



AFRL

Vision for Next-Gen Modeling & Simulations for Aerospace Propulsion Systems

Venke Sankaran

AFRL - Aerospace Systems Directorate

NASA Advanced Modeling & Simulations Seminar Series

June 24, 2021

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Outline

- **Introduction**
  - Definitions
  - Modeling & simulations pyramid
  - R&D vision
- **AFRL Rocket Lab**
  - Space access propulsion
  - Strategic & tactical propulsion
  - In-space propulsion
- **Examples**
  - Physics-based models
  - Multi-scale models
  - Multi-fidelity models
  - Digital twins
- **Summary**

AFRL Rocket Lab



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Introduction

"This 'digital trinity' – digital engineering and management, agile software, and open architecture – is … the next big paradigm shift for military tech dominance."
- There is No Spoon, Will Roper

"Across the board, we should focus on the power of digital engineering and new manufacturing techniques to rapidly innovate, iterate, and produce product improvements, and improve logistics support."
- AFRL/RQ Director's Intent

This talk is not on digital engineering – rather it is focused on what is needed in M&S tools development to serve the needs of the next-generation digital enterprise.



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Definitions

- **Modeling and simulation (M&S):**
  1. The discipline that comprises the development and/or use of models and simulations
  2. The use of models, including emulators, prototypes, simulators, and stimulators, either statically or over time, to develop data as a basis for making managerial or technical decisions
- **Analysis:**
  - The systematic, thoughtful, and rigorous employment of the scientific method to examine a problem, scenario, or issue in order to gain insights into relationships between constituent components, understand underlying principles, or answer a specific set of pre-identified questions
- **Digital engineering:**
  - An integrated digital approach using authoritative sources of system data and models as a continuum throughout the development and life of a system. Digital engineering updates traditional systems engineering practices to take advantage of computational technology, modeling, analytics, and data sciences.

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Modeling & Simulations Overview

Missions and Systems Analysis involves empirical fast-running models to evaluate systems and system of systems

Physics Modeling involves models at all levels of fidelity to perform single-point analysis, multi-point design, and digital twin development

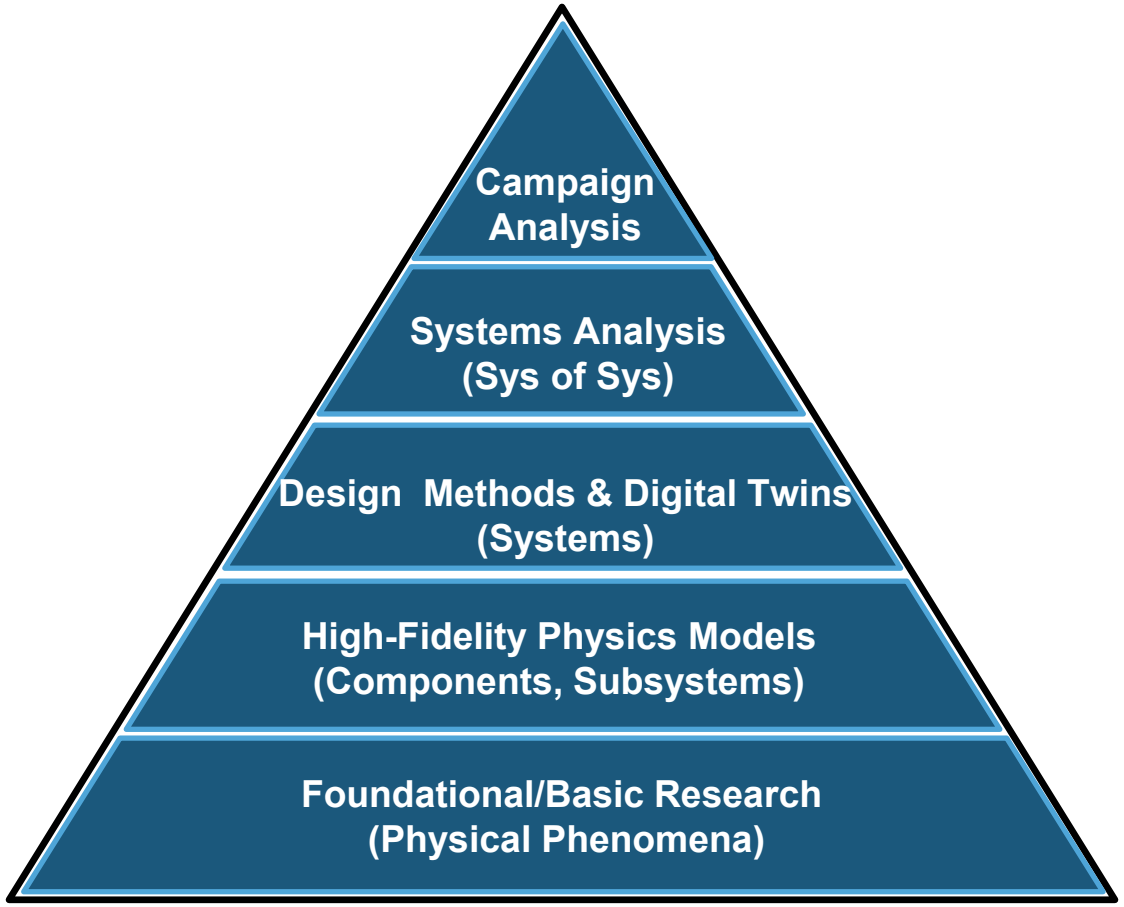


Key research focus areas: (1) multi-fidelity model development trained by high-fidelity physics-based models; (2) data assimilation of experimental/test/operational data

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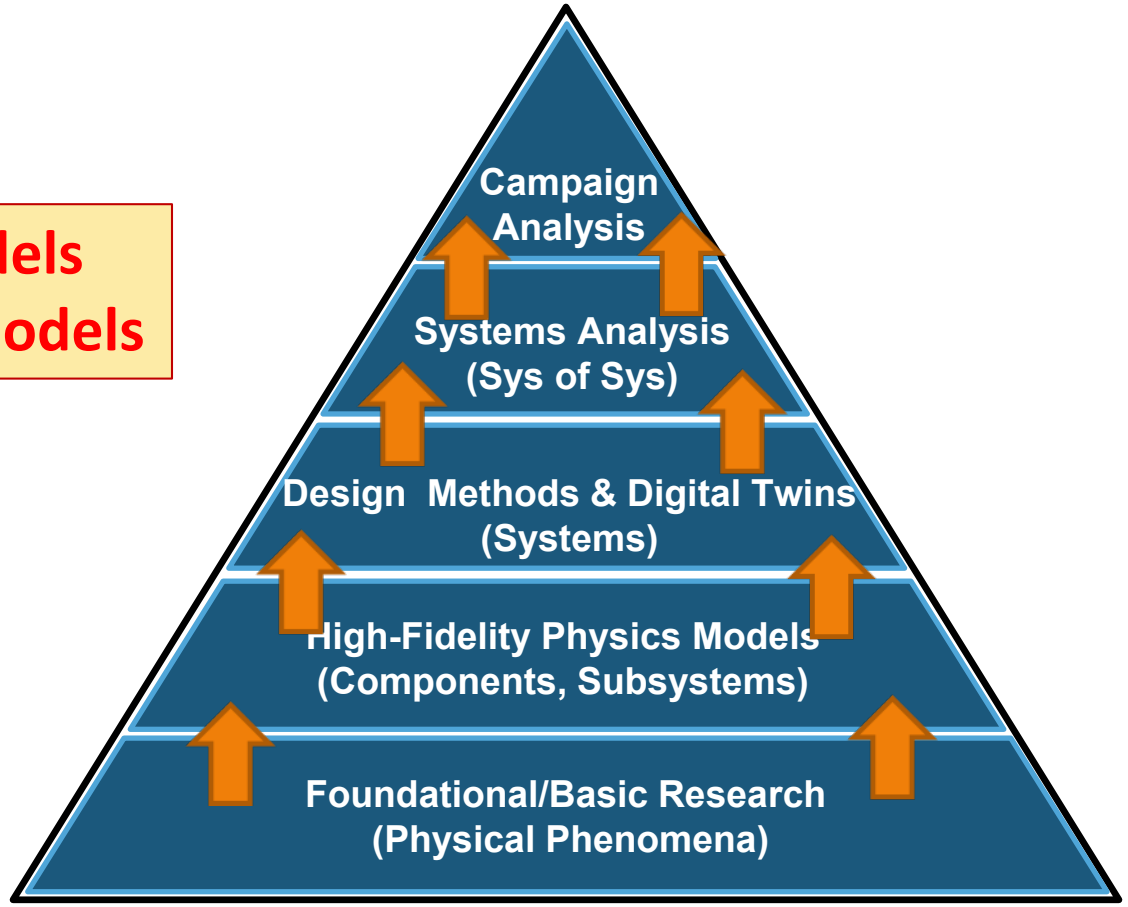
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Deconstructing the pyramid



