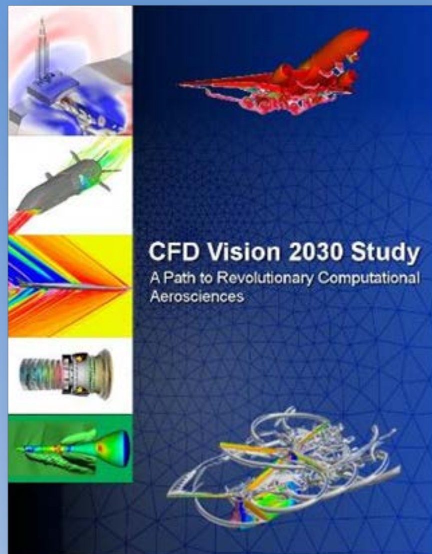
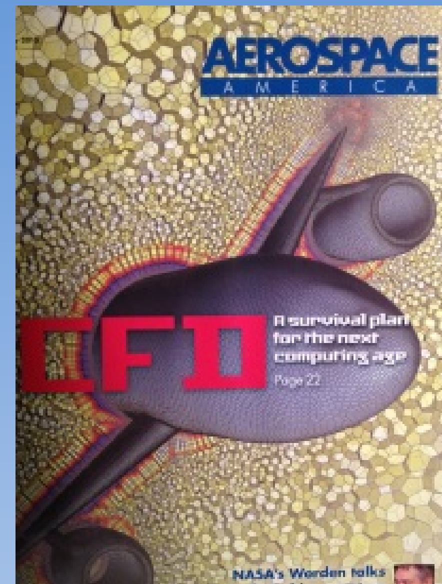
CFD Vision 2030 and its Implementation





"A Survival Plan for the Next Computing Age"

AIAA Aviation 2017

Denver, CO

June 7, 2017

Michael M. Rogers

Manager, Transformational Tools & Technologies (T^3) Project

Mujeeb R. Malik

Technical Lead, Revolutionary Computational Aerosciences (RCA)

Transformative Aeronautics Concepts Program

PROGRAM

GOAL:

- Cultivate concepts and technologies in all thrusts to enable aviation transformation

OBJECTIVES:

- ***Support and challenge*** strategic & tactical planning via early convergent innovation
- Provide ***transformative advancements*** within single disciplines and advanced methods

APPROACH:

- Provide environment to explore feasibility
- ***Explore never-done-before tools***
- Invest in advanced technologies
- ***Challenge external communities***
- Converging advancements in aeronautics and non-aeronautics sectors

PROJECTS

Convergent Aeronautics Solutions (CAS) Project

Performs rapid feasibility assessments of early-stage aeronautics innovations that challenge existing technical approaches, create alternate paths to solutions, or enable new strategic outcomes.

Transformational Tools and Technologies (T^3) Project

Performs deep-discipline research and development of first-of-a-kind capabilities to analyze, understand, predict, and measure performance of aviation systems; research and development of "tall-pole" technologies; all of which enables design of advanced aeronautics systems.

University Innovation and Challenges (UIC) Project

Addresses complex challenges in the strategic outcomes via independent, alternate path, multi-disciplinary University-led research projects; excites external community innovation to help fill-in the most difficult gaps via prizing.

T^3 SUB-PROJECTS

Revolutionary Tools and Methods

Development of revolutionary comprehensive physics-based aeronautics analysis and design capability. Philosophically based on Vision 2030 study recommendations

Critical Aeronautics Technologies

Development of critical aeronautics technologies that can enable revolutionary improvement in aircraft system design. Innovative ideas that may lead to patentable results.

Outline

- **CFD Vision 2030 Study Summary**
  - Objectives
  - The Vision
  - Grand Challenge Problems
  - Roadmap
  - CFD 2030 activities since report release
- **T^3 Technical Challenges supporting CFD Vision 2030**
  - Revolutionary Tools & Methods Sub-Project
  - Revolutionary Computational Aerosciences (RCA)
  - Multidisciplinary Design, Analysis, and Optimization (MDAO)
  - Combustion Modeling
- **Implementation Plan, Going Forward**
- **Summary**

CFD Vision 2030 Study Summary

The Study Objectives

- **CFD Vision 2030, an "N+3" Class Study** aimed at developing a comprehensive and enduring vision of future CFD technology and capabilities :
  - "…provide a **knowledge-based forecast** of the future computational capabilities required for **turbulent, transitional, and reacting flow simulations**…"
  - "…and to lay the foundation for the **development of a future framework/environment** where physics-based, accurate predictions of **complex turbulent flows, including flow separation**, can be accomplished routinely and efficiently in cooperation with **other physics-based simulations to enable multi-disciplinary analysis and design**."

