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ODEN INSTITUTE
FOR COMPUTATIONAL ENGINEERING & SCIENCES

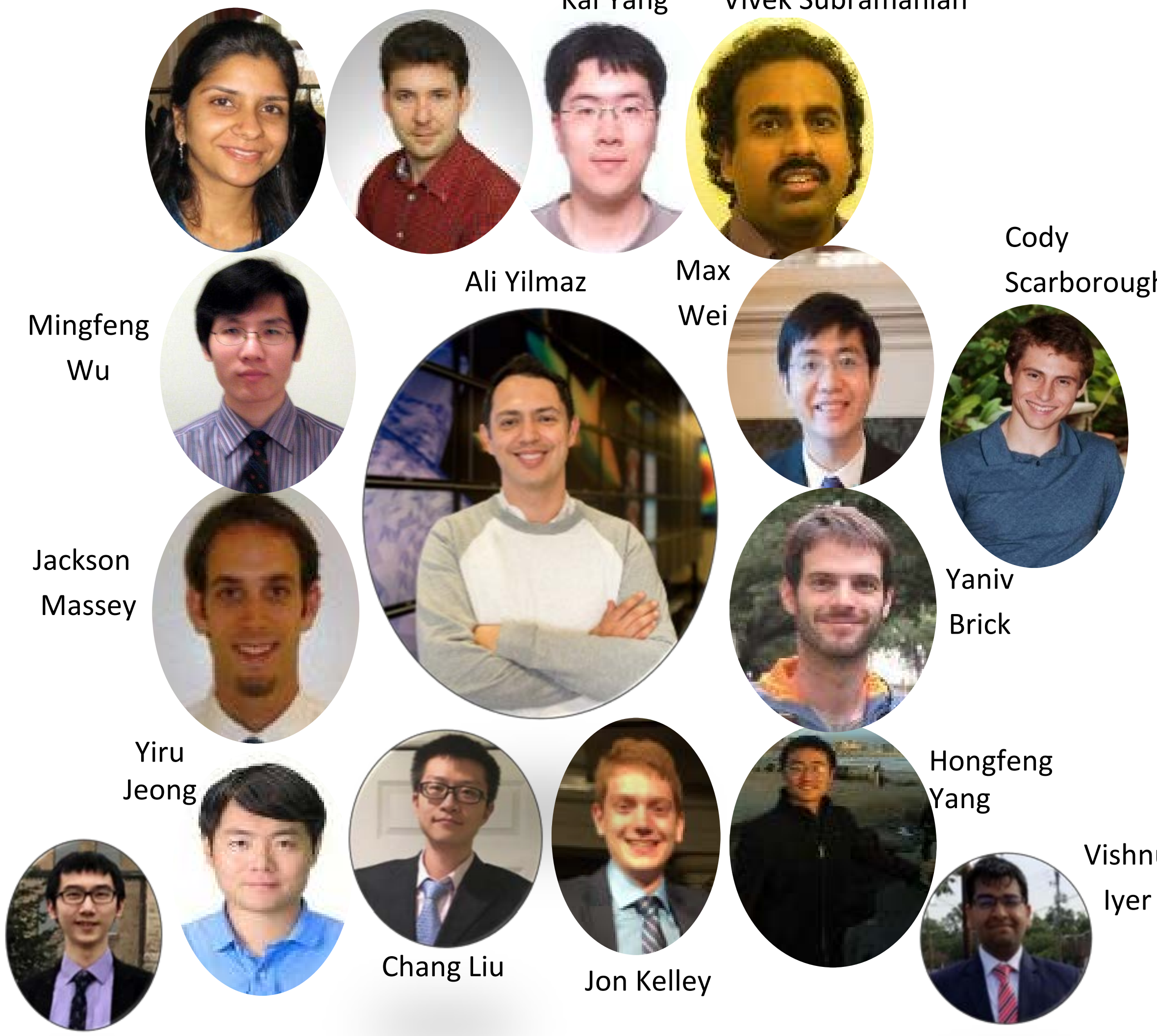
# Using (Super)Computers Judiciously for Higher Fidelity Electromagnetic Analysis


**Ali E. Yılmaz**

Oden Institute for Computational Engineering & Sciences
Department of Electrical & Computer Engineering
The University of Texas at Austin


MICDE Seminar
University of Michigan
Ann Arbor, MI, Oct. 10, 2019

# Acknowledgments


National Science Foundation
WHERE DISCOVERIES BEGIN

FULBRIGHT

GRFP
NSF GRADUATE RESEARCH FELLOWSHIP PROGRAM

NRF
National Research Foundation of Korea

XSEDE
Extreme Science and Engineering Discovery Environment

TACC
TEXAS ADVANCED COMPUTING CENTER

intel

SRC Semiconductor Research Corporation

U.S. DEPARTMENT OF ENERGY

Statoil

FORMATION EVALUATION
Joint Industry Research Consortium

# Outline

- Motivation: When Is Human Expertise/Judgment Needed?
  - Computational Solutions to Electromagnetics Problems
  - Judging Model Fidelity
  - Using Analysis Results to Make Better Judgments: A Reasonable Approach?
    - Prone to Distortions from Computational System/Method of Analysis
- Why Judging the Appropriate Computational System(s)/Method(s) is Hard
  - Computational Systems are Complex
  - Sea Change in Computing
  - Increasing Diversity of Algorithms
- A Possible Solution: Modern Benchmark Suites and Advanced Benchmarking
  - What is High Performance in CEM?
  - What is a Modern CEM Benchmark? Necessary Ingredients
  - Example from Our Ongoing Work: Austin RCS Benchmark Suite
- Conclusion

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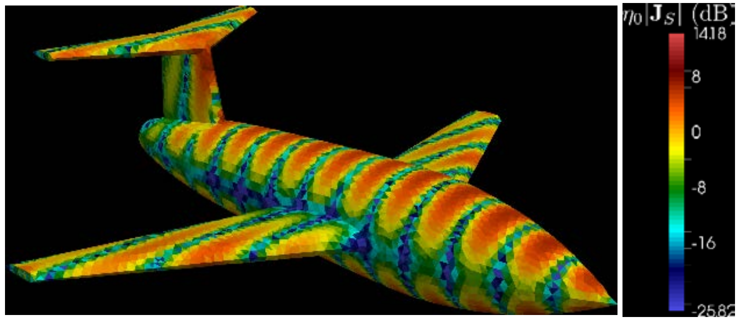
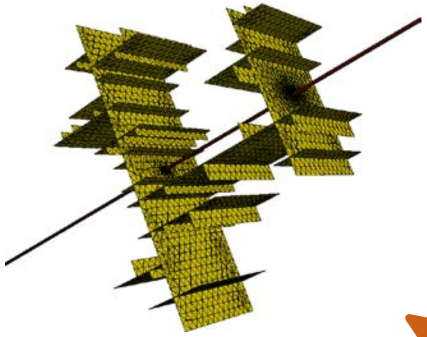
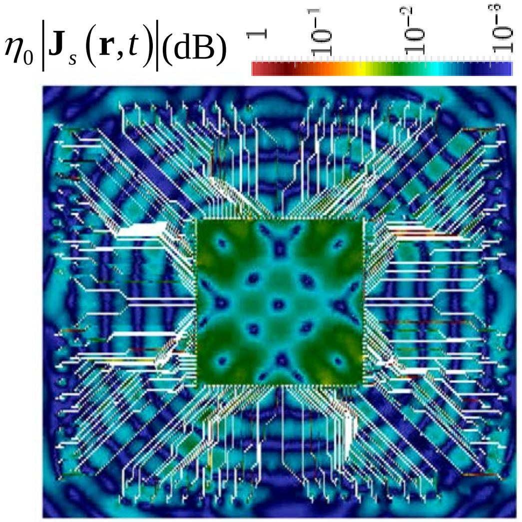
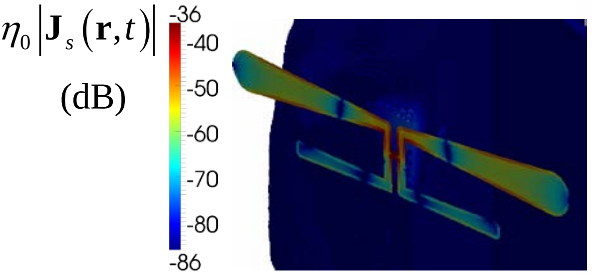
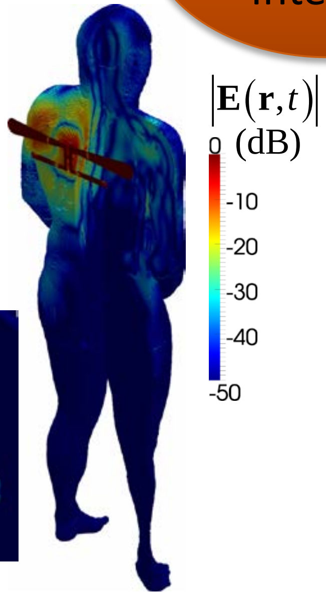
# Computational Solutions to Electromagnetics Problems





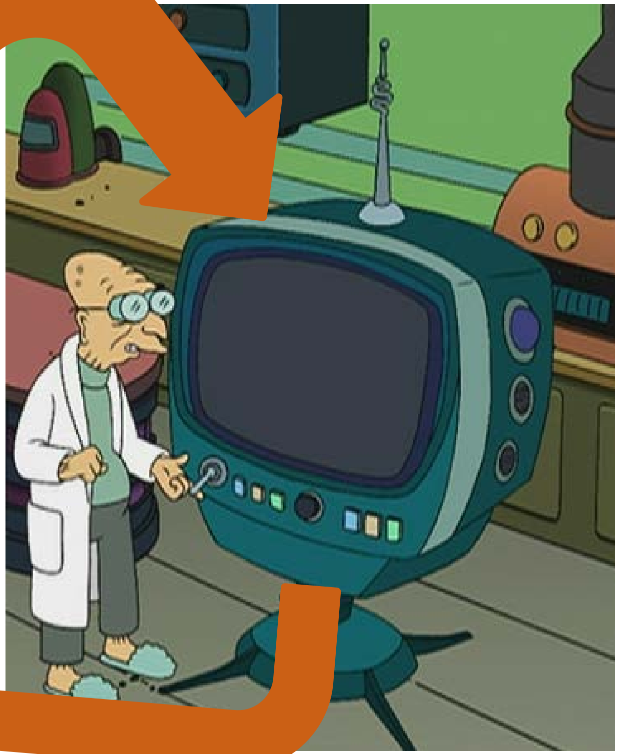

Problem Of Interest

Modeling (Computational)

- Choose "appropriate fidelity"
- Specify domain, geometry, frequency, EM material properties, sources, observers, …

Use Software

- Visualize & interpret results
- Investigate model parameters
- Pose & answer questions



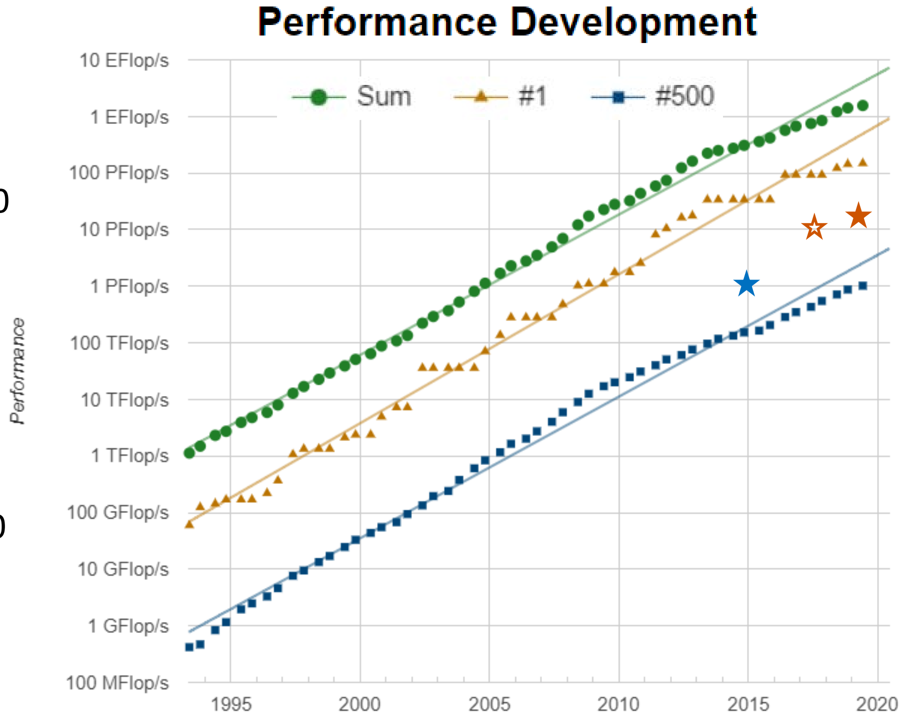
Original cartoon from: https://futurama.fandom.com/wiki/Who-Ask_Machine

# Top Supercomputers

June 2019 Rankings (top500.org)

1. Summit
IBM Power9
**2x22 cores** 3.07 GHz
+ Nvidia Volta GV100
2.41M+ cores
~148.6 Pflop/s

2. Sierra
IBM Power9
**2x22 cores** 3.1 GHz
+ Nvidia Volta GV100
1.57M+ cores
~94.6 Pflop/s

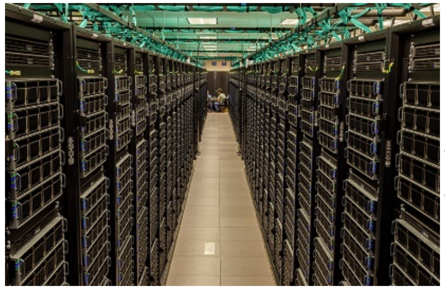



3. Sunway TaihuLight
Sunway SW26010
**4x64 cores** 1.45 GHz
10.6M+ cores
~93 Pflop/s

4. Tianhe-2A
Intel Xeon E5
**2x12 cores** 2.2 GHz
+Matrix-2000
4.98M+ cores
~61.4 Pflop/s

>500. Lonestar 5★
Intel Xeon E5
**2x12 cores** 2.6 GHz
30K cores
~1 Pflop/s

19. Stampede 2☆
Intel “Knights Landing”
Xeon Phi 7250
**68x4 cores** 1.4 GHz
367K cores
~10.7Pflop/s



5. Frontera★
Intel Xeon Platinum 8280
**2x28 cores** 2.7 GHz
~448K cores
~23.5 Pflop/s

# Top Supercomputers



Original images from:

http://www.pinterest.com/pin/482307441326840983

https://bringatrailer.com/listing/2004-ferrari-360-spider-5

https://en.wheelsage.org/hennessey/venom_gt/29384/pictures/512009/

https://www.cnet.com/roadshow/news/1600-horsepower-hennessey-venom-f5-a-car-of-singular-purpose/

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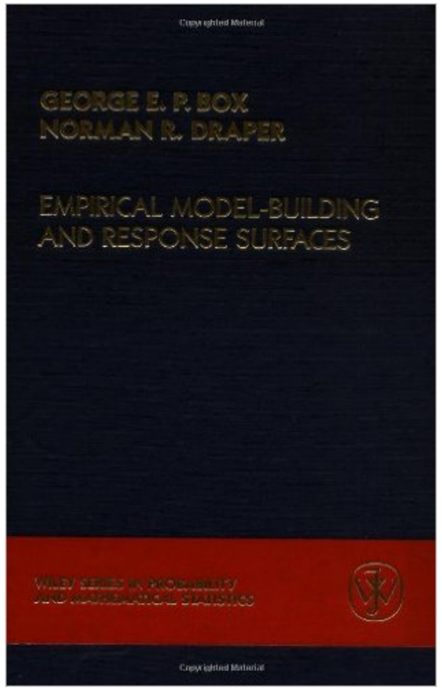
# Building Models and Analyzing Them




Remember that all models are wrong; the practical question is how wrong do they have to be to not be useful. (p. 74)

Essentially, all models are wrong, but some are useful. (p. 424)

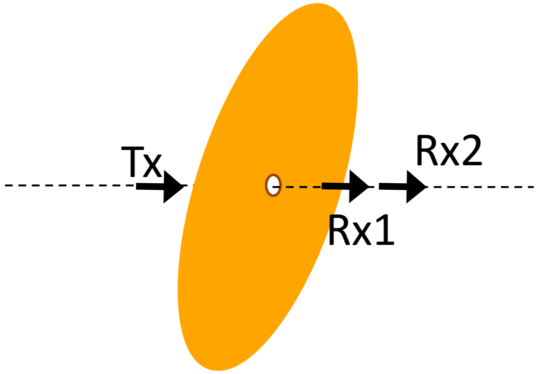
(G. E. P. Box and N. R. Draper)

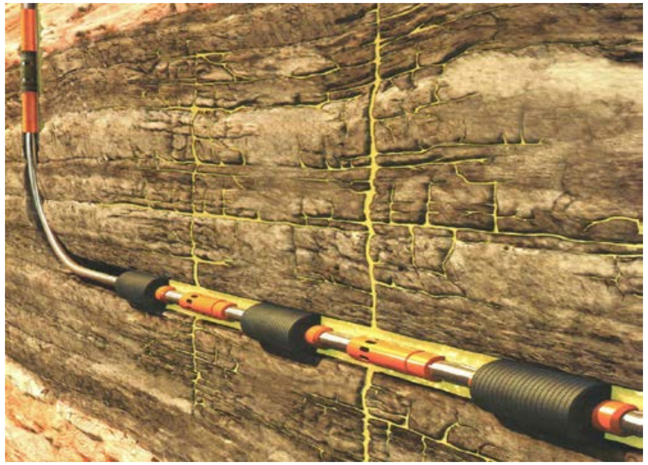

Original cartoon from:
http://blog.marksgroup.net/2013/05/zoho-crm-garbage-in-garbage-out-its.html

# What is the Appropriate Model Fidelity for this Problem?

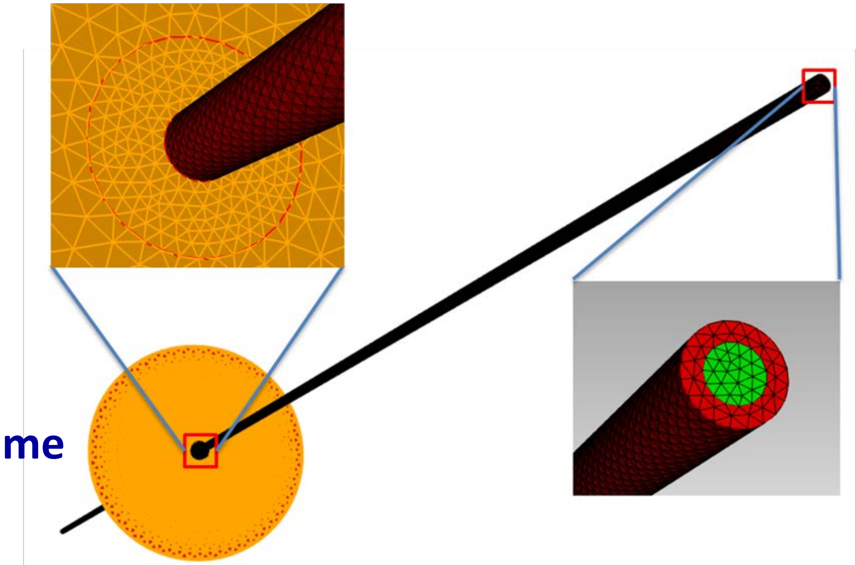
**(Over?)Simplified model**
- Simple fracture
- Circular conductive disc, uniform features/mesh
- Borehole not modeled

**2 mins of wall-clock time**



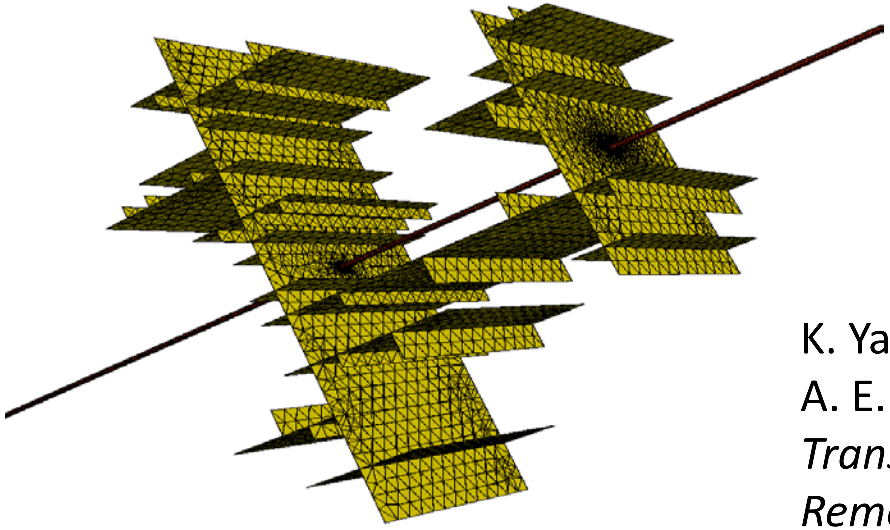



**Refined model**
- Simple fracture + borehole model



**10 mins**
**~~2 hrs of~~ wall-clock time**

**Higher-fidelity model**
- Complex fracture + borehole model



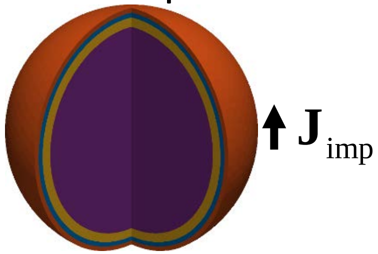
**2 hrs**
**~~800~~ hrs of wall-clock time**

