ODEN INSTITUTE FOR COMPUTATIONAL ENGINEERING & SCIENCES

UT ECE

MFIE-Induced RCS Errors in CFIE Simulations of a Fan-Loaded Camera Box

Andrew Maicke, Jon T. Kelley, and Ali E. Yilmaz

The University of Texas at Austin, Austin, TX 78712

ACES 2024, ORLANDO, FL

ODEN INSTITUTE FOR COMPUTATIONAL ENGINEERING & SCIENCES
UT ECE

Outline

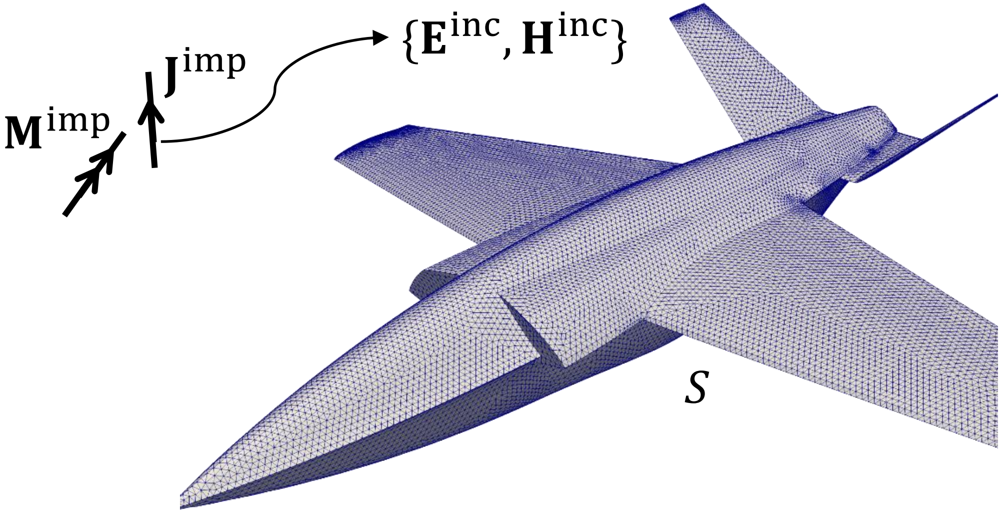
- **Background**
  - Integral equations
    - MFIE-induced errors
  - CameraBox Problem Set from Austin RCS Benchmark Suite
- Problem-specific MFIE Induced Error
  - RCS pattern
  - Induced currents
- Rectification techniques
  - α parameter variation
  - Global mesh refinement
  - Local mesh refinement
- Conclusions

ODEN INSTITUTE FOR COMPUTATIONAL ENGINEERING & SCIENCES

UT ECE

Background

- Integral-equation formulation
- Geometry discretized into elements
  - Basis functions defined on elements, eg. RWG basis functions
  - Fill impedance matrix $\mathbf{Z}$
    - EFIE is accurate, slow to converge
    - MFIE converges quickly, can be less accurate



$$\mathbf{Z}^{\mathrm{EFIE}}[m,n] = \begin{array}{l} j\omega\mu_{\mathrm{o}} \iint_S \iint_{S'} \mathbf{f}_m(\mathbf{r}) \cdot \mathbf{f}_n(\mathbf{r}') \dfrac{e^{-jkR}}{4\pi R} dS' dS \\ + \dfrac{1}{j\omega\epsilon_{\mathrm{o}}} \iint_S \iint_{S'} \nabla \cdot \mathbf{f}_m(\mathbf{r}) \nabla' \cdot \mathbf{f}_n(\mathbf{r}') \dfrac{e^{-jkR}}{4\pi R} dS' dS \end{array}$$

$$\mathbf{Z}^{\mathrm{MFIE}}[m,n] = \begin{array}{l} \dfrac{1}{2} \iint_S \mathbf{f}_m(\mathbf{r}) \cdot \mathbf{f}_n(\mathbf{r}') dS \\ + \iint_S (\mathbf{f}_m(\mathbf{r}) \cdot \hat{n}) dS \times \iint_{S'} \left(\mathbf{f}_n(\mathbf{r}') \times \nabla' \dfrac{e^{-jkR}}{4\pi R} \right) dS' \end{array}$$

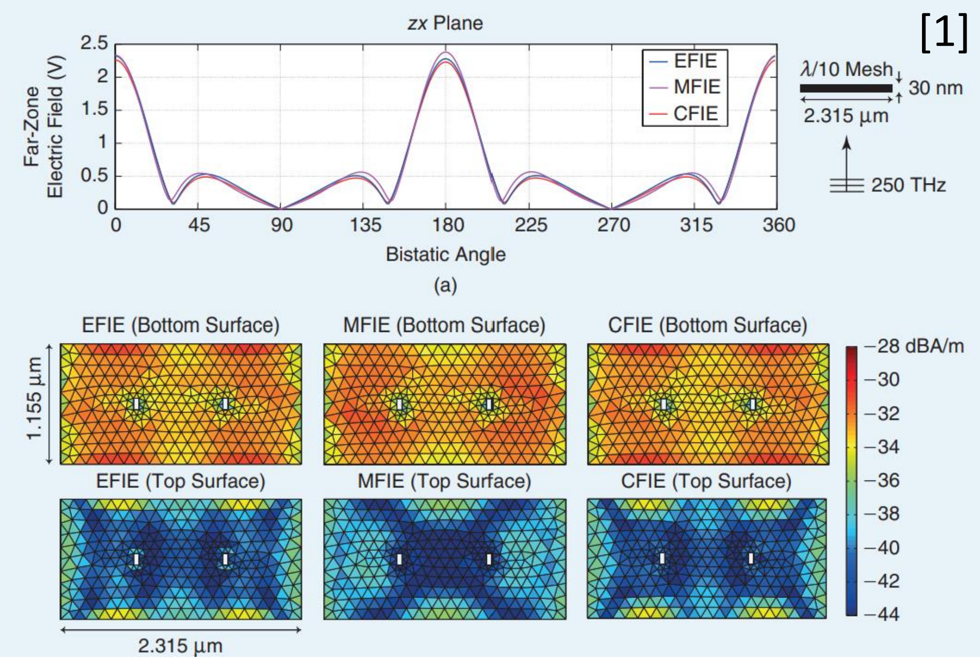
Background

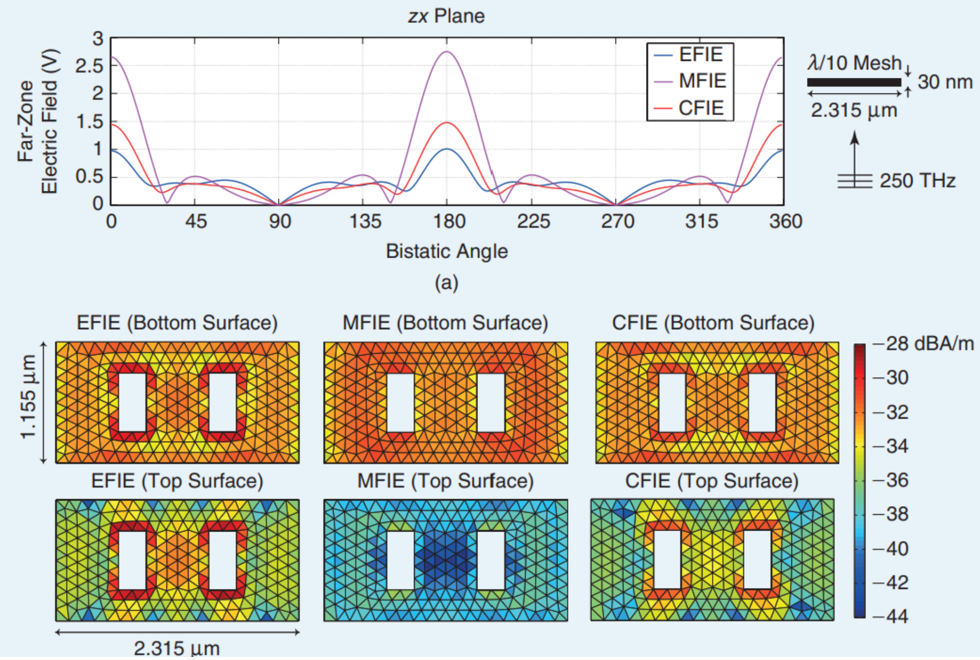
- Integral-equation formulation
- Geometry discretized into elements
  - Basis functions defined on elements, eg. RWG basis functions
  - Fill impedance matrix $\mathbf{Z}$
    - EFIE is accurate, slow to converge
    - MFIE converges quickly, can be less accurate
    - CFIE combines relative strengths of the two methods
      - Uses combination parameter α, often $\alpha = 0.5$

$$\mathbf{Z}^{\text{CFIE}} = \alpha\mathbf{Z}^{\text{EFIE}} + (1-\alpha)\mathbf{Z}^{\text{MFIE}}$$

  - CFIE formulation can still lead to inaccuracy for certain types of geometries
    - Holes, thin surfaces, small gaps, etc.
  - Has been demonstrated for pedagogical examples, but what about realistic geometries?

[1]

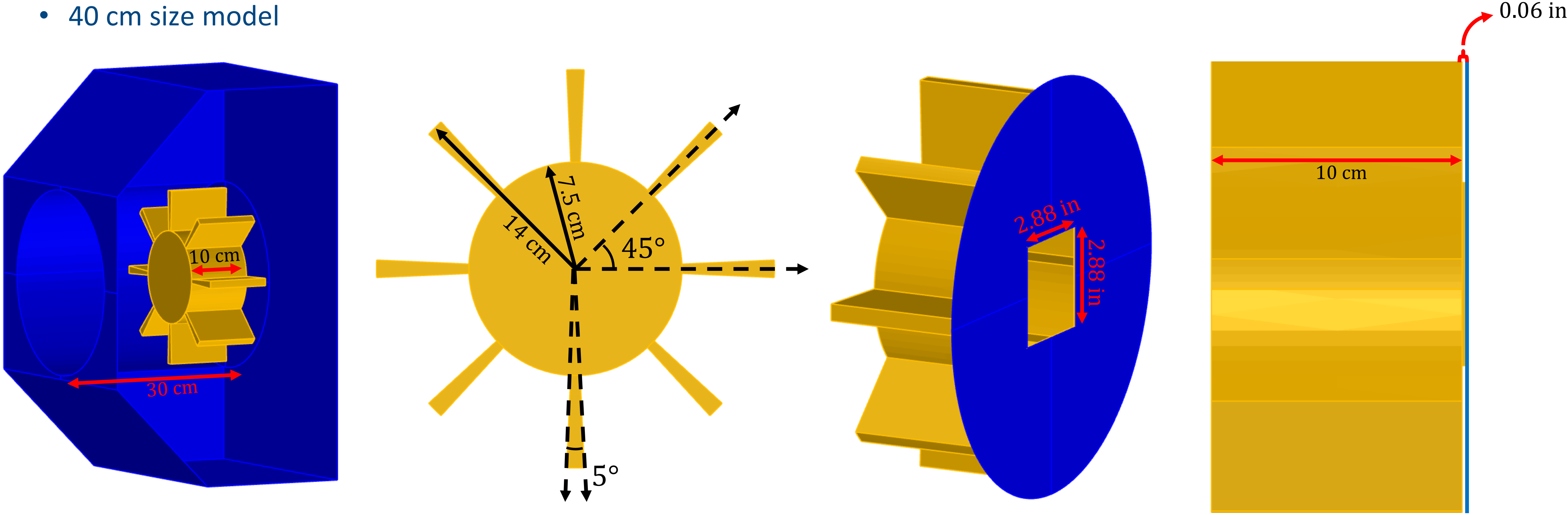




[1] A. E. Ofluoglu, *et al.*, "Magnetic Field Integral Equation," 2015

Fan Loaded Camera Box

- ❑ Austin RCS Benchmark Suite contains a number of complex geometries for Radar Cross-Section (RCS) analysis
- ❑ Problem Set IIISD describes a fan-loaded camera box
  - Small gap between back of fan-assembly and cavity wall
  - 40 cm size model

