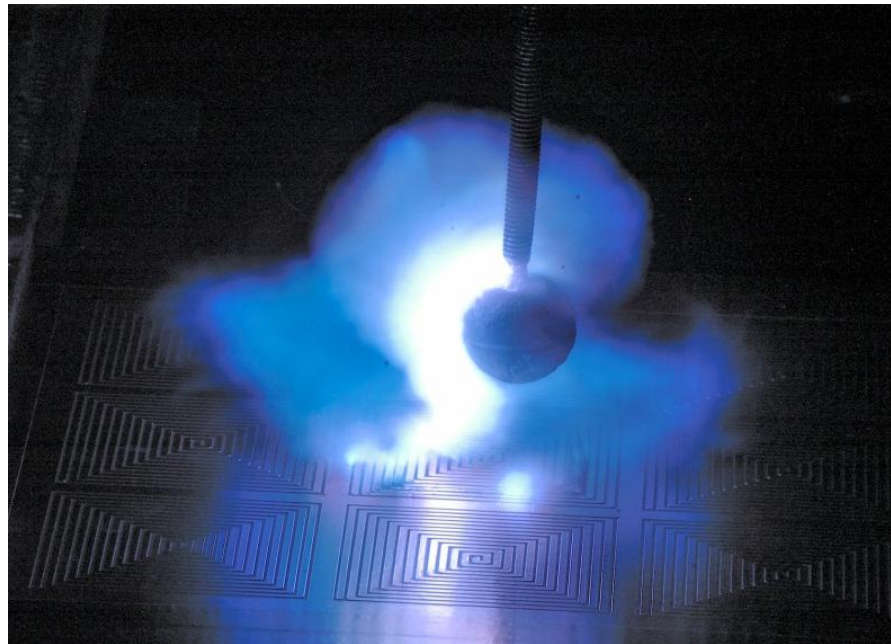


Open Circuit Resonant (SansEC) Sensor Technology for Lightning Mitigation and Damage Detection and Diagnosis for Composite Aircraft Applications



George Szatkowski & Kenneth Dudley
NASA Langley Research Center



Outline

- Background
- Objective
- SansEC Sensors
 - Description & Theory
 - Computational Electromagnetic Modeling
 - Physical Experiments
 - FY15 Research
- Lightning Experiments
 - Universal Common Practice Guidance
 - Test Bed
 - Experimental Data
 - FY15 Research
- Consortium
- Conclusion



Background – Org Chart



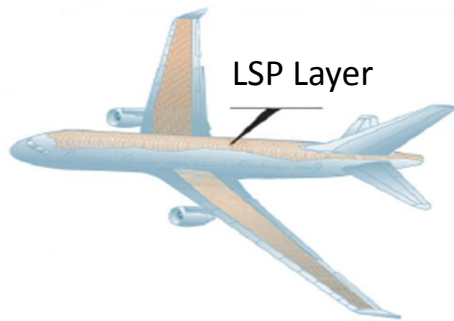
AHSM Technical Challenge: Improving and expanding remote sensing and mitigation of hazardous atmospheric environments and phenomena.

LEEM Thrust Areas –Mitigation of Lightning Hazards & Sensing Damage

Objective

State-of-the-Art of Lightning Strike Protection (LSP) for Composite Aircraft

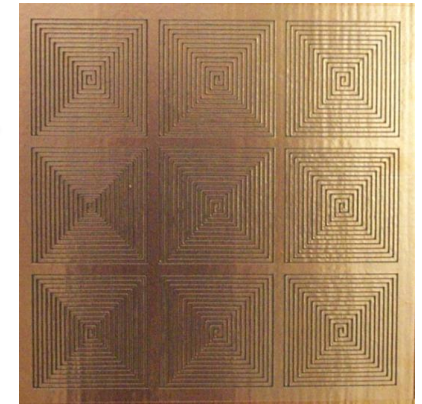
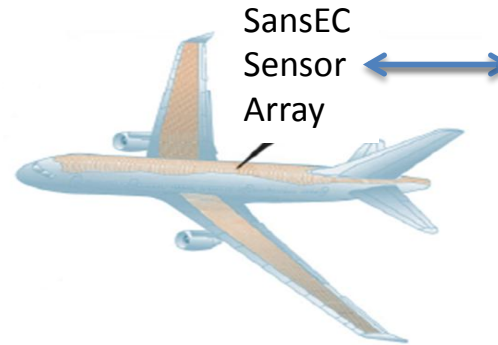
- Composite aircraft require a thin layer of metal in the outer skin to protect avionics and airframe from lightning damage.



- Post-flight ground inspection is conducted after a suspected lightning strike to identify continued air worthiness. (Visual inspections/Tap Test)

NASA Milestone – Demonstrate Multi-Functional LSP Smart Skin

- The lightning protection system can be redesigned to mitigate strike damage and facilitate damage detection and location



- LSP layer can be replaced with resonant sensors to provide comparable lightning mitigation characteristics with new features.
- Resonant sensors provide detection and diagnosis of composite damage regardless of the cause of damage. Not just lightning.



Objective – Smart Skin Functionality

<u>Functions</u>	SansEC Sensor	Metal Mesh
Lightning Protection	Yes	Yes
Damage Detection *In-situ	Yes	No
Shielding Effectiveness	Yes	Yes
Damage Diagnosis	Yes	No
<u>Potential Functions</u>		
Measuring Aerodynamic Loads	Yes	No
Fuel Quantity Indication	Yes	No
Icing Detection	Yes	No

SansEC Sensor – What is it?

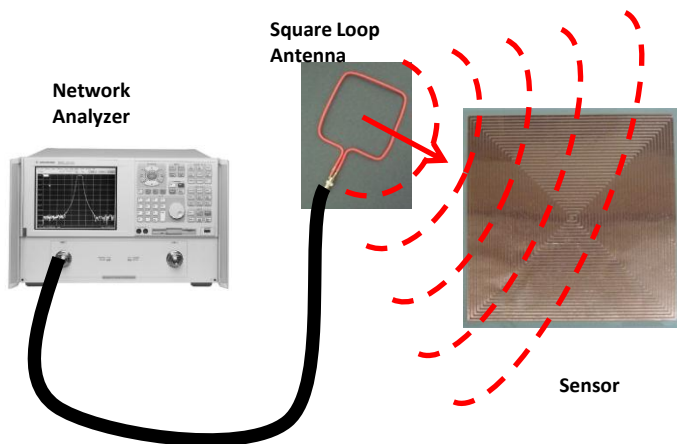


SansEC sensor technology is a new technical framework for designing, powering, and interrogating sensors to detect various types of damage in composite materials.

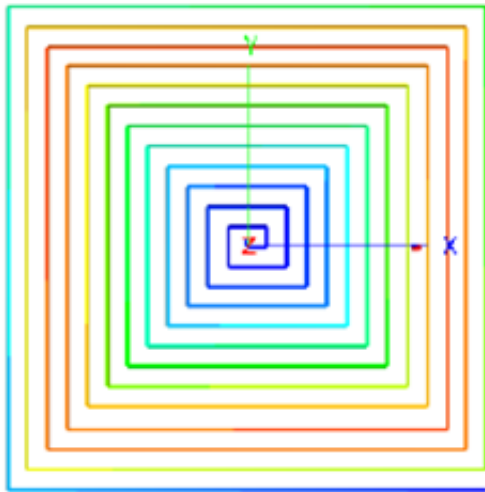
The unique electrical signatures (amplitude, frequency, bandwidth, and phase) are used for damage detection and diagnosis.

Damage in composite material is generally associated with a localized change in material permittivity and/or conductivity. These changes are sensed using SansEC.

The source cause of the in-service damage (lightning strike, impact damage, material fatigue, etc.) to an aircraft composite is secondary. The sensor will detect damage independent of the cause.



SansEC Sensor Theory



Current Distribution

$$I = I_0 \cos\left(\frac{\pi x}{l}\right) e^{-i\omega t}$$

Charge Distribution

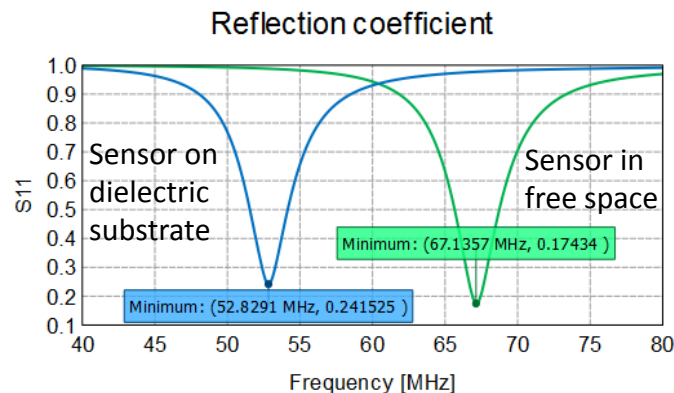
$$q = q_0 \sin\left(\frac{\pi x}{l}\right) e^{-i(\omega t + \frac{\pi}{2})}$$

Electric theory describes the LCR resonator by its lumped parameters of inductance L , capacitance C , and resistance R

$$L = \frac{\mu_0 \mu_r}{4\pi |I_0|^2} \iint \frac{\mathbf{J}(\mathbf{r}) \cdot \mathbf{J}(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} d\mathbf{r} d\mathbf{r}'$$

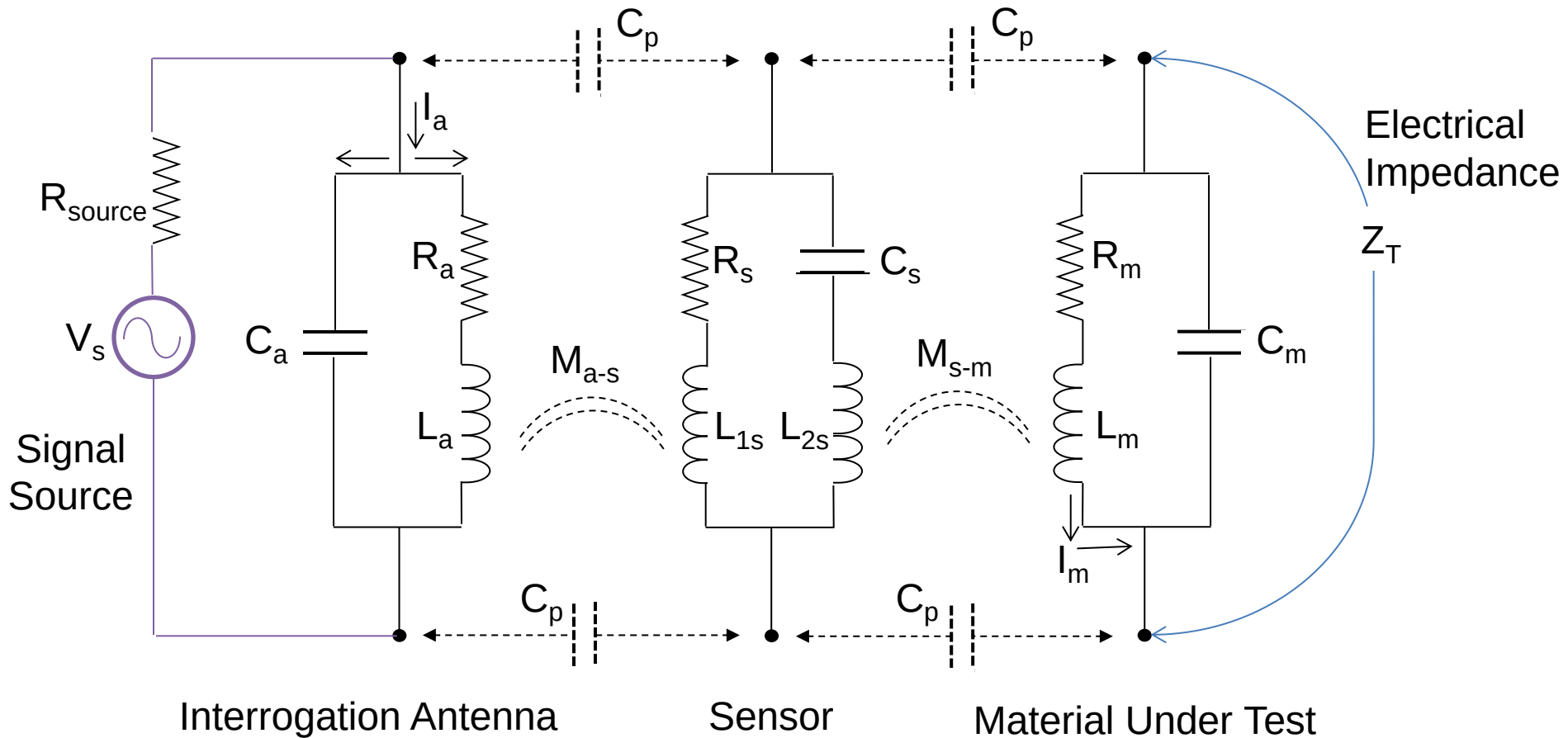
$$C^{-1} = \frac{1}{4\pi \epsilon_0 \epsilon_r |q_0|^2} \iint \frac{\boldsymbol{\rho}(\mathbf{r}) \cdot \boldsymbol{\rho}(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} d\mathbf{r} d\mathbf{r}'$$

