Lightning Strikes to a NASA Airplane Penetrating Thunderstorms at Low Altitudes

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During the 1984 season, the NASA Storm Hazards Program was devoted mainly to the investigation of lightning strikes to the NASA F-106B instrumented airplane penetrating storms at low altitudes in the vicinity of and below the lower center of lightning flash density (6-8 km), which coincides with a negative charge region of the thunderstorm. The F-106B airplane encountered 34 direct strikes, of which 10 were related to cloud-to-ground flashes as indicated by the ground strike location network. In 4 of these 10 cases, strikes to the airplane preceded return strokes to the ground and, in 6 cases, strikes followed the return strokes. All 10 strikes associated with cloud-to-ground flashes were their intracloud portions, which are known to have much smaller peak current values than the return strokes. The storm structure study (three storm cells) conducted with the S-band radar at Wallops Island, VA, simultaneously with storm penetrations by the F-106B shows that the majority of direct strikes to the airplane occurred during the decaying stage of cell evolution. Environmental conditions such as turbulence and rain intensity during the direct strikes at low-altitude flights are characterized by negligible to light levels of both. The probability of a direct strike to the airplane in a thunderstorm increases with the decreasing rate of lightning flashes. The same correlation was observed during the high-altitude storm penetrations in previous seasons. Analysis of the correlaton between the UHF-band radar data and visual (TV) images of lightning strikes to the F-106B shows that, with a known position of the airplane relative to the radar, the lightning channel motion can be quite adequately interpreted from the radar echo evolution.The same analysis provides strong evidence that the lightning radar echo is produced by a major, sometimes tortuous but not branching, ionized channel.

I. Introduction

To minimize lightning hazards to aircraft, we need 1) to protect aircraft and their systems from the effects of direct strikes and nearby flashes and 2) to decrease the probability of direct strikes to aircraft by avoiding those regions of storms where the risk of strikes is greatest. In investigating lightning hazards to aircraft in the first instance, the electromagnetic parameters of strikes to instrumented airplanes flying through thunderstorms are measured[1-3]; in the second, the environmental conditions where direct strikes occur are evaluated.[4,5]

Investigation of lightning hazards to aircraft in the United States and Europe started with and still concentrates on electrically active storms. The NASA Storm Hazards Program, which was conducted in the summers of 1982 and 1983 in Virginia using a NASA Langley Research Center F-106B instrumented airplane, found that there is intense lightning activity and an accompanying high risk that aircraft will be struck by lightning in the upper regions of thunderstorms.[6,7] Analysis of lightning echo signatures at the times of the strikes strongly suggests that strikes are triggered by the airplane itself.[6]

Results of the Storm Hazards Program for high-altitude flights changed the whole perception of aircraft safety when flying through or near the tops of thunderstorms. Aircraft can avoid penetrating storms at high altitudes when en route, but cannot avoid encounter with most of them during the descent to a terminal area at low altitudes. Therefore, of special concern to the aviation community and industry is whether an airplane will become involved with return strokes of cloud-to-ground flashes. This type of stroke, which has the highest current magnitudes and fastest rise times, would seem to be the most hazardous for an airplane to encounter. For the purpose of lightning strike avoidance, it is important to determine the regions of the storm and the stage of the storm evolution during which the probability of direct strikes to airplanes is highest. Another basic question of aircraft/storm interaction remains: Are the parameters of the direct strikes and environmental conditions during which the strikes occur at low altitudes similar to those at high altitudes? This paper attempts to address these questions using the results from the 1984 NASA Storm Hazards Program which was devoted to studying storm penetrations at altitudes of <8 km, as well as the results from high-altitude flights during the previous seasons.

II. Experimental Procedure

Guidance to the F-106B was based on observations of storm structures with the S-band radar and of lightning flash distribution with the UHF-band radar, both at Wallops Island, VA. The operational characteristics of the radar equipment are described in Mazur et al.[7] During a penetration, the F-106B was tracked by a C-band radar to which the UHF-band radar was "slaved," so that lightning echoes from nearby flashes and direct strikes to the F-106B were obtained with the UHF-band radar. Immediately after the penetration, while the F-106B was turning, a plan position indicator (PPI) sector scan at altitudes below that of penetration and a range/height indicator (RHI) scan approximately along the path of penetration were conducted with the S-band radar. Because of the lack of time for an extensive series of scans between penetrations, the radial direction of penetration seemed to be the only approach to study the storm structure with a single radar.

The data from the East Coast ground strike location network[8] was used for identification of cloud-to-ground (CG)

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flashes. Unfortunately, these data were not corrected for any azimuthal and range errors caused by conditions at the individual station sites. Because both the airplane and the network time were synchronized to WWV time standard (accuracy 1 ms), only a coincidence in time was used as a criterion for identifying a CG flash.

