Lightning Protection of Aircraft: Simulation & Test

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Lightning Threats

- Lightning is one of nature's most amazing phenomena, but it presents tremendous risks to vehicles and structures
- When an object is struck by lightning, it is subject to tremendous physical forces (Lorentz, thermal, acoustic) that can cause catastrophic damage
- Additionally, the flow of lightning current produces strong magnetic fields that couple to conductors (wire bundles) and cause upsets to electrical systems that it encounters
- These types of damage present considerable loss-of-life risks (in case of aircraft), and are extremely expensive in the case of damage to wind turbines and buildings

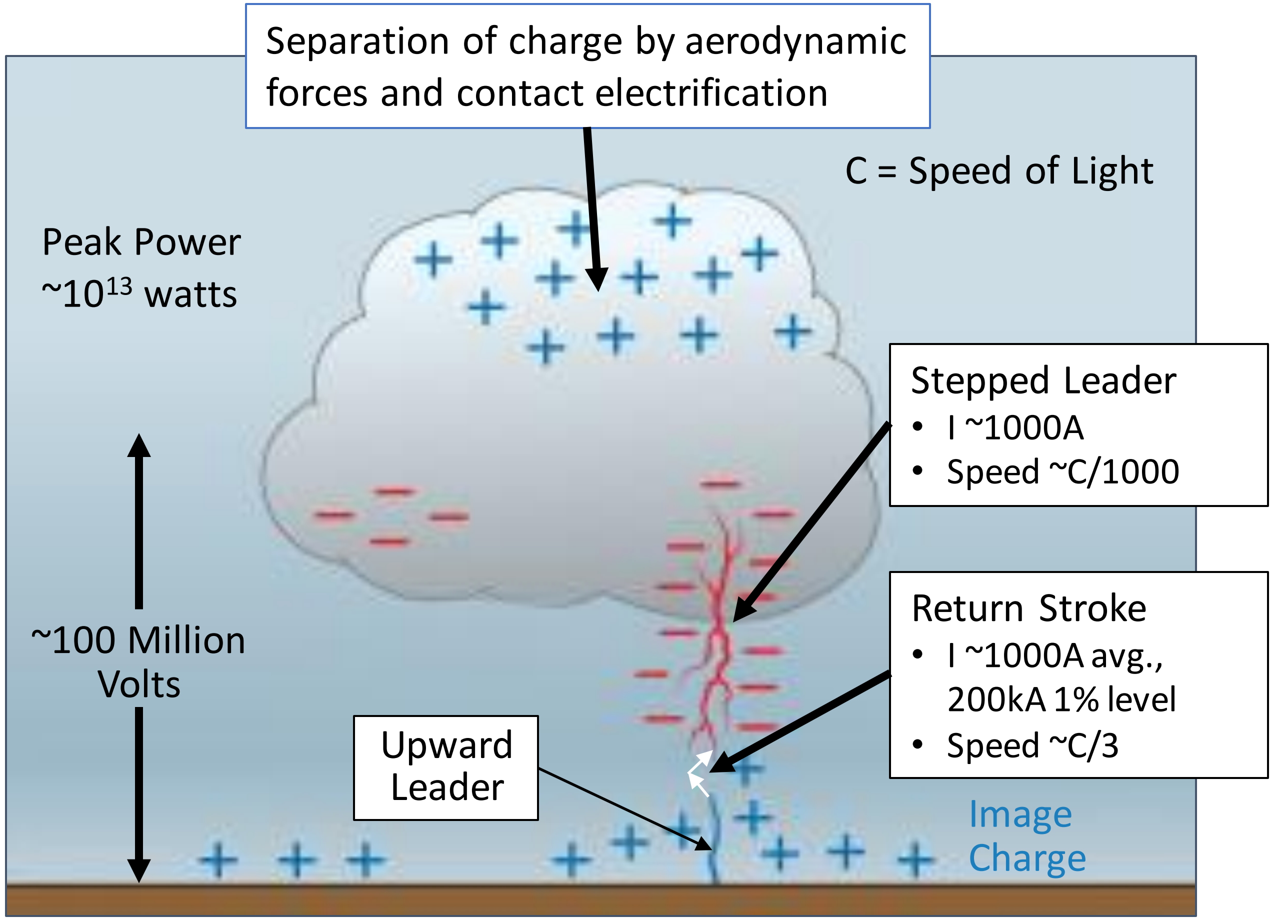
"Apollo 12, Kind Of A Rough Start" by James Hervat.

MENU

Lightning Cloud to Ground Scenario

Description

- Stepped leader starts at cloud and travels toward the earth
- At a distance of ~50 m from earth, upward going leader begins
- Upward going leader connects to stepped leader
- Return stroke with large current travels upward to cloud
- Process may repeat



Lightning Video

Lightning Video

One of the Few Photos of the Upward Going Leader

The Cloud is a Charge Reservoir

Not All Lightning Goes to Earth

Lightning Over 25nm Away from Convective Activity

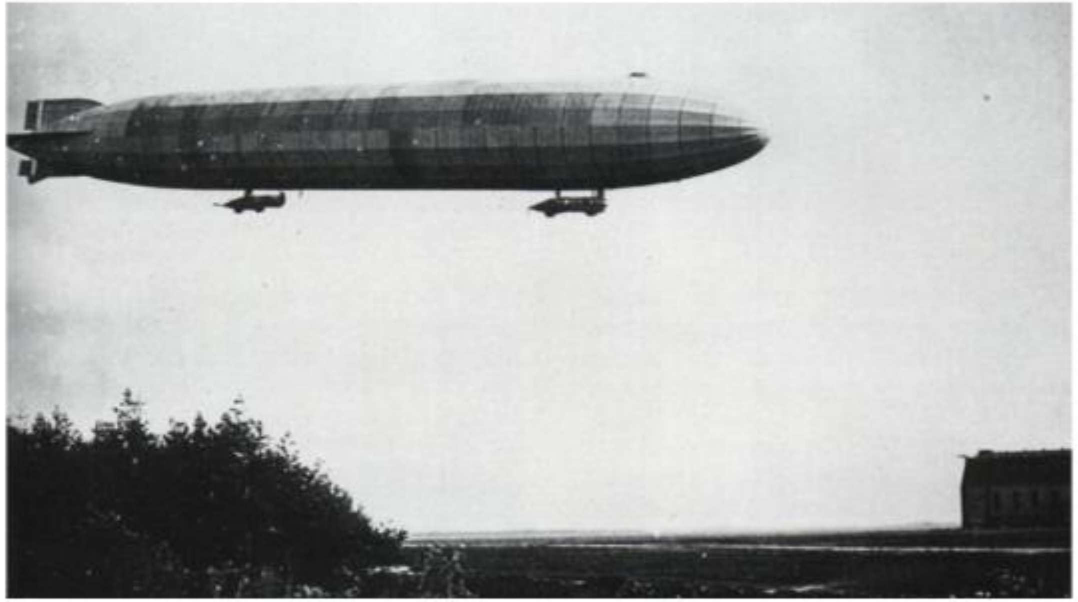
- Lightning flashes may extend farther outward from the storm center than does turbulence
- There are several reports of lightning strikes "in the clear" 25 or more miles from the nearest evident storm
- Lightning flashes can propagate 25 nm as is evident from ground photographs of very long, horizontal flashes
- Commercial aviation reports of "in the clear" lightning strike is as high as 1 in 100,000 flight hours

Lightning Statistics

- **1% Peak Current**: 200,000 amperes (100 watt light bulb uses about 1/2 ampere)
- **Largest measured**: ~450,000 amperes (Sea of Japan)
- **Restrikes in one flash**: Up to about 24
- **Most (90%) airplanes:** Create their own lightning strikes - triggered (the lightning would not exist without the presence of the aircraft)

The First Lightning Crashes of Aircraft

3rd September 1915



German Zeppelin LZ40 (L10)
Destroyed by lightning off Neuwerk Island, Germany.

3rd September 1929

Ford AT-5 Tri-Motor, *City of San Francisco*
Crash of first heavier-than-air aircraft destroyed by a lightning strike. All eight occupants died when the airplane struck Mt. Taylor in New Mexico.

- Early Lightning Avoidance Strategies**:

"Climb or descend through the freezing level as quickly as possible"

"Avoid all precipitation"

"Slow down to minimum safe speed, change altitude to avoid temperature of -7° C to 2° C"

"Lead a clean life"

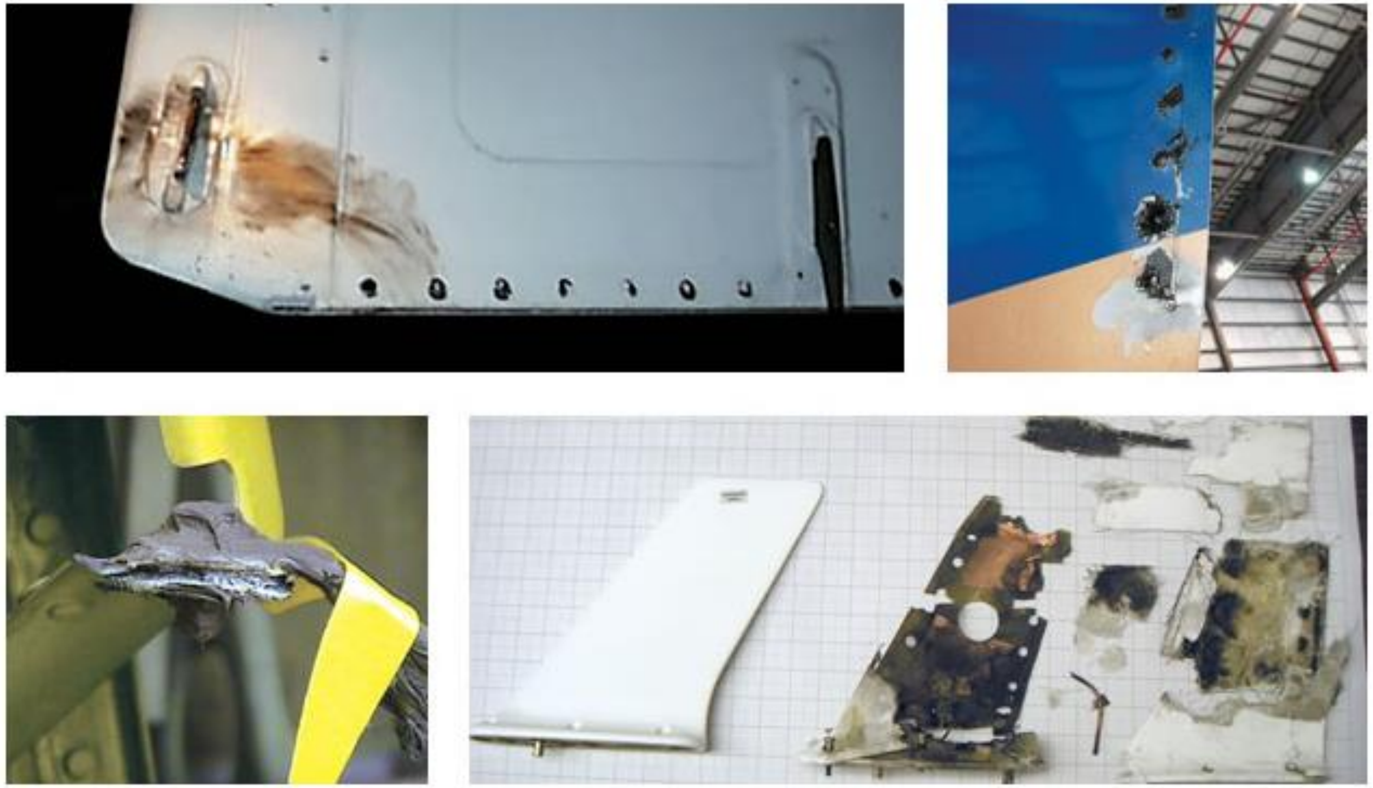
*******Lightning Protection of Aircraft*, F. A. Fisher, J. A. Plumer, R. A. Perala, 1990