Vision 2030 Team Members

NASA Technical Monitors – **Mujeeb Malik/Bil Kleb**

Jeffrey Slotnick
Principal Investigator
Boeing Research & Technology

Abdi Khodadoust
Project Manager
Boeing Research & Technology

Juan Alonso
Stanford University

David Darmofal
Massachusetts Inst. Of Technology

William Gropp
National Center for Supercomputing Applications

Elizabeth Lurie
Pratt & Whitney – United Technologies

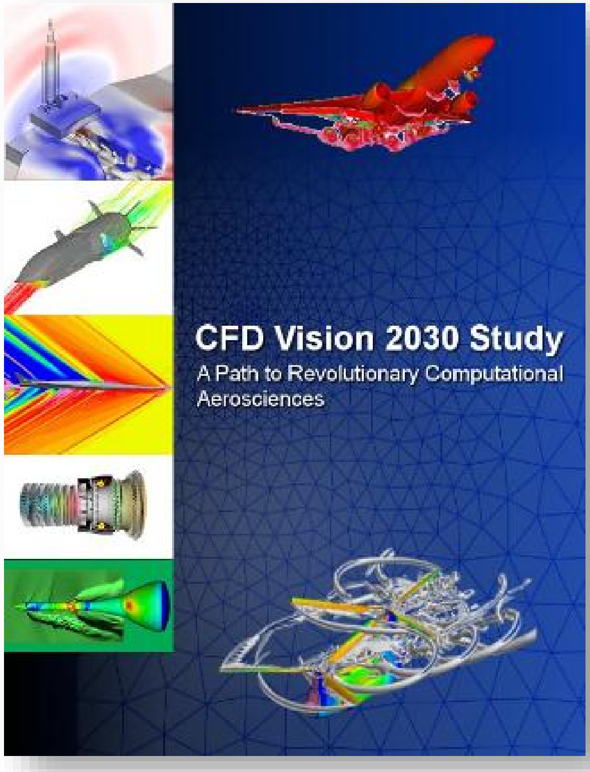
Dimitri Mavriplis
University of Wyoming

Extended Vision 2030 Team:

- **Joerg Gablonsky, Mori Mani, Robert Narducci, Philippe Spalart, and Venkat Venkatakrishnan** – *The Boeing Company*
- **Robert Bush** – *Pratt & Whitney*

CFD Vision 2030 Study Report

- **Elements of the study effort:**
  - Define and develop CFD requirements
  - Identify the most critical gaps/impediments
  - Create the vision
  - Develop a long-term, actionable research plan and detailed technology development roadmap
- **Report published March 2014**
- **Wide community support for the research roadmap, as evidenced by articles in Aerospace America, Aviation Week & Space Technology, The Connector, Science Daily, as well as speaking invitations from DoE and Pointwise.**



NASA CR 2014-218178

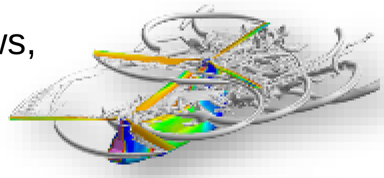
- **Report recommendations inform T^3 project planning**

Report available at:
https://www.nasa.gov/aeroresearch/programs/tacp/ttt/cfd-vision-2030-study

Vision of CFD in 2030

- **Emphasis on physics-based, predictive modeling**

  Transition, turbulence, separation, unsteady/time accurate, chemically-reacting flows, radiation, heat transfer, acoustics and constitutive models, among others.



- **Management of errors and uncertainties**

  Quantification of errors and uncertainties arising from physical models (epistemic), mesh and discretization, and natural variability (aleatory) and their effect on important engineering quantities of interest.

- **A much higher degree of automation in all steps of the analysis process**

  Geometry creation, meshing, large databases of simulation results, extraction and understanding of the vast amounts of information generated with minimal user intervention.

- **Ability to effectively utilize massively parallel HPC architectures that will be available in the 2030 time frame**

  Multiple memory hierarchies, latencies, bandwidths, programming paradigms and runtime environments, etc.

- **Flexible use of HPC systems**

  Capacity- and capability-computing tasks in both industrial and research environments.

- **Seamless integration with multidisciplinary analyses**

  High fidelity CFD tools, interfaces, coupling approaches, etc.

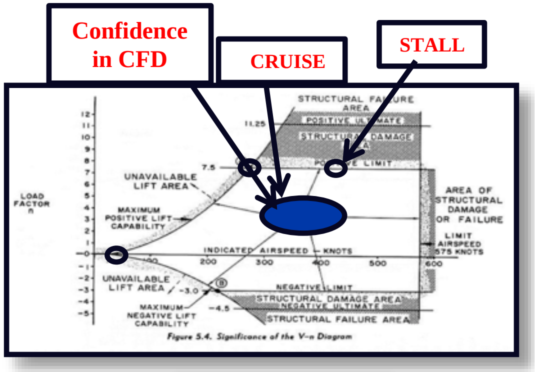
Physics-based tools required for timely analysis/design of novel configurations.