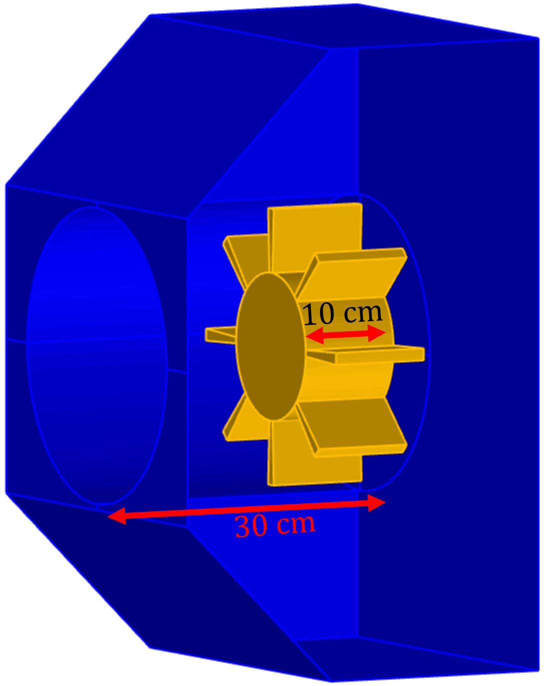


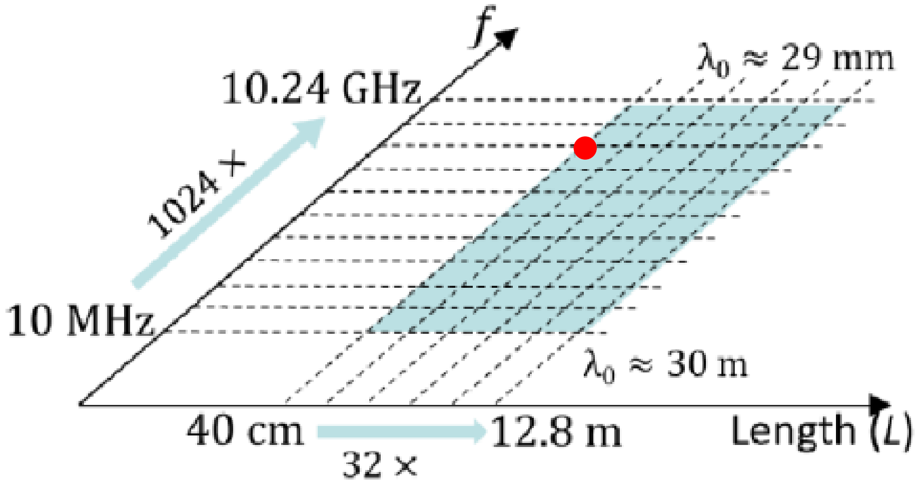
[2] https://github.com/UTAustinCEMGroup/AustinCEMBenchmarks
[3] J. T. Kelley, *et al.*, “Reproducible measurements of ‘fan blades in a pipe’ CEM benchmark,” 2023

Fan Loaded Camera Box

- ❑ Austin RCS Benchmark Suite contains a number of complex geometries for Radar Cross-Section (RCS) analysis
- ❑ Problem Set IIISD describes a fan-loaded camera box
  - Small gap between back of fan-assembly and cavity wall
  - Suite provides meshes at many densities

$f = 2.56$ GHz
$L = 40$ cm





IIISD		
	Average Edge Length (m)	Patch Count
Mesh YY	2.50E-02	6 084
Mesh YZ	1.80E-02	12 304
Mesh ZZ	1.30E-02	24 602
Mesh ZA	9.00E-03	48 462
Mesh AA	6.30E-03	96 244
Mesh AB	4.40E-03	192 968
Mesh BB	3.10E-03	384 328
Mesh BC	2.30E-03	770 348
Mesh CC	1.60E-03	1 588 708
Mesh CD	1.10E-03	3 139 192
Mesh DD	8.10E-04	6 065 984
Mesh DE	5.60E-04	11 945 578
Mesh EE	4.10E-04	24 282 792

[2] https://github.com/UTAustinCEMGroup/AustinCEMBenchmarks
[3] J. T. Kelley, *et al.*, “Reproducible measurements of ‘fan blades in a pipe’ CEM benchmark,” 2023

Outline

❑ Background

- Integral equations
  - MFIE-induced errors
- CameraBox Problem Set from Austin RCS Benchmark Suite

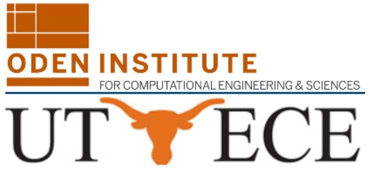
❑ **Problem-specific MFIE Induced Error**

- RCS pattern
- Induced currents

❑ Rectification techniques

- α parameter variation
- Global mesh refinement
- Local mesh refinement

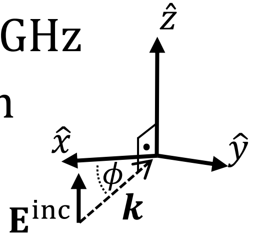
❑ Conclusions

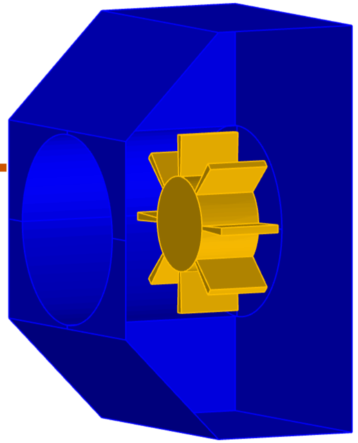


Problem Specific Error

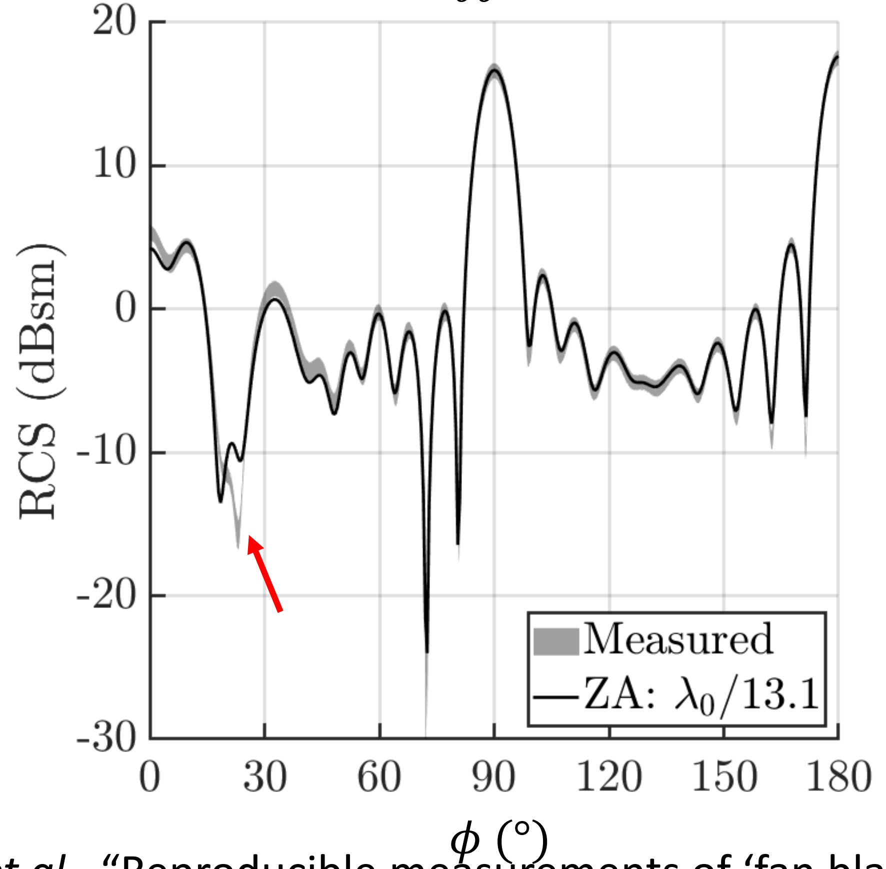
- Compute VV- and HH-polarized RCS patterns
- CFIE, $\alpha = 0.5$
- Mesh ZA, $\lambda_0/13.1$, 72 693 RWGs
- Most of look-angles agree with measurement; notable exception in $\sigma_{\theta\theta}$

