A Benchmark Suite for Quantifying RCS Simulation Performance on Modern Computers

Jackson W. Massey[1], Jon T. Kelley[1],
Clifton Courtney[2], David A. Chamulak[2], and Ali E. Yılmaz[1]

[1]The University of Texas at Austin, Austin, TX 78712
[2]Lockheed Martin Aeronautics Company, Palmdale, CA 93599

Boston, MA, July 10, 2018 2018 USNC-URSI Radio Science Meeting

Outline

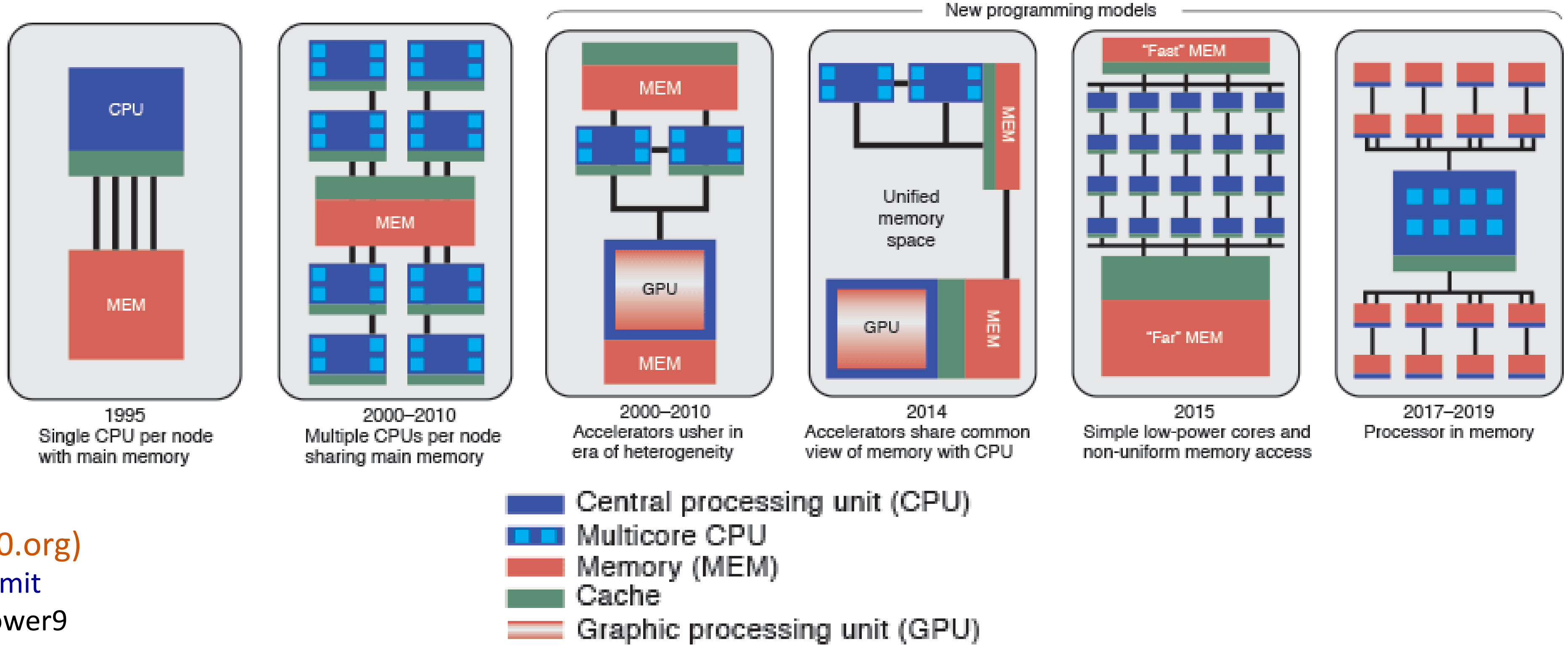
- Motivation
  - Modern computers
  - Proto-benchmarks vs. quantitative benchmarks
- Background
  - Designing modern CEM benchmark suites
  - Key ingredients
- Organizing the Many Dimensions
  - Vectors that increase EM simulation difficulty
  - 6 important dimensions
- Examples from the Austin RCS Benchmark Suite
  - Current list of problems
  - Exhaustive vs. recommended performance studies
  - Sample performance study with the suite
- Conclusion

Motivation

❑ Modern Computers

Gearing Up for the Next Challenge in High-Performance Computing

Research Highlights, Lawrence Livermore National Lab, Mar. 2015.



- June 2018 Rankings (top500.org)

1. Summit
IBM Power9
2x22 cores 3.07 GHz
+ Nvidia Volta GV100
2.28M+ cores
~122.3 Pflop/s

2. Sunway TaihuLight
Sunway SW26010
4x64 cores, 1.45 GHz
10.6M+ cores
~93 Pflop/s

3. Sierra
IBM Power9
2x22 cores 3.1 GHz
+ Nvidia Volta GV100
1.57M+ cores
~71.6 Pflop/s

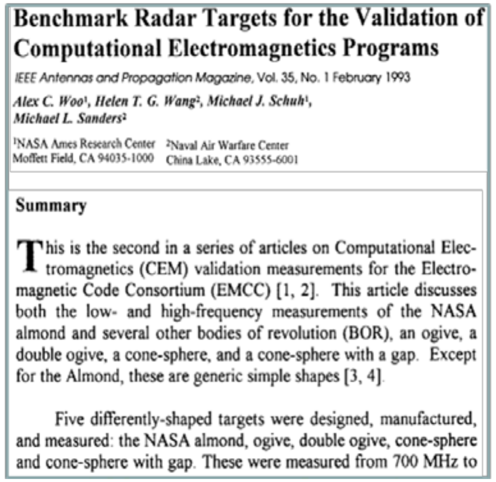
15. Stampede 2
Intel Xeon Phi 7250
68x4 cores 1.4 GHz
0.369M cores
~8.3Pflop/s

Motivation

- ❑ Proto-benchmarks vs. (quantitative) benchmarks
- ❑ Types of benchmarks

Benchmarks

Analytical reference for quantifying error	Measurement reference for quantifying error	Numerical reference for quantifying error & cost


Benchmark Radar Targets for the Validation of Computational Electromagnetics Programs

IEEE Antennas and Propagation Magazine, Vol. 35, No. 1 February 1993

Alex C. Woo[1], Helen T. G. Wang[2], Michael J. Schuh[1], Michael L. Sanders[2]

[1]NASA Ames Research Center Moffett Field, CA 94035-1000
[2]Naval Air Warfare Center China Lake, CA 93555-6001

Summary

This is the second in a series of articles on Computational Electromagnetics (CEM) validation measurements for the Electromagnetic Code Consortium (EMCC) [1, 2]. This article discusses both the low- and high-frequency measurements of the NASA almond and several other bodies of revolution (BOR), an ogive, a double ogive, a cone-sphere, and a cone-sphere with a gap. Except for the Almond, these are generic simple shapes [3, 4].

Five differently-shaped targets were designed, manufactured, and measured: the NASA almond, ogive, double ogive, cone-sphere and cone-sphere with gap. These were measured from 700 MHz to

?

"A benchmark has three components:
Motivating comparison…
Task sample…
Performance measures… performance is a measure of fitness for purpose.
A proto-benchmark is a set of tests that is missing one of these components. The most common proto-benchmarks lack a performance measure and are sometimes called case studies or examplars. These are typically used to demonstrate the features and capabilities of a new tool or technique, and occasionally used to compare different technologies in an exploratory manner."

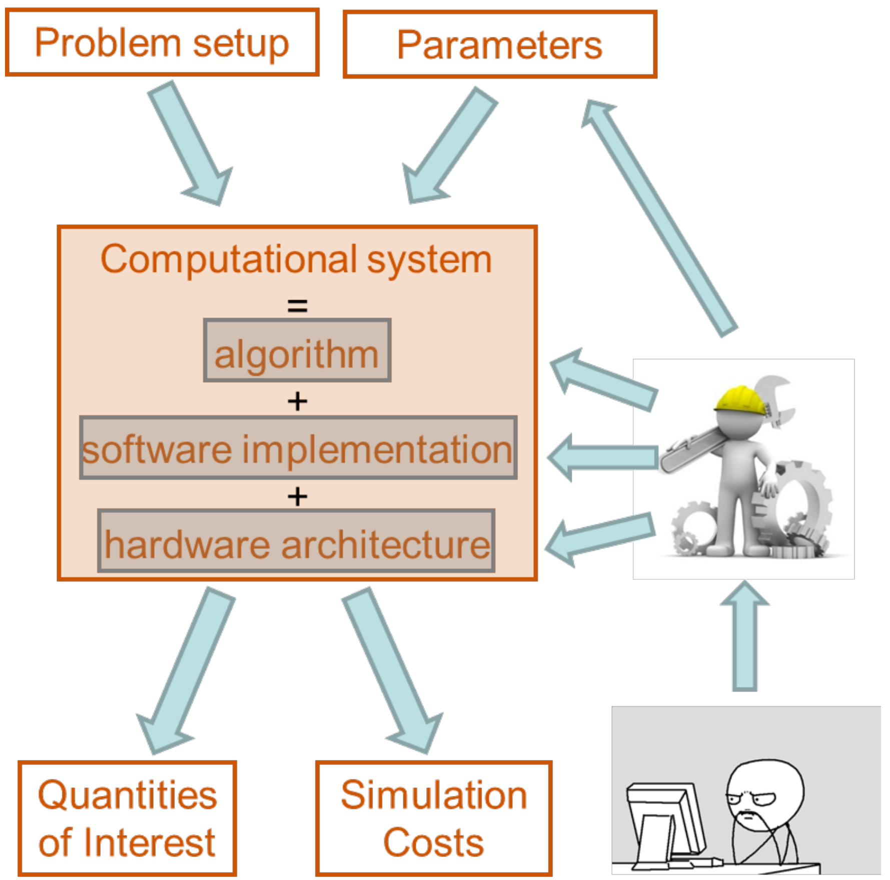
S. E. Sim, S. Easterbrook, R. C. Holt, "Using benchmarking to advance research: A challenge to software engineering," *Proc. Int. Conf. Software Eng.*, May 2003.

