AIAA 81-0083R

Electromagnetic Measurement of Lightning Strikes to Aircraft

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Recent in-flight, direct-strike lightning research, using a NASA F-106B aircraft, is reviewed. An instrumentation system which records the rates of change of electric and magnetic flux density at several locations on the aircraft and rate of change of strike current to the boom is described. The measurement parameters are the rate of change of electric flux density over a range of 50 A/m^2, rate of change of magnetic flux density over a range of 20,000 T/s, and rate of change of strike current over a range of 100 kA/μs. The isolated and shielded instrumentation system employs high-sample-rate digital transient recorders with augmented memory capacity and a wide-band analog recorder for data acquisition and recording. The data obtained during the 1980 flight test program are presented, and the data significance is discussed.

Introduction

THE NASA Langley Research Center is performing in-flight, direct-strike lightning research using a specially instrumented F-106B aircraft. The intent of this research is to refine the characterization of the lightning-generated electromagnetic environment affecting aircraft. The projected use of digital avionic systems, along with composite aircraft structure, compounds lightning related problems and provides the motivation for the present research. 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 in the past. 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 discussion and review (Ref. 1) supplemented by ground-based measurements (Ref. 2) has indicated that the rise times of lightning electromagnetics are around one order of magnitude faster than those used in current lightning-protection criteria.

The intent, rationale, and design goals of the instrumentation system developed at NASA Langley Research Center to aid in-flight lightning-hazard characterization are described in Ref. 3. The present report contains a brief review of the actual instrumentation system implementation and presents results recorded by the research instrumentation during the 1980 campaign. During the 1980 tests, electromagnetic measurements were made during nine direct strikes and several nearby strikes. Twelve records of 130,000 data words recorded at a 10-ns sample interval of the rates of change of electric and magnetic flux density were obtained along with several concurrent continuous wide-band (6 MHz) analog recordings of the rate of change of strike current to the boom.

Instrumentation System Overview

The instrumentation concept shown in Fig. 1 consists of a number of sensors which measure the electromagnetic fields during the lightning process. The data are then recorded in a shielded, isolated instrumentation enclosure. A photograph of the instrumentation system with its cover removed is shown in Fig. 2. The system is mounted in the missile bay of the F-106B.

Specially expanded Biomation transient waveform recorders (Ref. 4), which operate at a 10-ns sample interval and 6-bit resolution, provide a unique capability for recording lightning electromagnetic transients. The basic Biomation Model 6500 recorder memory was increased by over two orders of magnitude to allow a significant recording of 1.3 ms of data at the 10-ns sample interval. Upon acquisition of strike data by the transient waveform recorders, the data are automatically transferred to the data formatter and thence to the instrumentation recorder for permanent storage. The transfer of data from the transient recorders to permanent storage requires approximately 5 s, after which the transient recorders are automatically reset to acquire data from the next strike.

The wide-band RCA video recorder has 6-MHz bandwidth and is capable of recording continuously for 24 min. This continuous recorder is used to provide information on the overall lightning scenario.

The sensors used in the lightning instrumentation system are derived from designs developed for nuclear electromagnetic pulse measurements (Ref. 5). The sensors measure the rate of change of strike current to the noseboom (I-dot) along with the rate of change of electric and magnetic flux density (D-dot, B-dot) at a number of locations as shown in Fig. 3. 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

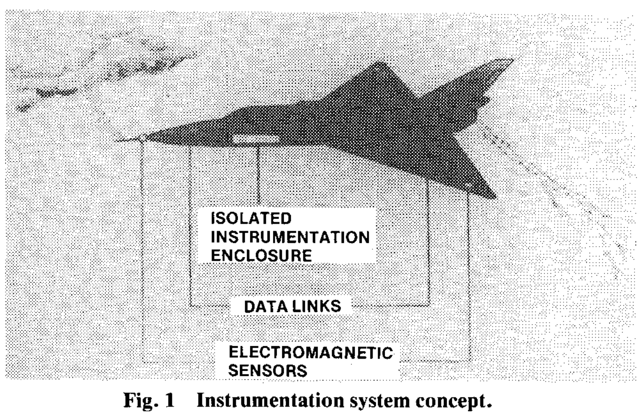

Fig. 1 Instrumentation system concept.