$f = 2.56$ GHz
$L = 40$ cm

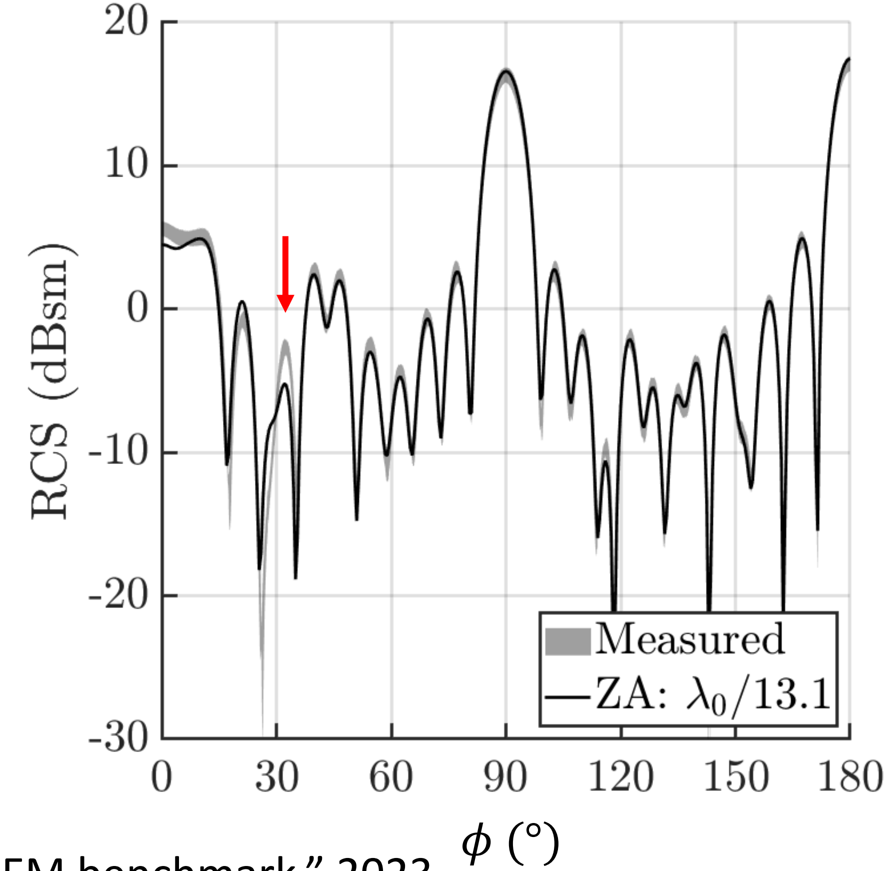




$\sigma_{\theta\theta}$



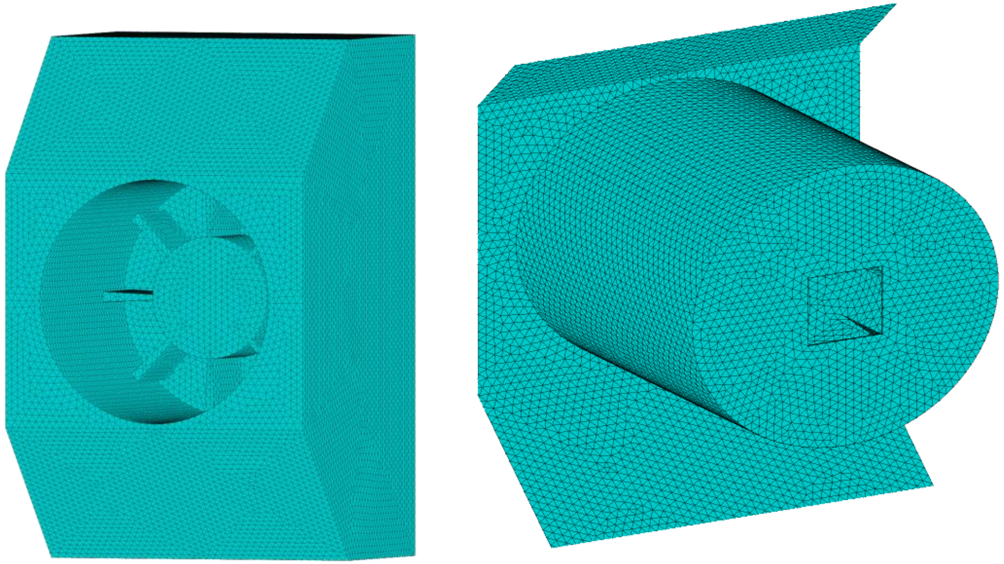
$\sigma_{\phi\phi}$

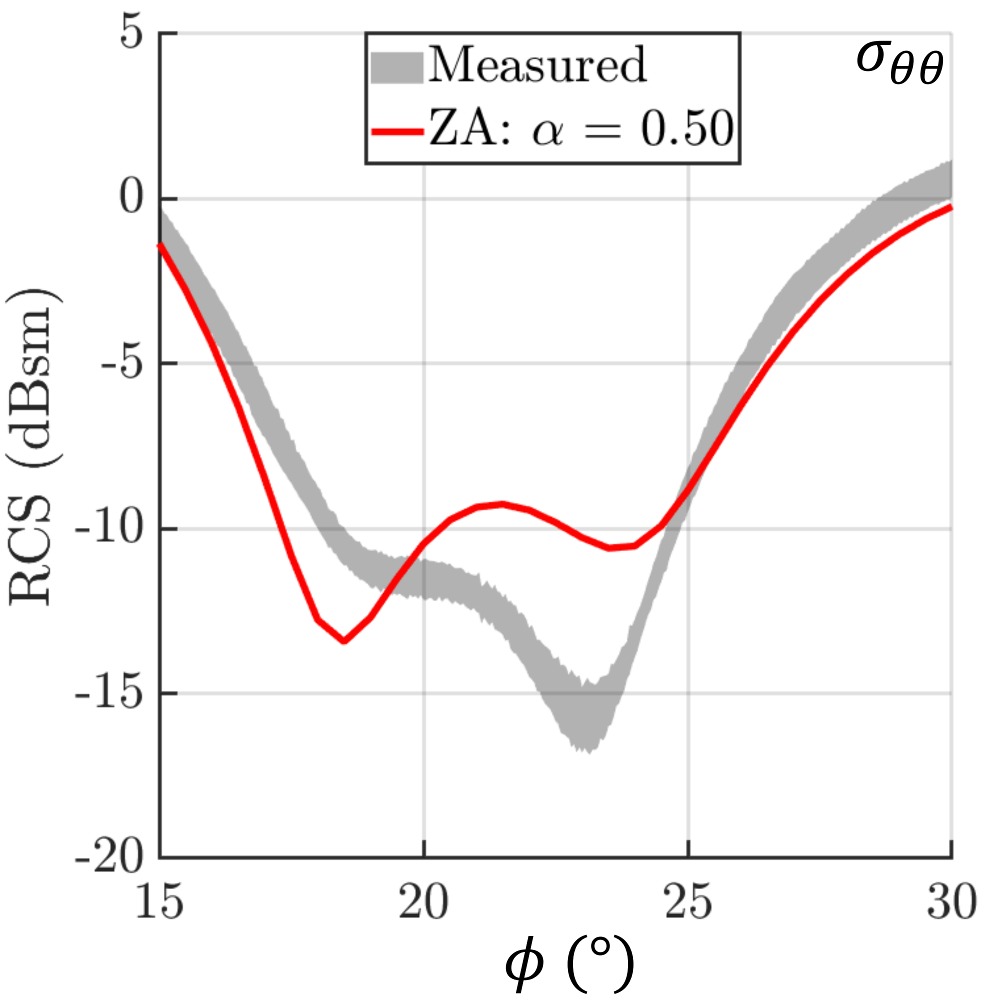


[3] J. T. Kelley, *et al.*, "Reproducible measurements of 'fan blades in a pipe' CEM benchmark," 2023

Problem Specific Error

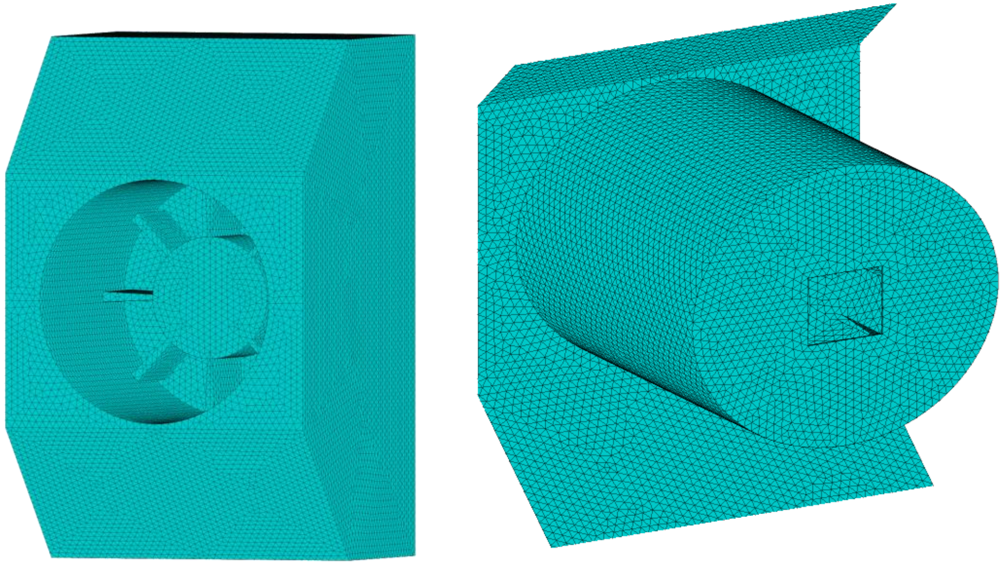
- Error in RCS simulation is due to MFIE error
  - Use mesh ZA from Benchmark Suite
  - 48 462 surface patches
  - Average edge length of 8.93×10^{-3} m
    - Mesh density is $\lambda_0/13.1$
  - $\alpha = 0.5$

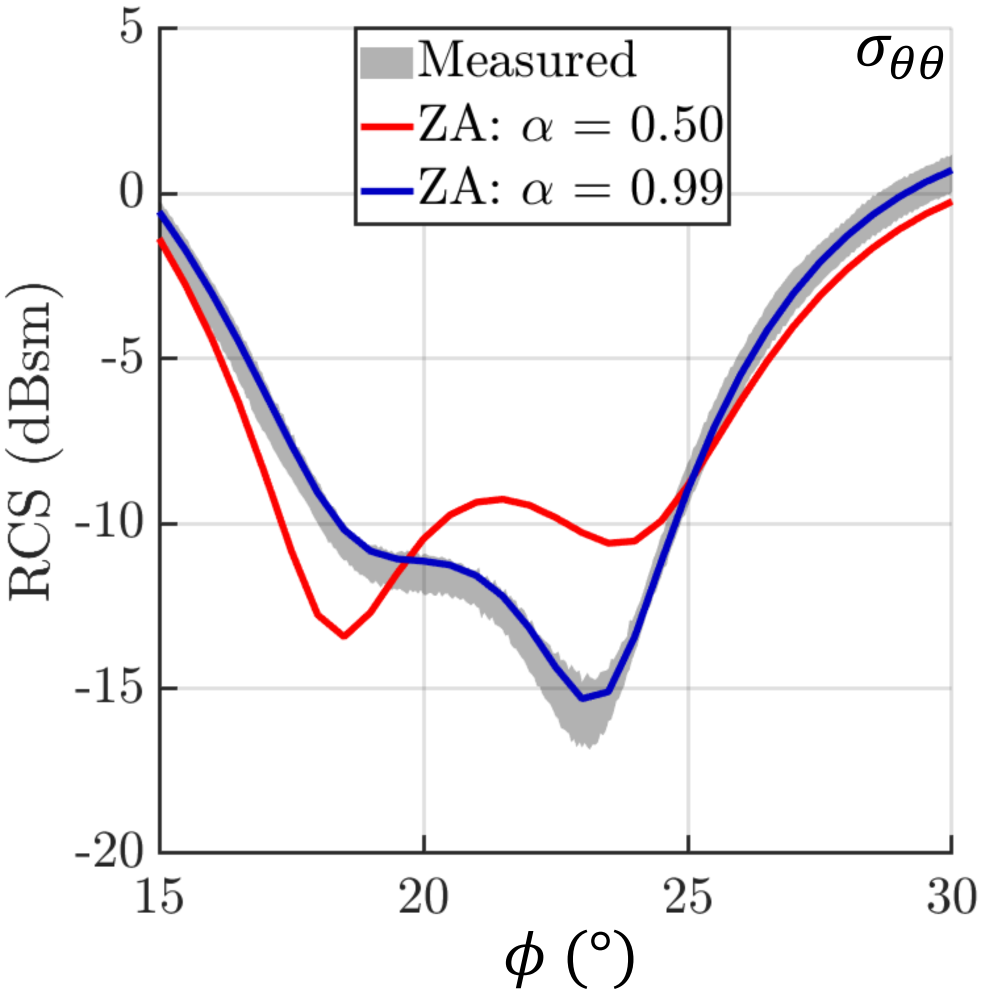




Problem Specific Error

- Error in RCS simulation is due to MFIE error
  - Use mesh ZA from Benchmark Suite
  - 48 462 surface patches
  - Average edge length of 8.93×10^{-3} m
    - Mesh density is $\lambda_0/13.1$
  - $\alpha = 0.5$
  - Increasing α dramatically improves results

