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The interaction of lightning with airborne vehicles

M.A. Uman*, V.A. Rakov

Department of Electrical and Computer Engineering, University of Florida, Gainesville, FL 32611, USA

Abstract

We review the available information on the mechanisms of lightning-aircraft interactions based primarily on studies involving four different instrumented aircraft. Further, we present available statistics on lightning-related aircraft incidents as a function of aircraft altitude and of ambient temperature. Finally, we examine the most significant aircraft and launch vehicle accidents attributed to lightning.

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*Corresponding author. Tel.: +1-352-392-0913; fax: +1-352-392-8671.
E-mail address: uman@ece.ufl.edu (M.A. Uman).

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1. Introduction

Not until the 1980s was it convincingly demonstrated that the vast majority of lightning strikes to aircraft are initiated by the aircraft, as opposed to the aircraft's intercepting a discharge already in progress. A video frame showing evidence of the initiation of lightning by an aircraft at relatively low altitude in Japan is found in Fig. 1a, that evidence being the different directions of channel branching above and below the aircraft. More information on this event is found in Section 5.4. A video frame of another lightning-aircraft interaction, this one soon after takeoff near San Francisco, California, is shown in Fig. 1b. Early arguments that aircraft could initiate lightning were based primarily on the many observed cases of lightning strikes to aircraft inside or near clouds that had not previously produced natural lightning (e.g. [1–4]). The first scientific evidence that aircraft could and did indeed initiate lightning was provided by Mazur et al. [5], as discussed in Section 4. Our understanding of the mechanisms of lightning initiation by aircraft is derived primarily from four airborne studies involving four different instrumented aircraft: an F-100F, an F-106B, a CV-580, and a C-160. Those airborne research programs are considered in Section 2. In Section 3 we review the available statistical data regarding lightning interactions with aircraft. In Section 5 we examine some aircraft and launch vehicle accidents attributed to lightning. A summary is found in Section 6.

2. Airborne studies

2.1. F-100F

The F-100F project, termed Rough Rider, took place from 1964 to 1966 and is described by Fitzgerald [3] and Petterson and Wood [6]. The F-100F, a single-engine jet, penetrated thunderstorms to measure turbulence and to obtain lightning photographic, shock wave, and electrical current records. Data were recorded for 49 lightning discharges. Measurements of lightning current on the F-100F were made on the nose boom, wing tips, and vertical stabilizer. Current data were displayed on oscilloscopes and recorded on photographic film, a rather primitive technique by today's standards. As a consequence, there were difficulties in adequately recording current rise time and rate-of-rise and often the oscilloscopes would trigger too soon and miss the potential event of interest, or the event of interest would occur during film advance [6].

2.2. F-106B

The NASA F-106B, a delta wing, single-engine jet aircraft of 21.5 m length including a sharp 3-m nose boom (a slender metal extension projecting from the plane's nose), flew about 1500 thunderstorm traversals at altitudes ranging from 5000 to 40,000 feet (1.5–12 km) and was struck by lightning 714 times between 1980 and 1986 [7]. Almost 10 times as many strikes were obtained for the high altitudes as for the low, the dividing altitude apparently being 6 km, although the number of high and low cloud penetration was not much different [8]. Statistics were compiled for aircraft surface electric and magnetic field derivatives and for lightning current and current derivative flowing through the aircraft. Detailed information on the instrumentation and data obtained are found in [5,8–23].

2.3. CV-580

The USAF/FAA CV-580, a two-engine turboprop transport aircraft of 24.7 m length, was instrumented as

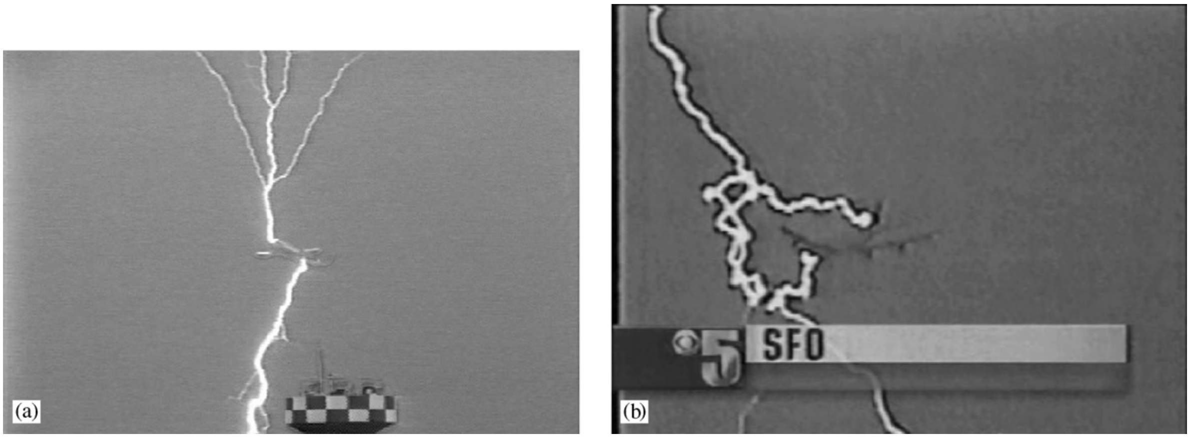


Fig. 1. (a) Video frame of a lightning strike to an aircraft on takeoff from the Kamatzu Air Force Base on the coast of the Sea of Japan during winter. Courtesy, Z.I. Kawasaki. (b) Video frame of a lightning strike to an aircraft after takeoff from San Francisco International Airport. Courtesy of KPIX Channel 5, 855 Battery St., San Francisco, CA.

described by Rustan [24], Reazer et al. [25], Mazur [22], Mazur and Moreau [26], and Lalande et al. [27], and was flown in 1984 and 1985. Five sensors that measured the time derivative of the surface electric field intensity and five sensors that responded to the rate-of-change of the surface current density (surface magnetic field intensity) were mounted at various positions on the CV-580. An electric field derivative sensor on the forward upper fuselage was combined with an active integrator to provide an electric field intensity with a lower-frequency response of 1 Hz and with relatively high sensitivity. Electric field sensors with lower sensitivity were mounted on the wingtips and left side of the vertical stabilizer. Five electric field "mills", mechanical devices that sensed the field from dc to about 1 kHz, were mounted at various locations on the fuselage, making possible the measurement of the ambient field and the estimation of the charge residing on the aircraft. A magnetic field sensor was mounted at the end of a 10-foot-long (about 3 m) horizontal boom attached to the tail of the aircraft. Current sensors were located at the base of the tail boom and at the base of horizontal booms installed on the two wingtips.

2.4. C-160

The C-160 research aircraft used in the Transall field programs in France during 1984 and 1988 was a two-engine aircraft similar to the CV-580 but somewhat larger, 32.4 m in length vs. 24.7 m for the CV-580. The C-160 program is described by Moreau et al. [28], Mazur [29], Mazur and Moreau [26], Lalande and Bondiou-Clergerie [30], and Lalande et al. [27]. There are apparently no data published from the 1984 program. For the 1988 study the C-160 was instrumented specifically for investigation of the initial processes of lightning attachment. The instruments used were a network of five electric field mills, a network of seven capacitive antennas with active integrators, current shunts, and a high-speed (200 frames per second) video system. Moreau et al. [28] give the amplitude and frequency ranges for all sensors. The bandwidth of the electric field mill system on the C-160 was too narrow (0–40 Hz) to characterize the field variation within the first several milliseconds of strike initiation but was used to determine the ambient field value and the charge on the aircraft prior to the strike. The capacitive antenna network had a bandwidth from 1.5 Hz to 5 MHz, was equipped with 100 MHz 10 bit digitizers, and was used to characterize the electric field on the aircraft surface on submicrosecond to tens-of-millisecond time scales.

A video camera having a recording speed of 200 frames per second and a "fish-eye" lens with a 197° viewing angle was located in a pylon under the right wing, 10 m from the fuselage. The camera, with a vertical resolution of 262 lines and a horizontal resolution of 200 pixels, simulated a still camera with a 5 ms time exposure and a 400 μs interval between frames. The video recording was synchronized to the electrical measurements to within 1 s.

3. Statistics on lightning strikes to aircraft

Fig. 2 summarizes the results of five studies of the altitude at which lightning-related aircraft incidents occur. These studies took place between the early 1950s and the mid-1970s. The statistics are similar for all types of aircraft. Older piston aircraft which cruise at 10,000 to 15,000 feet (about 3–4.5 km) show a similar pattern of strike occurrence as a function of altitude as modern jet aircraft which cruise at much higher altitudes. For jets, most strikes occur either in climbing to a cruising altitude, generally near 30,000 feet (about 9 km), or in landing, in both cases when the aircraft passes through the region of the cloud where the temperature is near 0°C. According to Fisher et al. [31] and Plumer et al. [32], the overwhelming majority of strikes occurs when the aircraft is within a cloud with only a few percent of strikes taking place when the aircraft is below or beside the cloud; the majority of strikes is associated with local airmass instability (27 percent) and organized fronts including squall line activity (53 percent); and the vast majority of strikes is associated with turbulence and precipitation: 70 percent with rain and another 12 percent with a mixture of rain and snow, sleet, or hail. Nevertheless, the fact that a typical thundercloud charge distribution is shown in Fig. 2 is not intended to imply that all lightning strikes are associated with such clouds. For example, strikes have been recorded in clouds described as composed entirely of ice crystals, and, according to Harrison [2], from United Air Lines data roughly 40 percent of all discharges involving aircraft occur in areas where no thunderstorms are reported, with thunder or lightning being reported in the general area in the remaining 60 percent, and with evidence for a thunderstorm at the spot of discharge being present in only 33 percent of all reported strikes. Harrison [2] further states that any weather situation producing precipitation appears to be capable of causing electrical discharges to aircraft in flight.

Data on the frequency of strikes to US commercial aircraft from 1950 to 1974 are found in Table 1. During the period studied, a typical commercial plane was struck once for each 3000 flight hours, or about once a year.