Presented as Paper 81-0083 at the AIAA 19th Aerospace Sciences Meeting, St. Louis, Mo., Jan. 12-15, 1981; submitted March 11, 1981; revision received July 22, 1981.

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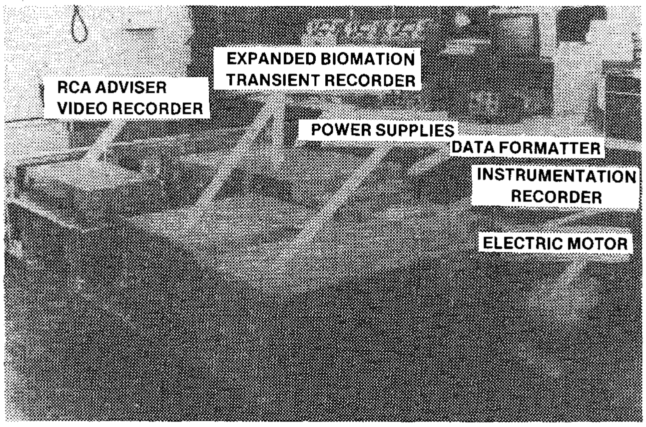

Fig. 2 Instrumentation system.

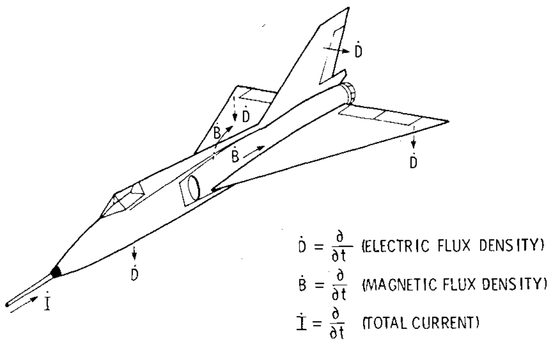

Fig. 3 Sensor locations.

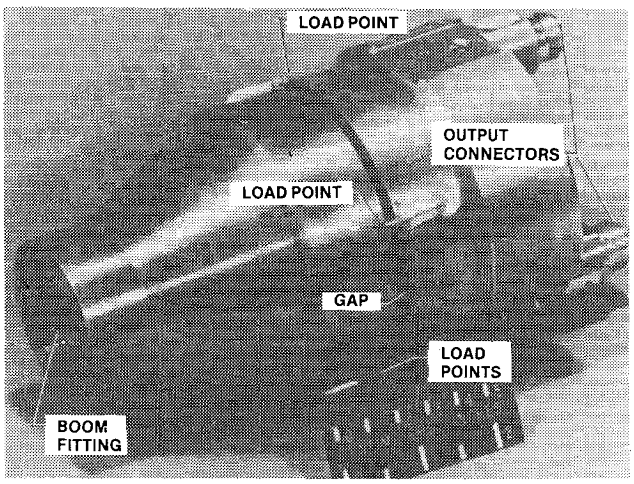

Fig. 4 I-dot sensor.

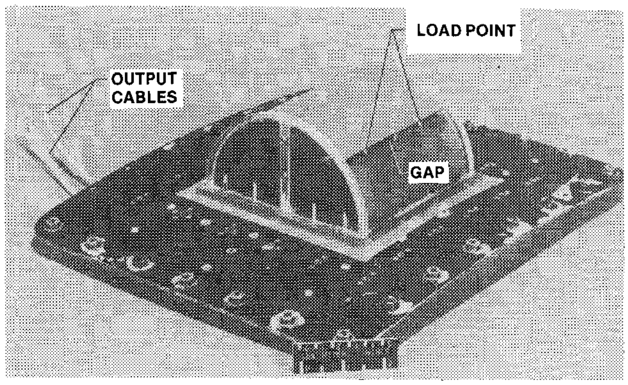

FIg. 5 B-dot sensor.

