# Aircraft Lightning Electromagnetic Environment Measurement

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## Abstract

Limited information about the natural lightning electromagnetic environment and its interaction with new composite airframes continues to add uncertainty to analysis and measurement needed for aircraft certification, inspection and operation. This paper outlines a NASA project plan for demonstrating a prototype lightning strike measurement system that is suitable for installation onto research aircraft that already operate in thunderstorms. This work builds upon past data from the NASA F106, FAA CV-580, and Transall C-180 flight projects, SAE ARP5412, and the European ILDAS Program. The primary focus is to capture airframe current waveforms during attachment, but may also consider pre and post-attachment current, electric field, and radiated field phenomena. New sensor technologies are being developed for this system, including a fiber-optic Faraday polarization sensor that measures lightning current waveforms from DC to over several Megahertz, and has dynamic range covering hundreds-of-volts to tens-of-thousands-of-volts. A study of the electromagnetic emission spectrum of lightning (including radio wave, microwave, optical, X-Rays and Gamma-Rays), and a compilation of aircraft transfer-function data (including composite aircraft) are included, to aid in the development of other new lightning environment sensors, their placement on-board research aircraft, and triggering of the on-board instrumentation system. The instrumentation system will leverage recent advances in high-speed, high dynamic range, deep memory data acquisition equipment, and fiber-optic interconnect. As a secondary system, the measurement system will leverage operational safety risks already considered for storm hazards. The prototype system will provide new data about the natural lightning environment and how it interacts with airframes. Data will improve the effectiveness of analysis and measurement needed for lightning certification of aircraft, and will lead to new lightning damage detection and diagnosis tools.

## 1. Introduction.

Today's idealized standard lightning environment for aircraft certification is estimated based upon limited in-flight lightning strike electrical current and magnetic field measurements, combined with data from ground-based lightning mapping arrays and strikes to towers and small rockets (launched into thunderstorms with trailing wire attached).[1, 2, 3] Occasionally, lightning attachments to aircraft result in damage and avionics effects beyond those expected from the idealized environment.[4, 5] Since the 1980's, when the present standard lightning environment for aircraft was set, new details about the aircraft lightning environment have been discovered.

The Lightning Electromagnetic Effects (LEEM) element of the Atmospheric Hazards Sensing and Mitigation (AHSM) task, in the U. S. National Aeronautics and Space Administration (NASA) Aviation Safety Program, is studying lightning damage mechanisms to composite airframes, new test methods, damage mitigation and multifunction sensors, and has a goal of demonstrating a prototype lightning strike measurement system to capture in-flight lightning events, by 2015.[6] An artist's concept for the system is shown in Figure 1.

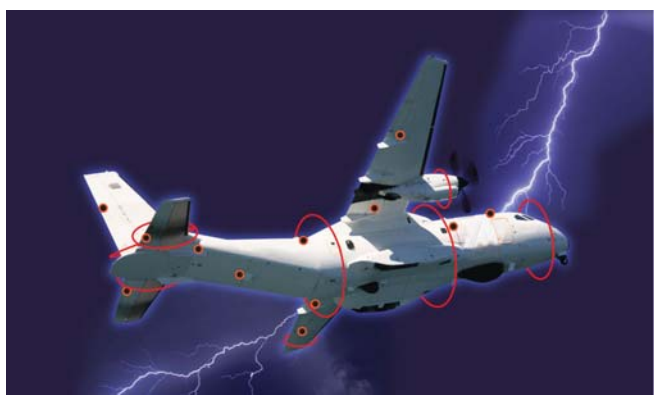

**Figure 1: Concept for In-Flight Lightning Strike Measurement System.[7]**

## 2. In-Flight Lightning Data, Background.

This new NASA effort builds upon a history of in-flight lightning measurement research. Between 1979 and 1986, the NASA F-106B experienced 714 direct lightning strikes while performing research flights through thunderstorms. Thunderstorm penetrations occurred at altitudes between 15 000 ft to 40 000 ft. Most of the lightning strikes were cloud-to-cloud, and triggered by the airplane itself. [8] Digital data were sampled at a 5-to-10 nanosecond interval in 327-to-654 microsecond windows (65 536 samples) with up to 8-bit maximum resolution and 12 channels[9]. Digital data were supplemented with peak detectors and low bandwidth (400Hz to 1 kHz) analog recorders. A photograph of the NASA F-106 is shown in Figure 2.