Lightning Effects on Aircraft

- **Direct Effects** – Physical damage effects
  - Verified by vehicle or representative coupon tests
  1. Melting or burning of components
     - Resistive temperature rise
  2. Destruction of components
     - Magnetic force effects
     - Acoustic shock waves
  3. Arcing and sparking at bonds, hinges and joints
  4. Ignition of vapors within fuel tanks
- **Indirect Effects** – Electric transients induced by lightning in aircraft electric circuits
  - Verified with bench tests on equipment with aircraft cable harnesses
  1. Damage circuits
  2. Upset equipment functionality

Direct Effects Damage

Clockwise from upper left: Lightning damage to a horizontal stabilizer, rudder, antenna, and bond jumper.



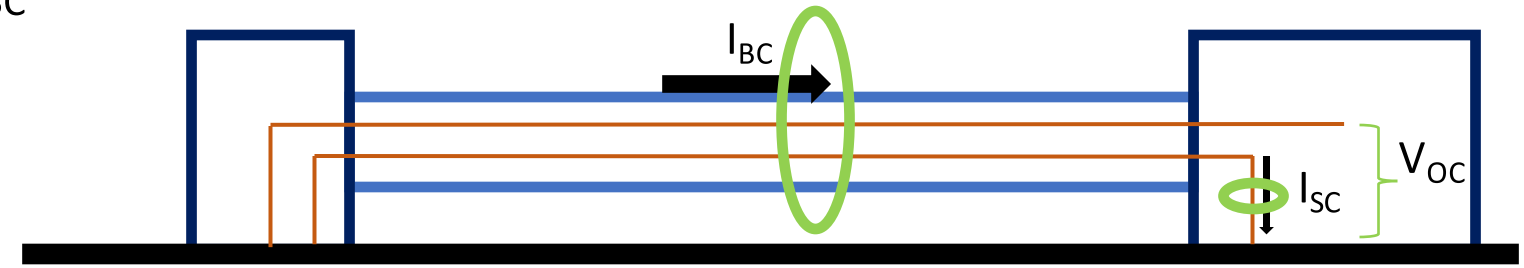
Note: bond straps can become crushed due to high magnetic forces

Composite panel delamination.

Damage to radome

Indirect Effects of Lightning

- As lightning currents distribute through aircraft conductors, transient pulses will be induced on electronics cables and systems. These induced transients may damage or upset electronic components circuits. The effects of induced lightning transients on electronic cable is referred to as indirect effects of lightning.
- Lightning transients typically defined in 3 quantities
  - Bundle current, I_B
  - Open circuit pin voltage, V_{OC}
  - Short circuit pin current, I_{SC}



NASA F-106 Lightning Research Program *(1982-1989)*

- Objective: Fly instrumented aircraft into thunderstorms to intercept lightning and collect data to understand it
- Experienced more than 700 strikes
- Most were aircraft triggered lightning

NASA F-106 Lightning Research Program
(1982-1989)

Pitts, Fisher, Mazur and Perala—Aircraft jolts from lightning bolts

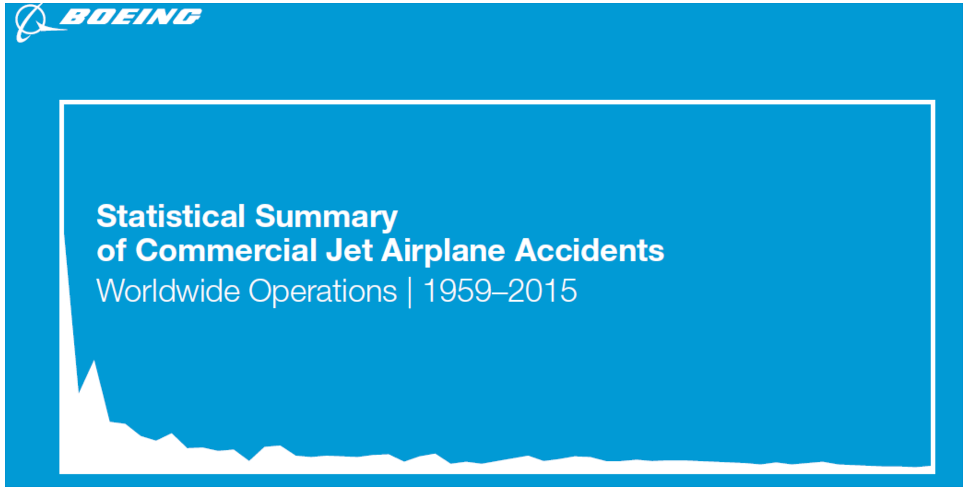
What Causes an Aircraft to Trigger Lightning?

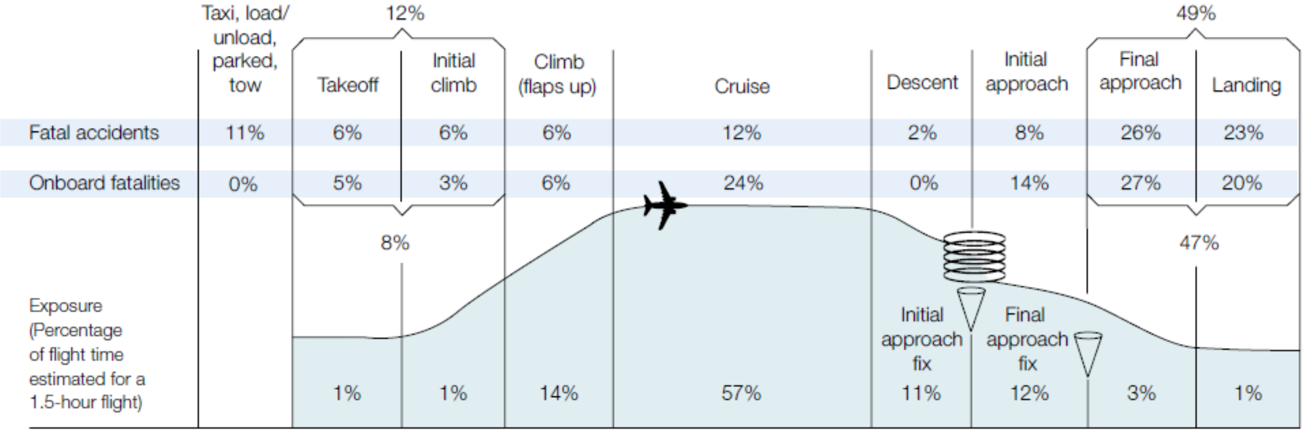
- The local electric field at an aircraft extremity becomes large enough to cause air breakdown

- Aircraft local E field, directly related to local charge density Q, has two components:
  - Aircraft net charge, caused by normal P-Static (precipitation static), including engine charging

Frequency of Lightning Strikes

- Commercial aircraft experience lightning with 1 strike per 3340 hours
- 82 % percent of flight time is outside of the lightning environment
- Vast majority jet aircraft lightning incidents happen during takeoff, initial climb, approach or landing
- Frequency of strike per flight hour must account for the exclusion of cruise
- Changes lightning frequency to 1 strike per 600 flight hours in the takeoff, climb, approach or landing altitudes

