A Benchmark Airplane Model with Ducts

Andrew Maicke[1], Jon T. Kelley[1], Brian MacKie-Mason[2], Clifton C. Courtney[2], Steven Cox[2], George Burchuk[2], David A. Chamulak[2], and Ali E. Yilmaz[2]

[1]The University of Texas at Austin, Austin, TX 78712

[2]Lockheed Martin Aeronautics Company, Palmdale, CA 93599

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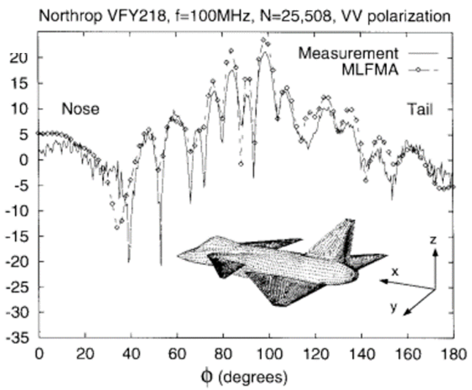
Outline

- Motivation
  - Complex aircraft models and reproducibility
  - Austin RCS Benchmark Suite
- Complex Realistic Model
  - PRIME model development
  - Addition of PRIME-Duct
- High-Fidelity CAD Models and Meshes
  - Model curing
  - Simulation validation
- Reliable Reference Results
  - Measurement campaign
    - Additive manufacturing
    - RCS measurements
- Simple Public Access
  - Github site
- Conclusion

Motivation

- Reproducibility in CEM
  - Numerous aircraft models presented in literature
  - Some are ‘more realistic’ than others
  - Reproducing simulation/measurement results is difficult or impossible [6]
  - Published plots, formulas, etc. are insufficient for corroboration
- Challenges
  - More realistic models increase difficulty
    - E.g. airplane models with open ducts
  - High-fidelity CAD model and mesh(es)
  - Simple public access

[1]



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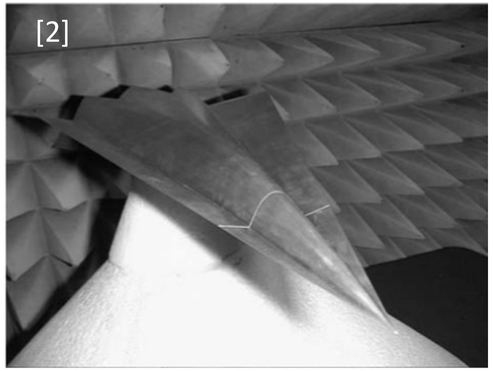

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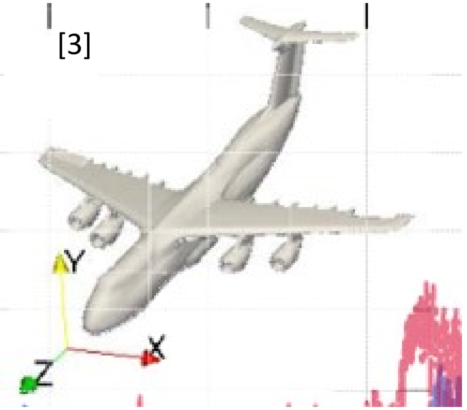

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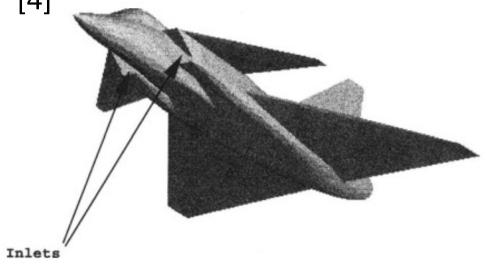

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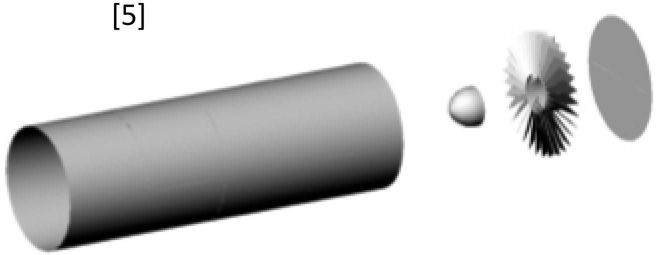

References:

[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] 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.

[4] L.C. Trintinalia, and H. Ling. “Feature extraction from electromagnetic backscattered data using joint time-frequency processing,” *Ultra-Wideband, Short-Pulse Electromagnetics 3*, pp. 305-312, Plenum Press, New York, 1997

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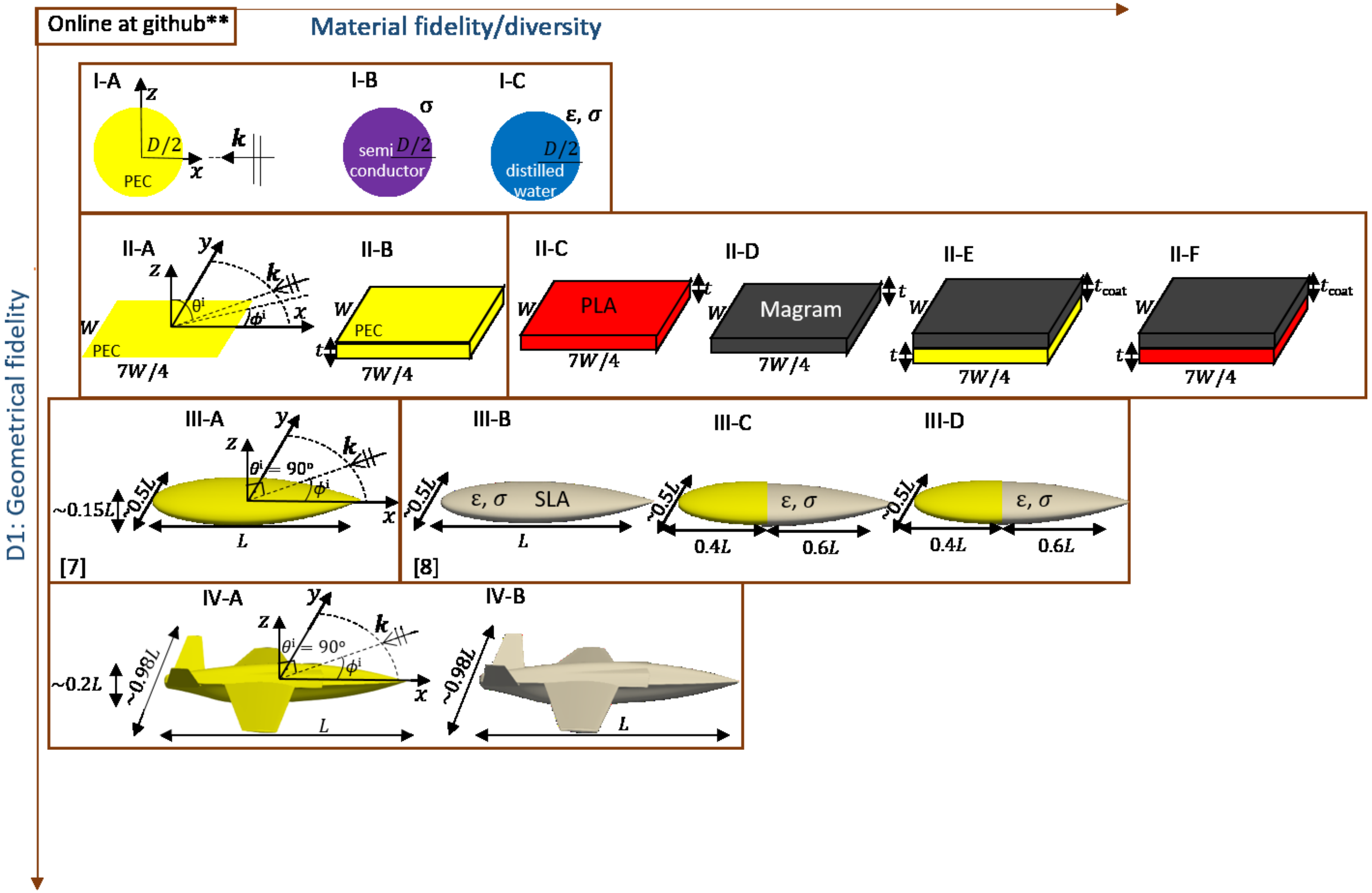
[6] D. G. Feitelson, “From repeatability to reproducibility and corroboration,” *ACM SIGOPS Oper. Sys. Rev.*, vol. 49, no. 1, pp. 3-11, Jan. 2015.

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



[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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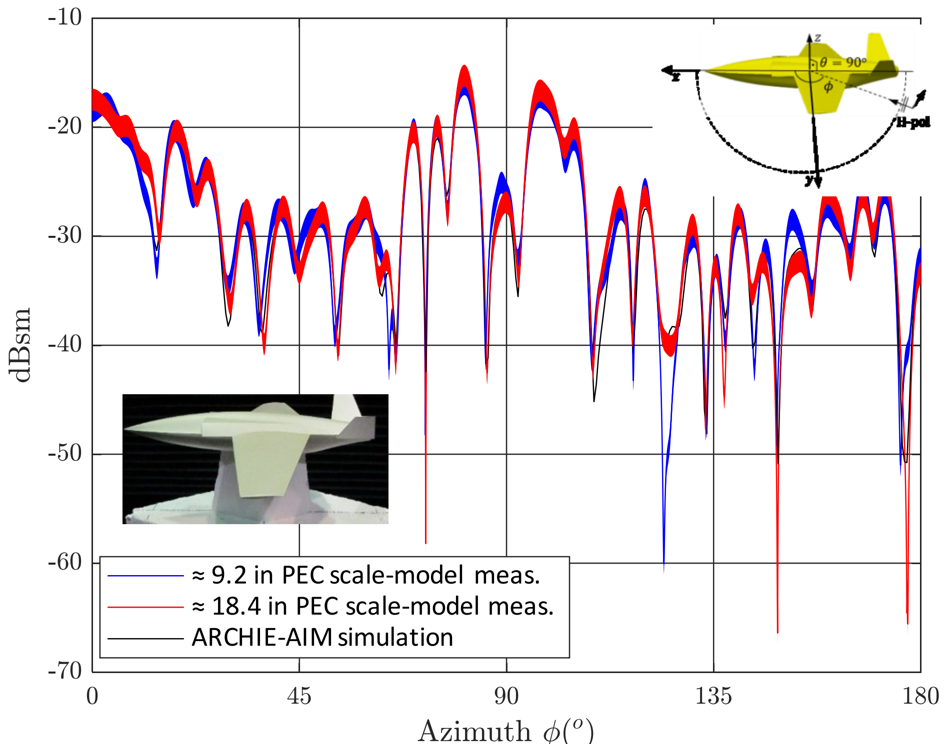
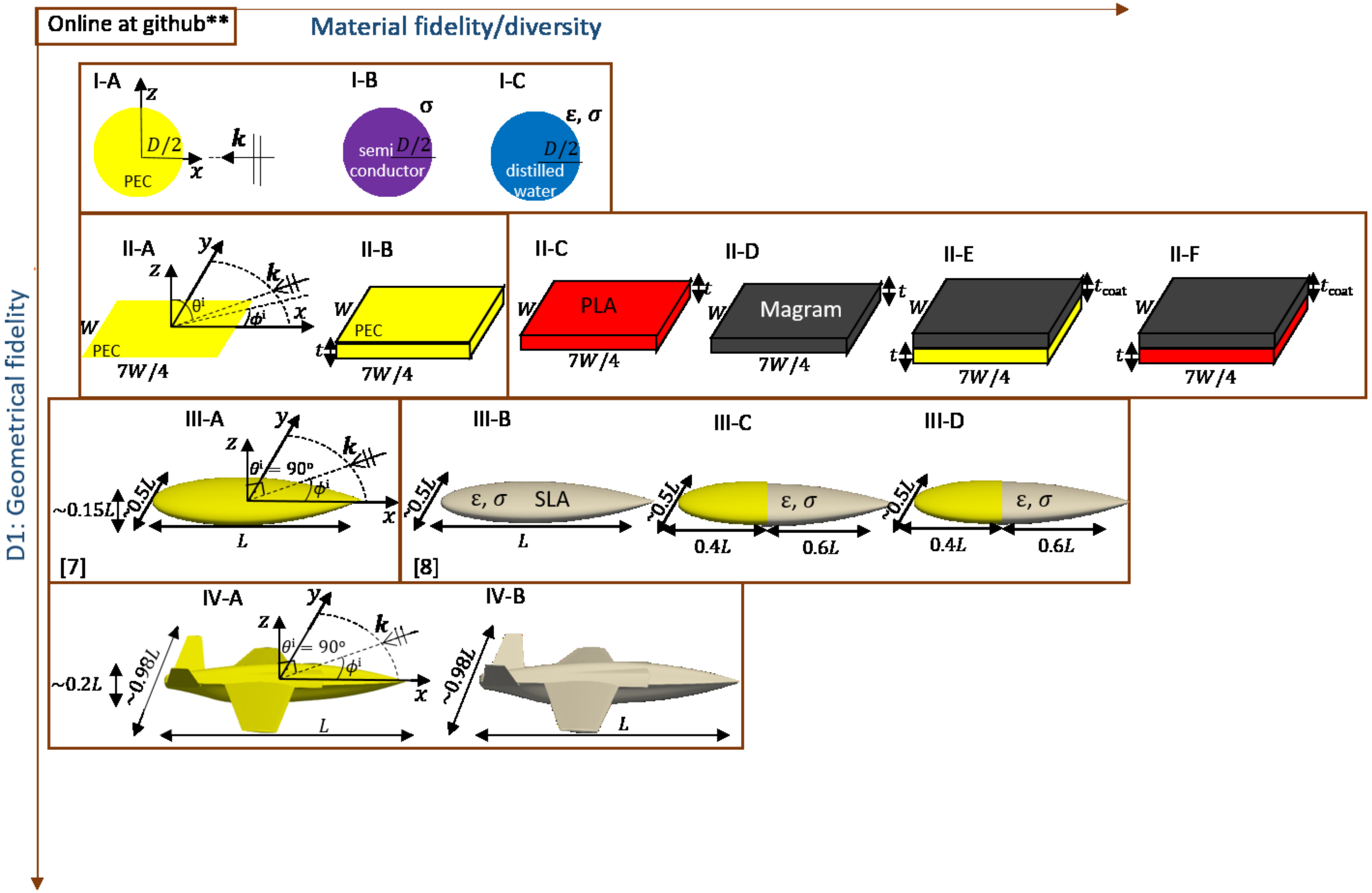
❑ Previous work: airplane model [9]





