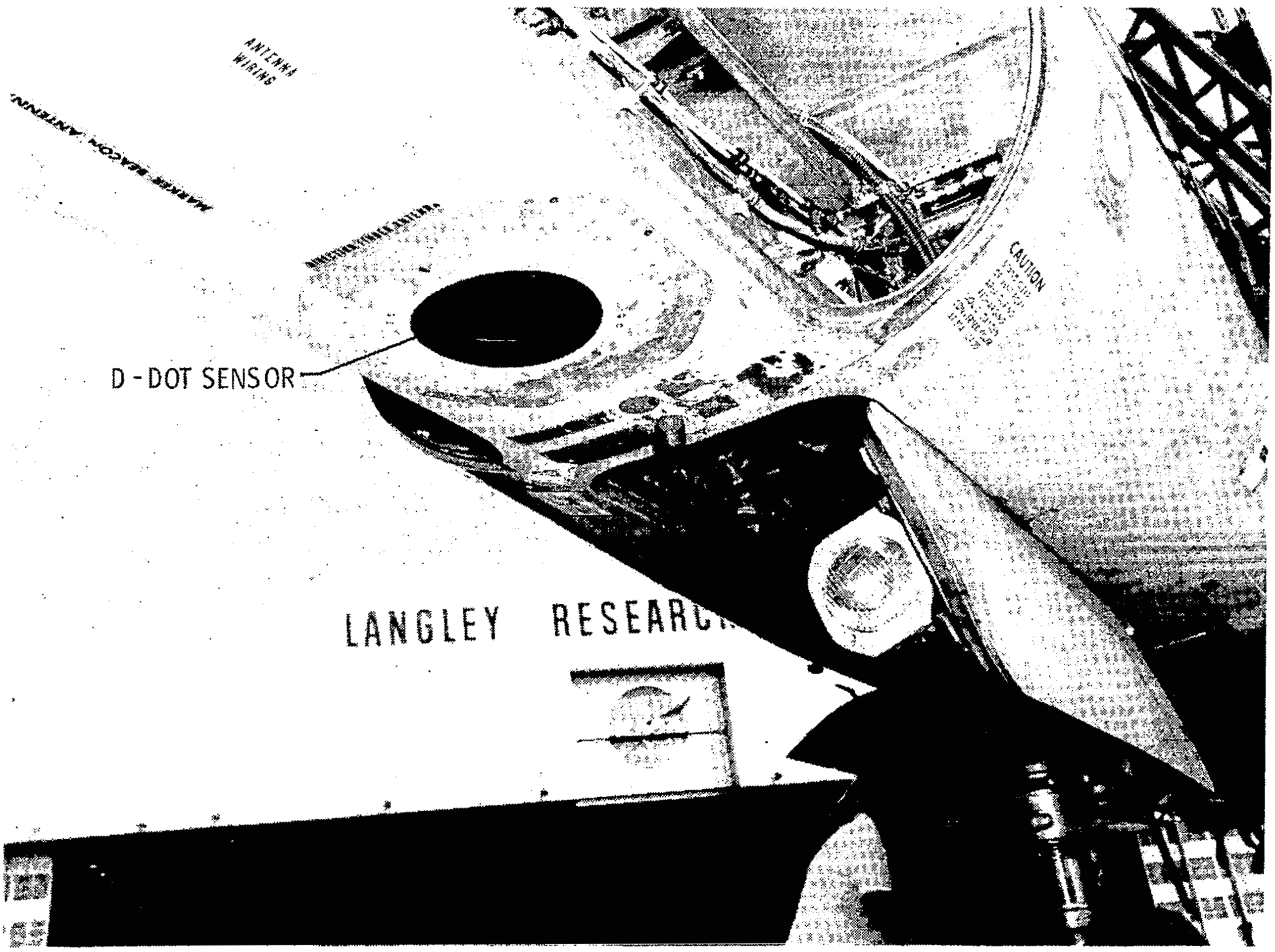


Figure 17

D-DOT SENSOR MOUNTED ON VERTICAL FIN

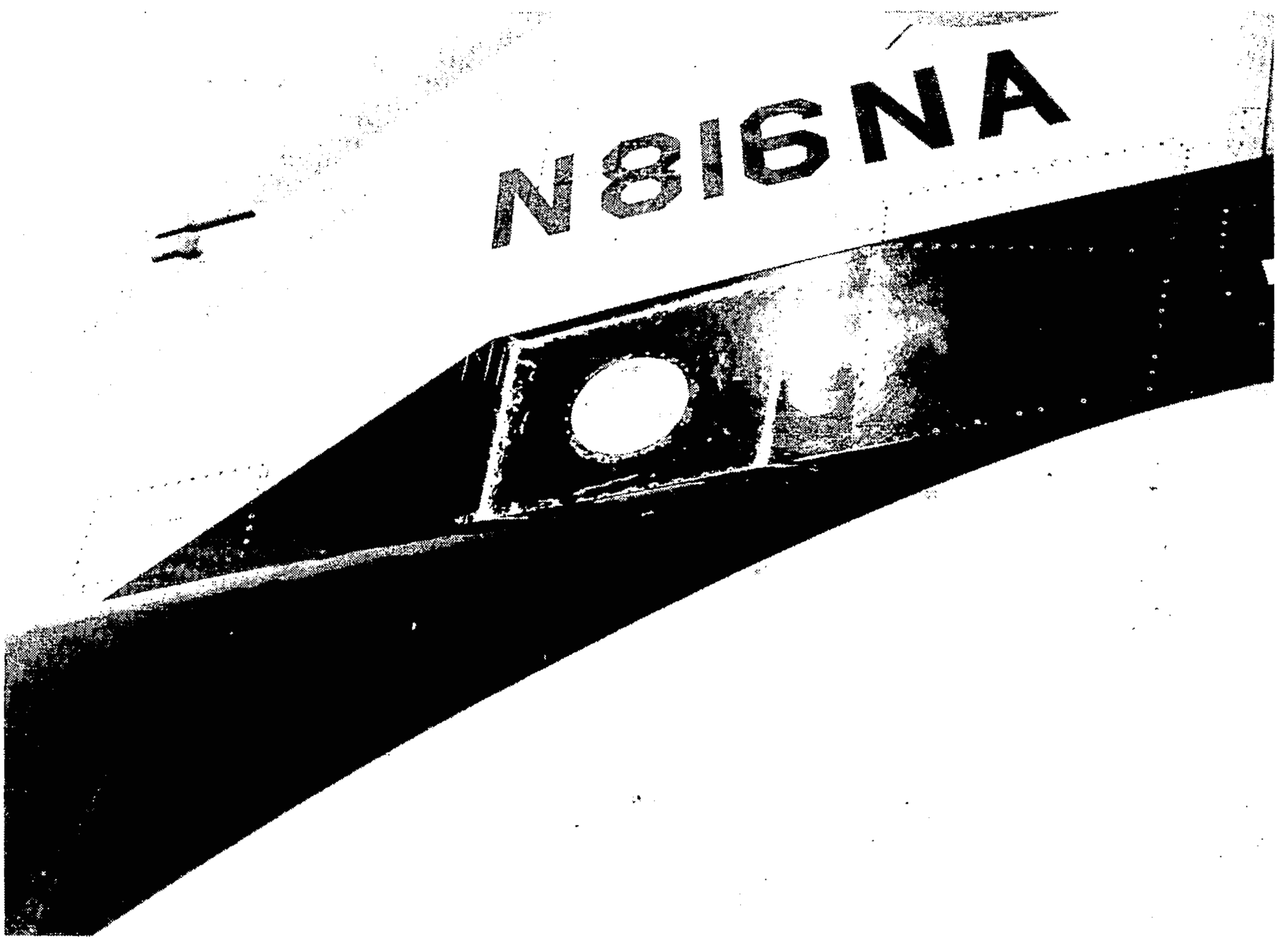


Figure 18

B-DOT SENSOR MOUNTED ON FUSELAGE

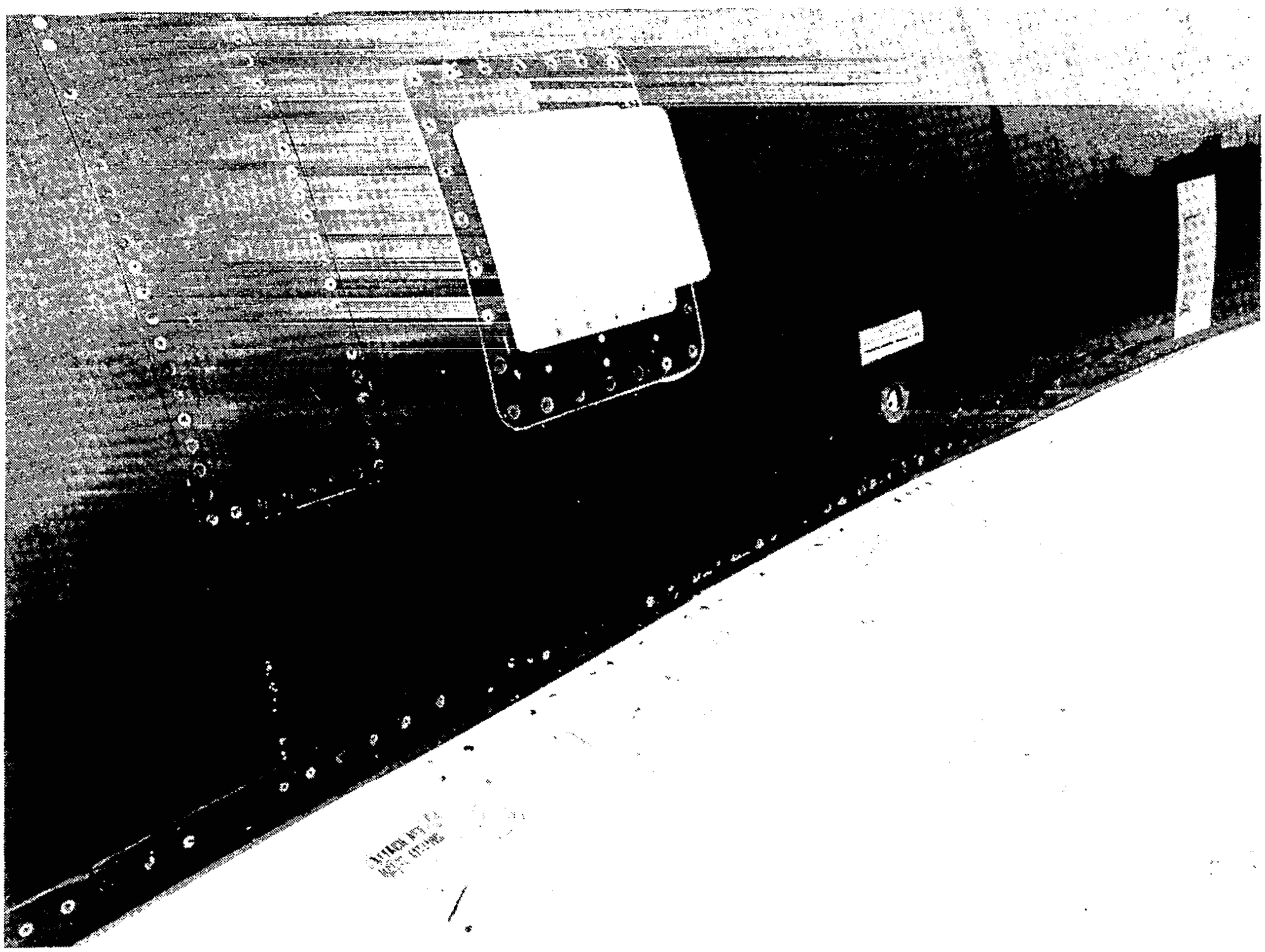


Figure 19

SIMULATED LIGHTNING SAFETY TEST

A simulated lightning safety survey test was performed on the aircraft to assess potential problems concerning aircraft systems safety. These tests were conducted by Lightning Technologies, Inc., and no safety hazards were disclosed by the tests. The safety survey tests also provided an opportunity for "end-to-end" instrumentation system fidelity and noise immunity tests. The tests were performed with the aircraft engine running and all flight systems operating on aircraft power. The instrumentation system measured and recorded the fields and currents on the aircraft in response to a current pulse of known amplitude and waveform (as determined from an external current transformer measurement) which was generated with a high-voltage capacitor discharge apparatus attached to the noseboom. The current exited from the aircraft tail and was returned to the generator using symmetrical return wires as shown in the test set-up photograph.

During subsequent tests, sensor cables were terminated in dummy 50-ohm loads, in lieu of the sensors, to investigate the noise immunity of the instrumentation system. The system did not respond during these tests, indicating that the noise level would be at least one order of magnitude below the flight configuration threshold.