Un-damped Resonance Inductive–Capacitive circuit

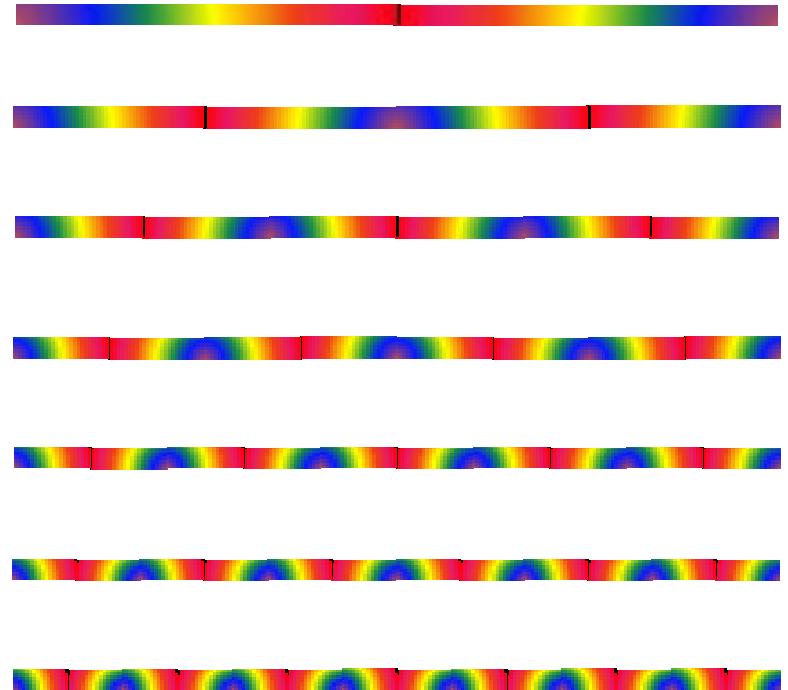
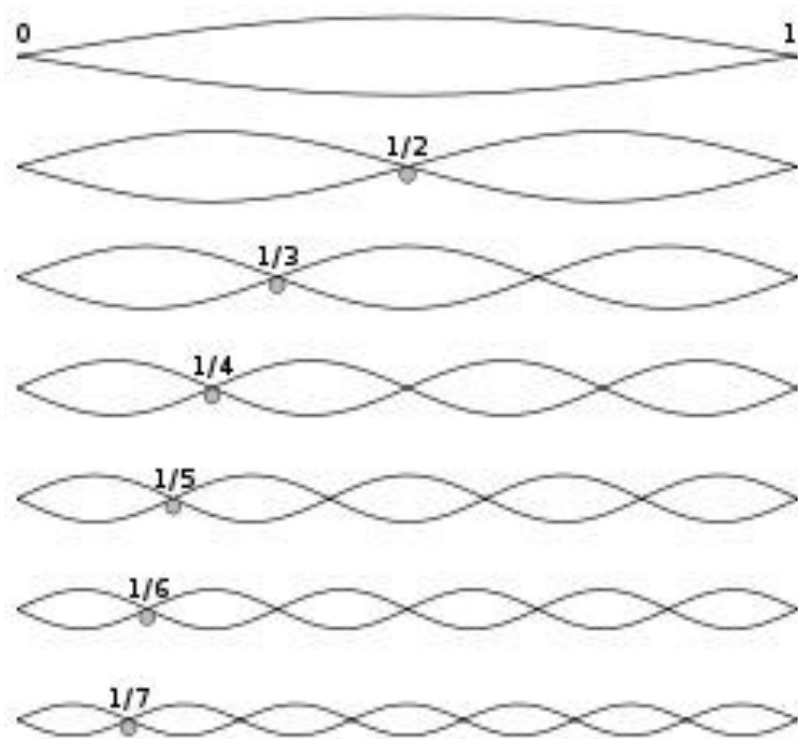


$$\omega = \frac{1}{\sqrt{LC}}$$

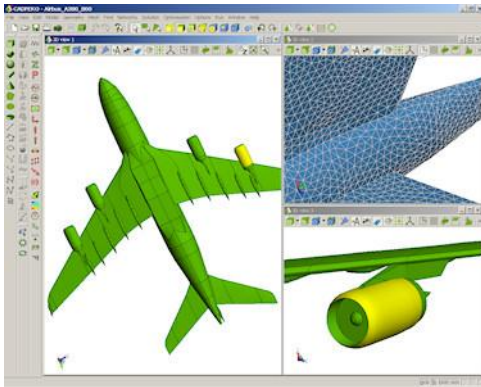
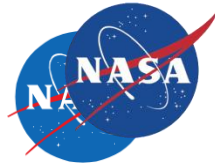
Equivalent Circuit Model



Resonant Modes



Computational Models



CAD-FEKO

FEKO is a comprehensive electromagnetic (EM) analysis software suite that uses computational EM (CEM) techniques to solve a wide range of electromagnetic problems.

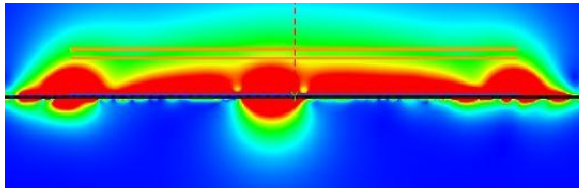
FEKO Method-of -Moments

The FEKO solver is based on the Method of Moments (MoM). There are Advanced features that enable complex models to be solved efficiently.

$$\begin{aligned}\vec{\nabla} \times \vec{H} &= \vec{J} + \varepsilon \frac{d \vec{E}}{dt} \\ \vec{\nabla} \times \vec{E} &= -\vec{M} - \mu \frac{d \vec{H}}{dt} \\ \vec{\nabla} \cdot \mu \vec{H} &= \sigma_m \\ \vec{\nabla} \cdot \varepsilon \vec{E} &= \sigma_e\end{aligned}$$

Post-FEKO

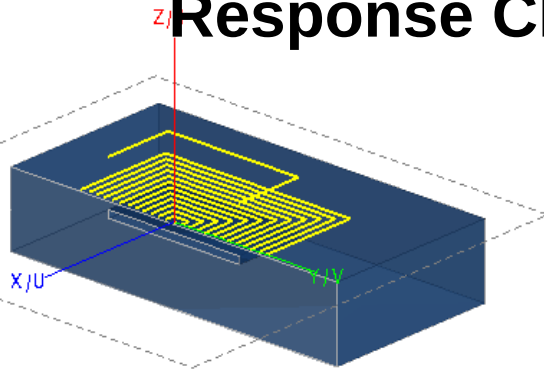
Analysis and Visualizations of complex shapes, multi-layer metallic, dielectric, composite structures. Test configurations converge to their electromagnetic solutions.



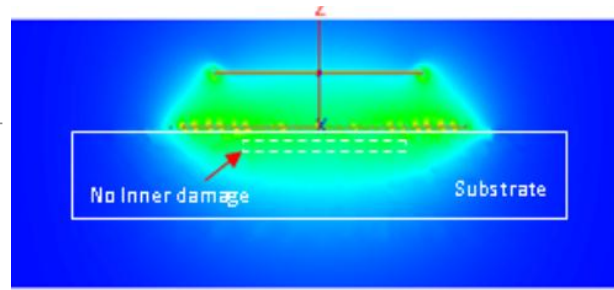
SansEC Sensor - Damage Detection Modeling



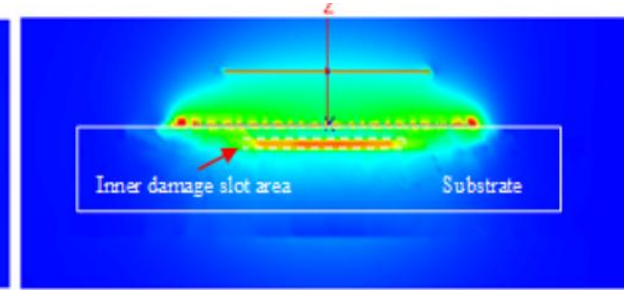
Response Characteristics of Internal Damage



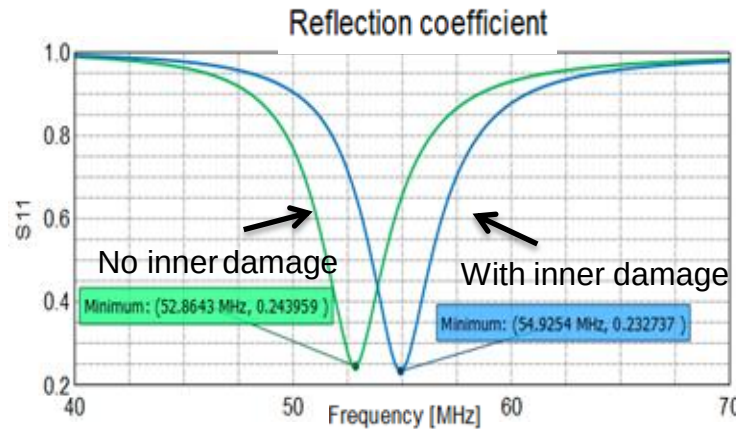
Fiberglass substrate model with inner damage



Electric field distribution
No Damage ($\epsilon_r=3$)



Electric field distribution
With Damage ($\epsilon_r=1$)

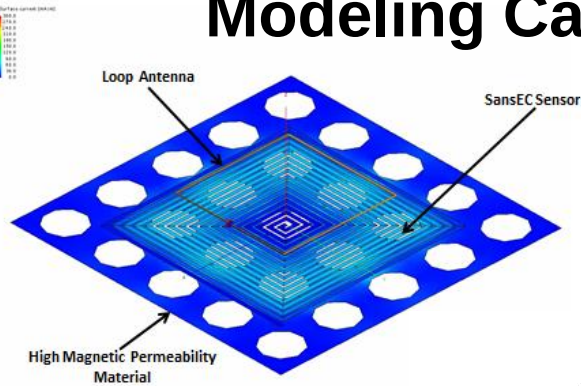


Computed SansEC resonant response

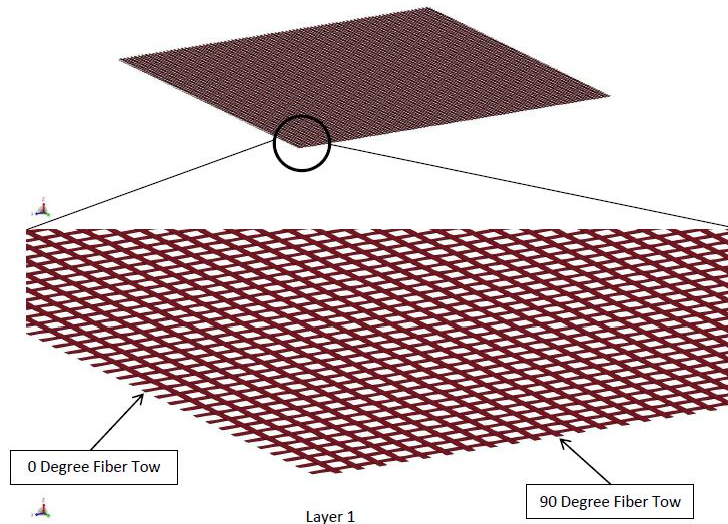
SansEC Sensor - Damage Detection Modeling



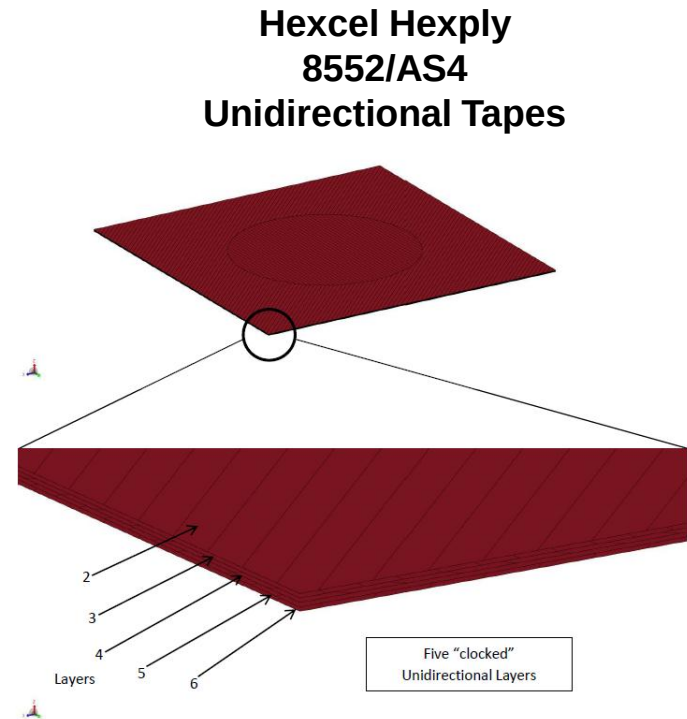
Modeling Carbon Fiber Reinforced Plastic (CFRP) Substrates