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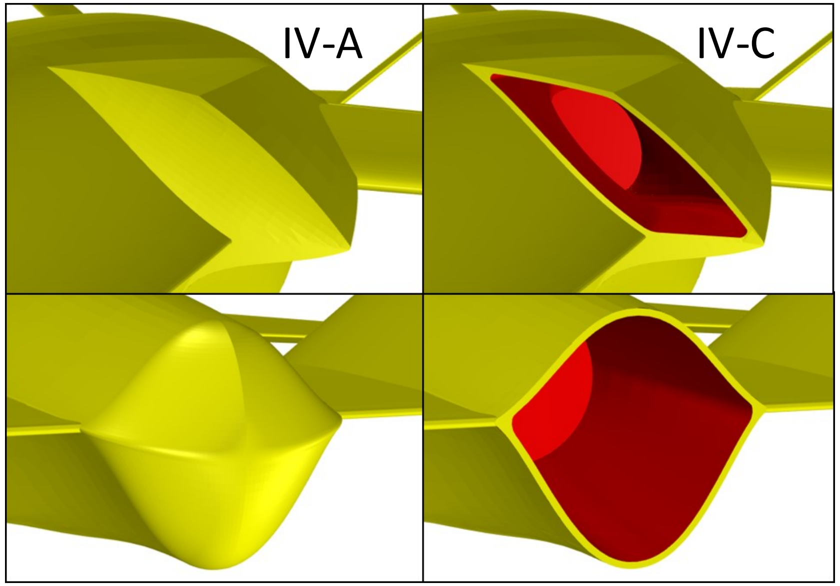
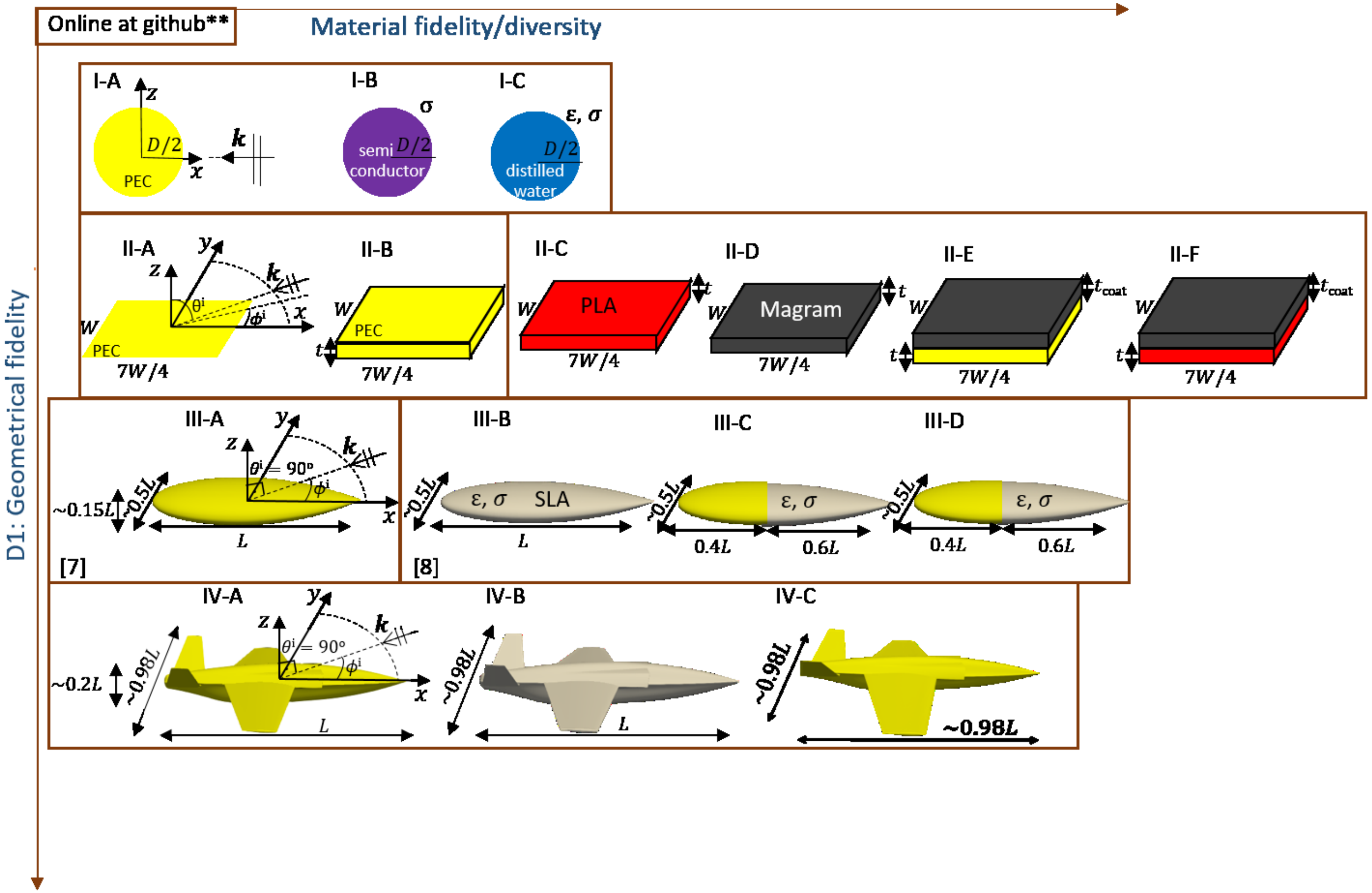
  - Contains analytical, measurement, and simulation reference data
  - Precisely defined quantities of interest, performance measures
  - Emphasis on replicability, publicly available
- Previous work: airplane model [9]
  - Model contained covered cavities
- Cavities greatly increase problem complexity





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UT ECE

Model Development

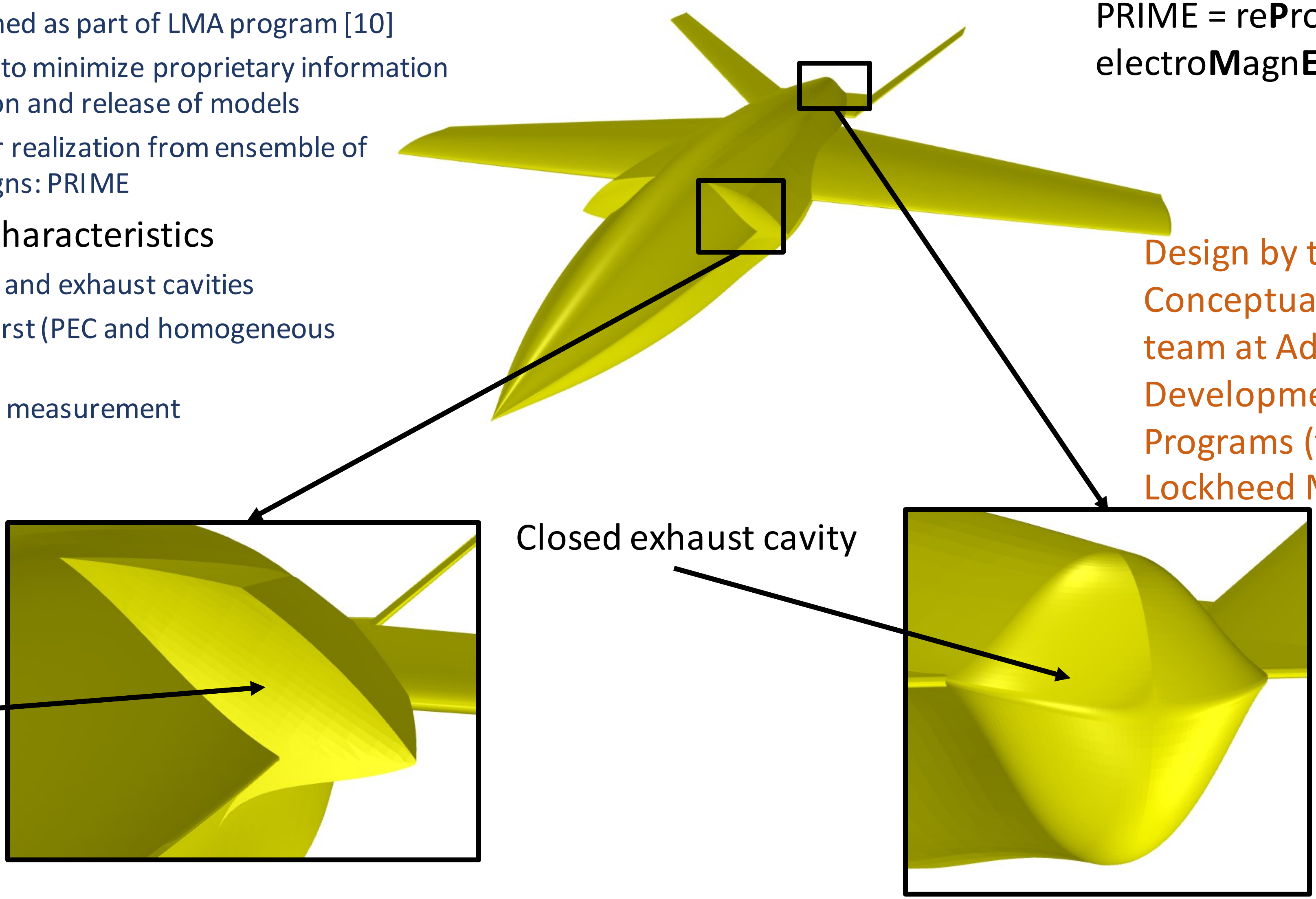
❑ Model Development Process

- Test platform designed as part of LMA program [10]
- Program structured to minimize proprietary information to allow collaboration and release of models
- Selected a particular realization from ensemble of parameterized designs: PRIME

❑ PRIME features and characteristics

- Closed engine intake and exhaust cavities
- Simple materials at first (PEC and homogeneous dielectric)
- Scale-models for RCS measurement

PRIME = re**P**roducible p**RI**ntable electro**M**agn**E**tic airplane model



Design by the Conceptual Design team at Advanced Development Programs (the Skunk Works) of Lockheed Martin Aeronautics

References:
[10] C. Davies, “Lockheed Martin overview of the AFRL EXPEDITE program,” in *Proc. AIAA Scietech*, Jan. 2019, pp. 1-12.

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  - Test platform designed as part of LMA program [10]
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  - Selected a particular realization from ensemble of parameterized designs: PRIME
- PRIME-Duct features and characteristics
  - Open engine intake and exhaust cavities
  - Ducts terminate partway in fuselage at simple, circular surfaces
  - Engine intake cavities merge inside plane body

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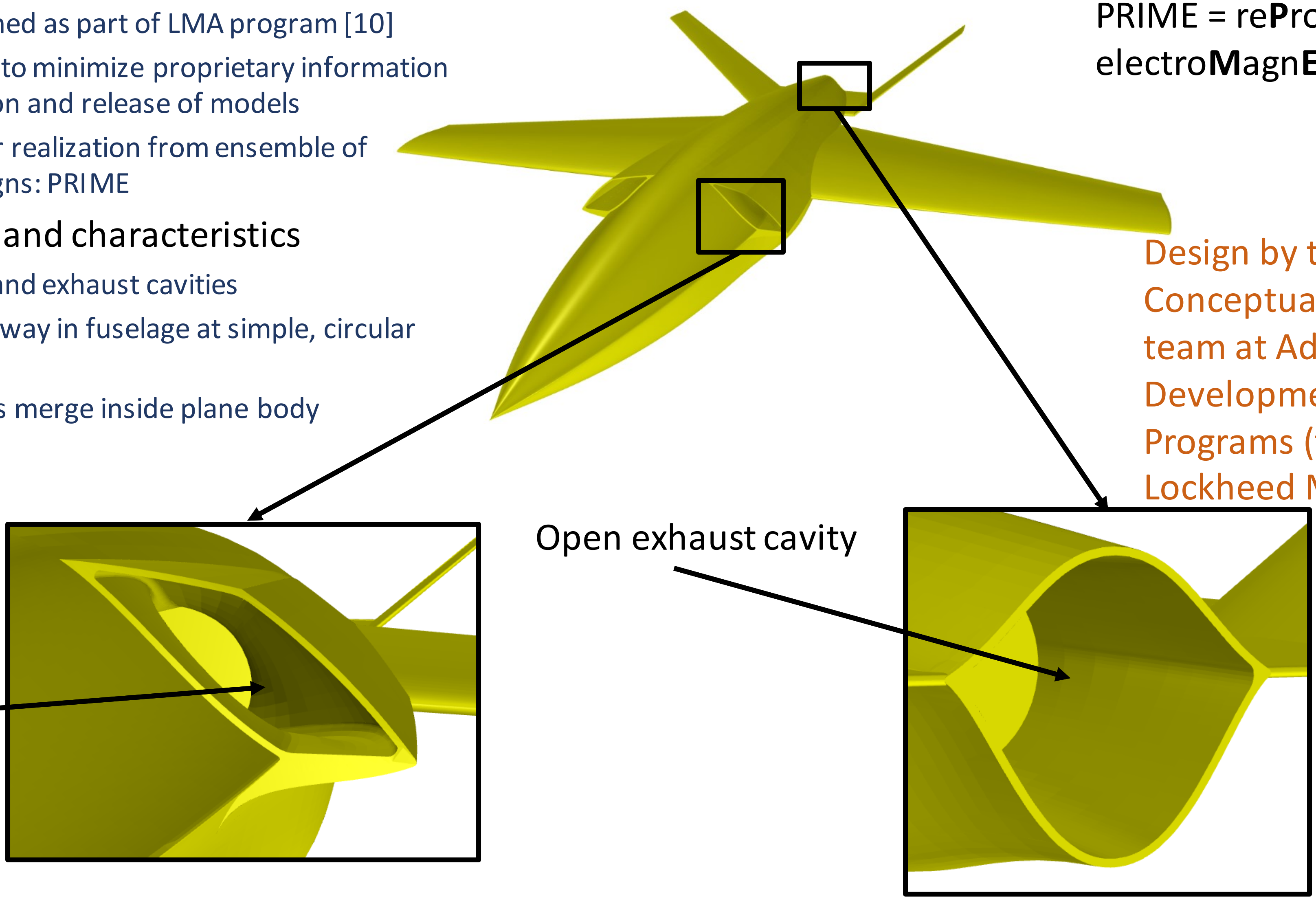