Penetrations of thunderstorms at low altitudes is a serious challenge, owing to flight restrictions imposed by possible heavy rain and hail damage evidenced by high radar reflectivity and by strong turbulence, which can exist at all altitudes within thunderstorms. Our initial approach to the selection of penetration pattern in storms was to fly just outside the 50 dBZ reflectivity core at altitudes between 6 and 8 km corresponding to the lower center of lightning flash density.[7,9] This is a region where both intracloud and cloud-to-ground flashes originate and where we believe chances for the F-106B to be struck by or to initiate both types of flashes are greatest. Most storms during July and August of 1984 in the vicinity of Wallops Island were thundershowers whose 50 dBZ tops did not exceed ~7.5 km altitude (−20°C). Because of the low rate of lightning activity in such storms, it was difficult to use the UHF-band radar to determine the concentration of lightning flashes so that an airplane could be directed there during short time intervals between penetrations (this was possible for high-altitude flights in storms with much higher flash rates). Therefore, during most of the 1984 season, the F-106B was guided mainly with the S-band radar through the 40 dBZ regions above the 50 dBZ core.

III. Results

A. Storm Structure

Presented here is an analysis of two flights, on Aug. 12 and 14, 1984, for which we were able to obtain storm structure information. During the flight on Aug. 12, a line of thundershowers located southwest of Wallops Island (WI) was investigated. Development of two storm cells in this line occurred sequentially and southward. The penetratons of both cells were at 5 km altitude and along side of the 50 dBZ region (Fig. 1). The first cell penetrated, starting at 1834 UT,[§] was growing and was located between 125 and 132 km from WI; it reached its peak of maturity at about 1855 and started decaying after that. The 40 and 50 dBZ cores had maximum heights of 7.3 and 4.7 km, respectively (Fig. 1b). During seven penetrations of this cell, we detected only one nearby flash and the F-106B was struck once by an intracloud (IC) flash at the early decaying stage of the cell (1858:27) in the 20 dBZ reflectivity region. Starting at 1908, the F-106B penetrated the second cell growing farther southwest, 150-160 km from WI. At about 1940, this cell was in its peak: the 40 dBZ contour reached a height of 12.5 km and the top of the 50 dBZ core was at 5.8 km (Fig. 1d). During five penetrations, we counted 10 nearby flashes and one direct strike in the 30 dBZ region (again an IC flash) that occurred at 1945:41 when the cell was in the decaying stage. Three nearby flashes were intracloud parts of CG flashes.

The difference in vertical development of the two storm cells corresponds to the observed difference in lightning activity around the F-106B; however, the number of direct strikes did not increase in the more active (second) cell. The study by Larsen and Stansbury[10] indicates that the critical value for the 40 dBZ core height in the storm is above 7 km for the beginning of lightning activity. We believe that the first and second cells had the 40 dBZ core heights just below and above this threshold, respectively.

The storm of interest on Aug. 14 was located 120-140 km west-southwest of WI and moved eastward. This storm also consisted of two cells with pronounced 40 dBZ towers. During the period of observation (1855-2009), the tallest cell (at 130-135 km range) had maximun heights of 13.6 and 7.3 km

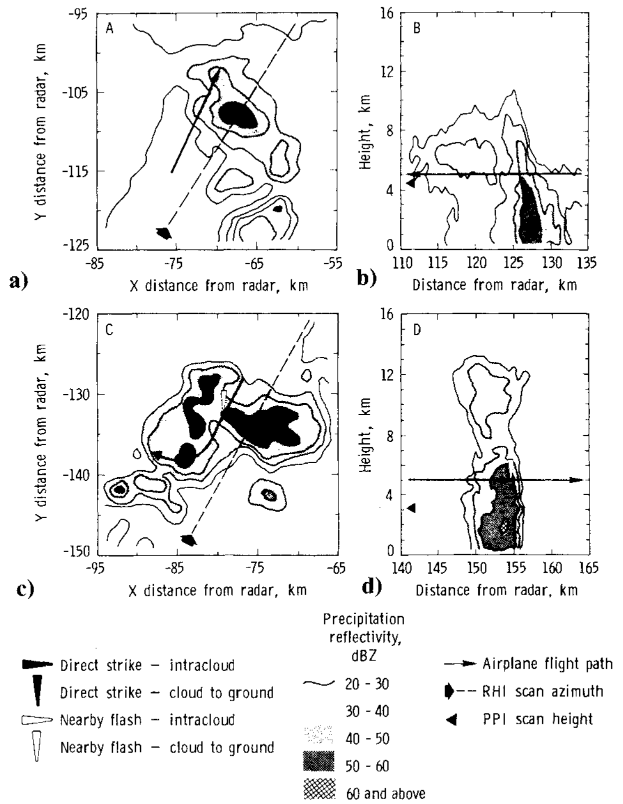


Fig. 1 Radar reflectivity structures and the F-106B penetration patterns for a flight on Aug. 12, 1984.

