The Lightning Threat to Aerospace Vehicles

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During 1984, the U.S. Air Force Wright Aeronautical Laboratories and the Federal Aviation Administration conducted a lightning measurement program flying a CV-580 aircraft in the vicinity of the Kennedy Space Center, FL. The aircraft was flown in thunderclouds where the regions of precipitation did not exceed 40 dBz between 2000 and 18,000 ft. The aircraft was instrumented to measure the current flow on the wingtips, the displacement and surface current densities on the fuselage and on the wings, the electrostatic field, and the VHF radiation during direct lightning attachment. The transient electromagnetic characteristics of lightning attachments were recorded using six Tektronix 7612D waveform digitizers with sample rates of 5 ns and a Honeywell 101 analog recorder with a 2 MHz frequency response. Data from 21 direct lightning attachments were recorded in the CV-580 aircraft during the program. The maximum displacement and surface current densities measured in the aircraft digital acquisition system during direct lightning attachments were 22 A/m^2 and 2950 T/s, respectively. The maximum charge and action integrals calculated from the analog data collected during direct lightning attachments were about 100 C and 2.9×10^4 A^2-s, respectively. This paper presents the characteristics of the fast transient pulses, the overall characteristics of the lightning flashes, and their relationship with the MIL-STD-1757A test qualification waveform.

Introduction

A LOW-altitude direct-strike lightning attachment program was designed by the Air Force and the Federal Aviation Administration (FAA) to expand the existing data base on direct lightning strikes to aircraft and to define and validate a lightning characterization model based on airborne aircraft lightning attachment data. Only a limited amount of data is presently available on the electromagnetic characteristics of lightning attachments to an aircraft in flight at altitudes from 2000 to 18,000 ft. There have been only five previous experimental programs[1-5] reported in the open literature that have tried to obtain aircraft lightning research data. Most of the available lightning attachment data have been recorded in the NASA F-106 aircraft at altitudes between 20,000 and 40,000 ft.[3,6,7] The valuable F-106 results have a frequency response between 1 kHz and near 100 MHz. Most of the data reported in the other programs are bandwidth-limited by the recording instrumentation. With the exception of the WC-130 program,[4] the previous airborne measurements did not have a frequency response below 1 kHz. 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, it was attempted to measure all 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 attachment to the aircraft.

A CV-580 turboprop aircraft, tail No. N49, was used to fly the missions to obtain the direct lightning attachment data. About 42 h were flown in central Florida inside or near active thunderstorms between July 11 and Sept. 5, 1984. The flights were performed at altitudes between 2000 and 18,000 ft in areas of radar reflectivity not to exceed 40 dBz.

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Instrumentation

Figure 1 shows the location of the external transient measurement 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 wingtip J_{NLWT}, right wingtip J_{NRWT}, top right wing J_{NTRW}, forward upper fuselage J_{NFUF}, and vertical stabilizer J_{NVS}. Two current shunts were mounted on the right wingtip (I_{RW}) and the left wingtip (I_{LW}).

All the surface current rate of change sensors, except the one mounted on the top left wing, J_{STLW}, were designed by EG&G.[8] The EG&G J_S sensors were a modified version of the radial multigap 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. The J_{STLW} sensor was designed in France and was provided by the Office National d'Etudes et de Recherches Aerospatiales (ONERA). The physical dimensions and shape of the French sensor were comparable to the MGL-5 sensor. The French sensor sensitivity was between 265 mA/m and 839 A/m, the 3-dB bandwidth was from 6 kHz to 130 MHz, and a risetime of 3.5 ns. The output voltages V_0 for the displacement current rate of change sensors were determined by applying Gauss' law as,

$$V_0 = A_{\mathrm{eq}} \frac{\mathrm{d}B}{\mathrm{d}t} \tag{1}$$

where A_{eq} is the sensor equivalent area and $\mathrm{d}B/\mathrm{d}t$ the rate of rise of the magnetic flux density in teslas per second. The sensor was designed to record a signal level between 500 and 20,000 T/s for $\mathrm{d}B/\mathrm{d}t$ 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.

All the displacement current rate of change sensors, except the one mounted on the top right wing, J_{NTRW}, were designed by EG&G.[8] The J_{NLWT}, J_{NRWT}, and J_{NVS} were the EG&G flush plate dipole (FPD) sensors with equivalent areas of 0.01 m^2. The J_{NFUF} was 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 was provided by ONERA for this project. The French sensor was a hollow spherical dipole (HSD) capable of detecting fields between 100 V/m and 316 kV/m with a frequency response from 100 Hz to 130 MHz and a risetime of 3.5 ns. The output voltages, V_0 for the displacement current rate of change sensors were determined by applying Gauss' law as,

$$V_0 = RA_{eq}\frac{dD}{dt} \tag{2}$$

where A_{eq} is the sensor equivalent area, R the load resistance of 50 Ω, and dD/dt the electric flux density in A/m². The J_{NLWT}, J_{NRWT}, and J_{NVS} were designed to record a signal between 1 and 40 A/m² in the digital recorder and an integrated level between 35.4×10^{-9} and 8.85×10^{-6} C/m² 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.