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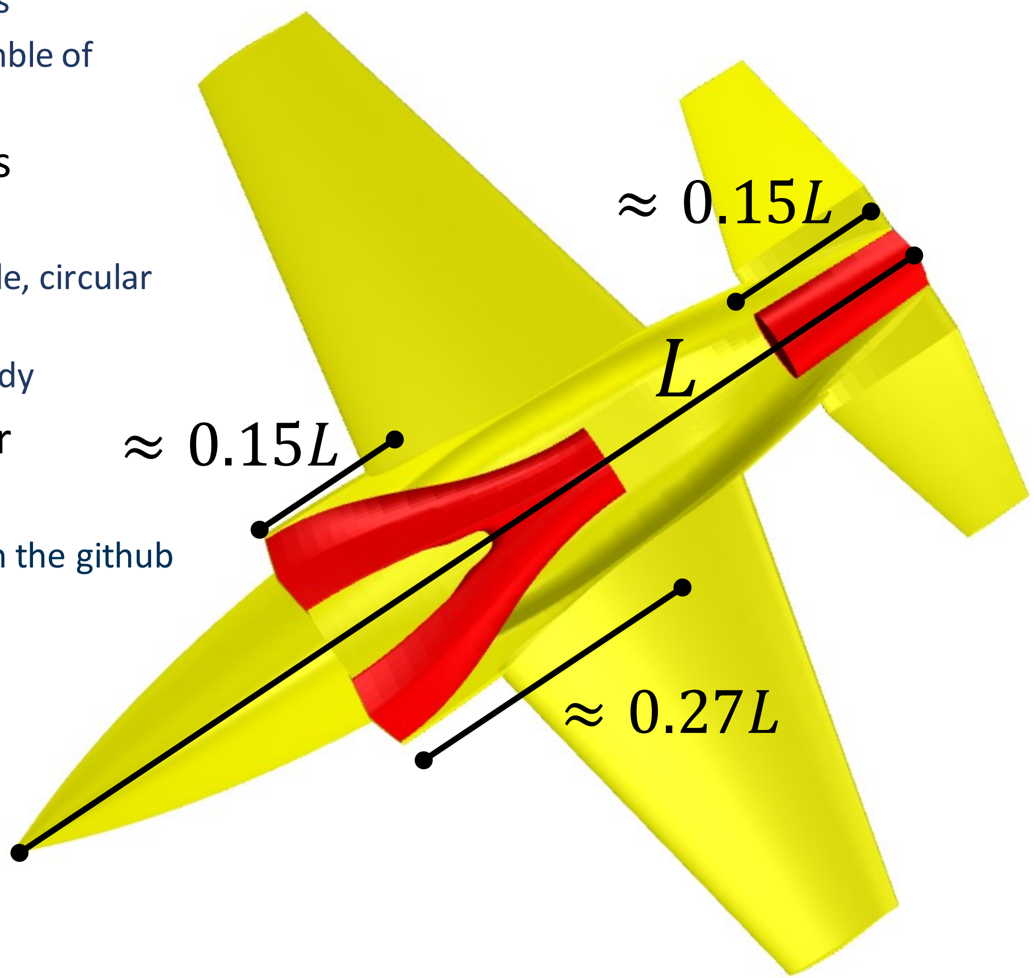
  - Selected a particular realization from ensemble of parameterized designs: PRIME
- PRIME-Duct features and characteristics
  - Open engine intake and exhaust cavities
  - Ducts terminate partway in fuselage at simple, circular surfaces
  - Engine intake cavities merge inside plane body
- PRIME-Duct defines a new problem for Benchmark Suite as IV-C
  - Models, meshes, and data made available on the github

PRIME = reProducible pRIntable electroMagnEtic airplane model



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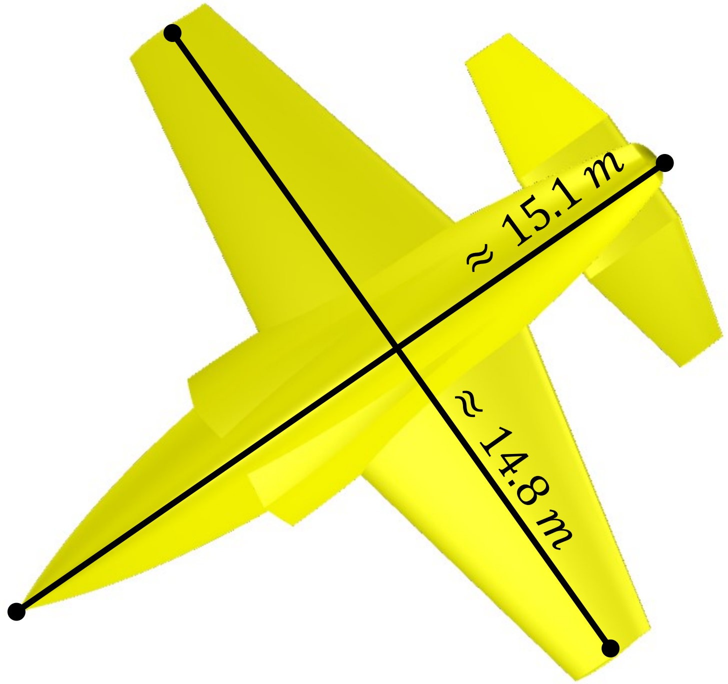
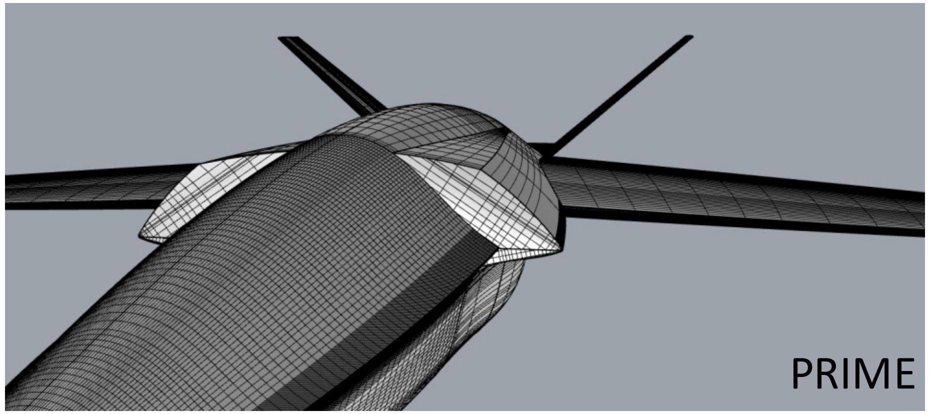
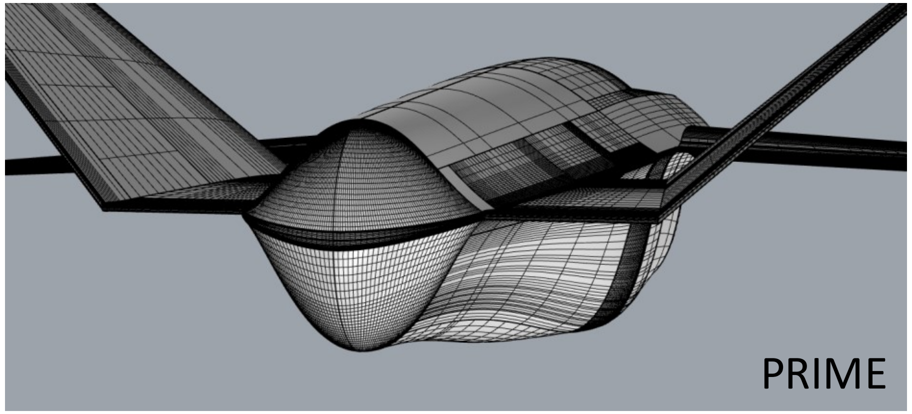
UT ECE

High-Fidelity CAD Model and Mesh(es)

- PRIME model originally developed in CAD software (CATIA 5) used to design the LMA test platform
  - Engine inlet and exhaust cavities covered by PEC surfaces
- PRIME IGS file was defeatured for ease of meshing [9]
  - IGS, STL, and mesh files made available on github
- Cavities surfaces also developed in CATIA, provided by LMA
- Cavity surface features:
  - 52 surfaces
  - Contains minute surfaces with edges smaller than 1 in.
  - Requires defeaturing
- Goal: Open cavities to PRIME to define a new PRIME-Duct model
- Goal: Improve cavity surfaces descriptions so they can be meshed
  - accurately
  - independently
  - relatively easily







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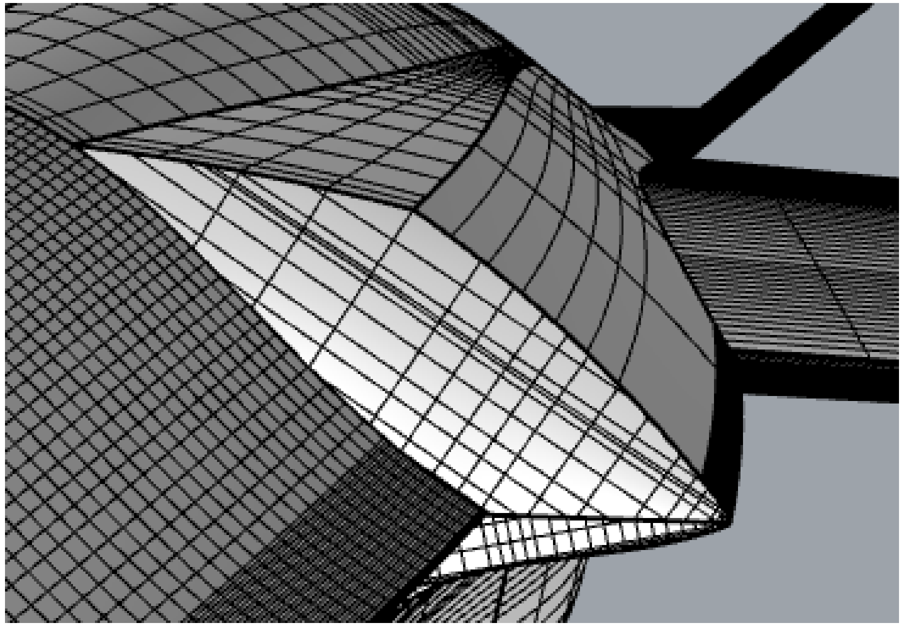
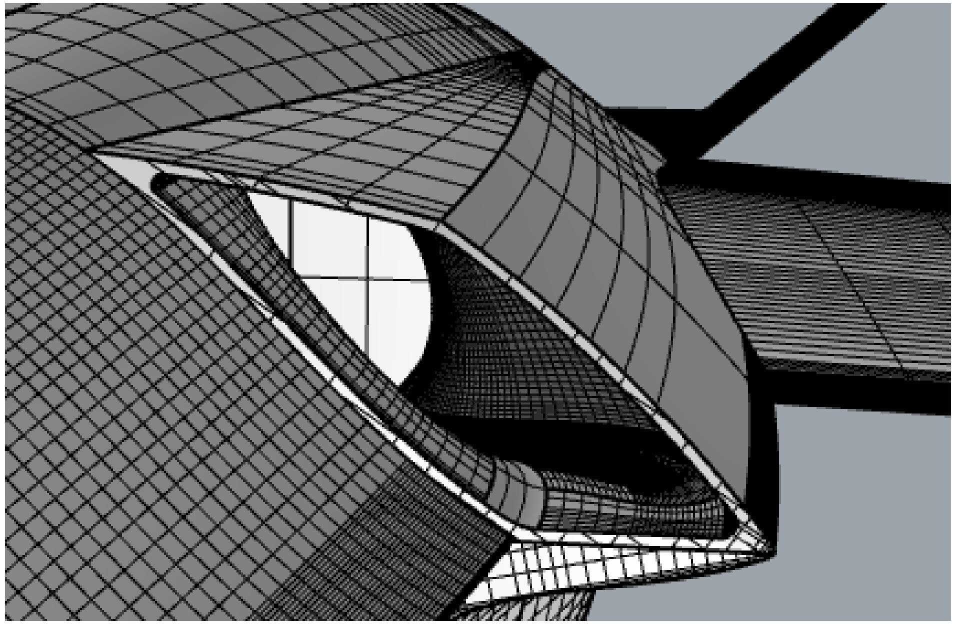
Model Curing

