2015 Americas ATC

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

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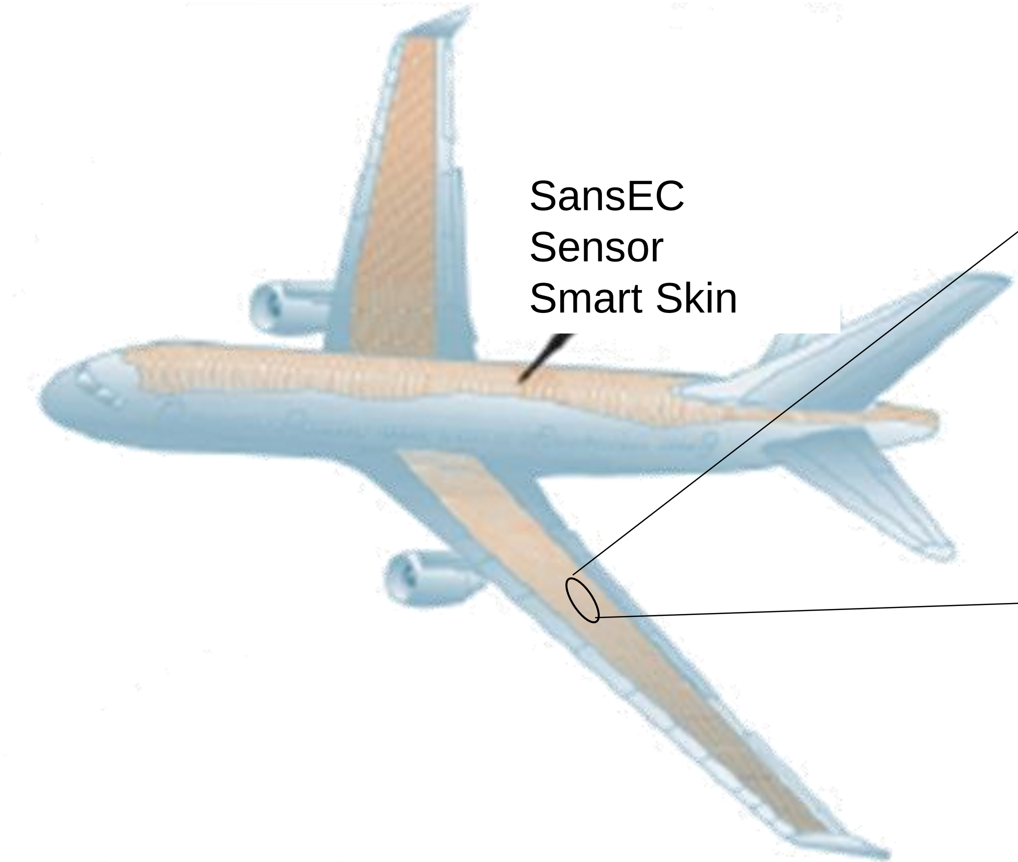
# Outline

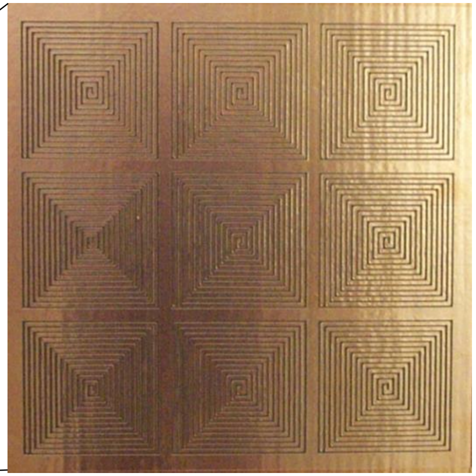
- Introduction
- A New Multi-Functional Concept
- Theory of Operation
- Lightning Protection
- Damage Detection
- Shielding Effectiveness
- Conclusions

# 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



SansEC Sensor Array

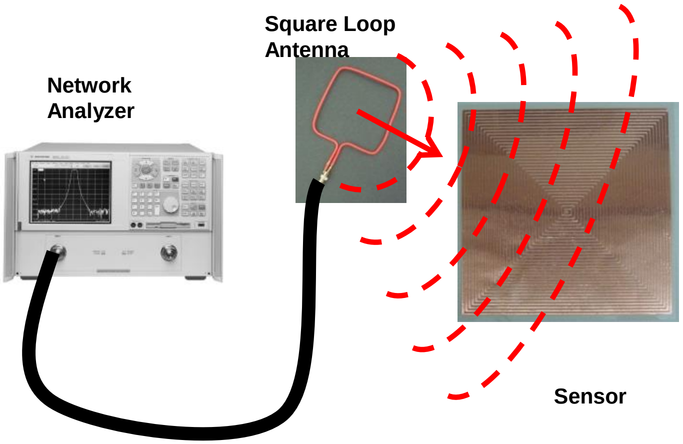
- **The concept is to apply an array of SansEC sensors to an aircraft surface forming a "Smart Skin" layer on the composite.**
- **Lightning Protection, Enhanced Shielding Effectiveness, Damage Detection and Diagnosis functions to composites.**

# 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

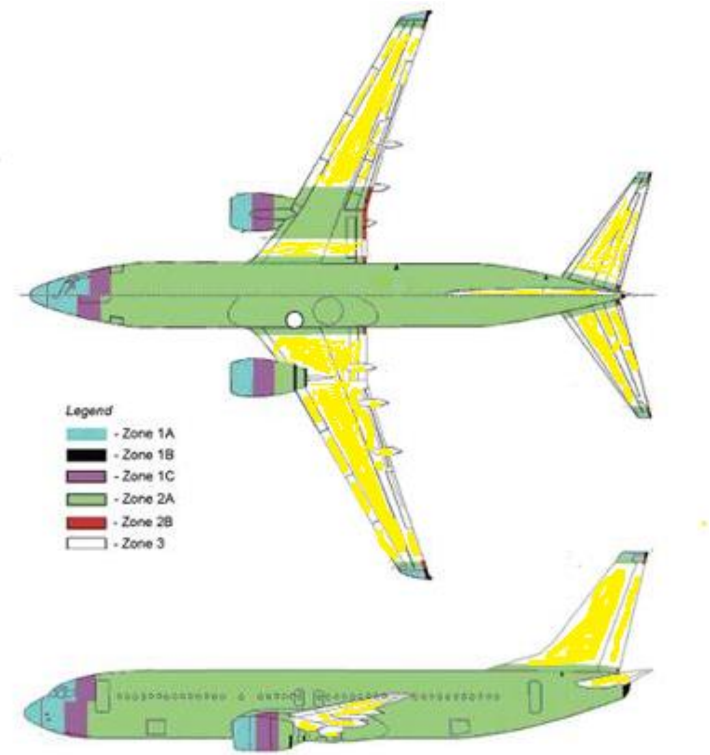
Atmospheric Environment Safety Technologies (AEST) Project

Atmospheric Hazard Sensing & Mitigation (AHSM) Task

Lightning Electromagnetic Effects & Mitigation (LEEM) Element

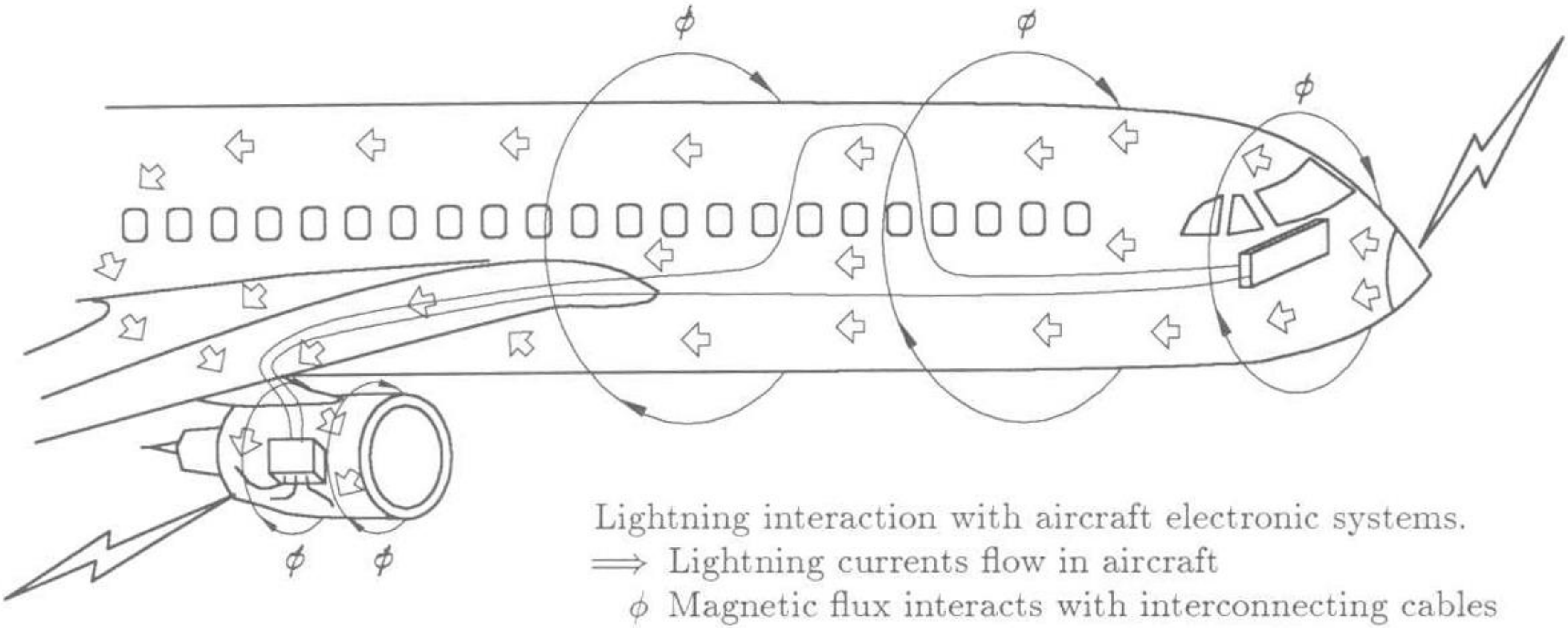
# A SansEC "Smart Skin" for Lightning Strike Protection