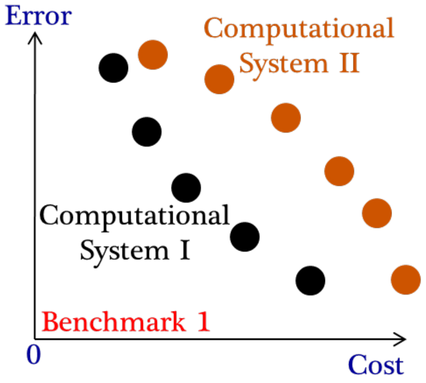
- Numerical benchmarks (with error vs. cost trade-off) underutilized in CEM [1]
- Next-generation benchmarks can
  - inform public and researchers in the field about state of the art
  - reveal performance of new algorithms, software, and hardware

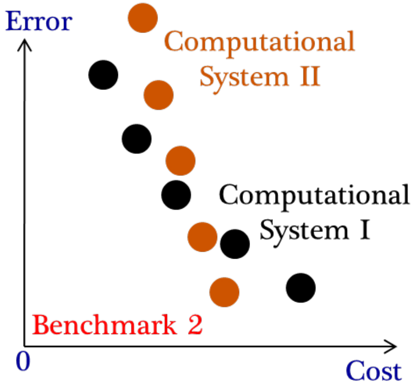
[1] A. E. Yilmaz, "Advancing computational electromagnetics research through benchmarking," in *Proc. URSI Meet.*, San Diego, CA, July 2017.

Designing Modern CEM Benchmark Suites

- Key ingredients for benchmark suites [1]
  - Application-specific list of scattering problems
    1. Span different difficulty levels
    2. Emphasize/exercise features of computational system relevant to application
    3. General enough to represent different types of problems encountered
    4. Problem set should evolve
  - Precisely defined quantities of interest
    1. Must obtain/use (much) more accurate reference results
    2. Reliable analytical references whenever possible
  - Performance measures
    1. Error and computational cost measures
    2. Also quantify computational power available to simulation and normalize costs across platforms
  - Online databases





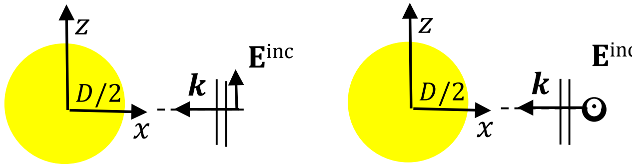


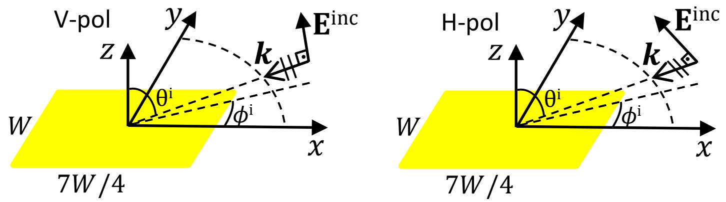
[1] J. W. Massey, C. Liu, and A. E. Yilmaz, "Benchmarking to close the credibility gap: a computational BioEM benchmark suite," in *Proc. URSI EMTS*, Aug. 2016.

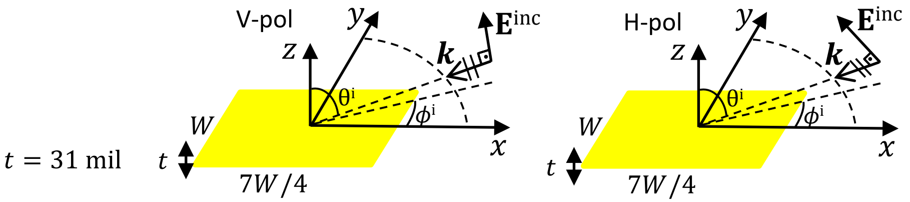
Organizing the Many Dimensions

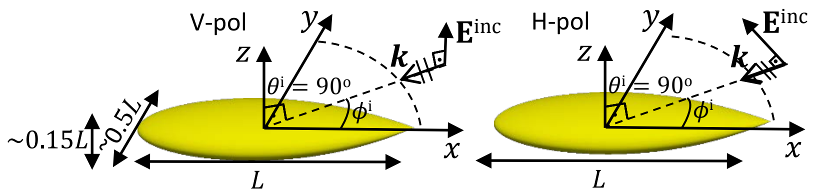
- 3 primary vectors increase difficulty of EM simulation and call for “better” simulations
  - Vector 1: Higher model fidelity (more features/complete models)
    1. More complex geometry (e.g., curvatures, sharp edges, cavities, …)
    2. More complex materials (e.g., partial coatings, composites, …)
  - Vector 2: Increasing model size (larger domain of analysis)
    3. Larger size (e.g., drone->passenger jet)
    4. Higher frequency (e.g., HF->X band)
  - Vector 3: Quantitatively improved simulation (more powerful algorithm+software+hardware)
    5. Lower error (e.g., high correlation -> low average error in dB RCS pattern)
    6. Lower cost (e.g., shorter wall-clock time, less memory, higher parallel efficiency)
  - Others: Qualitatively improved simulation (more portable, easy to maintain/upgrade, user friendly, …)
- Organize benchmark suite into 6 dimensions
  - Dimensions 1-2: Specify geometry & materials
  - Dimensions 3-4: Specify lengths & frequency
  - Dimensions 5-6: Quantify error & cost
- Problem I: Spheres Problem II: Plates Problem III: Almonds …
  - I-A: PEC spheres - II-A: Zero-thickness PEC plates - III-A: PEC almonds
  - I-B: Semiconductor spheres - II-B: Thin PEC plates

  ::Potential others::
  - I-C: Water spheres
  - I-D: Magneto-dielectric spheres
  - I-E: Coated spheres
  - I-F: Partially-coated spheres …









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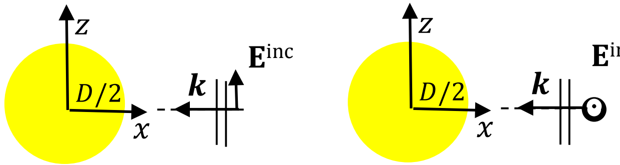
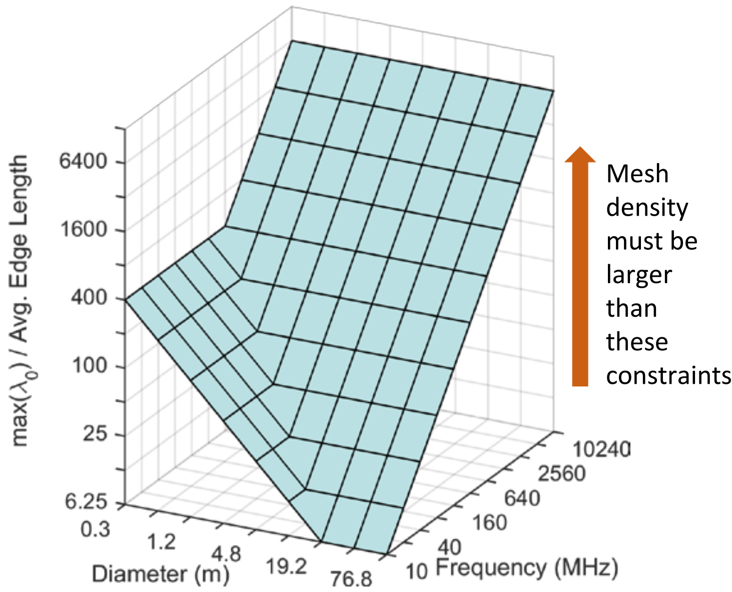
  - Others: Qualitatively improved simulation (more portable, easy to maintain/upgrade, user friendly, …)
- Organize benchmark suite into 3 sweeps
  - Two types of constraints on mesh density:
    - Wavelength dictated
    - Geometry size dictated