- ❑ Three steps for preparing IGS model for meshing
    1. Merging cavities into model





- ❑ Engine inlet cavity openings align with cavity cover surface
- ❑ Easy to attach to PRIME model

Model Curing

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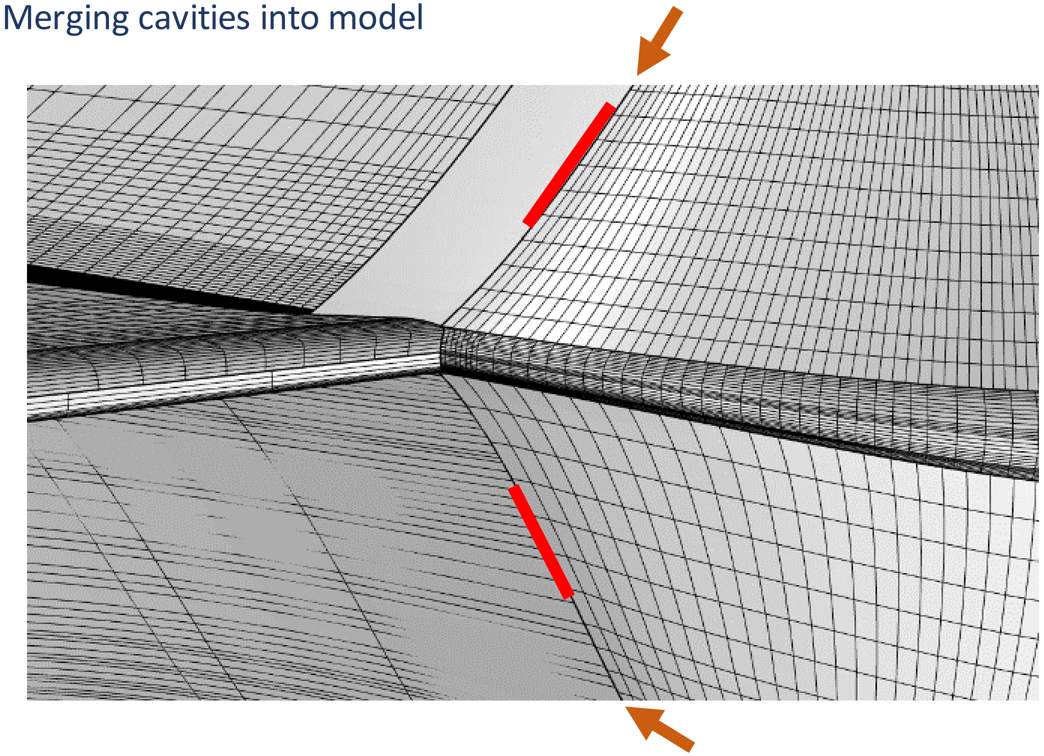

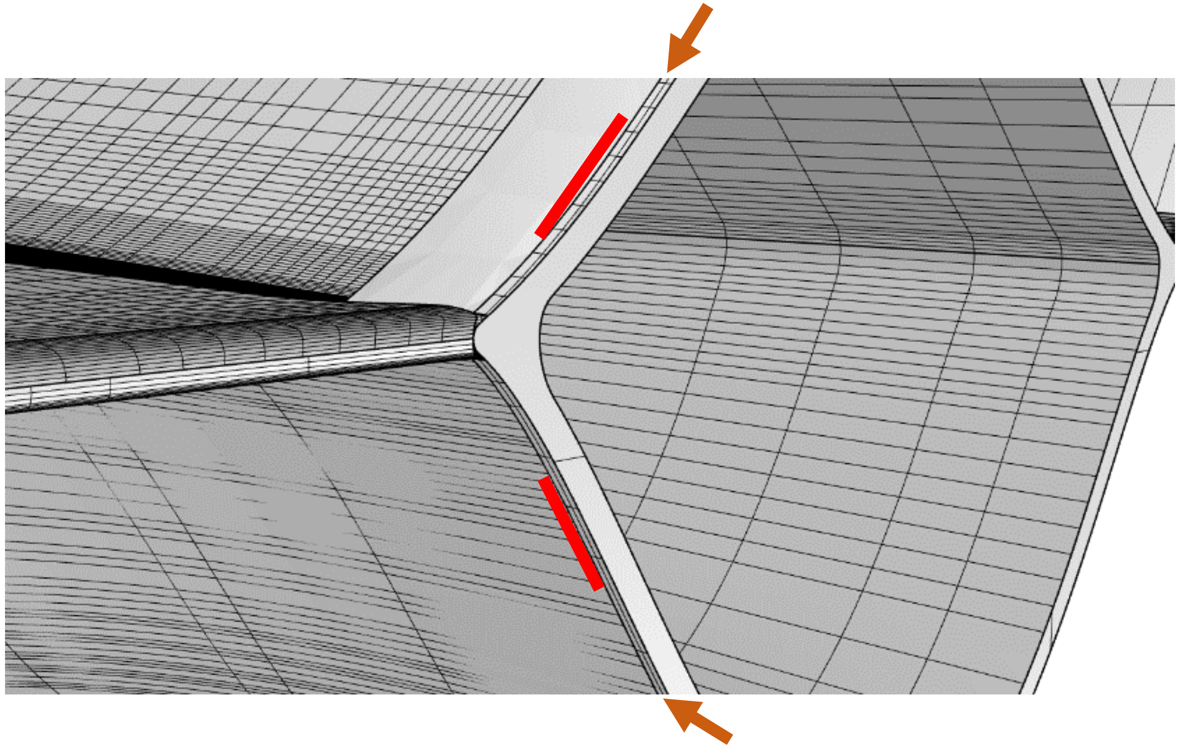

- ❑ Exhaust cavity more difficult to merge
- ❑ Cavity opening not aligned with PRIME surfaces
- ❑ Tail wing 'elbow' alignment is complicated

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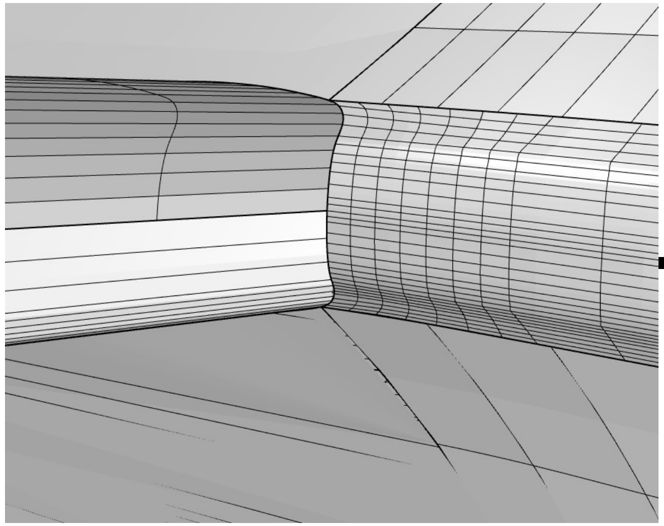
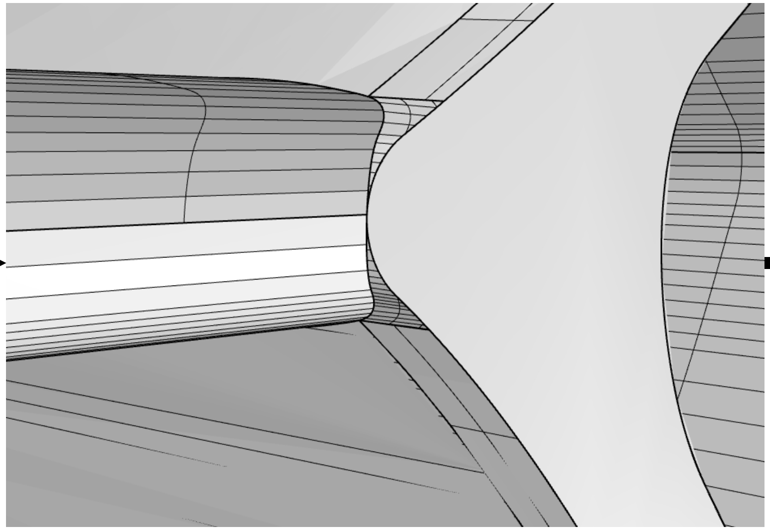
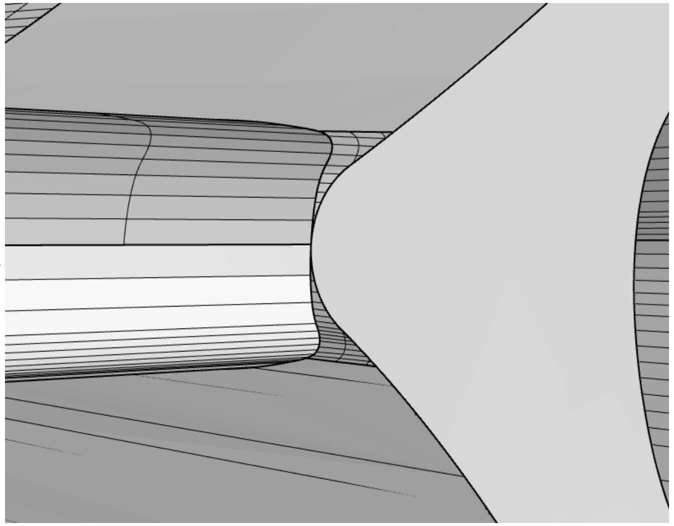


PRIME IGS



Opening cavity



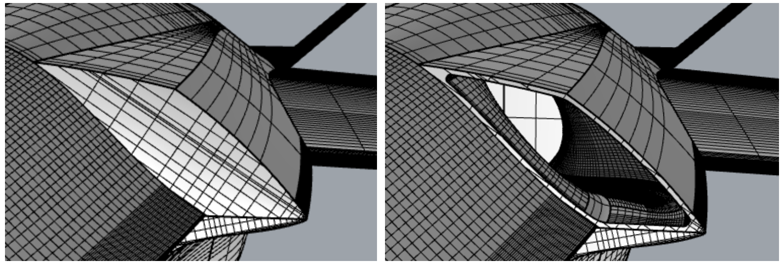
Extending back surfaces

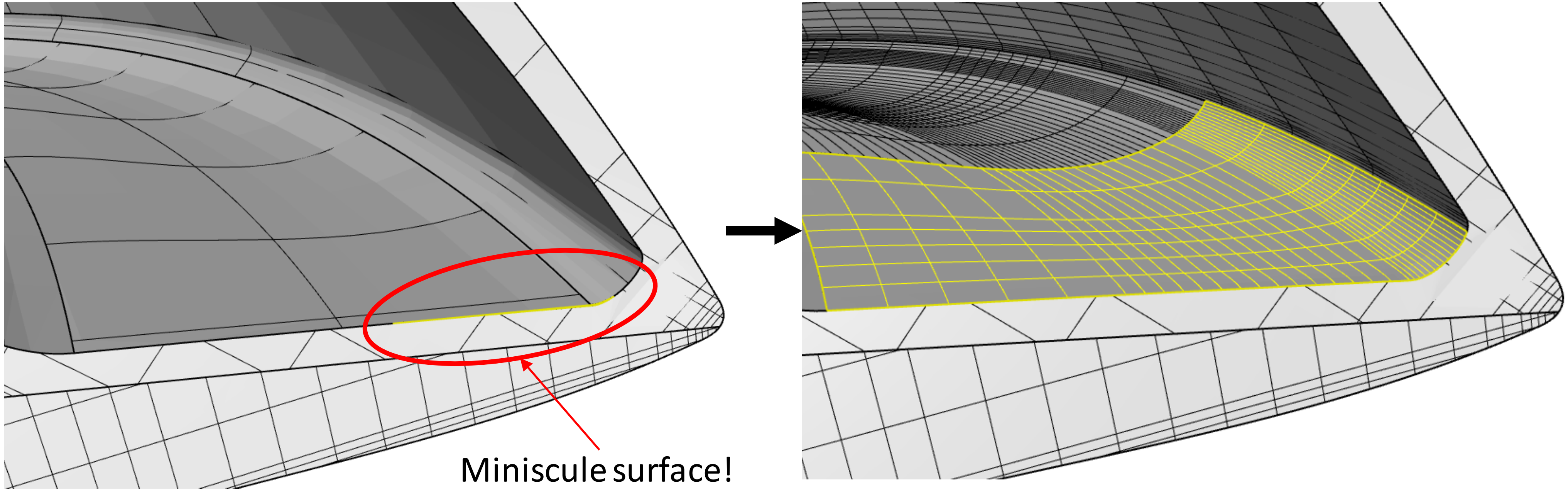
- ❑ Exhaust cavity more difficult to merge
- ❑ Cavity opening not aligned with PRIME surfaces
- ❑ Back surfaces of PRIME are extended to meet cavity opening

Model Curing

- Three steps for preparing IGS model for meshing
  1. Merging cavities into model
  2. Removing small features