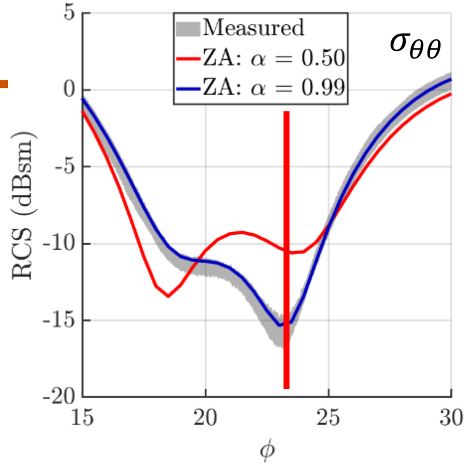




ODEN INSTITUTE FOR COMPUTATIONAL ENGINEERING & SCIENCES

UT ECE

Problem Specific Error

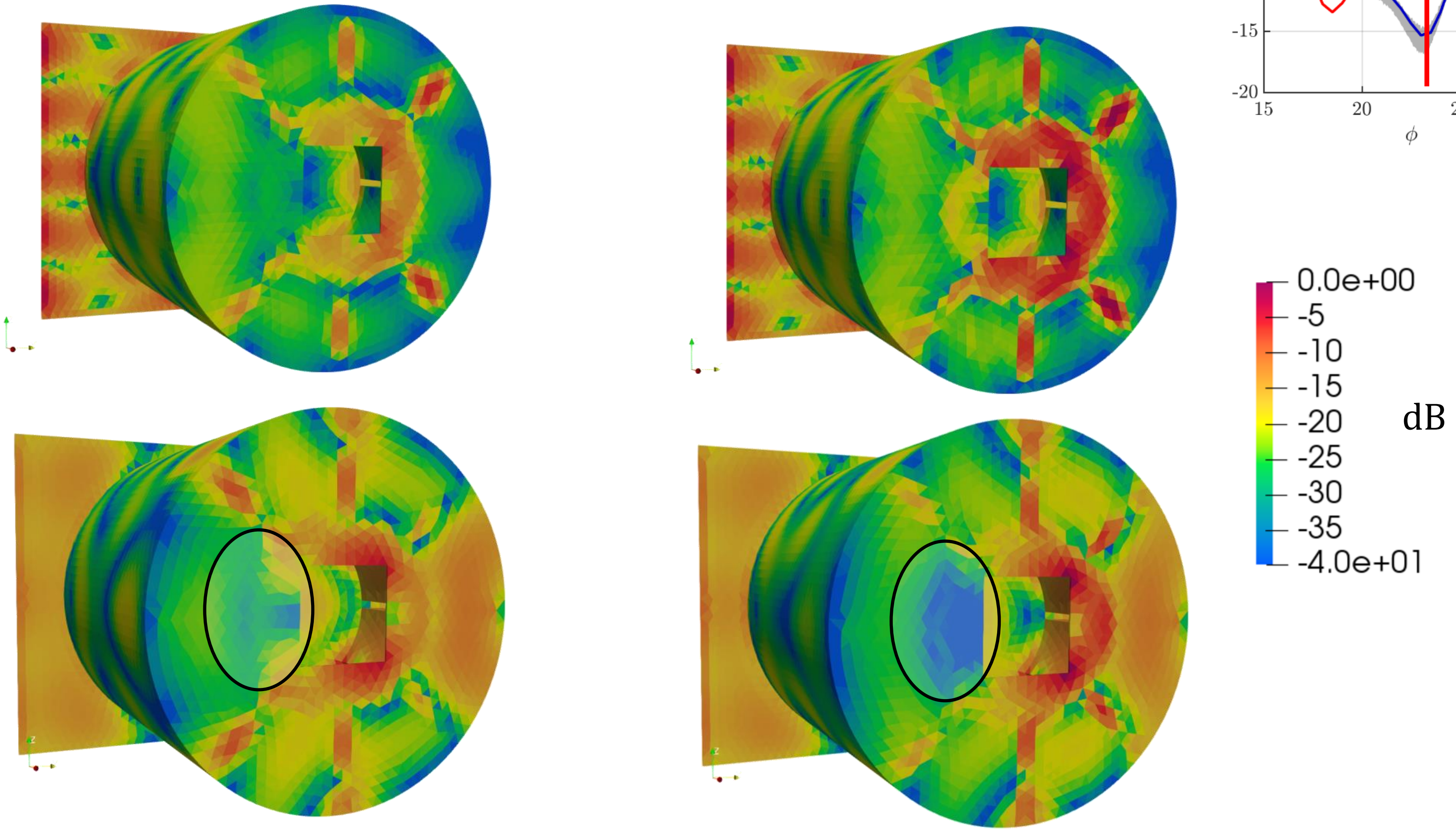


- Visualize surface currents on back plate with change in α

$\alpha = 0.5$ $\alpha = 0.99$

$\phi = 0°$

$\phi = 23°$



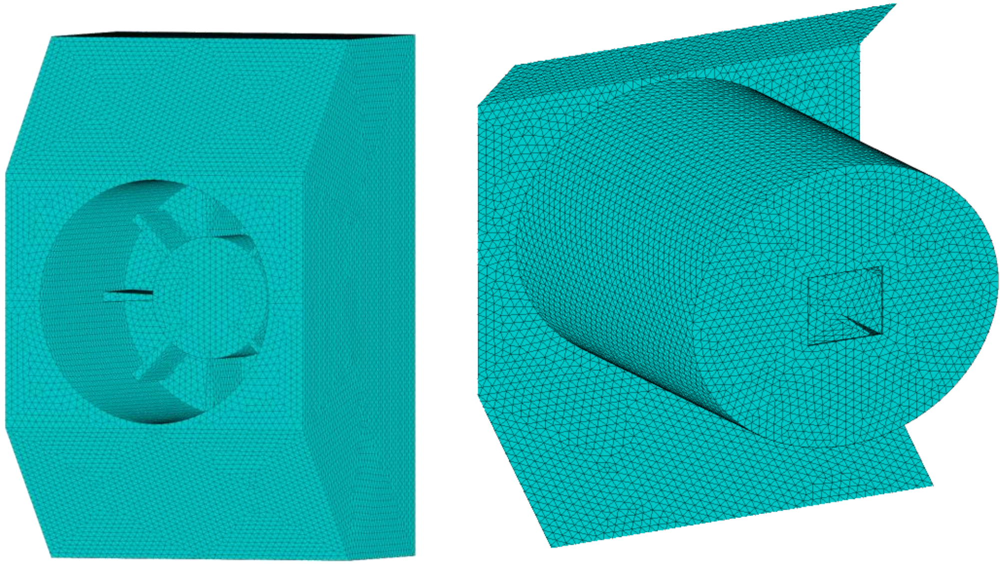
Outline

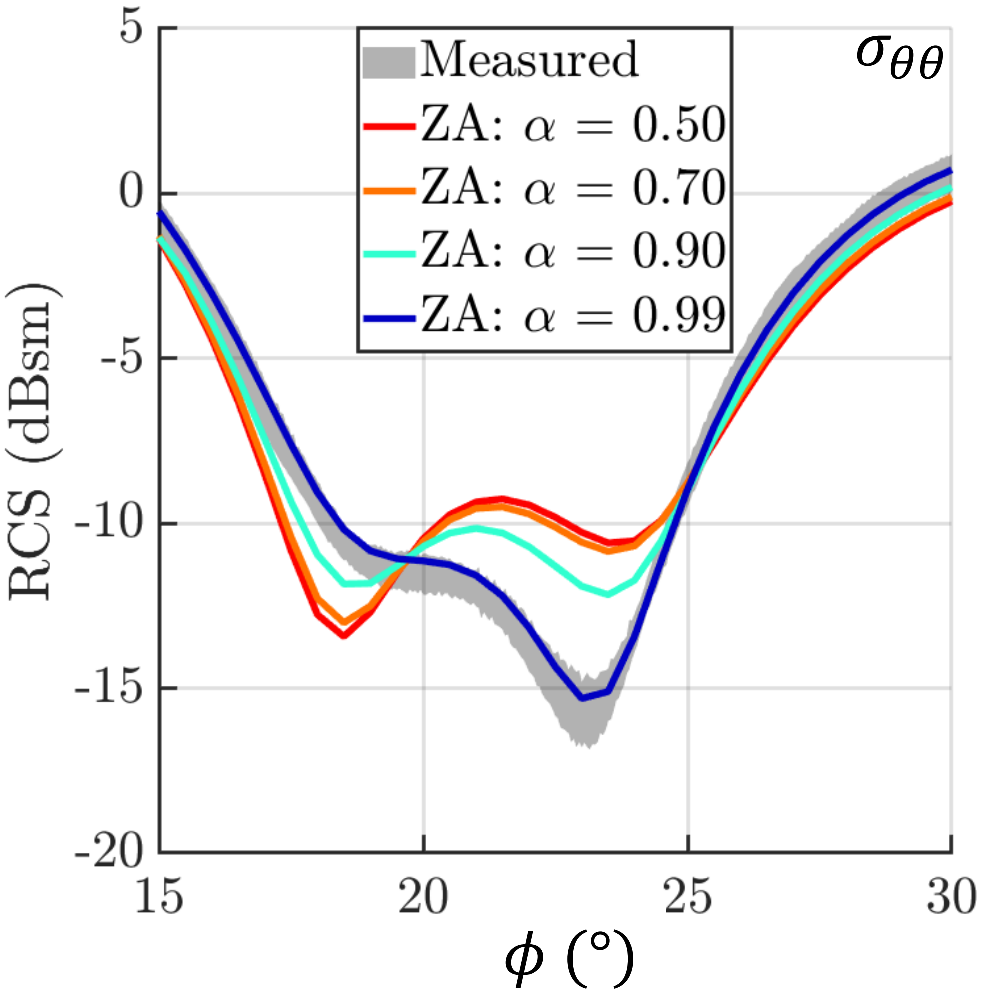
- ❑ Background
  - Integral equations
    - MFIE-induced errors
  - CameraBox Problem Set from Austin RCS Benchmark Suite
- ❑ Problem-specific MFIE Induced Error
  - RCS pattern
  - Induced currents
- ❑ **Rectification techniques**
  - α parameter variation
  - Global mesh refinement
  - Local mesh refinement
- ❑ Conclusions