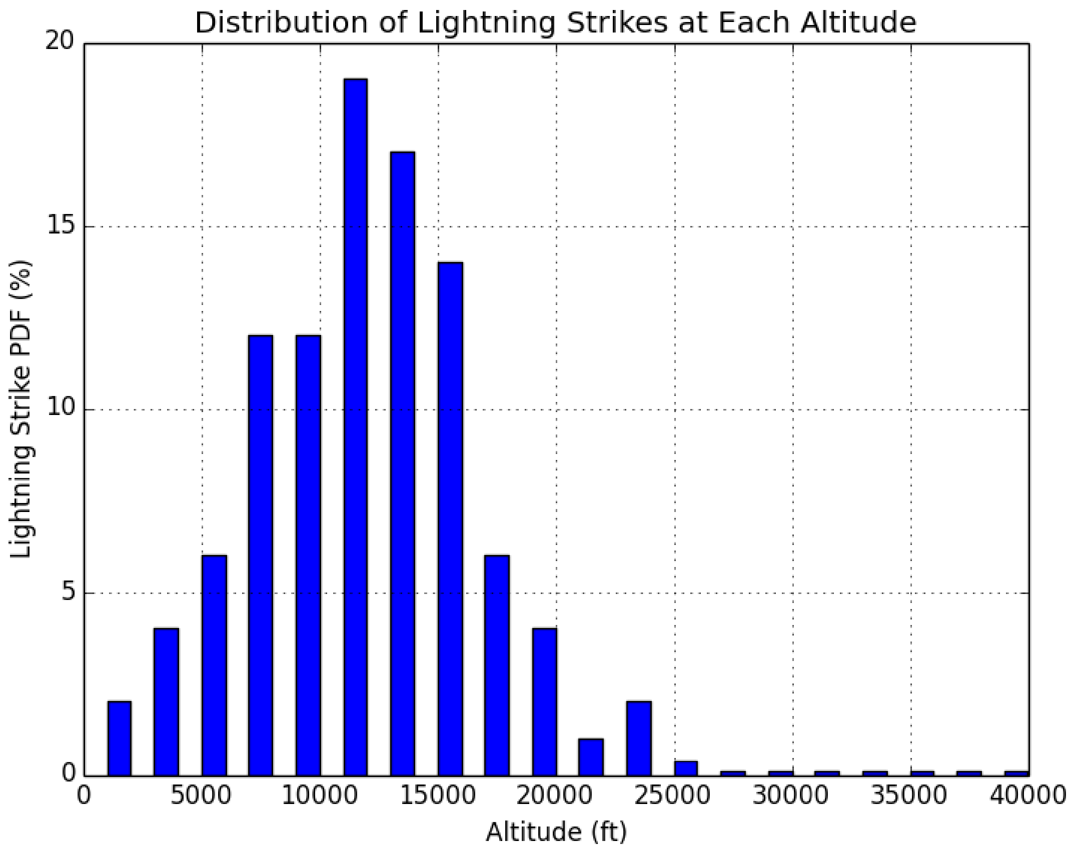




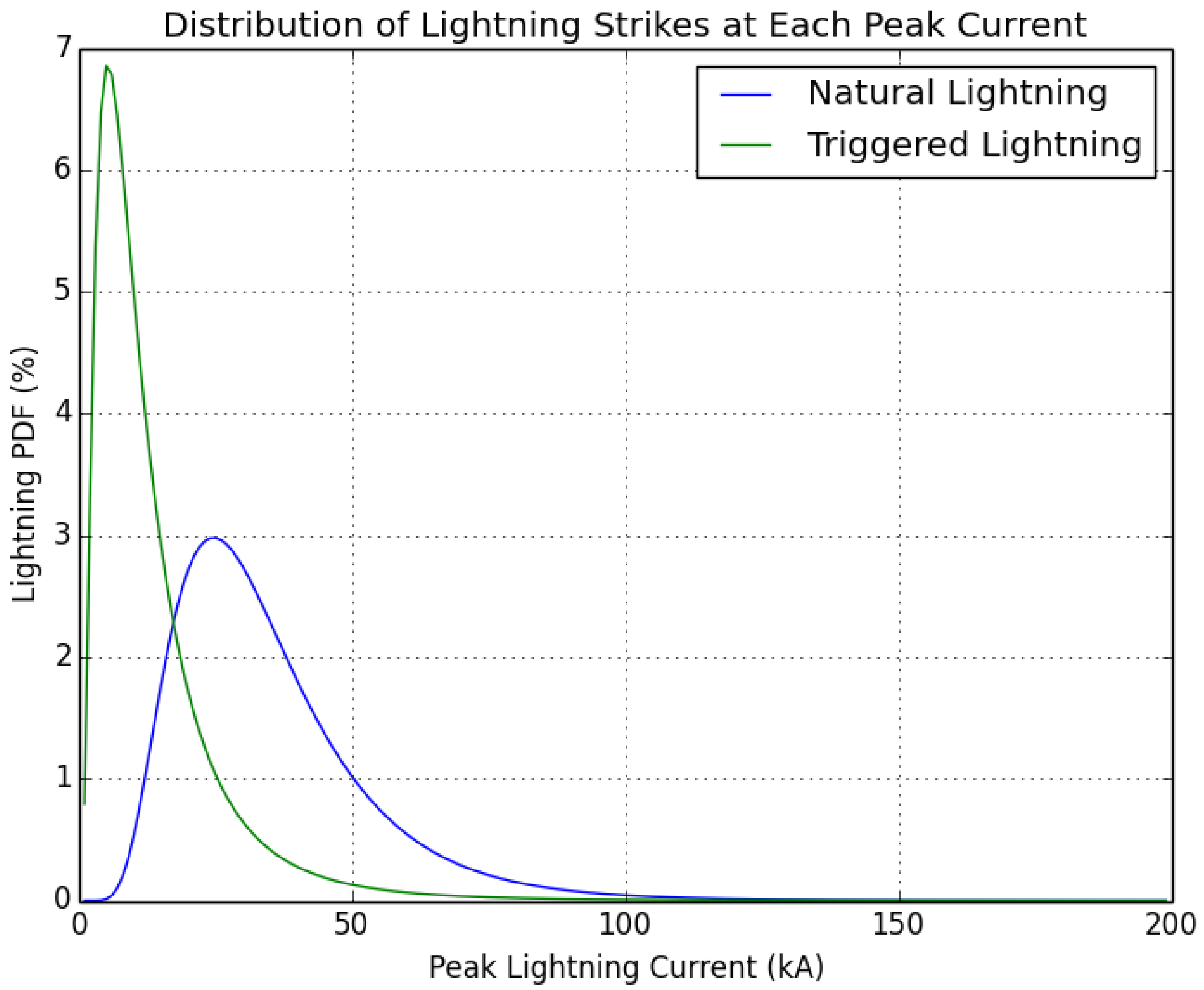
Note: Percentages may not sum to 100% due to numerical rounding.

Distribution of Strikes Based On Altitude

- Not all lightning strikes occur at the same altitude
- **N. O. Rasch, M. S. Glynn and J. A. Plumer,** “Lightning Interaction with Commercial Air Carrier Type Aircraft,” *International Aerospace and Ground Conference on Lightning and Static Electricity,* Orlando, Florida, 26-28 June, 1984, paper 21.



Distribution of Lightning Strikes at Each Peak Current



Model Input
MI#3

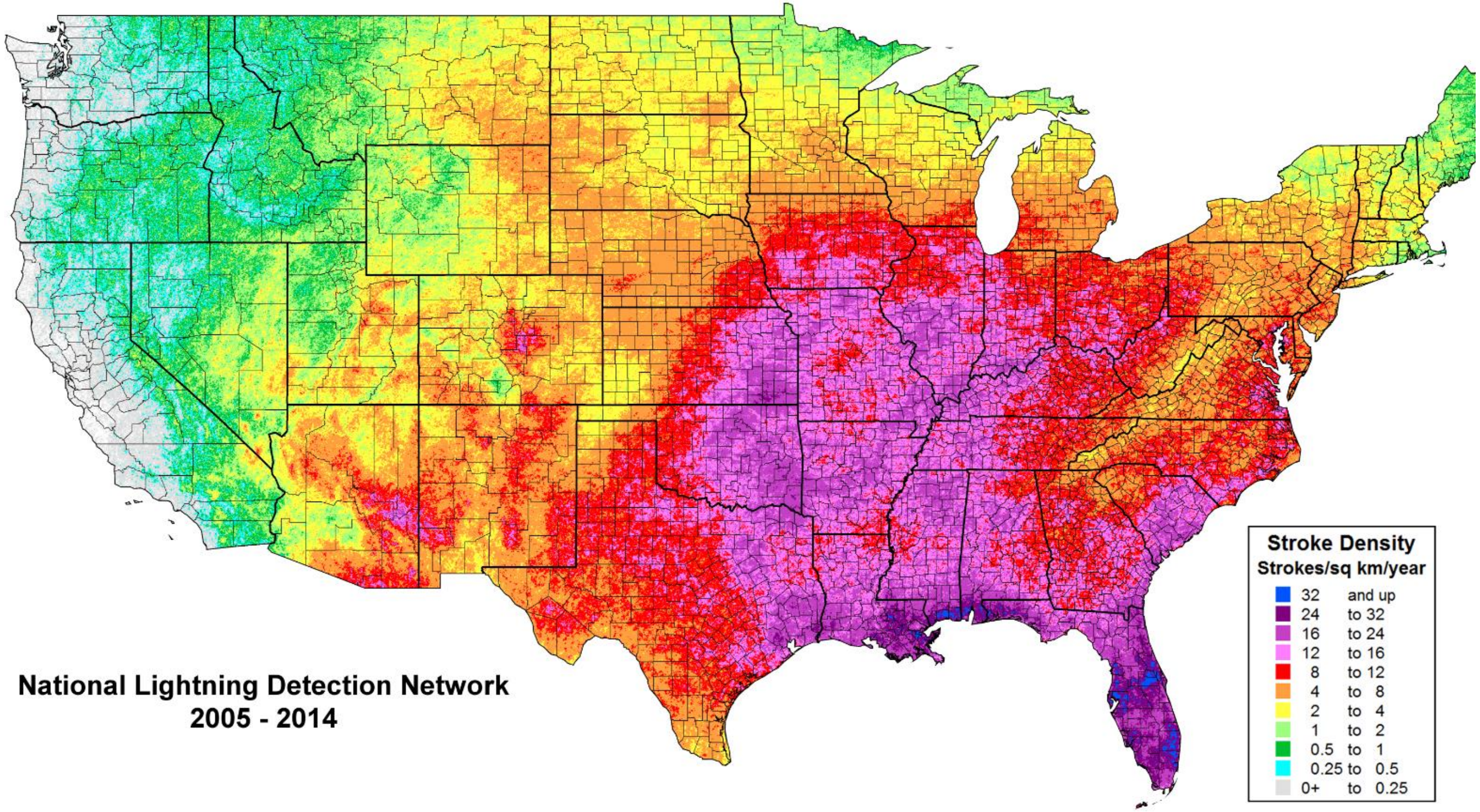
F. L. Pitts, L. D. Lee, R. A. Perala and T. H. Rudolph, "New Results for the Quantification of Lightning/Aircraft Electrodynamics," *J. of Electromagnetics,* Vol. 7, 1987, pp. 451-485.

Berger, K., R. B. Anderson, and H. Kröninger, "Parameters of Lightning Flashes," Electra, no. 41, pp. 23-37, July 1975.

J. Schoene, M. A. Uman, V. A. Rakov, K. J. Rambo, J. Jerauld, C. T. Mata, A. G. Mata, D. M. Jordan, G. H. Schnetzer, "Characterization of return-stroke currents in rocket-triggered lightning," *Journal of Geophysical Research, Atmospheres (1984-2012),* Volume 114, Issue D3, 16 February 2009.