**Figure 2: NASA F-106 aircraft with lightning attachment locations marked.[10]**

Between 1984 and 1985 the FAA and U. S. Air Force, assisted by the Office of Naval Research and France's ONERA, instrumented a Convair 580 airplane to focus upon low-altitude (between 2000 and 20 000 ft) lightning strikes. The FAA/USAF flights emphasized measurement of static electric field, and 52 direct attachments were experienced. Four current shunts were installed (each wingtip, tail boom and vertical tail boom). Digital data was sampled at a 5 nanosecond interval in 10 microsecond windows and up to 9 channels. There were no cases in which the aircraft was within the main channel of a cloud-to-ground return stroke at low altitude. Low altitude lightning attachment was identified to result in highest peak current levels.[11]

Between 1978 and 1988, the French government conducted three in-flight lightning strike measurement programs, using a C.160 "Transall" airplane.

During these flight projects, lightning strikes were found to occur in both thunderstorm and non-thunderstorm conditions, and at all temperatures and altitudes. However, no in-flight lightning strike electric current data has been obtained below 2000 ft. altitude, even though civil transport airplanes are commonly struck during the most-critical takeoff, approach and landing phases of flight.
At the 1994 ICOLSE, in Mannheim Germany, the U. S. Federal Aviation Administration (FAA) presented the FAA Research Electromagnetic Database (FRED), containing waveforms and environmental data on lightning strikes, collected during the F-106 and CV-580 airborne programs. For the 1995 ICOLSE, in Williamsburg, VA, the FAA updated FRED to operate on Windows, and included more F-106 Data. In 1998, FRED Version 2.0 was released, and included French C.160 Transall data also. Unfortunately, FRED does not operate with modern versions of the Windows operating system, so the data is no longer accessible to most researchers. NASA LaRC has been able to operate FRED by emulating the Windows 98 operating system using Virtual Box[12] software, and is presently evaluating the data.

Today's standard reference for aircraft lightning environment data exists in SAE Aerospace Recommended Practice ARP5412A.[13] (The FAA recognizes EUROCAE ED-84[14] to be technically equivalent to SAE ARP5412A.[15]) The environment and test waveforms in SAE ARP5412A account for the best lightning data and analysis currently available. SAE ARP5412A is maintained and updated by the SAE AE-2 Lightning Committee, which meets three times per year. SAE ARP5412 defines an "idealized standard lightning environment", composed of standardized current and voltage test waveforms derived to represent the lightning environment for the purpose of assessing the effects of lightning on aircraft. Cloud-to-ground data from towers and rocket-triggered flashes are used to approximate low-altitude attachments to aircraft because of the absence of actual aircraft data. Lightning mapping arrays, like the National Lightning Detection Network (NLDN)[16] have been used to update the SAE environment with statistics on lightning polarity, multiplicity of strokes, and peak current.

The European ILDAS (In-flight Lightning Damage Assessment System) Program plans to instrument a civilian transport airplane with electric field and current sensors to provide data for peak current, di/dt, action integral, charge transfer and multiplicity of lightning strokes and bursts.[17] Such data will substantially expand the understanding of the aircraft lightning environment. A three-year Air France Industries (AFI) study showed that in-flight lightning damage data could provide cost savings in maintenance actions. ILDAS is supported by the European Commission, and builds upon two previous European projects, FULMEN and EM-HAZ.[18, 19] The European projects have advanced the state-of-the-art in lightning sensors and onboard instrumentation technologies. For passenger and cargo airplanes, it is impractical to perform structural modifications such as mounting of booms to facilitate current measurement using shunts or transformers, so the ILDAS architecture relies upon measurement of induced electric and magnetic field at several key locations. Computational electromagnetic methods and airframe modelling are then used to reconstruct return stroke current waveforms. The ILDAS instrumentation system takes advantage of significant improvements in digital sample rates, dynamic range, and storage capacity for onboard sensor data, compared to 1980's data acquisition systems. The ILDAS prototype has not yet been flown on an airplane, and the project was formally completed in July 2009, but work presently continues.

