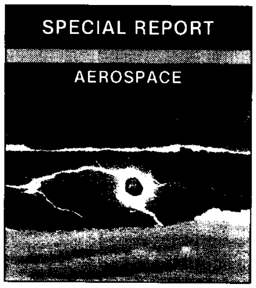
Aircraft jolts from lightning bolts

A milestone NASA study based on actual airplane data spurs the FAA to set new standards for protecting airborne electronic systems



U.S. commercial airliners are hit by lightning about once a year, on average, according to statistics gathered by the Federal Aviation Administration (FAA). Enormous electric currents flow through the outer metal skin of the airplane for up to a second. Almost instantly, the encounter is over. A bright flash may be a passenger's only clue that something unusual has happened.

On occasion, however, the phenomenon is not so harmless. For example, on Dec. 8, 1963, a lightning strike ignited fuel in the reserve tank of a Pan American jetliner in a holding pattern near Elkton, Md. The airplane's left wing was destroyed, and all 81 people on board perished. Fatal accidents also have occurred to military aircraft struck by lightning.

Though such incidents are very rare, a combination of trends in aircraft construction is making it vital that airplane designers better understand the effects of lightning. Rigorous measures must be taken to counter those effects if the aviation industry is to maintain its excellent lightning safety record.

One development is the use of nonmetallic composite materials in large areas of skin and structure in new airplanes, as opposed to the fully metallic structures in most airplanes now flying. Composites appeal to designers because they are strong yet light in weight. The other trend is the increasing reliance on digital electronics to control critical flight functions, as opposed to the analog electronic, mechanical, and hydraulic systems now used. That development is part of an almost universal tendency to replace analog control systems with digital controllers.

Both trends are especially pronounced in newly designed business and military aircraft, although some commercial aircraft designs are also moving in similar directions. The application of the two technologies has renewed the need to quantify the effects of lightning strikes to airplanes, since composite structures do not provide shielding equivalent to that of metal aircraft, and digital systems are potentially more susceptible to upset by electrical transients than are analog electronic systems. Overall, then, the main concern is designing aircraft so that when lightning strikes, currents and electromagnetic fields do not leak into the fuselage, disrupting the electronics, damaging the structure, or even injuring passengers or crew.

To better understand the danger, the National Aeronautics and Space Administration has for the past eight years run a research project, called the Storm Hazards Program, at its Langley Research Center in Hampton, Va. The project, one of the most extensive of its kind, has provided the first statistically significant measurements of the electromagnetic interaction between lightning and aircraft. The NASA investigations also have identified atmospheric conditions conducive to aircraft lightning strikes and helped to define the zones where lightning is most likely to attach itself to an airplane.

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NASA Langley confirmed one long-held assumption but challenged others. Measurements made on board a research airplane and on the ground proved for the first time what has long been suspected—that the aircraft itself, flying into a strong electric field, often triggers the lightning that strikes it.

Conversely, the peak rate of change of currents on an aircraft being struck by lightning was found to be far above the previously accepted "safe" value of 100 000 amperes per microsecond. The project's data base showed about twice that value for the highest 1 percent of measured rates of change of current. The safety criterion was set for the FAA and the Department of Defense by the Society of Automotive Engineers in Warrendale, Pa. (The society, one of several that set standards in aviation, is preeminent for lightning safety criteria.)

Also contrary to expectation, the airplane was rarely struck by lightning amid the heaviest turbulence and precipitation; the intensity of those two factors had no correlation at all with the number of direct lightning strikes. And, when flying through or near the tops of thunderstorms, the plane was most likely to be struck when the ambient temperature was below -40 °C; the assumption, based on reports of strikes to commercial aircraft, was that most strikes occur near 0 °C.

At present, there are no established criteria on acceptable rates of change of electric flux density on an airplane during a lightning strike. The NASA program recorded maximum rates of change under the nose of an airplane during a lightning strike in excess of 100 amperes per square meter. The current and flux density data are now being used by the Society of Automotive Engineers to develop new criteria on protection of aircraft electrical and electronic systems against lightning.