Deconstructing the pyramid

Train fast-running models using higher-fidelity models

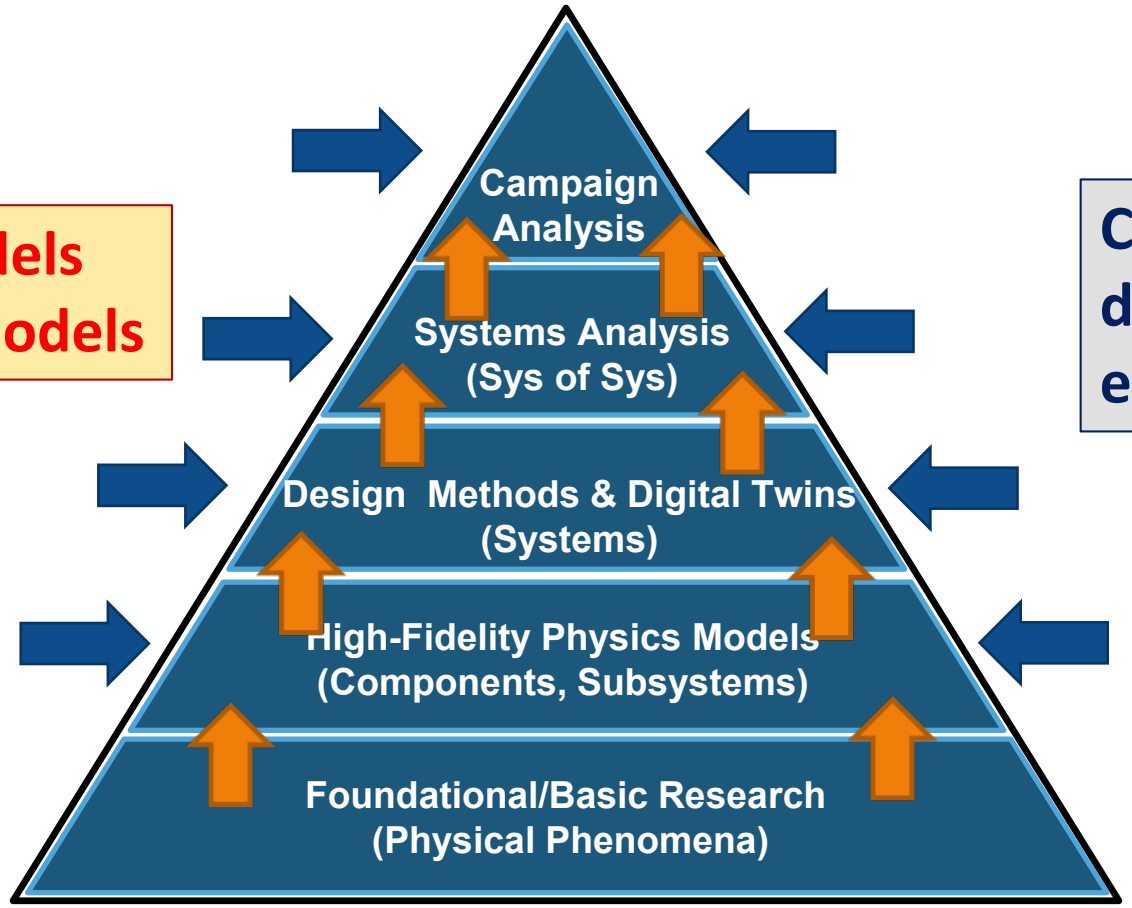


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Deconstructing the pyramid

Train fast-running models using higher-fidelity models



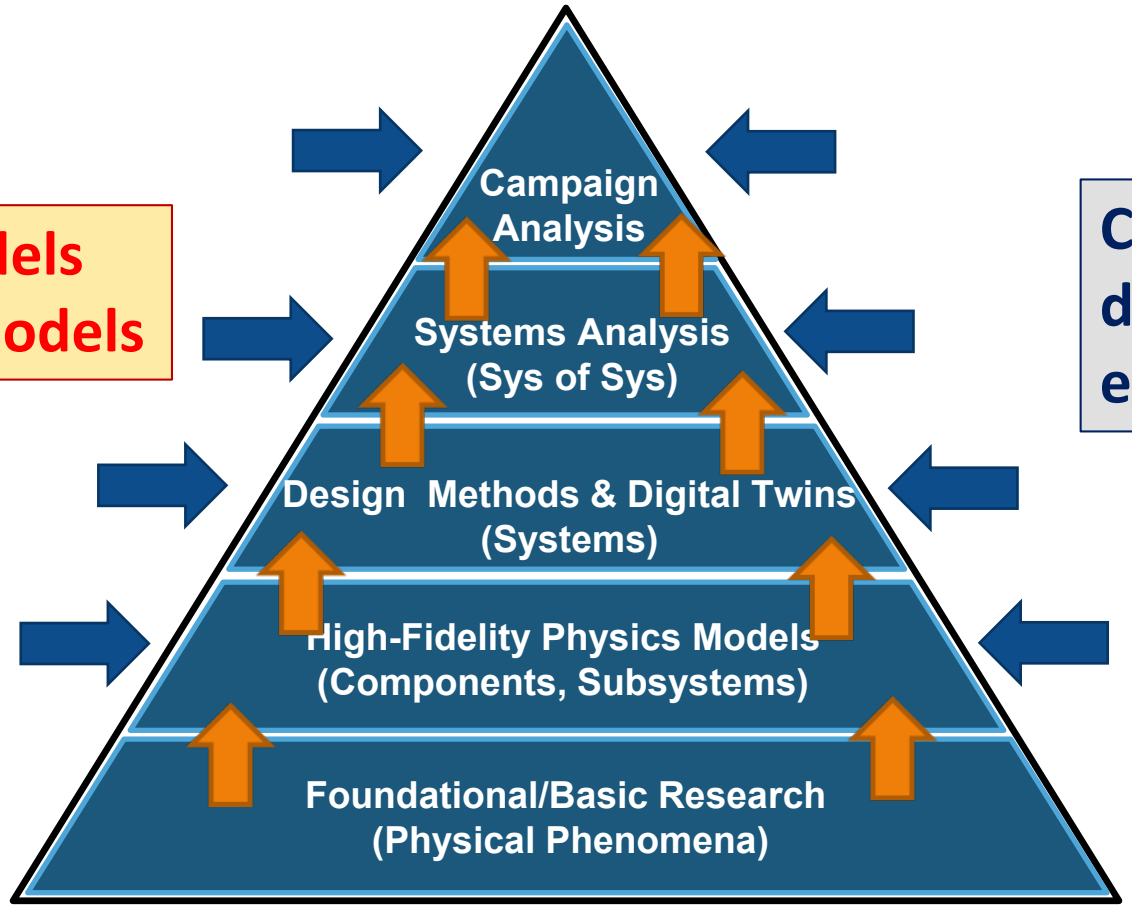
Calibrate models with data assimilation from expts/tests/operations

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Deconstructing the pyramid

Train fast-running models using higher-fidelity models



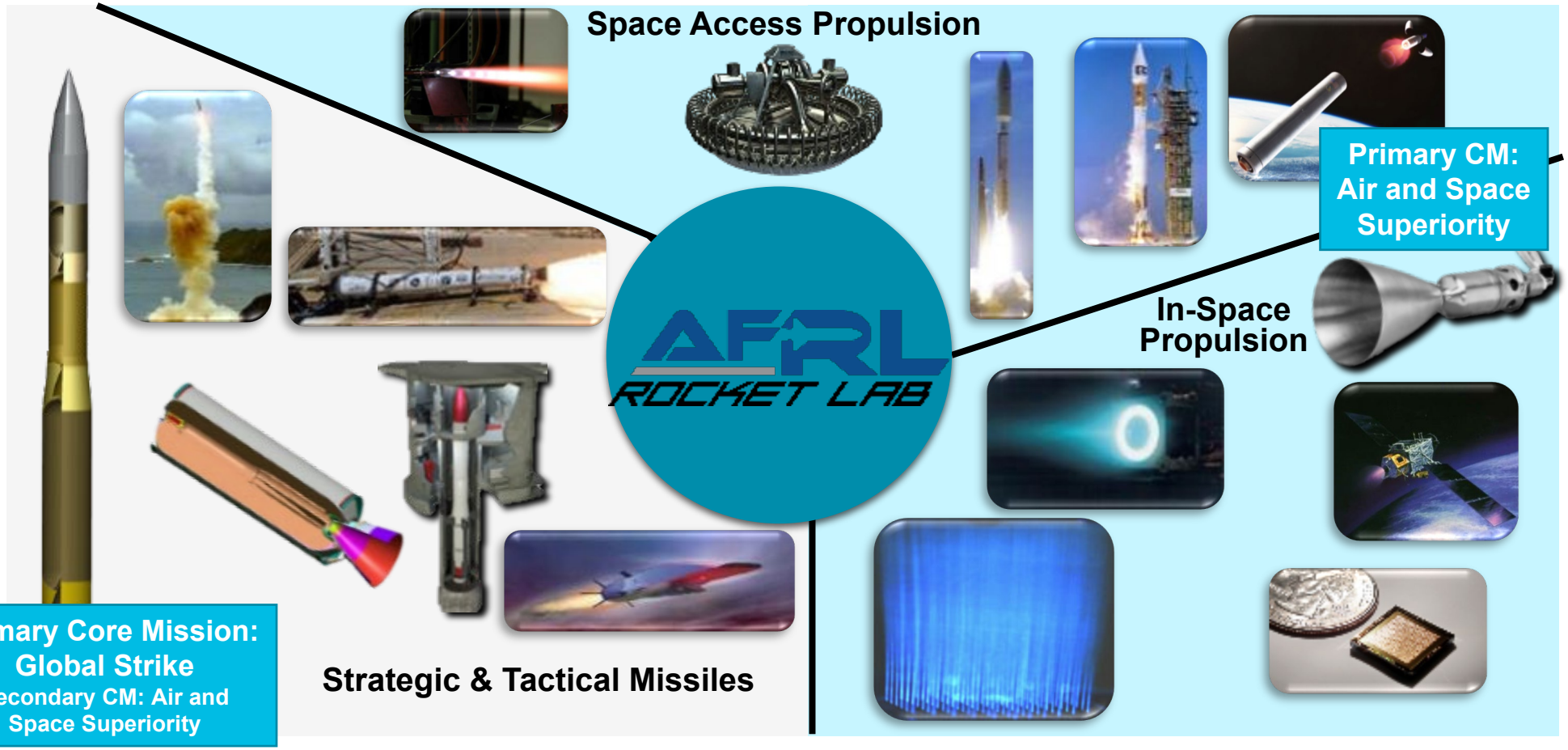
Calibrate models with data assimilation from expts/tests/operations

These two statements represent the research vision for next-gen M&S development

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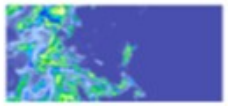
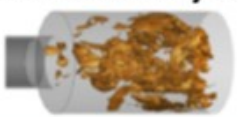
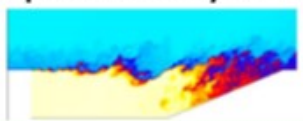
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Physics-Based Modeling

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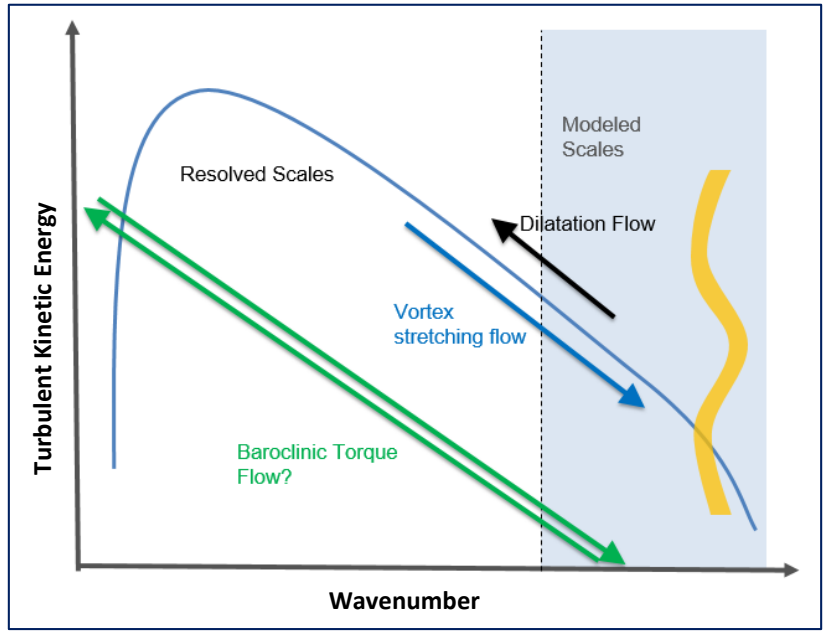
Physics-based modeling of combustion dynamics

