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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

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

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.

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.

Modeling & Simulations Overview

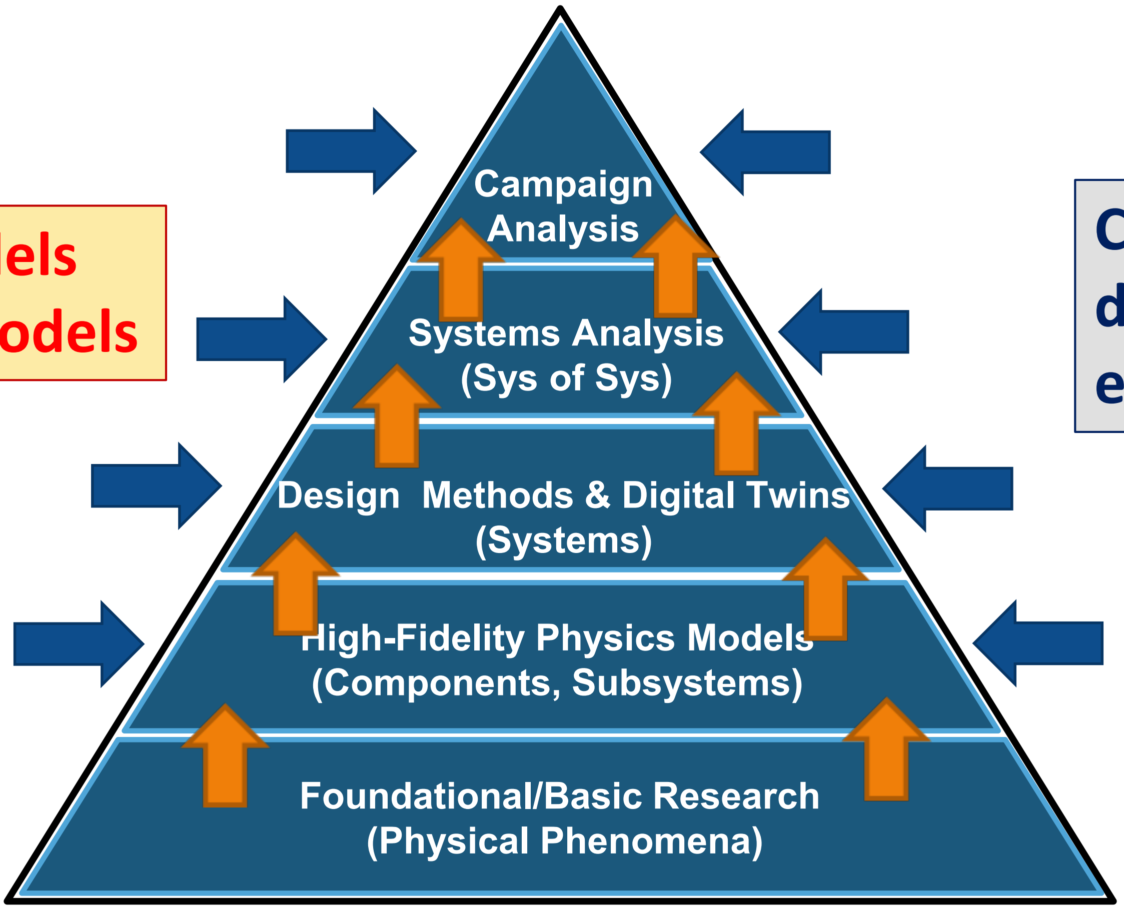
Missions and Systems Analysis involves empirical fast-running models to evaluate systems and system of systems

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

Deconstructing the pyramid

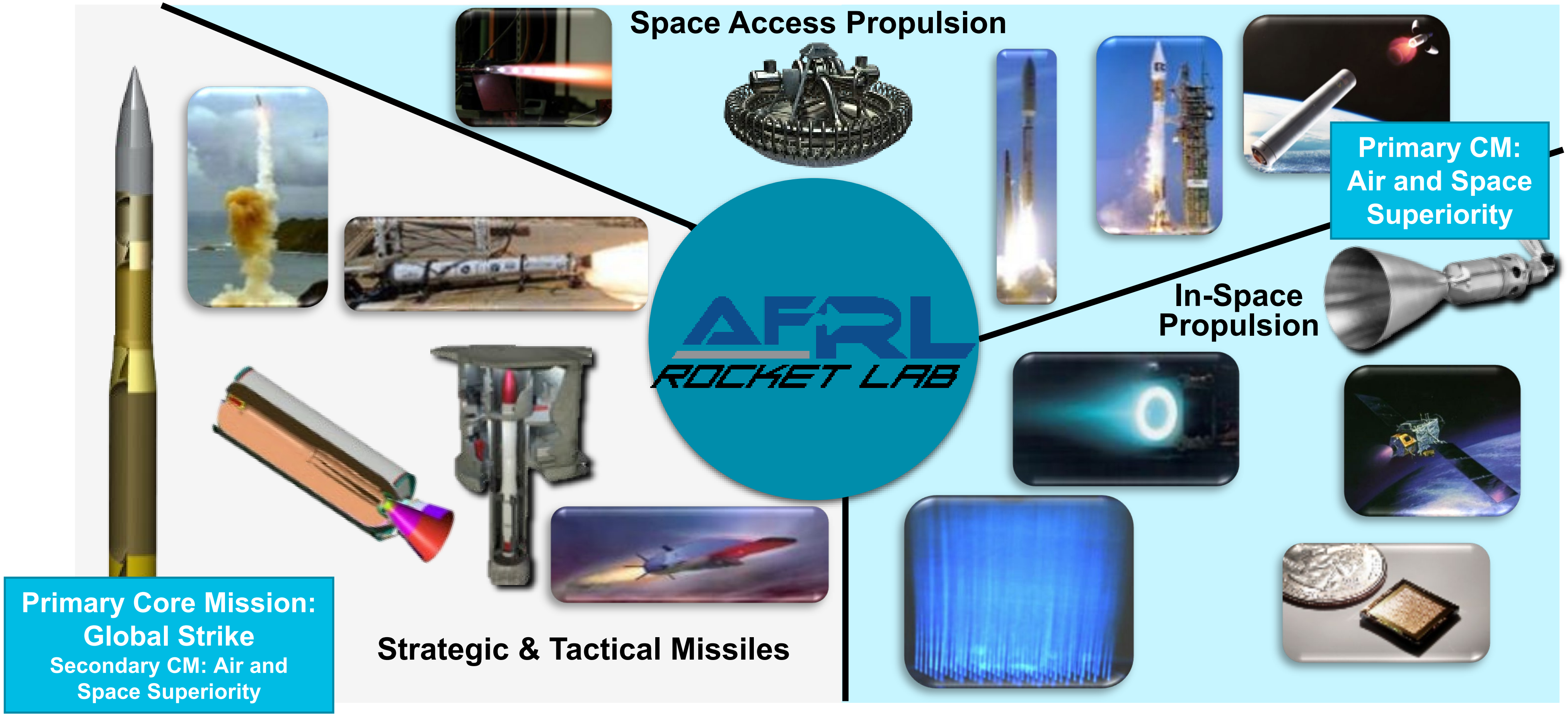
Train fast-running models using higher-fidelity models



Calibrate models with data assimilation from expts/tests/operations

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

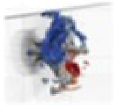
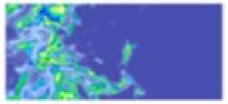
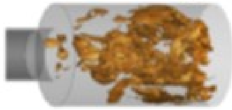
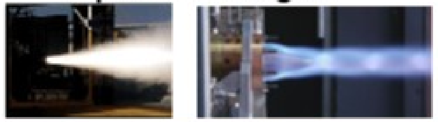
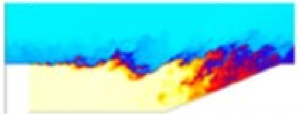
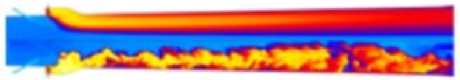
AFRL Rocket Lab