Lightning Flash Density Maps

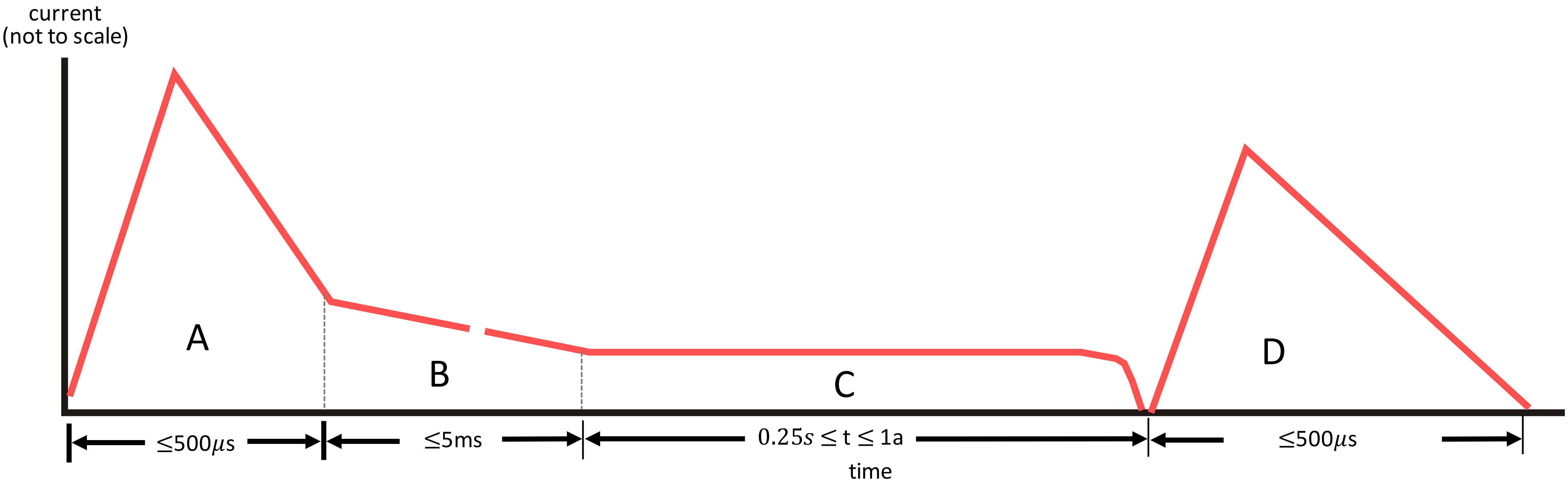
- Lightning is approximately 5.7 times more likely in central Florida vs. CONUS average



Certification Process

1. Establishing lightning zones
2. Define the lightning environment for each zone
3. Perform a Lightning Hazard Assessment
4. Incorporate protection with acceptance criteria
5. Verify compliance
6. Implement correct measures as needed

Simplified Lightning External Current Waveforms for Direct Effects



COMPONENT A (First Return Stroke)

Peak Amplitude	:	200kA (±10%)
Action Integral	:	2 x $10^6 A^2 s$ (±20%)(in 500μs)
Time Duration	:	≤ 500ms

COMPONENT B (Intermediate Current)

Max. Charge Tran.	:	10 Coulombs (±10)
Average Amplitude	:	2kA (±20%)
Time Duration	:	≤ 5ms

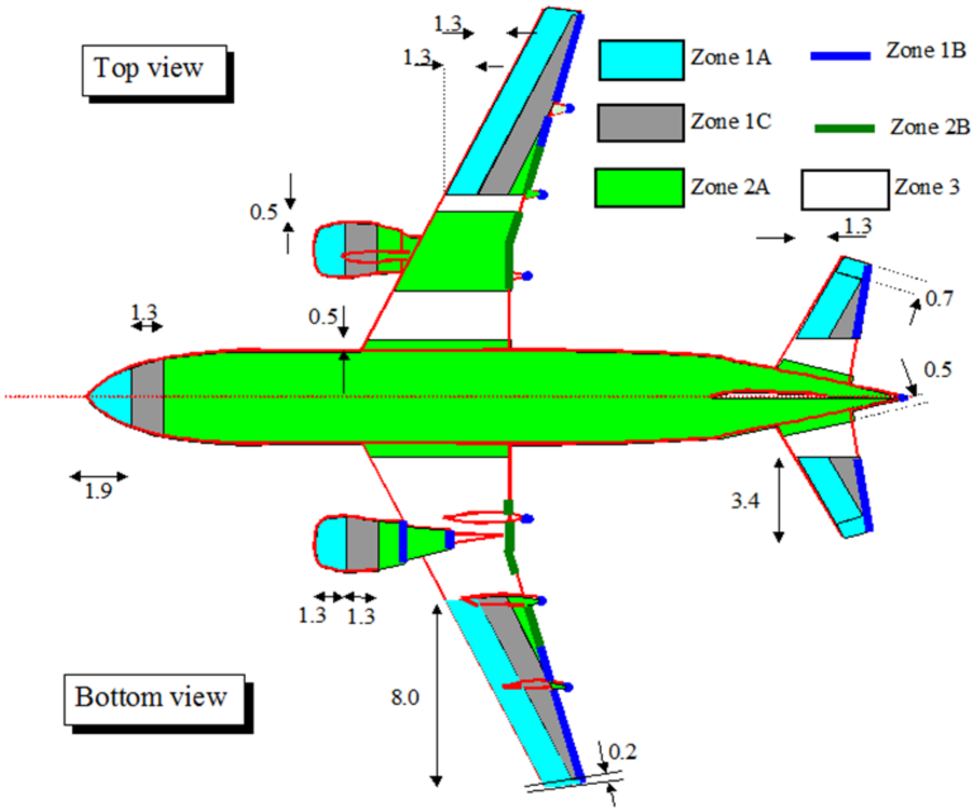
COMPONENT C (Continuing Current)

Amplitude	:	200 – 800A
Charge Transfer	:	200 Coulombs (±20%)
Time Duration	:	0.25 to 1 s

COMPONENT D (Subsequent Return Stroke)

Peak Amplitude	:	100kA (±10%)
Action Integral	:	0.25 x $10^6 A^2 s$ (±20%)(in 500μs)
Time Duration	:	≤ 500ms

Lightning Zoning



- **Zone 1A**: first return stroke initial lightning attachment
  - The lightning might not remain there
- **Zone 1B**: first return stroke initial attachment with long hang on
  - The lightning will likely remain there
- **Zone 1C**: transition zone for the first return stroke, where the first return stroke of reduced amplitude is likely
- **Zone 2A**: the swept stroke zone, to where a subsequent return stroke is likely to attach, with a low expectation of hang on
- **Zone 3**: current conduction zone, where any attachment of the lightning channel is unlikely

Lightning Zoning

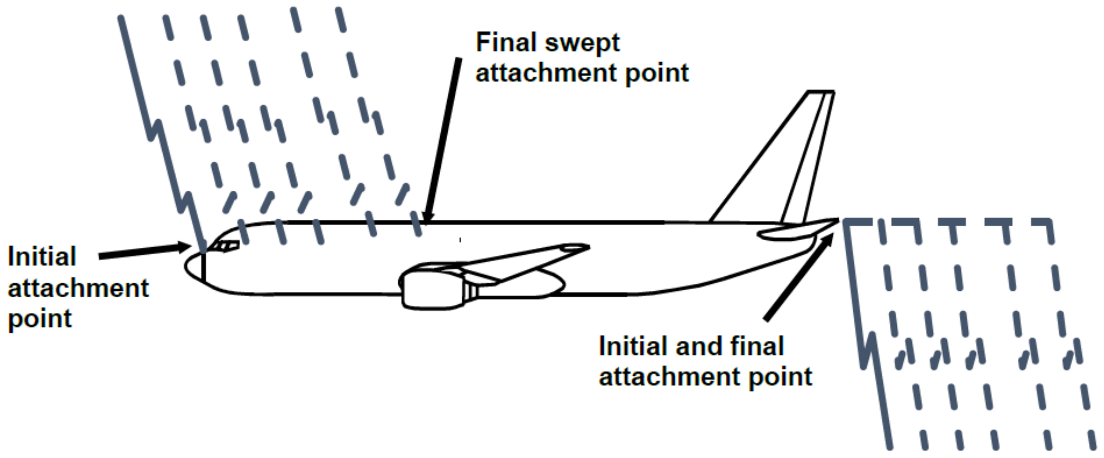
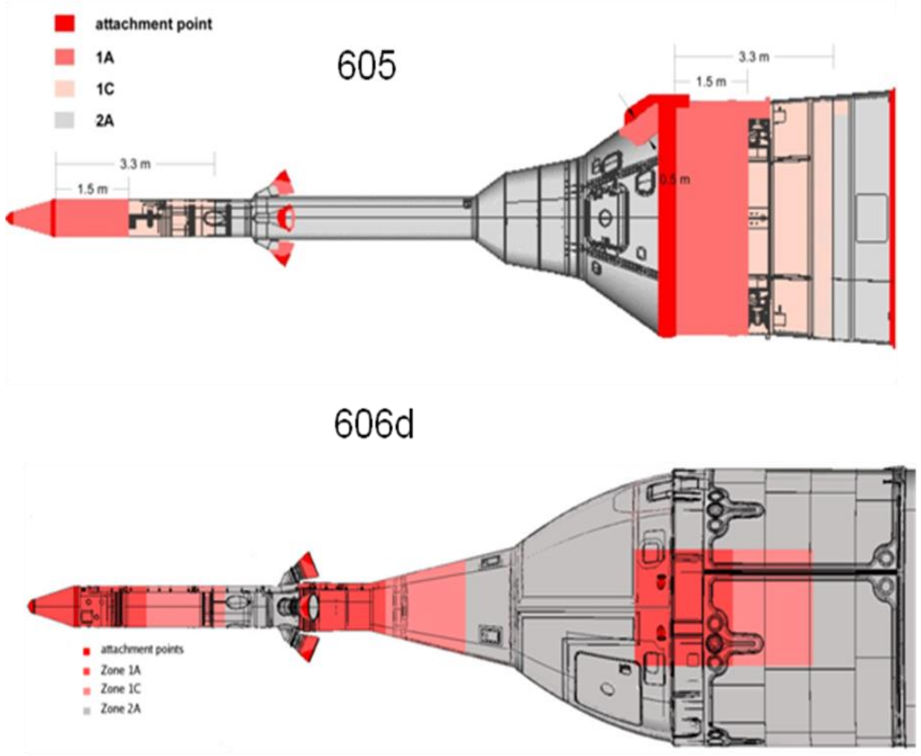


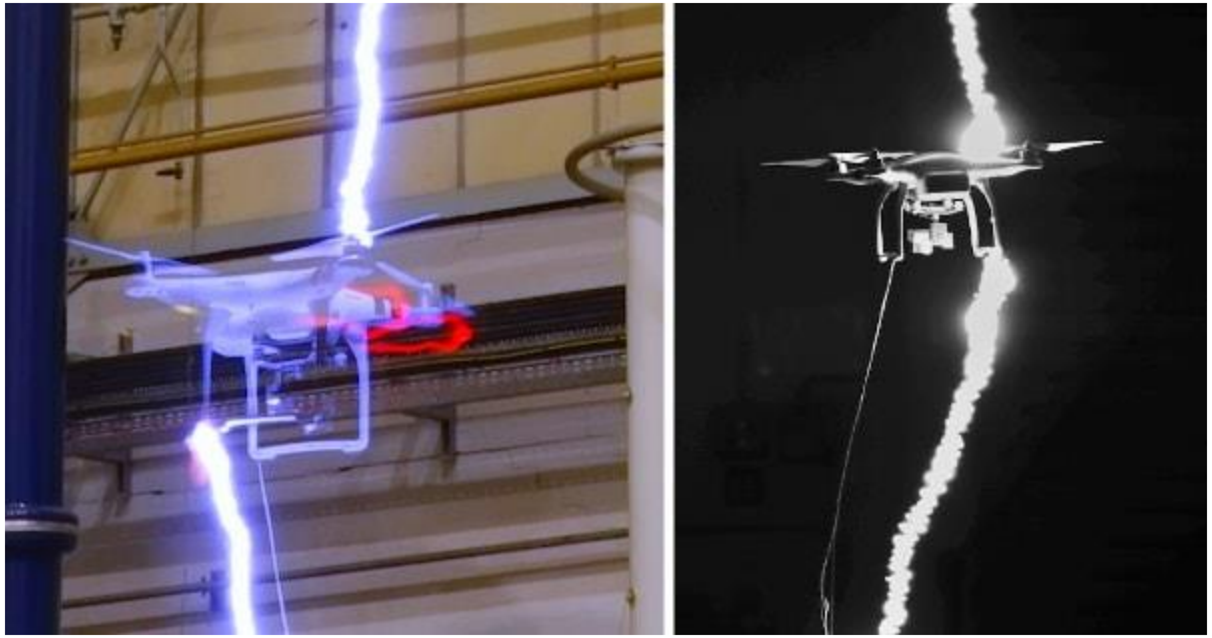
Figure 3 - Typical path of swept-channel attachment points



Lightning Zoning Analysis for Different Orion Space Capsule Launch Configurations

Why Not Just Test?