AFRL Turbulent Combustion Initiative

Unit Physics & Numerics	Canonical	Applications
Turbulent Combustion Physics, Chemistry & Numerics 	Bluff-Body Flame 	Gas Turbine Augmentor 
	Swirl Combustor 	Gas Turbine Combustor 
Turbulent Combustion Model Development 	Shear Co-Axial Injector 	Liquid Rocket Engine 
	Supersonic Cavity Flame 	Scramjet Engine 

Collaborations: 6.1 lab task ↔ 6.1/6.2 Projects ↔ 6.2/6.3 Projects

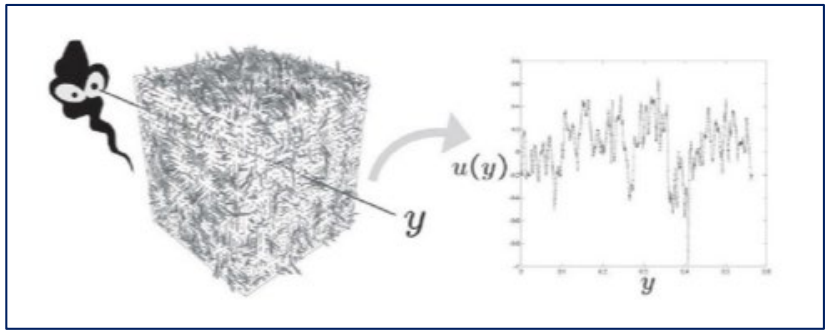
Energy Cascade



Turbulent combustion is more challenging than traditional turbulence due to the flame scale & the bi-directional energy transfer

AFOSR funding by Dr. Chiping Li

Physics & chemistry of turbulent combustion

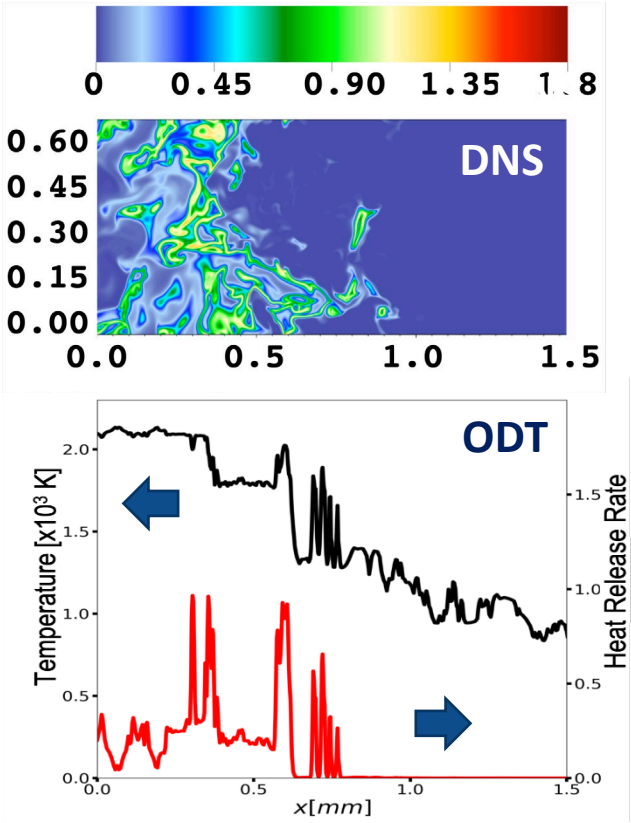


One-Dimensional Turbulence (ODT)

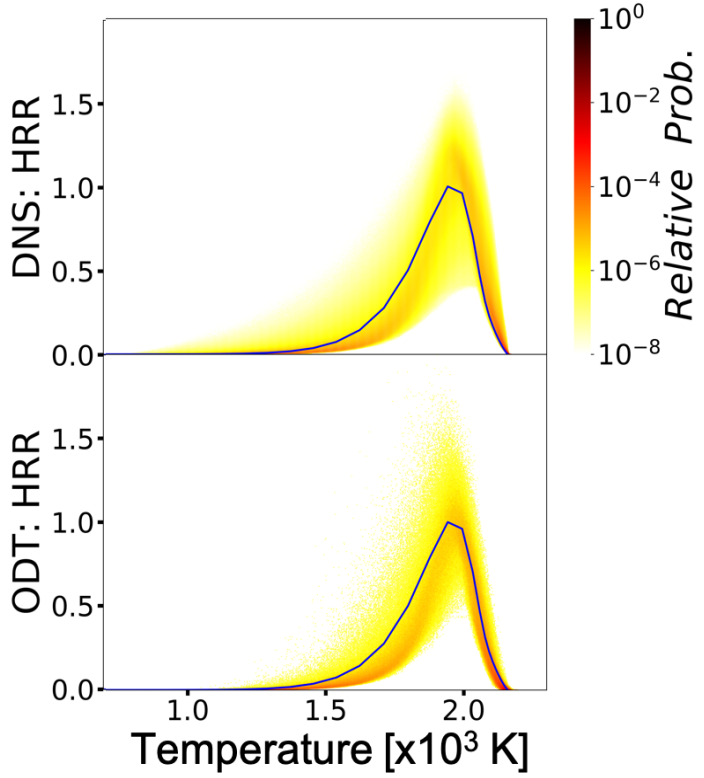
- Develop model as surrogate for Direct Numerical Simulations (DNS)
- Develop ODT-based multi-scale sub-grid closure model

Pioneered ODT as surrogate-DNS to efficiently assess turbulence effects on reduced chemistry mechanisms

Flame Structure



Heat Release Rate (HRR)



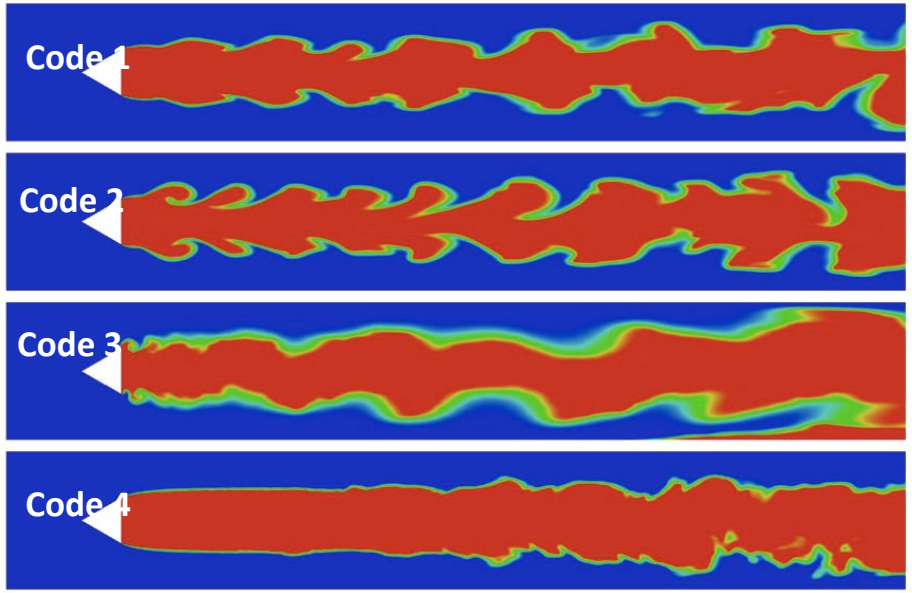
Researchers: Zoltan Jozefik, Matt Harvazinski, Sal Badillo-Rios

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Numerics of turbulent combustion

Implicitly-Filtered LES

Same model, different codes give different results

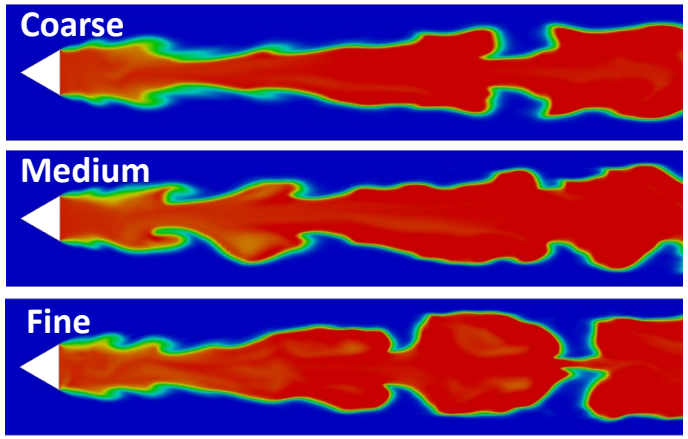


Explicitly-Filtered LES

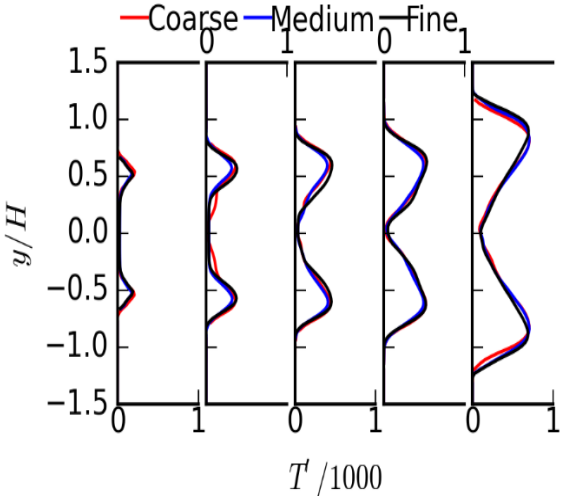
Problem - accuracy depends on grid → **Solution** – eliminate grid dependence