K. Yang, C. T.-Verdin A. E. Yilmaz, *IEEE Trans. Geosci. Remote Sensing*, Aug. 2015.

# What is the Appropriate Model Fidelity for this Problem?

**(Over?)simplified model**

Multilayered head-sized sphere + Hertzian Dipole




**<1 s of wall-clock time**

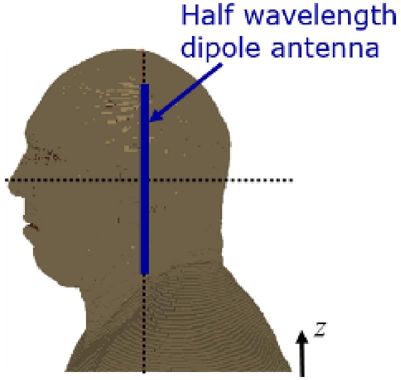
**Refined models**

AustinWoman + Hertzian Dipole


**3 hrs, 16K CPU cores**

**~~??~~ hrs of wall-clock time**

AustinMan +Half-Wavelength Dipole



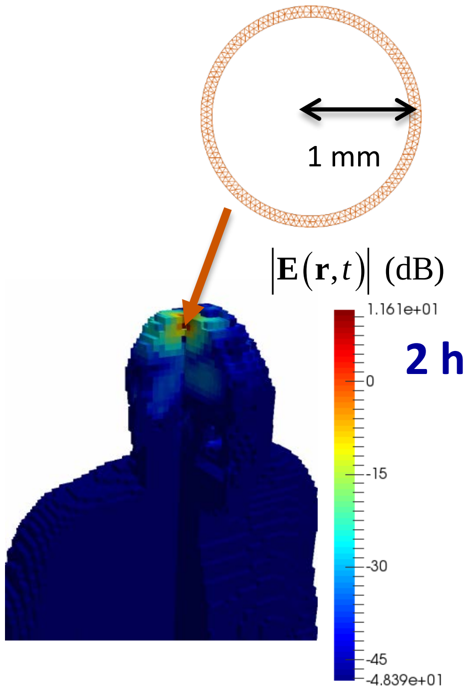

F. Wei and A. E. Yilmaz, in *Proc. ICEAA*, Sep. 2012.

**Higher-fidelity models**

AustinMan + AMF Antenna

J. W. Massey *et al.*, in *Proc. EuCAP*, Apr. 2016.

AustinWoman + Implanted Sensor



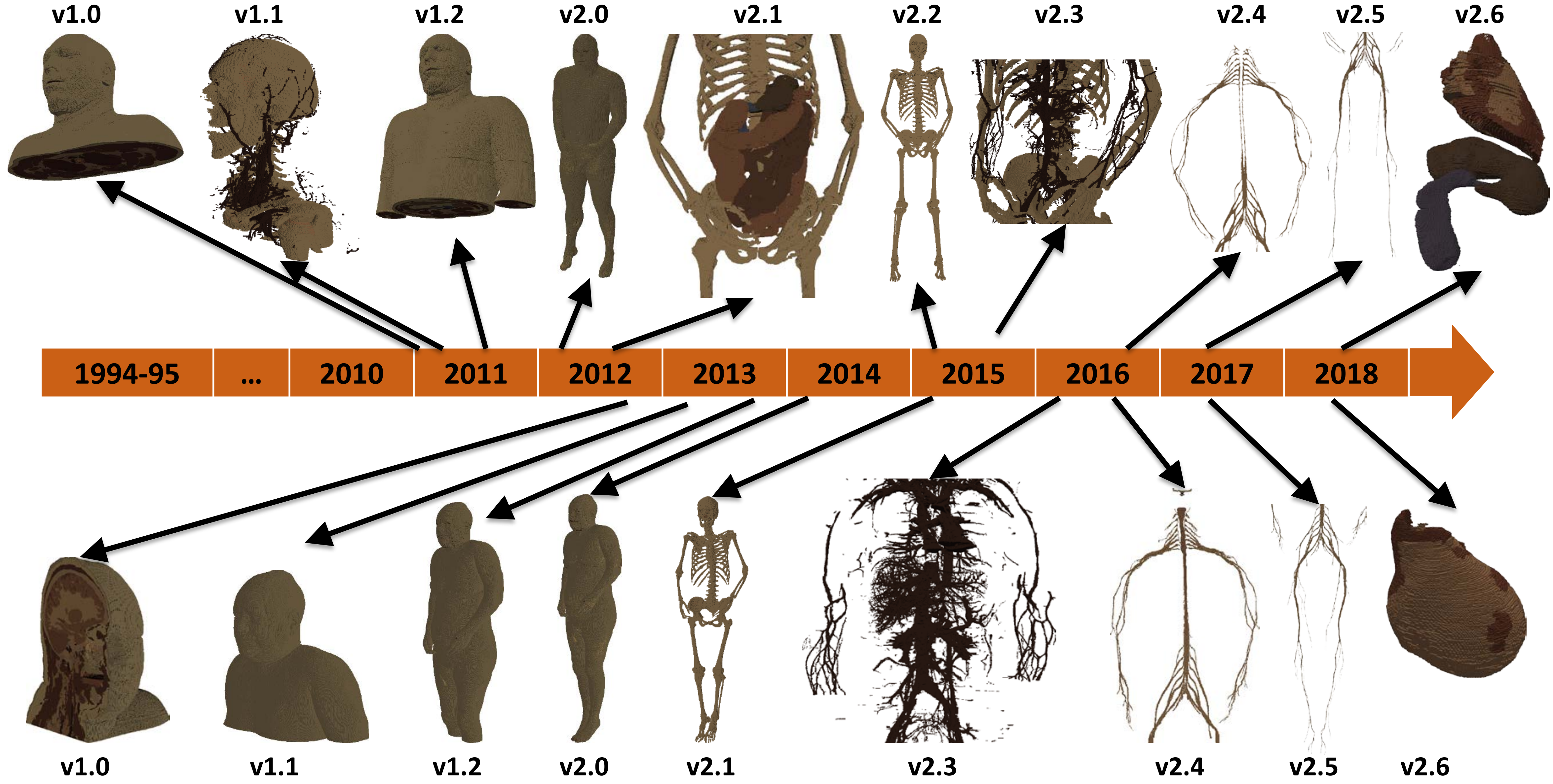

**2 hrs, 32 CPU cores**

**~~??~~ hrs of wall-clock time**

J. W. Massey and A. E. Yılmaz, in *Proc. URSI NRSM*, Jan. 2016.

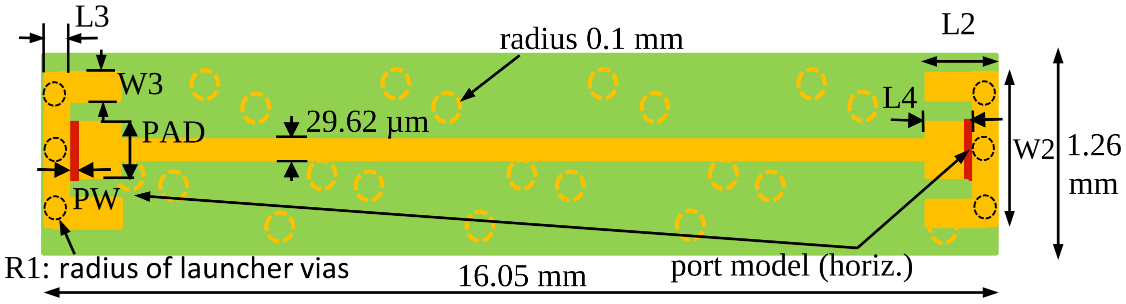
# Model Development History

AustinMan & AustinWoman models available at http://bit.ly/AustinMan



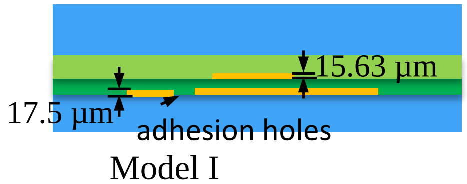
# What is the Appropriate Model Fidelity for this Problem?

Top-down view

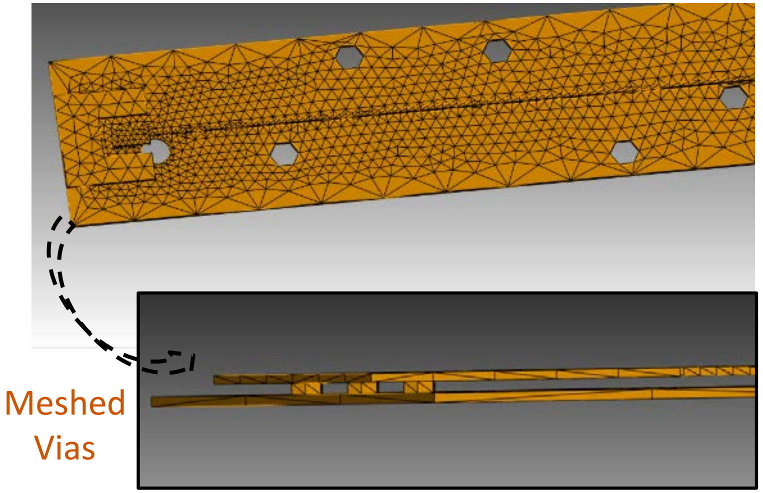



Cross-section view

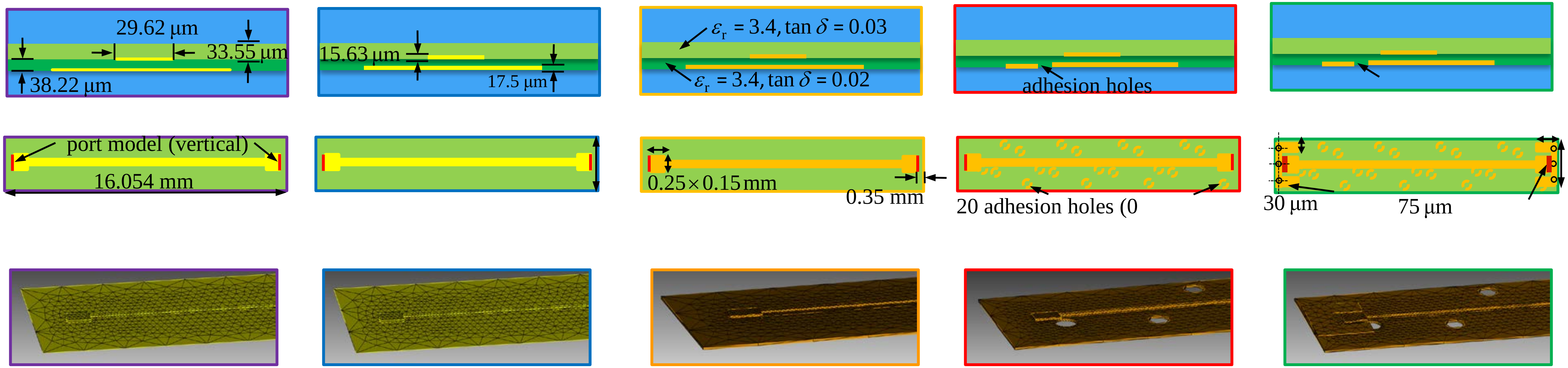
Copper    Port model




Mesh view

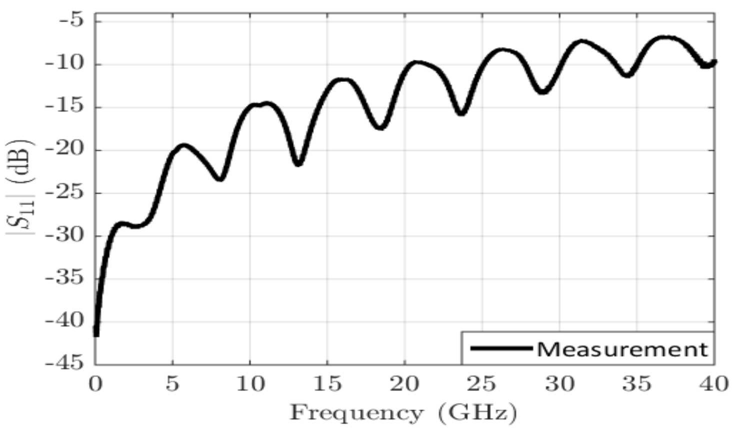


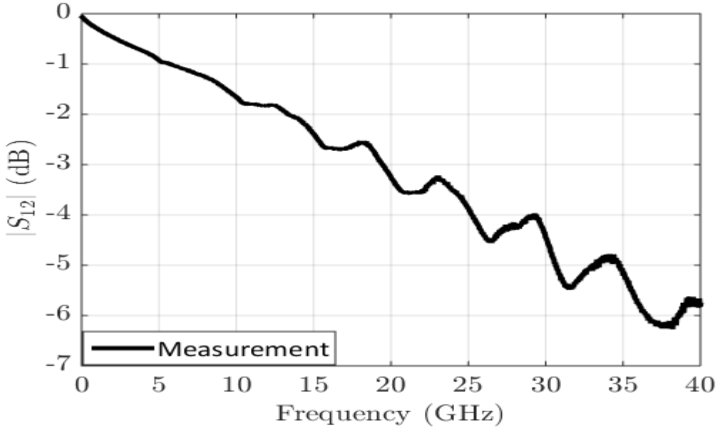

C. Liu, K. Aygun, and A. E. Yılmaz, *Int. J. Num. Modelling: Electron. Netw., Dev. and Fields*, Sep. 2019.



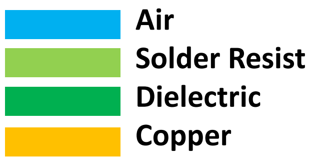
# What is the Appropriate Model Fidelity for this Problem? Analysis-Driven Modeling

## Measurement

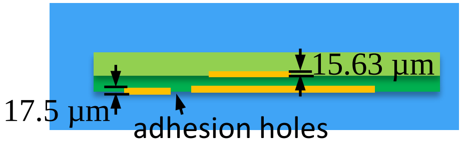



Single-Ended Microstrip:



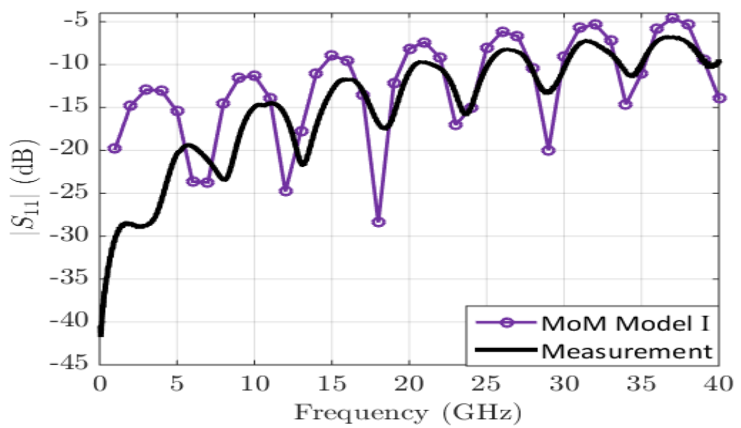

Cross-section view

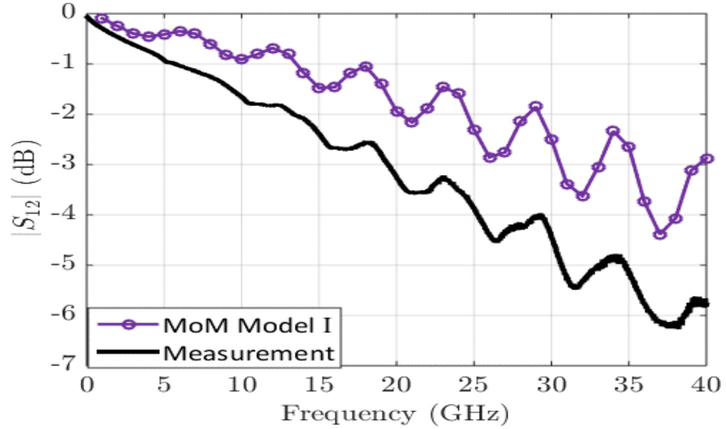


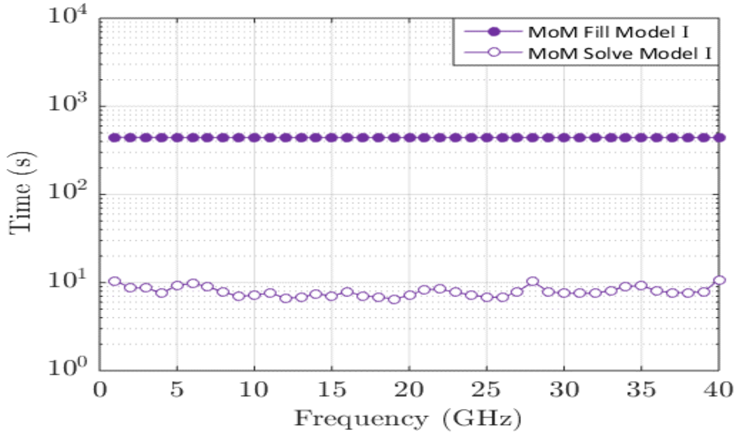
# What is the Appropriate Model Fidelity for this Problem? Analysis-Driven Modeling

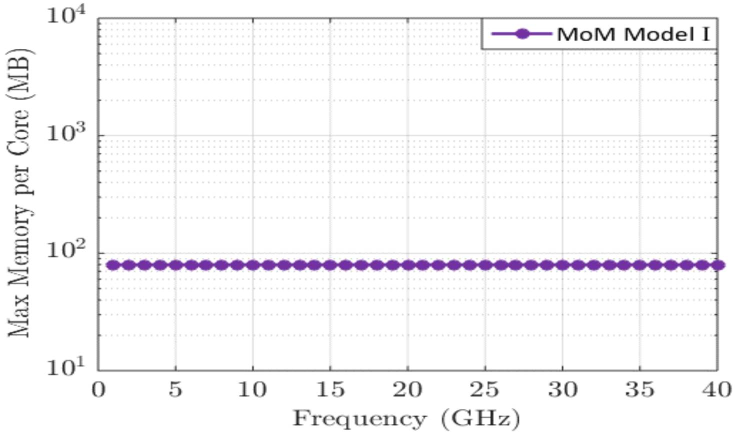
C. Liu, K. Aygun, and A. E. Yılmaz, *Int. J. Num. Modelling: Electron. Netw., Dev. and Fields*, Sep. 2019.

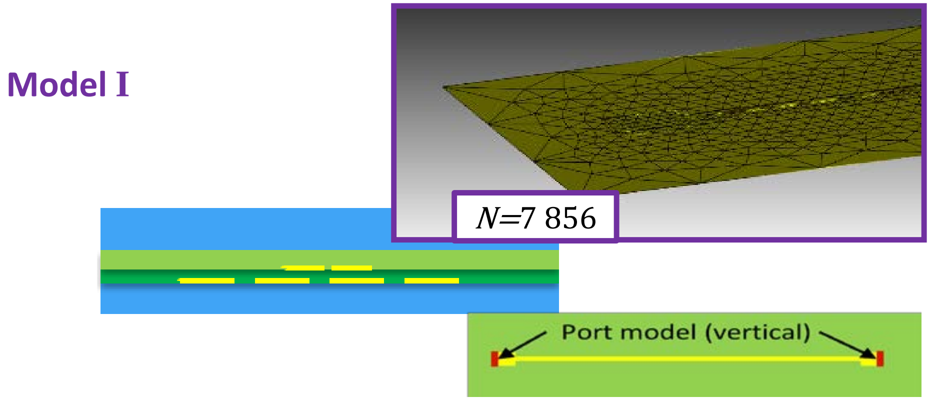
## Model I (thin PEC)




- Simplest model
- Sequential: ~2.5 hrs to fill, 2.5 mins to solve/freq, ~2 GB total memory
- 24 cores: ~6 mins to fill, 10 s to solve/freq, ~80 MB/core

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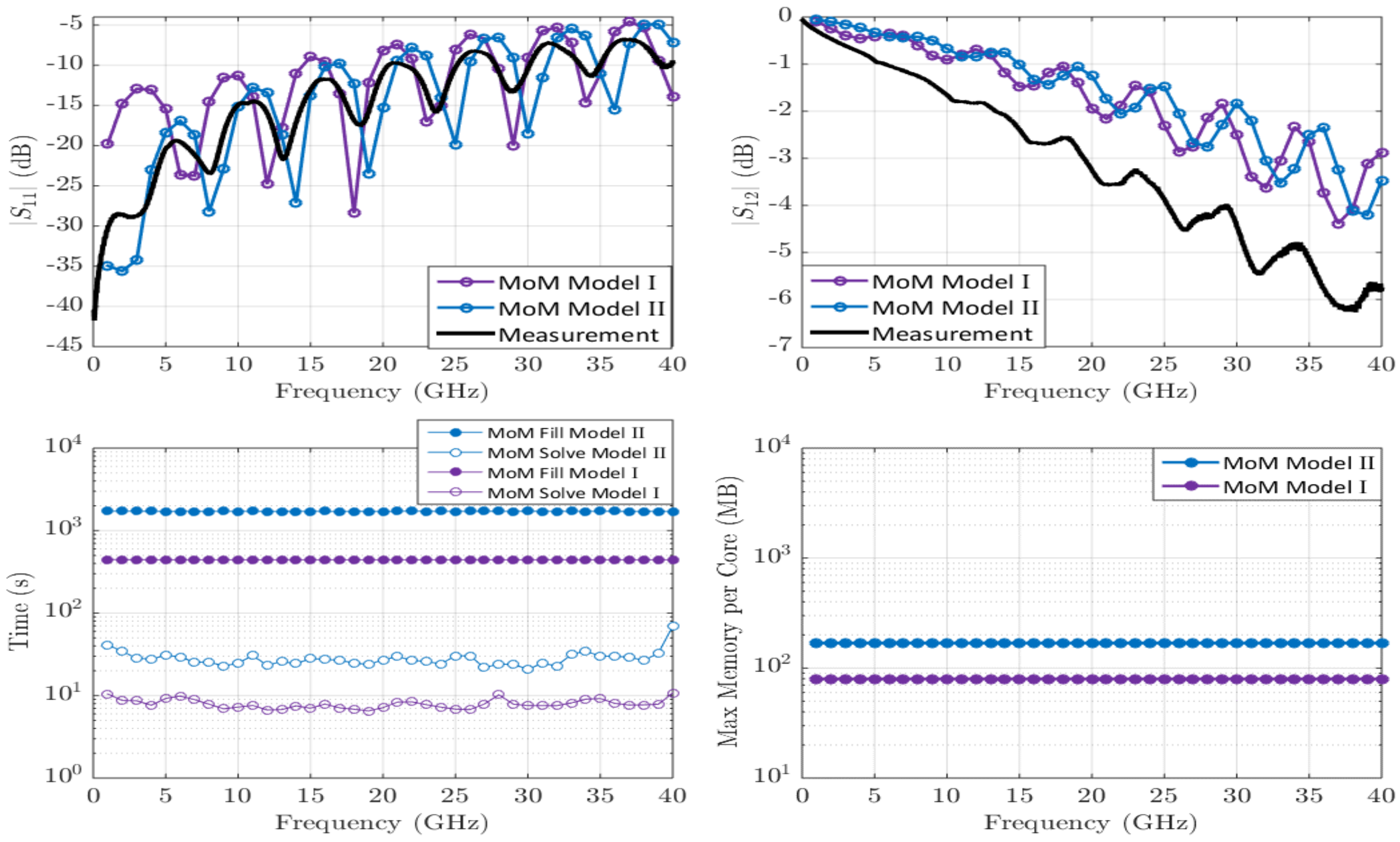
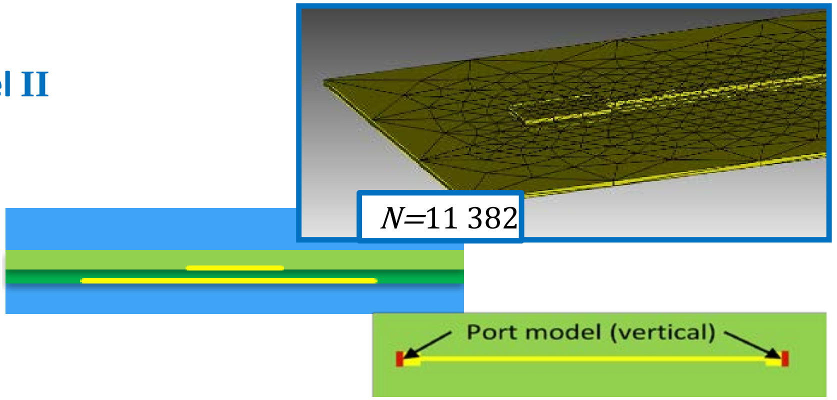
# What is the Appropriate Model Fidelity for this Problem? Analysis-Driven Modeling

**Model I (thin PEC)** vs. **Model II (thick PEC)**

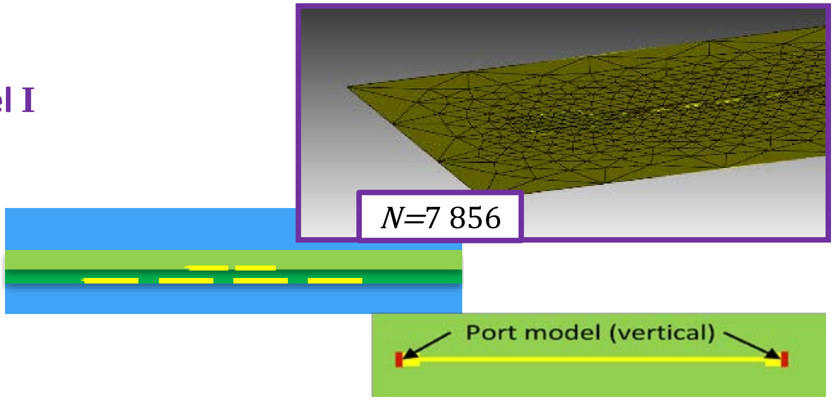
C. Liu, K. Aygun, and A. E. Yılmaz, *Int. J. Num. Modelling: Electron. Netw., Dev. and Fields*, Sep. 2019.




