Austin RCS Benchmark Suite Developments

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Atlanta, GA, July 9, 2019 2019 USNC-URSI Radio Science Meeting

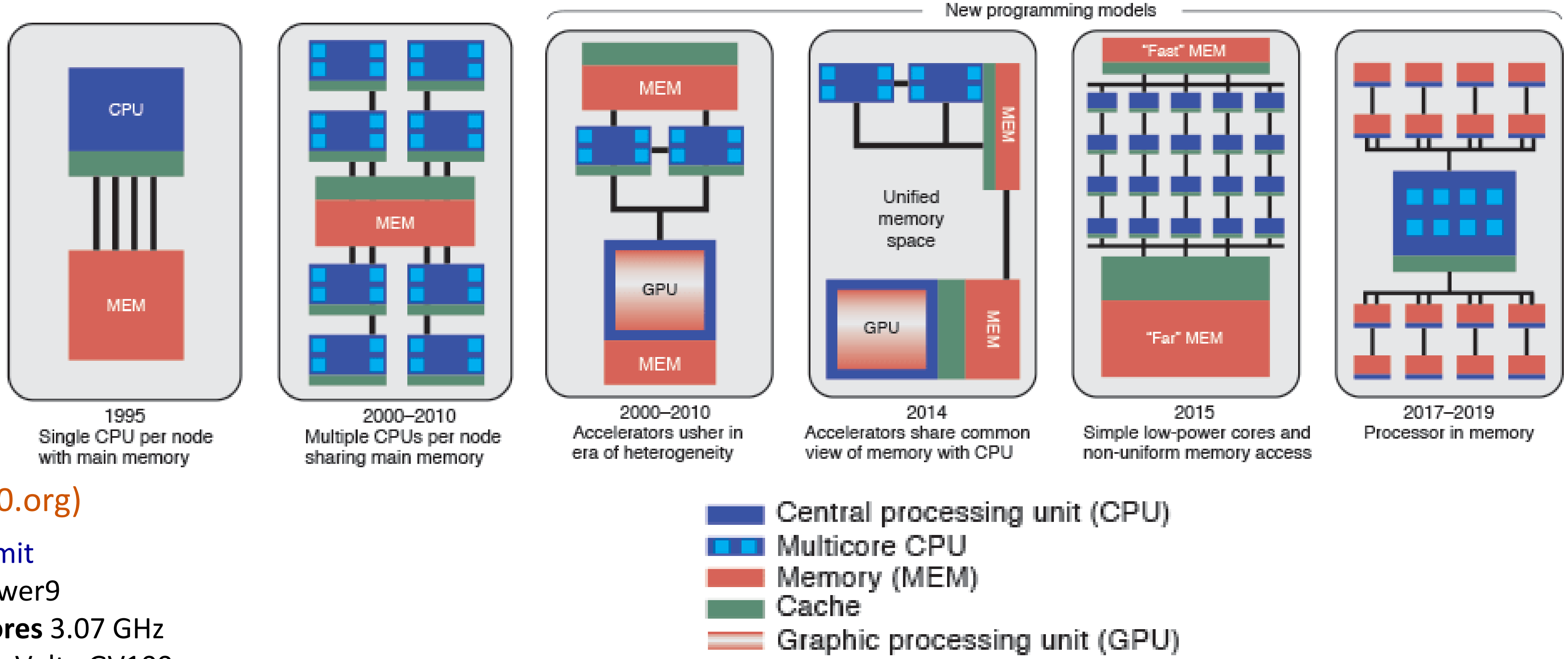
Outline

- 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
  - Recommended performance studies
  - Special case
- Conclusion

Motivation

- Modern Computers

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



- June 2019 Rankings (top500.org)

1. Summit
IBM Power9
2x22 cores 3.07 GHz
+ Nvidia Volta GV100
2.28M+ cores
~200.8 Pflop/s

2. Sierra
IBM Power9
2x22 cores 3.1 GHz
+ Nvidia Volta GV100
1.57M+ cores
~125.7 Pflop/s

5. Frontera
Intel Xeon Platinum 8280
56x28 cores 2.7 GHz
0.448M cores
~38.7 Pflop/s

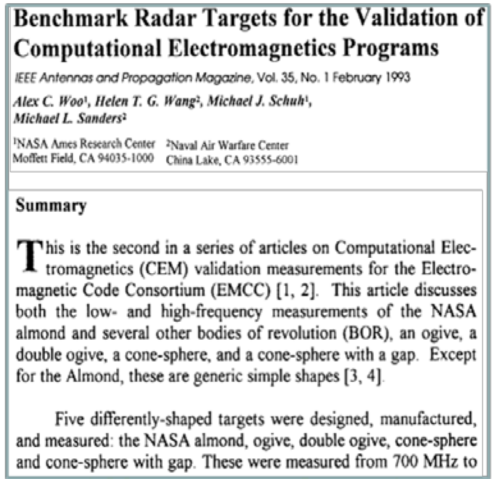
19. Stampede 2
Intel Xeon Phi 7250
68x4 cores 1.4 GHz
0.369M cores
~18.3 Pflop/s

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.

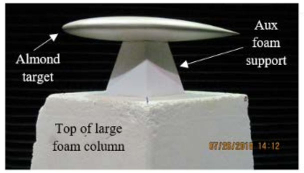
- Numerical benchmarks (with error vs. cost trade-off) underutilized in CEM [1]
- Next-generation benchmarks can
  - inform public and researchers in the field about state of the art
  - reveal performance of new algorithms, software, and hardware

[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]

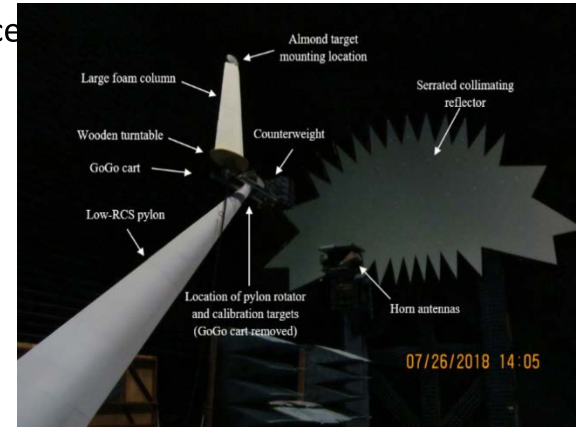
- Application-specific list of scattering problems
  1. Span different difficulty levels
  2. Emphasize/exercise features of computational system relevant to application
  3. General enough to represent different types of problems encountered
  4. Problem set should evolve
- Precisely defined quantities of interest
  1. Reliable analytical references whenever possible
  2. Must obtain/use (much) more accurate reference
- Performance measures
- Online databases

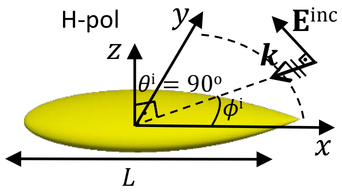


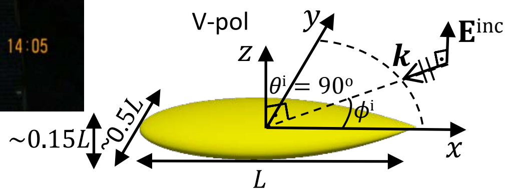
Measurement reference available [2]

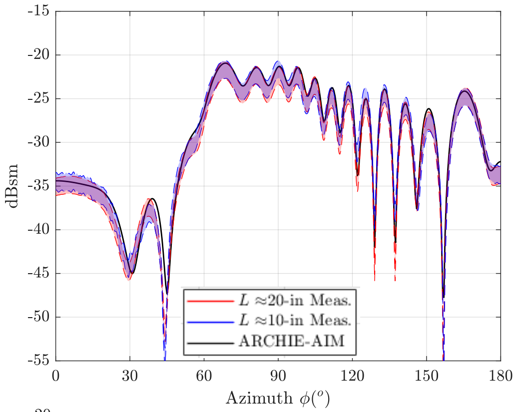
Rye Canyon RCS Measurements of Benchmark Almond Targets

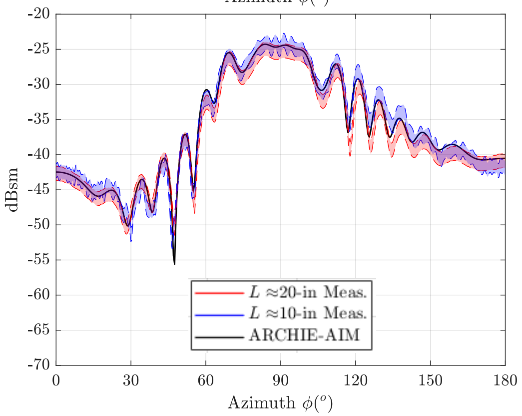
Jon T. Kelley, David A. Chamulak, Clifton C. Courtney, Ali E. Yilmaz











[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.

[2] J. T. Kelley, D. A. Chamulak, C. C. Courtney, and A. E. Yılmaz, “EM programmers notebook-Rye Canyon RCS measurements of benchmark almond targets” in *IEEE Ant. Popag. Soc. Mag.*, 2019.

Designing Modern CEM Benchmark Suites

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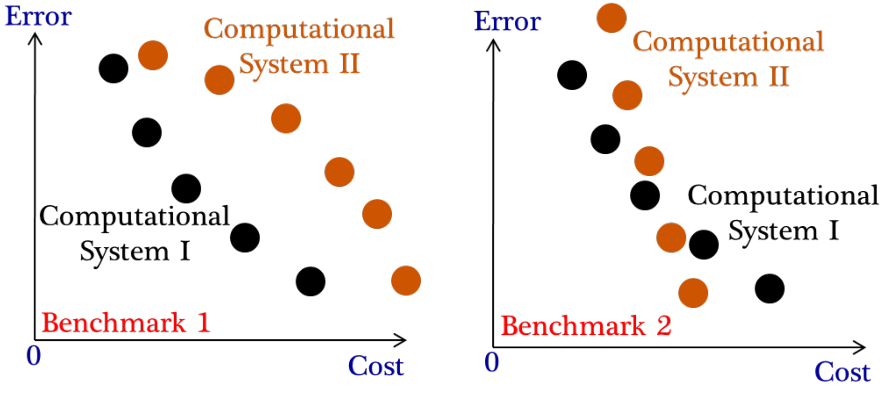
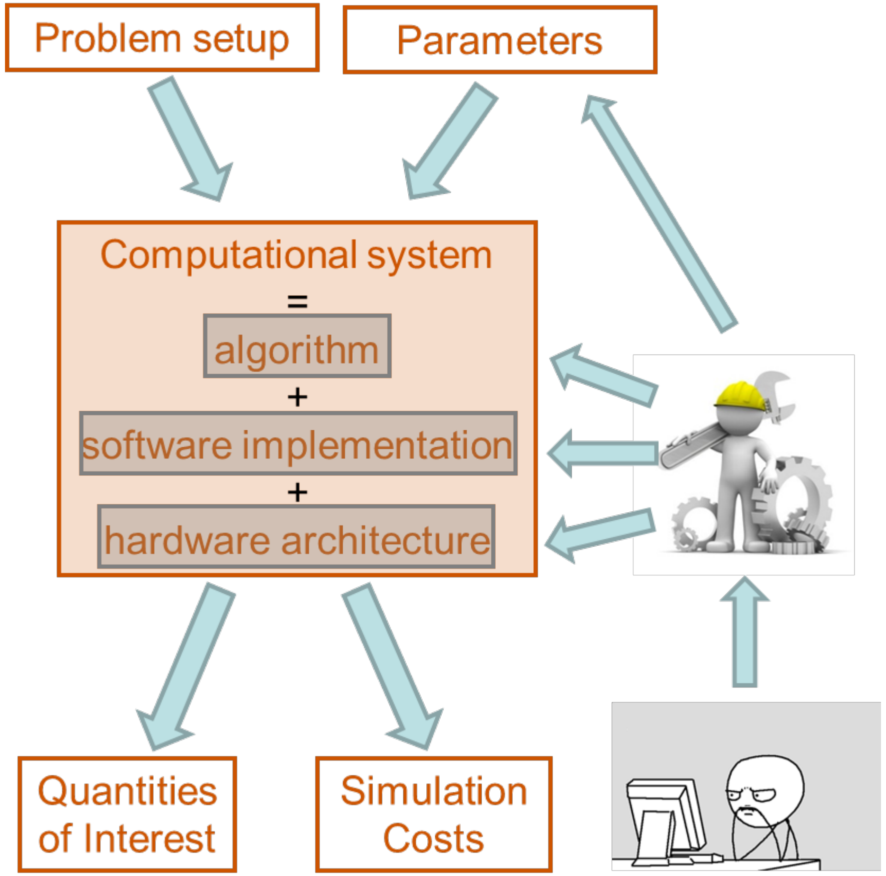
    4. Problem set should evolve
  - Precisely defined quantities of interest
    1. Reliable analytical references whenever possible
    2. Must obtain/use (much) more accurate reference results
  - Performance measures
    1. Error and computational cost measures
    2. Also quantify computational power available to simulation and normalize costs across platforms
  - Online databases

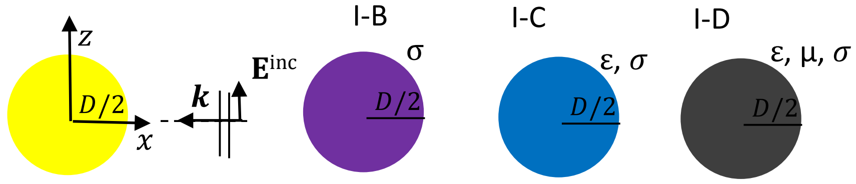


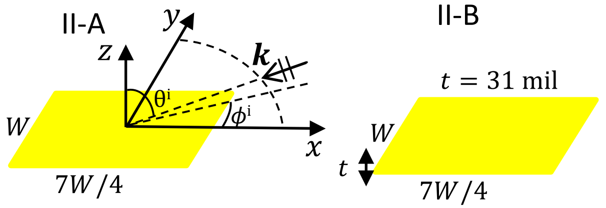


[1] J. W. Massey, C. Liu, and A. E. Yilmaz, "Benchmarking to close the credibility gap: a computational BioEM benchmark suite," in *Proc. URSI EMTS*, Aug. 2016.

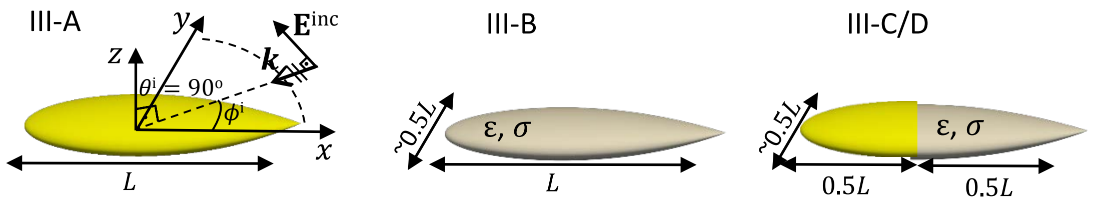
Organizing the Many Dimensions

- 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



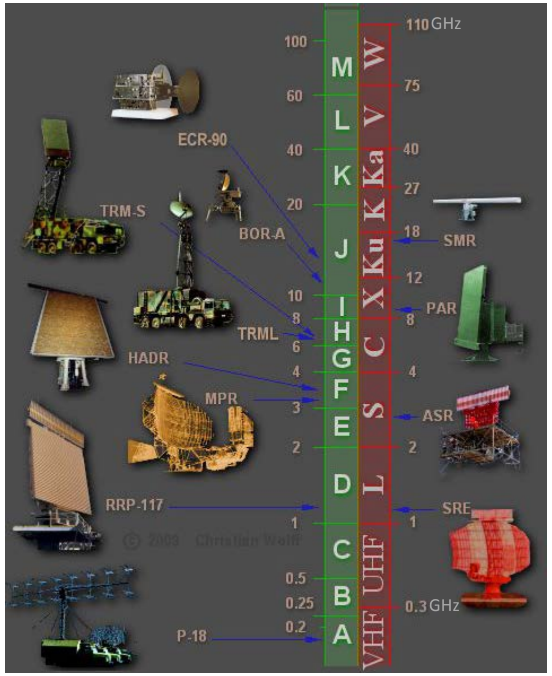
- Problem I: Spheres
  - I-A: PEC spheres
  - I-B: Semiconductor spheres
  - I-C: Water spheres
  - I-D: Magneto-dielectric spheres

Problem II: Plates
- II-A: Zero-thickness PEC plates
- II-B: Thin PEC plates

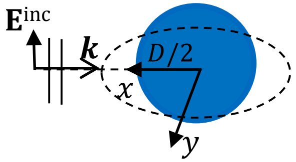
Problem III: Almonds
- III-A: PEC almonds
- III-B: Resin almonds
- III-C/D: Half-Coated almonds

