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Adding a Reproducible Airplane Model to the Austin RCS Benchmark Suite

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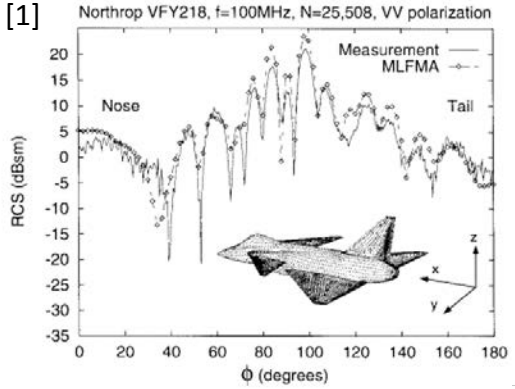
Outline

- ❑ Motivation
  - Complex aircraft models and Reproducibility
  - Austin RCS Benchmark Suite
- ❑ Complex Realistic Model
  - Model development
- ❑ Reliable Reference Results
  - Measurement campaign
    - Additive manufacturing
    - Material characterization
    - RCS measurement setup
    - Data processing
    - Simulation validation
- ❑ High-Fidelity CAD Model and Mesh(es)
  - Model curing
  - Validation
- ❑ Simple Public Access
  - Github site
- ❑ Conclusion

Motivation

- ❑ Complex Aircraft Models in CEM
  - Numerous aircraft models presented in literature
  - Simulation results using such models generally impossible to reproduce or corroborate [6]
  - Published data insufficient to objectively compare different algorithms, software, hardware
  - Partly because models are unavailable (inputs not replicable externally, or even internally after some time)
- ❑ Challenges for a Reproducible Airplane Model
  - Complex realistic model
  - Reliable reference results
  - High-fidelity CAD model and mesh(es)
  - Simple public access

[1]



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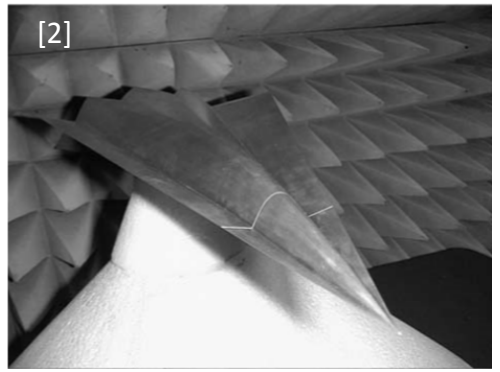

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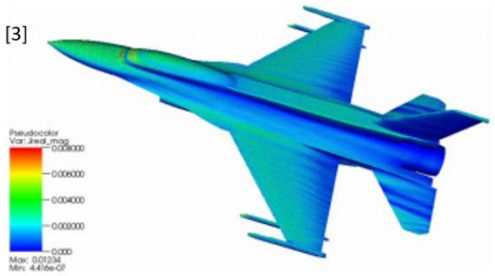
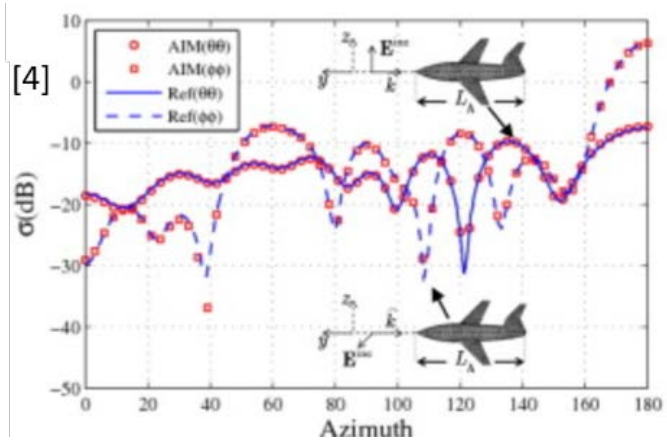


Fig. 19. Current distribution on the mock-up fighter jet at 10 GHz.

[4]



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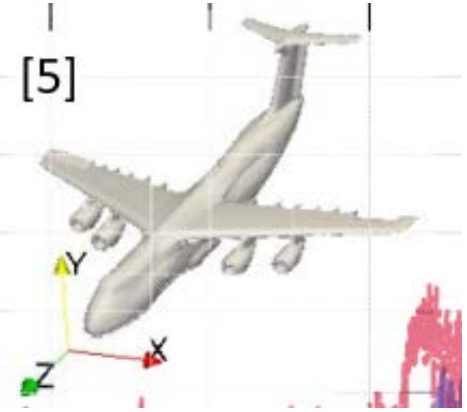

References:
[1] J. Song, C. C. Lu, and W. C. Chew, "Multilevel fast multipole algorithm for electromagnetic scattering by large complex objects," *IEEE Trans. Antennas Propag.*, vol. 45, no. 10, pp. 1488-1493, Oct. 1997.
[2] L. Gurel *et al.*, "Validation through comparison: Measurement and calculation of the bistatic radar cross section of a stealth target," *Radio Sci.*, vol. 38, no. 3, 1046, 2003.
[3] Z. Peng, X.-C. Wang, and J.-F. Lee, "Integral equation based domain decomposition method for solving electromagnetic wave scattering from non-penetrable objects," *IEEE Trans. Antennas Propag.*, vol. 59, no. 9, pp. 3328-3338, July 2011.
[4] F. Wei and A. E. Yilmaz, "A hybrid message passing/shared memory parallelization of the adaptive integral method for multi-core clusters," *Parallel Comp.*, vol. 37, no. 6-7, pp. 279-301, June-July 2011.
[5] S. Hughey *et al.*, "Parallel wideband MLFMA for analysis of electrically large, nonuniform, multiscale structures," *IEEE Trans. Antennas Propag.*, vol. 67, no. 2, pp. 1094-1107, Feb. 2019.
[6] D. G. Feitelson, "From repeatability to reproducibility and corroboration," *ACM SIGOPS Oper. Sys. Rev.*, vol. 49, no. 1, pp. 3-11, Jan. 2015.

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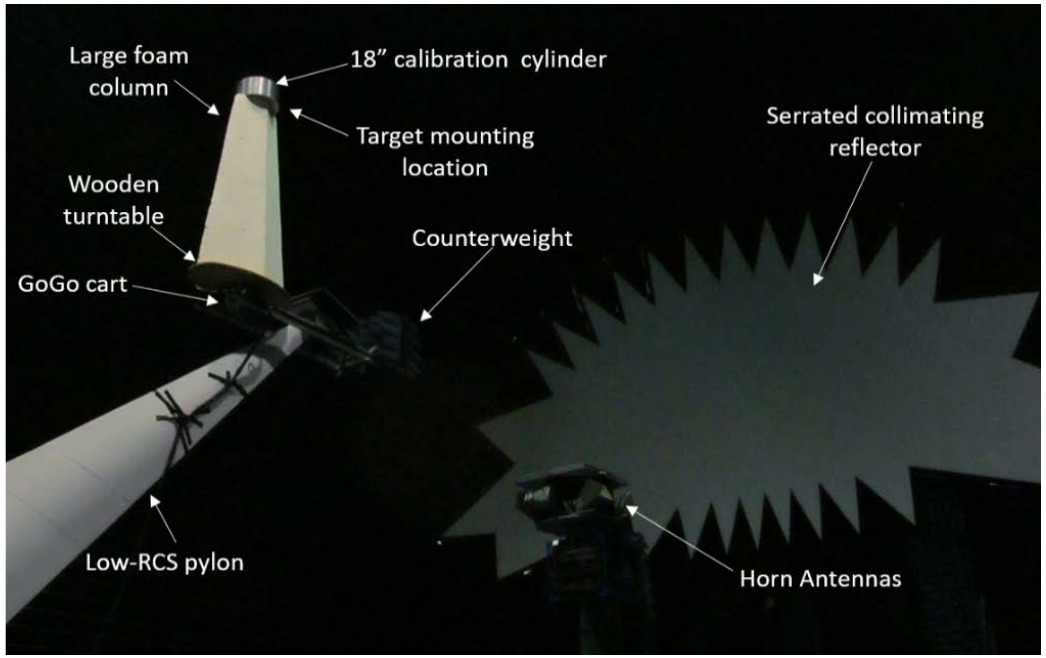
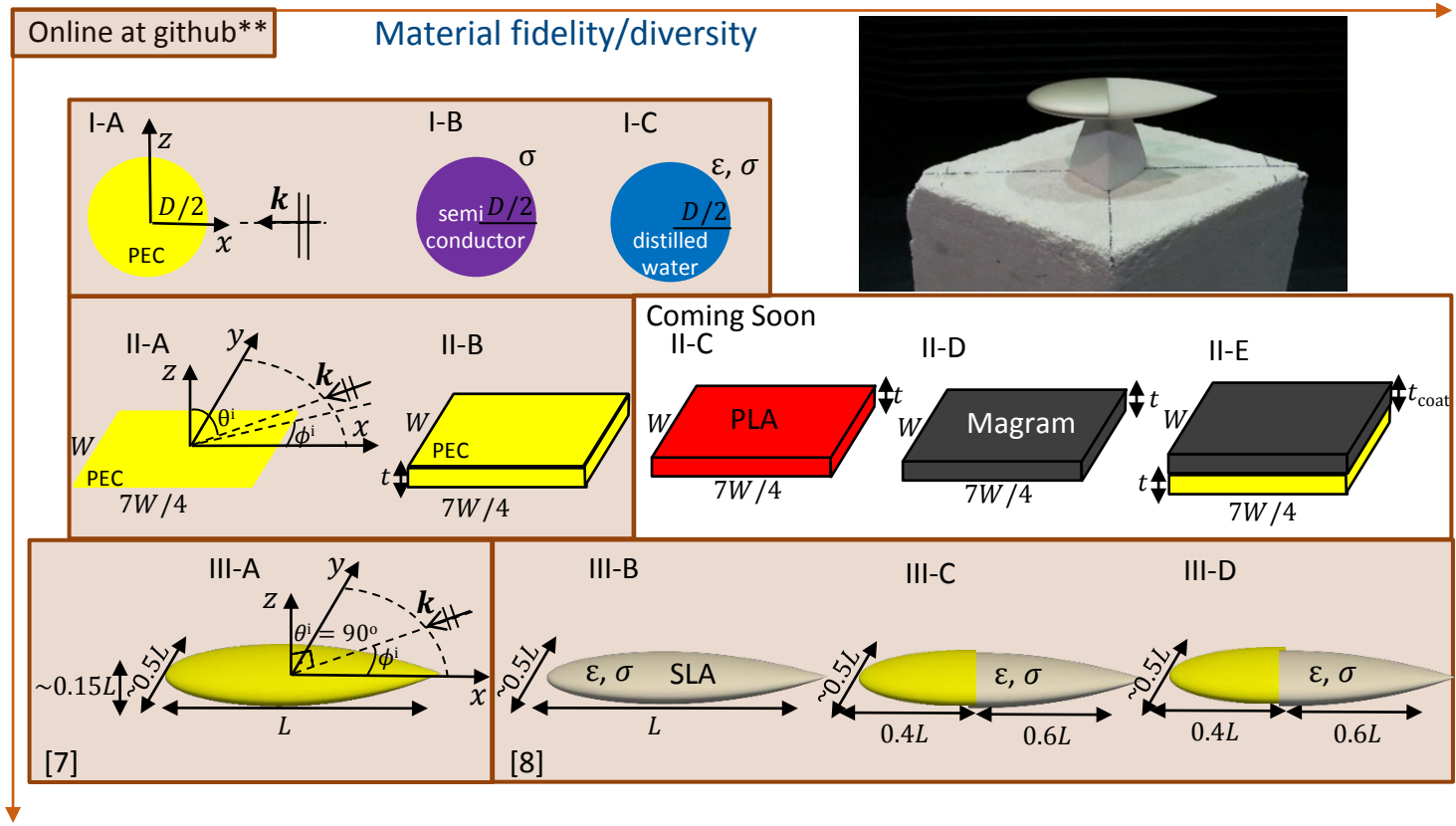
Motivation

❑ Austin RCS Benchmark Suite

- Highly structured, gradually populated with scattering problems spanning difficulty levels
- Contains analytical, measurement, and simulation reference data
- Precisely defined quantities of interest, performance measures
- Emphasis on replicability, publicly available





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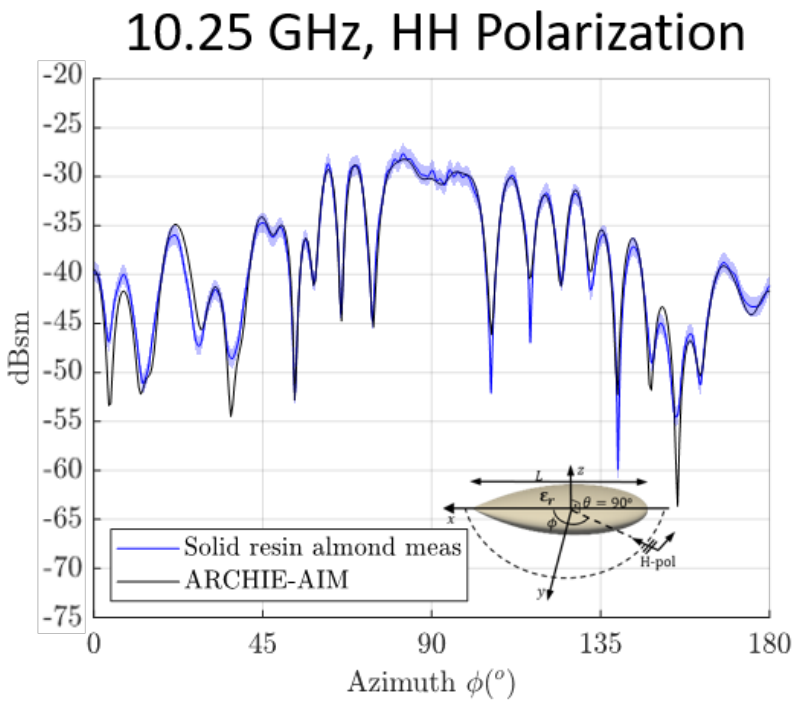