| 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 | |

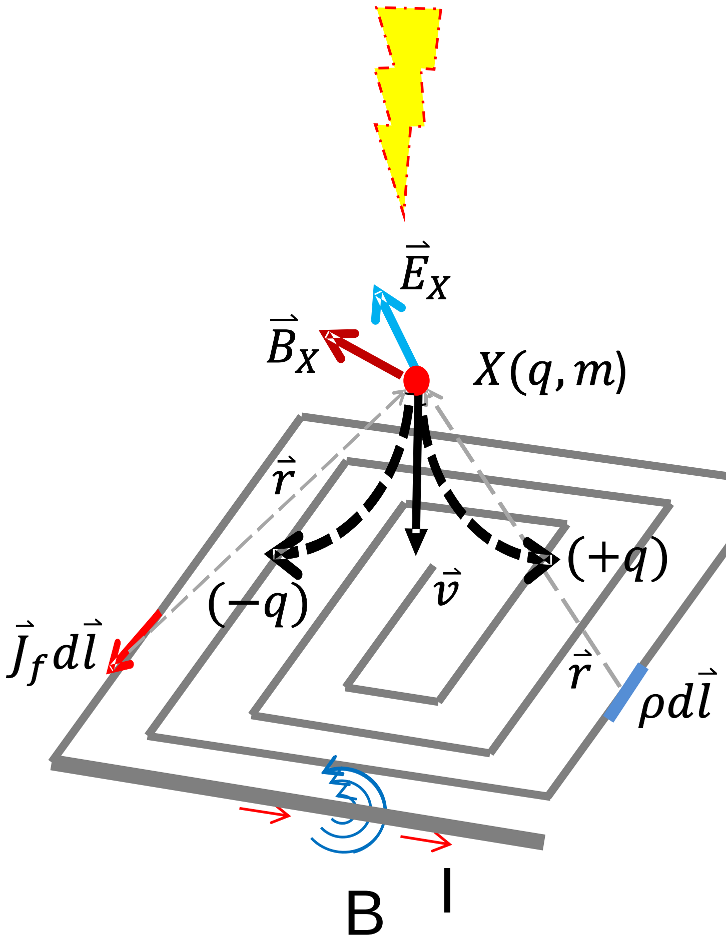



ARP5412- APPLICATION OF LIGHTNING ENVIRONMENT TO AIRCRAFT ZONES

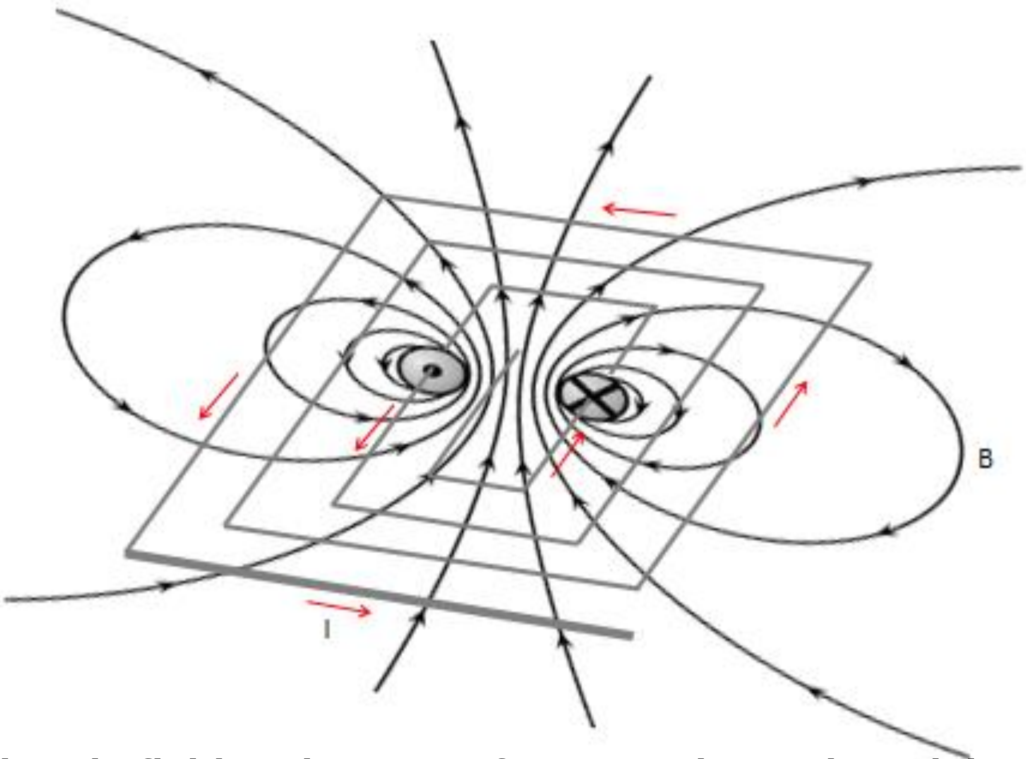
# A SansEC "Smart Skin" for Lightning Strike Protection