Model II




Model I

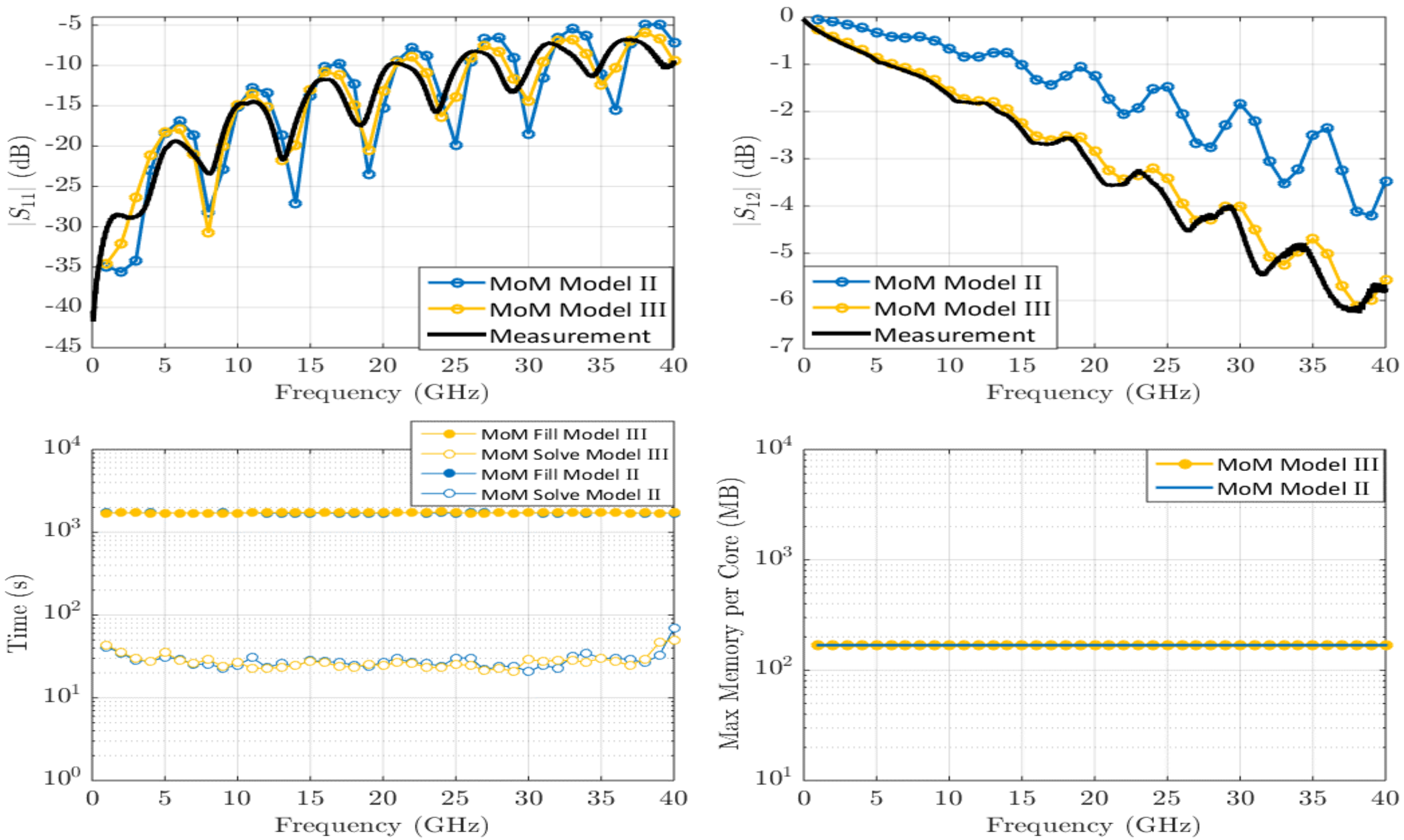



- Conductor thickness: Important?
- Thickness modeling significantly more expensive

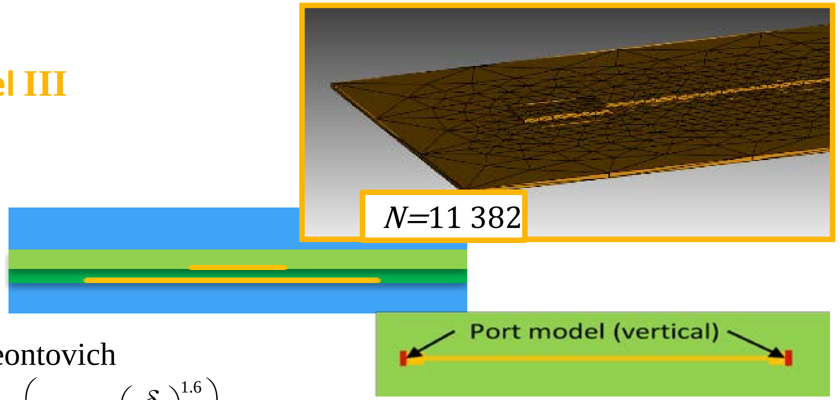
# What is the Appropriate Model Fidelity for this Problem? Analysis-Driven Modeling

## Model II (thick PEC) vs. Model III (thick IBC+SR)

C. Liu, K. Aygun, and A. E. Yılmaz, *Int. J. Num. Modelling: Electron. Netw., Dev. and Fields*, Sep. 2019.



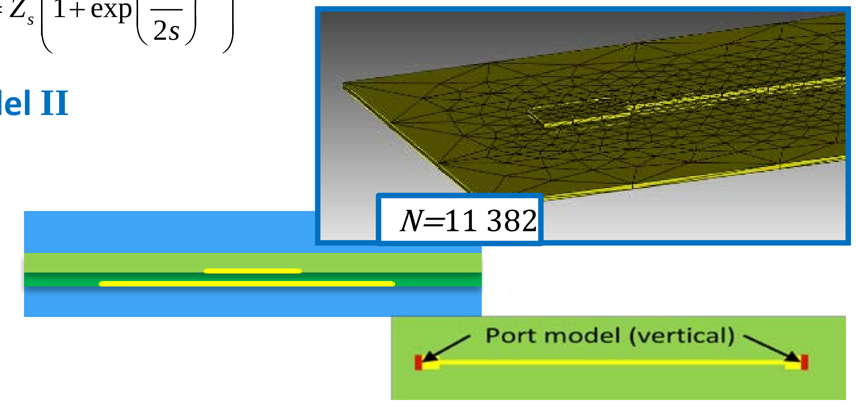

**Model III**




Groiss+Leontovich

$$Z_s^{\text{rough}} = Z_s\left(1+\exp\left(\frac{\delta}{2s}\right)^{1.6}\right)$$

**Model II**




- Simple IBC+SR model: sufficient?
- Costs: Negligible over PEC (for this IBC+SR model…)

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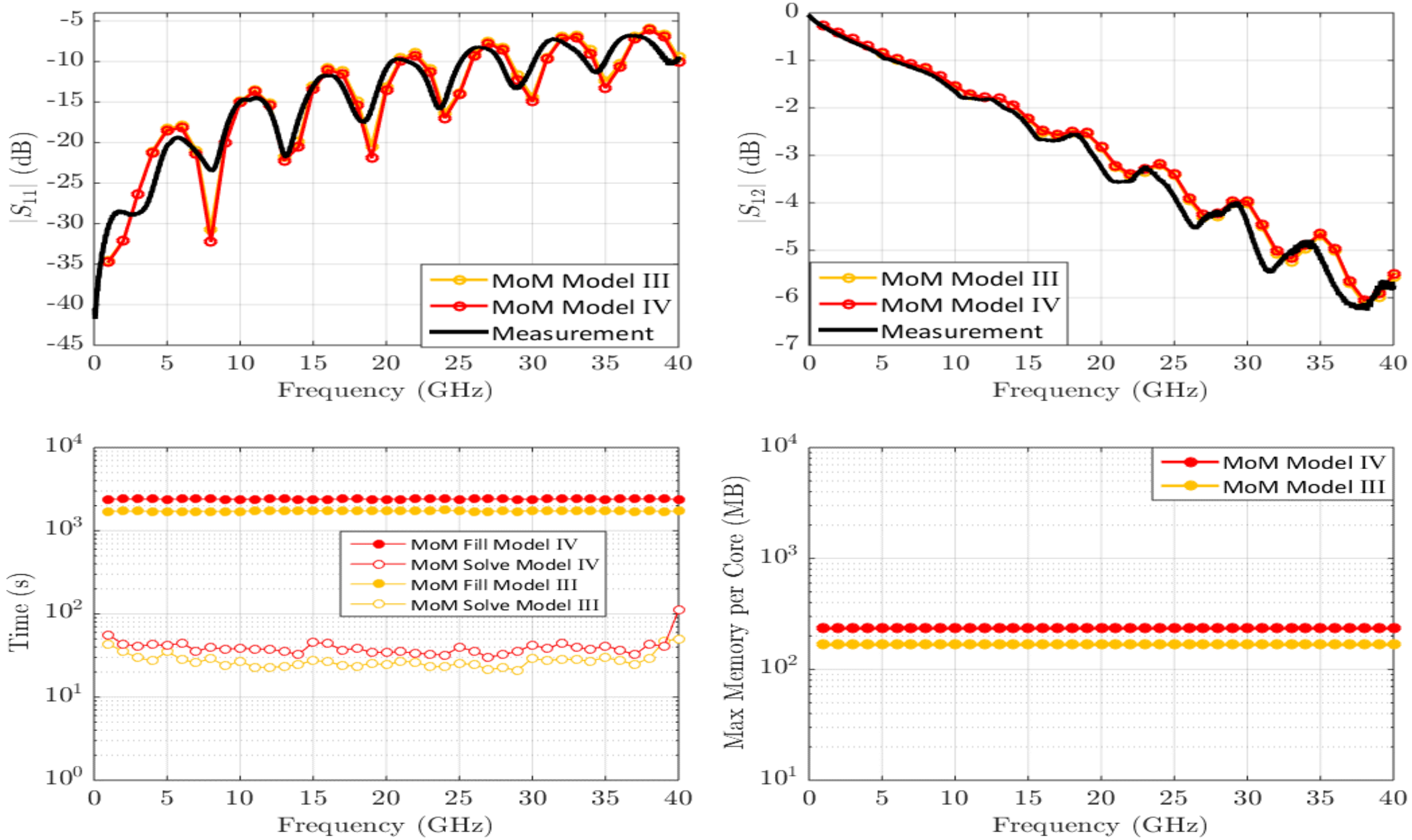
# What is the Appropriate Model Fidelity for this Problem? Analysis-Driven Modeling

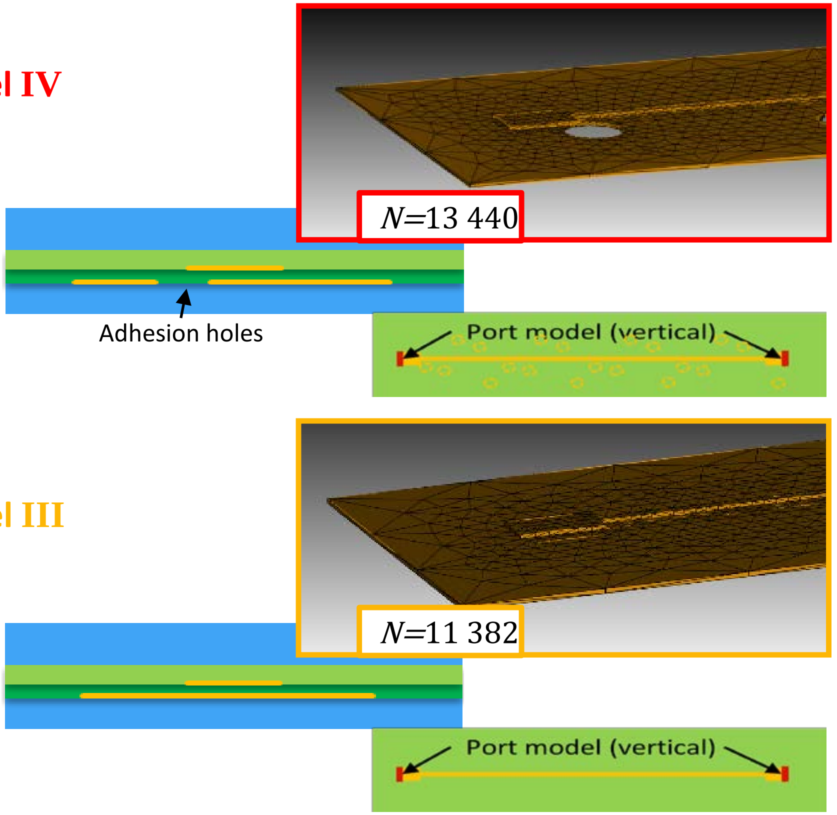
**Model III (thick IBC+SR)** vs. **Model IV (thick IBC+SR, adhesion holes)**

C. Liu, K. Aygun, and A. E. Yılmaz, *Int. J. Num. Modelling: Electron. Netw., Dev. and Fields*, Sep. 2019.




**Model IV**

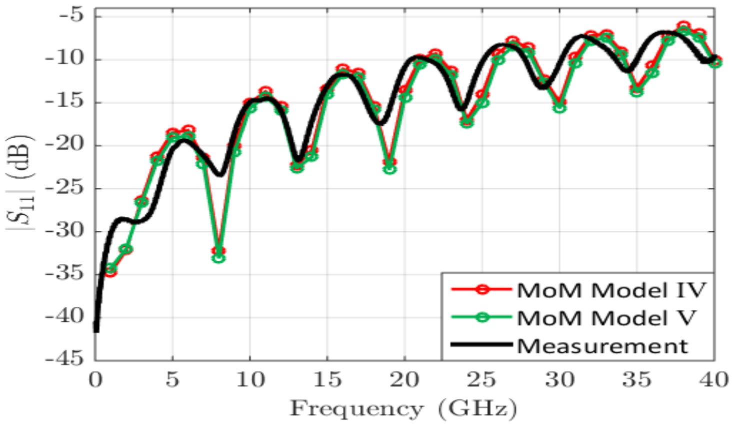
**Model III**

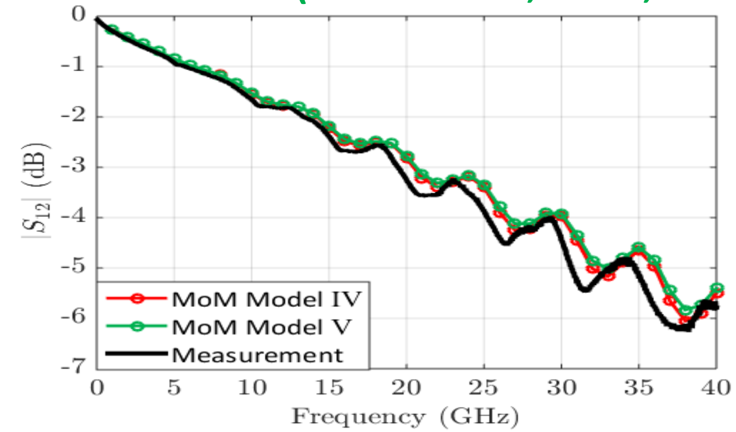


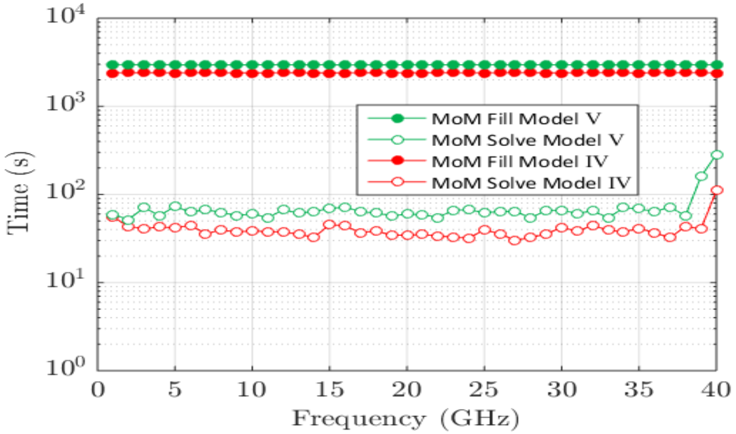
# What is the Appropriate Model Fidelity for this Problem? Analysis-Driven Modeling

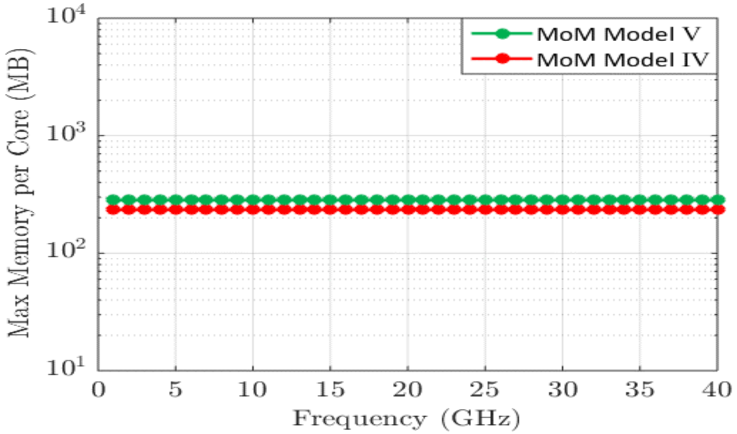
**Model IV (thick IBC+SR, holes)** vs **Model V (thick IBC+SR, holes, launcher)**

C. Liu, K. Aygun, and A. E. Yılmaz, *Int. J. Num. Modelling: Electron. Netw., Dev. and Fields*, Sep. 2019.

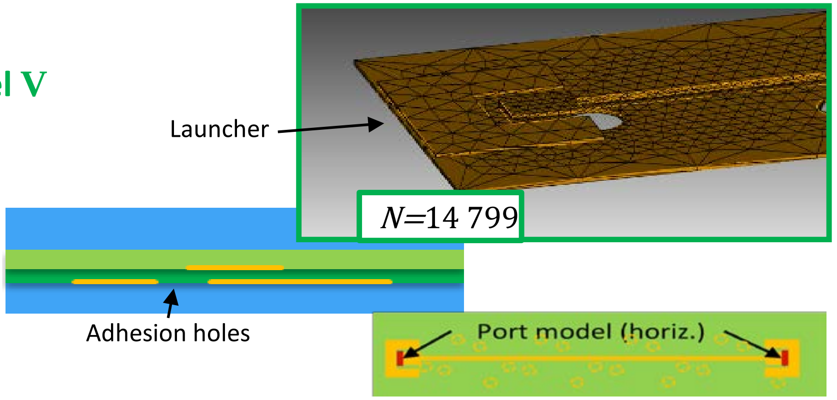


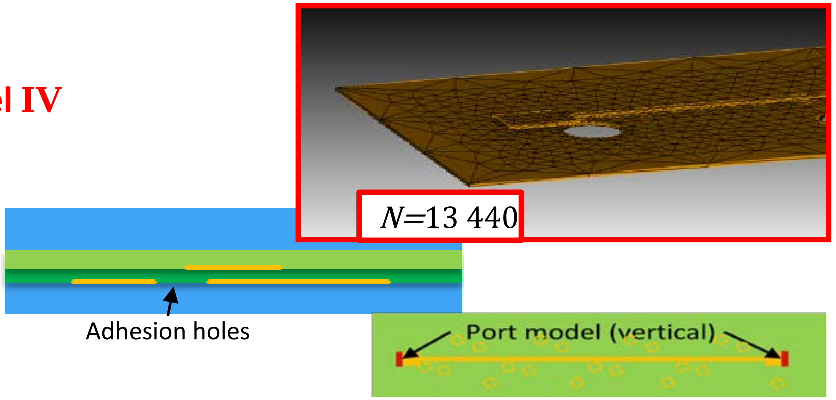




**Model V**




**Model IV**




- Launcher: Port basis change to horizontal

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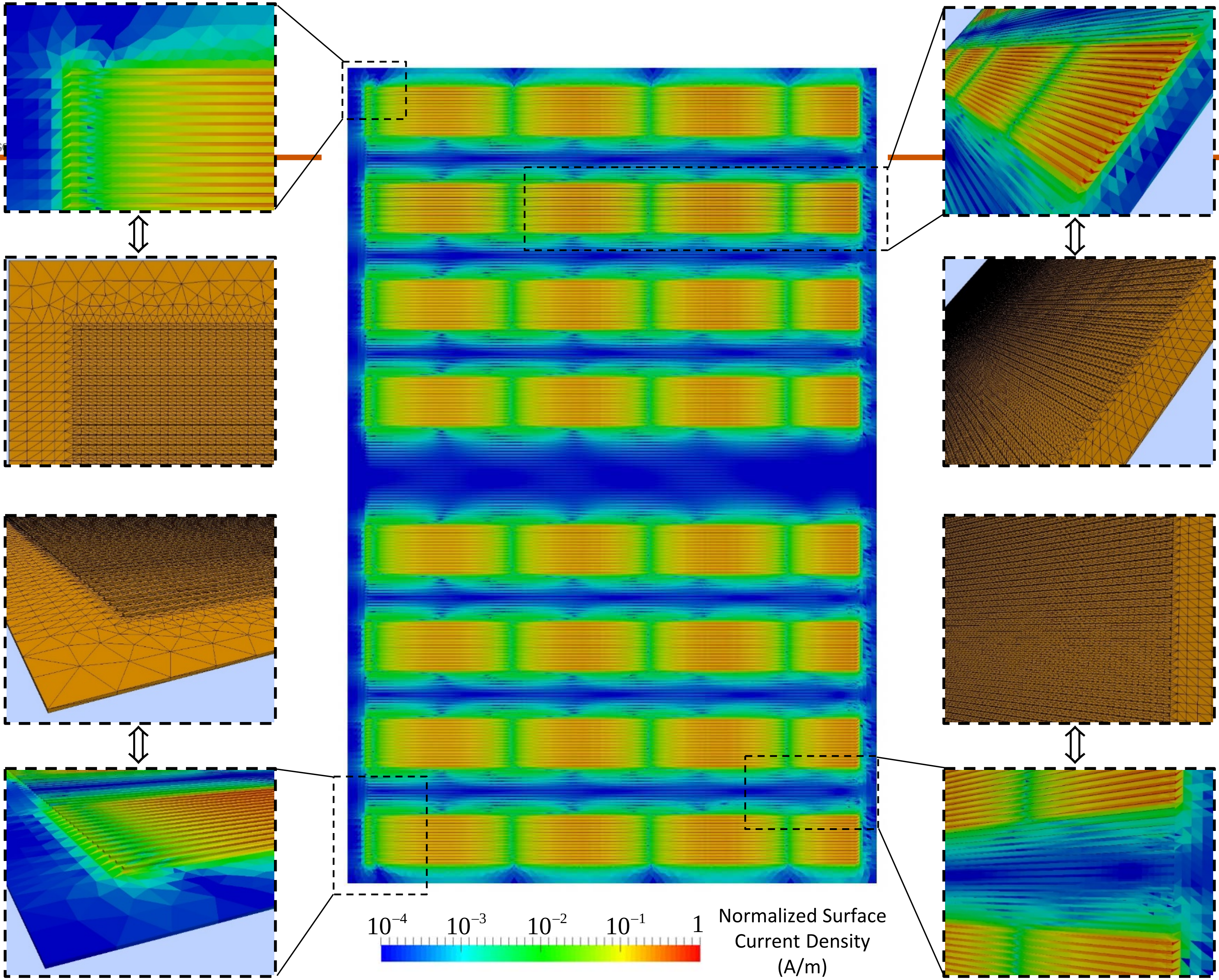


C. Liu, K. Aygun, and A. E. Yılmaz, *Int. J. Num. Modelling: Electron. Netw., Dev. and Fields*, Sep. 2019.

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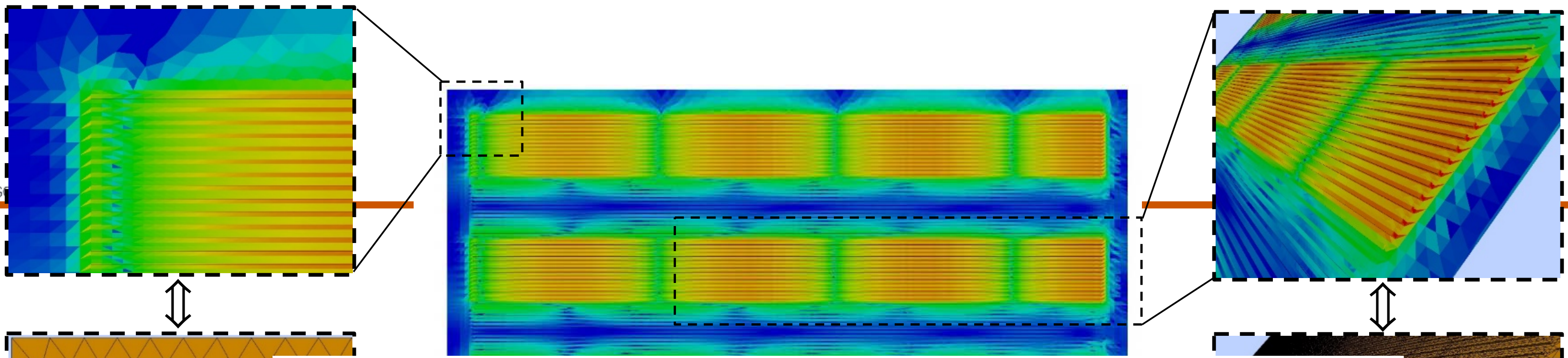
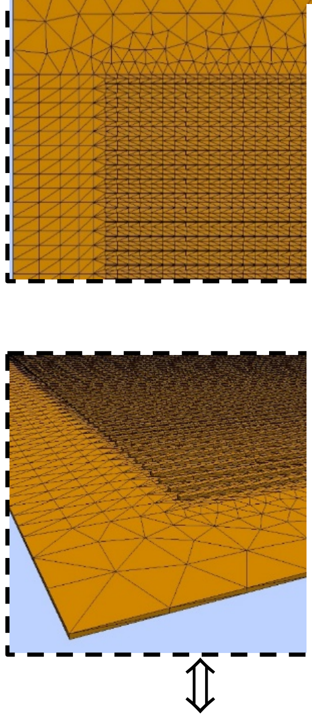
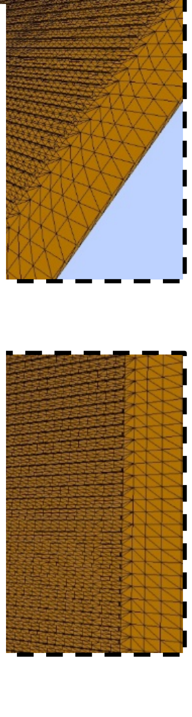
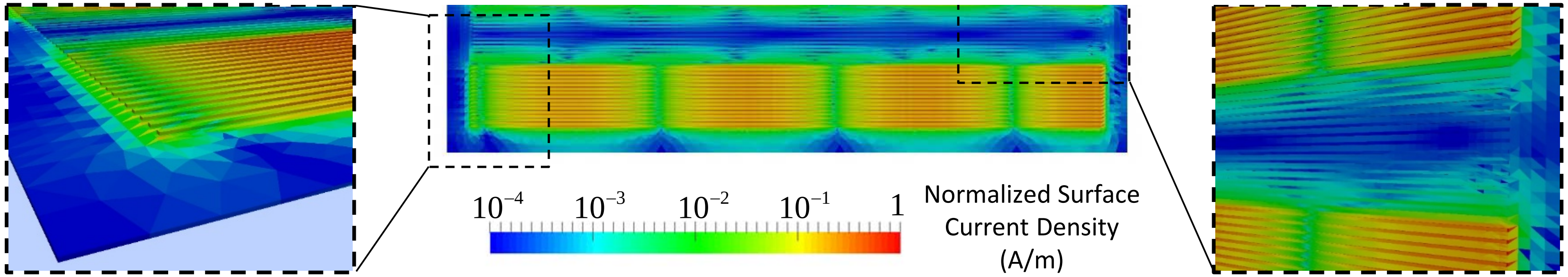







## Abstract

A parallel iterative layered-medium integral-equation solver is presented for fast and scalable network parameter extraction of electronic packages. The solver, which relies on a 2-D fast Fourier transform (FFT)-based algorithm and a sparse preconditioner to reduce computational complexity, is parallelized using three workload decomposition strategies, including a pencil decomposition that increases the scalability of the computationally dominant FFT-based multiplication stage. A set of increasingly difficult benchmark problems, which require network parameter computations for $N_{trace}$ = 1 to 257 package-scale interconnects, are solved on a petaflop scale computer to quantify the solver's accuracy, efficiency, and scalability. The total serialized computation time is observed to scale asymptotically as $N_{trace}^{2.6}\log N_{trace}$. For the largest problem, using ~1.14 million unknowns and 1536 processes, the solver requires a wall-clock time of ~0.05 s per iteration, ~1 minute per excitation, ~9 h per frequency, and ~424 hours to extract the 514-port network parameters at 40 sample frequencies between 1 to 40 GHz.

