A Multifunctional Aerospace Smart Skin Emerges from Computational Models and Physical Experiments

Kenneth L Dudley

NASA Langley Research Center

2015 Altair Technology Conference, May 5 - 7, Dearborn, MI

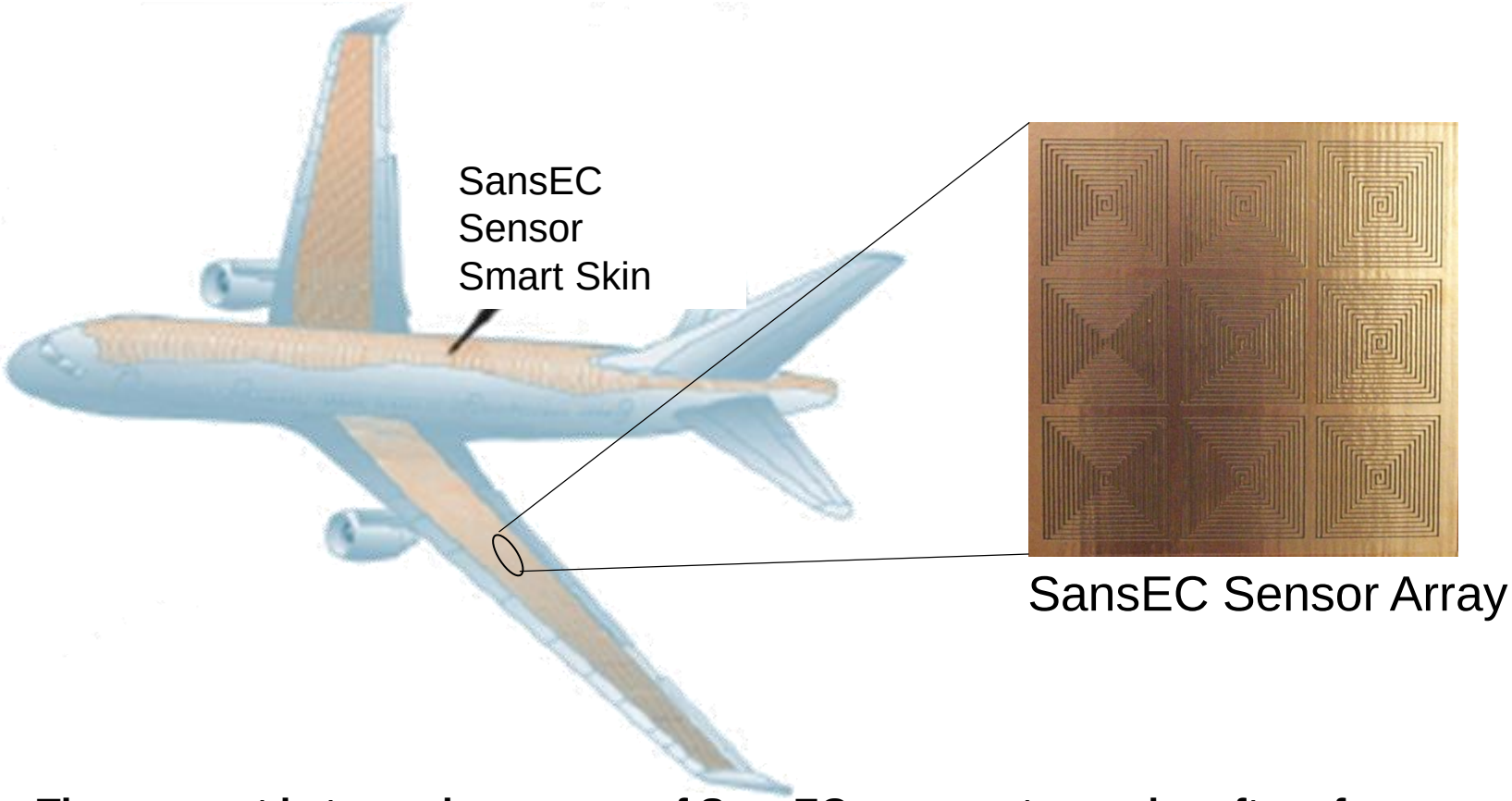
Outline

- Introduction
- A New Multi-Functional Concept
- Theory of Operation
- Lightning Protection
- Damage Detection
- Shielding Effectiveness
- Conclusions

Introduction

- To fully leverage the advantages of composites in new aerospace vehicles and applications requires continuous investigation of novel technologies beyond the current state-of-the-art.
- An open circuit resonant sensor has been developed for the purpose of in-situ damage detection and diagnostics in non-conductive and conductive aerospace composite materials.

A New Multi-Functional "Smart Skin" Concept



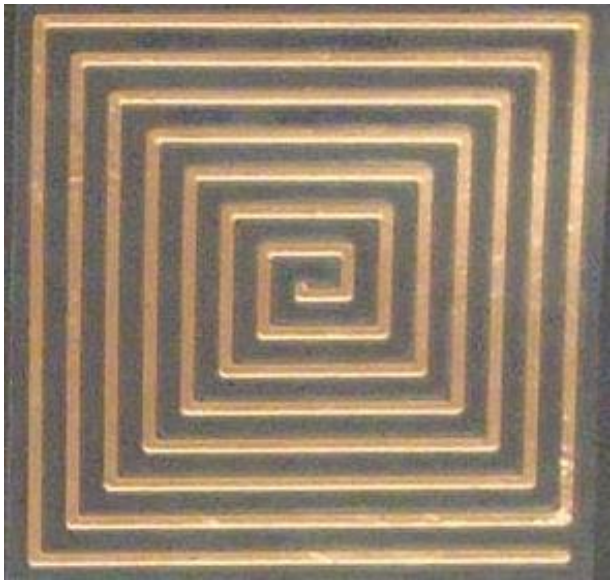
- **The concept is to apply an array of SansEC sensors to an aircraft surface forming a "Smart Skin" layer on the composite.**
- **Lightning Protection, Enhanced Shielding Effectiveness, Damage Detection and Diagnosis functions to composites.**

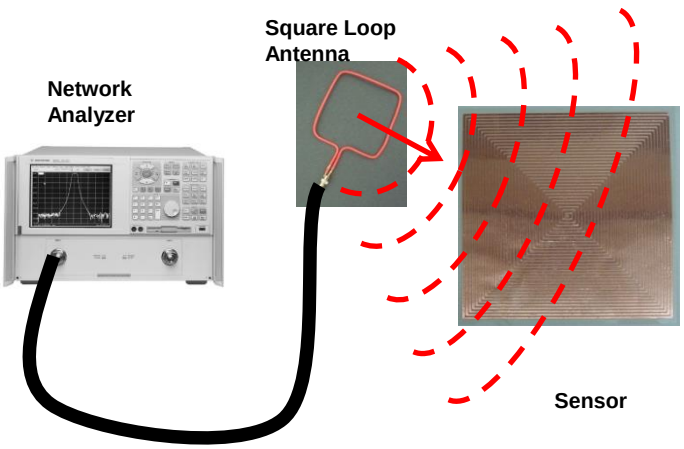
A New Multi-Functional "Smart Skin" Concept

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

- Replaces existing conductive LSP
- Sensor functions after damage
- Ability to steer lightning currents

What is SansEC…?





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

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.

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

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

A SansEC “Smart Skin” for Lightning Strike Protection

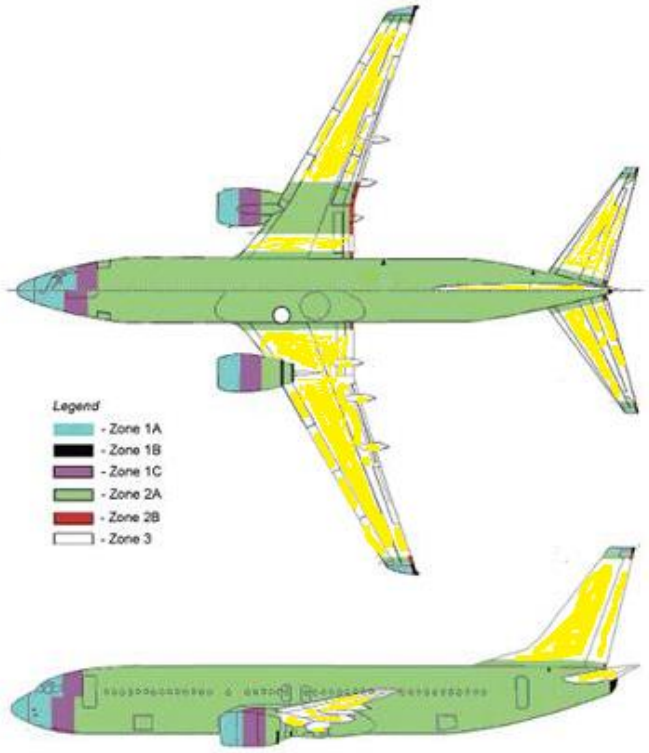
Atmospheric Environment Safety Technologies (AEST) Project

Atmospheric Hazard Sensing & Mitigation (AHSM) Task

Lightning Electromagnetic Effects & Mitigation (LEEM) Element

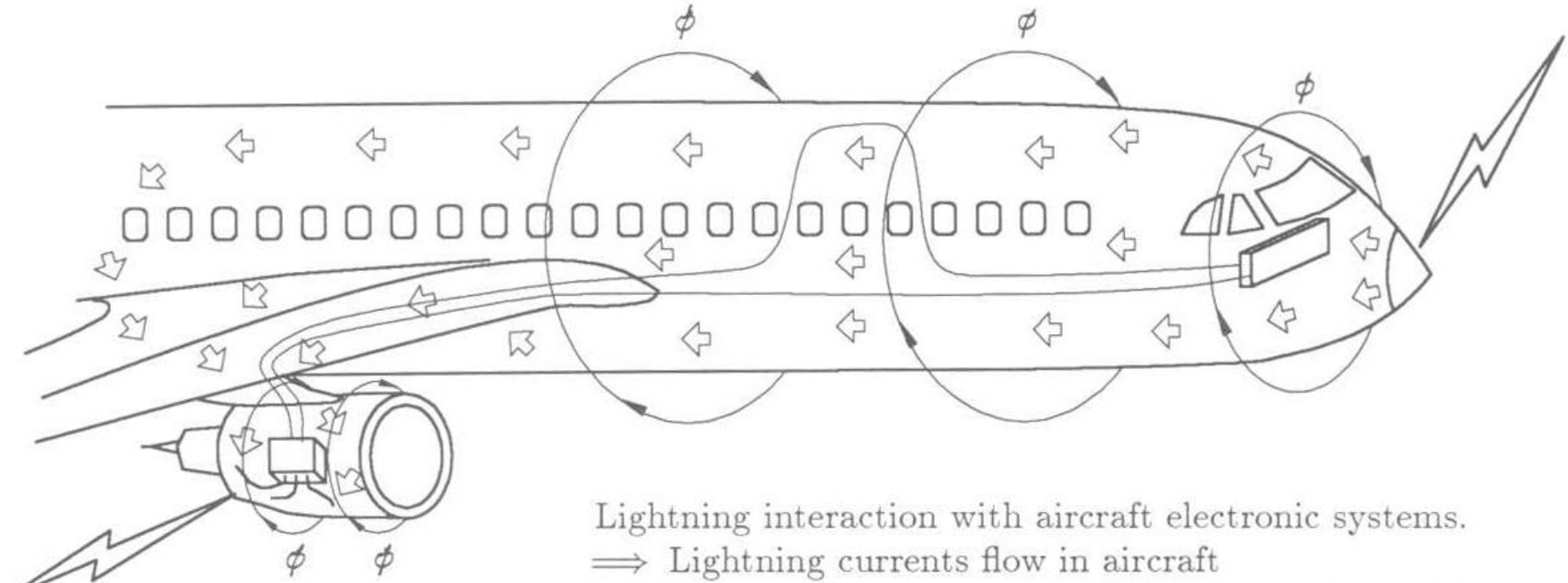
A SansEC “Smart Skin” for Lightning Strike Protection

