HFSS 13: Hybrid FE-BI for Efficient Simulation of Radiation and Scattering

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Agenda

- **FEM Mesh Truncation Methods**
  - Absorbing Boundary Condition
  - Perfectly Matched Layer
  - Finite Element-Boundary Integral
    - Overview
    - Solution Process
    - High Performance Computing
- **FE-BI: In Detail**
  - Distance From Radiator
  - Incident Angle
  - Arbitrary Shaped Boundary
  - Separated Volumes
- **WorkBench Integration**

Finite Element Method Mesh Truncation

- **Truncation of infinite free space into a finite computational domain**
  - Boundary conditions can be used to emulate the free space environment
    - **A**bsorbing **B**oundary **C**ondition
    - **P**erfectly **M**atched **L**ayer
    - **F**inite **E**lement-**B**oundary **I**ntegral
  - These boundary conditions are used to minimize reflections off of outer surfaces
    - Make solution appear as though it is in infinite free space
    - Similar concept as an anechoic chamber

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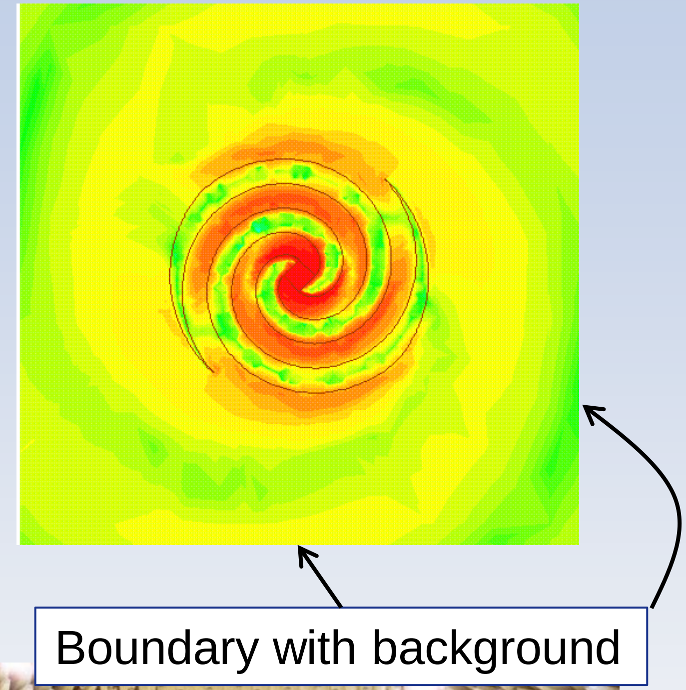

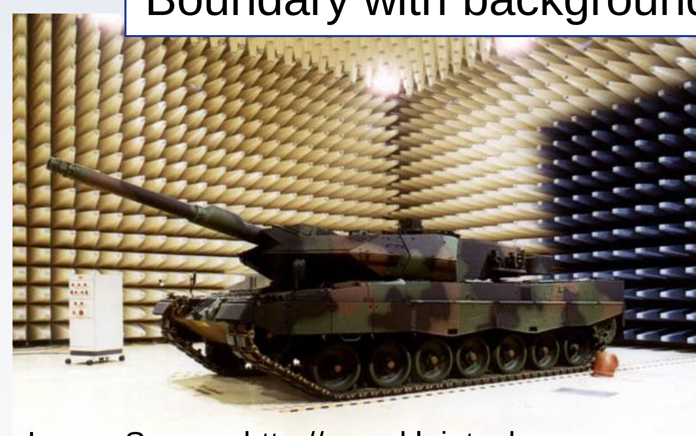

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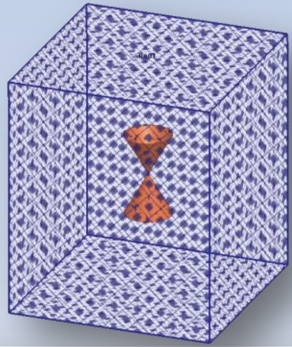
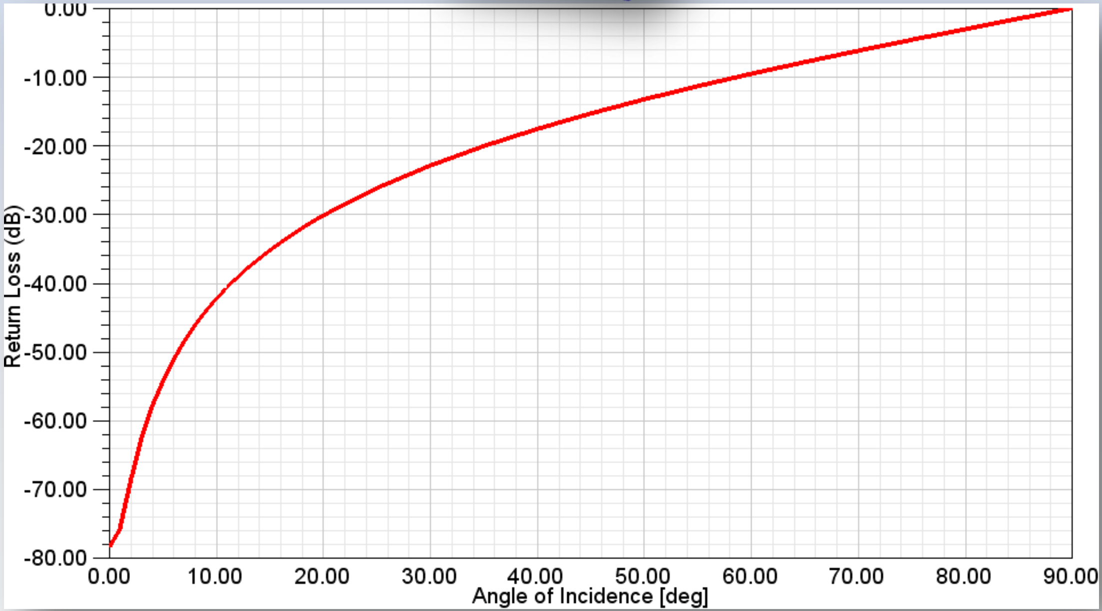
FEM Mesh Truncation Methods:

Absorbing Boundary Condition
Perfectly Matched Layer
Finite Element-Boundary Integral

Absorbing Boundary Condition

- **Mimics continued propagation beyond boundary plane with a mathematical boundary condition**
  - Boundary needs to maintain at least **λ/4 distance** from strongly radiating structures
  - Absorbs best when incident energy flow is **normal to surface**
  - Must be **concave** to all incident fields from within modeled space

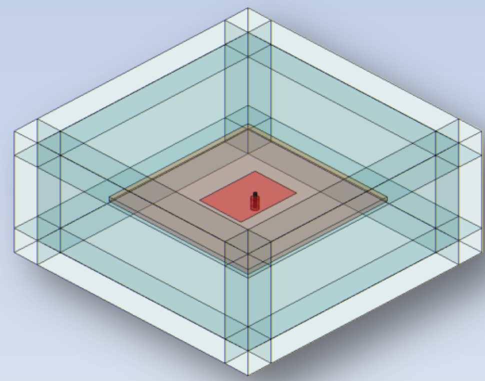


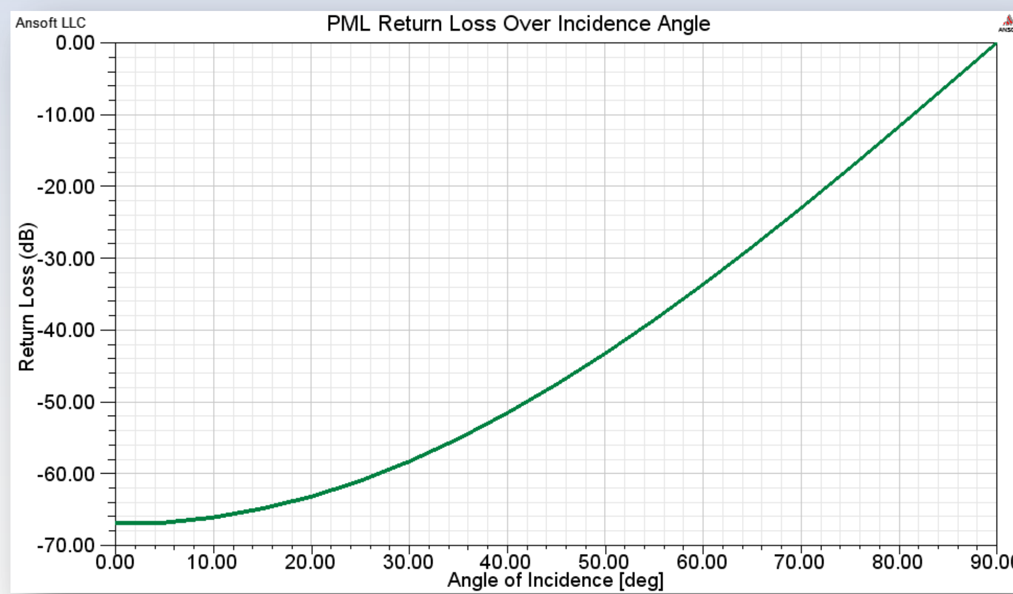


Reflection (dB) vs angle of incidence

Perfectly Matched Layer

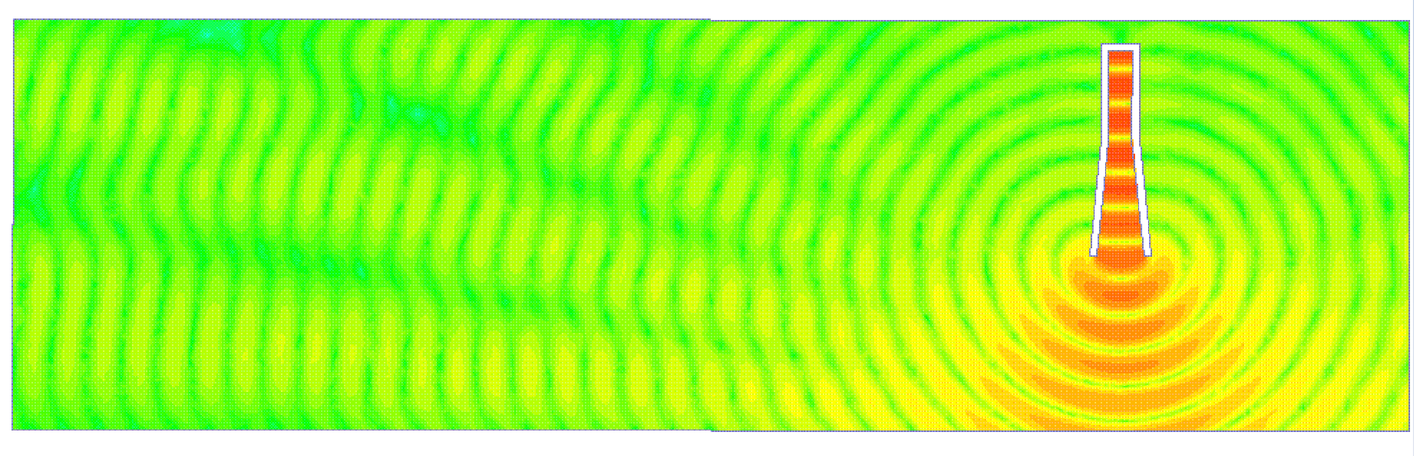
- **Fictitious lossy anisotropic material which fully absorbs electromagnetic fields**
- **Reflection coefficient of less than -20dB for incident angles up to 70 degrees**
  – Improved by increasing thickness of absorbing layers
- **Highly accurate even when PML boundaries are placed at a distance of λ/8 or closer**
- **PML is required to be placed on planar surfaces**
  – Thickness of PML increases volume of FEM domain



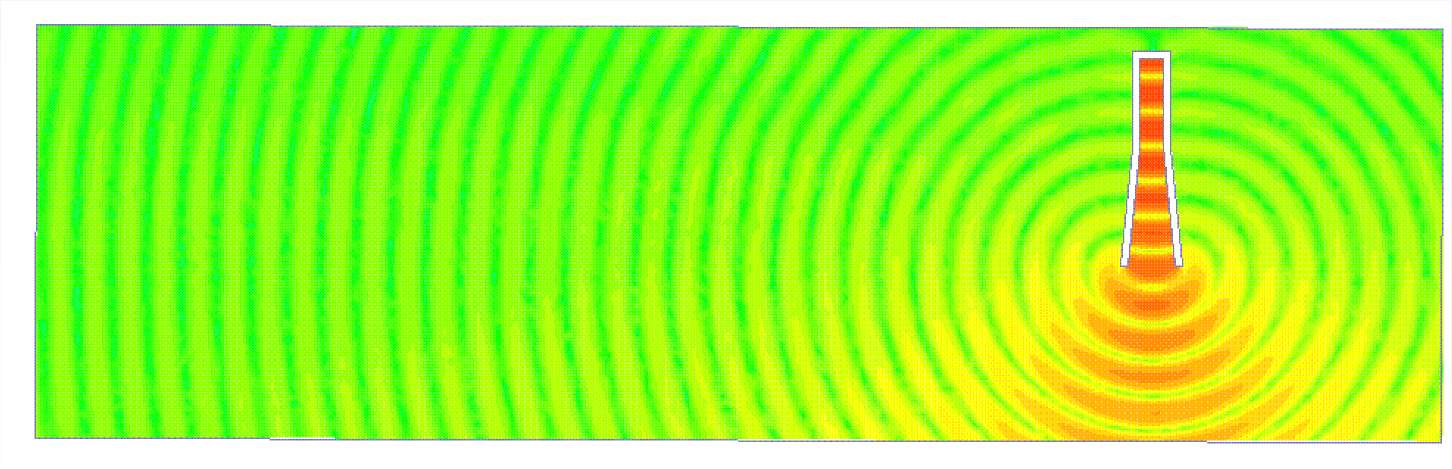


Incident Angle Reflections 90°

"absorbing" boundary

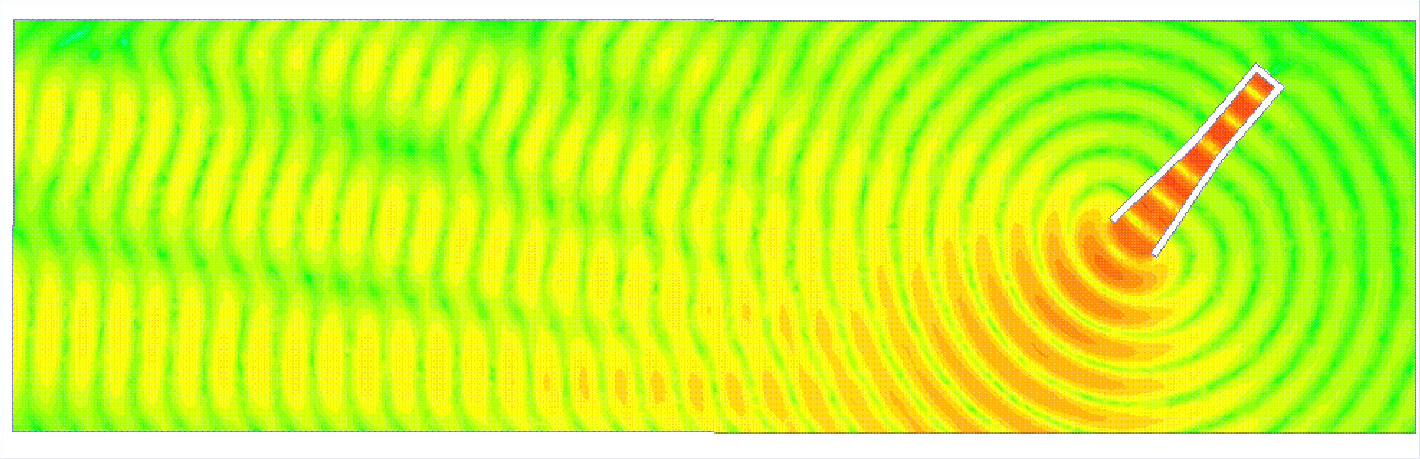


PML (Perfectly Matched Layer)



Incident Angle Reflections 50°

“absorbing” boundary



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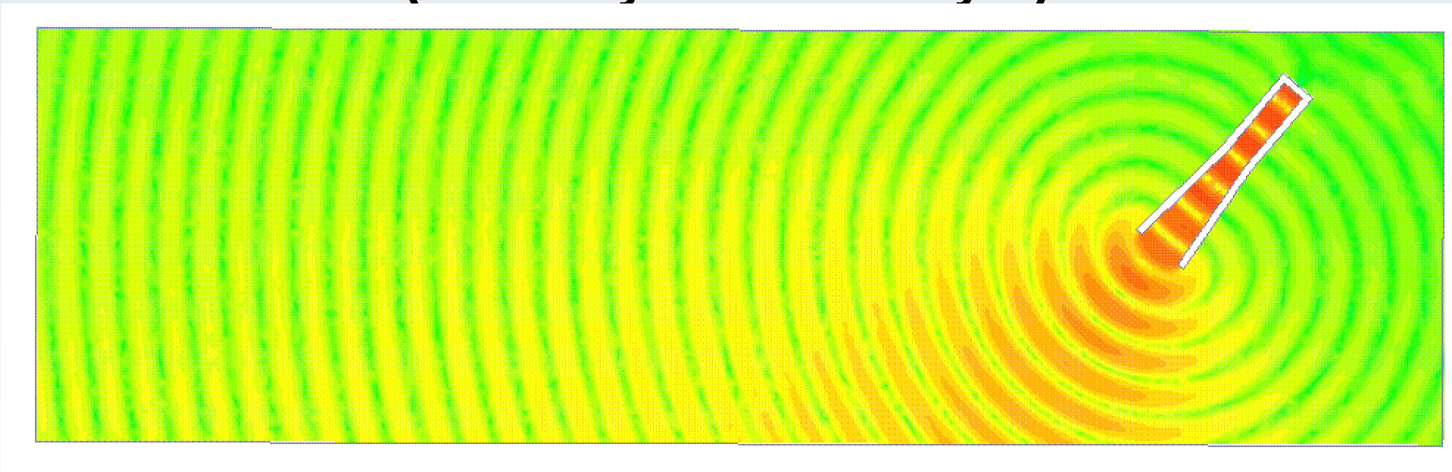
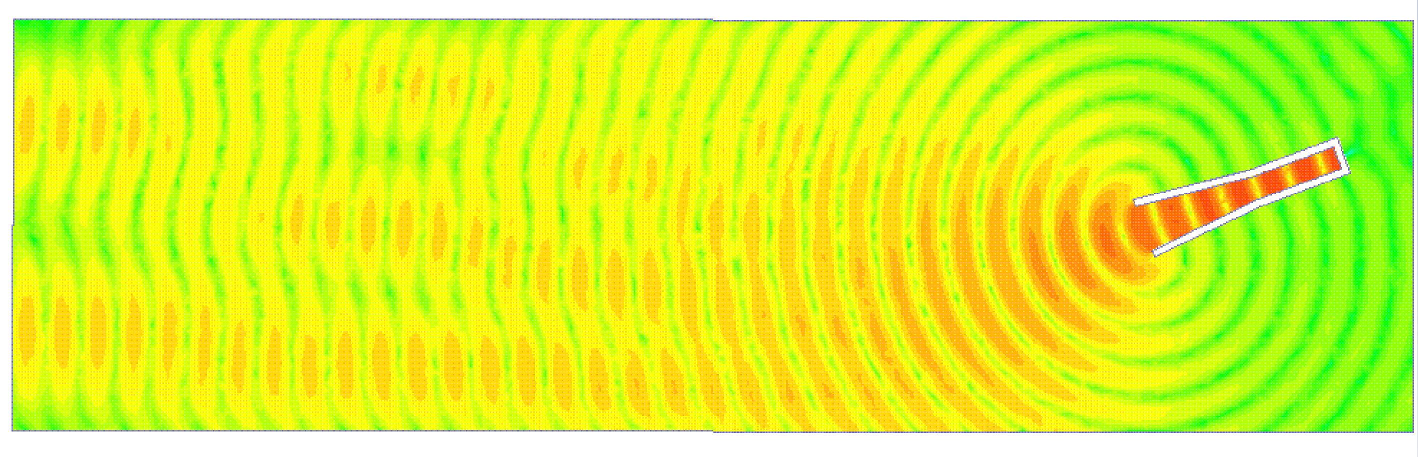