Murooka [33] has provided statistics on lightning strikes to commercial jets in Japan for the years of 1980 to 1991. Data on over 1000 strikes are shown separately for summer and winter in Figs. 3a and b, respectively. Murooka [33] found that the bulk of the strikes in

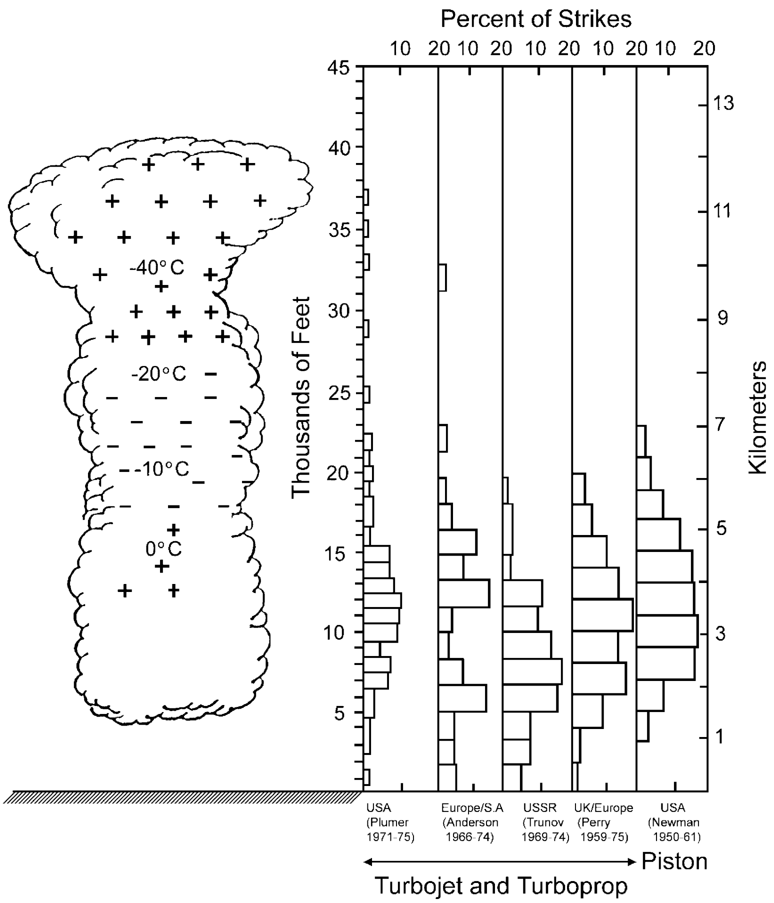


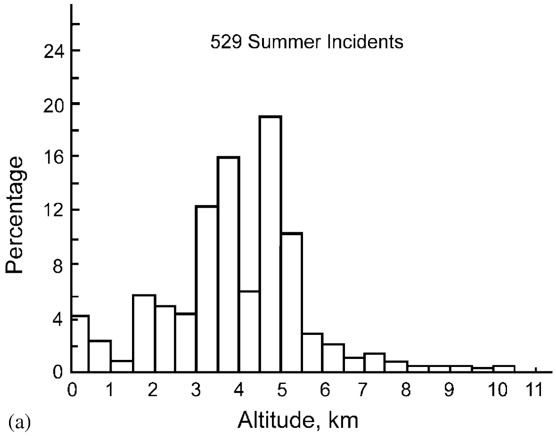
Fig. 2. Aircraft lightning incidents vs. altitude. Adapted from [31] with correction of their typical summer thundercloud charge distribution.

Table 1
Incidence of lightning strikes to commercial aircraft

	Newman (1950–1961)		Perry (1959–1974)		All data combined		
Aircraft type	Strikes	Flight hours	Strikes	Flight hours	Strikes	Hours	No. hours per strike
Piston	808	2,000,000	—	—	808	2,000,000	2,475
Turboprop	109	415,000	280	876,000	389	1,291,000	3,320
Pure jet	41	427,000	480	1,314,000	521	1,741,000	3,340
All	958	2,842,000	760	2,190,000	1,718	5,032,000	2,930

Adapted from [31].

summer and in winter individually occurs in the same temperature range, −5 to 0°C. The data from summer and winter are combined in Fig. 4. In Japanese winter storms the freezing level is near the ground and the cloud top is near 5 km. Hence, in winter the strikes occur at considerably lower altitudes than those in summer, as indicated in Fig. 3. Michimoto [34] has provided similar data for lightning strikes to military aircraft in Japanese winter storms for the period from 1961 to 1990. Goto and Narita [35] have compared the altitude and temperature of winter strikes in Japan with similar data from all seasons in South Africa, the USA, and the USSR. They find the most similarity between events in Japan and in the USSR.



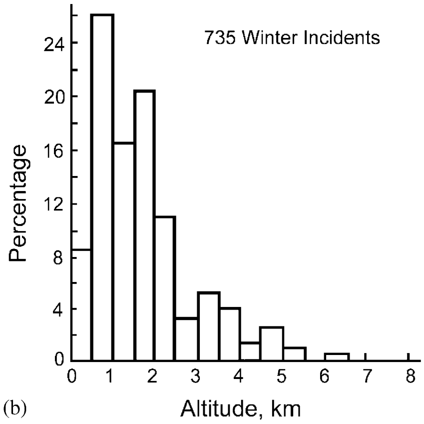


Fig. 3. Aircraft lightning incident rate vs. altitude (a) in summer and (b) in winter for commercial aircraft in Japan. Adapted from [33].

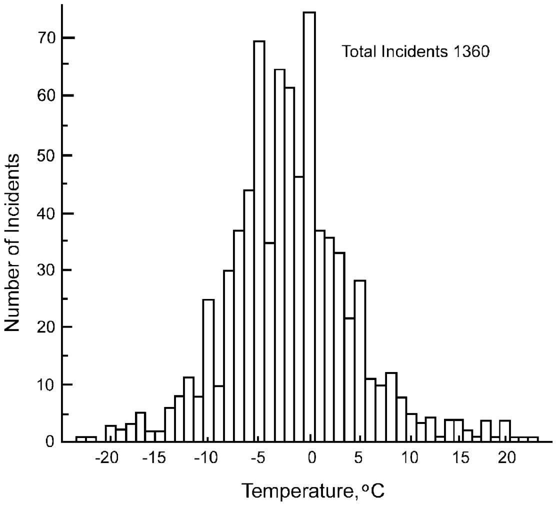


Fig. 4. Number of aircraft lightning incidents during all seasons vs. ambient temperature for commercial aircraft in Japan. Adapted from [33].

Anderson and Kroninger [36] have examined South African Airways lightning strike records from 1948 to 1974. Most strikes occurred 3–5 km above sea level. The number of strikes reported per 10, 000 h of flying time for different years varied between about 1 and 4, consistent with the data in Table 1.

The effects of lightning on aircraft are generally minimal, although the consequences of the interaction can be catastrophic, as we shall see in Section 5. Lightning damage is usually divided into "direct" and "indirect" (or "induced") effects. Direct effects occur at the points of the lightning contact and include holes in metal skins (see also Section 4.1), puncturing or splintering of non-metallic structures such as the plastic radomes that cover the radars located at the front of aircraft, welding or roughening of moveable hinges and bearings, damage to antennas and lights located at aircraft extremities, and fuel ignition. Indirect effects are those produced by deleterious voltages and currents induced within the aircraft by the lightning electric and magnetic fields and include upset or damage to any of the many aircraft electronic systems. Table 2 gives some statistics on indirect effects that occurred from 1971 to 1984 when 20 percent of 851 reported strikes resulted in indirect effects [31]. Fisher et al. [31] present additional details on various forms of damage to aircraft from lightning including photographs of damage due to direct effects. Anderson and Kroninger [36] report that aircraft frame or instrument damage occurred in 40 percent of the 245 recorded strikes to aircraft in South Africa between 1948 and 1974.

Table 2
Incidence of indirect effects in commercial aircraft during 214 lightning strikes

	Interference	Outage
HF communication set	—	5
VHF communication set	27	3
VOR receiver	5	2
Compass (all types)	22	9
Marker beacon	—	2
Weather radar	3	2
Instrument landing system	6	—
Automatic direction finder	6	7
Radar altimeter	6	—
Fuel flow gauge	2	—
Fuel quantity gauge	—	1
Engine rpm gauges	—	4
Engine exhaust gas temperature	—	2
Static air temperature gauge	1	—
Windshield heater	—	2
Flight director computer	1	—
Navigation light	—	1
AC generator tripoff	(6 instances of tripoff)	
Autopilot	1	—

Adapted from [31].

4. Mechanisms of lightning/aircraft interaction

4.1. Overview

The first direct evidence of the initiation of a lightning strike by an aircraft was provided by UHF radar echoes of lightning channel formation during strikes to the NASA F-106B research aircraft. These ground-based radar images showed that the initial leader channels originated at or very near (the radar resolution was 150 m) the F-106B and propagated away from it [5]. A much less common event, the interception of a lightning flash by the F-106B, as inferred from radar, is described by Mazur et al. [16].

The fact that aircraft initiate lightning has also been inferred from the analysis of measured electric field waveforms on the surface of aircraft. For example, Reazer et al. [25] showed that in 35 of 39 strikes to the CV-580 research aircraft the characteristics of the electric field waveforms were consistent and could be explained by an aircraft initiation hypothesis, although their suggested physical interpretation of the typical waveform does not represent the current consensus view (e.g. [22], while the other 4 waveforms were clearly different and could be interpreted as due to an aircraft's intercepting an independently initiated flash. Associated current measurements on the CV-580 and the C-160 research aircraft provided further evidence of aircraft initiation, as did high-speed video records of channel formation (e.g. [28,22]).

The mechanism for lightning initiation by a conducting object not attached to the Earth is often referred to as the "bidirectional leader" theory [37], and its application to lightning initiation by aircraft and other airborne vehicles has been considered, for example, by Clifford and Kasemir [4], Mazur [21,22], Mazur [29], and Mazur and Moreau [26]. In an ambient electric field typically near 50 kV m^{-1}, a common value in thunderclouds [38], the CV-580 and C-160 research aircraft flying near 5 km altitude are inferred, from interpretation of the measurements made on the two aircraft, to launch a positive leader in the direction of the electric field from one aircraft extremity and, a few milliseconds later, a negative leader in the opposite direction from a different extremity. Similar bidirectional leader development is inferred by Mazur [22] in the case of the F-106B except that the initial positive leader was apparently preceded by intense corona or other processes that caused a millisecond-duration electric field change opposite in polarity to that caused by the positive leader. It is reasonable to expect that a positive leader would occur first in the bidirectional leader development since, in general, positive leaders are initiated and can propagate in lower electric fields than negative leaders. Although it appears not to be the case according to the available literature, there is no obvious reason why a negative leader could not be emitted from an aircraft prior to a positive leader if the field enhancement at the extremity launching the negative leader was considerably greater than at the extremity launching the positive leader, a function both of the detailed shape and orientation of the aircraft and of the effects of corona that could potentially reduce the field enhancement.