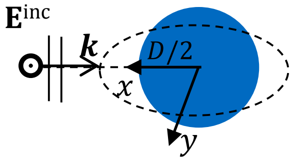
Problem I-C: Water Spheres

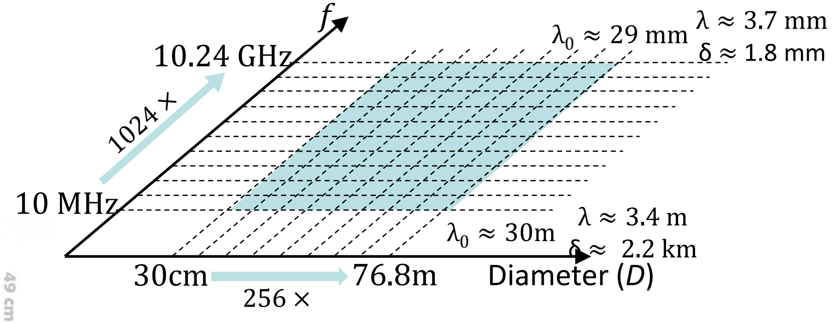
- Dimensions 3-4: Specify lengths & frequency



http://www.radartutorial.eu/07.waves/Waves%20and%20Frequency%20Ranges.en.html

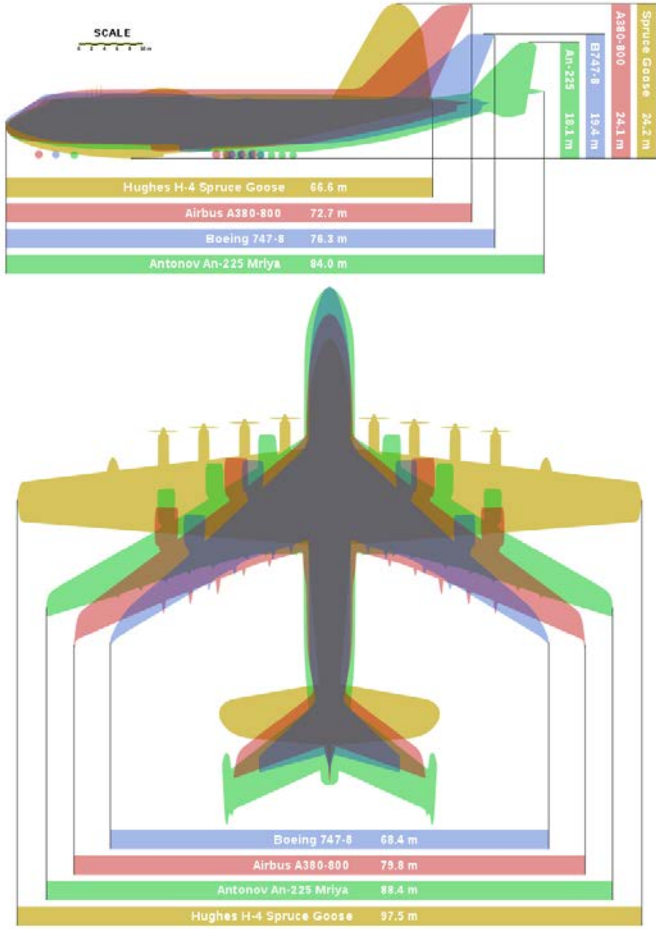






http://www.engabao.com/phantom-3-size-complete-measurements/

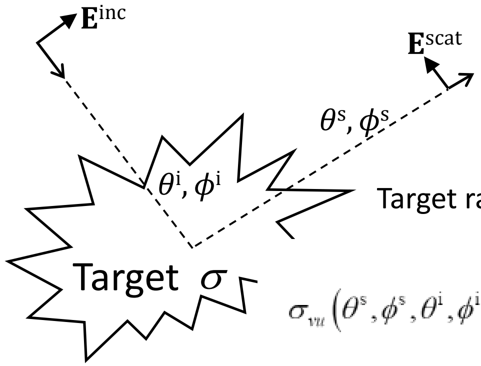
https://en.wikipedia.org/wiki/Airbus_A380#/media/File:Giant_planes_comparison_-_Updated.svg

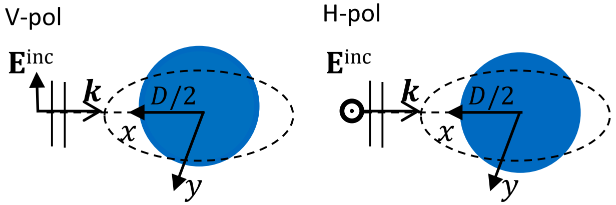


- Sample logarithmically: 9×11 = 99 cases
- All cases with same D/λ_0 are NOT identical
- $0.01 \leq D/\lambda_0 \leq 2624,\ 0.08 \leq D/\lambda \leq 20757$

Problem I-C: Water Spheres

Key ingredients for benchmark suites [1]





Target radar cross section (RCS):

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

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

- Application-specific list of scattering problems
- Precisely defined quantities of interest
  1. Bi-static RCS
  2. Set $\theta^{\mathrm{i}} = 90^{\mathrm{o}}$, $\phi^{\mathrm{i}} = 0^{\mathrm{o}}$, $\theta^{\mathrm{s}} = 90^{\mathrm{o}}$. Vary $0^{\mathrm{o}} \le \phi^{\mathrm{s}} \le 360^{\mathrm{o}}$
  3. Compute $\sigma_{\theta\theta}$, $\sigma_{\phi\phi}$ at N_{ϕ} = 3601 scattered directions
- Performance measures
  - Error measure:

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

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

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

Reference: G. Kaur, “Comprehensive Program for Analytical Scattering Solutions for Electromagnetics (COMPASS-EM) v1.0,” May 2013.

  - Cost measure:

- Observed wall-clock times ($t_{\mathrm{main}}^{\mathrm{wall}} = t_{\mathrm{fix}}^{\mathrm{wall}} + t_{\mathrm{var}}^{\mathrm{wall}} + t_{\mathrm{post}}^{\mathrm{wall}}$) & peak memory/core ($mem_{\mathrm{main}}^{\mathrm{maxcore}}$)

- N_{proc}: Number of processes used (and eventually, type of them)

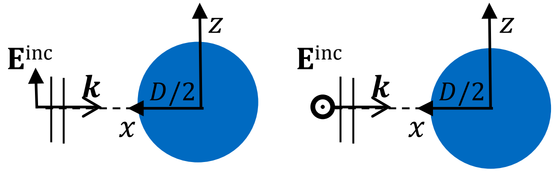
- Report at least 2 runs: “Efficient” (small N_{proc}), “Fast” (large N_{proc})

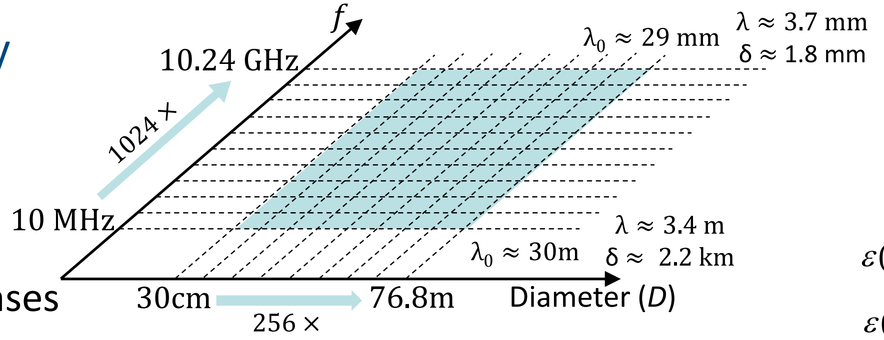
- Calculate “serialized” CPU Time ($t_{\mathrm{main}}^{\mathrm{total}} = N_{\mathrm{proc}} \times t_{\mathrm{main}}^{\mathrm{wall}}$), maximum memory ($mem_{\mathrm{main}}^{\mathrm{max}} = N_{\mathrm{proc}} \times mem_{\mathrm{main}}^{\mathrm{maxcore}}$)

[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 I-C: Water Spheres

- Dimensions 3-4: Specify lengths & frequency





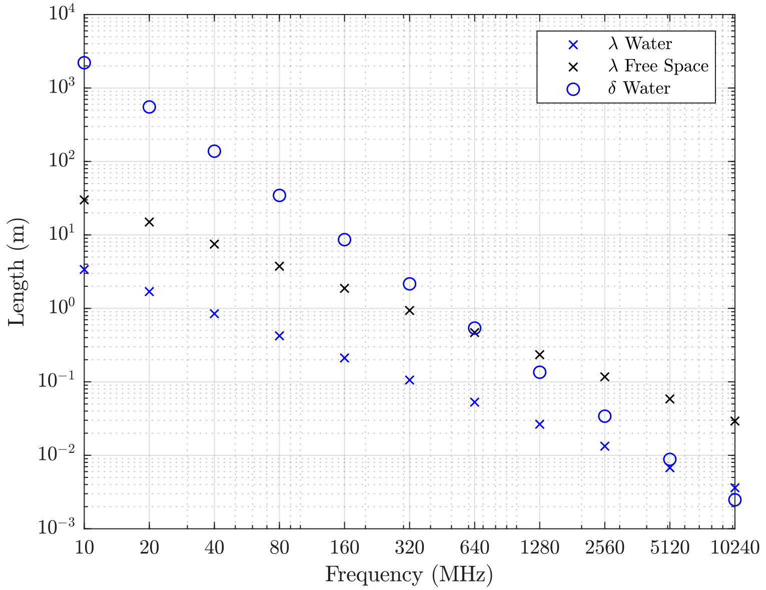
- Proposed: Sample logarithmically: 9×11 = 99 cases
- All cases with same D/λ_0 are NOT identical
- $0.01 \leq D/\lambda_0 \leq 2624$, bi-static RCS

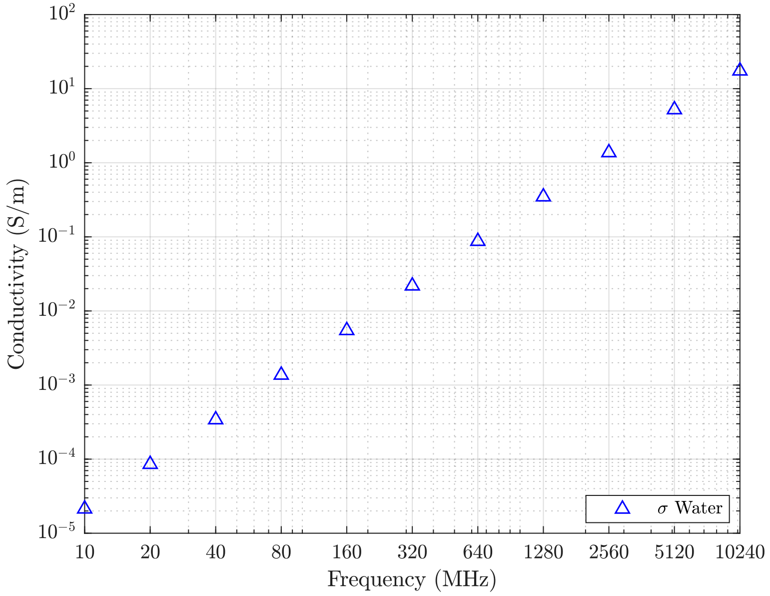
$$\varepsilon(\nu) = \varepsilon(\infty) + \frac{\varepsilon(0) - \varepsilon(\infty)}{1 + j\omega\tau}$$

$$\varepsilon(0) = 10^{(1.94404 - (1.991\times10^{-3})(T - 273.15))}$$

$$\varepsilon(\infty) = 5.77 - \left(2.74\times10^{-2}\right)\left(T - 273.15\right)$$

$$\tau = (3.745\times10^{-15})\times\left[1 + (7\times10^{-5})\times(T - 300.65)^2\right]\times e^{\frac{2.2957\times10^3}{T}}$$





Frequency (MHz)	ε′	ε″
10	78.44	-0.038
20	78.44	-0.077
40	78.44	-0.153
80	78.44	-0.306
160	78.44	-0.612
320	78.44	-1.225
640	78.36	-2.447
1280	78.12	-4.878
2560	77.16	-9.627
5120	73.56	-18.29
10240	62.15	-30.49

[1] U. Kaatze, "Complex permittivity of water as a function of frequency and temperature." *Journal of Chemical & Engineering Data*, vol. 34, no. 4, 1989, pp. 371–374., doi:10.1021/je00058a001.

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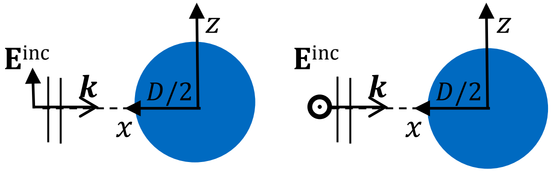
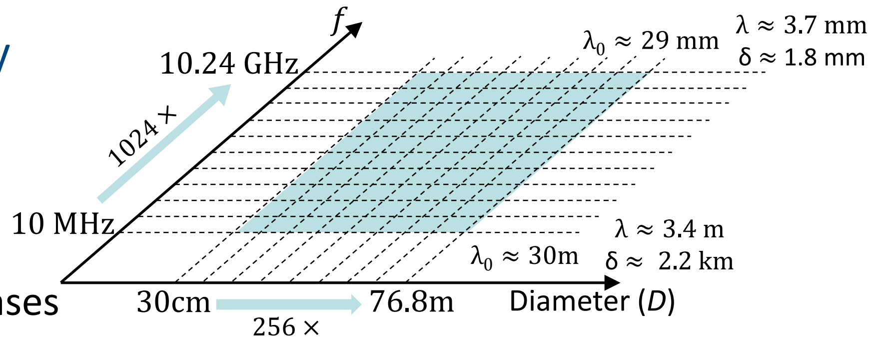
UT ECE

Problem I-C: Water Spheres

- Dimensions 3-4: Specify lengths & frequency





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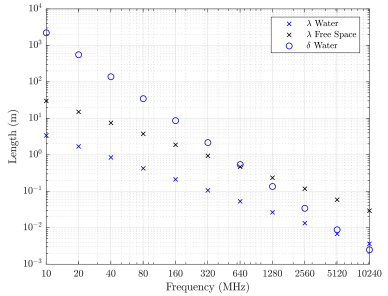
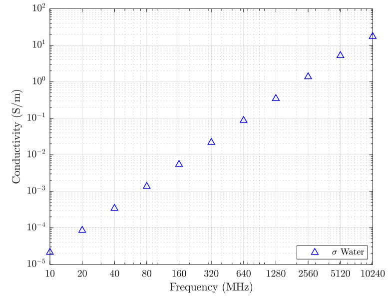
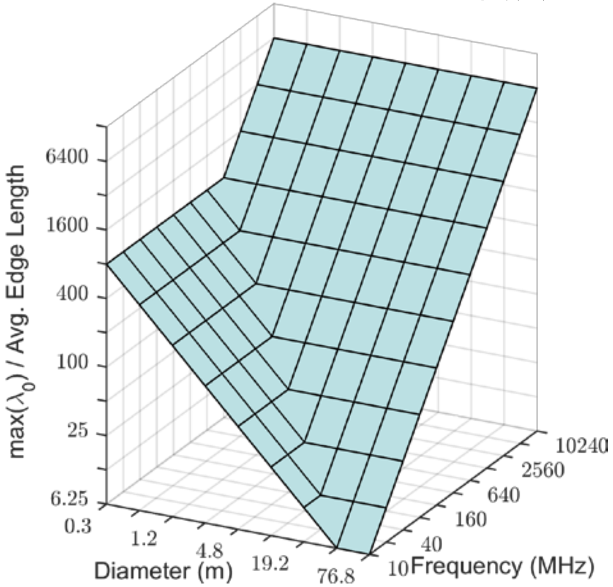




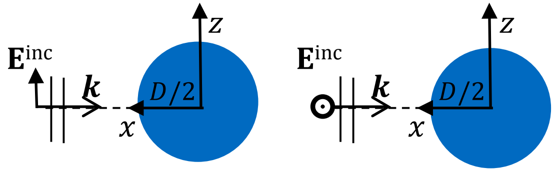
- Dimensions 5-6: Quantify error & cost
  - Exhaustive Study: Fix frequency, fix diameter -> 99 cases
    Simulate many error levels (proxy: mesh density) -> 3-5 mesh densities
    For each simulation, measure error & cost -> Plot error vs. cost
  - Two types of constraints on mesh density:
    - » Wavelength(s) dictated (here: avg. edge length $\leq$ min(λ_0/6.25, λ/3) and
    - » Geometry size(s) dictated (here: avg. edge length $\leq D/8$)

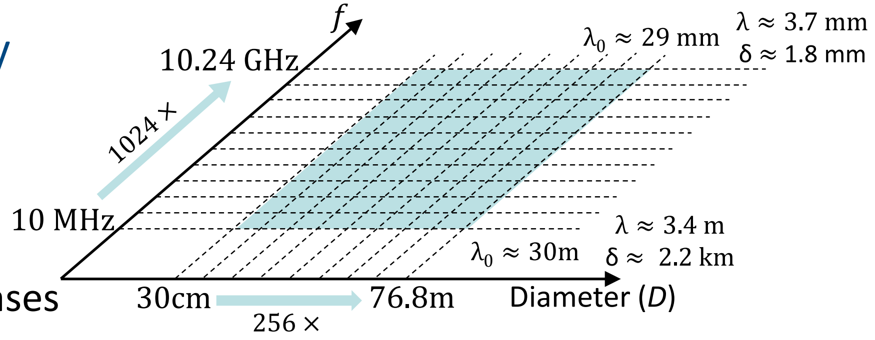


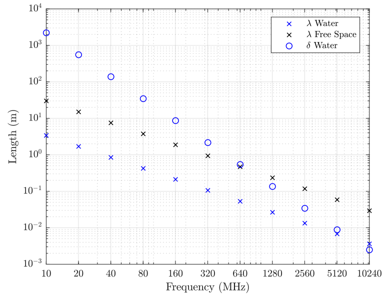
Mesh density must be larger than these constraints