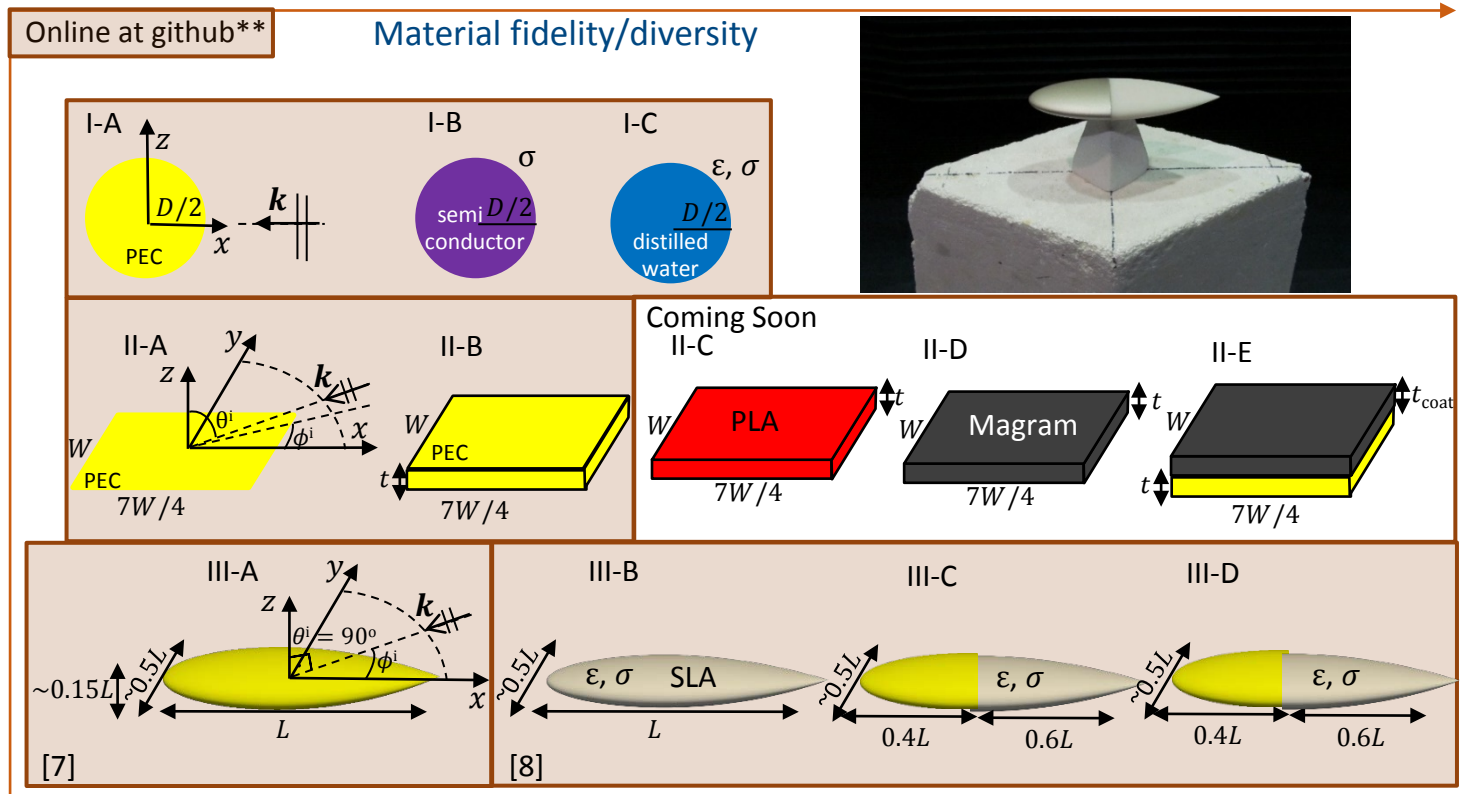

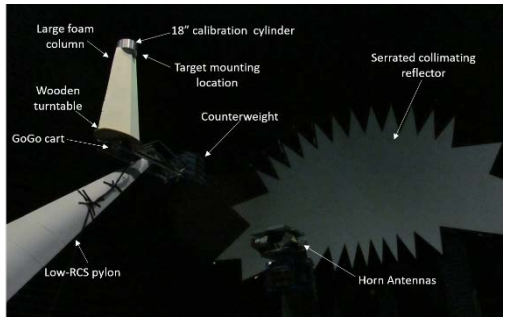

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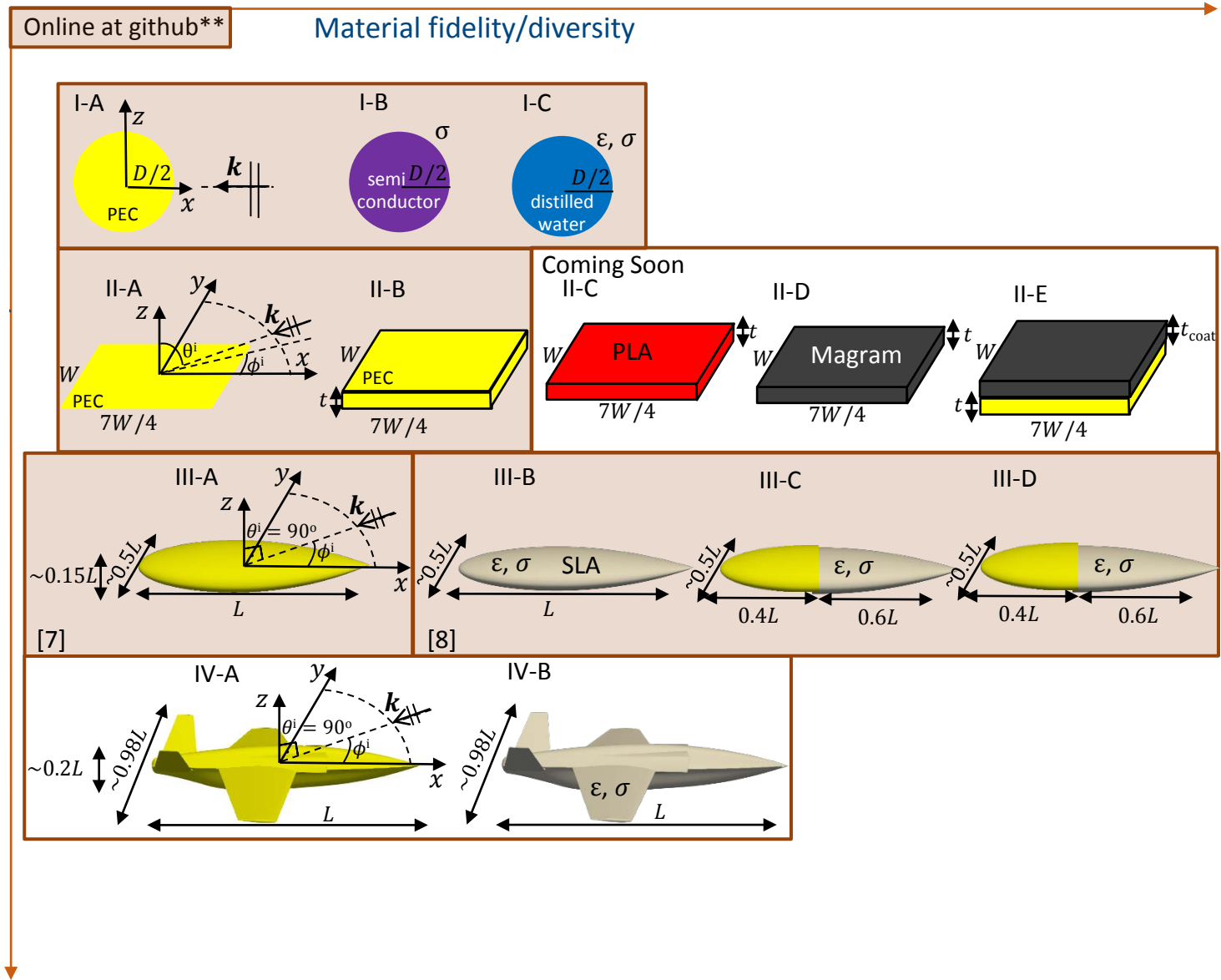
  - Contains analytical, measurement, and simulation reference data
  - Precisely defined quantities of interest, performance measures
  - Emphasis on replicability, publicly available
- ❑ Requirements for a Reproducible Airplane Model
  - Complex realistic model
  - Reliable reference results
  - High-fidelity CAD model and mesh(es)
  - Simple public access
- ❑ EXPEDITE-RCS Model
  - High-fidelity airplane model
  - Publicly available model and meshes
  - PEC and dielectric
  - Measurement and simulation reference data



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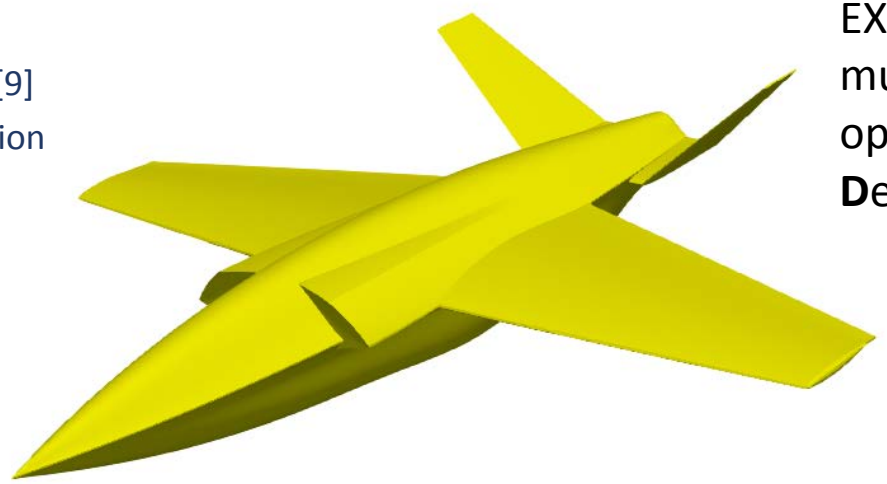
Model Development

- Model Development Process
  - Test platform designed as part of EXPEDITE program [9]
  - Program structured to minimize proprietary information to allow collaboration and release of models
  - Selected a particular realization from ensemble of parameterized designs: EXPEDITE-RCS



EXPEDITE = **EXP**anded muldisciplinary analysis and design optimization for **E**ffectiveness-based **D**es**I**gn **Te**chnologies

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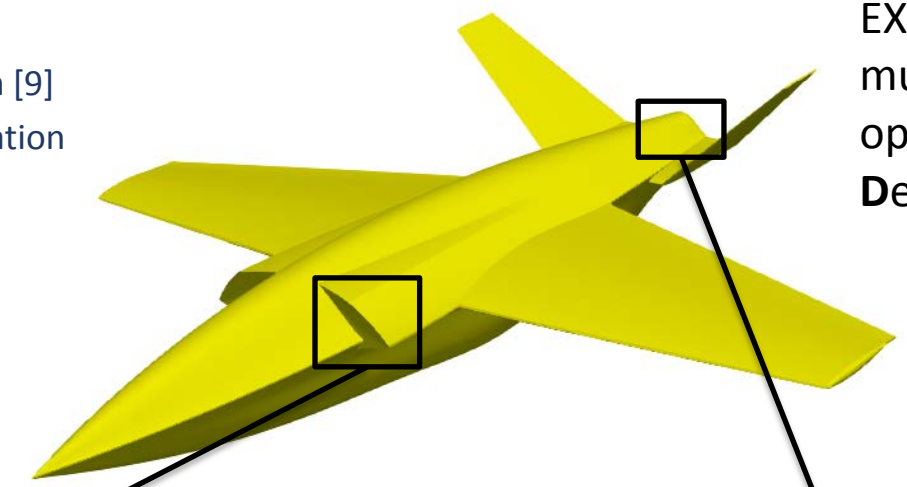
  - Selected a particular realization from ensemble of parameterized designs: EXPEDITE-RCS
- ❑ EXPEDITE-RCS features and characteristics
  - Closed engine intake and exhaust cavities
  - Simple materials at first (PEC and homogeneous dielectric)
  - Scale-models for RCS measurement



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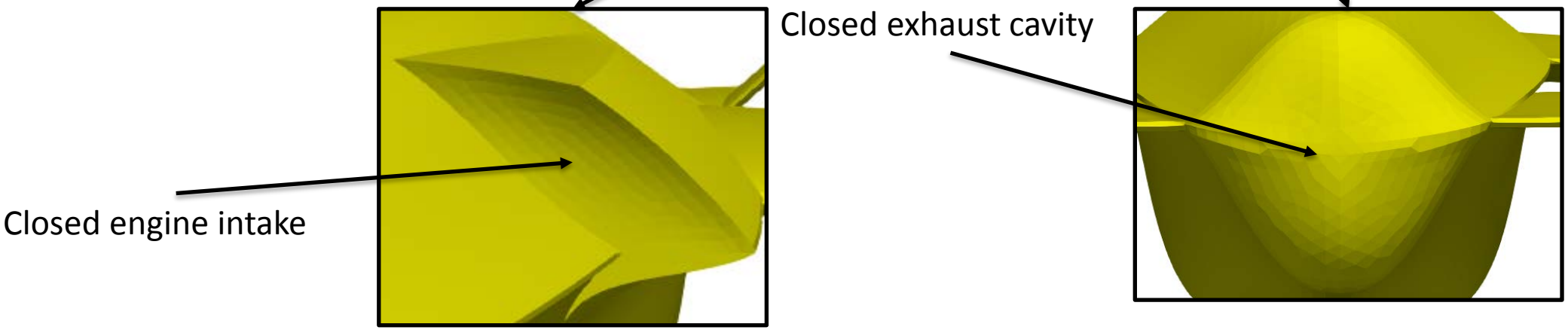