# A SansEC “Smart Skin” for Lightning Strike Protection

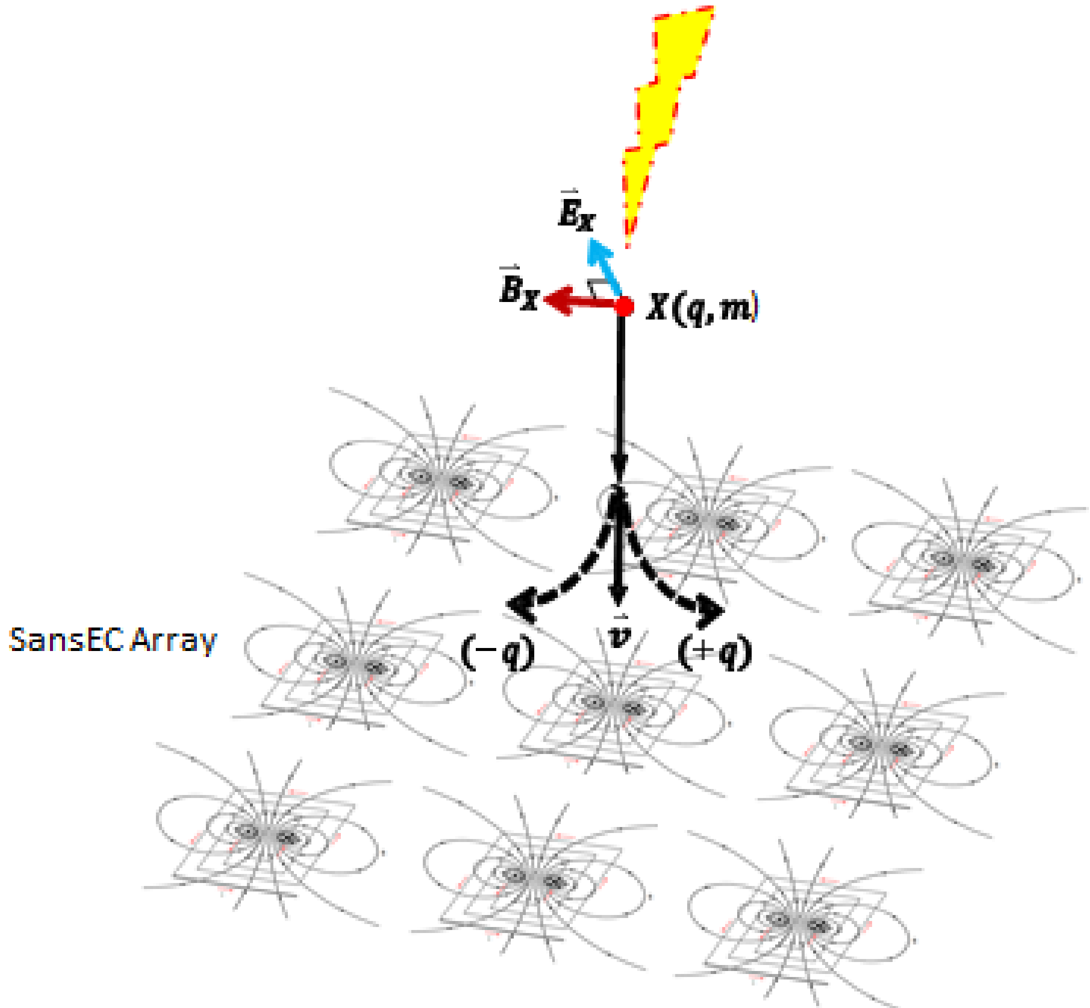



$$\vec{F} = q(\vec{v} \times \vec{B}_X + \vec{E}_X)$$



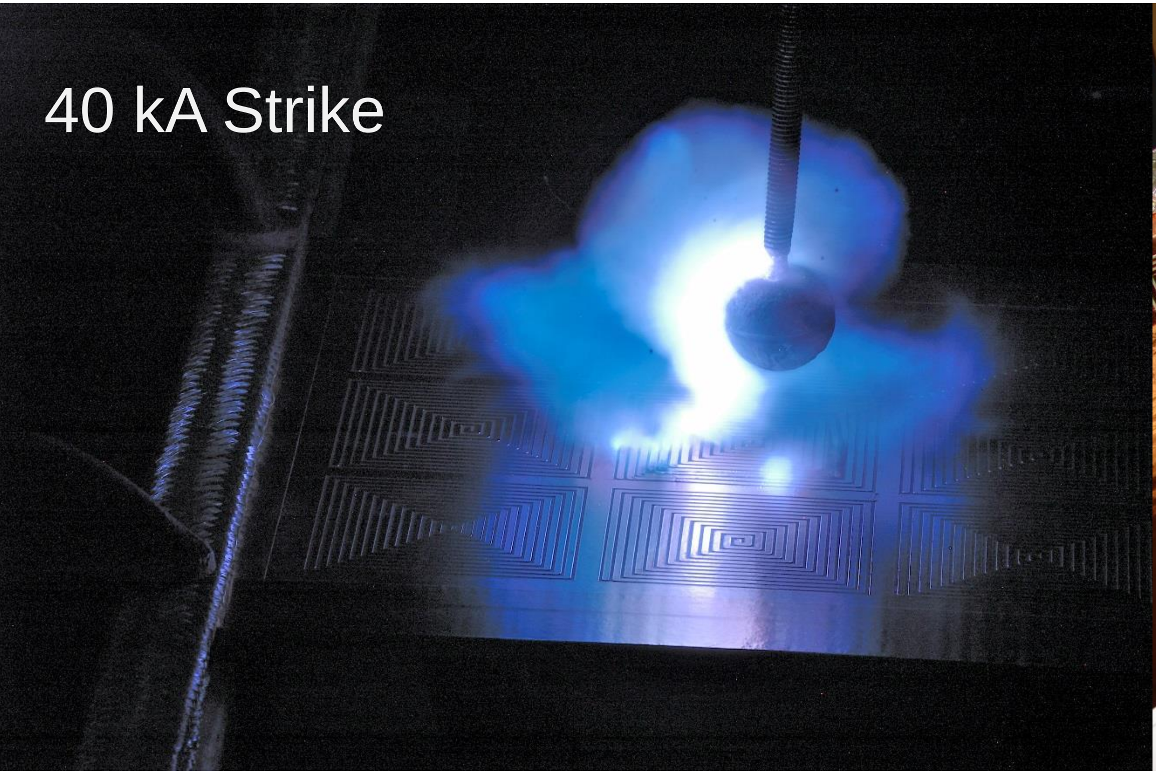

**SansEC generated magnetic and electric field and Lorentz force on charged particle**

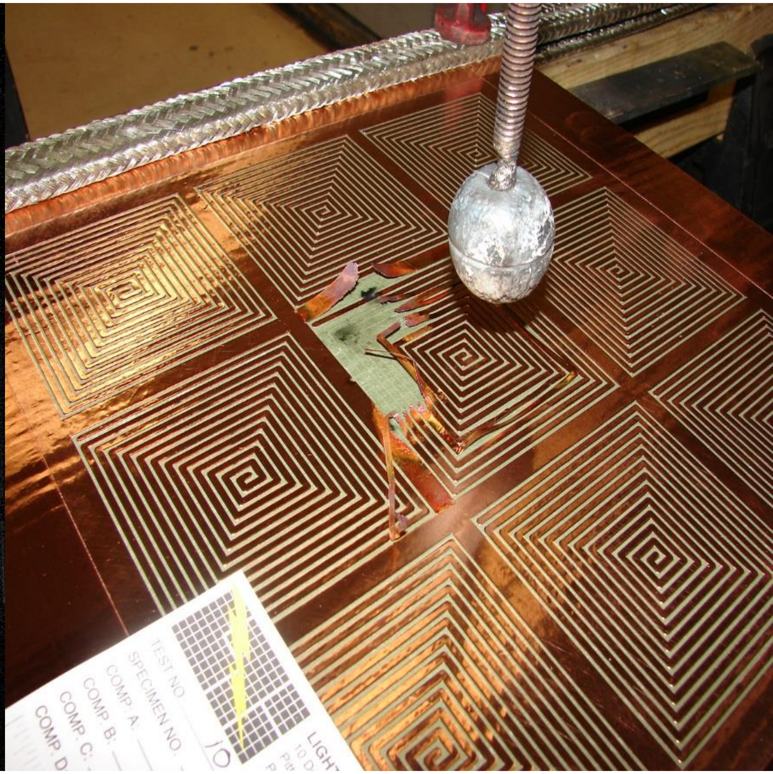
# A SansEC "Smart Skin" for Lightning Strike Protection