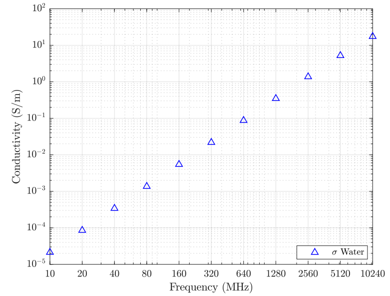
Problem I-C: Water Spheres

- Dimensions 3-4: Specify lengths & frequency









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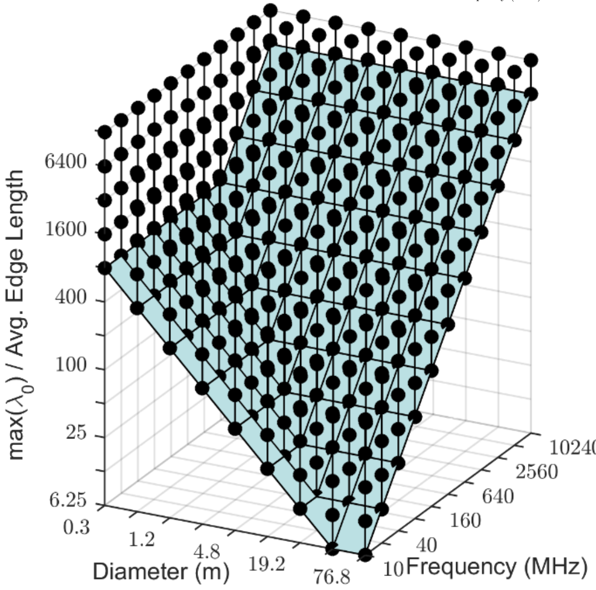
    Simulate many error levels (proxy: mesh density) -> 3-5 mesh densities
    For each simulation, measure error & cost -> Plot error vs. cost
    - Comprehensive sweep
    - High dimensional space: too many simulations
  - Alternative:
    - 3 sweeps: error level, frequency, size



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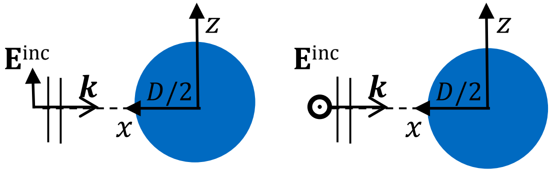

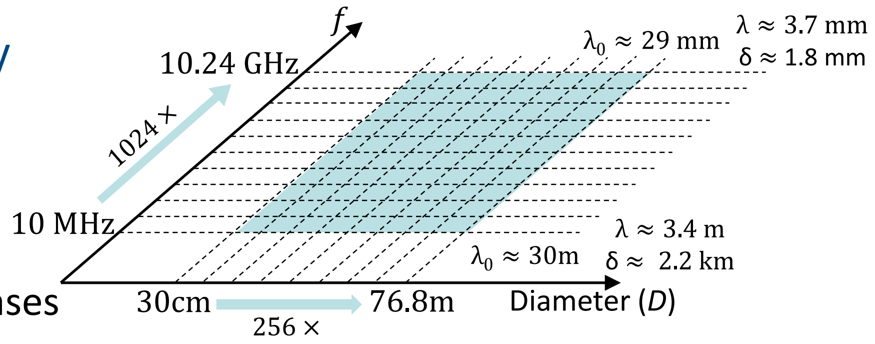

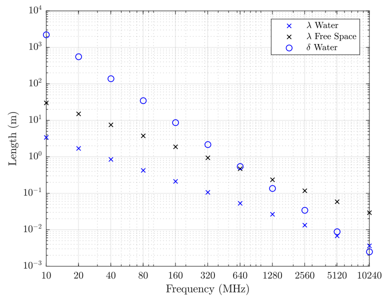

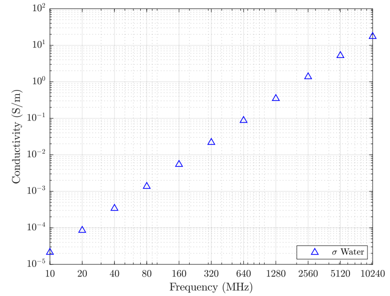

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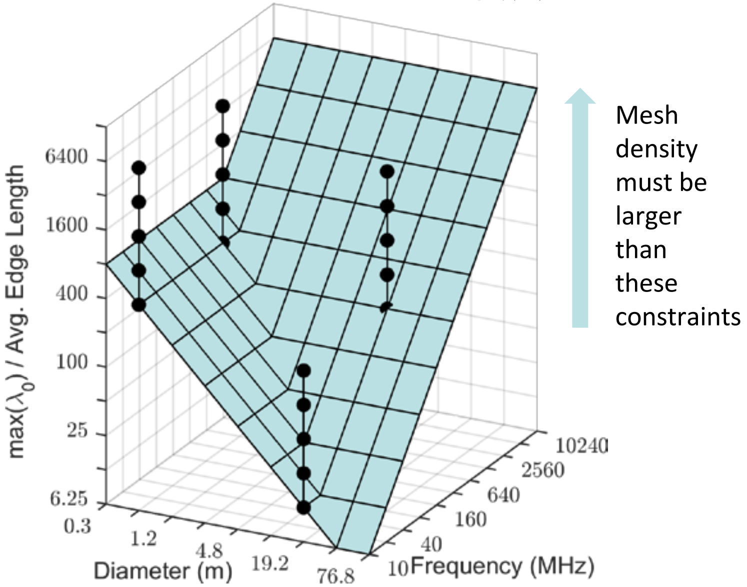
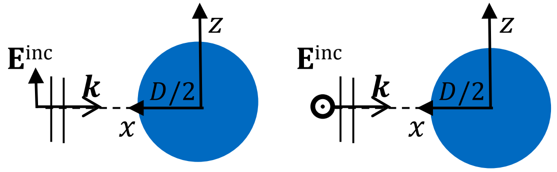
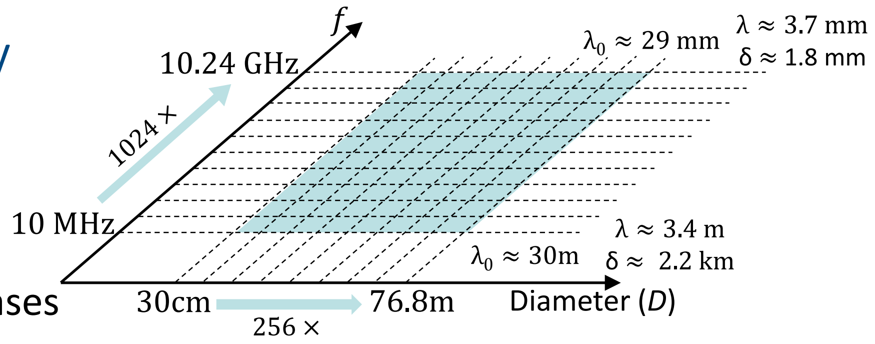
    - » Geometry size(s) dictated (here: avg. edge length $\le D/8$)
  - Sweep 1: Fix frequency, fix diameter
    Simulate many error levels (proxy: mesh density) -> Plot error vs. cost

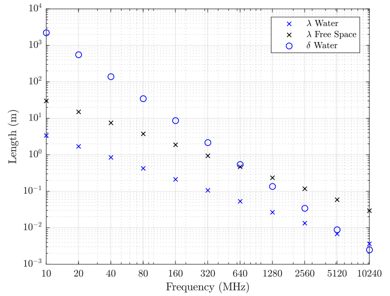


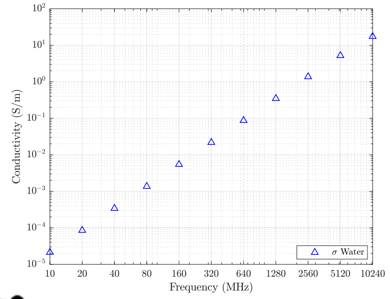
Problem I-C: Water Spheres

- Dimensions 3-4: Specify lengths & frequency

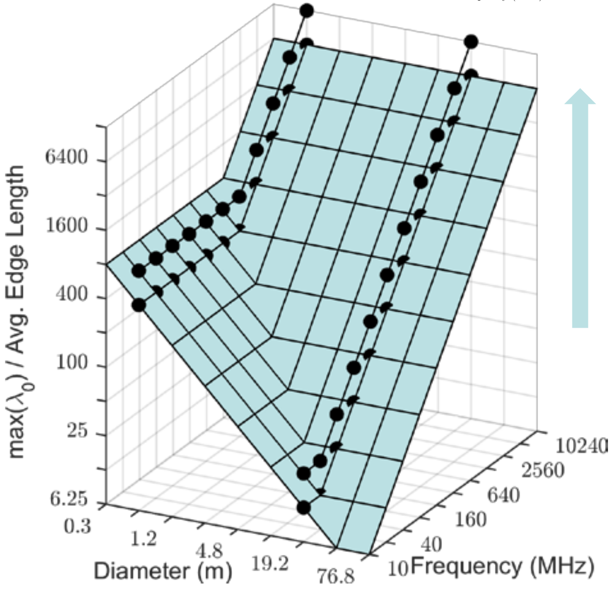








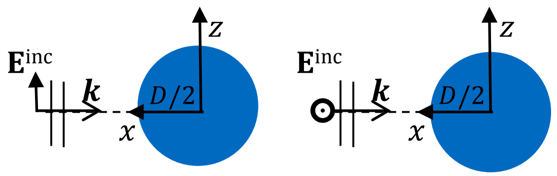
  - Proposed: Sample logarithmically: 9×11 = 99 cases
  - All cases with same D/λ_0 are NOT identical
  - $0.01 \leq D/\lambda_0 \leq 2624$, bi-static RCS
- Dimensions 5-6: Quantify error & cost
  - Exhaustive Study: Fix frequency, fix diameter -> 99 cases
    Simulate many error levels (proxy: mesh density) -> 3-5 mesh densities
    For each simulation, measure error & cost -> Plot error vs. cost
  - Two types of constraints on mesh density:
    - » Wavelength(s) dictated (here: avg. edge length $\leq \min(\lambda_0/6.25,\ \lambda/3)$ and
    - » Geometry size(s) dictated (here: avg. edge length $\leq D/8$)
  - Sweep 1: Fix frequency, fix diameter
    Simulate many error levels (proxy: mesh density) -> Plot error vs. cost
  - Sweep 2: Fix diameter, fix error level (proxy: mesh density)
    Simulate many frequencies -> Plot error & cost vs. frequency

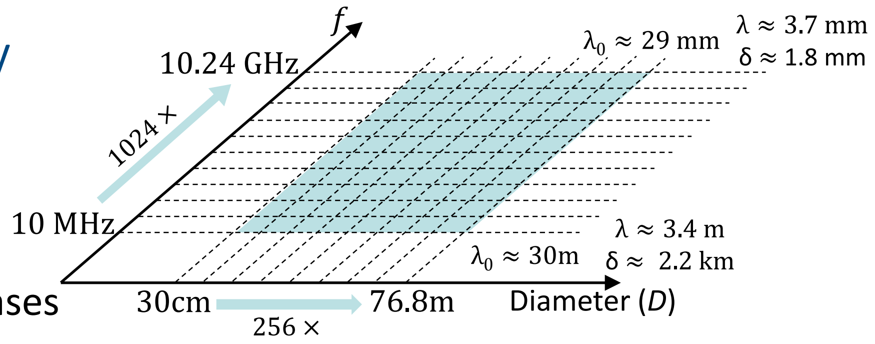


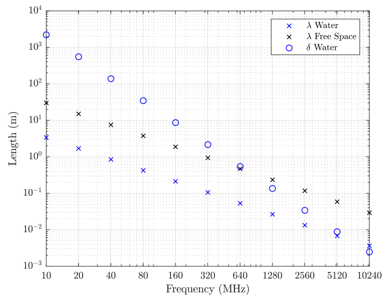
Mesh density must be larger than these constraints

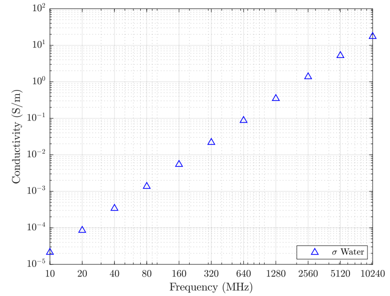
Problem I-C: Water Spheres

- Dimensions 3-4: Specify lengths & frequency

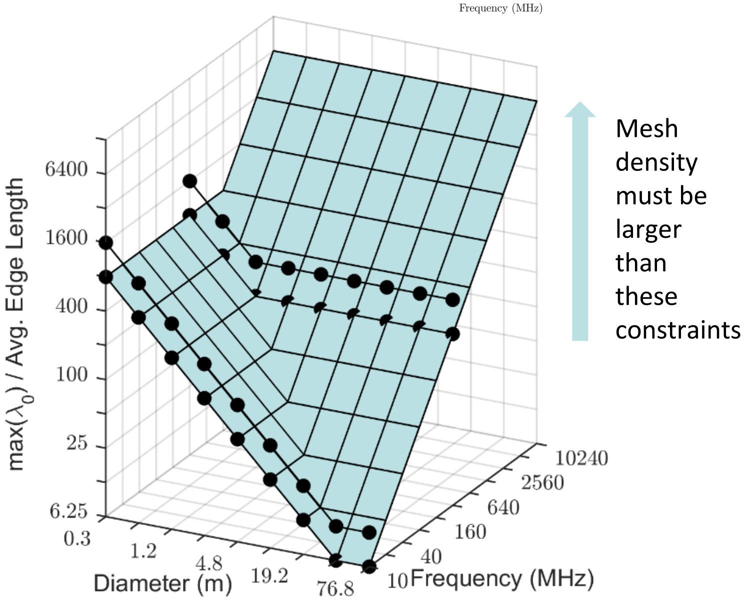






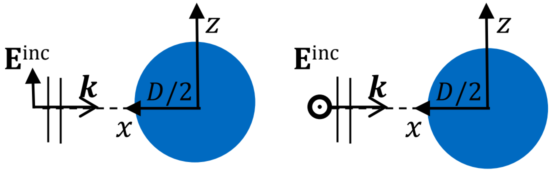


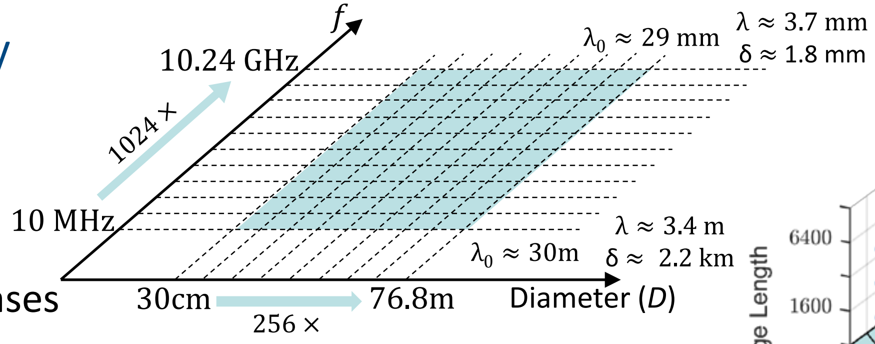
  - Proposed: Sample logarithmically: 9×11 = 99 cases
  - All cases with same D/λ_0 are NOT identical
  - $0.01 \leq D/\lambda_0 \leq 2624$, bi-static RCS
- Dimensions 5-6: Quantify error & cost
  - Exhaustive Study: Fix frequency, fix diameter -> 99 cases
    Simulate many error levels (proxy: mesh density) -> 3-5 mesh densities
    For each simulation, measure error & cost -> Plot error vs. cost
  - Two types of constraints on mesh density:
    - » Wavelength(s) dictated (here: avg. edge length $\leq$ min(λ_0/6.25, λ/3) and
    - » Geometry size(s) dictated (here: avg. edge length $\leq D/8$)
  - Sweep 1: Fix frequency, fix diameter
    Simulate many error levels (proxy: mesh density) -> Plot error vs. cost
  - Sweep 2: Fix diameter, fix error level (proxy: mesh density)
    Simulate many frequencies -> Plot error & cost vs. frequency
  - Sweep 3: Fix frequency, fix error level (proxy: mesh density)
    Simulate many diameters -> Plot error & cost vs. diameter

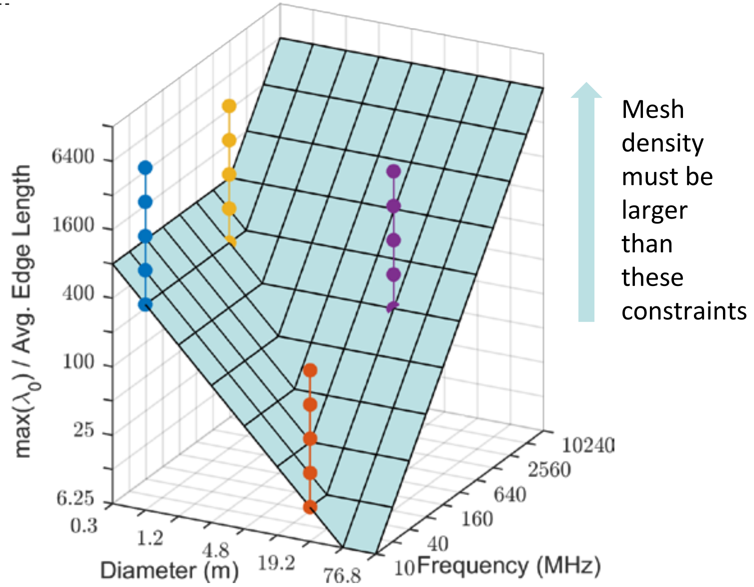


Problem I-C: Water Spheres

- Dimensions 3-4: Specify lengths & frequency



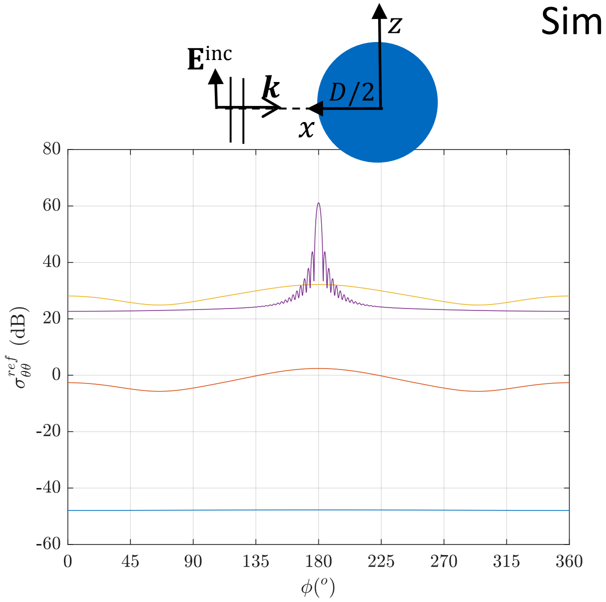


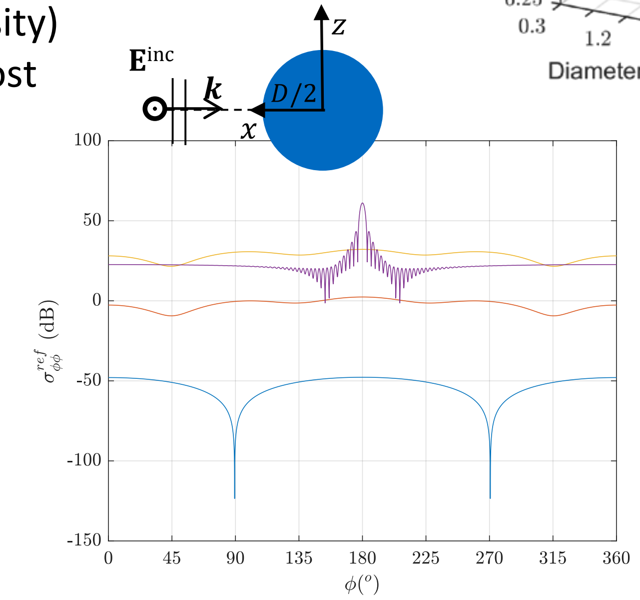


  - Proposed: Sample logarithmically: 9×11 = 99 cases
  - All cases with same D/λ_0 are NOT identical
  - $0.01 \leq D/\lambda_0 \leq 2624$, bi-static RCS
- Dimensions 5-6: Quantify error & cost
  - Sweep 1: Fix frequency, fix diameter: 4 cases