a) Superposition of isolines of reflectivities (dBZ) from the sector scan of the northern cell of the storm between 1855:52 and 1856:17 (peak of maturity) and the airplane flight path between 1853:11 and 1854:26. The altitude of the sector scanning in the vicinity of the airplane pattern is 4.6 km. Dashed line with arrow is along the 212 deg azimuth of the RHI scan shown in Fig. 1b.

b) Vertical RHI scan through the northern cell between 1855:09 and 1855:22 at 212 deg azimuth. The solid line with the arrowhead indicates the nominal altitude and direction of the F-106B pentration.

c) Superposition of reflectivity contours (dBZ) from the sector scan of the southern cell of the storm between 1938:27 and 1938:51 and the airplane flight path between 1936:01 and 1937:26. An average altitude of the sector scanning in the vicinity of the airplane pattern is 3.1 km. Open and solid arrow heads indicate a nearby flash and a direct strike, respectively. A downward-pointing arrow head symbolizes a CG flash and a horizontally pointing head an IC flash. The dashed line with the larger arrow is along the 209.5 deg azimuth of the RHI scan shown in Fig. 1d.

d) Vertical RHI scan through the southern cell between 1937:43 and 1937:59 at an azimuth of 209.5 deg.

for the 40 and 50 dBZ cores, respectively. The altitude of the F-106B penetrations was above the top of the 50 dBZ core of the tallest cell and within the 40 dBZ region (Fig. 2). The flight altitudes varied between 6 and 7.7 km, which correspond approximately to the temperatures between −10 and −20°C. The storm continued to grow until about 1925 and then began weakening. During the first seven penetrations, in the growing stage of the storm (16 min of total time), there were 39 nearby flashes, about 2.4 flashes/min of flight inside the storm. Sixteen of these nearby flashes were associated with CG flashes. The F-106B was struck only once by a flash that was part of a CG flash. During the next 11 penetrations of the weakened storm (33 min of total time), 50 nearby flashes were counted, about 1.5 flashes/min inside the storm. Thirty of them were associated with CG flashes. The four direct strikes to the F-106B occurred when the storm was in the decaying stage. Two direct strikes were parts of CG flashes.

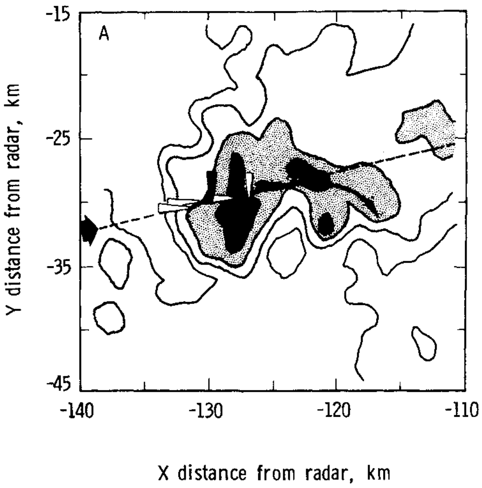
In this case study, we observed that the number of strikes to an airplane increases with decreasing lightning activity during a decaying stage of the storm.

§Here and further in the paper, time is indicated in universal time (UT).

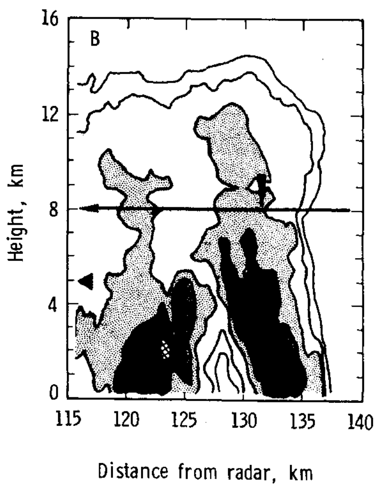
Table 1 Summary of lightning flash and strike data

Day of 1984	Nearby flashes			Direct strikes			Δt (CG), ms[a]	
	Total	IC	CG	Total	IC	CG	Before	After
July 16	35	31	4	6	5	1	90	—
Aug. 8	23	18	5	5	5	0	—	—
Aug. 9	72	43	29	5	1	4	10	50
							30	100
Aug. 12	11	8	3	2	2	0	—	—
Aug. 13	38	26	12	4	2	2	110	90
Aug. 14	89	43	46	5	2	3	—	50
								20
								40
Total	268	169	99	27	17	10		

[a] Δt is the time difference between a direct strike to the F-106B and a return stroke from a CG flash. Columns "before" and "after" refer to occurrence of the strike before or after the return stroke.



a) Superposition of isolines of reflectivities (dBZ) from the sector scan of the storm between 1918:33 and 1919:04 and the airplane flight path between 1919:41 and 1921:06. The altitude of sector scanning in the vicinity of the airplane pattern is 5.0 km. The dashed line with the larger arrow is along the azimuth of 25 deg of the RHI scan shown in Fig. 2b. For symbol identification, see Fig. 1.



b) Vertical RHI scan of the storm along the penetration pattern (257 deg azimuth) between 1921:43 and 1921:55. The nominal airplane altitude was 7.7 km. Only the direct strike is shown.