Physics-Based Modeling

Physics-based modeling of combustion dynamics

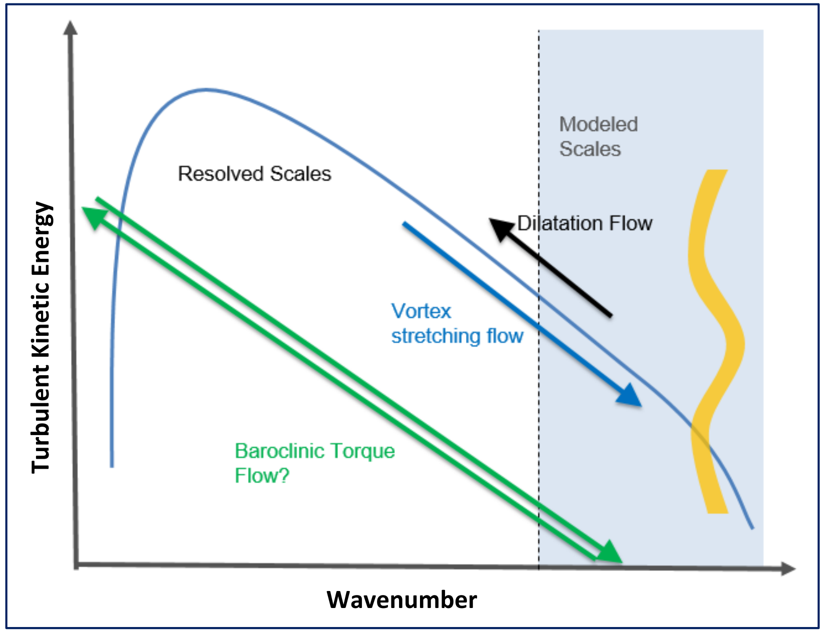
AFRL Turbulent Combustion Initiative

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

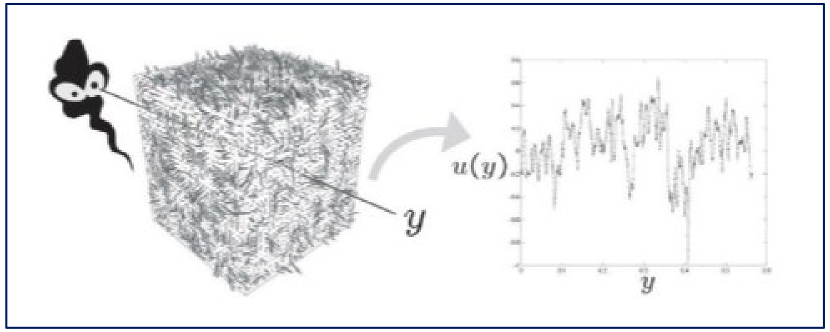
AFOSR funding by Dr. Chiping Li

Energy Cascade



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

Physics & chemistry of turbulent combustion

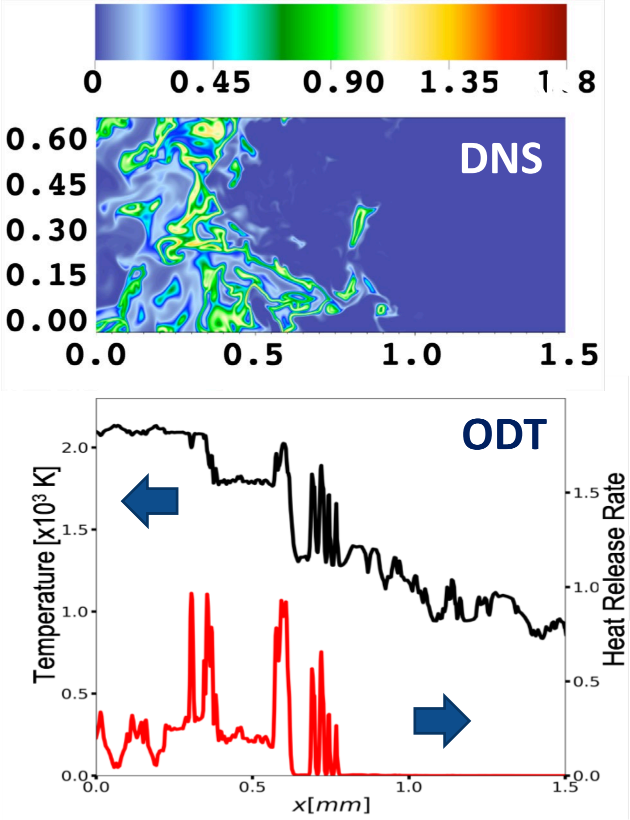


One-Dimensional Turbulence (ODT)

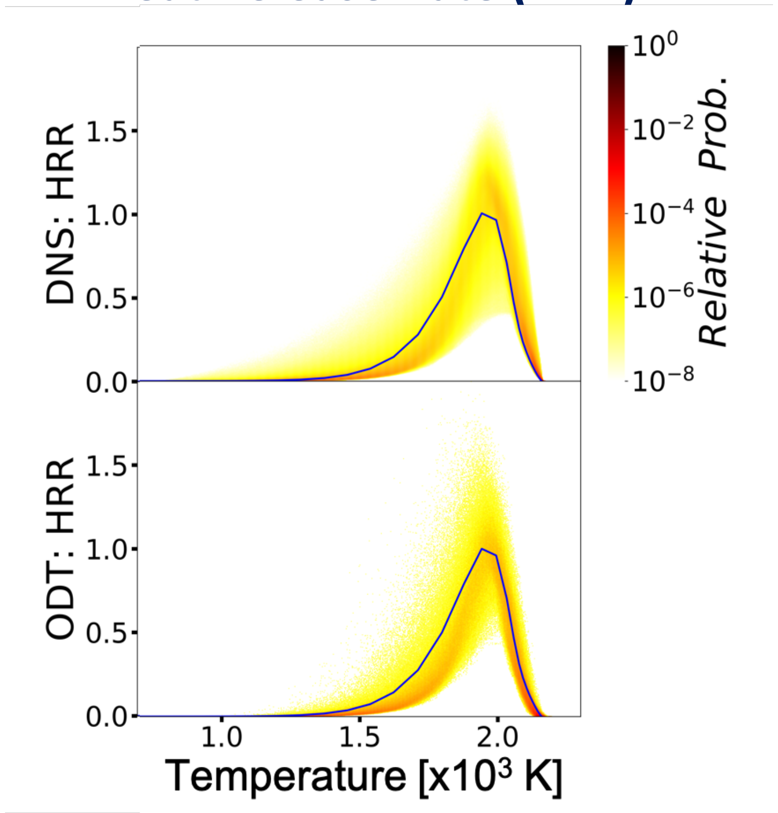
- Develop model as surrogate for Direct Numerical Simulations (DNS)
- Develop ODT-based multi-scale sub-grid closure model

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

Flame Structure



Heat Release Rate (HRR)