    Simulate many error levels (proxy: mesh density)

    Measure error & cost -> Plot error vs. cost





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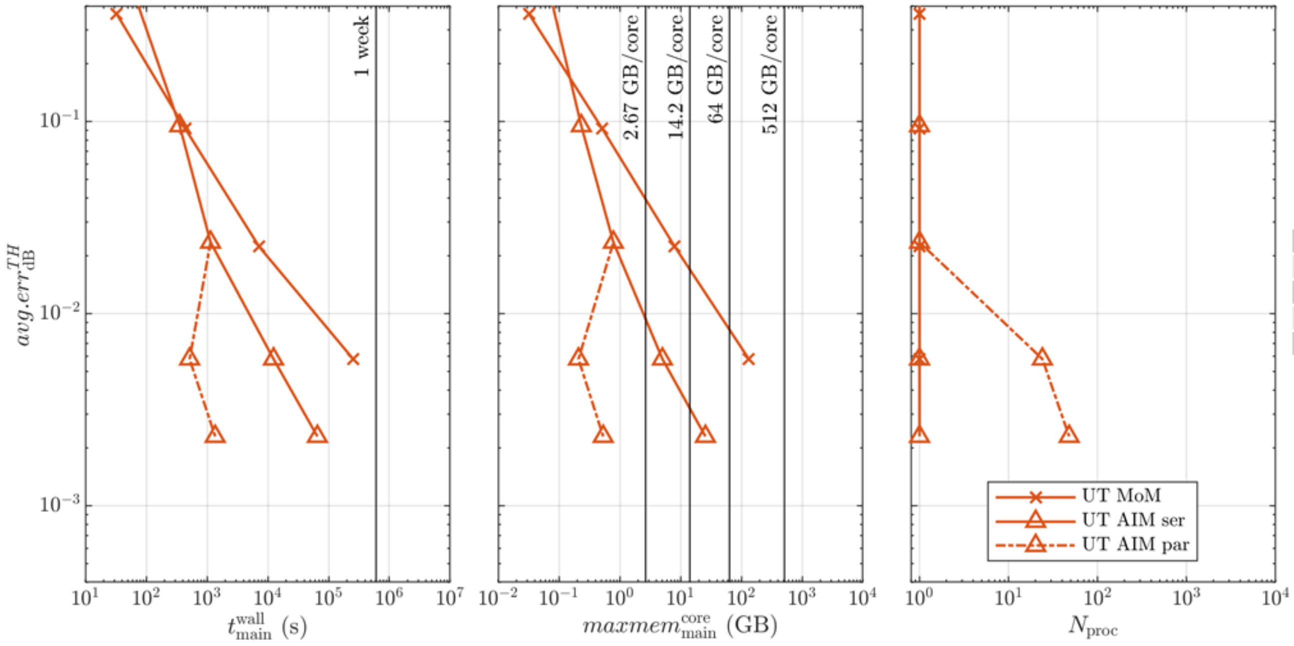
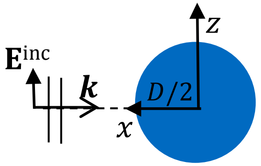
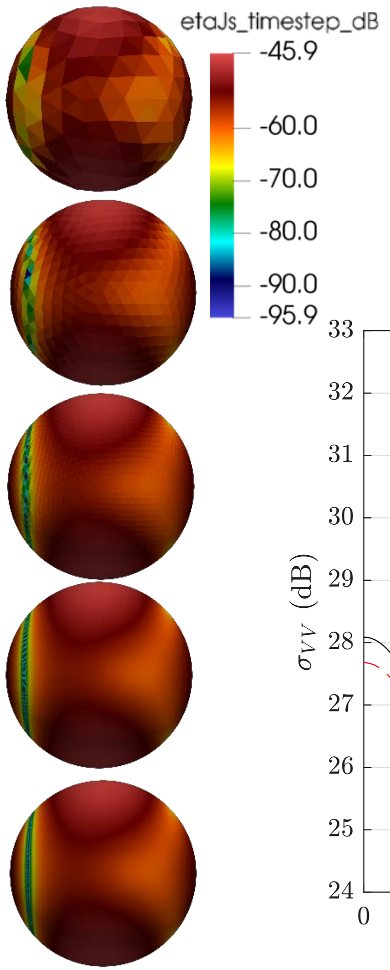
Problem I-C: Water Spheres

- Dimensions 5-6: Quantify error & cost
  - Sweep 1: Fix frequency, fix diameter: 4 cases
    Simulate many error levels (proxy: mesh density)
    Measure error & cost -> Plot error vs. cost

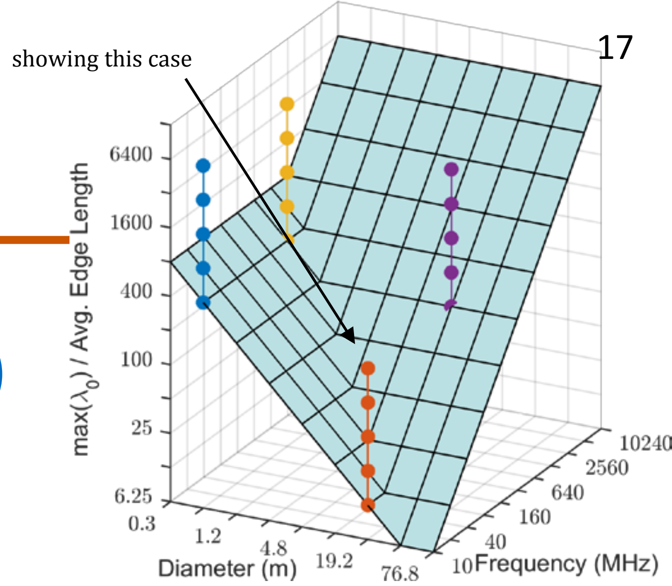
vs. Wall-Clock Time | vs. Memory/Core | vs. # Processes





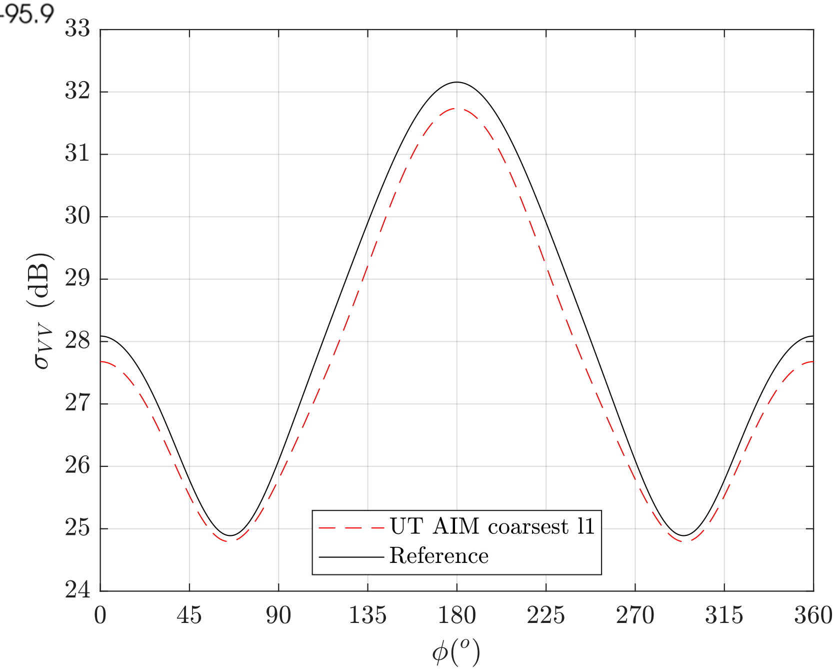


2N
1 458
5 874
23 154
94 206
374 004



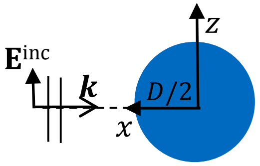
❑ Observations

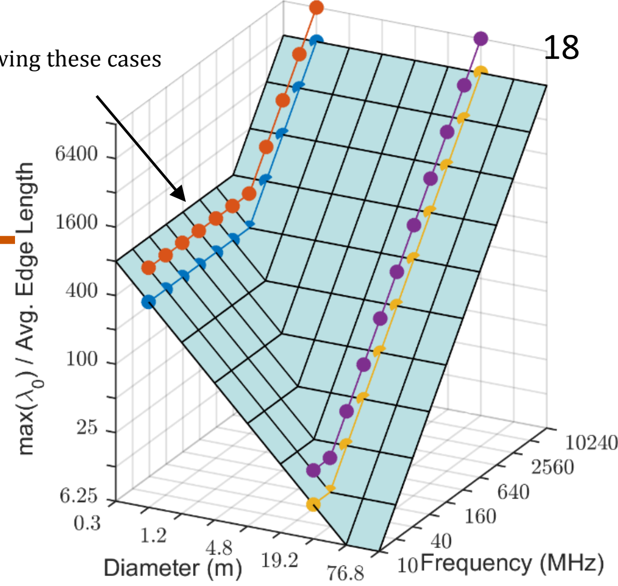
- Single incident angle



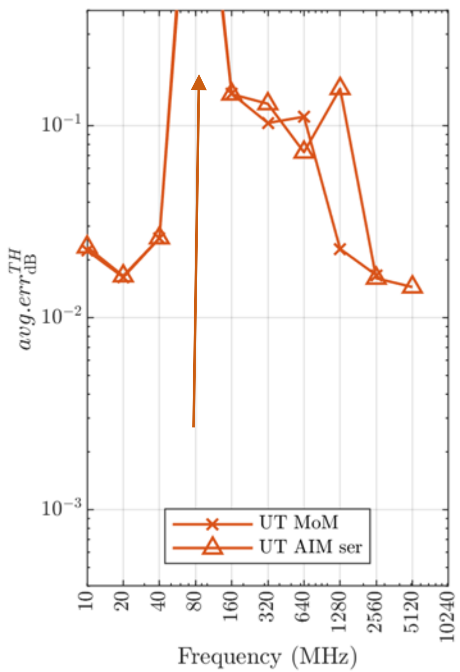
Problem I-C: Water Spheres

- Dimensions 5-6: Quantify error & cost
  - Sweep 2: Fix diameter, fix error level (proxy: mesh density)
    Simulate many frequencies
    Measure error & cost -> Plot error & cost vs. frequency

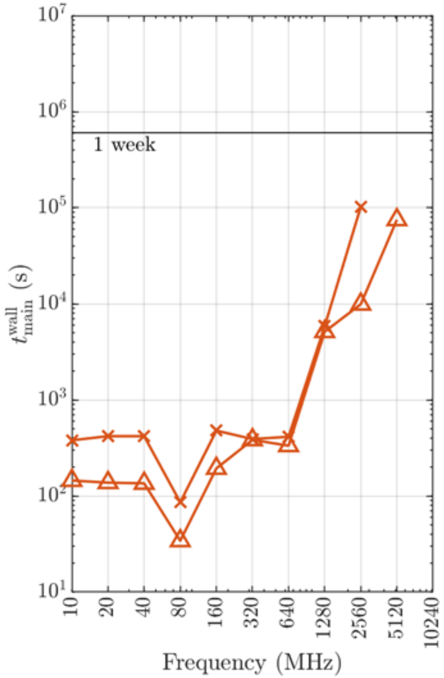




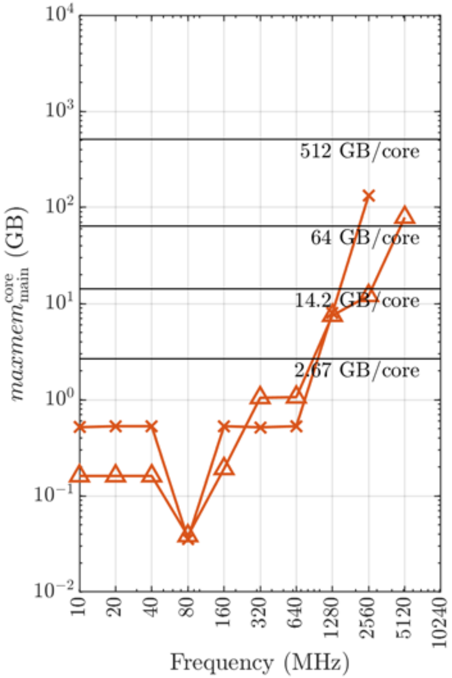
Error



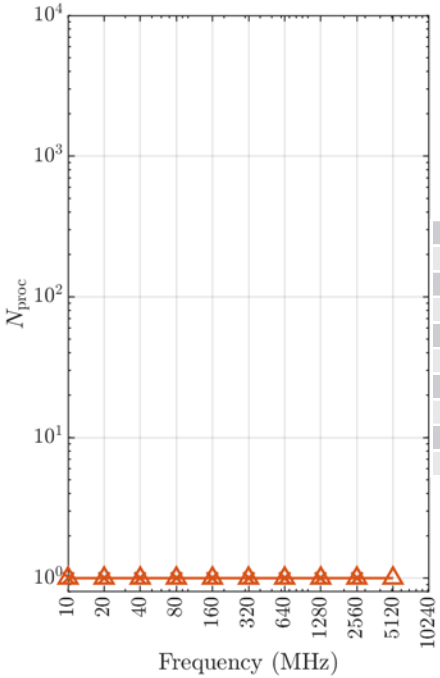
Wall-Clock Time



Memory / Core



Processes



2N
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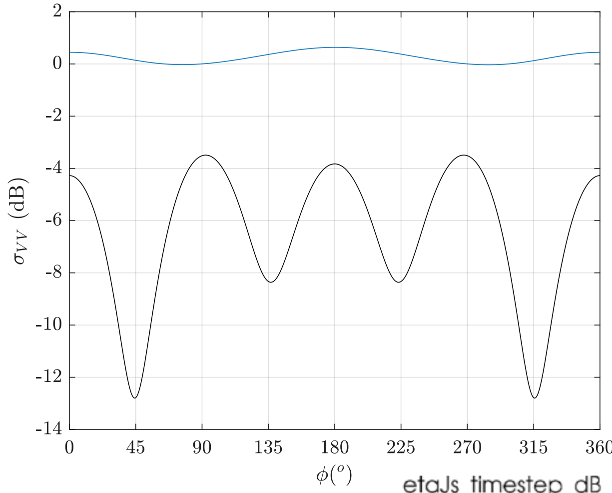
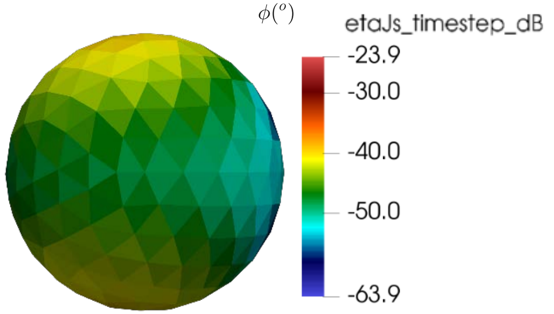
374 004





N = 1 458

λ_o = 3.75 (m)

λ_{water} = 0.421669 (m)

$\frac{\lambda_o}{\lambda_{water}}$ = 8.89

l = .0736 (m)