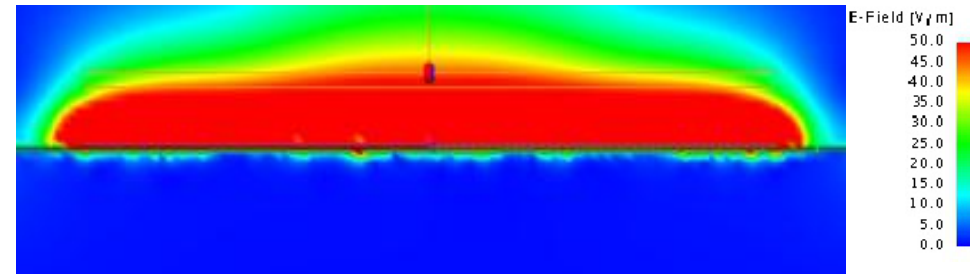
**SansEC CFRP
High Permeability
Impedance Coupling**



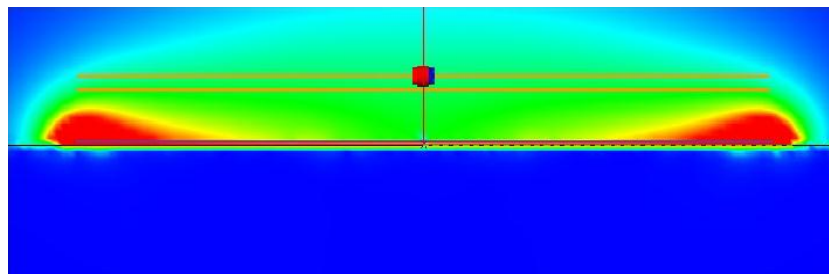
**Hexcel Hexply
8552/A193-PW.3K-70-PW
Plain Weave Fabric**



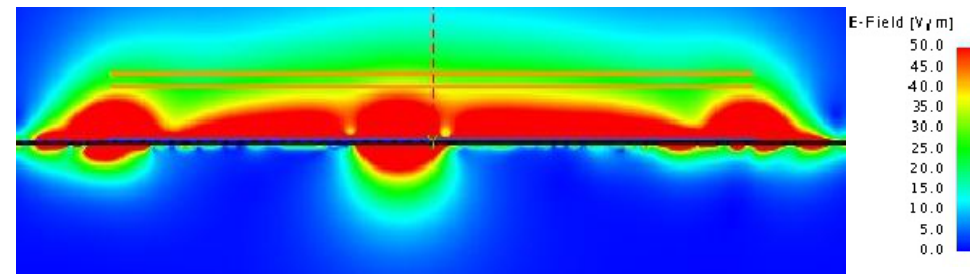
Response Characteristics of CFRP Damage



Delamination

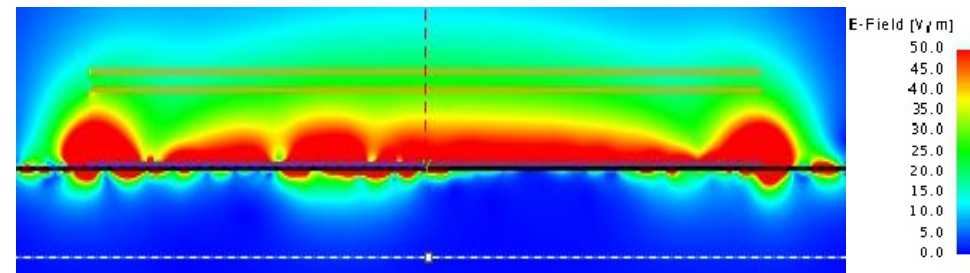


No Damage



Puncture

Electric Field Visualizations

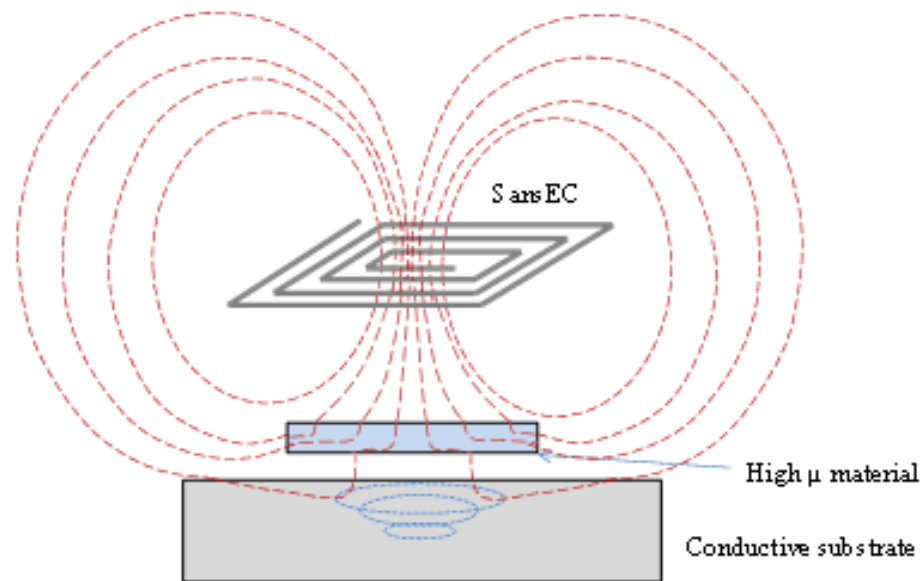


Void

SansEC Sensor – Experiments

SansEC Operation on CFRP Substrates

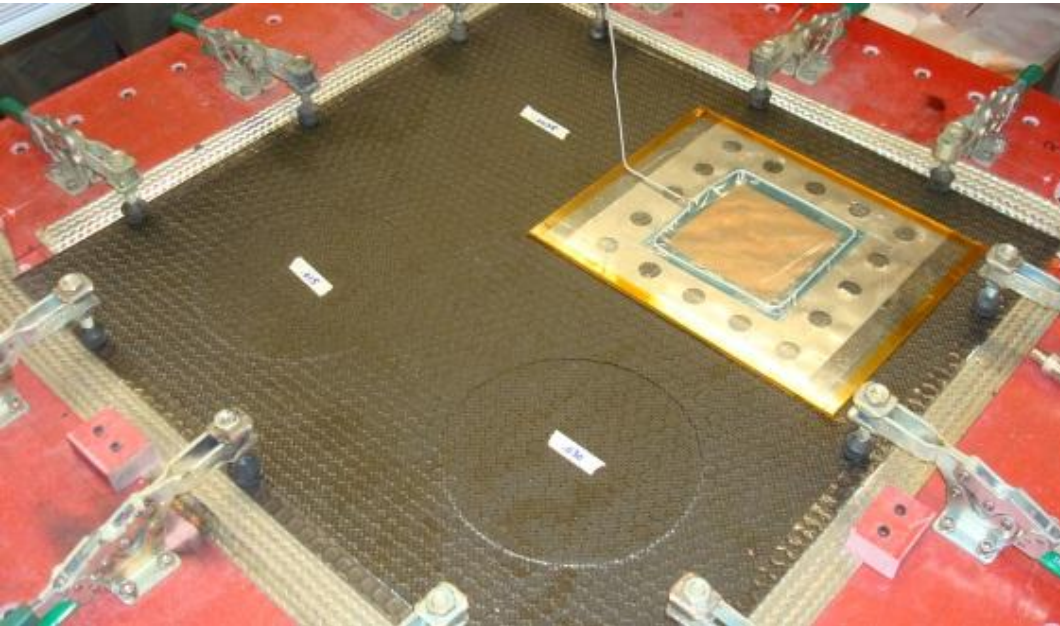
Thin layer of High permeability material is added between the sensor and CFRP to control the magnetic field coupling. Prevents fields from shorting out.



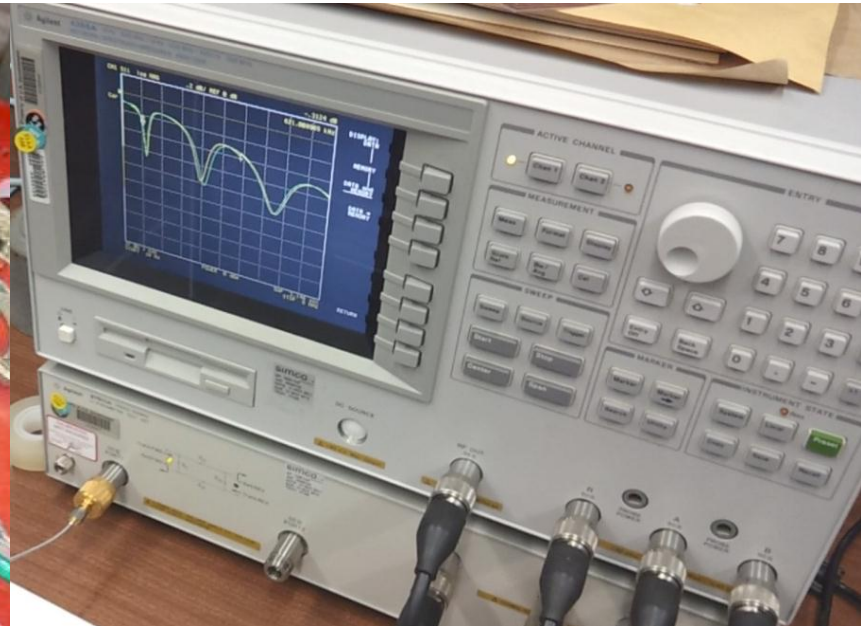
SansEC Sensor - Experiments



Seeded Fault Delamination Experimental Setup



SansEC Laboratory Experiment



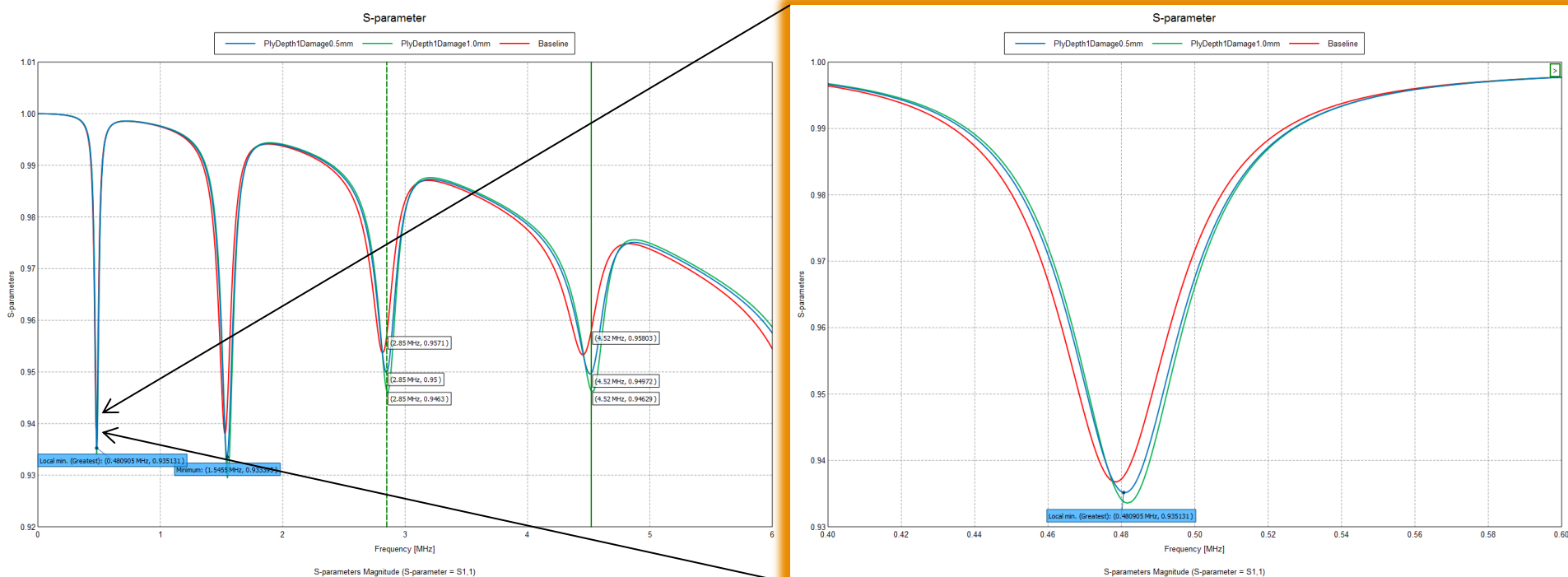
PNA Measurement

Seeded Fault Delamination Hexcel CFRP Test Panel Baseline, Small, Medium, Large, Delaminations

SansEC Sensor - Experiments



Seeded Fault Delamination Experimental Data Damage Signature through Scattering Parameters