Protecting craft and crew

Since 1980 the NASA Langley team has flown a NASA-owned F-106B airplane through thunderstorms about 1500 times at altitudes between 5000 and 40 000 feet (1500 to 12 000 meters). The airplane, lightning-hardened and outfitted with special instru-

Defining terms

Attachment point: a spot where a lightning flash makes contact with an airplane.
Coupling: the electromagnetic phenomenon by which currents are induced in an object in a strong electric field.
Corona: a luminous discharge caused by a difference in potential between the aircraft and the surrounding atmosphere.
Leader: the preliminary breakdown that forms an ionized path for charge to be channeled toward the center of opposite charge.
Lightning channel: the path along which the charge flows.

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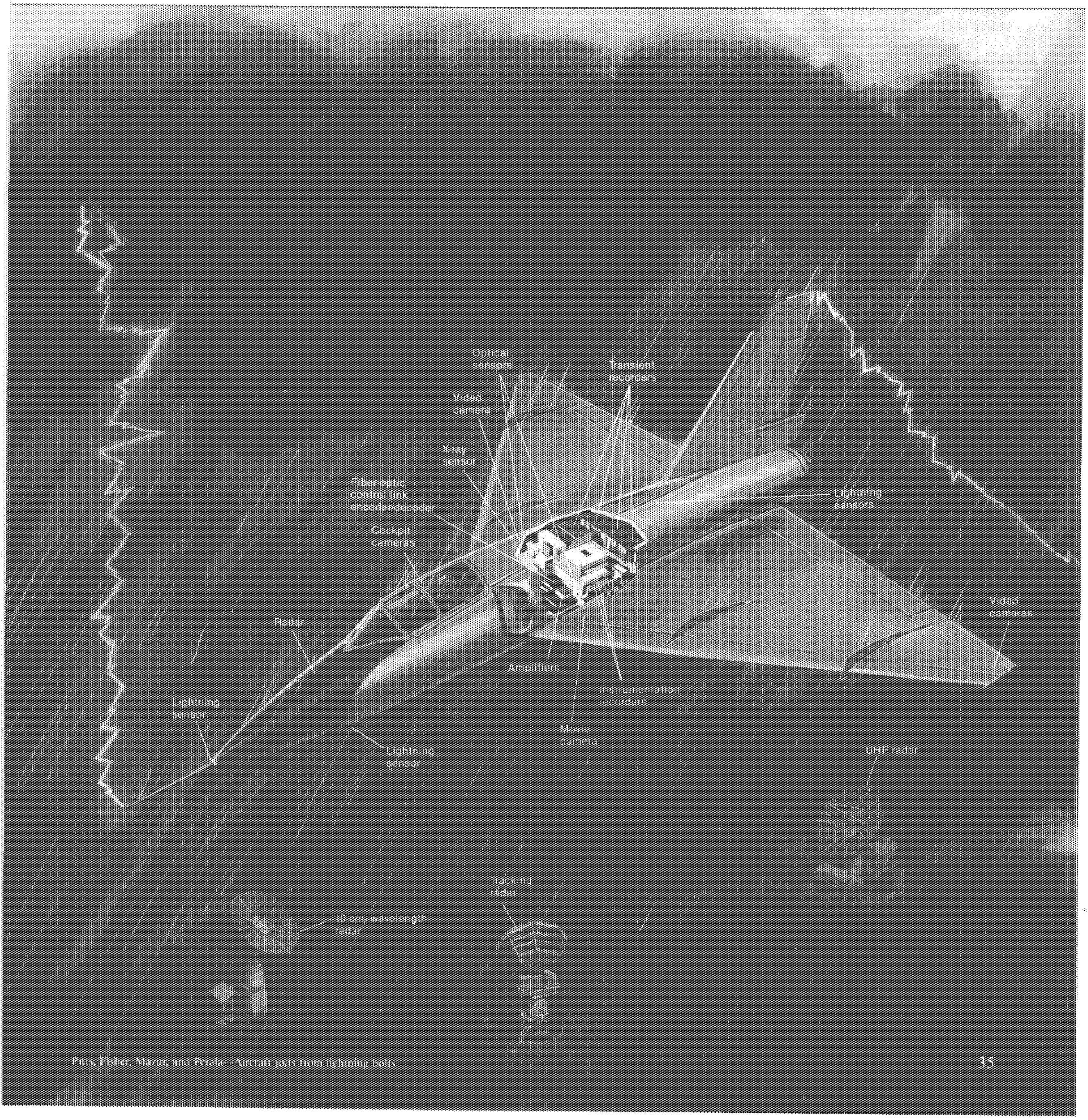
ments, was hit by lightning 714 times. Ground-based NASA radars located across the Chesapeake Bay on Wallops Island, Va., were used to guide the airplane into the upper regions of thunderstorms, which are the most electrically active.