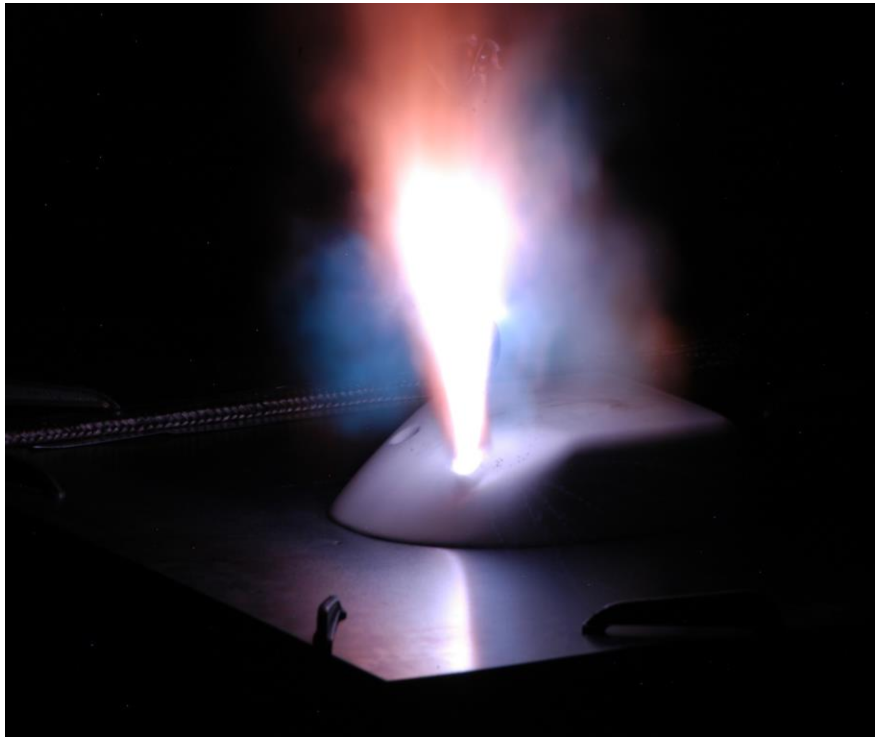
- Relying solely on testing brings in substantial risk
- Before you can test something, you have to build it
  - Requires manufacturing, procurement, etc.
  - If the lightning protection design fails, you may end up with a total re-design ($$$)



(Credit Sia Magazine)

Testing

- Testing can be destructive
  - This makes determining the cause of the failure troublesome, and you have to build “more” to evaluate different areas on an object, typically

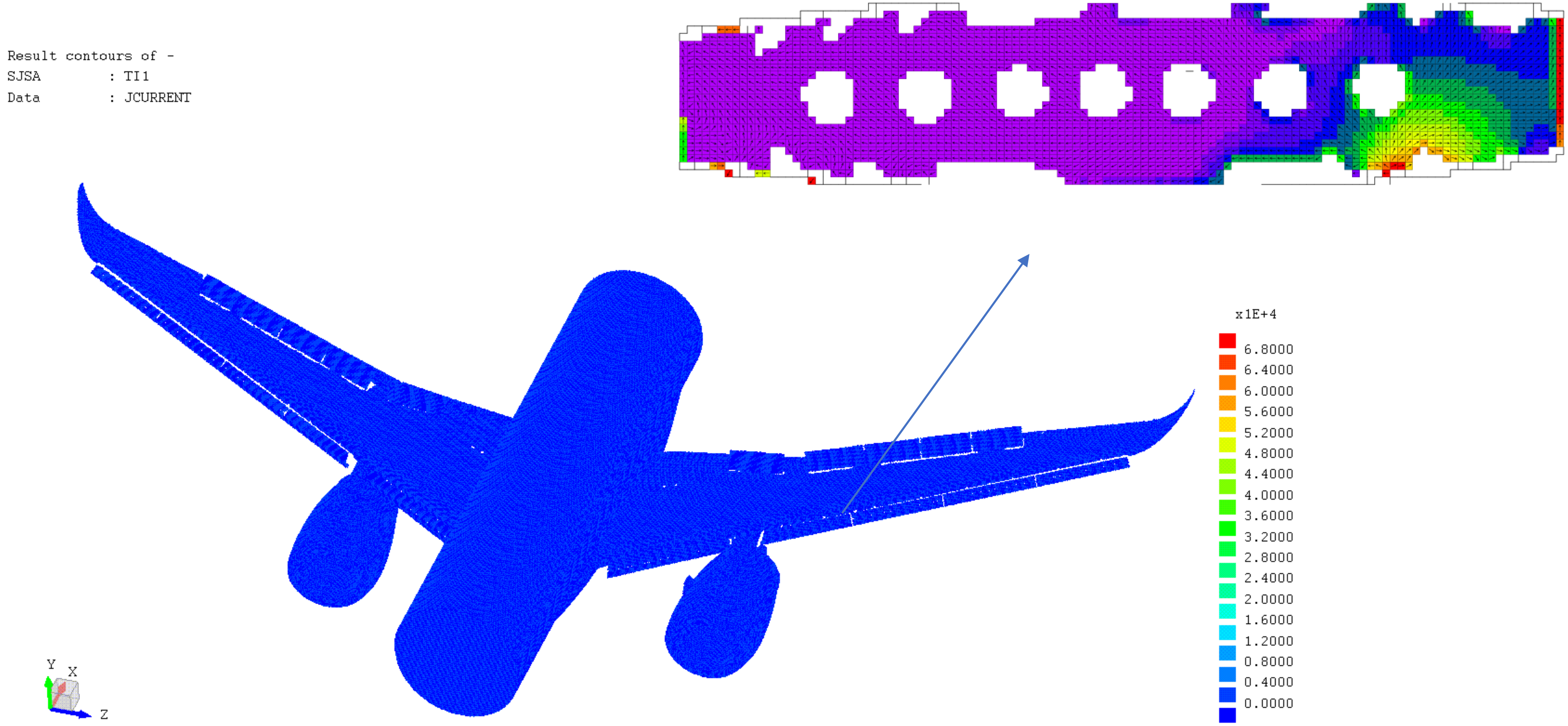


Testing vs. Simulation

- Testing gives you a snapshot of a particular scenario
  - Expensive to re-run multiple iterations
- 3D simulations allow us to investigate many different scenarios
  - Different coupling mechanisms (direct vs. indirect)
  - Different physical configurations (fastener spacing, bonding values, materials)
  - Different electrical parameters (transfer impedance, shield terminations)
- Model re-use allows the user to answer multiple questions once a single high-fidelity model is built in the software
  - Never destroyed by running a simulation

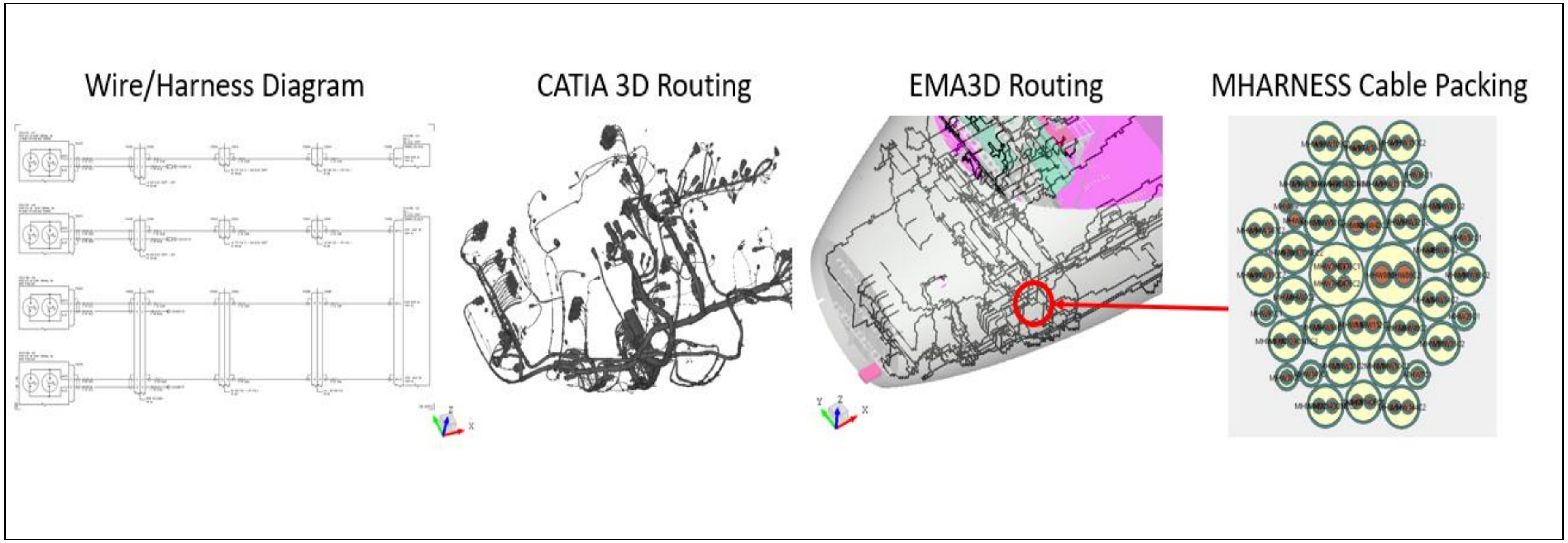
Detailed Current Mapping

- Detailed current density mapping



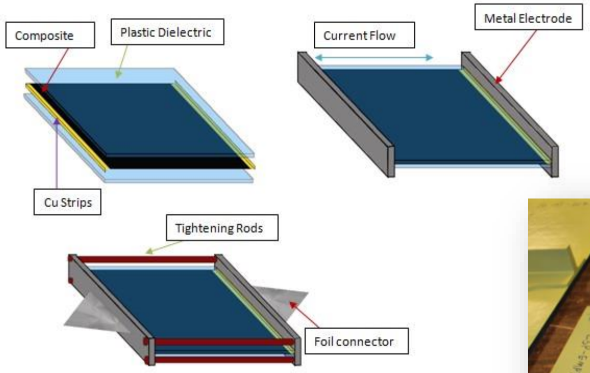
Intentional Lightning Current Paths to Extremities