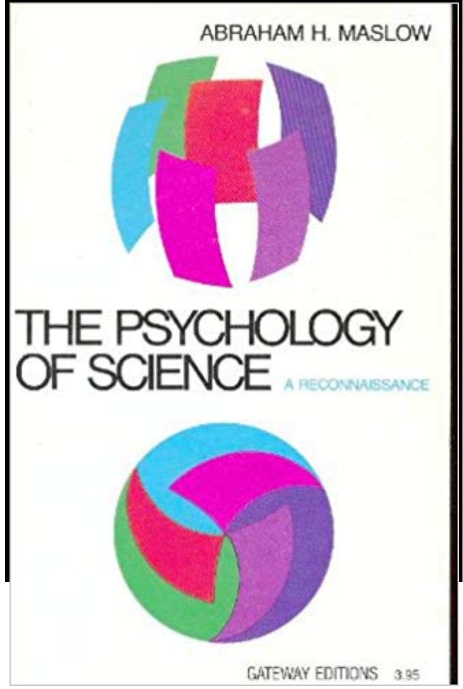
UT ECE

ODEN INSTITUTE FOR COMPUTATIONAL ENGINEERING & SCIENCES

# Judging the "Appropriate Method" for a Given Model (Some Methods are Inefficient for Some Problems)

Original image from: https://www.dreamstime.com/stock-photos-hammer-screw-image3879063

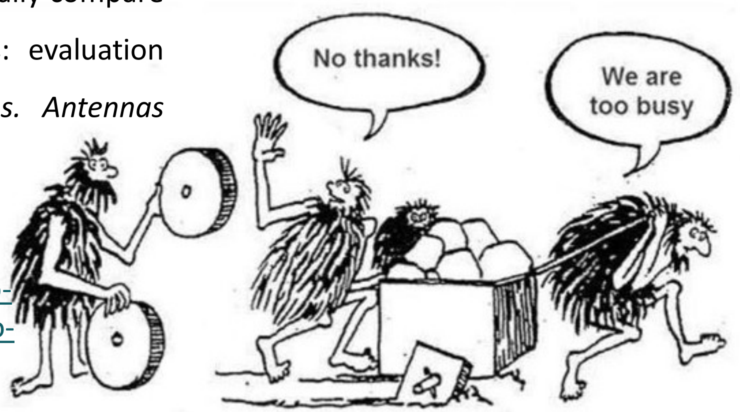
I suppose it is tempting, if the only tool you have is a hammer, to treat everything as if it were a nail. (p. 15)




Reviewer's Comment: "The manuscript provides a rather comprehensive comparison of several numerical methods…It is the opinion of this reviewer that the manuscript represents a high standard of research and will be a valuable source of information in bioelectromagnetics."

Track Editor's Comment: "My own feeling is that people generally choose the method they are most familiar with and/or the one that provides the capabilities most important to them. I'm not sure that at this point a comparison is needed. The general advantages of method A vs. method B is known."

J. W. Massey *et al.* "A methodology to empirically compare computational bioelectromagnetics methods: evaluation of three competitive methods," *IEEE Trans. Antennas Propag.*, Aug. 2018.

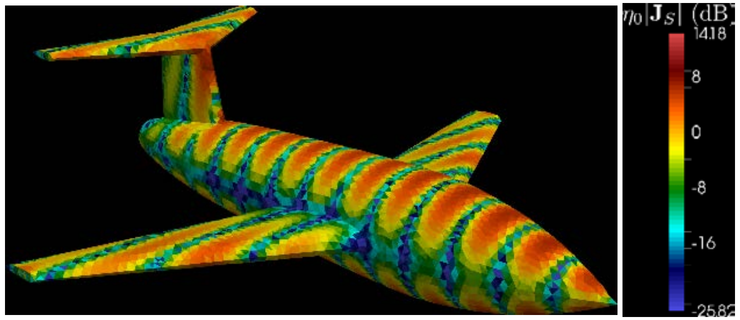


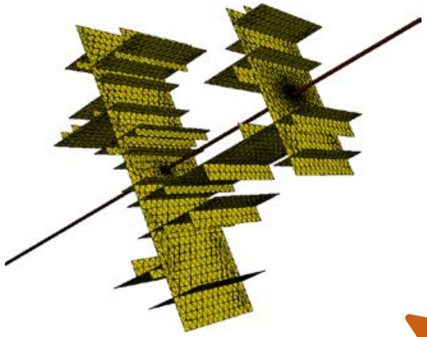

Original cartoon from: https://www.optimisation-conversion.com/wp-content/uploads/2014/10/no-thanks-were-too-busy-optimisation-conversion-e1412662937341.jpg

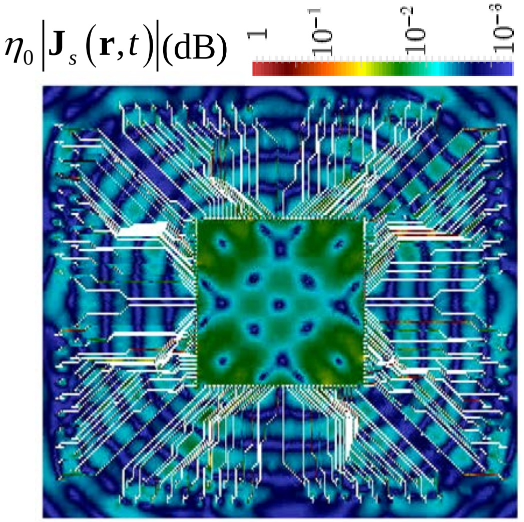
# Outline

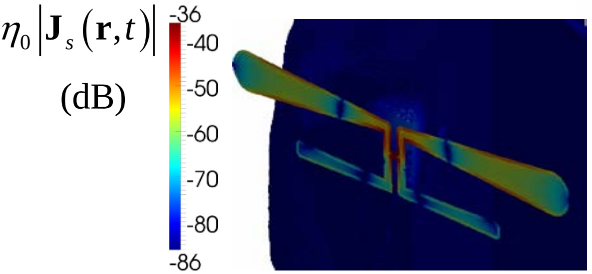
- Motivation: When Is Human Expertise/Judgment Needed?
  - Computational Solutions to Electromagnetics Problems
  - Judging Model Fidelity
  - Using Analysis Results to Make Better Judgments: A Reasonable Approach?
    - Prone to Distortions from Computational System/Method of Analysis
- Why Judging the Appropriate Computational System(s)/Method(s) is Hard
  - Computational Systems are Complex
  - Sea Change in Computing
  - Increasing Diversity of Algorithms
- A Possible Solution: Modern Benchmark Suites and Advanced Benchmarking
  - What is High Performance in CEM?
  - What is a Modern CEM Benchmark? Necessary Ingredients
  - Example from Our Ongoing Work: Austin RCS Benchmark Suite
- Conclusion

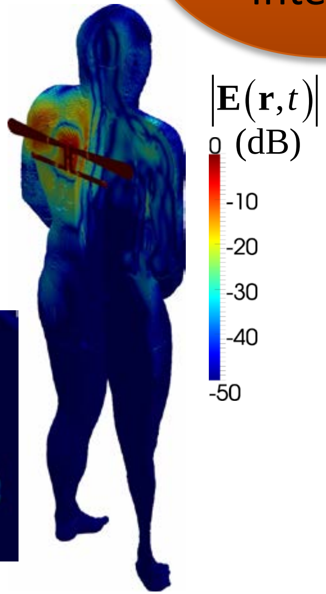
# Computational Solutions to Electromagnetics Problems





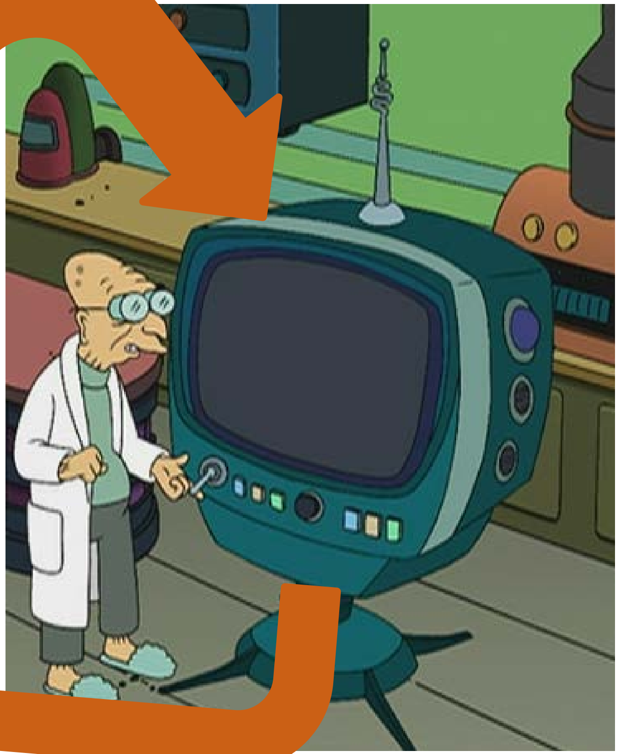

Problem Of Interest

Modeling (Computational)

- Choose "appropriate fidelity"
- Specify domain, geometry, frequency, EM material properties, sources, observers, …

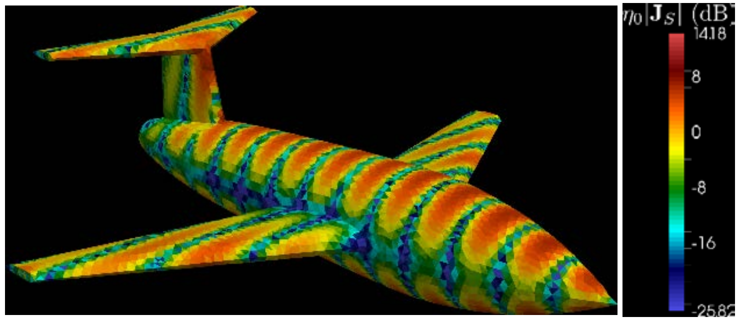
Use Software

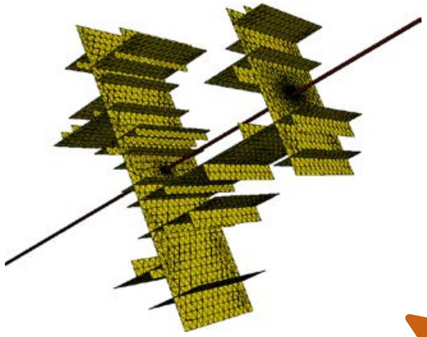
- Visualize & interpret results
- Investigate model parameters
- Pose & answer questions

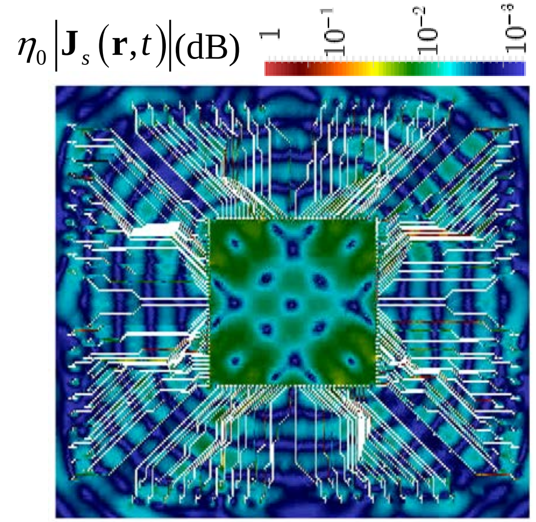


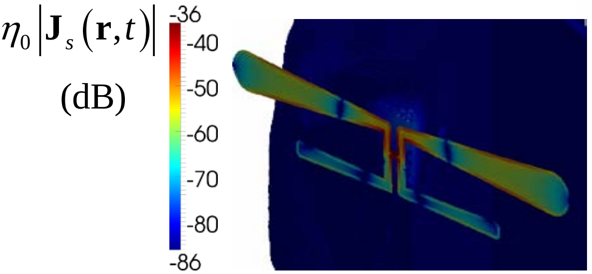
Original cartoon from: https://futurama.fandom.com/wiki/Who-Ask_Machine

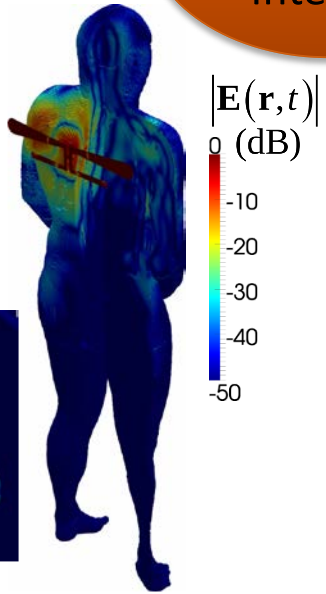
# Computational Solutions to Electromagnetics Problems






**Problem Of Interest**

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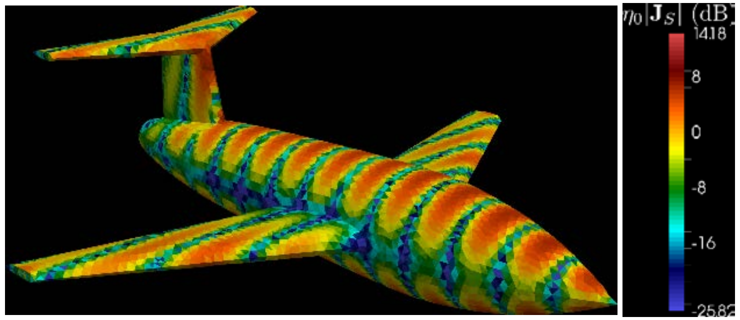
- Choose "appropriate fidelity"
- Specify domain, geometry, frequency, EM material properties, sources, observers, …

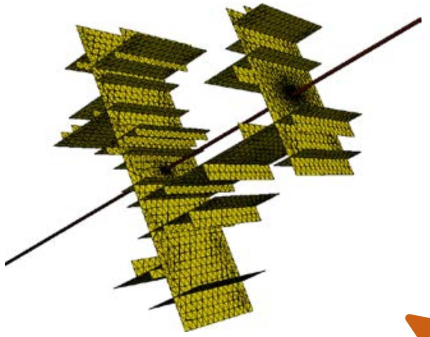
**Computational system** = algorithm + software implementation + hardware architecture

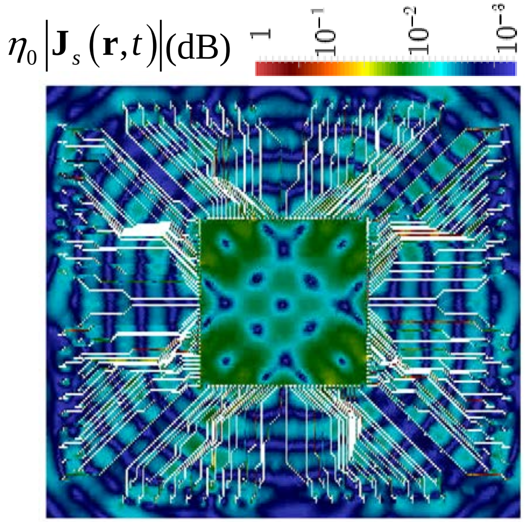
**Use Software**

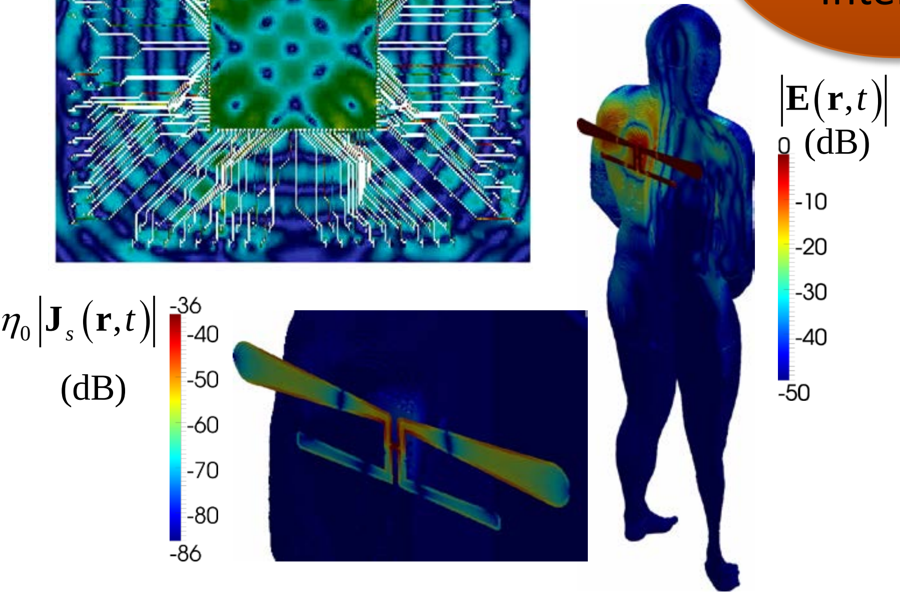
- Visualize & interpret results
- Investigate model parameters
- Pose & answer questions

# Computational Solutions to Electromagnetics Problems



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## Computational system

**Algorithm**

- Numerical methods
- Parallelization
- Basis functions
- Solvers
- Pre- & post-processing

**Software Implementation**

- Coding
- Verification, validation
- Optimization
- User interface

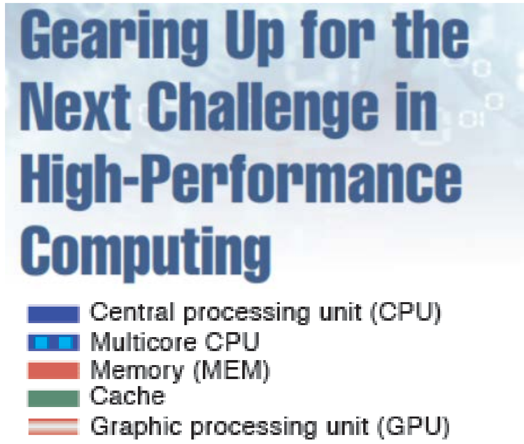
**Hardware Architecture**

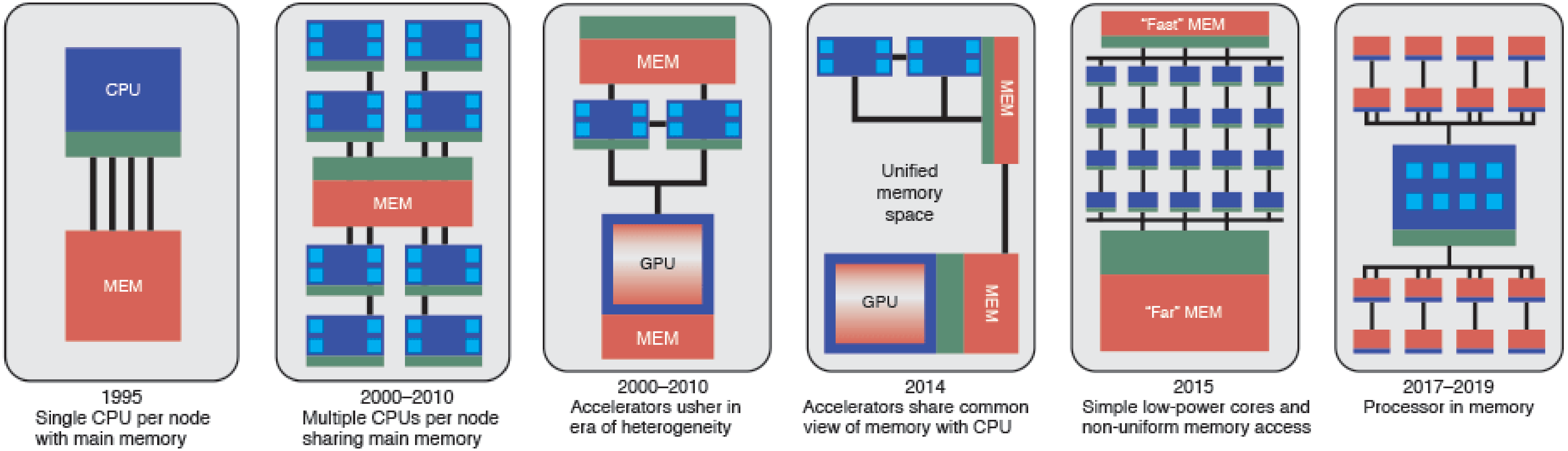
- CPU, GPU, cluster
- Cache/memory hierarchy
- Communication network

# Sea Change In Computing: Performance Scaling Through Hardware No Longer a Given

- Modern Computers

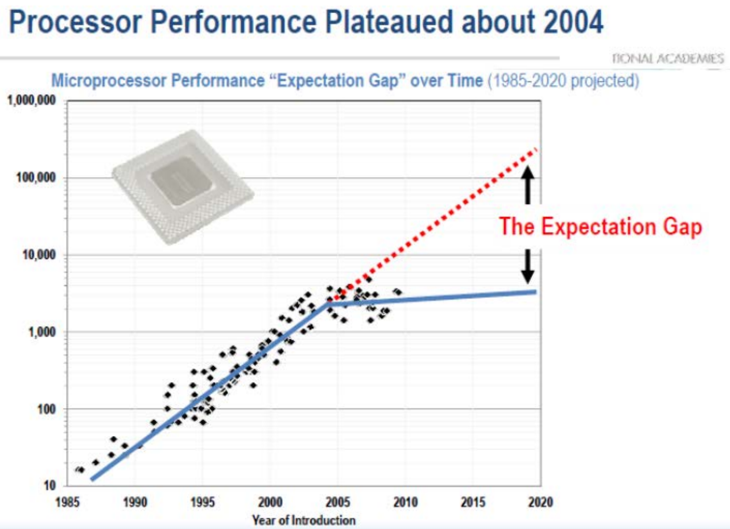
Research Highlights, Lawrence Livermore National Lab Mar. 2015.