The aircraft extremities provide the region of high electric field needed to initiate a lightning discharge by enhancing the ambient electric field to breakdown values, 3×10^3 kV m^{-1} near sea level and about half that value at 6 km altitude. Thus, at flight altitudes a reasonable aircraft enhancement factor of the order of ten is required to initiate lightning in the observed ambient fields. The shape of the aircraft is the most important factor in determining the increase of the local electric field at, for example, wingtips or vertical stabilizer to magnitudes that make the initiation of lightning possible. After the initial stage of the discharge, which is characterized by impulsive currents near 1 kA, apparently associated with the steps of the negative stepped leader, the observed current through the research aircraft is generally composed of a continuing component and a variety of impulses, probably not unlike a natural intracloud flash (e.g. [21]). Occasionally, aircraft initiate or otherwise become involved in cloud-to-ground lightning, this being more likely when they are closer to the Earth (e.g. [16,23,26]). Clearly, if an aircraft initiates lightning at low enough altitudes, such as soon after takeoff, as in the case illustrated in Fig. 1a and likely in Fig. 1b, that aircraft will necessarily be involved in a ground flash.

According to Harrison [2], who studied 99 lightning strikes to United Air Lines aircraft, electrical discharges to aircraft in flight exhibit three common features:

1. bright flash, sometimes blinding
2. loud explosive "boom", sometimes muffled
3. minor damage to aircraft in one third to one half of all cases

Pilots often distinguish between two types of lightning-aircraft interaction which they call, in layman's terms, "static discharge" and "lightning". The former, "static discharge", is characterized by radio static on the pilot's earphone of some seconds duration and a corresponding corona discharge (when it is dark, the luminous corona is visible and is commonly referred to as St. Elmo's fire) on the aircraft prior to the major observed electrical discharge. The latter, "lightning", is an electrical discharge that occurs without much prior warning. "Static discharges" are the much more common occurrence and apparently correspond to aircraft-initiated lightning. Interestingly, many pilots view events in the "static discharge" category as caused by the neutralization of the charge stored on the aircraft, which is typically of the order of 1 mC, much too small to produce the damage often observed to the aircraft skin after these discharges have occurred. Typically, this skin damage involves a sequence of burn marks or burn holes along a line due to the changing lightning channel attachment point as the aircraft moves relative to the lightning, the so-called swept stroke phenomenon (e.g. [39–41]). Such aircraft skin damage coupled with laboratory testing provides evidence that the so-called static discharges can transfer charges similar to those of natural lightning and hence are actually aircraft initiated lightning. The "lightning" category apparently includes primarily flashes initiated independently of the presence of the aircraft which the aircraft then intercepts.

4.2. *Aircraft-initiated lightning*

Mazur [22], from an analysis of electric field and current records obtained on the F-106B and the CV-580, has proposed a mechanism of lightning initiation by aircraft that is accepted by most researchers. Moreau et al. [28] and Lalande et al. [27] have reviewed and summarized the data from the CV-580 and C-160 studies, including the high-speed video observations on the C-160 of Moreau et al. [28], and have described the initiation process in essentially the same way. Fig. 5 shows a drawing of the typical electric field waveform observed on either the CV-580 or the C-160 during events interpreted as aircraft-initiated lightning, along with the typical time-correlated current through the aircraft. Also shown in Fig. 5 are sketches illustrating the bidirectional leader behavior inferred from field, current, and photographic measurements. Measured electric field and current waveforms from the C-160 experiment are shown in Fig. 6. From examinations of the correlated electric field and current records, both Moreau et al. [28] and Lalande et al. [27] infer that about 90 percent of the lightning strikes to the CV-580 and the C-160 were triggered by the aircraft. The following description of the processes occurring in aircraft-initiated discharges to the CV-580 and C-160 is taken from Mazur [22], Moreau et al. [28], and Lalande et al. [27]: The aircraft-initiated lightning events can be divided into two phases. The first phase involves the initiation and development of a bidirectional leader that begins when the aircraft flies into a region of the cloud where the ambient electric field is typically near 50 kV m^{-1}. Interestingly, the orientation of the ambient field during strikes to the C-160 was mostly vertical while for the CV-580 it was mostly horizontal, which according to Lalande and Bondiou-Clergierie [30] may be due to the fact that the C-160 flew in France at an altitude of 4.6 km (ambient temperature −5°C), which was in the main negative charge center of the French thunderclouds while the CV-580 flew in Florida at 4.5 km (ambient temperature 0°C), near the bottom of the main negative charge center in Florida thunderclouds. As noted in Section 4.1, in a sufficiently high field, the first discharge-related event on the CV-580 or C-160 is inferred to be the initiation of a positively-charged leader from the aircraft, as shown in Fig. 5. The leader propagates in the direction of the ambient field. During the development of this positive leader, from

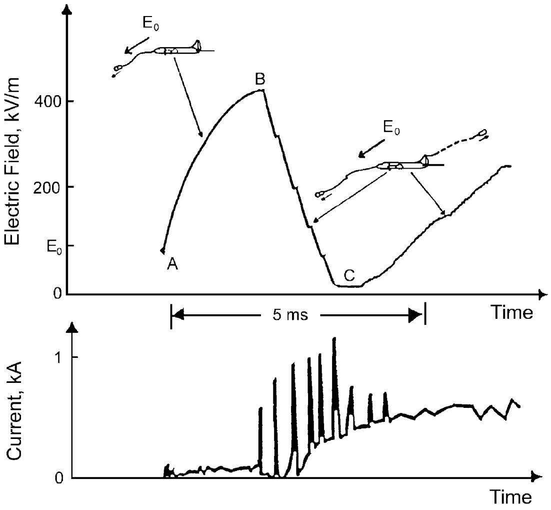


Fig. 5. Typical electric field intensity, current, and schematic representation of leader development during the initial phase of a typical aircraft-initiated lightning. E_0 is the ambient electric field at lightning initiation. Adapted from [27].

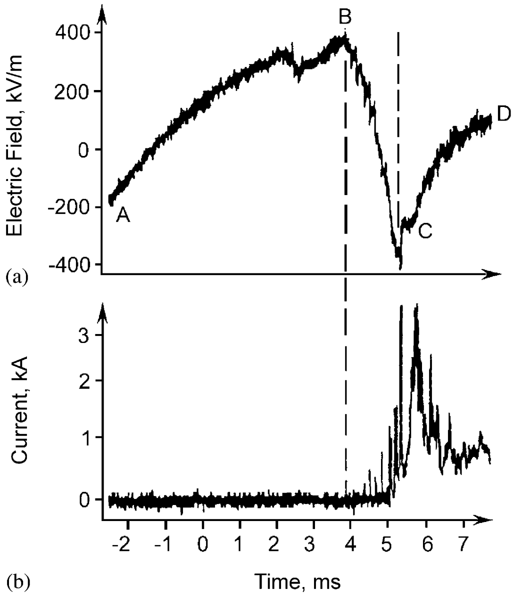


Fig. 6. Correlated electric field change and current recorded on the C-160 aircraft: (a) electric field at the forward upper fuselage and (b) current in the nose boom. Adapted from [28].

A to B in Figs. 5 and 6, a net negative charge increases on the aircraft due to the removal of positive charge by the propagating positive leader, and the field enhancement on the aircraft increases due to the increasing length of the overall conducting system of aircraft plus positive leader. The increase in negative charge on the aircraft produces an increase in the electric field pointing toward the aircraft surface at all points on the aircraft surface. In Figs. 5 and 6 this increase (A–B) is plotted as a positive field change although the vector direction depends on where on the aircraft the field is measured. Further, the relation between the directions of the ambient field and the field change AB is also aircraft-position dependent. A few milliseconds after the initiation of the positive leader, the electric field value on the aircraft necessary for launching a negative leader, the field near point B in Figs. 5 and 6, is reached. The negative leader develops from an opposite extremity of the aircraft (see Fig. 5) and propagates in a direction opposite to both the ambient electric field and the direction of extension of the positive leader. The negative leader development serves to reduce the negative charge on the aircraft leading to a reduction in the electric field pointing toward the aircraft surface, from B to C in Figs. 5 and 6, although the negative leader may be initiated prior to B. According to Lalande et al. [27], as the negative leader propagates, the positive leader accelerates and branches, producing a positive increase in the aircraft electric field, after C in Figs. 5 and 6. In the view of Lalande et al. [27], from B to C the negative leader is more efficient in removing charge from the aircraft than the positive leader whereas after C the positive leader is the more efficient because of branching and higher speed, but the details of the physics of the bidirectional leader development are certainly unclear. According to Lalande et al. [27], currents of only a few amperes are associated with the initial positive leader, the current level being deduced from electric field change measurements since it was below the level that could be directly measured with the instrumentation used. Moreau et al. [28] present, as noted earlier, 200 frame-per-second video records which show images of a positive leader (phase AB) prior to negative leader initiation, although the video and electrical (fields and current) measurements were only synchronized to about 1 s. Moreau et al. [28] estimate from the magnetic field variations observed on the CV-580 during the AB phase that the steady current in the positive leader is about 1 A. The total evidence for the existence of the positive leader is apparently (1) the electric and magnetic field variations during the AB phase, which could be subject to other interpretations, (2) the high-speed video imaging that was inferred to be associated with the AB phase, and (3) the fact that laboratory studies of positive leaders in long gaps indicate currents increasing in a few milliseconds to a value of the order of 1 A with a current rate of rise of 6.6×10^2 A s^{-1}. During the first few milliseconds of the negative leader formation, identified by Moreau et al. [28] as phase BC in Figs. 5 and 6, there are typically ten or so impulses of current of nearly 1 kA amplitude separated by a mean time interval of 250 μs and superimposed on a relatively steady current which increases to about 300 A.