**SansEC Array and Lorentz force on charged particle**

# A SansEC "Smart Skin" for Lightning Strike Protection



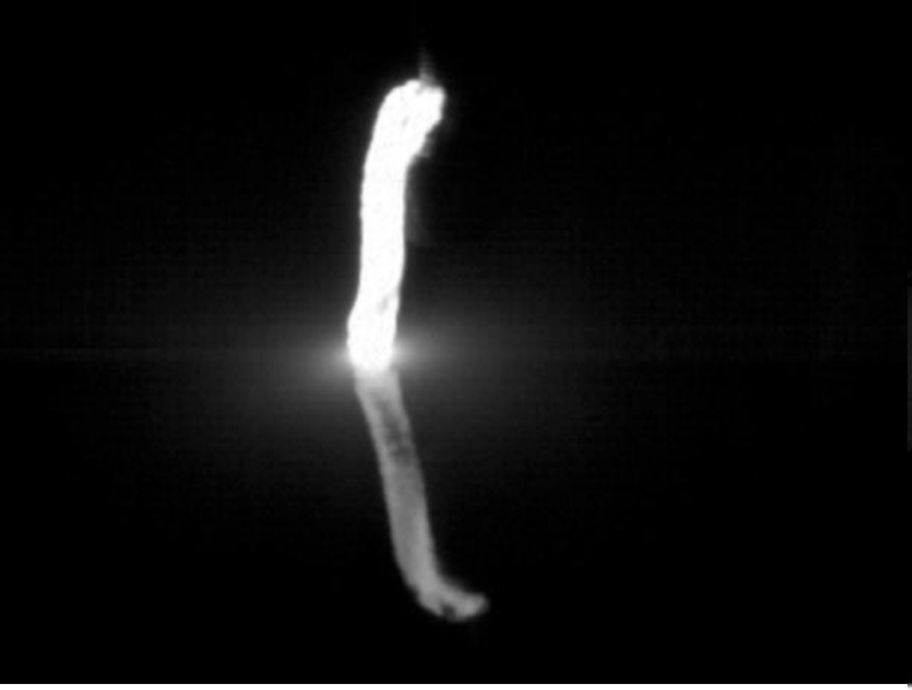




**Test Strike on Panel** **Post-Strike Test Panel**

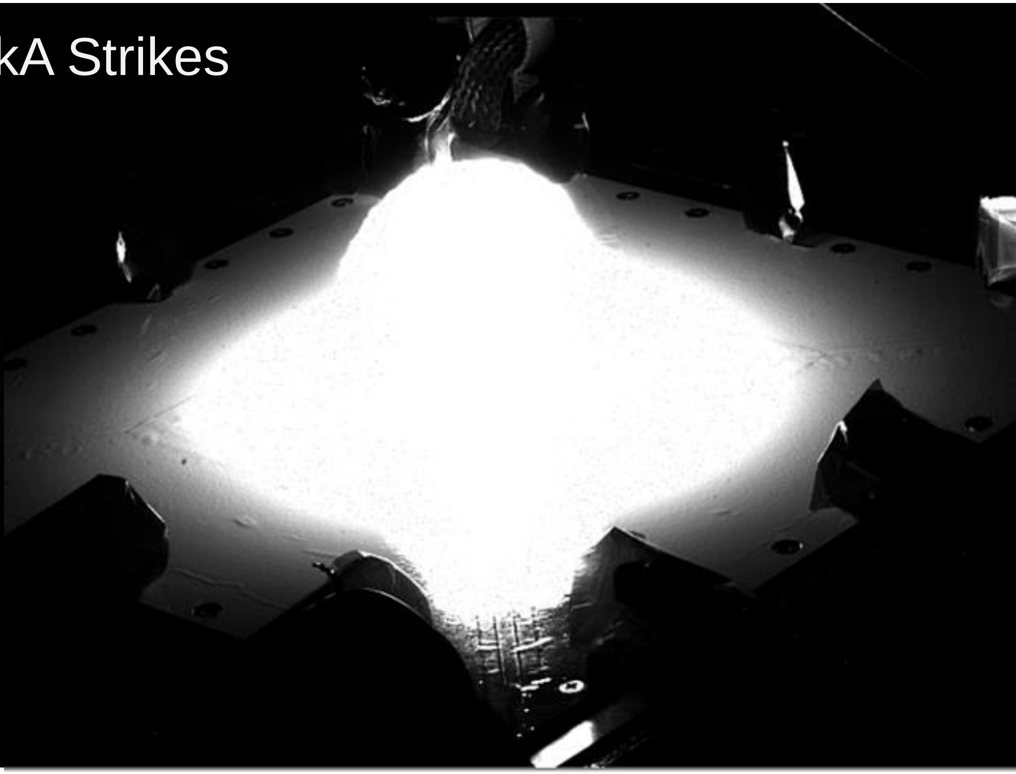
**3 inch SansEC 3x3 Array**

# A SansEC "Smart Skin" for Lightning Strike Protection

## Two 100 kA Strikes



**High Speed Video First Frame showing Lightning Strike Initial Attachment on <u>Mesh Protected</u> CFRP Panel**

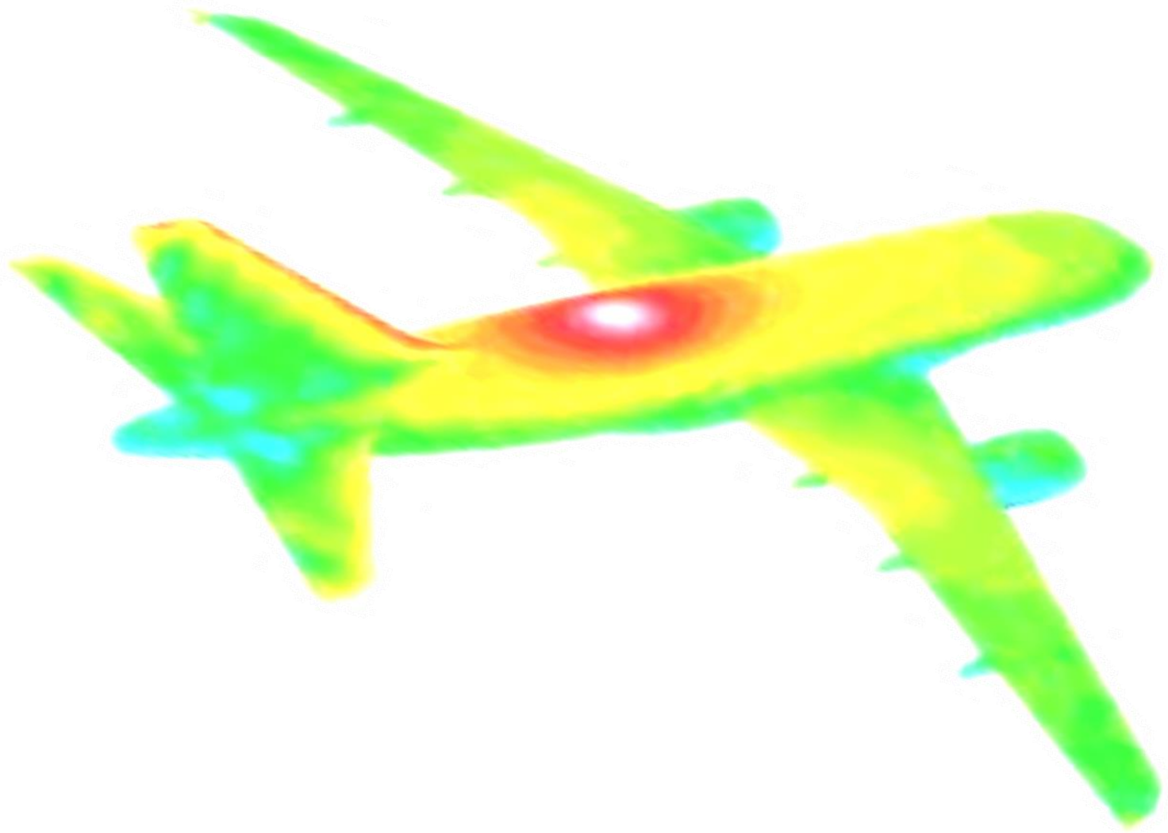


**High Speed Video First Frame showing Lightning Strike Initial Attachment on <u>SansEC Protected</u> CFRP Panel**

# A SansEC "Smart Skin" for Lightning Strike Protection

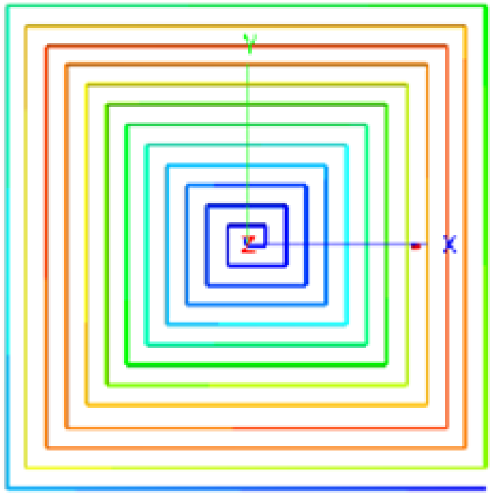
- Develop tools and test procedures to quantify lightning damage mechanisms, capture current direction, thermal & mechanical parameters
- Develop mitigation strategies to improve aircraft lightning protection designs through passive or active methods.
- Develop & validate lightning damage models (with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

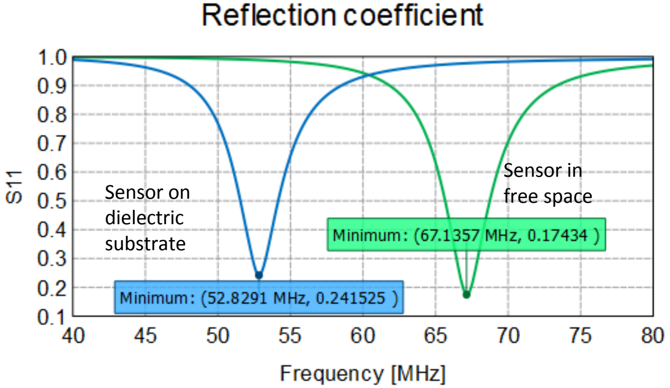
$$q = q_0 sin(\frac{\pi x}{l})e^{-i(\omega t+\frac{\pi}{2})}$$

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

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

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

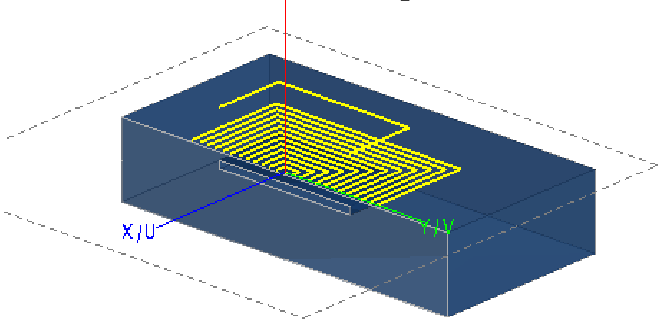
**Un-damped Resonance Inductive–Capacitive circuit**



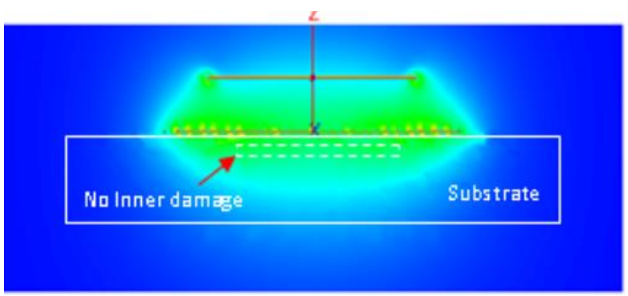

$$\omega = \frac{1}{\sqrt{LC}}$$

# A SansEC "Smart Skin" for Damage Detection

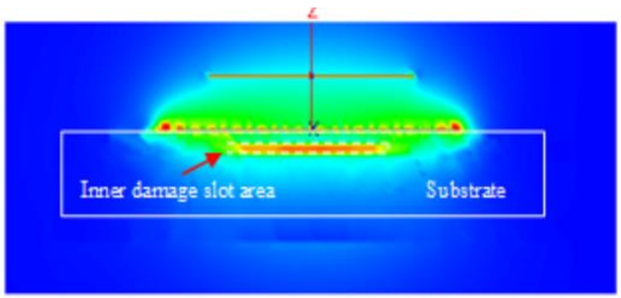
## Response Characteristics of Internal Damage




Inner damage model

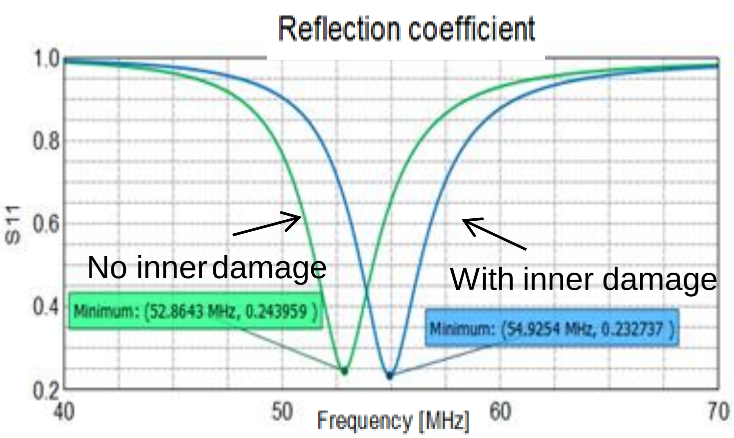



Electric field distribution
No Damage ($\varepsilon_r$=3)




Electric field distribution
With Damage ($\varepsilon_r$=3)

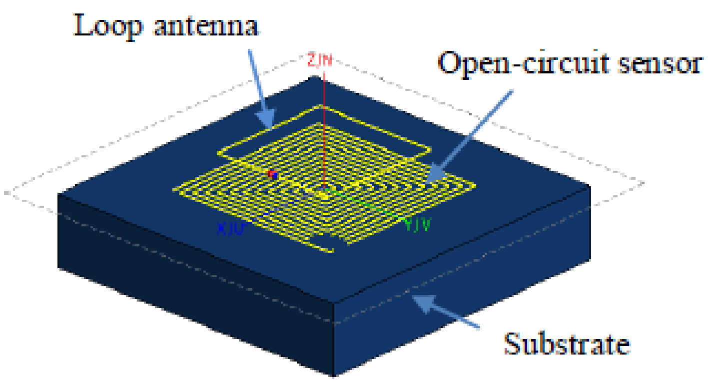
**For this case Substrate is FRP**
**Electric Field Penetration**
**Dominant Mode Excitation**
**Tenth inch free space slot Damage**
**Resonant Frequency Shift**



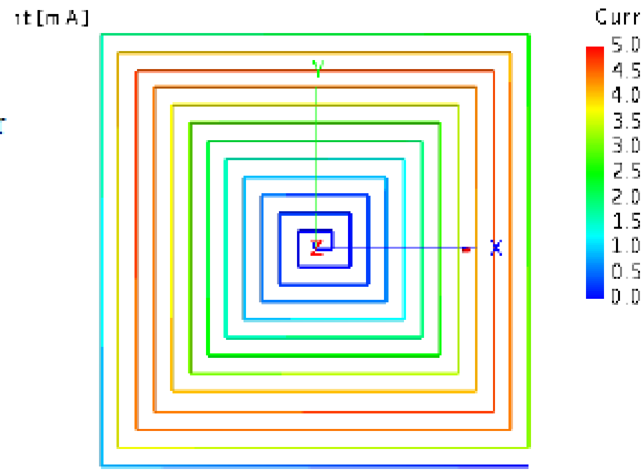

Computed SansEC resonant response

# A SansEC “Smart Skin” for Damage Detection

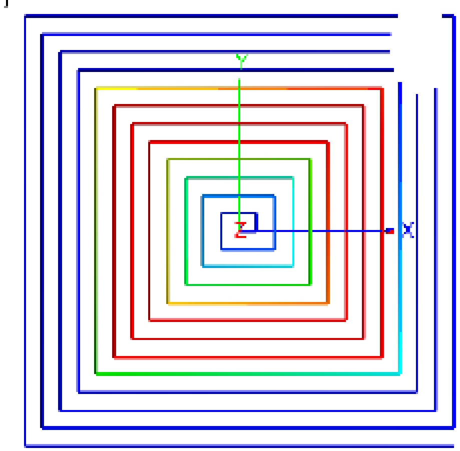
## Response Characteristics of Surface Damage