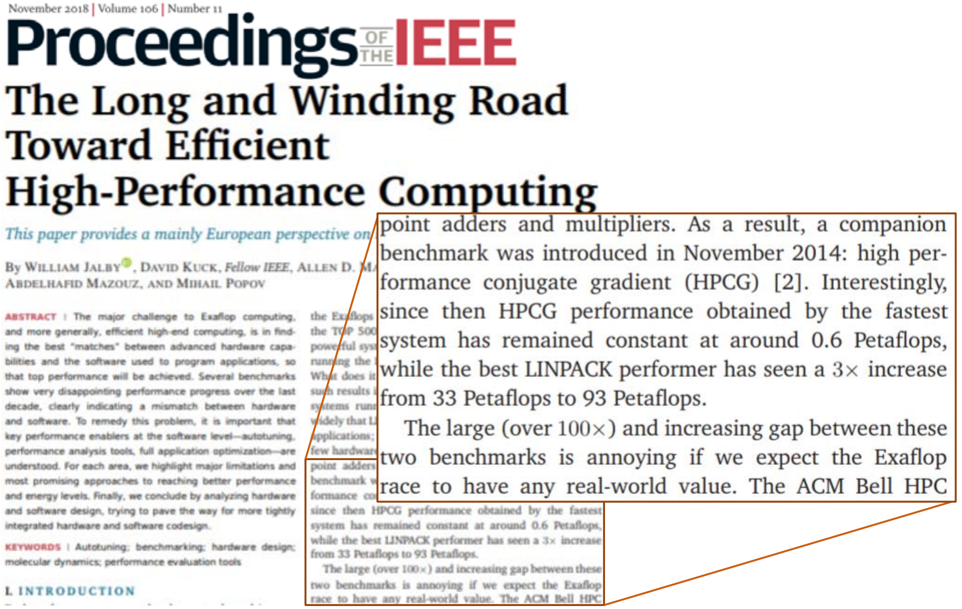



S. H. Fuller, L. I. Millett, Eds.; National Research Council, 2011.

"The end of the exponential runup in uniprocessor performance and the market saturation of the general-purpose processor mark the end of the "killer micro." This is a golden time for innovation in computing architectures and software. We have already begun to see diversity in computer designs to optimize for such metrics as power and throughput. The next generation of discoveries will require advances at both the hardware and the software levels."



November 2018 | Volume 106 | Number 11

Proceedings of the IEEE

**The Long and Winding Road Toward Efficient High-Performance Computing**

*This paper provides a mainly European perspective on ...*

By William Jalby, David Kuck, Fellow IEEE, Allen D. Ma... Abdelhafid Mazouz, and Mihail Popov

ABSTRACT | The major challenge to Exaflop computing, and more generally, efficient high-end computing, is in finding the best "matches" between advanced hardware capabilities and the software used to program applications, so that top performance will be achieved. Several benchmarks show very disappointing performance progress over the last decade, clearly indicating a mismatch between hardware and software. To remedy this problem, it is important that key performance enablers at the software level—autotuning, performance analysis tools, full application optimization—are understood. For each area, we highlight major limitations and most promising approaches to reaching better performance and energy levels. Finally, we conclude by analyzing hardware and software design, trying to pave the way for more tightly integrated hardware and software codesign.

KEYWORDS | Autotuning; benchmarking; hardware design; molecular dynamics; performance evaluation tools

I. INTRODUCTION

point adders and multipliers. As a result, a companion benchmark was introduced in November 2014: high performance conjugate gradient (HPCG) [2]. Interestingly, since then HPCG performance obtained by the fastest system has remained constant at around 0.6 Petaflops, while the best LINPACK performer has seen a 3× increase from 33 Petaflops to 93 Petaflops.

The large (over 100×) and increasing gap between these two benchmarks is annoying if we expect the Exaflop race to have any real-world value. The ACM Bell HPC

# Increasing Diversity of Computational Systems

"In this age of specialization men who thoroughly know one field are often incompetent to discuss another." R. P. Feynman, May 1956.

"A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it." (aka: "science advances one funeral at a time." ) Max Planck, 1948.

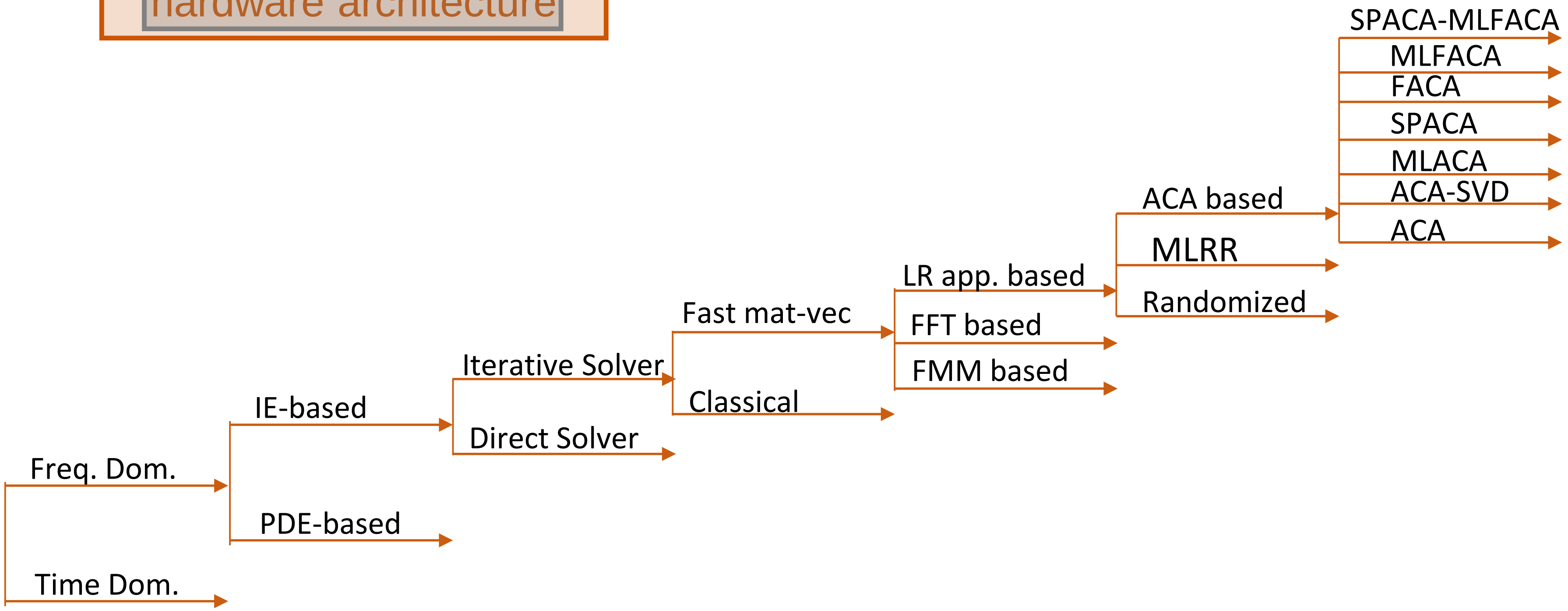
Many systems, no universal best system.

Computational system
=
algorithm
+
software implementation
+
hardware architecture

2B3-2 Proceedings of ISAP2016, Okinawa, Japan

SPACA-MLFACA Algorithm for Fast Solution of Electromagnetic Scattering Problems

Xinlei Chen[1,2], Chao Fei[1], Yang Zhang[1], Zhuo Li[1,2], and Changqing Gu[1]
[1]Key Laboratory of Radar Imaging and Microwave Photonics, Ministry of Education, College of Electronic and Information Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China.
[2]State Key L aboratory of Millimeter Waves, Southeast University, Nanjing 210096, China.
e-mail: chenxl@nuaa.edu.cn



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# What is Benchmarking?

**bench·mark**
/ˈben(t)SHmärk/

*noun*
noun: **benchmark**; plural noun: **benchmarks**

1. a standard or point of reference against which things may be compared or assessed.
   "a benchmark case"
   *synonyms:* standard, point of reference, gauge, guide, guideline, guiding principle, norm, touchstone, yardstick, barometer, indicator, measure, model, exemplar, pattern, criterion, specification, convention
   "the settlement became the benchmark for all future negotiations"
   - a problem designed to evaluate the performance of a computer system.
     "Xstones is a graphics benchmark"

A tentative definition…

Benchmarking: A (scientific) method to judge the "performance" of a (complex) system based on experiments & empirical evidence.

**comp.benchmarks FAQ**

```
comp.benchmarks Frequently Asked Questions, With Answers
Version 1.0, Sat Mar 16 12:12:48 1996
Copyright 1993-96 Dave Sill
Not-for-profit redistribution permitted provided this notice is
included.

SECTION 1 - General Q/A

1.2. What is a benchmark?

    A benchmark is test that measures the performance of a system or
    subsystem on a well-defined task or set of tasks.

1.3. How are benchmarks used?

    Benchmarks are commonly used to predict the performance of an
    unknown system on a known, or at least well-defined, task or
    workload.

Benchmarks can also be used as monitoring and diagnostic tools.
By running a benchmark and comparing the results against a known
configuration, one can potentially pinpoint the cause of poor
performance.  Similarly, a developer can run a benchmark after
making a change that might impact performance to determine the
extent of the impact.

Benchmarks are frequently used to ensure the minimum level of
performance in a procurement specification.  Rarely is performance
the most important factor in a purchase, though.  One must never
forget that it's more important to be able to do the job correctly
than it is to get the wrong answer in half the time.
```

In computer business and high-performance computing:

"Poor performance" often means "slow speed"

Occasionally, the concept of (hardware) "error" appears.

# Typical Benchmarks for Computer Systems

spec

## Standard Performance Evaluation Corporation

Home | Benchmarks | Tools | Results | Contact | Site Map | Search | Help

**The Standard Performance Evaluation Corporation (SPEC)** is a non-profit corporation formed to establish, maintain and endorse a standardized set of relevant benchmarks that can be applied to the newest generation of high-performance computers. SPEC develops benchmark suites and also reviews and publishes submitted results from our member organizations and other benchmark licensees.


## CPU Stress / Torture Testing

Over the years, Prime95 has become extremely popular among PC enthusiasts and overclockers as a stability testing utility. It includes a "Torture Test" mode designed specifically for testing PC subsystems for errors in order to help ensure the correct operation of Prime95 on that system. This is important because each iteration of the Lucas-Lehmer depends on the previous one; if one iteration is incorrect, so will be the entire primality test.

The stress-test feature in Prime95 can be configured to better test various components of the computer by changing the fast fourier transform (FFT) size. Three pre-set configurations are available: Small FFTs and In-place FFTs, and Blend. Small and In-place modes primarily test the FPU and the caches of the CPU, whereas the Blend mode tests everything, including the memory.

| Comparison of CPU core power | Frequency | Cores | FFT | | Trial factoring | TDP |
|---|---|---|---|---|---|---|
| Prime95 benchmark[5][6] | (per core) | | 2048k | 4096k | 64-bit | |
| Platform CPU model | MHz | | ms | ms | ms | Watts |
| Intel Atom 330 | 1600 | 2 | 621 | 1166 | 46 | 8 |
| Intel Atom D510 | 1664 | 2 | 586 | 1954 | 25.7 | 13 |
| Intel Pentium III | 1151 | 1 | 438 | 923 | 50.6 | 30 |
| AMD Athlon | 1054 | 1 | 457 | 774 | 56.0 | 68 |
| AMD Fusion E-350 | 1596 | 2 | 222 | 491 | 15.2 | 18 |
| AMD Athlon XP 2000+ | 1640 | 1 | 201 | 448 | 32.8 | ~60 |
| Intel Pentium 4 | 3078 | 1 | 72.4 | 162 | 14.9 | 86 |
| AMD Phenom II X4 | 3414 | 4 | 34.9 | 76.3 | 4.59 | 125 |
| Intel Core 2 Duo E8600 | 3334 | 2 | 34.2 | 73.1 | 4.89 | 65 |
| Sandy Bridge Pentium G620T | 2159 | 2 | 41.1 | 72.5 | 4.99 | 35 |
| AMD Phenom II X6 1100T | 3310 | 6 | 32.7 | 69.5 | 3.85 | 125 |
| Intel Core i5-2500K | 3330 | 4 | 23.9 | 53.2 | 3.49 | 95 |
| Intel Core i5-2500K | 4400 | 4 | 3.3 | 7.1 | 2.61 | 95 |
| Intel Core i7-2600K | 3463 | 4 | 21.8 | 45.4 | 3.67 | 95 |
| Intel Core i7-3770K | 4222 | 4 | 3.978 | 9.450 | 3.788 | 77 |

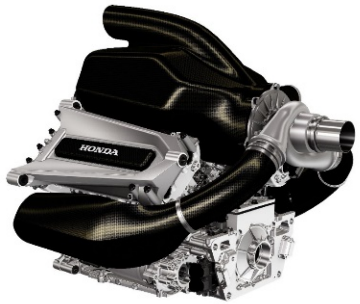
Command Window

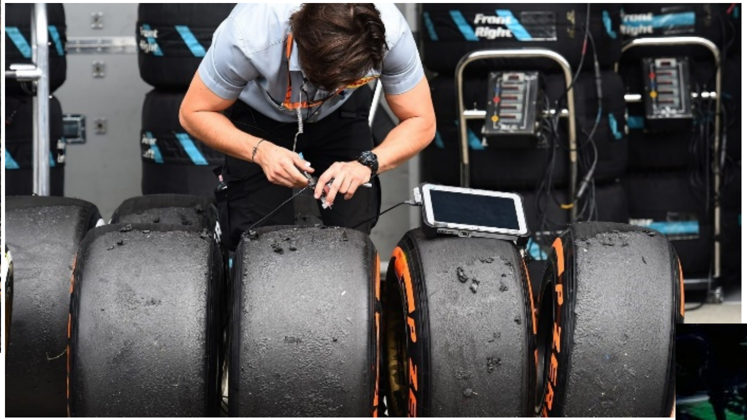
New to MATLAB? See resources for Getting Started.

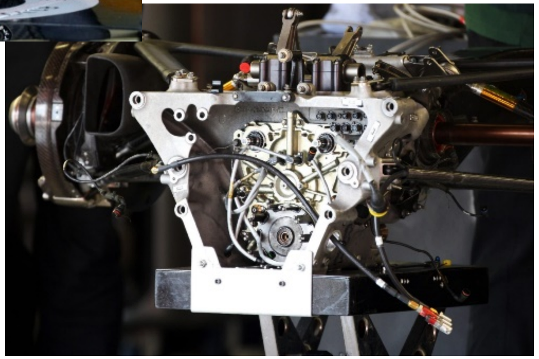
```
>> help bench
 bench  MATLAB Benchmark
    bench times six different MATLAB tasks and compares the execution
    speed with the speed of several other computers.  The six tasks are:

     LU       LAPACK.                          Floating point, regular memory access.
     FFT      Fast Fourier Transform.          Floating point, irregular memory access.
     ODE      Ordinary diff. eqn.              Data structures and functions.
     Sparse   Solve sparse system.             Sparse linear algebra.
     2-D      2-D Lissajous plot.              Animating line plot.
     3-D      3-D SURF(PEAKS)and HGTransform.  3-D surface animation.
```

# Another Speed/“Time-to-Target” Oriented Benchmark





Benchmarking: A (scientific) method to judge the “performance” of a (complex) system based on experiments & empirical evidence.

Original images from:
http://seatingchartview.com/circuit-americas/
https://www.wired.com/2014/05/formula-1-steering-wheels/
https://www.formula1.com/en/championship/inside-f1.html
https://www.formula1.com/en/championship/races/2016/Monaco.html

# Computational Science & Eng.: Verification, Validation, Error

ELSEVIER
Available online at www.sciencedirect.com
ScienceDirect
Nuclear Engineering and Design 238 (2008) 716–743
Nuclear Engineering and Design
www.elsevier.com/locate/nucengdes

## Verification and validation benchmarks

William L. Oberkampf[a,*], Timothy G. Trucano[b]
[a] *Validation and Uncertainty Estimation Department, Sandia National Laboratories, Albuquerque, NM 87185-0828, USA*
[b] *Optimization and Uncertainty Estimation Department, Sandia National Laboratories, Albuquerque, NM 87185-0819, USA*

Received 5 December 2006; received in revised form 23 January 2007; accepted 26 February 2007

**Abstract**

Verification and validation (V&V) are the primary means to assess the accuracy and reliability of computational simulations. V&V methods and procedures have fundamentally improved the credibility of simulations in several high-consequence fields, such as nuclear reactor safety, underground nuclear waste storage, and nuclear weapon safety. Although the terminology is not uniform across engineering disciplines, code verification

This paper focuses on one aspect of the needed improvements to software reliability and physics modeling, namely, the construction and use of highly demanding V&V benchmarks. The benchmarks of interest are those related to the accuracy and reliability of physics models and codes. We are not interested here in benchmarks that relate to computer performance issues, such as the computing speed of codes on different types of computer hardware and operating systems.

Computational Engineering Science:
"Poor performance" ≡ "large error"
High-Performance Computing:
"Poor performance" ≡ "slow" /
"too much power"

42nd AIAA Fluid Dynamics Conference and Exhibit
25 - 28 June 2012, New Orleans, Louisiana

## Numerical Benchmark Solutions for Laminar and Turbulent Flows

Tyrone S. Phillips,[1] Joseph M. Derlaga,[1] and Christopher J. Roy[2]
*Virginia Tech, Blacksburg, Virginia 24061*

**Numerical benchmark solutions are numerical solutions that have been computed using a verified code and with a high degree of rigorously assessed numerical accuracy. They can bridge the gap between simple problems where the analytic solution to the differential equations is known and more complex problems where exact solutions are not known. In particular, benchmark numerical solutions can be used for code verification (i.e., algorithm and code correctness), assessing discretization error estimators, and evaluating solution adaptation strategies. The requirements for establishing a numerical benchmark solution are discussed. A numerical benchmark is created for a**

"The scientific method's central motivation is the *ubiquity of error*—… mistakes and self-delusion can creep in absolutely anywhere … computation is also highly error-prone. From the newcomer's struggle to make even the simplest computer program run to the seasoned professional's frustration when a server crashes in the middle of a large job, all is struggle against error….the ubiquity of error has led to many responses: special programming languages, error-tracking systems, disciplined programming efforts, organized program testing schemes. The tendency to error is central to every application of computing."

D. L. Donoho *et al.*, "Reproducible research in computational harmonic analysis," *Comp. Sci. Eng.*, Jan.-Feb. 2009.

# Computational EM: Verification, Validation, Error

## The Role of Analysis in an Age of Computers: View From the Analytical Side

*Robert E. Collin*
*Case Western Reserve University*
*Cleveland, Ohio, 44106*

**1. Introduction**

In recent years, high speed computers with large capacity memories (personal computers and work stations) have become readily available to almost every engineer and scientist. For large-scale problems, supercomputers are also available to most researchers. A natural consequence of having such easy access to computer resources is to solve problems numerically on a computer, and to forego analysis beyond that which is required to formulate the problem for numerical

In current applied electromagnetics research, it is interesting to note how often codes written to solve certain classes of problems are tested against analytical solutions – analytical solutions appear to be the preferred benchmark solutions. Large complex computer codes are difficult to validate. As long as the code is logically sound, numerical answers are obtained, but are they the correct answers? Analysis plays an important role in current computationally-oriented research by providing robust problem formulations and analytical benchmark solutions. In addition,

IEEE ANTENNAS AND PROPAGATION MAGAZINE, AUGUST 1990

From observations made on the current activities in computational electromagnetics, it is concluded that insufficient effort is being made to establish the accuracy and reliability of numerical results being produced. Hopefully, in the future, more attention will be devoted to this aspect of numerical work. Numerical results with unknown accuracy are not acceptable. If computational electromagnetics is going to fulfill its ultimate potential, we must find efficient ways to validate the numerical results, since in new problem areas, analytical results are not available for comparison.

#1 on the first Top 500 list, 1993

*The innovative Connection Machine, CM-5, was the first massively parallel supercomputer at Los Alamos. It was built by the Thinking Machines Corporation.* (Photo: Los Alamos)

Original image from:
https://www.lanl.gov/discover/publications/national-security-science/2013-april/_assets/docs/punchcards-petaflops.pdf

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IEEE ANTENNAS AND PROPAGATION MAGAZINE, AUGUST 1990

From observations made on the current activities in computational electromagnetics, it is concluded that insufficient effort is being made to establish the accuracy and reliability of numerical results being produced. Hopefully, in the future, more attention will be devoted to this aspect of numerical work. Numerical results with unknown accuracy are not acceptable. If computational electromagnetics is going to fulfill its ultimate potential, we must find efficient ways to validate the numerical results, since in new problem areas, analytical results are not available for comparison.

IEEE ANTENNAS AND PROPAGATION MAGAZINE, DECEMBER 1990

## Comments on "The Role of Analysis in an Age of Computers: View From the Analytical Side"

*David M. Pozar*
*Dept. of Electrical & Computer Engineering*
*University of Massachusetts*
*Amherst, MA 01003*

The recent feature article by Collin on the comparative roles of analysis and numerical solutions in modern electromagnetics [R.E. Collin, *IEEE Ant. Prop. Magazine*, **32**, August, 1990, pp. 27-31] was interesting, and I wholeheartedly agree that analysis is indispensable for providing physical insight into problems in electromagnetics, and for the development of robust and efficient numerical solutions for such problems. This is especially true when comparing the efficacy of a "brute-force" numerical solution, such as a finite-difference method, to a more analytically-based solution.

But I disagree with the implication that analytical solutions are the only way, or even the best way, to check the accuracy of numerical solutions, and I was surprised that the article made no mention of verifying solution accuracy by comparison with measured data. Since exact solutions exist for only a few electromagnetics problems of practical interest, analytical solutions usually involve simplifications of the original problem, or approximations to the solution of the problem. Such solutions might be labelled as "analytical," but the results obtained from them are not necessarily correct. Thus, we can encounter the same problem, with analytical solutions, that Collin describes for numerical solutions —that is, how do we verify the correctness of a solution? Measurements provide what is often the best way of verifying the accuracy of a solution to a practical problem in electromagnetics, regardless of the extent to which the solution is "analytical" or "numerical." After all, we are modeling a physical problem, so comparison with measured data should be the ultimate test

# Computational EM: Verification, Validation, Error

## The Role of Analysis in an Age of Computers: View From the Analytical Side

*Robert E. Collin*
*Case Western Reserve University*
*Cleveland, Ohio, 44106*

**1. Introduction**

In recent years, high speed computers with large capacity memories (personal computers and work stations) have become readily available to almost every engineer and scientist. For large-scale problems, supercomputers are also available to most researchers. A natural consequence of having such easy access to computer resources is to solve problems numerically on a computer, and to forego analysis beyond that which is required to formulate the problem for numerical

In current applied electromagnetics research, it is interesting to note how often codes written to solve certain classes of problems are tested against analytical solutions – analytical solutions appear to be the preferred benchmark solutions. Large complex computer codes are difficult to validate. As long as the code is logically sound, numerical answers are obtained, but are they the correct answers? Analysis plays an important role in current computationally-oriented research by providing robust problem formulations and analytical benchmark solutions. In addition,

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### Three Pillars of Science


CENTER FOR COMPUTATIONAL RESEARCH
University at Buffalo The State University of New York

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Original image from:
http://www.slideshare.net/ultrafilter/trends-challenges-in-supercomputing-for-eitaeitc-2012

# Another Error-Oriented Benchmark


Benchmarking: A (scientific) method to judge the "performance" of a (complex) system based on experiments & empirical evidence.

Original images from:
https://www.maxitlegends.com/factors-to-be-considered-while-purchasing-archery-set/
http://thsraidertimes.com/1136/sports/archery-is-important-too/
http://reowilde.com/news/us-open

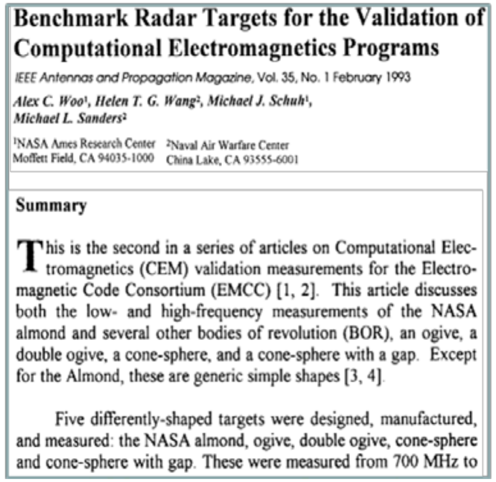
# Outline

- Motivation: When Is Human Expertise/Judgment Needed?
  - Computational Solutions to Electromagnetics Problems
  - Judging Model Fidelity
  - Using Analysis Results to Make Better Judgments: A Reasonable Approach?
    - Prone to Distortions from Computational System/Method of Analysis
- Why Judging the Appropriate Computational System(s)/Method(s) is Hard
  - Computational Systems are Complex
  - Sea Change in Computing
  - Increasing Diversity of Algorithms
- A Possible Solution: Modern Benchmark Suites and Advanced Benchmarking
  - What is High Performance in CEM?
  - What is a Modern CEM Benchmark? Necessary Ingredients
  - Example from Our Ongoing Work: Austin RCS Benchmark Suite
- Conclusion

# What is a Modern CEM Benchmark?

❑ Proto-benchmarks vs. (quantitative) 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.