Lalande et al. [27] have summarized data for 31 aircraft-initiated lightning events involving the CV-580 and 12 involving the C-160. Additional details from this analysis are found in the report by Lalande and Bondiou-Clergerie [30]. The average duration of all the aircraft-initiated flashes was 400 ms with a minimum of 140 ms and a maximum of 1 s. For the CV-580, the mean ambient electric field just prior to the time of the lightning occurrence was 51 kV m^{-1} with a range from 25 to 87 kV m^{-1}; for the C-160, 59 kV m^{-1}, with a range from 44 to 75 kV m^{-1}. This ambient field value (E_0) is shown at point A in Figs. 5 and 6. For the CV-580 the electric field change attributed to the positive leader, from A to B in Figs. 5 and 6, had a mean value of 342 kV m^{-1} and occurred in a mean time of 3.9 ms; 551 kV m^{-1} in 4.3 ms for the C-160. The field change from A to B for the combined data varied from about 200 to 800 kV m^{-1} and the time interval from about 1 to 9 ms. During the period in which the negative stepped leader is assumed to be initiated and propagating away from the aircraft, B to C, the electric field on the surface of the aircraft is reduced to near zero in a mean time of 1 ms for the CV-580 and 2 ms for the C-160. From combined data for both aircraft, the mean duration of the steady current was 188 ms, with a mean amplitude of 330 A, and a mean maximum value of 910 A. For the combined data, the mean charge, the integral of the current that flowed through the aircraft during the total duration of its interaction with the lightning, was 60 C.

Moreau et al. [28] present 7 examples of electric field waveforms from the C-160 and one from the CV-580 during aircraft-initiated strikes, one of these being shown in Fig. 6. Additionally, Moreau et al. [28] provide statistical data, similar to those presented by Lalande et al. [27], on 33 lightning events inferred to be initiated by the CV-580 and 16 by the C-160, that is, two more events than do Lalande et al. [27] for the CV-580 and 4 more for the C-160. Moreau et al. [28] state that the data are from storm penetrations in central Florida (CV-580) and in southern France (C-160) at altitudes of 6 km and lower while Lalande and Bondiou-Clergerie [30] state that generally the CV-580 flew at an altitude of 4.5 km and the C-160 at 4.6 km. Why the later data analysis of Lalande et al. [27] contains fewer events than the earlier analysis of Moreau et al. [28] is not explicitly stated, but one might assume that Lalande et al. [27] excluded some data that they felt were not of sufficient quality for analysis, and Lalande and Bondiou-Clergerie [30] state that their analysis involved waveforms previously printed on paper since the original tape-recorded data were degraded or otherwise not available for analysis. Lalande et al. [27] present their statistical data in tables, Moreau et al. [28] present theirs in the form of histograms. The values presented by Moreau et al. [28] and Lalande et al. [27] for aircraft-initiated lightning are generally similar, but Moreau et al. [28] apparently present additional data with shorter time duration and smaller field change for the AB and BC phases (Figs. 5 and 6) than do [27].

The first correlated electric field and current waveforms of the type illustrated in Fig. 5 and 6 and interpreted as indicating aircraft-initiated lightning were apparently recorded on the CV-580 in 1984 [24,25]. Reazer et al. [25] show three examples of 35 such correlated pairs of field and current waveforms obtained on the CV-580 in 1984 and 1985, one pair being reproduced in Figs. 6a and b. The initial portion of these waveforms is similar to that of the waveforms found in Figs. 5 and 6. Reazer et al. [25], however, do not interpret the AB phase of the waveforms (see Figs. 5 and 6) as due to a positive leader removing positive charge from the aircraft, as have most other investigators. Mazur [22] interprets Reazer et al. [25] as attributing the AB phase to a variation in charge near the aircraft caused by an approaching positive leader and states that in the view of Reazer et al. [25], the aircraft initiated an intracloud discharge “that was about to happen” by flying some distance from a cloud charge region. This distance is calculated as the product of an assumed leader velocity, 1.5×10^5 m s^{-1}, and the duration of the electric field variation, a few milliseconds, which makes it equal to a few hundred meters. Mazur [22] argues against such an interpretation from two points of view: (1) a discharge in the proximity of aircraft should not begin more readily on a hydrometeor than on an aircraft extremity and (2) based on the polarization mechanism which we will discuss later when intercepted lightning is considered, opposite electric field polarity changes should be observed at positions on the airplane located near to and far from the approaching leader. Such an effect is not seen, however, in the records of the four field mills on the CV-580 [42] for the lightning strikes analyzed by Mazur [22]. During the initial period of each strike, the electric field changes in all field mill records were of the same polarity.

Research on the NASA F-106B was primarily aimed at providing statistics and maximum values for the derivatives of the current, electric flux density, and magnetic flux density [18]. Results from the F-106B study found in [18] include the measurement of a maximum current rate-of-change of 3.8×10^{11} A s^{-1}, a maximum current of 54 kA, and a maximum rate-of-change of electric flux density (displacement current density) of 97 A m^{-2}, which was the upper limit of the measurement, all obtained with peak recorders. The maximum measured current time-rate-of-change (current derivative) was about 4 times greater than that in the existing aircraft test standard for that parameter and prompted an increase in that value in the standard. The current rate-of-change is an important parameter because indirect effects (Table 2) of lightning strikes are thought to be related to the magnitude of the current rate-of-change. Mazur et al. [16] state that current pulses observed during the initial period of F-106B initiated lightning have the following characteristics:

1. Pulse repetition rate from one pulse every 100 μs to one pulse every 20 ms.
2. Current pulse duration from a fraction of a microsecond to several microseconds.
3. Current pulse amplitude 2–20 kA.
4. Duration of pulse series 2–35 ms.

The pulses are unipolar and asymmetric and sometimes contain fine structure superimposed. The steady current amplitude ranges from hundreds of amperes to 3 kA. Steady current has a duration from tens to hundreds of milliseconds as observed on video records of lightning channels attached to the tail and wing tips of the F-106B.

According to Lalande et al. [27], the second phase of the aircraft initiated discharge begins roughly 50 ms after the positive leader initiation, apparently tens of milliseconds after C in Figs. 5 and 6, and is characterized by groups of current impulses, called bursts, separated by a few tens of milliseconds, as illustrated as Fig. 8 and evident in Figs. 7a and b. Mazur [21] argues that the second phase of the aircraft-initiated lightning is similar to the late (final) stage of natural intracloud flashes (e.g. [43]). Some of the current bursts shown in Figs. 8 and 7a and b are apparently superimposed on steady current. Lalande et al. [27] attributed the current pulses in the second phase to “recoil streamers”, traditionally thought to be in-cloud mini-return strokes generated when a leader encounters a pocket of opposite charge. The peak current in the current bursts in the second phase of the discharge is indicated in Fig. 8 as being up to a factor of 3 or so larger than the 1 kA or so peak current shown for the negative leader pulses occurring between B and C (Figs. 5 and 6). On the C-160, the highest measured current derivative after C, was 2×10^{10} A s^{-1} (mean 6.5×10^9 A s^{-1}) and the highest current was 20 kA (mean 4.8 kA), but Lalande et al. [27] caution that these values may not be representative because of the relatively few events recorded and the difficulty in measuring peak current. In recent aircraft/lightning test standards (e.g., ARP5412 (ED84), “Aircraft Lightning Environment and Related Test Waveforms”, www.sae.org/products/standards/ARP5412.htm; eurocae@eurocae.com), the pulse burst specification, the

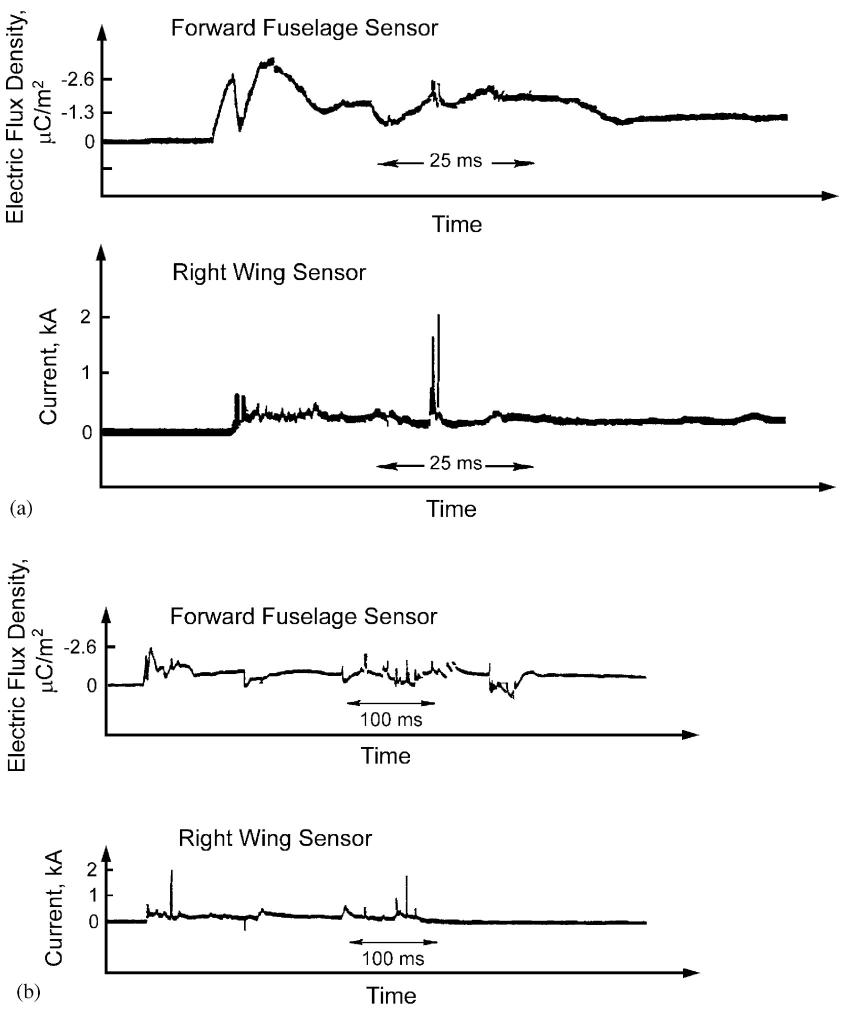


Fig. 7. (a) Electric field and current waveforms during the first 100 ms of lightning initiation by the CV-580, (b) field and current waveforms for the event shown in (a) but on a longer time scale. Adapted from [25].

so-called component H, derived from interpretation of the F-106B, CV-580, and C-160 airborne measurements, assumes that these pulses have an amplitude of 10 kA. Bursts of pulses observed in the electromagnetic fields of both cloud and ground flashes, which must be associated with bursts of channel current pulses, and their relation to these test standards are discussed by Rakov et al. [44].