A 3-ft-long boom was mounted on each of the wingtips to provide a path for lightning attachement. A current viewing resistor, usually referred to as a current shunt, was mounted on each of the booms. The current shunt consisted of a resistance of 5 Ω with a 200-MHz bandwidth and a 2 ns risetime. The current shunt was designed by T&M Research Products and was calibrated to measure currents between 10 A and 25 kA.

Table 1 contains a summary of the aircraft transient measurements made with the I, J_S, and J_N sensors, the measurement ranges, and their corresponding frequency responses.

Figure 2 shows the aircraft instrumentation block diagram. A solid shield semirigid 0.25-in. heliax cable (FSJ1-50) was used to carry the signals from the external I, J_N, and J_S sensors to the signal conditional panels. The corrugated solid-copper outer conductors of the heliax cables were grounded at intervals of at least 2 ft throughout the aircraft to prevent any low-frequency ground loops from affecting the measurements. The splitters, attenuators, amplifiers, buffers, and integrators were located inside a signal conditional panel.

A trigger system was used to select the desired threshold level based on the magnitude of the signal on the J_S sensor. The trigger system consisted of eight trigger level select modules and a trigger control unit controlled by software commands through a PDP 11/35 controller. If any one of the eight trigger levels was exceeded, the system was activated acquiring simultaneous digital data in all the digitizer channels.

Six Tektronix 7612 waveform digitizers were instrumented in the CV-580 aircraft. Each channel consisted of 2048 samples and was used with a 5-ns sampling rate producing a total window of 10.24 μs. A 400-sample pretrigger interval was used for all the channels. This pretrigger interval located in the triggered sample contains about one-fifth the width of the acquisition window as shown by the digital data in this paper. All the digitizer signals are shown in Fig. 2. All the digitizers were programmed and armed by using a PDP 11/35 computer. After a set of digital data had been acquired, the time needed for the digitizers to be rearmed was approximately 1s. The digital data were stored on either a nine-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 record

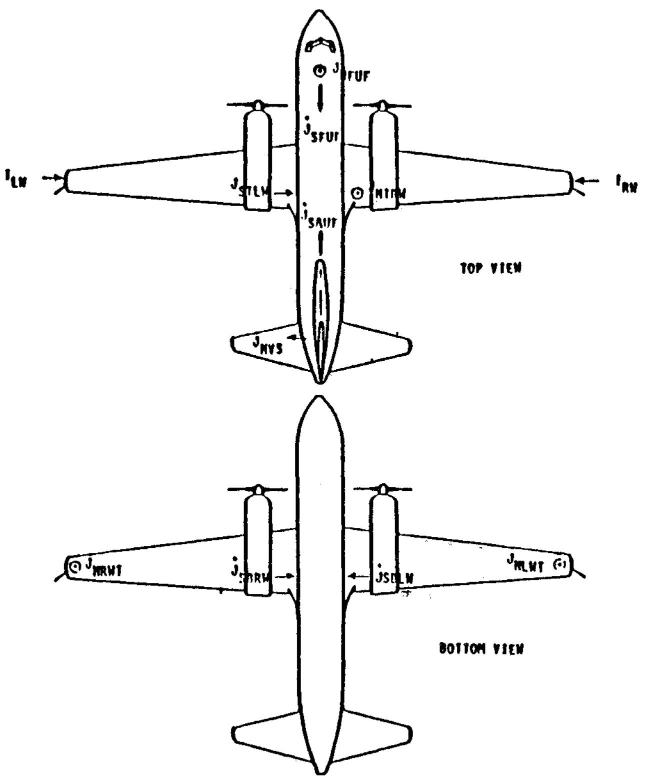


Fig. 1 CV-580 transient electromagnetic sensor locations (arrows indicate positive direction of current flow).

Table 1 Aircraft exterior transient measurements

Sensor	Type	Area/ sensitivity	Measurement range	Frequency range
I_{LW}, I_{RW}	Resistive	5mΩ	10 A-2 kA 2 kA-25 kA 100 A-25 kA	dc-5000 kHz[a] 400 Hz-2 MHz[b] 40 Hz-80 MHz[c]
J_{SBLW}, J_{SBRW}, J_{SFUF}, J_{SAUF}	Multigap loop	10^{-3} m²	5×10^{-6}-0.5×10^{-3} 5×10^{2}-2×10^{4} T/s	400 Hz-2MHz[b] 40 Hz-80 MHz[c]
J_{SILW} (ONERA),	Multi gap loop		265 mA/m-839 A/m	400 Hz-2 MHz[b] 100 Hz-80 MHz[c]
J_{NLWT}, J_{NVS}, J_{NRWT}	Flush Plate Dipole	10^{-2} m²	3.54×10^{-8}-8.85×10^{-6}C/m² 1-40 A/m²	400 Hz-2 MHz[b] 40 Hz-80 MHz[c]
J_{NFUF}	Flush Plate Dipole	5×10^{-3} m²	2.25 kV/m-2.25 MV/m	0.5 Hz-500 kHz[a]
J_{NIRW} (ONERA)	Hollow Spherical Dipole		100 V/m-316 kV/m	400 Hz-2 MHz[b] 6 kHz-80 MHz[c]