Incident Angle Reflections 20°

“absorbing” boundary



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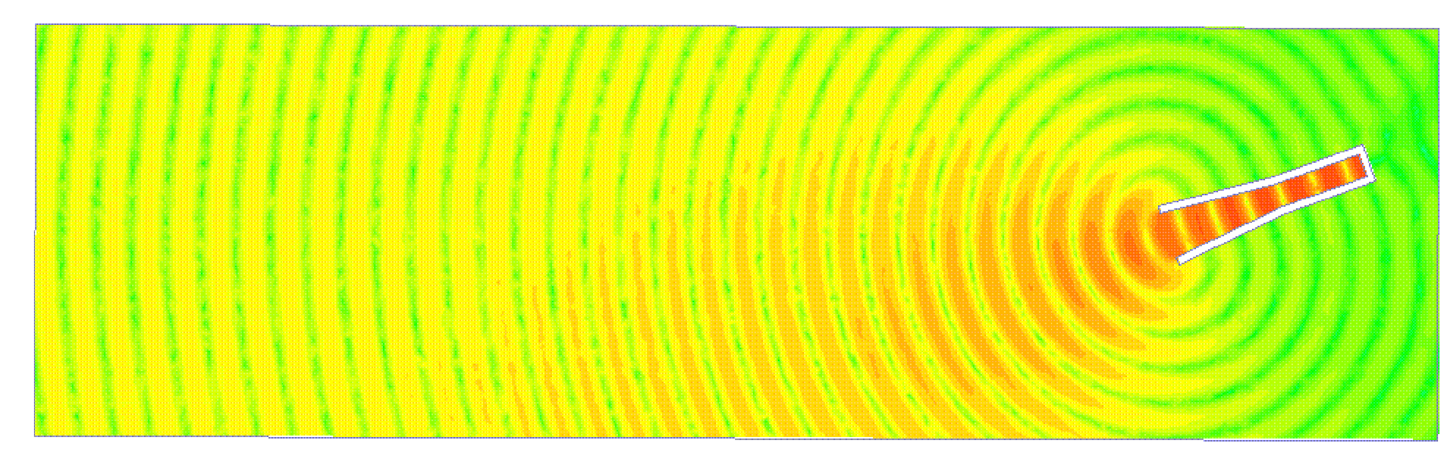
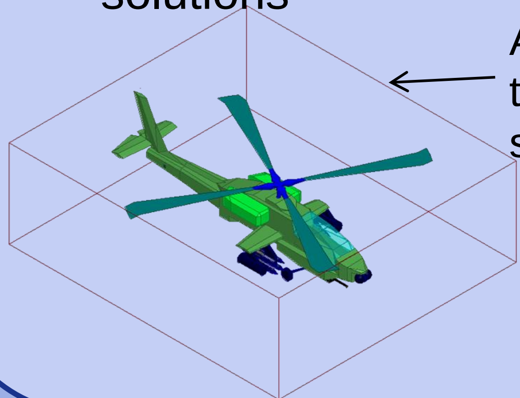


Hybrid Finite Element-Integral Equation Method

- **Finite Element Based Method**
  - HFSS
  - <u>Efficient handle complex material and geometries</u>
  - Volume based mesh and field solutions



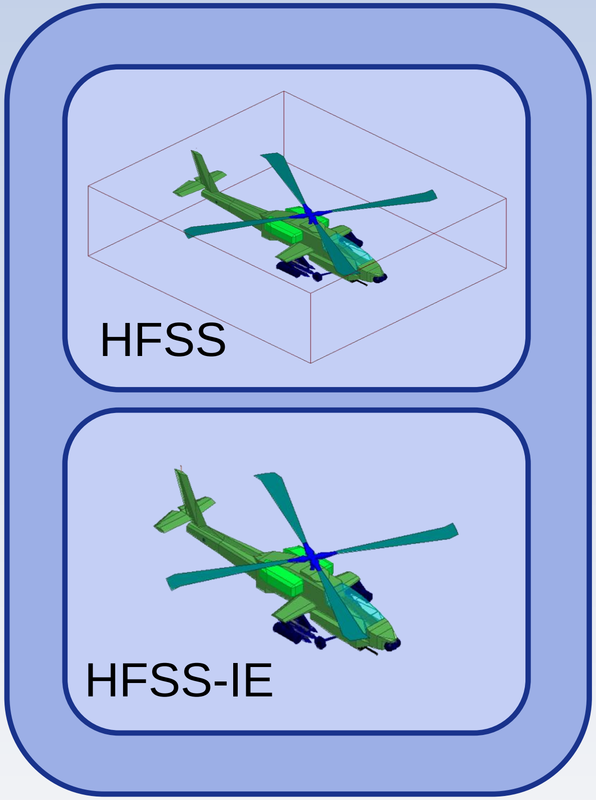
Airbox required to model free space radiation

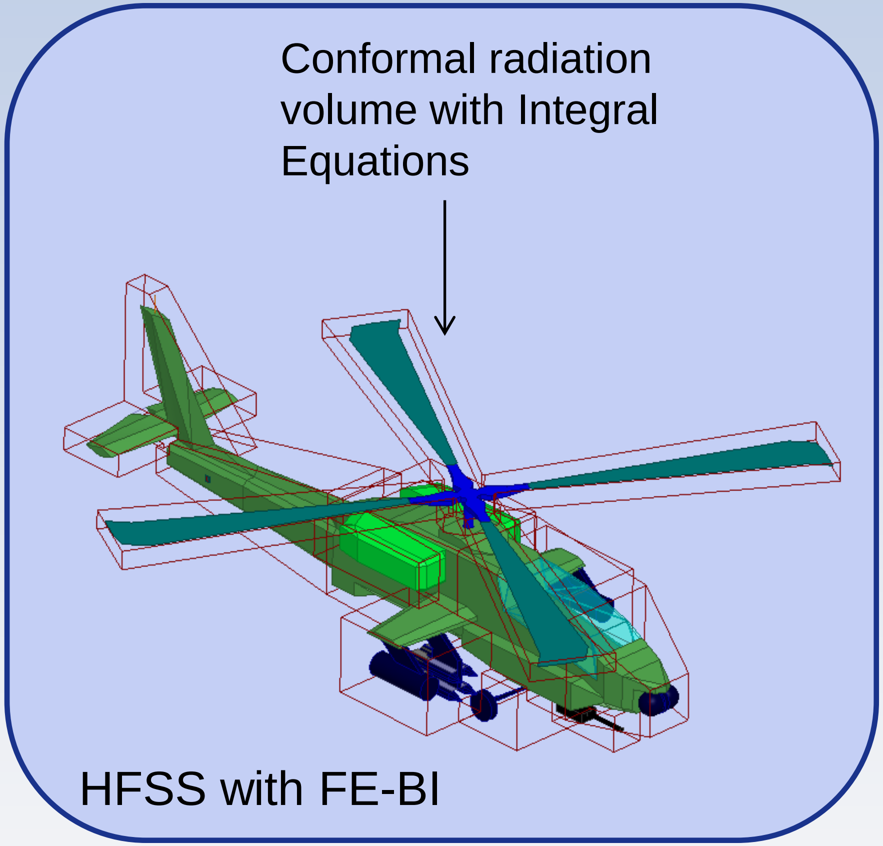
- **Integral Equation Based Method**
  - HFSS-IE
  - <u>Efficient solution technique for open radiation and scattering</u>
  - Surface only mesh and current solution

Airbox not needed to model free space radiation

Finite Elements vs. Integral Equations

Hybrid Finite Element-Integral Equation Method

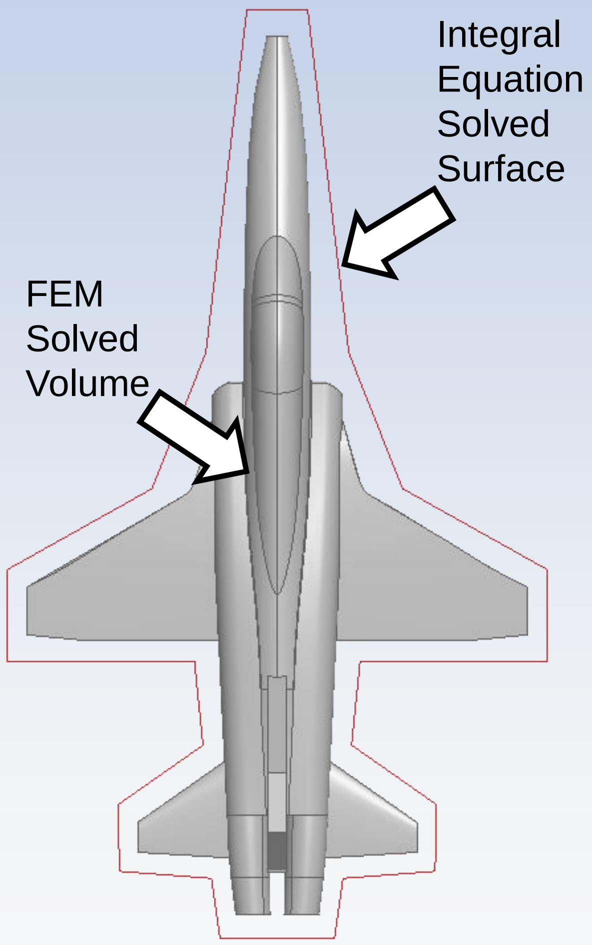




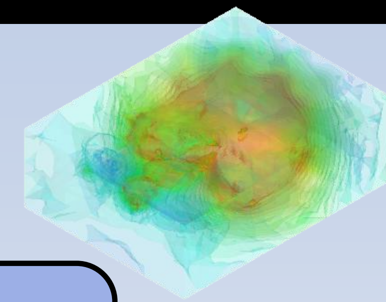
This Finite Element-Boundary Integral hybrid method leverages the advantages of both methods to achieve the most accurate and robust solution for radiating and scattering problems

Finite Element–Boundary Integral (FE-BI)

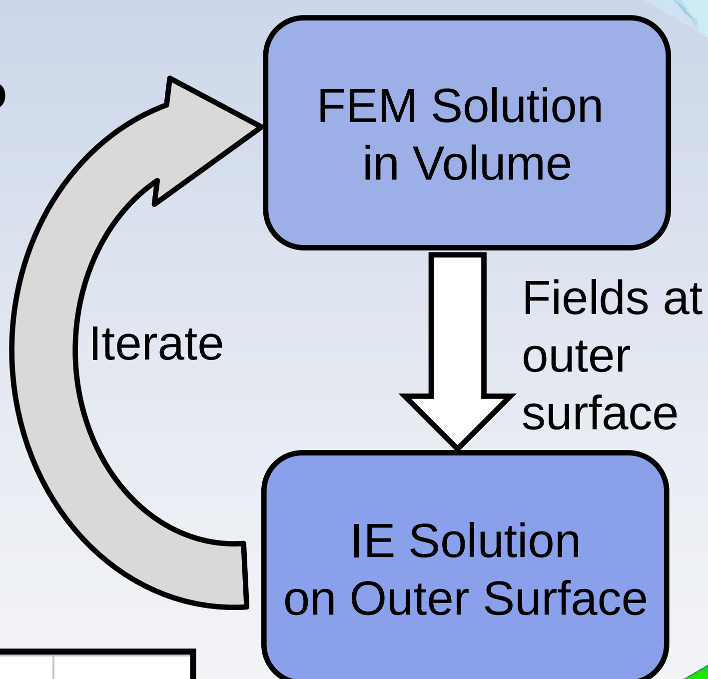
- **No theoretical minimum distance from radiator**
  - Advantage over ABC
  - Easy setup for broadband frequency sweeps
- **Reflectionless boundary condition**
  - Ability to absorb incident fields is not dependent on the incident angle
  - Highly advantageous over ABC boundary condition
- **Arbitrary shaped boundary**
  - Outward facing normals can intersect
  - Can contain separated domains
  - Conformal boundary can eliminate air volume required when using PMLs or ABCs
- **FE-BI comes with a computational cost**
  - Ability to create Airbox with smaller volume than ABC or PML can significantly offset this cost



Finite Element-Boundary Integral: Solution Process



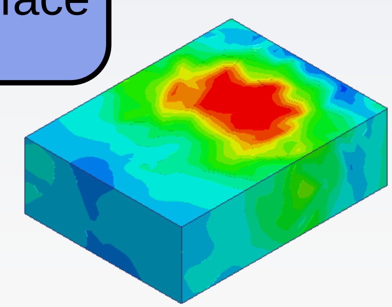
- **The FEM solution is applied to volume enclosed by an Airbox**
  - ABC boundary applied to outer surface
- **Fields on outer surface are passed to the Integral Equation solver to calculate a correction factor**
- **Correction factor passed back to the FEM solver where the fields are recalculated**
  - Iterations of this process continue until a converged solution is found



Example Profile

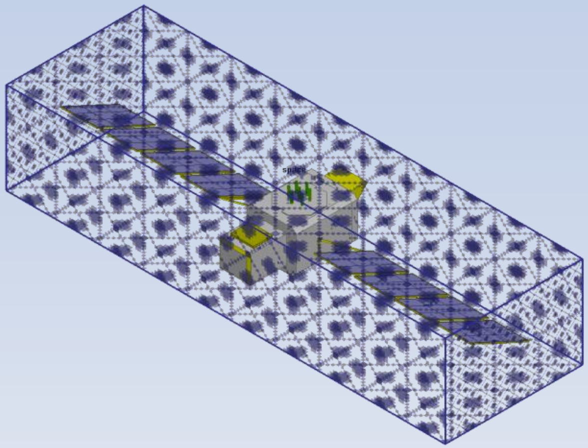
FEM Domain → Matrix Assembly/Solver MCS4
IE Domain → Matrix Assembly/Solver DCS4, IE
Iteration Process → Iterations

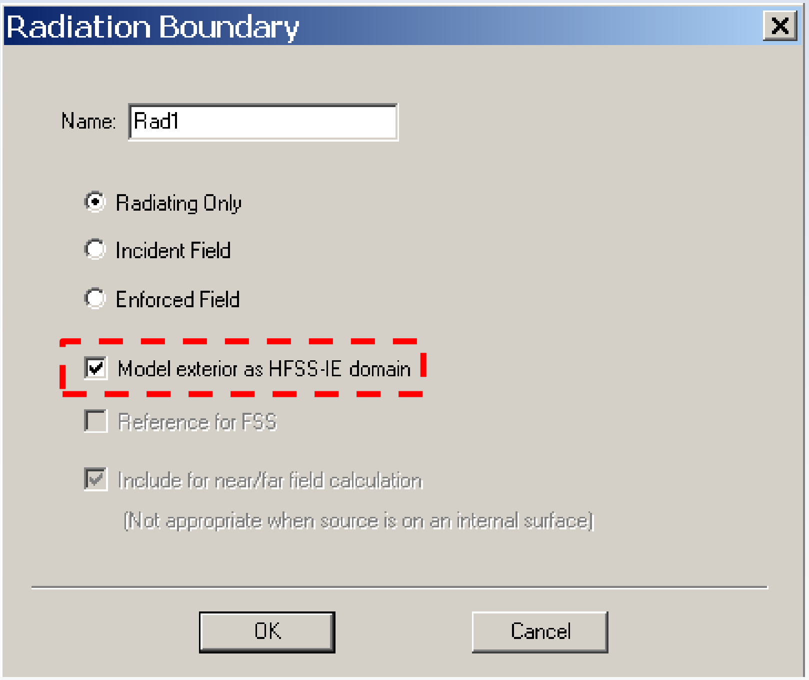
Adaptive Pass 1			
Matrix Assembly/Solver MCS4	00:02:53	00:07:28	2.76 G
Matrix Assembly/Solver DCS4, IE	00:01:25	00:03:47	4.77 G
Iterations	00:03:18	00:04:18	4.77 G



Finite Element-Boundary Integral: Boundary Condition Setup

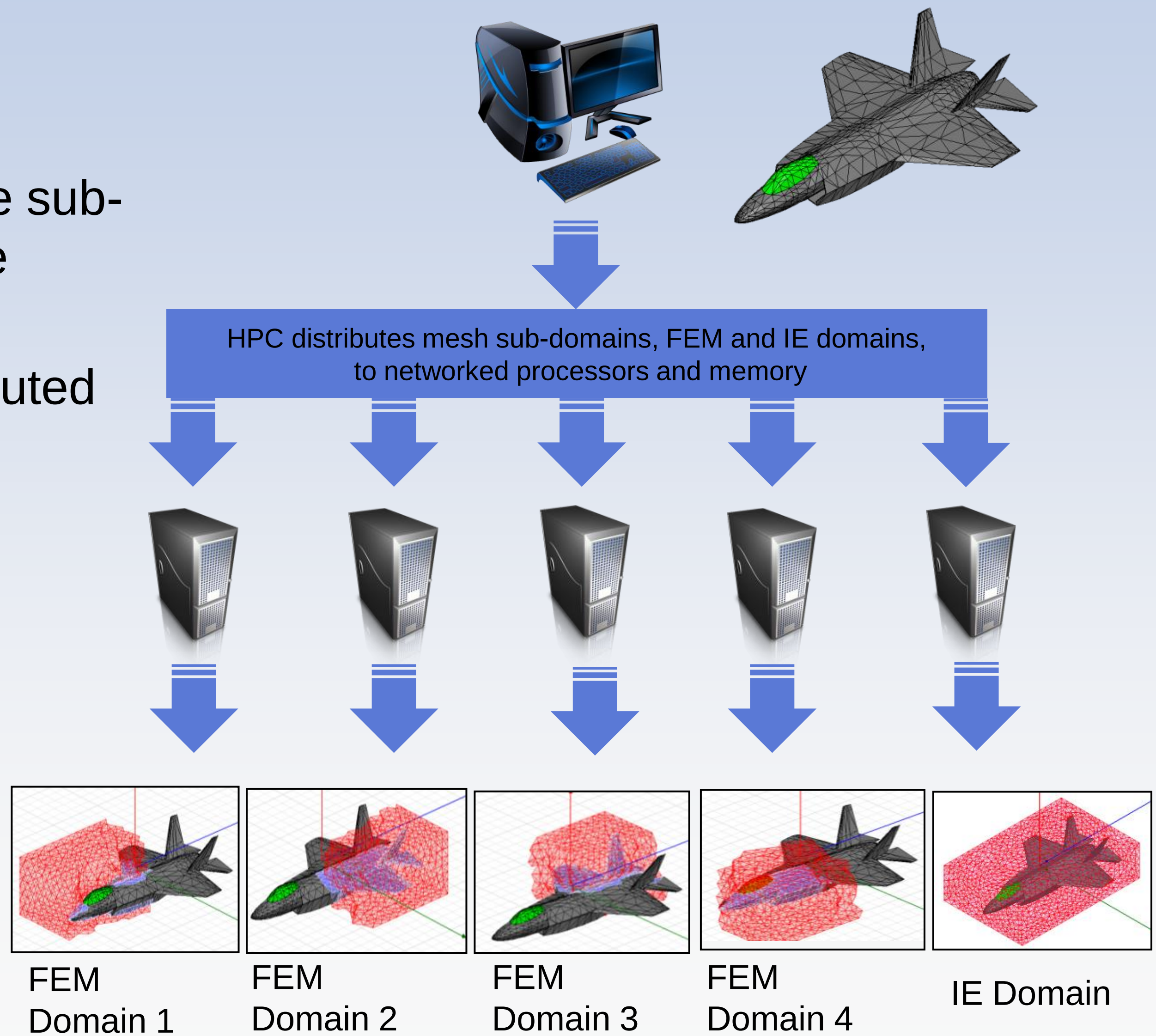
- **Boundary condition is enabled with HFSS-IE**
- **Setup is similar to ABC boundary condition**
  - Enabled by selecting "Model exterior as HFSS-IE domain"
- **Radiation surface must enclose entire geometry**
  - 1 infinite ground plane allowed
- **Direct vs. Iterative Matrix Solver**
  - Direct Matrix Solver
    - Preferred method with FE-BI
    - Quickest solution
  - Iterative solver
    - Uses the least amount of RAM