$\frac{\lambda_o}{l}$ = 51

$\frac{\lambda_{water}}{l}$ = 5.7292

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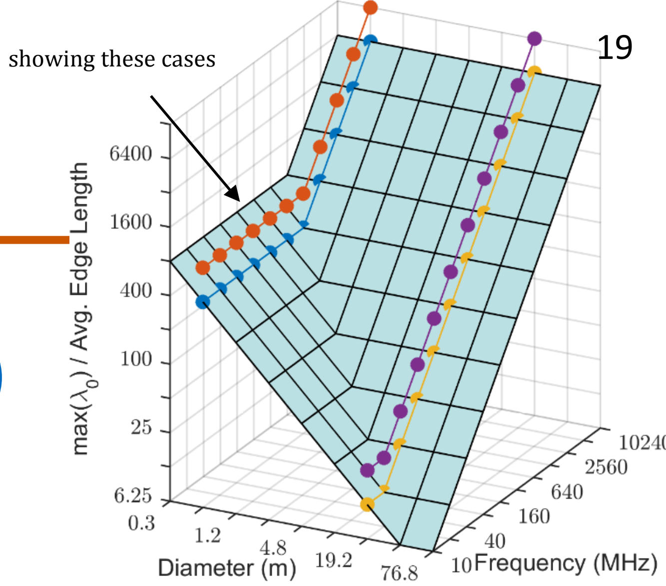
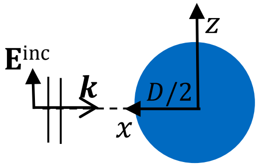
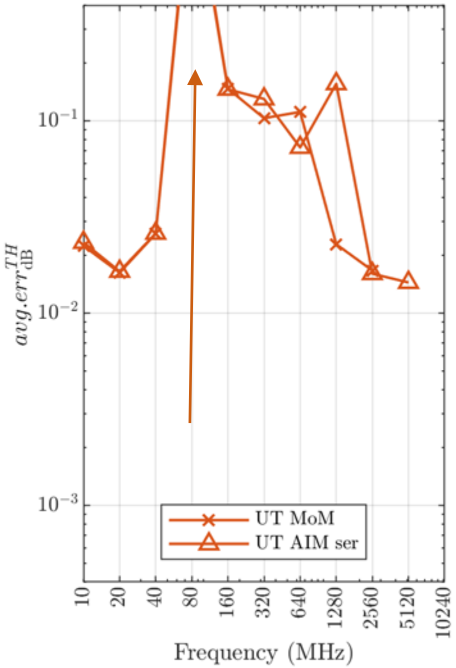
Problem I-C: Water Spheres



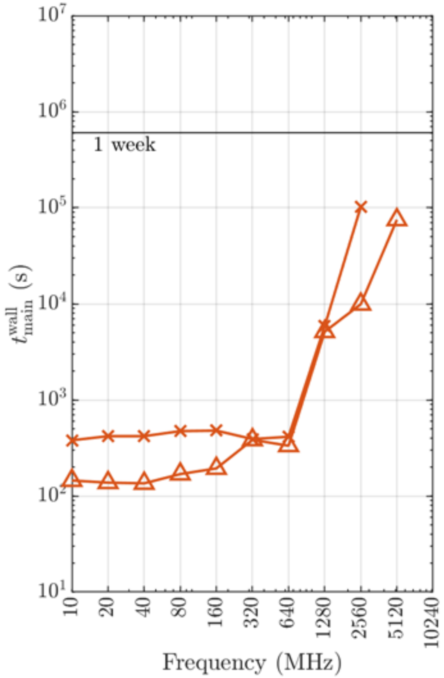
- Dimensions 5-6: Quantify error & cost
  - Sweep 2: Fix diameter, fix error level (proxy: mesh density)
    Simulate many frequencies
    Measure error & cost -> Plot error & cost vs. frequency



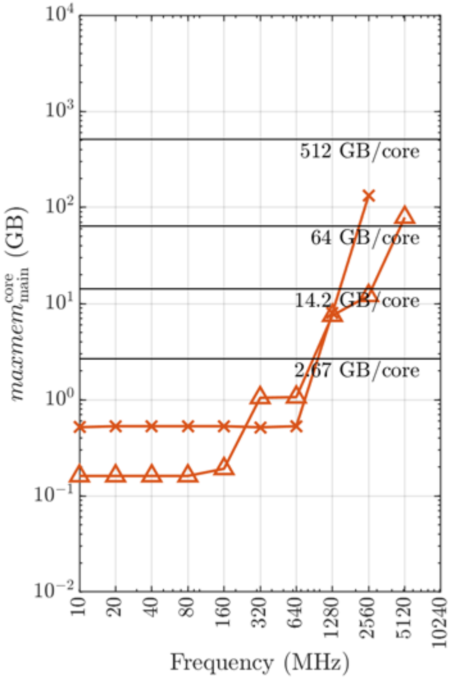
Error



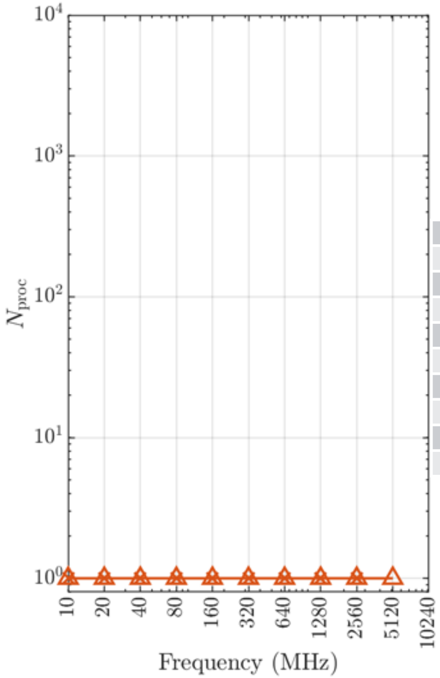
Wall-Clock Time



Memory / Core



Processes



2N
5 874
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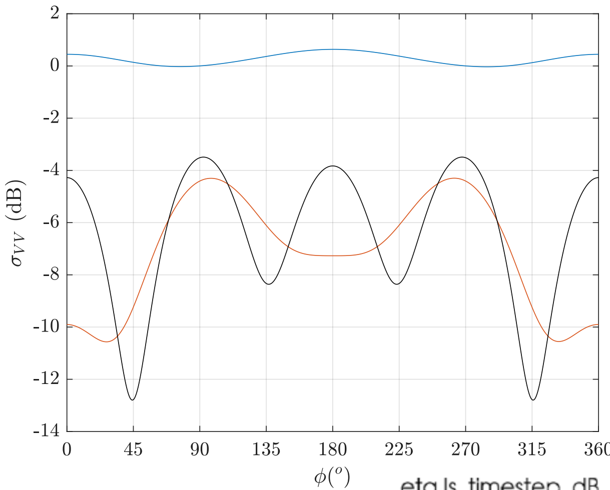
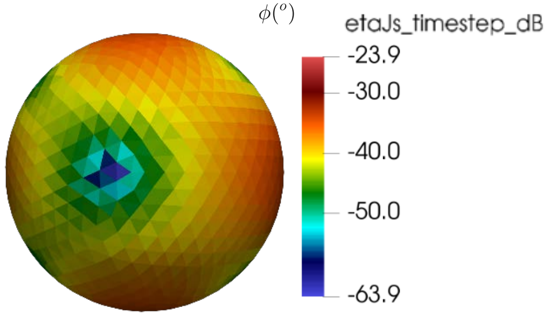
5 874
23 154
94 206
374 004

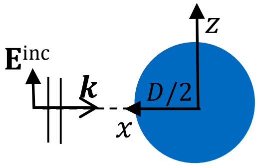


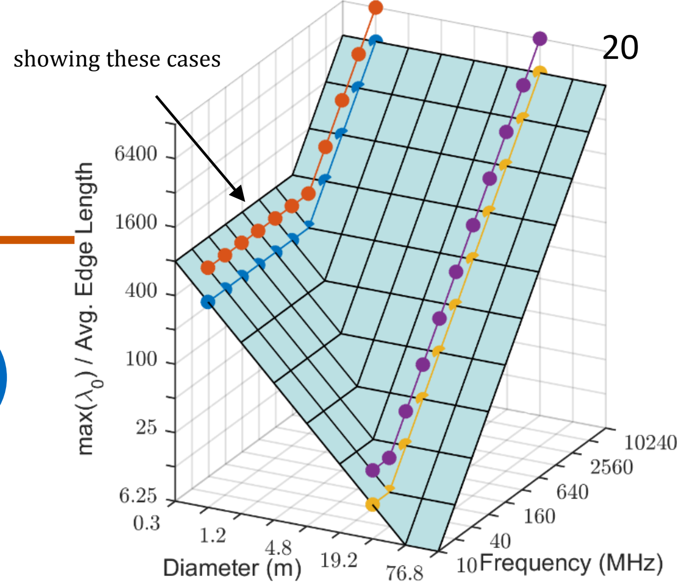


N = 5 874 $\quad \lambda_o = 3.75$ (m) $\quad \lambda_{water} = 0.421669$ (m) $\quad \dfrac{\lambda_o}{\lambda_{water}} = 8.89 \quad l = .03677$ (m) $\quad \dfrac{\lambda_o}{l} = 102 \quad \dfrac{\lambda_{water}}{l} = 11.5$

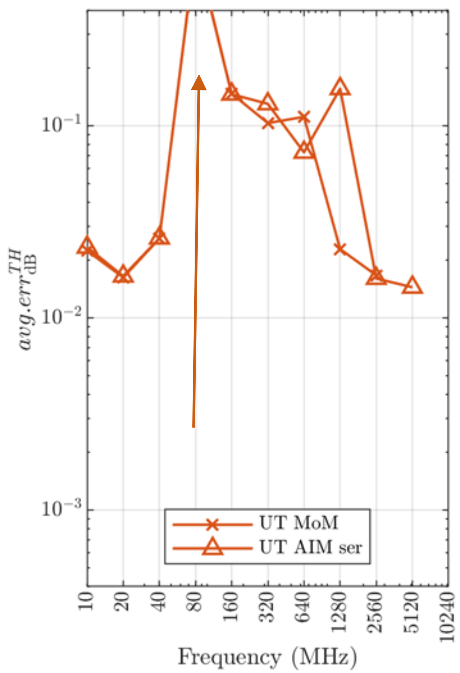
Problem I-C: Water Spheres

- Dimensions 5-6: Quantify error & cost
  - Sweep 2: Fix diameter, fix error level (proxy: mesh density)
    Simulate many frequencies
    Measure error & cost -> Plot error & cost vs. frequency

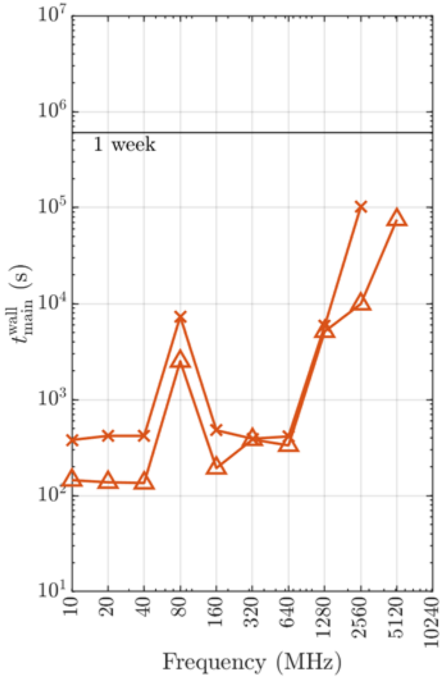




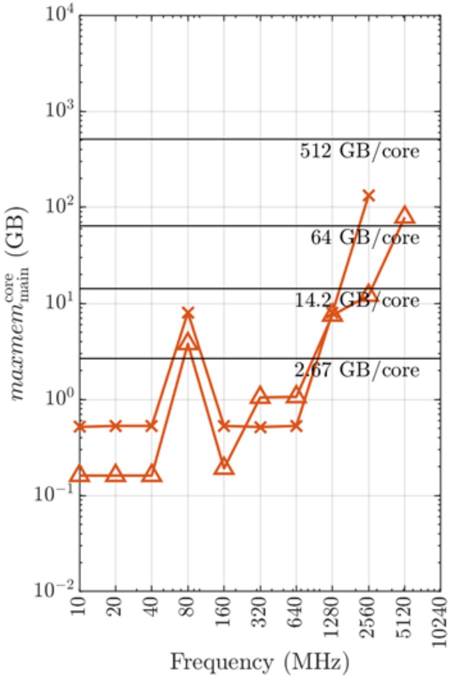
Error



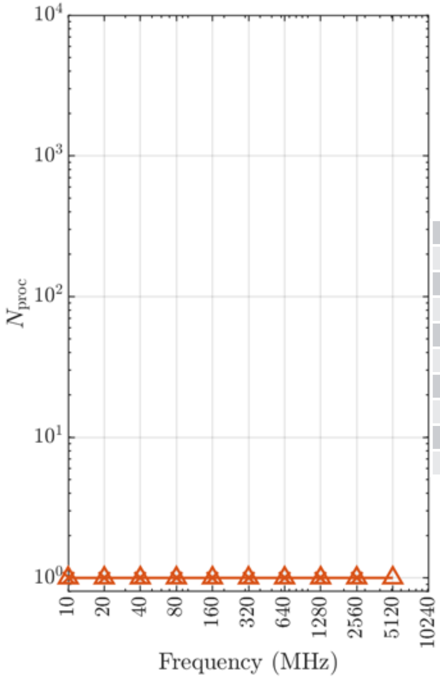
Wall-Clock Time



Memory / Core



\# Processes



2N
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23 154
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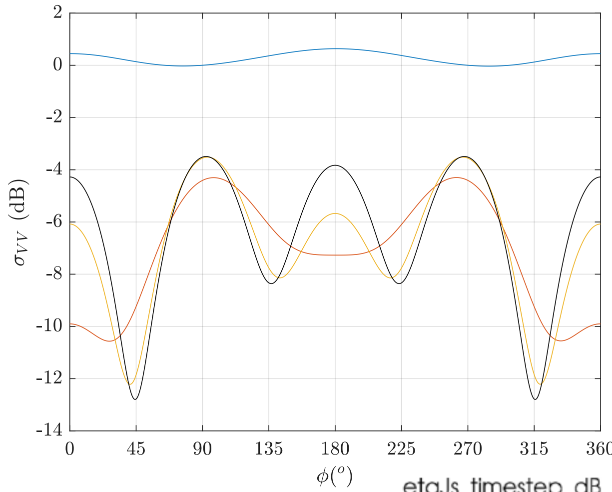

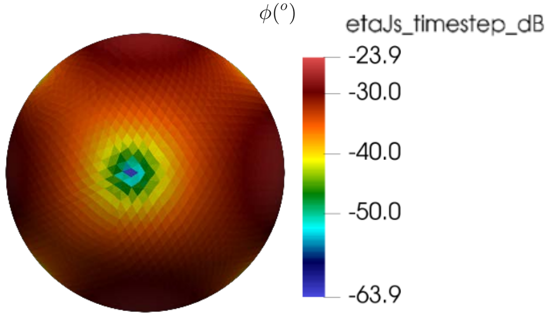

N = 23 154 $\quad \lambda_o = 3.75\ (m) \quad \lambda_{water} = 0.421669\ (m)$

$\frac{\lambda_o}{\lambda_{water}} = 8.89 \quad l = .01852\ (m) \quad \frac{\lambda_o}{l} = 203 \quad \frac{\lambda_{water}}{l} = 23$

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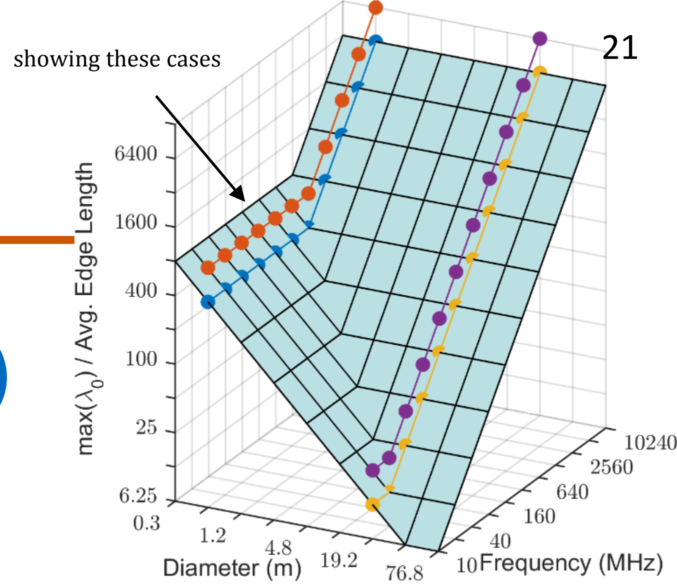
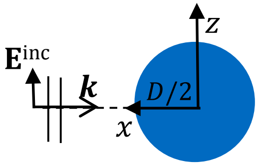
Problem I-C: Water Spheres



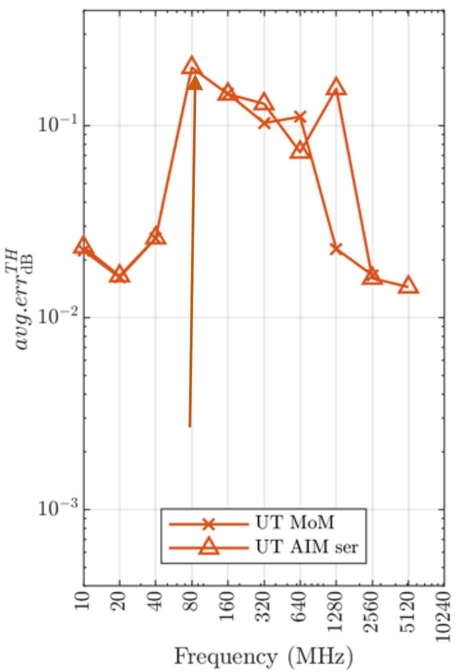
- Dimensions 5-6: Quantify error & cost
  - Sweep 2: Fix diameter, fix error level (proxy: mesh density)