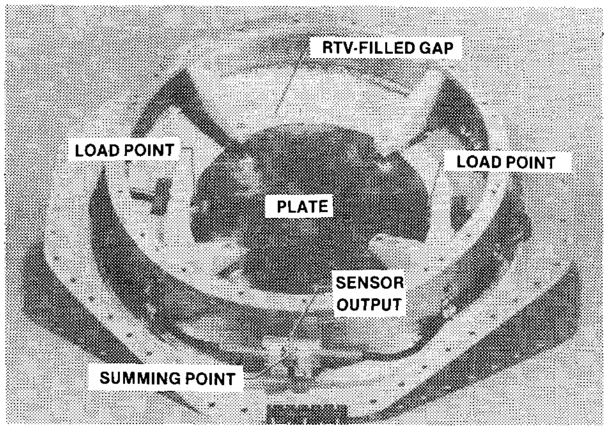

Fig. 6 D-dot sensor.

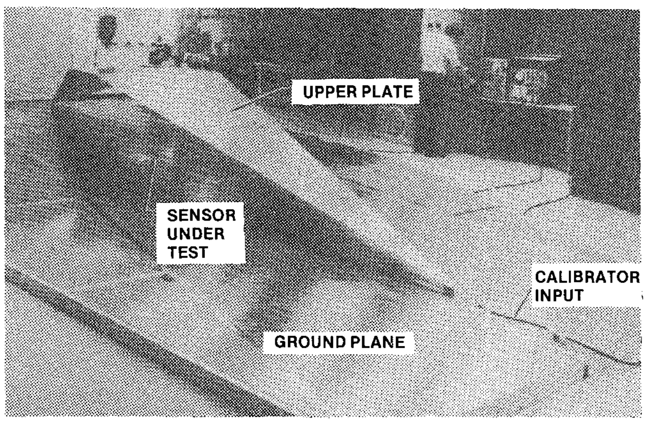

Fig. 7 Calibrator.

Table 1 1980 direct-strike data summary

Date	Flight	Strike altitude, km	Approximate temperature, °C	No. strikes (comments)	D-dot FWD[a]	B-dot LONG[a]	I-dot[b]	D-dot right wing[b]
June 17	80-018	4.8	−22	1	1	0	0	0
				(boom)				
	80-019	4.8	−5	2	1	0	0	0
				(boom)	...	c	d	...
Sept. 1	80-036	6.56	−25	1	1	1	e	0
				(nose)				
Sept. 3	80-038	10.5	−48	5	3	4	5	0
				(boom)				

[a]Expanded Biomation digital transient recorder 10-ns/sample. [b]RCA adviser 62 6-MHz B.W. analog recorder. [c]X 10 gain change. [d]X 100 gain change. [e]Boom not involved.

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 (Ref. 6) and then checked using a parallel-plate, transmission-line calibrator. Figures 4, 5, and 6 are photographs of the I-dot, B-dot, and D-dot sensors, respectively; Fig. 7 is a photograph of the flat-plate, transmission-line calibrator.

Power system isolation for the instrumentation is obtained using a motor-generator set. A three-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, three-phase, 400-Hz ac generator located within the enclosure to power the system.

Lightning Data

The 1980 campaign resulted in data being recorded during nine direct strikes to the aircraft from 19 storm penetration flights. Table 1 summarizes the data recorded and the particulars concerning the flights, including altitudes and approximate temperatures at which the strikes occurred. The entries under D-dot FWD and B-dot LONG are the number of 1310-μs records acquired during strikes from the D-dot forward and B-dot longitudinal sensors at the 10-ns sample interval. The five entries under the I-dot column represent the number of separate strike events recorded from the I-dot sensor on the 6-MHz analog video tape recorder. The sign convention for polarity resolution of the measured fields and currents is such that an increasing electric field from the aircraft is positive, increasing current from forward to aft is positive, and results in positive clockwise circumferential magnetic field B-dot LONG.