Processes occurring in the second phase of aircraft-initiated lightning are similar to processes occurring in the latter part of aircraft-intercepted lightning, according to Mazur and Moreau [26], and are considered in the discussion of aircraft intercepted lightning in Section 4.3.

4.3. Aircraft-intercepted lightning

As illustrated in the drawing in Fig. 9 of the typical field changes attributed to aircraft-intercepted flashes, the millisecond-scale electric field variation from t1 to t2 observed on the CV-580 and C-160 research aircraft had a different sign for sensors at different locations on the aircraft, as determined from data for 3 strikes to the CV-580 and for 3 to the C-160. An example of actual data from the C-160 experiment is given in Fig. 10. The different field change polarity observed by different sensors is generally interpreted to indicate that an externally applied electric field due to an approaching lightning leader produced a polarizing effect on the aircraft [28]: negative charge was induced on one part of the aircraft, positive charge on the opposite part, rather than a change in charge of the same sign everywhere on the aircraft, as in the AB phase of aircraft-initiated strikes (Figs. 5 and 6). According to Lalande et al. [27], the fact that the electric field change from t2 to t3 in Fig. 9 from the different electric fields sensors is similar indicates that the aircraft has acquired a net positive

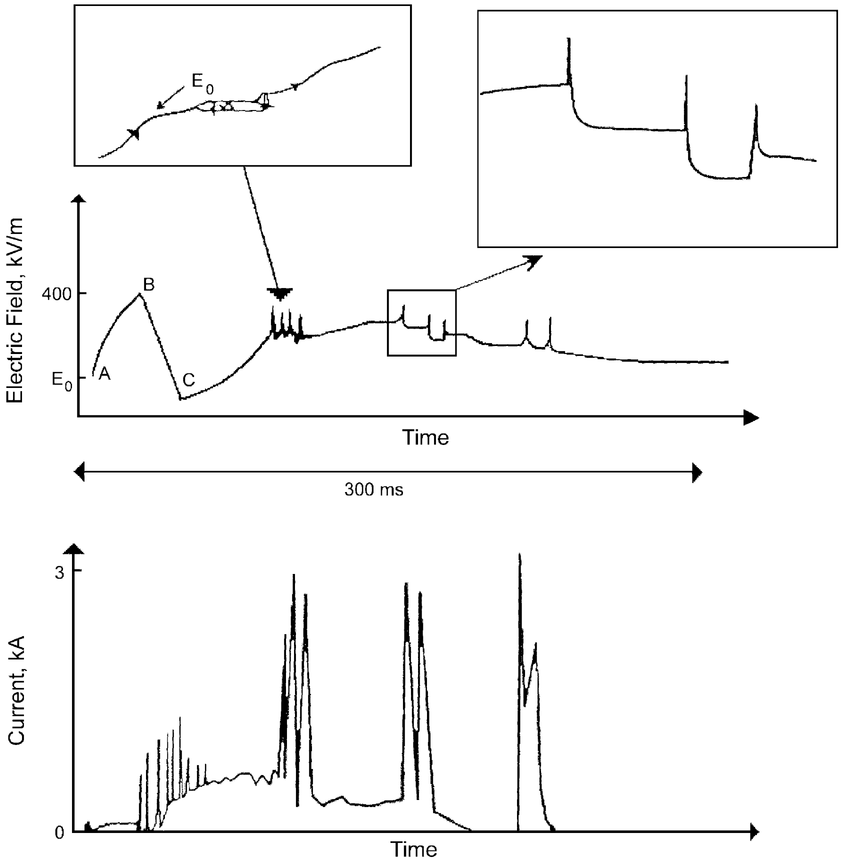


Fig. 8. Typical electric field intensity and current during the total duration of a typical aircraft-initiated lightning. E_0 is the ambient electric field at lightning initiation. Adapted from [27].

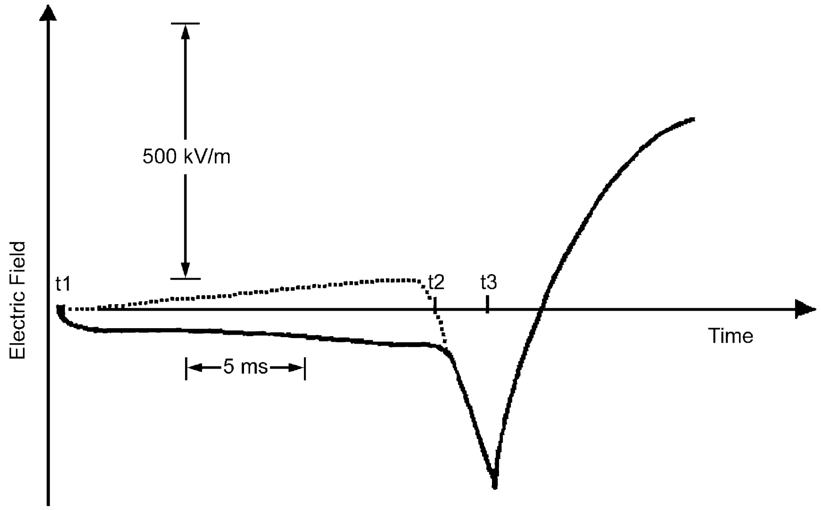


Fig. 9. Sketches of electric field waveforms observed by two sensors (dotted and solid lines) during the first part of a lightning strike intercepted by an aircraft. From t1 to t2, electric field changes have different polarities depending on sensor location. Adapted from [27].

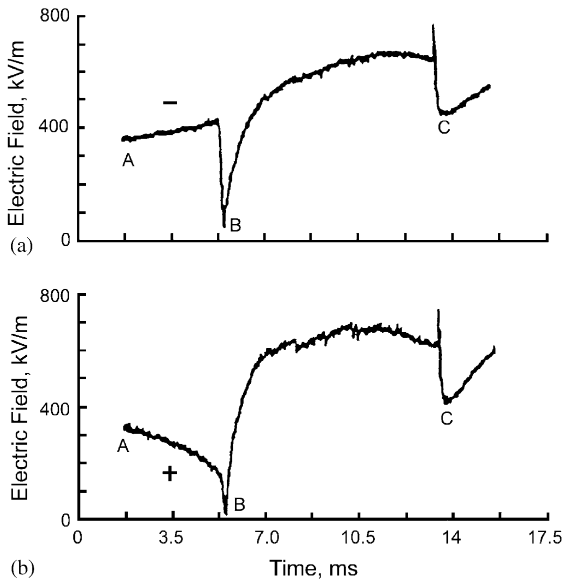


Fig. 10. Electric field variation recorded on the C-160 for an intercepted lightning flash at (a) rear fuselage sensor and (b) front fuselage sensor. Note the positive field change at the rear sensor corresponding to induced negative charge (minus sign) and negative field change at the front sensor corresponding to induced positive charge (plus sign) during the A–B phase (t1-t2 in Fig. 9). Adapted from [28].

charge. This result, according to Lalande et al. [27] could be due to the nearly simultaneous inception of a positive and a negative leader, the latter leaving a larger (positive) charge on the aircraft, or even to the inception of a single negative stepped leader. After t3, the electric field observed by all sensors increases toward a positive value as observed from the time following C in the aircraft initiated case (Fig. 8). The remainder of the intercepted discharge is generally similar in characteristics to the aircraft-initiated case.

Moreau et al. [28] give a different interpretation of the interception process from an analysis of waveforms such as those shown in Fig. 10. They consider that charge separation (polarization) on the aircraft due to an approaching leader occurs until point B in Fig. 10 (t_3 in Fig. 9), which they postulate is the time of attachment. According to Moreau et al. [28], the rapid positive field change on both sensors at B indicated attachment and charging by a negative leader, and the rapid negative field change at C in Fig. 10 indicates that the negative leader has exited the aircraft.

Reazer et al. [25] show examples of correlated current and electric field change for electric field changes of the type shown in Figs. 9 and 10, one case being presented in Fig. 11. The current waveform is noisy, but it appears to indicate that a current pulse or pulses of a few hundred amperes likely occurred near t3 of Fig. 9 and B of Fig. 10, with no large pulses in the millisecond or so before or after t3 (Fig. 9) or B (Fig. 10). Reazer et al. [25] interpreted the “hooked shape of the electric field” as having been “produced by the leader as it approaches the aircraft”, an interpretation of the electric field waveform different from those of Lalande et al. [27] and Moreau et al. [28] discussed above.

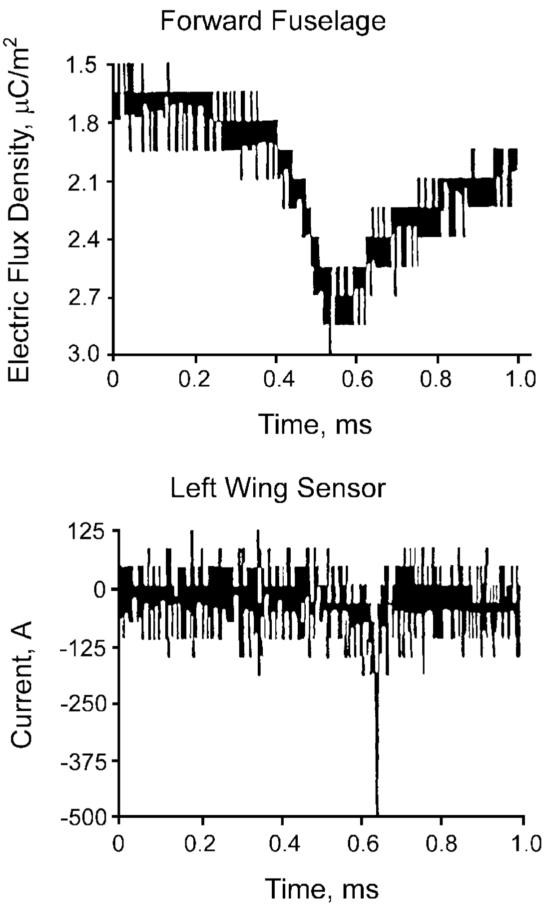


Fig. 11. Initial electric field and current recorded on the CV-580 for an intercepted flash at an altitude of 15,000 feet (about 5 km). Adapted from [25].