FE-BI Available with Domain Decomposition

- Distributes mesh sub-domains to network of processors
  - FEM volume can be sub-divided into multiple domains
  - IE Domain is distributed to last computer in distributed list of computers
- Significantly increases simulation capacity
- Multi-processor nodes can be utilized



Radiating Boundary Conditions Summary: ABC, PML, FE-BI

Boundary Condition	Computation Resources	Minimum Distance from Radiator	Shape	Setup Complexity
ABC	Lowest	$\lambda/4$	Concave only	Easy
PML	Middle	$\lambda/8$	Planar and concave only (rectangular box)	Moderate
FE-BI*	Highest	No Limit	Arbitrary	Easy

- **FE-BI's higher computational resources can be offset by eliminating free space volume from FEM solution**

*Requires HFSS-IE License Feature

FE-BI: In Detail

Distance From Radiator

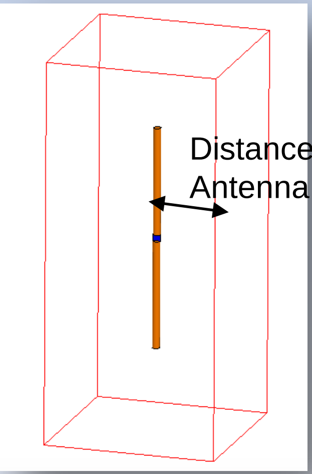
Incident Angle

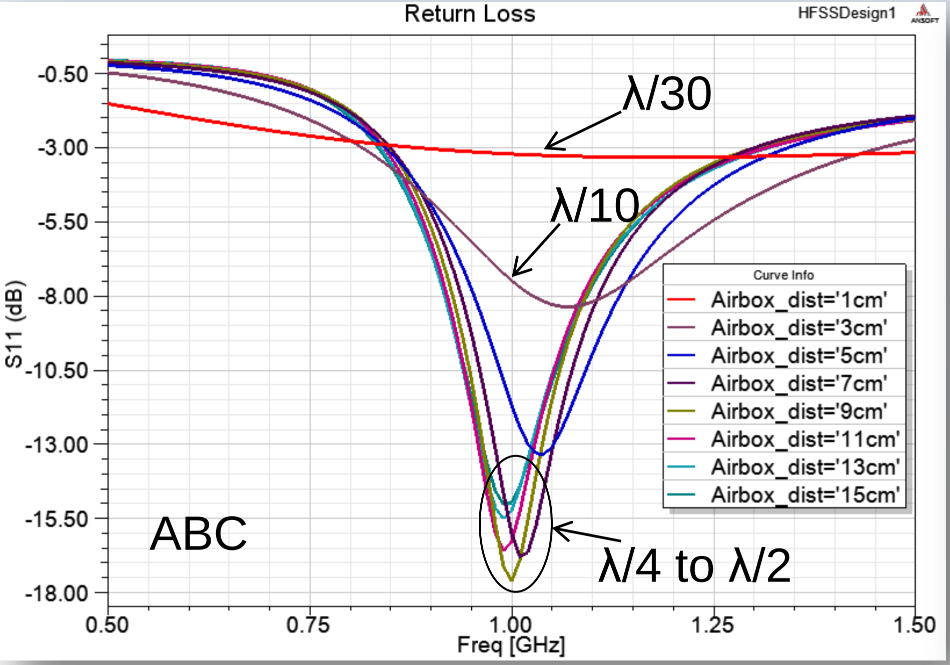
Arbitrary Shaped Boundary

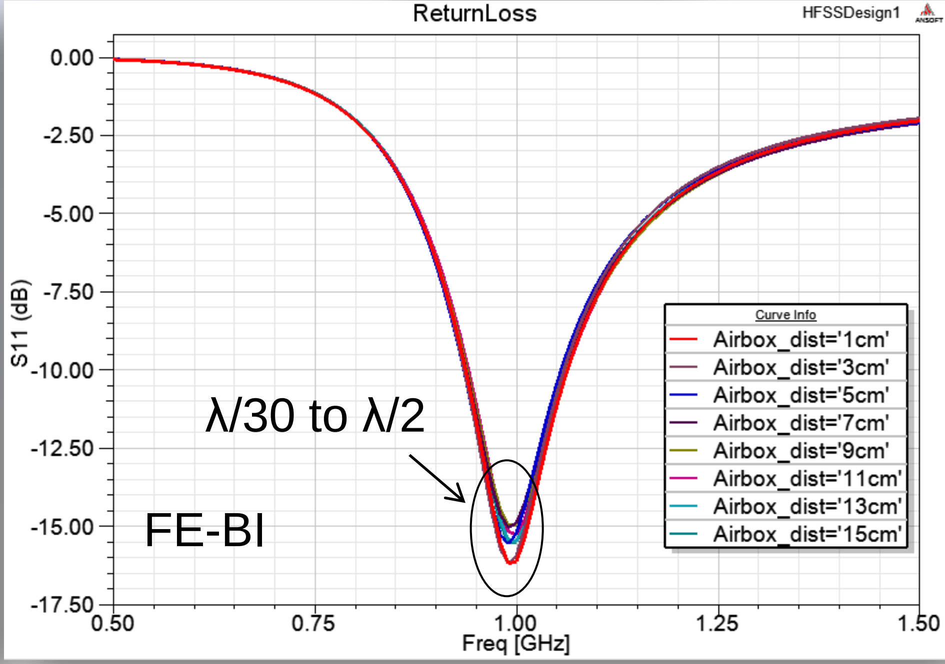
Separated Volumes

Distance from Radiator:
Comparison of ABC and FE-BI

- **FE-BI has no theoretical limitation on how close it can be placed from a radiator**
  - ABCs should not be placed any closer than λ/4
  - Simulation can benefit from simplified setup for broadband frequency sweeps and reduced computation volume vs. PML and ABC
- **Comparison between ABC and FE-BI placement**
  - Return loss is unaffected by distance from antenna for FE-BI

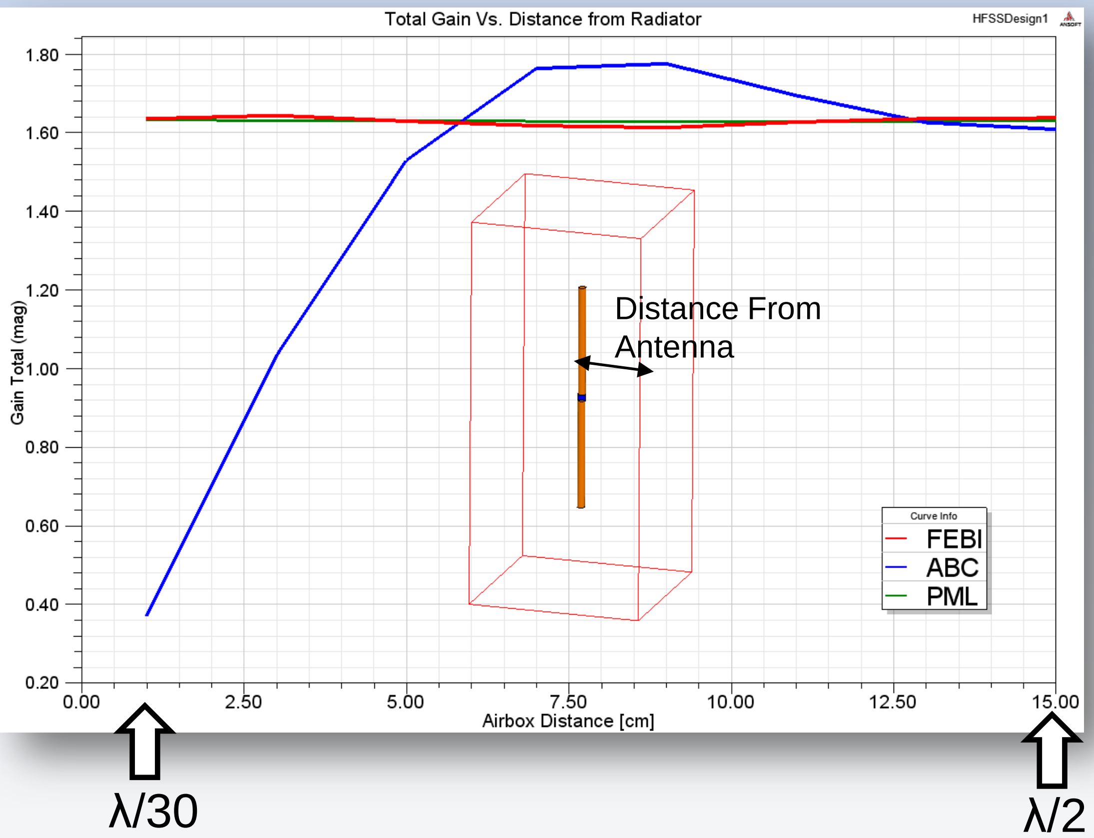






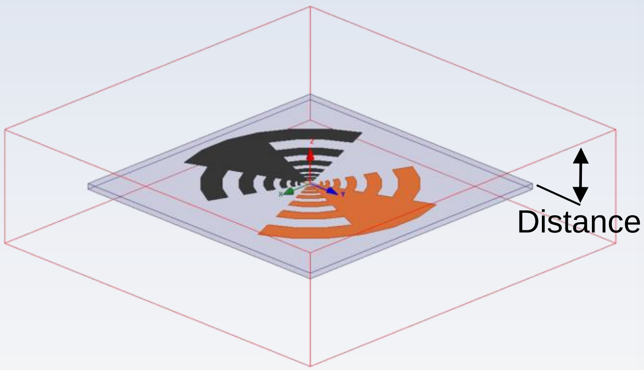
Distance from Radiator

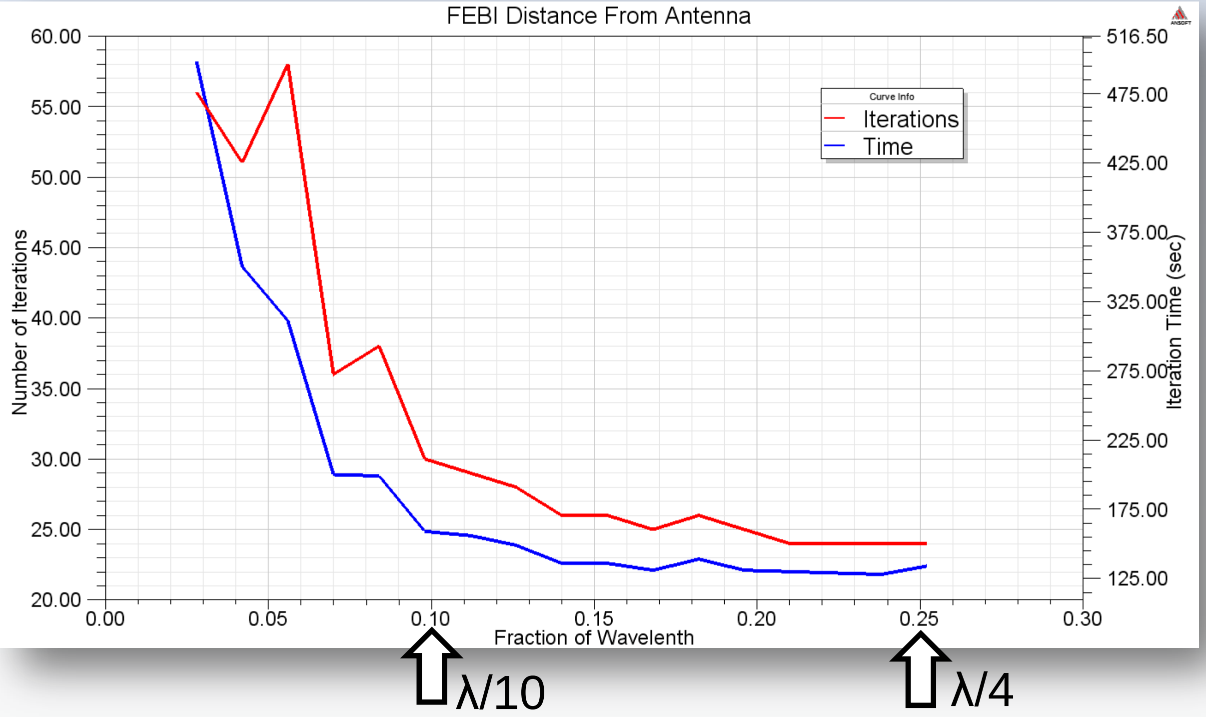
- **Peak gain vs. Airbox sizing**
  - ABC needs at least λ/4 spacing from antenna element to yield accurate far field results
  - PML and FE-BI accurately predicts gain, even as close as λ/30



FE-BI Distance From Radiator: Effect on Simulation Time

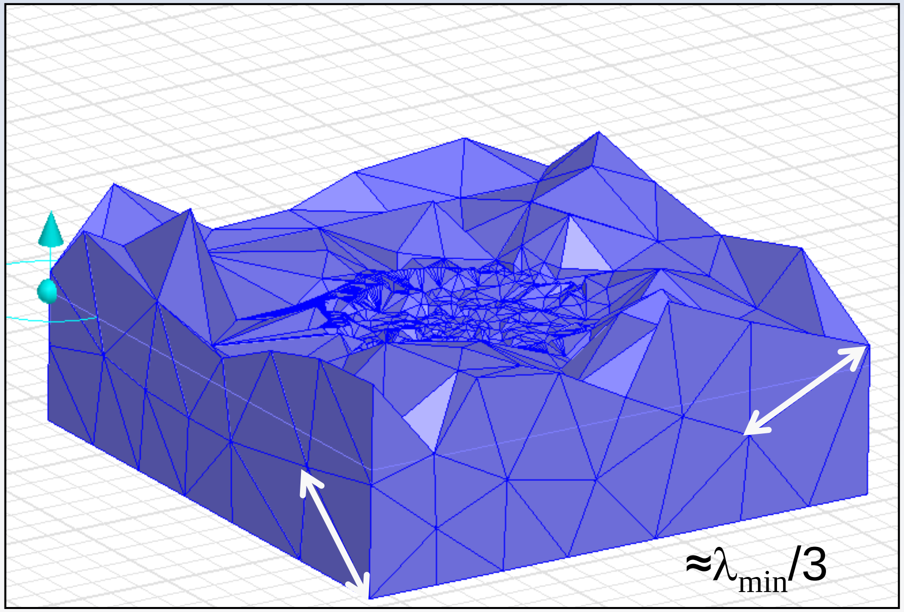
- **The accuracy of FE-BI is not dependent on its spacing from the radiator**
  - Simulation time is dependent on spacing
  - The number of iterations required between the FEM and IE domain will increase as the spacing between the radiator and boundary conditions decreases
- **A spacing of λ/10 or larger will yield the least number of iterations and minimum simulation time**



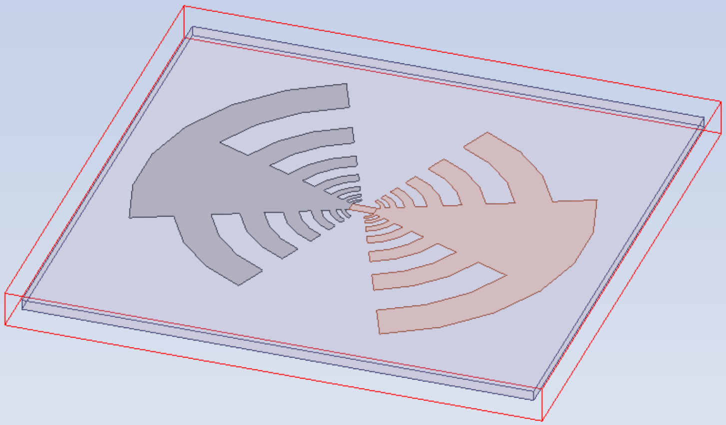


FE-BI for Broadband Antennas

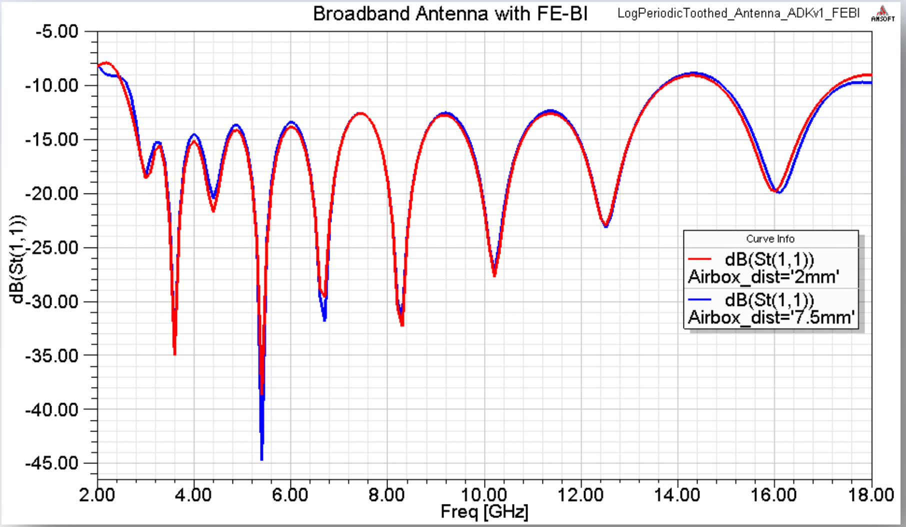
- **Conflicting requirements for broadband antennas (this is a very general issue and not specific to FEM):**
  - **Lowest frequency determines the total volume.**
  - **Highest frequency sets a minimum value for the largest tetrahedron edge length.**



Broadband Antenna



- **Airbox at any distance gives the same result**
  – Broadband antenna setup is simple with FE-BI
- **Airbox at a distance of 2mm**
  – ~λ/100 @ 2 GHz
  – ~λ/10 @ 18 GHz
- **Airbox at a distance of 7.5mm**
  – ~λ/20 @ 2 GHz
  – ~λ/2 @ 18 GHz



FE-BI: In Detail

Distance From Radiator

<u>Incident Angle</u>

Arbitrary Shaped Boundary

Separated Volumes

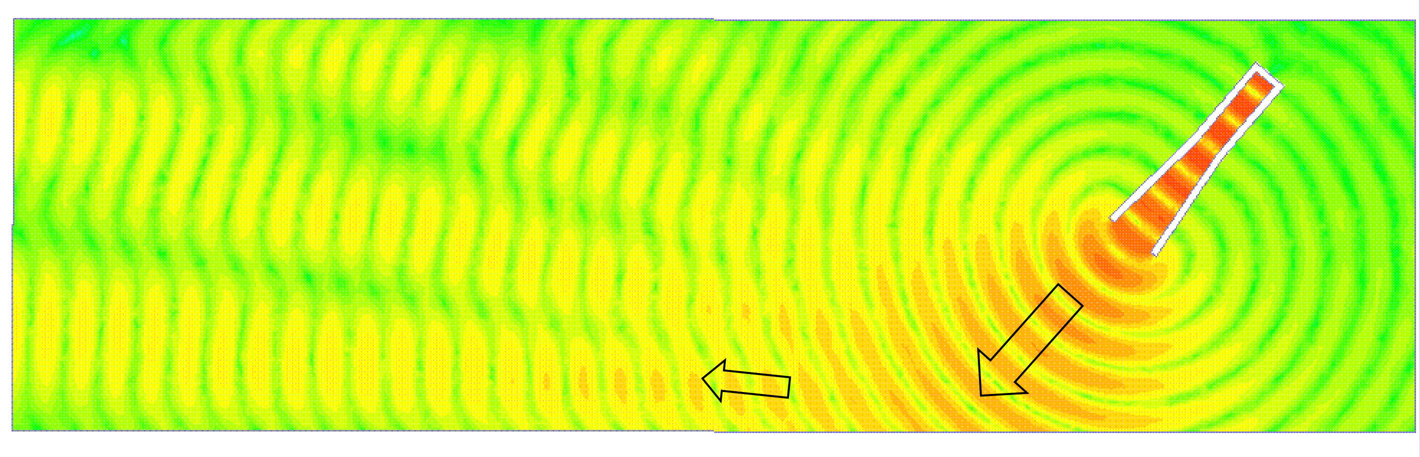
Incident Angle Reflections

- **The Finite Element-Boundary Integral has a significant advantage of the Absorbing Boundary Condition for fields incident on the boundary at oblique incident angles**