    Simulate many frequencies

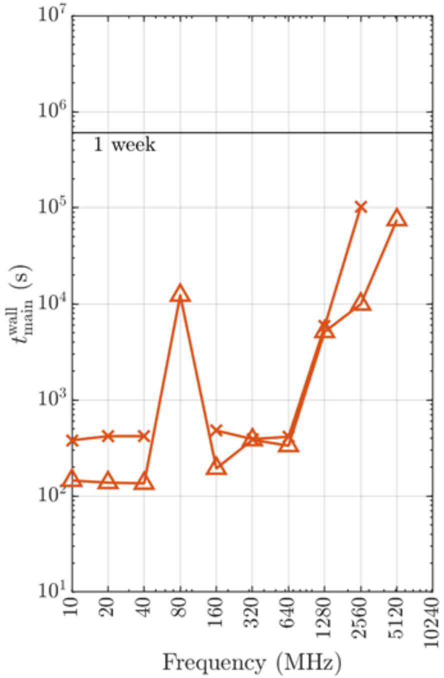
    Measure error & cost -> Plot error & cost vs. frequency



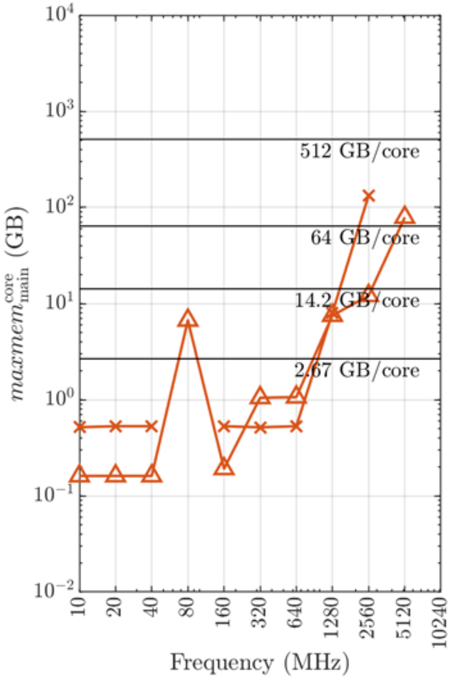
Error



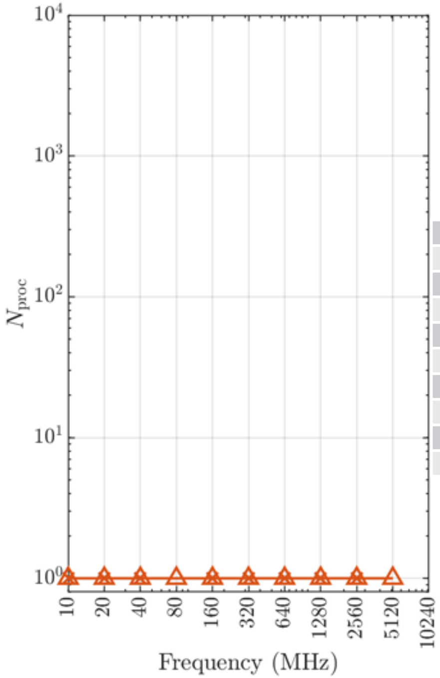
Wall-Clock Time



Memory / Core



Processes



2N
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94 206
5 874
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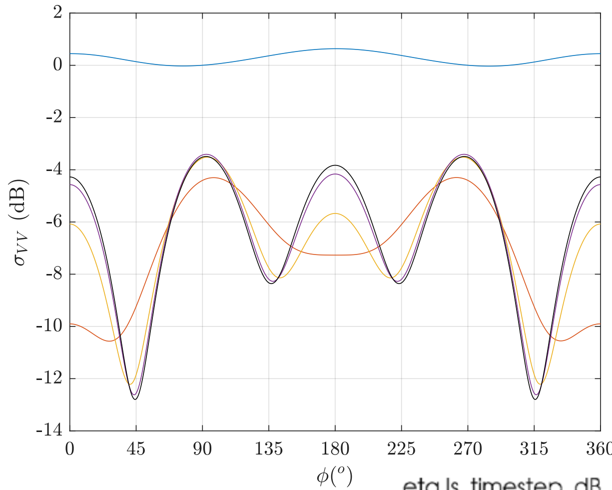
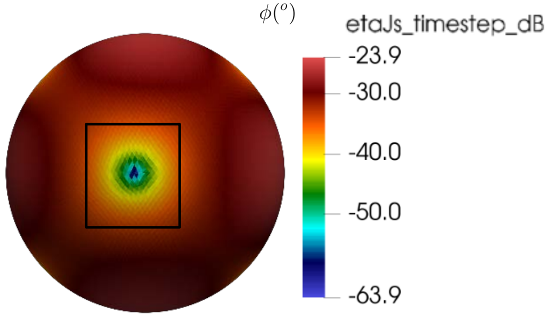
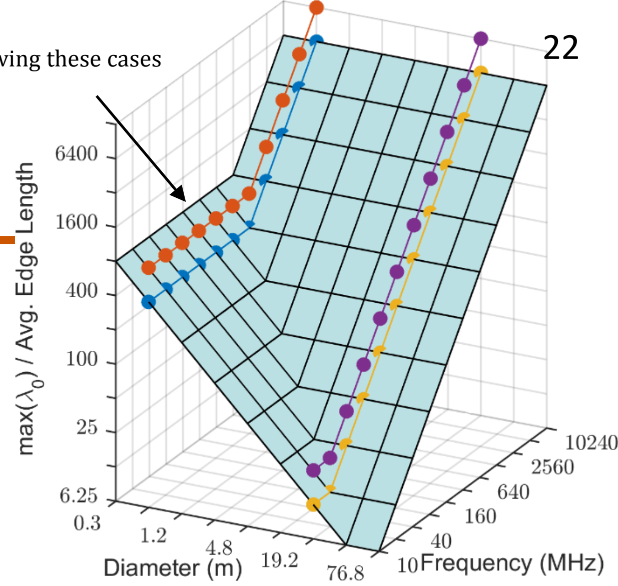
5 874
23 154
94 206
374 004



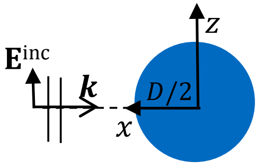


N = 94 206 $\lambda_o = 3.75$ (m) $\lambda_{water} = 0.421669$ (m) $\frac{\lambda_o}{\lambda_{water}} = 8.89$ $l = .0092$ (m) $\frac{\lambda_o}{l} = 409$ $\frac{\lambda_{water}}{l} = 46$

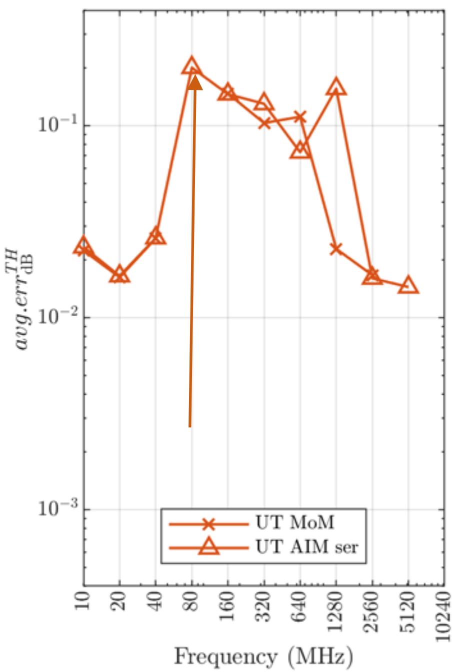
Problem I-C: Water Spheres



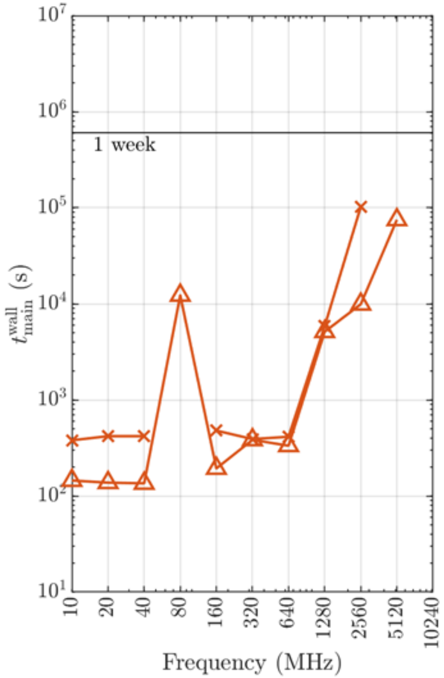
- Dimensions 5-6: Quantify error & cost
  - Sweep 2: Fix diameter, fix error level (proxy: mesh density)
    Simulate many frequencies
    Measure error & cost -> Plot error & cost vs. frequency



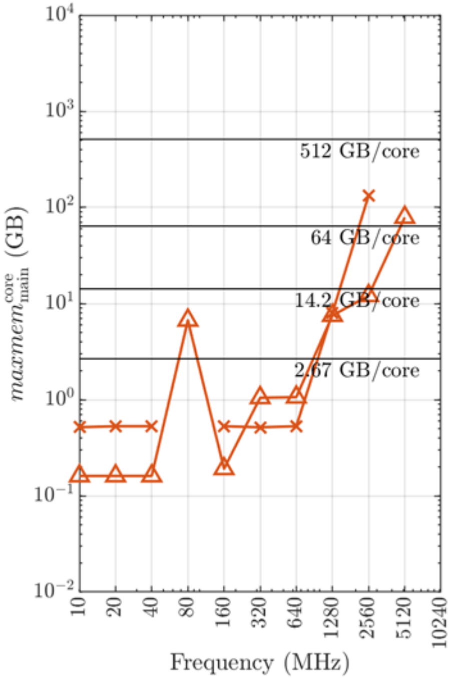
Error



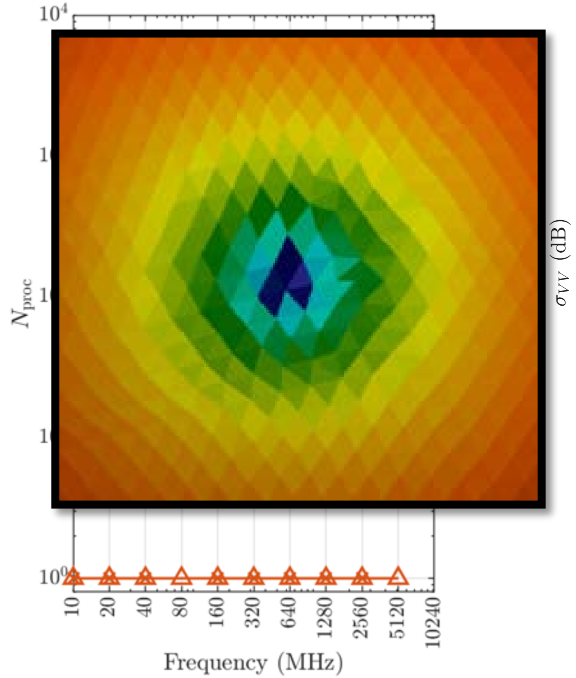
Wall-Clock Time

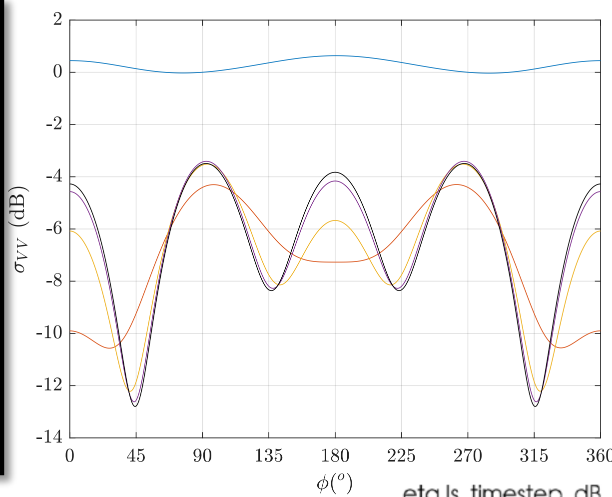


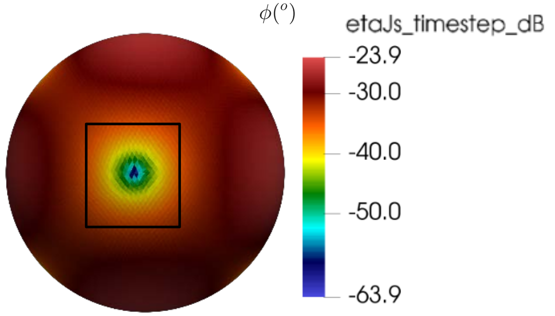
Memory / Core



Processes



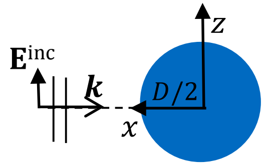


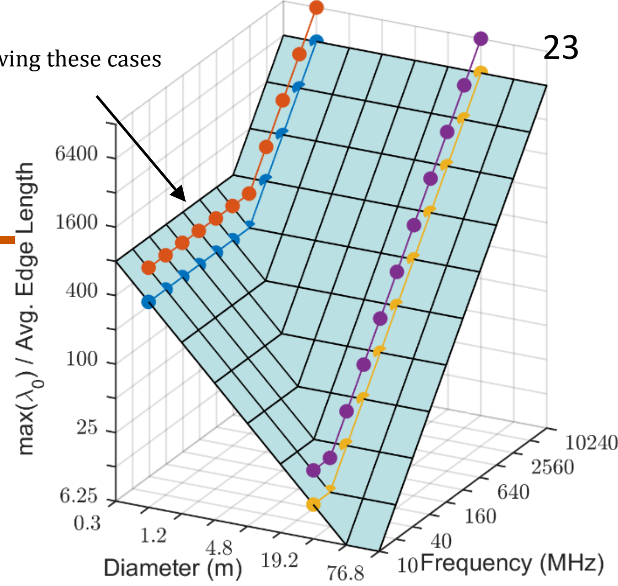


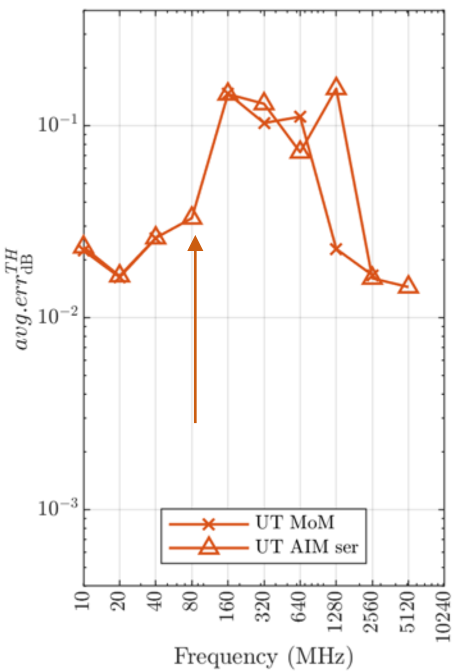
N = 94 206 $\lambda_o = 3.75\ (m)$ $\lambda_{water} = 0.421669\ (m)$ $\frac{\lambda_o}{\lambda_{water}} = 8.89$ $l = .0092$ (m) $\frac{\lambda_o}{l} = 409$ $\frac{\lambda_{water}}{l} = 46$

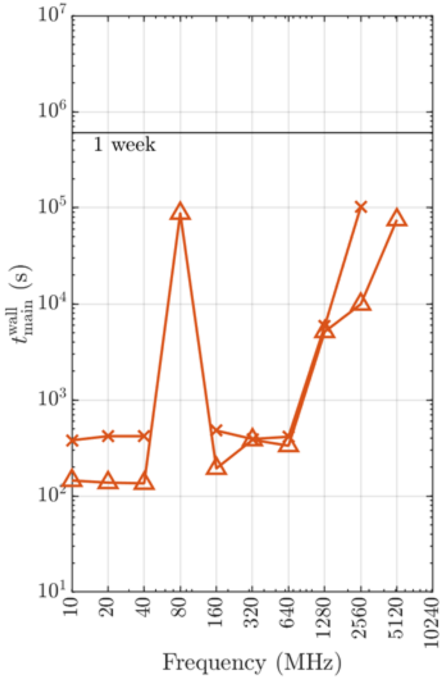
Problem I-C: Water Spheres

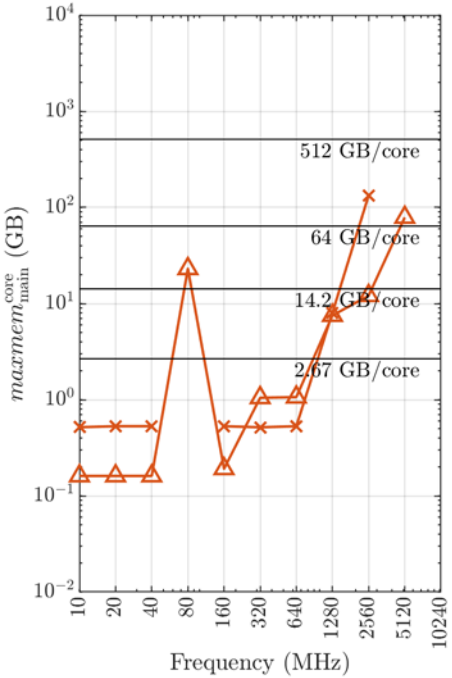
- Dimensions 5-6: Quantify error & cost
  - Sweep 2: Fix diameter, fix error level (proxy: mesh density)
    Simulate many frequencies
    Measure error & cost -> Plot error & cost vs. frequency