Mazur and Moreau [26] examined seven strikes to the CV-580 and eleven to the C-160 in order to try to understand “processes taking place during the intra-cloud propagation of lightning strikes initiated or intercepted by the airplane”. They identify “recoil streamers”, dart leader/return stroke sequences, and “secondary initiations of new discharges”. The former two processes are discussed in [45]. Recoil streamers are

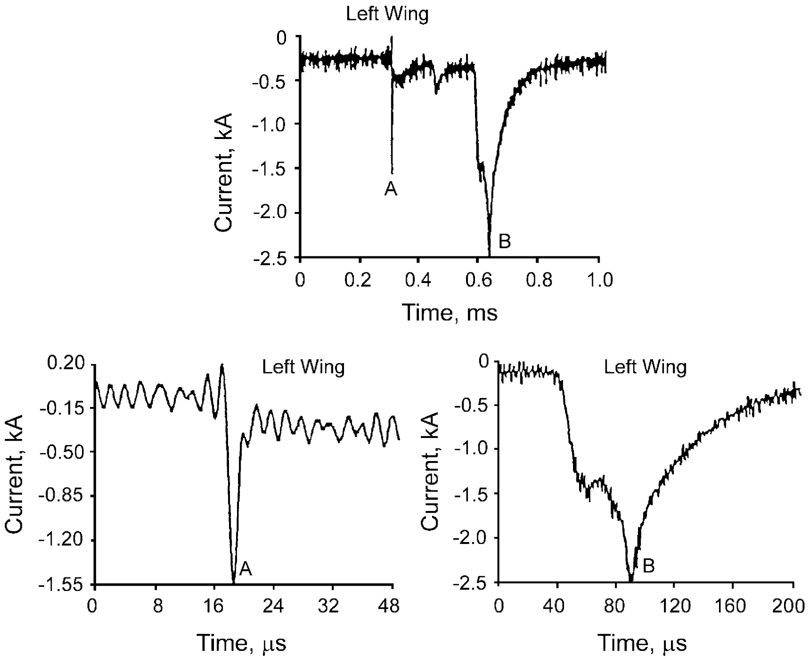


Fig. 12. Current pulses recorded on the CV-580, shown on different time scales, inferred to be due to a dart leader (A) and subsequent return stroke (B) passing through the aircraft as part of a cloud-to-ground flash. Adapted from [25].

defined by Mazur and Moreau [26] as current pulses that originate near the tip of the positive leader and propagate back toward the aircraft (see also [46,47]). The fields and currents attributed to recoil streamers occur generally in the latter part of the flash and are associated with the deposition of a negative charge on the aircraft. The current pulses interpreted as being due to recoil streamers generally occur in bursts with a typical time between pulses in a burst of a few milliseconds, although sometimes they are single pulses. Mazur and Moreau [26] hypothesize that current pulse bursts are associated with rapidly branching channels encountering opposite charges. Mazur and Moreau [26] present data for two strikes to the CV-580 which include field and current waveforms that can be interpreted as dart leader/return stroke sequences. An example of such a sequence from [25] is shown in Fig. 12. The so-called "secondary initiations of new discharges" identified by Mazur and Moreau [26] have currents and fields resembling the primary initiation processes but occur during the overall discharge development and have positive and negative leaders inferred to be of shorter duration than the initial ones. These inferred secondary initiations can occur several times during the overall discharge, each time producing bursts of pulses presumably due to negative stepped leaders launched from the aircraft.

4.4. Other inferences and results

Petterson and Wood [6] present many photographs of lightning channels attached at two extremities of the F-100F. The maximum current measured was 22 kA, with 1–5 kA being common. Altogether, data were recorded for 49 strikes at altitudes mostly near 30,000 feet (about 9.1 km) where the temperature was near −40°C with a few strikes near 15,000–21,000 feet (about 4.5–6.4 km). Twenty six of 29 strikes to the nose boom exhibited positive currents (e.g., negative leaders leaving the nose boom) which Petterson and Wood [6] suggest is due to the aircraft "leaving a negative cell and approaching a positive cell which was centered at some higher level". The F-100F made most cloud traversals at higher altitudes than the CV-580 and C-160 could fly and where commercial aircraft would not be likely to enter a thunderstorm and may well have encountered a different environment relative to the case of aircraft-initiated lightning. As noted earlier, most strikes to commercial aircraft take place in the 3–5 km altitude range, on ascent or descent, or for the older propeller planes, while at cruise altitudes, a region probably just below the primary negative cloud charge location.

Mazur et al. [5] describe several aspects of the 1982 NASA F-106B program and give data for 36 cloud penetrations by the F-106B. They show that the greatest probability of initiating lightning with an aircraft of the F-106B type is in the upper portions of the thunderstorm where the ambient temperature is $-40°C$ or colder, when turbulence and precipitation are light to negligible, and when the lightning flash rate is less than $10\,\text{min}^{-1}$. Fisher et al. [8] give detailed statistics on the number of strikes vs. ambient temperature and pressure for the 1980–1985 F-106B program (note that data considered in Section 2.2 include the 1986 study) including the number of cloud penetrations by year at high and low altitude and the resultant strike statistics. The dividing altitude between high and low is apparently 6 km. There were 839 high penetrations of thunderclouds and 539 low ones. The high penetrations resulted in 615 strikes, whereas the low ones resulted in 75.

Mazur et al. [23] describe a multiple-stroke cloud-to-ground lightning discharge triggered by the F-106B when it was flying at an altitude of 5 km where the ambient temperature was $-1°C$, there was light turbulence, and no precipitation was observed. The East Coast Lightning Detection Network registered six return strokes, while eight events were interpreted as dart leader/return stroke sequences in the airborne data, at least three passing through the F-106B. Previously, Reazer et al. [25] had provided evidence that the CV-580 was involved with two cloud-to-ground events, one in the main channel to ground of a subsequent return stroke; and Mazur et al. [16] reported a correspondence within about 100 ms between return strokes and strikes to the F-106B. In the aircraft-initiated flash examined by Mazur et al. [23], the F-106B apparently initiated the lightning about 70 ms before strokes to ground were observed. Mazur et al. [23] admit that “some interpretation of lightning processes made in this paper may seem questionable in view of using the limited resolution airborne data that characterizes processes only in the time domain”. The dart leader/return stroke sequence was identified by two sequential current pulses of the same polarity within a time sufficient for the dart leader to reach the ground and the return stroke to propagate from the ground to the F-106B, similar to the data shown in Fig. 12 for the CV-580.

5. Some accidents involving lightning

Lightning damage to aircraft varies from minor pitting of the aluminum skin to complete destruction of the aircraft. Most lightning-aircraft interactions are isolated occurrences. However, sometimes weather conditions are apparently such as to make lightning triggering by aircraft more likely and then multiple aircraft may be involved. This was apparently the case on February 24, 1987 when in a period of a few hours at least six aircraft were struck by lightning arriving in or departing from airports in the Los Angeles area. The weather was characterized by showers and occasional lightning. Four Boeing 727s, flying between 3800 and 8000 feet (between about 1.1 and 2.4 km), suffered lightning-caused holes in their radomes, and a Boeing 737 suffered unspecified damage at 3200 feet (about 1 km) [48]. A NASA T-38A jet flown by two astronauts suffered a lightning-induced in-flight explosion at 2500 feet (about 0.75 km) followed by a fire that extensively damaged the center fuselage. The T-38A, still on fire, landed at a military base near Los Angeles. The crew escaped injury. The official report describing the T-38A incident is found in [49].

In the remainder of this section we examine a number of crashes or near-crashes of commercial aircraft where lightning did or may have played a role, discuss an extraordinary lightning strike to a small commercial aircraft on takeoff, consider two related incidents, and discuss the initiation of lightning, and its effects, by two space vehicles, Apollo 12 and Atlas-Centaur 67, during their launches from the Kennedy Space Center and the adjacent Cape Canaveral Air Force Station, respectively.

5.1. Boeing 707 in 1963

On December 8, 1963, a Pan American World Airways Boeing 707-121 was in a holding pattern at 5000 feet (about 1.5 km) near Elkton, Maryland. Ninety-nine witnesses reported a cloud-to-ground lightning flash near or on the aircraft at about the time it burst into flames. All aboard, 73 passengers and 8 crew members, were killed. An investigation determined that three fuel tanks had exploded and that there were lightning strike marks and holes on the left wing tip. Photographs of this lightning damage are found in Uman [50]. Evidence indicated that the left reserve fuel tank, the outermost fuel tank in the left wing, exploded first, followed by the center and right reserve fuel tanks. There was lightning damage about 30 cm from the edge of the left reserve fuel tank vent outlet. The largest single indication of lightning was an irregular-shaped hole about 4 cm in diameter burned through the top of the wing. Exactly how the fuel tanks were ignited could not be determined. Possibly an attached lightning channel burned through the wing surface into a fuel tank (the fuel tank container is the wing skin in some areas) or sufficiently heated the inside surface to cause the explosion, or possibly lightning ignited combustible fumes at the left reserve fuel tank vent outlet. Further, laboratory tests showed that lightning-like currents injected over fuel filler caps and access plates on the 707 wing could produce sparks inside the fuel tanks. After the accident and as a result of further research [51], the thickness of the aluminum skin enclosing the fuel on 707s and on other aircraft was increased and fuel filler caps and access plates were better bonded to the airframe. The official report, Aircraft Accident Report, Boeing 707-121 N709PA Pan American World Airways, Inc., near Elkton, Maryland, December 8, 1963, Civil Aeronautics Board File No. 1-0015, February 25, 1965, attributes the disaster to "lightning-induced ignition of the fuel/air mixture in the No. 1 reserve fuel tank with resultant explosive disintegration of the left outer wing and loss of control".

5.2. Boeing 747 in 1976

On May 9, 1976, an Imperial Iranian Air Force B-747, Flight ULF48, was struck by lightning near Madrid, Spain with catastrophic results. The last radio contact was made as the aircraft was descending to 5000 feet (about 1.5 km) in clouds, probably near an altitude of 6000 feet (about 1.8 km). Since the Boeing 747 was used extensively worldwide, and, in view of the nature of the accident, the US National Transportation Safety Board requested and was granted permission to assist in the investigation. The resultant report is labeled NTSB-AAR-78-12, October 1978: Special Investigation Report-Wing Failure of Boeing 747-131, Near Madrid, Spain, May 9, 1976, from which the discussion in this section is taken.