**Damaged Sensor**
**On Dielectric Substrate**

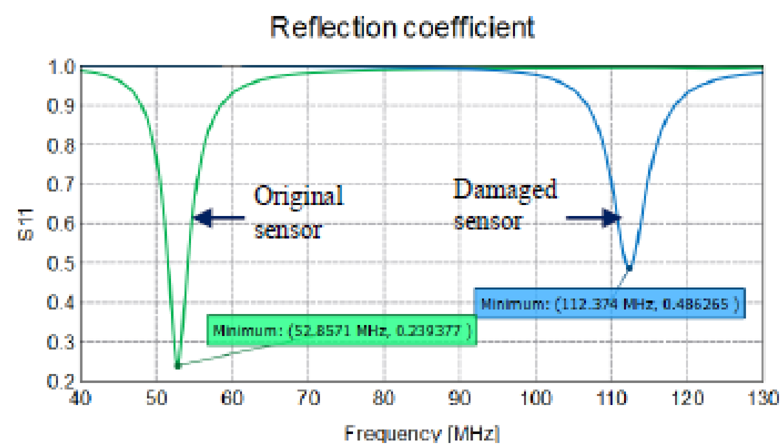



**Un-damaged Sensor**
**Current Distribution**



**Damaged Sensor**
**Current Distribution**

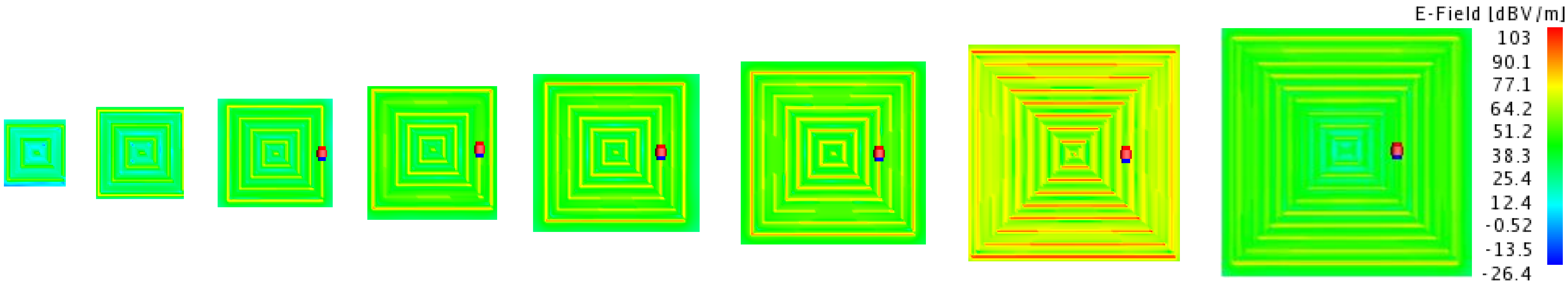
For this case Substrate is FRP
Sensor Resilience when Damaged
Cosine Current Distribution
Dominant Mode Excitation
Resonant Frequency Shift