[a]FM record on Honeywell 101 instrumentation recorder. [b]Direct record on Honeywell 101 instrumentation recorder. [c]Recorded on Tektronix 7612D waveform digitizer.

continuously the fields and currents produced by lightning strikes to the aircraft. The analog recorder measurement ranges are shown in Table 1. The signals from the J_S and J_N external sensors were also integrated by using two analog channels per sensor to cover the entire dynamic range. Fourteen of the 16 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 were recorded on FM modules. Additionlly, two analog signals with different ranges were obtained from each of the two current sensors and recorded on FM modules. An IRIG B time-code signal was transmitted to the aircraft from a ground station located at the easternmost tip of the Cape Canaveral Air Force Station.

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

Results

The CV-580 aircraft was struck by lightning 21 times between July 11 and Sept. 5, 1984. There were 14 strikes at 18,000 ft, 4 strikes at 14,000 ft, 2 strikes at 4000 ft, and 1 strike at 2000 ft. However, these strikes were not proportional to the amount of hours flown at the various altitudes. About 42 h were flown inside or in the immediate vicinity of active thunderstorms. Six hours were flown at 18,000 ft, 5 h at 14,000 ft, 3 h at 10,000 ft, 12 h at 6000 ft, 4 h at 4000 ft, and about 12 h at 2000 ft. For this paper, some of the most significant data recorded on the analog and digital recorders have been selected.

On Aug. 7, 1984, at 21:41:23 Z, the aircraft was struck by lightning near Lakeland, FL. The aircraft was flying inside the clouds at 18,000 ft mean sea level (MSL). This was an area of low turbulence and the outside air temperature (OAT) and barometer pressure were 21.2°F and 7.35 psi, respectively. There was a light boom heard inside the aircraft. It appeared that this flash swept across the right wing and over the fuel tank. Many swept stroke pit marks could be found on top of the wing. The swept stroke pit marks were perpendicular to the wing and about 3 ft from the J_{NRWT} sensor on Fig. 1.

Figure 3 shows (from top to bottom) the trigger pulse and the readings of the J_{NFUF}, J_{NRWT}, J_{NVS}, and J_{NLWT} sensors during the beginning of the discharge. These data were obtained by playing back some of the analog recorder channels directly on the strip chart recorder. The lightning flash lasted about 800 ms and the digital system triggered on the first large pulse at the beginning of the flash as shown in Fig. 3. The J_{NFUF} sensor saturated in the negative direction for tens of milliseconds near the beginning of the flash. The scale values of the electric field shown on Fig. 3 were calculated by hardware integration of $\mathrm{d}D/\mathrm{d}t$ with the proper scale constants of Eq. (2) assuming the permittivity of free space. However, the relative permittivity of the medium during direct lightning attachment is not unity and these electric field values should be divided by the relative permittivity of the medium which is not known.

Figure 4 shows a 1.2 μs window of the triggered pulse from the J_{NRWT} sensor located just a few feet from the path of the discharge. The $\mathrm{d}D/\mathrm{d}t$ value of 22.52 $\mathrm{A/m^2}$ was the largest nonsaturated displacement current density value measured during the summer of 1984. There were few $\mathrm{d}D/\mathrm{d}t$ values measured in other flashes with magnitudes fairly close to the one in Fig. 4. Figure 5 shows a displacement current density, $\mathrm{d}D/\mathrm{d}t$, with a maximum level of 20.36 $\mathrm{A/m^2}$ for a lightning strike to the right wing of the aircraft about 2 min after the previous strike.