Grand Challenge Problems

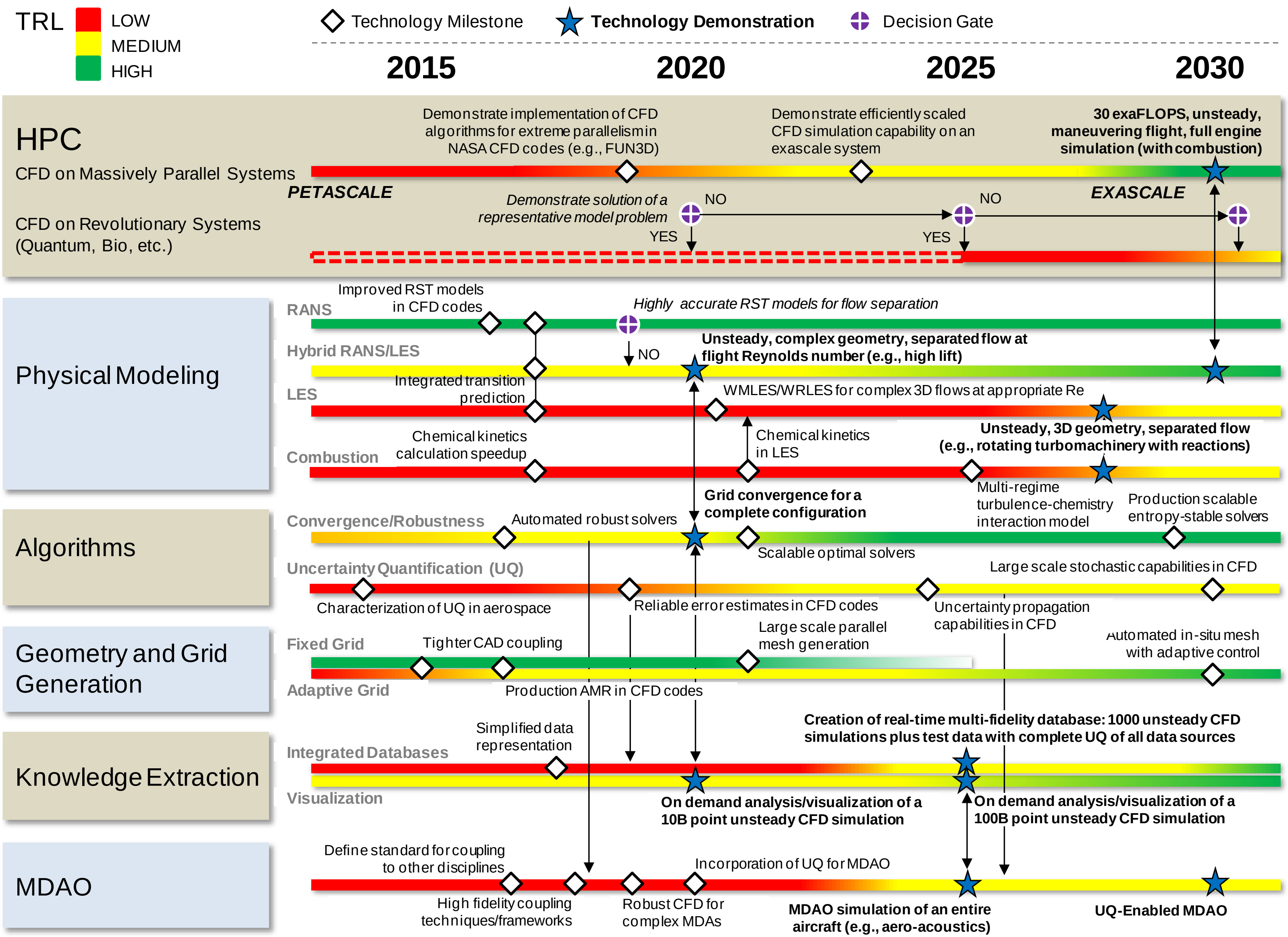
- **Highlight critical step changes needed in engineering design capability**
- **May not be routinely achievable by 2030**
- **Represent key elements of major NASA missions**

Credit: The Boeing Company

1. Large Eddy Simulation (LES) of a powered aircraft configuration across the full flight envelope
2. Off-design turbofan engine transient simulation
3. Multi-Disciplinary Analysis and Optimization (MDAO) of a highly-flexible advanced aircraft configuration
4. Probabilistic analysis of a powered space access configuration



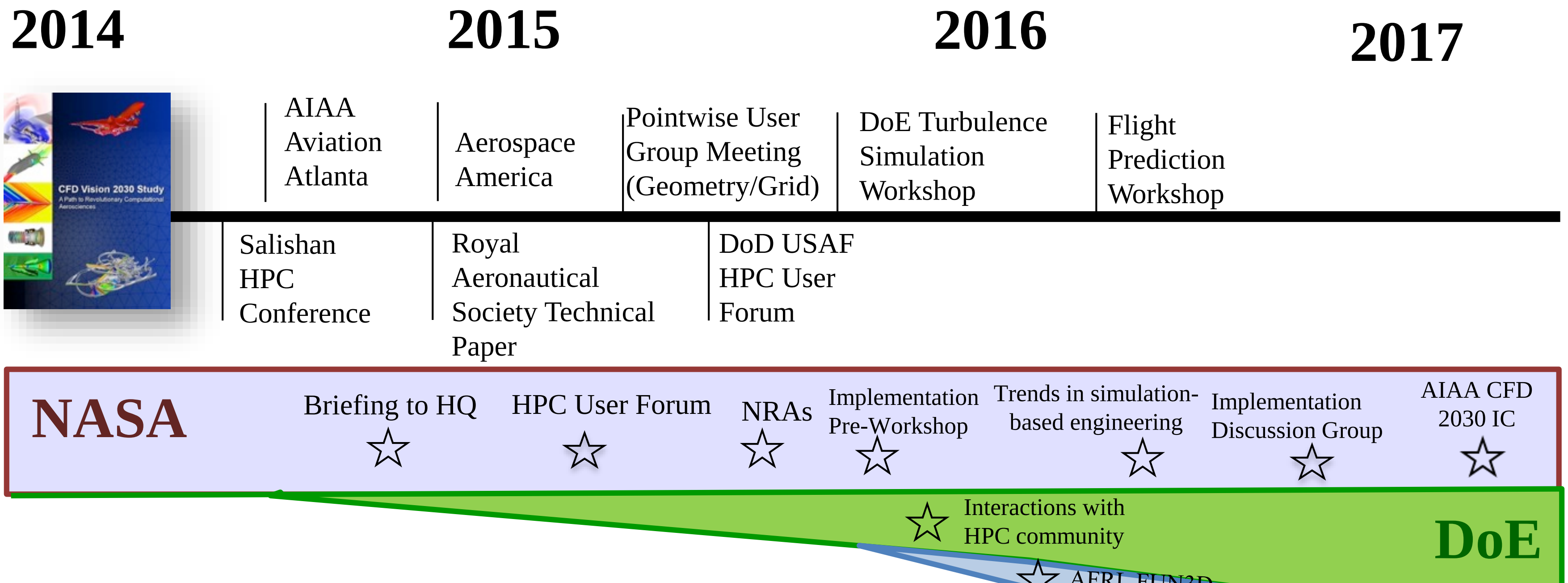
Technology Development Roadmap



CFD Vision 2030 Recommendations

1. NASA should develop, fund and sustain a base research and technology (R/T) development program for simulation-based analysis and design technologies.
2. NASA should develop and maintain an integrated simulation and software development infrastructure to enable rapid CFD technology maturation.
3. HPC systems should be made available and utilized for large-scale CFD development and testing.
4. NASA should lead efforts to develop and execute integrated experimental testing and computational validation campaigns.
5. NASA should develop, foster, and leverage improved collaborations with key research partners and industrial stakeholders across disciplines within the broader scientific and engineering communities.
6. NASA should attract world-class engineers and scientists.