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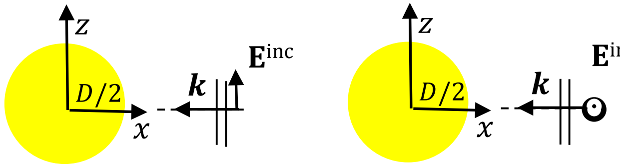
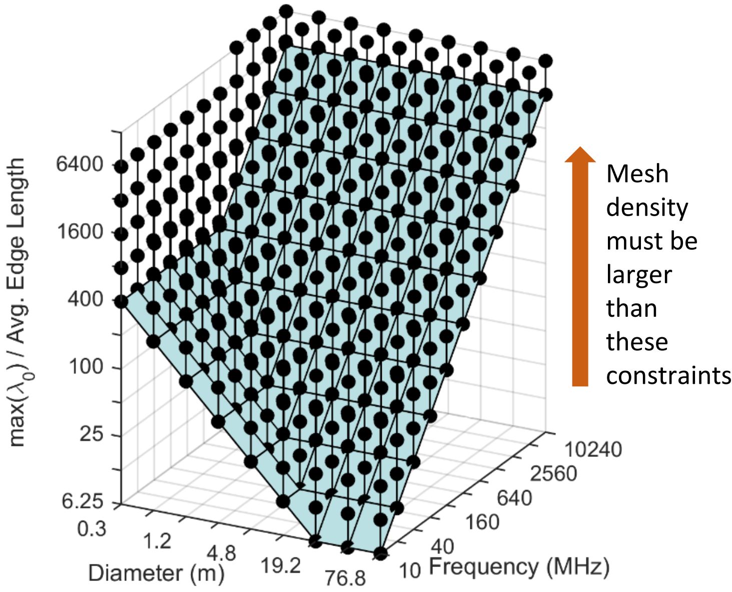
- Organize benchmark suite into 3 sweeps
  - Two types of constraints on mesh density:
    - Wavelength dictated
    - Geometry size dictated
  - Comprehensive sweep
    - High-dimensional space: too many simulations





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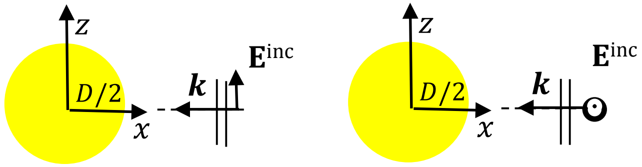
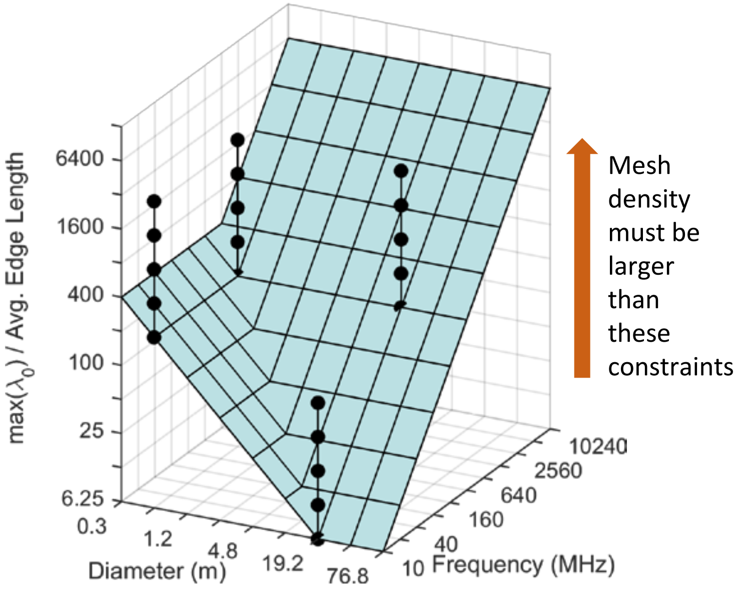
- Organize benchmark suite into 3 sweeps
  - Two types of constraints on mesh density:
    - Wavelength dictated
    - Geometry size dictated
  - Proposed sweep 1: Fix frequency, fix diameter
    - Simulate many error levels (proxy. mesh density)
    - Plot error vs. cost





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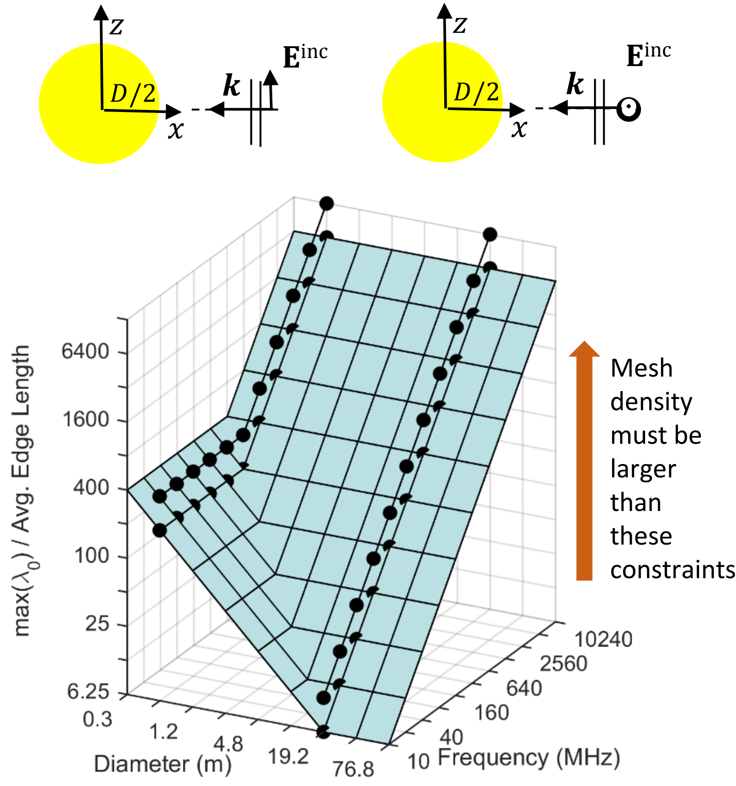
    6. Lower cost (e.g., shorter wall-clock time, less memory, higher parallel efficiency)
  - Others: Qualitatively improved simulation (more portable, easy to maintain/upgrade, user friendly, …)
- ❑ Organize benchmark suite into 3 sweeps
  - Two types of constraints on mesh density:
    - Wavelength dictated
    - Geometry size dictated
  - Proposed sweep 2: Fix diameter, fix error level (proxy: mesh density)
    - Simulate many frequencies
    - Plot error vs. cost



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- Organize benchmark suite into 3 sweeps
  - Two types of constraints on mesh density:
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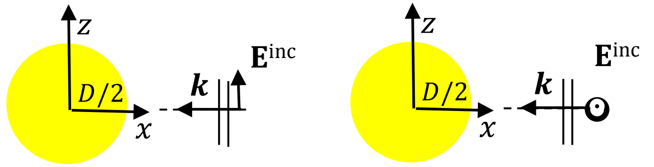
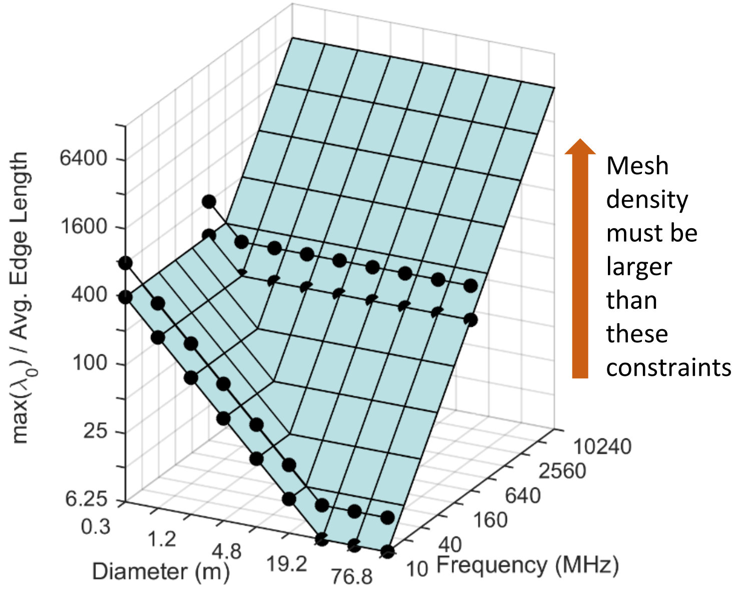
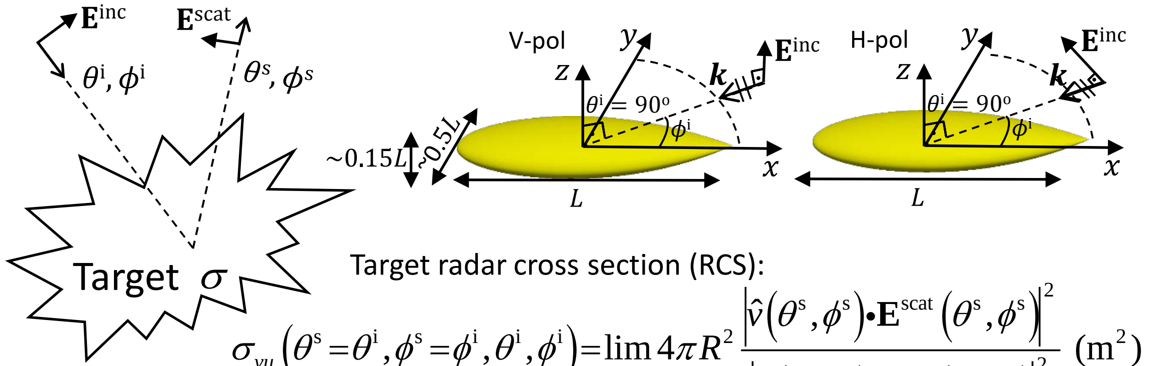
    - Geometry size dictated
  - Proposed sweep 3: Fix frequency, fix error level (proxy: mesh density)
    - Simulate many diameters
    - Plot error vs. cost





