Simulating Lightning and EMP Effects in Aerospace Applications

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VP of Engineering and Support, CST of America

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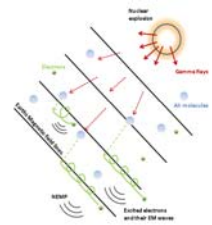
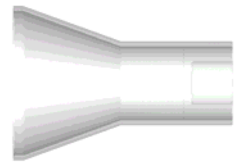
Sources of EMP





Nuclear explosion (HEMP)

Virtual Cathode Oscillator

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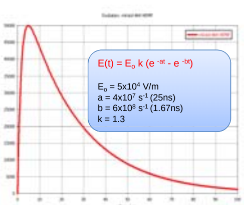
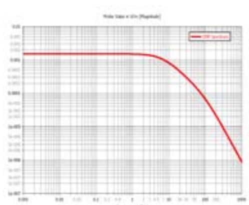
MIL-STD-464 HEMP waveform





High-altitude EMP waveform → FFT → Broadband Spectrum

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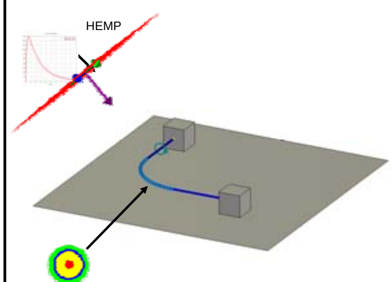
Cable over ground



Bi-directional coupling required in order to capture all EM effects

FIT, TLM   MoM/TL

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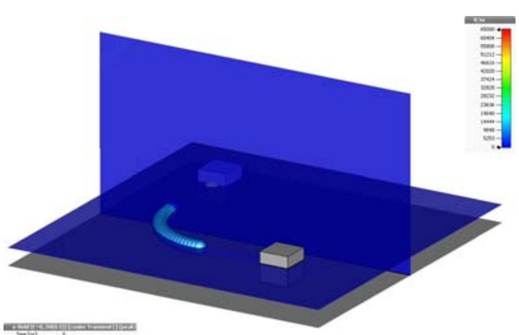
Time animation



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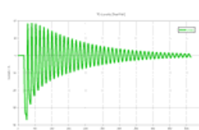
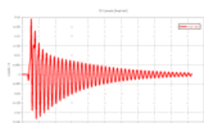
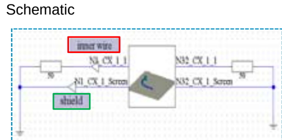
Cable currents