Instantaneous Temperature

Different grids, same filter size



RMS Temperature Fluctuations



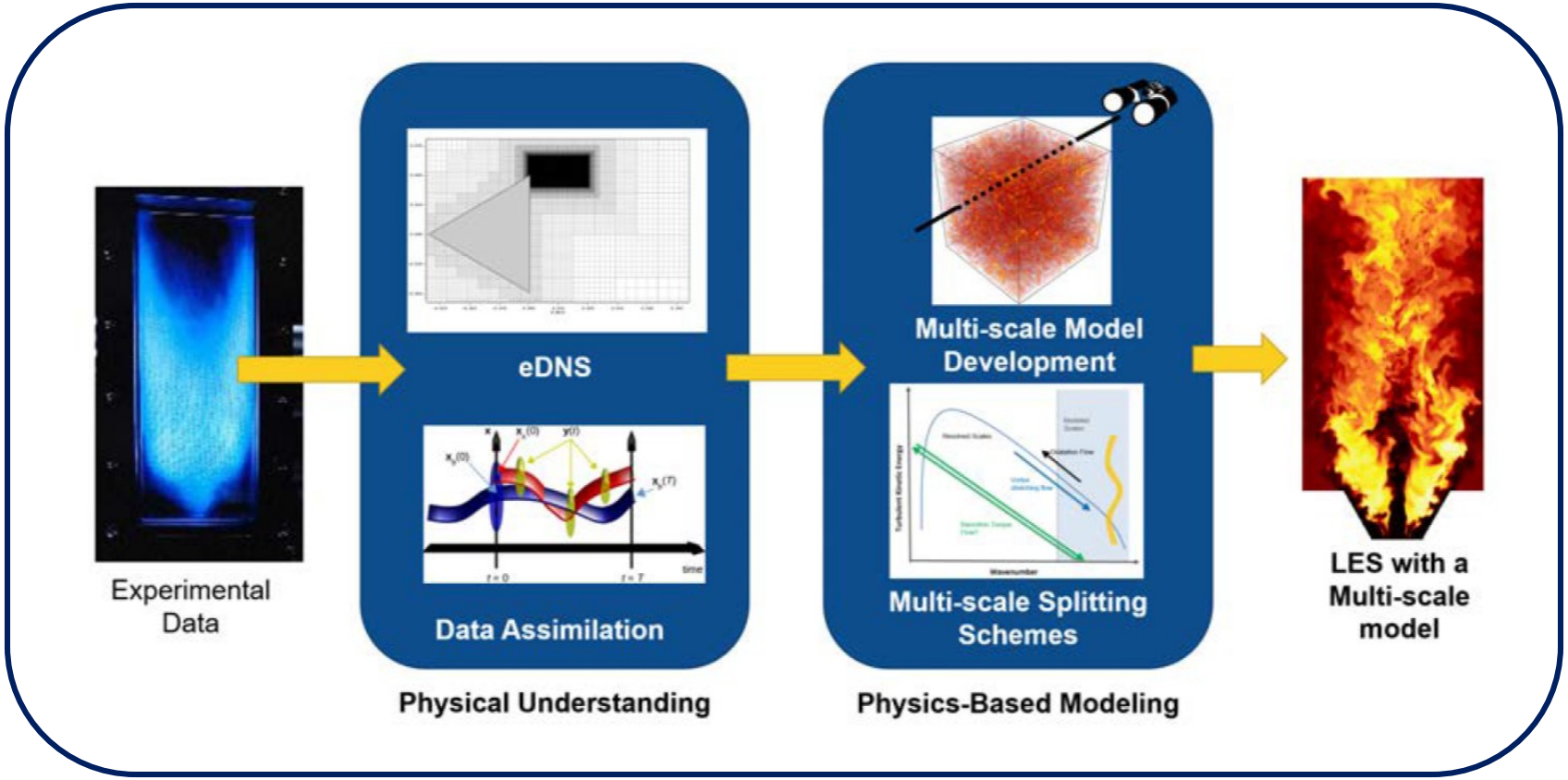
Demonstration of grid convergence of bluff-body stabilized flame with explicitly filtered LES allows evaluation of sub-grid closure models

Researchers: Tim Gallagher and Ayaboe Edoh

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Model development



Researchers: Matt Harvazinski, Ramakanth Munipalli, Tim Gallagher, Ayaboe Edoh & Adam Comer

Utilize physics understanding from direct numerical simulations anchored by experimental data to develop multi-scale turbulent combustion closure model

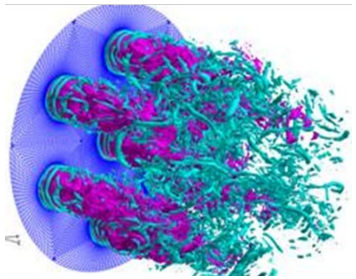
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Liquid rocket combustion stability modeling

Rocket Propulsion Division (RQR)

Combined 6.1/6.2 experimental and computational program on high pressure liquid rocket combustion stability





SMC Supported Projects:

VISP (AF-RIF):

High-fidelity physics-based codes

Based on ALREST computational platform

CSTD-I (Aerospace corp., SMC):

Design Tool for combustion instability

Design of Experiments based parameter search

Driven by CFD and Acoustics solver data

CSTD – II (SpaceX) and III (Aerospace Corp):

Extension to high pressure and multi-injector cases

Researchers: Doug Talley, Matt Harvazinski, Ramakanth Munipalli, Tomas Houba

University Collaborators

AFOSR-funded

UCI University of California, Irvine

PURDUE AERONAUTICS & ASTRONAUTICS

Georgia Tech

External Collaborators

HYPERCOMP, INC. Leader in High Performance Computing

AEROSPACE

SPACEX

AEROJET ROCKETDYNE

Advanced Liquid Rocket Engine Stability Technology (ALREST)

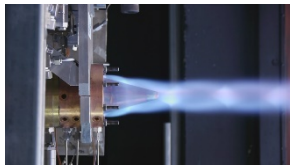
- Developed & successfully transitioned virtual testing capability of liquid rocket engine injectors/chambers to mitigate combustion instabilities via coordinated experimental & computational programs

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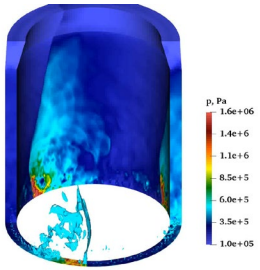
Rotating detonation rocket engines

Rocket Propulsion Division (RQ)

Rocket (RDRE)



Dr. Eric Paulson
RDRE Lead



Turbine Engine Division (RQ)

Airbreathing

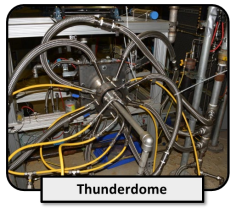
Dr. Alex Schumaker
6.1/Co-6.2 RDE Lead

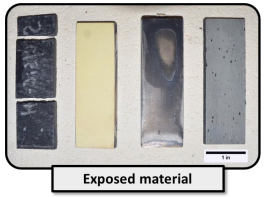
AFOSR: RDE Fundamentals – Physics, Chemistry, Optimization

Dr. Chiping Li & Dr. Martin Schmidt
AFOSR PO

Materials Directorate (RX)

Material Solutions





Dr. Garth Wilks
RDE Material lead

Program Partnerships

Sensors - Modeling/Simulation - Experiments

Government

Academia

Industry

Joint 6.1 & 6.2 effort on shock-based combustion

- To gain physics understanding of propellant injection/mixing, heat transfer, structural interactions, nozzle coupling, etc. and leading to a lab scale demonstration for target air and rocket applications

Researchers: Chris Lietz, Armani Bautista, Matthias Ross, Jason Burr, Tim Gallagher

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Multi-Fidelity Modeling

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Data-driven methods

Rocket Propulsion Division (RQR)
Reduced Basis Models (RBM), Machine Learning (ML) Methods and tools

AFOSR (co-sponsored COE):
Dr. Fariba Fahroo
AFOSR Computational Math
Dr. Mitat Birkan
AFOSR Propulsion & Power

University Collaborators

Aerospace Engineering
University of Michigan

Purdue Aeronautics & Astronautics

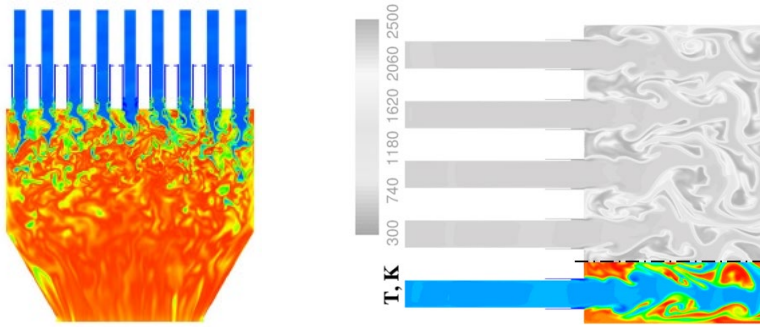
The University of Texas at Austin

NYU Courant Institute of Mathematical Sciences

Component research activities:

1. Center of Excellence on reduced models – U.Michigan, Purdue, U. Texas-Austin, NYU
2. OSD-LUCI Fellowship – U.Texas - Austin
3. AFOSR STAR team award
4. VISP, ALREST - high fidelity models
5. Phase-II STTR – CRAFT Tech. - Transition

Researchers: Ramakanth Munipalli, Doug Talley



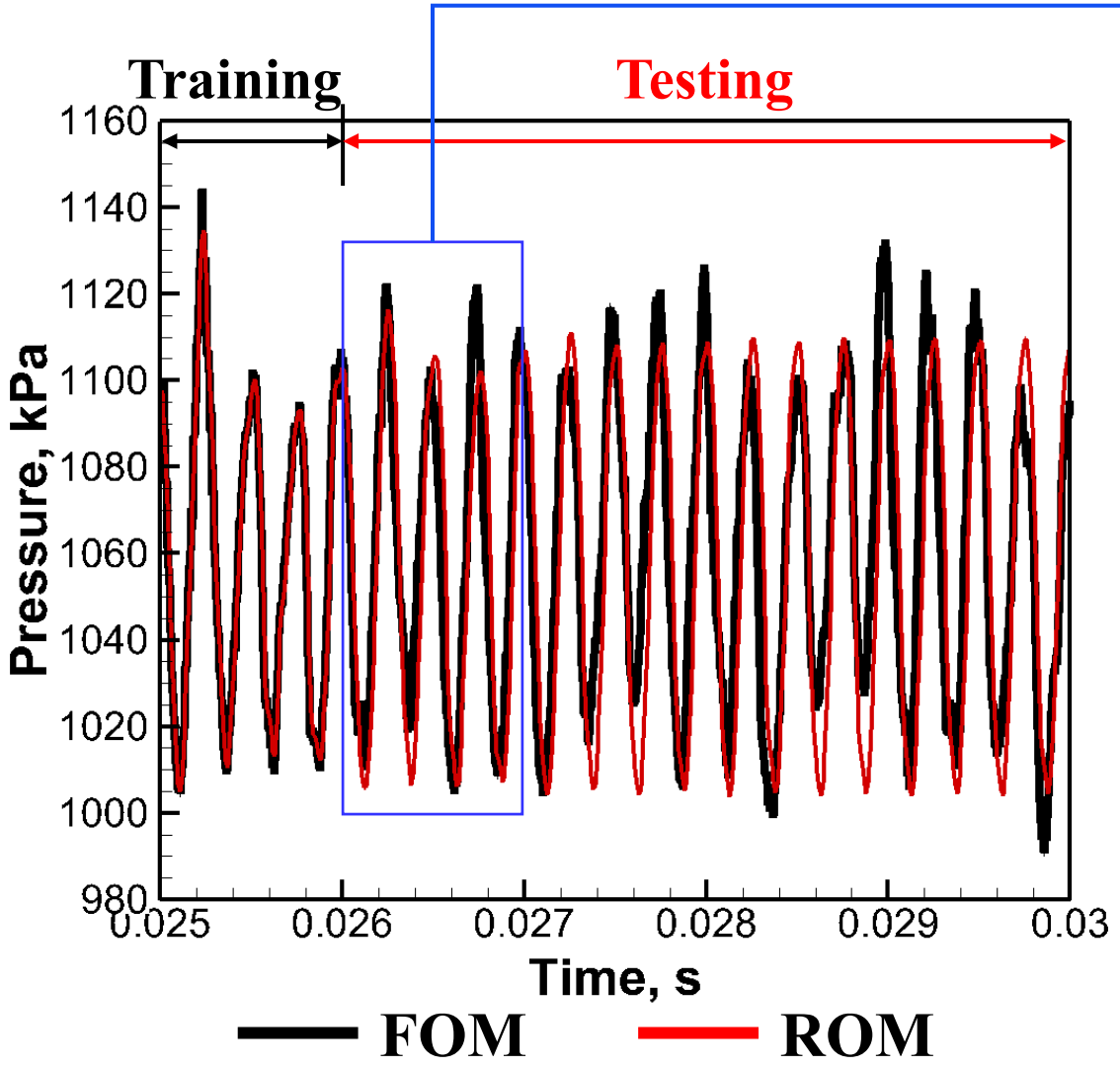
Data-driven Reduced Order Models (ROMs)
Network of reduced models for multi-element rocket chambers