Fig. 2 Radar reflectivity and the F-106B penetration pattern for a flight on Aug. 14,1984.

B. Cloud-to-Ground Strikes to the F-106B Airplane

From the UHF-band radar data we determined echoes of lightning flashes that propagated through the radar resolution volume containing the F-106B without striking the airplane. These flashes, called nearby flashes, were in the majority of cases verified by visual observations of the crew. The accuracy of the time measurements (from the TV-formated record of UHF-band radar data) for the nearby flashes is 33 ms (one TV frame). The estimated starting time of a lightning echo could only be later (within 33 ms) than that of the flash because it is defined as a time of the first TV frame with an echo. The time accuracies of the cloud-to-ground strikes (from the East Coast lightning detection network) and direct strikes (from onboard measurements) are equal to that of Wallops Flight Facility, i.e., 1 ms. A summary of the nearby flashes, direct strikes to the F-106B, and time differences between direct strikes and return strokes of CG flashes for six days (seven flights) are shown in Table 1.

Time differences between CG return strokes and strikes to the F-106B are in scale of tens of milliseconds, that is, long enough to exclude a possibility that the F-106B was struck by the CG return stroke channel,[11] which travels with an average speed of 5×10^7 m·s^{-1}. As determined by the time difference analysis, two types of direct strikes associated with CG flashes were observed. The first was a strike to the F-106B by an intracloud portion of a CG flash that later developed the return-stroke channel to the ground (column "before" in Table 1, 4 of 10 cases). The second type (6 of 10 cases) was most probably an intracloud part of the CG flash developed after the return stroke, because these strikes occurred after the CG flashes reached the ground. Two direct strikes to the F-106B encountered during the flight on Aug. 13 were 200 ms apart and the cloud-to-ground return stroke followed the first strike in 110 ms. We believe that both strikes to the airplane were intracloud parts of the same CG flash, of the first and second types, respectively.

C. Environmental Conditions during Direct Strikes

The environmental conditions included in the analysis were rain and turbulence intensity, ambient temperature, and an average lightning flash rate in a storm cell during a penetration. The precipitation and turbulence were evaluated by the plane crew and expressed in four degrees of intensity (none, light, moderate, and heavy). However, in none of the penetrations during the 1984 storm season did direct strikes occur in severe turbulence or heavy precipitation. The ambient temperature was measured on the plane and lightning flash rate was obtained from the UHF-band radar data.

The concept of the probability of a direct strike to an airplane in a thunderstorm (PDS), based on the UHF-band radar observations of lightning echoes in the radar resolution volume containing the airplane, was introduced by Mazur et al.[6] The PDS is calculated as a ratio of the number of direct

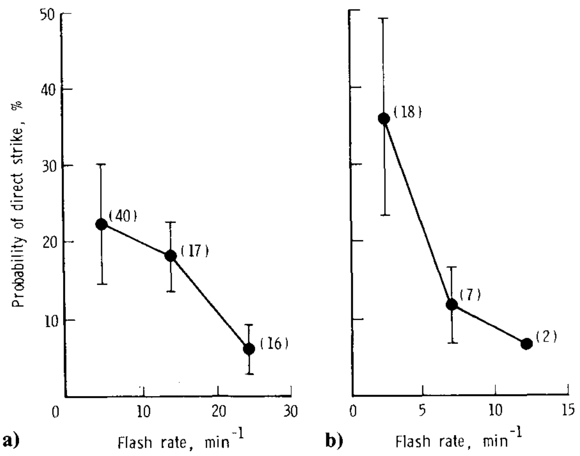


Fig. 3 Lightning flash rate and probability of direct strike in a penetrated storm (dots are the average probability of direct strike, vertical bars are the 90% confidence intervals for the average PDS in each category; the actual number of samples is given in parentheses). There are only two cases in the third category of group B; therefore the PDS is represented with the average value only. a) High-altitude flights (1982-1984 seasons, 73 penetrations, 108 strikes). b) Low-altitude flights (1984 season, 27 penetrations, 27 strikes).