In the U. S., NASA, the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF), and Department of Defense (DOD) have continued to instrument aircraft with electric field mills for meteorological science data missions. These include the T-28 storm penetrating aircraft operated by the South Dakota School of Mines,[20,21] and a lightning instrumentation package (LIP) used on the NASA ER-2 high altitude aircraft[22] and a Global Hawk UAV[23], two NOAA WP-3D Orion Hurricane Hunter aircraft,[24] and a U. S. Air Force Reserves WC-130J Weatherbird weather reconnaissance aircraft.[25] The T-28, WP-3D and WC-130J aircraft fly into thunderclouds and are likely struck by lightning during missions, but the ER-2 and Global Hawk UAV generally avoid flying through clouds. None of these airplanes are instrumented for measuring electrical current from lightning attachment.

Since the 1980's, when the present standard lightning environment for aircraft was set, new details about current waveforms, compact intra-cloud discharges (CIDs, also called narrow bipolar pulses)[26], Gigantic Blue Jets[27], and even X-Ray and Gamma-Ray emissions[28, 29, 30] have been discovered. In 2009, the U. S. Defense Advanced Research Projects Agency (DARPA) issued a Broad Area Announcement for the Nimbus program, soliciting innovative research and development (R&D) proposals on the underlying science of lightning. Nimbus initially seeks to solve the mysteries of lightning initiation and propagation, with an ultimate goal of reducing the probability of lightning strikes in a given area in the presence of a thunderstorm.[31]
The NASA, NOAA, NSF and DOD meteorological research programs will surely improve the understanding of the aircraft lightning environment, and may also provide opportunities for leveraging new sensor technologies for aircraft lightning effects measurement and in-flight testing.

## 3. Approach.

The NASA AHSM-LEEM approach focuses on the development of novel new sensor technologies for measuring lightning current waveforms and attachment locations, improving the understanding of lightning radiated spectrum and aircraft transfer function, and developing an instrumentation system and operations strategy required to perform in-flight lightning measurements. This approach fits with the AHSM Technical Challenge of "Improving and expanding remote sensing and mitigation of hazardous atmospheric environments and phenomena."

**Sensors**
Perhaps the most promising new sensor technology involves using the Faraday polarization rotation effect in a fiber-optic cable, whereby the magnetic field induced by lightning interacts with the fiber material, rotating the plane of polarization of laser light in proportion to the intensity of the magnetic field. The strength of the magnetic field is determined by measuring the change in polarization of light. The Faraday sensor measures total current directly, without computational reconstruction of lightning current waveforms from distributed multi-sensor data. Compared to other approaches, complexity and cost for an in-flight system will be greatly reduced, and data will be much easier to evaluate in situations involving ringing, multiple attachments, tracking swept stroke attachments, etc. A diagram of the fiber optic Faraday sensor system is shown in Figure 3, and further details about the system are provided in another 2011 ICOLSE paper.[32]

The design goal for the fiber optic Faraday sensor is to measure DC to over 1 MHz with a dynamic range of over 50 dB. The sensor and associated instrumentation should consume low power, have low weight, and be easy to install.