On Aug. 17, 1984, at 21:36:01 Z, the aircraft was struck by one of the channels of a cloud-to-ground flash about 20 miles north of Lake Okeechobee, FL. The aircraft was flying at about 4000 ft MSL. The aircraft was slightly inside the cloud base estimated at 3500 ft by the ground radar. There was a light boom heard inside the aircraft. There were no iden-

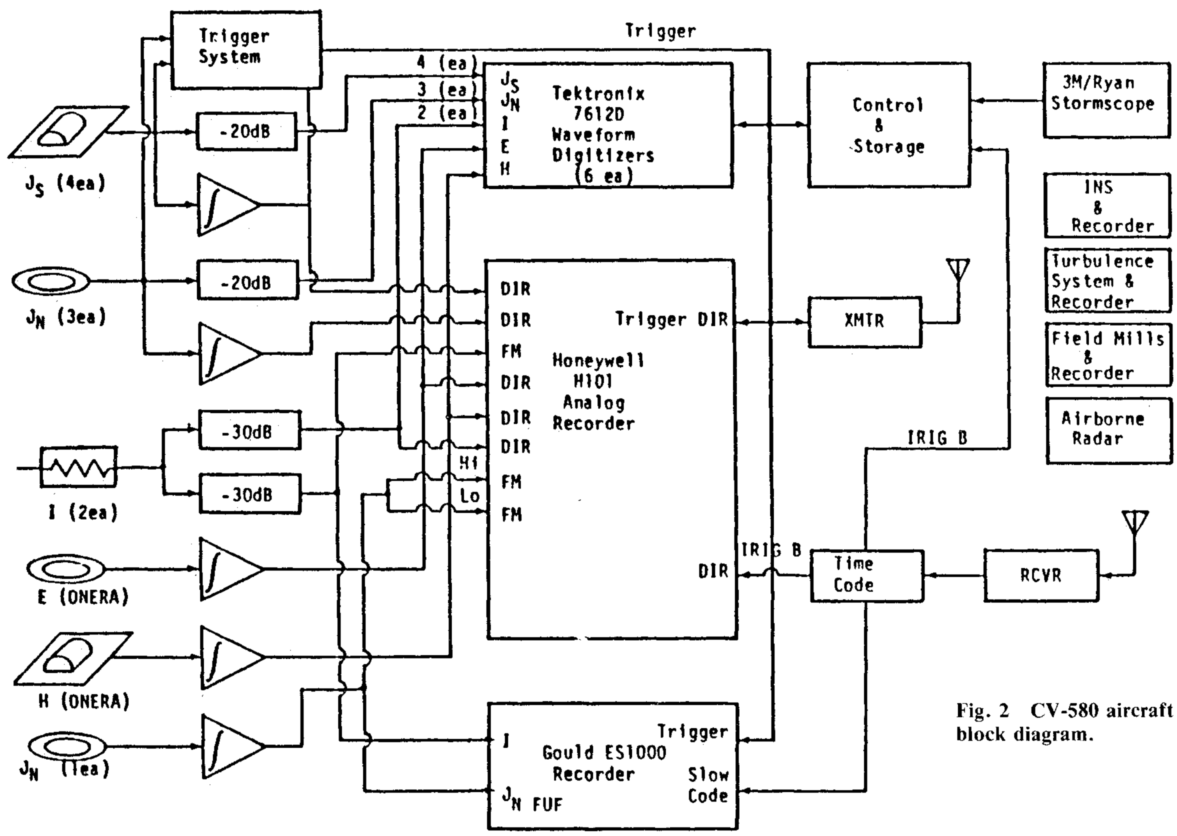


Fig. 2 CV-580 aircraft instrumentation block diagram.

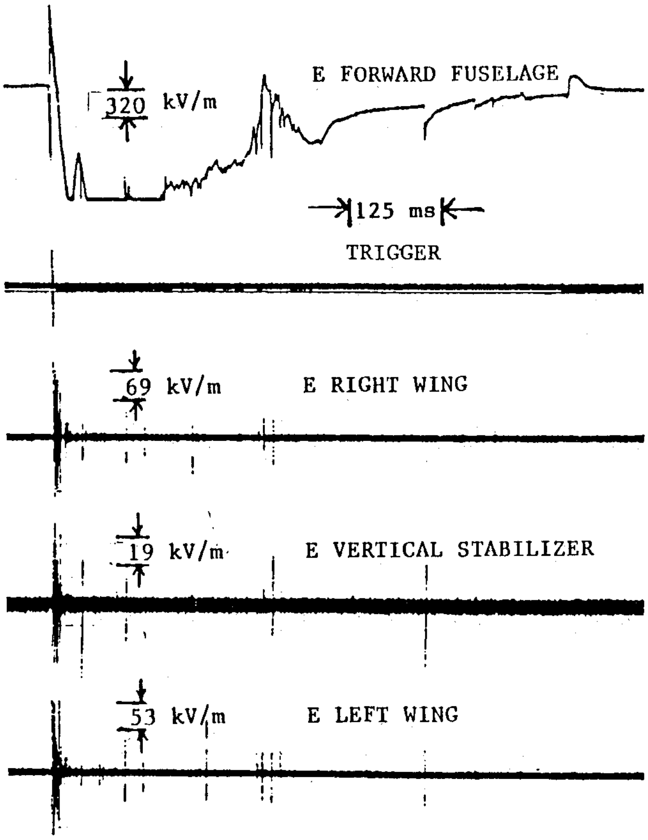


Fig. 3 Analog record of direct lightning strike on Aug. 7, 1984, at 21:41:23 Z.