Problem III-A: PEC Almonds



Target radar cross section (RCS):

$$\sigma_{vu}\left(\theta^{\text{s}}=\theta^{\text{i}},\phi^{\text{s}}=\phi^{\text{i}},\theta^{\text{i}},\phi^{\text{i}}\right)=\lim_{R\to\infty}4\pi R^{2}\frac{\left|\hat{v}\left(\theta^{\text{s}},\phi^{\text{s}}\right)\bullet\mathbf{E}^{\text{scat}}\left(\theta^{\text{s}},\phi^{\text{s}}\right)\right|^{2}}{\left|\hat{u}\left(\theta^{\text{i}},\phi^{\text{i}}\right)\bullet\mathbf{E}^{\text{inc}}\left(\theta^{\text{i}},\phi^{\text{i}}\right)\right|^{2}}\ (\text{m}^{2})$$

$$\sigma_{vu,\text{dB}}\left(\theta^{\text{s}}=\theta^{\text{i}},\phi^{\text{s}}=\phi^{\text{i}},\theta^{\text{i}},\phi^{\text{i}}\right)=10\log_{10}\sigma_{vu}\ (\text{dB})$$

❑ Key ingredients for benchmark suites [1]

- Application-specific list of scattering problems
- Precisely defined quantities of interest
  1. (*For problem III-A*) Mono-static RCS (emulating measurement)
  2. Set $\theta^{\text{i}} = 90^{\text{o}}$. Vary $0^{\text{o}} \le \phi^{\text{i}} \le 180^{\text{o}}$.
  3. Compute back-scattered $\sigma_{\theta\theta}, \sigma_{\phi\phi}$ at N_{ϕ} directions
- Performance measures
  - Error measure:

$$avg.err_{uu,\text{dB}}^{TH}=\frac{1}{2\pi}\int_{0}^{\pi/2}\left|err_{uu,\text{dB}}^{TH}\left(\phi^{\text{s}}\right)\right|d\phi^{\text{s}}\approx\frac{\sum_{n=1}^{N_{\phi}}\left|err_{uu,\text{dB}}^{TH}\left(\phi^{\text{s}}\right)\right|}{N_{\phi}}(\text{dB})\qquad u\in\{\theta,\phi\}$$

$$err_{uu,\text{dB}}^{TH}=\sigma_{uu,\text{dB}}^{TH}-\sigma_{uu,\text{dB}}^{\text{ref},TH}\quad(\text{dB})$$

$$TH_{\text{dB}}=\max_{\phi^{\text{i}}}\sigma_{uu,\text{dB}}^{\text{ref}}-80\ (\text{dB})$$

Reference: Best simulation data

  - Cost measure:

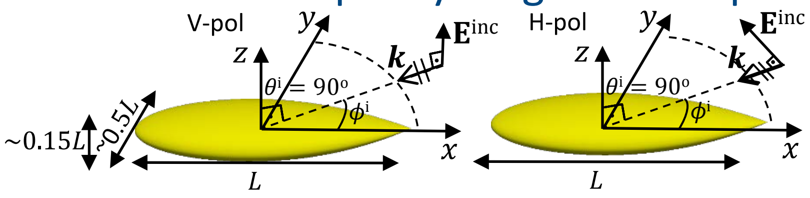
- Observed wall-clock time ($t_{\text{main}}^{\text{wall}}$) & peak memory/core ($mem_{\text{main}}^{\text{maxcore}}$)
- N_{proc}: Number of processes used (and eventually, type of them)
- Report at least 2 runs: “Efficient” (small N_{proc}), “Fast” (large N_{proc})
- Calculate “serialized” CPU Time ($t_{\text{main}}^{\text{total}} = N_{\text{proc}} \times t_{\text{main}}^{\text{wall}}$), maximum memory ($mem_{\text{main}}^{\text{max}} = N_{\text{proc}} \times mem_{\text{main}}^{\text{maxcore}}$)

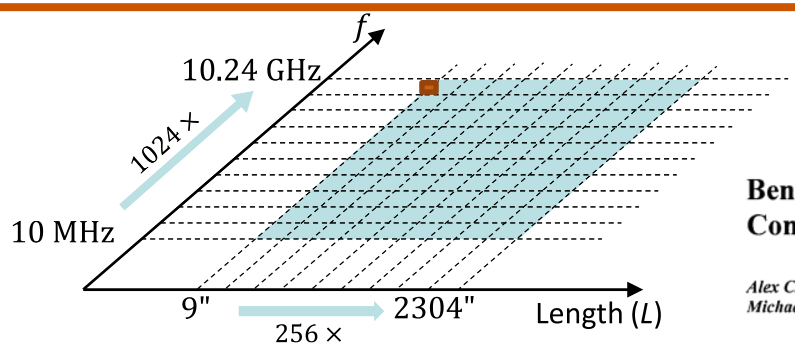
- Online databases

[1] J. W. Massey, C. Liu, and A. E. Yilmaz, “Benchmarking to close the credibility gap: a computational BioEM benchmark suite,” in *Proc. URSI EMTS*, Aug. 2016.

Problem III-A: PEC Almonds

- Dimensions 3-4: Specify lengths & frequency





Measurement reference available [1]
7 GHz (extra frequency)
$L = 9.936''$

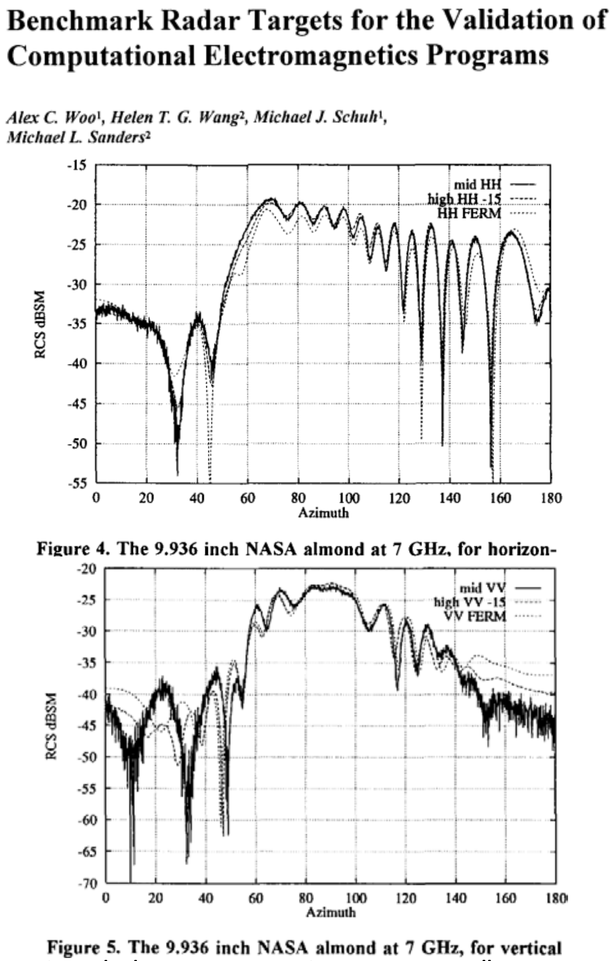

Benchmark Radar Targets for the Validation of Computational Electromagnetics Programs

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Figure 4. The 9.936 inch NASA almond at 7 GHz, for horizon-

Figure 5. The 9.936 inch NASA almond at 7 GHz, for vertical

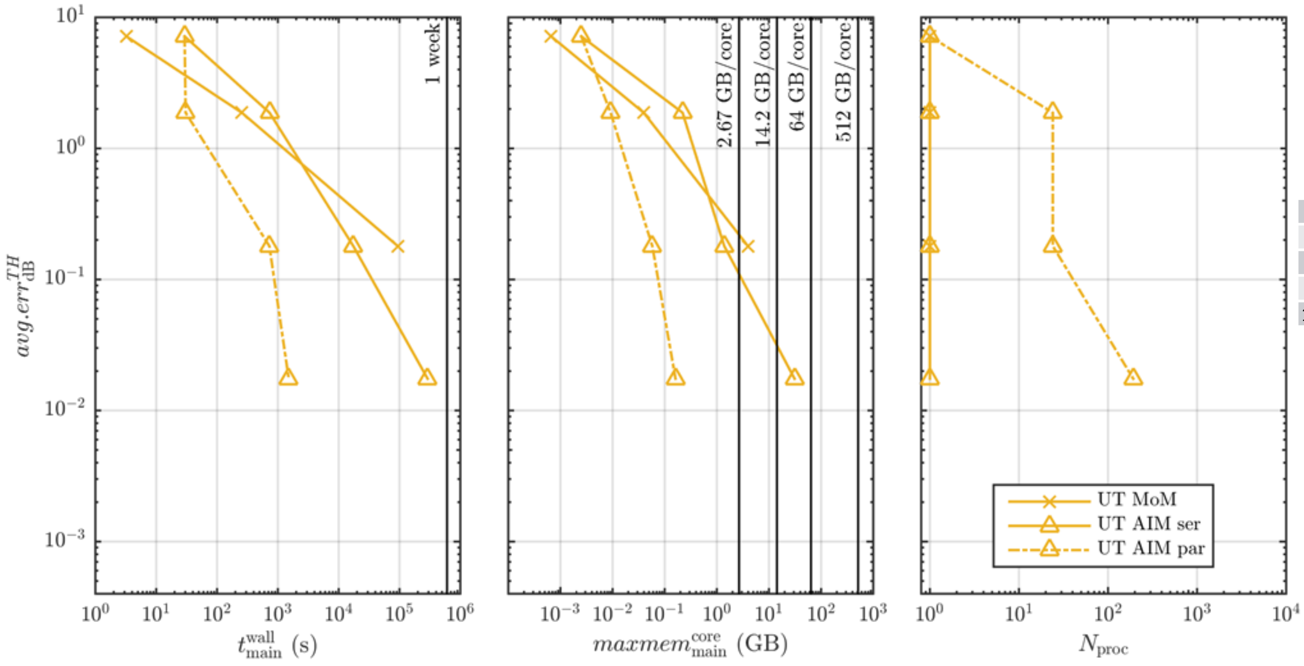
  - Proposed: Sample logarithmically: 9×11 = 99 cases
    + 1 case to validate with measurement
  - (*For this problem*) All cases with same L/λ_0 are identical: 19+1 unique cases
  - $0.0076 \le L/\lambda_0 \le 1998$
- Dimensions 5-6: Quantify error, cost, error-cost tradeoff for different simulators
  - Exhaustive Study: Fix frequency, fix length-> 100 (20) cases
    Simulate many error levels (proxy: mesh density) -> 3-5 mesh densities
    For each simulation, measure error & cost -> Plot error vs. cost

[1] A. C. Woo, H. T. G. Wang, M. J. Schuh and M. L. Sanders, "EM programmer's notebook-benchmark radar targets for the validation of computational electromagnetics programs," in *IEEE Ant. Propag. Mag.*, vol. 35, no. 1, pp. 84-89, Feb. 1993.