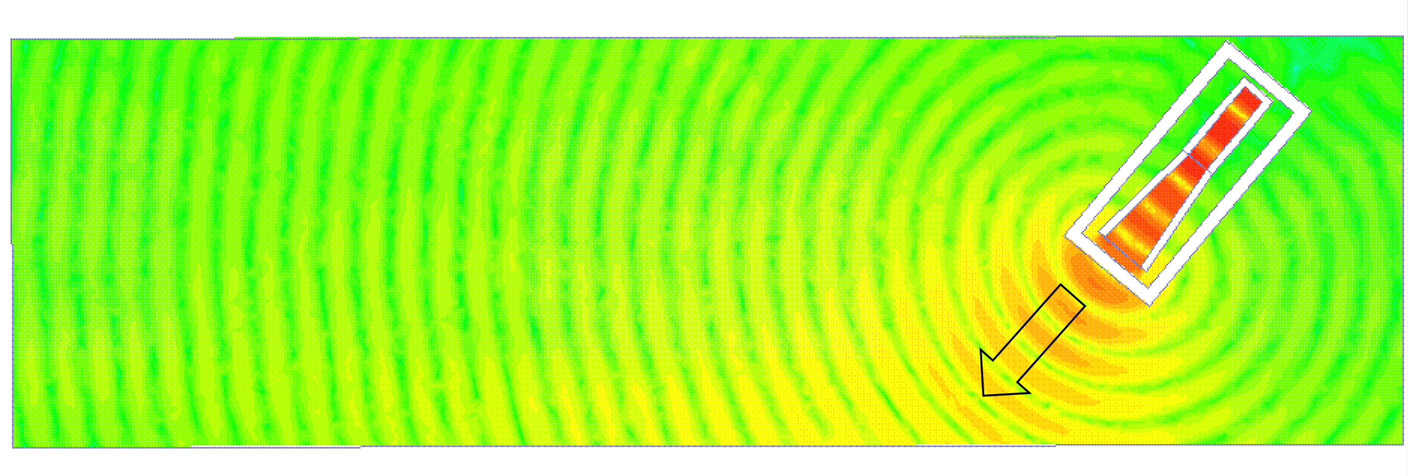
- **This difference can clearly be seen in the radiated fields from a horn antenna incident on an ABC and FE-BI**

Incident Angle Reflections 50°

“absorbing” boundary

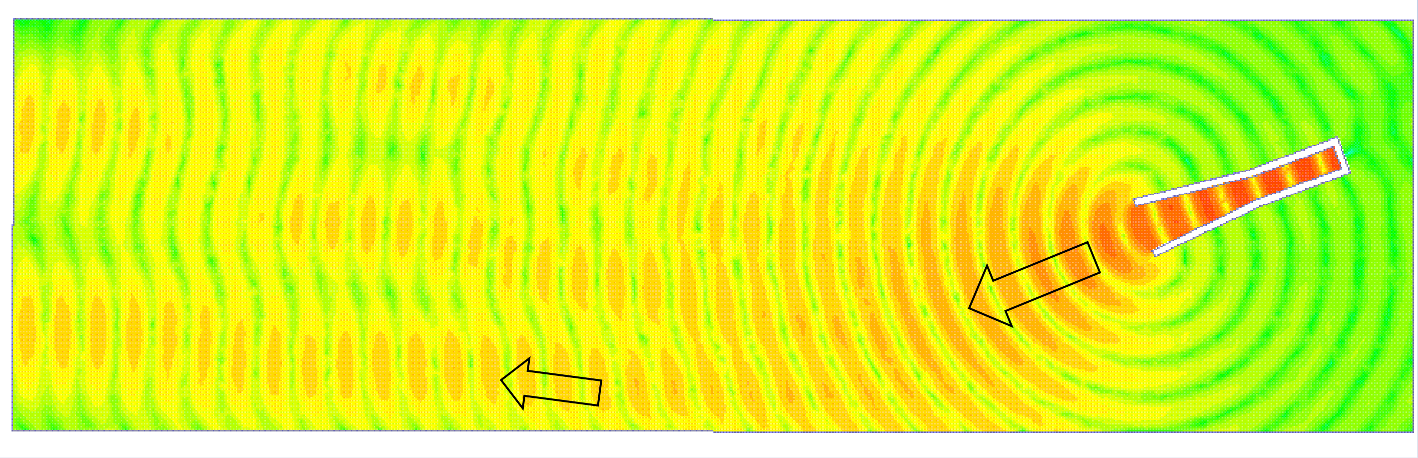


IE-ABC

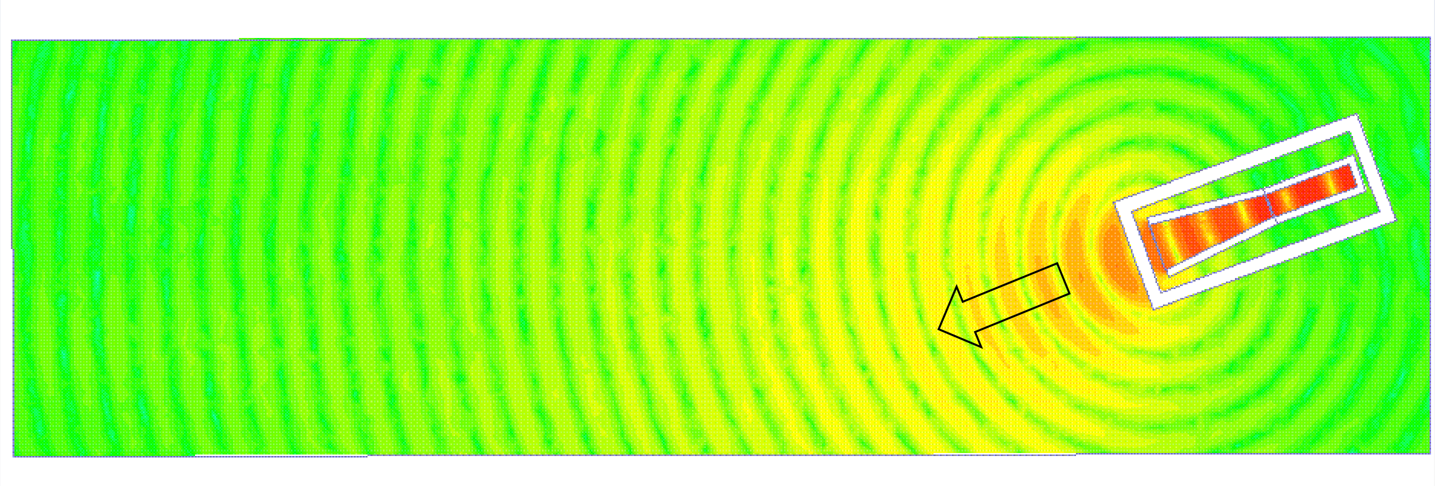


Incident Angle Reflections 20°

“absorbing” boundary



IE-ABC



FE-BI: In Detail

Distance From Radiator

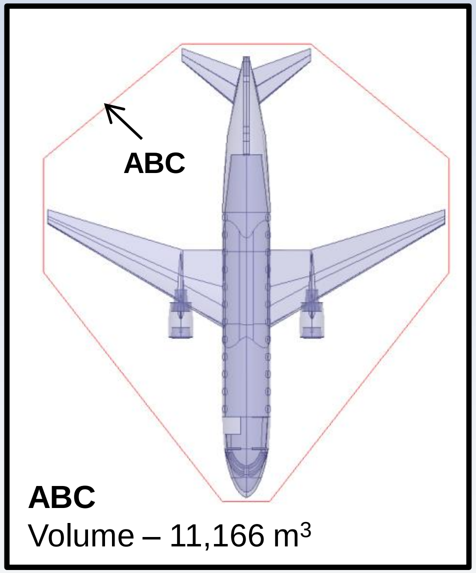
Incident Angle

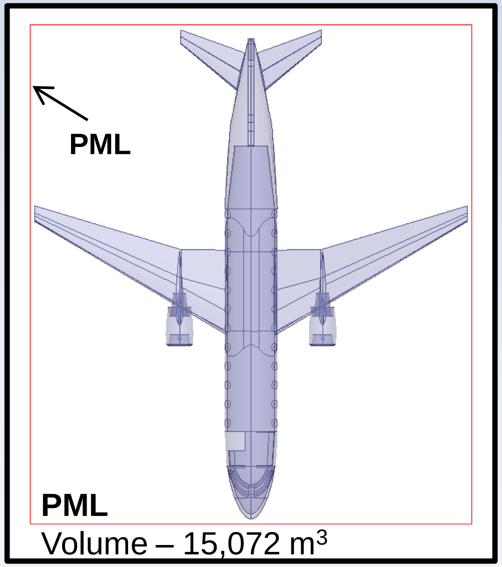
Arbitrary Shaped Boundary

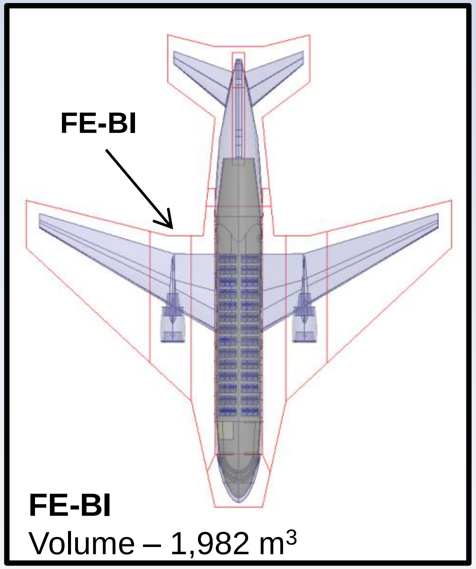
Separated Volumes

FE-BI: Arbitrary Shaped Boundary

- **FE-BI can be created on any arbitrary shape**
- **This can result in smallest possible FEM computational domain for certain geometries**
  - Internal angles of ABCs must be concave
  - PMLs must be placed on planar surfaces
    - A rectangular box is usually required



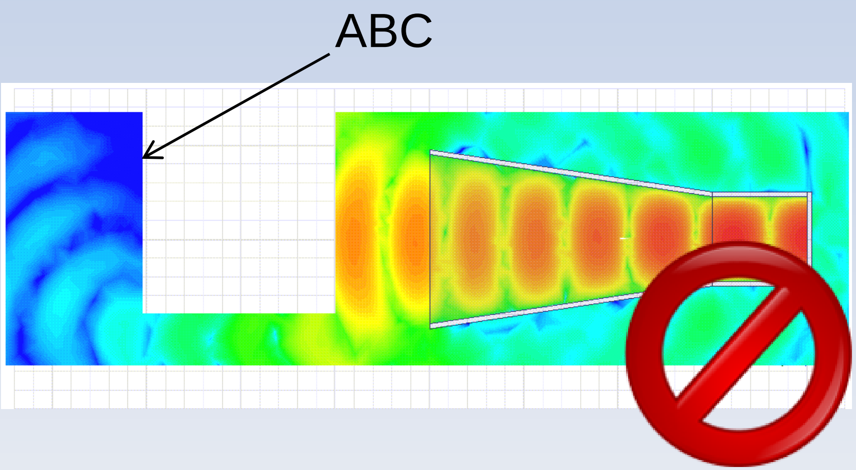


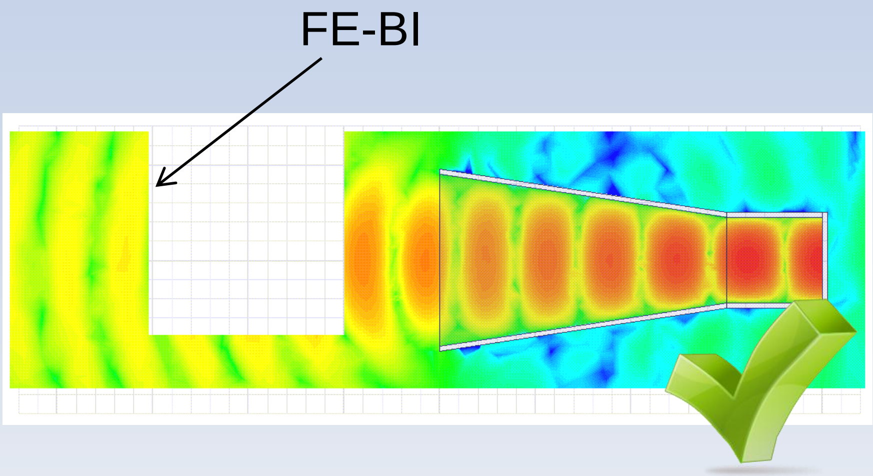


- **Required air volume to model free space around an aircraft using ABC, PML and FE-BI**
- **FE-BI results in an FEM computational domain that is ~7.5x smaller than the PML solution space**

Arbitrary Shaped Boundary

ABC and FE-BI applied to outer surface Airbox with cutout in air volume



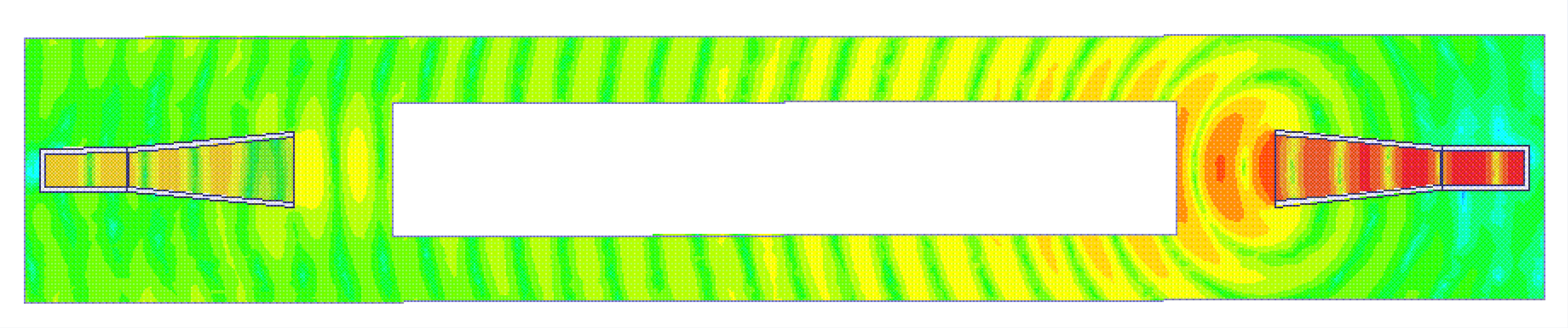


- **An ABC or PML must be concave to all incident fields**
  - **Outward facing normals must never intersect**
- **Waveguide example demonstrates how an ABC incorrectly models the fields when the boundary is not concave to all incident fields**

- **A FE-BI can be any arbitrary shape**
- **Field propagation through the cut-out in surrounding air volume is correctly modeled**

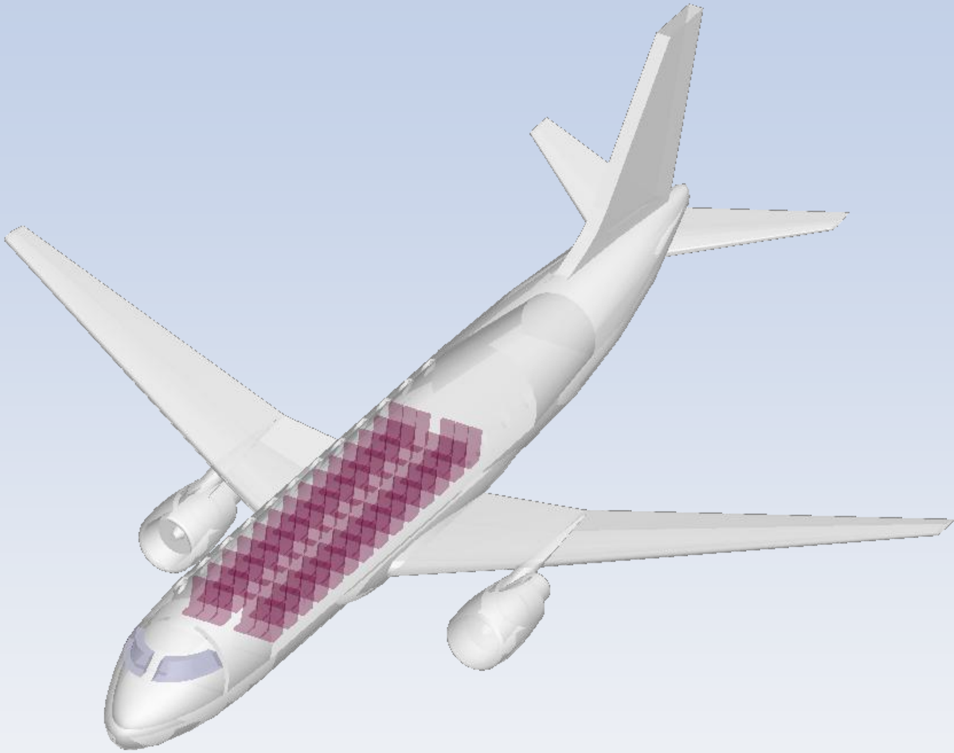
Internal Boundary

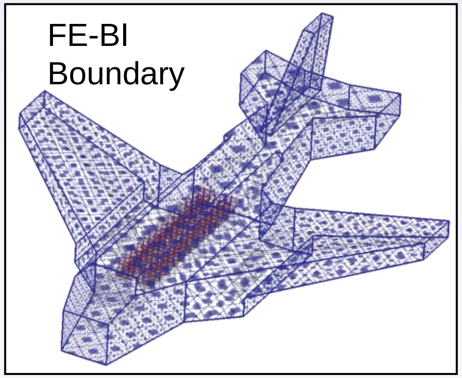
- **Internal air volume can be handled analytically.**



RF Wave Propagation in Passenger Aircraft

- **Personal electronic devices operating in cabin of commercial aircraft**
  - Possible interference with flight computer and communication systems
  - Complex propagation environment
    - Seats, Windows, Cylindrical Cavity of Cabin

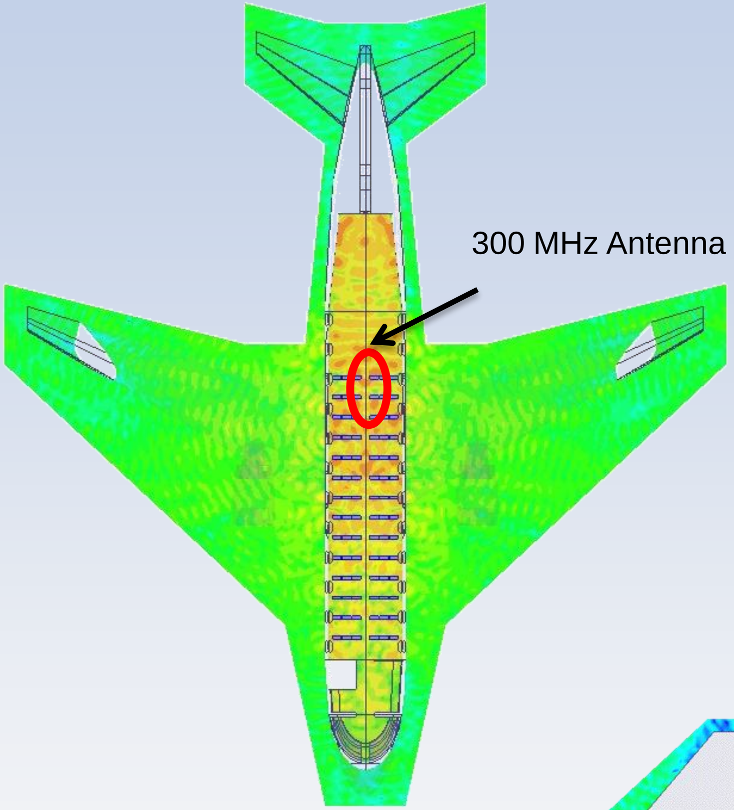


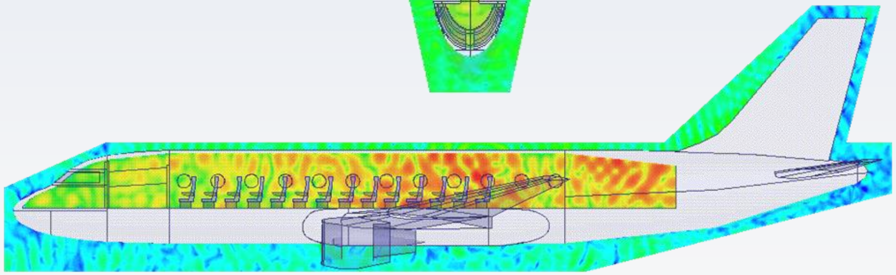


RF Wave Propagation in Passenger Aircraft

- **Leakage through windows could results in increased coupling to external antennas**
  - Model includes interior cabin and exterior portion of aircraft
- **300 MHz source excited towards tail, inside passenger cabin**