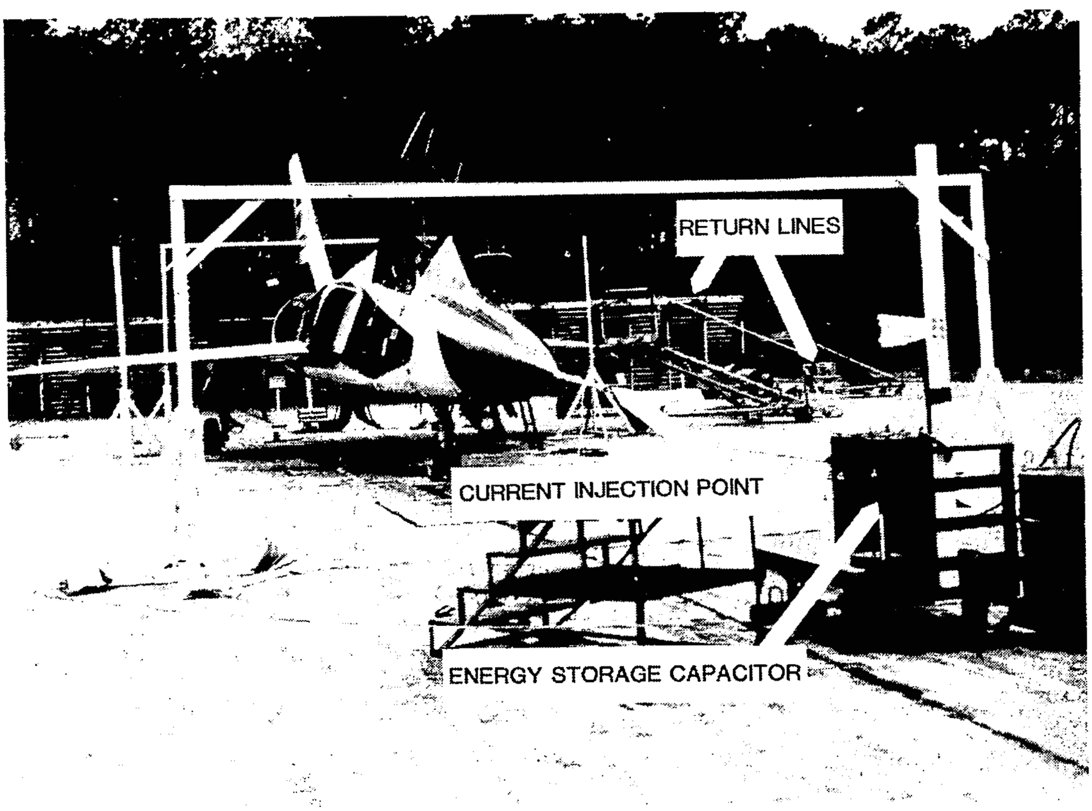


Figure 20

I-DOT SENSOR RESPONSE

This waveform shows typical I-Dot sensor response to an input current to the noseboom, recorded during the safety test. The input was a damped sinusoidal current oscillating at 86 000 Hz, with a peak amplitude of 10 500 amperes. The I-Dot measurement agrees with the rate of change of input current within about 10 percent.