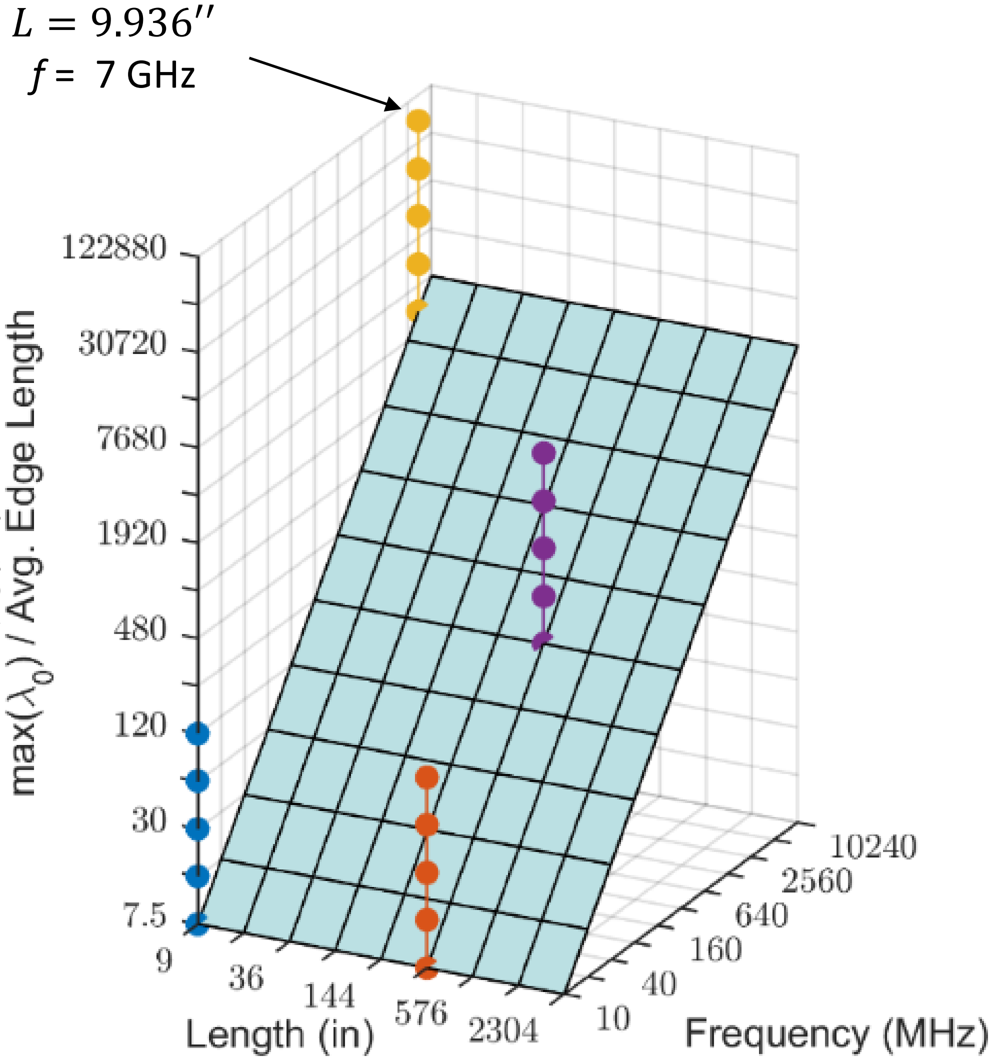
Problem III-A: PEC Almonds

- Dimensions 5-6: Quantify error & cost
  - Sweep 1: Fix frequency, fix dimensions
    Simulate many error levels (proxy: mesh densities)
    Measure error & cost -> Plot error vs. cost

vs. Wall-Clock Time | vs. Memory/Core | vs. # Processes



N
198
1533
16 158
151 119
1 495 911



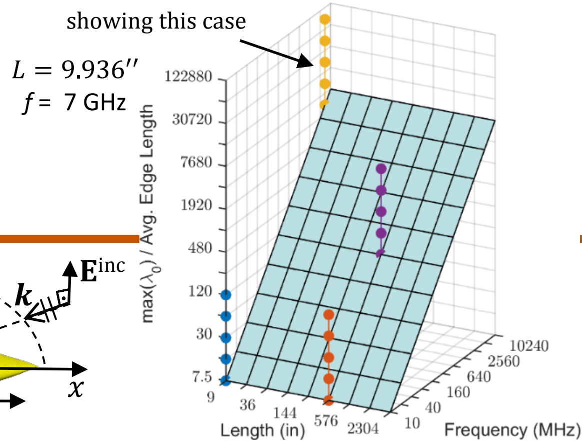
Error definition:

$$avg.err^{TH}_{uu,\mathrm{dB}} = \frac{1}{2\pi}\int_0^{2\pi}\left|err^{TH}_{uu,\mathrm{dB}}\left(\phi^s\right)\right| d\phi^s \approx \frac{\sum_{n=1}^{N_\phi}\left|err^{TH}_{uu,\mathrm{dB}}\left(\phi^s\right)\right|}{N_\phi} \text{(dB)}$$

$$err^{TH}_{uu,\mathrm{dB}} = \max(\sigma_{vu,\mathrm{dB}}, TH_{\mathrm{dB}}) - \max(\sigma^{\mathrm{ref}}_{vu,\mathrm{dB}}, TH_{\mathrm{dB}}) \quad \text{(dB)}$$

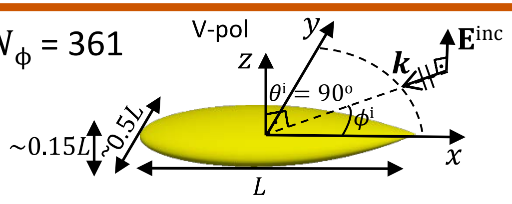
$$TH_{\mathrm{dB}} = \max_{\phi^s} \sigma^{\mathrm{ref}}_{uu,\mathrm{dB}} - 80 \text{ (dB)}$$

Problem III-A: PEC Almonds



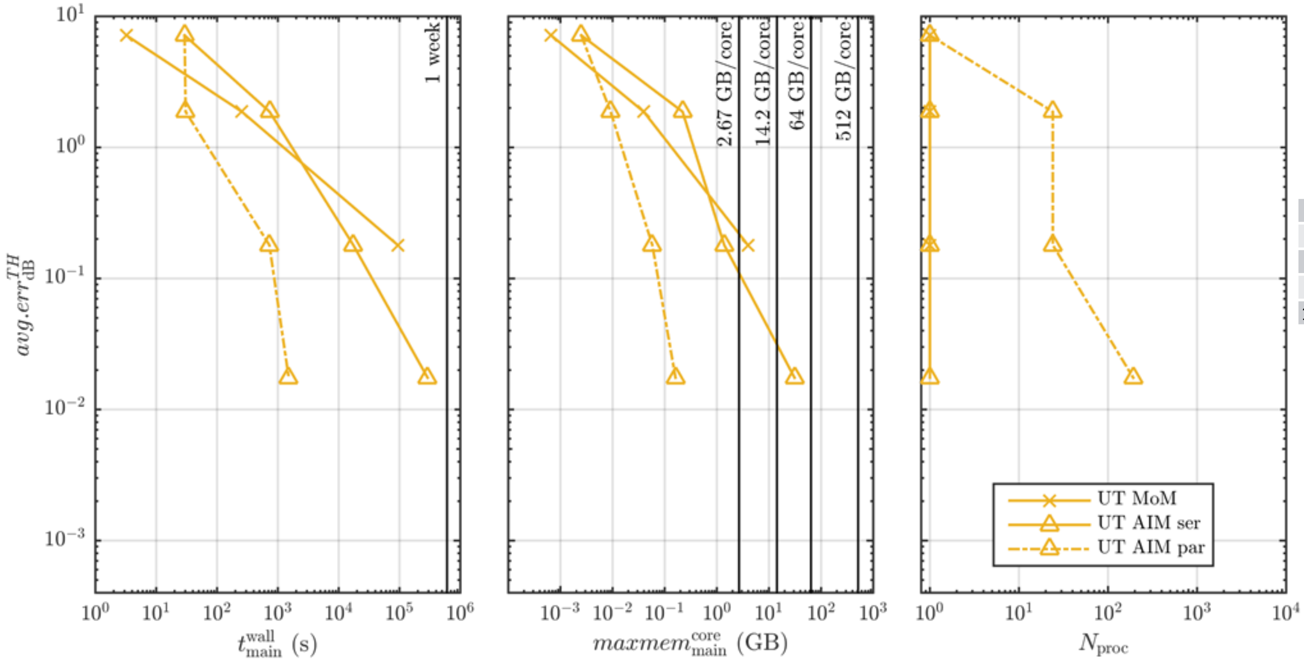
- Dimensions 5-6: Quantify error & cost
  - Sweep 1: Fix frequency, fix dimensions
    Simulate many error levels (proxy: mesh densities)
    Measure error & cost -> Plot error vs. cost