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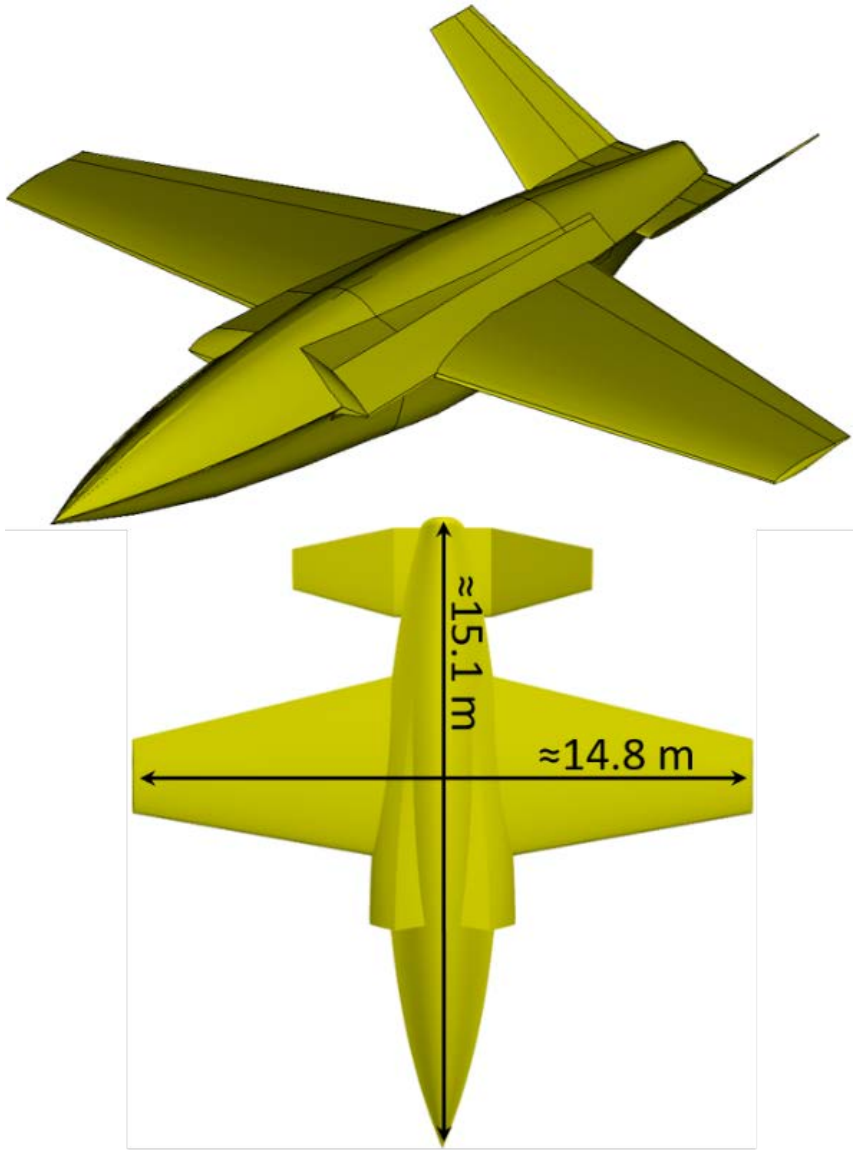
Measurement Campaign

- EXPEDITE-RCS Dimensions
  - Nose-to-tail length ≈15.1 m



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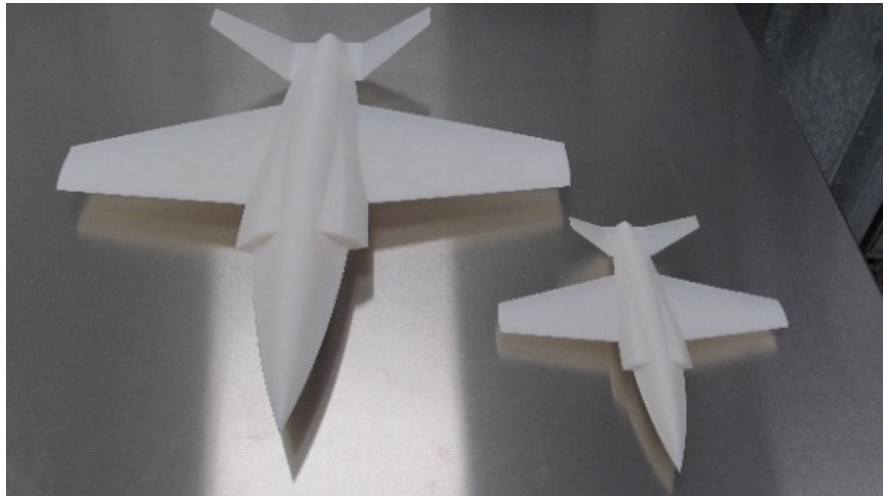
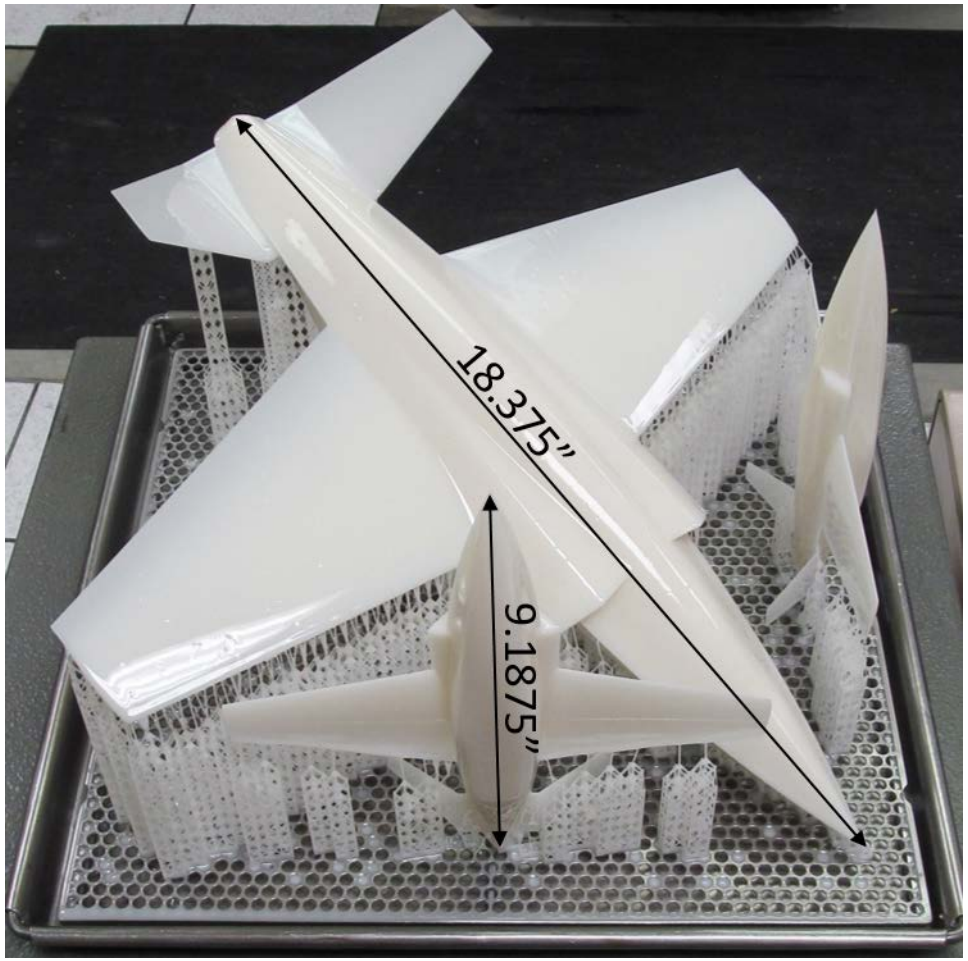
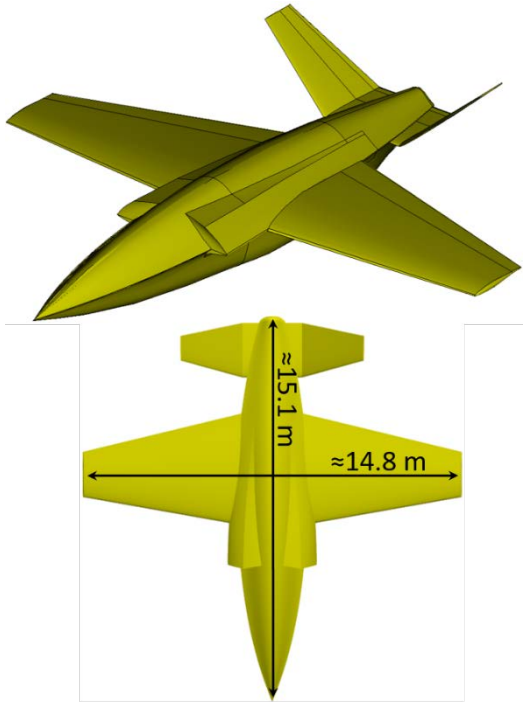
  - Printed via stereolithography (SLA)
  - Two scale models approx. 1/64 and 1/32 of the full-size model







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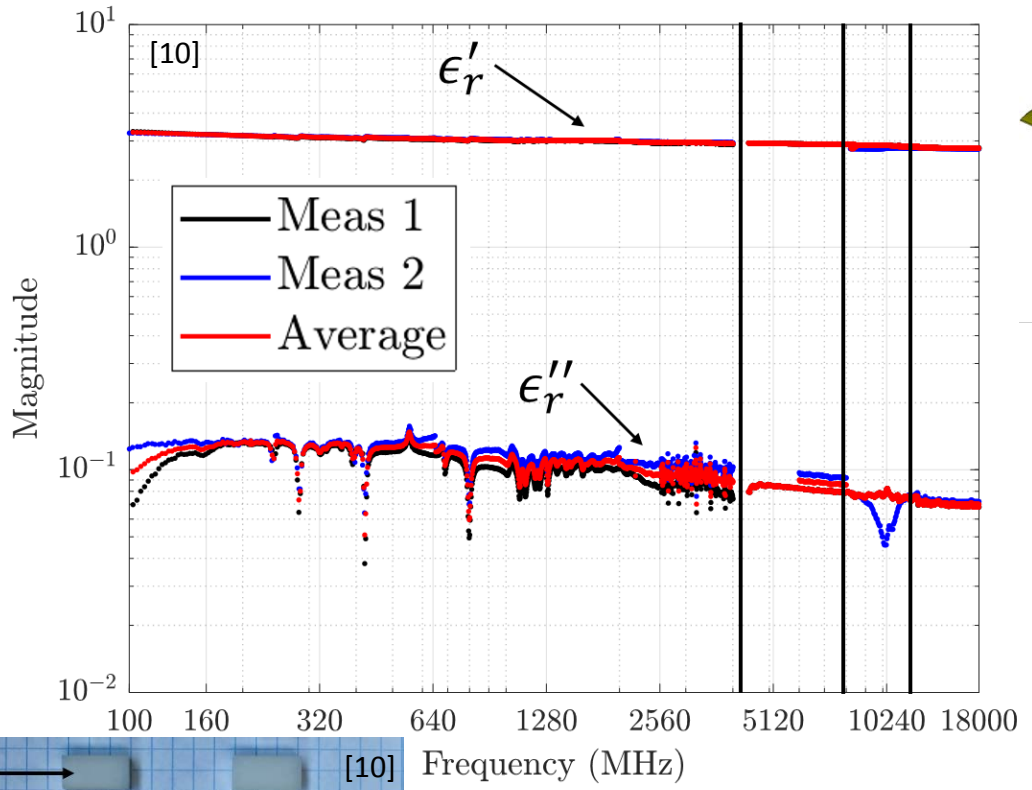
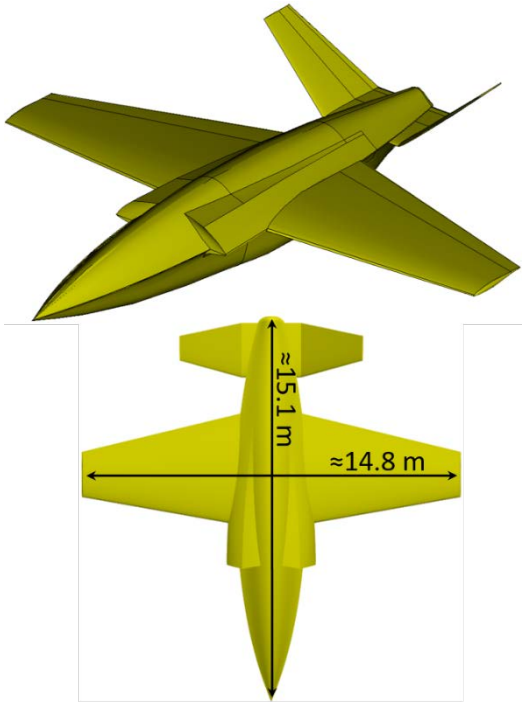
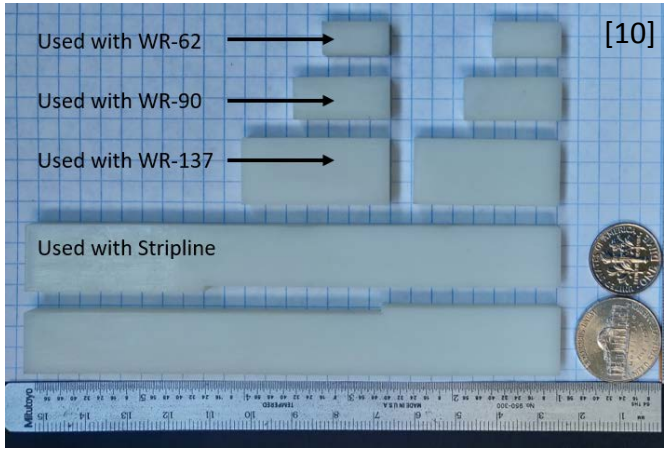
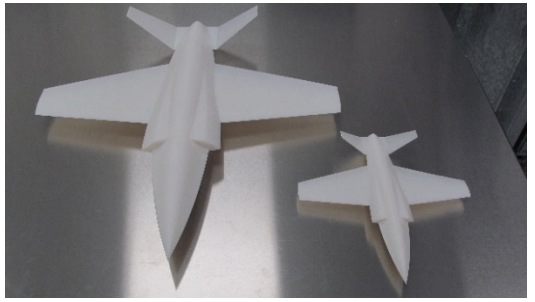
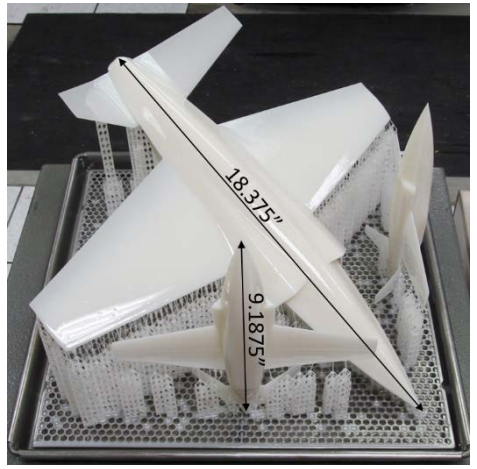
  - Accura Xtreme White 200 photopolymer resin
  - Permittivity measured using well-known techniques with four test fixtures for different frequency bands