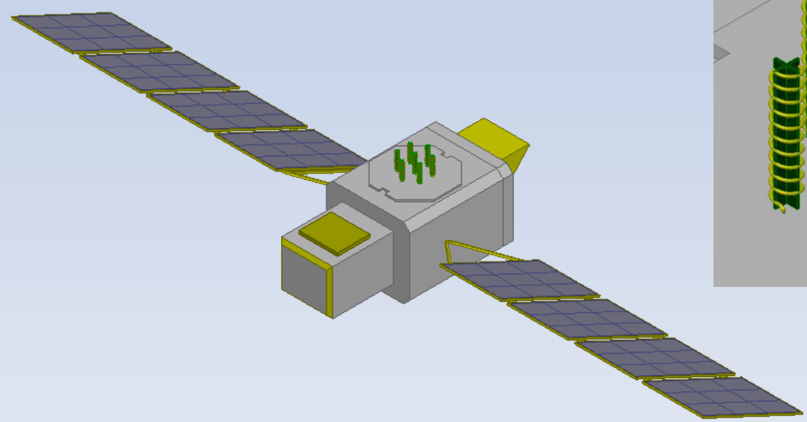
Boundary Type	Airbox Volume	Total RAM (GB)	Elapsed Time (hours)
FE-BI	2k λ^3	14	4

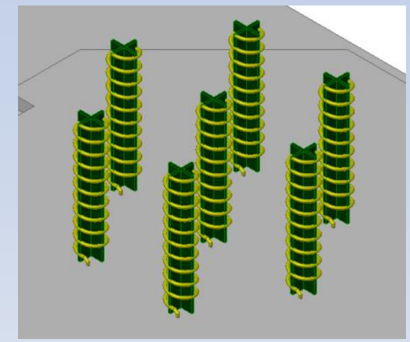


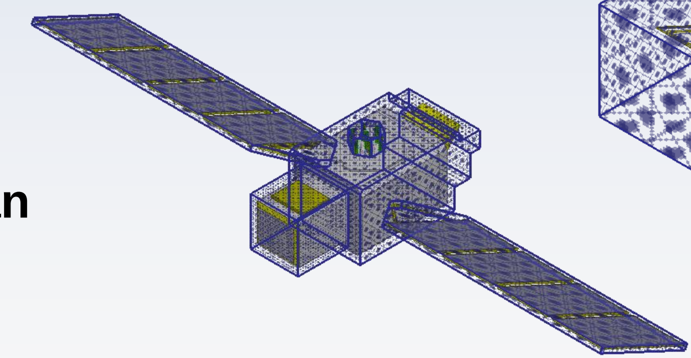


Array on Spacecraft

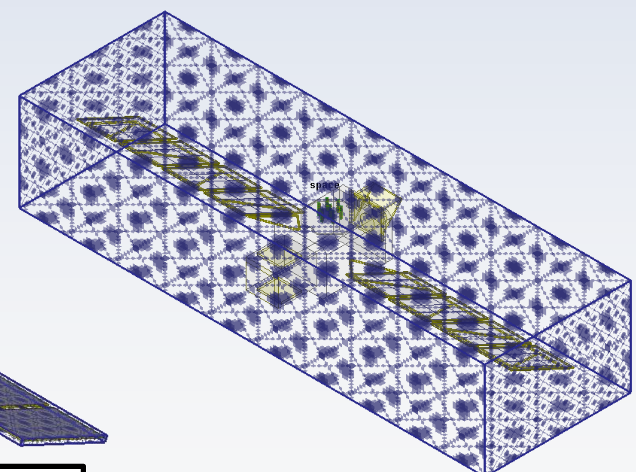
- **7 Element Helix Antenna Array integrated on satellite platform**
  - Dielectric solar panels and antenna supports do not make this problem ideal for HFSS-IE
- **Inclusion of solar panels creates an electrically large model**
  - 64λ wide at 3.5 GHz
- **Using ABC or PML boundary would require an Airbox equal to 21k λ^3**
- **FE-BI can reduce the required Airbox to 1.2k λ^3**







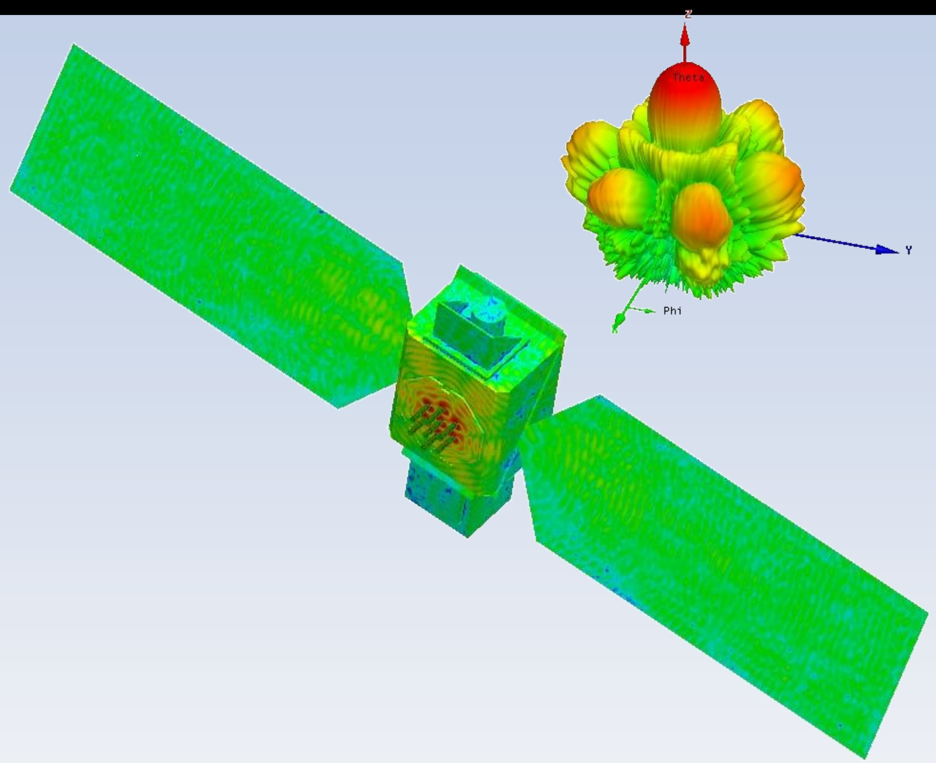
FE-BI Applied to conformal Airbox



ABC or PML would be applied to much larger Airbox

Array on Spacecraft: Results

- **Array platform integration simulated with conformal FE-BI**
  - RAM requirements reduced by 10x
  - RAM reduction as a result of removing the surrounding free space
    - Only possible using FE-BI

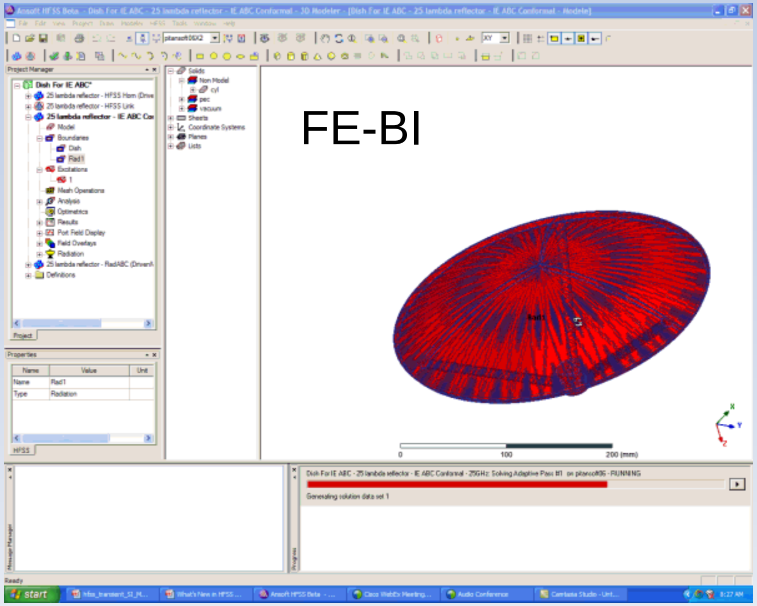


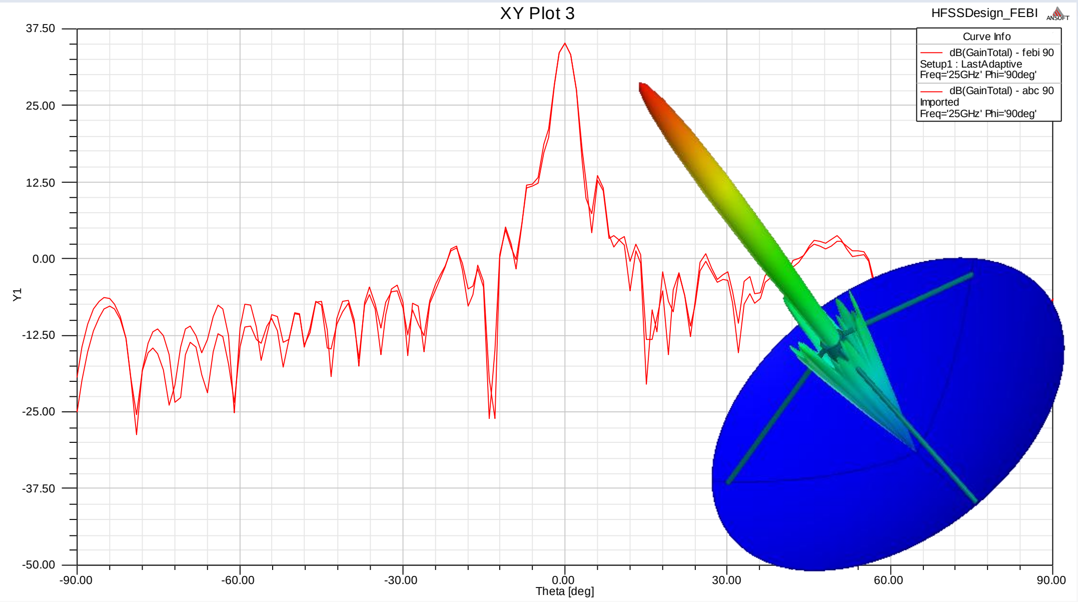
Boundary Type	Airbox Volume	Number of Domains	Total RAM (GB)	Elapsed Time (hours)
ABC	21k λ^3	34	210	12
FE-BI	1.2k λ^3	12	21	12

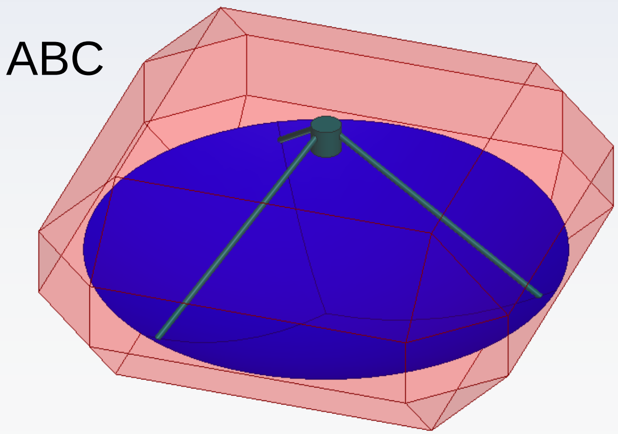
Reflector With Struts

- **Reflector with supporting struts**
  - FE-BI can be created so that it is conformal to entire geometry
  - Very small FEM volume needed with conformal FE-BI compared to ABC boundary

Boundary Type	Total RAM (GB)
ABC	45
FE-BI	13

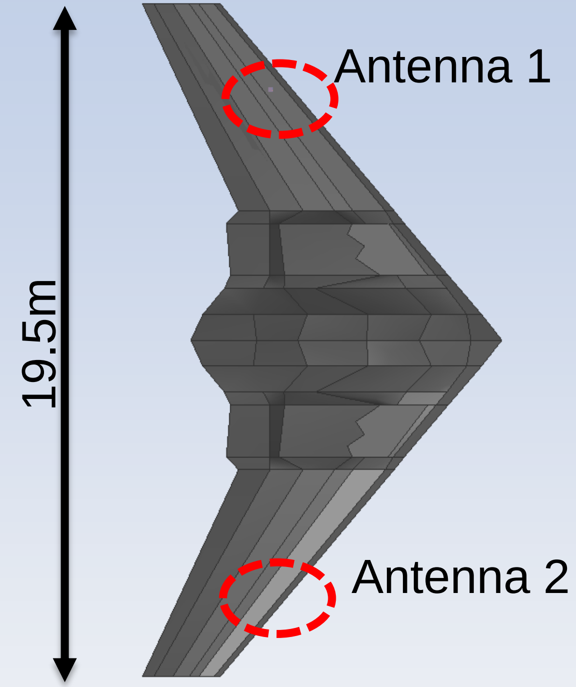


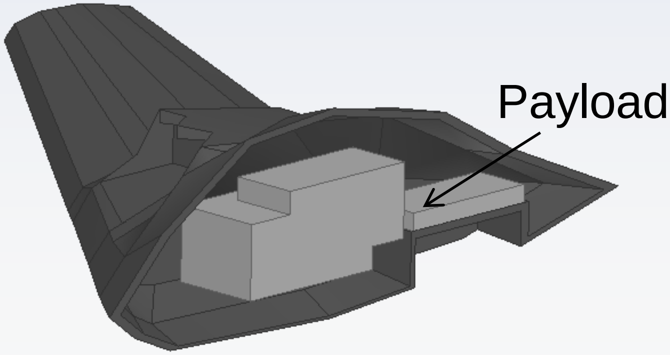




Composite Body UAV

- **Most UAV Airframes are composed of composite materials**
  - Light weight materials can increase endurance
- **Electrically large platform**
  - HFSS FEM solution is the most robust solution for this type of problem
    - Solution volume required when using PML or ABC may be computationally demanding
  - FE-BI can be used to create conformal boundary condition to minimize the FEM solution domain

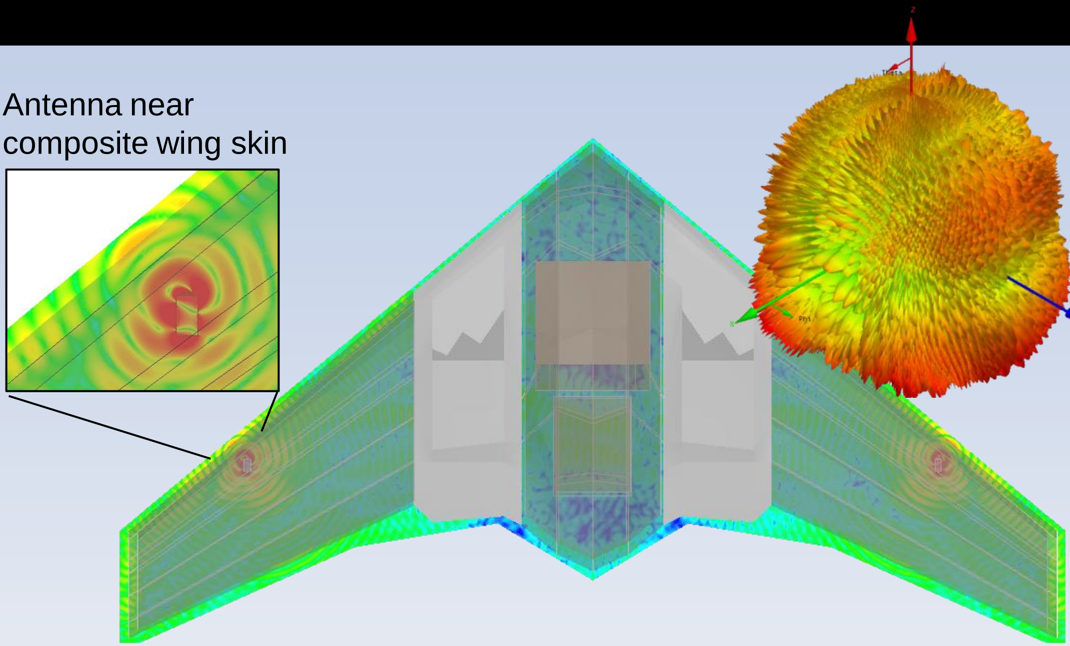




Cross-sectional view

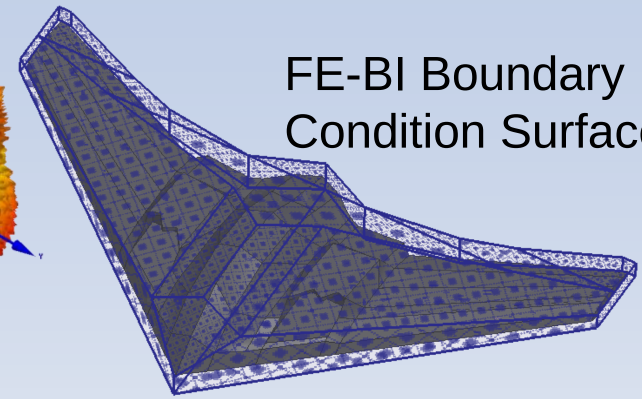
Composite Body UAV

Antenna near
composite wing skin



900 MHz

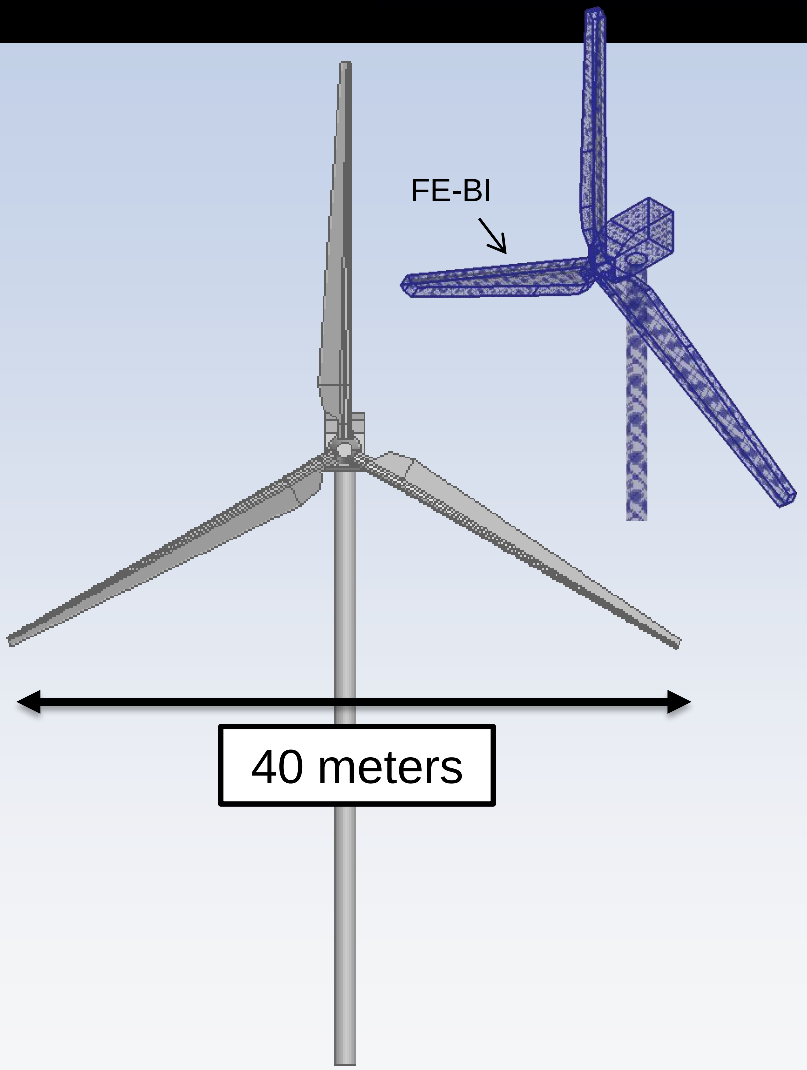
FE-BI Boundary
Condition Surface



Boundary Type	Airbox Volume	Number of Domains	Total RAM (GB)	ΔS
PML	15600 λ^3	8	>128	1.16 (2 passes)
FE-BI	4400λ^3	8	68	0.017 (6 passes)