$0^{\circ} \leq \phi^{i} \leq 180^{\circ}$, N_{ϕ} = 361



$\theta^{i} = 90^{\circ}$, $\phi^{i} = 0^{\circ}$ case

vs. Wall-Clock Time | vs. Memory/Core | vs. # Processes



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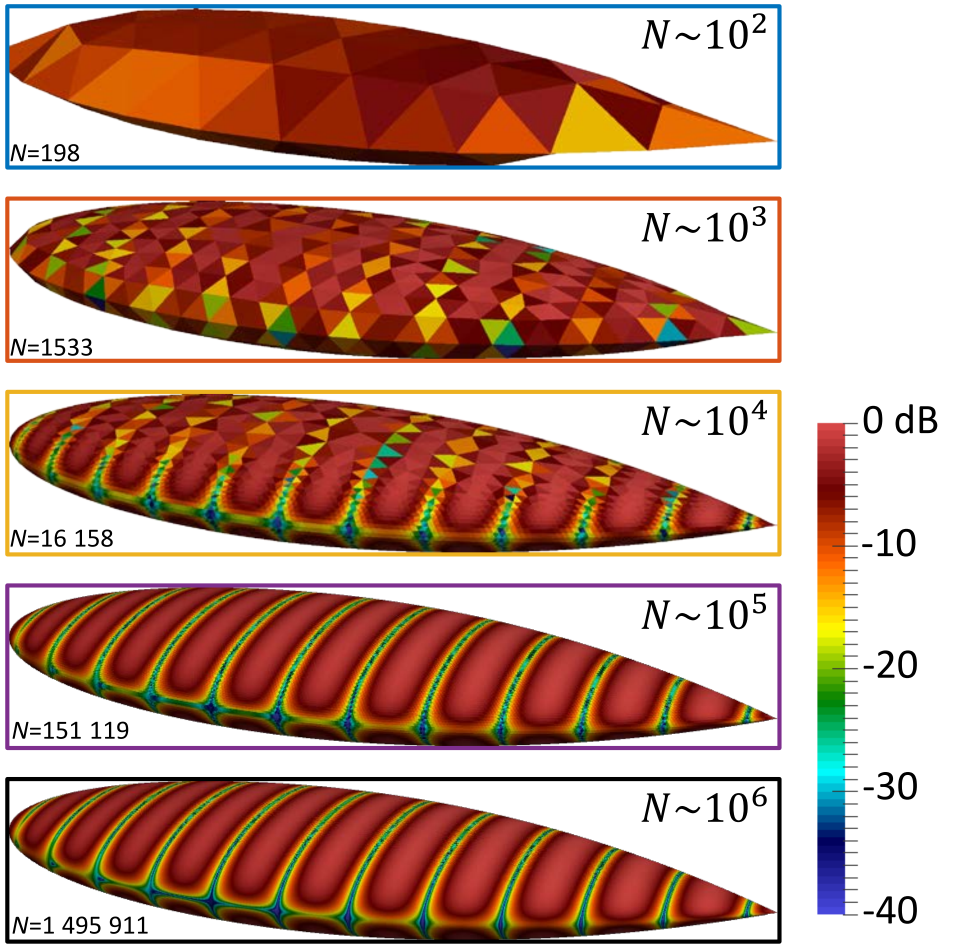

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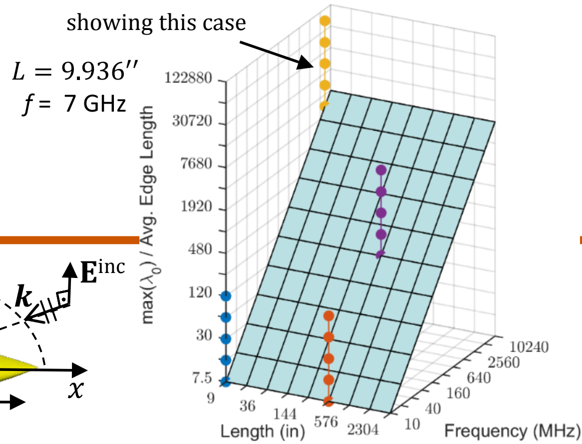
$$err^{TH}_{uu,\mathrm{dB}} = \max(\sigma_{vu,\mathrm{dB}}, TH_{\mathrm{dB}}) - \max(\sigma^{\mathrm{ref}}_{vu,\mathrm{dB}}, TH_{\mathrm{dB}}) \text{ (dB)}$$

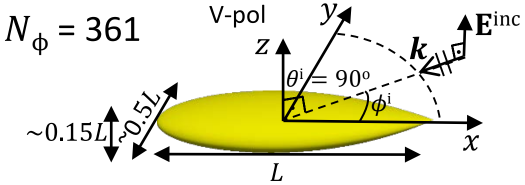
$$TH_{\mathrm{dB}} = \max_{\phi^{s}} \sigma^{\mathrm{ref}}_{uu,\mathrm{dB}} - 80 \text{ (dB)}$$

Problem III-A: PEC Almonds

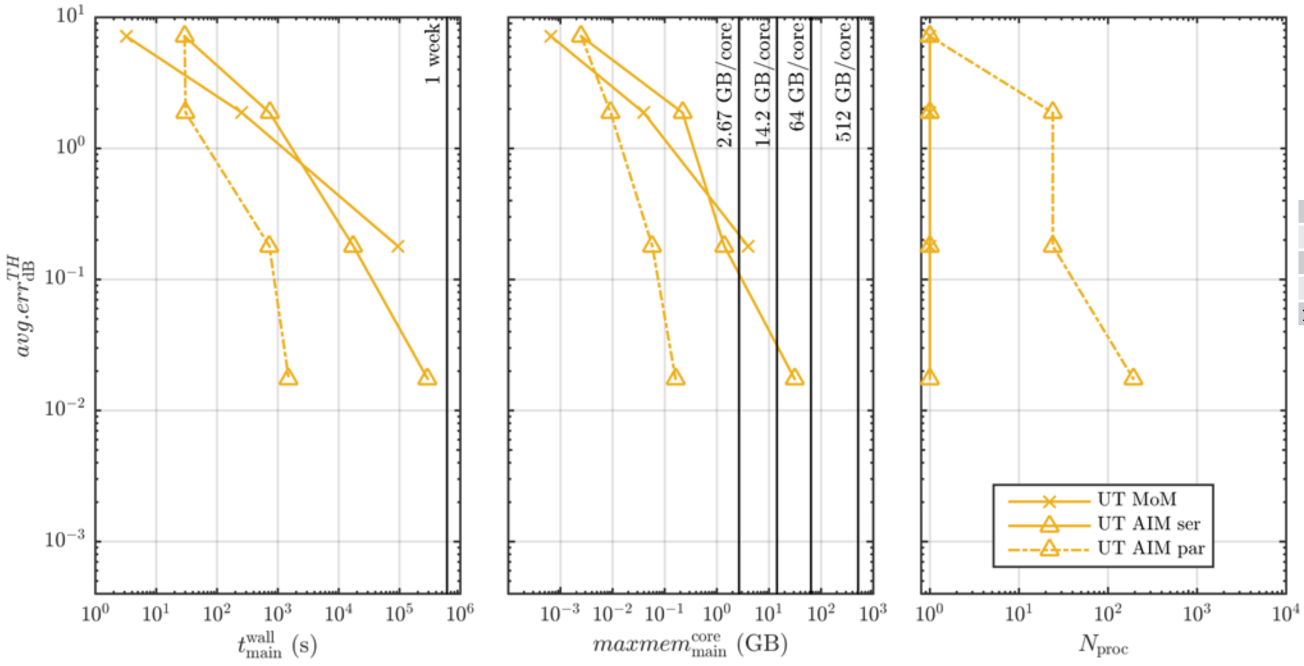


- Dimensions 5-6: Quantify error & cost
  - Sweep 1: Fix frequency, fix dimensions
    Simulate many error levels (proxy: mesh densities)
    Measure error & cost -> Plot error vs. cost