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	



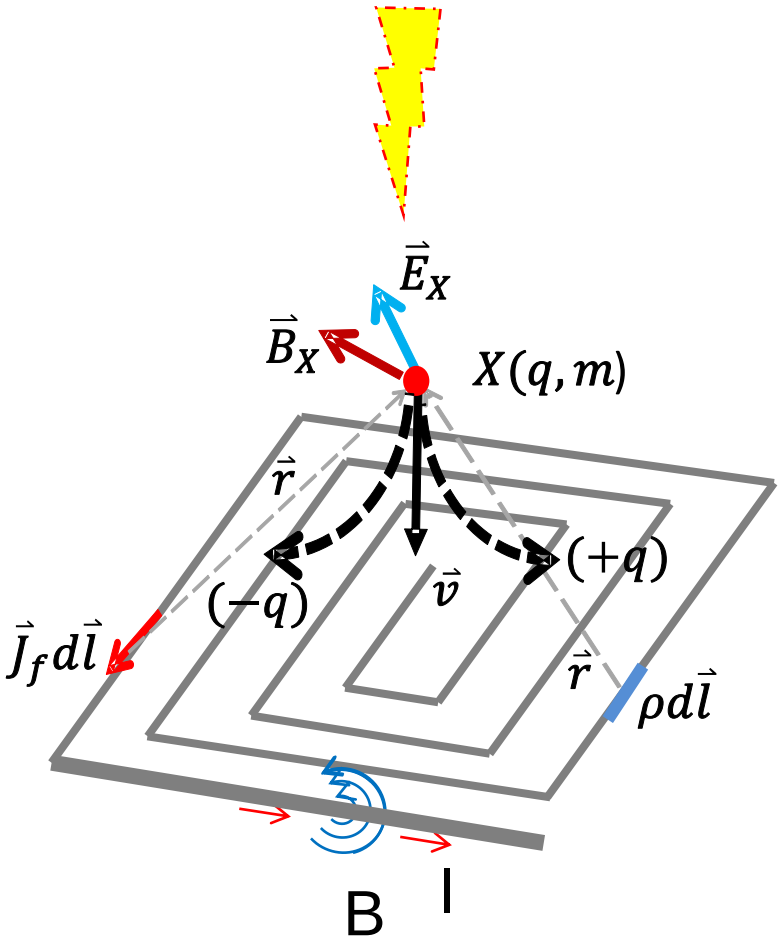
ARP5412- APPLICATION OF LIGHTNING ENVIRONMENT TO AIRCRAFT ZONES

A SansEC “Smart Skin” for Lightning Strike Protection

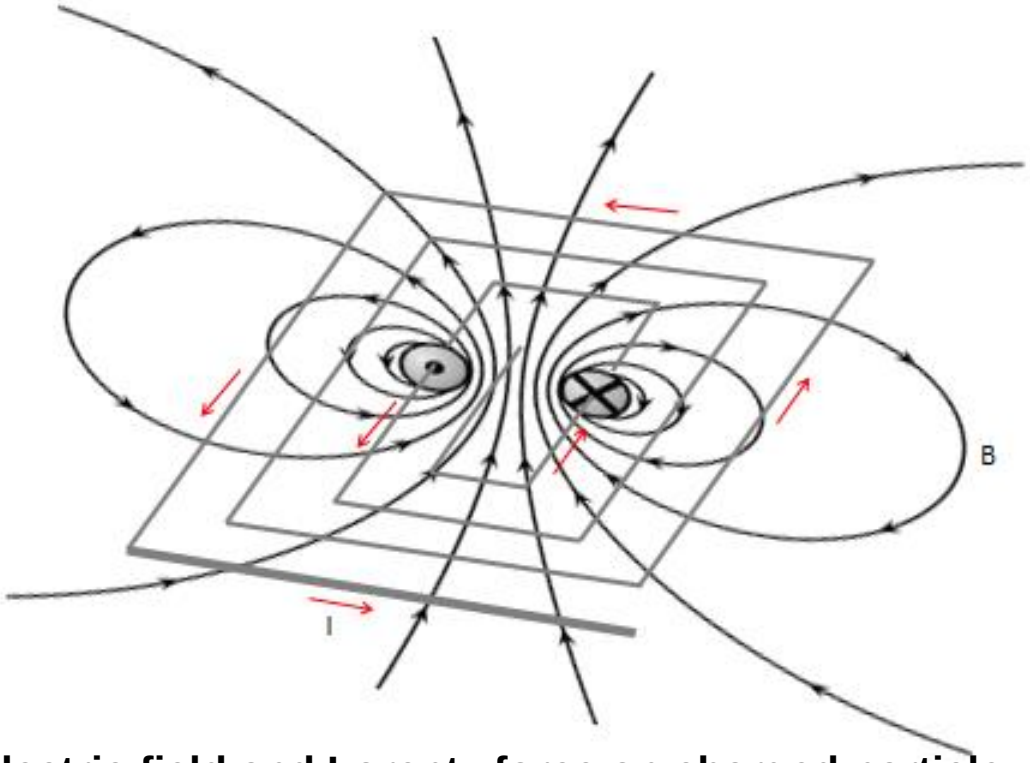


Lightning interaction with aircraft electronic systems.
$\Longrightarrow$ Lightning currents flow in aircraft
ϕ Magnetic flux interacts with interconnecting cables