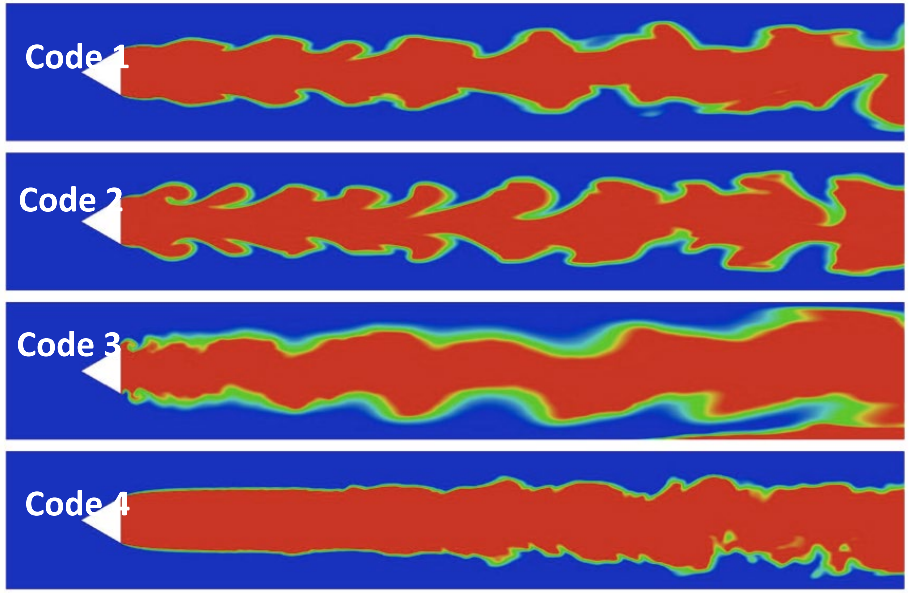
Researchers: Zoltan Jozefik, Matt Harvazinski, Sal Badillo-Rios

Numerics of turbulent combustion

United Technologies Research Center

Implicitly-Filtered LES

Same model, different codes give different results

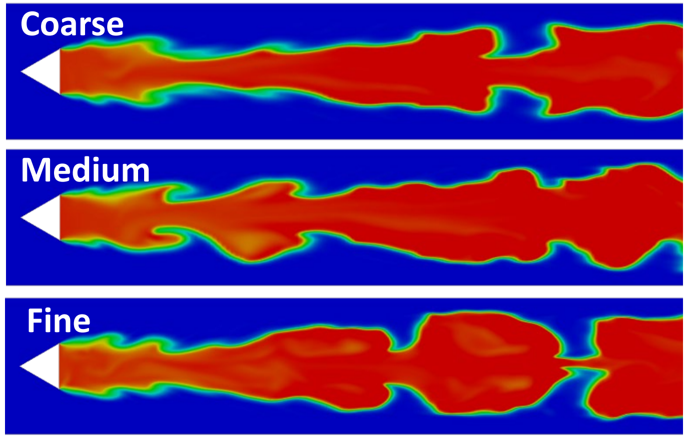


Explicitly-Filtered LES

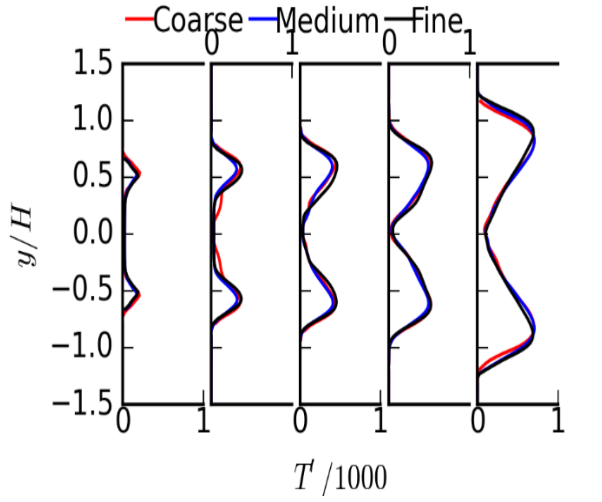
Problem - accuracy depends on grid → **Solution** – eliminate grid dependence

Instantaneous Temperature

Different grids, same filter size



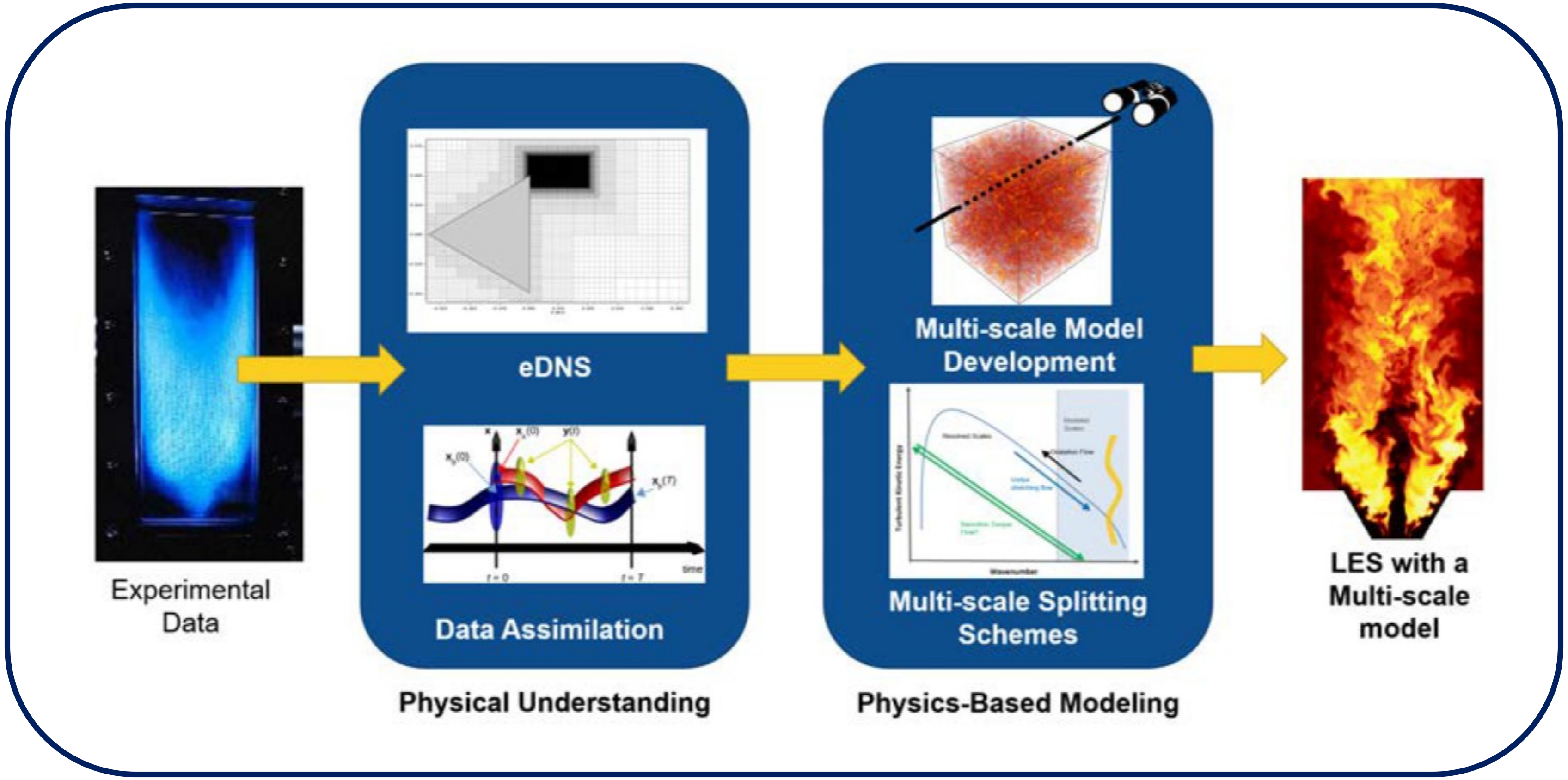
RMS Temperature Fluctuations



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

Model development



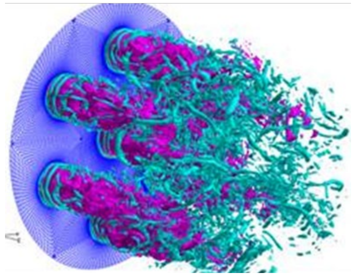
Researchers: Matt Harvazinski, Ramakanth Munipalli, Tim Gallagher, Ayaboe Edoh & Adam Comer