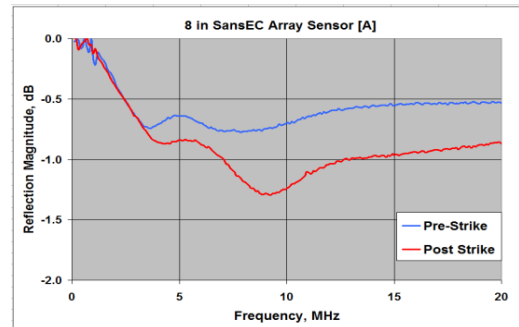
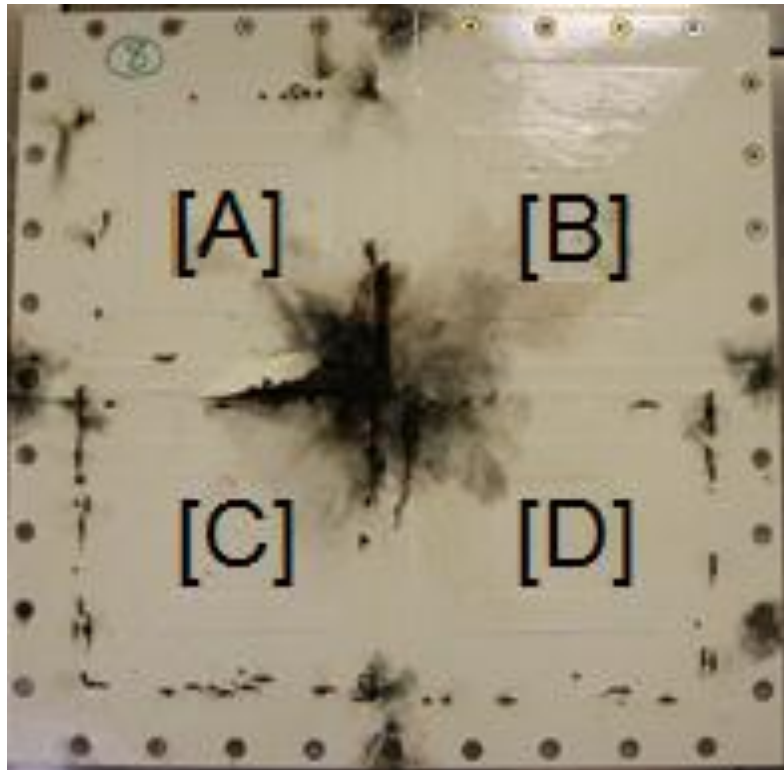


Seeded Fault Delamination Hexcel CFRP Test Panel Baseline, Small, Medium, Large, Delaminations

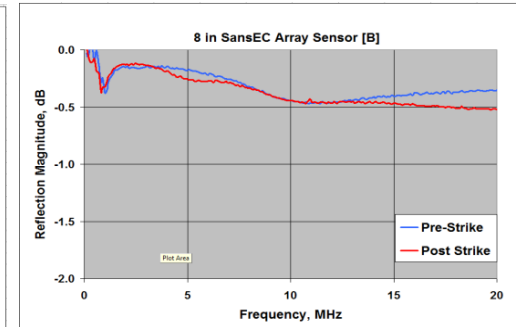
SansEC Sensor - Experiments



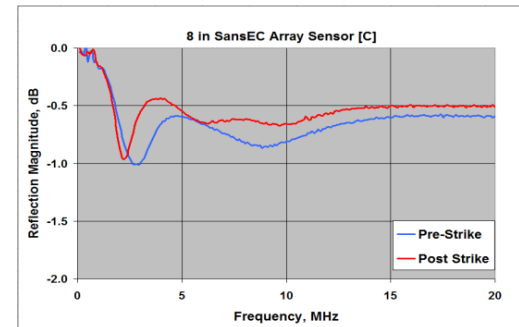
Lightning Strike Demonstration Experimental Data



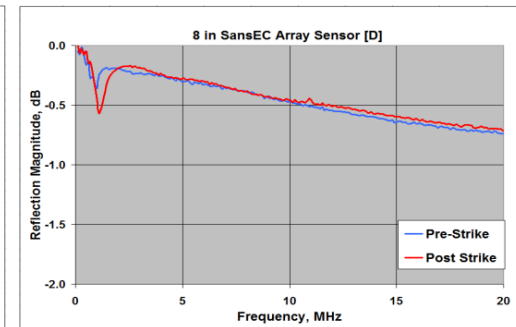
(A) Sensor A upper left quadrant.



(B) Sensor B upper right quadrant.



(C) Sensor C bottom left quadrant.



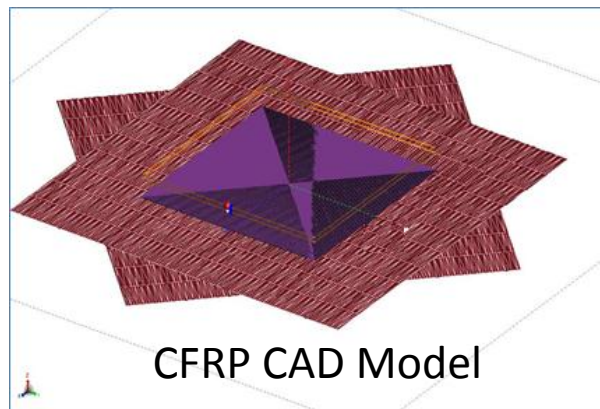
(D) Sensor D bottom right quadrant.

Reflection coefficient plots for four 8 in Lightning SansEC Sensors on CFRP substrate showing pre and post lightning strike measurements.

SansEC Sensor- Summary

Accomplishments: Experimental data and computational simulations demonstrated SansEC sensors can be designed to detect damage in carbon fiber composite laminates.

- A thin layer of high permeability material placed between the sensor and carbon substrate is used to control the field coupling and enable sensor operation.
- Developed very efficient modeling capability using the Surface Modeling Method in the FEKO Computational Electromagnetic Modeling software to quickly generate solutions on pristine and damaged carbon composite substrates.
- **Why It Matters:** The research has demonstrated SansEC sensor technology is a viable alternative to existing Non Destructive Evolution (NDE) practices and may play an important role in future Integrated Vehicle Health Management (IVHM) and Structural Health Monitoring (SHM) for carbon composite aircraft.

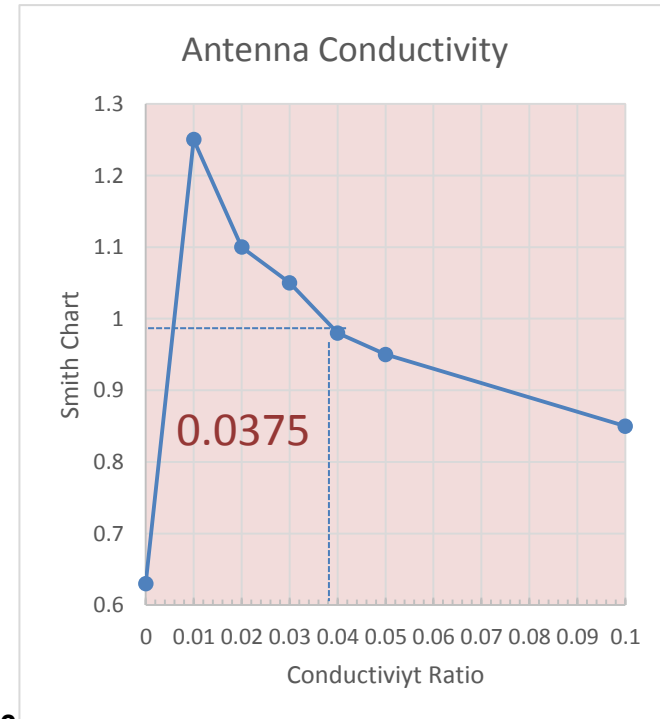
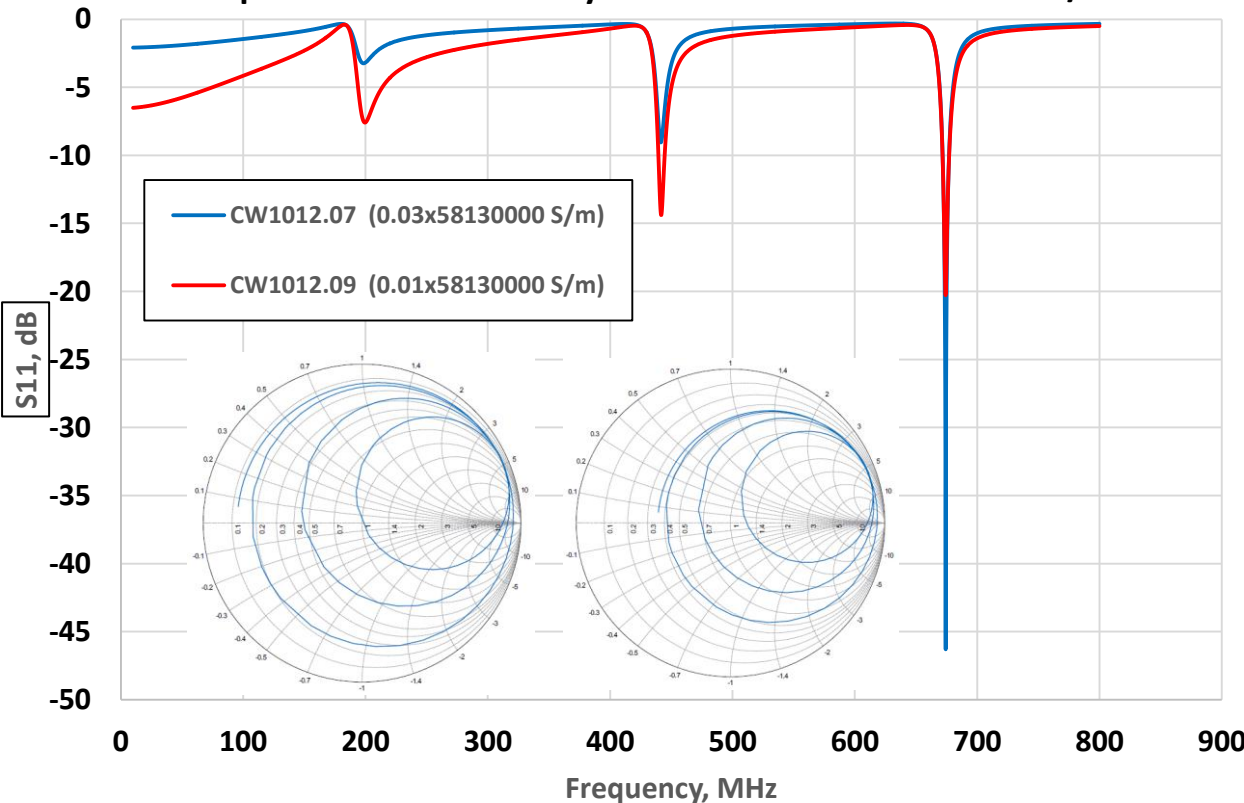


SansEC Sensor - FY15 Efforts



- **Sensor CFRP Optimization**
 - Develop sensor geometry with maximum achievable resonates.
 - Develop high permeability layer geometry to balance weight and performance.

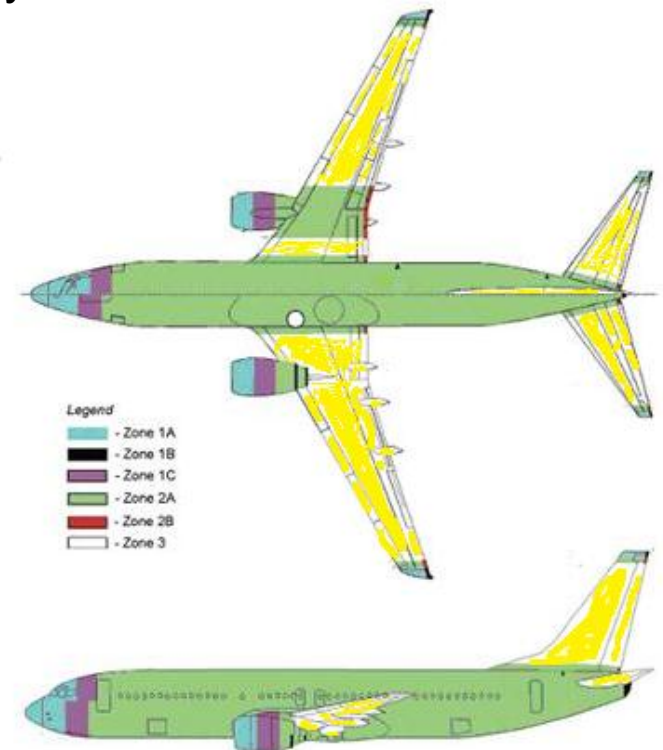
Comparison of Conductivity at 0.03 and 0.01 x 58130000 S/m



Background - Lightning Threat to Aircraft

- FAA certified aircraft are tested to mitigate against a 200KAmp lightning strike.
- Aluminum aircraft legacy practices don't guarantee compliance for composites.
- Sections of aircraft are “zoned” based on probability of attachment.