A SansEC "Smart Skin" for Lightning Strike Protection

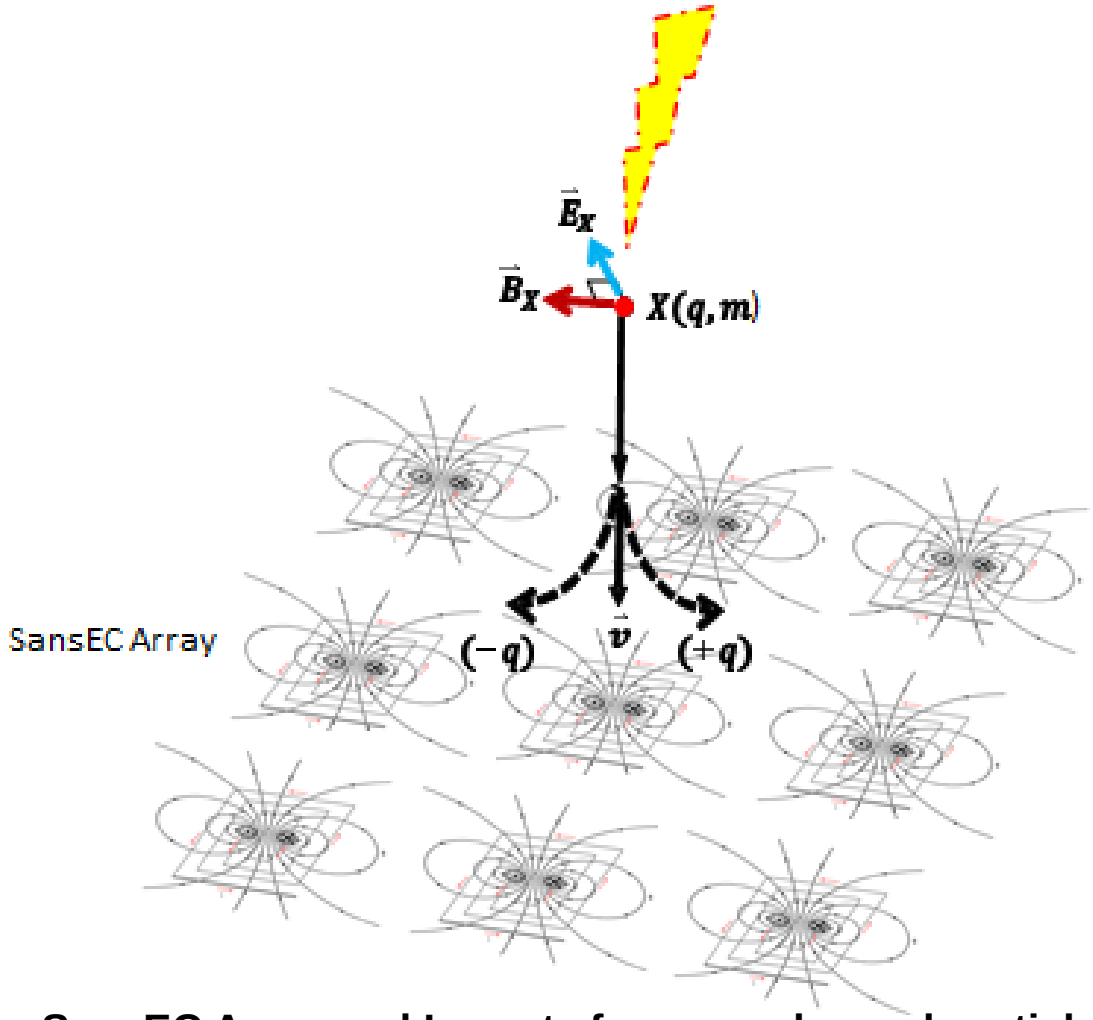


$$\vec{F} = q(\vec{v} \times \vec{B}_X + \vec{E}_X)$$



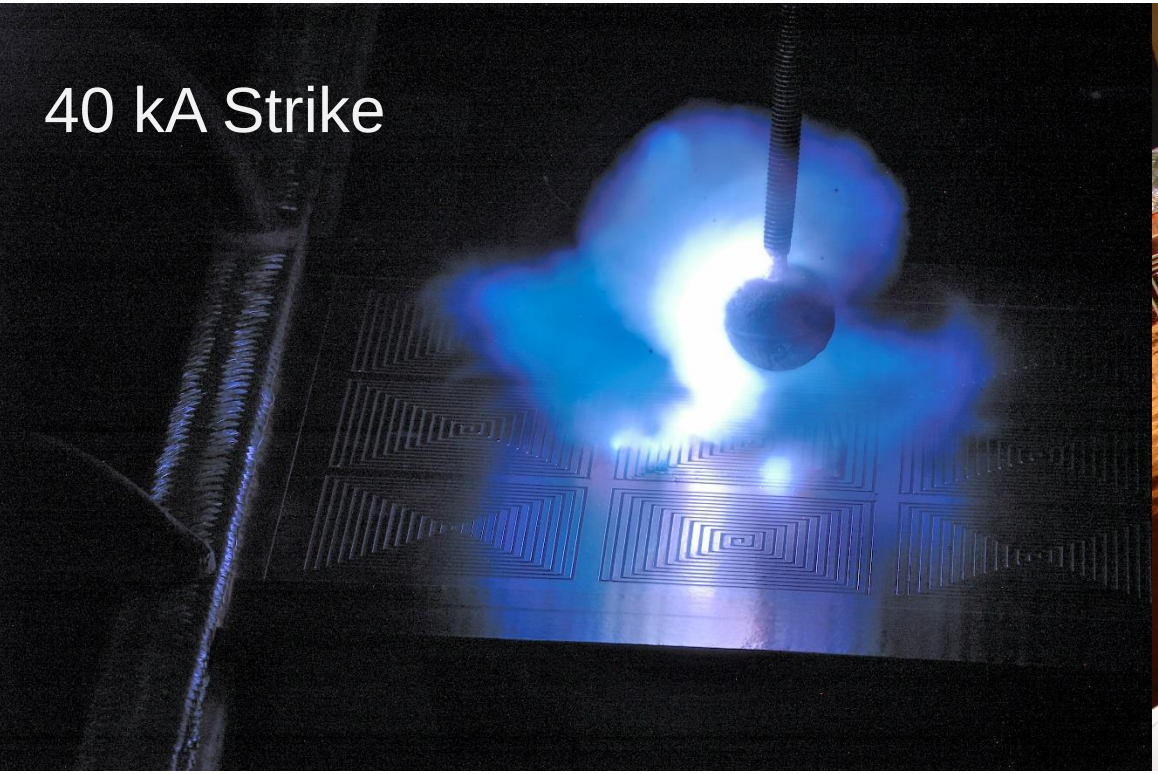
SansEC generated magnetic and electric field and Lorentz force on charged particle

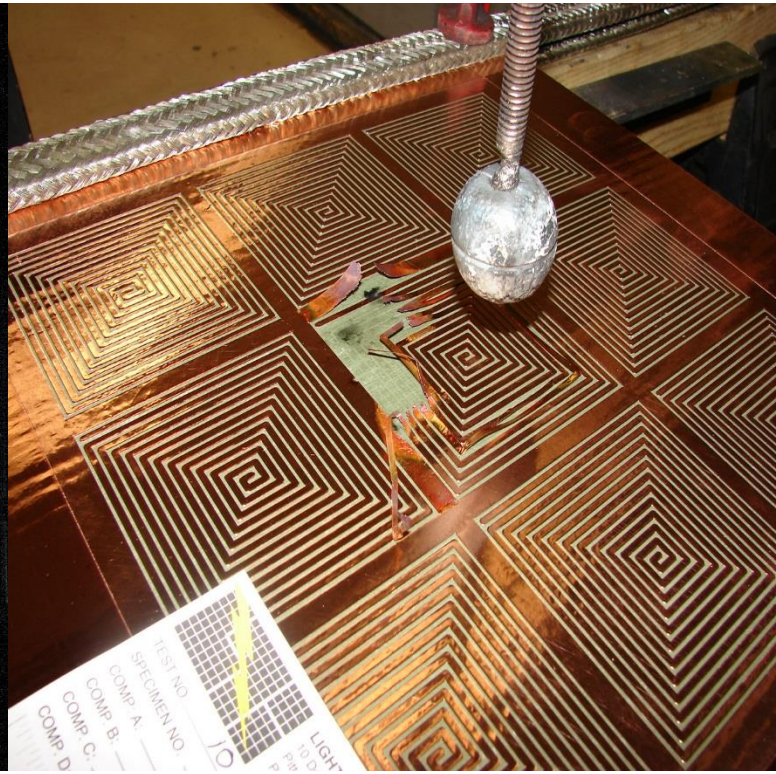
A SansEC “Smart Skin” for Lightning Strike Protection



SansEC Array and Lorentz force on charged particle

A SansEC “Smart Skin” for Lightning Strike Protection



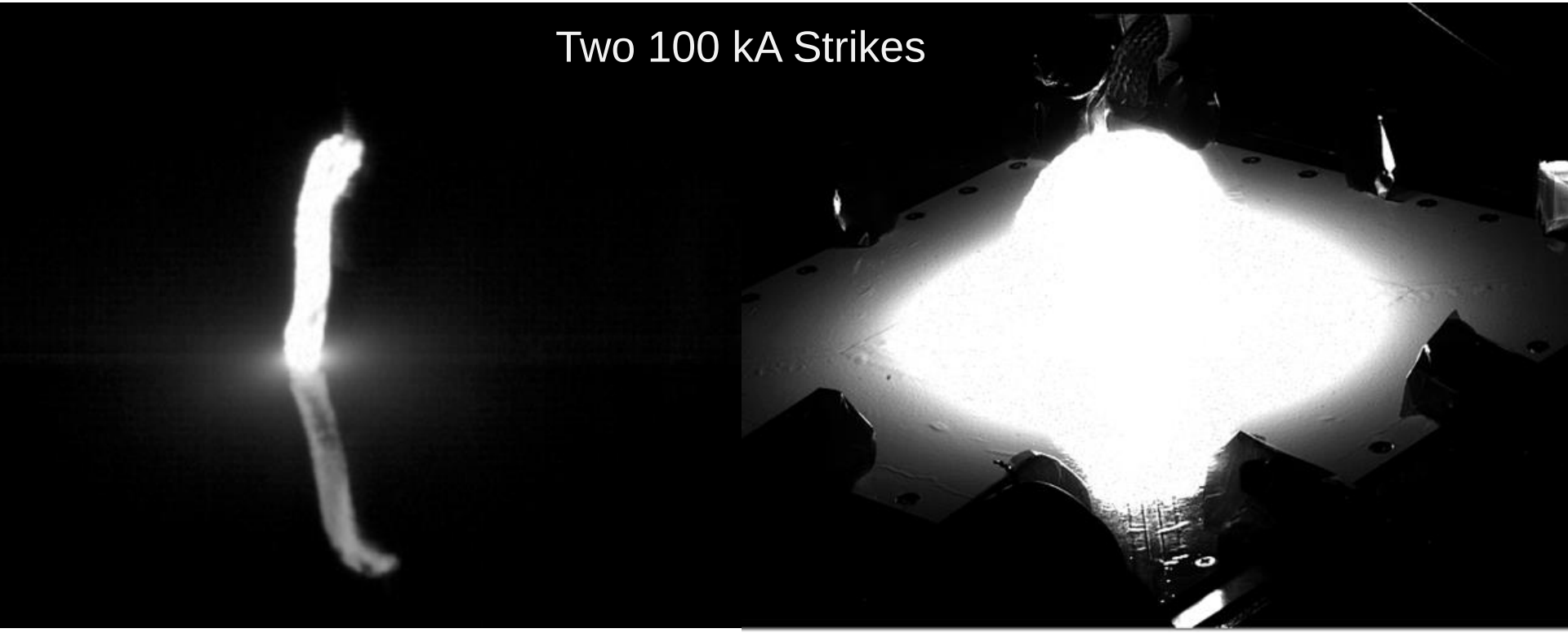


Test Strike on Panel

Post-Strike Test Panel

3 inch SansEC 3x3 Array

A SansEC “Smart Skin” for Lightning Strike Protection



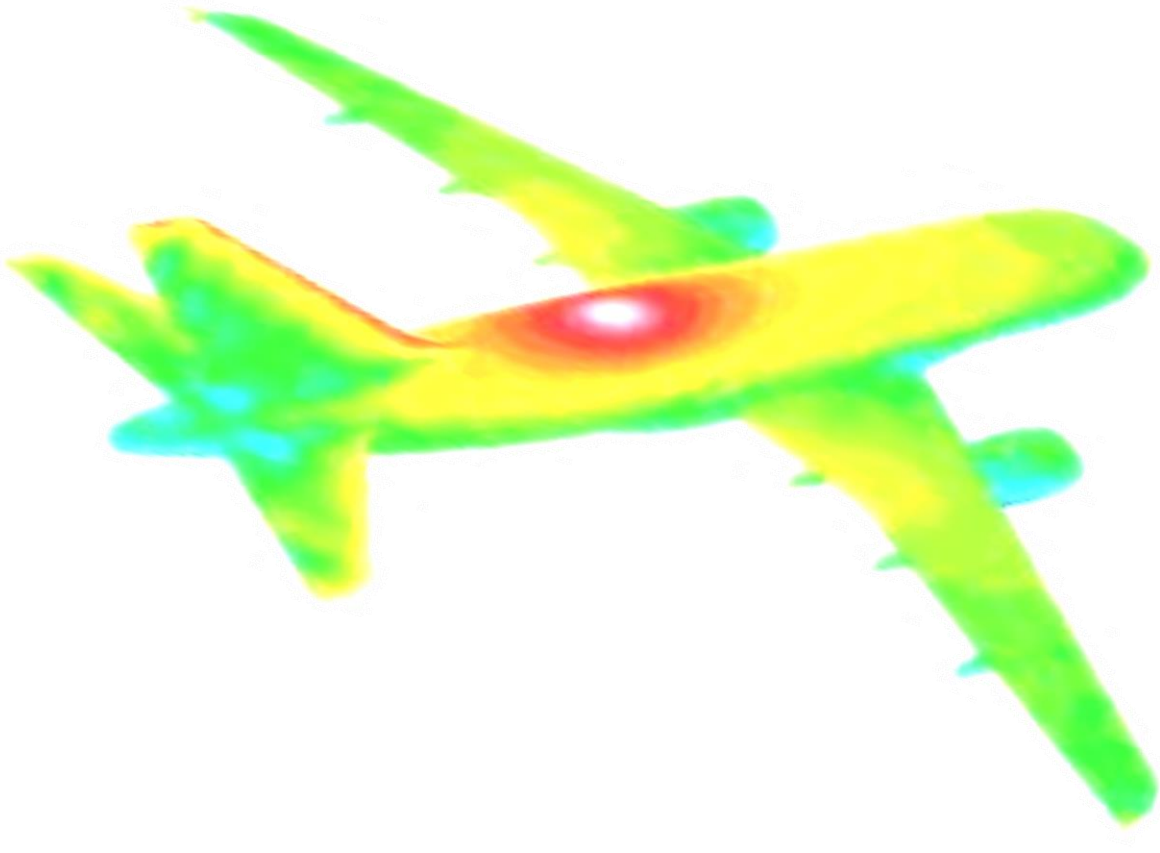
High Speed Video First Frame showing Lightning Strike Initial Attachment on Mesh Protected CFRP Panel