Table 2 lists the characteristics of the instrumentation system as initially configured for the flight tests. The full-scale ranges of the recording system were chosen to accommodate submicrosecond rise-time lightning charac-

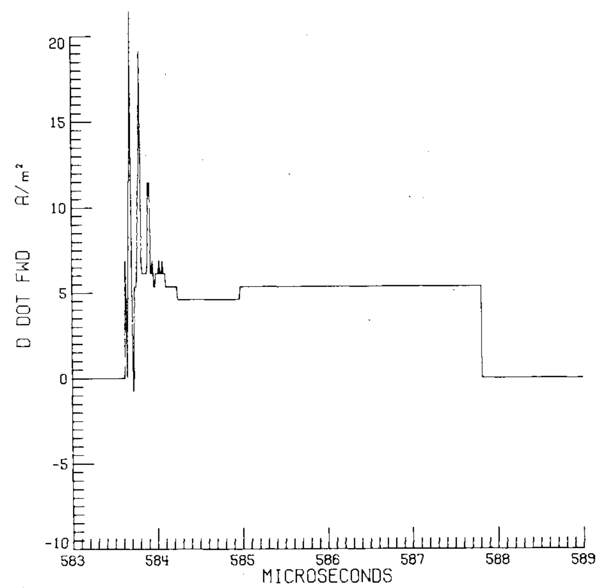

Fig. 8 D-dot sensor (flight 80-018).

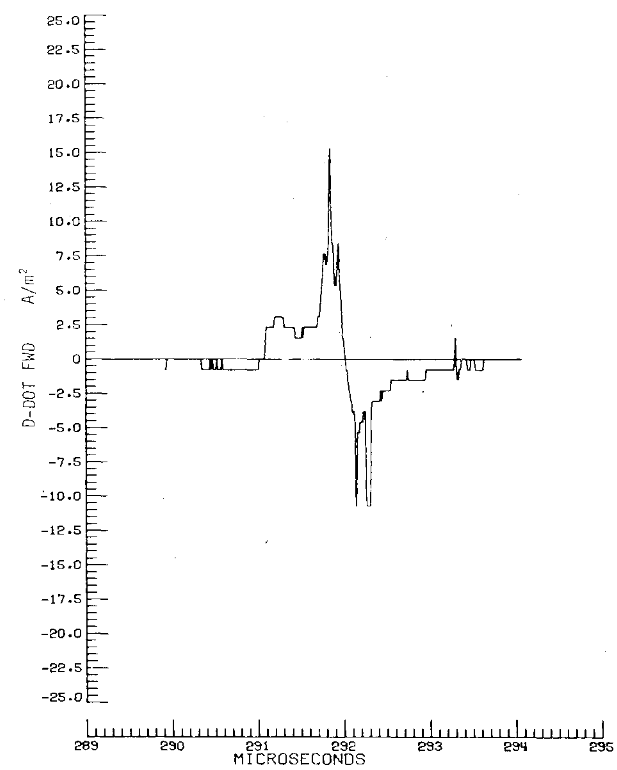

Fig. 10 D-dot sensor (flight 80-038).