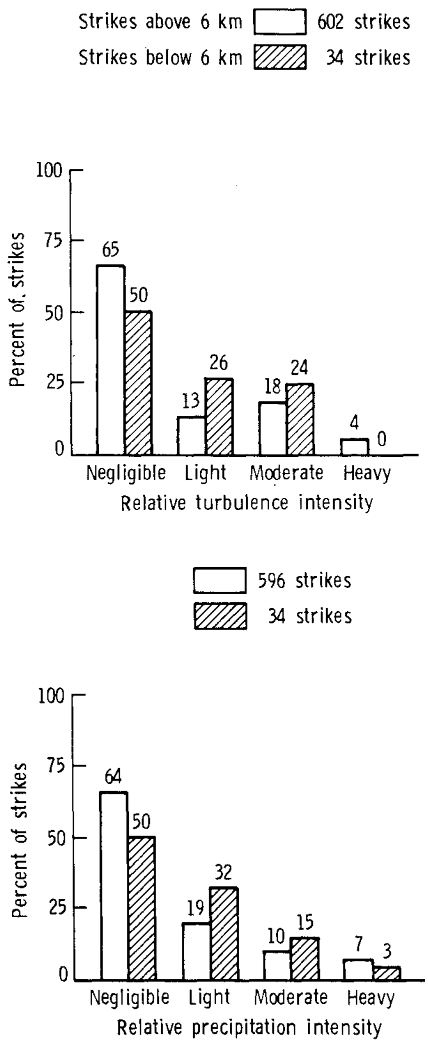


Fig. 4 Relationship of lightning strikes to relative turbulence (a) and precipitation (b) intensities. Shaded columns represent data obtained during low-altitude flights (1984 season, 34 strikes); nonshaded columns represent data obtained during high-altitude flights (1980-1984 seasons, about 600 strikes.

strikes to the F-106B to the total number of lightning flashes that occurred in or propagated through the radar resolution volume containing the airplane, which is a 150 m long section of a conical radar beam. The diameter of the UHF-band radar beam is $0.045R$, where R is a range. We calculated the PDS for the F-106B for all penetrations with direct strikes and analyzed the PDS relationship with environmental parameters of averaged values such as the ambient temperature and lightning flash rate in the storms penetrated. The probability of a direct strike to an airplane increases with decreasing lightning flash rate in a penetrated storm cell (Fig. 3). This trend also exists at high-altitude flights.[6] Studies of three storm cells described in Sec. III.A indicate that the same trend is noticed when storm cells with different lightning rates are compared (e.g., first vs second cell, storm on Aug. 12) as well as the growing and decaying stages of the same cell (storm on Aug. 14). As for ambient temperature, the PDS is almost the same through the range of temperatures of 0 to $-20°C$: The average PDS with 90% confidence intervals is $30 \pm 12\%$ for the region 0 to $-10°C$ and $26 \pm 14\%$ for the region -10 to $-20°C$.

Because of a significant variability of precipitation and turbulence intensities along the penetration path at low altitudes as opposed to more stable levels of both parameters along the penetration path at high altitudes, the frequency distribution of strikes was calculated instead of the PDS vs average environmental conditions at the moments of strikes. The histograms in Fig. 4 show that, for all altitudes, the majority of direct strikes occur in thunderstorm regions with negligible to light turbulence and precipitation.

D. Visual Image and Radar Echo of Direct Strikes to an Airplane

Development of the radar echoes from direct strikes to the F-106B has been used in an earlier study to interpret whether a strike is triggered by the airplane or is an intercepted, naturally occurring flash.[6] The echo from a triggered flash appears directly at the location of the airplane radar echo, whereas the echo of an intercepted flash is seen on an A-scope of radar first at some distance from the airplane echo and then moving toward the airplane. It is of interest to estimate the accuracy of the strike development picture from the radar data in comparison with both visual images of strikes from an onboard TV camera and the strike electromagnetic parameters recorded onboard the F-106B. Two strikes considered to be of different types were selected for analysis: triggered and intercepted.

The lightning strike on Aug. 13, 1984, at 1950:05.8 is illustrated in Fig. 5 by the series of radar echo pictures from TV-formated UHF-band radar data and the series of images of strikes from an onboard TV camera with a 60 deg view angle pointing toward the tail section of the airplane. (The possible error of alignment of the first frames of the two series is less than or equal to one frame interval—33 ms.) The electromagnetic characteristics of the strike were also analyzed: displacement currents on the frontal part of the fuselage and the left wing, current pulses to the nose boom and tail fin cap, luminosity pulses indicated by the light sensor installed behind the cockpit and pointed vertically, and the low-frequency (d.c., 400 Hz) currents flowing through the nose and tail fin cap of the airplane.

The airplane's right wing was pointed toward and the left one away from the radar at the time of the strike (Fig. 6). Lightning attachment to the F-106B airplane occurred in the nose (indicated in the waveform record at 1950:05.827) and the tip of the left wing. This conclusion was supported by the following simultaneous observations: current pulses to the nose boom, no current pulses to the tail, an attachment to the left wing seen in the TV image of the lightning strike (Fig. 5a), continuous direct current through the nose boom for about 20 ms. Figure 5a (radar echo) is the first frame with a noticeable change in the F-106B echo because of the strike (at 1950:05.84). The radar echo of this strike developed initially on top of the F-106B echo.