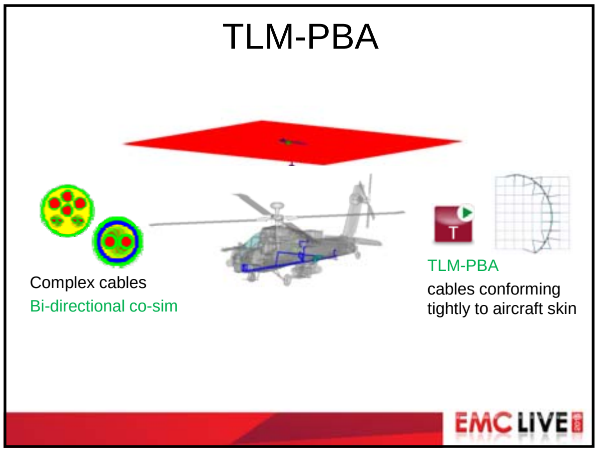


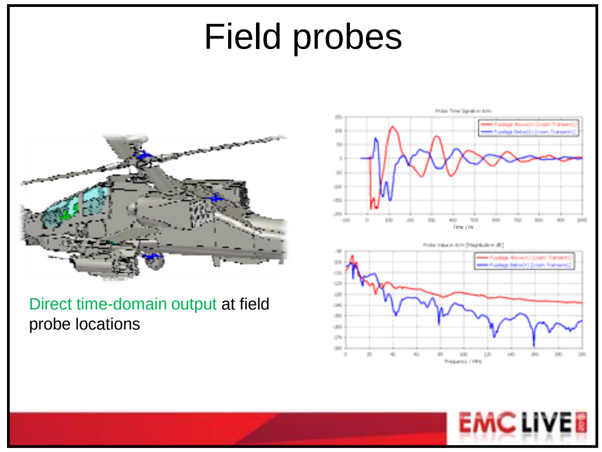
Schematic

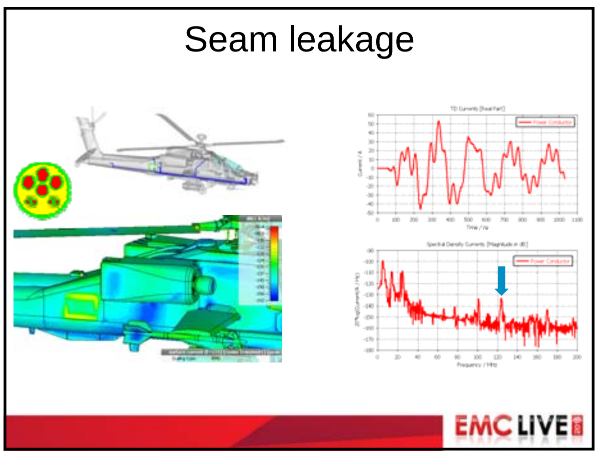


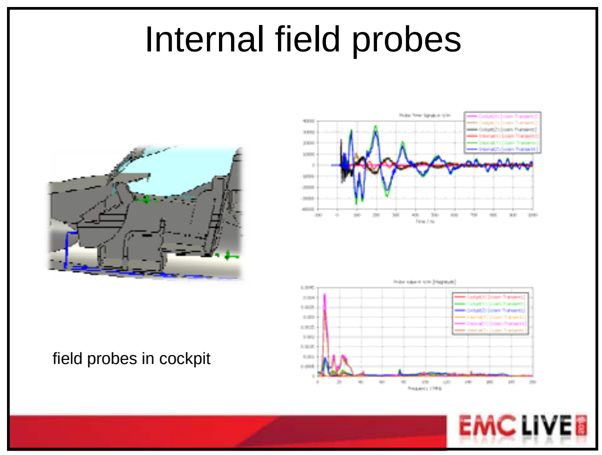
Currents recorded at cable pins

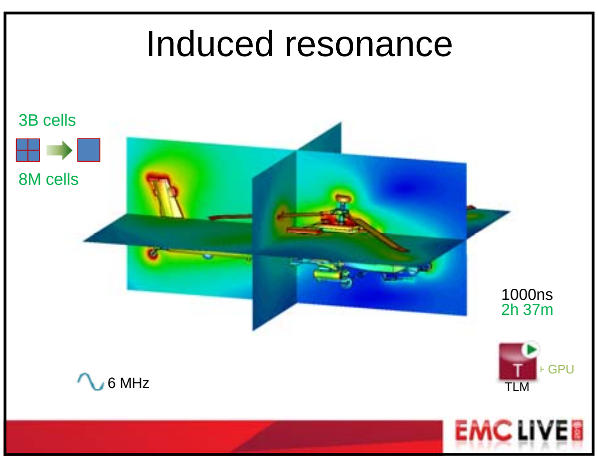
EMC LIVE


TLM-PBA
Complex cables
Bi-directional co-sim
TLM-PBA
cables conforming
tightly to aircraft skin
EMC LIVE


Field probes
Direct time-domain output at field
probe locations
EMC LIVE


Seam leakage
EMC LIVE


Internal field probes
field probes in cockpit
EMC LIVE


Induced resonance
3B cells
8M cells
1000ns
2h 37m
6 MHz
TLM
+ GPU
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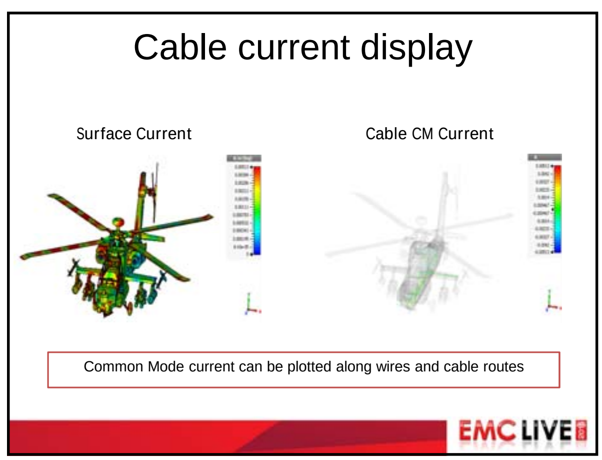
Cable current display
Surface Current
Cable CM Current
Common Mode current can be plotted along wires and cable routes
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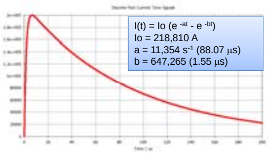
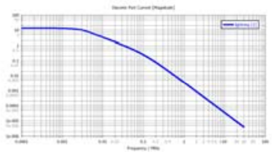
Lightning