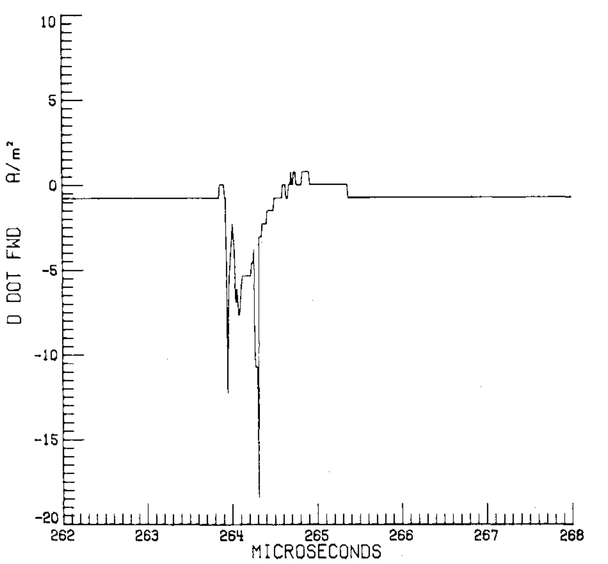

Fig. 9 D-dot sensor (flight 80-036).

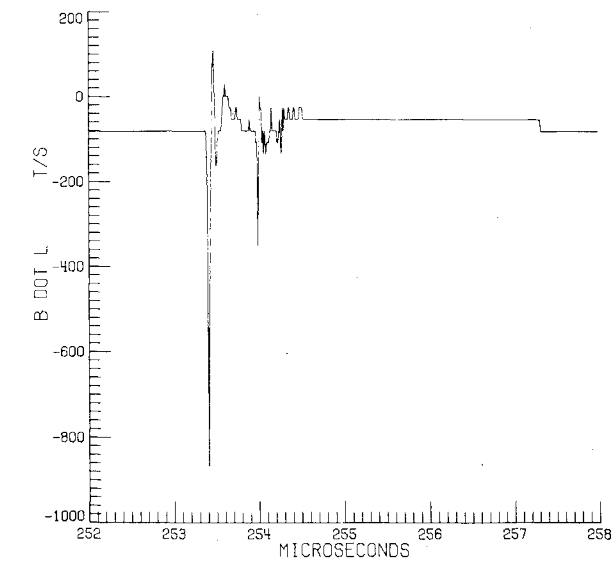

Fig. 11 B-dot sensor (flight 80-036).

Table 2 Measurement configuration for flights 80-018 and 80-019

Sensor	Recorder	Sample rate (bandwidth), MHz	p-p Full scale	Threshold
D-dot FWD	Transient	100 (50)[a]	± 24.5 A/m^2	± 4.9 A/m^2
B-dot LONG	Transient	100 (50)[a]	± 8695 T/s	± 1739 T/s
D-dot right wing	Wide-band analog	(6)	± 28 A/m^2	± 2.8 A/m^2
I-dot	Wide-band analog	(6)	$\pm 4.7 \times 10^{10}$ A/s	$\pm 4.7 \times 10^{9}$ A/s

[a] Four-pole linear phase low-pass filter 3-dB point at 50 MHz.

Table 3 Measurement configuration for flights 80-023 through 80-038

Sensor	Recorder	Sample rate (bandwidth), MHz	p-p Full scale	Threshold
D-dot FWD	Transient	100 (50)[a]	± 24.5 A/m^2	$+3.7$ A/m^2
B-dot LONG	Transient	100 (50)[a]	± 870 T/s	$+130$ T/s
D-dot right wing	Wide-band analog	(6)	± 28 A/m^2	± 2.8 A/m^2
I-dot	Wide-band analog	(6)	$\pm 4.7 \times 10^{8}$ A/s	$\pm 4.7 \times 10^{7}$ A/s

[a] Four-pole linear phase low-pass filter 3-dB point at 50 MHz.