Aircraft Zone	Voltage Waveforms(s)	Current Component(s)
1A	A, B, D	A, B, C*, H(200KA)
1B	A, B, D	A, B, C, D, H
1C	A	Ah, B, C*, D, H
2A	A	D, B, C*, H (100KA)
2B	A	D, B, C, H
3 (Conducted)	-	A, B, C, D, H
3 (Direct attachment)	A	A/5, B, C* (40KA)
Model Tests	C	



ARP5412- APPLICATION OF LIGHTNING ENVIRONMENT TO AIRCRAFT ZONES



Lightning Experiments – Common Practice

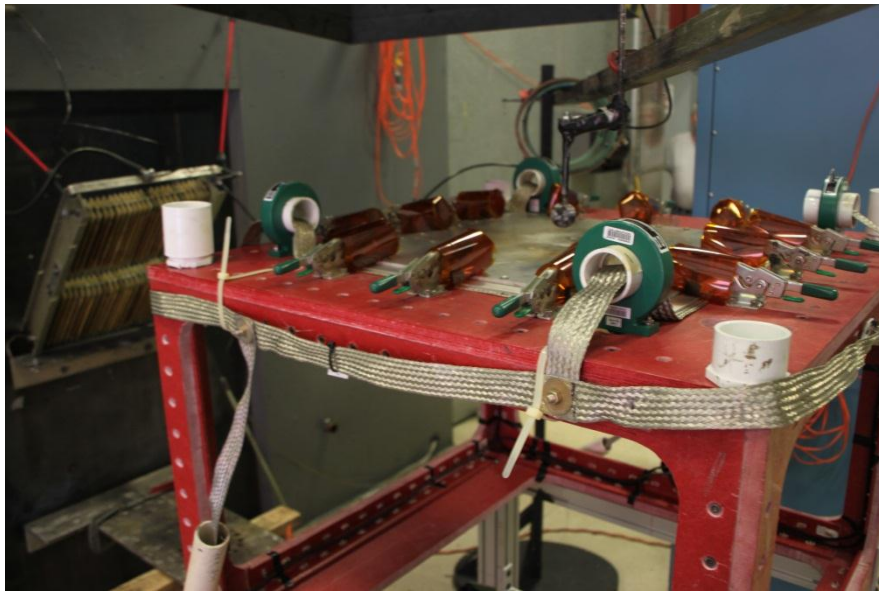
Development of a Universal Common Practice Guide for Lightning Damage Testing of Composites

NASA Contract was awarded to Boeing to develop test procedures.

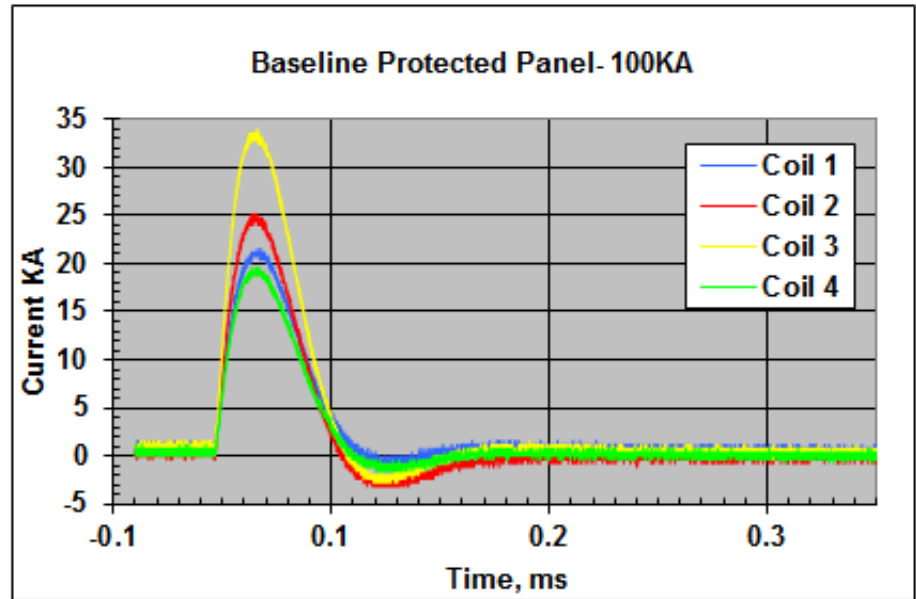
- Define baseline unprotected & protected CFRP panel (including finishes and grounding scheme) to be used as a baseline performance standard.
- Define Pre-test Non-Destructive Inspection (NDI) and post-test Destructive Inspection methods to aid in quantification of results.
- Define Lightning Test Operations Manual that elaborates on the provisions contained in ARP5416 to address inconsistencies in the generation of damage protection performance data, so as to provide for maximum-achievable correlation across capable lab facilities.
- Define a means to quantify the multi-physical phenomena surrounding a lightning direct attachment, in support of predictive model development. (Capture temperature, mechanical displacement & electrical current propagation during strike test.)

Lightning Experiments – Test Bed

Electrical Current on the 4 Edges of the Test Panel were Independently Monitored during Lightning Test



Pearson Probes mounted on Test Bed



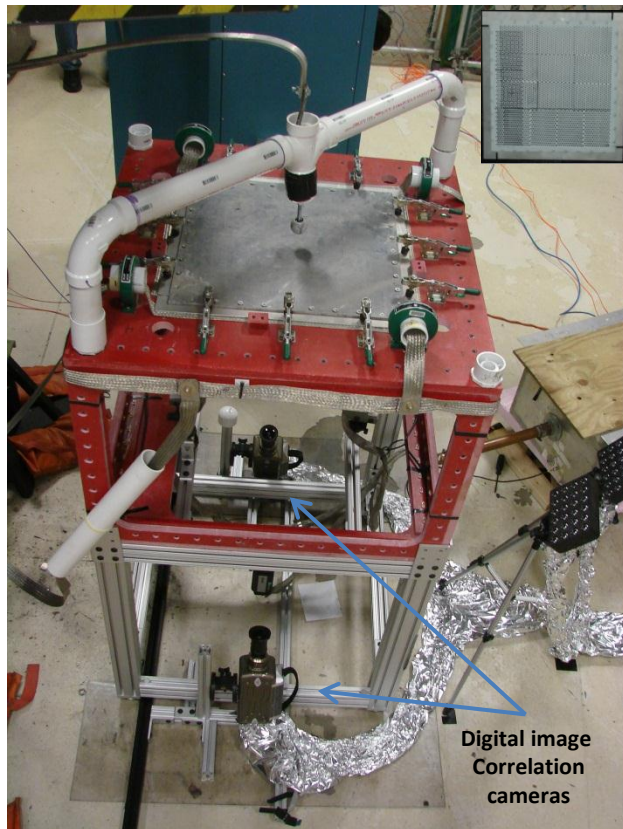
Current Data collected July 2013.

- 4 independent current monitors enable measurements on the 4 edges
- Inductive effects from ground strap installation should be minimized

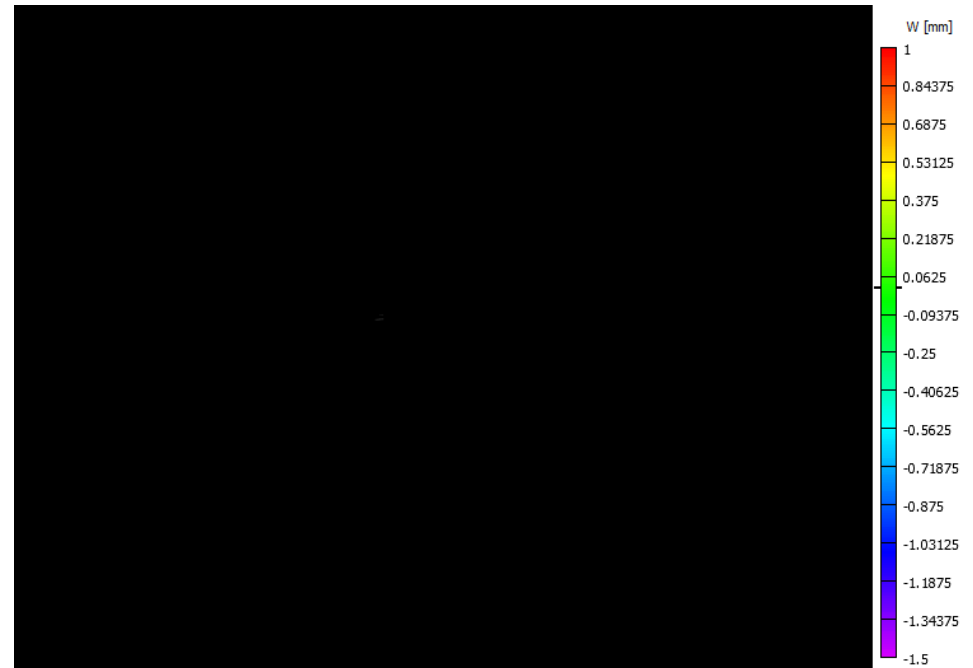
Lightning Experiments– Test Bed



Mechanical deflection is measured using optical sensors or digital image correlation cameras

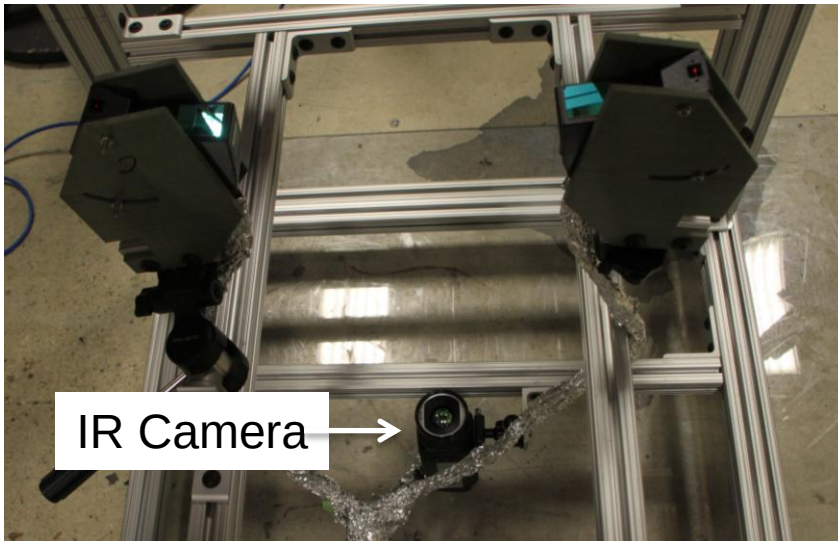


Digital Image Correlation Video

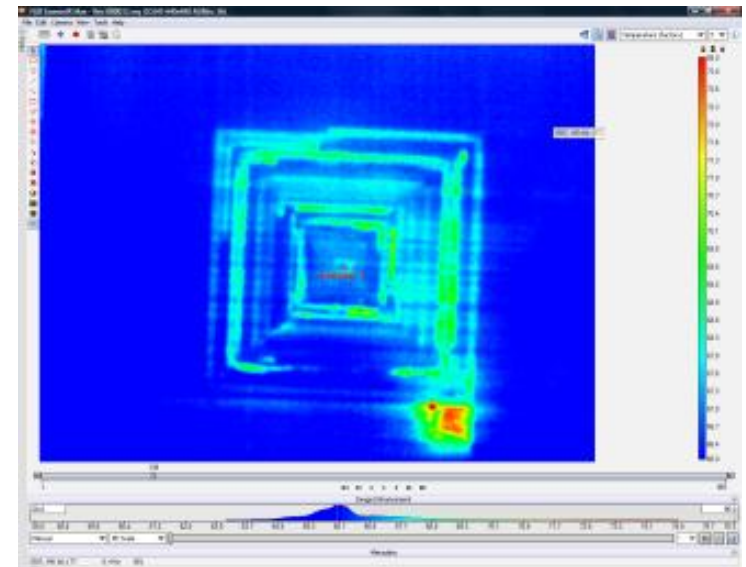


Lightning Experiments— Test Bed

Backside Thermal Data was Acquired using FLIR Systems SC645 IR Camera



IR Camera Setup



Backside IR image of 8" SansEC LSP on Fiberglass Substrate

Lightning Experiments – Backside Temperatures

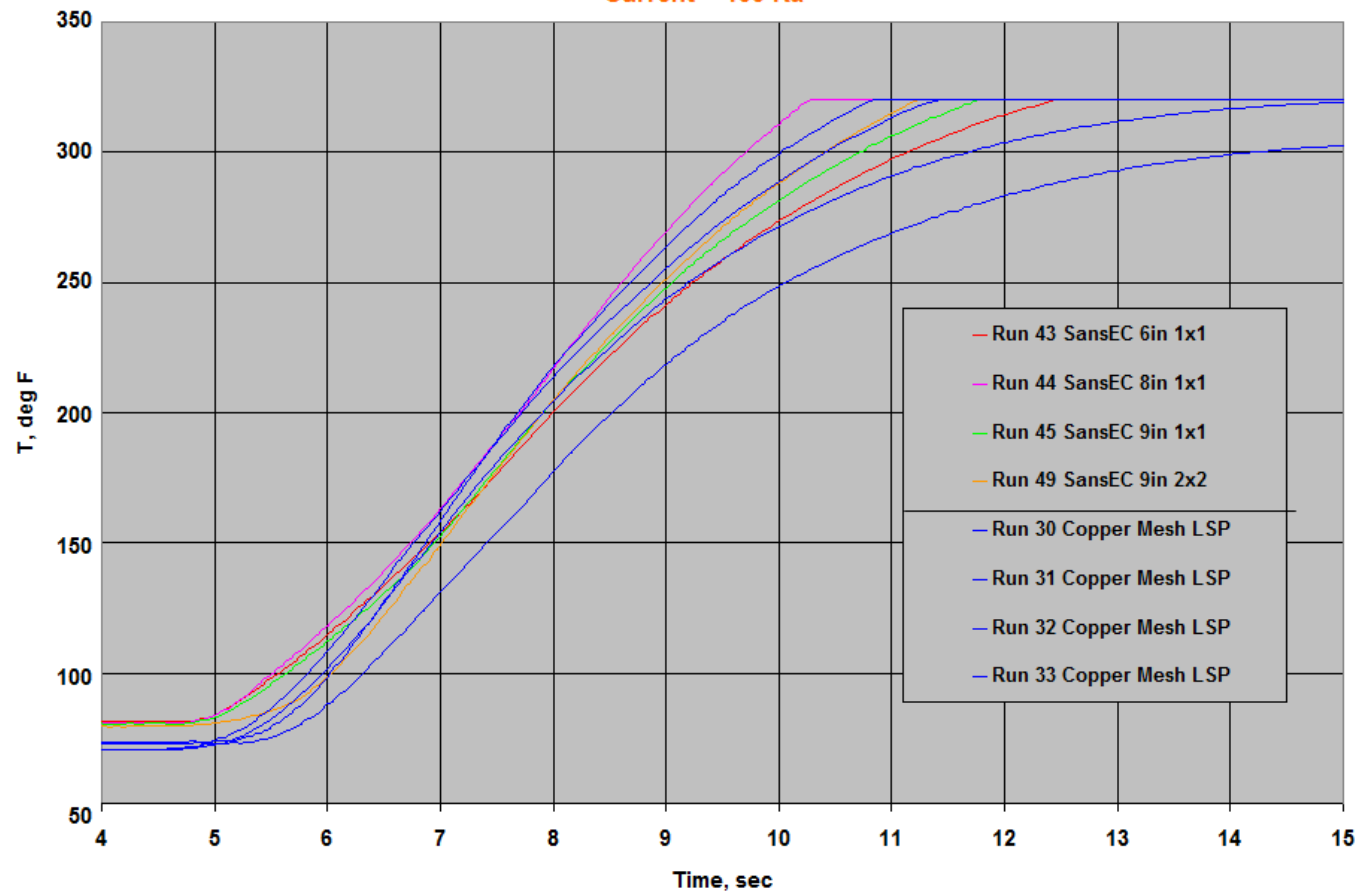


Temperature Profiles on Hexcel Panels– September 2012

Temperatuere Rise Time Comparison of SansEC LSP and 3 mil Copper Mesh LSP

(Start Time Aligned at Temp Rise)