ODEN INSTITUTE FOR COMPUTATIONAL ENGINEERING & SCIENCES
UT ECE

α Parameter Variation

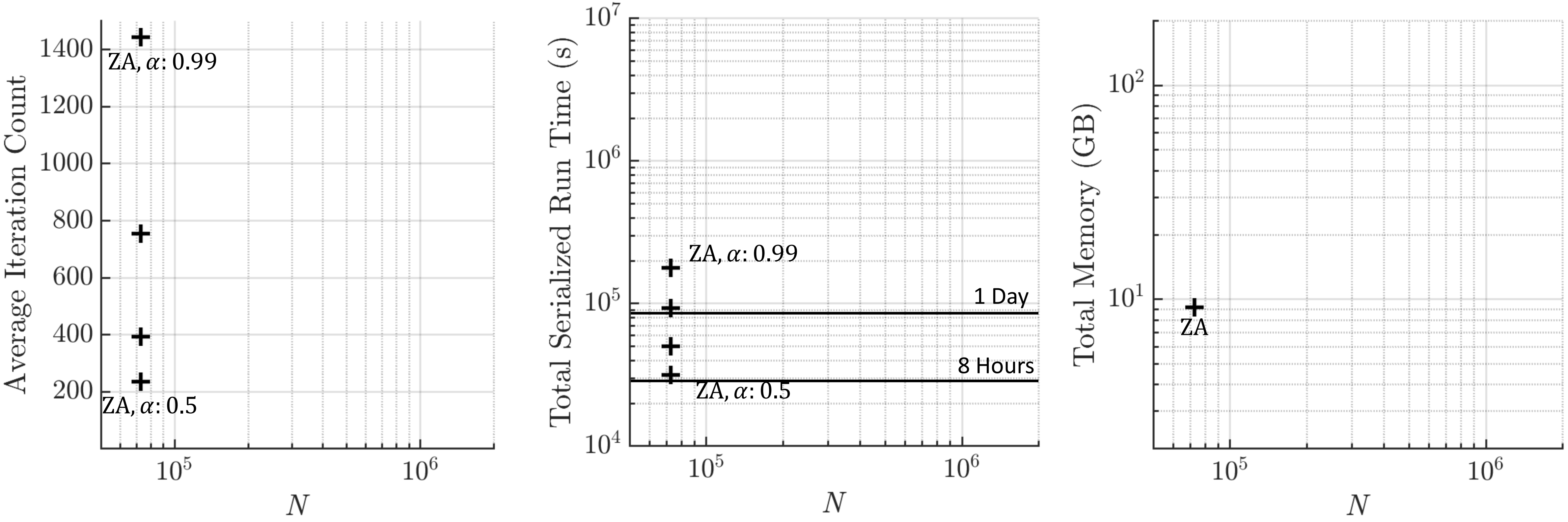
- Error in RCS simulation is due to MFIE error
  - Use mesh ZA from Benchmark Suite
  - 48 462 surface patches
  - Average edge length of 9×10^{-3} m
    - Mesh density is $\lambda_0/13.1$
  - $\alpha = 0.5$
  - Need to push all the way to EFIE to see improvement





α Parameter Variation

- Increasing α increases the number of iterations necessary to converge in solve stage
  - TFQMR convergence is at 1×10^{-4}
  - Number of iterations increases by $\sim \times 7$
  - Serialized run-time increases by $\sim \times 6$
    - Only are computing in narrow window; solve stage dominates full RCS sweep



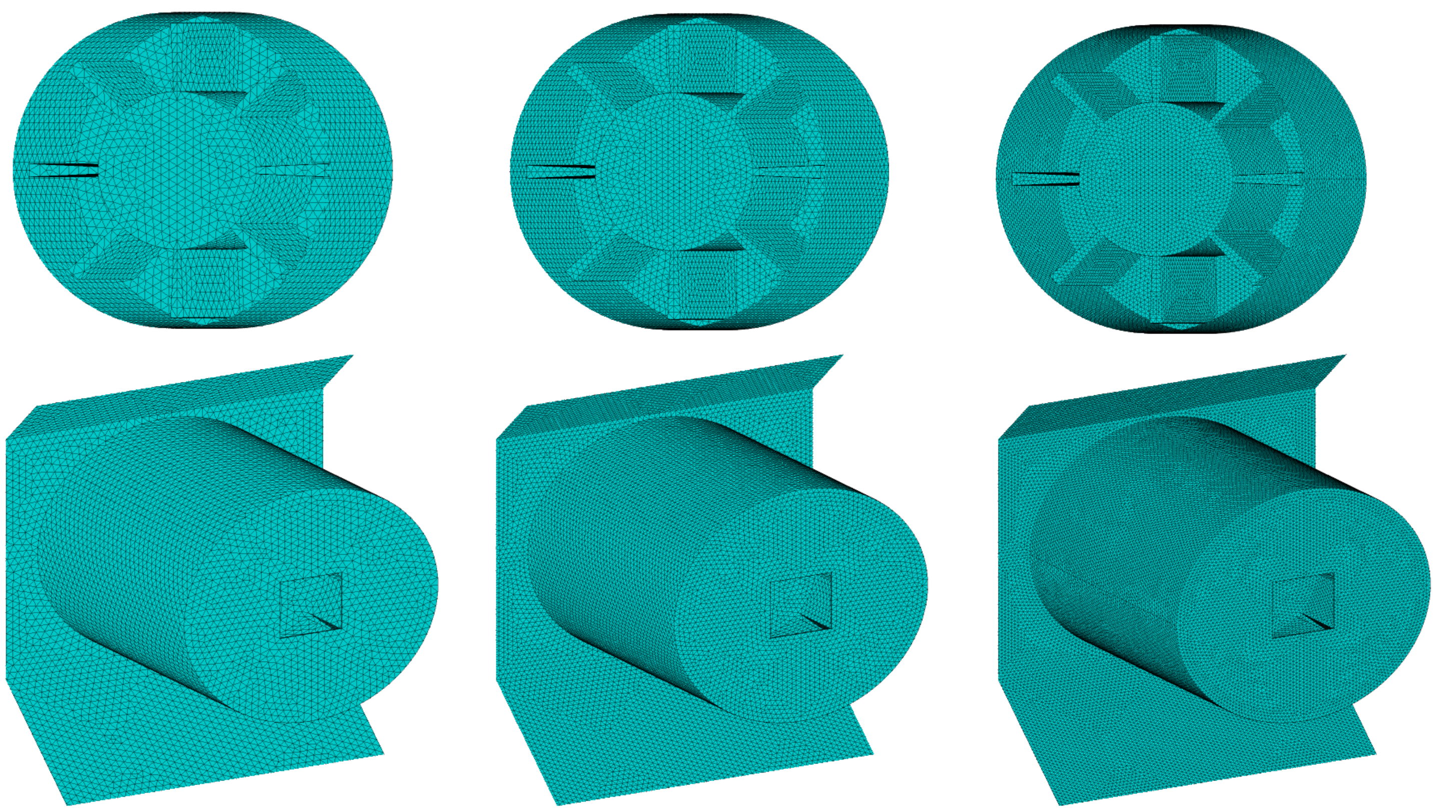
ODEN INSTITUTE FOR COMPUTATIONAL ENGINEERING & SCIENCES

UT ECE

Global Mesh Refinement

- Instead of increasing α, can refine the mesh
  - Increased resolution will allow more accurate capture of currents in problem region
  - Densest mesh is $\lambda_0/52.4$