At the time of the accident, the weather near Madrid was cloudy with rain and lightning; visibility was good. Severe thunderstorms were in the area. Two witnesses reported seeing lightning strike the aircraft. Some witnesses stated that they saw an in-flight fire confined to the No. 1 engine. Other witnesses reported seeing an in-flight explosion and fire followed by the separation of aircraft parts. Pitting and localized burn areas typical of lightning attachment damage were found on the left wingtip and on the vertical fin. No holes were burned into any of the fuel tanks. The left wing had separated into 15 major pieces before ground impact and parts of it were found at a number of locations.

The first significant event on the cockpit voice recorder was the exclamation "We're in the soup!" Approximately 3 s later a signal characteristic of an electrical transient occurred on the tape which has been interpreted by the investigating team as indicating that the aircraft was struck by lightning. An explosion occurred 0.2 s after the electrical transient. A sound interpreted as thunder was heard before the explosion.

Several motor-operated valves were present in the fuel tanks, and the electric motors which operated these valves were mounted on the outside surfaces of the front or rear spar. The motors were connected to the valves by mechanical couplings or drive shafts which penetrated the spars. The motor for the valve in the No. 1 fuel tank was never recovered. The drive shaft was found and was determined to be electrically insulated at the spar penetration. The mechanical coupling/drive-shaft arrangement may have provided a path for an electric current to enter the tank and cause a spark. The level of residual magnetization in this area of the valve was indicative of high currents.

The evidence (1) that the explosion in the No. 1 tank occurred in the immediate area of a motor-driven fuel valve, (2) that the motor was never recovered, (3) that a high level of residual magnetization existed in the ferrous material in this area, (4) that certification tests showed this area to be a likely lightning-attachment point, (5) that lightning strikes are known to have disabled the motors on other aircraft, and (6) that no other possible ignition source could be determined, provided the foundation for the hypothesis that the tank explosion was likely ignited by a spark at this motor-driven valve.

The official report (NTSB-AAR-78-12, see above), from which we quote directly, states that "assuming that a lightning strike can generate a source of ignition to fuel vapors, aircraft fuel explosions could occur more frequently. However, events must combine simultaneously to create the explosion, and this combination would occur rarely. In this case, the qevents were (1) an intermittently conductive path which closed and opened an electrical loop, (2) a lightning-induced current of sufficient intensity flowed in this path and formed a spark, and (3) a flammable vapor surrounded this spark. Possibly this combination of events has occurred a number of times before, in the following accidents: (a) Milan, Italy (Constellation); (b) Elkton, Maryland (B-707); (c) Madrid, Spain (USAF KC-135); (d) KSC, Florida (USAF F-4); (e) Pacallpa, Peru (L-188)". Accident (b) is discussed in Section 5.1.

5.3. Fairchild Metro III in 1988 and Fokker F28 MK 0100 in 1998

In the previous two sections we have discussed cases in which aircraft fuel vapor was ignited by lightning. In the present section we examine two accidents in which the lightning damage was less direct but potentially as fatal: (1) the lightning-caused failure of the electrical system in a Fairchild Metro III which led to the loss of the aircraft and the deaths of its occupants and (2) the lightning-caused failure of the hydraulic system of a Fokker F28 which nearly caused similar results.

On February 8, 1988 a Fairchild Metro III commuter airliner powered by two turboprop engines and carrying 19 passengers and two crew members on a flight from Hannover to Düsseldorf, Germany was struck by lightning and subsequently crashed, killing all on board. The Fairchild Metro III was approaching Düsseldorf at an altitude of about 3000 feet (about 0.9 km). There were thunderstorms in the area. The pilot had lowered the landing gear although the copilot had argued with him that he should not do so. When the gear was lowered the plane fell and rose in altitude between 2500 and 3000 feet (between about 0.75 and 0.9 km) as the pilots tried to trim the aircraft for proper descent. The cockpit voice recorder provided a record of the pilot and copilot's conversation. As they were stabilizing the aircraft, lightning struck it and apparently disconnected all batteries and generators from the aircraft's electrical system, also terminating the cockpit voice recorder record. Without electrical power, the pilots evidently had no control of the landing gear and limited control of the flaps. The aircraft was inside a cloud and had no cockpit lights so the pilots would probably not have been able to read their instruments. Emergency flashlights apparently were not present in the aircraft as they were supposed to be, or at least none was found at the crash scene. Observers on the ground saw the aircraft dive out of the cloud base and then climb again into the cloud, this pattern being repeated two or three times. On one of these oscillations in altitude, the right landing gear was torn from the aircraft, further destabilizing it. The subsequent aircraft motion resulted in a wing being separated from the aircraft. The Fairchild went into a spiral dive and crashed. A reconstruction of the electrical system failure pointed to the failure of a critical relay. Overall, the accident was probably due to a combination of poor pilot judgment or skill and the lightning-caused electrical failure. Whether the electrical system was properly designed is also an issue. The official report of the accident is found in "Bericht über die Untersuchung des Flugunfalles mit dem Flugseug SA Z27-AC, Metro III, D-CABB, am 8. Februar 1988 bei Kettwig AZ.: 1X001/88, Flugunfallenuntersuchungsstelle beim Luftfahrt-Bundesamt, Bundesrepublik Deutschland."

On February 26, 1998, a US Airways Fokker F28 MK 0100 flying from Charlotte, NC to Birmingham, AL carrying 87 passengers and 5 crew members was struck by lightning with no immediate effect. However, within a few minutes the aircraft suffered a failure of both of its hydraulic systems. In order to make an emergency landing, the landing gear and flaps were extended via an alternate method but without control of the nose landing gear steering. A number of brake applications were also possible in an alternate mode to the hydraulic. On landing, the aircraft traveled about 1100 feet (about 330 m) in the grass off the left side of the runway. The nose landing gear separated from the aircraft and the nose section came to rest on a taxiway about 540 feet (about 160 m) from the aircraft. Airport personnel reported finding pieces of the main landing gear tires on the runway, and the left main landing gear shimmy damper reservoir was found on the left side of the runway. Examination of the two hydraulic system reservoirs of the airplane revealed that both were empty and hydraulic fluid was noted on the vertical stabilizer. When the hydraulic systems were pressurized, a leak occurred from a hole in the No. 1 elevator pressure line approximately three-quarters of the way up the vertical stabilizer and a leak from a second hole in the No. 2 elevator return line, this hole being located behind the rudder flutter damper approximately half way up the vertical stabilizer. Examination of the airframe revealed that the right exterior fuselage skin exhibited approximately 103 lightning burn marks which ranged in size from 1/16 to 5/8 in (0.16–1.6 cm) in diameter. Additionally, the right stabilizer showed evidence of scorching at the outboard corner of the upper surface at the trailing edge. The outboard static wick on the right stabilizer was missing with evidence of heat at its base. Additionally, a bonding strap that provided an electrical connection between the horizontal and vertical stabilizers failed and the strap was discolored. The tail of the airplane had been designated by the aircraft manufacturer as a "swept stroke area", lightning zone 2B, and the interface between the horizontal and vertical stabilizers was designated as zone 3 (see ARP5414 (ED 91), "Aircraft Lightning Zoning", www.sae.org/products/standards/ARP5414.htm; eurocae@eurocae.com). Apparently, the trailing edges should have been designated zone 1B since a hinge bonding strap used on the tail assembly of the Fokker could fail when subjected to lightning currents at or below the zone 3 current specifications, according to the accident report referenced below. The bonding strap was located near the hydraulic tubes, on the left side of the vertical stabilizer. It appears that lightning current flowing in the bonding strap between the vertical and horizontal stabilizers side-flashed to the hydraulic lines, burning through them and releasing the hydraulic fluid.

A report on this accident by the US National Transportation Safety Board is found at www.ntsb.gov/aviation/MIA/98A089.htm.

5.4. *Aircraft struck by lightning at very low altitude*

Fig. 1a shows a commercial aircraft initiating lightning at low altitude after take off from an airport in Japan during winter. At the time of this writing, a video of the event is found at http://lightning.pwr.eng.osaka-u.ac.jp/lrg/temp/plane.html. Frame 1 shows the aircraft, apparently a few hundred meters above ground, without any lightning evident. Frame 2 is given in Fig. 1a. That frame shows evidence of a downward branched leader below the aircraft and an upward branched leader above the aircraft, the branching being indicative of the direction of leader propagation, both away from the aircraft. The two leaders have likely been illuminated by a return stroke that has propagated from ground (termination point of the downward leader) upward through the aircraft, catching up with the top at the upward-propagating leader channel, as has been observed to be the scenario in altitude rocket-triggered lightning [52]. The next four frames (3–6) show the luminosity of the channel decaying, with no channel branches apparent by frame 6. Frame 7 is overexposed, perhaps because of a downward-propagating dart leader-upward-propagating return stroke sequence similar to subsequent strokes in natural lightning [45]. Frame 8 shows a single channel of high and uniform brightness between the top and bottom of the frame, through the aircraft to Earth, as would be expected from continuing current following a return stroke. Because of the limited time-resolution of the video system, other interpretations than those given above are possible.

Vonnegut [53] reproduces a pilot's report of a lightning strike to a small commercial aircraft during takeoff, while the aircraft was still above the runway. The event involved a Convair aircraft, Flight 517, taking off from the Salt Lake City Airport on October 15, 1965. At the time of the event, there was some light rain in the area but apparently no lightning other than the event to be described. During takeoff, an extremely loud noise occurred. The first officer stated to the pilot that he believed they had sustained a lightning strike, subsequently confirmed by observers in the control tower, based on his observation of a blue-white glow around the nose of the aircraft at the time of the explosion. The aircraft returned to the airport. Three large holes were found in the runway which exactly matched the dimensions of the two main landing gear and the nose wheel. The largest hole, under the right main gear, was nearly 2 m in diameter and 15–20 cm deep. Pieces of asphalt as large as 0.3 m had been hurled 30–50 m down the runway. The aircraft suffered numerous burns to the wheel rims and fuselage just aft of the nose wheel-well. The rotating beacon, the grounding wire on the right main gear, and the fixed vertical stabilizer cap were burned off. The fact that there was little if any lightning in the area at the time of the strike to the Convair would imply that the aircraft initiated the lightning.