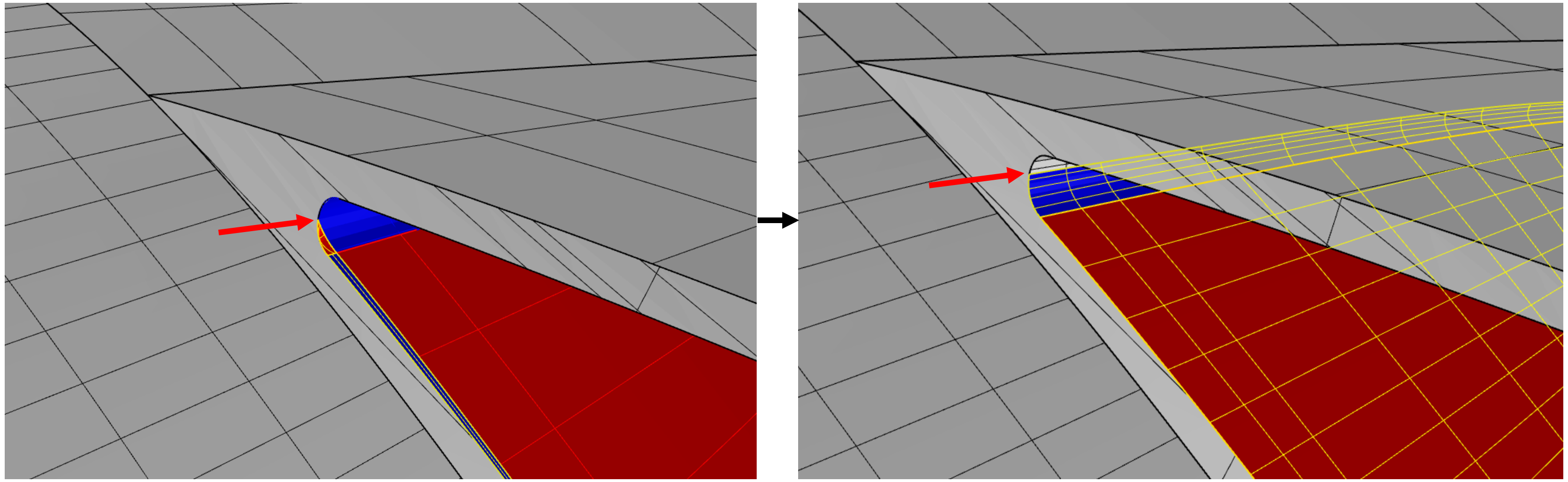
Merging cavities into model



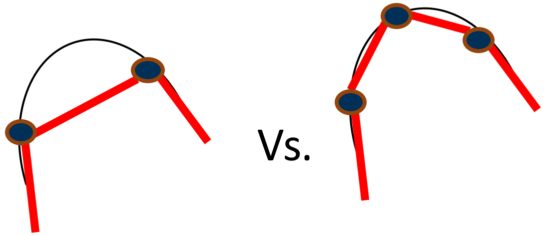


Model Curing

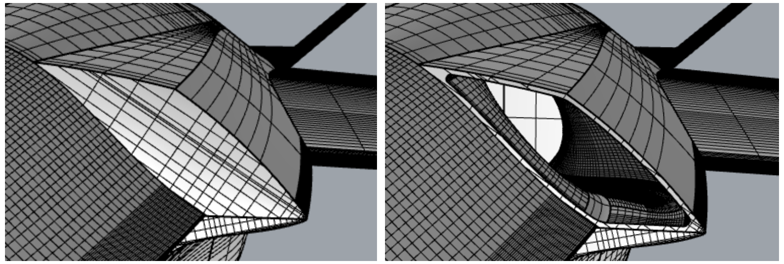
- ❑ Three steps for preparing IGS model for meshing
  1. Merging cavities into model
  2. Removing small features
  3. Aligning edges for ease of meshing



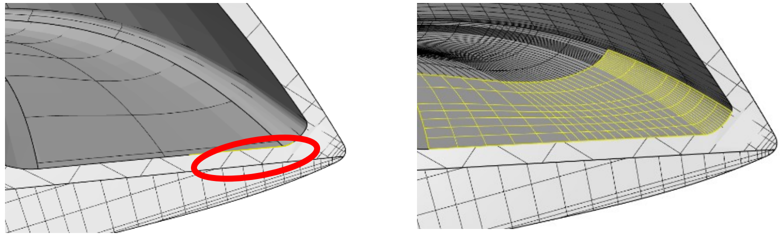
- ❑ Cavity surface edges are adjusted to align with each other
- ❑ Allows mesh elements to conform across edges
- ❑ ‘Guide edges’ used to accurately capture curvature



Merging cavities into model

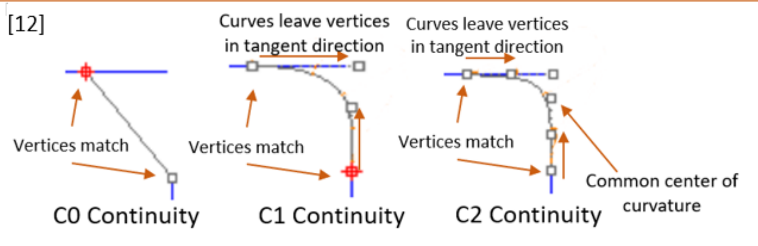


Removing small features



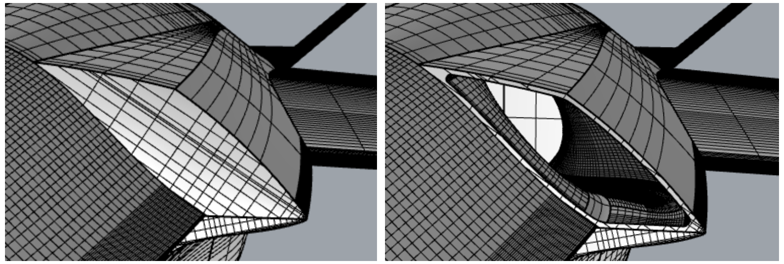
Model Curing

- Three steps for preparing IGS model for meshing
    1. Merging cavities into model
    2. Removing small features
    3. Aligning edges for ease of meshing
- Model cured with Rhinoceros 6 [11] software
    - Surfaces merged or reshaped by extracting surface isocurves, building new surfaces, and ensuring at least C1 curve continuity

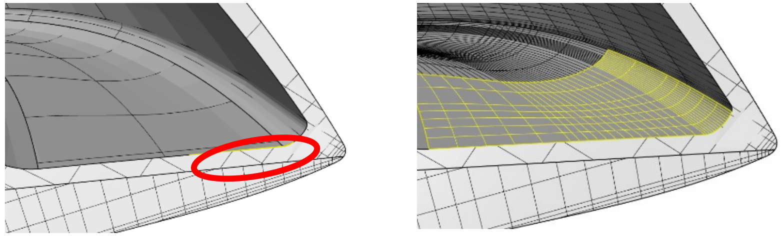


	PRIME	PRIME-Duct
Total # of Surfaces	108	166
Total # of Internal Edges	251	375
Smallest Edge Length	1 inch	0.5 inches

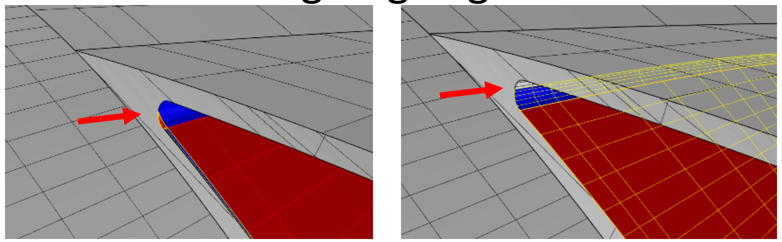
Merging cavities into model



Removing small features

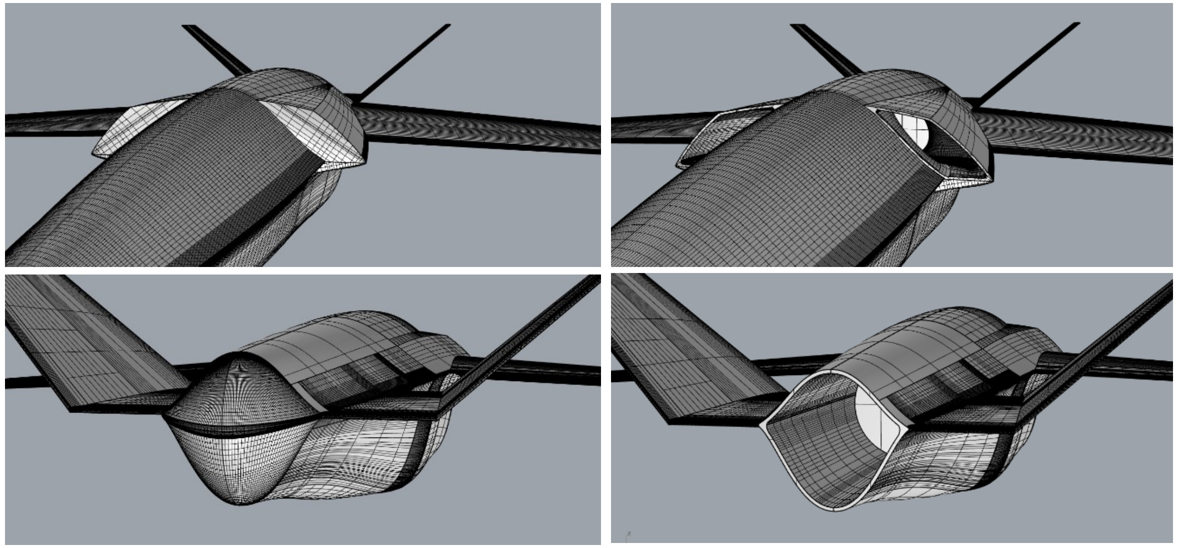


Aligning edges



PRIME (IV-A)

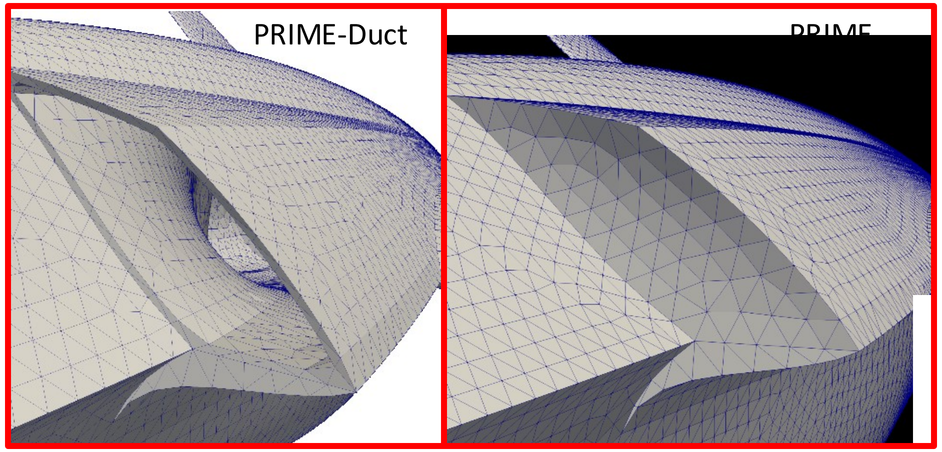
PRIME-Duct (IV-C)



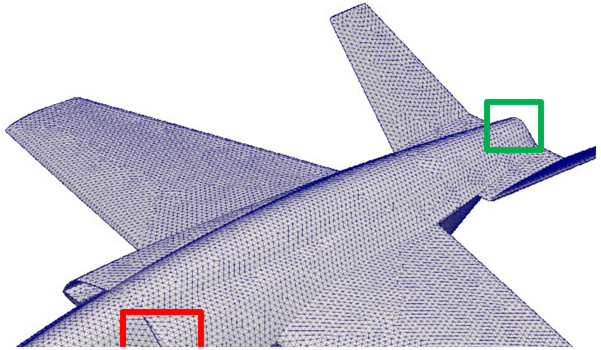
[11] https://www.rhino3d.com/
[12] http://docs.mcneel.com/rhino/5/help/en-us/commands/networksrf.htm

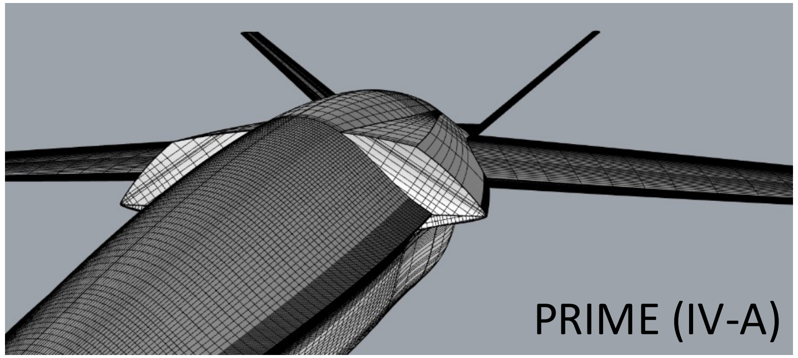
Mesh Validation

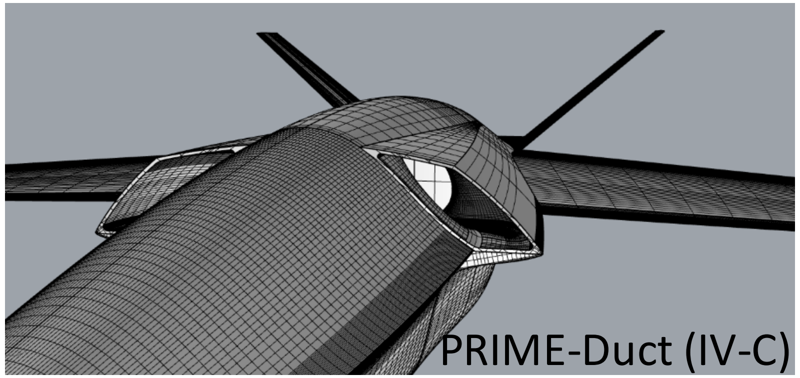
- ❑ Models were successfully imported into and meshed in Trelis 17.5