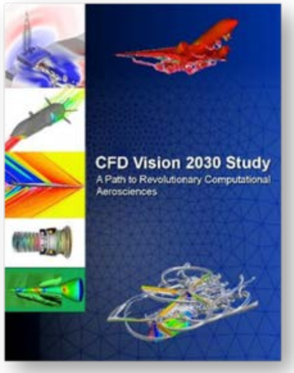
CFD 2030 Activities Since Report Release



- Steady, significant progress in socializing CFD Vision 2030 message to aerospace and science communities
- AIAA CFD 2030 Integration Committee is intended to engage both traditional and non-traditional (e.g., applied math, computer scientists) stakeholders in aerospace

AIAA CFD Vision 2030 Integration Committee

Goal: Create a community of practice to advance CFD Vision 2030



Approach

Establish a CFD Vision 2030 Integration Committee (CFD2030 IC) to advocate for, inspire, and enable community activities recommended by the CFD Vision 2030 Study for revolutionary advances in the state-of-the-art of computational technologies needed for the analysis, design, certification, and qualification of future aerospace systems.

Proposed Charter Statement

The CFD Vision 2030 Integration Committee (CFD2030 IC) will establish and promote a community of practice engaged in developing methods, models, physical experiments, software, and hardware for revolutionary advances in computational simulation technologies for analysis, design, certification, and qualification of aerospace systems. The CFD2030 IC serves as the focal point for activities to achieve the 2030 Vision by leveraging and integrating enabling technologies such as high performance computing, physical modeling, numerical methods, geometry/grids, validation quality experiments, and multidisciplinary analysis and optimization, with quantified uncertainty. The CFD2030 IC will communicate with technical committees to assure that the AIAA membership engages with their peers and external non-AIAA constituencies in shaping the future of the simulation-based engineering.

T^3 Technical Challenges supporting CFD Vision 2030

Revolutionary Tools & Methods Sub-Project

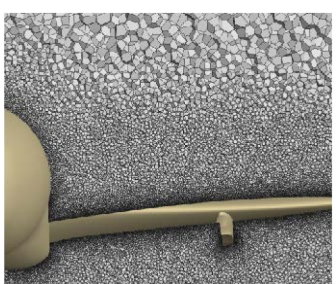
Development of revolutionary comprehensive physics-based aeronautics analysis and design capability, based on Vision 2030 study recommendations.

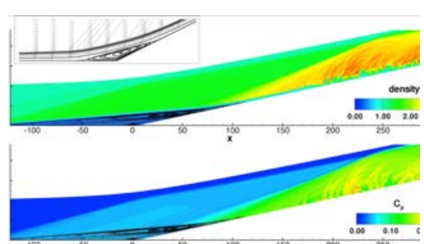
Technical Challenges (TCs)	Roadmap Swim Lanes Supported
Physics-Based Turbulence Models & Simulations (2018): Identify and downselect critical turbulence, transition, and numerical method technologies for 40% reduction in predictive error against standard test cases for turbulent separated flows, evolution of free shear flows, and shock-boundary layer interactions on state-of-the-art high performance computing hardware.	**Physical Modeling:** 1. Advanced RANS 2. Large eddy simulation (LES) 3. Hybrid RANS/LES approaches 4. Validation experiments for turbulence and transition **Algorithms:** 1. High-order entropy stable numerical schemes 2. Uncertainty quantification 3. Adjoint-based methods for sensitivity analysis
MDAO (2022): Develop advanced design and optimization tools for coupled multidisciplinary analysis with a range of fidelities to shorten the design cycle of revolutionary new vehicles. Use X-Plane ground and flight test data to validate the implementation of critical physics required to model new concept aircraft.	**MDAO:** 1. Aero-structural, propulsion-airframe integration 2. Perception-influenced acoustic design 3. Reduced order models development 4. Mixed fidelity optimization 5. High-fidelity MDAO 6. OpenMDAO framework development
Combustion Modeling (2022): Predict the sensitivity of lean blowout and soot emissions to changes in fuel composition occurring with the use of alternative fuels (or blends) where the relative difference in fuel sensitivity between simulations and experiments is less than 20%.	**Physical Modeling:** 1. Develop turbulent combustion models, including chemistry, spray, soot 2. Large eddy simulation methods for combustion 3. Validation experiments, with multiple fuels

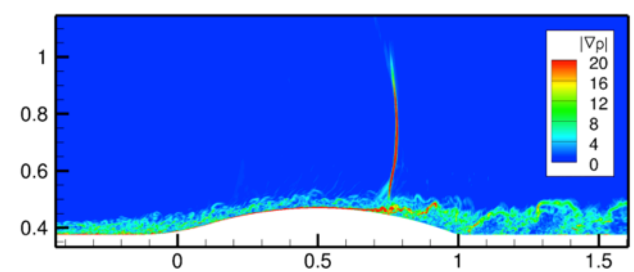
RTM NASA Research Announcements (NRAs)