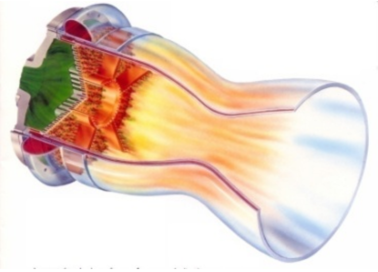
Utilize physics understanding from direct numerical simulations anchored by experimental data to develop multi-scale turbulent combustion closure model

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

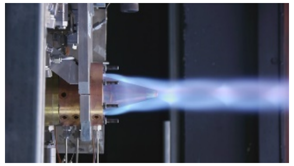
Advanced Liquid Rocket Engine Stability Technology (ALREST)

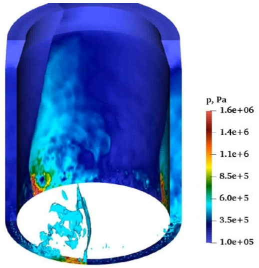
- Developed & successfully transitioned virtual testing capability of liquid rocket engine injectors/chambers to mitigate combustion instabilities via coordinated experimental & computational programs

Rotating detonation rocket engines

Rocket Propulsion Division (RQ)

Rocket (RDRE)





Dr. Eric Paulson
RDRE Lead

Turbine Engine Division (RQ)

Airbreathing

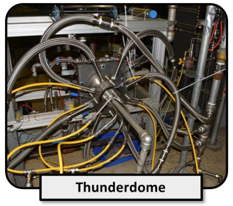
Dr. Alex Schumaker
6.1/Co-6.2 RDE Lead

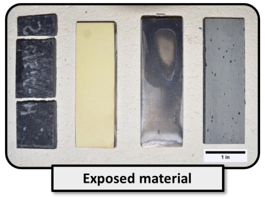
AFOSR: RDE Fundamentals – Physics, Chemistry, Optimization

Dr. Chiping Li & Dr. Martin Schmidt
AFOSR PO

Materials Directorate (RX)

Material Solutions





Dr. Garth Wilks
RDE Material lead

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

Program Partnerships

Sensors - Modeling/Simulation - Experiments

Government

AIR FORCE RESEARCH LABORATORY · AIR FORCE OFFICE OF SCIENTIFIC RESEARCH · NASA

Academia

Purdue Propulsion · GT · UCLA · Michigan · W · University of Central Florida · M

Industry

Opto Knowledge · INSPACE LLC · PSI Physical Sciences Inc. · GHKN LLC · VOX SPACE · Aerojet Rocketdyne · Virgin Orbit

Multi-Fidelity Modeling

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

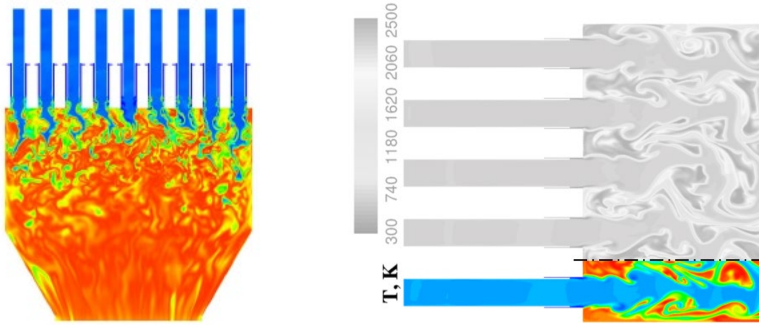
University Collaborators

Aerospace Engineering, University of Michigan
Purdue Aeronautics & Astronautics
Texas, 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