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

A SansEC “Smart Skin” for Lightning Strike Protection

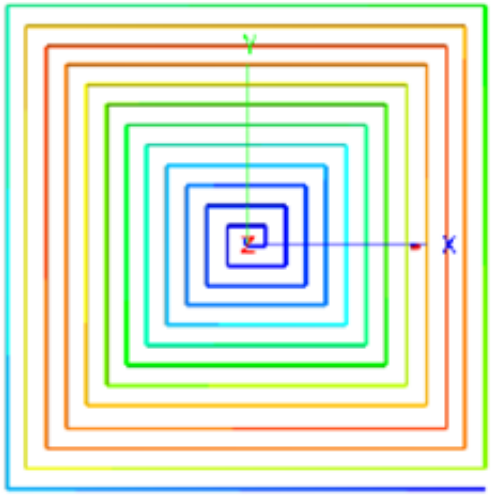
- Develop tools and test procedures to quantify lightning damage mechanisms, capture current direction, thermal & mechanical parameters
- Develop mitigation strategies to improve aircraft lightning protection designs through passive or active methods.
- Develop & validate lightning damage models (with NASA Glenn, Boeing & NIAR)

A SansEC “Smart Skin” for Damage Detection



Lightning induced Damage Insult

Theory of Operation



Current Distribution

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

Charge Distribution

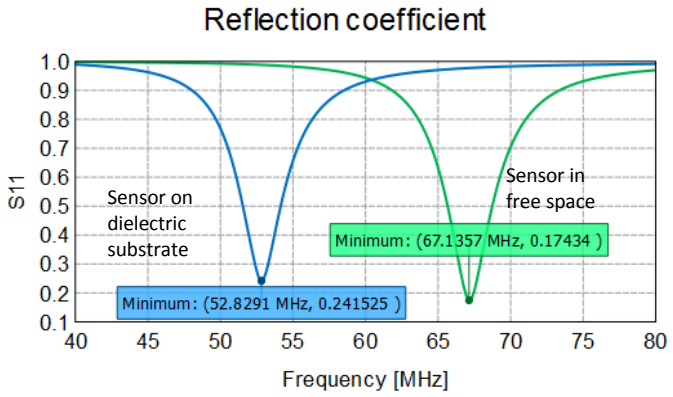
$$q = q_0 sin(\frac{\pi x}{l}) e^{-i(\omega t + \frac{\pi}{2})}$$

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

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

$$C^{-1} = \frac{1}{4\pi \varepsilon_0 \varepsilon_r |q_0|^2} \iint \frac{\boldsymbol{\rho}(\mathbf{r}) \cdot \boldsymbol{\rho}(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} d\mathbf{r} d\mathbf{r}'$$

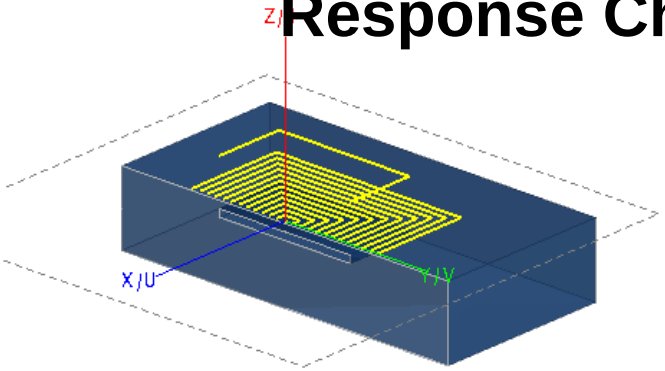
Un-damped Resonance Inductive–Capacitive circuit



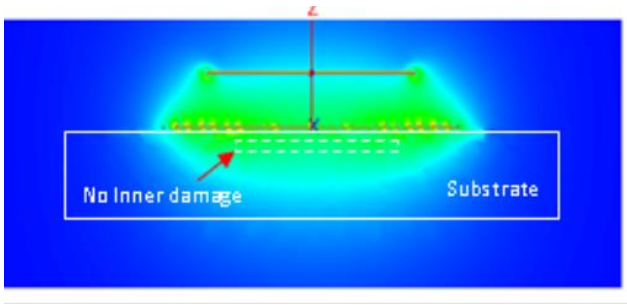
$$\omega = \frac{1}{\sqrt{LC}}$$

A SansEC "Smart Skin" for Damage Detection

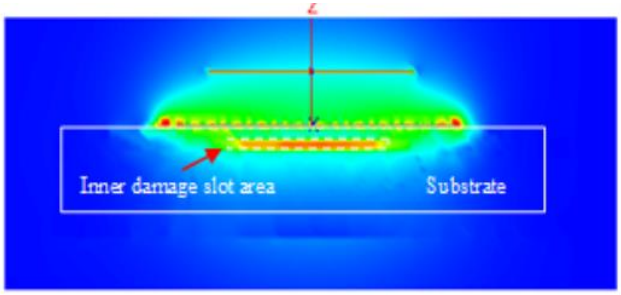
Response Characteristics of Internal Damage



Inner damage model

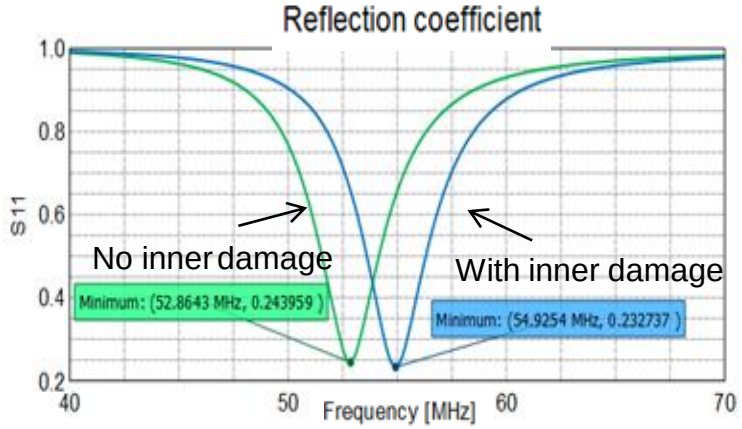


Electric field distribution
No Damage (ε_r=3)



Electric field distribution
With Damage (ε_r=3)

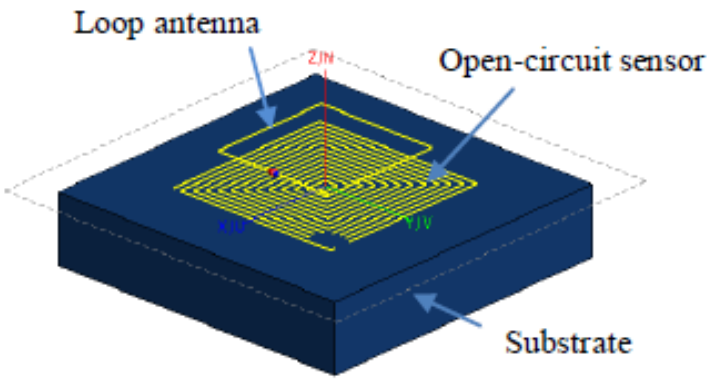
For this case Substrate is FRP
Electric Field Penetration
Dominant Mode Excitation
Tenth inch free space slot Damage
Resonant Frequency Shift



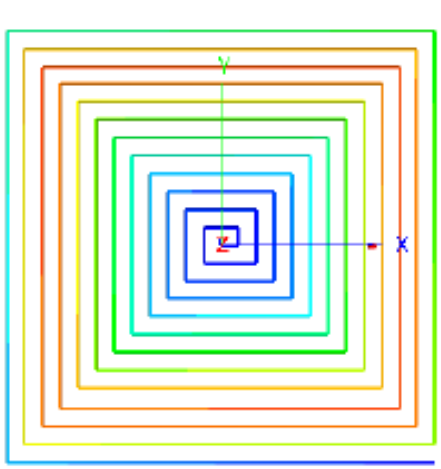
Computed SansEC resonant response

A SansEC “Smart Skin” for Damage Detection

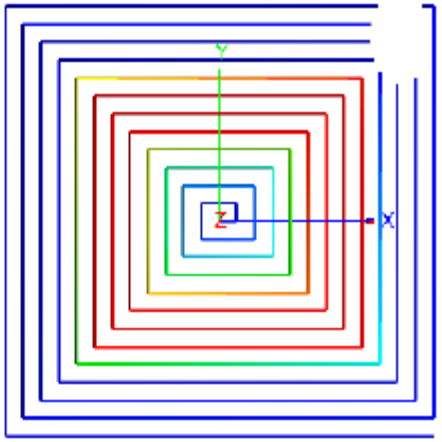
Response Characteristics of Surface Damage



Damaged Sensor
On Dielectric Substrate

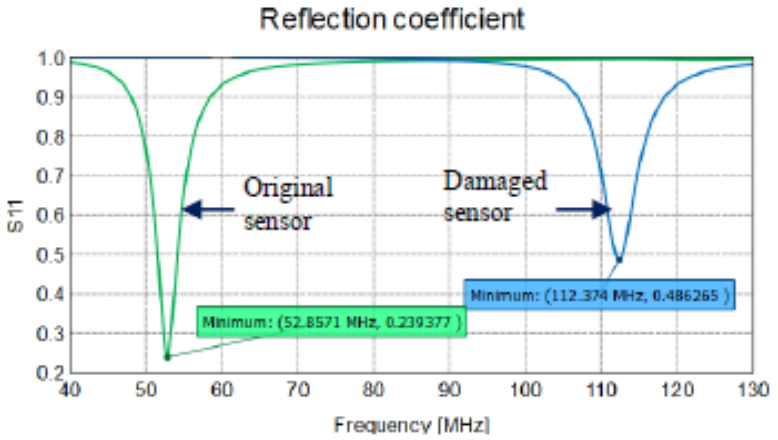


Un-damaged Sensor
Current Distribution



Damaged Sensor
Current Distribution

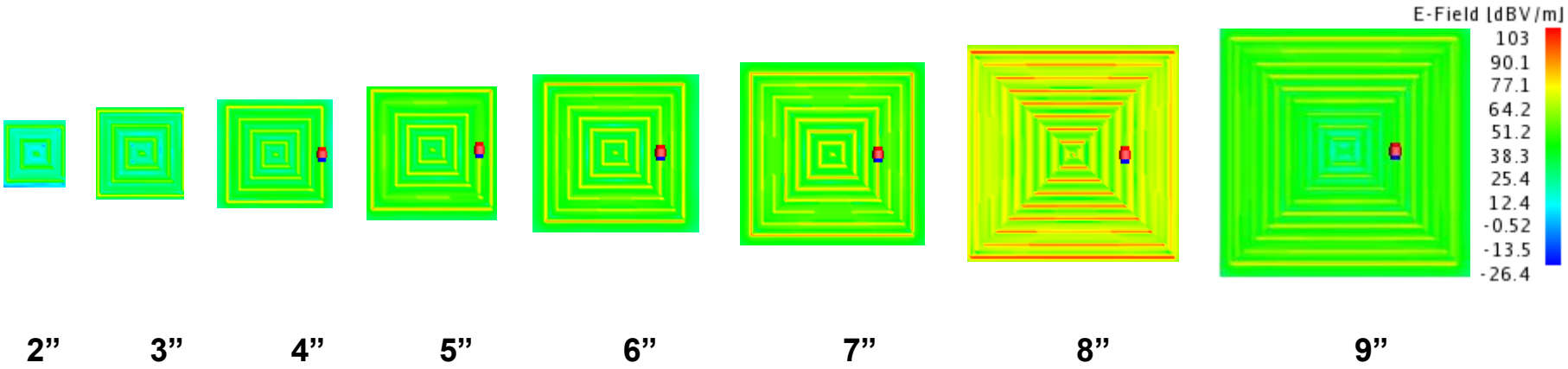
For this case Substrate is FRP
Sensor Resilience when Damaged
Cosine Current Distribution
Dominant Mode Excitation
Resonant Frequency Shift