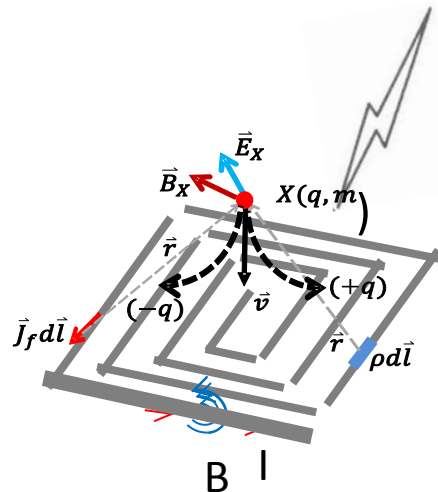
Current = 100 Ka



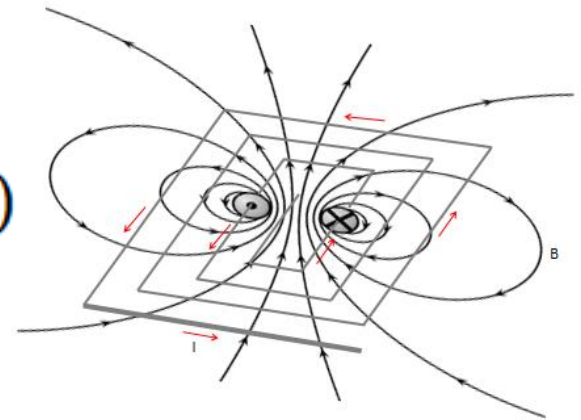
Lightning Experiments - Theory

What We Know

- Propagation lightning leaders (current) in the atmosphere creates lightning radiated emissions to provide an excitation waveform to establish the resonant modal structure on the sensor, in turn generating high electric field regions on the trace before the lightning reaches the sensor. This influences lightning attachment.
- Lorentz forces are generated from the SansEC geometry and will act on the incoming charge to change its direction of propagation.



$$\vec{F} = q(\vec{v} \times \vec{B}_x + \vec{E}_x)$$



SansEC generated magnetic and electric field and Lorentz force on charged particle

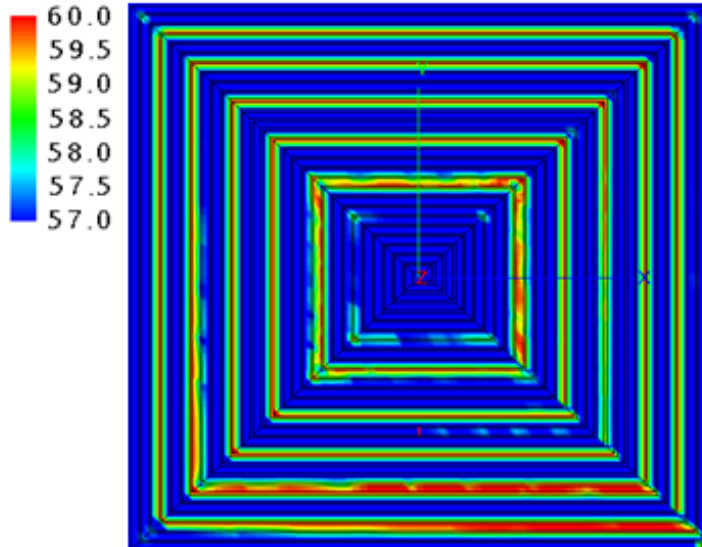
Lightning Experiments – Strike Attachment

What We Did to Study Attachment

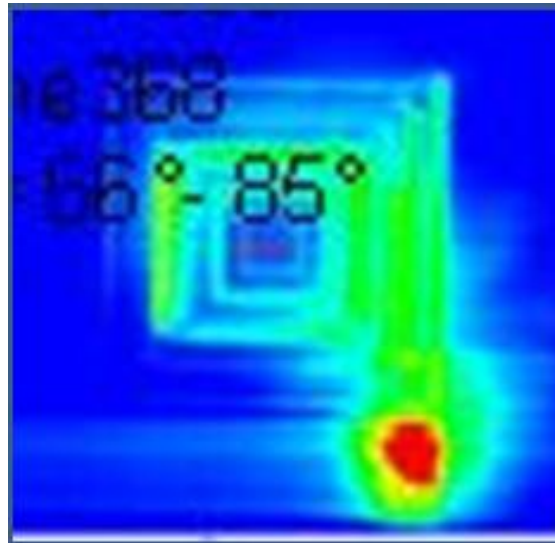
- Electromagnetic computational simulations were conducted to determine the electric field distribution just above the the SansEC sensor's conductive trace at its primary resonance.
- The hotter temperatures in the IR image represent the location of lightning attachment or current propagation. If a portion of the SansEC trace is immediately destroyed/removed off the panel the IR image may not sense an increase in temperature at that location.
- Visual observations of the post-strike panel can be useful to determine attachment and propagation.

7" LSP SansEC Sensor Data

XYZ E-Field [dBV/m]



Computed E Field



Backside Temperature

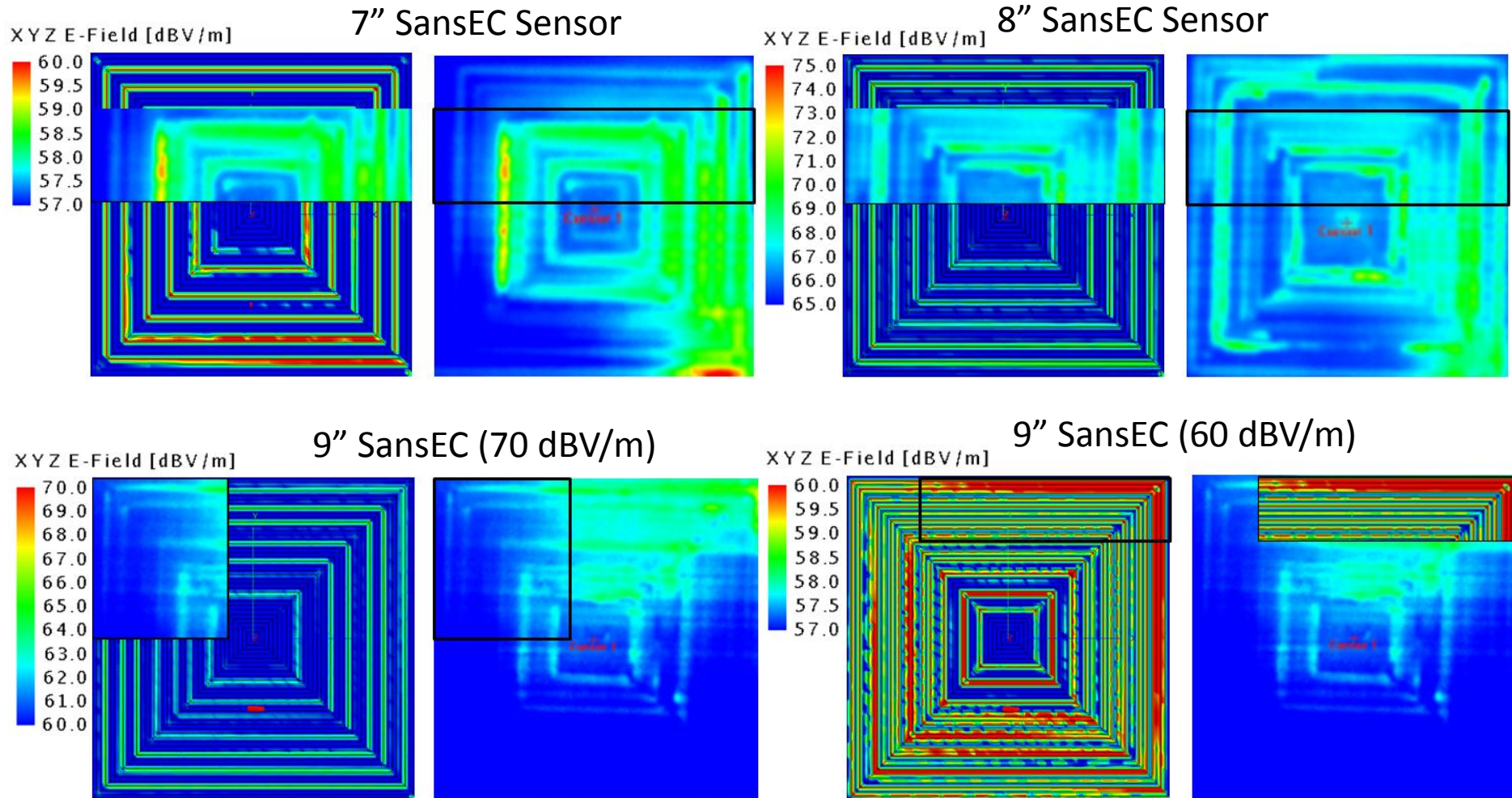


Post Strike Damage²⁷

Lightning Experiments – Strike Attachment

What We Learned

- Correlation between high E-fields and higher temperatures suggests attachment occurs at high E Fields.



Lightning Experiments – Strike Attachment

What We Captured on Camera

- SansEC sensor can spread or disperse the arc root attachment to the higher E Field regions on the trace.

Two 100 kA Strikes



4 second time lapse photograph showing
Lightning Strike Attachment
on Mesh Protected CFRP Panel

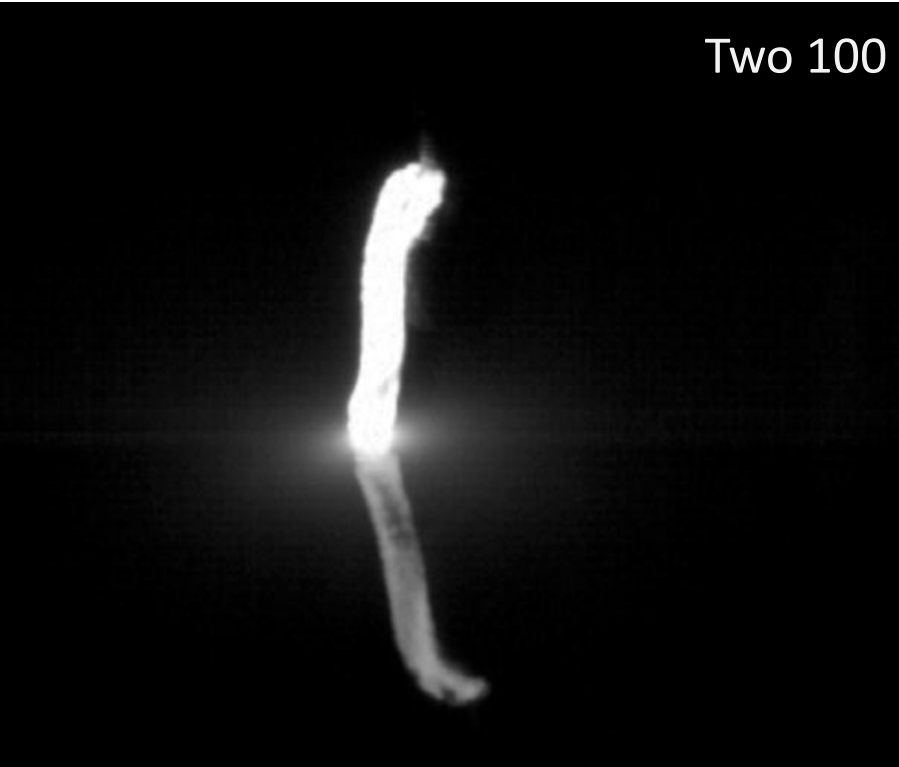
4 second time lapse photograph showing
Lightning Strike Attachment
on 6" SansEC Protected CFRP Panel