Considerable attention was paid to protecting the crew during these potentially dangerous missions. To minimize the possibility that a lightning bolt might melt through or damage the airplane's exterior, paint was removed from most exterior metal surfaces, to deter the lightning from lingering, or "dwelling," on them. JP-5 (Jet A) fuel was used exclusively rather than the more volatile JP-4 (Jet B) variety normally used in the Air Force F-106 fleet, and fuel tanks were regularly inspected for electric continuity of the fuel lines and for evidence of arcing or sparking. Each spring, before the thunderstorm season, the lightning hardening was checked during ground tests in which simulated lightning cur-

Pilots from the National Aeronautics and Space Administration flew a specially modified Convair F-106B airplane into thunderstorms in order to gather information on lightning strikes to airplanes. The NASA airplane, equipped with electromagnetic sensors, data recorders, still and video cameras, and other instruments, was struck by lightning 714 times. Three ground-based radars (in the foreground) were used to guide the airplane into the upper, electrically active regions of the storms. A UHF radar was used to locate lightning flashes while a 10-cm-wavelength radar provided data on the structure of storm clouds. The third radar tracked a transponder on board the F-106B airplane, providing the airplane's position to the other two radars.

Tony Leonardi



rents and high voltages were conducted through the airplane, while a full crew was on board and all systems were operating.

The staff of the Storm Hazards Project was responsible for launching and recalling the F-106B airplane, selecting storms and altitudes of interest, and supporting and guiding missions. Housed in NASA Langley's flight service station, they worked with their counterparts at NASA Wallops, discussing radar data and flight strategy during missions over a dedicated phone link. People at both sites talked to the flight crews by radio. Generally, the airplane was flown within 150 nautical miles (275 kilometers) of NASA Langley to maintain line-of-sight communications. During actual missions, the pilot always made the final decision on whether to continue a flight and enter a storm system.

Until the NASA Storm Hazards Program, standards for lightning protection of airplanes were derived from data recorded during strikes to towers equipped with instruments. These standards have sufficed for today's aircraft, with their rugged analog electronics and all-metal frames and skins. Typically, the interference and outages reported in weather radar, navigation and communication systems, and engine instruments have been infrequent and annoying rather than catastrophic.

Up to 200 000 amperes

When lightning strikes an airplane, it may take more than a second before the extremely fast and interactive electromagnetic effects die away. Currents between 10 000 and 200 000 amperes may flow through the airplane's metal skin, setting up electromagnetic fields that may propagate into the airplane's interior through open apertures, diffusion, or other mechanisms.

To measure these phenomena the F-106B airplane had three sets of basic instruments: continuous analog recorders, digital transient recorders, and peak recording instruments.

The continuous analog recorders had bandwidths of 400 hertz to 100 kilohertz. They could not record fast current pulses and electromagnetic fields with acceptable fidelity, but were capable of recording data during the entire storm penetration. Although their nominal minimum bandwidth is 400 Hz, the analog recorders could record continuous (dc) currents using frequency-division multiplex recording techniques.