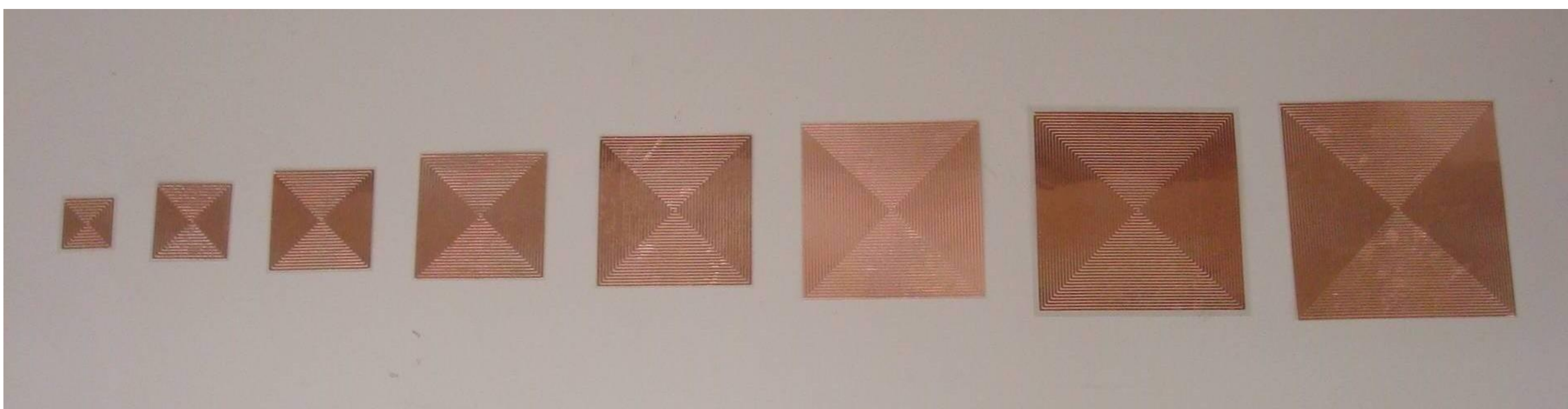

**Computed SansEC resonant response**

# A SansEC “Smart Skin” for Damage Detection

## Realistic SansEC Sensor Models



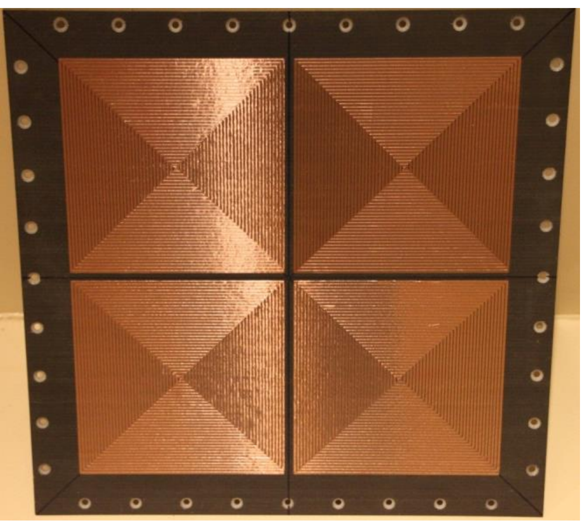

**2” 3” 4” 5” 6” 7” 8” 9”**



# A SansEC "Smart Skin" for Damage Detection

## Real SansEC FRP Test Panels

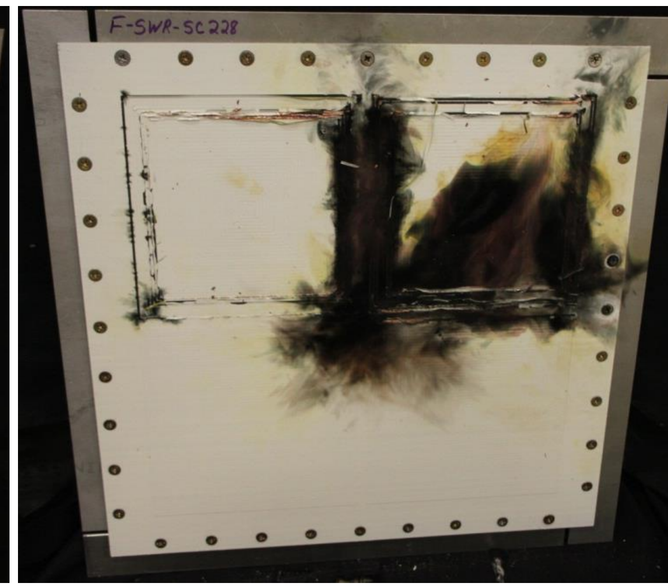
**Pre-Paint Test Panel**



**8 inch SansEC Array**

**Pre-Strike Test Panel**

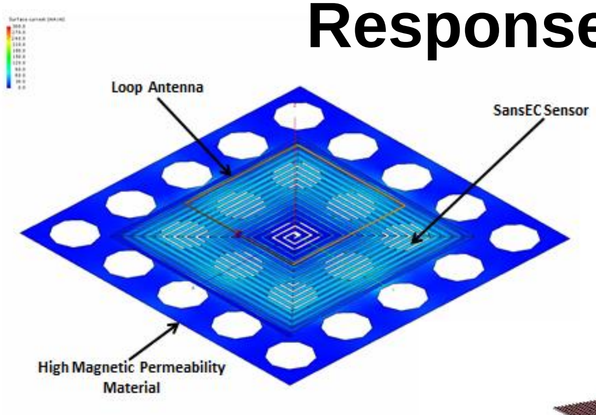

**Post-Strike Test Panel**



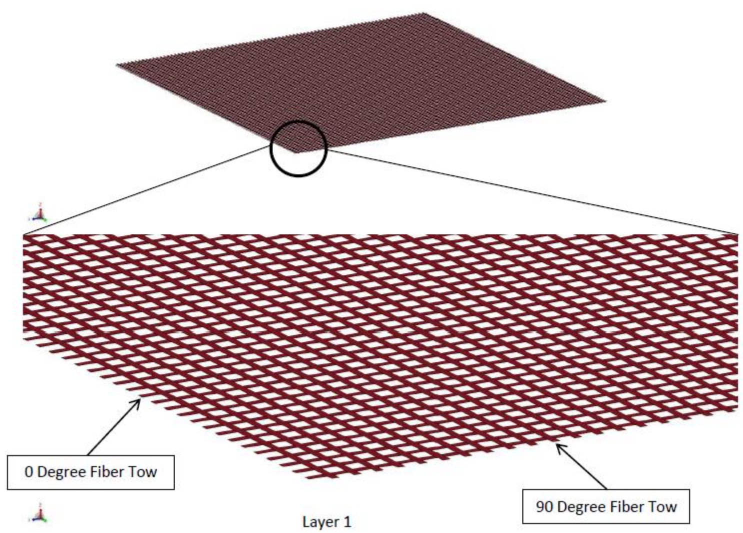

## Visual Damage Assessment

# A SansEC “Smart Skin” for Damage Detection

## Response Characteristics of CFRP Damage

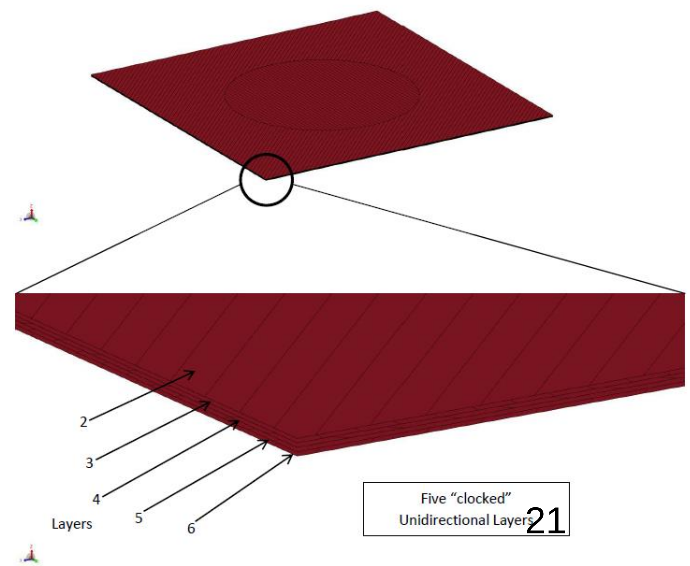



**SansEC CFRP**
**High Permeability**
**Impedance Coupling**

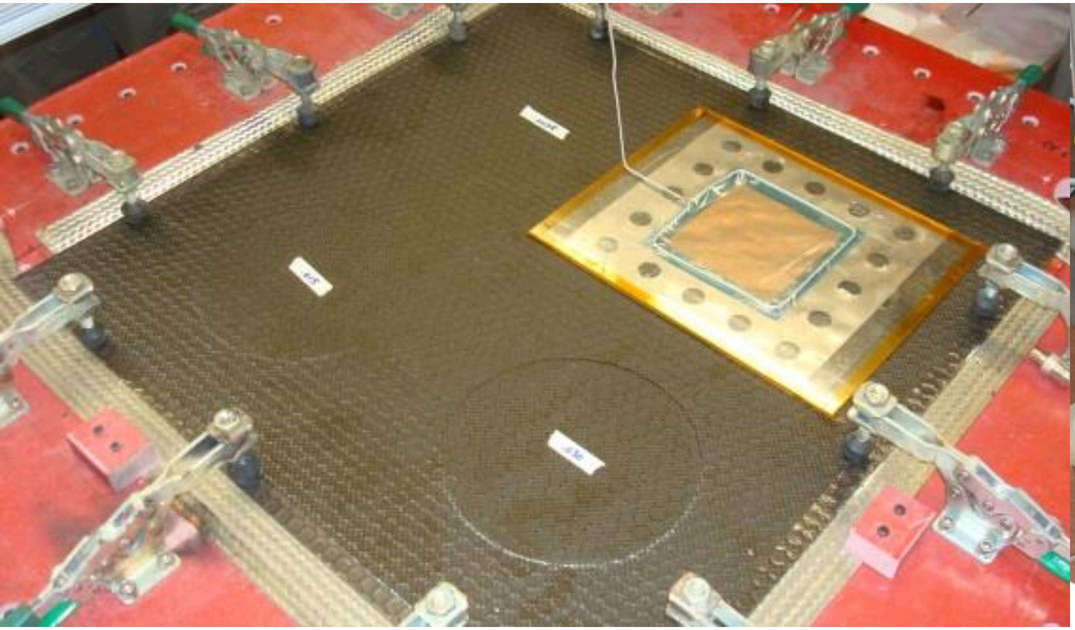



**Hexcel Hexply**
**8552/A193-PW.3K-70-PW**
**Plain Weave Fabric**

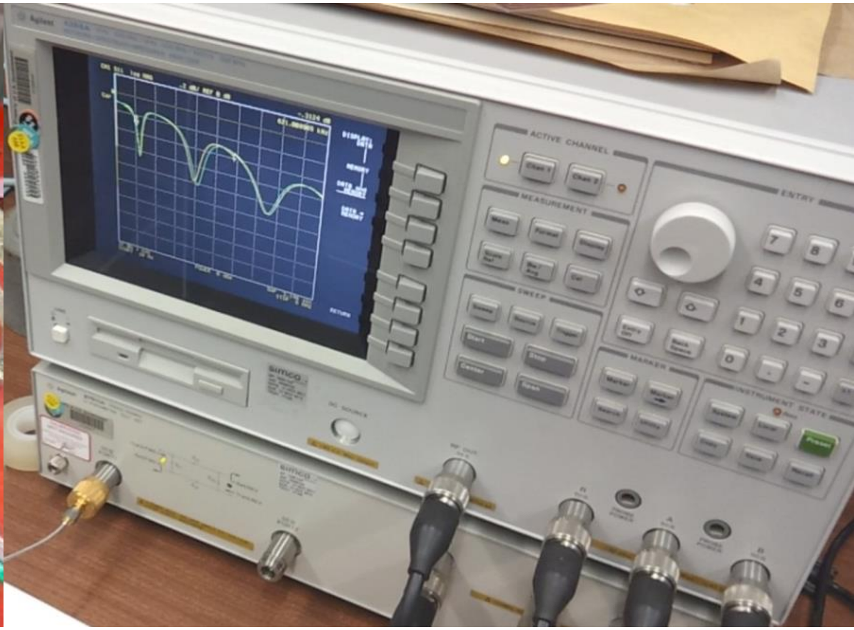
**Hexcel Hexply**
**8552/AS4**
**Unidirectional Tapes**



# A SansEC “Smart Skin” for Damage Detection



**SansEC Laboratory Experiment**

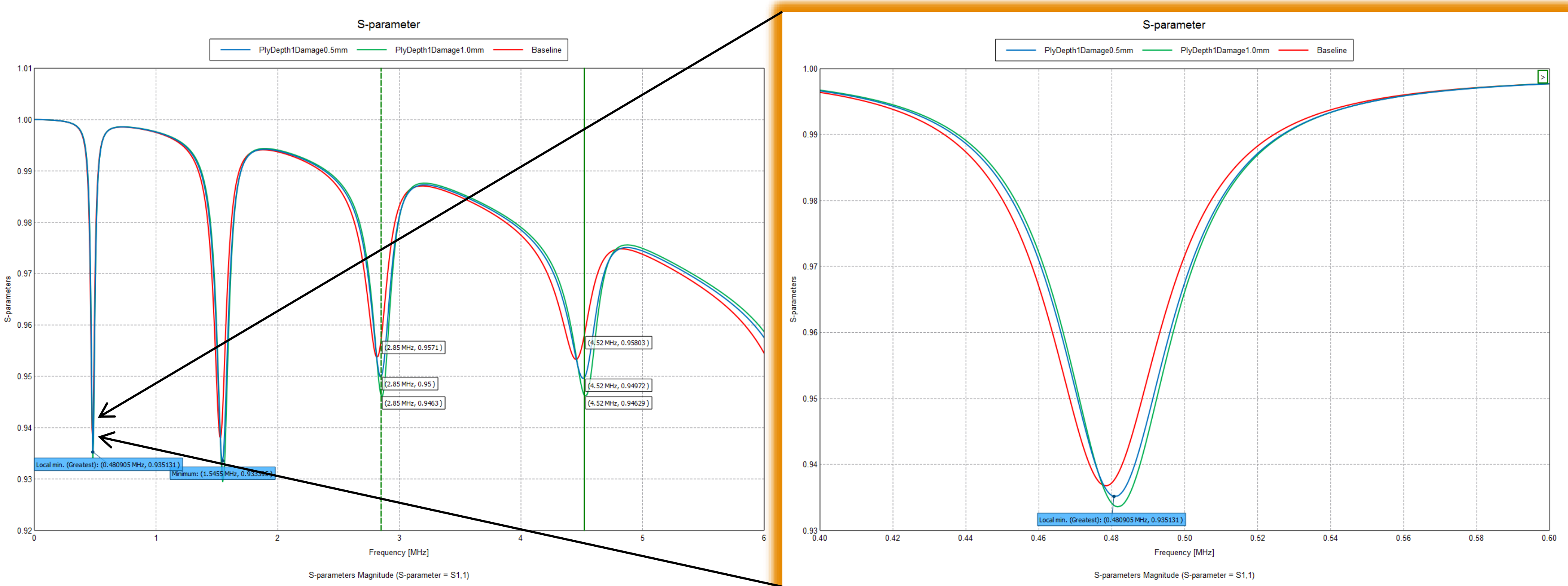


**PNA Measurement**

**Seeded Fault Delamination Experimental Setup**

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

# A SansEC "Smart Skin" for Damage Detection

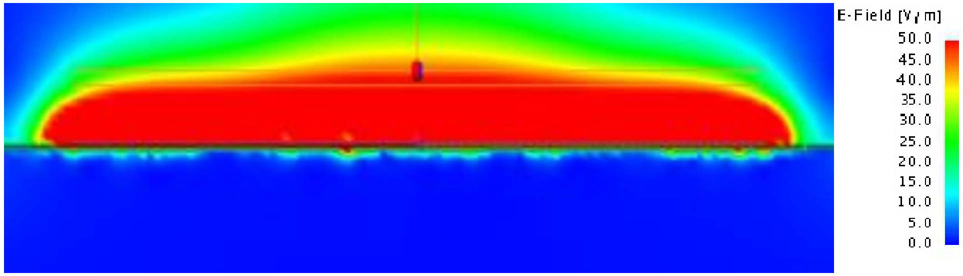



## Damage Signature through Scattering Parameters

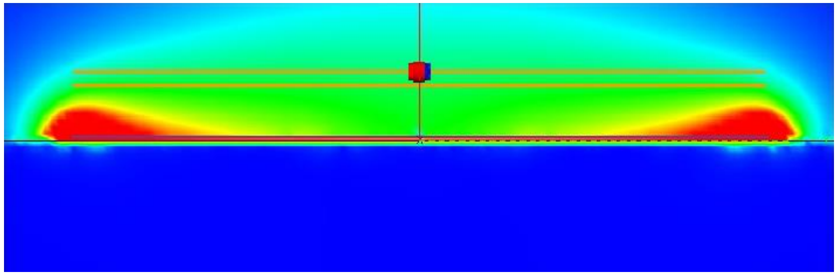
**Seeded Fault Delamination Hexcel CFRP Test Panel**
**Baseline, Small, Medium, Large, Delaminations**

# A SansEC "Smart Skin" for Damage Detection

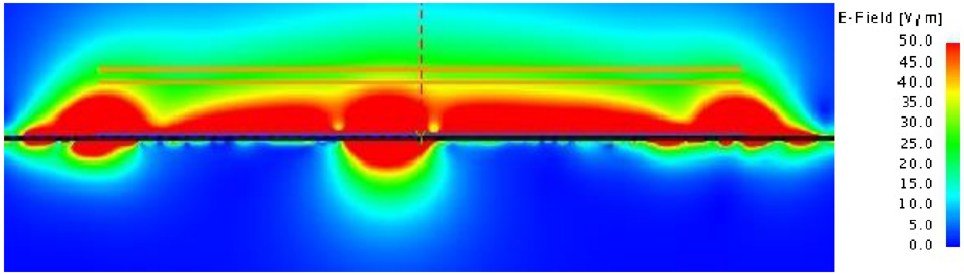
**Response Characteristics of CFRP Damage**