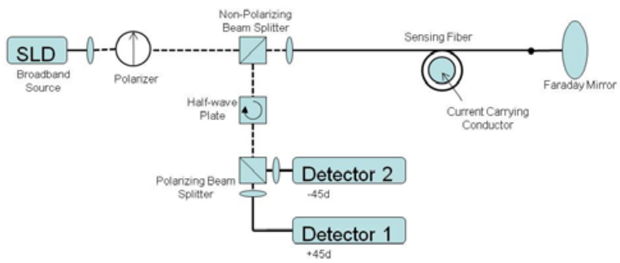


**Figure 3: Fiber Optic Faraday Lightning Current Sensor Schematic Diagram.**

In 2010, NASA funded a study of Surface-borne Time-Of-Reception Measurements (STORM) system, by Invocon, Inc., that demonstrated proof-of-concept for determining lightning attachment locations on a surface, by triangulation. The system successfully identified attachment locations on a carbon-fiber composite test panel, using a Marx generator. Signal propagation velocity on the composite material was determined to be 8.7 inches-per-nanosecond.[33]

Other approaches for measuring damage parameters on carbon-fiber-composites are also being considered, including heat, acoustic shock and diffusion current.

**Lightning Radiated Spectrum**

The NASA AHSM-LEEM research plan includes a task for compiling lightning electromagnetic emission data from available sources, and converting to common units if/as appropriate (i.e. E (f) at a common distance). In 1986, D. Le Vine published a review of measurements of the RF spectrum of radiation from lightning that accomplished much of this goal, but identified the difficulty in separating data for inter-cloud (IC) and cloud-to-ground (CG) flashes, and individual strokes and leader formation within a flash.[34] The Le Vine report also noted that flash events differed in such parameters as channel length, peak current, and tortuosity characteristics, which were not recorded for comparison. The report considered measurement data collected between 1939 and the 1970's, so the instrumentation capabilities were very limited in frequency response and dynamic range as compared to modern equipment.

Today, ground-based lightning detection and locating networks are well-established in many parts of the world, and most operate using radiated emissions in the VLF, LF, HF and VHF radio frequency ranges. The primary U. S. networks are identified in Table 1, along with the type of lightning flashes they are designed for (IC versus CG), and the detection technique used-magnetic direction finding (MDF), time-of-arrival (TOA), or interferometry (IF). A useful summary of the detection techniques and networks may be found in Royal Meteorological Institute of Belgium Report 2010/0526/56.[35] NLDN and ENTLN data are often combined with static electric field measurements to improve prediction capability.

**Table 1:** RF bands for lightning detection & mapping networks used in the U. S.

| Band | Hz | System/ Type/ Technique |
|---|---|---|
| VLF | 3k to 30k | WWLLN[36] /IC&CG /TOA |
| LF | 30k to 300k | NLDN[37] /CG /MDF&TOA |
| HF | 3M to 30M | ENTLN[38] /IC&CG /TOA |
| VHF | 30M to 300M | NLDN /CG /TOA&IF |

World Wide Lightning Location Network (WWLLN), National Lightning Detection Network (NLDN), Earth Networks Total Lightning Network (ENTLN- "Weatherbug")

The extremely low frequency (ELF, 3 to 300 Hz) range contains global lightning energy due to Schumann resonances, and has been studied for monitoring worldwide lightning activity.[39] Lightning ELF emissions propagate nearly loss-free in the "Earth-ionosphere waveguide" and resonate at particular frequencies (7.83, 14.3, 20.8, 27.3, 33.8 Hz), making flash-localization impractical.

Lightning Emissions in the UHF (300 MHz to 3 GHz), radio frequency ranges have been correlated to lightning leader formation.[40, 41] It may be useful to investigate how this phenomena relates to X-Ray and Gamma-Ray emissions from lightning (discussed below).

No references have been found by these authors exploring lightning radiated emissions in the SHF (3 to 30 GHz), a EHF (30 to 300 GHz) and THz (300 to 3000 GHz) ranges.

Optical emissions are used for earth-orbiting satellite detection and localization of lightning flashes. For example, the lightning imaging sensor (LIS) is one of five sensors on the NASA Tropical Rainfall Measuring Mission (TRMM) spacecraft. The LIS uses a 128x128 charge coupled device (CCD) array that is sampled at about 500 frames per second, and views a 600 km x 600 km area of earth for about 90 seconds as it passes overhead.[42] The next-generation LIS will be installed in the Geostationary Lightning Mapper for GOES-R, and will filter-out all optical emissions except the 777.4 nm wavelength oxygen multiplet, in order to reduce false alarms due to solar radiation.[43]

In 1996, the NASA Compton Gamma Ray Observatory discovered terrestrial gamma ray flashes (TGFs). Subsequently, TGFs were linked to lightning. X-ray and Gamma-ray emissions are now believed to be related to lightning leader formation. The DARPA Nimbus program is sponsoring rocket-triggered lightning research into these phenomena, and NASA supports a graduate student involved in the research.