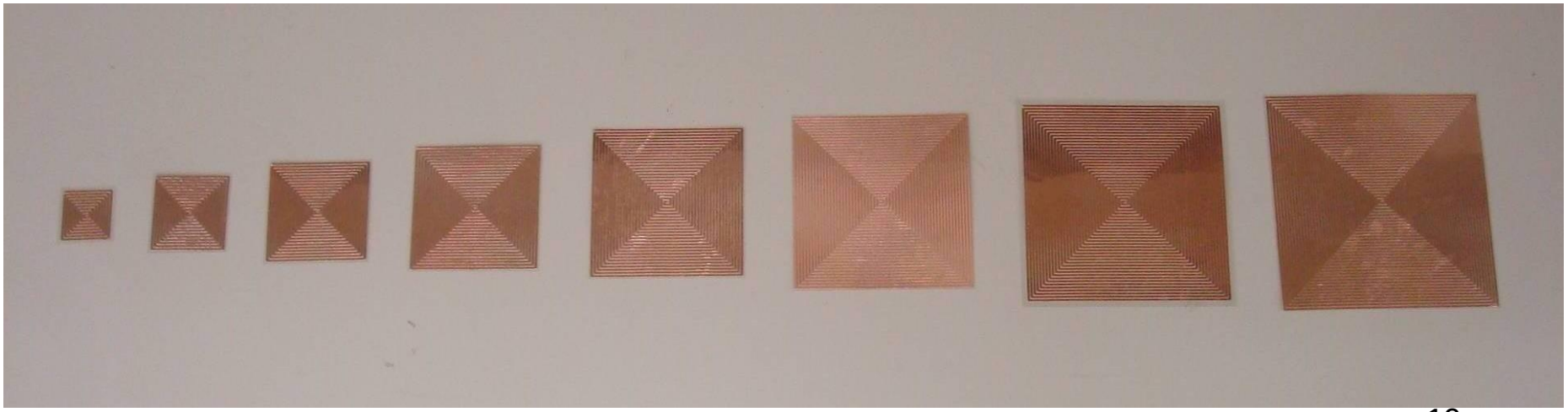


Computed SansEC resonant response

A SansEC “Smart Skin” for Damage Detection

Realistic SansEC Sensor Models

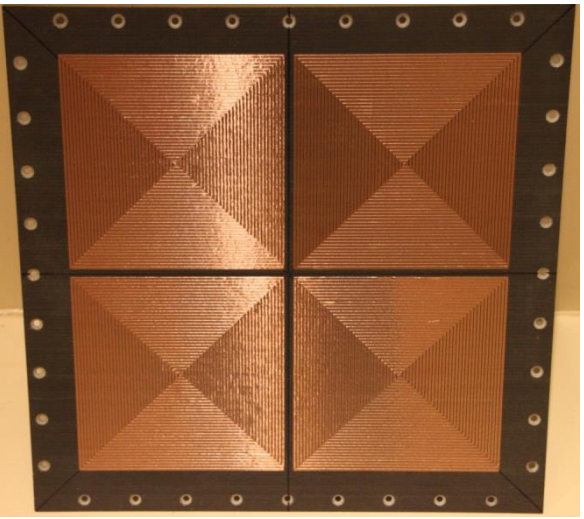




A SansEC “Smart Skin” for Damage Detection

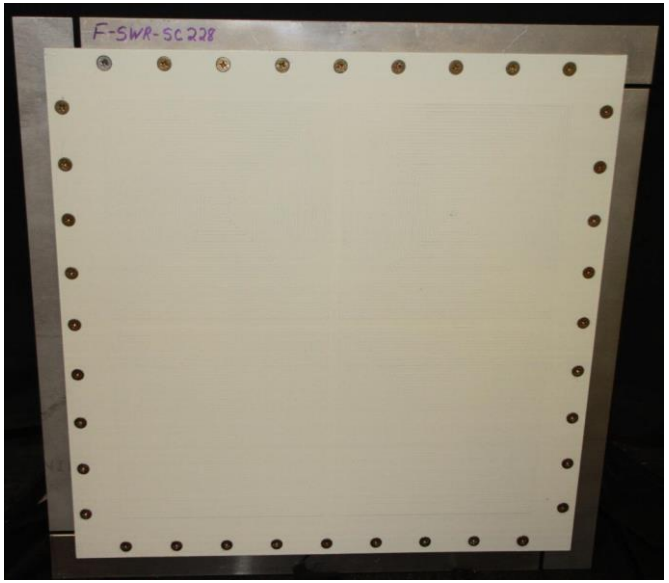
Real SansEC FRP Test Panels

Pre-Paint Test Panel

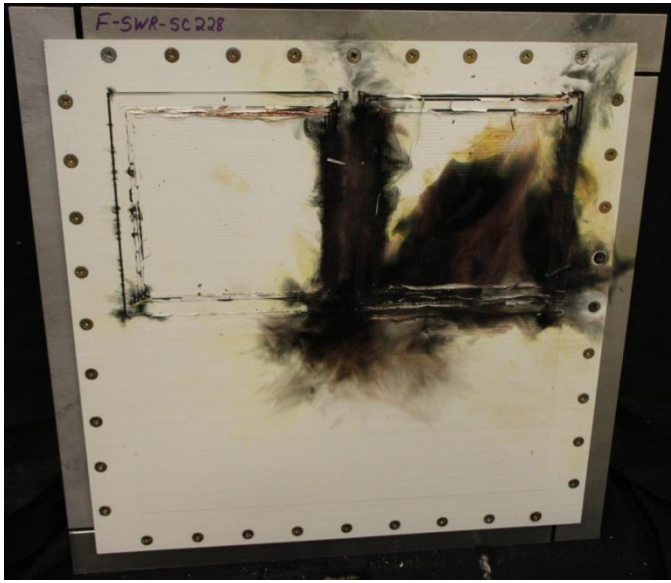


8 inch SansEC Array

Pre-Strike Test Panel



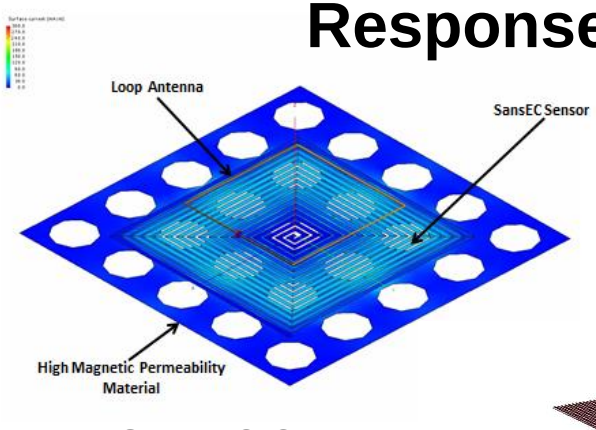
Post-Strike Test Panel



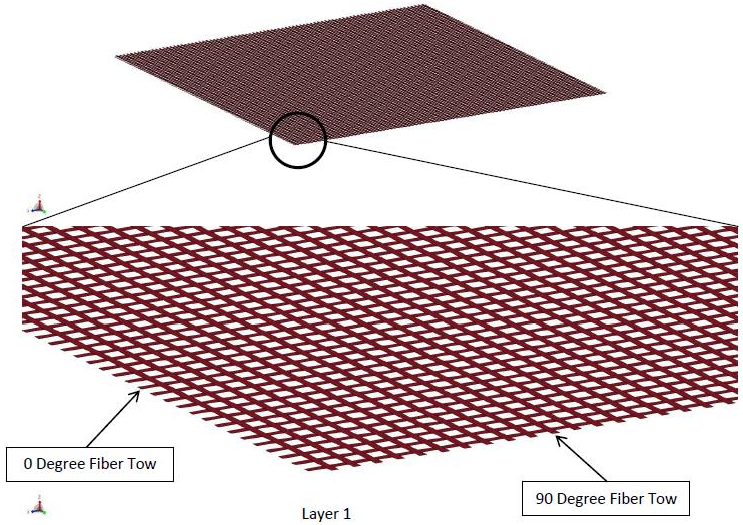
Visual Damage Assessment

A SansEC "Smart Skin" for Damage Detection

Response Characteristics of CFRP Damage

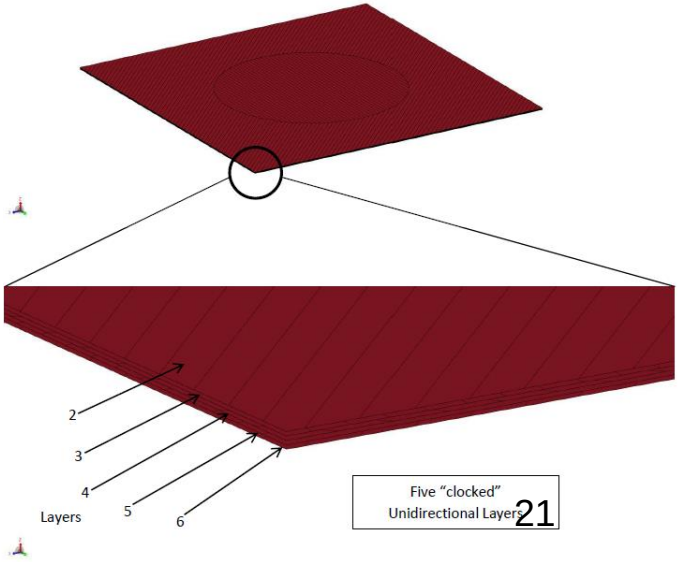


SansEC CFRP
High Permeability
Impedance Coupling

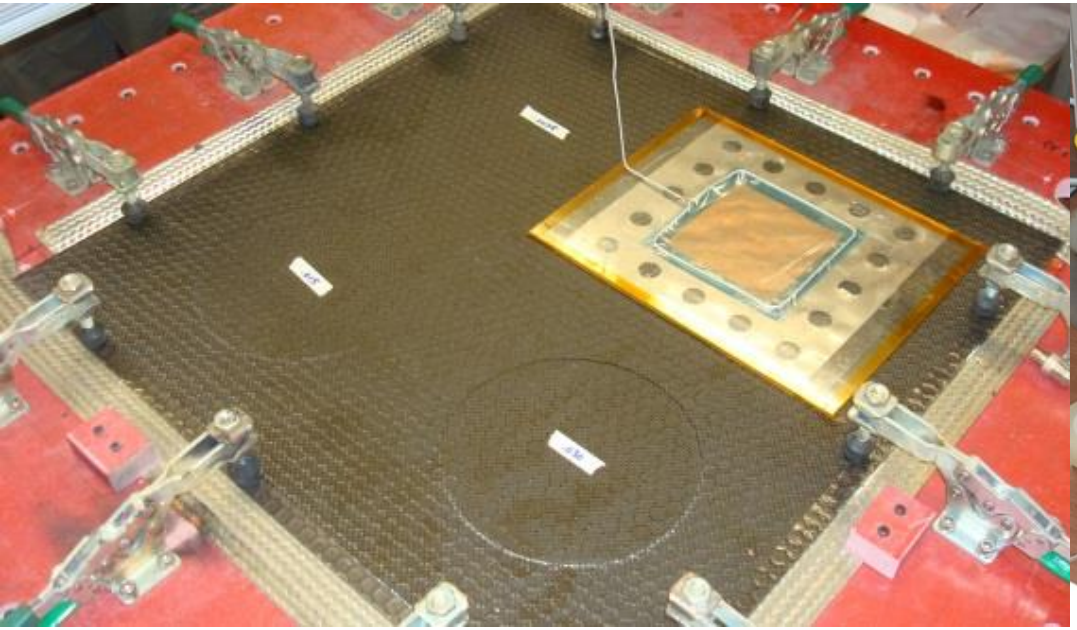


Hexcel Hexply
8552/A193-PW.3K-70-PW
Plain Weave Fabric

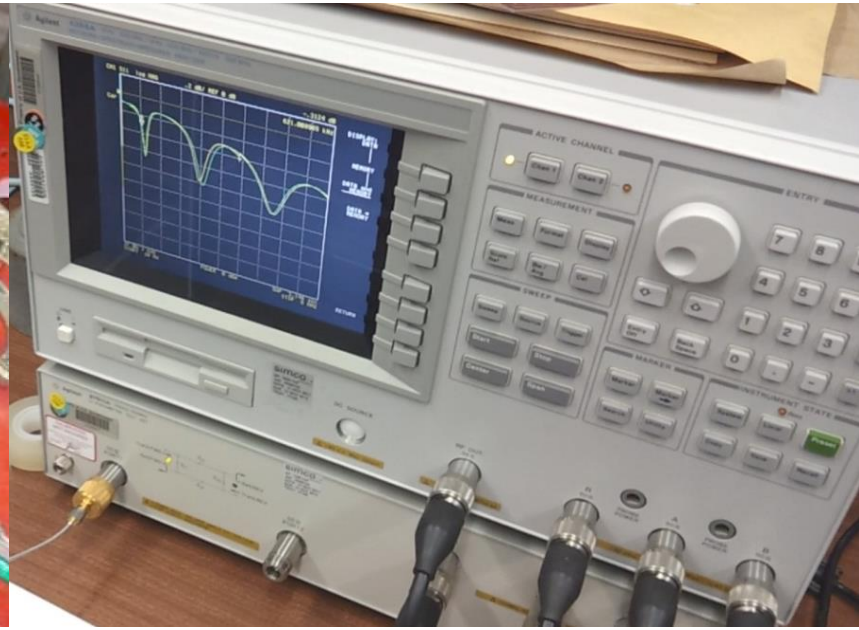
Hexcel Hexply
8552/AS4