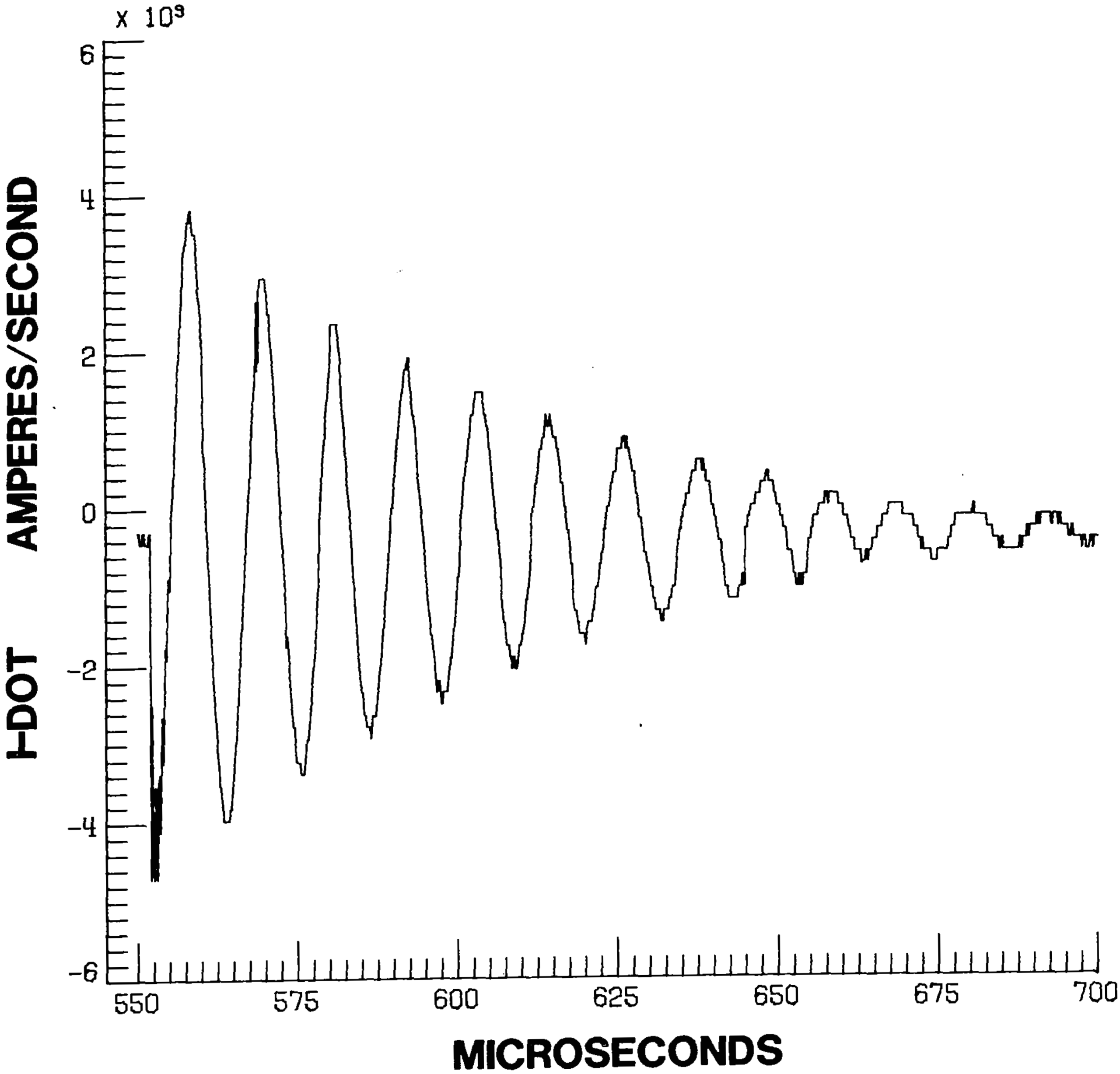


Figure 21

DIRECT STRIKE LIGHTNING DATA

The aircraft sustained three strikes while in the vicinity of the National Severe Storms Laboratory, Norman, Oklahoma, on June 17, 1980. The strikes occurred with the aircraft at an altitude of 4 800 meters (16 000 feet) at a speed of 154 meters per second (300 knots); the approximate freezing level was at the aircraft operating altitude. These strikes were not particularly energetic in that the magnetic characteristics (I-Dot, B-Dot) did not exceed system thresholds and only information from the forward D-Dot sensor was recorded. The portions of the above strike data records with the largest rates of change of electric flux density follow (fig. 23). The electric field changes for these data have been calculated as $1/\varepsilon_a$ times integral of D-Dot and also follow (fig. 24). Interpretation and analysis of the data are continuing; the following observations are offered at this point: (1) the utility of the derivative (D-Dot) sensor is clearly demonstrated by comparing the amplitude resolution of the "faster" changing portions of the D-Dot data with its integral during the first microsecond of the event; (2) the data indicate significant changes in the strike electric characteristics during submicrosecond intervals; and (3) a large electric field change accompanies the strike.