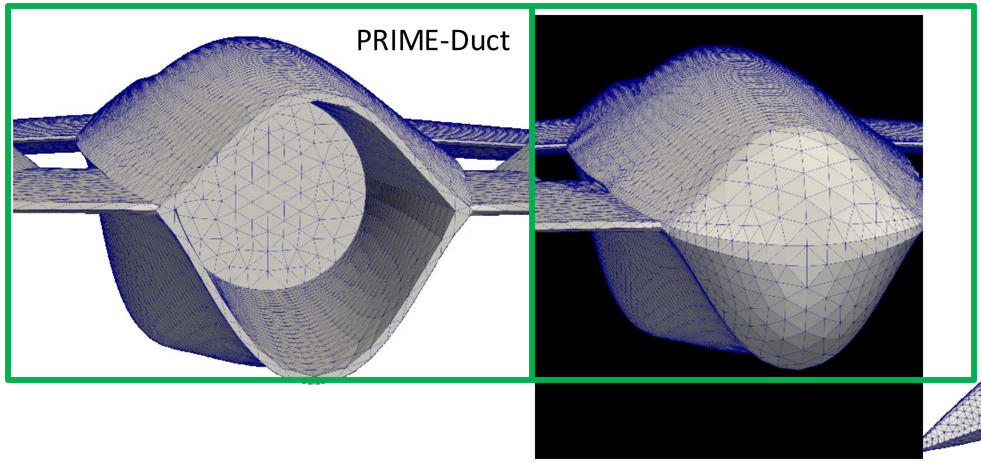


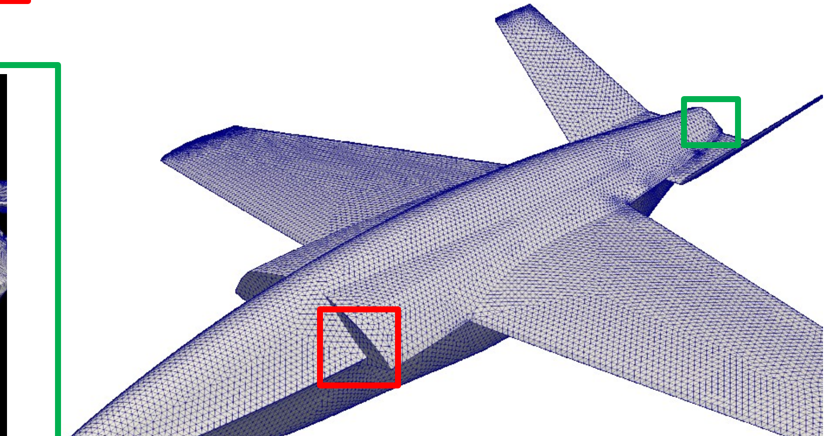
PRIME-Duct 4 inch mesh







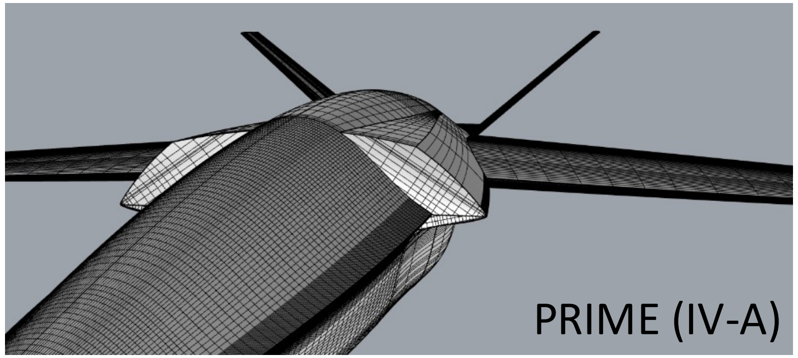


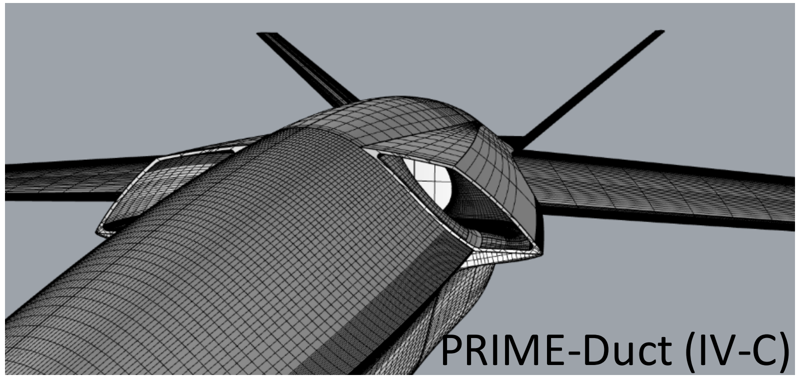


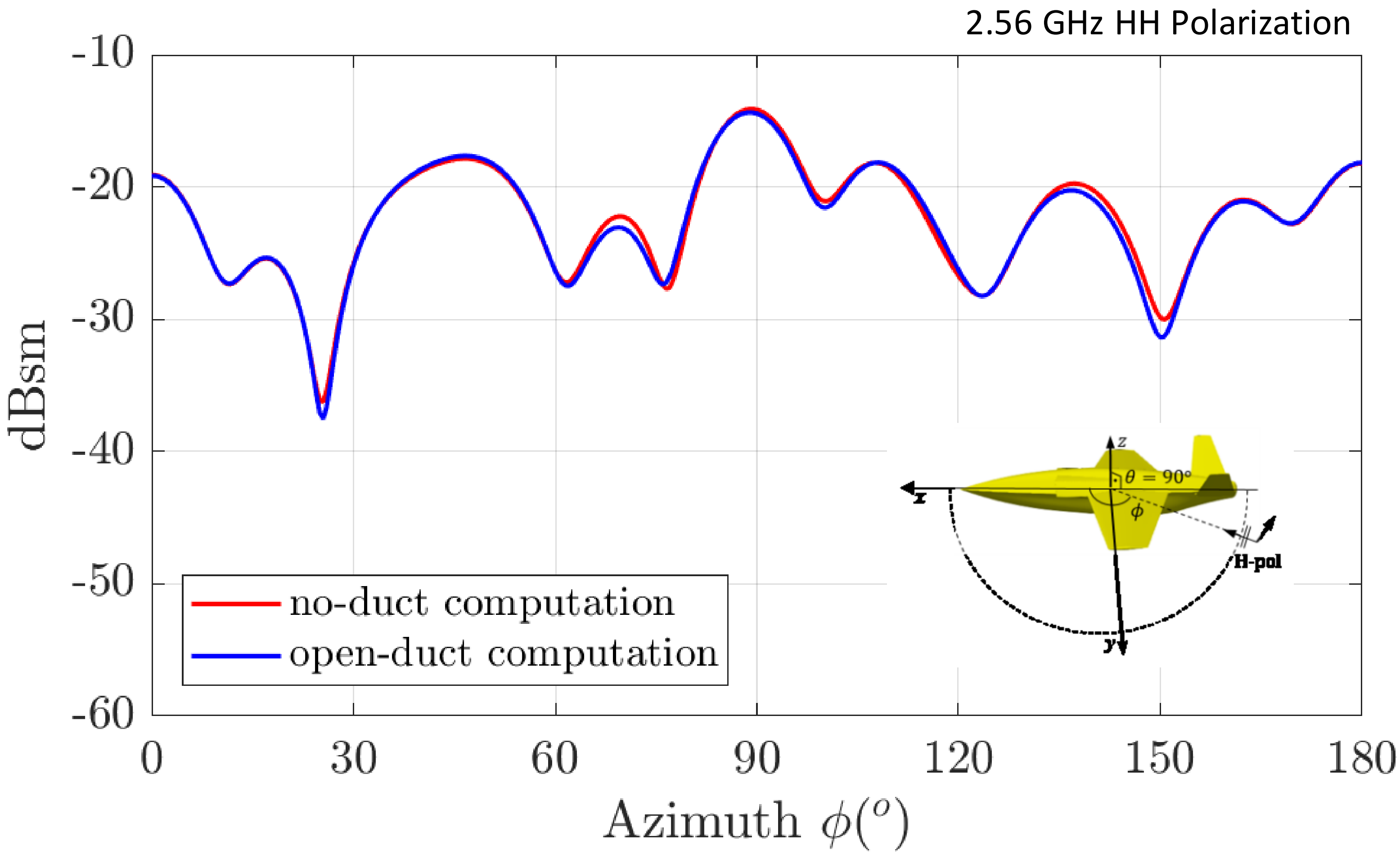
PRIME 4 inch mesh

Mesh Validation

- ❑ Compare RCS return of PRIME and PRIME-Duct below and above cavity cutoff
- ❑ Below cutoff, expect similar patterns

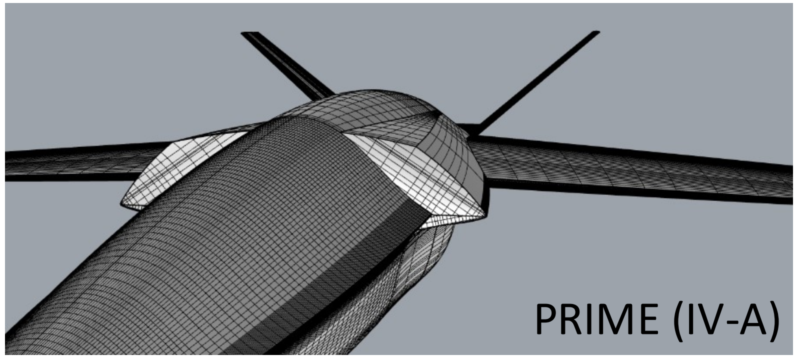


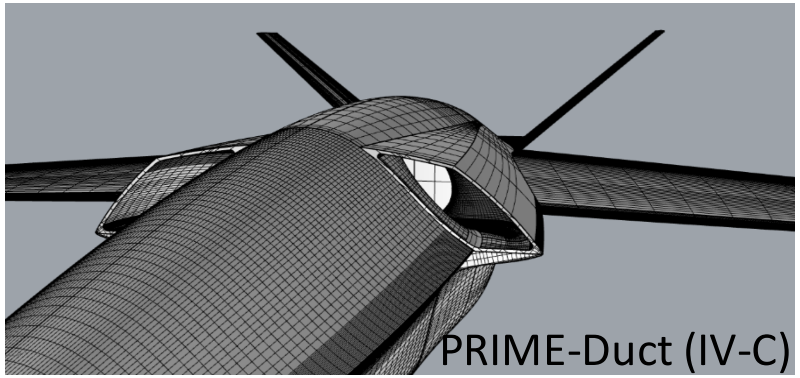




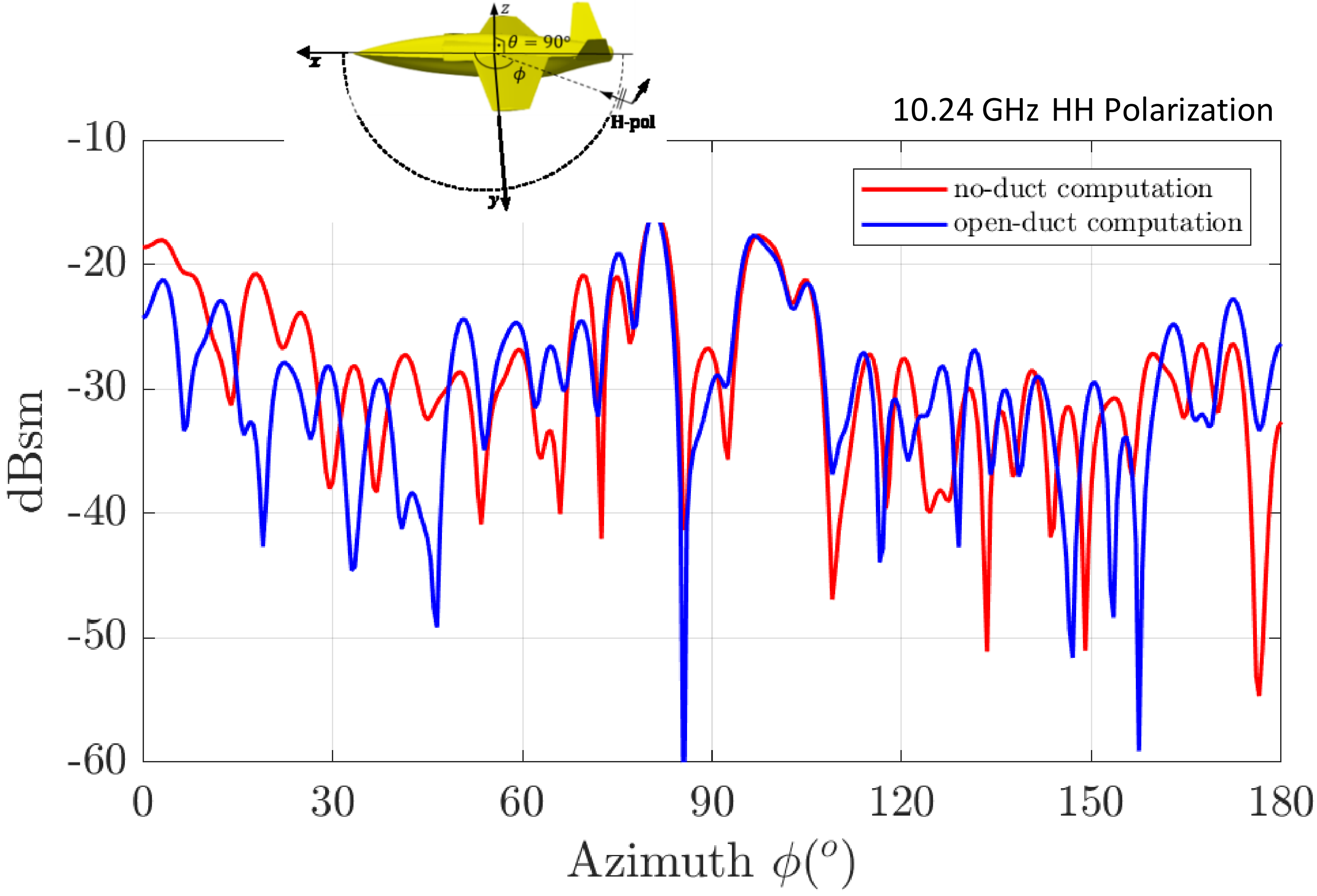
Mesh Validation

- Compare RCS return of PRIME and PRIME-Duct below and above cavity cutoff
- Below cutoff, expect similar patterns
- Above cutoff, patterns differ