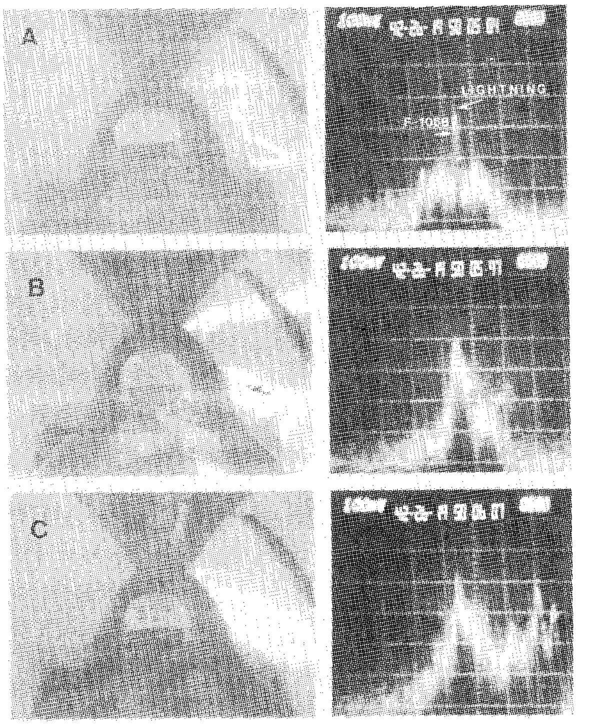


Fig. 5 Development of the strike to the F-106B that occurred on Aug. 13, 1984, at 1950:05.84, from TV visual images and the UHF-band radar data. (TV camera is installed in the cockpit and is pointed toward the wings of the F-106B; range between vertical divisions in the radar data is 3 km).

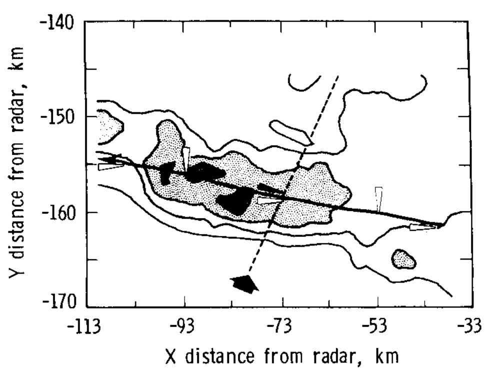


Fig. 6 Storm reflectivity structure and the F-106B penetration pattern for a flight on Aug. 13, 1984. The direct strike occurred at 1950:05.84.

In Fig. 5a, the lightning channel is seen "behind" the F-106B developing along the flight path. This corresponds to the propagation of the flash perpendicular to the radar beam without significant radial expansion. The motion of the channel to the left of the airplane (Figs. 5b and 5c) is also seen in the radar data as an appearance of lightning echo farther in range, which is on the left side of the airplane according to the penetration path. Thus, the channel motion from the radar data coincides with that from the visual images.

The strike scenario may be summarized in four phases presented in Fig. 7:

1) Strike initiation with the lightning channel oriented as shown in Fig. 7a. The initial points of attachment are at the nose boom and the left wing tip (from waveform record and Fig. 5a).

2) Swept flash as the airplane flew forward from the region of strike initiation (Fig. 7b). The channel (front part) swept back down the left side of the fuselage across the overhead canopy rail to the trailing edge of the rudder; the rear part of the channel trailed aft from the left wing tip. The bright luminosity of the channel moving swiftly along and above the left side of cockpit is also recorded by the optical sensor.

3) Front and rear channel convergence (Figs. 7c and 7d). As the airplane continued to fly forward, the front channel hung onto the rudder and the rear channel hung onto the left wing tip; the front and rear channels were converging on the left wing.

4) Channel rejoining behind the airplane after the front channel brushed against the left wing tip and combined with the rear channel (Figs. 7e and 7f).

The F-106B flew toward the charge region, where the frontal part of the ionized channel terminated at the time of strike initiation, and dragged the channel behind and along the penetration pattern, thus providing a continuity of a current flow. The lightning flash continued propagating in space after the channel detached from the F-106B.

The strike at 1950:05.8 was most likely triggered by the presence of the airplane and started in a cloud near it. From an analysis of electromagnetic parameters, we found that a displacement current (E-field derivative), which indicates a breakdown process, preceded the current attached to the nose boom by 2.7 ms. This corresponds to the maximum range of about 400 m between a possible point of strike initiation and the F-106B, traveled by a streamer with an average speed of 1.5×10^5 $m \cdot s^{-1}$. The luminosity of the channel for almost 330 ms (e.g., Figs. 5a-5c) can be explained only by the presence of continual current in the flash.