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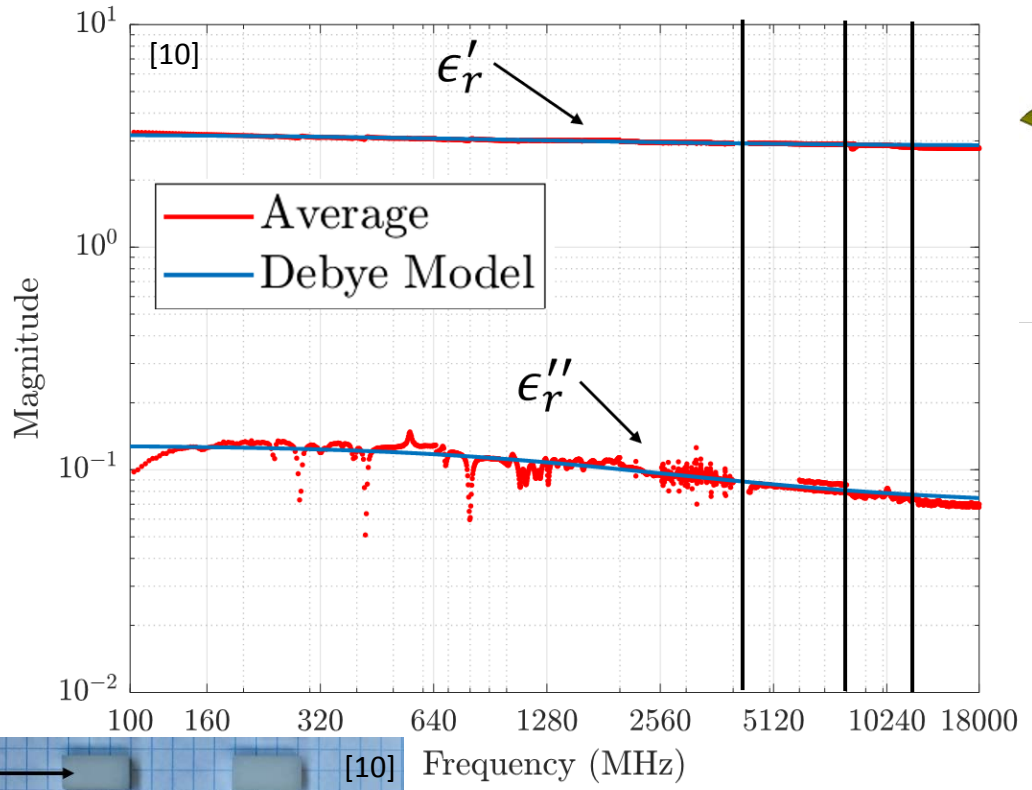
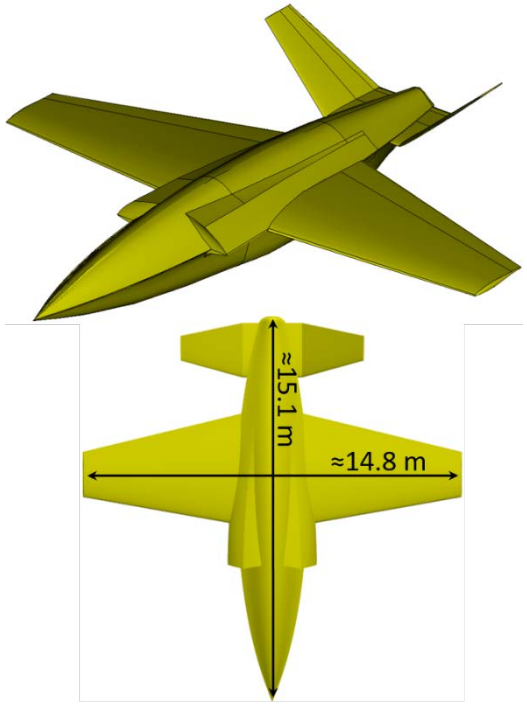
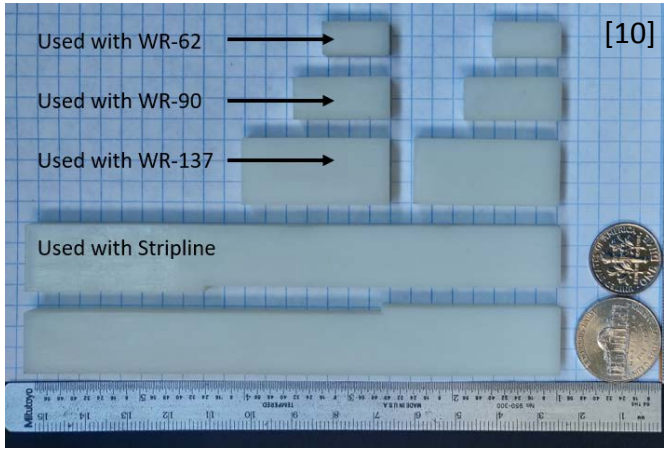
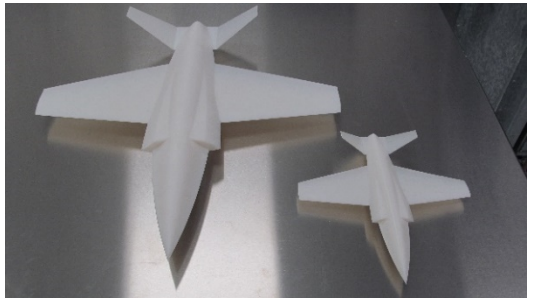
  - Fit measured data to a Debye Model

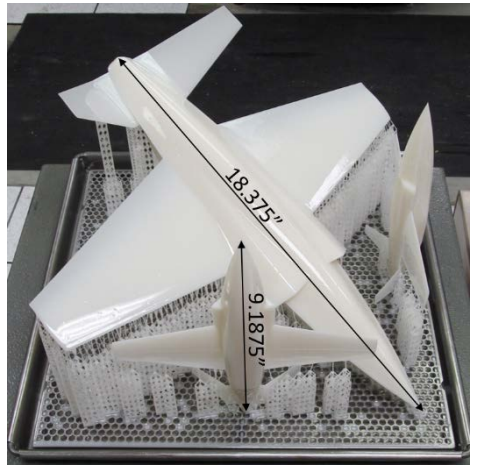
$$\epsilon_r(f) = A + \frac{B}{1 - jfC}$$











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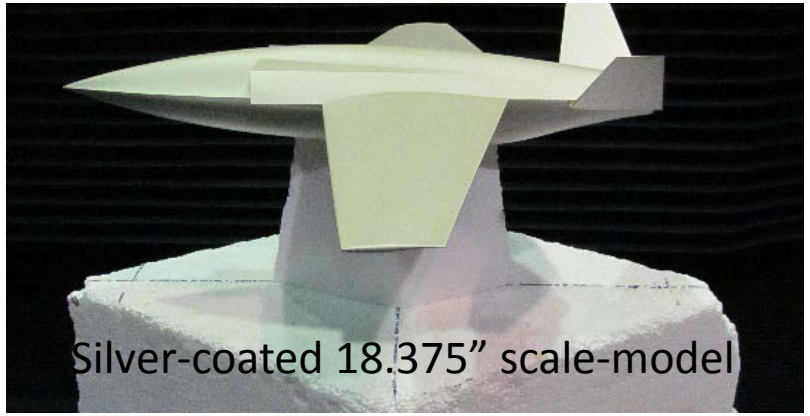
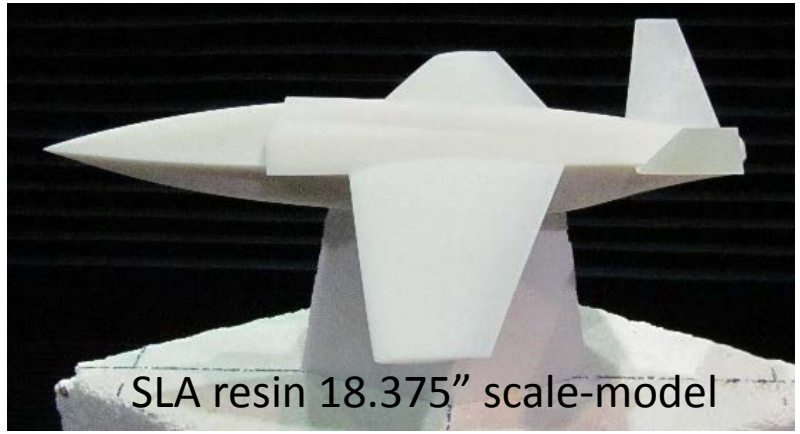
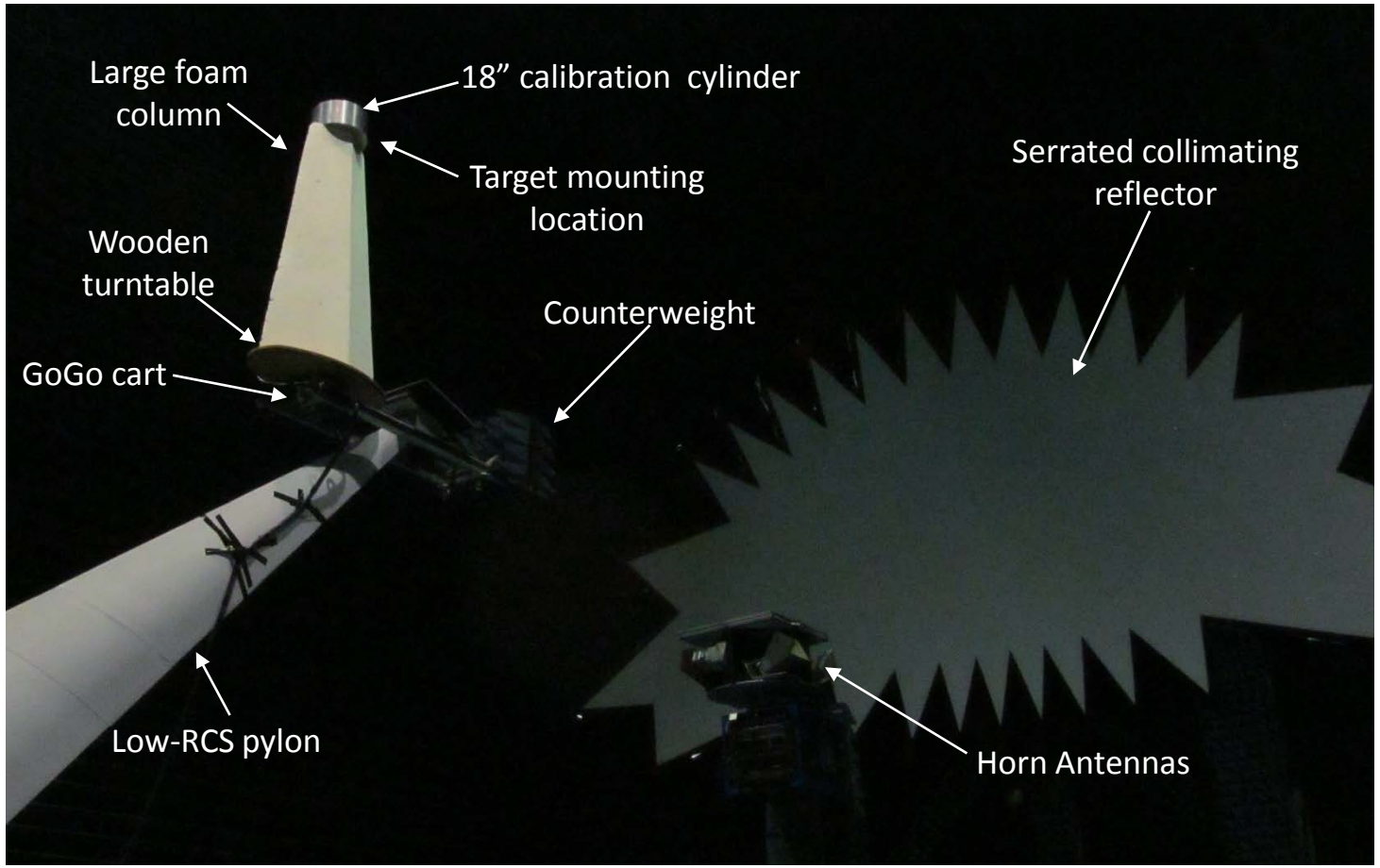
Monostatic RCS Measurement