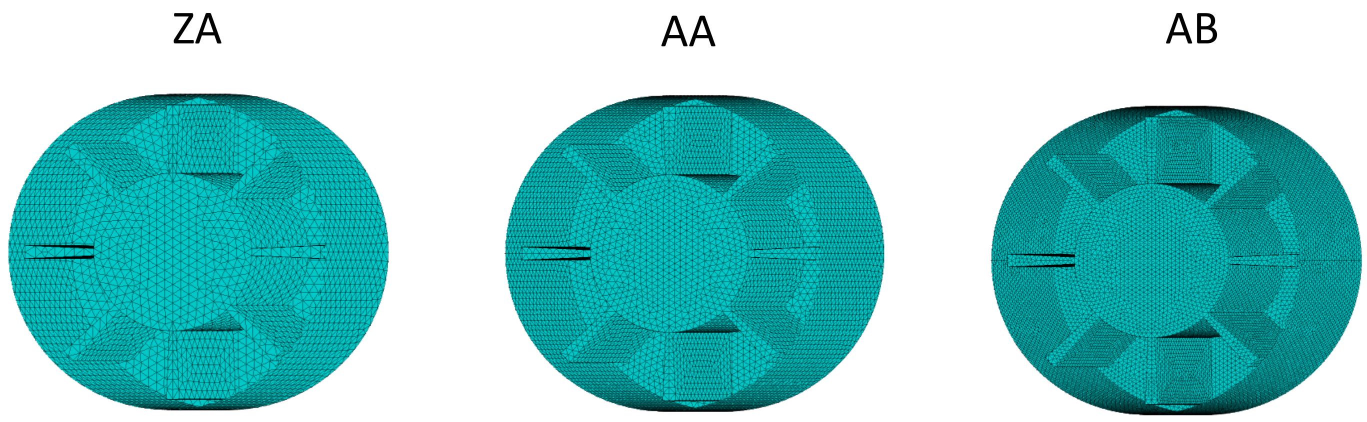
ZA AA AB

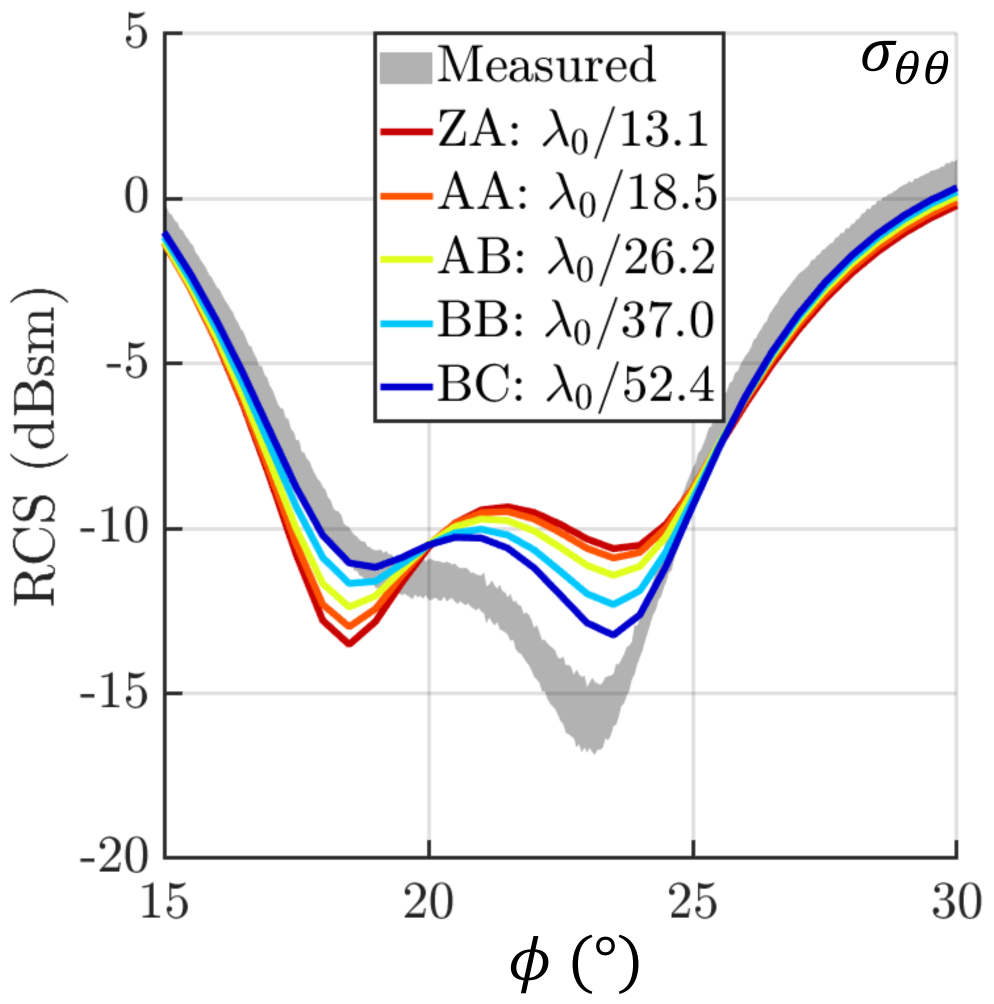


IIISD		
	Average Edge Length (m)	Patch Count
Mesh YY	2.50E-02	6 084
Mesh YZ	1.80E-02	12 304
Mesh ZZ	1.30E-02	24 602
Mesh ZA	9.00E-03	48 462
Mesh AA	6.30E-03	96 244
Mesh AB	4.40E-03	192 968
Mesh BB	3.10E-03	384 328
Mesh BC	2.30E-03	770 348
Mesh CC	1.60E-03	1 588 708
Mesh CD	1.10E-03	3 139 192
Mesh DD	8.10E-04	6 065 984
Mesh DE	5.60E-04	11 945 578
Mesh EE	4.10E-04	24 282 792

Global Mesh Refinement

- Instead of increasing α, can refine the mesh
  - Increased resolution allows more accurate capture of currents in problem region
  - Densest mesh is $\lambda_0/52.4$
- Accuracy improves more slowly than α increase



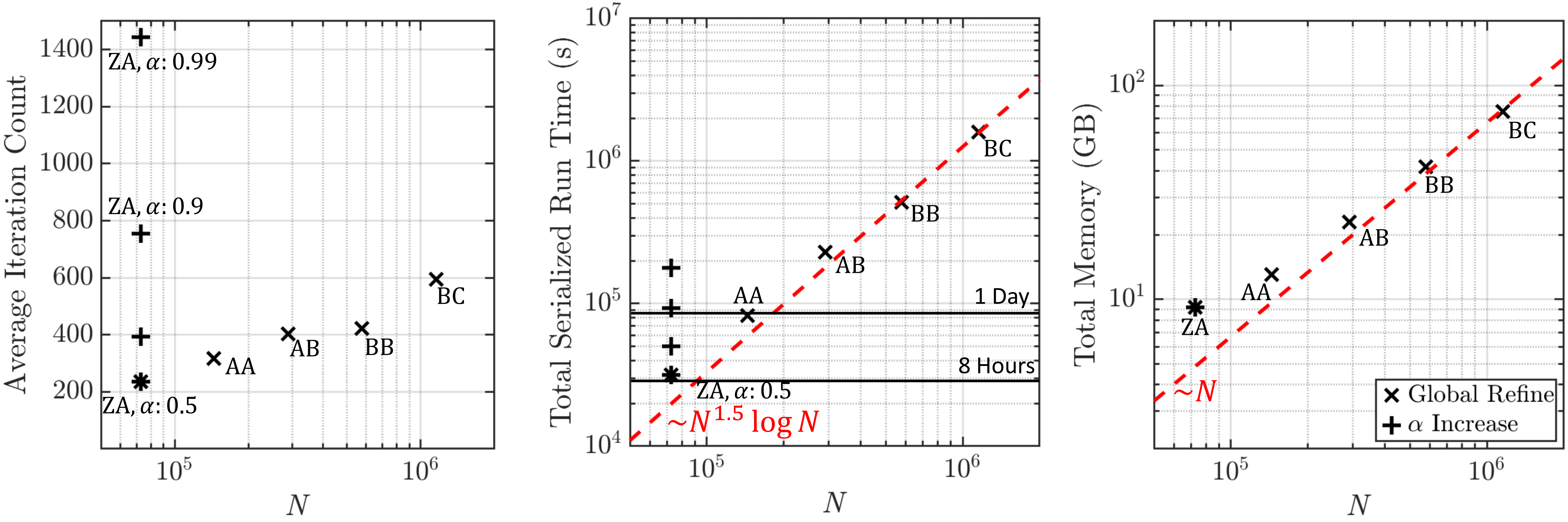


ODEN INSTITUTE FOR COMPUTATIONAL ENGINEERING & SCIENCES

UT ECE

Global Mesh Refinement

- Compared to α increase, global mesh refinement iterations grow much more slowly
- Increased memory costs in fill stage, increased time costs

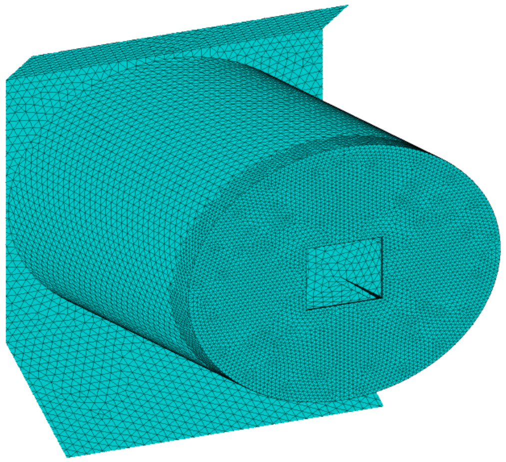


ODEN INSTITUTE FOR COMPUTATIONAL ENGINEERING & SCIENCES
UT ECE

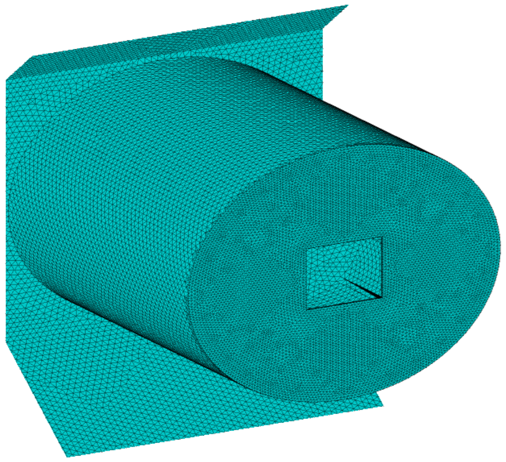
Local Mesh Refinement

- No need to globally refine mesh
  - Locally refining the mesh in the problem region can save on computational costs
  - One level of refinement from ‘base’ mesh