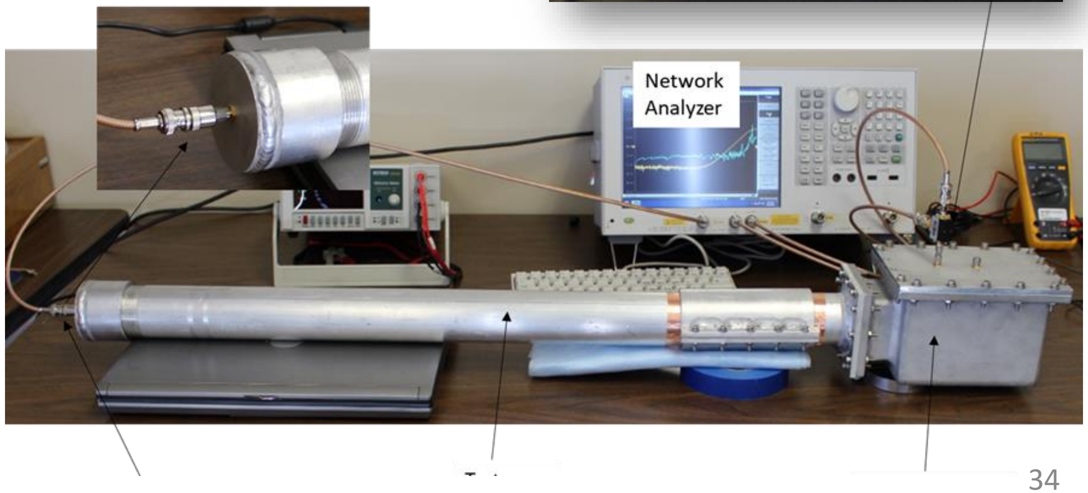
- Leveraging simulation and modeling allows for the "whole picture" to be analyzed
- Many fewer logistics than testing (scheduling, resources/people testing, etc.)
  - Significantly more cost effective to leverage simulation, and in many cases, faster
  - You can analyze the "big" and "small" – Sub models



Critical EM Parameter Measurement

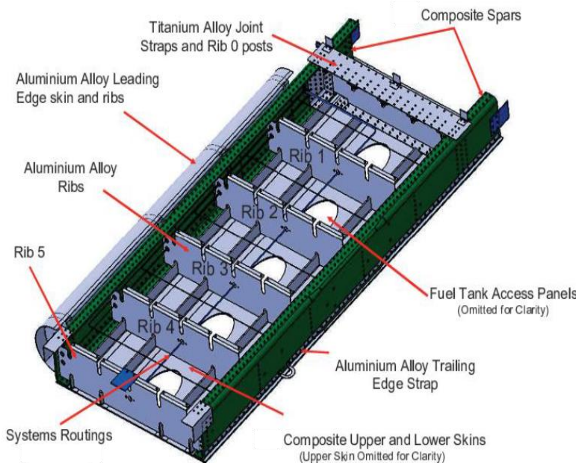
- Accurate simulation predictions can only be expected if the aircraft properties are accurately know
- EMA has measured thousands of aerospace seams and joints to improve simulation accuracy for over 40 years, and maintains several material parameter databases
- We have developed a materials property lab to quickly and inexpensively measure the properties of inexpensive aerospace coupons
- Measurements include:
    - Cable shield transfer impedance
    - Joint/seam transfer impedance or contact resistance
    - Material surface conductivity (anisotropic tensor)
    - Impedance non-linearity characterization

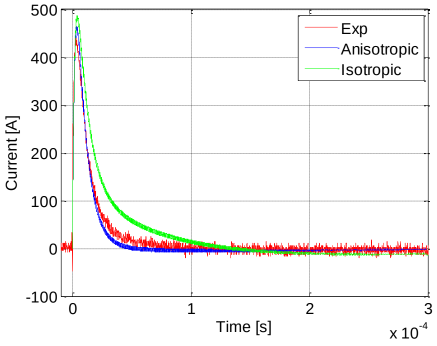


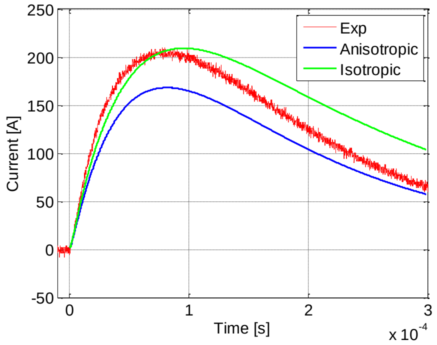


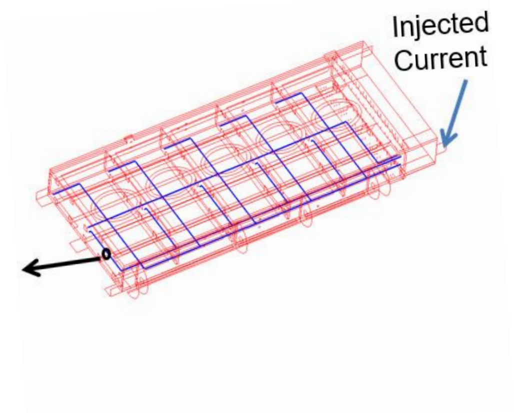
CSeries/A220 Certification by Simulation

- Comparisons were made between experimental and simulation results to validate the numerical techniques and parameters

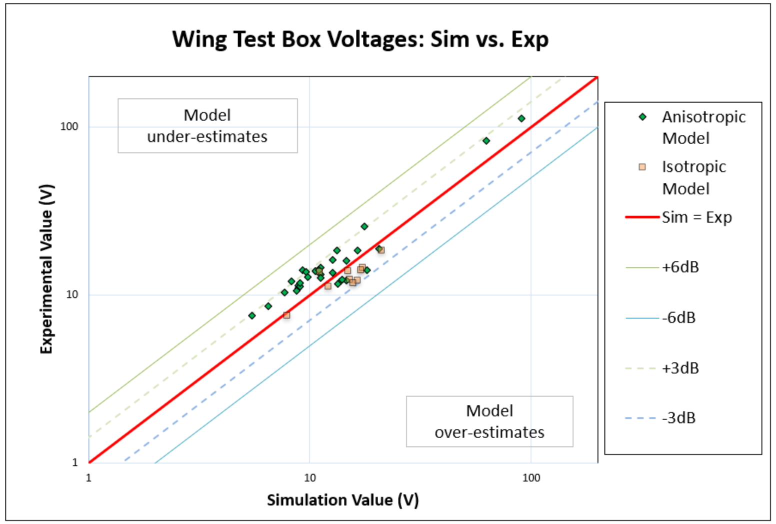








Wire Bundle Cross Section at Rib 0 in MHARNESS



E2-175

Best Paper of the Conference

2019 International Conference on Lightning and Static Electricity (Wichita, Kansas)

Validation of Numerical Simulation Approach for Lightning Transient Analysis of a Transport Category Aircraft

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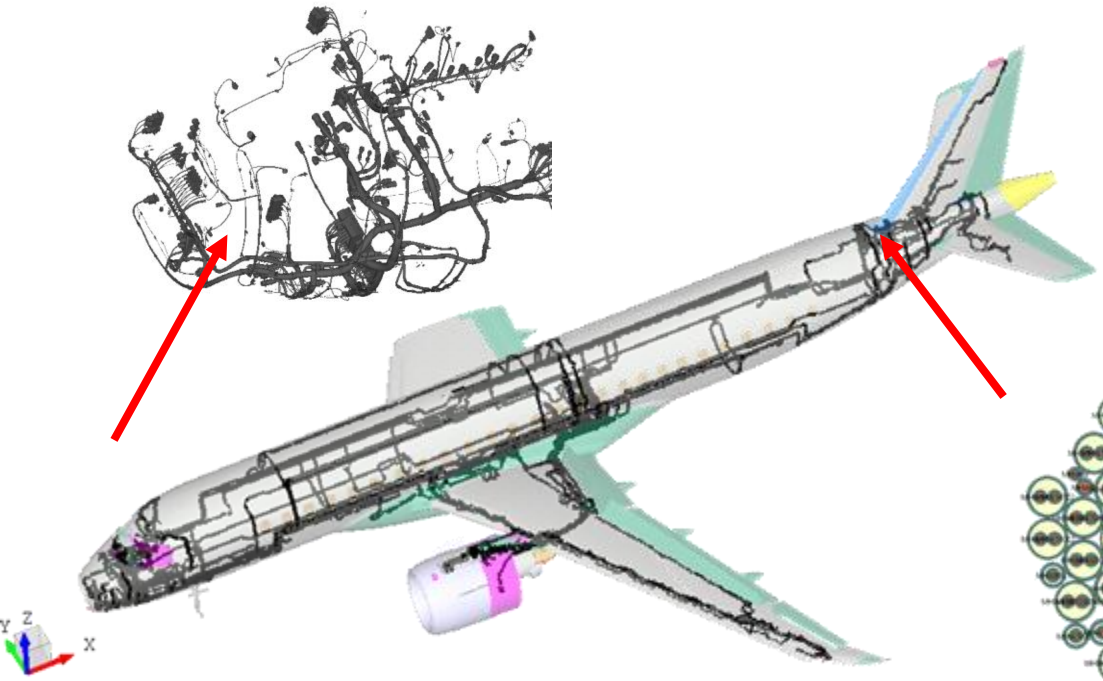
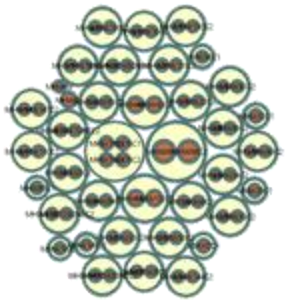
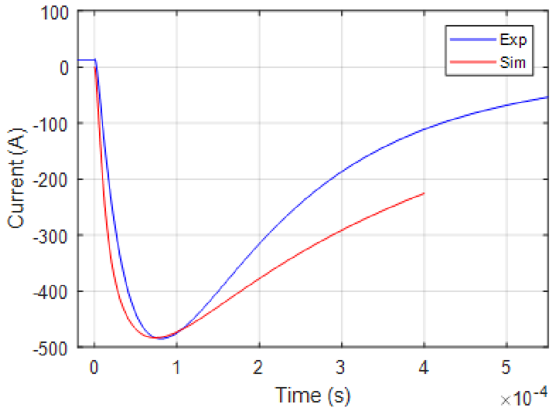