- Measurement Setup
  - Compact chamber

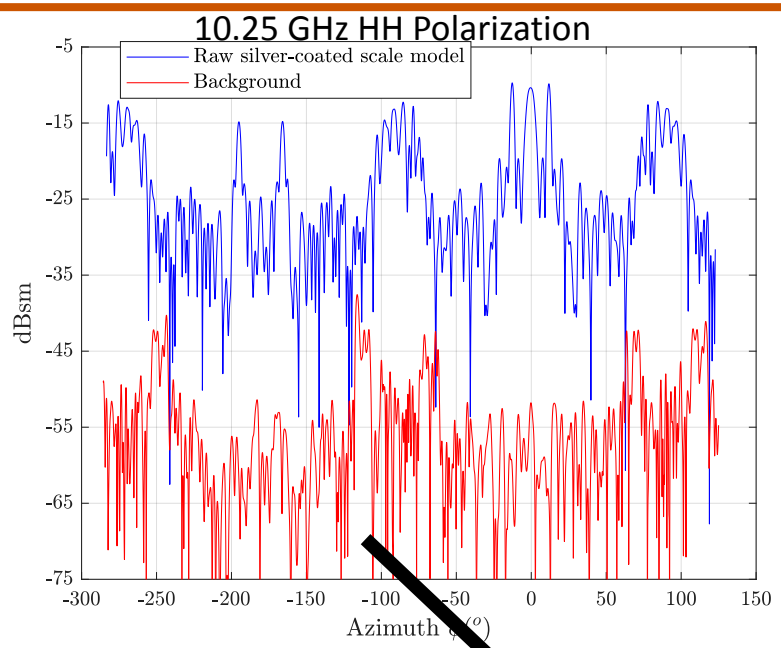




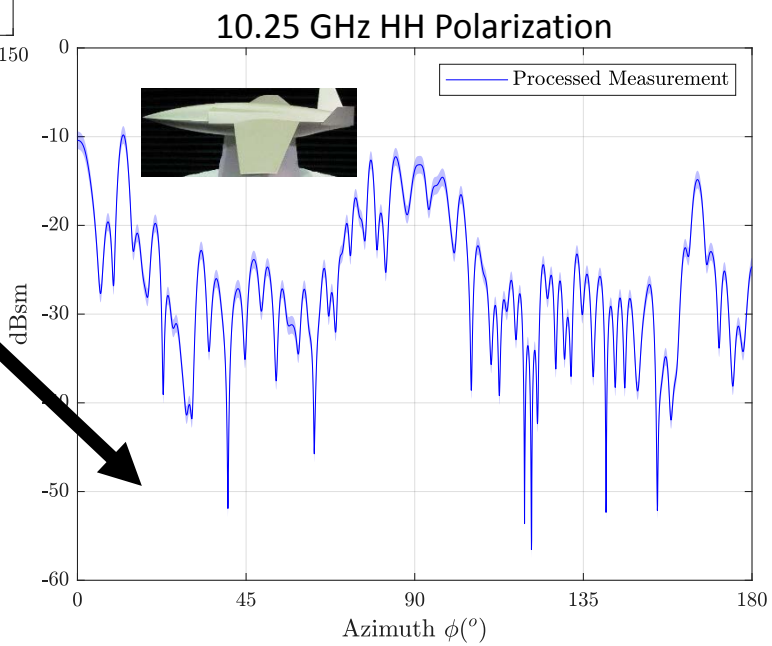


Monostatic RCS Measurement

- Measurement Setup
  - Compact chamber
- Data Collection [8]
  - Dual calibration method
  - Coherent background subtraction: background measurements taken frequently
  - Data collected from $\phi \in [-30°, 390°]$ azimuthal range
  - Rotation rate of $0.29°/s$: 24 min per polarization per target
  - Symmetry and averaging: correct for azimuthal misalignment and average data from two sides
  - Correlate with CEM predictions



Post-Processing



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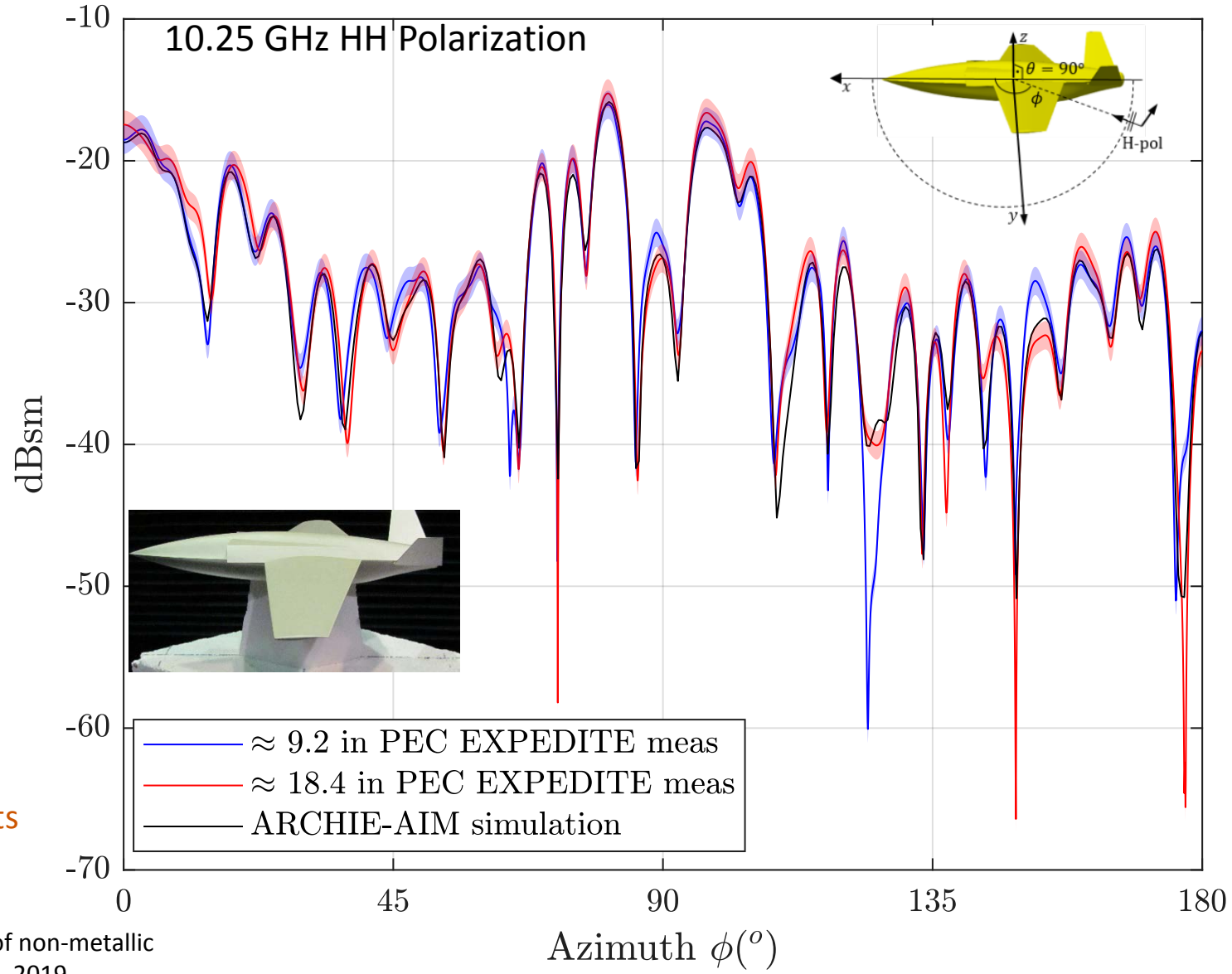
  Simulations supporting measurement campaigns:

  1. reduce measurement uncertainties
  2. increase confidence in measured results
  3. provide reference data to validate measurements and adjust them in real time



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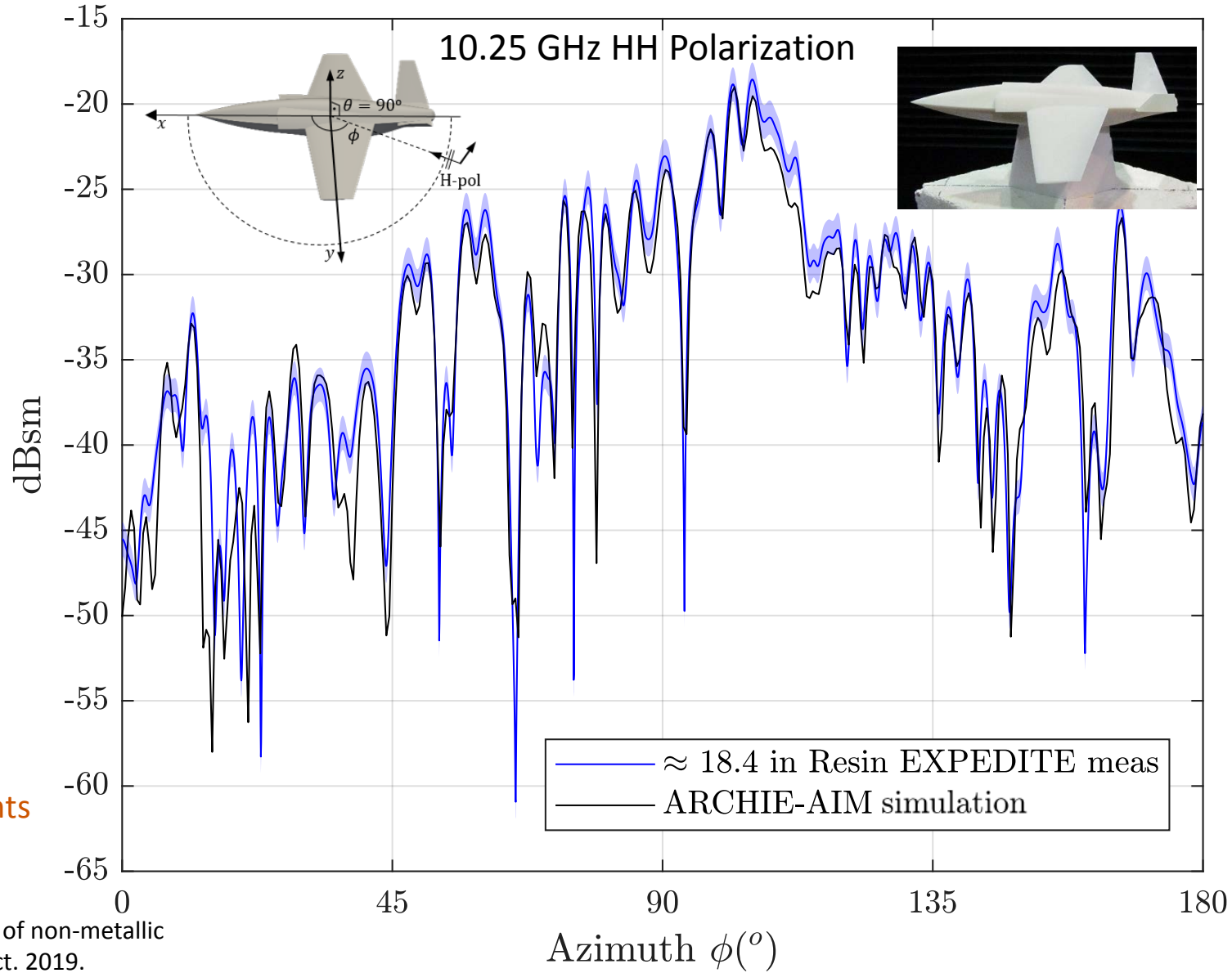