MIL-STD-464 Severe Stroke Comp A





High-altitude EMP waveform FFT Broadband Spectrum

A400M lightning analysis

Lightning channel

CFRP

Aluminum

Composites
- Wing and main spars
- Tail, stabilizers and control surfaces
- Ribs, spars and 'sword' of the vertical stabilizer
- Rear cargo door and undercarriage bays
- Propeller blades

30% CFRP Composite Airframe

Composite skin modeling

Complex curved surfaces can be extracted to create thin panel representations by creating shapes from picked faces, applying solid to sheet conversion or a metal sheet simplification tool

Advanced multi-layer thin panel material used for composites

Cockpit and fuselage surfaces extracted and treated as thin panels

Surface current response

Skin depth

- Electrically thin panel defined as less than 1 skin depth thick
- Current diffuses through the panel
- 1 mm aluminum has a skin depth cutoff frequency at 14.5 KHz

$$\delta = \sqrt{\frac{1}{\pi f . \mu\sigma}} \Rightarrow F_{\delta} = \frac{1}{\pi . \mu\sigma . T^2}$$

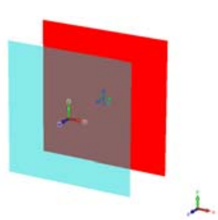
Amplitude reduced by 1/*e* or 37%

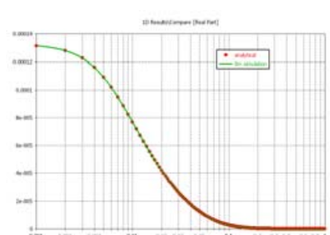
Skin Depth Cutoff Frequencies

¼ mm aluminum	23.1 MHz
1 mm aluminum	14.5 KHz
1 mm graphite	12.6 MHz

Transient TLM solver uses a thin panel material representation to model electrically thin panels efficiently

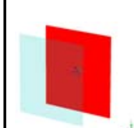
Graphite Panel Validation

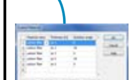




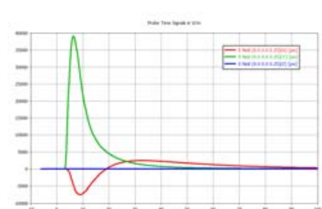
Multi-layer composite panel air/cfc/air/cfc/air layers (1mm thick)

Multi-layer thin panel



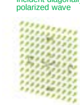


Laminate stackup

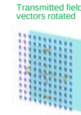


Diffusion through anisotropic composite panel shows different waveforms for resolved x/y field components

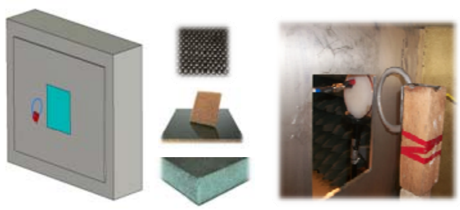
Incident diagonally polarized wave



Transmitted field vectors rotated



Magnetic shielding validation

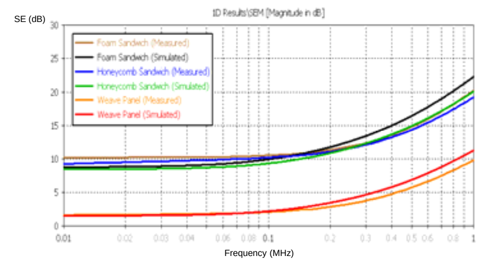


Magnetic SE Model

Magnetic SE Test

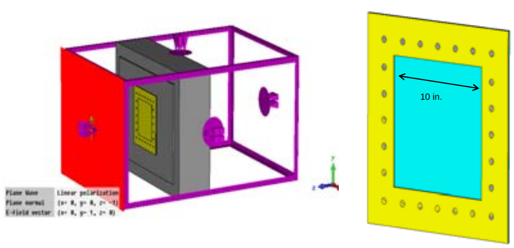
*Many thanks to Jeff Viel at NTS Boxborough MA for conducting the tests