NASA Research Announcements (NRAs) provide a mechanism to collaborate with academia and industry, a recommendation of the CFD Vision 2030 Study (20 New NRAs awarded FY15 & FY16, a significant investment)

NRAs Awarded	Roadmap Swim Lanes Supported
5 Turbulence Modeling/Simulation NRAs: (1) Stanford, (2) UT-Austin, (3) U. Colorado, (4) Notre Dame, (5) U. Illinois-UC	Physical Modeling, including Validation Experiments
2 Numerical Methods NRAs: (1) MIT, (2) U. Wyoming	Algorithms
2 Grid Generation NRAs: (1) ODU, (2) Syracuse U.	Geometry and Grid Generation
5 MDAO NRAs: (1) MIT, (2) Georgia Tech, (3) Georgia Tech, (4) U. Alabama, (5) UC-Berkeley	MDAO
6 Combustion NRAs: (1) Stanford, (2) Stanford, (3) Georgia Tech, (4) U. Connecticut, (5) Arizona State, (6) U. Michigan	Physical Modeling







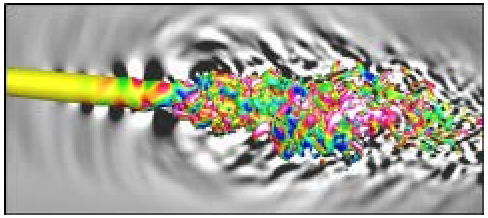
SBIR Phase I Awards on Geometry and Grid Generation

Business Name	Proposal TITLE	PM/PI
Pointwise, Inc.	High Order Mesh Curving and Geometry Access	Richard Matus
Helden Aerospace Corporation	HeldenSurface: A CAD Tool to Generate High-Quality Surfaces	John Hooker
D&P, LLC	A Fully Automated Mesh Generation Tool	Lei Tang
CFD Research Corporation	A Software Tool for High-Order Element Mesh Generation	Silvia Harvey

T³ Revolutionary Computational Aerosciences (RCA)

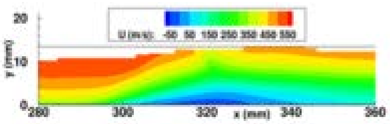
Current Technical Challenge:

Identify and downselect critical turbulence, transition, and numerical method technologies for 40% reduction in predictive error against standard test cases for turbulent separated flows, evolution of free shear flows and shock-boundary layer interactions on state-of-the-art high performance computing hardware.



Technical Areas and Approaches:

- Development of more accurate physics-based methods (e.g. higher moment closure, large eddy simulation (LES))
- Advanced numerical methods
- Transition prediction and modeling
- Validation experiments
- Multidisciplinary analysis and design (high fidelity)

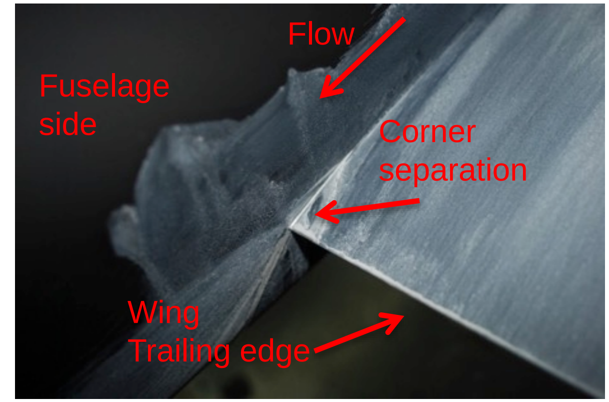


Benefit/Pay-off:

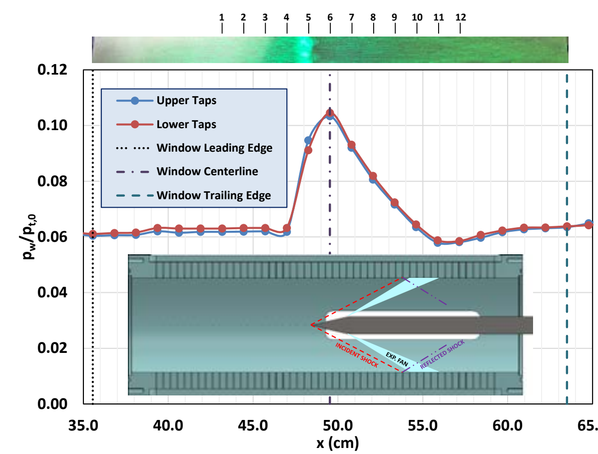
- Capability will be used by the aeronautics community to improve designs and reduce design cycle times.
- Facilitates accelerated introduction of advanced air vehicles and propulsion systems into the airspace system.
- Supports ARMD Strategic Thrusts # 3 (primary), 2 and 4.
- Enables aircraft certification by analysis.

CFD Validation Experiments - 1

- **Juncture Flow Experiment**
  - Prediction of trailing edge corner separation a challenge
  - Risk reduction experiments used for final design
  - First 14x22 FT entry in November 2017
- **Shock Wave/Boundary Layer Interaction**
  - Mach 2.5 Axisymmetric SBLI (attached and separated)
  - Mean and turbulent stress data
- **2D Separation**
  - NRA to Notre Dame (Flint and Corke)
  - Data for attached and separated (incipient, small, large) flow
- **Axisymmetric Separation**
  - Low speed boat tail configuration
  - May extend to high speed
- **2D Compressible Mixing Layer**
  - NRA to U-Illinois (Dutton and Elliott)
  - Full documentation of BC and mean/turbulence data
- **CRM in Fluid Dynamics Lab**
  - Wake flow