Integrated 6.1-6.2 Application of Multi-Fidelity, Reduced-Order and Machine Learning Methods

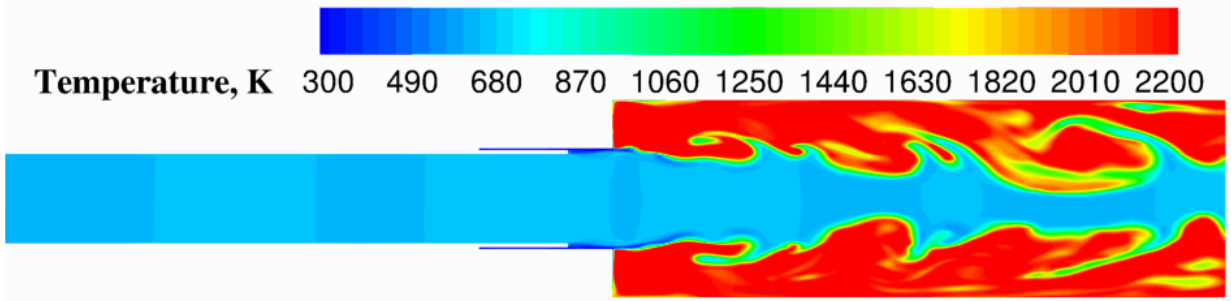
- Data-driven learning from high-fidelity physics-based models to reduced models
- Enabling multi-parameter design and optimization under uncertainty

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Reduced order modeling

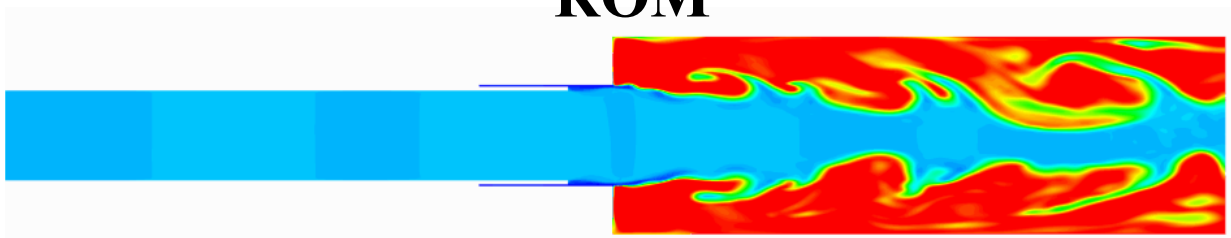


CFD (3D Reacting Flow)



8h to simulate 1*ms*

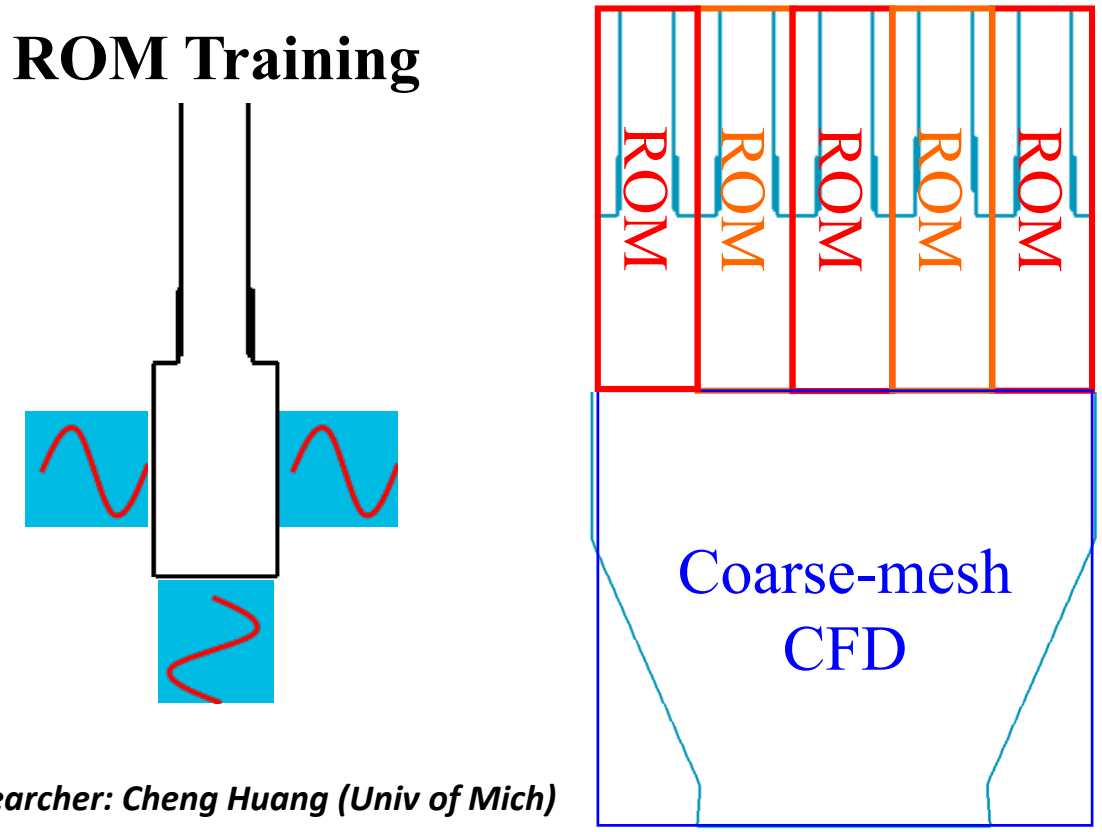
ROM



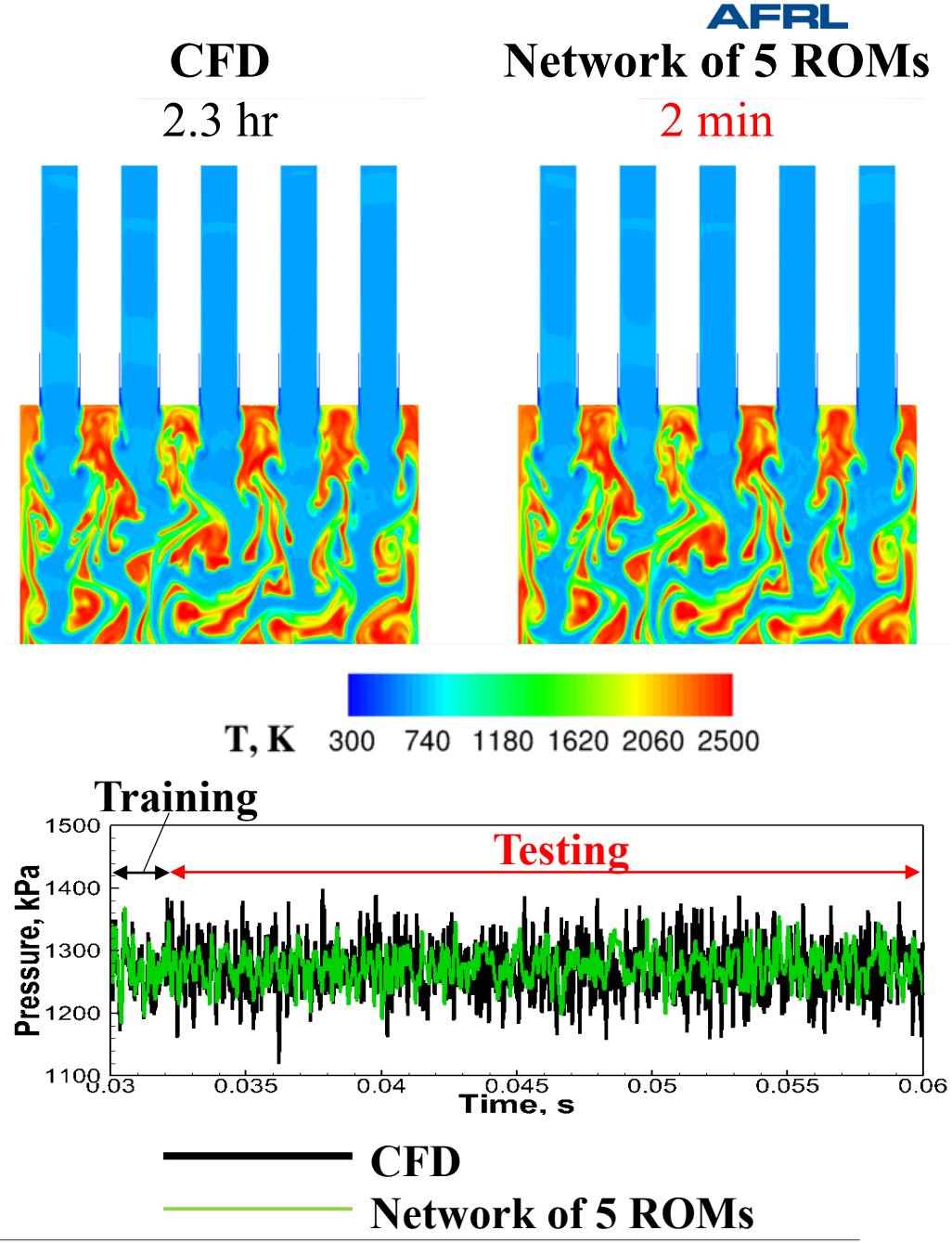
1.5 min to simulate 1*ms* (< 10% error)