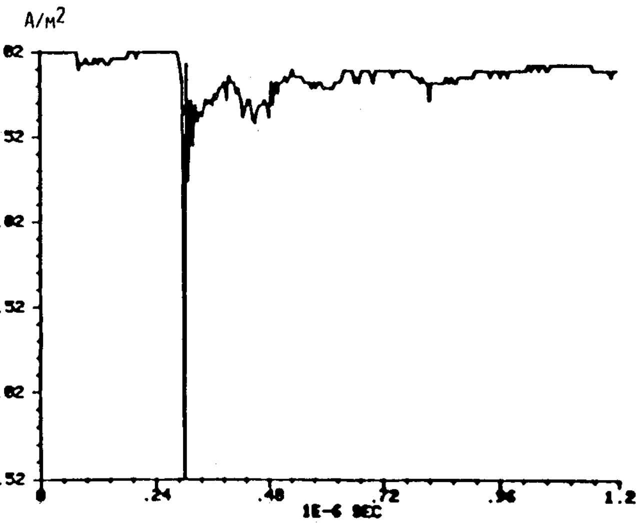


Fig. 4 A 1.2-μs window of the J_{NRWT} digital data recorded during Aug. 7, 1984, 21:41:23 Z.

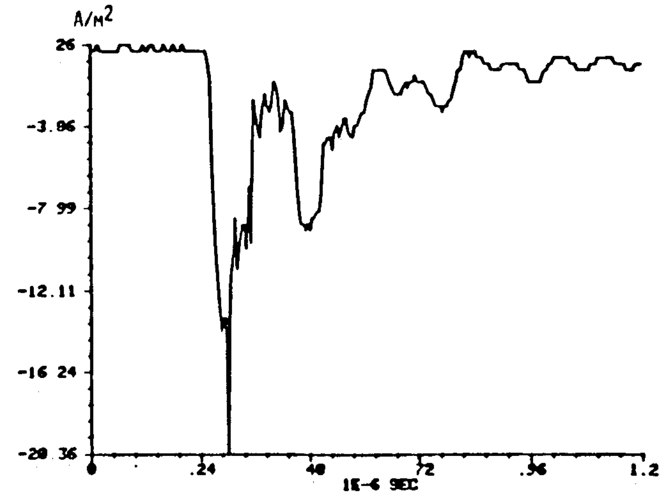


Fig. 5 A 1.2-μ window of the J_{NRWT} digital data recorded during the trigger on Aug. 7, 1984, at 21:43:26 Z at 18,000 ft.

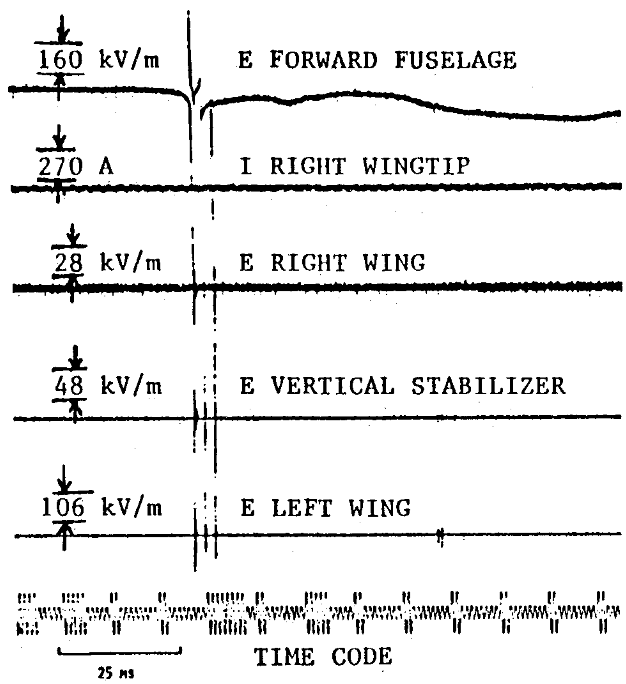


Fig. 6 Analog record of direct lightning strike on Aug. 17, 1984, at 21:36:01 Z.

tifiable pit marks or any traces of the lightning channel outside the aircraft. Two silicon-intensified target RCA TV cameras mounted inside the aircraft and pointing at each of the wings showed a vertical channel attaching to the left wing and current flow on the right wing. At that time, the Kennedy Space Center ground lightning location system identified a cloud-to-ground flash near the location of the aircraft.

Figure 6 shows (from top to bottom) the analog data from the J_{NFUF}, I_{RWT}, J_{NRWT}, J_{NVS}, and J_{NLWT} sensors as well as the time code. This flash lasted only tens of milliseconds. Assuming free-space permittivity, the maximum electric field change for this flash was about 380 kV/m on the forward fuselage and about 200 kV/m on the left wing.