Magnetic shielding results



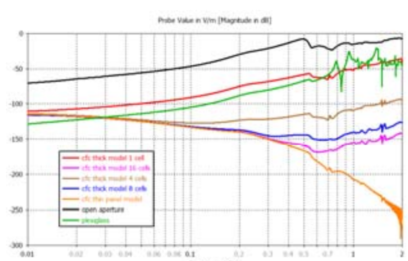
Good correlation between model and test data

Plane wave shielding



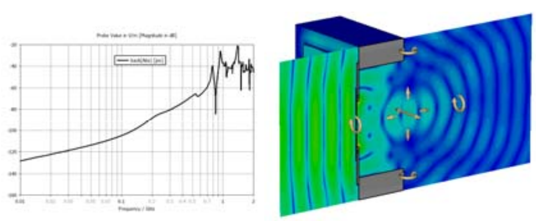
Model of CF Panel Mounted in Chamber Wall using Bolted Frame

Plane wave shielding results



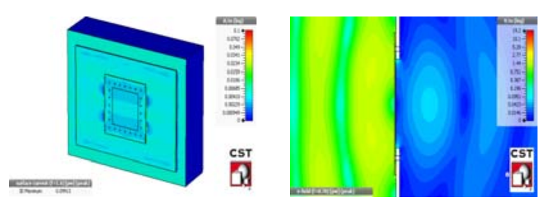
Results demonstrate advantage of integrating diffusion physics into the field solver rather than relying on brute force meshing

Transmitted field spectrum



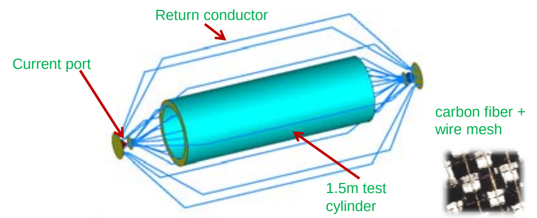
Plexiglas panel used to represent painted lap-joint
Shielding dependent on panel size and bolt spacing

Resonance at 1.4 GHz



Resonance occurs when aperture dimensions are a multiple of half-wavelengths

Lightning validation case



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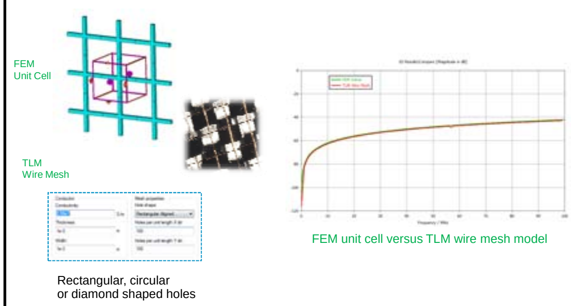
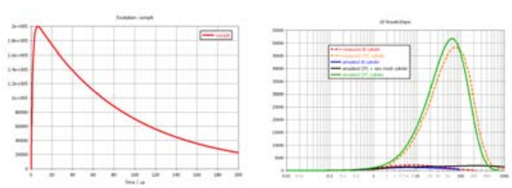
Wire mesh material



EMC LIVE

Validation



Lightning current waveform injected into cylinder

Ref: "Lightning induced currents in aircraft wiring using low level injection techniques", E Stevens (ERA) & D Jordan (RAE), NASA Technical report 19910023380.

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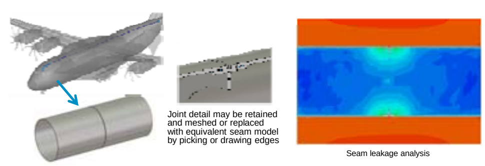
Joint modeling

Complex joint between skin and ribs can be modeled in detail

Preferable to use special joint model to reduce mesh complexity and maximize time-step

Joint gap and overlap dimensions may be specified, or simplified using a "compact seam"



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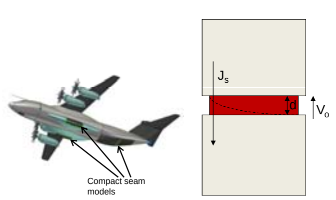
Compact seam model