❑ CEM R&D needs modern benchmarking
- Rapidly fragmenting computing landscape
- Empirical results make theoretical science better
- Benchmark suites can reveal performance, encourage and support R&D
- Judging methods tightly linked to judging models

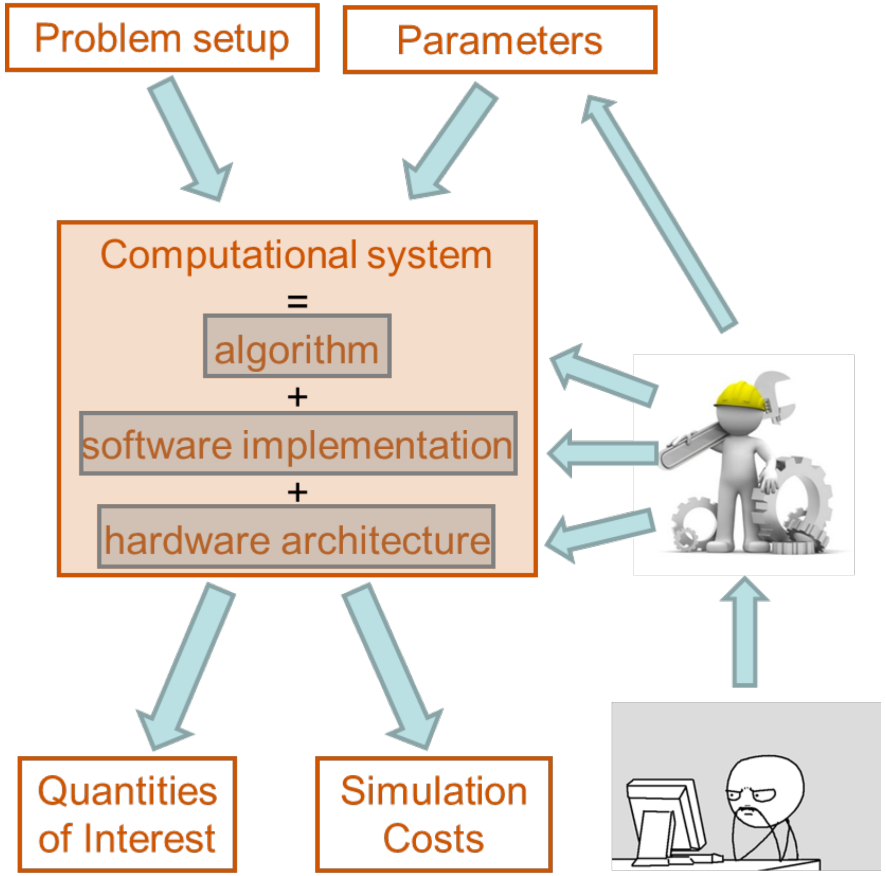
❑ Rich history of "proto-benchmarks" in CEM
- Many problems, methods, and data in journal/conference publications
- Most non-replicable, not precise enough for quantitative benchmarking

❑ Modern computing infrastructure key enabler
- Easier to preserve/share/visualize data
- High precision comparisons possible—Plots vs. numbers
- Full replicability possible—Version control tools

# Designing Modern CEM Benchmark Suites

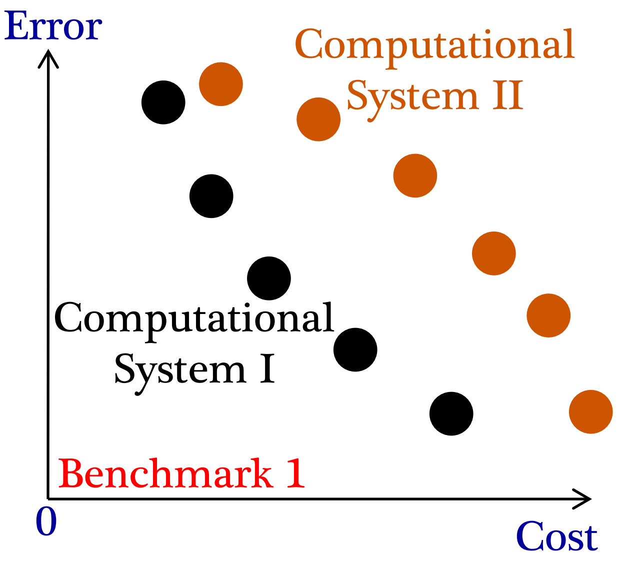
❑ Key ingredients for benchmark suites [1]

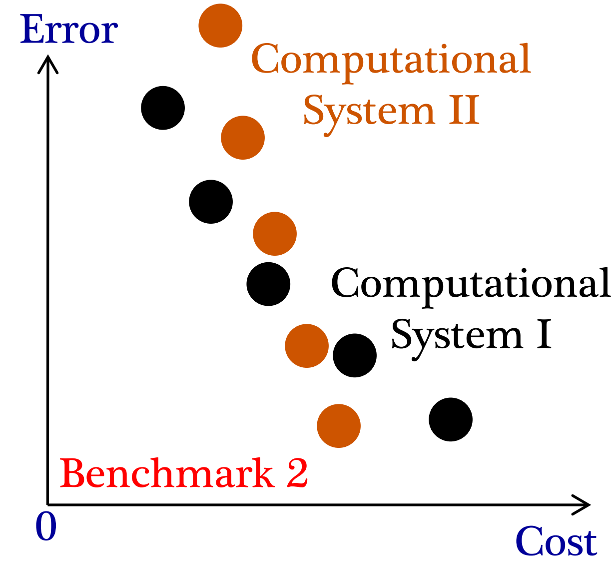
- Application-specific list of scattering problems
  1. Span different difficulty levels
  2. Emphasize/exercise features of computational system relevant to application
  3. General enough to represent different types of problems encountered
  4. Problem set should evolve
- Precisely defined quantities 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.

# Benchmarking for CEM R&D



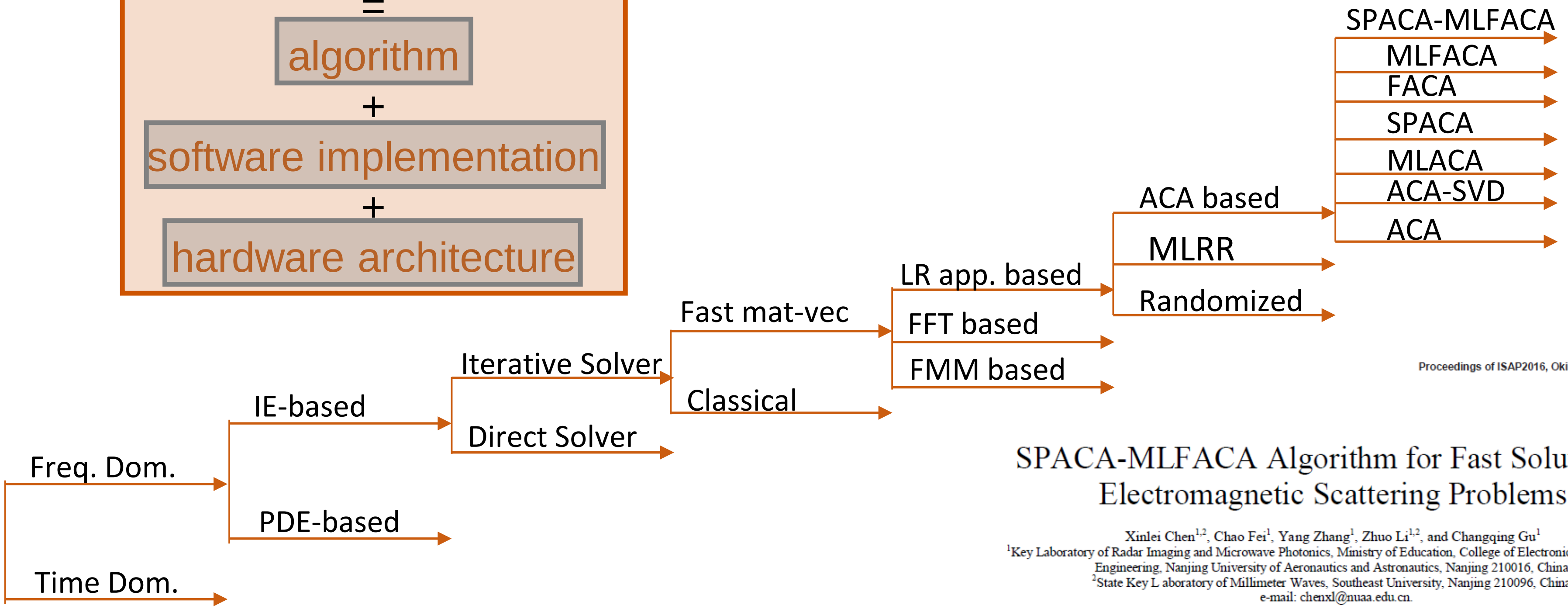




Performance definition should include error, cost, and trade-off between error and cost.

Computational system = algorithm + software implementation + hardware architecture

Many systems, no universal best system. Corollaries:

- Different computational systems ⇔ different trade-offs between error and cost.
- Relative performance of systems will change from benchmark to benchmark.
- Need appropriate benchmarks!




Proceedings of ISAP2016, Okinawa, Japan

SPACA-MLFACA Algorithm for Fast Solution of Electromagnetic Scattering Problems

Xinlei Chen[1,2], Chao Fei[1], Yang Zhang[1], Zhuo Li[1,2], and Changqing Gu[1]
[1]Key Laboratory of Radar Imaging and Microwave Photonics, Ministry of Education, College of Electronic and Information Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China.
[2]State Key Laboratory of Millimeter Waves, Southeast University, Nanjing 210096, China.
e-mail: chenxl@nuaa.edu.cn

# Outline

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https://github.com/UTAustinCEMGroup/AustinCEMBenchmarks

# Benchmarking Database

## Features

- **Problem Description**
  Precisely defines the model and the quantities of interest
- **Reference Data**
  Measurement or analytical reference results
- **Simulation Data**
  Sample results for benchmark problems produced by UT Austin

Branch: master ▾ AustinCEMBenchmarks / Austin-RCS-Benchmarks /

UTAustinCEMGroup 2019 URSI update

..

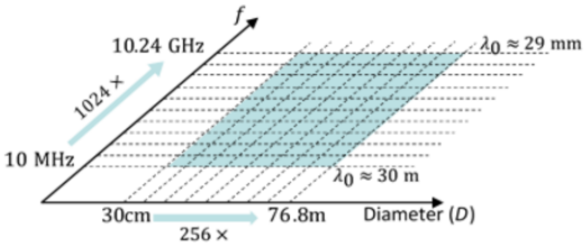
| | |
|---|---|
| Problem I-Spheres | 2019 URSI update |
| Problem II-Plates | Updated reference data |
| Problem III-Almonds | 2019 URSI update |
| HowToParticipate.md | Populating placeholder message |

Problem Set 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; the ranges are logarithmically sampled to yield 99 scattering problems. Because the spheres are PEC, there are only 19 unique scattering problems in Problem Set IA. In these problems, the sphere sizes are in the range $0.01 \le D/\lambda_0 \le 2624$, where $\lambda_0$ is the free-space wavelength.

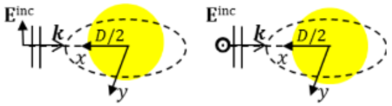
**Interesting Features**

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

**Quantities of Interest**

Radar cross section (RCS) definition

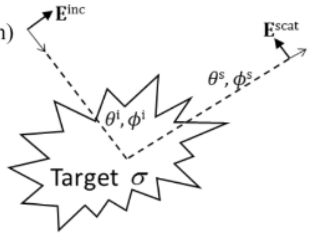
$$\sigma_{vu}(\theta^s,\phi^s,\theta^i,\phi^i)=\lim_{R\to\infty}4\pi R^2\frac{\left|\hat{v}(\theta^s,\phi^s)\cdot\mathbf{E}^{scat}(\theta^s,\phi^s)\right|^2}{\left|\hat{u}(\theta^i,\phi^i)\cdot\mathbf{E}^{inc}(\theta^i,\phi^i)\right|^2} \quad : \text{RCS (m}^2\text{)}$$




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

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

1. Set $\theta^i = 90^o$, $\phi^i = 0^o$, $\theta^s = 90^o$. Vary $0^o \le \phi^s \le 360^o$.
2. Compute both $\sigma_{\theta\theta,dB}$ and $\sigma_{\phi\phi,dB}$ (the VV- and HH-RCS in dB) at $N_\phi = 721$ scattering directions (every $0.5^o$ in the interval $0^o \le \phi^s \le 360^o$).




**Performance Measures**

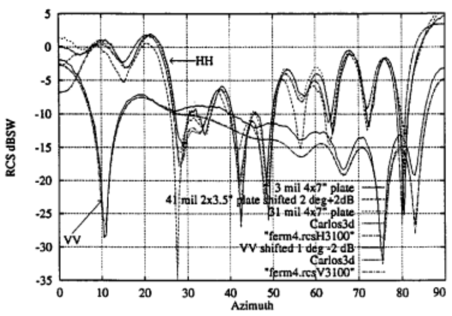



Figure 11. The RCS, in dB $\lambda^2$, plotted against the azimuthal angle, in a 10°-elevation conical cut, for the Case 4 flat plate of dimensions 4"×7". Results for plates with thicknesses of 3 mils, 31 mils, and 41 mils are included. Normal incidence to the 2λ-long short edge is 0°.

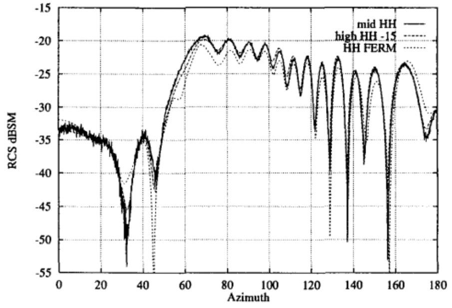



Figure 4. The 9.936 inch NASA almond at 7 GHz, for horizontal polarization: "mid-HH" and "high-HH" denote the measured cases (see the text), and "HH FERM" denotes the computed results.

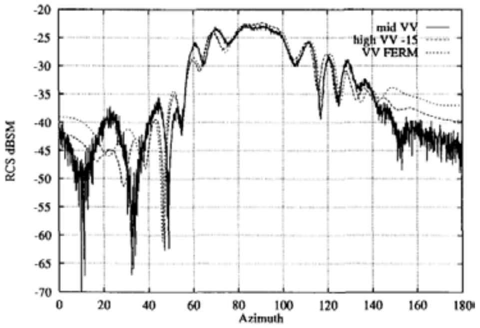
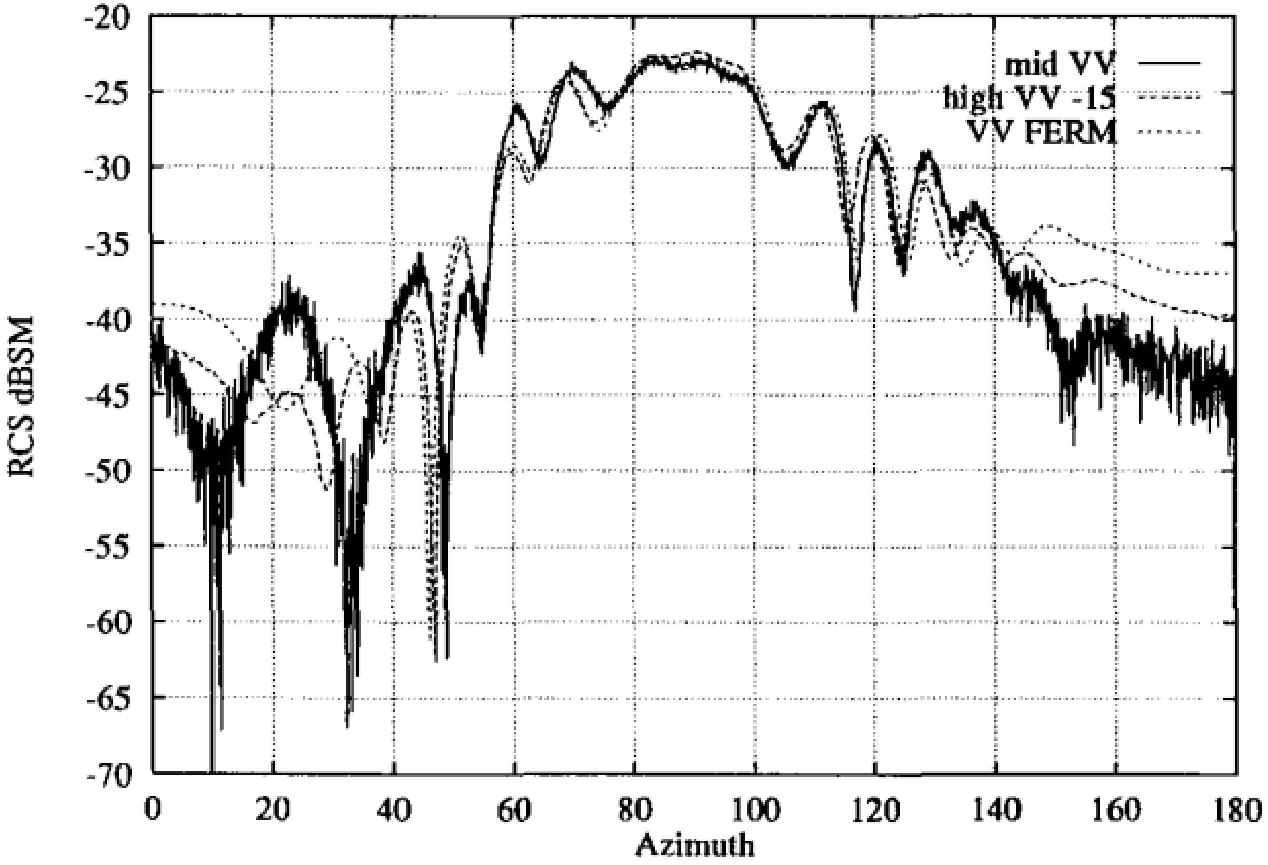



Figure 5. The 9.936 inch NASA almond at 7 GHz, for vertical polarization. The curves are labeled the same as in Figure 4.


[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.

# Measurement Uncertainty/Error/Repeatability

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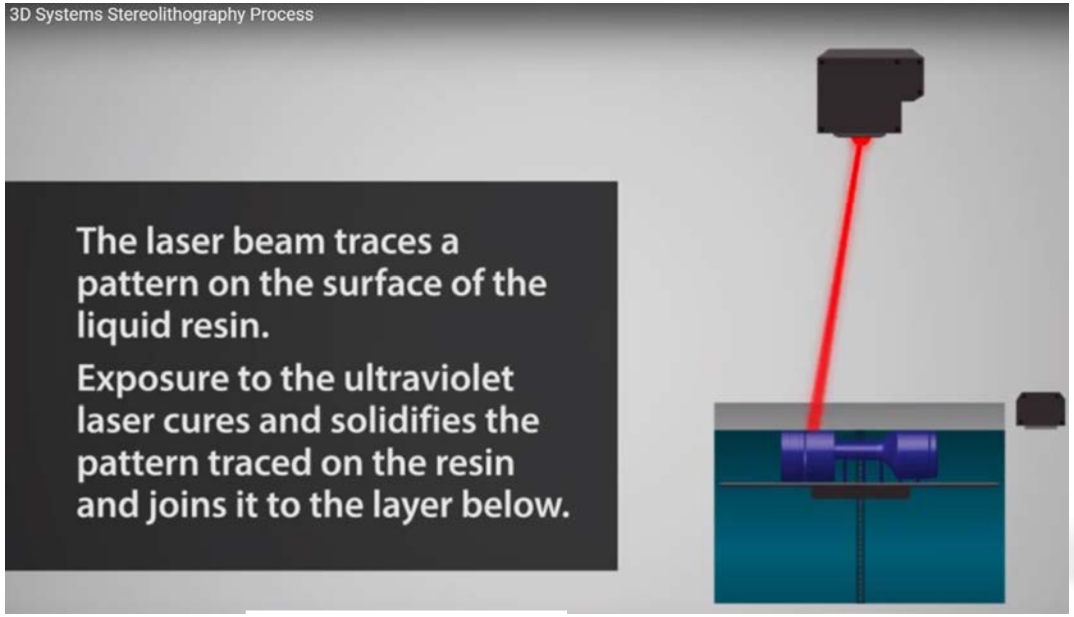
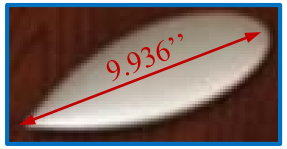
https://github.com/UTAustinCEMGroup/AustinCEMBenchmarks

# Problem III: Almonds-Measurements



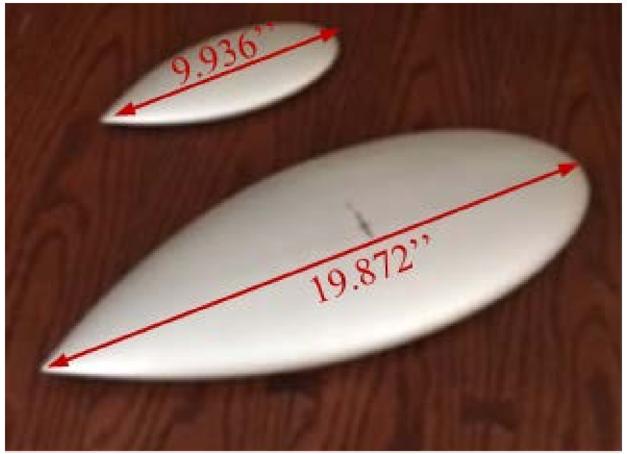




small almond


large almond

J. T. Kelley *et al.*, "Rye Canyon RCS measurements of benchmark almond targets," to appear in *IEEE Ant. Propag. Mag.*, 2019.

**Fig. 3:** The two almonds additively manufactured at the Rye Canyon site using an SLA printer. The picture shows the ~10-in almond and the ~20-in almond after they were sanded, polished, and coated. The center-of-mass mark for the ~20-in almond is also visible here.