Wind Turbine RCS

- **Wind farm effect on radar systems**
  - Shadow regions due to wind turbine placement can be a safety hazard to air traffic control
  - Ineffective long range surveillance radar can be a national security threat
  - Minimizing and determining the RCS of a wind turbine is an important topic with the increasing number of wind farms
- **Wind turbine blades are typically constructed from fiberglass and other composite materials**
  - Not ideally simulated in HFSS-IE due to a significant amount of dielectric materials
  - Resulting Airbox required for PML or ABC boundary would be significantly larger than required with FE-BI

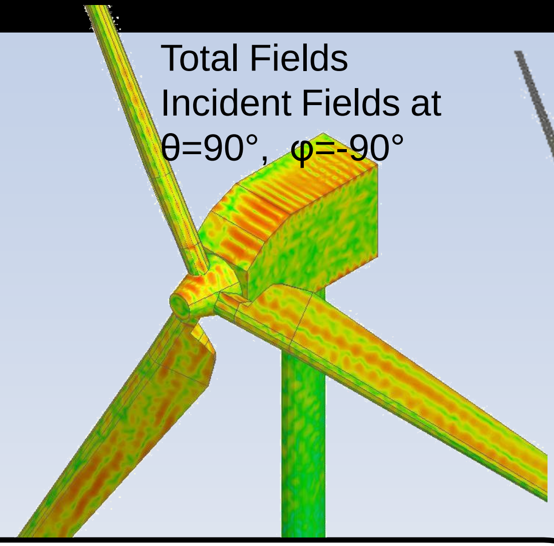


Wind Turbine RCS: 500 MHz

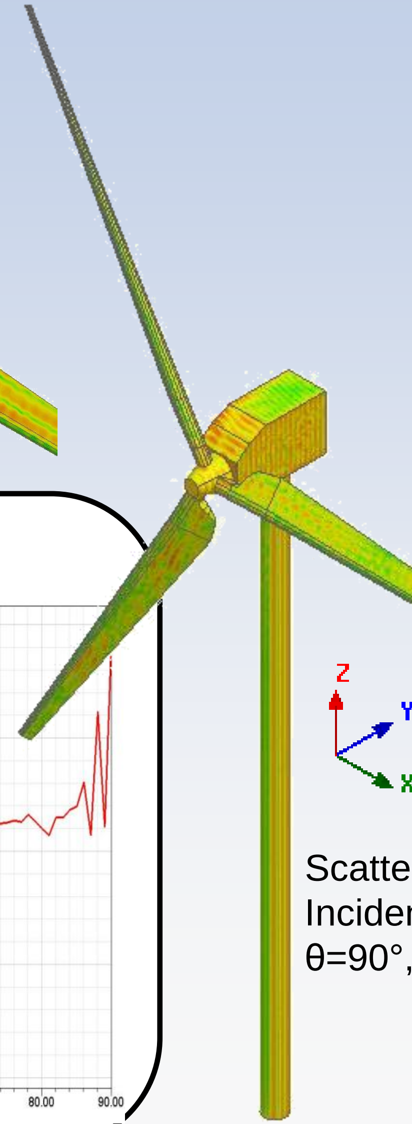
Boundary Type	Airbox Volume	Total RAM (GB)
FE-BI	1000 λ^3	28

An ABC boundary condition would contain a volume of greater that 75000 λ^3

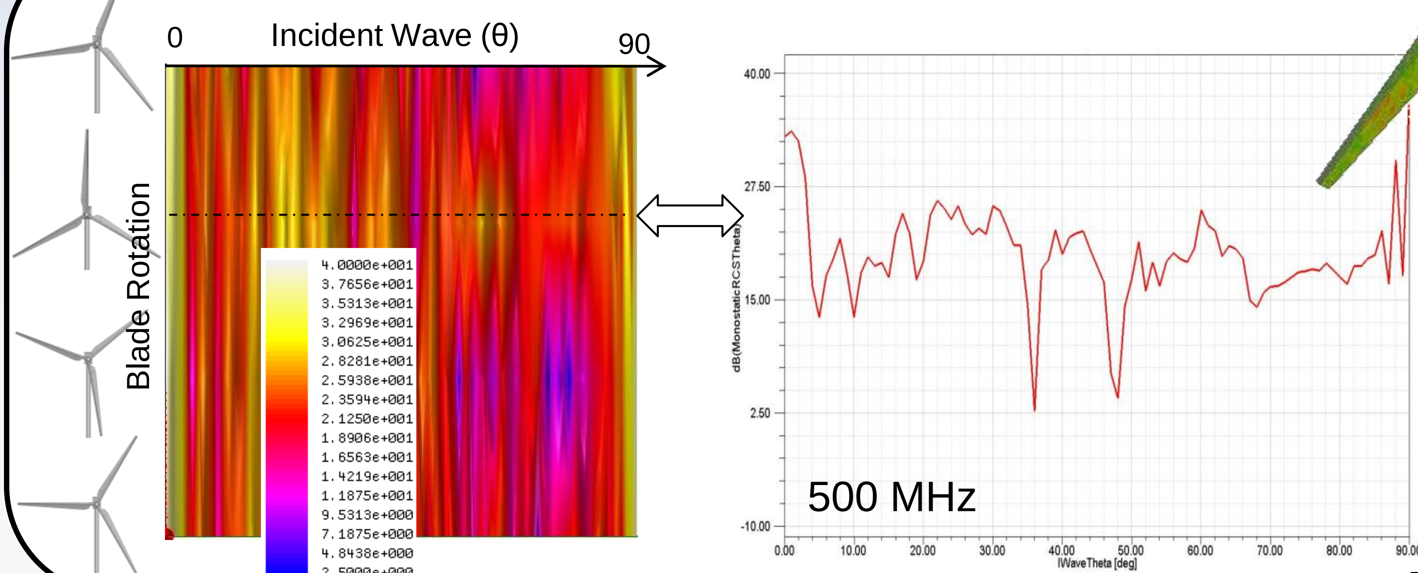
Total Fields
Incident Fields at
θ=90°, φ=-90°



Scattered Fields
Incident Fields at
θ=90°, φ=-90°



Monostatic RCS (θθ)



FE-BI: In Detail

Distance From Radiator

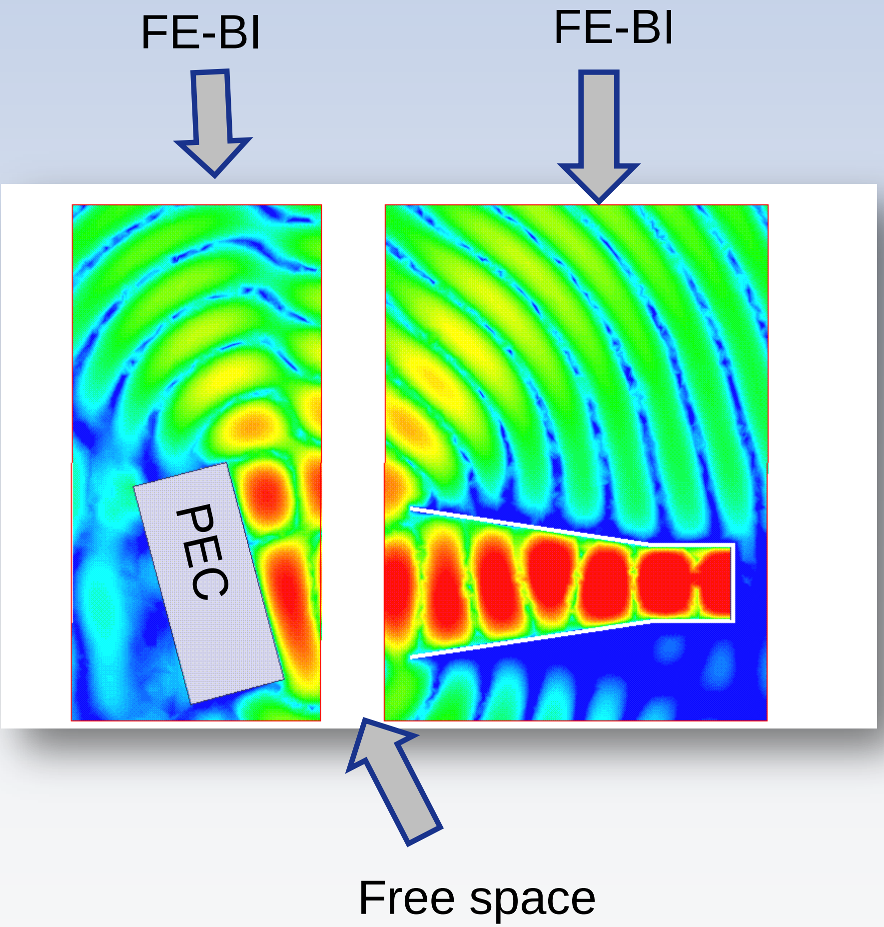
Incident Angle

Arbitrary Shaped Boundary

<u>Separated Volumes</u>

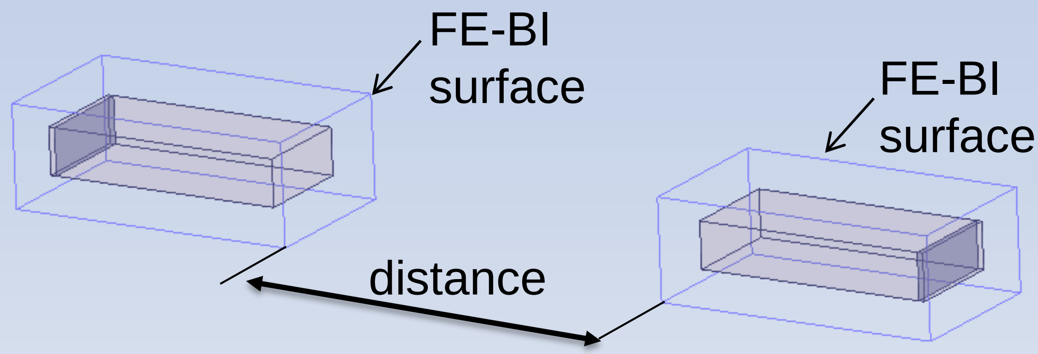
FE-BI: Separating Volumes

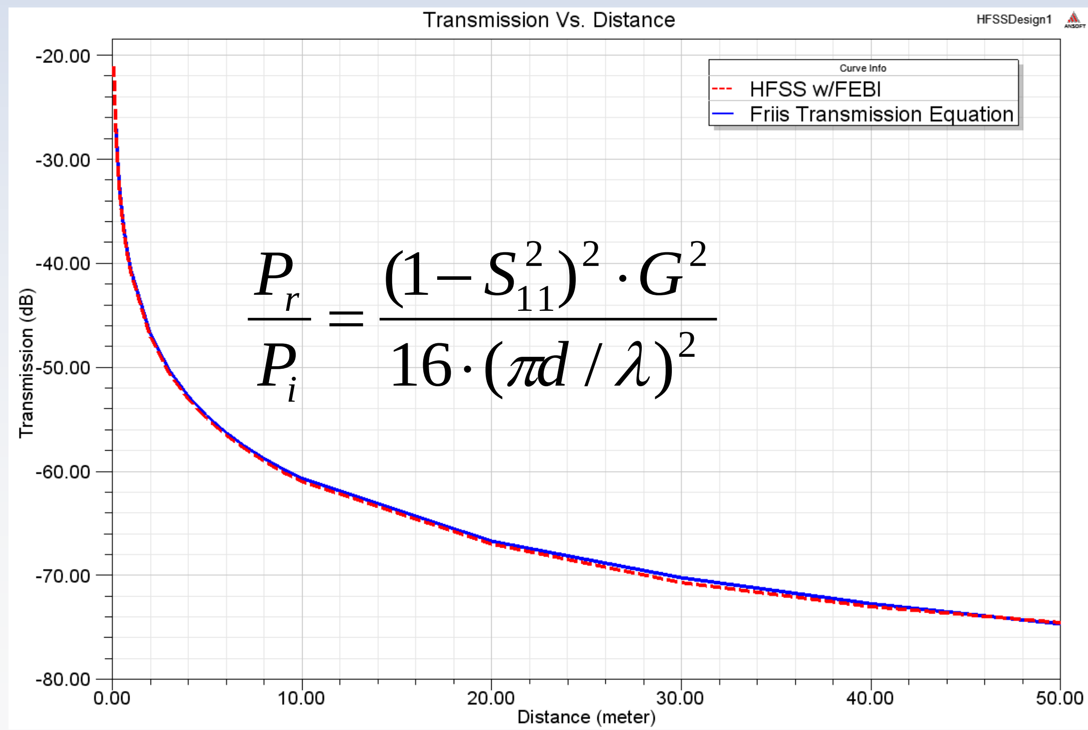
- **FE-BI does not require a single volume enclosure**
- **Separation into more than 1 domain can often reduce the total air volume**
  - Separate volumes will be fully coupled with FE-BI



Friis Transmission Equation and FE-BI Comparison

- **Open Ended waveguides**
  - Each waveguide surrounded by a separate FE-BI surface
  - Free space modeled with IE method
- **Comparison between Friis Transmission Equation and HFSS with FE-BI**
- **Excellent agreement to 50 meter separation at 10 GHz**

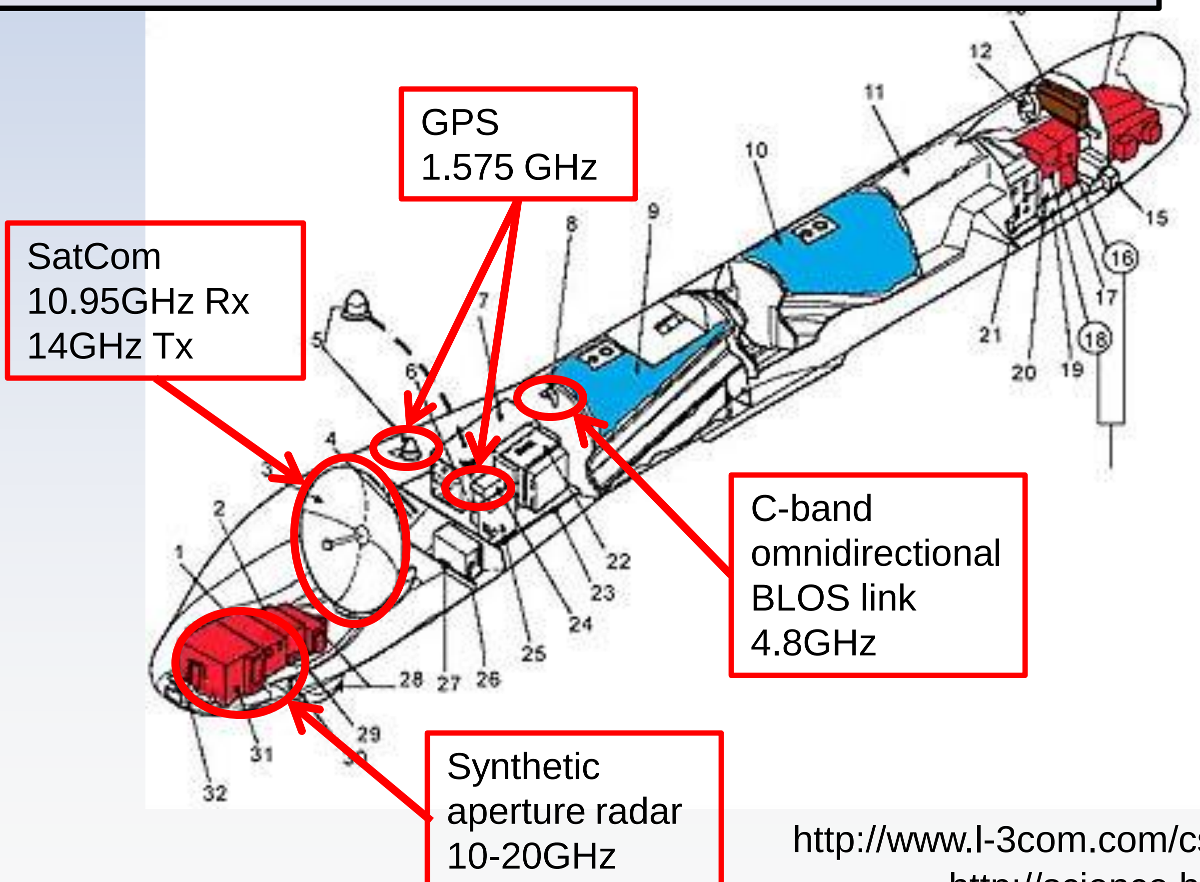




$$\frac{P_r}{P_i} = \frac{(1 - S_{11}^2)^2 \cdot G^2}{16 \cdot (\pi d / \lambda)^2}$$

Predator UAV Antennas

Motivation: "Let's see if we can do on of the harder antennas on a UAV. The 14GHz SatCom reflector AND radome?!"

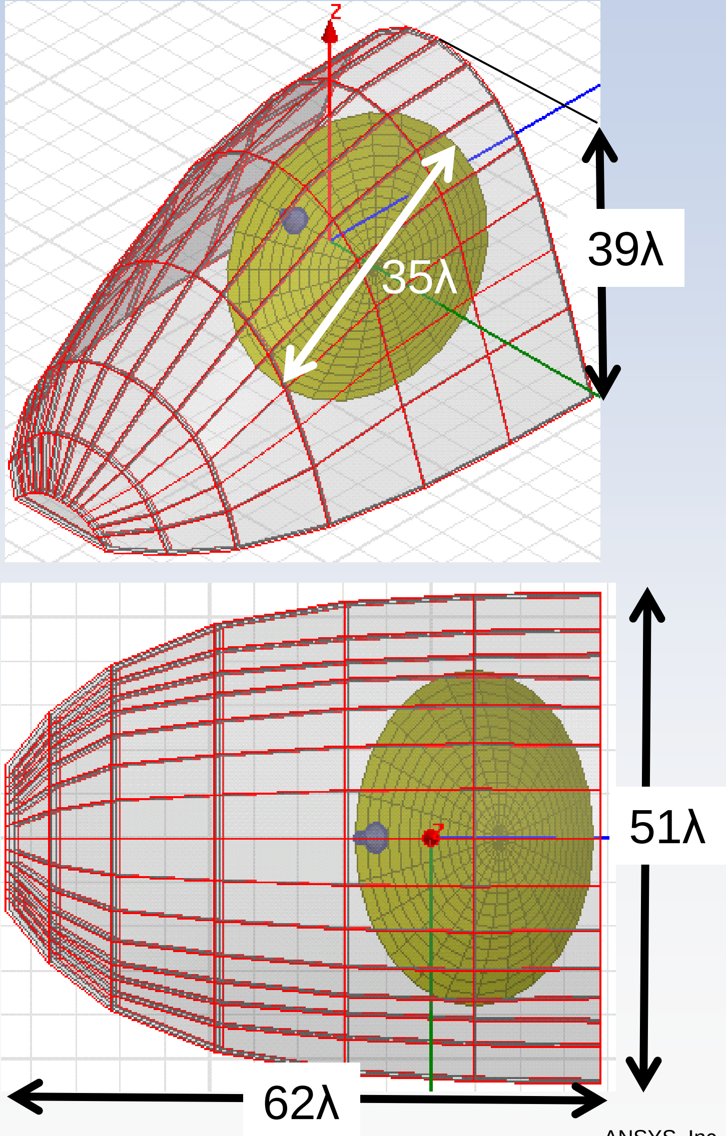


- **Antennas**
  1. Synthetic aperture radar (10-20GHz)
  3. SatCom (10.95GHz Rx, 14GHz Tx)
  5. GPS antennas [two] (1.575GHz)
  8. C-band omnidirectional antenna bracket (4.8GHz)
- Note: Frequencies are best guesses

http://www.l-3com.com/csw/Product/docs/08-Predator.pdf
http://science.howstuffworks.com/predator2.htm

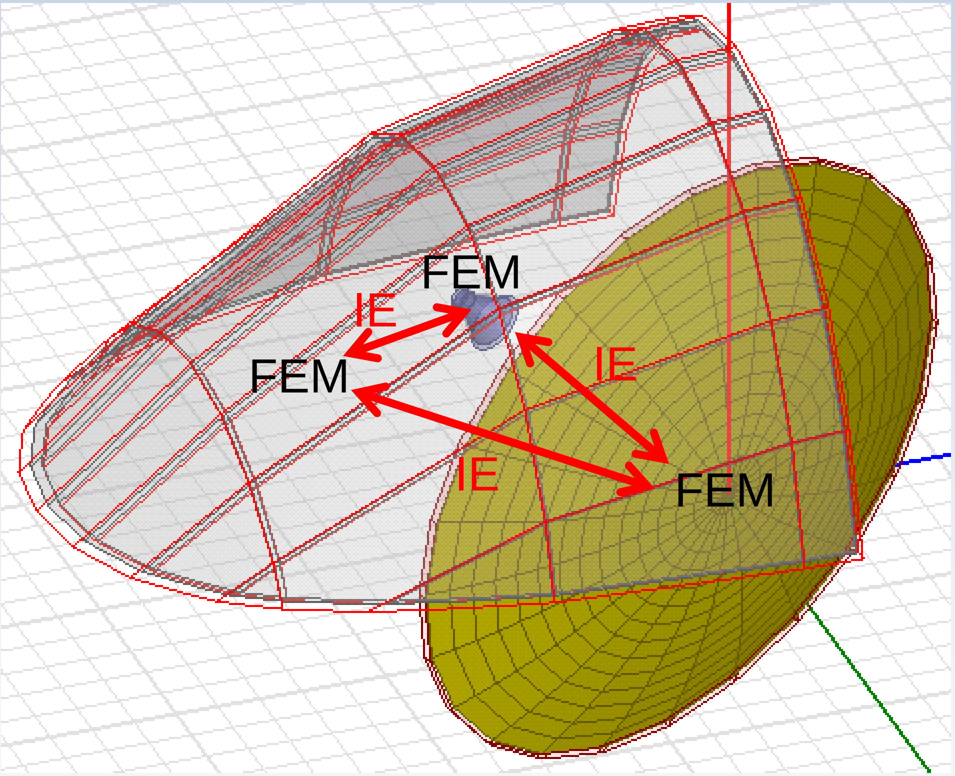
Modeling the Feed, Dish, AND Radome?