The digital transient recorders had a large enough bandwidth—up to 100 megahertz—but could record only during a small interval of the lightning encounter. The digital recorders triggered on only those pulses that exceeded a certain threshold, and once actuated, recorded a brief portion of the event with a time resolution of 5 to 10 nanoseconds. In fact, the maximum bandwidth of 100 MHz could only be obtained with the instrument's minimum sampling period of 5 ns per 8-bit sample. Since each of the recorder's 12 channels could store a maximum of 65 536 samples, the data window was just 327 microseconds at the maximum sampling rate.

The peak recorders supplemented the analog and digital recorders by capturing the maximum voltages picked up by selected sensors during a flight. Generally, they monitored the peak rate of change of current in the nose boom (a slender metal extension projecting from the plane's nose) and the rate of change of flux density under the forward fuselage.

Approximately 2500 individual time-domain waveforms were logged from the various sensors during the strikes, and 130 peak recorder readings were obtained during about 400 of the strikes. The highest value recorded by the peak recorder of a rate of change in current through the nose boom of the plane was 380 000 A/μs; the maximum rate of change of electric flux density under the forward fuselage exceeded the peak recorder's maximum range of 97 A/m^2; and the largest peak current at the tip of the vertical tail was 54 000 A.

A flying, hardened, laboratory

The custom F-106B airplane that housed those recording instruments was, in a sense, a flying laboratory. Its instruments were installed in a shielded, self-contained package in the aircraft's weapons bay, in the bottom of the fuselage. Power for the instruments was provided by a motor-generator, which completely decoupled them from the aircraft's power system and hence from unwanted lightning-induced transients as well.

Sensors for measuring the current, the rate of change of current, and the rate of change of electric and magnetic fields were mounted in the nose, the vertical tail, under the forward and aft portions of the fuselage, at the base of the vertical tail, and under each wing [see diagram, p. 35]. A few internal wires also picked up induced voltages.

Three radars at the NASA Goddard Space Flight Center's Wallops Flight Facility and one radar in the F-106B airplane guided the flight crew, documented storm structures, and confirmed lightning strikes triggered by the airplane. One of the ground-based radars had a 10-centimeter wavelength and was used to determine the reflectivity profile of storm clouds. Another, an ultrahigh-frequency (UHF) radar with a 70.5-cm wavelength, was used to locate lightning flashes by detecting backscattering signals from ionized lightning channels. Both radars followed the F-106B airplane by electrical commands from a third ground-based radar, which tracked a special transponder mounted on the airplane.

Radar wavelengths of at least tens of centimeters are needed for good detection of ionized lightning channels inside storm clouds, while an antenna with a narrow beam is needed for good spatial resolution of lightning locations. NASA's UHF radar at Wallops Island is one of the few radars that has both features.

To select a storm of interest and region of penetration, the NASA staff would analyze information on the storm's location and structure, along with data on how lightning flashes were distributed within it. The goal was to guide the F-106B airplane through the storm so that it encountered lightning while avoiding potentially damaging hail or heavy rain. When approaching a storm, the F-106B pilots used their on-board 3-cm-wavelength weather radar to verify the safety information from the 10-cm-wavelength radar at NASA Wallops. During the penetration, the UHF radar tracked the F-106B airplane, to detect near-misses and direct strikes.

Ideally, the F-106B airplane flew through a storm of interest along a preselected heading directly toward or away from the 10-cm-wavelength radar, which conducted a series of vertical scans along the heading to define the storm conditions surrounding airplane lightning strikes. The data from these scans were used to reconstruct the evolution and structure of the storms for comparison with the electromagnetic and turbulence data recorded on board the airplane.

Film and video cameras both supplemented radar and instrument data and helped determine the zones on the airplane's exterior where lightning attached itself. These data helped determine whether the airplane had triggered the strike or encountered a naturally occurring lightning channel.

The F-106B airplane was equipped with a total of eight cameras. Two black and white video cameras were mounted in the cockpit, which is covered by a clear glass canopy. One camera faced forward and the other backward. Two other black and white video cameras were installed in a pod on the upper surface of the left wing tip and together gave overlapping views of the whole airplane, from just ahead of the nose boom to the trailing edge of the vertical tail.