The excessive damage to the runway just described would imply a relatively large peak current and a relatively large action integral (the integral of square of the current over time), as apparently can occur, for example, in Japanese winter storms (e.g. [54,55]) and has been observed in strikes to airborne vehicles in Europe in winter (e.g., a lightning strike to a glider at 2500 feet (about 760 m) in England, April 1999: AAIB Bulletin No.: 12/99 Ref: EW/C99/04/02 Category: 3.0 at www.open.gov.uk/aaib/dec1999htm/bga3705.htm; a lightning strike to a helicopter at 3000 feet (about 910 m) over the North Sea, January 1995: AAIB Accident Report No.: 2/97 (EW/C95/1/1) at www.open.gov.uk/aaib/gtigk/gtigk.htm). In the case of the glider, a hollow tube that was part of the wing structure was crushed by the lightning. Laboratory tests involving currents over 300 kA and action integrals in excess of 2.5×10^7 A^2 s have not been able to reproduce this damage. In the case of the helicopter, damage to portions of the main rotor blade assembly indicated an extremely large action integral.

A Boeing 727, Eastern Air Lines Flight 66, with 124 passengers and crew struck the approach light towers near the end of the runway while making its final approach to New York's John F. Kennedy International Airport at about 4 p.m. on June 24, 1975. A violent thunderstorm was in progress. The pilot had been warned of severe windshear near an altitude of 500 feet (about 150 m) by the pilot of an aircraft that had previously taken the same approach path and landed successfully. According to an Associated Press report (e.g., Gainesville Sun, June 25, 1975), a Nassau County policeman saw a lightning bolt hit the plane: "It tilted to the right and went about 20 more yards, then hit the ground". Another witness who said he was about 150 m from the crash said "It was almost like lightning hit it and blew it up in a ball of fire". A number of eyewitnesses, most of them motorists on nearby Rockaway Boulevard, said they saw a bolt of lightning which appeared to hit the plane just before it burst into flames. Nevertheless, the official report (see below) found no evidence of "in-flight fire, explosion, bird strike, or lightning strike". One hundred thirteen individuals were killed in the crash, but 11 survived. A discussion of possible indirect effects of lightning to the 727 control electronics is found in "Postmortem for Flight 66", IEEE Spectrum, 12, p. 35, July 1975. The official report of the crash (NTSB-AAR-76-8, dated March 1976, Eastern Airlines, Inc., Boeing 727-225, John F. Kennedy International Airport, Jamaica, New York, June 24, 1975) attributes the crash to "adverse winds associated with a very strong thunderstorm".

In an incident similar to Eastern Flight 66, Delta Flight 191, a Lockheed L-1011 jumbo jet was descending through stormy weather toward the Dallas-Fort Worth Airport on August 2, 1985 and was about a mile (1.6 km) away at 1000 feet (about 300 m) altitude when, according to a witness (Newsweek, August 12, 1985, p. 30), it was struck by lightning, turned incandescent orange, and almost simultaneously plunged abruptly downward where it hit cars on Highway 114, skimmed along the ground hitting ground-based structures, and broke up in a ball of fire. The official report (see reference below) contains no such eyewitness accounts of a lightning strike but does indicate that an examination was made of the limited wreckage for evidence of lightning and that none was found. One-hundred thirty-four individuals died. Twenty nine survived. The official report of the crash, NTSB-AAR-86-05 dated August 15, 1986 Delta Airlines, Inc., Lockheed L-1011-3 85-1, N726DA, Dallas-Fort Worth International, June 24, 1975, attributes it to "microburst-induced, severe wind shear from a rapidly developing thunderstorm".

5.5. Apollo 12 in 1969

The Apollo 12 space vehicle was launched from the NASA Kennedy Space Center (KSC), Florida on November 14, 1969. Within a minute of liftoff major electrical disturbances occurred that were later determined to be due to two separate vehicle-initiated lightning events. Nine non-essential instrumentation sensors were permanently damaged. Temporary upsets of equipment included momentary loss of communications, disturbances on instruments, illumination of various warning lights and alarms in the crew compartment, disconnection of three fuel cells from their busses, loss of attitude reference by the inertial platform, and disturbances to various clocks. All critical system problems were subsequently corrected, and the mission successfully delivered two astronauts to the surface of the Moon and returned them to Earth.

At the time of launch (11:22 a.m. EST) a cold front was passing through the launch area. The tops of isolated cumulus congestus within 50 km reached a maximum height of 23,000 feet (about 7 km). In the vicinity of the launch complex, broken clouds were reported at 800 feet (about 0.25 km) with a solid overcast from about 10,000 to 21,000 feet (about 3–6 km). The freezing level was near 12,400 feet (about 3.8 km). No lightning was reported in the KSC area 6 h prior to or after the launch, although the instrumentation available for detecting lightning was primitive.

The vehicle apparently initiated a lightning discharge to ground 36.5 s after launch when it was at an altitude of about 6400 feet (about 1.9 km) and then triggered a cloud discharge at 52 s when it was at about 14,400 feet (about 4.4 km). In the 20 min prior to launch the vertical electric field at ground near the launch site was rapidly varying, but the crude electric field measuring devices used at the time were not properly calibrated. The possibility that the Apollo vehicle could initiate lightning had not been previously considered, according to Godfrey et al. [56], the official report that presents the findings of the team that investigated the incident.

According to Godfrey et al. [56], if a 300-m-long (including the total exhaust plume) Saturn V vehicle with a 5 m radius and a 10 cm radius-of-curvature top cap were placed in an electric field of 7.5 kV m^{-1}, the field at the top cap would be enhanced 320 times to produce a breakdown field of 2.4 MV m^{-1} at an altitude of 6000 feet (about 1.8 km). The Saturn vehicle is 110 m long, its opaque exhaust is about 40 m, and its total visible exhaust about 200 m [57]. The effective electrical length is probably between 150 and 300 m, since it is not clear how much of the exhaust plume contributes to the overall electrical length. Breakdown fields at the vehicle tip could easily be achieved for an enhancement factor between 10 and 300 in rather moderate cloud fields (commonly-observed high field values in cumulonimbus are 50 to 100 kV m^{-1} [38]).

5.6. Atlas-Centaur 67

The Atlas-Centaur 67 vehicle was launched on March 26, 1987 at 4:22 p.m. local time from the Cape Canaveral Air Force Station, Florida, adjacent to the Kennedy Space Center. Weather conditions were similar to those at the time of the Apollo 12 launch. There was a broad cloud mass covering most of Florida and the Gulf of Mexico, and a nearly stationary cold front, oriented southwest-northeast, extended across northern Florida well north of Cape Canaveral. A weak squall line, also oriented southwest-northeast, was centered over the eastern Gulf of Mexico and was moving eastward over the Florida peninsula. This squall line produced substantial amounts of cloud-to-ground lightning activity throughout the day, but almost without exception this activity was well west of the Cape. At the launch site, there was heavy rain, and layer clouds were reported at altitudes between 8000 and 20,000 feet (about 2.4 and 6.1 km). No cloud-to-ground lightning had been observed within 5 nautical miles (9.3 km) of the launch site in the 42 min prior to launch and only one discharge was within 10 nautical miles (18.5 km) during this time. A cloud discharge apparently occurred about 2 min prior to launch, undetected by KSC lightning detection instrumentation, but reported to one of the authors (MAU) after the launch by members of the press corps. Forty-nine seconds after launch a lightning flash was observed below cloud base. That flash produced at least 4 strokes to ground which were recorded by television cameras. The first two strokes followed one channel to ground, the latter two followed two separate and different channels to ground. At the time of lightning initiation, the vehicle was at a height near 12,000 feet (about 3.6 km) where the temperature was +4°C, while the freezing level was at 14,400 feet (about 4.4 km) and inside a cloud having a radar echo level of 10 dBz, considerably lower than the value of 40 dBz generally observed in thunderclouds in that area. From the magnetic field signal recorded by the KSC lightning locating system, the first stroke current was determined to be of negative polarity and was estimated to have a peak value of 20 kA.

At the time of the lightning strike there was a memory upset in the part of the vehicle guidance system called the digital computation unit leading to an unplanned vehicle rotation. The stresses associated with this motion caused the vehicle to begin breaking apart. About 70 s after lift-off, the range safety officer ordered the Atlas-Centaur destroyed. Substantial portions of the fiber-glass-honeycomb structure that covered the front 6–7 m of the vehicle were subsequently recovered from the Atlantic Ocean. These showed physical evidence of lightning attachment. Approximately 40 percent of the telemetry outputs showed anomalous electrical behavior at the time of the event.

The Atlas-Centaur vehicle, which was about 40 m in length, would enhance any uniform ambient electric field by about a factor of 30–50 [58]. Thus a breakdown field of near 2 MV m^{-1} would exist at the nose of the vehicle in an ambient field of 50–80 kV m^{-1}.

All of the information given in this section and further details of the Atlas-Centaur 67 event including radar echoes from the vehicle-initiated lightning and reference to lightning events on two earlier Atlas-Centaur vehicles are found in [58], the official report on the incident, and in [59].

6. Summary

About 90 percent of the lightning discharges to aircraft are thought to be initiated by the aircraft themselves. The initiation apparently involves a bi-directional leader whose positive and negative parts develop from opposite sides of the aircraft. The typical fields and currents associated with flashes initiated by aircraft at 5–6 km altitude in summer, beneath or in the lower part of the cloud main negative charge center, are fairly well established, at least for the lightning initiation stage, from the F-106B, CV-580, and C-160 research aircraft programs. Characteristics of strikes to aircraft relatively high in the cloud, near an altitude of 10 km and a temperature of −40°C, apparently above the main negative charge center, are available from the F-100F and F-106B studies, although these events are much less well documented than strikes at lower altitudes. About 10 percent of strikes to aircraft are thought to involve interception of an independently initiated flash, an inference from the CV-580 and C-160 programs. Aircraft can become part of the lightning path of either cloud or ground discharges, the probability of the latter increasing with decreasing flight altitude, although there are no reliable statistics on this issue, only a few observations. Lightning damage to aircraft is generally minimal but can be occasionally catastrophic. There are two well-documented cases of lightning being initiated by large rockets launched from Earth, the Saturn V vehicle of NASA's Apollo 12 and US Air Force's Atlas-Centaur 67. The former was able to fulfill its mission, while the latter suffered damage that led to the loss of the vehicle and its payload.

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