Experimental surface flow visualization



Axisymmetric SWBLI – 13.5° Cone Angle

JUNCTURE FLOW EXPERIMENT

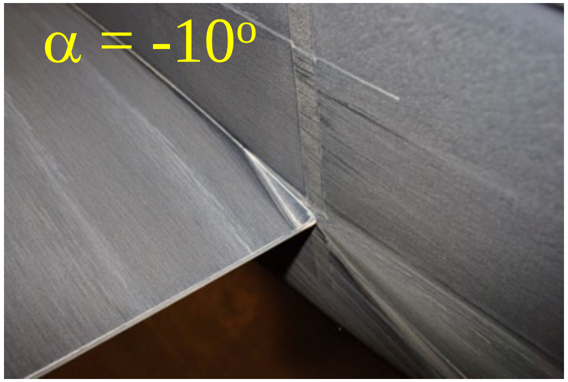
FY15 and FY16 Risk Reduction Experiments

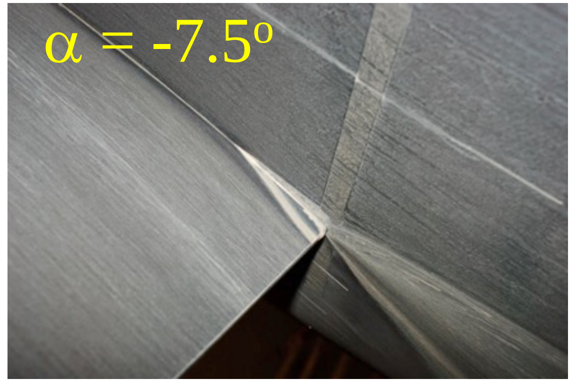
3% Semi-span Juncture Flow Model in the ARC Fluid Mechanics Lab Jun 2015
Model loaned to Caltech for Boeing/Caltech test

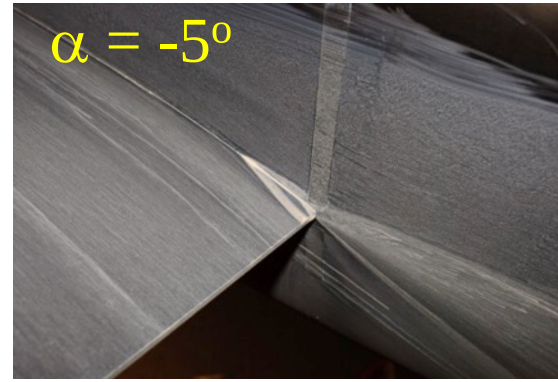
2.5% Juncture Flow Model in the VA Tech 6-foot Stability Wind Tunnel Aug 2015
Model loaned to VA Tech for further testing and educational use

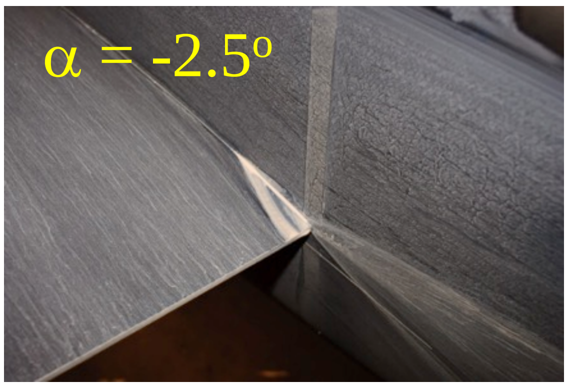
6% Juncture Flow Model in the LaRC 14’X22’ Wind Tunnel Nov/Dec 2015

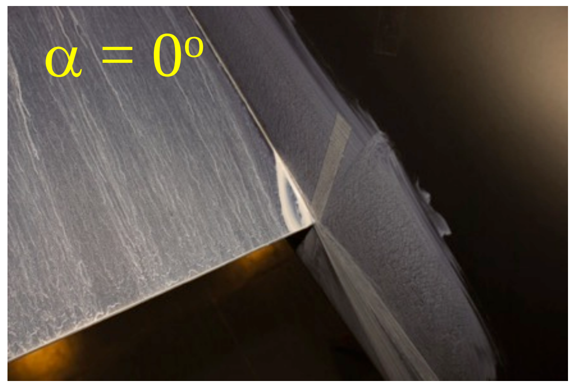
F6 Wing without Horn (Port Side): Re_c = 2.4 million