Table 4 Summary of data characteristics

	D-dot		B-dot		I-dot[a]	
Flight	Max p-p, A/m^2	Duration, μs	Max p-p, T/s	Duration, μs	Max p-p, $\times 10^9$ A/s	Duration, μs
80-018	22	4.2	...	...	...	...
80-019	30.5	0.25	...	...	...	...
80-036	19	1.6	980	4.0	...	...
80-038	...	...	675	1.3	0.72	1.8
	17.5	2.8	b	b	0.37	2.0
			240[b]	0.3	0.43	2.5
	19	2.5	1160	1.8	0.54	4.0
	26	2.7	980	0.9	0.57	2.2

[a] Recorder has step response limitation of 100 ns. [b] Memory read-out in process from previous strike.

teristics: specifically, electric field changes of 500 kV in 0.1 μs and current changes of 10 kA in 0.1 μs. Details of the waveforms recorded during the initial three strikes were reported in Ref. 7; these data were noteworthy in that the electric characteristics (D-dot) spanned 60% of full scale, whereas the magnetic characteristics (B-dot, I-dot) did not exceed the thresholds shown in Table 2. Subsequently, the gain of the B-dot and I-dot data channels was increased by one and two orders of magnitude, respectively. Also, the trigger thresholds of the transient recorders were reduced to 15% from 20% of full scale, as shown in Table 3, which summarizes the final flight configuration. Both the electric and magnetic characteristics were recorded during subsequent strikes, as noted in Table 1.

Examples of D-dot records showing several different characteristic waveforms recorded from the forward D-dot sensor during flights 80-018, 80-036, and 80-038 are shown in Figs. 8-10. Both unipolar and bipolar D-dot data were recorded; the waveform structure shown in these figures is typical of those recorded. The D-dot data shown in Fig. 9 and the B-dot data shown in Fig. 11 were recorded concurrently during the strike to the aircraft nose during flight 80-036. Figures 10, 12, and 13 show data recorded concurrently from

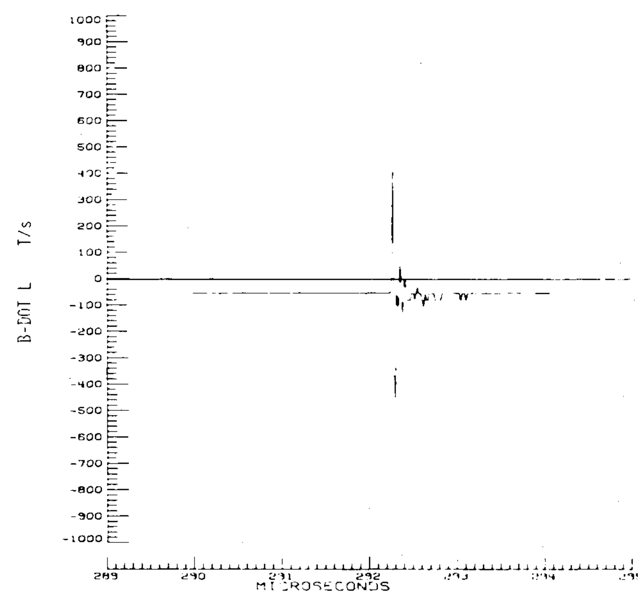

Fig. 12 B-dot sensor (flight 80-038).

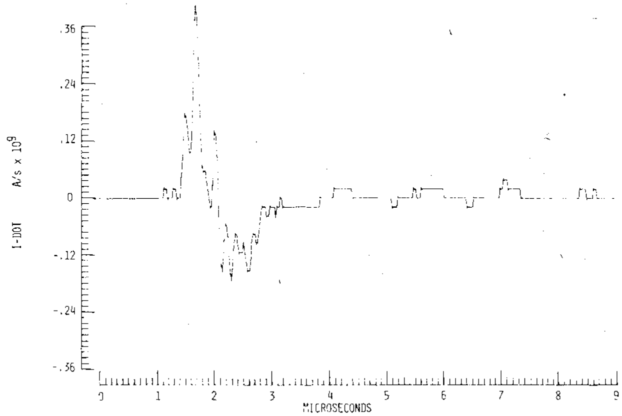

Fig. 13 I-dot sensor (flight 80-038).

the D-dot, B-dot, and I-dot sensors during a strike on flight 80-038. The symbols used on the lightning data figures are as follows: D-dot amperes per square meter (A/m^2), B-dot tesla per second (T/s), and I-dot amperes per second (A/s).