Another example of correlation between the radar data and the visual image of a lightning strike to the F-106B is an intercepted flash on Aug. 14 at 1936:51.450. The lightning flash started at 1936:50.890 about 7 km from the airplane location (see Fig. 8a) and propagated first away from and then toward the F-106B. Radar data (Figs. 8b and 8c) show that the channel approached the F-106B from the left wing side, which coincides with the visual images (Fig. 8b). At that time, the airplane was positioned with its right wing pointed toward and the left one away from the radar (see Fig. 9). A strike was indicated onboard the F-106B at 1936:51.441 in the high-frequency record of the current pulse at the nose boom and the optical sensor. However, the record of direct current at the nose as well as at the tail fin cap does not show any continuous current flow through these extremities. The lightning channel passed the F-106B to the right (Fig. 8c), as is also seen in Fig. 8c of the radar data. The strike scenario of this intracloud flash is summarized in five phases presented in Fig. 10:

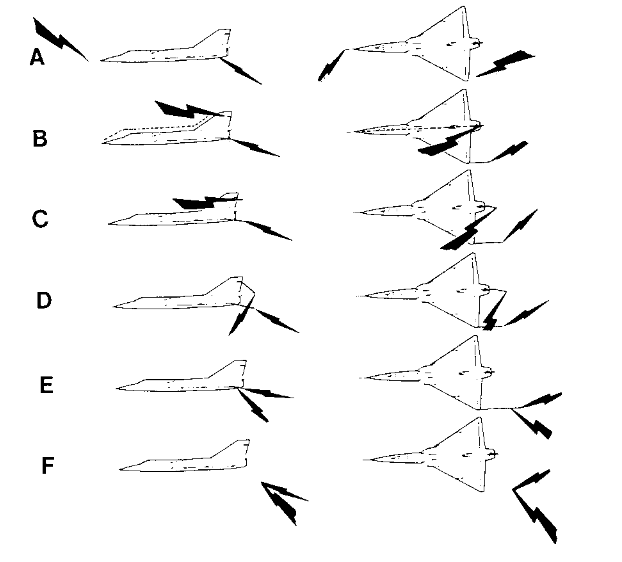


Fig. 7 Phases of lightning channel attachment to the F-106B from the moment of strike initiation by the airplane until the channel detachment. The start time of the strike is 1950:05.84 on Aug. 13, 1984. (Video frames refer to Fig. 5.)

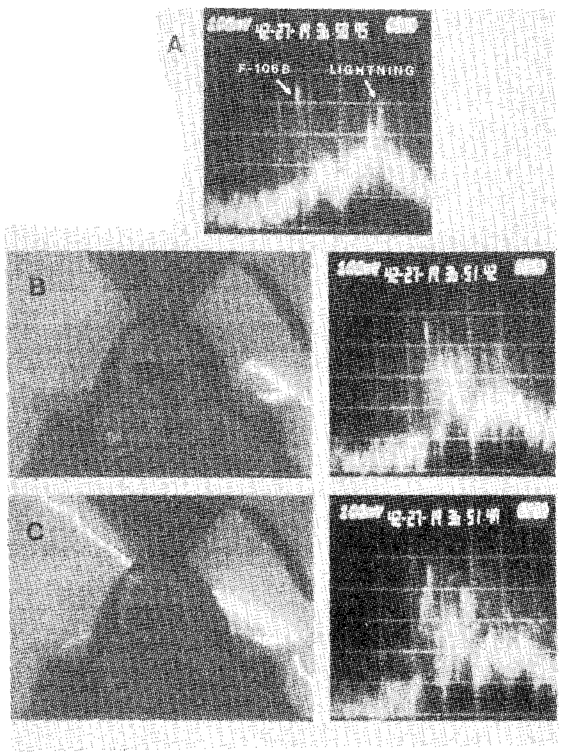


Fig. 8 Development of the strike to the F-106B that occurred on Aug. 14, 1984, starting at 1936:51.42 from the UHF-band radar data and TV visual images. Part A shows that the flash started away from the F-106B (see comments to Fig. 5).

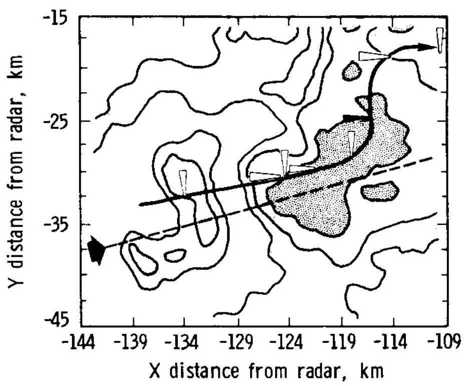


Fig. 9 Storm reflectivity structure and the F-106B penetration pattern for a flight on Aug. 14, 1984. The strike occurred at 1936:51.42.