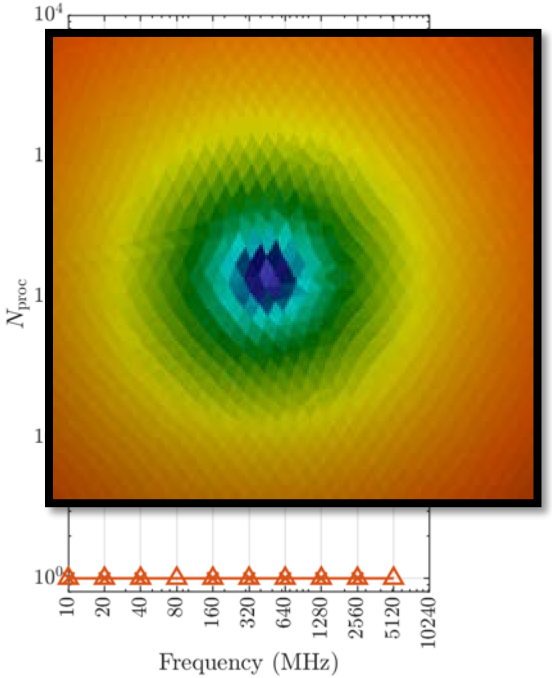


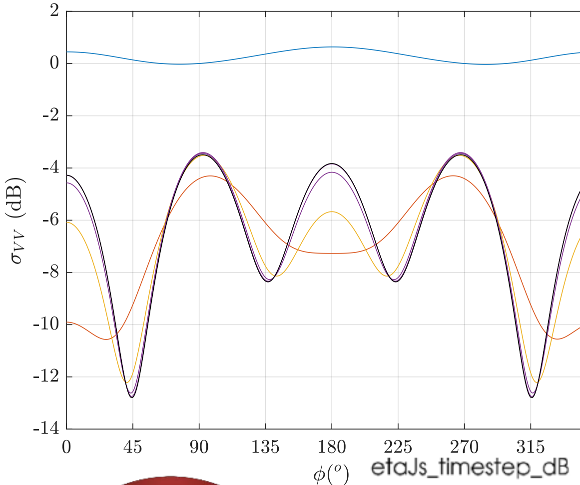


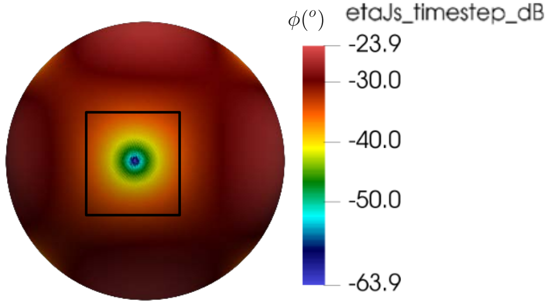






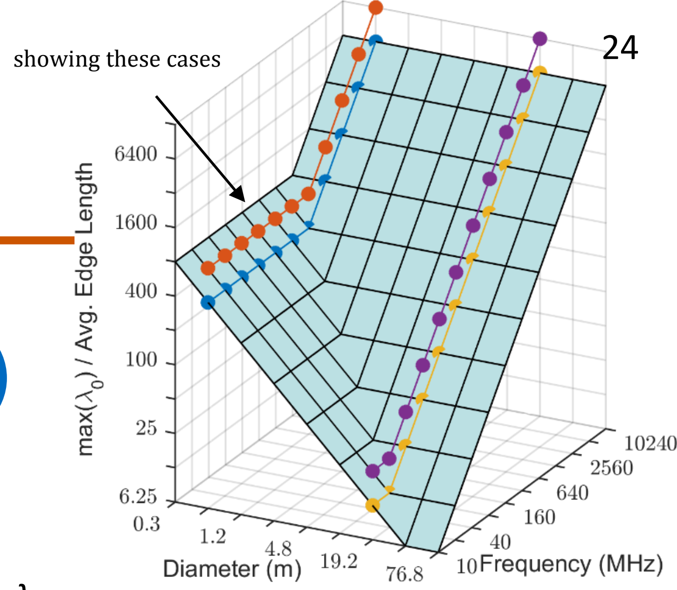




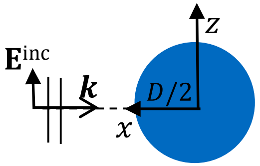


N = 372 004 λ_o = 3.75 (m) λ_{water} = 0.421669 (m) $\frac{\lambda_o}{\lambda_{water}}$ = 8.89 l = .0046 (m) $\frac{\lambda_o}{l}$ = 815 $\frac{\lambda_{water}}{l}$ = 92

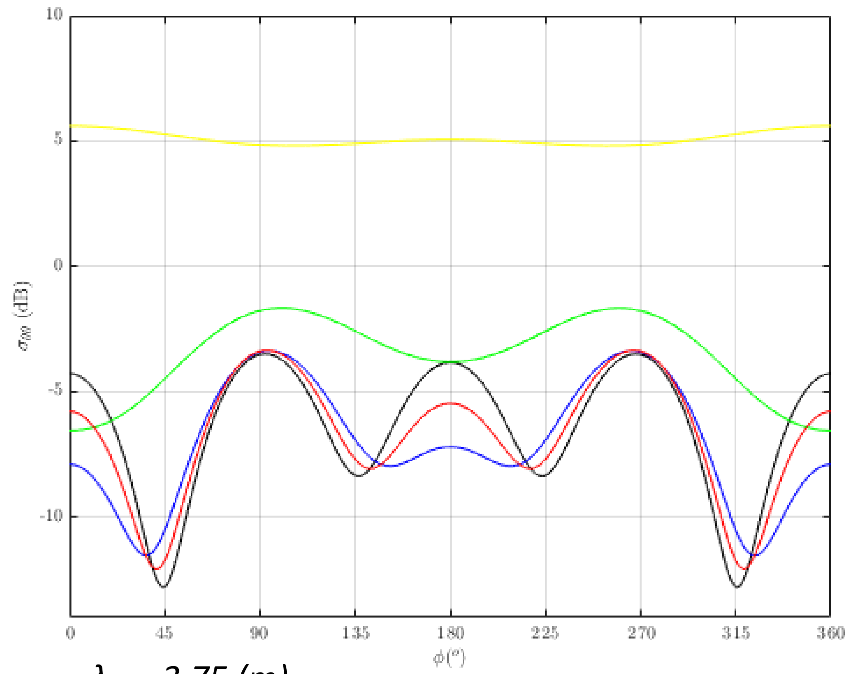
Problem I-C: Water Spheres



- Dimensions 5-6: Quantify error & cost
  - Sweep 2: Fix diameter, fix error level (proxy: mesh density)
    Simulate many frequencies
    Measure error & cost -> Plot error & cost vs. frequency



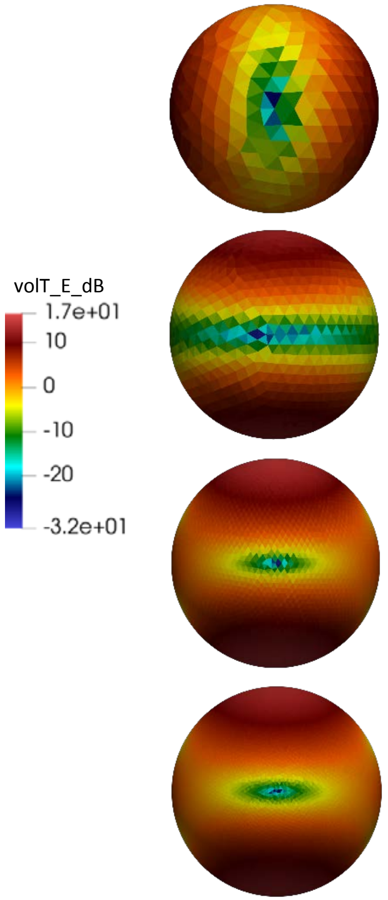
ARCHIE-AIM with VOLUME-EFIE formulation:



$\lambda_o = 3.75$ (m)

$\lambda_{water} = 0.421669$ (m)

$\frac{\lambda_o}{\lambda_{water}} = 8.89$



N = 19 936 $\quad \frac{\lambda_o}{l} = 77 \quad \frac{\lambda_{water}}{l} = 9$

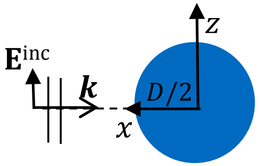
N = 95 098 $\quad \frac{\lambda_o}{l} = 130 \quad \frac{\lambda_{water}}{l} = 15$

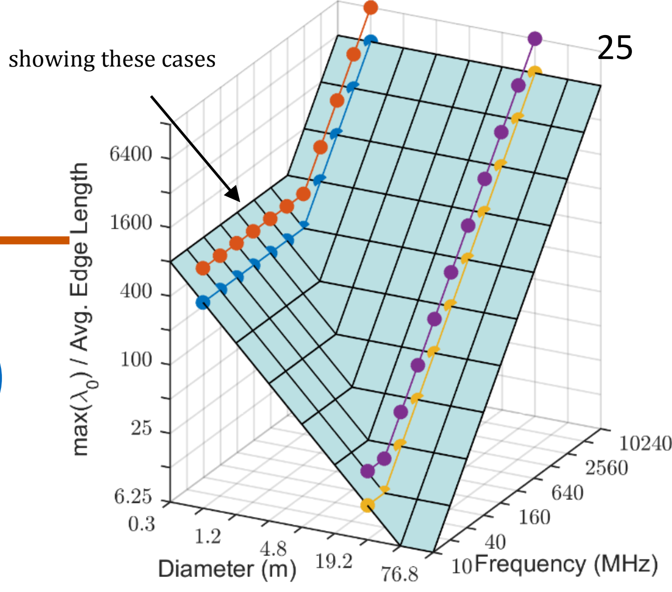
N = 682 155 $\quad \frac{\lambda_o}{l} = 252 \quad \frac{\lambda_{water}}{l} = 28$

N = 2 404 396 $\quad \frac{\lambda_o}{l} = 501 \quad \frac{\lambda_{water}}{l} = 55$

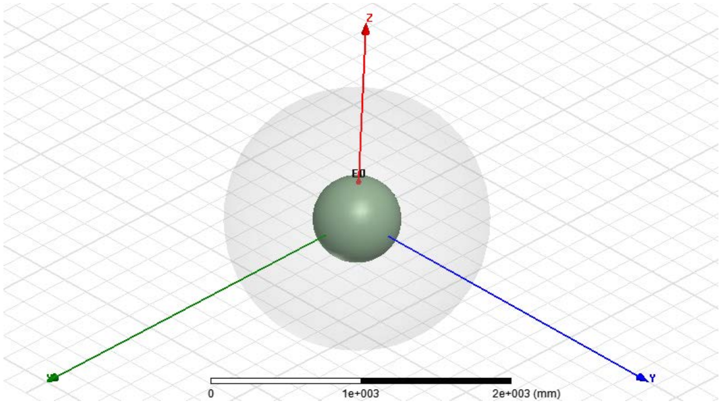
Problem I-C: Water Spheres

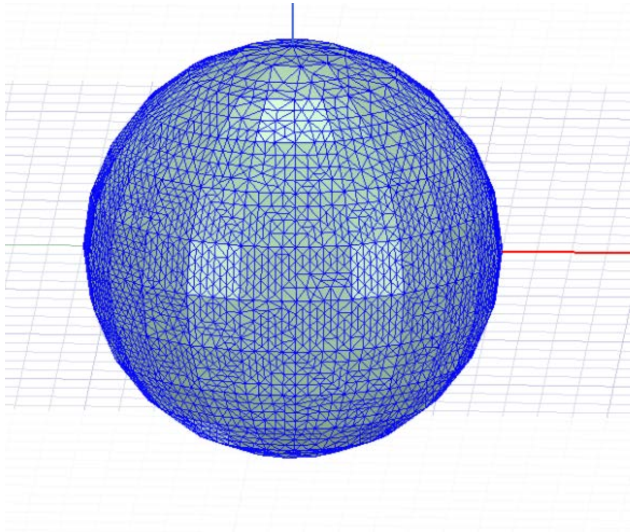
- Dimensions 5-6: Quantify error & cost
  - Sweep 2: Fix diameter, fix error level (proxy: mesh density)
    Simulate many frequencies
    Measure error & cost -> Plot error & cost vs. frequency

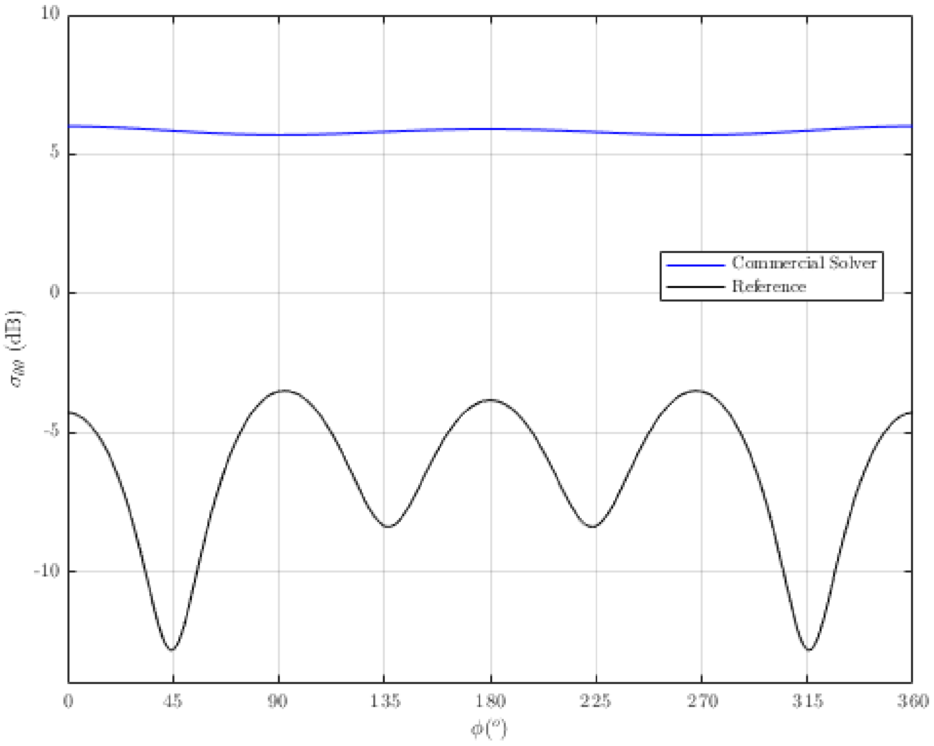




Commercial Solver's Solution:

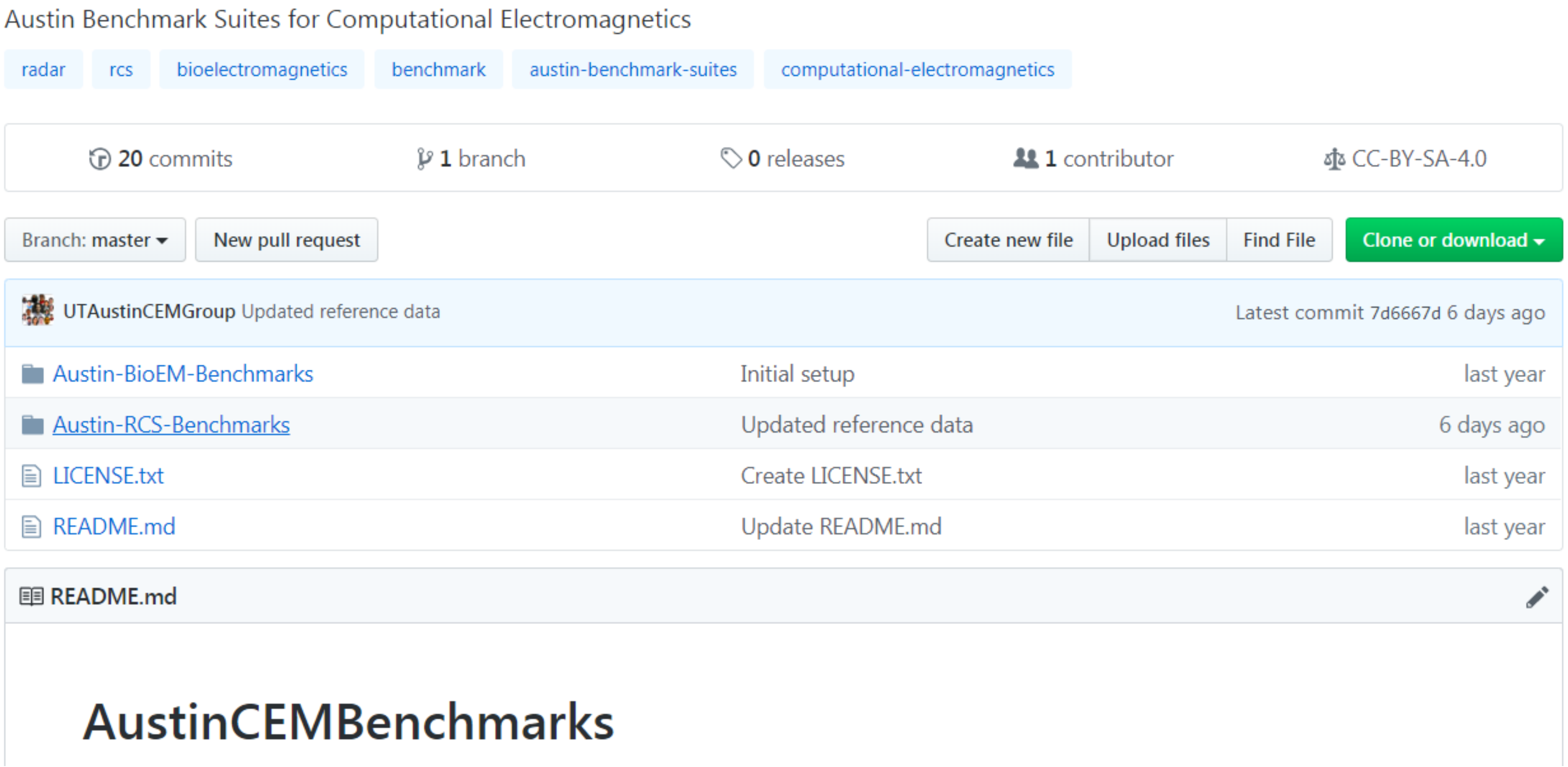






Benchmarking Database

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



Website:
github.com/UTAustinCEMGroup/AustinCEMBenchmarks

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Benchmarking Database

- **Features Available**
  - Problem Description
    Precisely defines the model and the quantities of interest
  - Reference Data
  - Simulation Data

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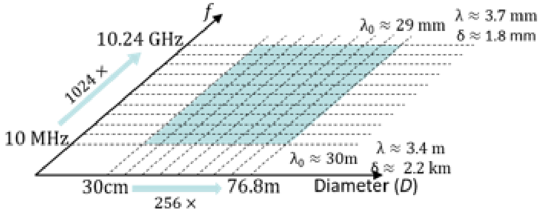
QuantitiesofInterest.md	Populating placeholder messages	last year
README.md	Update README.md	last year
References.md	Populating placeholder messages	last year
Simulator1Description.md	Populating placeholder messages	last year
URSI2018presentation.pdf	Add files via upload	last year

Problem Set IC- Water Spheres — Austin RCS Benchmark Suite

Description of Scattering Object
A semiconductor 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; the ranges are logarithmically sampled to yield 99 unique scattering problems. In these problems, the sphere sizes are in the range $0.01 \le D/\lambda_0 \le 2624$ and $0.03 \le D/\delta \le 4.26 \times 10^4$, where λ_0 is the free-space wavelength and δ is the penetration depth in the sphere.