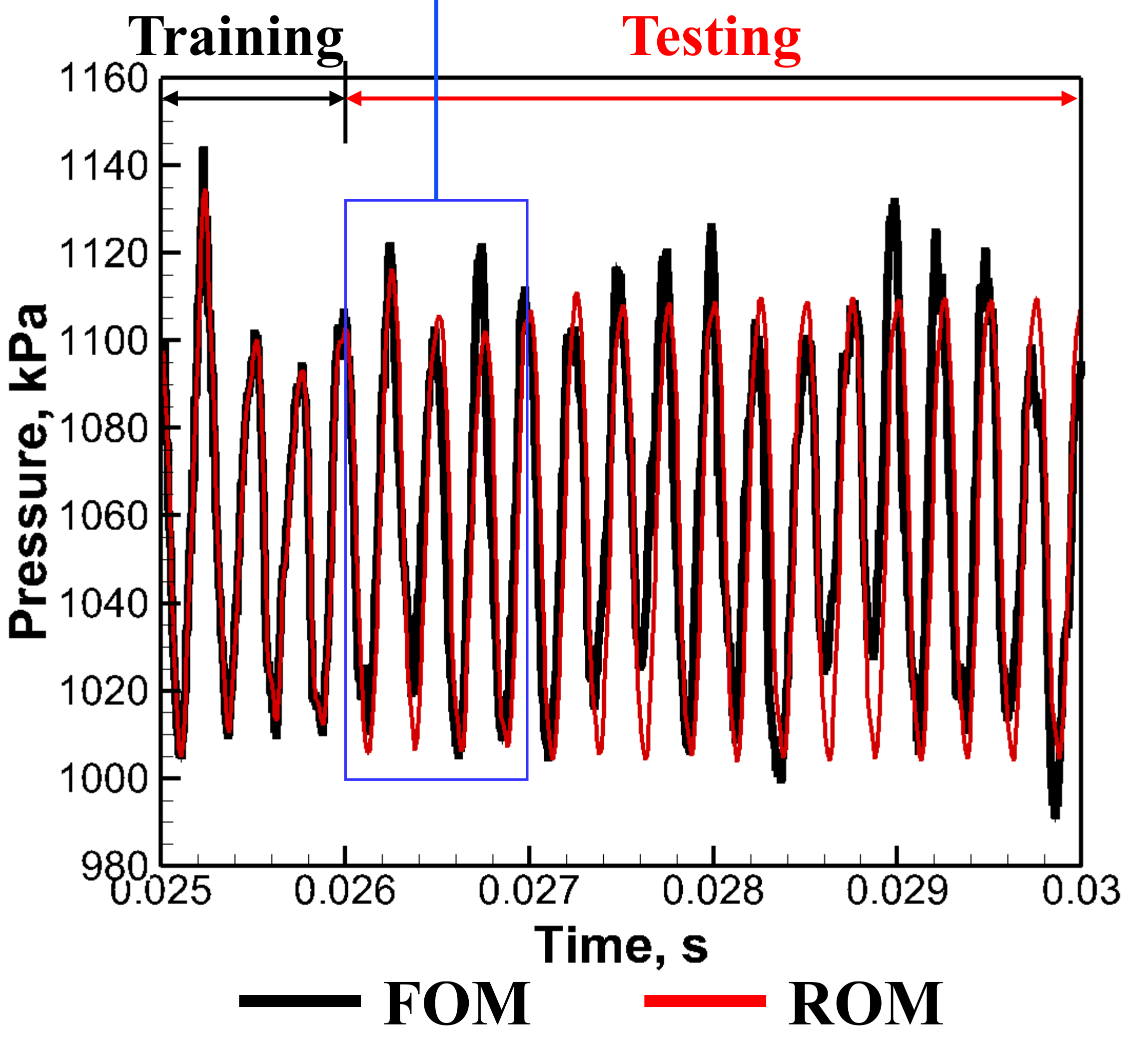


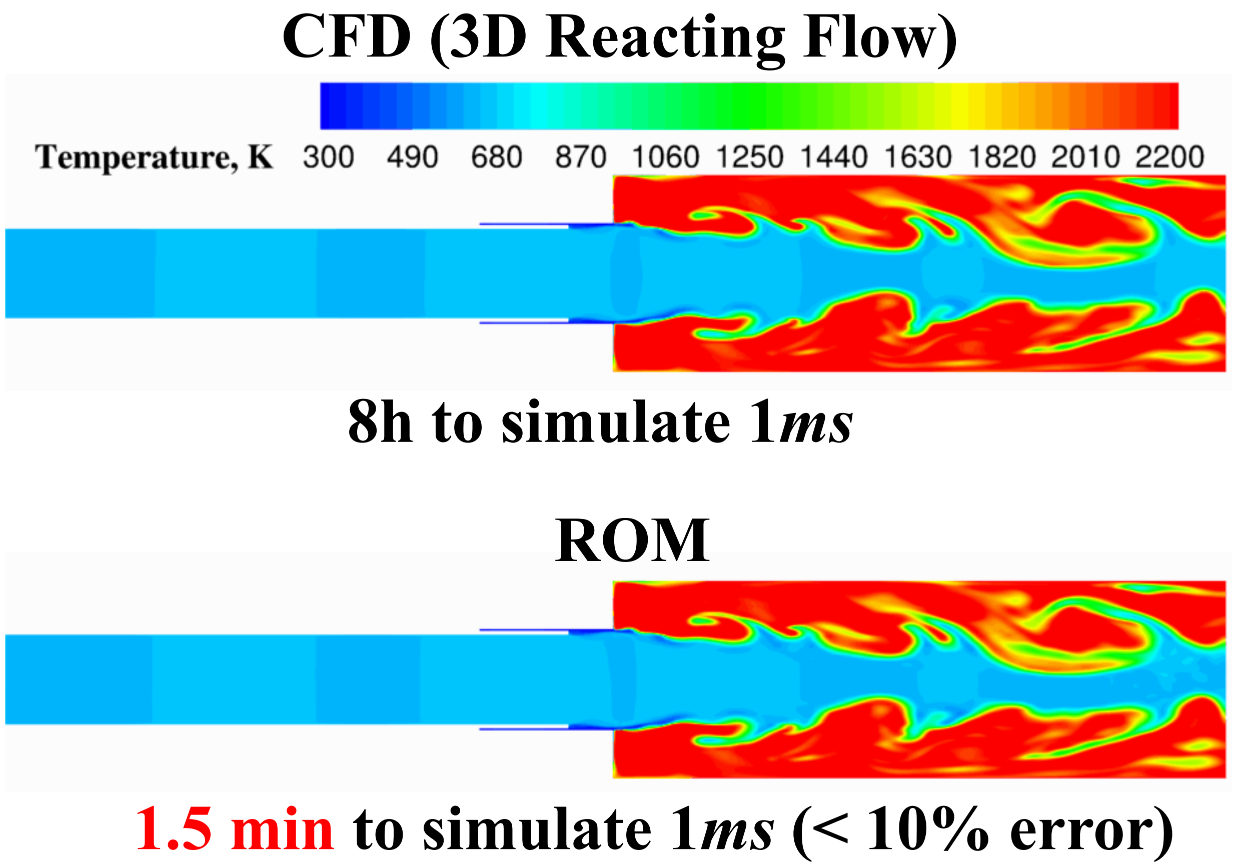
Data-driven Reduced Order Models (ROMs)
Network of reduced models for multi-element rocket chambers

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

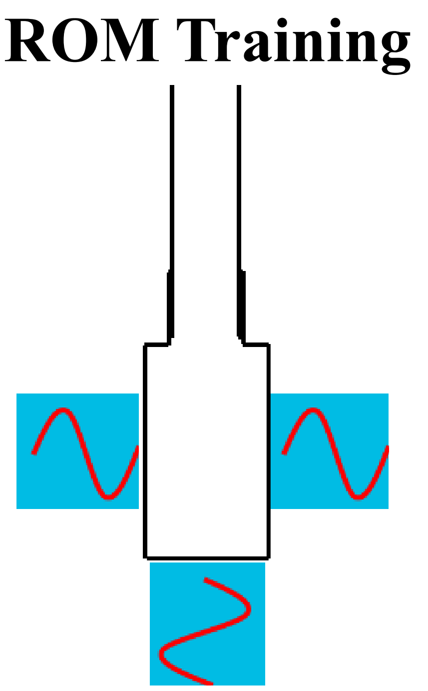
Reduced order modeling



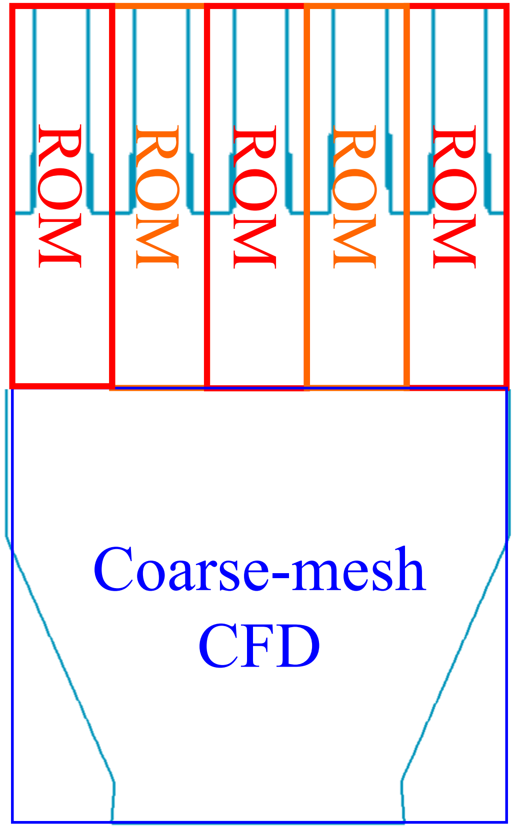


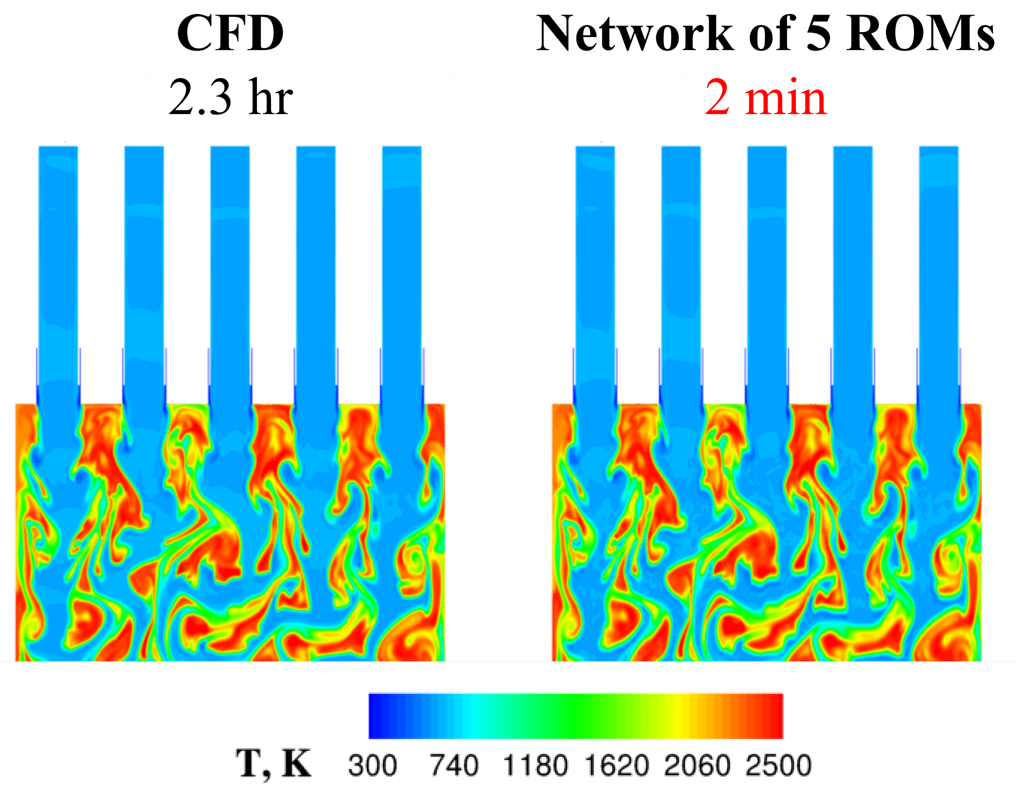
Researcher: Cheng Huang (Univ of Mich)