Figure 7 shows the J_{SAUF} waveforms recorded at the time of the digital trigger which occurred on the first of the three main pulses during the flash. Figure 7a shows the dB/dt waveform and Fig. 7b the integrated B pulse. The subsequent three smaller pulses after the large pulse in Fig. 7a show the reflection of the first pulse from the current extremities. This was the largest nonsaturated surface current density (J_S) pulse recorded during the program.

During the Aug. 17 flash, the aircraft was hit by lightning at the nose and the fields propagated through the fuselage and into the wings. The largest surface current density waveform ever recorded was measured at the forward fuselage for this flash. Figure 8 shows an overlay of the forward and aft fuselage (Fig. 7a) field waveforms as the current propagated from the nose to the tail and into the wings. The forward fuselage signal saturated at 3950 T/s and, by observing the width of the pulse at the saturation level, one might except a maximum value near 8000 T/s.

The integrated waveform in Fig. 7b is proportional to the current propagating in the channel. Assuming a uniform cur-

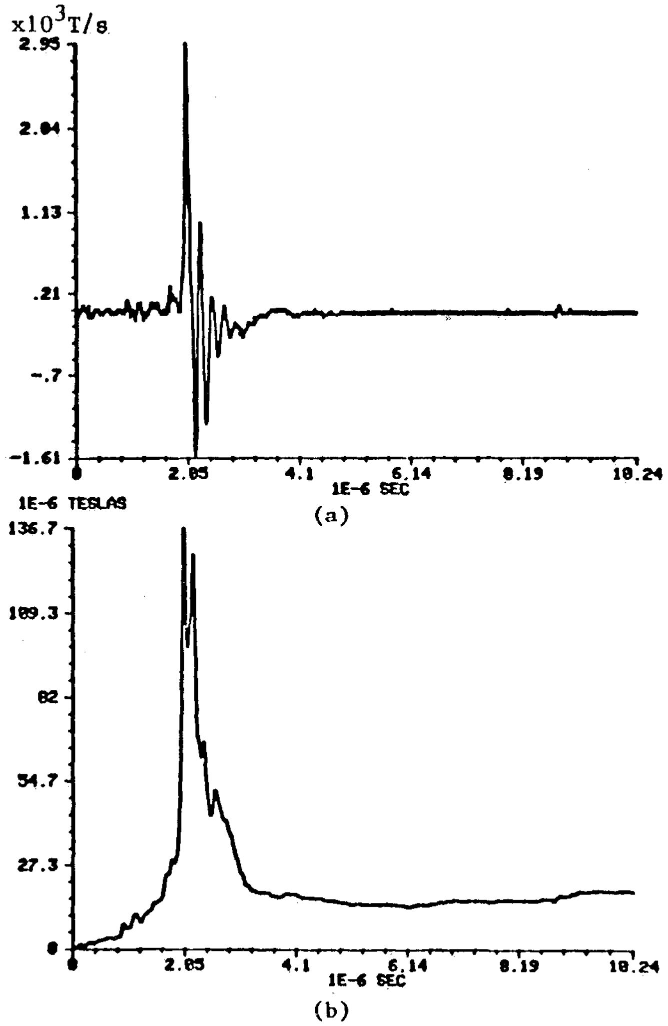


Fig. 7 a) A 10.24-μs window of the J_{SAUF} digital data recorded during the trigger on Aug. 17, 1984. b) The J_{SAUF} integrated signal from a.

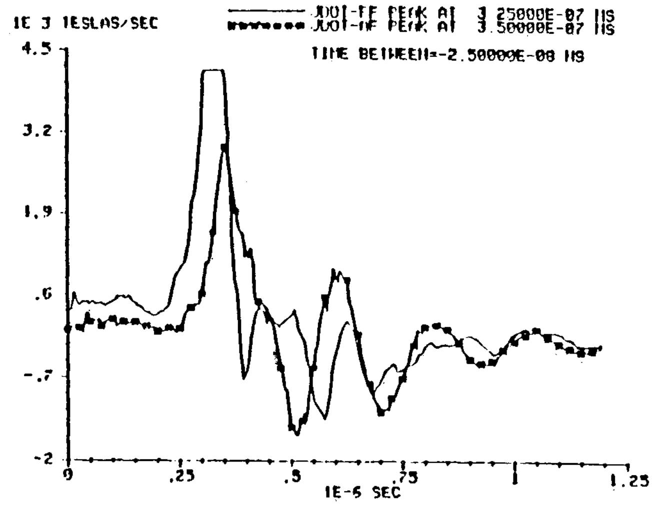


Fig. 8 Overlays of the surface current density at the forward and aft fuselage sensors showing the time delay as the current propagated from the attachment point at the nose through the fuselage and into the wings. Flash on Aug. 17, 1984, at 21:36:01 Z.