A high-speed 16-mm movie camera, normally loaded with color film, was mounted under a fairing on the left side of the fuselage, looking to the rear with a view including the left wing tip and vertical tail. Three 70-mm still cameras, with 45-μs-response shutters and loaded with color film, shared the cockpit video cameras' platform, with two facing forward for stereo views and the third providing much the same view as the rear-facing cockpit video camera. The video cameras were operated continuously during flights, while the movie and three still cameras were triggered automatically by inputs from light-sensitive diodes mounted throughout the cockpit.

A lightning channel may persist for more than a second after an airplane has entered it, remaining relatively stationary while the airplane moves forward within it. Two or more attachment points occur simultaneously and are typically located at airplane extremities, such as the nose boom and tips of the wings. Other attachment points may then be caused by the airplane's motion as it moves through the channel.

For example, when a forward extremity such as a nose boom becomes an initial attachment point, the plane continues through the channel, which appears to sweep back over the airplane's surface in what is called the "swept-stroke" phenomenon. On the other hand, when an initial attachment occurs at a trailing edge, the lightning channel clings there, streaming behind the plane.

The NASA data and photographs indicated that much, if not all, of the exterior surface of an aircraft with a geometry similar to that of an F-106B may be exposed to direct or swept lightning attachments. Therefore, new delta-wing aircraft and designs incorporating wings with highly swept leading edges probably will require protection from lightning strikes over their entire exterior—especially if a design is based on surfaces made of composite materials.

Aircraft triggers lightning

Researchers since the 1950s have debated whether an aircraft, instead of merely intercepting a naturally occurring lightning flash, could trigger one. The facts supporting this notion were reports of airplanes being struck by lightning in certain electrified clouds that were not known to generate lightning naturally. But the evidence was clearly circumstantial.

Analysis of radar returns (echoes) to the NASA-Wallops UHF radar from a majority of lightning strikes to the F-106B airplane showed lightning echoes starting directly on top of the airplane's echo and subsequently traveling away from the airplane. The data, confirmed by video sequences observed with the on-board cameras, were the first to actually capture an airplane in the act of triggering a lightning flash.

Strikes not triggered by the aircraft were seen as a different sequence on the monitors. Echoes from both a lightning flash and the F-106B appeared at some distance from each other; then the lightning echo moved toward the airplane echo; and finally the two echoes overlapped at the moment of the reported strike.

The electromagnetic data and visual images are now being used in conjunction with the ground-based lightning echo data to develop a model of how lightning strikes begin. Preliminary indications are that lightning starts with the formation of leaders of opposite charge at various extremities of the airplane.

The leaders develop simultaneously, bidirectionally, and probably three-dimensionally around the airplane. The entire process is governed by the ambient electric field and the electrical circuit that includes the capacitances and conductivities of the aircraft and the leader channels.

Unsafe at any altitude

The probability of a direct strike to the F-106B airplane, whether triggered or intercepted, was defined as the ratio of the number of direct strikes to the total number of flashes occurring within the minimum volume (containing the airplane) that could be resolved with the UHF radar. Correlations between the probability of a direct strike and the ambient temperature, the intensity of rain, and the intensity of turbulence indicated that the highest risk for the F-106B airplane in the upper regions of thunderstorms occurred when ambient temperatures were -40 °C or colder, and precipitation and turbulence were negligible or light. It should be noted, however, that lightning strikes were encountered at nearly all temperatures and altitudes, indicating that at no altitude is an aircraft safe from being struck in a thunderstorm.

Studies of storm structures during the penetrations with strikes showed that the majority of strikes at low altitudes (below 6 km) occurred while the storm cells were decaying. Curiously, at all altitudes, the probability of a direct lightning strike increased when the rate of lightning flashes decreased. This relationship reflects the decrease in the natural occurrences of lightning with the decay of the storm.