PRIME (IV-A)


PRIME-Duct (IV-C)

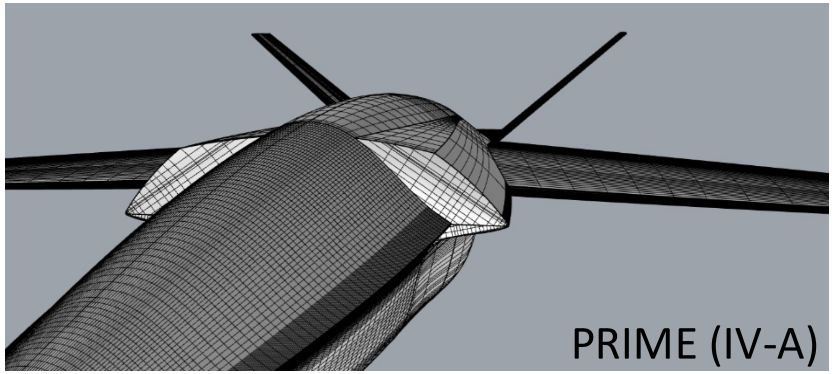
10.24 GHz HH Polarization

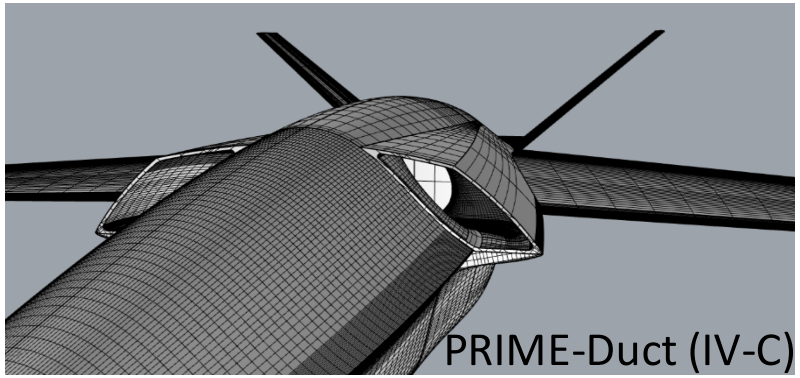


Mesh Validation

- Compare RCS return of PRIME and PRIME-Duct below and above cavity cutoff
- Below cutoff, expect similar patterns
- Above cutoff, patterns differ
- 13 each of PRIME and PRIME-Duct meshes provided
  - Element edges scale from $1/8^{th}$ of an inch to 8 inches in factors of $\sqrt{2}$

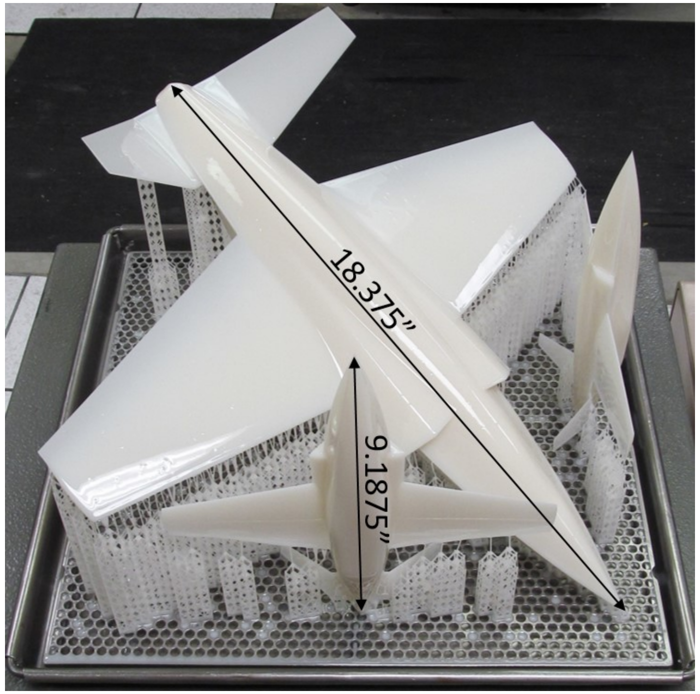
	PRIME			PRIME-Duct		
Target edge size [in]	Max/Min Edge Ratio	Average [in]	# elems	Max/Min Edge Ratio	Average [in]	# elems
$1/8$	5.7	0.12	45 008 820	5.7	0.12	49 322 762
$\sqrt{2}/8$	7.3	0.18	20 864 076	5.2	0.18	24 106 500
$1/4$	5.2	0.24	11 912 040	7.1	0.25	11 773 268
$\sqrt{2}/4$	5.2	0.36	5 222 704	5.7	0.35	6 033 086
$1/2$	5.5	0.46	3 095 098	6.4	0.5	3 049 326
$\sqrt{2}/2$	7	0.7	1 282 414	5.3	0.7	1 482 410
1	5.3	1	711 538	6.6	1	758 014
$\sqrt{2}$	5.2	1.4	321 572	5.4	1.4	371 302
2	6.7	2	155 432	7.9	2	191 074
$2\sqrt{2}$	8.8	2.9	80 214	9	2.9	92 764
4	10.6	3.9	43 528	14.1	4	48 284
$4\sqrt{2}$	15	5.7	20 360	17.8	5.7	23 626
8	20.9	8	10 404	21	7.9	12 236

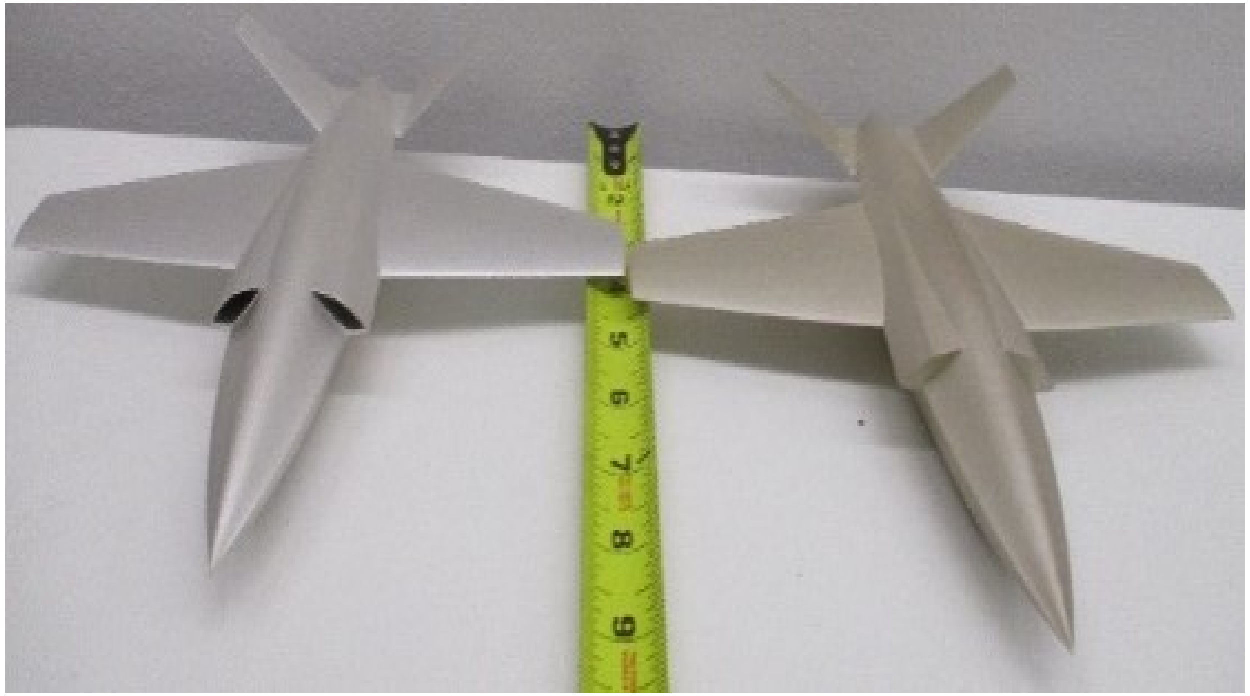

PRIME (IV-A)

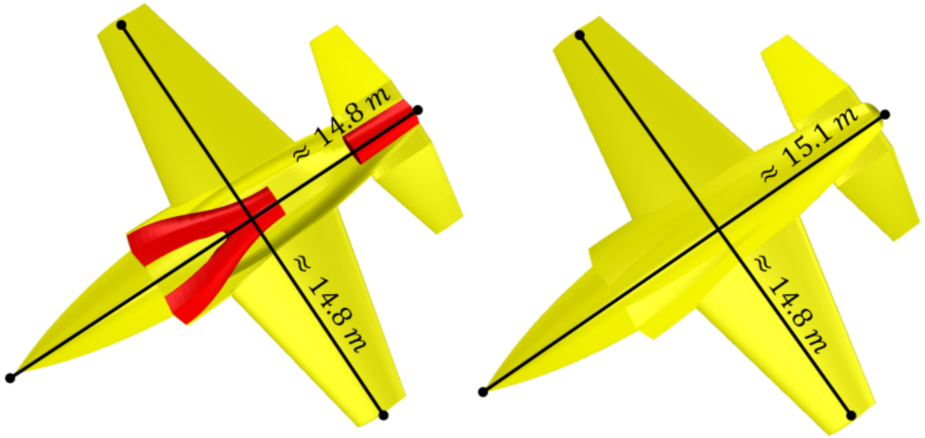

PRIME-Duct (IV-C)

Measurement Campaign

- PRIME Dimensions
  - Nose-to-tail length ≈15.1 m
- PRIME-Duct Dimensions
  - Nose-to-tail length ≈14.8 m
- Additive Manufacturing Scale-Models
  - Printed via stereolithography (SLA)
  - Two scale models approx. 1/64 of the full-size model

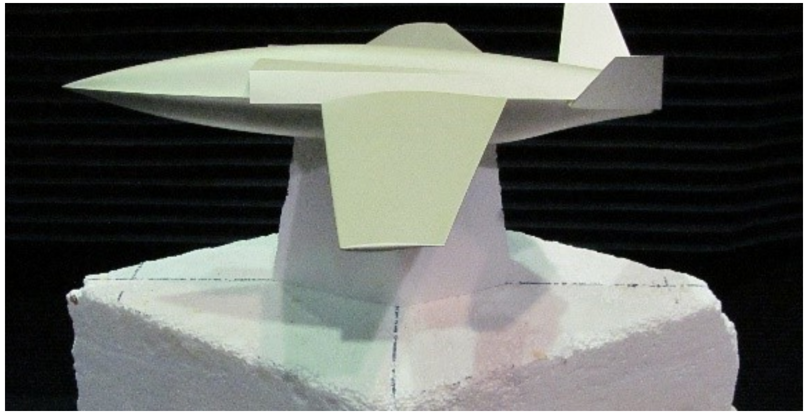




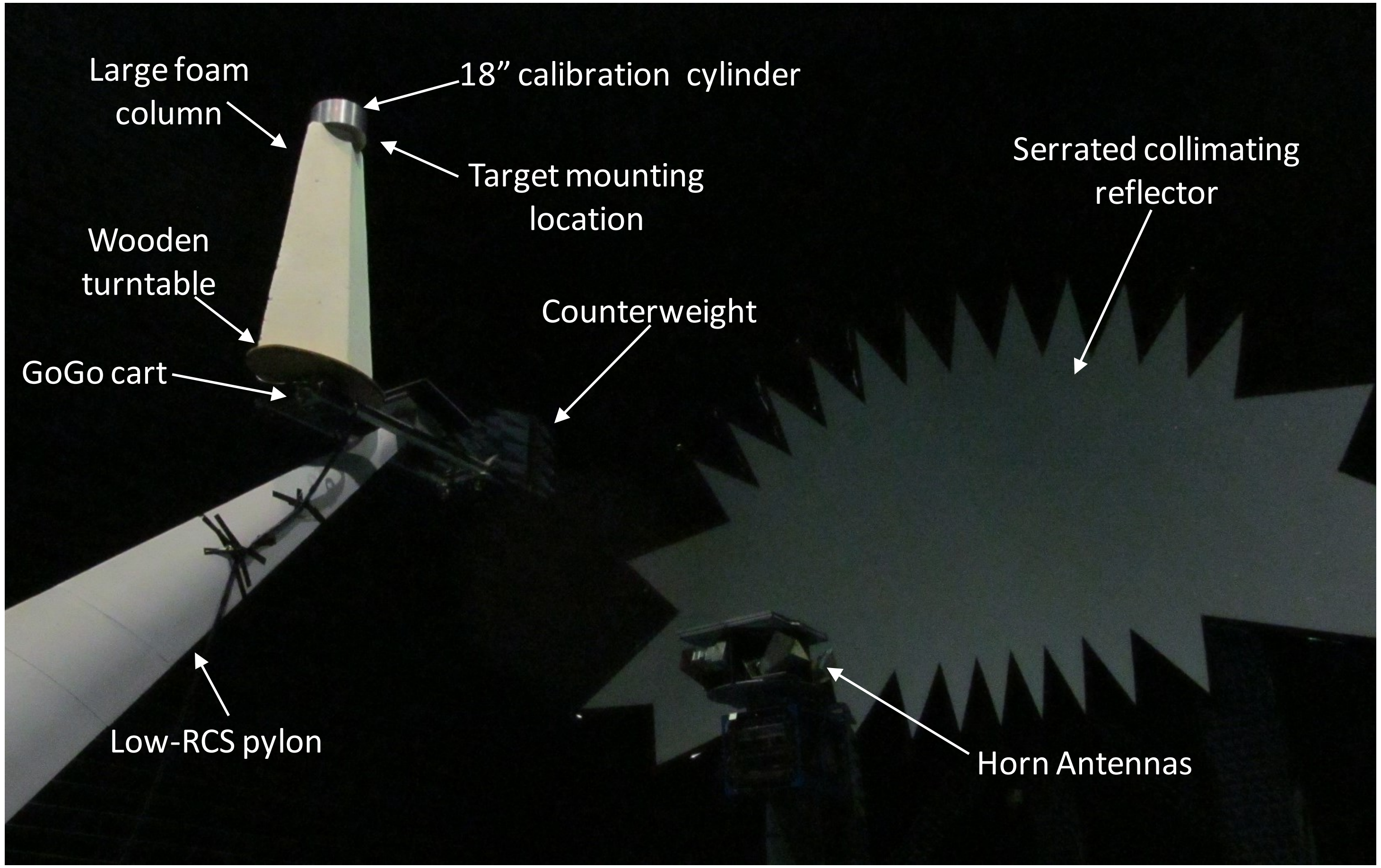


Monostatic RCS Measurement

- Measurement Setup
  - Compact chamber



Silver-coated 18.375” scale-model



[7] J. T. Kelley, D. A. Chamulak, C. C. Courtney, and A. E. Yılmaz, “EM programmers notebook-Rye Canyon RCS measurements of benchmark almond targets” in *IEEE Ant. Prop. Soc. Mag.*, Feb. 2020.