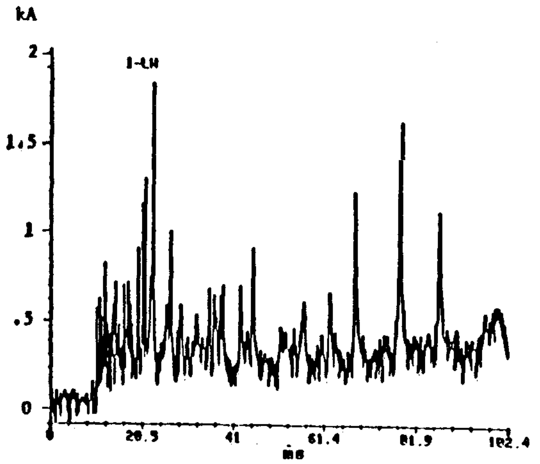


Fig. 9 Current flow on the left wingtip of a flash on Aug. 7, 1984, at 21:20:57 Z.

rent distribution, the peak current flow at the aft fuselage during the pulse in Fig. 7b is about 2.4 kA. Relating the magnitude of the field waveforms at the forward fuselage, it appears that the magnitude of the current pulse at the nose was about 8 kA.

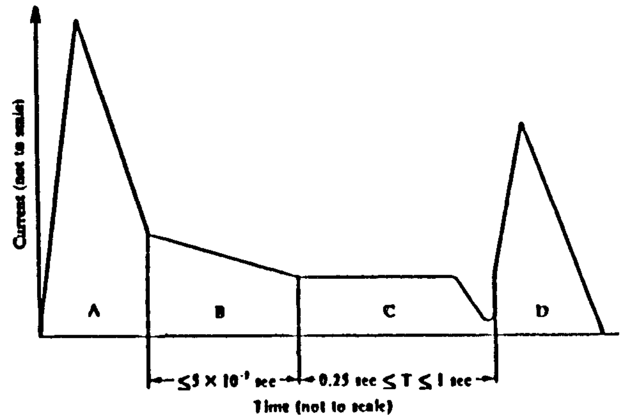
On Aug. 7, 1984, at 21:20:57 Z, the aircraft was struck by lightning while flying at the edge of a thunderstorm at 18,000 ft. The lightning discharge entered the aircraft at the left wingtip boom and propagated throughout the aircraft. Figure 9 shows the current waveform on the left wingtip during the first 100 ms of the flash. Over the first 100 ms, a charge of about 30 C was transferred through the aircraft. The flash lasted about 460 ms and transferred a charge of about 100 C. The action integral $\int i^2 dt$, which is a representation of the energy transferred, was about 3×10^4 A^2-s for the entire flash. The high pulse repetition rate and charge transfer shown on Fig. 8 appear to be typical of all of the direct lighning attachments at 14,000 and 18,000 ft.

Discussion

Military Standard 1757 (MIL-STD-1757A) establishes the lightning qualification test techniques for aerospace vehicles and hardware and also defines direct and indirect lightning effects. The direct effect of lightning is the physical damage to the external structure of the aerospace vehicle which is mainly caused by the charge and energy transfer and the high voltage and current effects. The indirect effect is primarily the electric circuit malfunction inside the aerospace vehicle caused by the electromagnetic coupling of the current and voltage inside the vehicle. Figure 10 shows the MIL-STD-1757A four current components (*A, B, C,* and *D*) used for qualification testing. These components were derived from ground current measurements during cloud-to-ground lightning discharges. It is important to relate the actual airborne lightning measurements in the CV-580 with the qualification current waveform in MIL-STD 1757A.

Components *A* and *D* refer to the peak amplitudes of the current pulses, their time duration, and action integrals. These current pulses last less than 0.5 ms with peak currents of 200 and 100 kA and action integrals of 2×10^6 and 0.25×10^5 A^2-s. These types of current pulses will produce direct and indirect effects on the aircraft. The direct effects are the results of the high currents which produce magnetic forces that can spark conductive joints and punctures on dielectric materials. The indirect effects will be the prime effect of the *A* and *D* components. The high rate of rise of the current and fields will couple to the aircraft interior producing electrical circuit malfunctions.

Components *B* and *C* refer to the intermediate and continuing current levels, time duration, and charge transfer during these phases of the discharge. The current level for these components ranges between a few hundred amperes and a few kiloamperes, and the charge transferred is between 10 and 200 C. Aircraft direct effects will be the main problem caused by



Component A (Initial Stroke)
Peak amplitude = 200kA ± 10%
Action integral = $2 \times 10^6 A^2 \cdot s \pm 20\%$
Time duration $\leq 500\mu$

Component B (Intermediate Current)
Maximum charge transfer = 10 Coulombs
Average amplitude = 2kA ± 10%

Component C (Continuing Current)
Charge transfer = 200 Coulombs ± 20%
Amplitude = 200-800A

Component D (Restrike)
Peak amplitude = 100 kA ± 10%
Action integral = $0.25 \times 10^6 A^2 \cdot s \pm 20\%$
Time duration $\leq 500\ \mu s$

Fig. 10 MIL-STD-1757A current waveform.

the *C* and *D* components. The large charge and energy transfers can produce large holes in metallic aircraft skins and shred composite materials. This direct effect can cause a puncture and an explosion in an aircraft fuel tank. However, most of the damages occur at the point where the lightning channel exits the aircraft.