Delamination

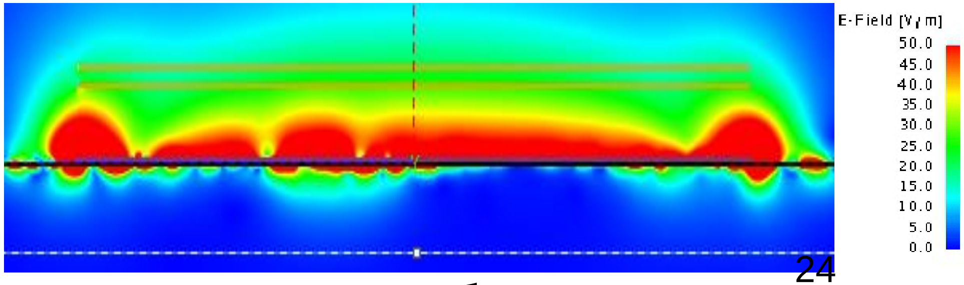


No Damage




Puncture

**Electric Field Visualizations**

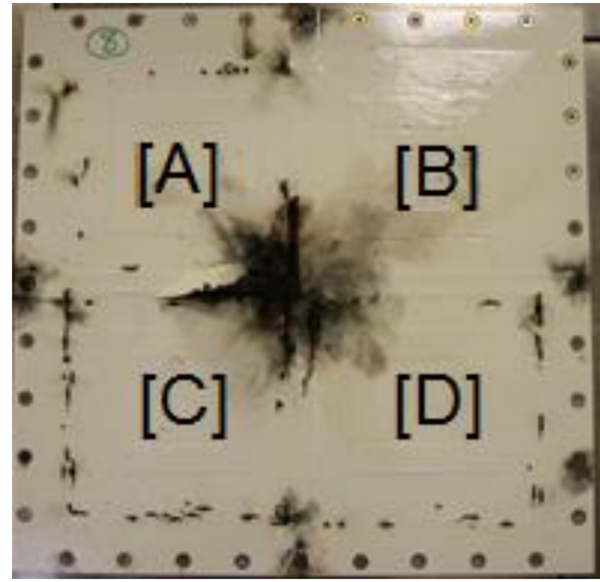



Void

# A SansEC "Smart Skin" for Damage Detection


**8 inch SansEC Array (before paint)**

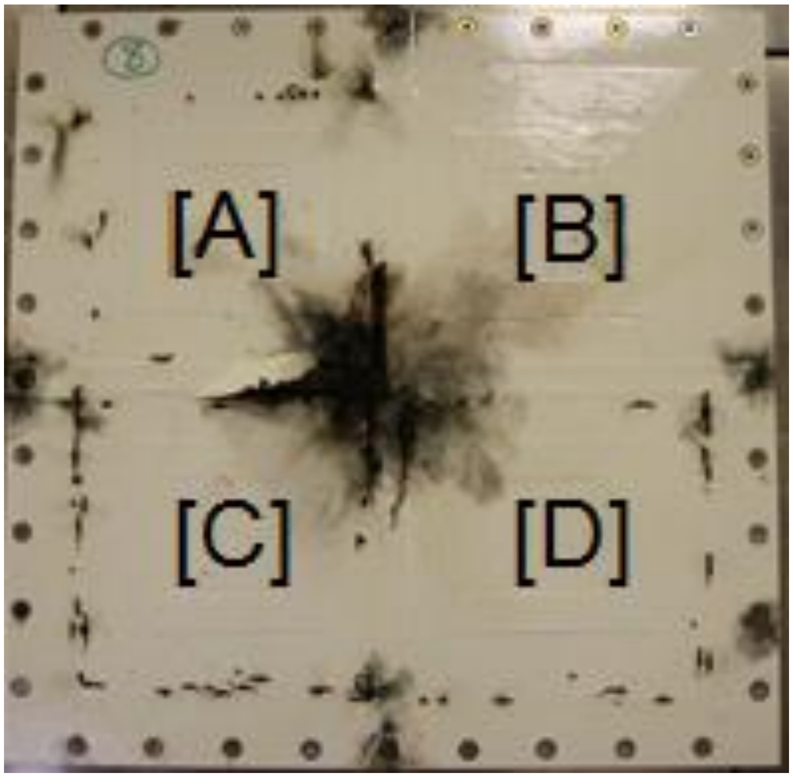
**Pre-Strike Test Panel (with Aerospace Paint)**

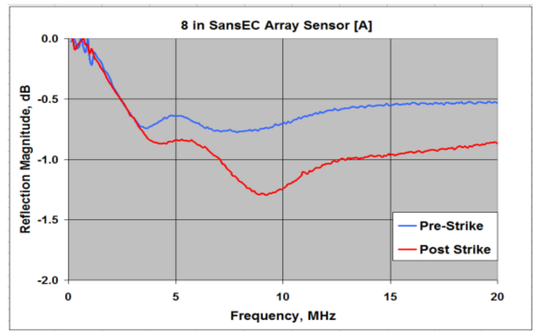



**Post-Strike Test Panel**

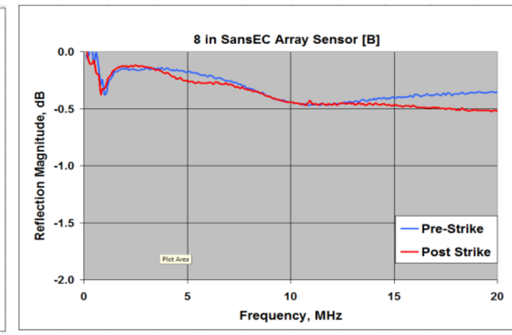
**Real SansEC CFRP Test Panels**

# A SansEC "Smart Skin" for Damage Detection

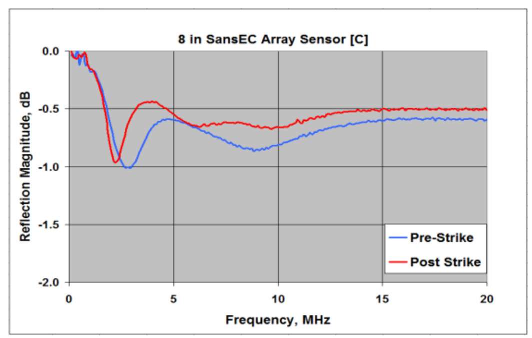


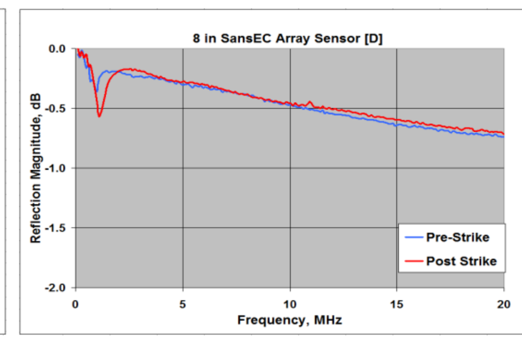

(A) Sensor A upper left quadrant.




(B) Sensor B upper right quadrant.



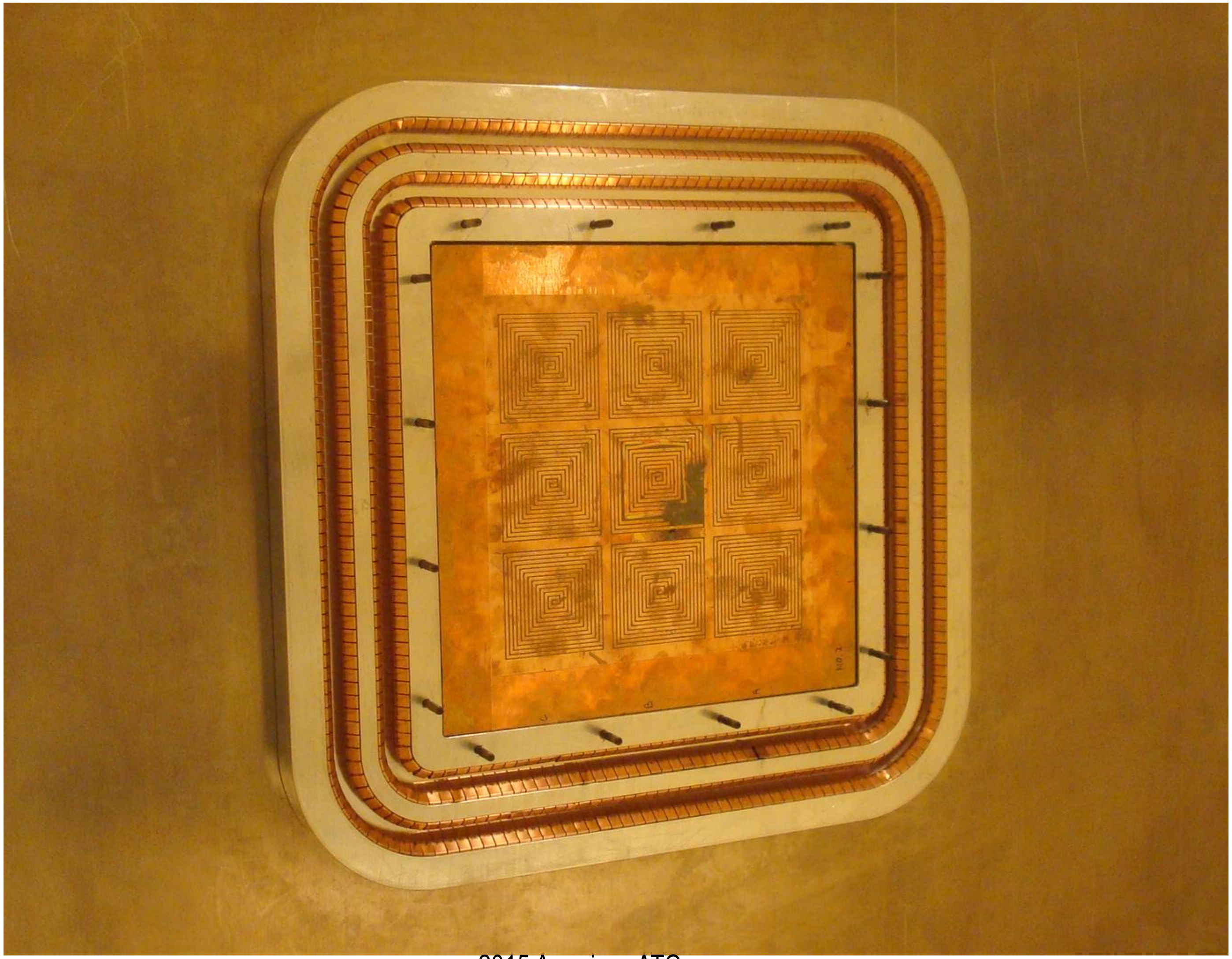

(C) Sensor C bottom left quadrant.