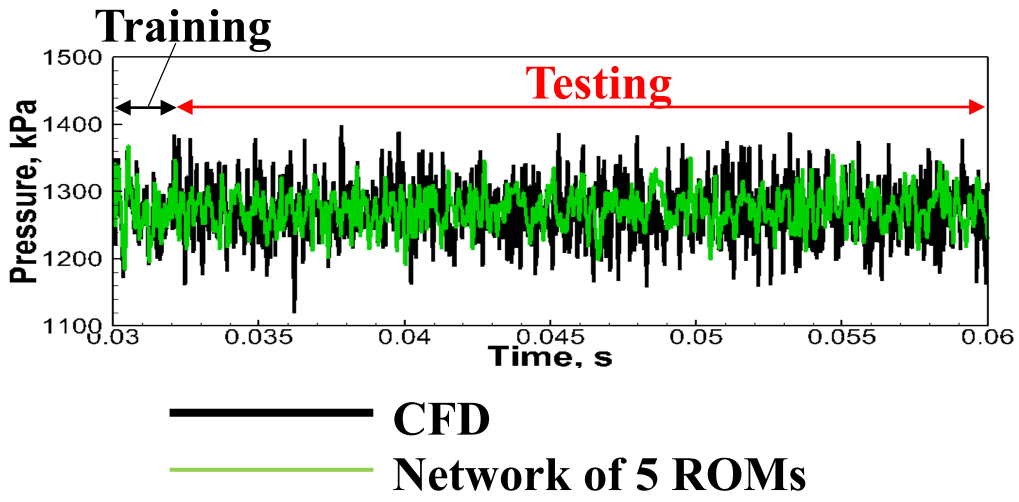
Network of ROMs



Researcher: Cheng Huang (Univ of Mich)

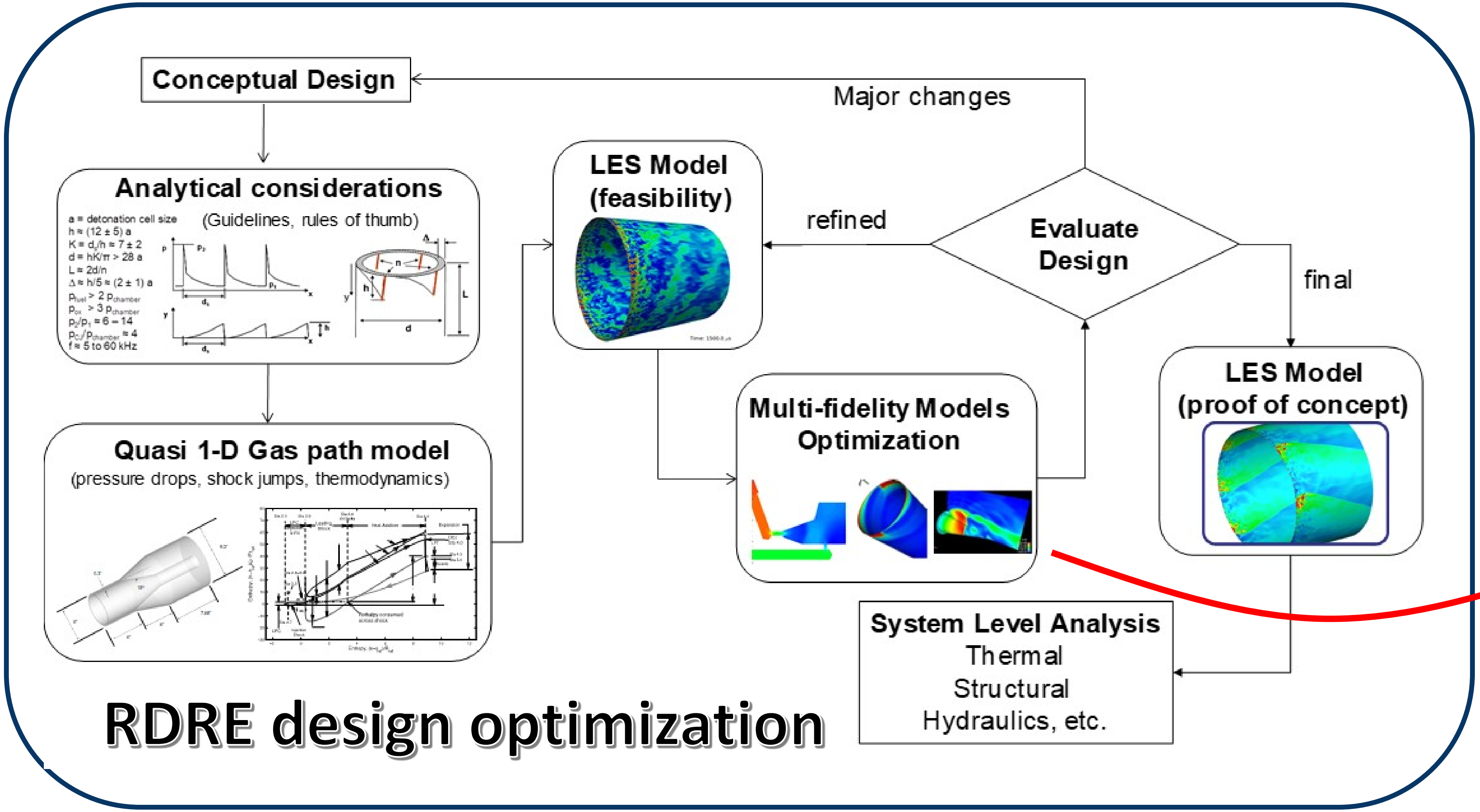






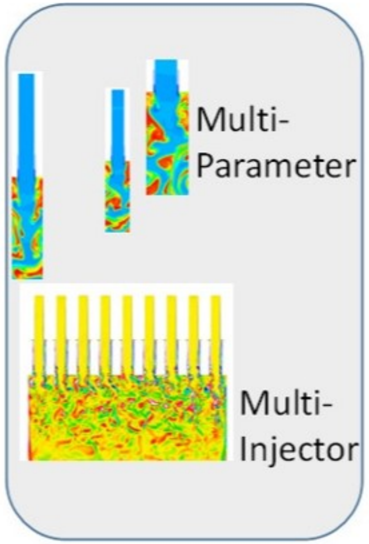
- ROM trained with **2ms** data produces reasonable predictions of unseen dynamics for **28ms**