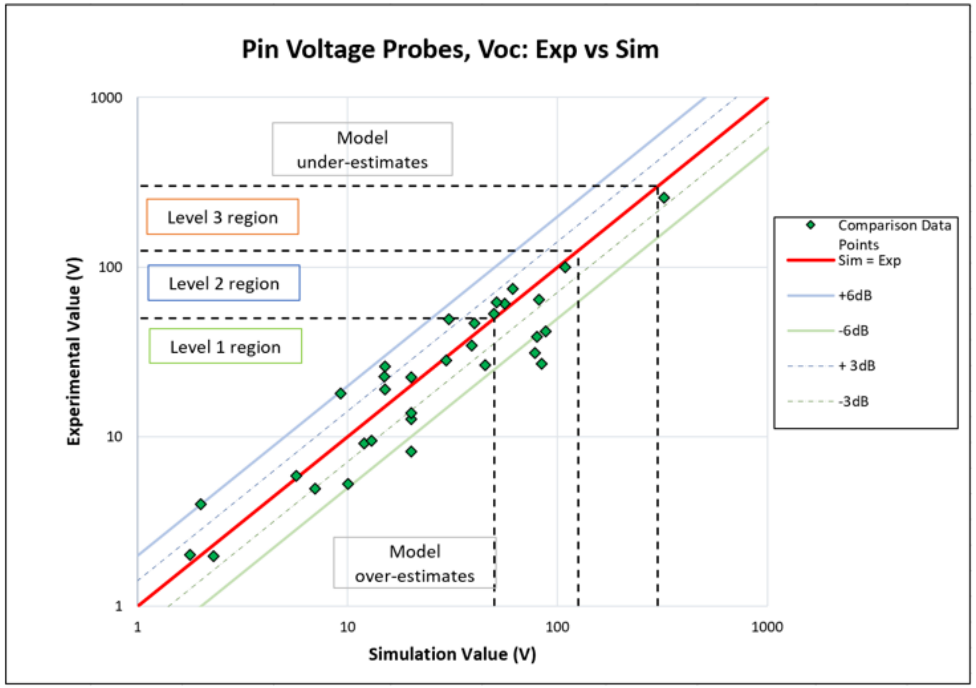


DO-160 WF and Level Specification

Table 22-2 Generator Setting Levels for Pin Injection

Level	Waveforms 3/3 Voc/Isc	4/1 Voc/Isc	5A/5A Voc/Isc
1	100/4	50/10	50/50
2	250/10	125/25	125/125
3	600/24	300/60	300/300
4	1500/60	750/150	750/750
5	3200/128	1600/320	1600/1600





MD-90 Certification by Simulation

- MD-80 Simulation Compared to Test Data
- High degree of correlation and similarity of aircraft designs allowed for IEL **certification of MD-90 by simulation without testing**
- **Programmatic savings of more than $1Million**

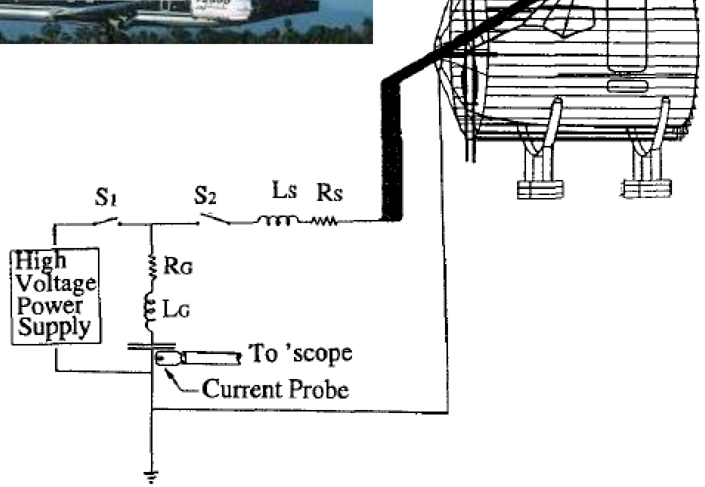


Figure 1: Nose Section Test Setup.

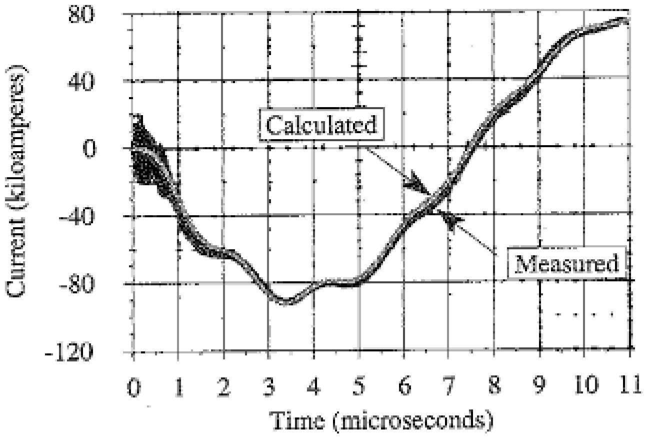


Figure 9: Comparison of Engine-Pylon Test and Analysis Drive Current Waveforms.

Table IV: Comparison of Engine-Pylon Measured and Calculated Peak Voltage Levels. Row with Lower Transient Level Is Shaded.

WR #	TEST VOLTAGE (V)	T3DFD VOLTAGE (V)	PERCENT VARIATION
3	435	585	+34
4	426	660	+55
1	421	585	+39
2	76.0	24.0	-68

Table V: Comparison of Engine-Pylon Measured and Calculated Peak Current Levels.

WR #	TEST CURRENT (A)	T3DFD CURRENT (A)	PERCENT VARIATION
3	11	28	+155
4	11	30	+173
1	12	28	+133
2	N/A	N/A	N/A

Full Aircraft Tests

- Usually performed on a production level flight test vehicle
- Multiple attach/detach scenarios should be included in the test plan
- Appropriate number of Level A, B, C system transients must be included
- 3 types of full vehicle tests
  - High level lightning pulse
  - Low level lightning pulse
  - CW frequency tests

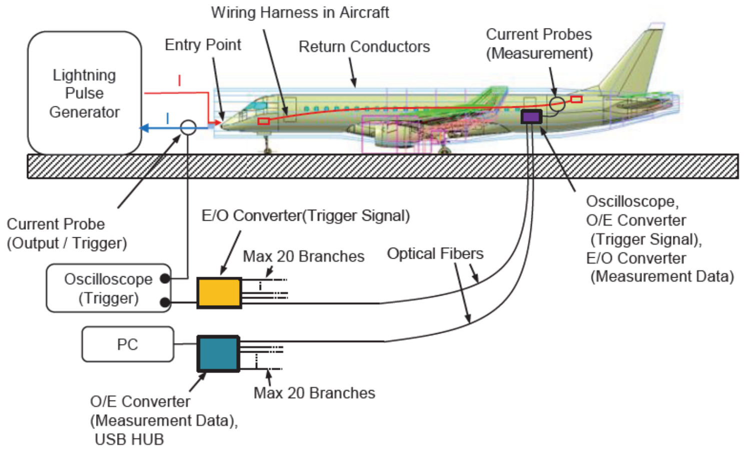


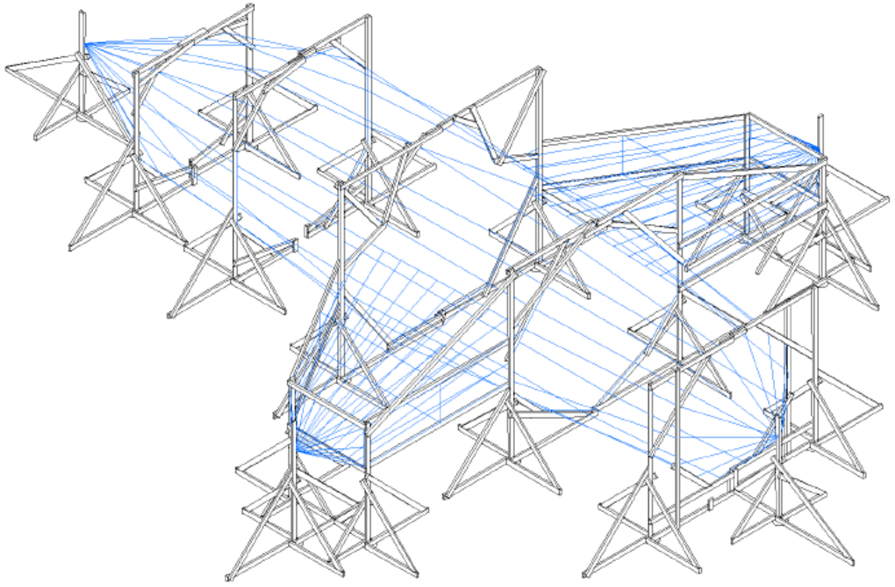
Fig.4 Outline of Measurement System

TABLE 6-1 - COMMON TEST ENTRY/EXIT POINTS

Entry	Exit
Nose Radome	Wing Tip
Nose Radome	Landing Gear
Nose Radome	Vertical Tail
Nose Radome	Horizontal Stabilizer
Nose Radome	Engine Nacelle
Wing Tip	Tail
Wing Tip	Wing Tip
Engine Nacelle	Opposite Wing Tip
Engine Nacelle	Tail