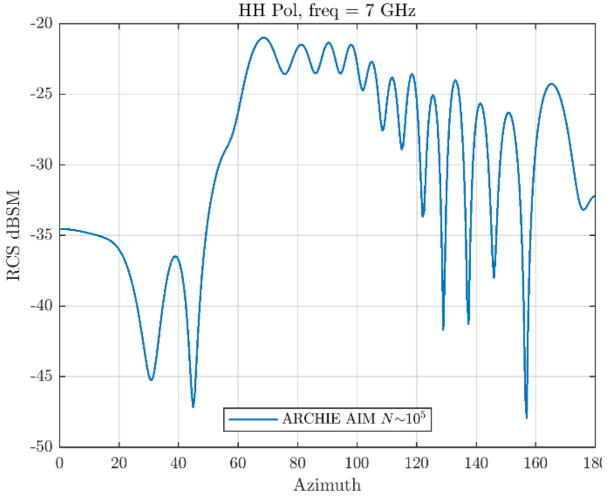
$0^{\circ} \le \phi^{i} \le 180^{\circ}$, $N_\phi = 361$



vs. Wall-Clock Time | vs. Memory/Core | vs. # Processes



N
198
1533
16 158
151 119
1 495 911



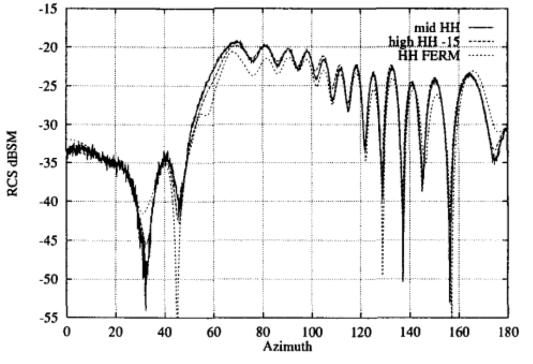
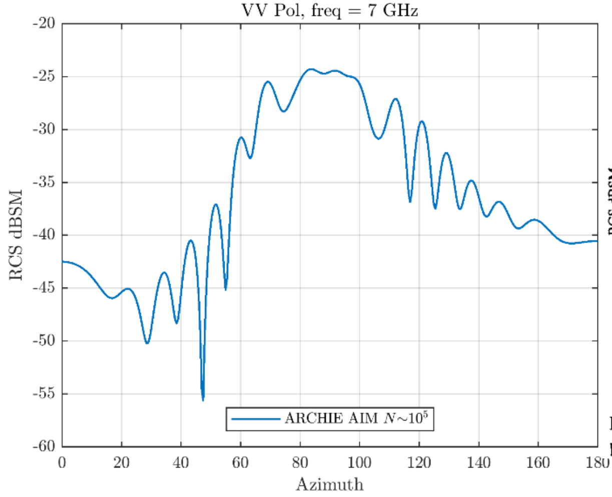


Figure 4. The 9.936 inch NASA almond at 7 GHz, for horizontal polarization: "mid-HH" and "high-HH" denote the measured cases (see the text), and "HH FERM" denotes the computed results.



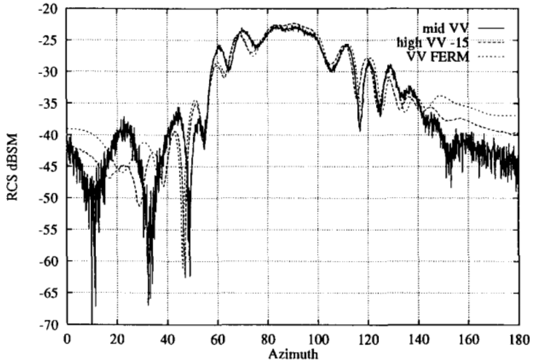


Figure 5. The 9.936 inch NASA almond at 7 GHz, for vertical polarization. The curves are labeled the same as in Figure 4.

Error definition:

$$avg.err^{TH}_{uu,\text{dB}} = \frac{1}{2\pi}\int_0^{2\pi}\left|err^{TH}_{uu,\text{dB}}\left(\phi^{s}\right)\right| d\phi^{s} \approx \frac{\sum_{n=1}^{N_\phi}\left|err^{TH}_{uu,\text{dB}}\left(\phi^{s}\right)\right|}{N_\phi} \text{ (dB)}$$

$$err^{TH}_{uu,\text{dB}} = \max(\sigma_{vu,\text{dB}}, TH_{\text{dB}}) - \max(\sigma^{\text{ref}}_{vu,\text{dB}}, TH_{\text{dB}}) \text{ (dB)}$$

$$TH_{\text{dB}} = \max_{\phi^{s}} \sigma^{\text{ref}}_{uu,\text{dB}} - 80 \text{ (dB)}$$

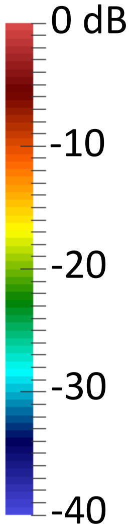
Problem III-A: PEC Almonds

- **New measurement results**
  - State of the art measurement facility

    Obtain accurate measurement results for all Austin-RCS-Benchmarks going forward
  - Comparison of measured and computed results to reference results in [1]
  - Additional reference data

    Measurement data that corresponds to frequencies defined in the Austin-RCS-Benchmark Suite
  - Facilitate comparison

    Public access to both measurement RCS plots and data files



N = 16 455 054 L = 423’ 11” f = 320 MHz

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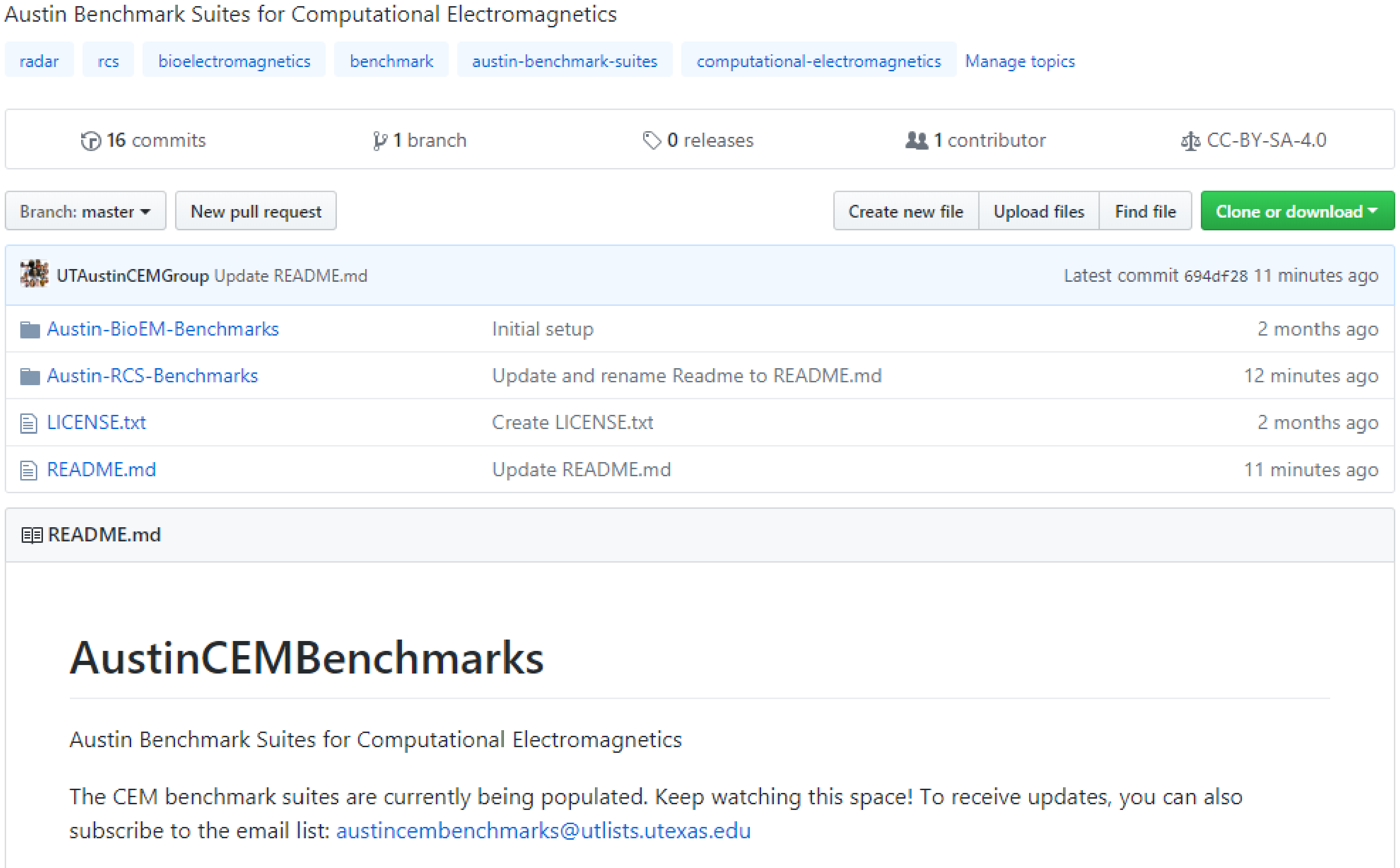
Benchmarking Database

- **Features Available**
  - Problem Description
  - Reference Data
  - Simulation Data



Website:
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Benchmarking Database

Features Available

- **Problem Description**
  Precisely defines the model and quantities of interest
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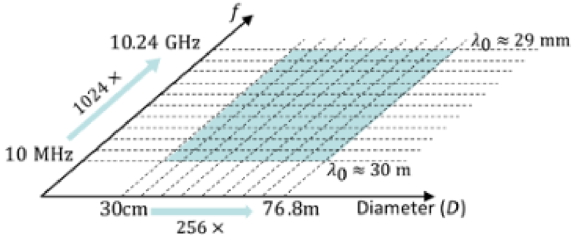
Problem IA-PEC Spheres — Austin RCS Benchmark Suite

Description of Scattering Object
A perfect electrically conducting (PEC) sphere of radius $D/2$.

Length Scale and Frequency Range



The problems of interest cover a range of 256x in physical length scale and 1024x in frequency that are logarithmically sampled to yield 99 scattering problems. Because the sphere is PEC, there are only 19 unique scattering problems in Problem IA. In these problems, the sphere sizes are in the range $0.01 \leq D/\lambda_0 \leq 2624$, where λ_0 is the free-space wavelength.