Multi-fidelity design



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

Reduced Order Models

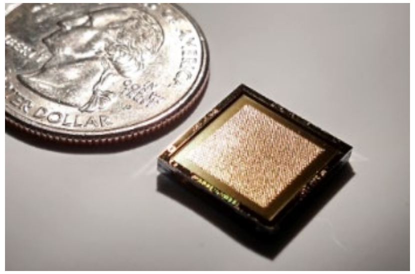


Ramakanth Munipalli, Ananda Himansu

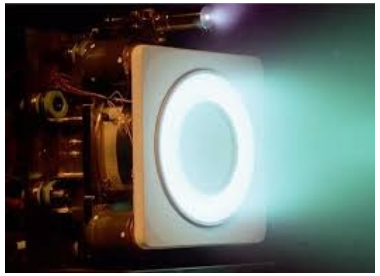
Digital Twins

In-Space Propulsion Portfolio

High Efficiency EP thruster technology

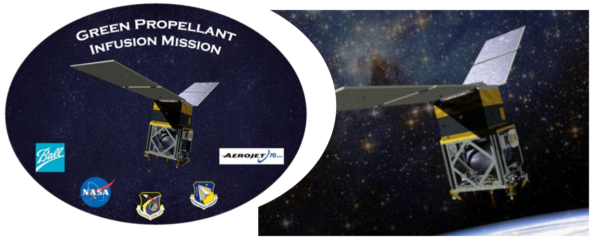


Low power (<100W)
Electrospray



High Power (>1 kW)
HET

ASCENT monopropellant thruster maturation



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

2012: DOT Assigned 1.4 Hazard Classification
2015: MILSPEC approved

Discovery → *Basic Science* → *2000s* *Applied R&D* → *2010s* *Dev & Test* → *2020s* *Space Demos*

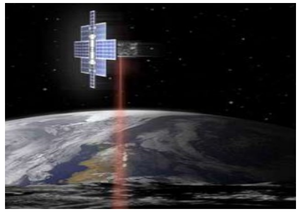
1997: Initial ASCENT Formulation

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

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



Physics-based modeling

Thermophysics Universal Research Framework (TURF)

Spacecraft-Plume Interaction: (Legacy COLISEUM Capability)

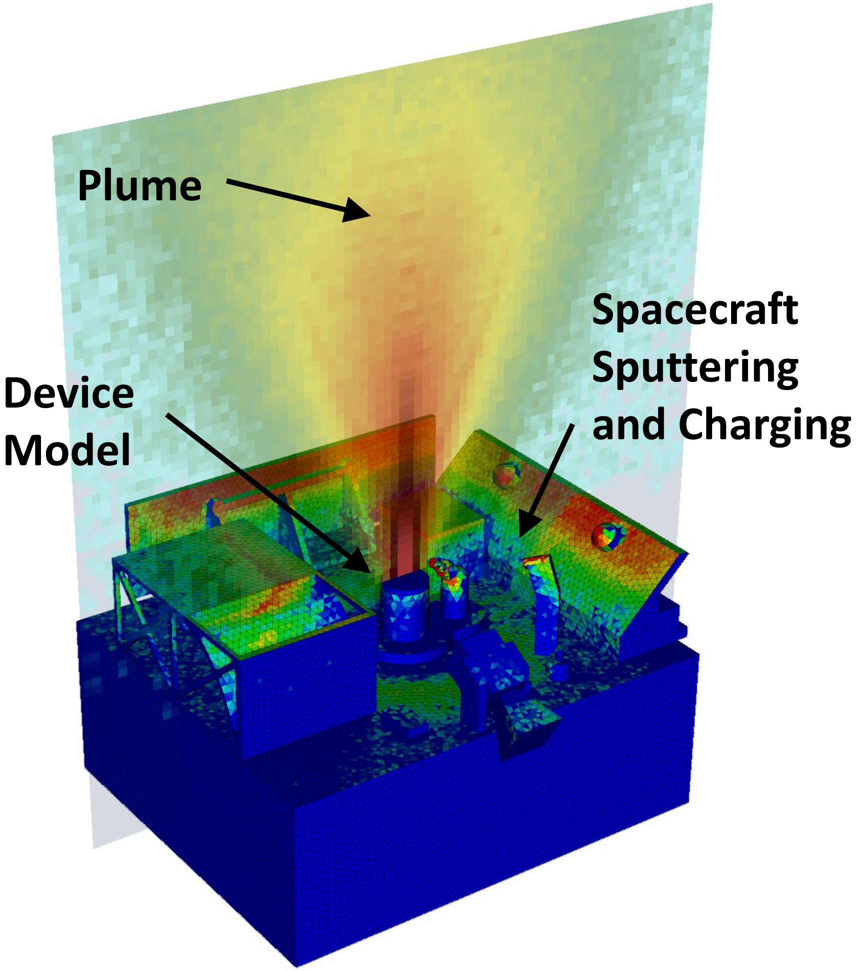
- Detailed DSMC/MCC Charge Exchange (CEX) Models
- Detailed Surface Sputter and Redeposition Models
- Thermalized Potential and Hybrid Boltzmann Electrons
- Detailed Fluid Electrons (Beta)

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

In-space digital twin vision

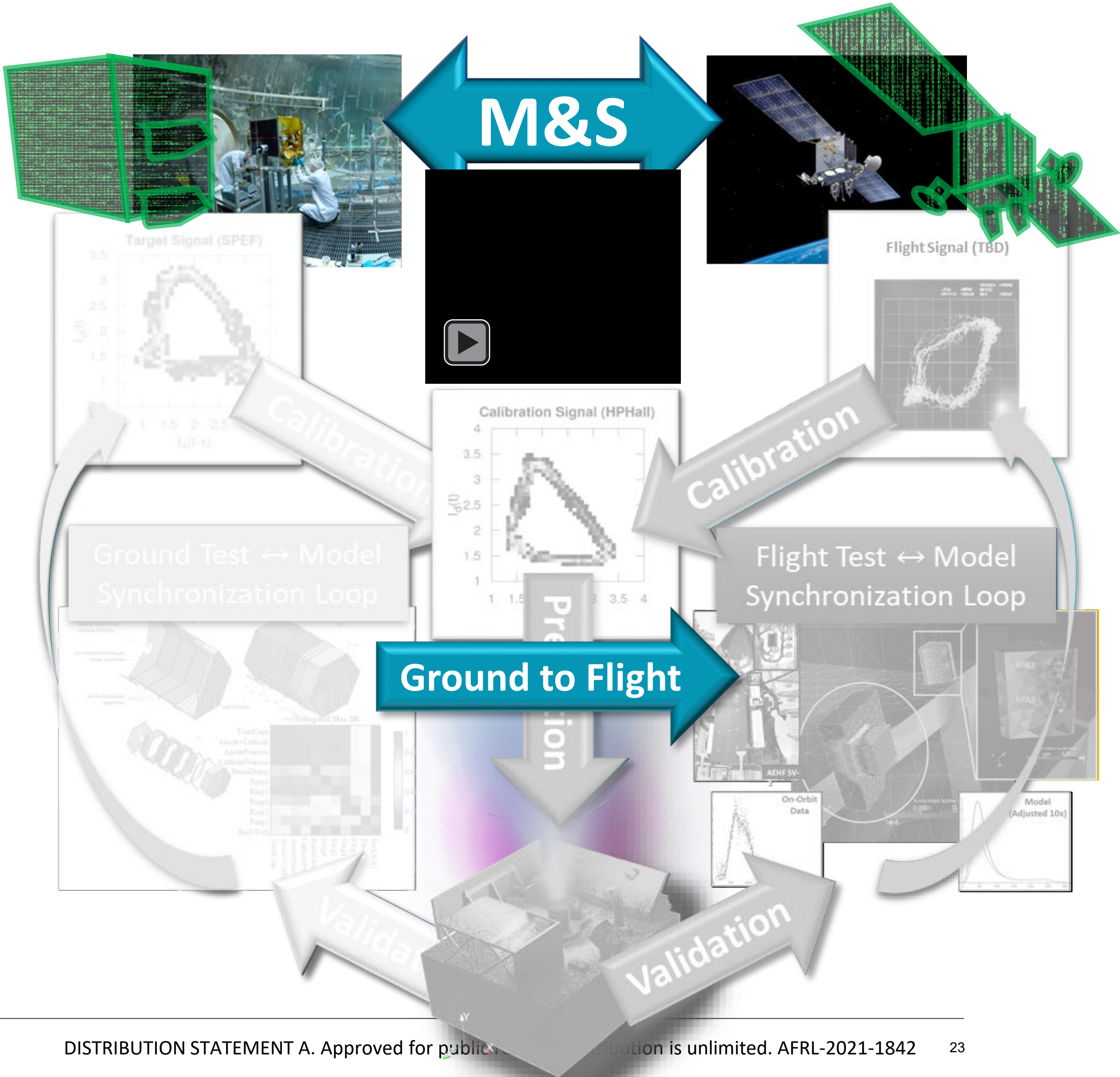
High Fidelity M&S Designed to Bridge Ground/Flight Gap