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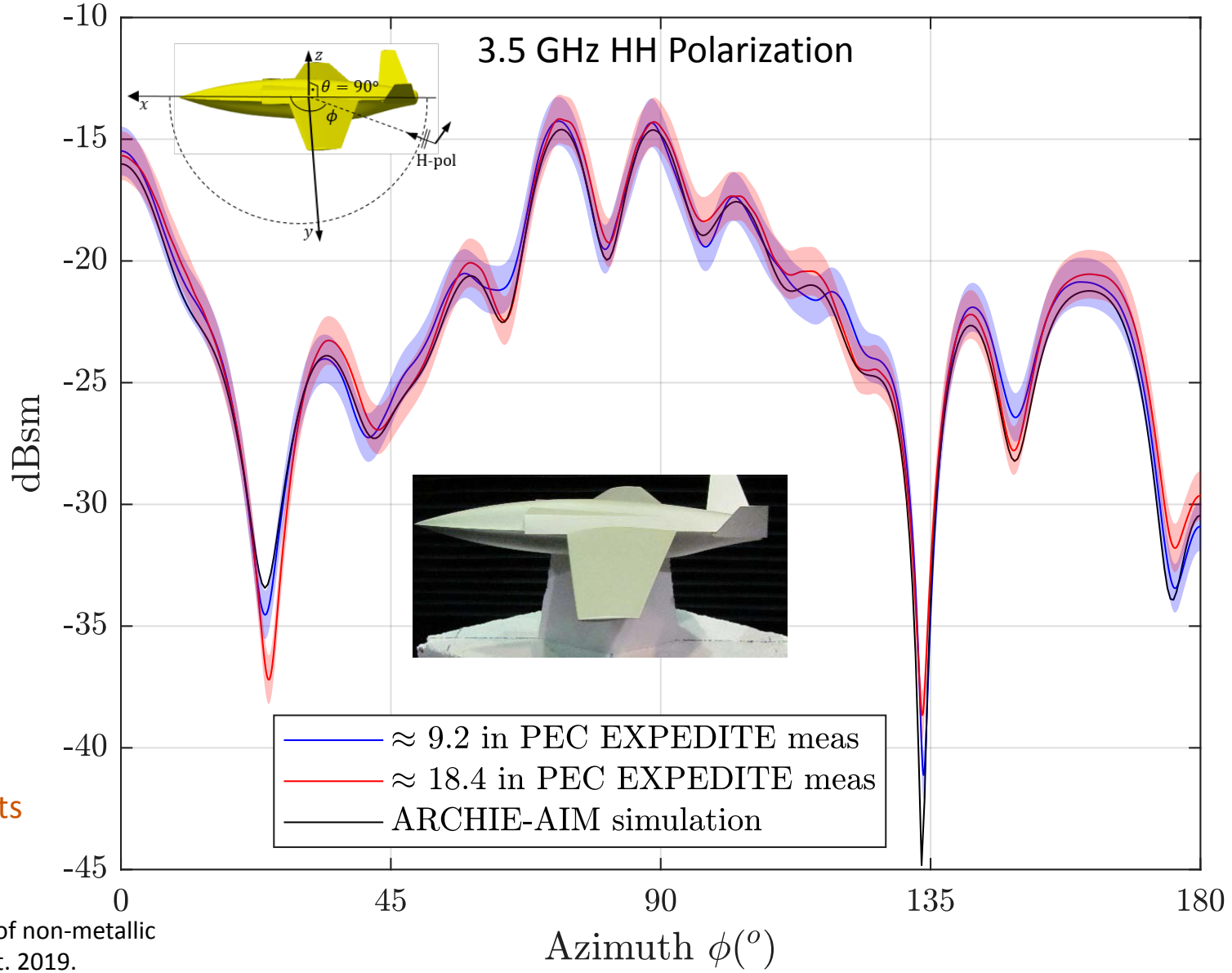
  - Symmetry and averaging: correct for azimuthal misalignment and average data from two sides
  - Correlate with CEM predictions

Simulations supporting measurement campaigns:

1. reduce measurement uncertainties
2. increase confidence in measured results
3. provide reference data to validate measurements and adjust them in real time



References:
[8] J. T. Kelley, D. A. Chamulak, C. C. Courtney, and A. E. Yılmaz, "Measurements of non-metallic targets for the Austin RCS Benchmark Suite," in *Proc. Ant. Meas. Tech. Assoc.*, Oct. 2019.

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Outline

- ❑ Motivation
  - Complex aircraft models and Reproducibility
  - Austin RCS Benchmark Suite
- ❑ Complex Realistic Model
  - Model development
- ❑ Reliable Reference Results
  - Measurement campaign
    - Additive manufacturing
    - Material characterization
    - RCS measurement setup
    - Data processing
    - Simulation validation
- ❑ High-Fidelity CAD Model and Mesh(es)
  - Model curing
  - Validation
- ❑ Simple Public Access
  - Github site
- ❑ Conclusion

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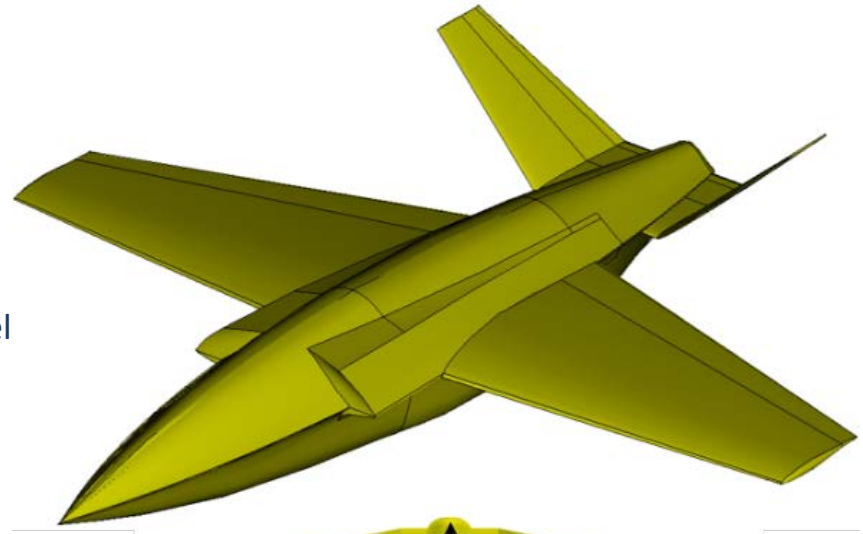
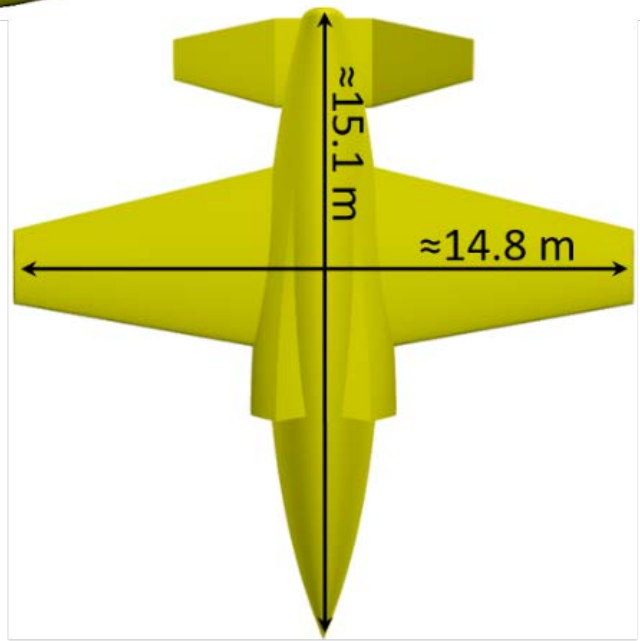
High-Fidelity CAD Model and Mesh(es)

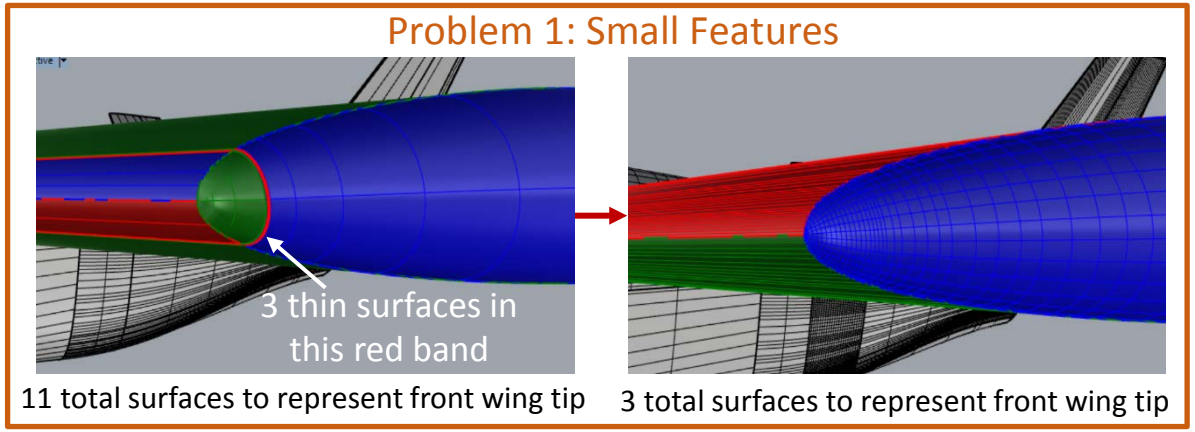
- ❑ EXPEDITE-RCS model originally developed in CAD software (CATIA 5) used to design EXPEDITE test platform
- ❑ CATIA model's surface description
  - exported in STL format → successfully used for additive manufacturing
  - meshed using CATIA tools → successfully used to compute RCS and support measurements
  - exported in IGS format → imported into common meshing tool (Trelis 16.5) → failed to mesh model
- ❑ IGS file
  - 220 surfaces
  - many were artifacts; including minute surfaces with edges smaller than 1 in.
  - requires defeaturing
- ❑ Goal: Improve surface description in IGS format so it can be meshed
  - accurately
  - independently
  - relatively easily





Model Curing

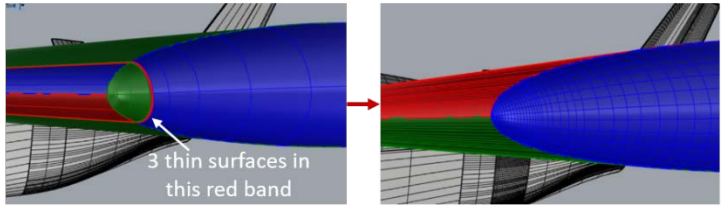
- Identified three general qualities in original IGS file which make meshing more difficult
  1. Small features



Model Curing

- Identified three general qualities in original IGS file which make meshing more difficult
  1. Small features
  2. Misaligned edges

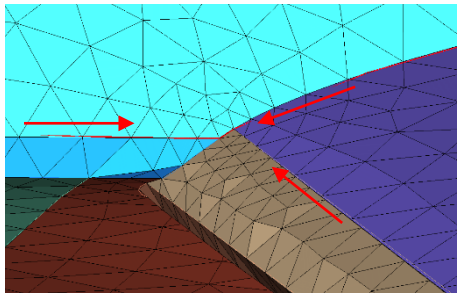
Problem 1: Small Features



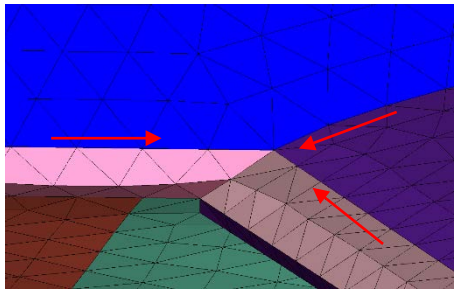
11 total surfaces to represent front wing tip

3 total surfaces to represent front wing tip

Problem 2: Misaligned Edges



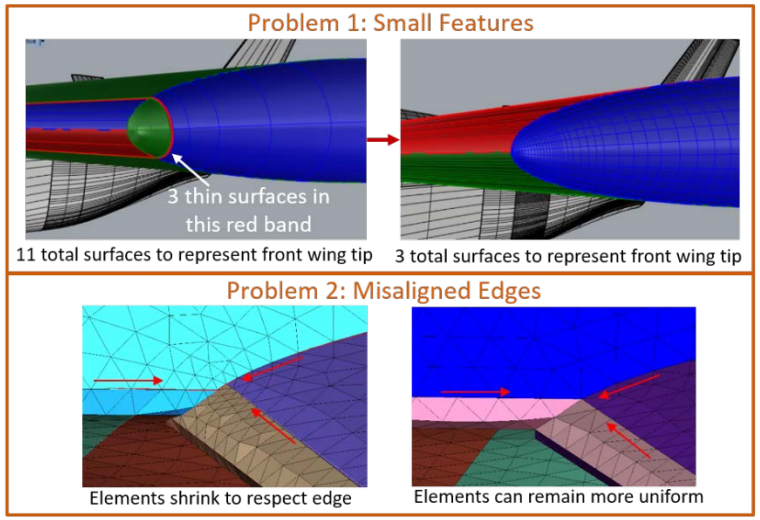
Elements shrink to respect edge

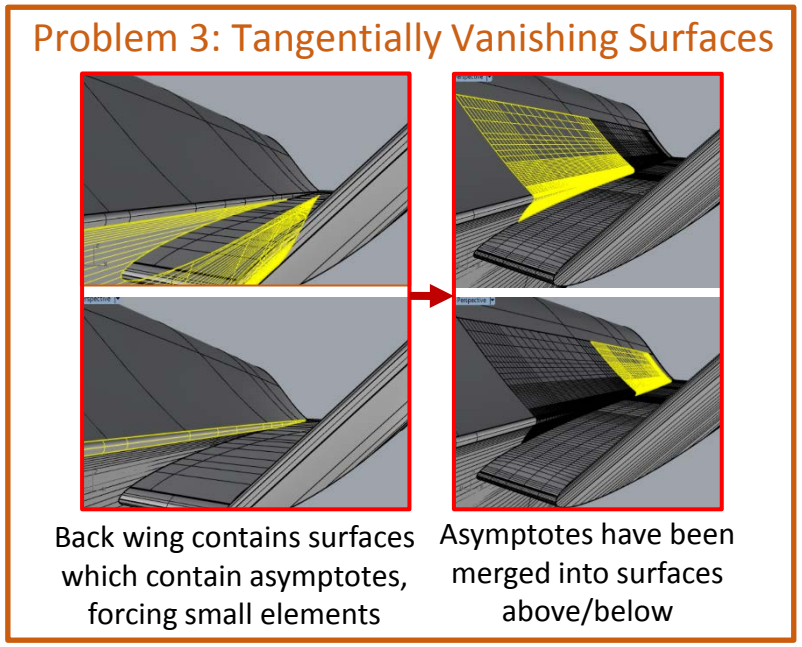


Elements can remain more uniform

Model Curing

- Identified three general qualities in original IGS file which make meshing more difficult
  1. Small features
  2. Misaligned edges
  3. Tangentially vanishing surfaces