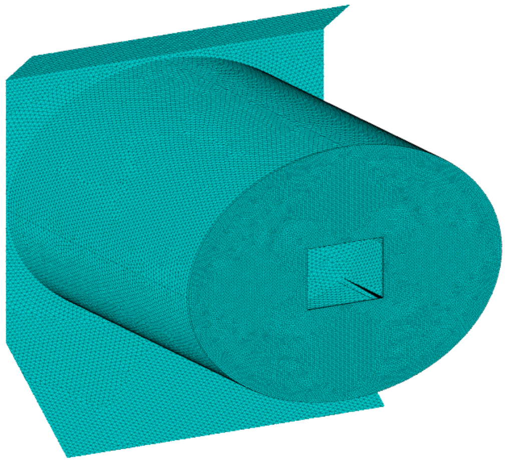
ZA.R1



AA.R1



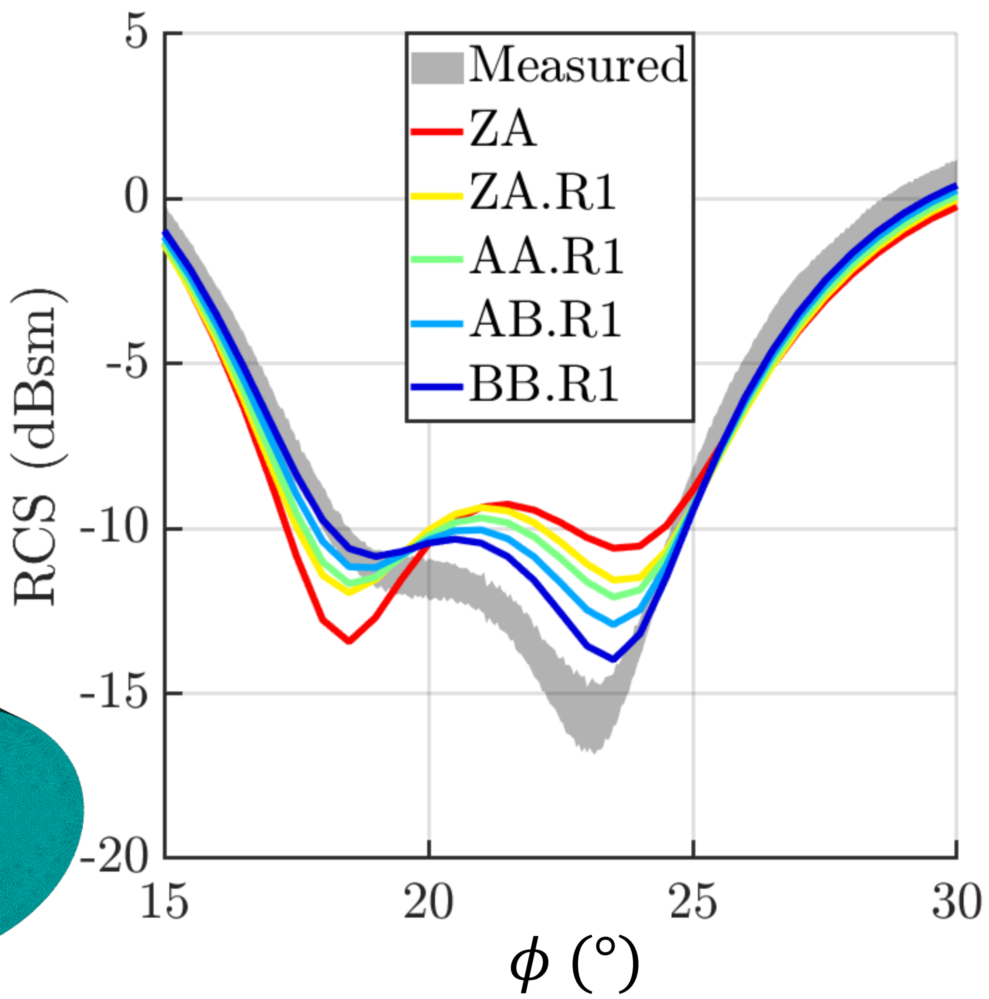
AB.R1



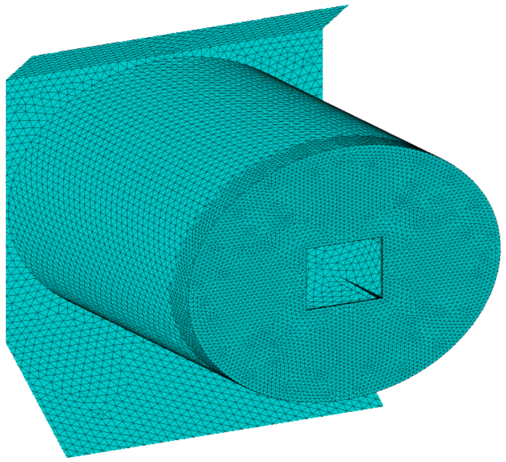
IIISD		
	Average Edge Length (m)	Patch Count
Mesh YY	2.50E-02	6 084
Mesh YZ	1.80E-02	12 304
Mesh ZZ	1.30E-02	24 602
Mesh ZA	9.00E-03	48 462
Mesh ZA.R1	7.70E-03	61 826
Mesh AA	6.30E-03	96 244
Mesh AA.R1	5.70E-03	112 120
Mesh AB	4.40E-03	192 968
Mesh AB.R1	4.10E-03	223 394
Mesh BB	3.10E-03	384 328
Mesh BB.R1	2.90E-03	447 066
Mesh BC	2.30E-03	770 348
Mesh CC	1.60E-03	1 588 708
Mesh CD	1.10E-03	3 139 192
Mesh DD	8.10E-04	6 065 984
Mesh DE	5.60E-04	11 945 578
Mesh EE	4.10E-04	24 282 792

Local Mesh Refinement

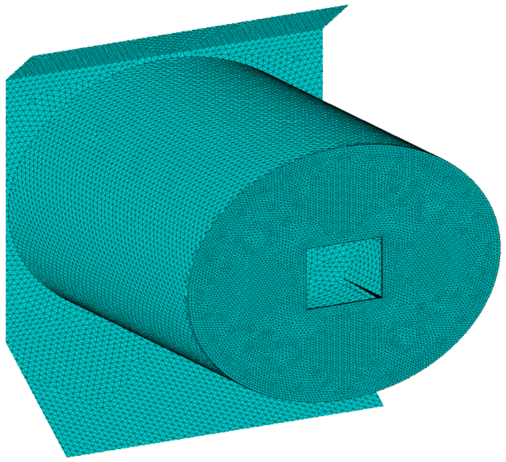
- No need to globally refine mesh
  - Locally refining the mesh in the problem region can save on computational costs
  - One level of refinement from ‘base’ mesh



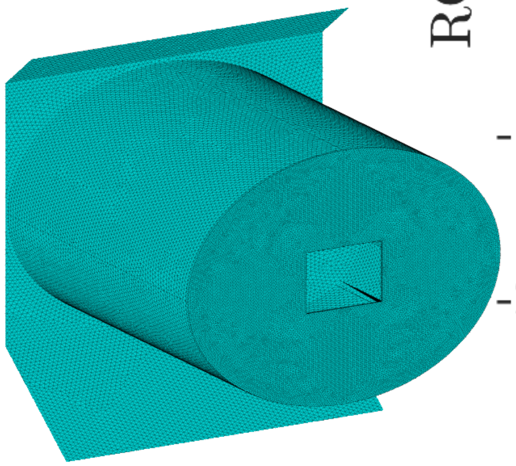
ZA.R1



AA.R1



AB.R1

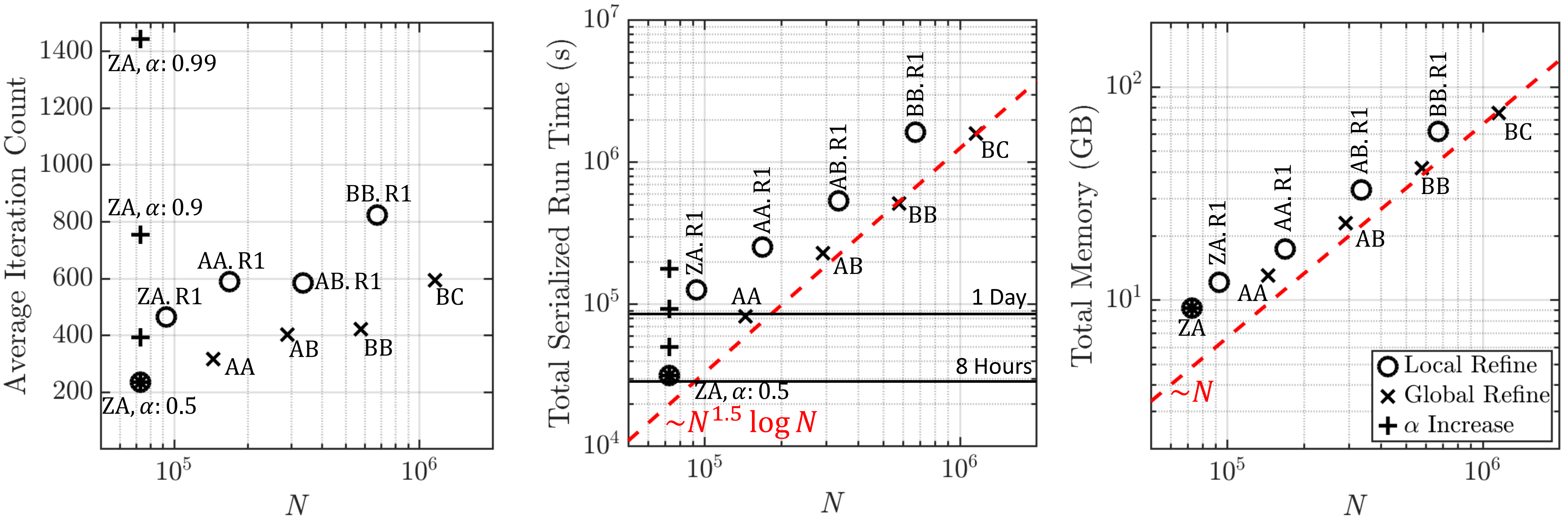


ODEN INSTITUTE FOR COMPUTATIONAL ENGINEERING & SCIENCES

UT ECE

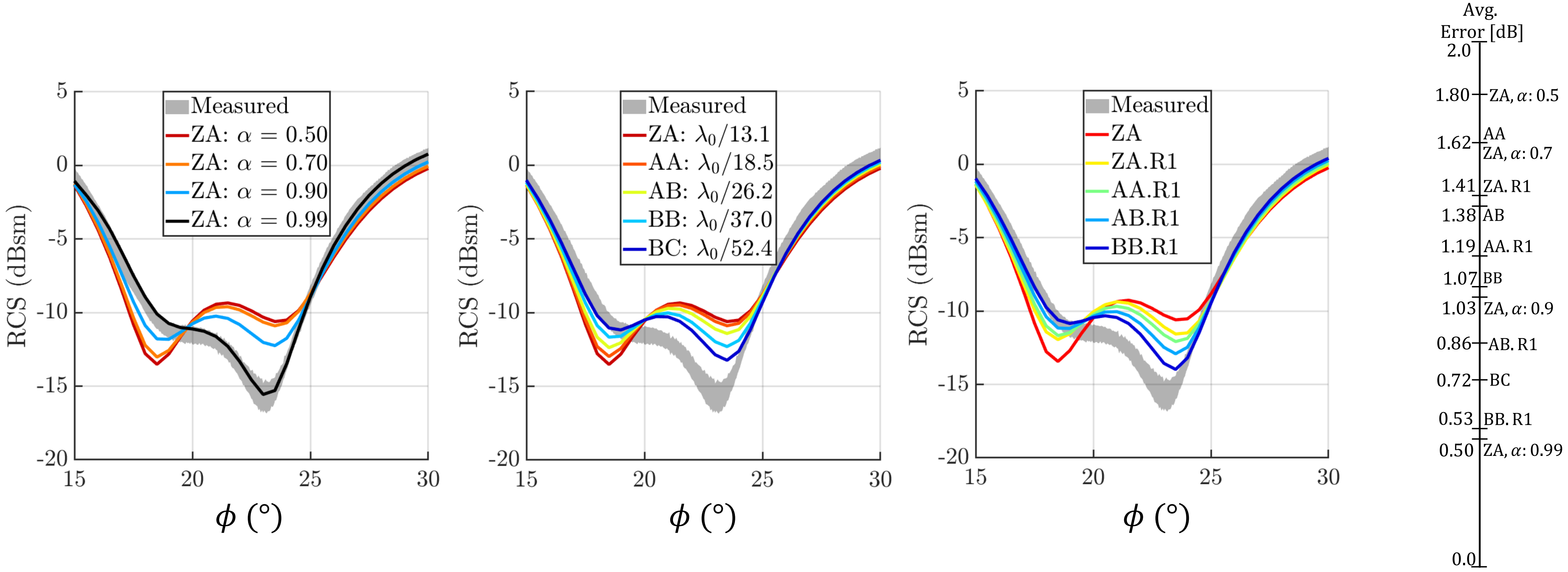
Local Mesh Refinement

- Compared to global refine, iterations grow more quickly due to uneven mesh
- Costs appear to grow at similar rate
  - How do we more accurately compare local vs. global refine strategies?