In summary, lightning radiated emissions provide information across most parts of the electromagnetic spectrum. Such emissions are expected to be useful for triggering a prototype lightning strike measurement system to capture in-flight lightning attachment events, and hold promise for remotely sensing the storm environment, fuselage damage, and even detecting and diagnosing avionics system responses during/after attachment.

**Aircraft Transfer Function**

As part of the design, construction and certification process, aircraft manufacturers employ extensive analysis, measurement and computational modelling to ensure that lightning strikes do not create a hazard to safe flight. It's an integrated process, balancing structural integrity, addition of shielding materials, weight & balance, lightning strike zoning, cost, functional hazard assessment, maintainability, and avionics and wiring design. SAE ARP5415 provides guidance for the certification of electrical/electronic systems for the indirect effects of lightning.[44] The idealized lightning environment defined in SAE ARP 5412 is used as a basis for determining SAE ARP5415 transfer functions, which eventually lead to a selection of transient control levels (TCLs), equipment transient design levels (ETDLs) and waveform sets that are used to test airborne equipment (per RTCA DO-160/EUROCAE ED-14 Section 22 and 23 procedures). These data are obtained at great cost, and are regarded as valuable proprietary information. Data are provided to aircraft certification authorities (i. e. FAA, JAA) to demonstrate compliance with aviation regulations and airworthiness requirements.

The NASA AHSM-LEEM research plan includes a task for compiling existing transfer function data from the FAA, industry and universities, and summarizing it into a publicly accessible format. The summary is planned to include data from aluminium as well as composite-skinned aircraft. Such data are believed to be usable for the placement of on-board sensors to estimate the external lightning environment, and possibly detecting and diagnosing fuselage damage and avionics system effects. This NASA effort is interested in broad-spectrum transfer function inside an aircraft, resulting from the external lightning environment, even when attachment does not occur (i. e. leader formation and nearby flashes). It may be possible to extrapolate transfer function for high intensity radiated fields (HIRF) for this purpose, but likely that new measurements will be needed if this approach is found to have merit.

**Instrumentation System**

Figure 1 shows the concept for an in-flight lightning strike measurement system. The red loops around the body, wings, rudder and elevators represent embedded fiber-optic electrical current sensors. The various distributed nodes (red dots) could represent attachment-localization sensors located on or below the fuselage skin.

The NASA AHSM-LEEM research plan includes a task for capturing a lightning current waveform at a minimum 10 Msample/second rate (100 ns interval), with over 50 dB dynamic Range, and sample time extending to over a 1 second lightning flash duration. The ability to store multiple flash data is also desirable. Such instrumentation goals would have been considered science fiction during the time of the NASA F-106 program, but are now achievable. The NASA lightning instrumentation system for Kennedy Space Center launch complex 39B provides a working example.[45] The KSC system utilizes state-of-the-art HBM GEN16t mainframe unit and isolated HBM 7600 model fiber-optic digitizer. HBM (Hottinger Baldwin Messtechnik GmbH) manufactures a smaller, portable version that may provide a suitable base for an in-flight system. (See Figure 4.)

The prototype instrumentation system will be demonstrated on a flight vehicle. Storage capacity, number of channels, and sample rate will be determined as the project progresses.