Figure 22

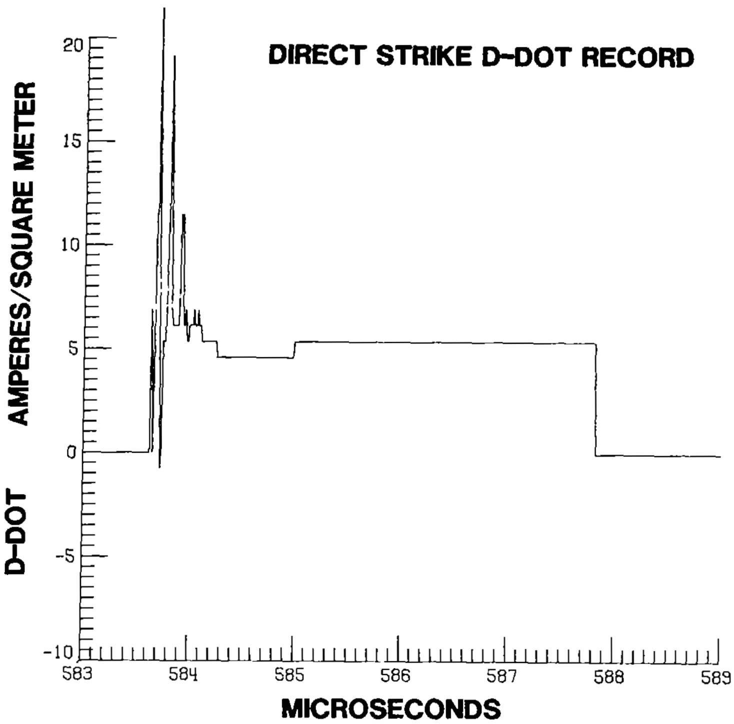


Figure 23

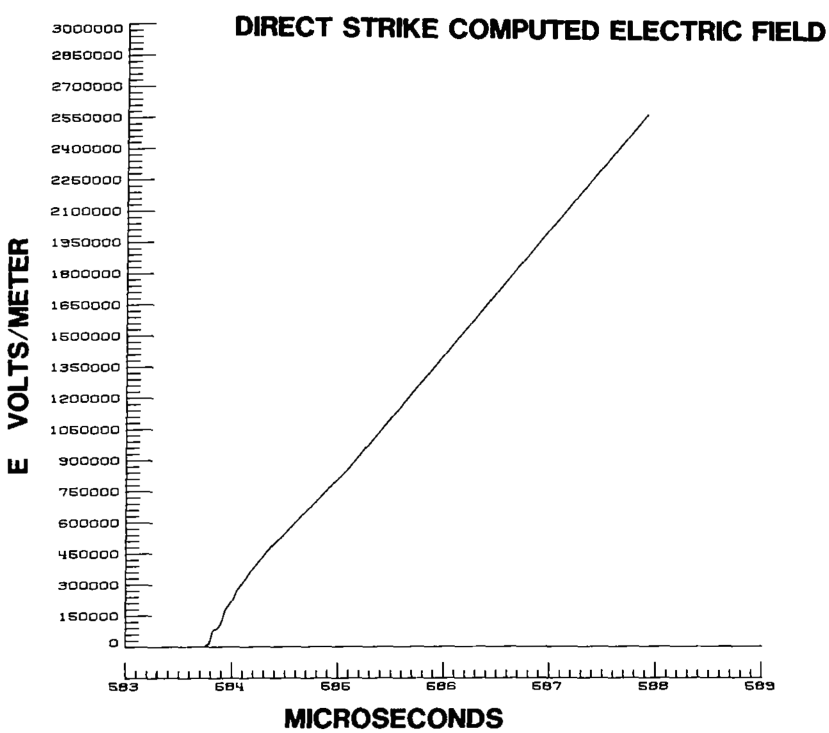


Figure 24

SUMMARY OF LIGHTNING EXPERIMENTS ON NASA F-106B AIRCRAFT

- LANGLEY RESEARCH CENTER DIRECT STRIKE
- BOEING DATA LOGGER EVALUATION
- LANGLEY RESEARCH CENTER ATMOSPHERIC CHEMISTRY (N_2O, CO)
- NATIONAL SEVERE STORM LABORATORY OPTICAL SIGNATURE
- UNIVERSITY OF WASHINGTON X-RAY EMISSION

Figure 25

FY 81 PLANS

- CONTINUE DIRECT STRIKE FLIGHT TESTS
  - 12 CHANNEL DIGITAL TRANSIENT RECORDER
  - 15 MHz VIDEO RECORDER
- DATA INTERPRETATION/ANALYSIS

REFERENCES

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