Lightning Experiments – Strike Attachment

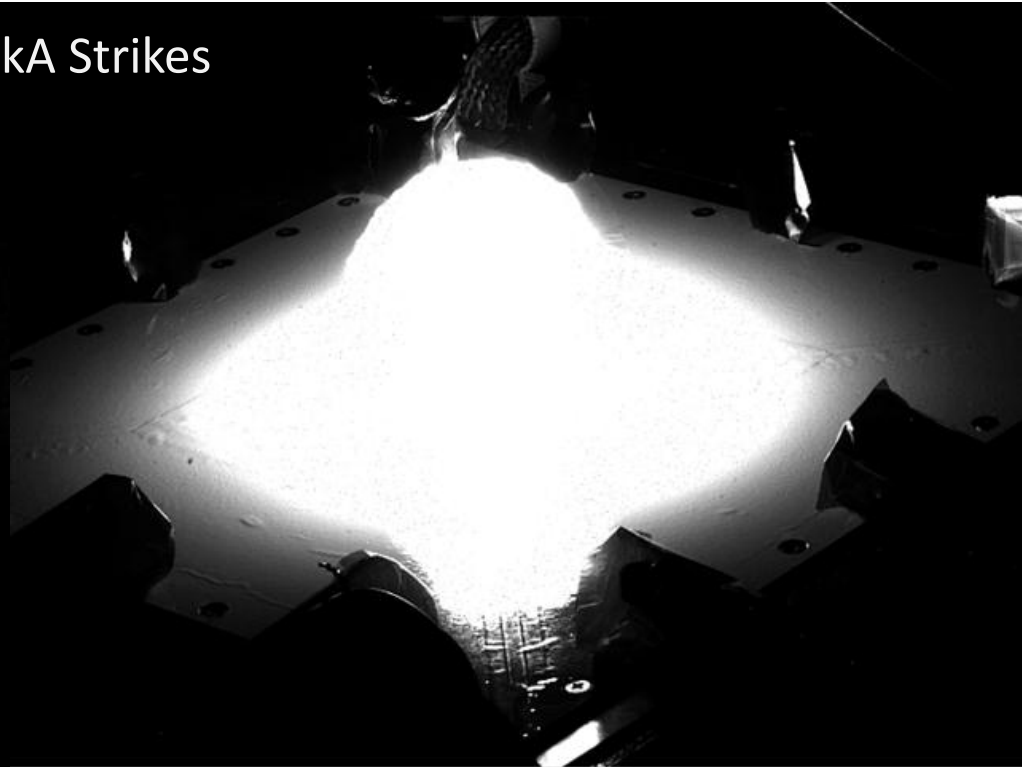


What We Learned

Two 100 kA Strikes



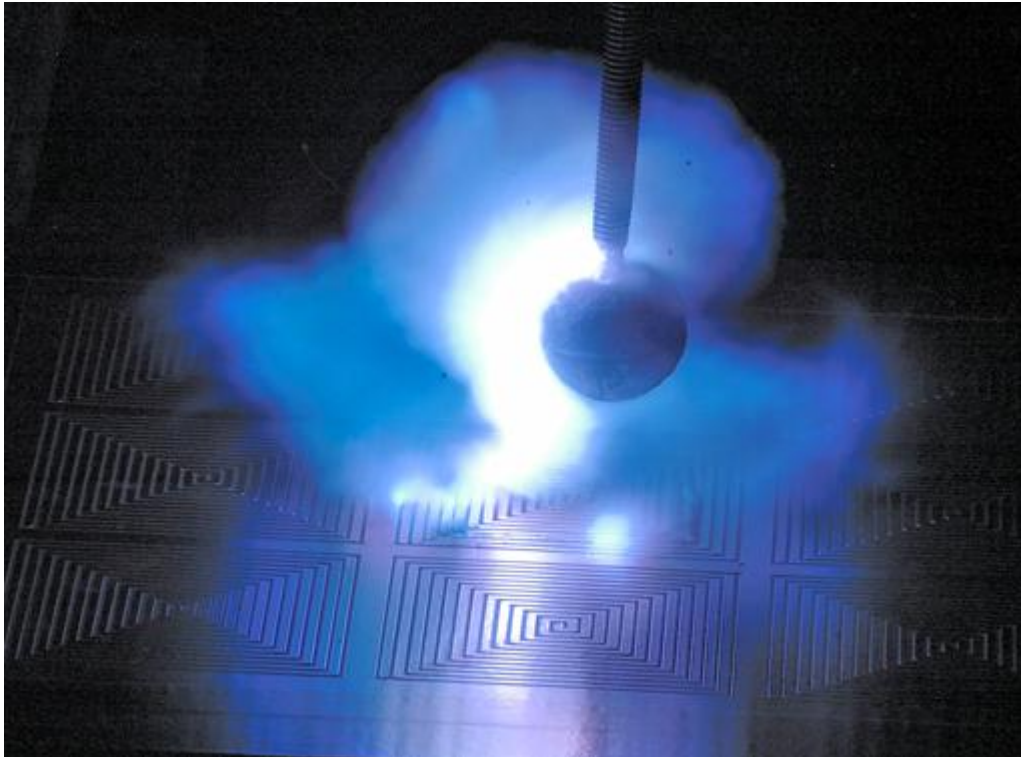
High Speed Video First Frame showing
Lightning Strike Initial Attachment
on Mesh Protected CFRP Panel



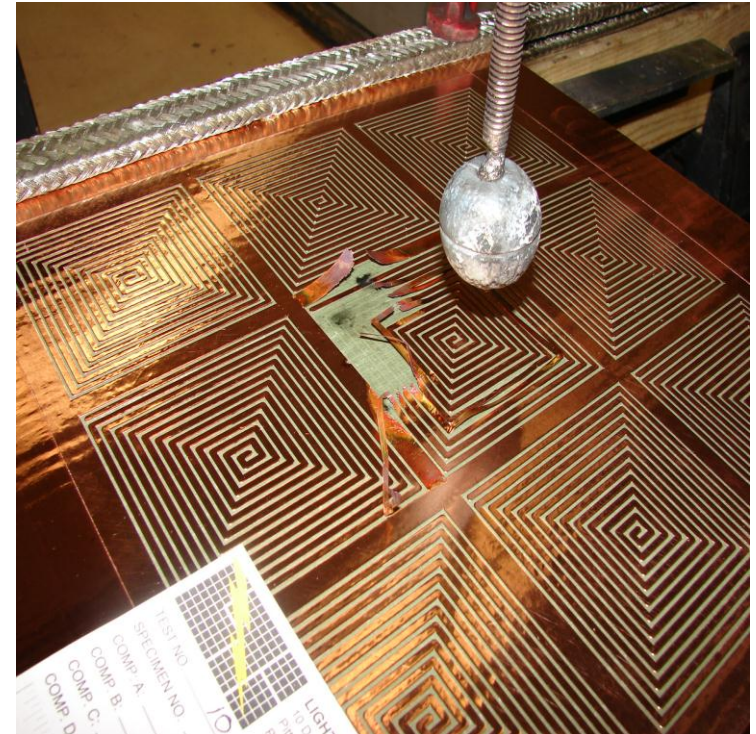
High Speed Video First Frame showing
Lightning Strike Initial Attachment
on SansEC Protected CFRP Panel

Lightning SansEC – Lorentz Force

Lorentz Force acting on Lightning Channel 3 inch 3x3 SansEC



Test Strike on Panel



Post-Strike Test Panel



Lightning Experiments - Summary

Accomplishments: Lightning direct effect tests conducted on SansEC panels following guidance defined in the Universal Common Practice showed comparable damage metrics as an FAA accepted lightning strike protection method. A lightning test bed was used to acquire damage mechanisms (electrical, thermal & mechanical) during lightning insult. The test results substantiate the use of open circuit resonant devices to influence attachment location & arc root dispersion and offers new design approaches for lightning mitigation. The SansEC LSP system aerial weight were comparable to LSP mesh, but further research is needed to improve future designs.

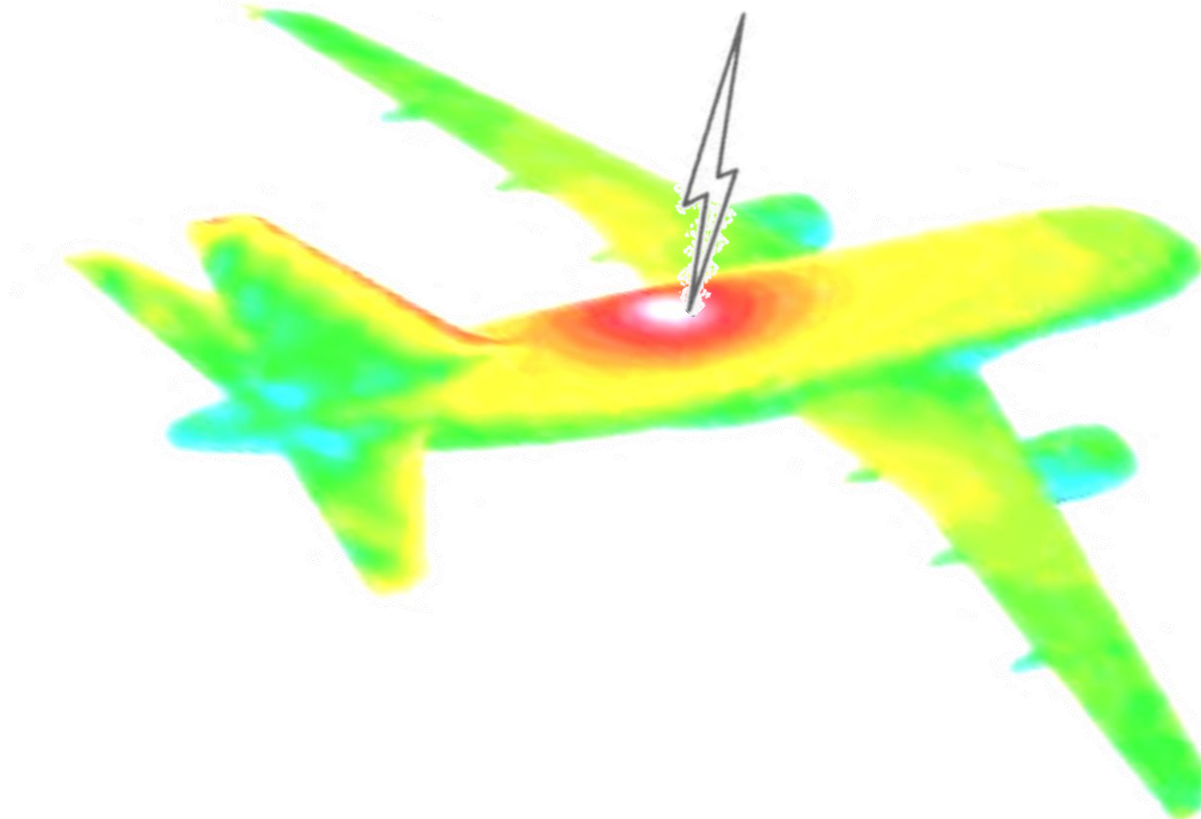
Why It Matters: SansEC sensors can be designed using the lightning strike protection conductive layer to achieve multi-functionality. Arc root disbursement can help in lightning mitigation and future designs could incorporate features to attach and channel lightning currents to desired locations which could lead to zoning changes.

Test Panel - # Averaged	Peak I (KA)	Average Damage Depth per PE (in)	Average Damage Area per TTU (in2)
Protected -3	100	0.041	5.97
SansEC -1	100	0.035	5.33
SansEC Array -1	100	0.013	8.14

Comparison of Damage Depth & Area

Lightning SansEC Sensor - FY15 Efforts

- **Study lightning attachment characteristics within time and resources.**
 - **Conduct LSP tests on optimized designs.**
 - **Establish lightning attachment modeling capability to explore attachment.**
 - **Conduct high voltage validation experiment.**





NASA/Industry SansEC Aeronautics Consortium

- Goal - Establish pathway for continued research
 - Technology Transfer
- Consortium concept
 - **First step is an NIA contract to study AERO commercialization**
 - Draft proposal is close to being completed
 - Industry will determine need and scope
 - Managed by external contractor (NIA/NIAR/Other)
 - Technical support staff from NIAR & NASA LaRC
 - Mesoscribe Direct Write technology Partner
 - Altair Computational Support (FEKO)
 - NASA TAC Program has some directed funding in FY15
 - Future NASA program funding would be pursued
 - Multiple Partners kicking in \$\$\$/year
 - Technology Objectives determined by Steering Committee
 - Increase SansEC TRL
 - Lighting Mitigation
 - Damage Diagnosis
 - Fuel Quantity Indicator System

Future Opportunities - Other Applications



Fuel Quantity Indication System (FQIS)



Icing Detection

Application Areas are Unlimited

**Aerospace, Automotive, Mining, Medical, Transportation
Industrial, Security, Others...**



Other Applications

Aerospace

**Wireless Fuel Tank
Structures monitor
Lightning
Fluid levels
Ice detection
Shuttle Tile**

Automotive

**Tire pressure
Fluid Levels
Dirty Oil Sensor
Highway/Parking Sensors
Traffic Management**

Medical

**Imaging
Non-intrusive sensor
Heart monitor
Brain monitor**

Mining

**Drilling
Core assessment**

Transportation

Rail, Ships, Buses, Elevators,

Industrial

**Fluid Flow, Pressure, Temperature, Etc
Chemical**

Military

**Uniform Sensor
All classes of vehicles**

Security

**EM Monitor
Motion Sensor**

Shipping

**Location
Damage monitor**

Residential

**Mailbox Sensor
Driveway**



Conclusion

- Through the use of lightning strike testing, experimental damage test coupons, and computational modeling NASA LaRC has demonstrated that SansEC sensors can be effectively used for lightning strike protection and in-situ damage detection of composites.
- The foundation for damage diagnostics is established.
- The feasibility for realistic applications on both fiberglass and carbon fiber composites is confirmed.
- A NASA/Industry Consortium is needed to advance the Smart Skin Concept

Acknowledgements



TEAM SansEC

Technical

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Business

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Jennifer Viudez, Sheri Beam

Legal

Robin Edwards, Andrea Warmbier, Jennifer Reilly,
Elaine McMahon, Sandra Pretlow

Thank You ... Questions?