- Electric field coupling associated with air gaps (capacitance)
- Magnetic field can penetrate through finite conductivity joints



$$Z_T = \frac{V_o}{J_s}$$

Transfer impedance Z_T

Transient TLM solver uses slot/seam representation to model air gaps and finite conductivity joints efficiently

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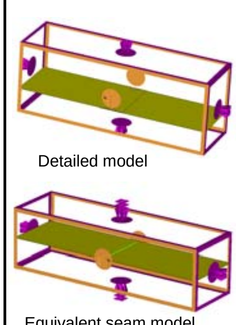
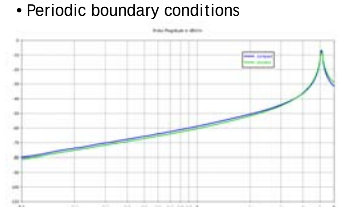
Lap Joint seam model

- 8 mil gap (paint thickness)
- 1.2 inch pitch between rivets
- Periodic boundary conditions





Good agreement between detailed and equivalent seam model

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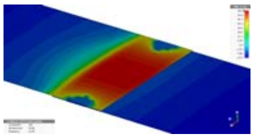
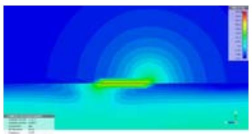
Current and Electric field at 5 GHz



Surface current distribution showing resonance between rivets



Electric field distribution showing aperture leakage

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Transient surface current

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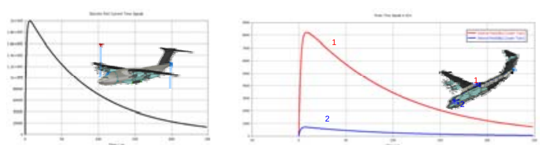
Induced magnetic fields



Transient magnetic field at external and internal locations
12 hr solve time for 250 ms response using 2x C2075 GPU

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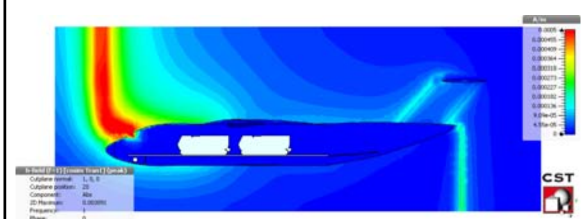
Magnetic field at 1 MHz



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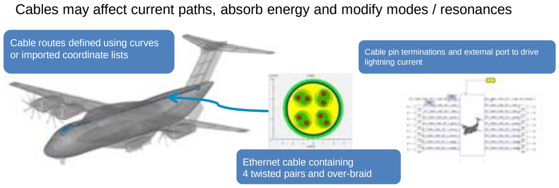
Cable harness modeling

CST CABLE STUDIO enables complex harness cross-sections to be modeled efficiently

Full bi-directional coupling between 3D field solver, cable solver and circuit solver

Cables may affect current paths, absorb energy and modify modes / resonances



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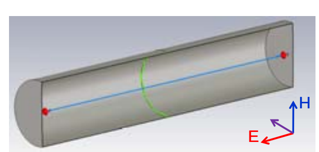
Bi-directional coupling



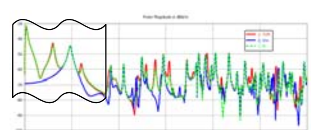
10m long, 1m radius PEC cylinder with circumferential slot