1) Intracloud flash channel propagation toward the F-106B from the left wing side (Fig. 10a).

2) Attachment to left wing tip and triggering an electrical breakdown process at the nose boom (Fig. 10b).

3) Swept flash as the airplane flew forward from the region of lightning intersection (Fig. 10c).

4) Front channel hanging onto the vertical tail (not the tail fin cap) and rear channel hanging onto the left wing tip (Fig. 10d).

5) Channel detachment from the airplane (Fig. 10e).

After intercepting the intracloud flash, the F-106B pulled the ionized channel behind and along the penetration path, making a horizontal loop in the channel; the general direction of propagation would otherwise be from the left and below the airplane to the right and above it. The TV images indicate continuous luminosity of the lightning channel for almost 150 ms, which is evidence of the continuous current in a flash.

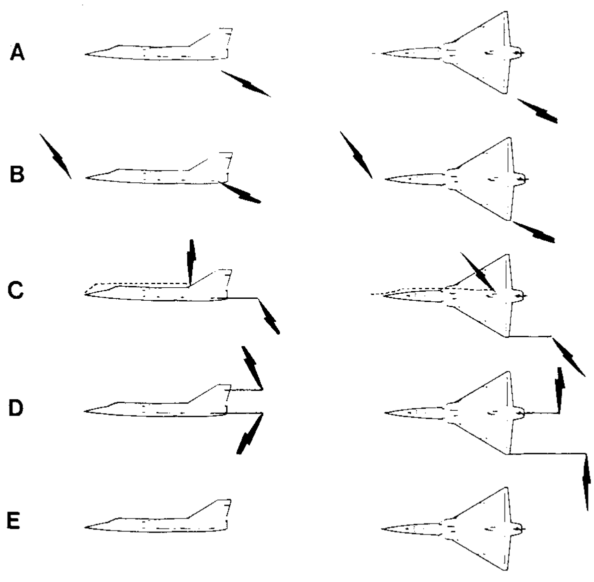


Fig. 10 Phases of lightning channel attachment to the F-106B from the moment of interception with the naturally occurring intracloud flash by the airplane until the channel detachment from the vertical tail and left wing. The start time of the strike is 1936:51.42 on Aug. 14, 1984. Further description of the phases is given in the text. (Video frames refer to Fig. 8.)

V. Discussion and Conclusions

Before starting an investigation of low-altitude strikes to the F-106B we asked the following questions:

1) Is it possible for an airplane to be struck by a CG flash (return stroke or intracloud portion of the flash) or to trigger one?

2) During what stage of storm development and in what environmental conditions is the risk greatest for an airplane to be struck by lightning?

Preliminary analysis of the seven flights presented here answers the first question positively. Ten direct strikes to the F-106B were associated with CG flashes. In 4 of these 10 cases, strikes preceded the return strokes to the ground and, in 6 cases, strikes followed the return strokes. All of the strikes were intracloud portions of CG flashes.

The strategy for penetrating storms to encounter direct strikes to the F-106B at low altitude seems successful for two storms whose structures are presented here, but it needs to be proved with many more case studies. In answer to the second question, strikes to the F-106B usually occurred during the decaying stage of the storm cells, as shown by the analysis of the flights on Aug. 12 and 14. A similar observation was made by Fitzgerald.[4] This trend may be a major contributing factor hidden in the relationship between the probability of direct strikes to an airplane and the lightning flash rate in a penetrated storm cell that we observed both in high- and low-altitude flights, i.e., increasing probability of strikes with decreasing flash rate.

Environmental conditions such as rain and turbulence intensity during strikes to an airplane were very much the same as those at high-altitude regions of thunderstorms.[6] However, analysis of the relationship between the ambient temperature and the PDS did not show a statistically significant difference between the average PDS through the range of temperatures between 0 and $-20°C$. The limitations on flying time and changes in altitude during the flight did not allow a thorough investigation of this matter with equal time at each temperature level.

Analysis of the correlation between the radar data and visual images of the lightning strike showed that, if the airplane position relative to the radar is known, the lightning channel motion can be interpreted from the lightning echo pictures quite adequately. It is also clearly seen from this comparison that the lightning radar echo is produced by a major, sometimes tortuous but not branching, ionized channel. This conclusion is made with reservation because of the limited field of view from the F-106B cockpit. Our observation supports the hypothesis that the main channel of overdense (highly luminous) plasma is a dominant contributor to the lightning radar cross section[12] and contradicts the suggestion by Holmes et al.[13] that the radar cross section is produced by the properly oriented elements of an extended array of small-diameter underdense plasma channels.

Acknowledgments

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