(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.**

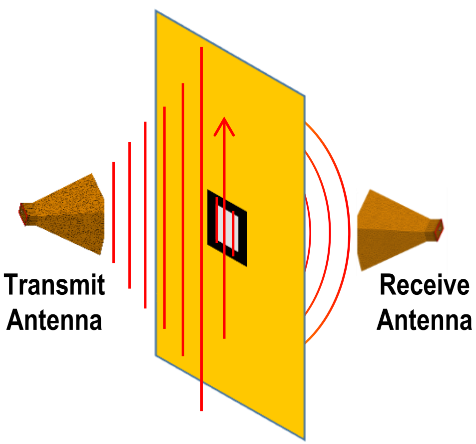
# A SansEC "Smart Skin" for EMI Shielding Effectiveness



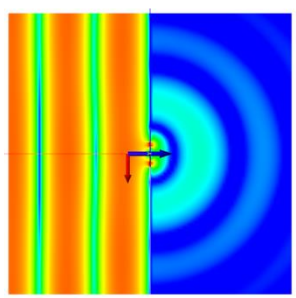
## Shielding Effectiveness of SansEC Sensors

- 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.

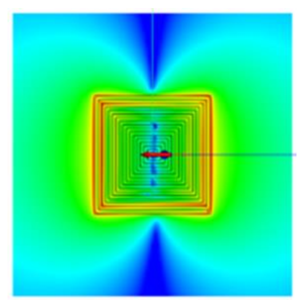
$$SE_{\mathrm{dB}} = 20\ \log_{10} \frac{F_b}{F_a}$$



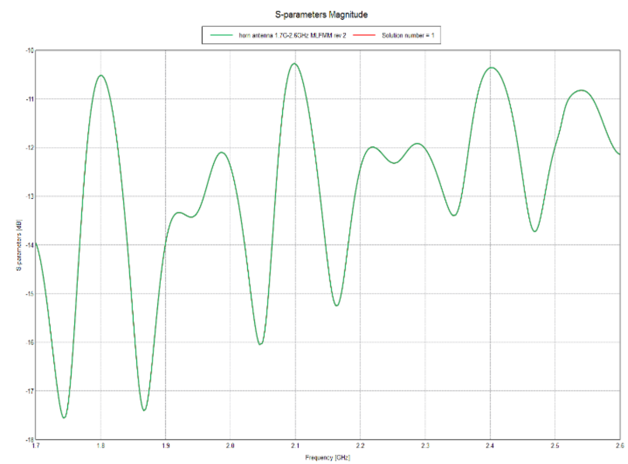

Perfect Electrical Conducting Boundary (PEC)



Incident Plane Wave on PEC Boundary Thru SansEC Aperture



Resulting SansEC Surface Currents

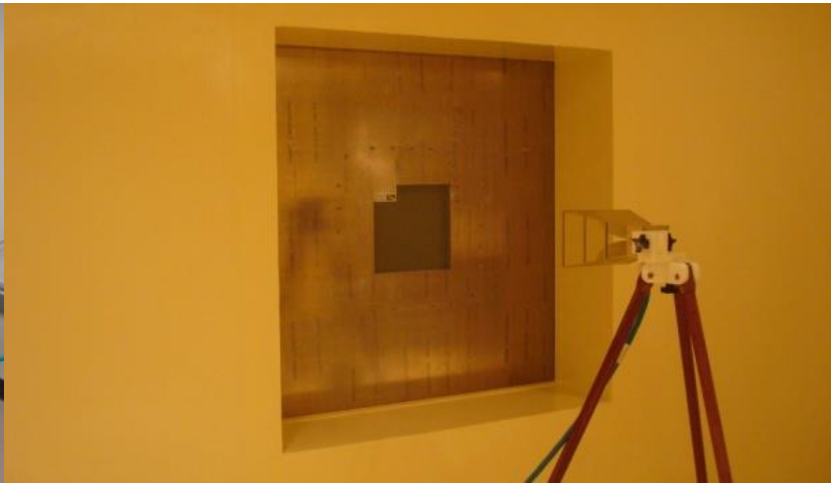



Predicted Shielding Effectiveness

# A SansEC “Smart Skin” for EMI Shielding Effectiveness

Chamber B (Port 1 Side)

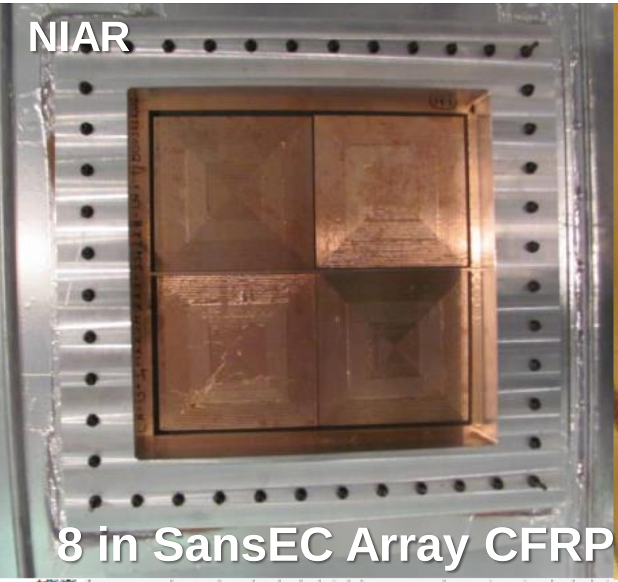
PNA

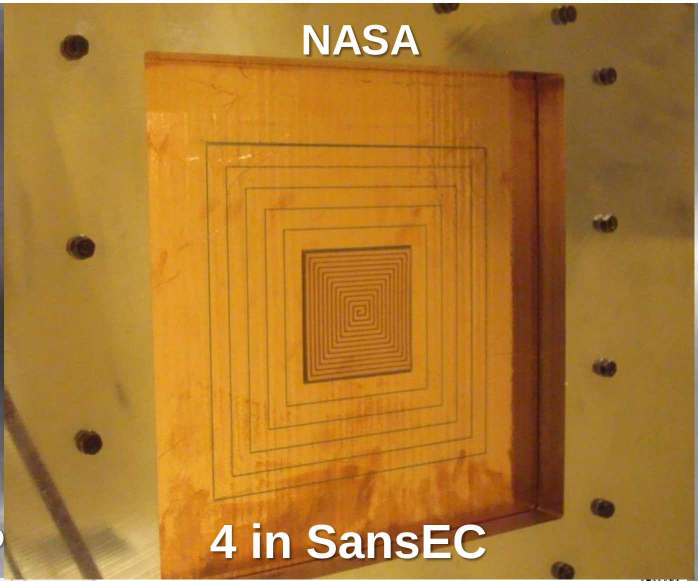


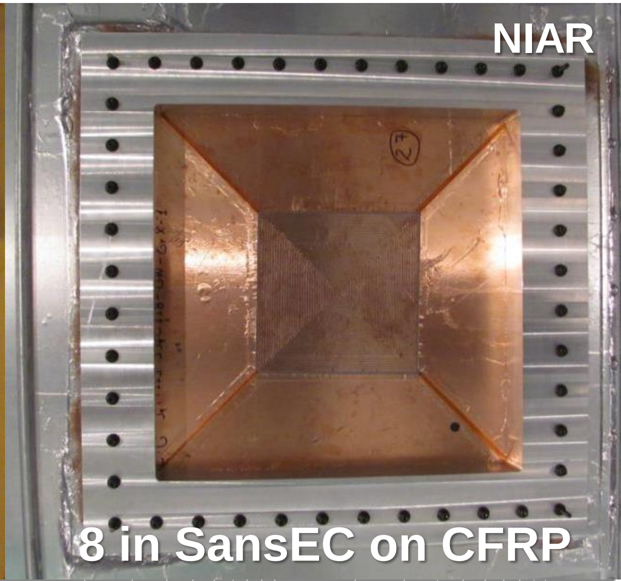
Chamber A (Port 2 Side)

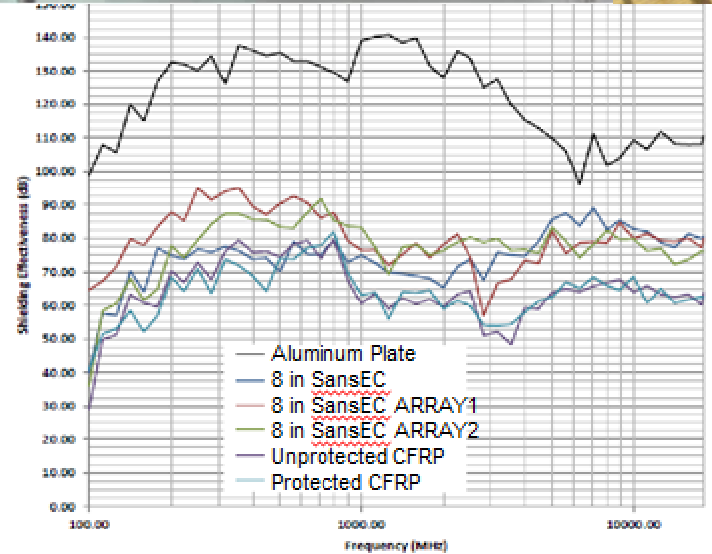
Chamber Setup for Shielding Effectiveness Measurements

# A SansEC "Smart Skin" for EMI Shielding Effectiveness




Chamber Test Fixtures and Shielding Effectiveness Data

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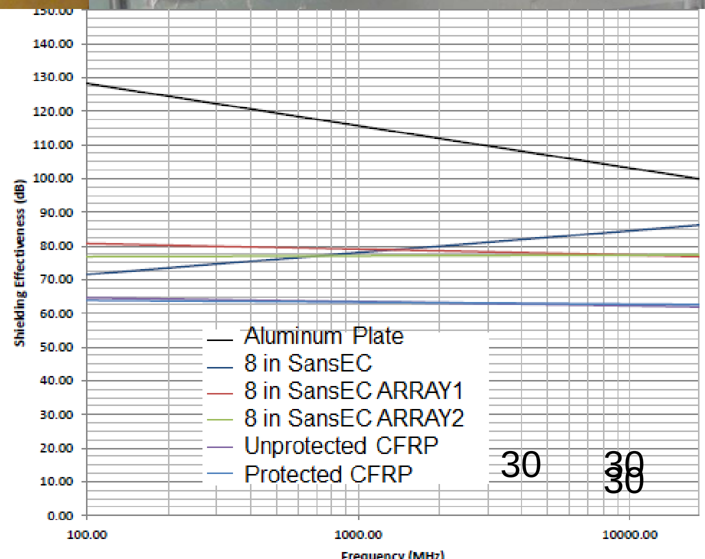



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# Conclusions

- **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?