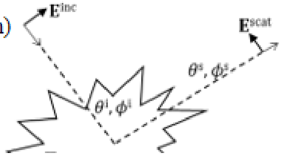
Interesting Features
1. Highly accurate, Mie-series analytical solutions are available for Problem IB.
2. Bi-static rather than mono-static RCS is used as the quantity of interest.

Quantities of Interest
Radar cross section (RCS) definition

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

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

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



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

Website:
github.com/UTAustinCEMGroup/AustinCEMBenchmarks

Benchmarking Database

❑ Features Available

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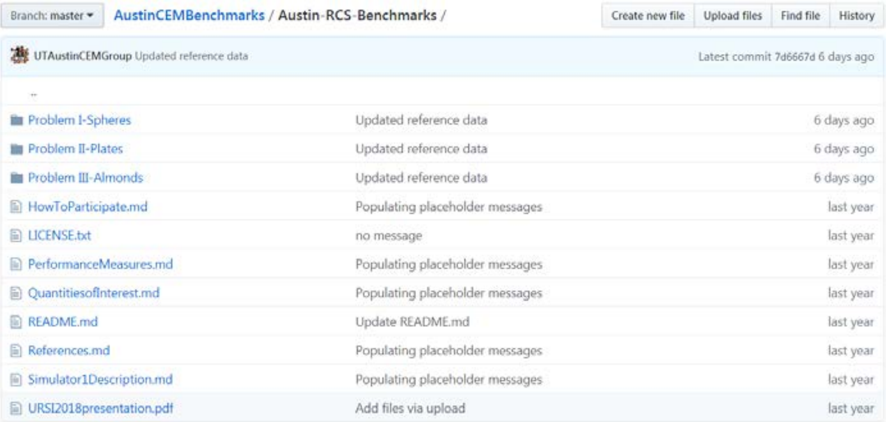
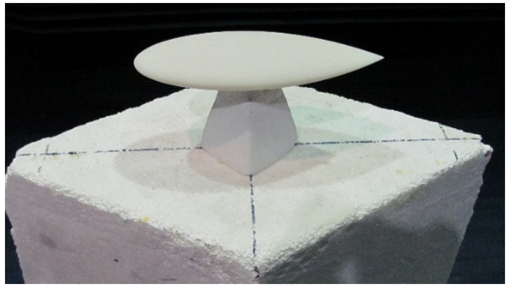
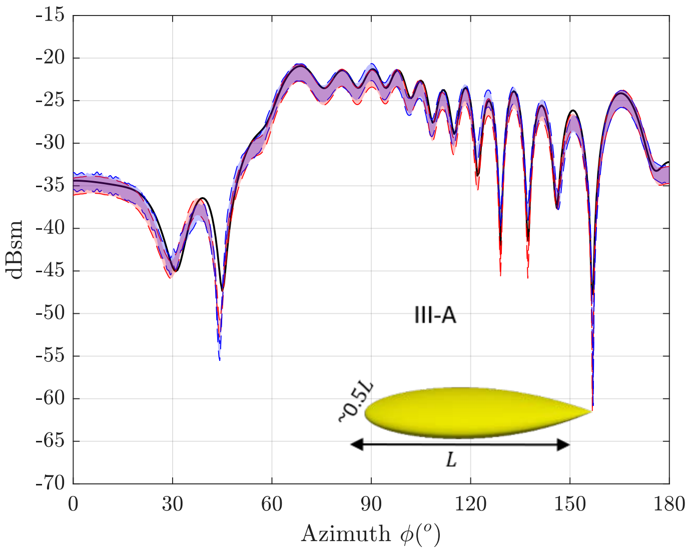
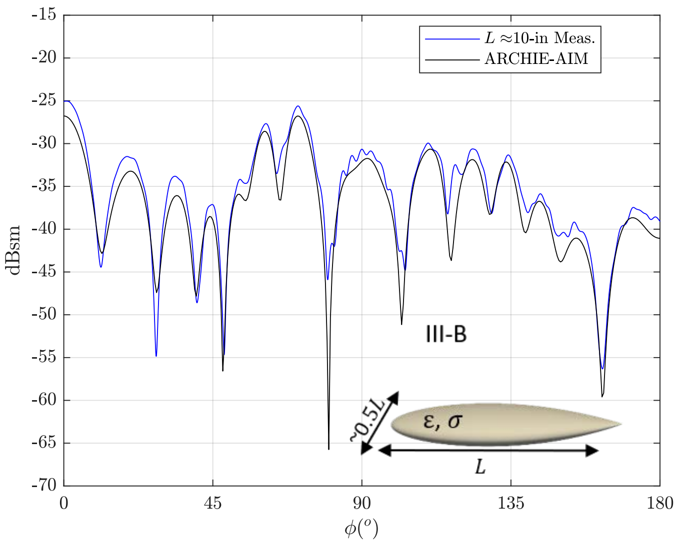
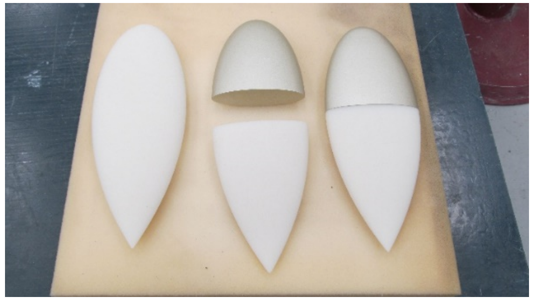
  Precisely defines the model and the quantities of interest
- Reference Data
  Measurement or analytical reference results
- Simulation Data

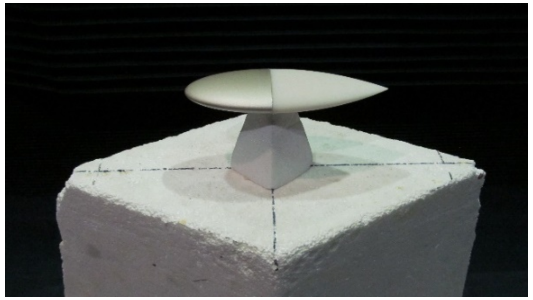












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[1] A. C. Woo, H. T. G. Wang, M. J. Schuh and M. L. Sanders, "EM programmer's notebook-benchmark radar targets for the validation of computational electromagnetics programs," in *IEEE Ant. Propag. Mag.*, vol. 35, no. 1, pp. 84-89, Feb. 1993.

Benchmarking Database

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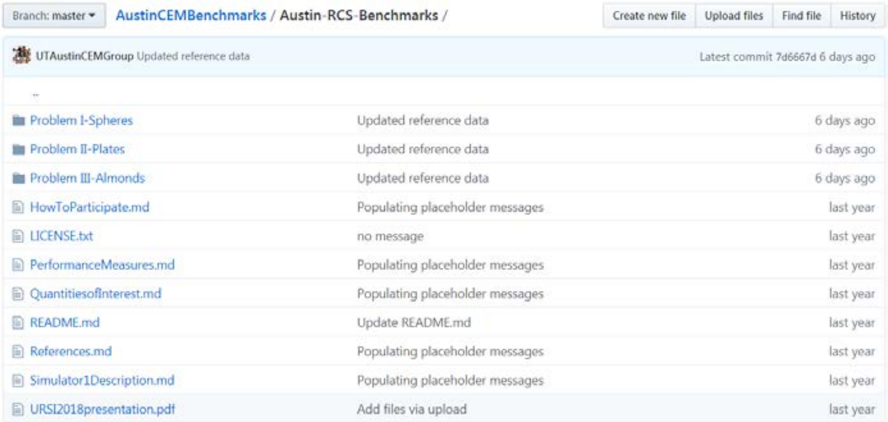
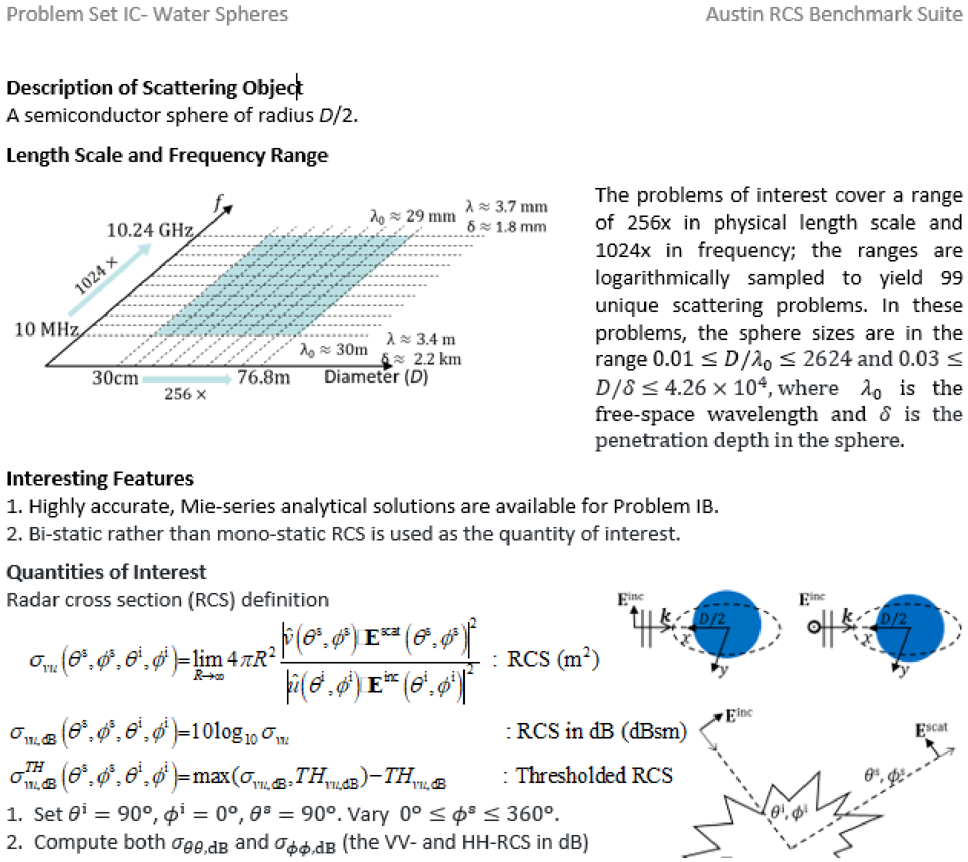
    Measurement or analytical reference results
  - **Simulation Data**
    Sample results for benchmark problems produced by UT Austin





Problem Set IC- Water Spheres — Austin RCS Benchmark Suite

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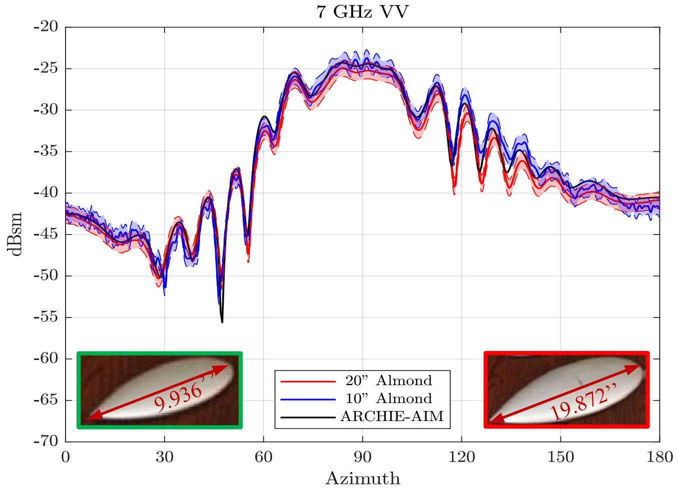

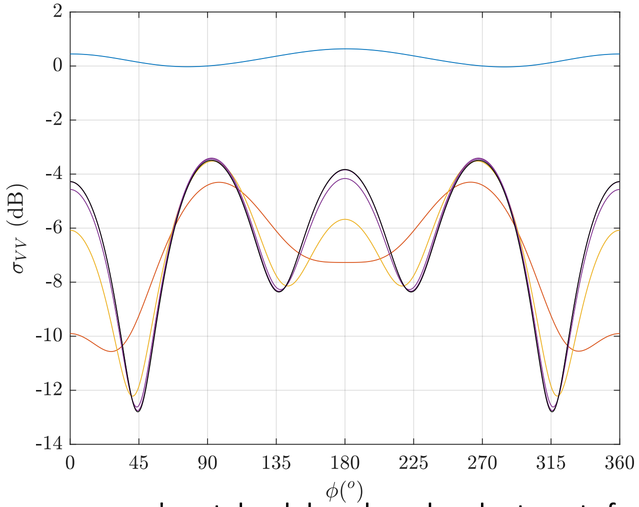

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Conclusions

- 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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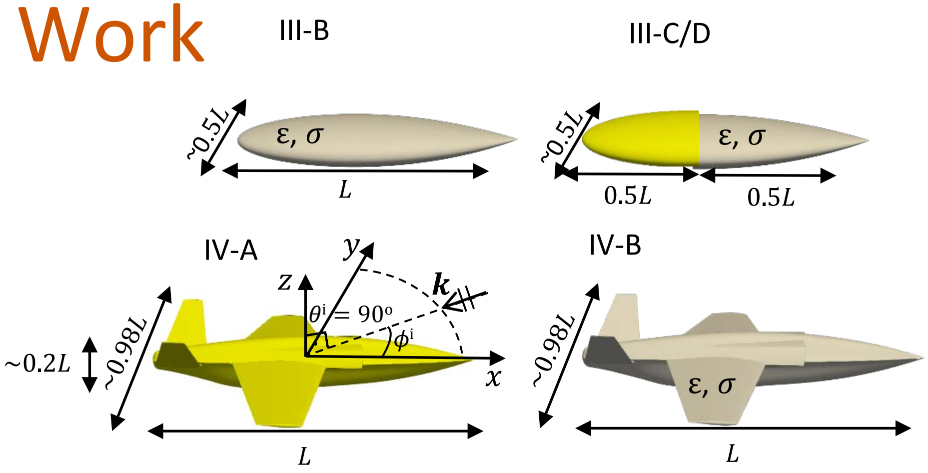
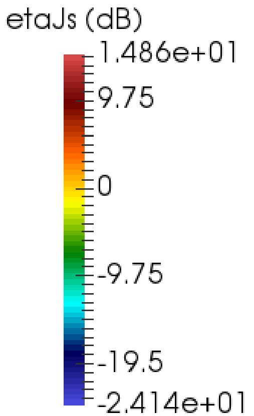
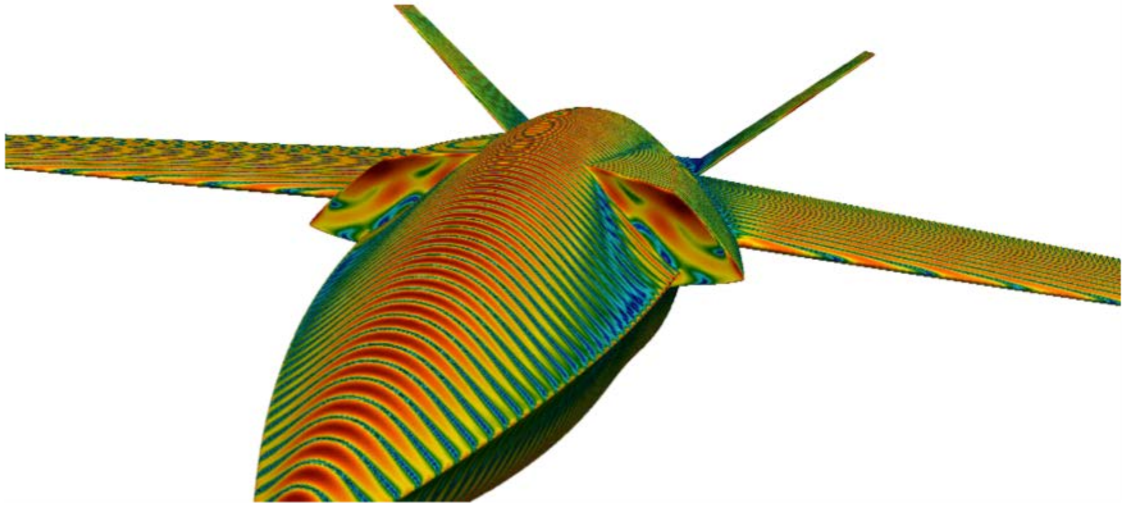
Conclusions

❑Ongoing Work





ARCHIE-AIM
1 GHz
VV Polarization
N = 3 970 857



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