- **The electrical size of the whole nose is very large**
- **If the whole nose was modeled as filled air space it would be about 58,000λ^3**
- **Can this be modeled in FEM?**

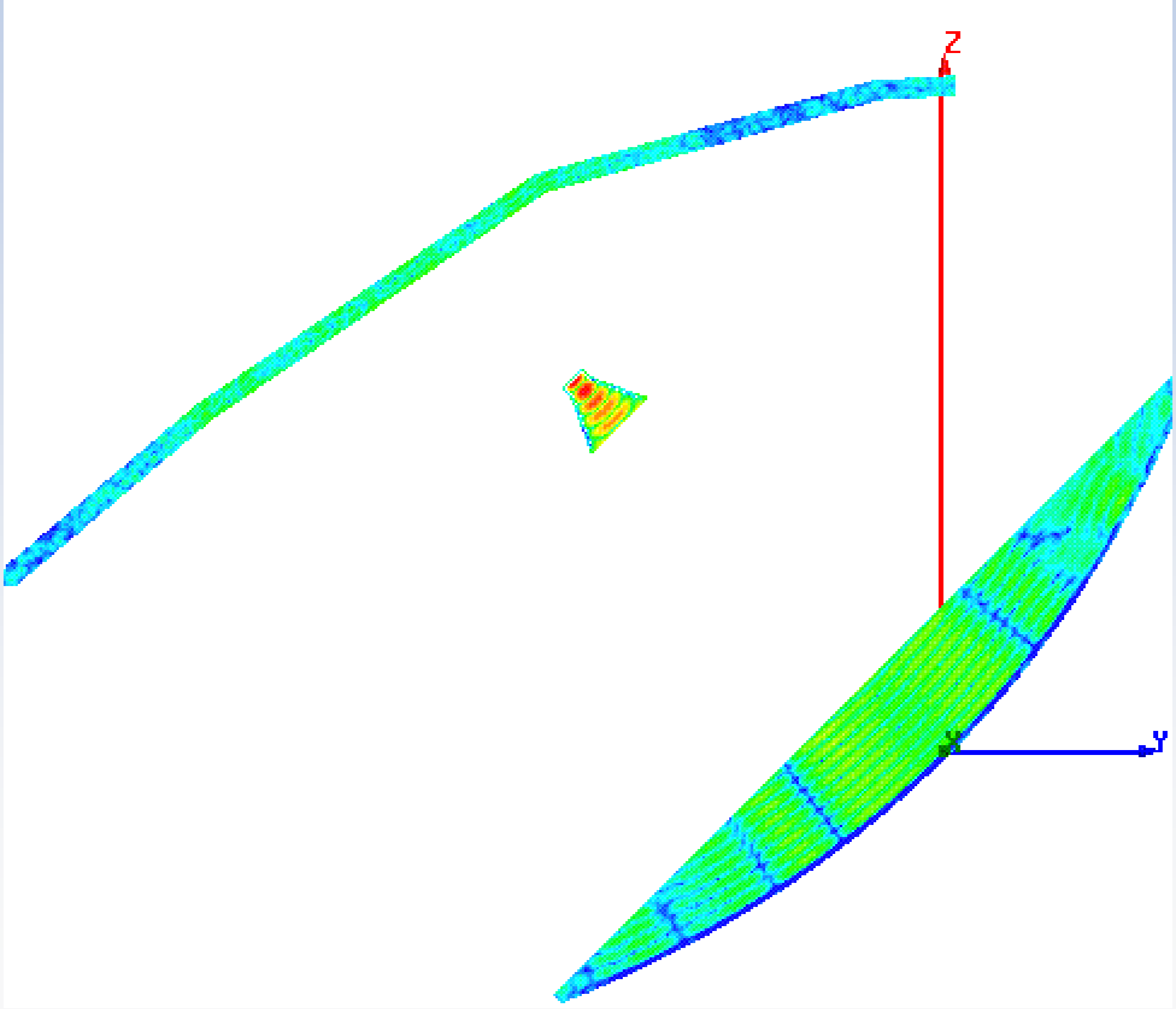


Yes, solving in FEM by Breaking the Problem into Domains!

- **Three FEM domains are linked through the new FEBI radiation boundary which includes:**
  - Full coupling between domains
  - Perfectly matched free space condition regardless of incidence angle or radiation boundary shape
- **Each domain is surrounded by a small gap of air space between geometry and the boundary integral radiation boundary**
- **Air space between domains does not need to be solved**
- **Accuracy of FEM, efficiency of IE!**

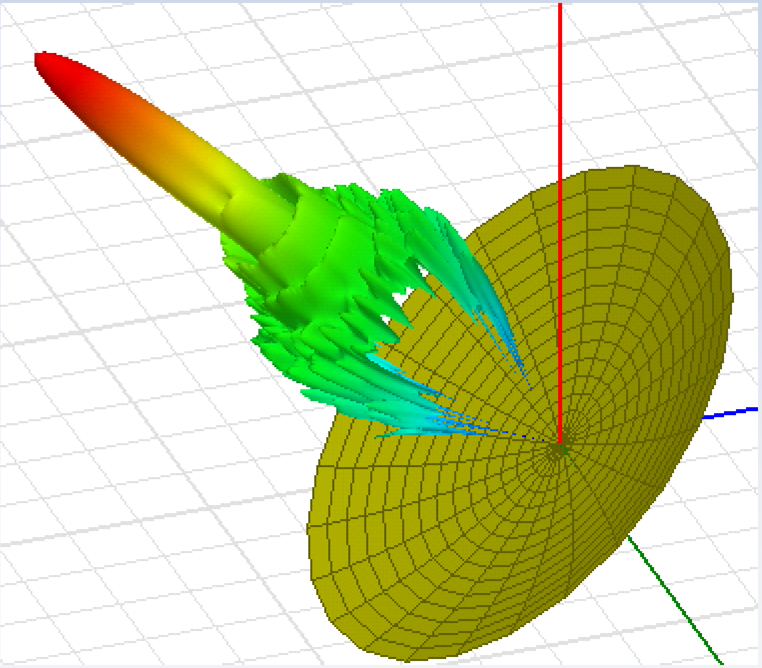


All Three Domains

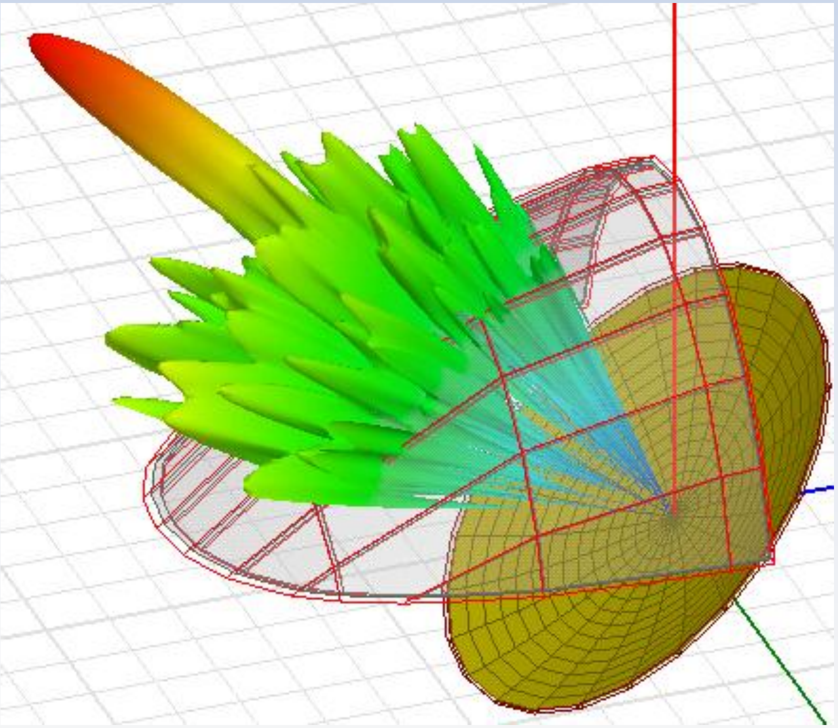


Pattern With/Without Radome

Dish and feed only



Dish and feed with dielectric radome



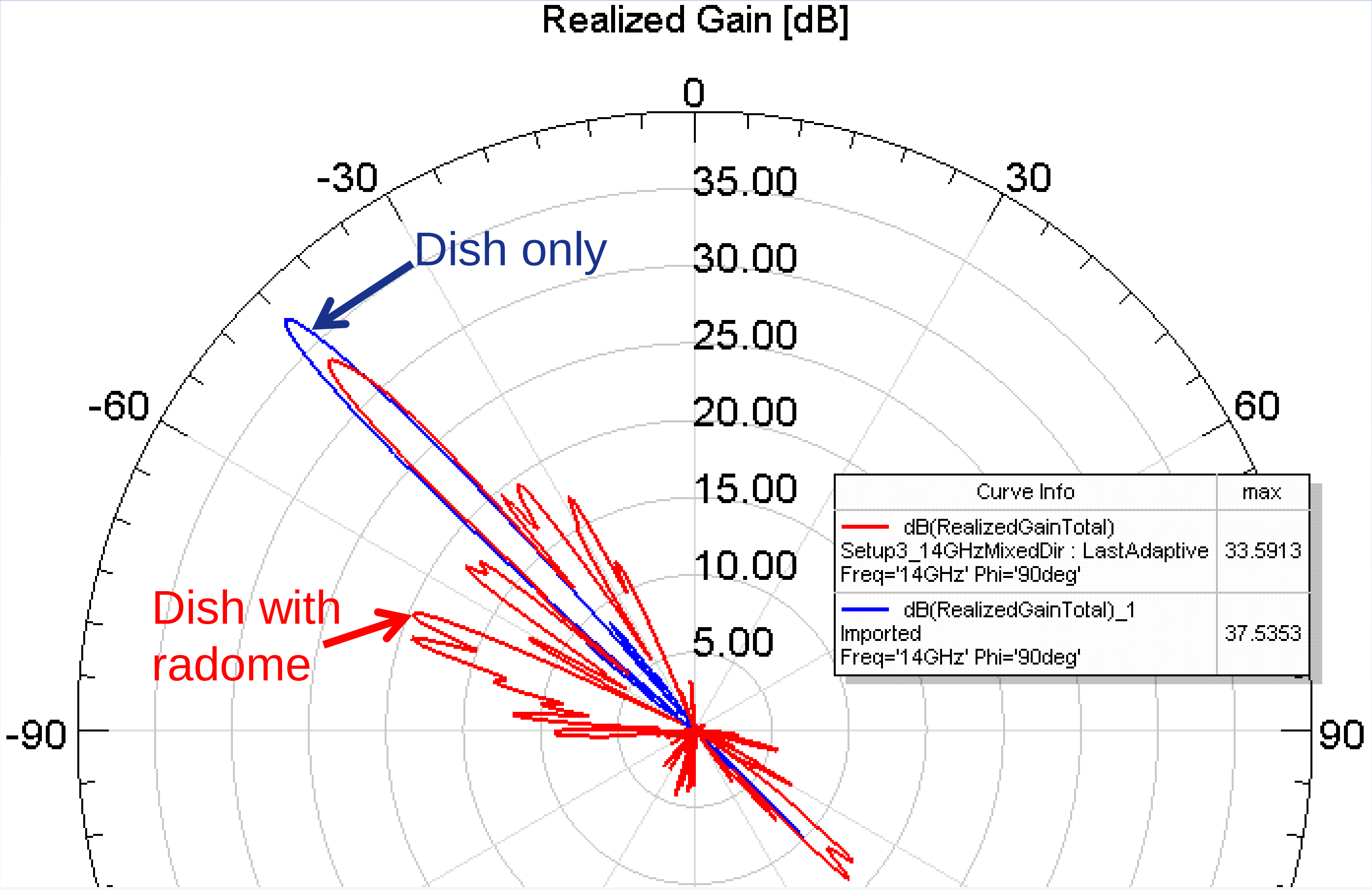
Pattern With/Without Radome (cont.)

Radome pattern effects:

- A ~4dB reduction in realized gain

- ~0.5° shift in direction

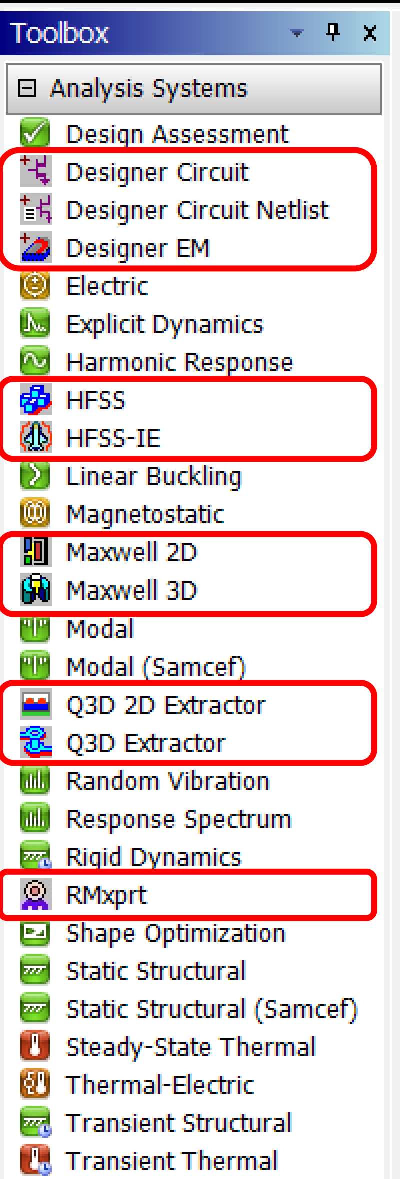
- Major sidelobes



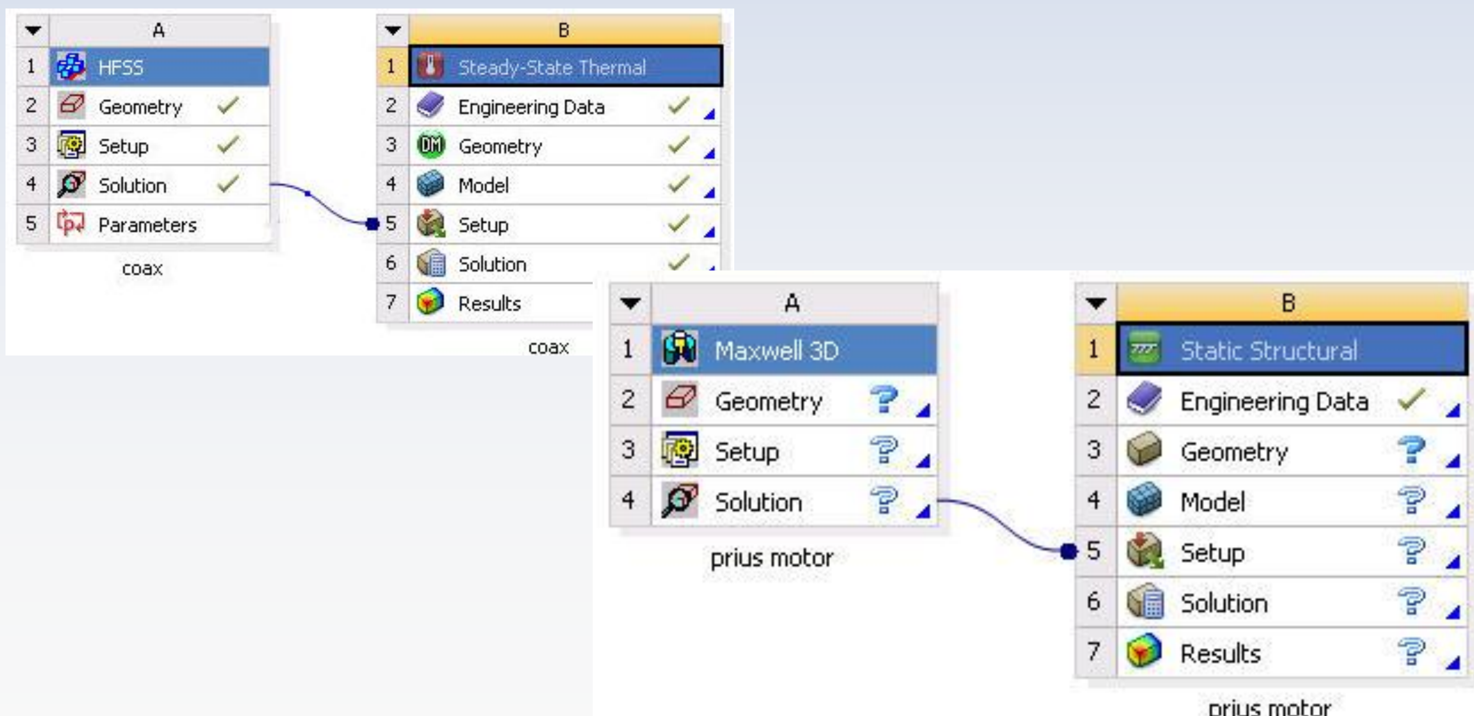
Summary

- **HFSS**
  - Excellent solution to RF/microwave and SI simulations
    - ABC and PML used for computational domain truncation
- **HFSS-IE**
  - Ideal solution for electrically large, primarily conducting structures
- **HFSS with FE-BI**
  - Perfect free space truncation for FEM simulations
  - Best solution for problems in which a large volume of free space can be removed by the application of FE-BI
  - Typically used for open radiating and scattering problems
    - Antenna platform integration, Co-site Analysis, EMI, RCS, …etc.
    - HFSS with FE-BI is a perfect complement to HFSS and HFSS-IE, making efficient simulation of electrically large antenna and scattering models possible