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

<u>Ways Predictive Models become IMPOSSIBLE</u>

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

<u>Solution</u>: Realtime Data Assimilation



Researchers: Dan Eckhardt, Robert Martin

Data assimilation

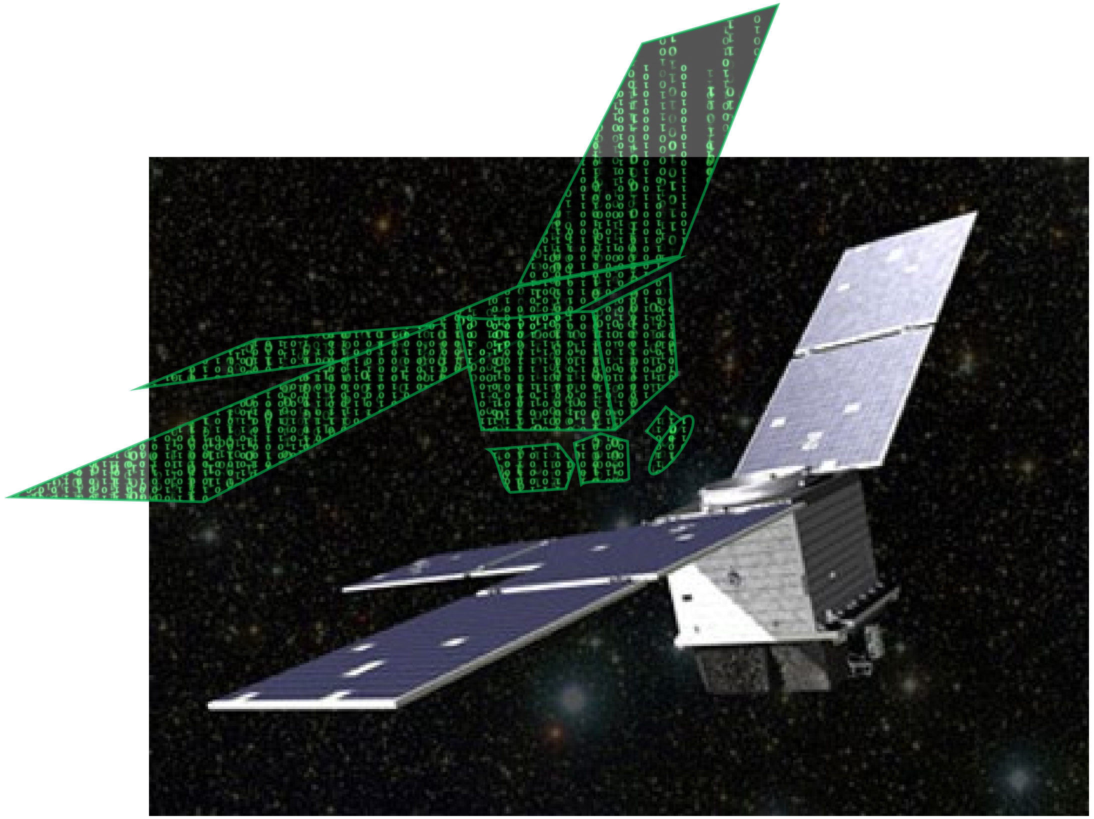
Ingredients:

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

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

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

Digital Twin

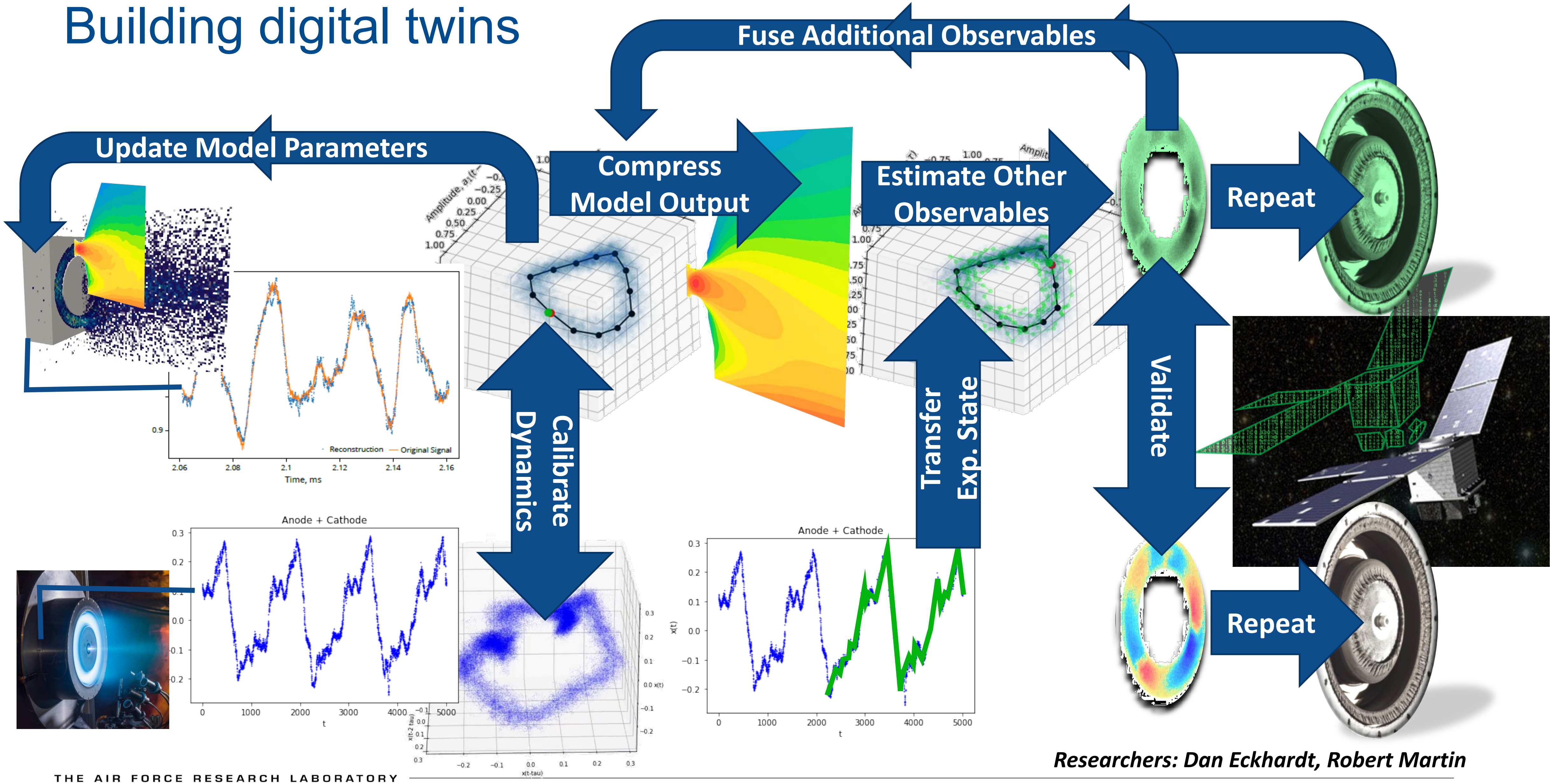


(Just Add Data*)

(*Fine Print: Easier Said than Done…)

Researchers: Dan Eckhardt, Robert Martin

Building digital twins



Researchers: Dan Eckhardt, Robert Martin

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