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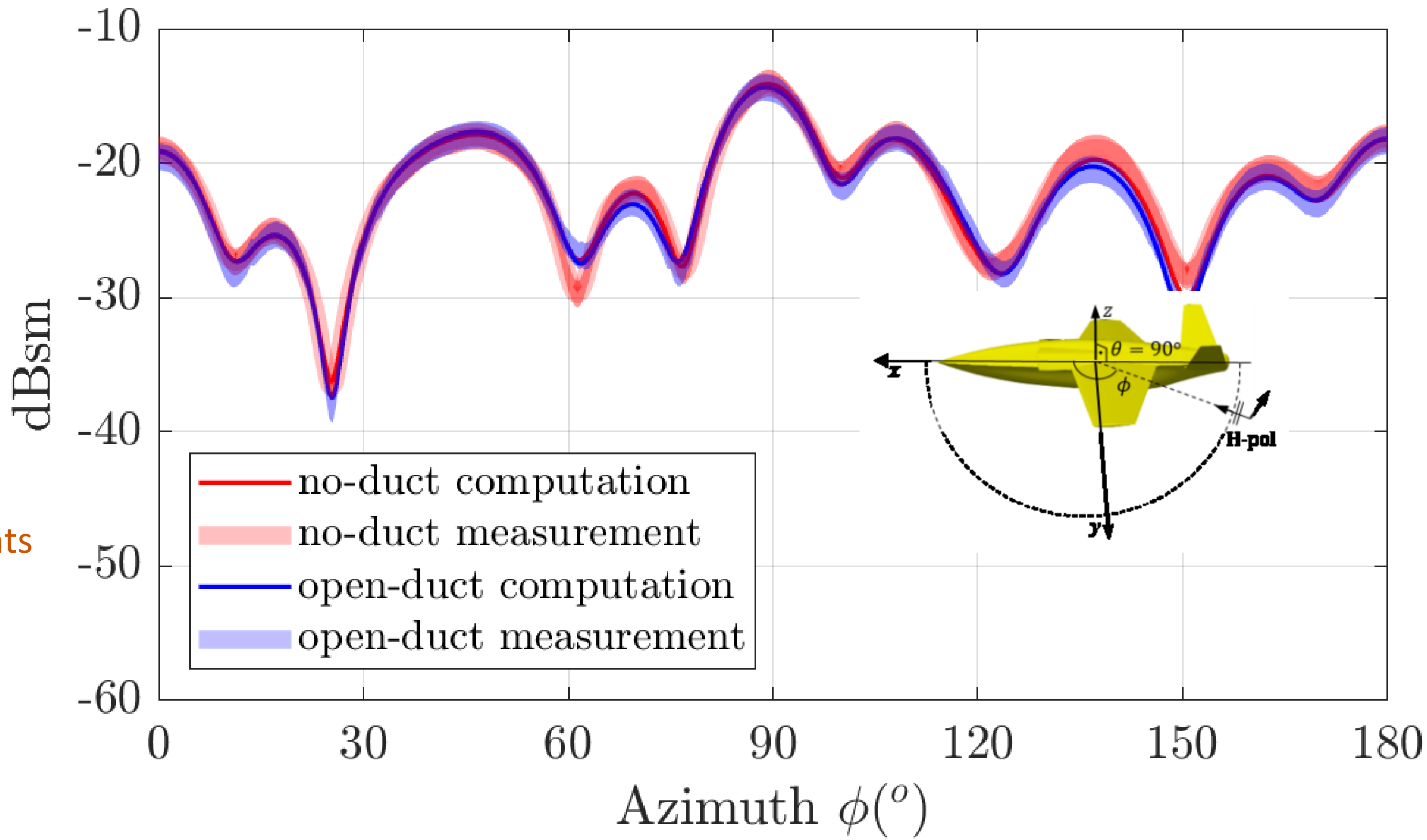
Measurement Validation by Simulation

- Measurement Setup
  - Compact chamber
- Data Collection [8]
  - Dual calibration method
  - Coherent background subtraction: background measurements taken frequently
  - Shaded regions represent minimum measurement uncertainty (±1dB)
  - 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

2.56 GHz HH Polarization



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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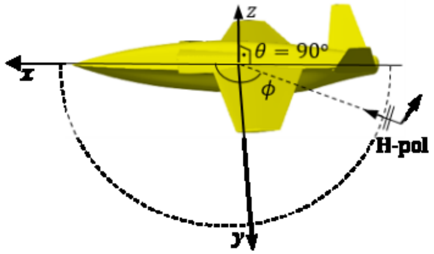
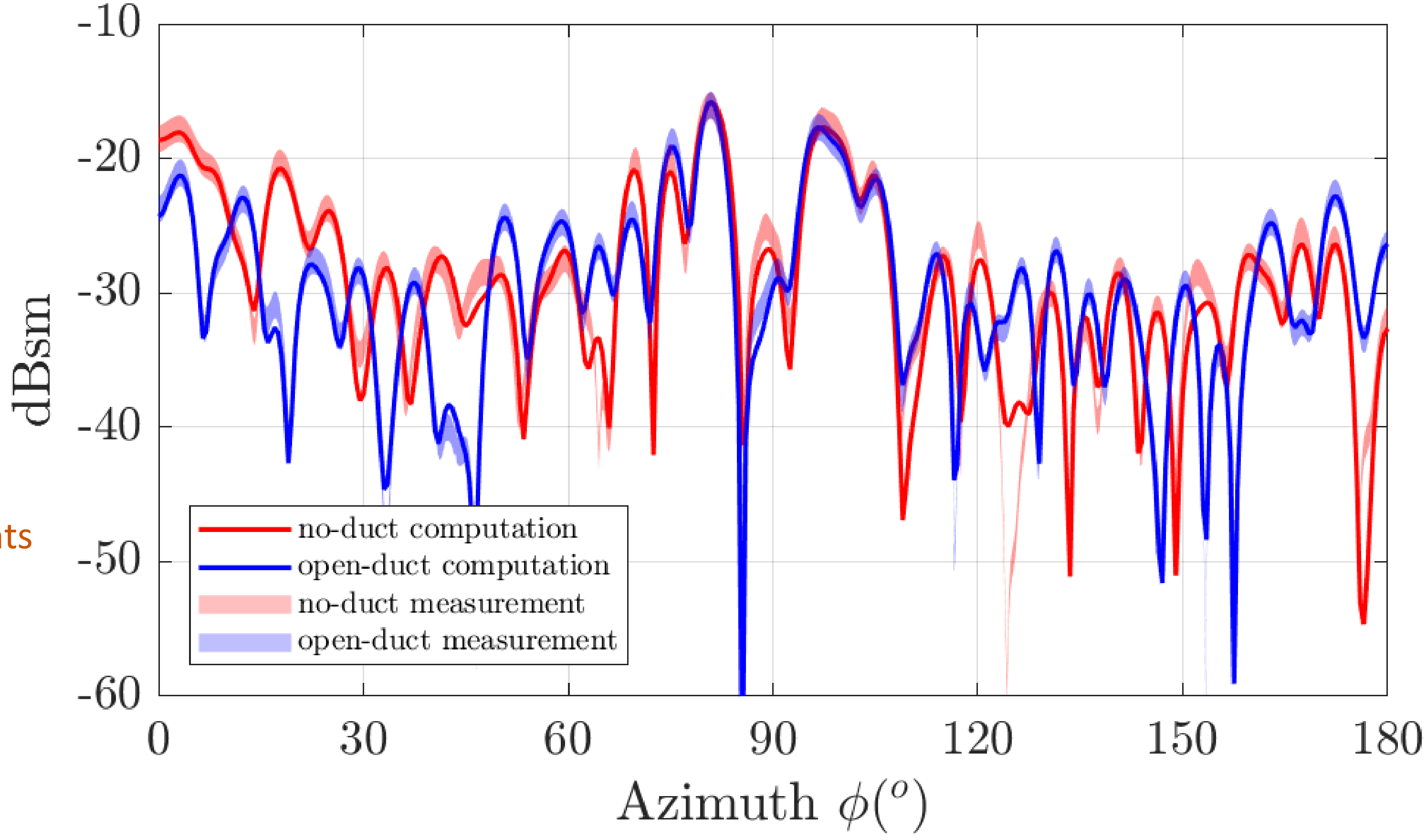


10.24GHz HH Polarization



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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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Public Release

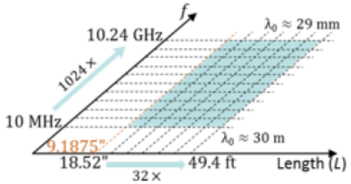
❑ Austin RCS Benchmark Suite

- Feature Available:
  - Problem Descriptions
  - Reference Data
  - Simulation Data
  - Models
  - Meshes

Description of Scattering Object

A perfect electrically conducting (PEC) complex aircraft model.

Length Scale and Frequency Range

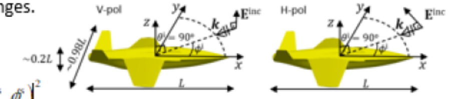


The problems of interest cover a range of ~64x in physical length scale and 1024x in frequency; the ranges are logarithmically sampled to yield 99 scattering problems. Because the aircrafts are PEC, there are only 17 + 12 unique scattering problems in Problem Set IVA. In these problems, the model sizes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

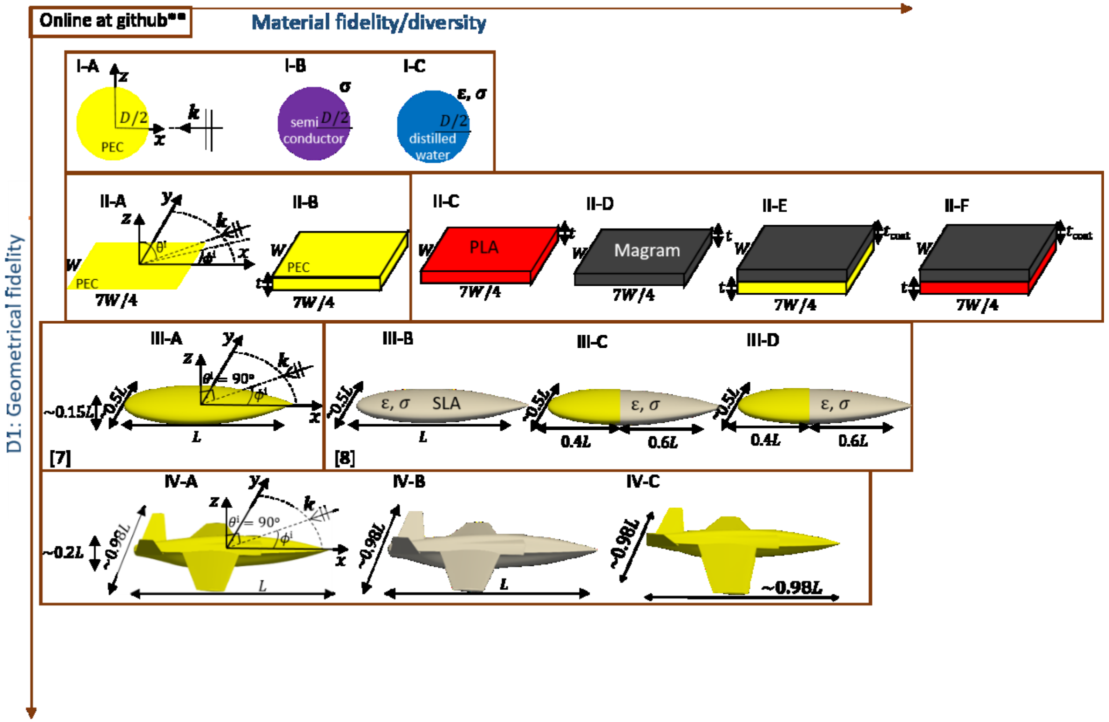
2. The model cannot be described sufficiently with a few equations, drawings, or pictures [1]; it presents modeling, meshing, and reproducibility challenges.



Quantities of Interest

Radar cross section (RCS) definition

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



UTAustinCEMGroup 2021 Summer Update

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Problem I-Spheres	2020 ACES Update
Problem II-Plates	2020 AMTA Update
Problem III-Almonds	2021 Summer Update
Problem IV-EXPEDITE-RCS Aircrafts	2021 Summer Update

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

Conclusion

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

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