To quantize the lightning threat to aerospace vehicles, it is necessary to relate the MIL-STD-1757A waveform used for qualification tests with the actual waveforms obtained when the aircraft is struck by lightning when flying near thunderstorms. The *A* and *D* components can be compared to the digital data acquired on the J_S and J_N sensors while the *B* and *C* components can be compared to the analog data recorded in all of the sensors. The displacement current densities data on Figs. 4 and 5 and the surface current densities on Figs. 7 and 8 imply current pulses of 2-8 kA flowing on the aircraft surface. However, these pulses have risetimes as low as 30 ns. The maximum inferred value for the rate of rise of the current is about 2×10^{11} A/s, obtained from an inferred current of 6 kA with a risetime of about 30 ns. The maximum inferred value of dI/dt in MIL-STD-1757A is 1×10^{11} A/s, obtained from a current of 200 kA with a risetime of 2 μs. Our slightly larger inferred rate of rise of the current value can cause unexpected circuit malfunctions inside the aircraft. The isolated pulses acquired by the digital acquisition shown in Figs. 4,5,7, and 8 represent the first pulse that exceeded a preset threshold level. However, during a lightning strike to the aircraft, there are hundreds or thousands of pulses with similar characteristics as shown in Figs. 3 and 9. The effect of the pulse repetition rate, e.g., 10^3 or 10^4 pulses/s, observed in all of the lightning attachments at 14,000 and 18,000 ft, has never been considered during analysis or testing for aircraft lightning certification. The thermal time constants of semiconductor devices are large compared to the transient times associated with lightning for a single pulse and the high repetition rate will cause additional heating and failure of the devices. In addition, the high pulse-repetition rate could activate internal clock circuits causing system malfunction. The *B* and *C* components can be related to the aircraft lightning data by studying the analog data shown in Figs. 3 and 9. The *B* or intermediate current component in MIL-STD-1757A lasts a few milliseconds whereas the *C* or continuing current component can last several hundred milliseconds. Figure 9 shows the current flow in the aircraft during the first 100 ms of the discharge. This type of current waveform appears to be typical of all of the lightning attachments at 14,000 and 18,000 ft. A charge of about 30 C was transferred during the first 100 ms of the discharge and at least 100 C was transferred for the entire discharge. From the low-frequency J_{NFUF} electric field data in some of the other flashes, it was inferred that the 200 C ±20% charge transfer on MIL-STD-1757A component *C* was exceeded for some of the flashes.

Conclusion

The largest lightning pulses measured during flight in the CV-580 aircraft are presented, and their relationship to the lightning qualification test waveform in MIL-STD-1757A is discussed. The measured characteristics of lightning attachment to the CV-580 aircraft between 2000 and 18,000 ft should be comparable with those obtained when any aircraft is hit by lightning at the same altitudes. The lightning attachment patterns, however, are a function of the aircraft shape. The distance between the wingtips in the CV-580 aircraft is 24 ft longer than the nose-to-tail distance, making the wings more vulnerable to lightning than in most aircraft.

The maximum measured levels of displacement current density, of 22 A/m^2, and of surface current density, in excess of 3950 T/s, are in general compliance with the *A* and *D* components of MIL-STD-1757A. The inferred rate of rise of the current of the measured pulse is nearly a factor of 2 larger than the implied rate of rise of the *A* component in MIL-STD-1757A. The charge and energy transfers measured in the CV-580 aircraft for the entire duration of the discharge are in compliance with the *B* and *C* components of MIL-STD-1757A, but it appears that a charge transfer in excesss of the maximum qualification number of 200 C ±20% occurred for some of the flashes between 14,000 and 18,000 ft. The only parameter measured for all of the flashes at 14,000 and 18,000 ft that is not considered in MIL-STD-1757A was the pulse repetition rate. There are hundreds of pulses in the aircraft lightning discharges inside the cloud level. These flashes can have pulse repetition rates in excess of 10^4 pulses/s over a portion of the discharge, but these pulses usually do not exceed a few kiloamperes. These pulses are often riding on top of a continuing current flow through the aircraft and occurred regardless of whether or not the aircraft triggered the discharge.[9] It is not practical to provide a qualification test waveform to account for this very large pulse repetition rate but these pulse types should be analyzed and the results incorporated into the test waveform using a reasonable technique.

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