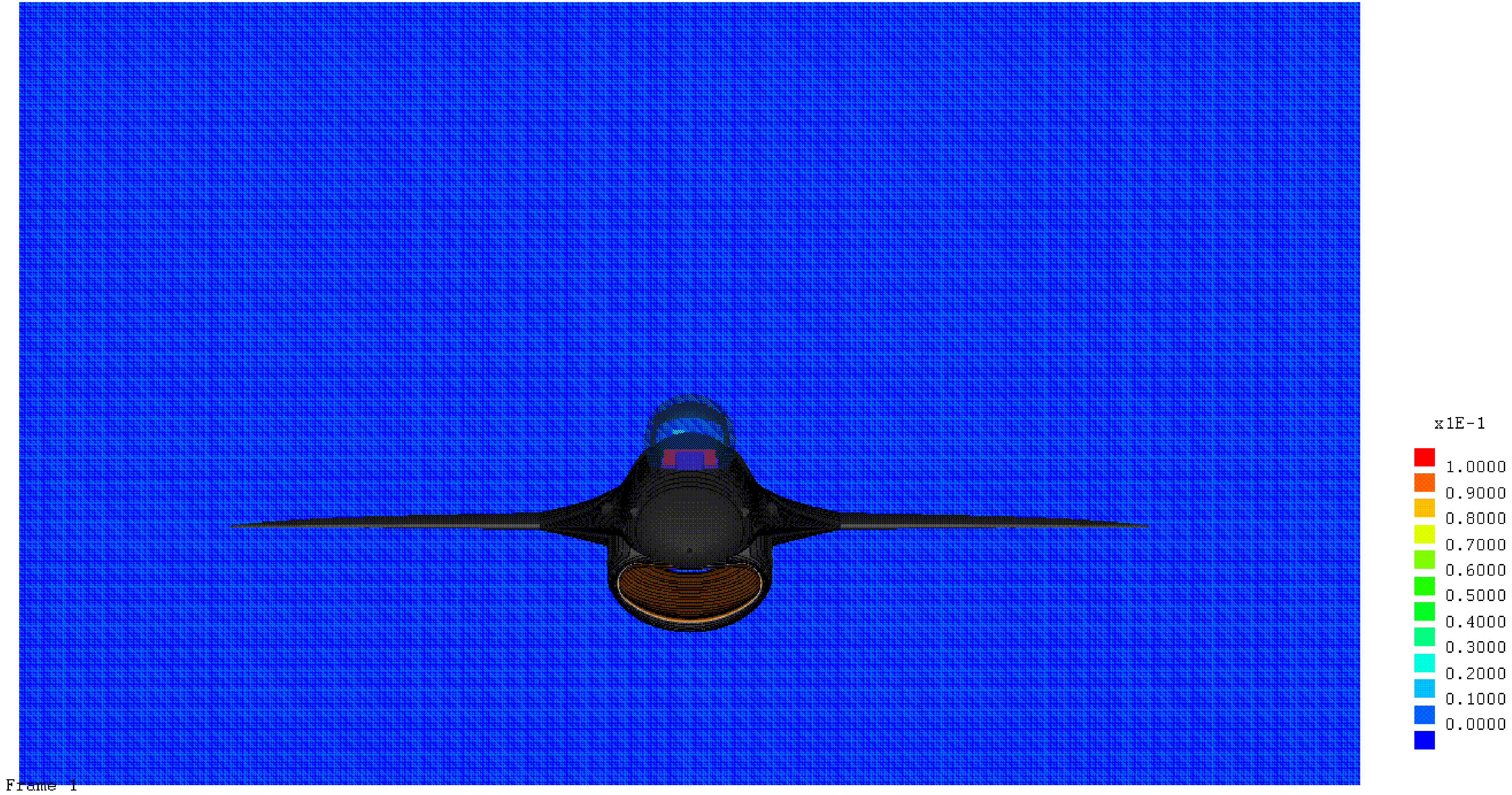
Full Aircraft Tests

- Authorities or DER must witness certification testing
- Conformity for all test articles with proper documentation
  - Should be performed well in advance of the test to avoid schedule conflicts
- Ensure adequately functioning equipment prior to testing
- Aircraft configuration harnessing
- Clear Pass/Fail requirements in test plan and results
- Define aircraft return conductor (RCS) system for testing

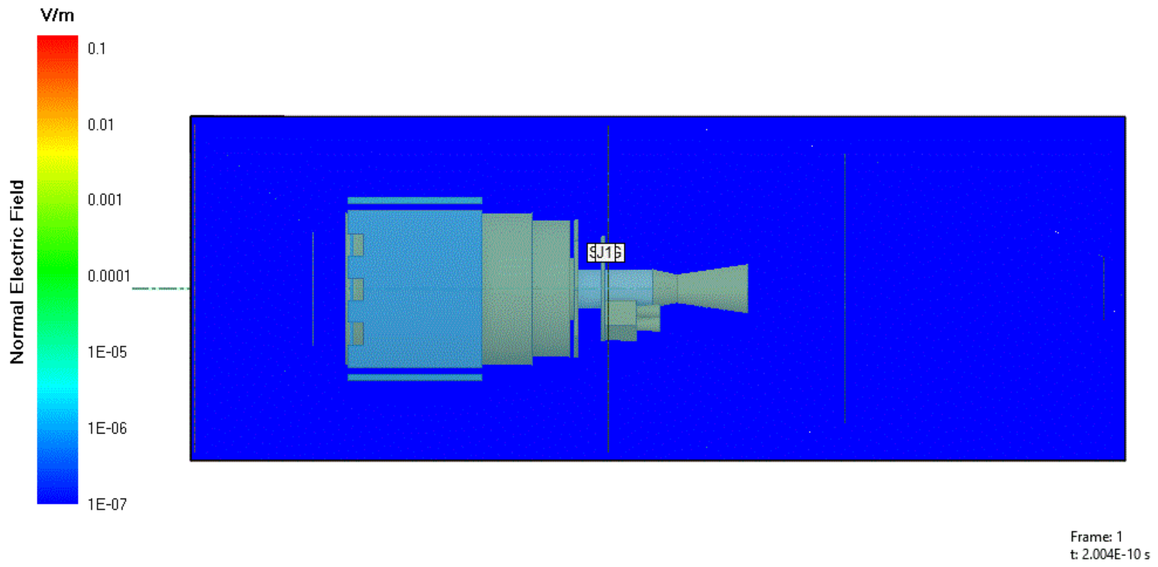


Full Aircraft RCS

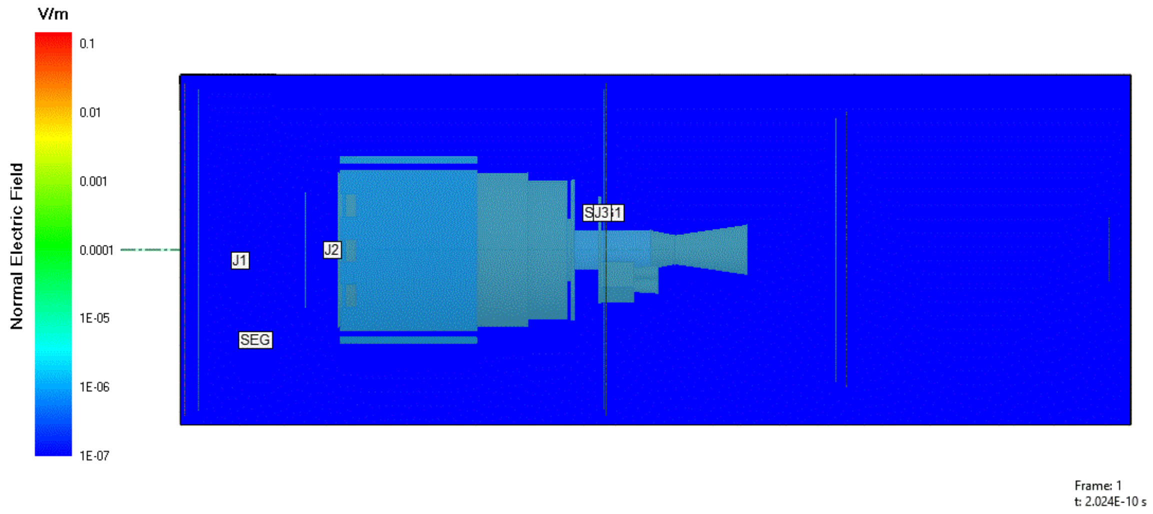
Other Capabilities - HIRF



Other Capabilities – Field Modeling

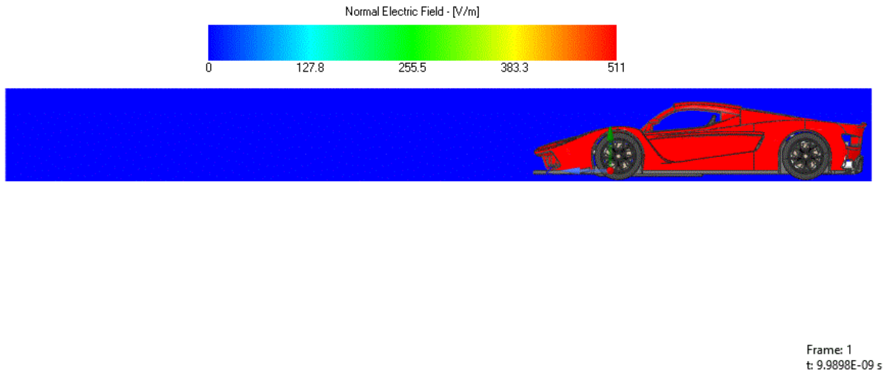


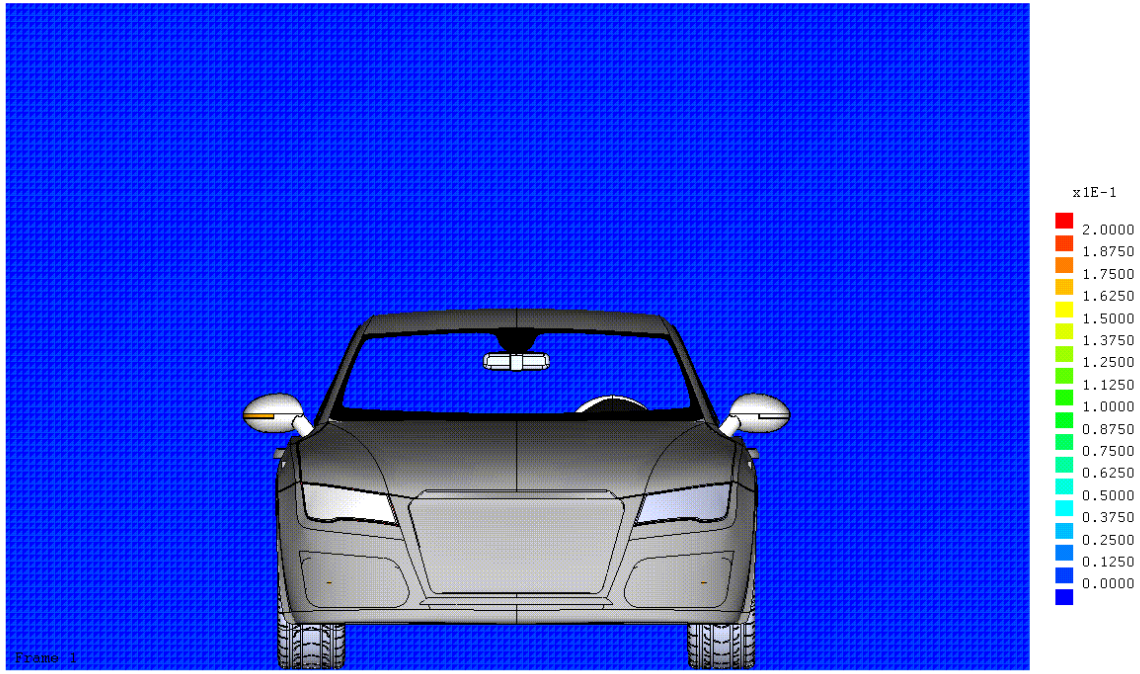
Sine wave
source
2.5 GHz



Sine wave source
Acoustic foam exterior coating
Cable harness on cone at base

Other Capabilities – RE/RI





Questions?

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