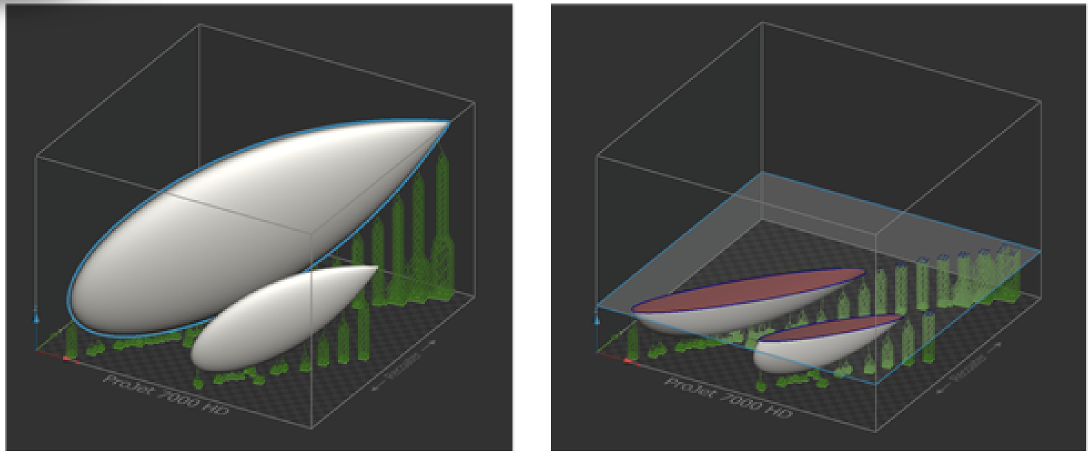
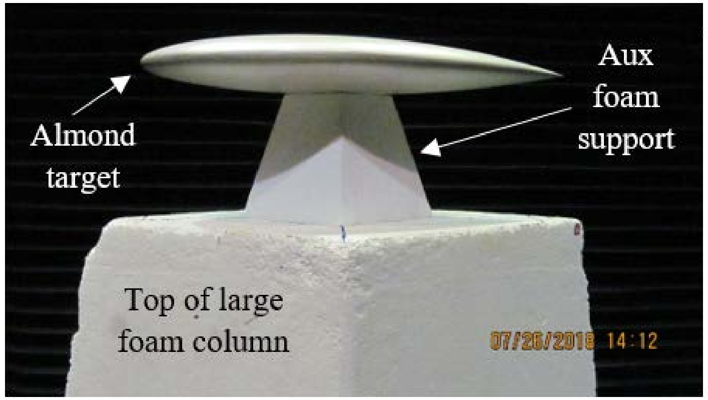



**Fig. 4:** The orientation of the second ~10'' almond and the ~20'' almond in the resin tank. Left: The final form of the printed parts. Right: An earlier instant in the process. The structures supporting the almonds during the process are also visible.

https://github.com/UTAustinCEMGroup/AustinCEMBenchmarks

# Problem III: Almonds-Measurements


# Measurement Uncertainty/Error/Repeatability

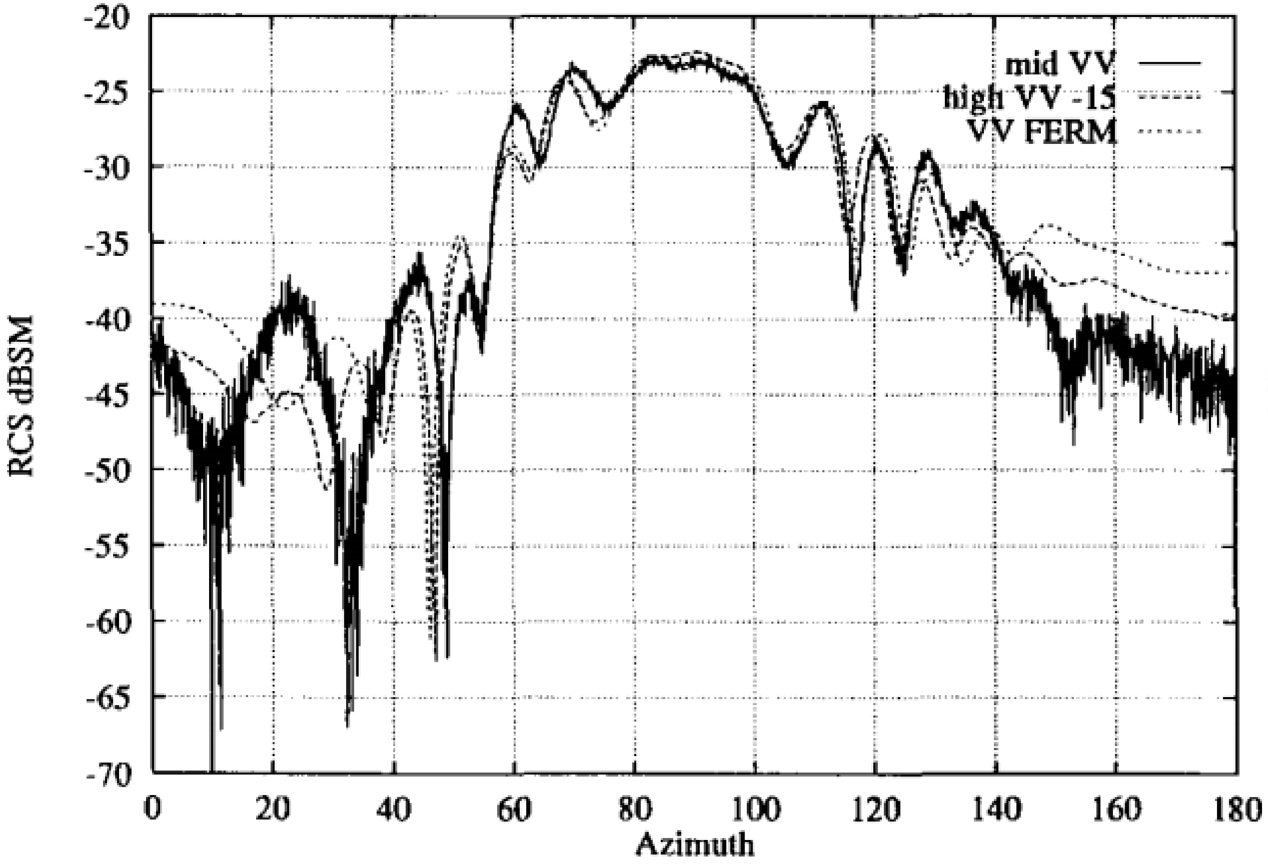
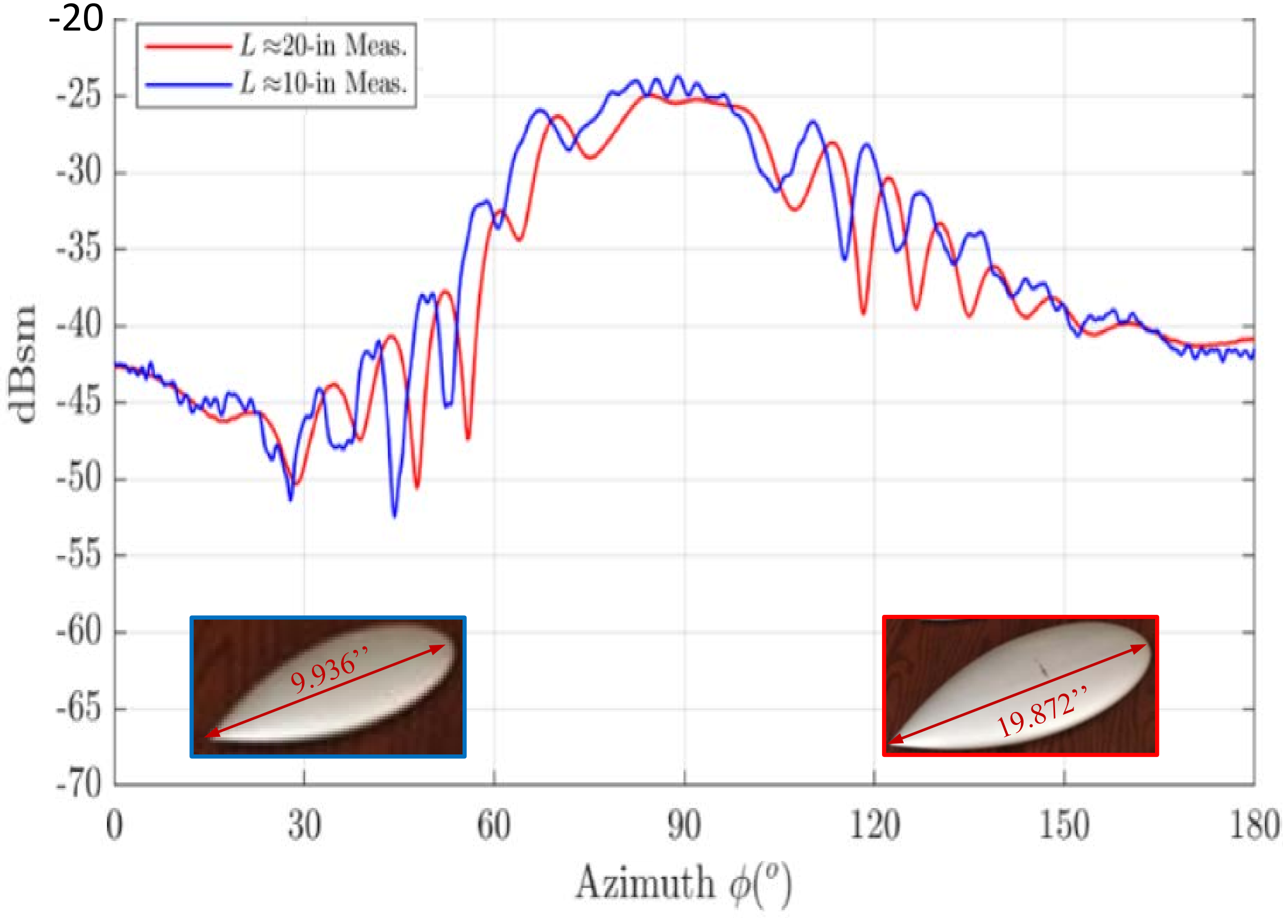



Figure 5. The 9.936 inch NASA almond at 7 GHz, for vertical polarization. The curves are labeled the same as in Figure 4.

Data from two measurements

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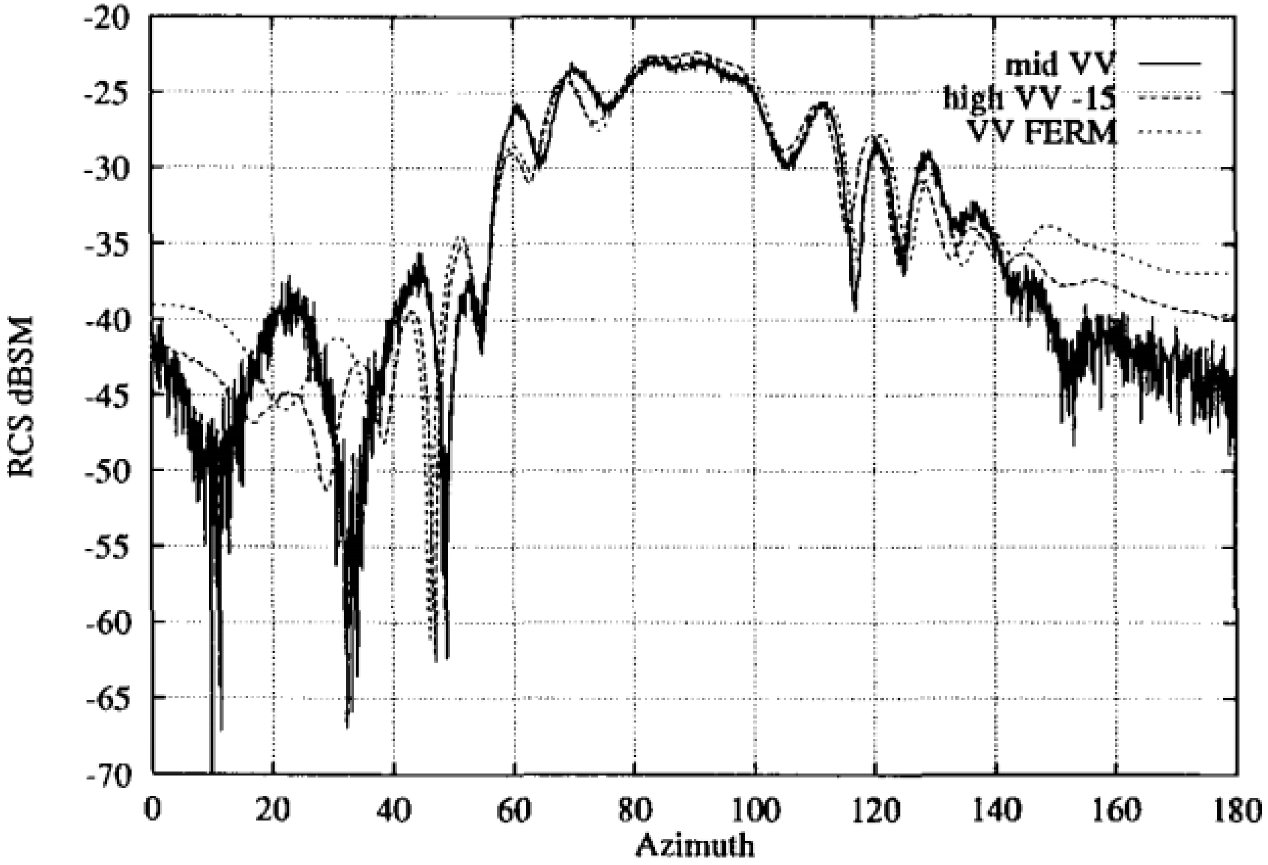


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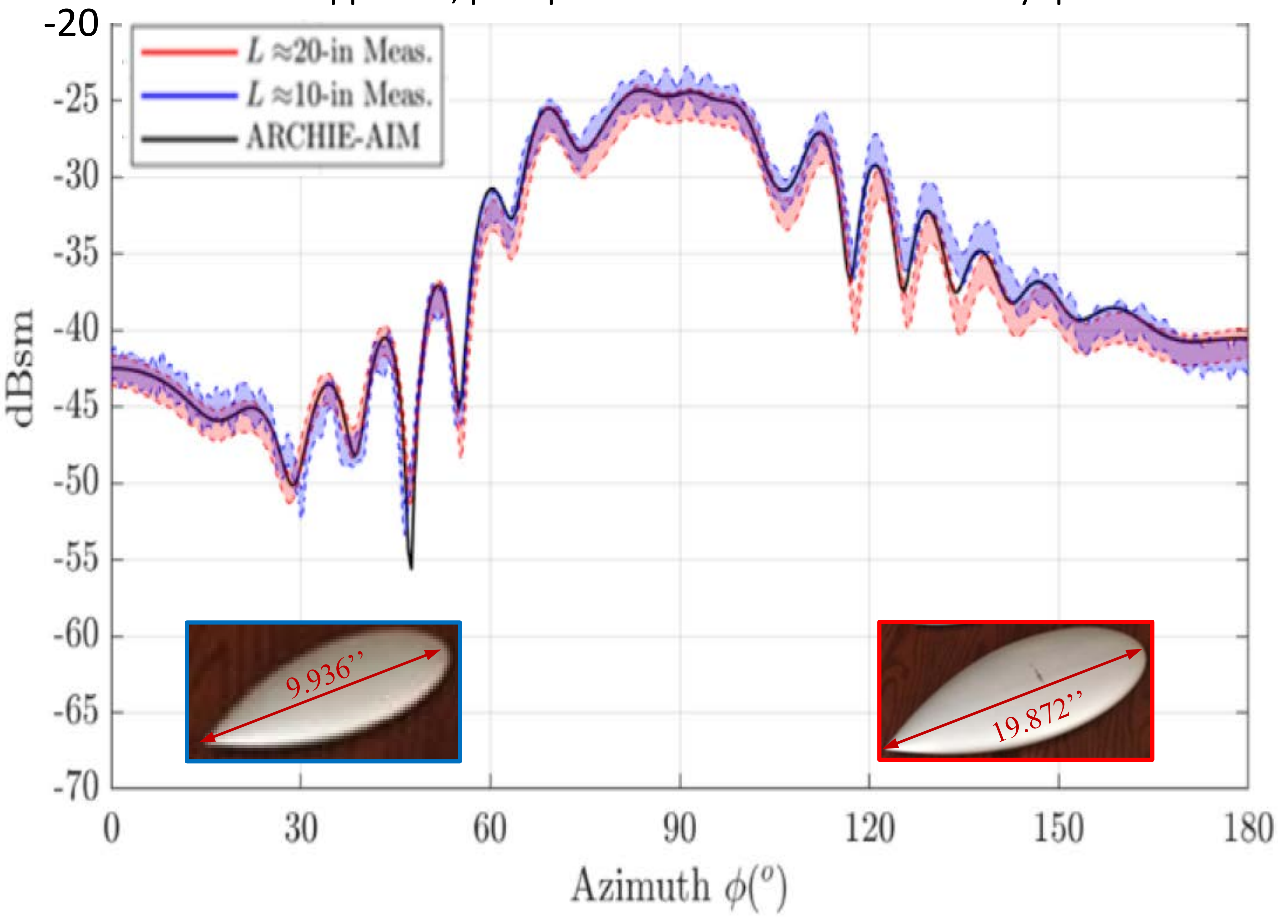
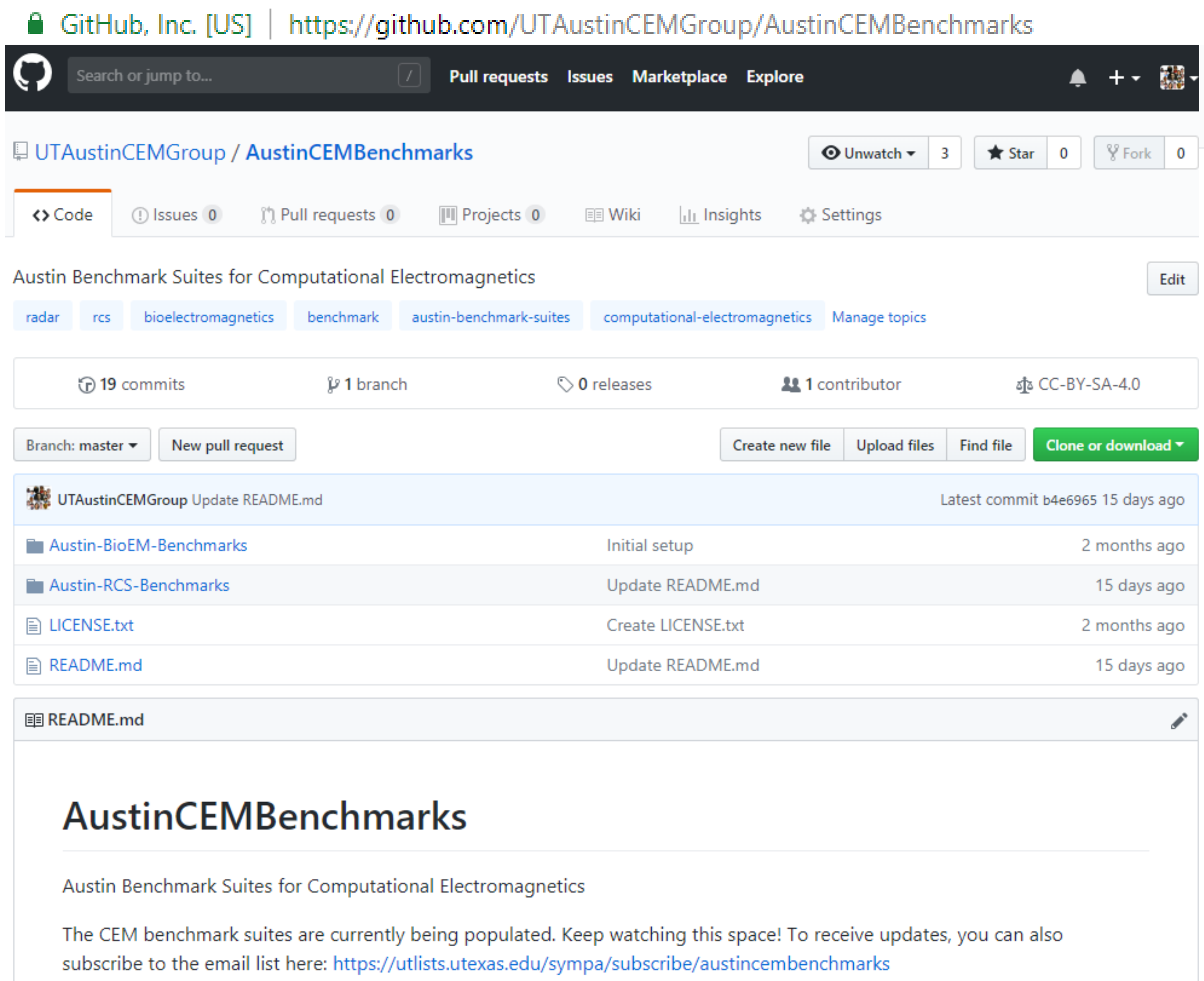
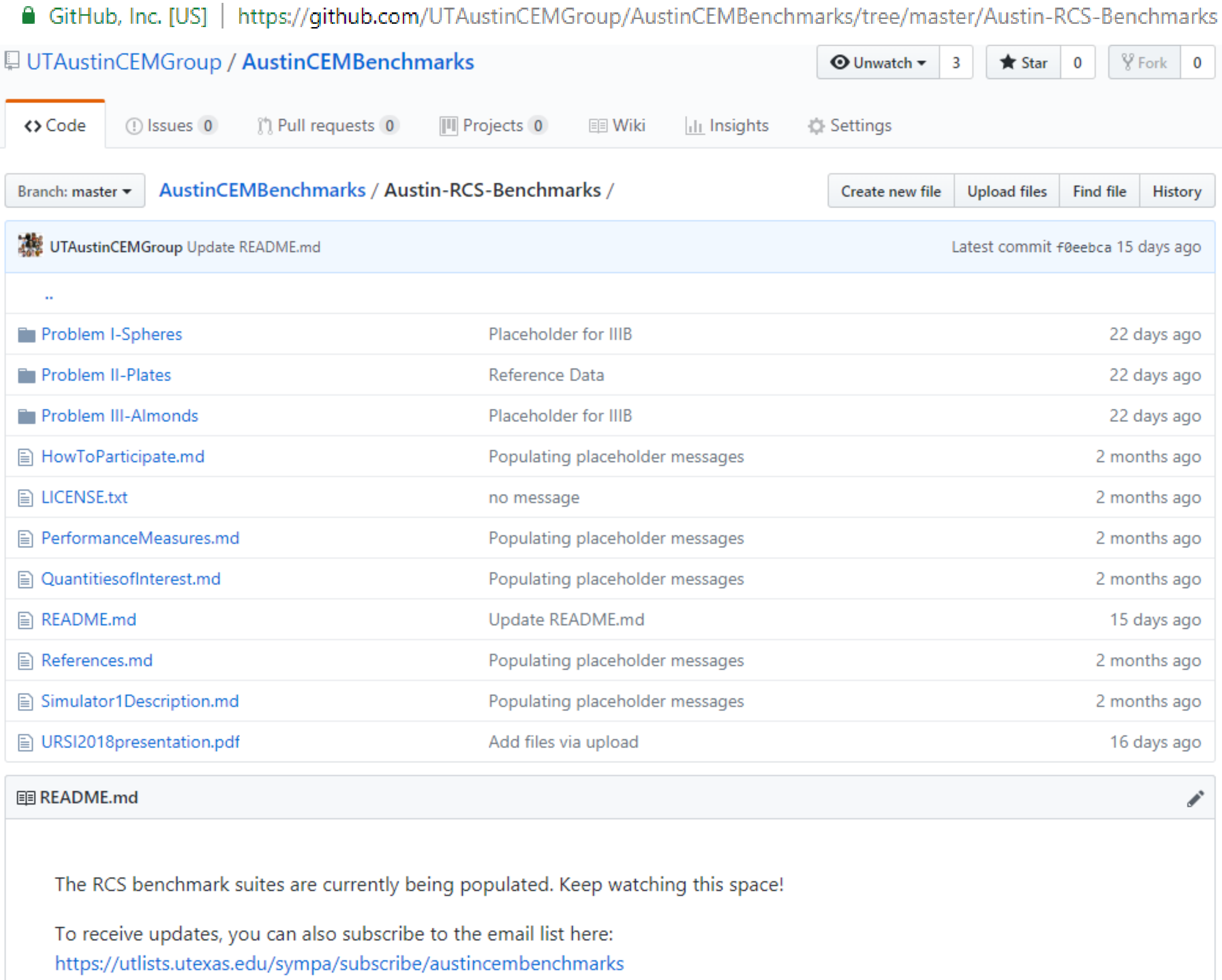
Simulation-supported, post-processed data with uncertainty quantification




J. T. Kelley *et al.*, "Rye Canyon RCS measurements of benchmark almond targets," to appear in *IEEE Ant. Propag. Mag.*, 2020.

# Online Benchmark Repository: GitHub Site



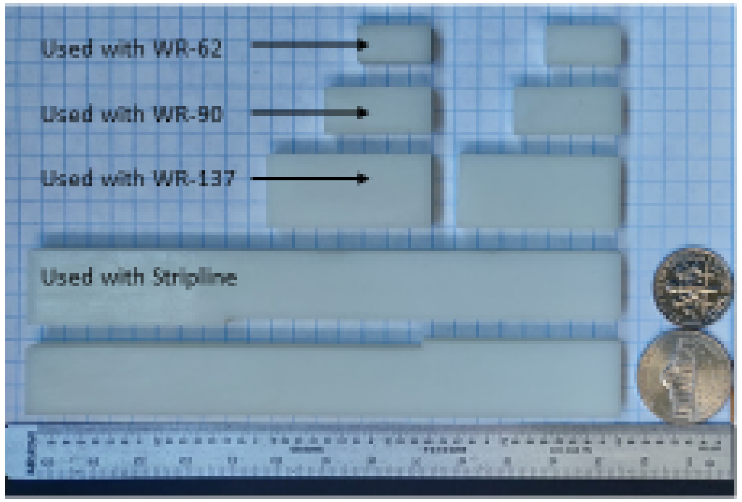



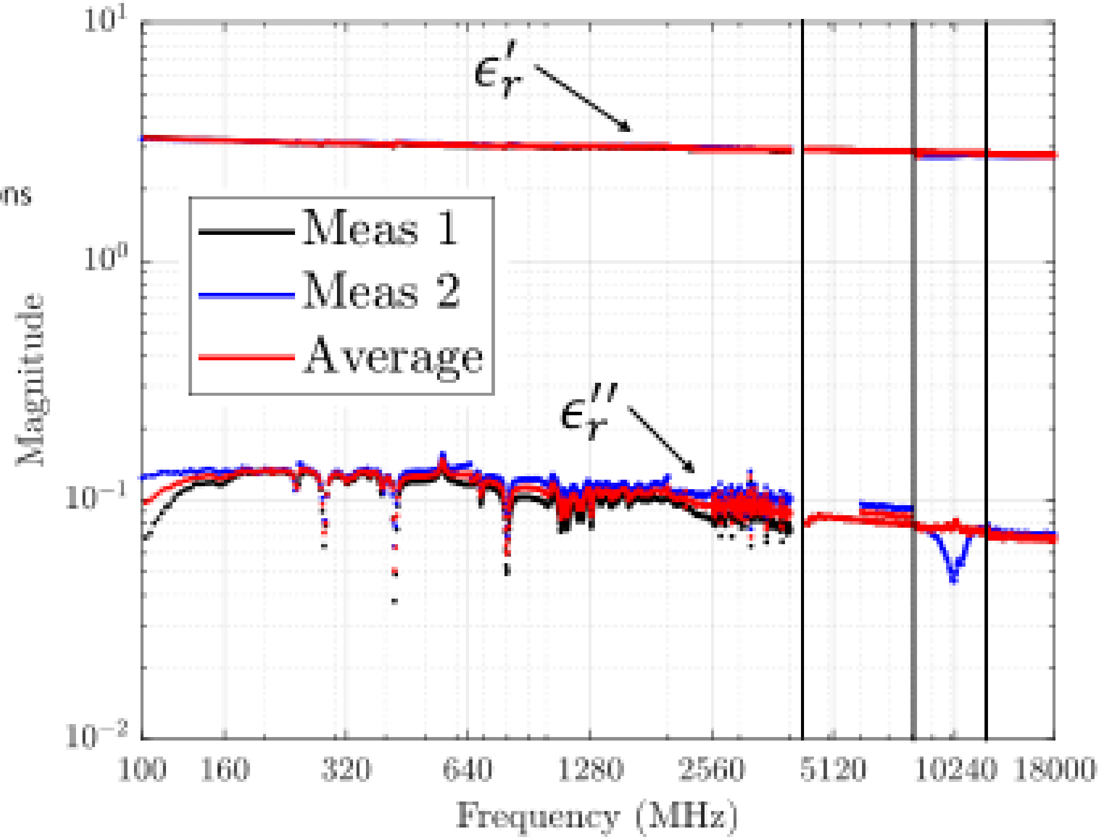
# Austin RCS Benchmark Suite: What is Coming?