Integration with WorkBench

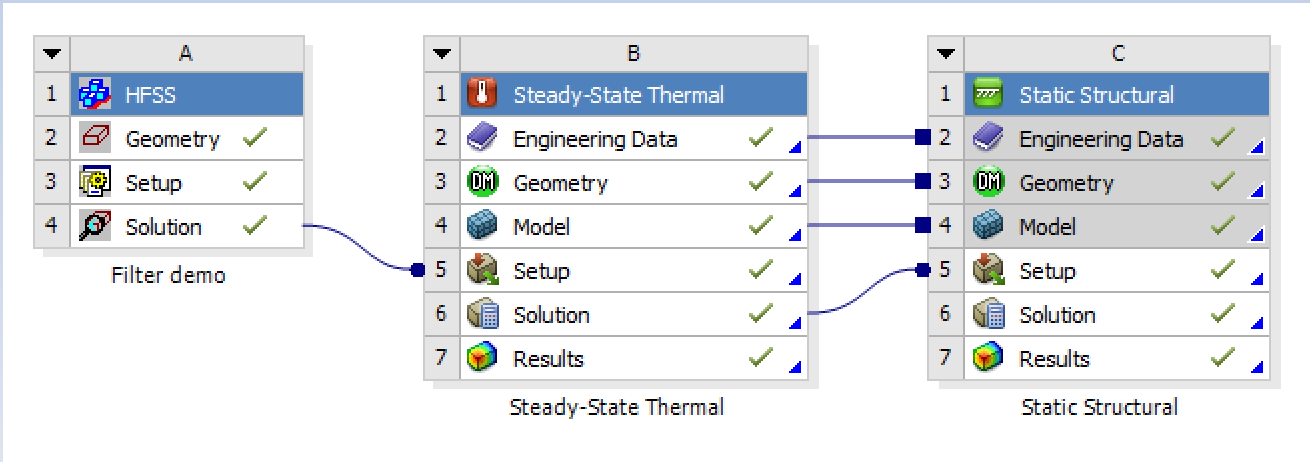


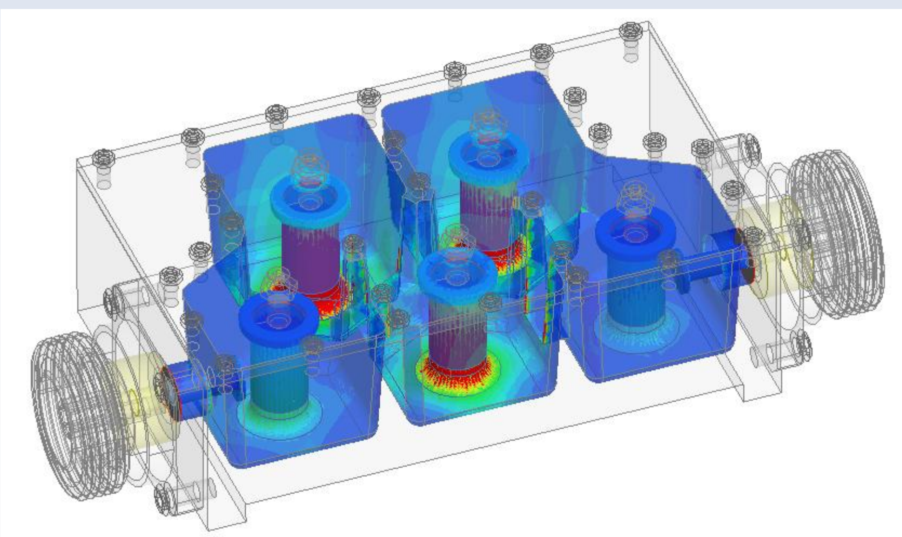
- **Ansys R13 has integration of Electronics tools for coupled electromagnetic-thermal-mechanical analysis as appropriate.**
- **ICEPAK and SIwave also have direct linkage for exchange of power dissipation and temperature mapping**



Workbench Integration

Synthesis | Optimization | Realisation | **Verification**



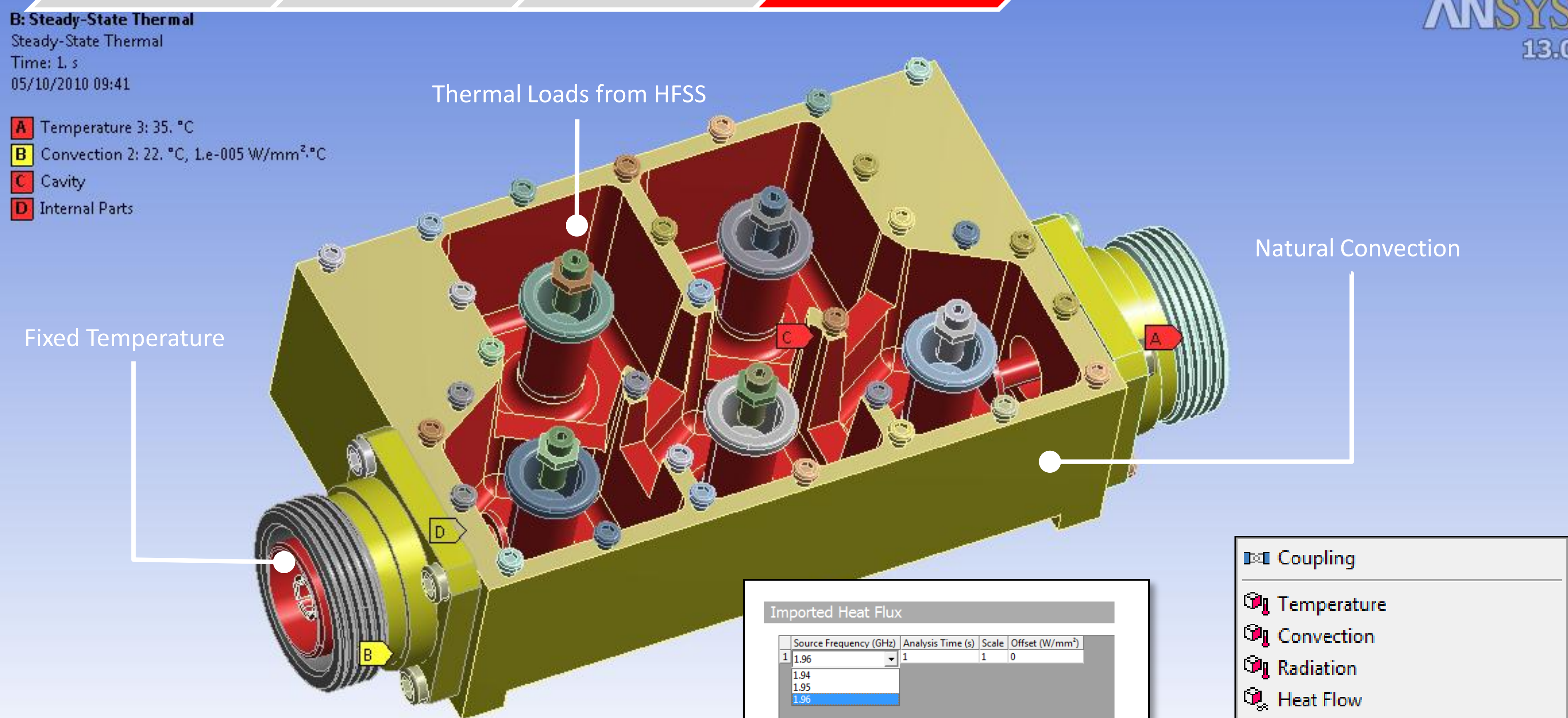


- HFSS v13 integrated into Workbench 13.
- Results from HFSS as source for the thermal simulation…

Thermal Simulation Example

ANSYS

Synthesis | Optimization | Realisation | **Verification**



Imported Heat Flux

	Source Frequency (GHz)	Analysis Time (s)	Scale	Offset (W/mm²)
1	1.96	1	1	0

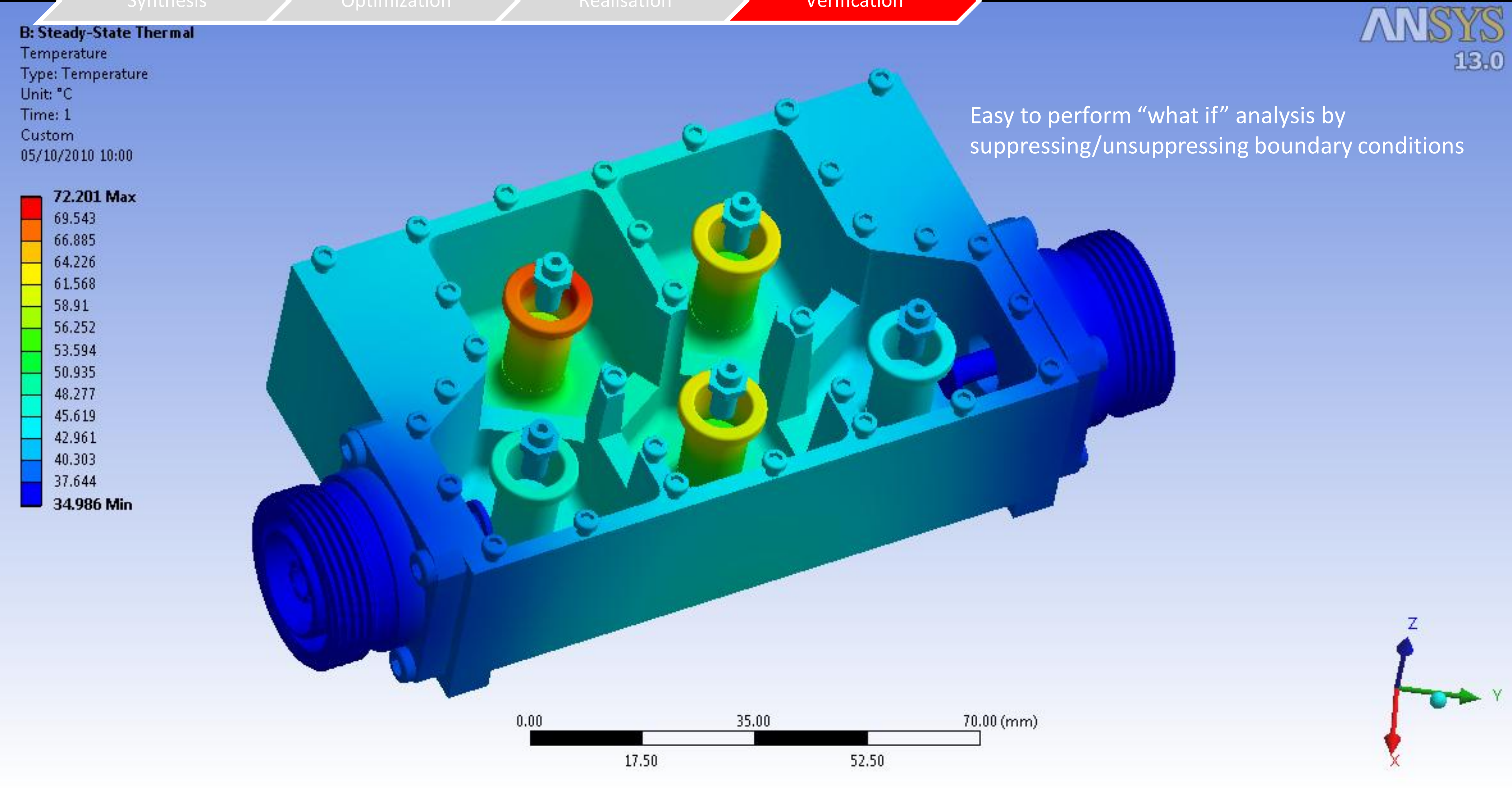
1.94
1.95
1.96

Scope	
Scoping Method	Geometry Selection
Geometry	Apply
Definition	
Type	Imported Heat Flux
Suppressed	No
Transfer Definition	
Ansoft Solution	Setup1 : points
Ansoft Surface(s)	AllSurfaces

- Coupling
- Temperature
- Convection
- Radiation
- Heat Flow
- Perfectly Insulated
- Heat Flux
- Internal Heat Generation
- Commands

Thermal Simulation Example

Synthesis | Optimization | Realisation | Verification

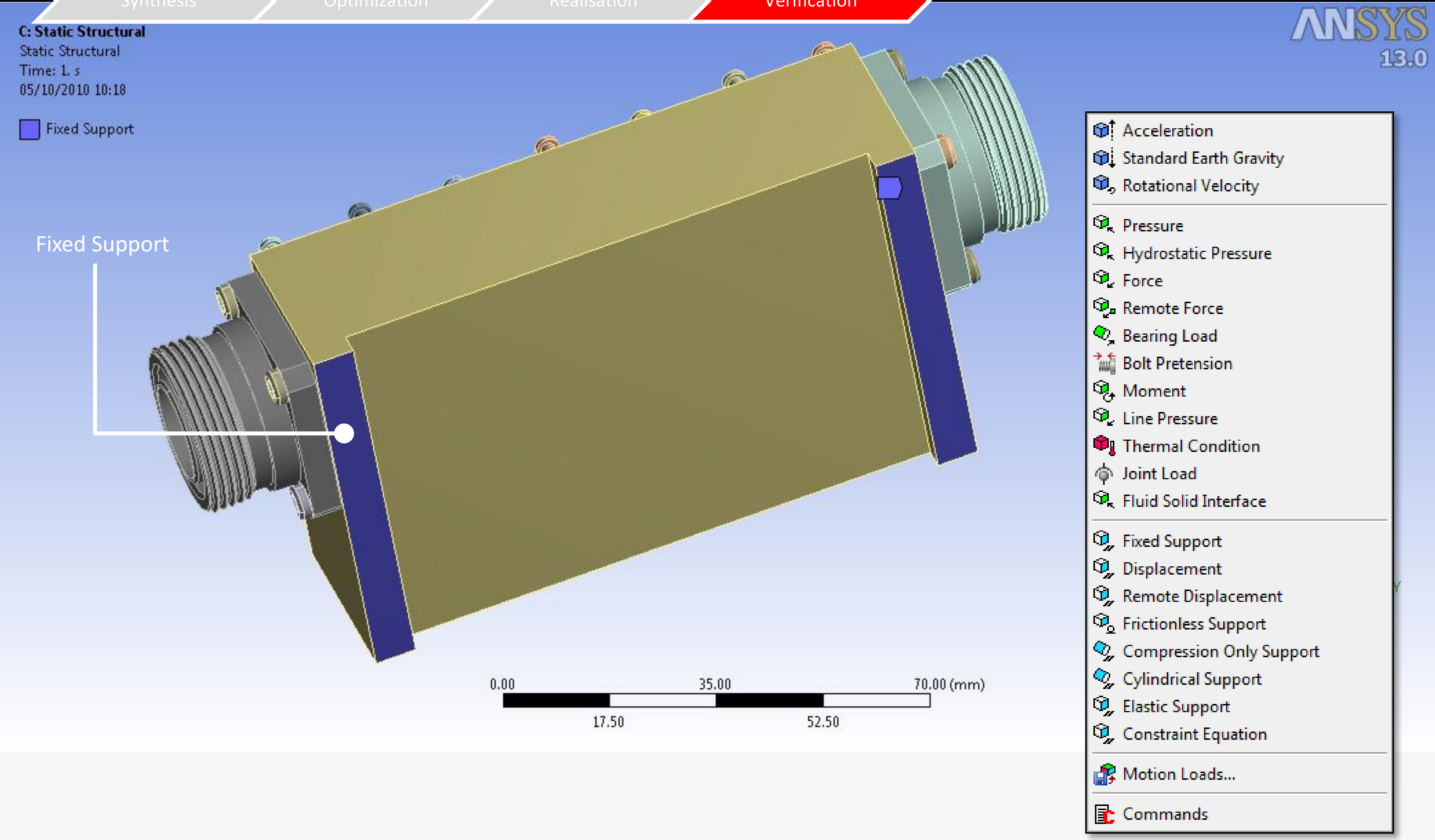


Easy to perform "what if" analysis by suppressing/unsuppressing boundary conditions

- Use results as source in Mechanical simulation...

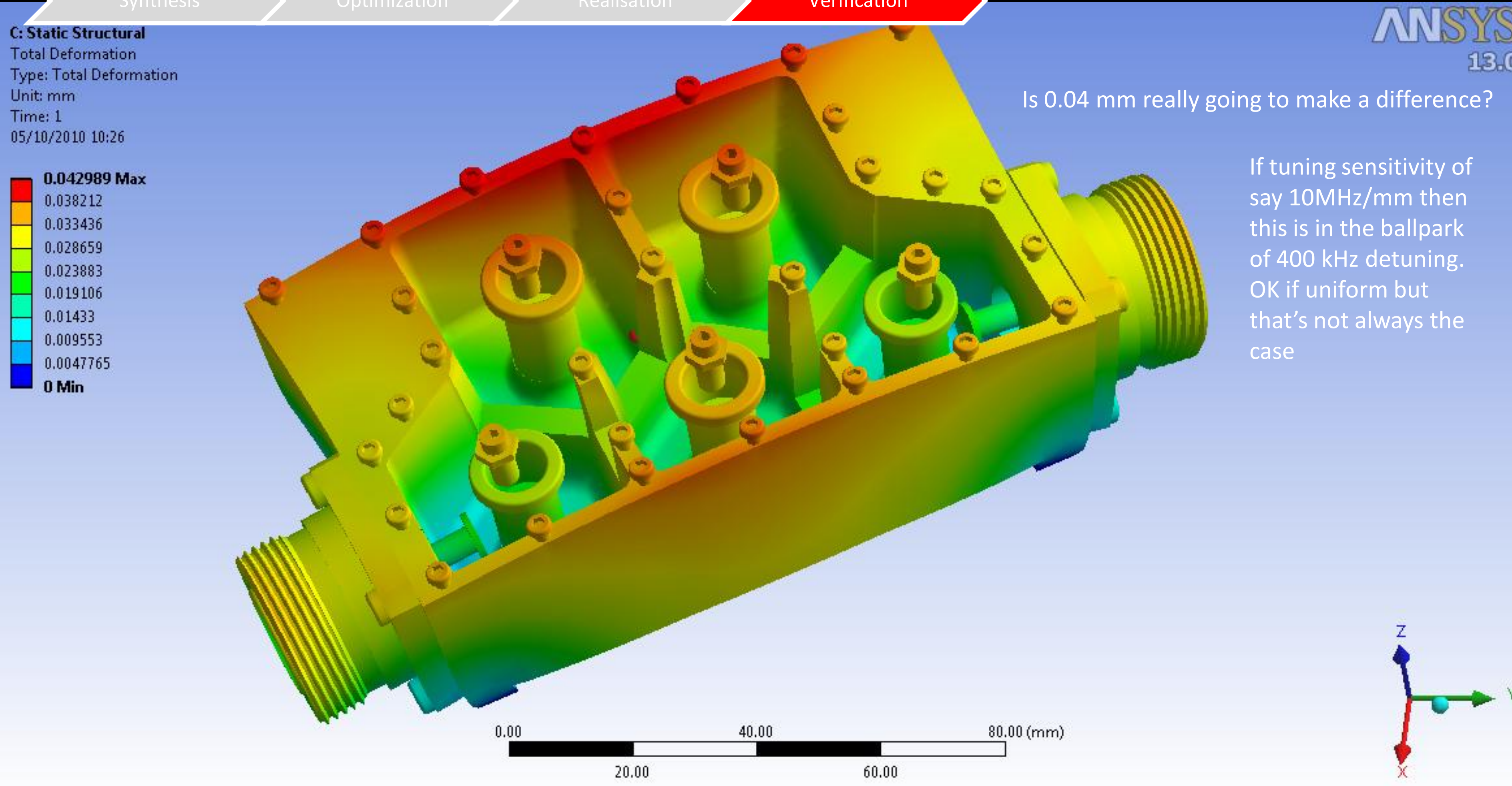
Mechanical Simulation Example

Synthesis | Optimization | Realisation | Verification



Mechanical Simulation Example

Synthesis | Optimization | Realisation | **Verification**



Is 0.04 mm really going to make a difference?

If tuning sensitivity of say 10MHz/mm then this is in the ballpark of 400 kHz detuning. OK if uniform but that’s not always the case

Questions?