Unidirectional Tapes



A SansEC “Smart Skin” for Damage Detection



SansEC Laboratory Experiment

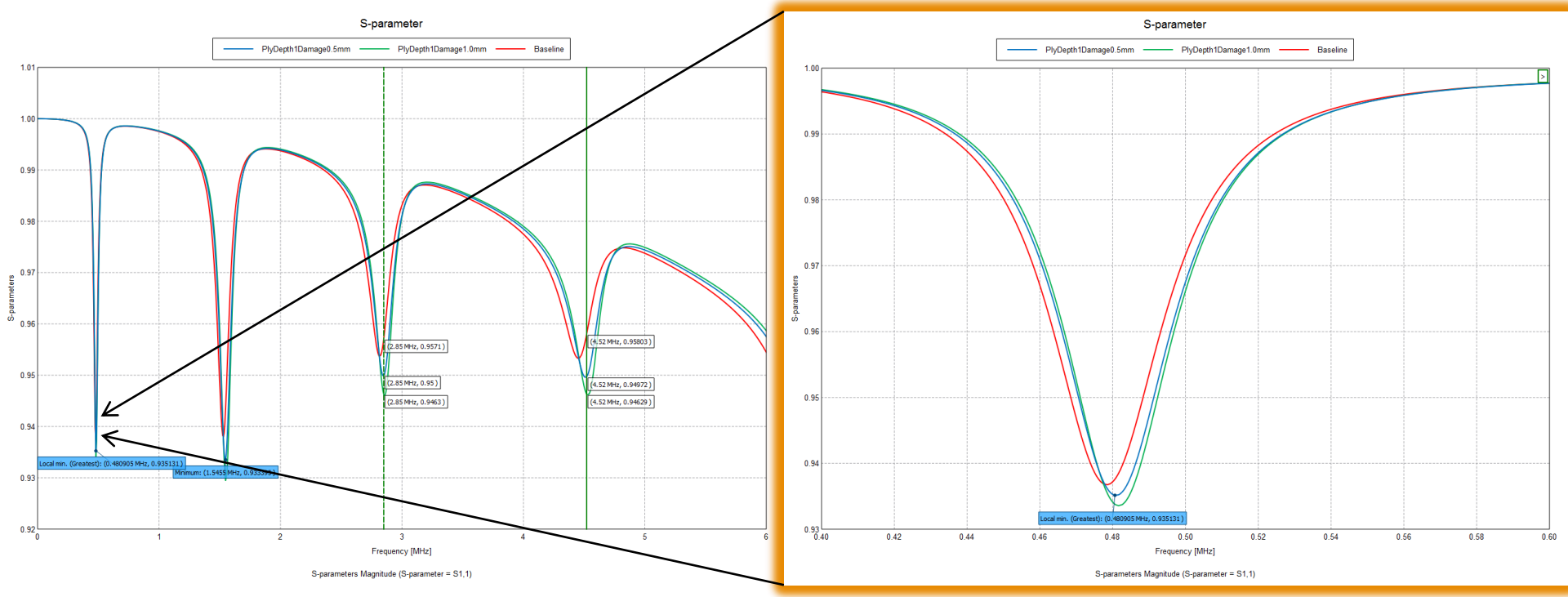


PNA Measurement

Seeded Fault Delamination Experimental Setup

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

A SansEC “Smart Skin” for Damage Detection

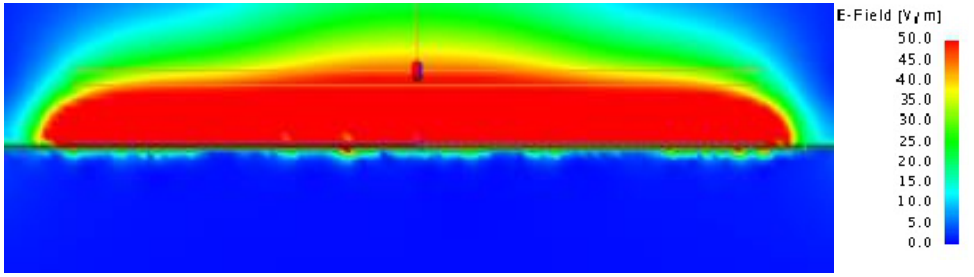


Damage Signature through Scattering Parameters

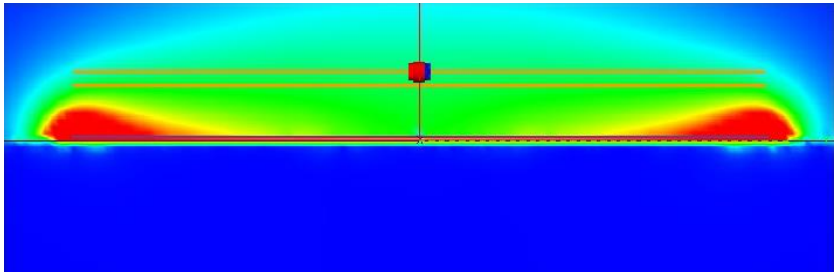
Seeded Fault Delamination Hexcel CFRP Test Panel
Baseline, Small, Medium, Large, Delaminations

A SansEC "Smart Skin" for Damage Detection

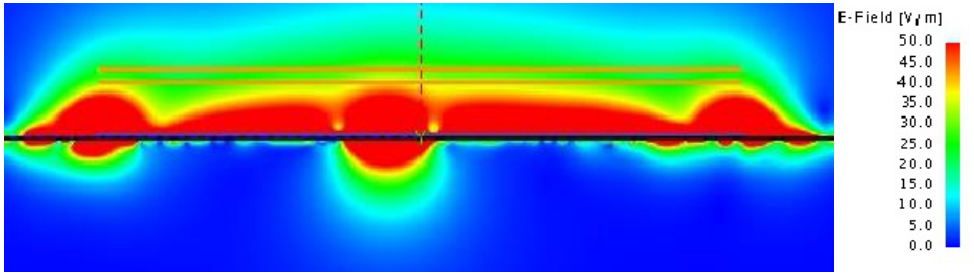
Response Characteristics of CFRP Damage



Delamination

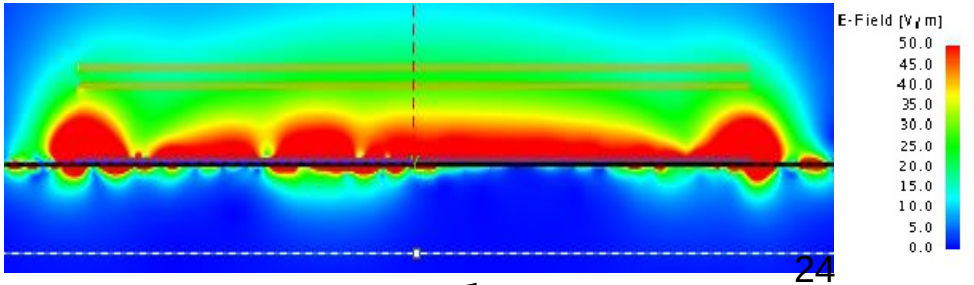


No Damage



Puncture

Electric Field Visualizations

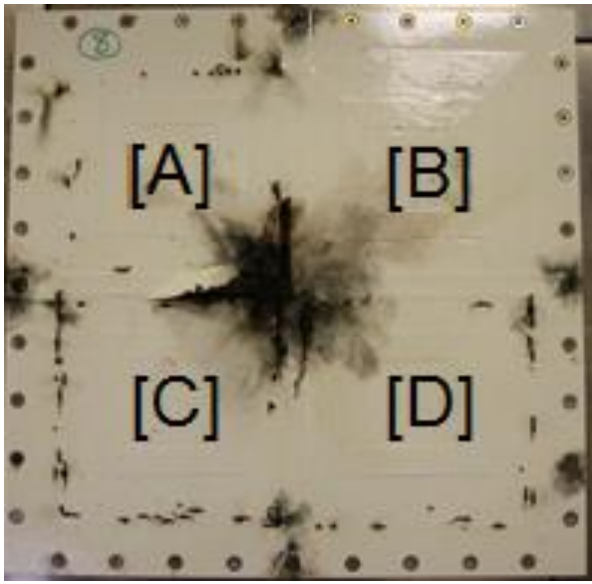


Void

A SansEC “Smart Skin” for Damage Detection

8 inch SansEC Array (before paint)