Model Curing

- Identified three general qualities in original IGS file which make meshing more difficult
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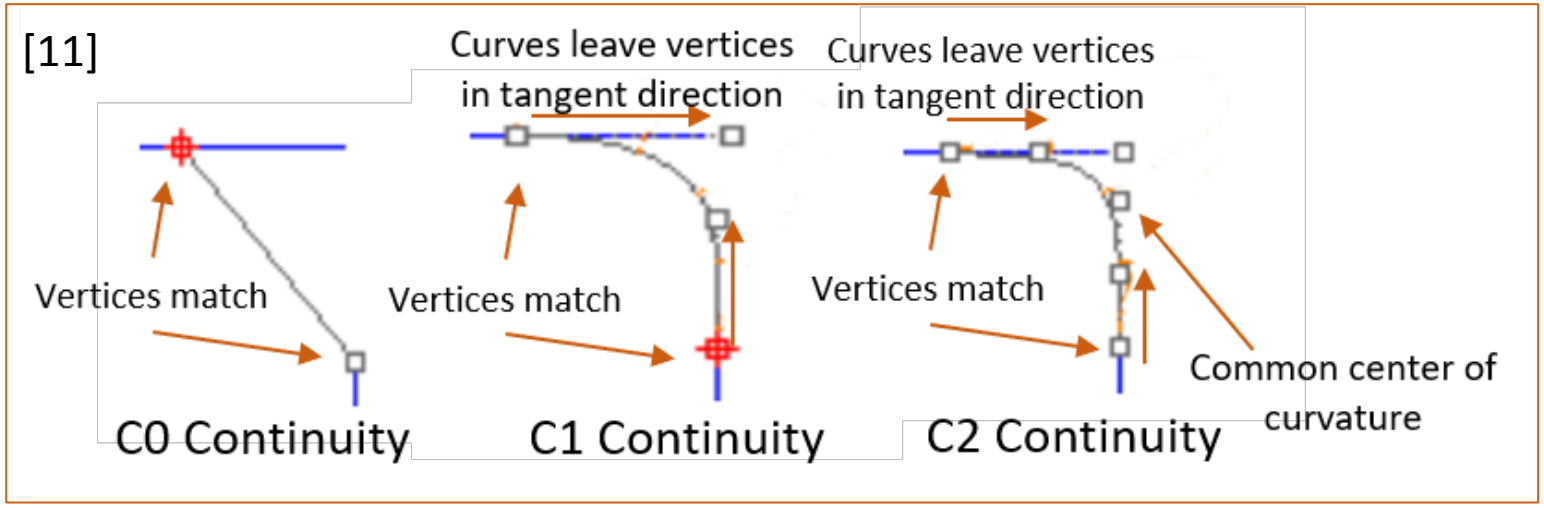
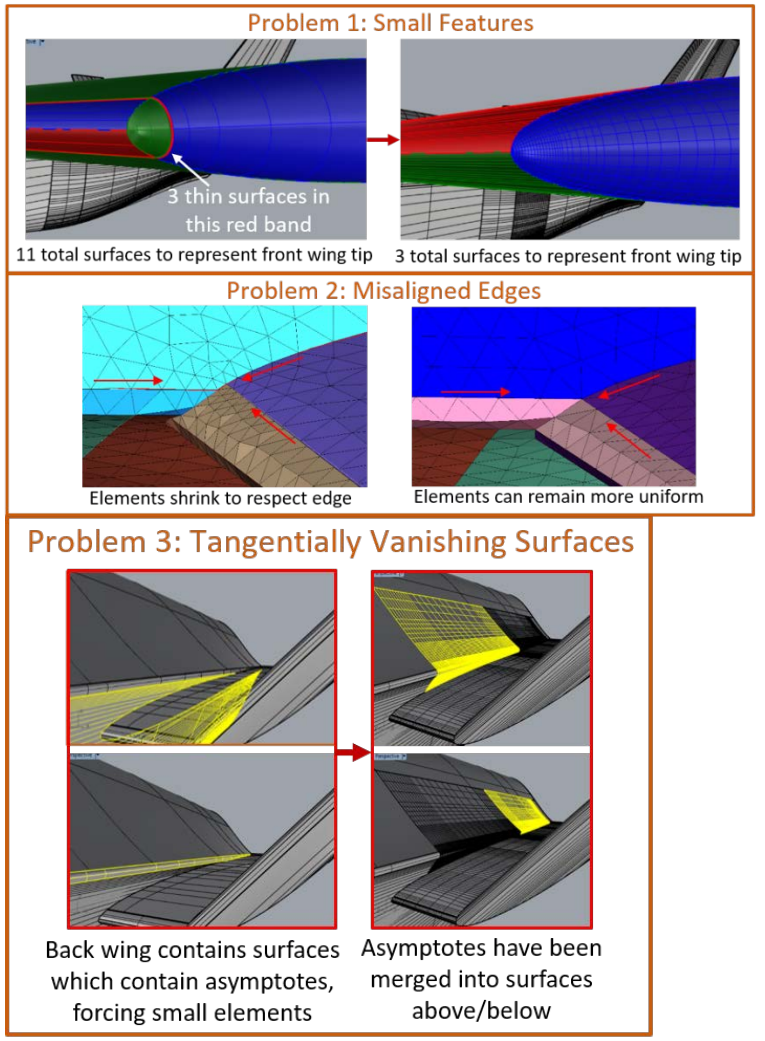
- Model cured with Rhinoceros 5 [10] software
  - Surfaces merged or reshaped by extracting surface isocurves, building new surfaces, and ensuring at least C1 curve continuity





[10] https://www.rhino3d.com/
[11] http://docs.mcneel.com/rhino/5/help/en-us/commands/networksrf.htm

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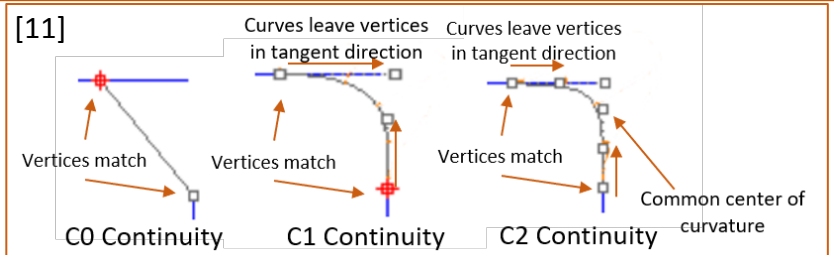
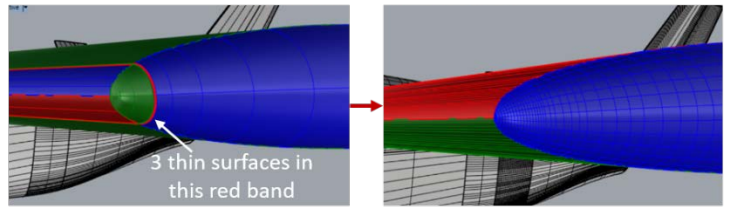


Summary of Changes

	Original	Cured
Total # of Surfaces	220	108
Total # of Internal Edges	524	251
Smallest Edge Length	0.01 in.	1 inch
File Size	6 kB	15.3 kB

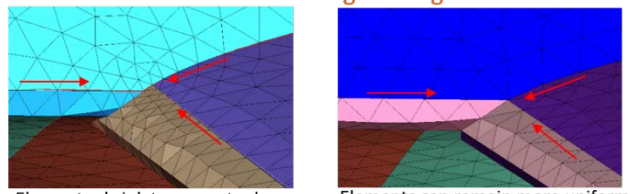
Problem 1: Small Features



11 total surfaces to represent front wing tip

3 total surfaces to represent front wing tip

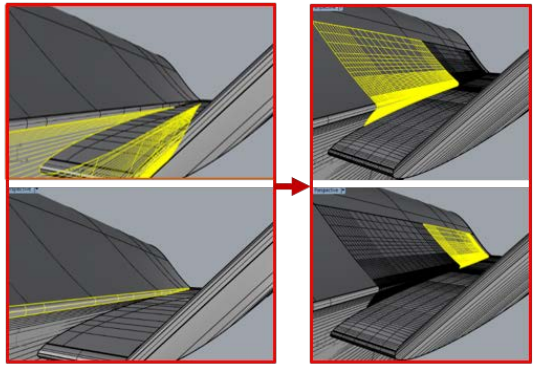
Problem 2: Misaligned Edges



Elements shrink to respect edge

Elements can remain more uniform

Problem 3: Tangentially Vanishing Surfaces



Back wing contains surfaces which contain asymptotes, forcing small elements

Asymptotes have been merged into surfaces above/below

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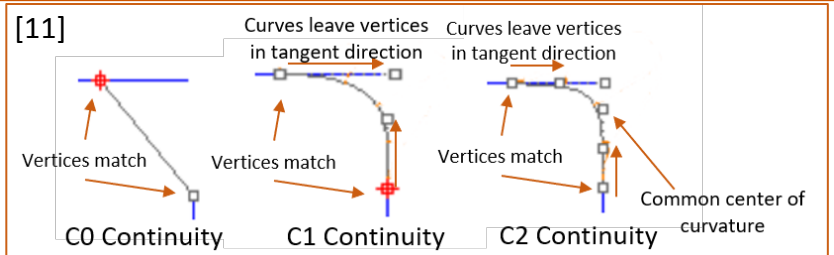

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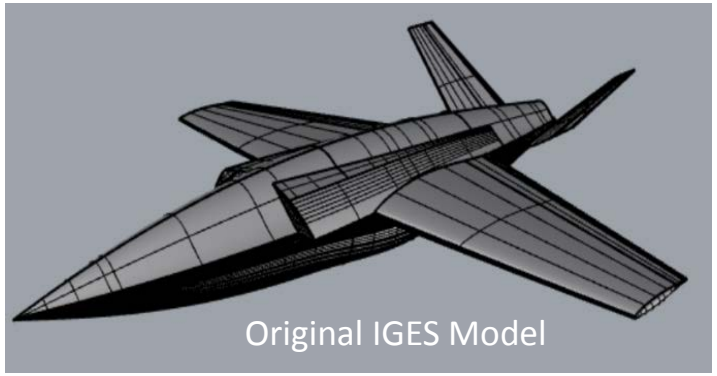
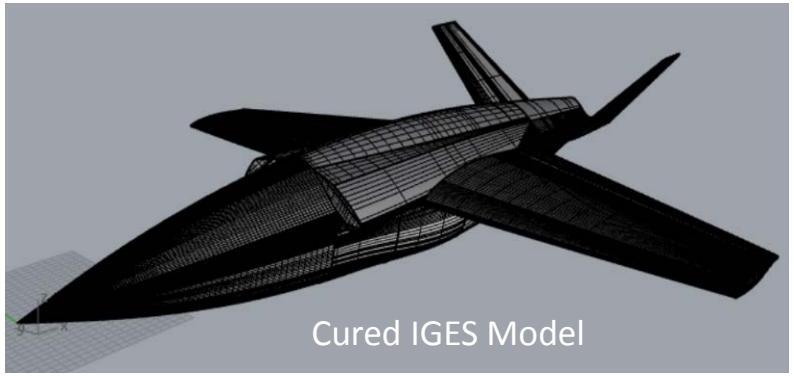
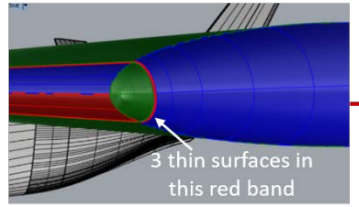
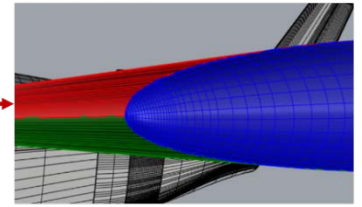

Original IGES Model


Cured IGES Model

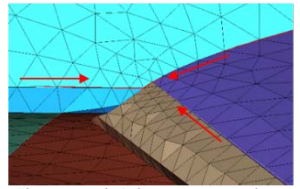
Problem 1: Small Features

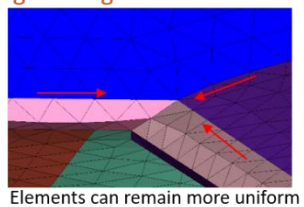


11 total surfaces to represent front wing tip


3 total surfaces to represent front wing tip

Problem 2: Misaligned Edges


Elements shrink to respect edge


Elements can remain more uniform

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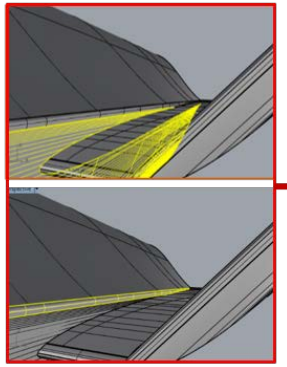
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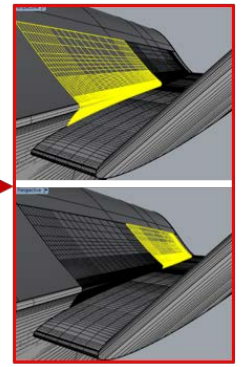
Asymptotes have been merged into surfaces above/below