Table 4 summarizes the maximum peak-to-peak (p-p) D-dot, B-dot, and I-dot values recorded during the nine strikes along with the approximate duration of activity adjacent to the peaks. Multiple entries in the rows of Table 4 indicate data that were recorded simultaneously.

Discussion and Conclusion

Interpretation and analysis of the lightning strike data are beginning. The following are a few first-order observations offered at this point. The effects of these particular lightning strikes on the aircraft structure were of a very superficial, minor, cosmetic nature. Even so, the data recorded indicated that significant D-dot changes accompany such relatively low intensity strikes: the electric measurement (D-dot sensor) reached approximately 40-60% of its full-scale value, whereas the magnetic measurements (B-dot, I-dot) did not exceed the instrumentation system thresholds (until the gains were increased). The characteristics of the D-dot waveforms indicate several distinctively different lightning encounters; some with fast rising, mostly unipolar waveforms (of either polarity, see Figs. 8 and 9) and others with slower rising, definitely bipolar waveforms (see Fig. 10). The unipolar D-dot waveforms are of particular interest since integration, and scaling (by one over permittivity) to obtain electric field, results in final values which do not return to zero. One explanation is that the lightning terminated on the aircraft and deposited charge which subsequently leaked off the aircraft at a slow rate. Finally, the derivative measurements obtained in the lightning channel exhibit times between peaks of fractions of microseconds and thus have temporal characteristics comparable with the recently reported submicrosecond components of lightning radiation fields reported in Ref. 2.

Characteristics of the in-flight lightning electromagnetic environment, in a statistical sense, will require a much wider data base than reported herein. With that motivation, plans are being made for future flight tests; the instrumentation capability is being increased to 12 channels; and the analog recorder bandwidth is being increased to 15 MHz. In addition to improvements in the airborne instrumentation, plans for the 1981 campaign include simultaneous ground-based measurements as a first step in developing a methodology for correlating airborne data with the large existing body of ground-based measurements.

References

[1]Clifford, D.W., Krider, E. P., and Uman, M.A., "A Case for Submicrosecond Rise-Time Lightning Current Pulses for Use in Aircraft Induced Coupling Studies," *1979 IEEE International Symposium on Electromagnetic Compatibility,* San Diego, Calif., Oct. 1979, pp. 143-149.

[2]Weidman, C.D. and Krider, E.P., "Submicrosecond Risetimes in Lightning Radiation Fields," *Lightning Technology,* NASA CP-2128, 1980, pp. 29-38.

[3]Pitts, F.L., Thomas, M.E., Campbell, R.E., Thomas, R.M., and Zaepfel, K.P., "In-Flight Lightning Characteristics Measurements System," Federal Aviation Administration, Florida Institute of Technology Workshop on Grounding and Lightning Technology, FAA-RD-79-6, March 1979, pp. 105-111.

[4]Thomas, R. M. Jr., "Expanded Interleaved Solid-State Memory for a Wide Bandwidth Transient Waveform Recorder," *Lightning Technology,* NASA CP-2128, 1980, pp. 119-129.

[5]Baum, C.E., Breen, E.L., Giles, J.C., O'Neill, J., and Sower, G.D., "Sensors for Electromagnetic Pulse Measurements Both Inside and Away From Nuclear Source Regions," *IEEE Transactions on Electromagnetic Compatibility,* Vol. EMC-20, No. 1, Feb. 1978, pp. 22-35.

[6]Trost, T.F. and Zaepfel, K.P., "Broadband Electromagnetic Sensors for Aircraft Lightning Research," *Lightning Technology,* NASA CP-2128, 1980, pp. 131-152.

[7]Pitts, F.L. and Thomas, M.E., "Initial Direct Strike Lightning Data," NASA TM-81867, 1980.