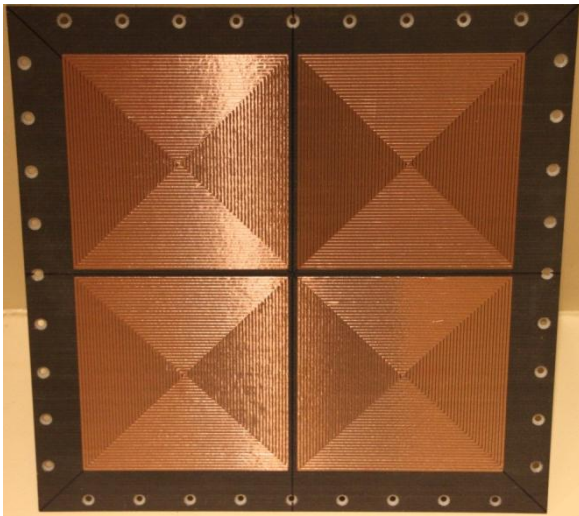
Back Up Slides



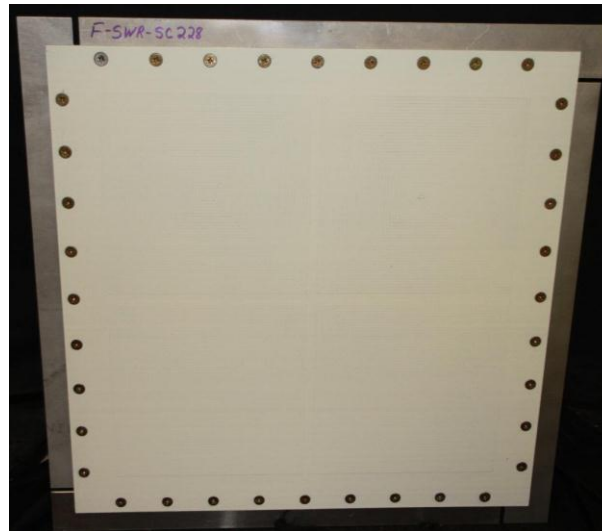
Lightning Experiments – Test Panels

SansEC Fiberglass Reinforced Plastic LSP Test Panels

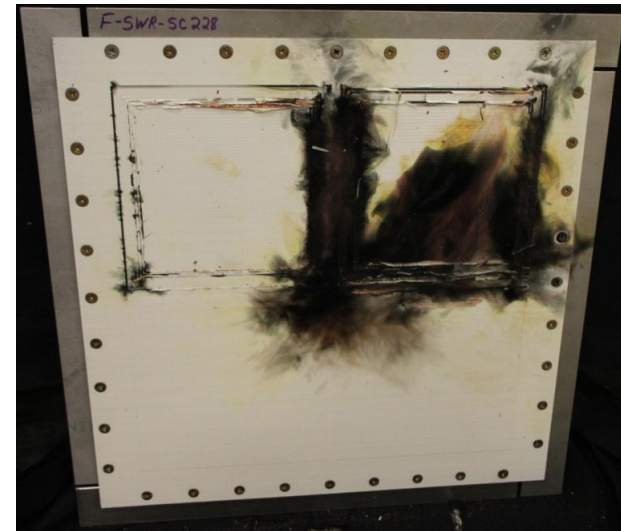
Pre-Paint Test Panel



Pre-Strike Test Panel



Post-Strike Test Panel



8 inch SansEC Array

Lightning Experiments – Substrate Design

Universal Common Practice Guide for Lightning Damage Testing of Composites Panel Design

Layup: 16 ply tape with 2 ply fabric

[(SURF)(ECF)(0/90F)/45/90/-45/0/45/90/-45/0/0/-45/90/45/0/-45/90/45/(0/90F)]

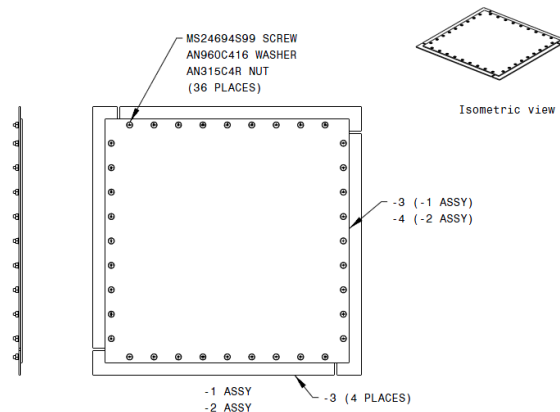
Tape: Hexcel 8552/AS4 (HexPly 8552/AS4),

Fabric: Hexcel 8552/AS4 (HexPly 8552 / A193-PW, 3K-70-PW)

Lightning Protection: Dexmet 3CU7-100FA (3mil copper mesh)

Primer: 0.5-1.5 mils thickness

Top coat: 4 to 6 mils per Mil-F-18264 or equivalent.

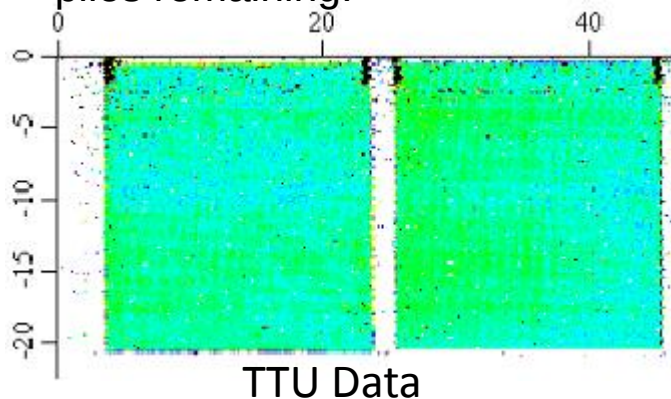


CFRP LSP Test Panel

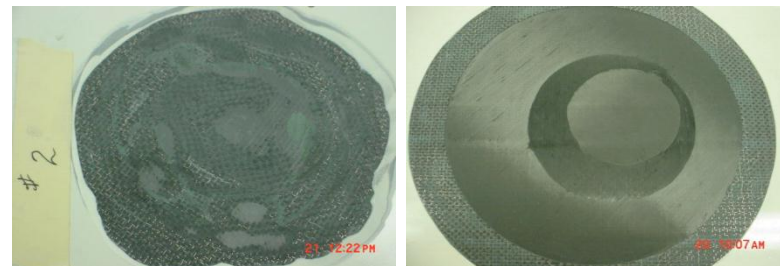
Lightning Experiments – Damage Assessment

Universal Common Practice Guide for Lightning Damage Testing of Composites NDI Assessments

- Pre-Test NDI: Inspect the cured panel with a through transmission ultrasonic (TTU)'C' scan inspection at 5 MHz. A defect is defined as an area with ultrasonic attenuation that is at least 6db larger than the attenuation of the adjacent areas without flaws greater than 0.50 inch in diameter. Multiple defects are allowed, up to three (3) per panel as long as they are at least 1.00 inch apart.
- Post-Test NDI: Pulse-Echo Ultrasonic Assessment, X-ray Assessment (Optional)
 - Areas with ultrasonic attenuation >6dB larger than adjacent areas without flaws or defects.
- Destructive Damage Assessments
 - Taper sand to remove damaged material, use P-E Ultrasonics to verify. Then count plies remaining.



Photos from NASA Document Number: DOC-128697



Damage Assessment

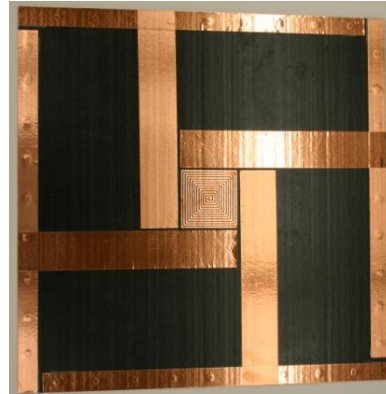
Lightning Experiments – Test Panels



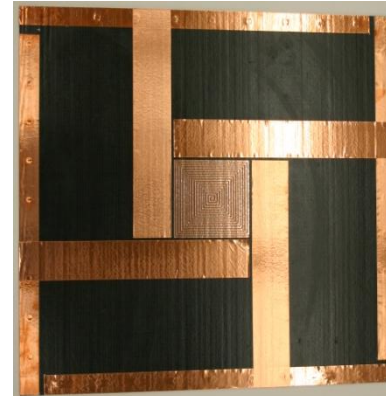
SansEC Test Coupons tested in February 2012



2 in. SansEC LSP-002
LTI TEST #6
Feb 2012



3 in. SansEC LSP-003
LTI TEST #7
Feb 2012



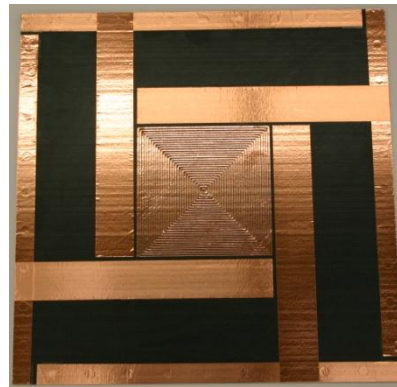
4 in. SansEC LSP-004
LTI TEST #8
Feb 2012



5 in. SansEC LSP-005
LTI TEST #9
Feb 2012



6 in. SansEC LSP-006
LTI TEST #10
Feb 2012



7 in. SansEC LSP-007
LTI TEST #11
Feb 2012



8 in. SansEC LSP-008
LTI TEST #12
Feb 2012

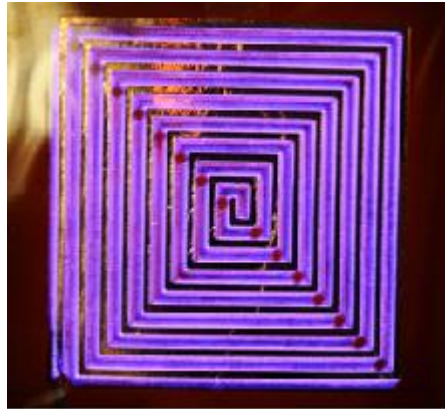
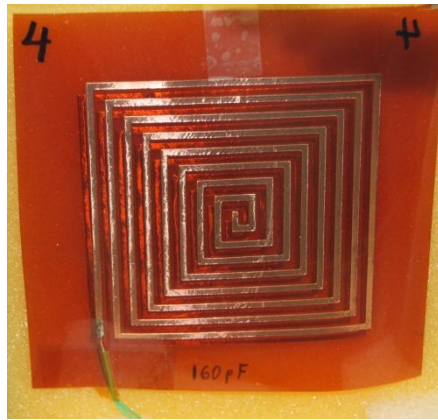


9 in. SansEC LSP-009
LTI TEST #13
Feb 2012

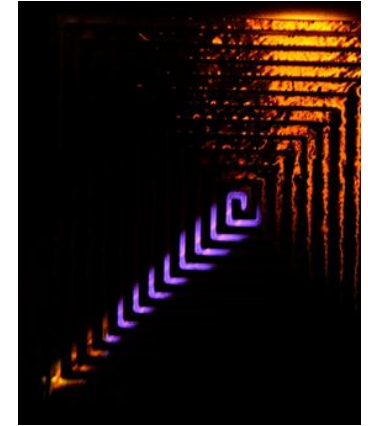
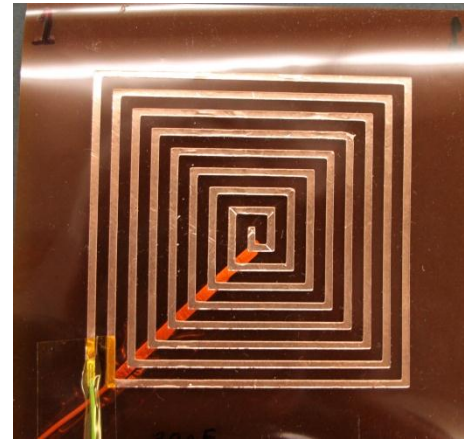
Future Opportunities - Other Applications

- SansEC dielectric barrier discharge (DBD) sensors for sensing and mitigation.

4' SansEC, double sided, offset



4" SansEC, diagonal trace on back



Voltage +/- 10kv

Current