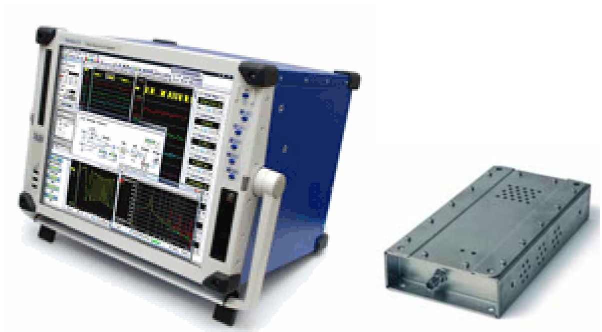

**Figure 4: Example of a portable data acquisition system and fiber-optic-connected digitizer unit** that can obtain 100Ms/s, exceeds 80dB dynamic range (14 bit resolution) and supports up to 20 high-speed channels. Up to 2GB RAM per channel is possible (with 5 channels). (Photos courtesy of HBM, Inc. http://www.hbm.com/.)

**Operations Strategy**
Research flights into thunderstorms are dangerous and expensive, especially if intending to collect cloud-to-ground lightning attachment data. A more economical approach may be to install equipment on board aircraft that have reasonable likelihood of being struck during their normal operations, like hurricane hunter and storm-penetrating aircraft, and possibly even U. S. Coast Guard airplanes. As a secondary system, the lightning strike measurement equipment will need to be simple to install, lightweight, rugged, relatively autonomous, and low maintenance. The system will be useful to Weather Science and Flight Operations communities to identify the impact of lightning strikes on their data and operations.

A milestone schedule is shown in Figure 5.

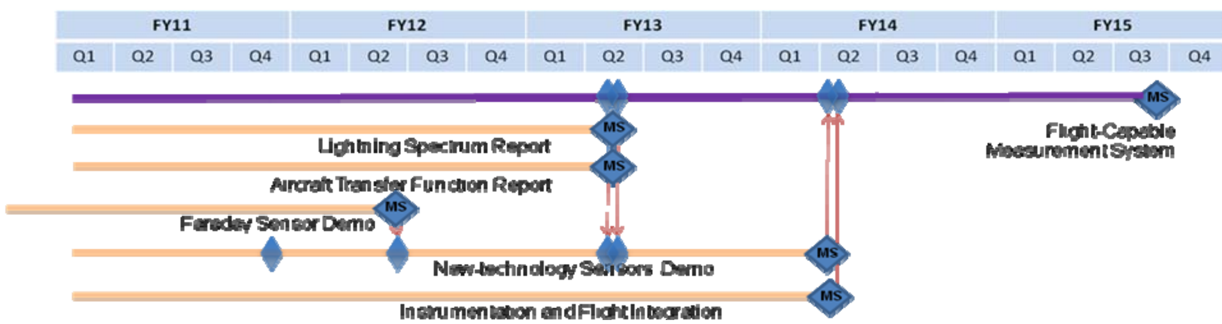


**Figure 5: Milestone Schedule.**

## 4. Progress and Perspective

At present, this NASA effort is new and has limited resources, but is part of a growing portfolio of lightning research in NASA's Aviation Safety Program. The NASA LEEM effort includes high-level (up to 200 kA) laboratory testing, which will provide opportunities to test and validate new sensor technologies.

Extensive opportunities for collaboration have been identified with the NASA meteorological science and lightning protection communities. The fiber-optic Faraday current sensor has been demonstrated in the laboratory and is presently being evaluated using rocket-triggered lightning under a contract between NASA KSC and University of Florida's International Center for Lightning Research and Testing (ICLRT). The DARPA NIMBUS program is likely to greatly extend our understanding of lightning radiated emissions spectrum.

Improved understanding of the aircraft lightning environment and aircraft shielding characteristics, combined with low-cost wireless instrumentation, with energy scavenging technology, should present a workable business case for building in-flight lightning strike damage assessment into all transport category airplanes.

## 5. Conclusions

The prototype lightning strike measurement system will provide new data about the natural lightning environment and how it interacts with aircraft, especially new composite airframes. Data will improve the effectiveness of analysis and measurement needed for lightning certification of aircraft, and will lead to new lightning damage detection and diagnosis tools.

The instrumentation system will leverage recent advances in high-speed, high dynamic range, deep memory data acquisition equipment, and fiber-optic interconnect. As a secondary system, the measurement system will leverage operational safety risks already considered for storm hazards.

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