Method Comparison

- Reference is the data published on the Benchmark Suite

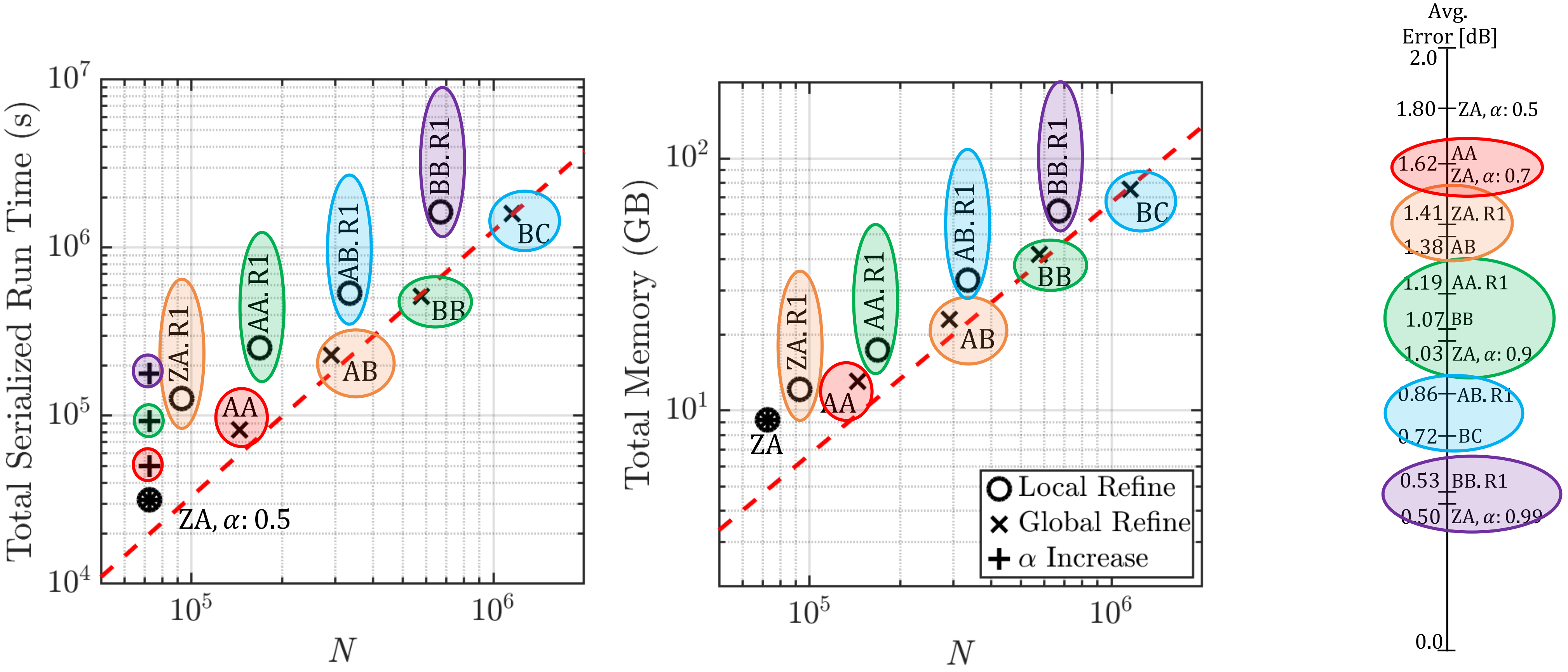


ODEN INSTITUTE FOR COMPUTATIONAL ENGINEERING & SCIENCES

UT ECE

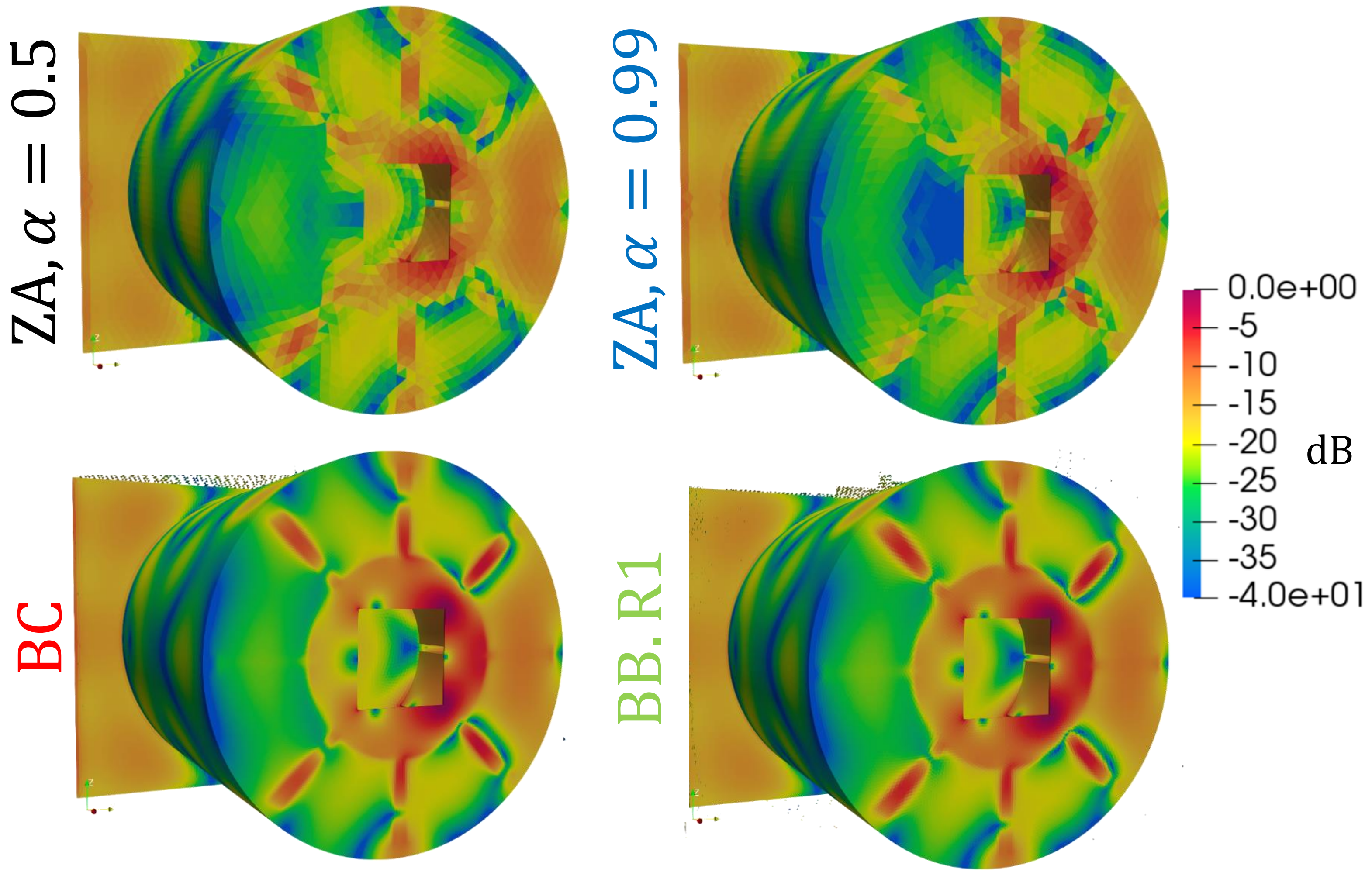
Method Comparison

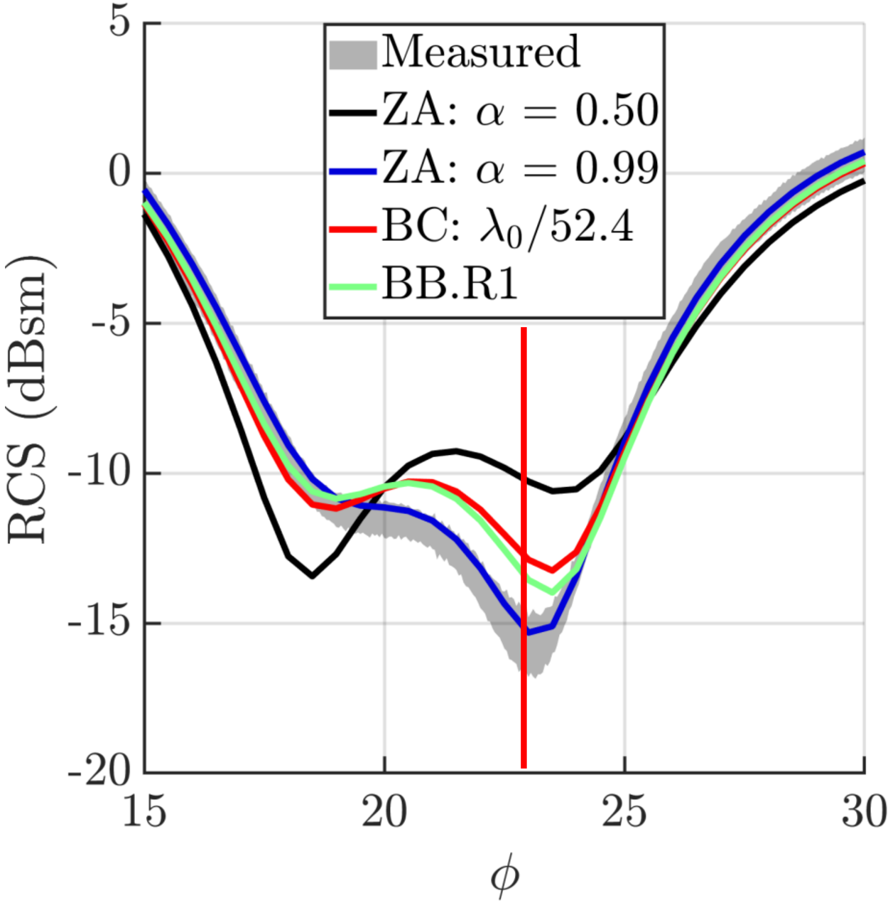
- Reference is the data published on the Benchmark Suite



Method Comparison

- Visualize surface currents on back plate for most accurate/expensive simulation from each method





ODEN INSTITUTE FOR COMPUTATIONAL ENGINEERING & SCIENCES

UT ECE

Conclusions

- In a realistic, complex geometry, MFIE can on occasion induce large errors in RCS
- Investigated 3 ways to decrease errors
  - α control
    - No memory increase
    - Number of iterations grows quickly
    - Moderate increase in solve time
  - Global mesh refinement
    - Largest memory and cost increases
    - Slow iteration count growth
  - Local mesh refinement
    - Moderate-large cost increase
    - Moderate iteration count growth
- Best results from combination of strategies, or more targeted local mesh refinement

TACC

TEXAS ADVANCED COMPUTING CENTER