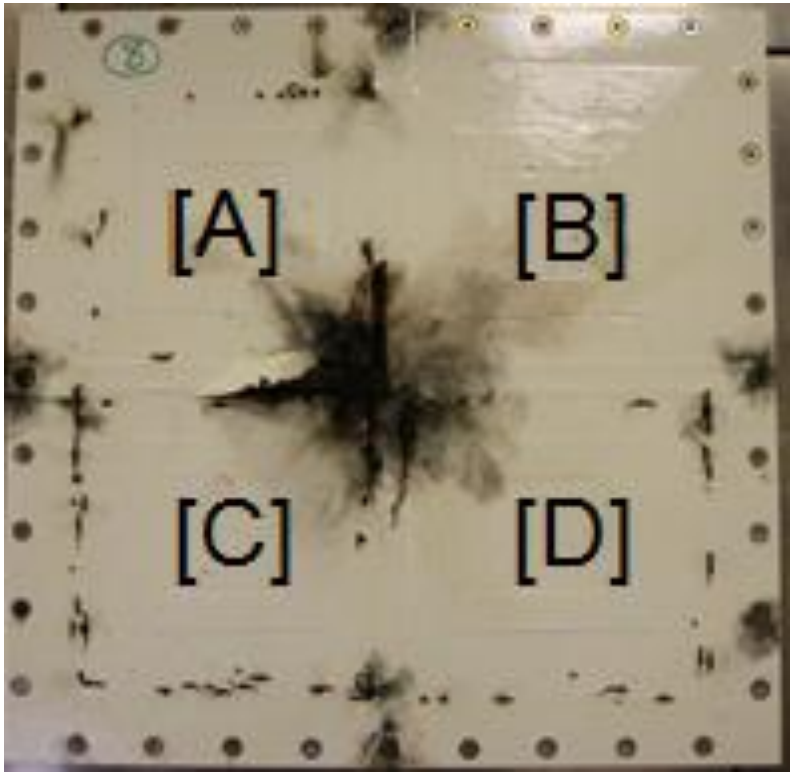
Pre-Strike Test Panel (with Aerospace Paint)

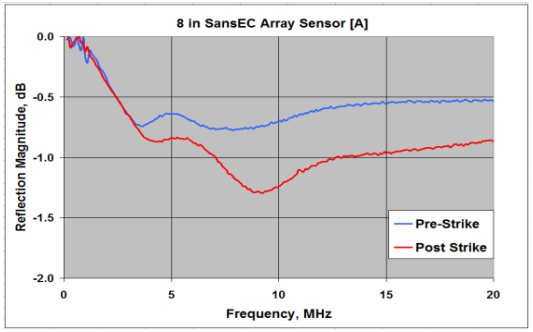


Post-Strike Test Panel

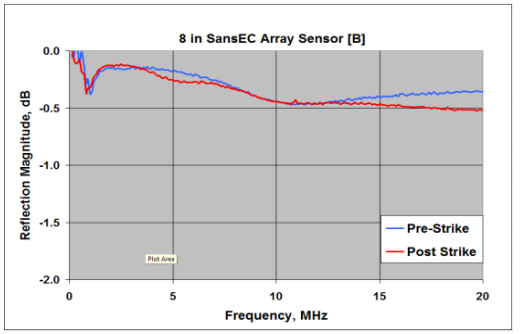
Real SansEC CFRP Test Panels

A SansEC “Smart Skin” for Damage Detection

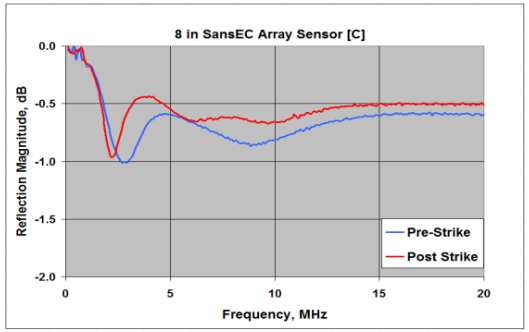




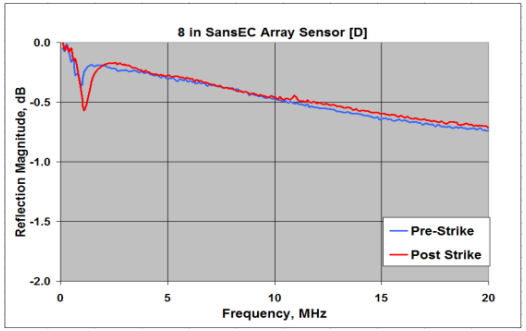
(A) Sensor A upper left quadrant.



(B) Sensor B upper right quadrant.



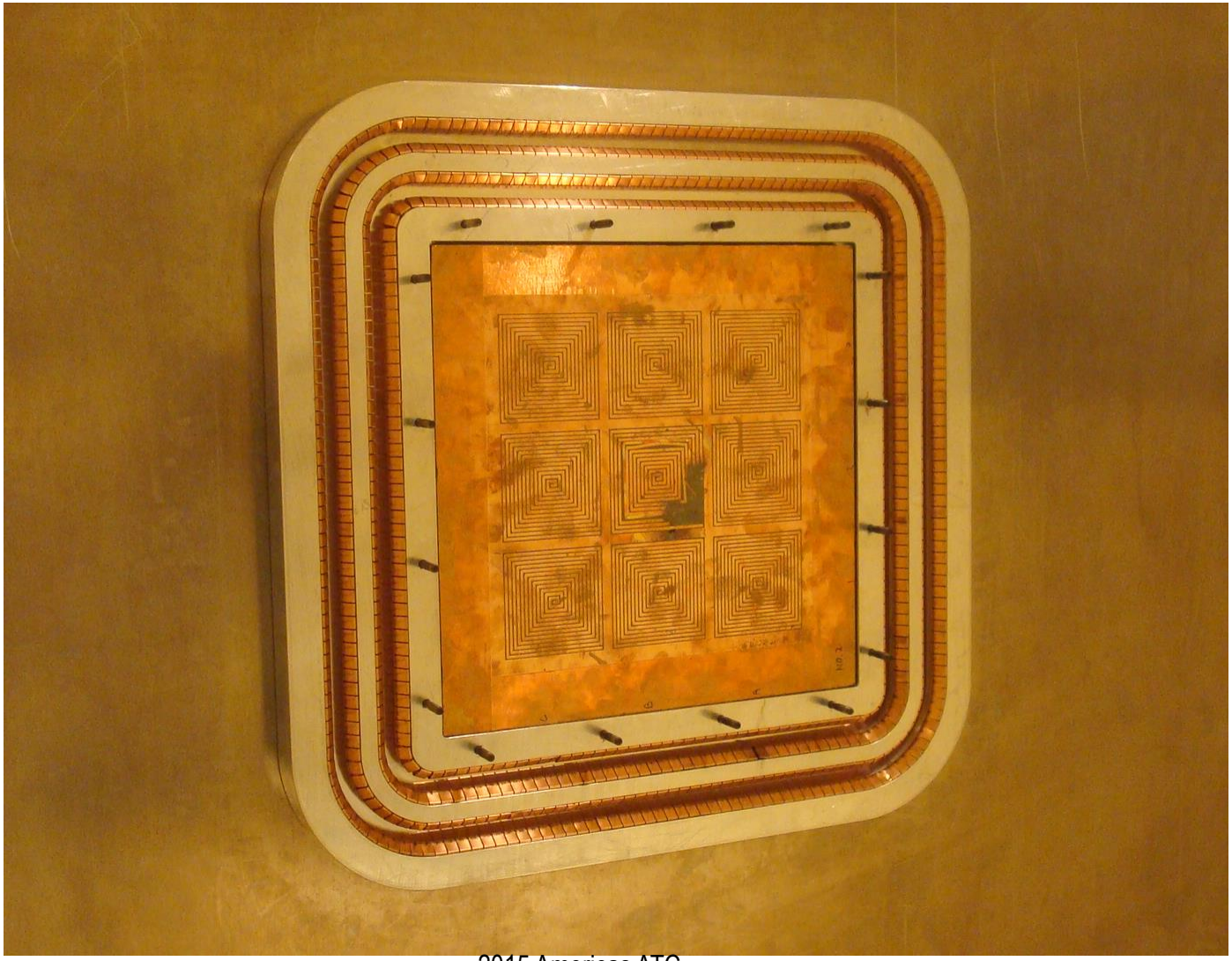
(C) Sensor C bottom left quadrant.



(D) Sensor D bottom right quadrant.

Reflection coefficient plots for the four sensors 8 in SansEC Sensor Array LSP test panel showing pre and post lightning strike.

A SansEC “Smart Skin” for EMI Shielding Effectiveness

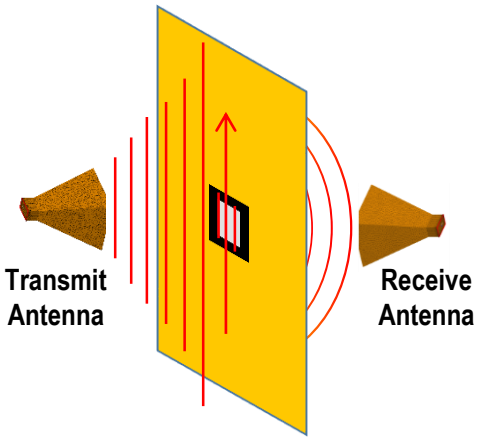


A SansEC "Smart Skin" for EMI Shielding Effectiveness

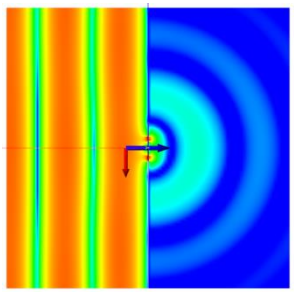
Shielding Effectiveness of SansEC Sensors

- The shielding effectiveness of an aircraft structure is defined as the logarithmic ratio of the electromagnetic field strength from a propagating plane wave outside of the aircraft to the field strength inside the aircraft.