Researcher: Cheng Huang (Univ of Mich)

Network of ROMs



Researcher: Cheng Huang (Univ of Mich)

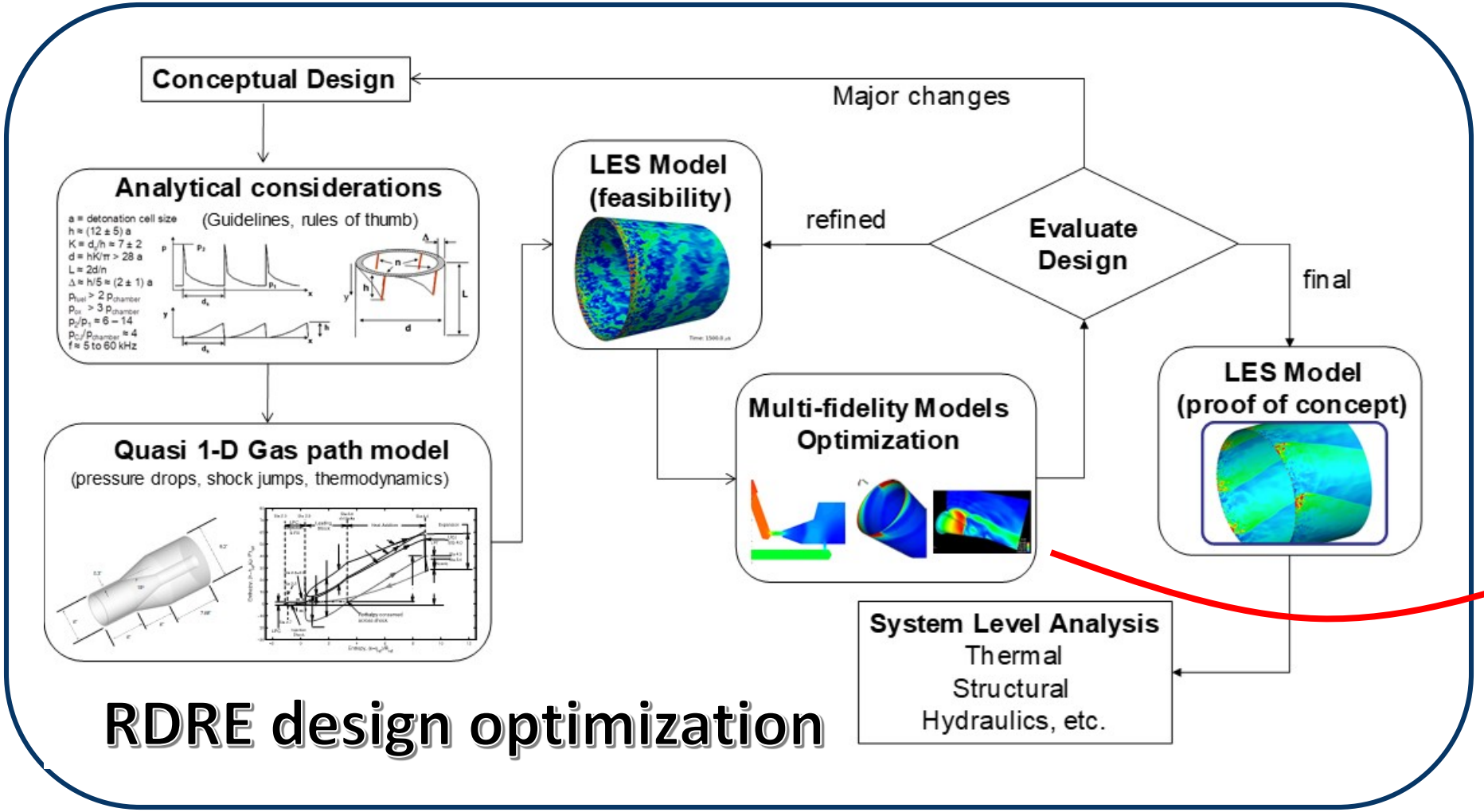


- ROM trained with **2ms** data produces reasonable predictions of unseen dynamics for **28ms**

Unclassified

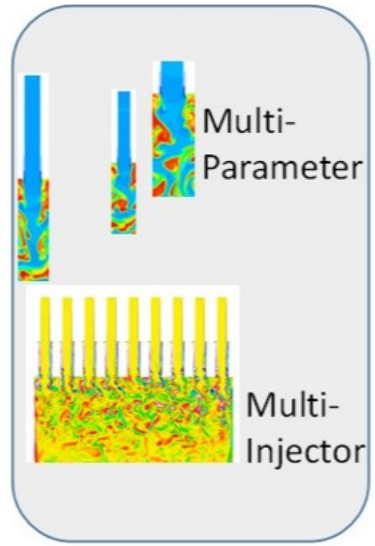
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Multi-fidelity design



Use of reacting-LES to train reduced order models (ROMs)

Reduced Order Models



Ramakanth Munipalli, Ananda Himansu

Unclassified

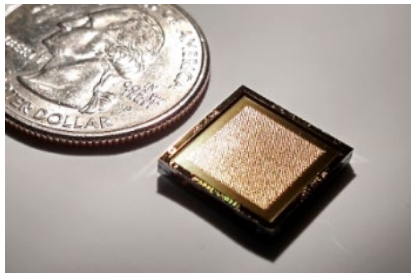
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Digital Twins

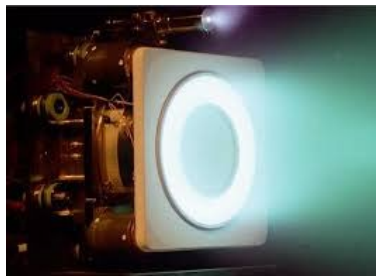
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In-Space Propulsion Portfolio

High Efficiency EP thruster technology



Low power (<100W) Electrospray



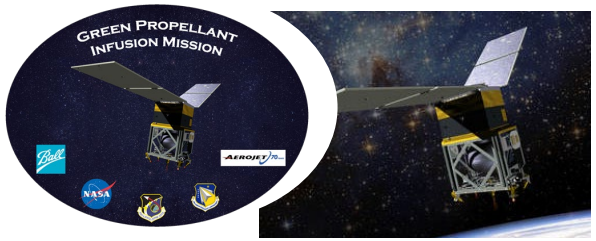
High Power (>1 kW) HET

ASCENT monopropellant thruster maturation





2012: DOT Assigned 1.4 Hazard Classification
2015: MILSPEC approved



2019: First On-orbit ASCENT Demo
Green Propellant Infusion Mission (GPIM)

1997: Initial ASCENT Formulation





2000s: Propellant Design & Characterization
Chemical, physical, friction, ESD, impact, toxicity, thermal stability

Basic Science

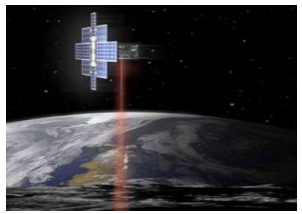
Discovery



2000s: Thruster S&T
Propellant ignition, catalyst, materials

2010s: Thruster Dev & Test
1st Generation chemical monopropellant thrusters with ASCENT

2021: NASA LFPS – Demonstration capability for CubeSats; innovative propulsion systems demonstrations



Applied R&D — 2000s — 2010s — Dev & Test — 2020s — Space Demos

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Physics-based modeling

Thermophysics Universal Research Framework (TURF)

Spacecraft-Plume Interaction: (Legacy COLISEUM Capability)

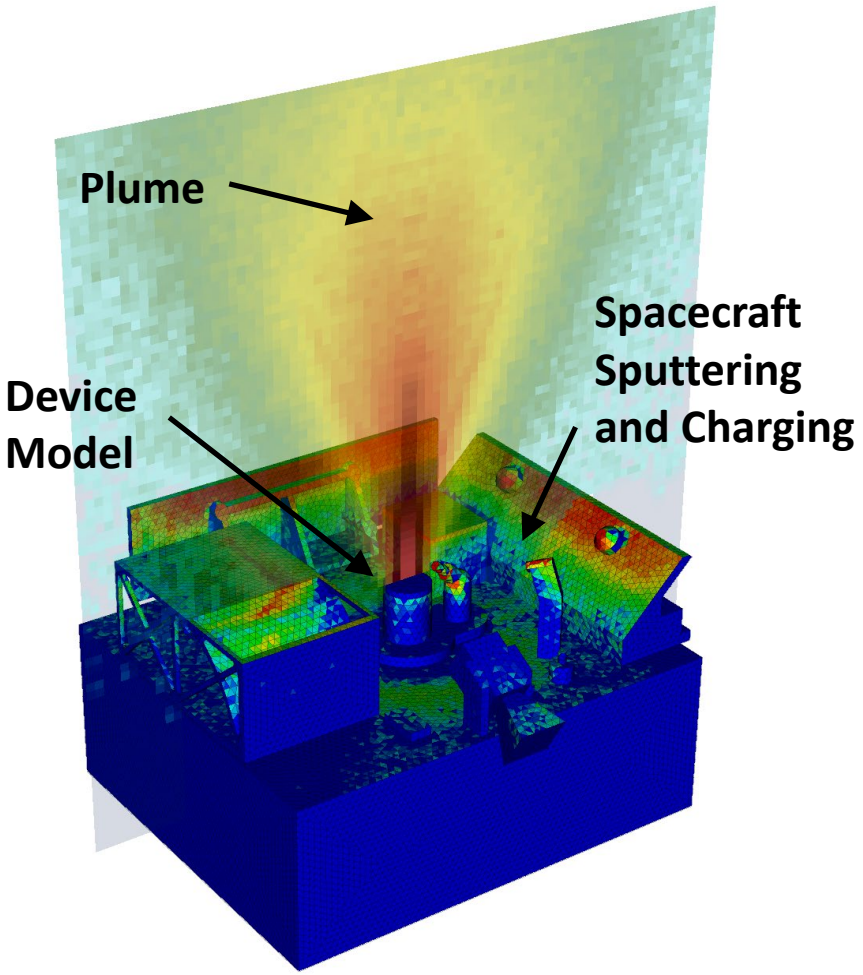
- Detailed DSMC/MCC Charge Exchange (CEX) Models
- Detailed Surface Sputter and Redeposition Models
- Thermalized Potential and Hybrid Boltzmann Electrons
- Detailed Fluid Electrons (Beta)