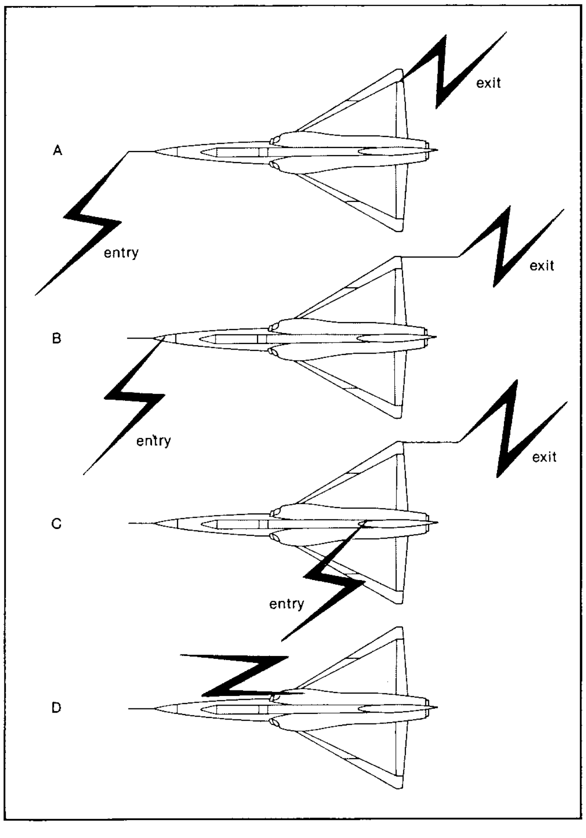
Solving Maxwell's equations

The airborne sensors and instruments provided the raw data for computer-simulated modeling of aircraft encounters with lightning. An important application of that model was predicting the indirect effects of lightning strikes.

Indirect effects are hazards caused by electromagnetic coupling—for example, transient voltages and currents induced in antennas, cables, and internal avionics. Direct effects, on the other hand, are more easily observable and measurable and include pitting, burning, and magnetic deformation.

The computer modeling technique gave predicted internal transient voltages and currents that were in excellent agreement with actual sensor responses. The technique can be used as a first step in the complex problem of predicting internal induced effects in arbitrary aircraft designs.

The main analytical tool used to model aircraft lightning strikes is a program called T3DFD, for Time Domain 3-Dimensional Finite Difference Code. The code, used by Electro Magnetic Applications Inc. in Denver, Colo., is based on an earlier program developed at the Department of Energy's Lawrence Radiation



Typically, lightning enters an airplane through an extremity. Common entry points include the nose boom, a slender, pole-like extension to the nose (A); the nose itself (B); or the vertical tail (C). The airplane moves forward during the strike, through the lightning, so the exit point is typically a trailing edge, like a rear wing tip (A). In some cases, the lightning appears to cling to the trailing edge, streaming behind the plane, as in B and C. Finally, airplanes often record near-misses (D), in which no contact is observed.

Laboratory. Running on NASA Langley's Control Data Corp. Cyber 205 computer, it solves Maxwell's equations in three dimensions. The software models the complex geometry of the F-106B airplane and the space- and time-varying characteristics of the ambient electrical environment. The program has been enhanced with a model of atmospheric chemistry, so that air conductivities around large electric fields may be calculated.

In the computer model, the simulated F-106B airplane had all electric fields tangential to its conductive surface set to zero at all times. The assumption of a conductive surface is a good approximation except for the immediate vicinity of the cockpit, where large panels of glass create apertures.

Electromagnetic coupling includes both external and internal aspects. External coupling refers to the generation of surface currents and charges on the airplane (or tangential magnetic fields and normal electric fields). Internal coupling refers to the generation of electromagnetic fields, currents, and voltages on the inside of the aircraft.

The equations for external coupling can be solved first and the solutions then used to define the sources of the internal response. This approximation is adequate when the internal coupling does not significantly feed back into and so alter the external coupling. This feedback happens mainly in instances involving large apertures, such as an open weapons bay or wheel wells, or a large window or other nonconducting panel.