0.5mm diameter bare copper wire on the inside

Illuminated by 1V/m horizontally polarized plane wave

Comparison of H-Field inside the cylinder

Integrated TLM Thin Wire
Uni-Direction Coupling
Bi-Directional Coupling



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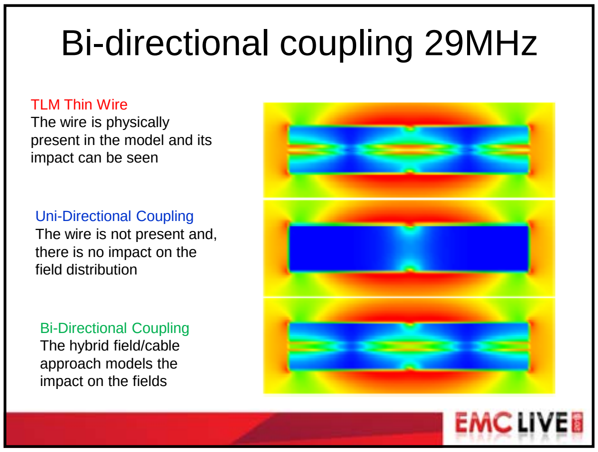
Bi-directional coupling 29MHz
TLM Thin Wire
The wire is physically present in the model and its impact can be seen
Uni-Directional Coupling
The wire is not present and, there is no impact on the field distribution
Bi-Directional Coupling
The hybrid field/cable approach models the impact on the fields
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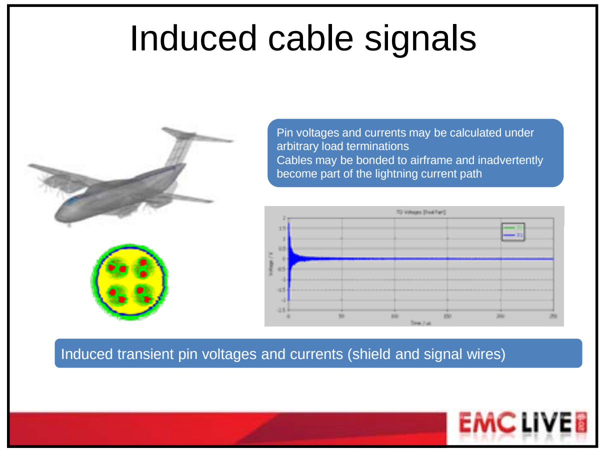
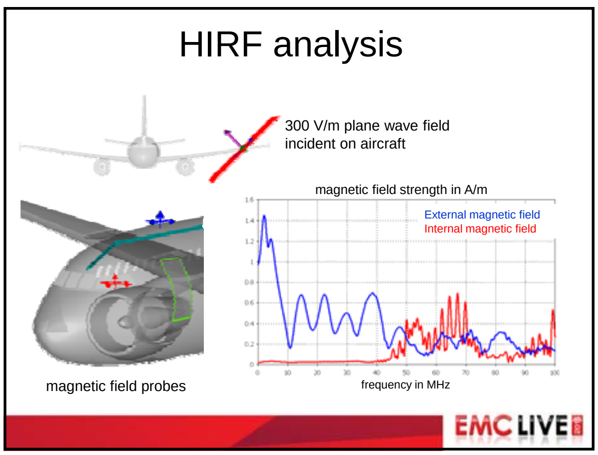
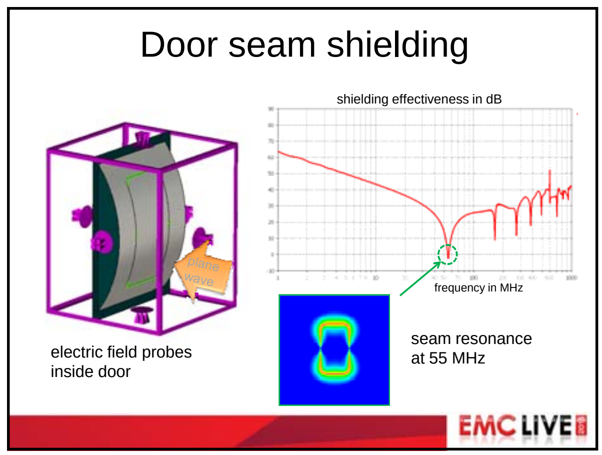
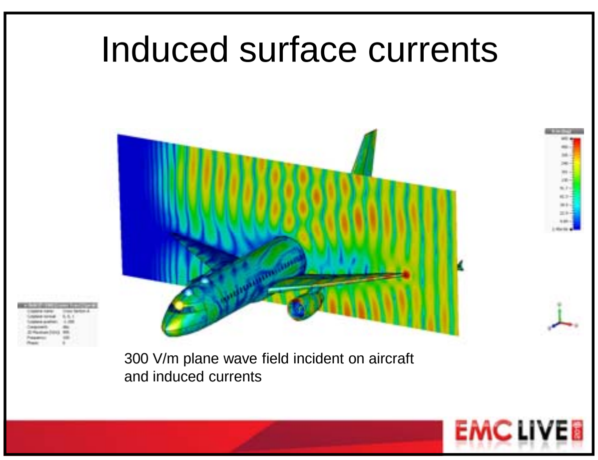
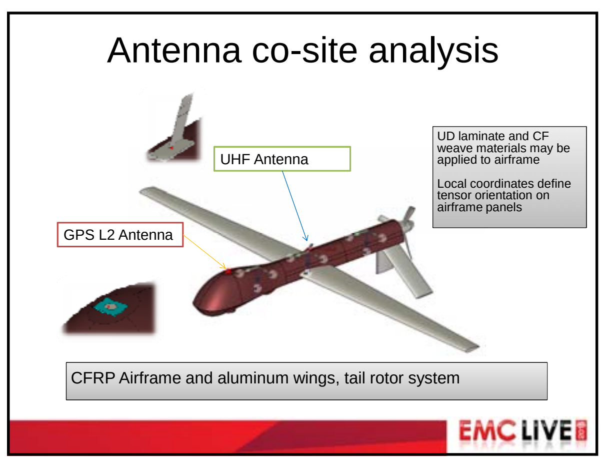