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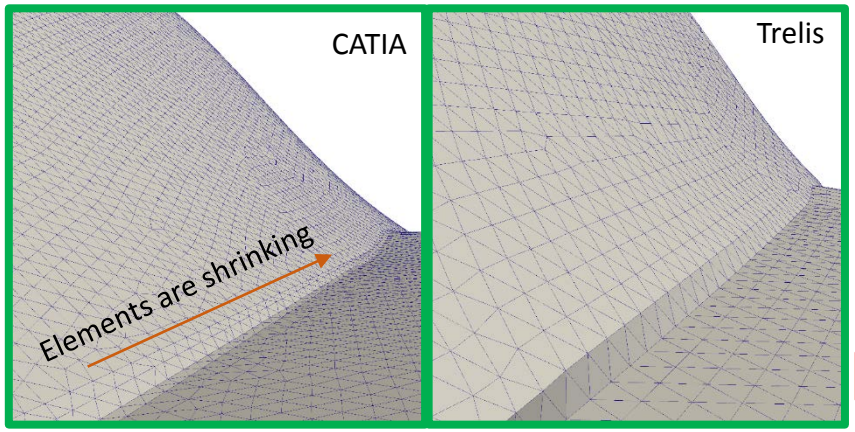
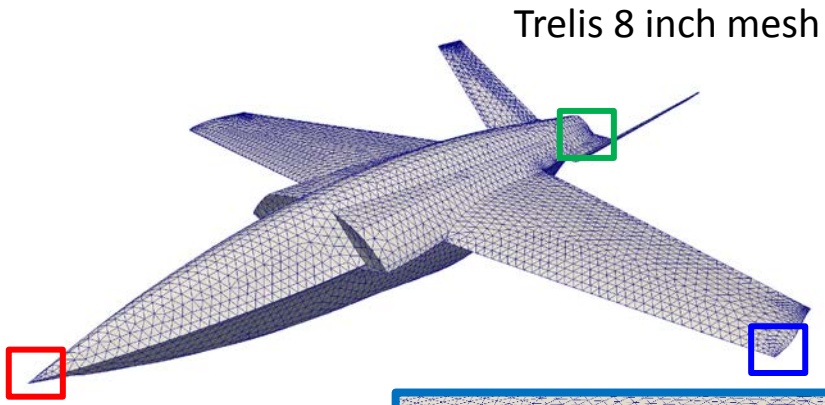
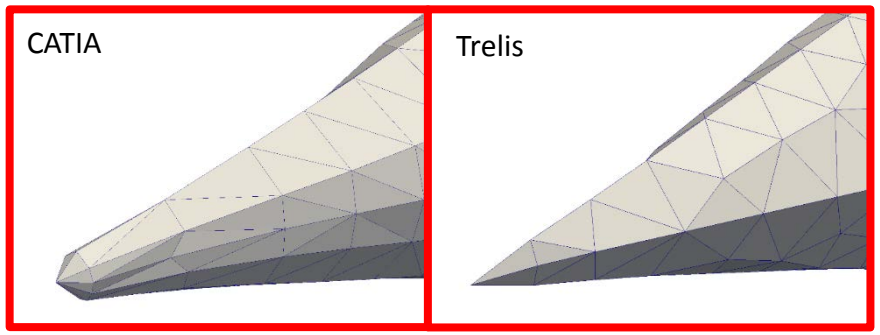
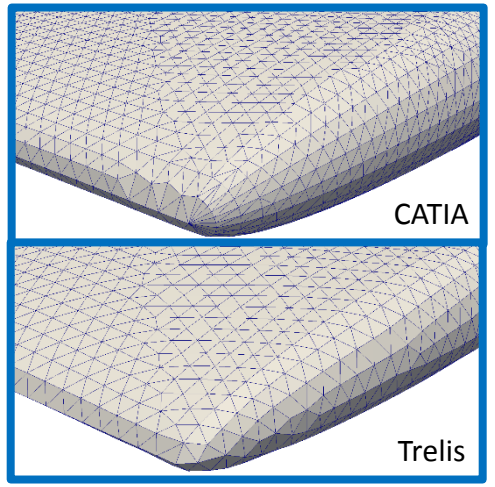
Mesh Validation

- Cured model yields more uniform meshes





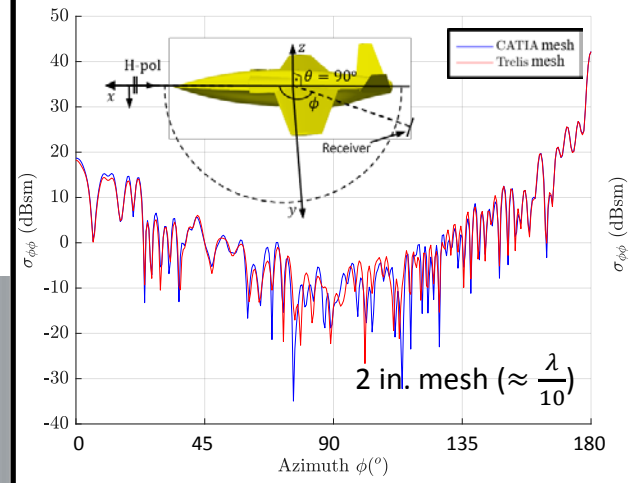


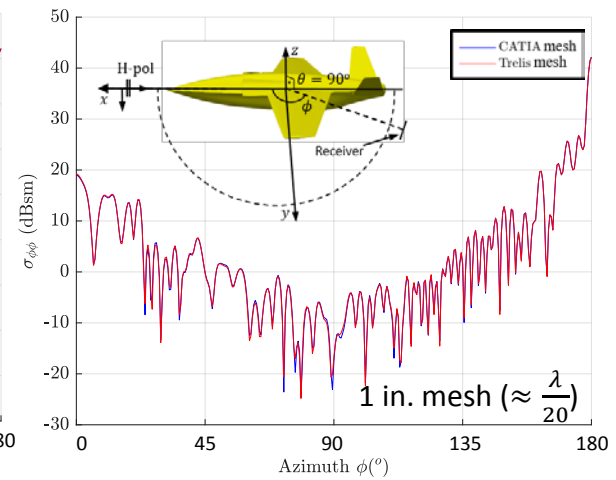


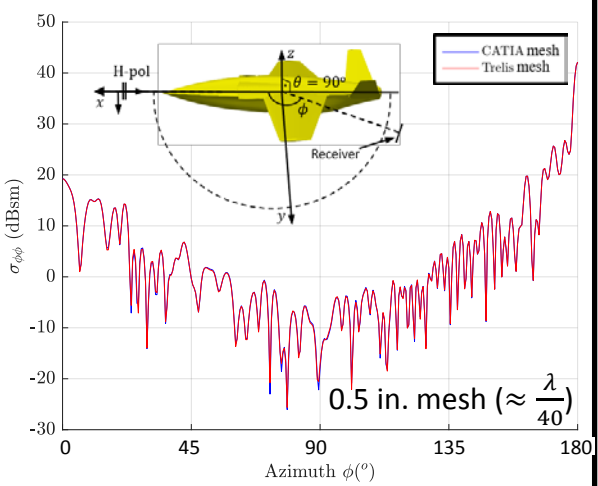
Mesh Validation

- Cured model yields more uniform meshes
- Confirm surface defeaturing did not impact EM analysis
- 7 EXPEDITE-RCS meshes made publicly available

Decreasing element size







HH-polarized bistatic RCS (incident from nose) at 640 MHz (λ≈18.5 in.)

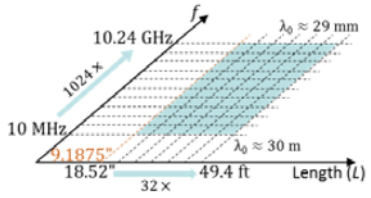
		Target Edge Length [in]						
		0.125	0.25	0.5	1	2	4	8
Trelis Meshes	Average Edge Length	0.121	0.24	0.46	0.96	1.8	3.6	6.4
	Max Edge Length	0.2	0.36	0.66	1.4	2.6	5.6	11.8
	Min Edge Length	0.04	0.07	0.12	0.27	0.39	0.45	0.46
	Max/Min Edge Ratio	5.7	5.1	5.5	5.2	6.7	12.4	25.6
	Number of Elements	4.5×10^7	1.2×10^7	3.1×10^6	7.1×10^5	2.0×10^5	5.1×10^4	1.4×10^4

Public Release

- Austin RCS Benchmark Suite
  - Feature Available:
    - Problem Descriptic
    - Reference Data
    - Simulation Data
    - Models
    - Meshes

Description of Scattering Object
A perfect electrically conducting (PEC) complex aircraft model.

Length Scale and Frequency Range



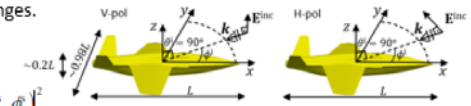
The problems of interest cover a range of ~64x in physical length scale and 1024x in frequency; the ranges are logarithmically sampled to yield 99 scattering problems. Because the aircrafts are PEC, there are only 17 + 12 unique scattering problems in Problem Set IVA. In these problems, the model sizes are in the range $0.007 \le L/\lambda_0 \le 514$, where λ_0 is the free-space wavelength.

Interesting Features

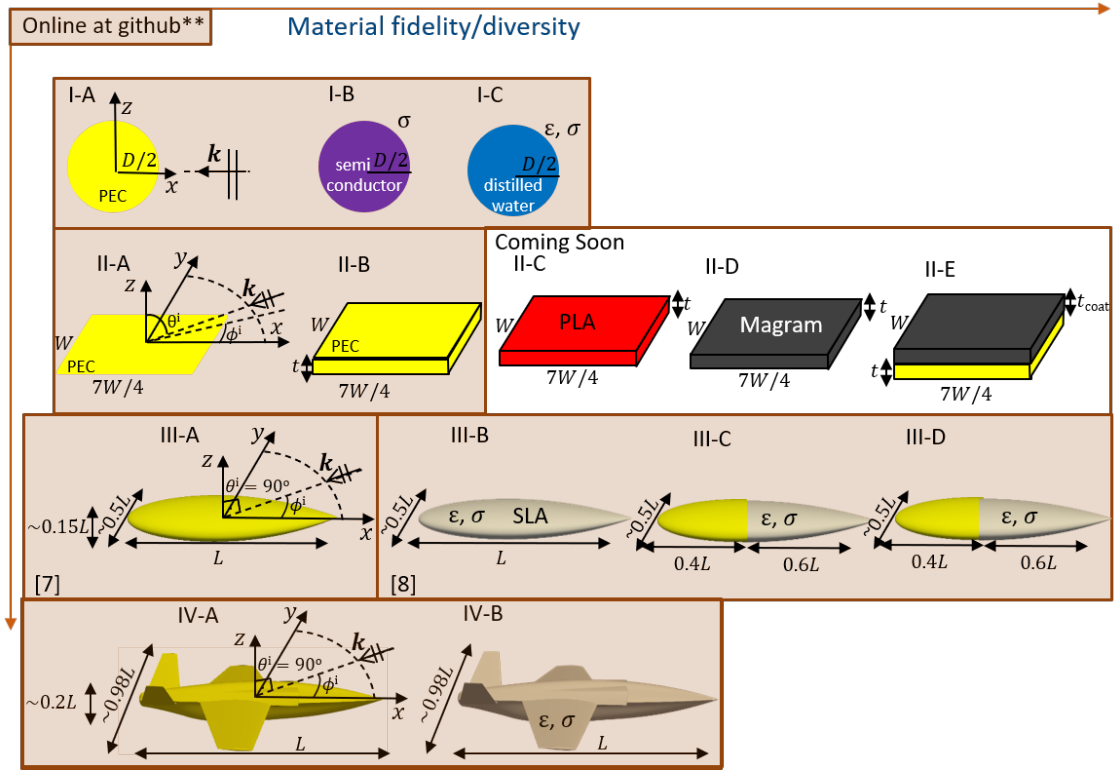
1. The logarithmic sampling is distorted along the size axis for the smallest model: the smallest EXPEDITE-RCS aircraft has L=9.1875'' (instead of L≈9.261''). The sampling is also distorted along the frequency axis: scattering from the smallest aircraft at frequencies $f \in$ {10, 20, 40, 80, 160, 320, 640, 1280, 2580, 5120, 7000, 10250} MHz are included in the problem set. These distortions are because of publicly available measurement data [1] and add 12 unique scattering problems to the set.

2. The model cannot be described sufficiently with a few equations, drawings, or pictures [1]; it presents modeling, meshing, and reproducibility challenges.

Quantities of Interest
Radar cross section (RCS) definition



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



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

UTAustinCEMGroup 2019 AMTA update	
..	
Problem I-Spheres	2019 AMTA update
Problem II-Plates	Updated reference data
Problem III-Almonds	2019 AMTA update

Website:
https://github.com/UTAustinCEMGroup/AustinCEMBenchmarks/tree/master/Austin-RCS-Benchmarks

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Conclusion

- ❑ Modern Benchmark for Advancing CEM
  - Reproducible
  - Realistic airplane model
  - CAD model and meshes
  - Reference measurement and simulation data
  - Easily accessible
- ❑ Acknowledgments

Website:
https://github.com/UTAustinCEMGroup/AustinCEMBenchmarks/tree/master/Austin-RCS-Benchmarks

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