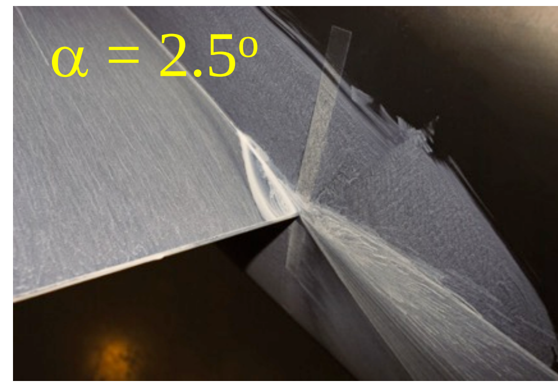


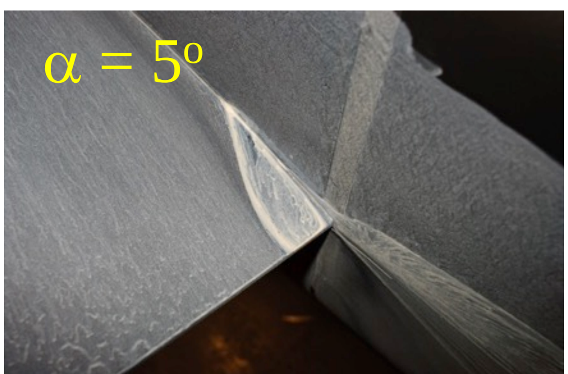


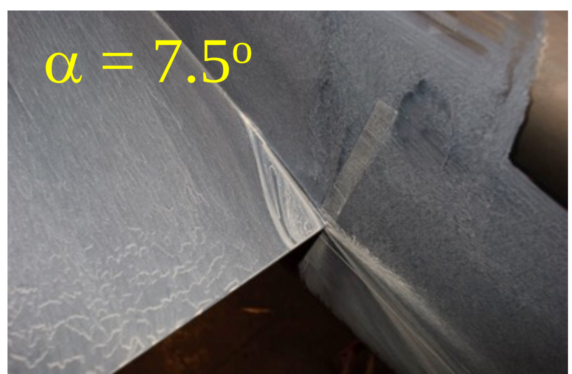


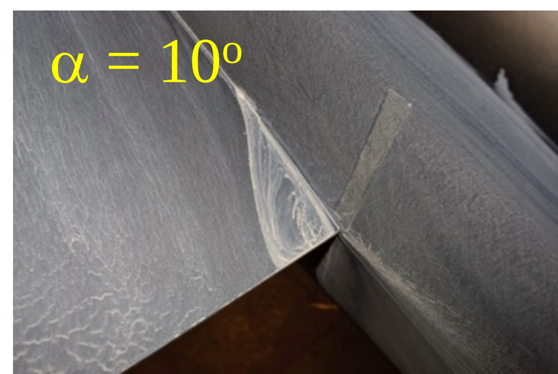




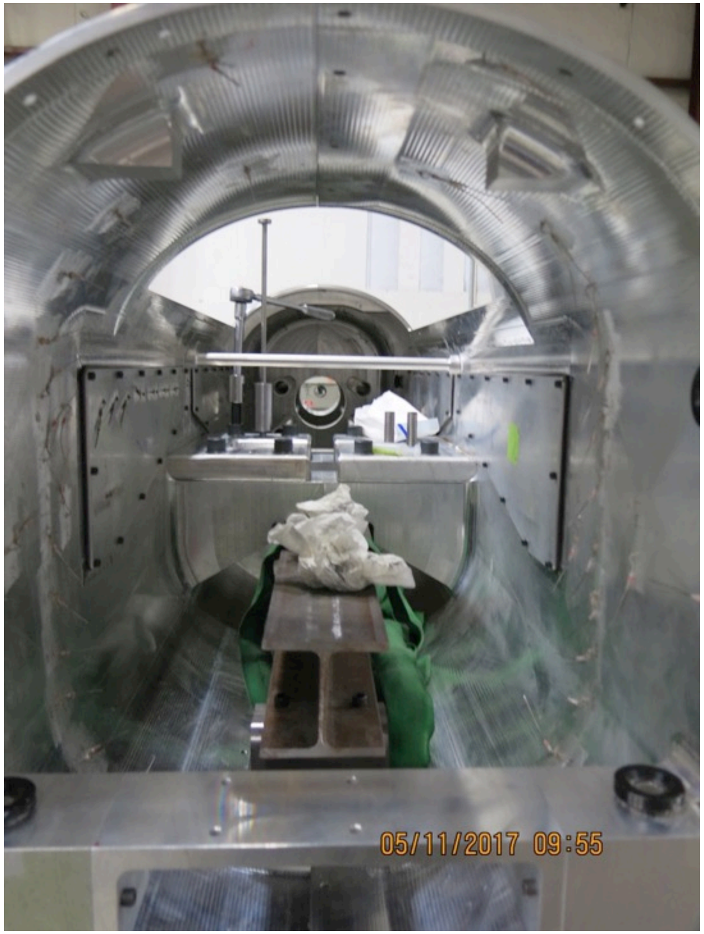








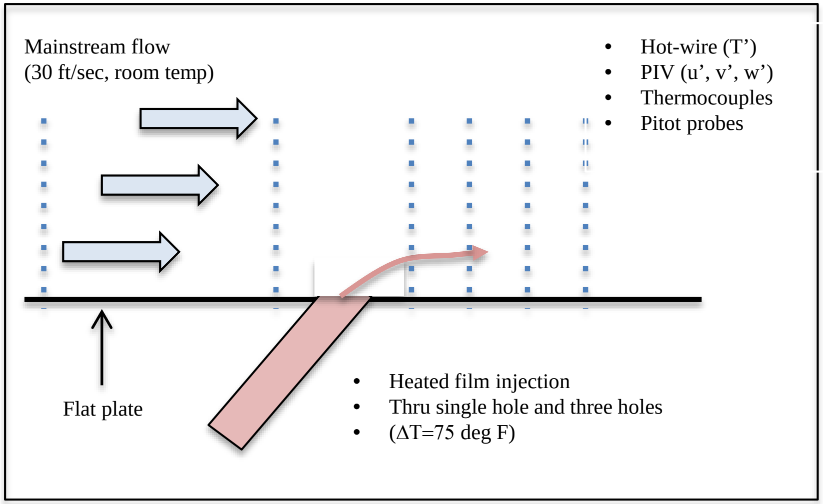
JUNCTURE FLOW EXPERIMENT

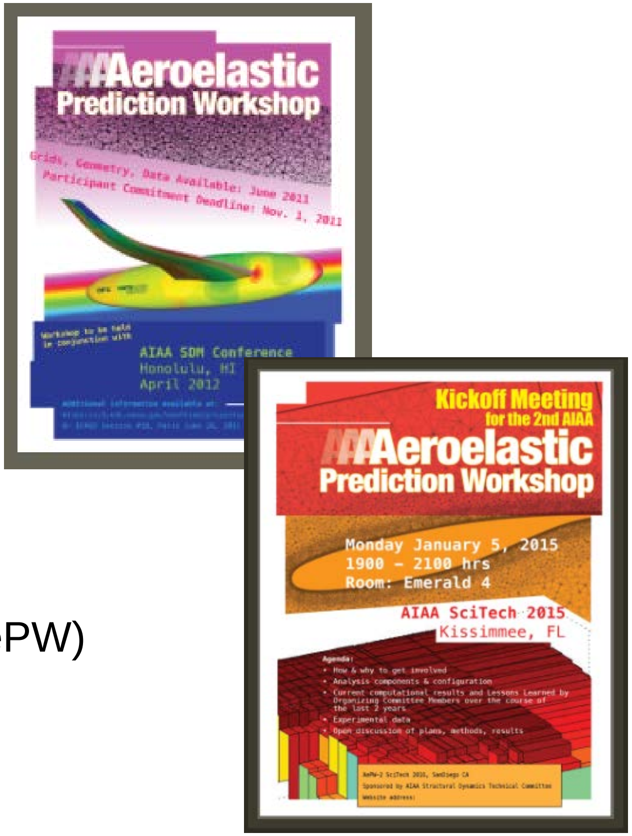


8% Juncture Flow Model for LaRC 14'X22' Wind Tunnel test (first entry Nov 2017)

CFD Validation Experiments - 2

- **Turbulent Heat Flux (THX) Experiment**
  - Improving models for turbulent heat flux and cooling hole boundary conditions
  - Low-speed flat plate with single/three holes and heated film injection flow (SW-6)
  - Heated (1300F) high-speed jet (Small Hot Jet Acoustics Rig), RAMAN spectroscopy
  - Flat plate test installed in a hot high-speed jet (SHJAR in Aero-Acoustic Propulsion Laboratory) with ambient temperature film cooling flow injected through a single or multiple holes



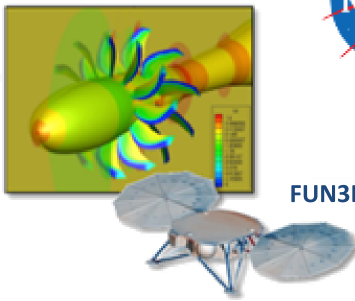


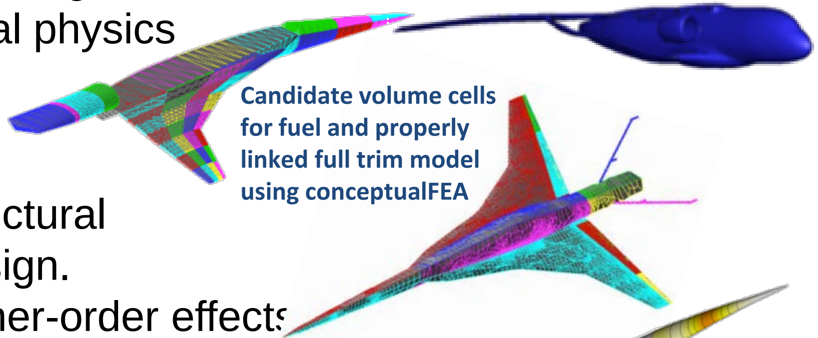
- **Aeroelastic Experiment**
  - Informed by the Aeroelastic Prediction Workshop (AePW)
  - Transonic Dynamic Tunnel at LaRC
  - Design of experiment in FY17-18
  - Experiments to be conducted in FY19-21

T³ MDAO/Systems Analysis Tools

Technical Challenge:

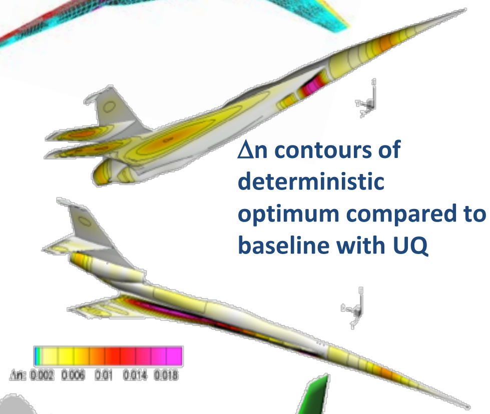