Electromagnetic energy penetrates an airplane in three ways: through apertures, along exposed conductors, and by diffusion. Apertures include engine exhaust ports, wheel wells, seams on doors and panels, windows, and areas covered by dielectrics like Kevlar or fiberglass. Exposed conductors include antennas, airspeed probes, and some electrical or control cables, which may be struck directly by lightning or energized by fields induced by nearby lightning channels.

Diffusion describes the induction by surface currents of a tangential electric field inside the airplane, by means of a surface transfer impedance that relates the internal electric field to the surface current. The transfer impedance is a function of the surface material, its thickness, and the frequencies of the lightning waveform. At low frequencies, the internal tangential field is simply the resistive voltage drop along the surface.

Another challenging software problem was modeling the growth of corona, a nonlinear phenomenon crucial to the modeling of how an airplane triggers a lightning strike in a strong electric field. The mathematical model for corona solves for the conductivity of the air around the airplane. The model first calculates the densities of positive ions, negative ions, and electrons as a function of space and time. Next it solves a rate equation for each kind of charge for the ion and electron densities. Those solutions are then used to calculate the conductivity of the air.

The conductivity of air from the corona model is then integrated with the T3DFD code through the conductivity term in Maxwell's equations, to calculate the aircraft's electromagnetic response to the lightning strike.

Safer standards

Although NASA's Storm Hazards Program has concluded, interpretation of the data gathered during storm missions is continuing at Electro Magnetic Applications Inc. The T3DFD software for modeling lightning strikes, developed by Electro Magnetic Applications and the Lawrence Radiation Laboratory, will soon be made available to other researchers through the University of Georgia's Computer Software Management Information Center in Athens.

The data on conditions conducive to lightning strikes are also being used by commercial and military aircraft operators to plan their flights so as to avoid such conditions, when practical. The data demonstrated a lack of correlation between the probability of a direct strike and lightning flash rate, as well as the frequent lack of correlation between aircraft lightning strikes and turbulence and precipitation.

The last two findings are being used by operators to provide more realistic interpretations of the outputs of airborne severe weather detection systems. Finally, the NASA Storm Hazards operational data are influencing the new "launch commit" weather criteria being developed by NASA and the Defense Department for the Space Shuttle and expendable launch vehicles.

New threat criteria, based on NASA Langley's direct strike data, are being included by the FAA in a new advisory circular titled "Protection of Aircraft Electrical and Electronic Systems against Lightning." The same criteria are also being adopted by the Department of Defense (DOD Standard 1795A) for lightning protection of aerospace vehicles and hardware. The criteria were also published in a report, "Protection of Aircraft Electrical/Electronic Systems Against the Indirect Effects of Lightning," by the Society of Automotive Engineers (SAE AE4L Committee Report: AE4L-87-3).

As a final note, it must be recognized that the results of the NASA Storm Hazards Program were achieved exclusively in thunderstorms at altitudes ranging from 5000 to 40 000 feet, where strikes were easy to obtain. Lightning-aircraft electrodynamics and the conditions conducive to aircraft lightning strikes have yet to be quantified at low altitudes in thunderstorms and in nonthunderstorm, weakly convective clouds.

To probe further

Recent reports include "New Methods and Results for Quantification of Lightning-Aircraft Electrodynamics" by Felix L. Pitts, Larry D. Lee, Rodney A. Perala, and Terence H. Rudolph (NASA Technical Paper 2737), available from the National Aeronautics and Space Administration, Washington, D.C. "Managing Risks From Lightning Strikes to Aircraft" by Bruce D. Fisher and J. Anderson Plumer was presented at the Flight Safety Foundation's Fortieth International Air Safety Seminar in Tokyo in October 1987. Vladislav Mazur presented "Lightning Initiation on Aircraft in Thunderstorms" at the 1988 International Aerospace and Ground Conference on Lightning and Static Electricity in Oklahoma City, Okla., last April.

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