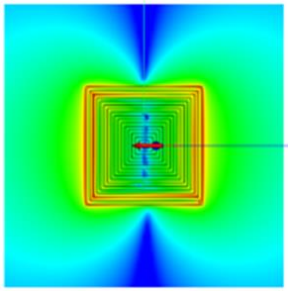
$$SE_{\mathrm{dB}} = 20 \log_{10} \frac{F_b}{F_a}$$



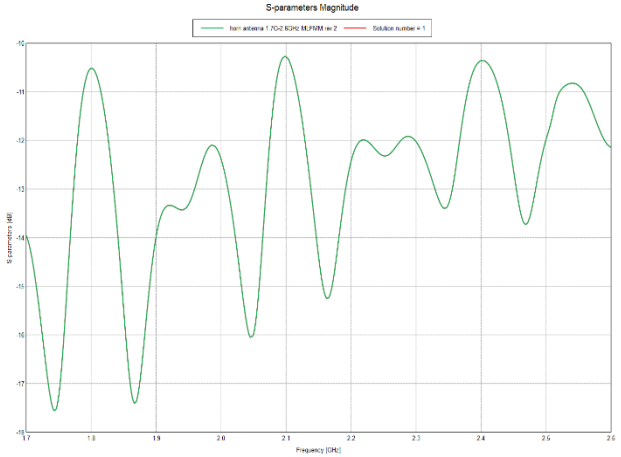
Perfect Electrical Conducting Boundary (PEC)



Incident Plane Wave on PEC Boundary Thru SansEC Aperture



Resulting SansEC Surface Currents

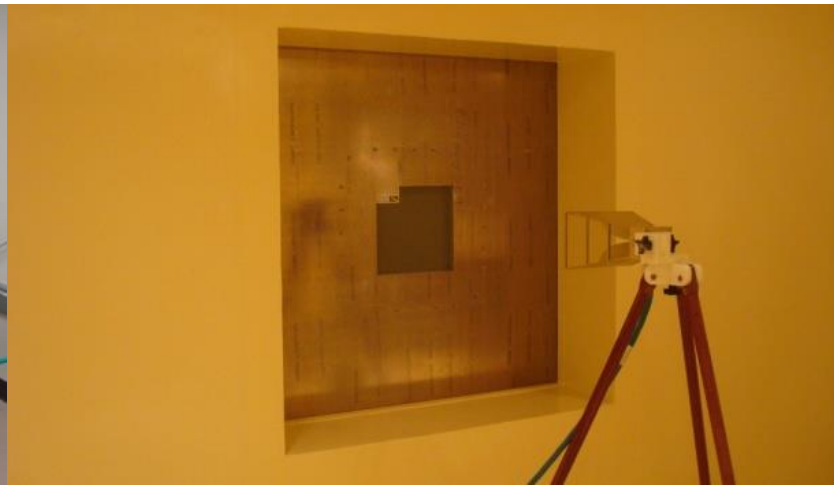


Predicted Shielding Effectiveness

A SansEC “Smart Skin” for EMI Shielding Effectiveness

Chamber B (Port 1 Side)

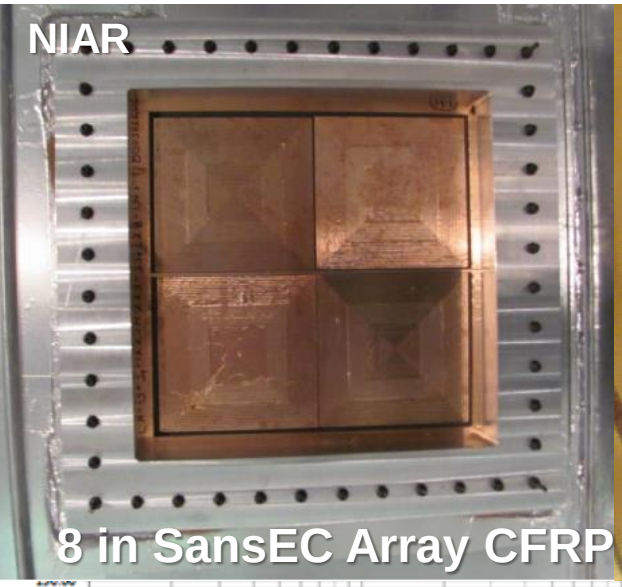
PNA

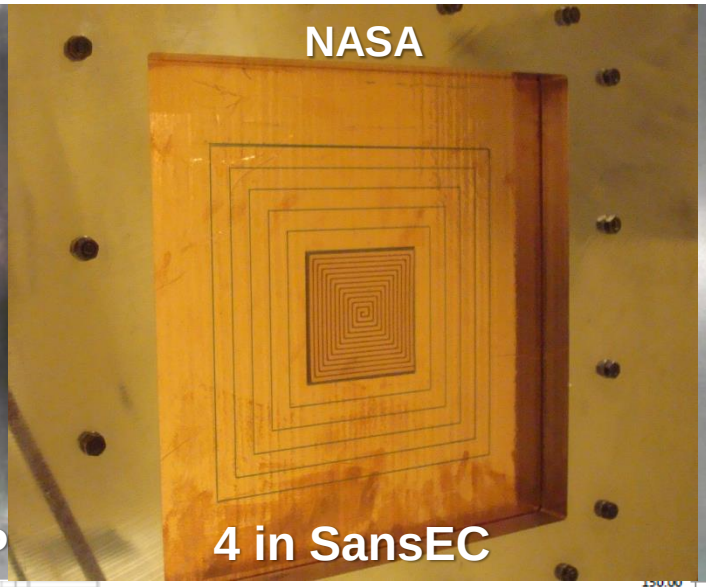


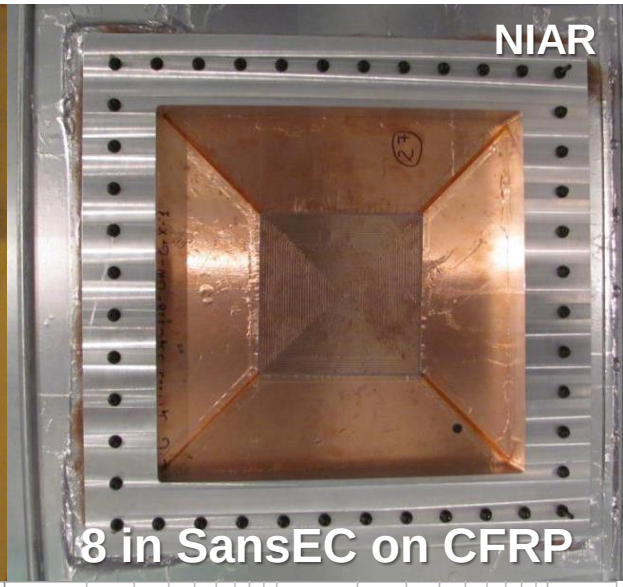
Chamber A (Port 2 Side)

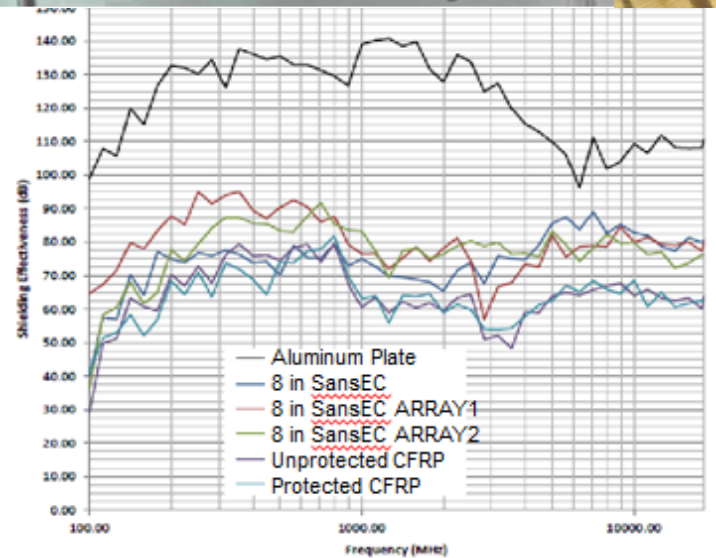
Chamber Setup for Shielding Effectiveness Measurements

A SansEC “Smart Skin” for EMI Shielding Effectiveness

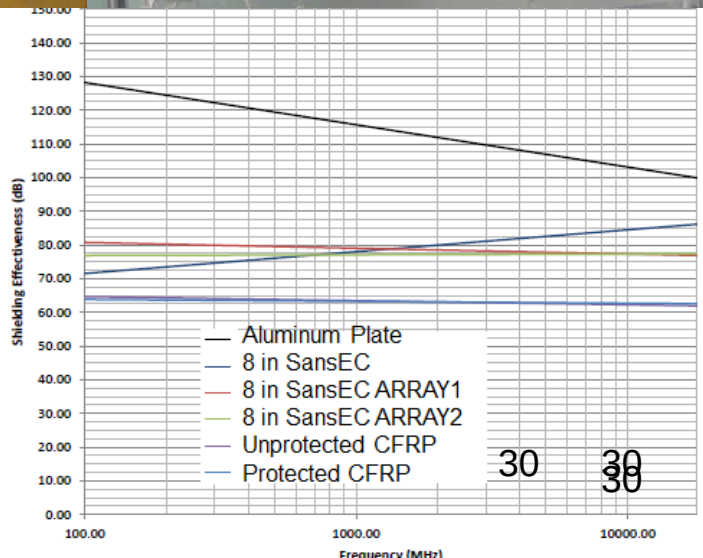








Chamber Test Fixtures and Shielding Effectiveness Data



Conclusions

- **A NEW MULTI-FUNCTIONAL CONCEPT**
  - **The SansEC sensor array used on the surface of composite structures is intended as a means for aircraft lightning strike protection, damage detection / diagnostics and enhanced shielding.**
  - **SansEC's could serve as a "Smart Skin" on future Aircraft, UAV's, Airships**
- **LABORATORY AND COMPUTATIONAL EXPERIMENTS**
  - **Through the use of lightning strike testing, experimental damage test coupons, and computational modeling NASA LaRC is demonstrating that SansEC sensors can be effectively used for lightning strike protection and in-situ damage detection of composites.**
  - **The feasibility for realistic damage detection applications on both fiber glass and carbon fiber composites is confirmed**
  - **The feasibility is confirmed for using high permeability material to control the electromagnetic field coupling between the sensor and the composite substrate.**
  - **More detailed Theoretical Development, Computational Simulations, and Physical Experiments are considered for future study.**

Back Up Slides

- Thank You!
- Any Questions?