Induced cable signals
Pin voltages and currents may be calculated under arbitrary load terminations
Cables may be bonded to airframe and inadvertently become part of the lightning current path
Induced transient pin voltages and currents (shield and signal wires)
EMC LIVE


HIRF analysis
300 V/m plane wave field incident on aircraft
magnetic field strength in A/m
External magnetic field
Internal magnetic field
frequency in MHz
magnetic field probes
EMC LIVE


Door seam shielding
shielding effectiveness in dB
frequency in MHz
electric field probes inside door
seam resonance at 55 MHz
EMC LIVE


Induced surface currents
300 V/m plane wave field incident on aircraft and induced currents
EMC LIVE


Antenna co-site analysis
UHF Antenna
UD laminate and CF weave materials may be applied to airframe
Local coordinates define tensor orientation on airframe panels
GPS L2 Antenna
CFRP Airframe and aluminum wings, tail rotor system
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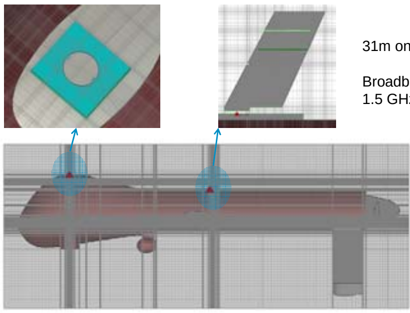
TLM cell lumping



31m on 2 GPU Tesla 2075

Broadband solution up to 1.5 GHz

140M cells → 48M cells

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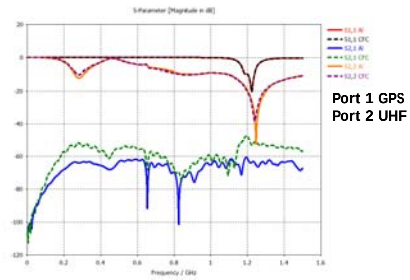
Antenna return loss and coupling



Simulation predicts CF material has impact on antenna coupling

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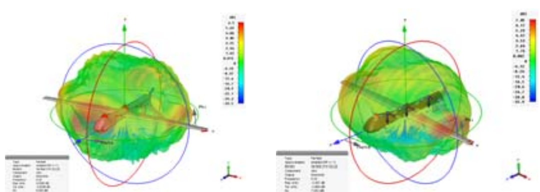
Installed pattern (UHF)



Aluminum | CF Composite

UHF pattern noticeably affected by composite materials

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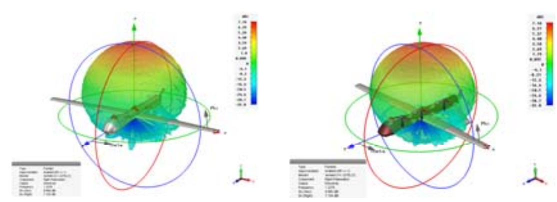
Installed pattern (GPS)



Aluminum | CF Composite

GPS RHC pattern slightly affected by composite materials

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Summary

- Transient effects of EMP and lightning
  ⇨ direct time-domain simulation utilizing efficient algorithms for critical coupling mechanisms
- Bi-directional field – cable – circuit co-simulation
  ⇨ tight integration of different solver technologies (EM, cable, circuit)
- Solution: Complete Technology by CST

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