Multiple Thruster Source Device Models:

- Legacy HPHall Direct MPI Connect
- In-House HallTPM: Embedded 3D Ion/1D Hybrid Electron
- Generic RPA Based Experimental Data Source
- Ion Thruster Beamlet Model (Beta)

Basic Plume-Spacecraft Charging Capability

- Implicit Steady-State Surface Charge Migration
- Thin-Sheath Subgrid Plume Model



Researchers: Dan Eckhardt, Robert Martin, David Bilyeu, Justin Koo, Samuel Araki

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In-space digital twin vision

High Fidelity M&S Designed to Bridge Ground/Flight Gap



But M&S Only Provides Approximate and Divergent Future State Predictions

Ways Predictive Models become IMPOSSIBLE

- Speed Limits Resolution → Model Errors
- Initial Conditions Uncertain → State Errors
- Open Systems → Boundary Condition Errors
- Chaotic Physics → Trajectories Diverge

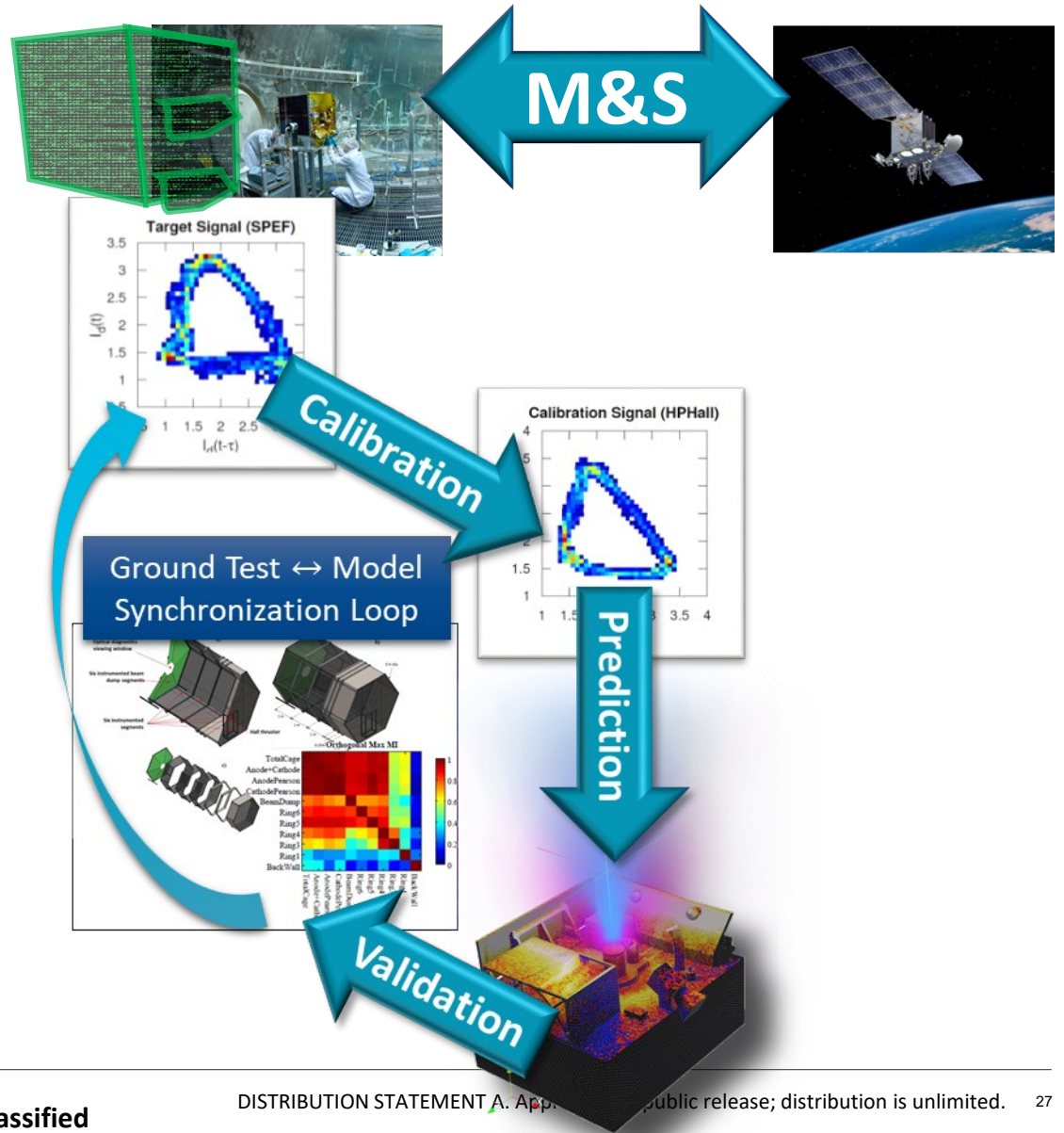
Solution: Realtime Data Assimilation

Researchers: Dan Eckhardt, Robert Martin

In-space digital twin vision

High Fidelity M&S Designed to Bridge Ground/Flight Gap

But M&S Only Provides Approximate and Divergent Future State Predictions



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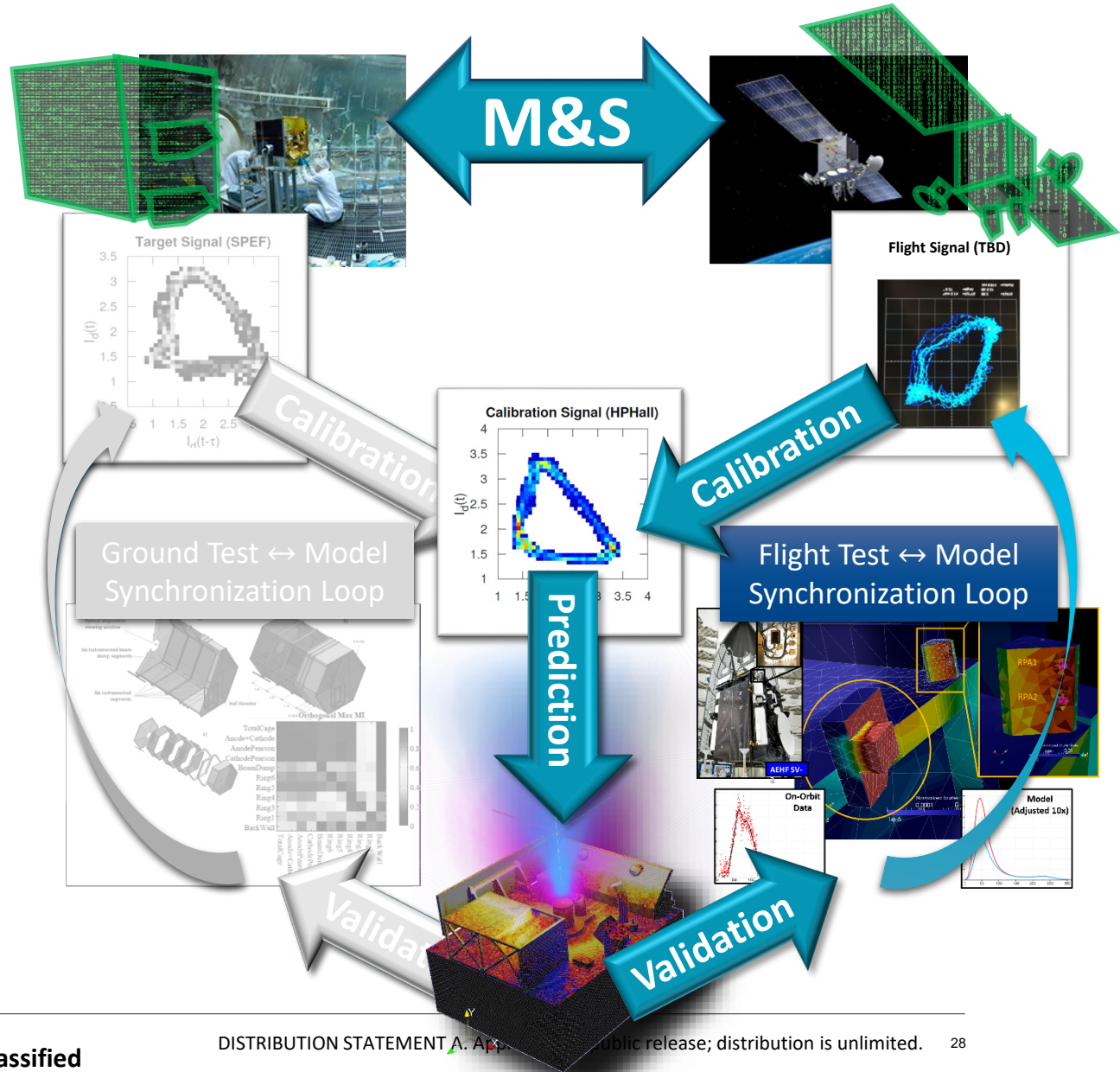
Solution: Realtime Data Assimilation

Researchers: Dan Eckhardt, Robert Martin

In-space digital twin vision

High Fidelity M&S Designed to Bridge Ground/Flight Gap

But M&S Only Provides Approximate and Divergent Future State Predictions



Ways Predictive Models become IMPOSSIBLE

- Speed Limits Resolution → Model Errors
- Initial Conditions Uncertain → State Errors
- Open Systems → Boundary Condition Errors
- Chaotic Physics → Trajectories Diverge