## Material Characterization

ODEN INSTITUTE
UT ECE

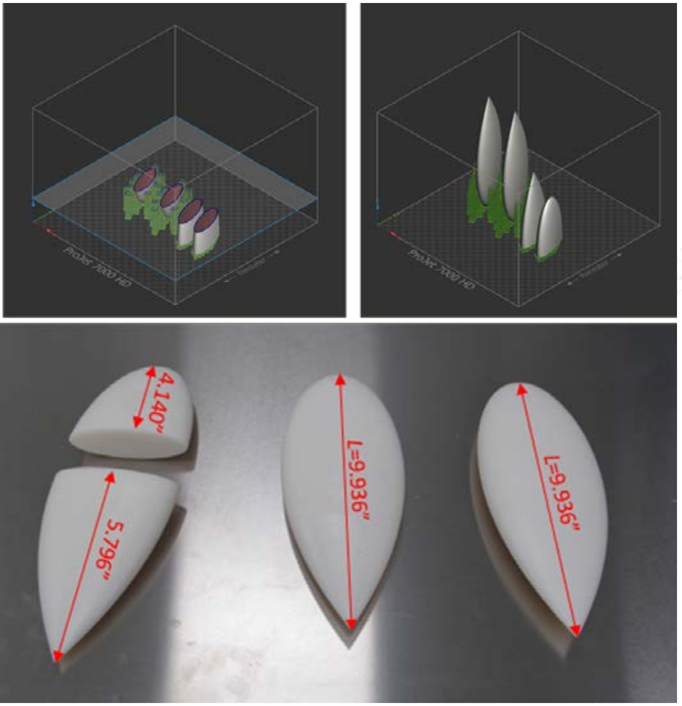
- ❑ Material Description
  1. Accura Xtreme White 200 photopolymer resin
- ❑ Measurement Process
  - Manufacture test coupons for resin
  - Calibrate VNA and validate with standard material coupons
  - Measure S parameters of test coupons
  - Use NRW algorithm to compute dielectric properties
  - Fit measured data to Debye Model



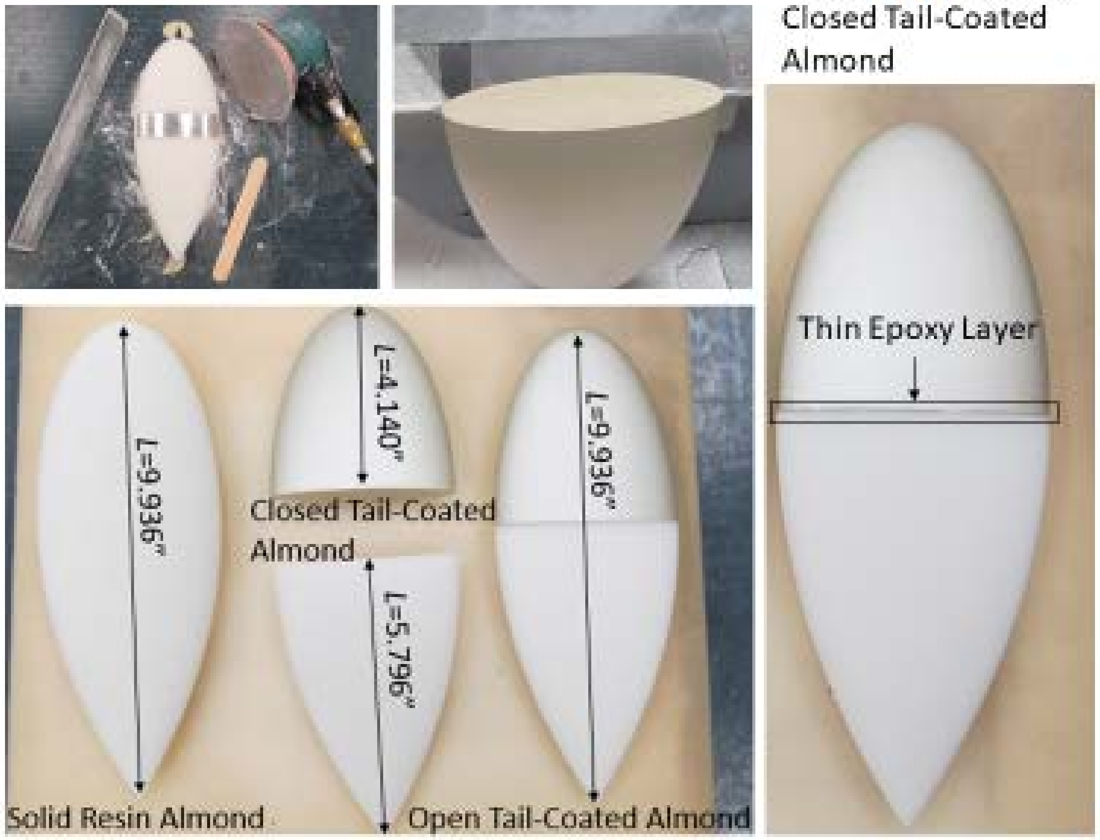



# Austin RCS Benchmark Suite: What is Coming?

## Target Preparation




- Target Description
  - Three Targets Based on NASA Almond [1] Geometry
    1. Solid Resin Almond
    2. Closed Tail-Coated Almond
    3. Open Tail-Coated Almond
- Target Manufacturing
  - Additively manufactured via Stereolithography (~29 hr)
  - Targets were cured in a UV oven
  - Targets were then sanded and the Closed/Open Tail-Coated Almonds were coated with silver paint
  - The tip and tail of the Closed Tail-Coated Almond were joined together with an epoxy



# Austin RCS Benchmark Suite: What is Coming?

## Monostatic RCS Measurement

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- Measurement Setup
  - LMA Rye Canyon Anechoic Chamber
  - Dual Calibration Technique
    - 18" and 15" NIST squat cylinders
- Data Collection
  - Background measurements taken frequently
    - Included small foam mount
  - Data collected from $\phi \in [-30°, 390°]$ azimuthal range
  - Rotation rate of $0.29°/s$ for a total of 24 minutes per polarization per target

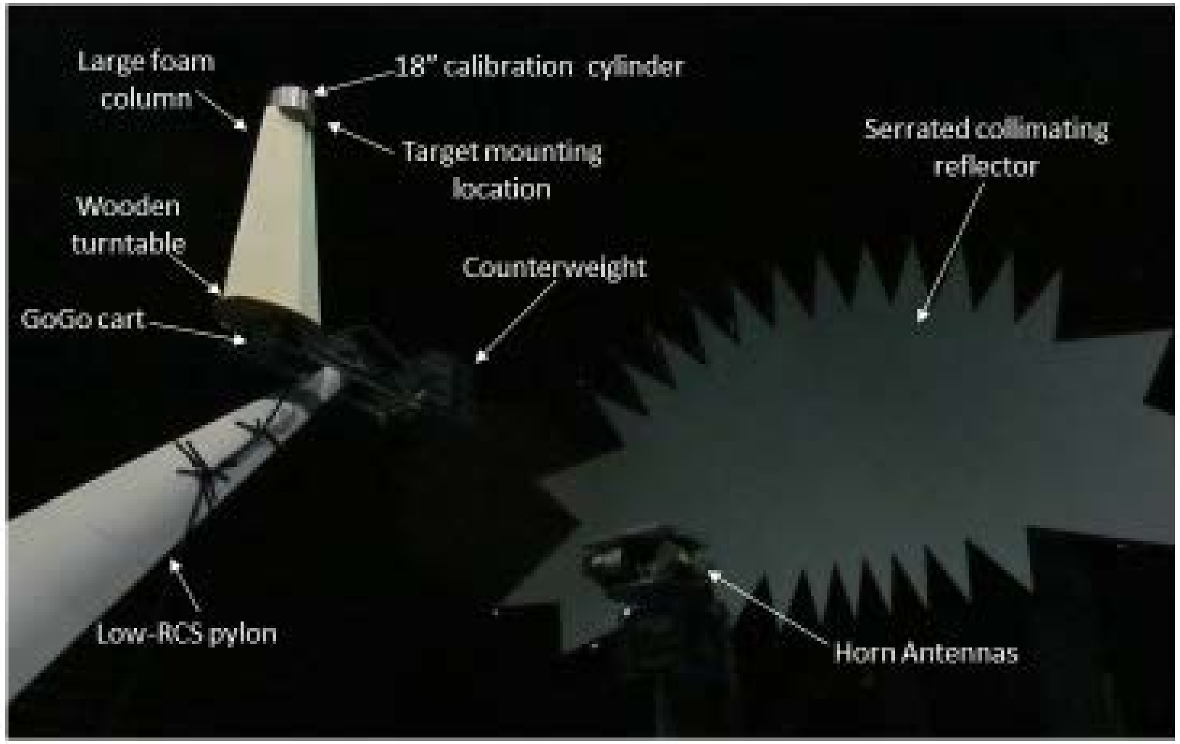
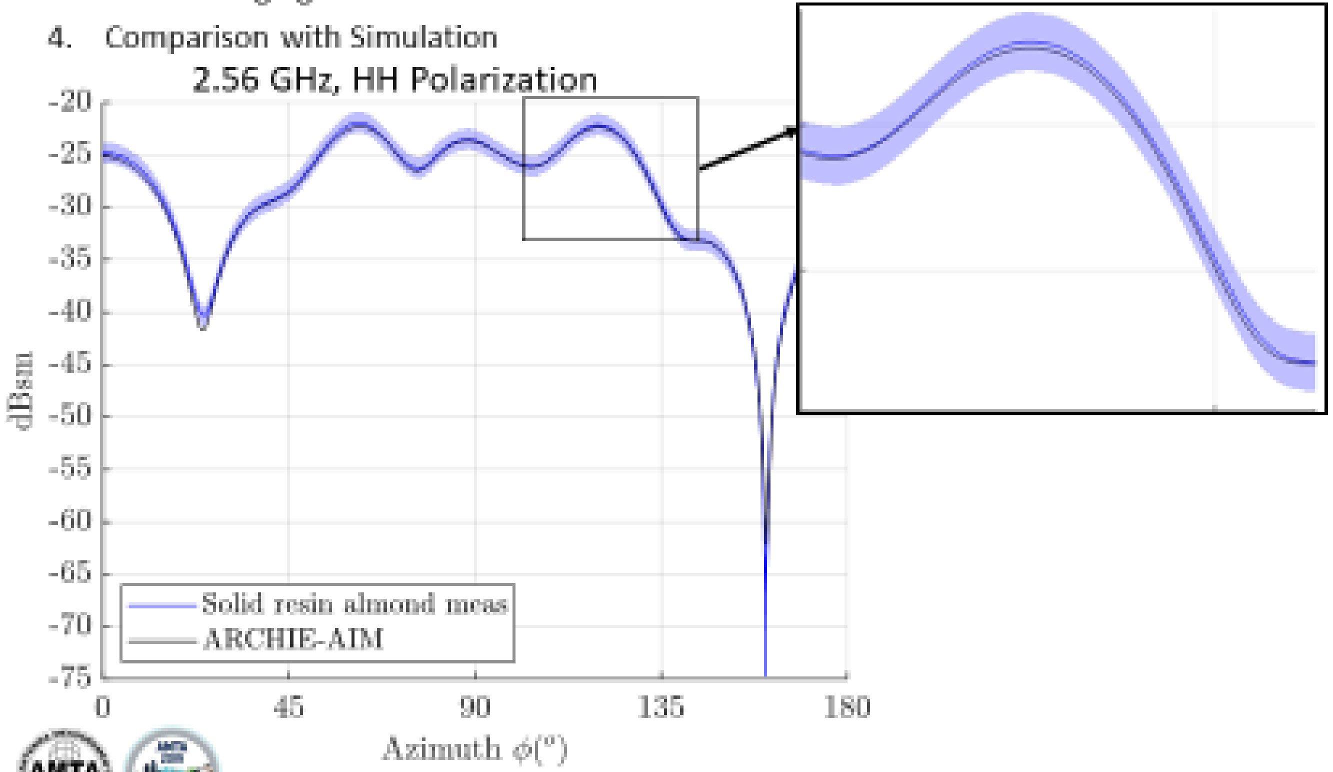



Image from: J. T. Kelley, D. A. Chamulak, C. C. Courtney, and A. E. Yilmaz, "EM programmers notebook-Rye Canyon RCS measurements of benchmark almond targets" in *IEEE Ant. Prop. Soc. Mag.*, 2019.

# Austin RCS Benchmark Suite: What is Coming?

## Measurement Post-Processing

- Measurement Post-Processing
  1. Background Subtraction
  2. Symmetry Alignment: Can use the symmetry of the target to reduce measurement uncertainty
  3. Data Averaging
  4. Comparison with Simulation

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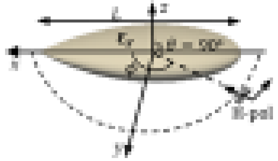
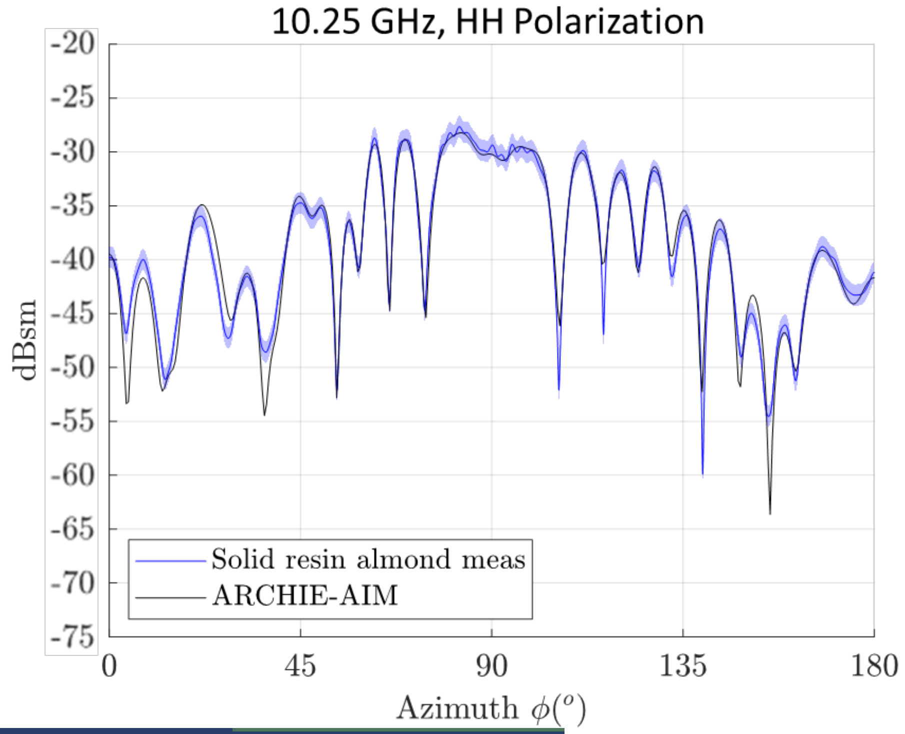
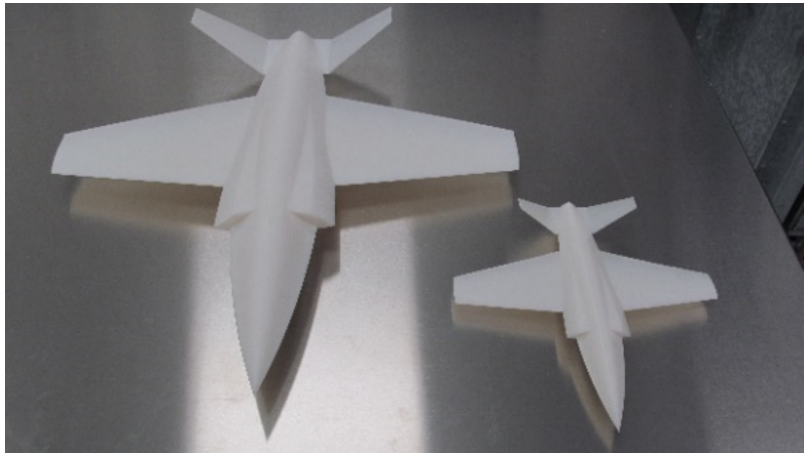
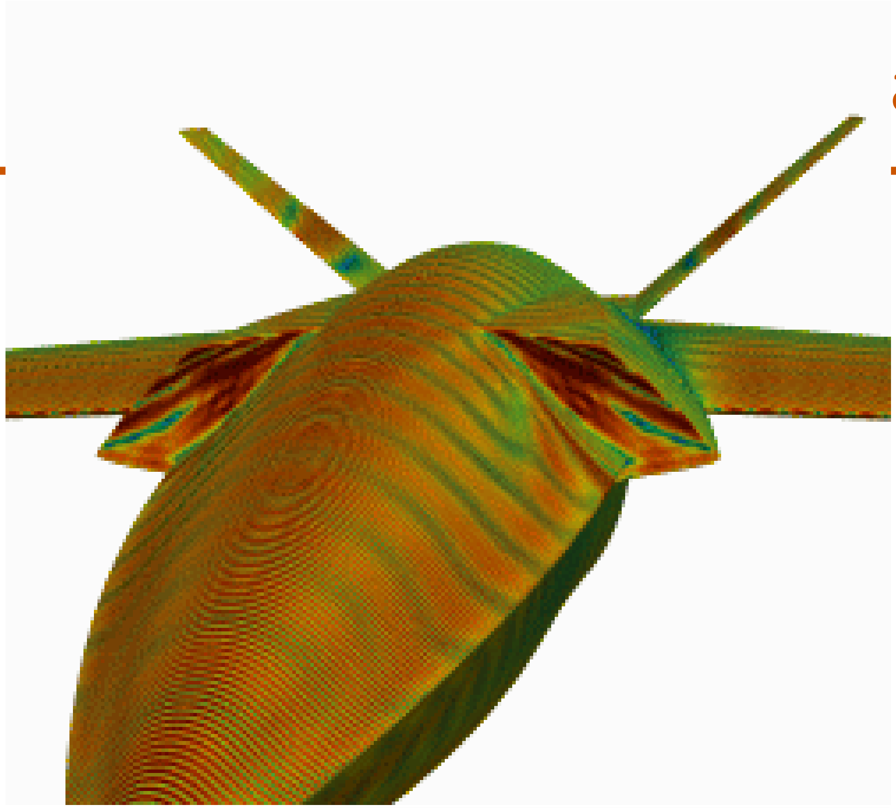
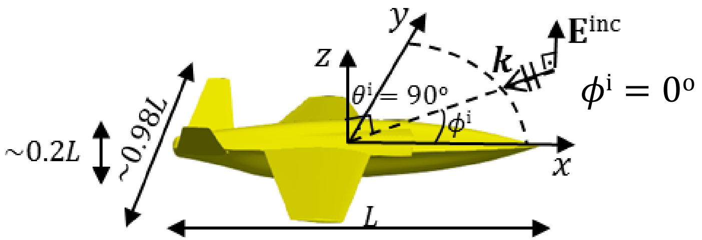


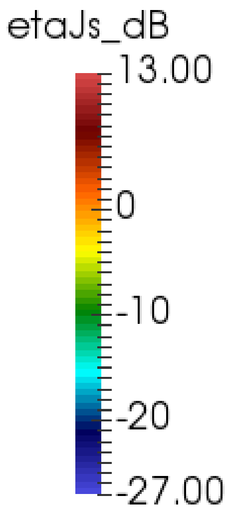


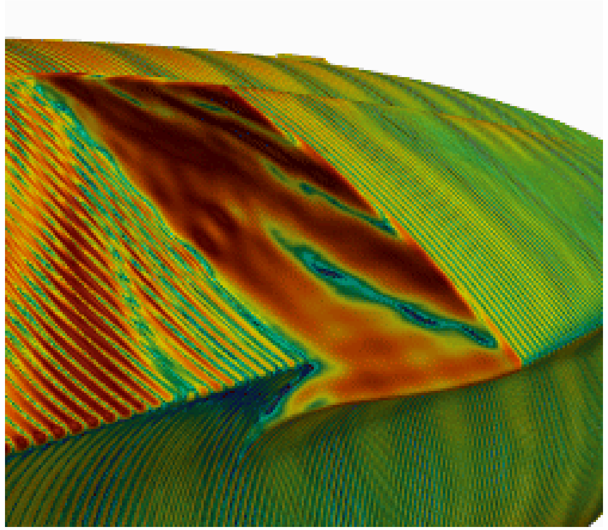
# Austin … at is Coming?

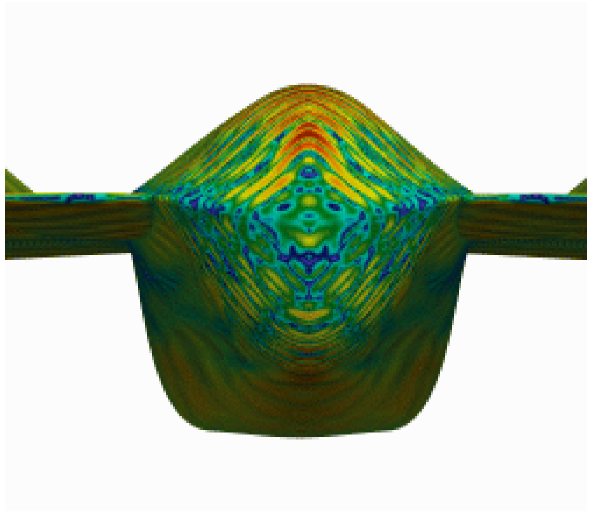








| Computational Costs (Lonestar5) | |
|---|---|
| *f*, *L* | 10.25 GHz, ~49ft |
| *N* | 63 522 600 |
| Cores | 4 032 |
| Wall solve time | 2 514 s |
| Wall fill time | 1 413 s |
| Memory / core | 2.4 GB |
| Iterations | 121 |

# Summary & Conclusion

## Judging Models

- Is this an appropriate model? Is it too simple? Unknown *a priori*.
- One way to answer: Simulate as high-fidelity as practical, then decide. (Experimental/evolutionary approach)
- Problem: Computational system/method of analysis influences/distorts answer
  - Analysis might appear too expensive if inappropriate method is used
  - Accuracy might appear saturated (if error floor dictated by method, not model)
- Must also judge computational methods'/systems' suitability for a given model/problem
  - Methods/systems advance/evolve rapidly
  - Everyone cannot be an expert in everything
  - Method researchers/developers often know weaknesses of methods best and rarely expose them (until next paper)
  - Objectivity, reproducibility => far from trivial

## A Possible Solution: Modern Benchmark Suites and Advanced Benchmarking

- Next-generation, publicly available benchmarks can help
  - Increase credibility of computational scientists & engineers
  - Reduce importance of subjective factors
  - Keep all of us better informed about latest state of EM problems & solution methods
  - Combat ubiquity of human error, misleading claims, misinformation