Interesting Features
1. Highly accurate, Mie-series analytical solutions are available for Problem IA.
2. Bi-static rather than mono-static RCS is the quantity of interest.

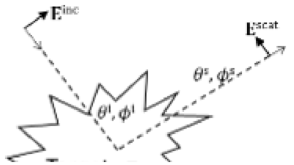
Quantities of Interest
Radar cross section (RCS) definition

$$\sigma_{vu}(\theta^s,\phi^s,\theta^i,\phi^i) = \lim_{R\to\infty} 4\pi R^2 \frac{\left|\hat{v}(\theta^s,\phi^s)\cdot\mathbf{E}^{scat}(\theta^s,\phi^s)\right|^2}{\left|\hat{u}(\theta^i,\phi^i)\cdot\mathbf{E}^{inc}(\theta^i,\phi^i)\right|^2} \quad : \text{RCS } (\text{m}^2)$$

$$\sigma_{vu,dB}(\theta^s,\phi^s,\theta^i,\phi^i) = 10\log_{10}\sigma_{vu} \quad : \text{RCS in dB (dBsm)}$$

$$\sigma^{TH}_{vu,dB}(\theta^s,\phi^s,\theta^i,\phi^i) = \max(\sigma_{vu,dB}, TH_{dB}) - TH_{vu,dB} \quad : \text{Thresholded RCS}$$

1. Set $\theta^i = 90°, \phi^i = 90°, \theta^s = 90°$. Vary $0° \leq \phi^s \leq 360°$.
2. Compute both $\sigma_{\theta\theta,dB}$ and $\sigma_{\phi\phi,dB}$ (the VV and HH-RCS in dB)



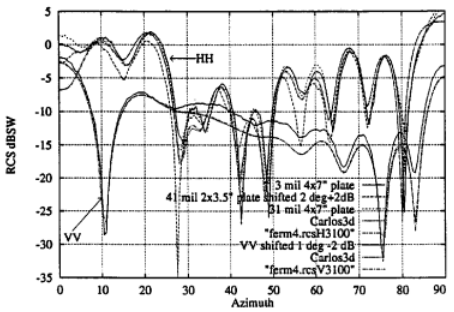
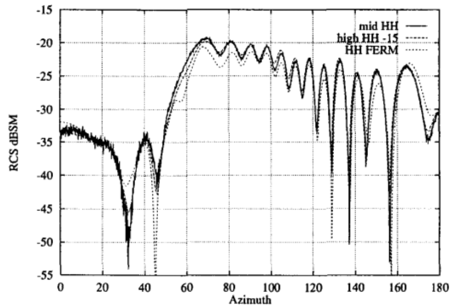


Figure 11. The RCS, in dB λ^2, plotted against the azimuthal angle, in a 10°-elevation conical cut, for the Case 4 flat plate of dimensions 4"×7". Results for plates with thicknesses of 3 mils, 31 mils, and 41 mils are included. Normal incidence to the 2λ-long short edge is 0°.



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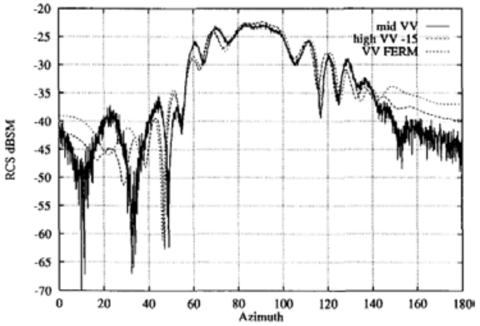

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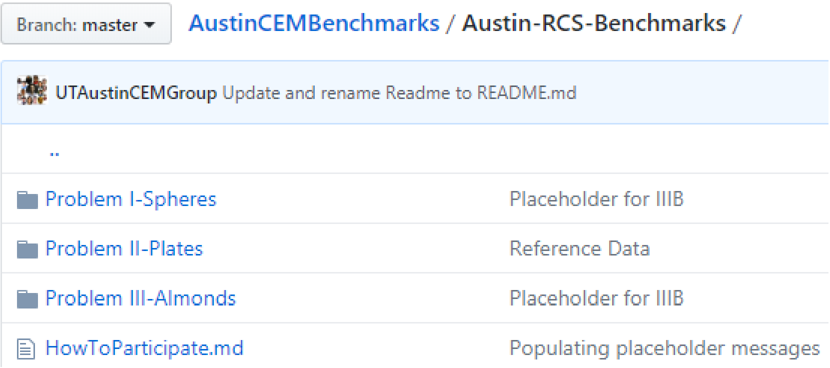
- **Reference Data**
  Measurement or analytical reference results
- **Simulation Data**
  Sample results for benchmark problems produced at UT Austin



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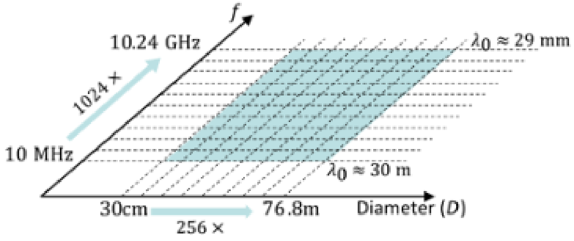

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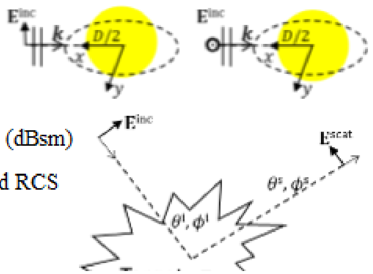

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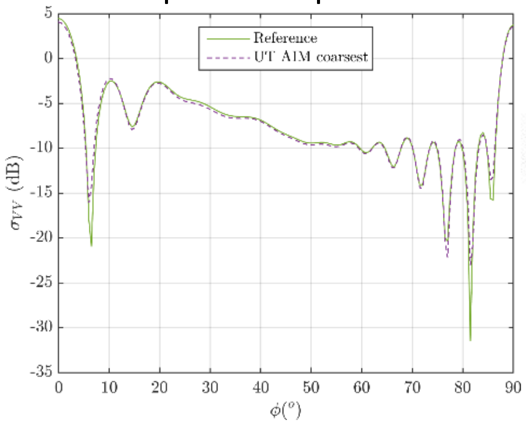

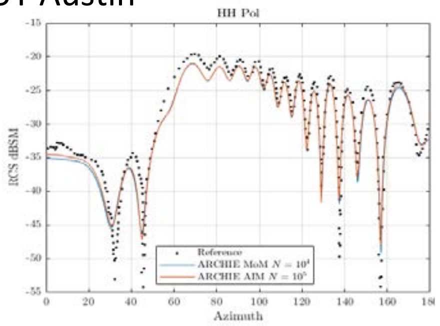

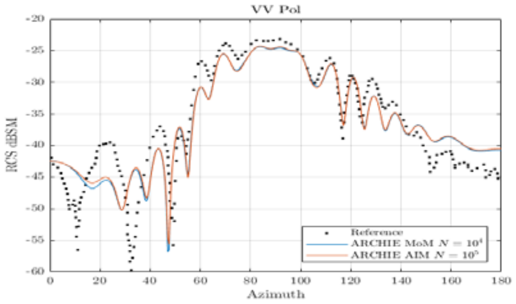

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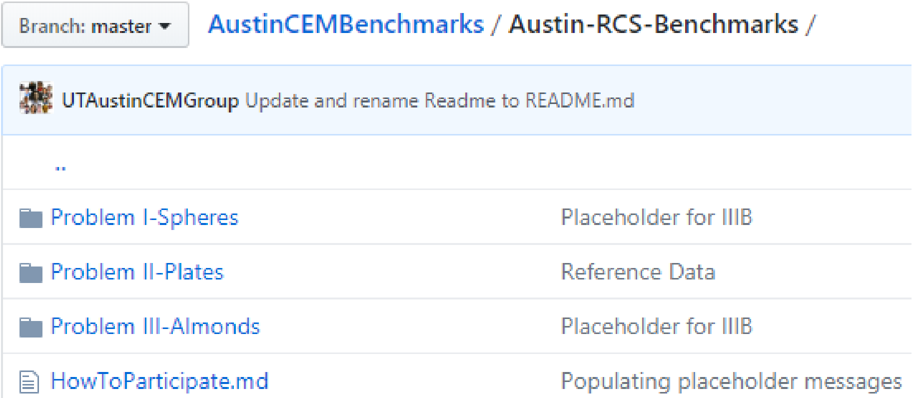
Conclusions

- CEM R&D needs modern benchmarks and benchmarking
  - Rapidly fragmenting computing landscape in post-Moore's law era
  - Non-testable claims
  - Empirical results make theoretical science better
  - Benchmark suites encourage and support R & D
- Rich history of "proto-benchmarks"
  - Many problems, methods, and data in journal and conference publications
  - Most are non-replicable
  - Most not precise enough for quantitative benchmarking
- Modern computing infrastructure enables "quantitative benchmarking"
  - Easy to share data—Internet repositories
  - High precision possible—Plots vs. numbers
  - Full replicability possible—Version control tools
- Austin RCS Benchmark Suite
  - Publicly available
  - Being populated with problems spanning difficulty levels
  - Contains reference solutions—including new measurement data
  - Also contains quantitative performance data



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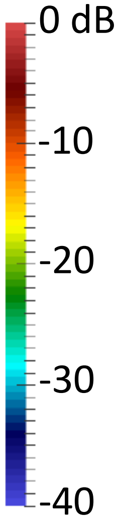

- Acknowledgment

TEXAS ADVANCED COMPUTING CENTER