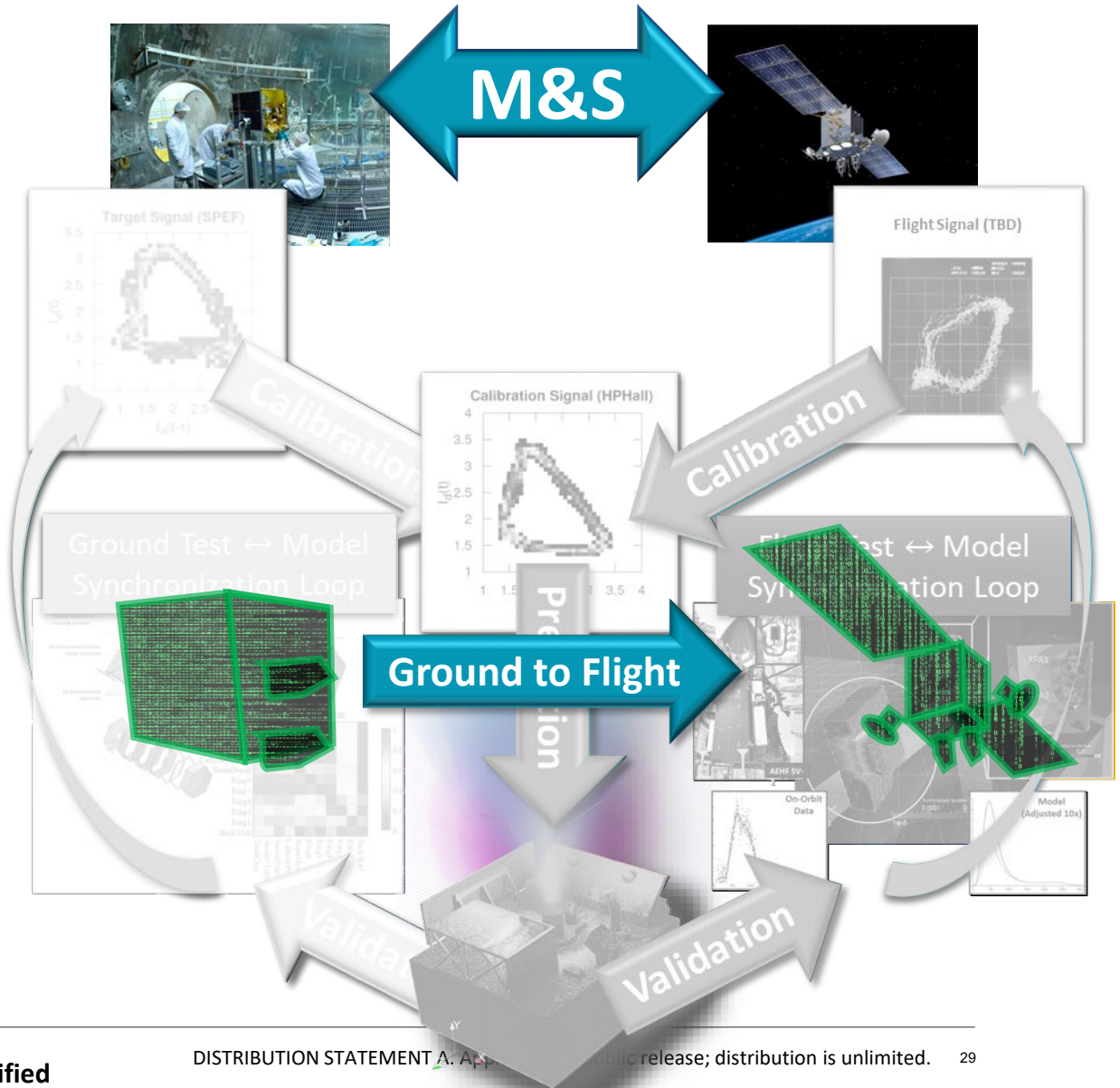
Solution: Realtime Data Assimilation

Researchers: Dan Eckhardt, Robert Martin

In-space digital twin vision

High Fidelity M&S Designed to Bridge Ground/Flight Gap

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Data assimilation

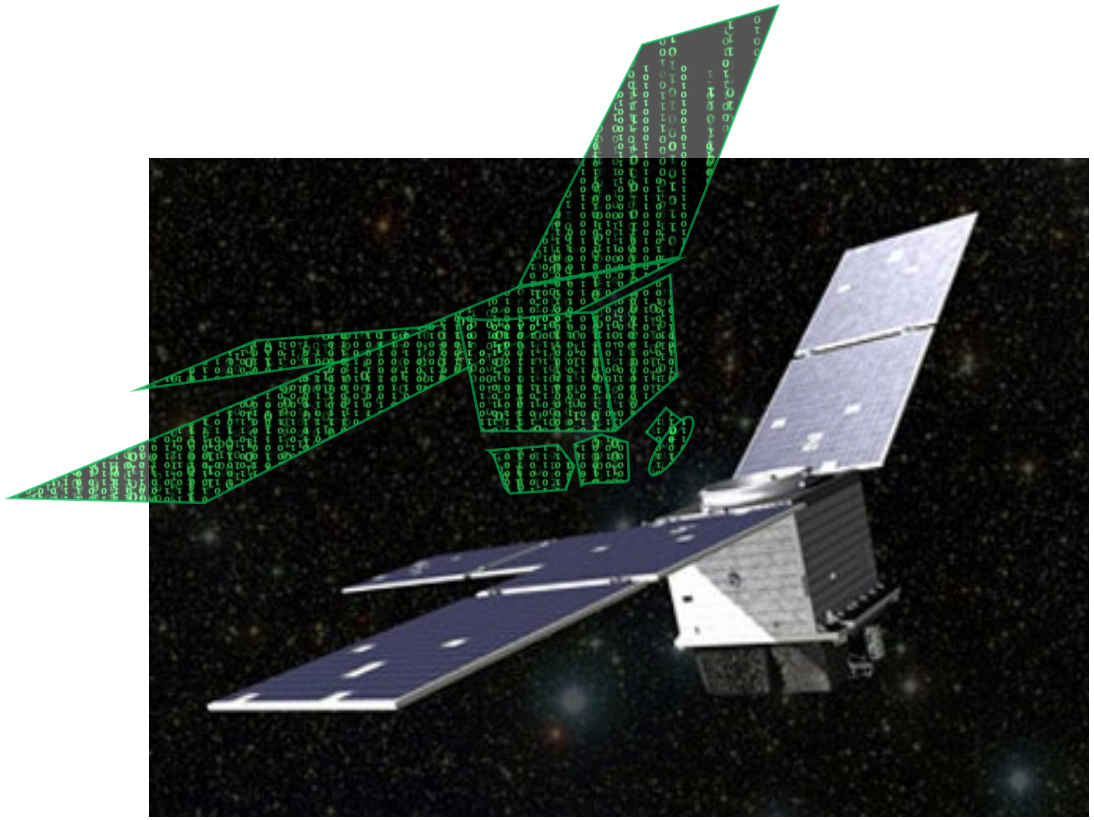
Ingredients:

1) The Model: $\dot{\vec{s}} = f(\vec{s})$

\+ 2) The State: $\vec{s}$

\+ 3) The Observables: $g(\vec{s})$

Digital Twin



(Just Add Data*)

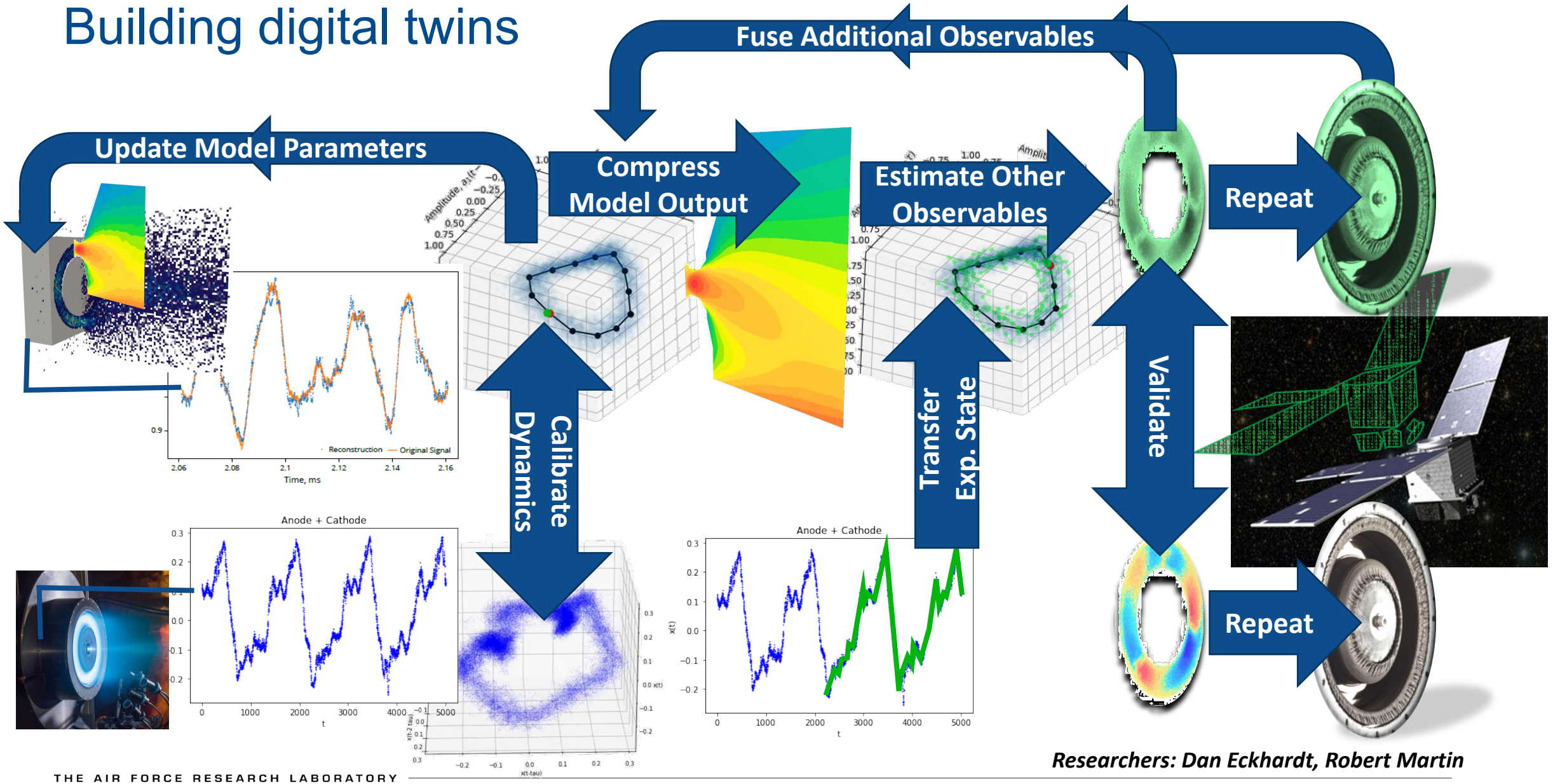
(*Fine Print: Easier Said than Done…)

Researchers: Dan Eckhardt, Robert Martin

Unclassified

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Building digital twins



Researchers: Dan Eckhardt, Robert Martin

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Summary

- Vision for M&S research & development to support next-generation digital engineering tools
- M&S pyramid
  - Utilization of high-fidelity physics-based models to train fast-running engineering models
  - Assimilation of data from experiments, testing and operations to build authoritative virtualization
- Research focus:
  - High-fidelity multi-scale model development
  - Multi-fidelity model development and design optimization
  - Digital twins
  - Data assimilation at all levels of fidelity and scales
- AFRL application areas:
  - Rockets: liquid rockets, rotating detonation engines, solid rocket motors, in-space thrusters
  - Air-breathing: rotating detonation engines, scramjet combustion, swirl combustors, augmentors

Unclassified

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