Develop advanced design and optimization tools for coupled multidisciplinary analysis with a range of fidelities to shorten the design cycle of revolutionary new vehicles. Use X-Plane ground and flight test data to validate the implementation of critical physics required to model new concept aircraft.





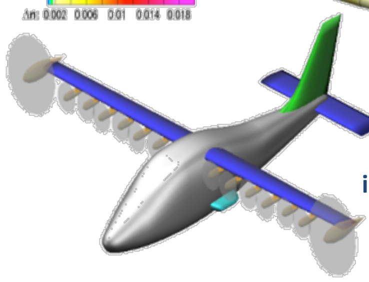
Technical Areas and Approaches:

- Focus on Propulsion-Airframe Integration, Aero-Structural Integration, and Perception-Influenced Acoustic Design.
- Develop lower-order models to better represent higher-order effects to enable timely solution for rapid conceptual design.
- Enable mixed fidelity optimization to tailor solution for user needs and resources.
- Enable high-fidelity multidisciplinary analysis and optimization with adjoints (solved as a coupled system in a single optimization cycle).



Benefit/Pay-off:

- Supports advanced vehicle configurations, which require coupled models.
- Better multidisciplinary designs support Thrusts 2, 3, and 4 goals.
- Reduced design cycle time with efficient model evolution.



Technical Challenge - MDAO/Systems Analysis Tools

Conventional versus Revolutionary Vehicle Design

Conventional design of aircraft deliberately decoupled components to allow each to be considered independently

This simplifies the analysis, but limits the design choices

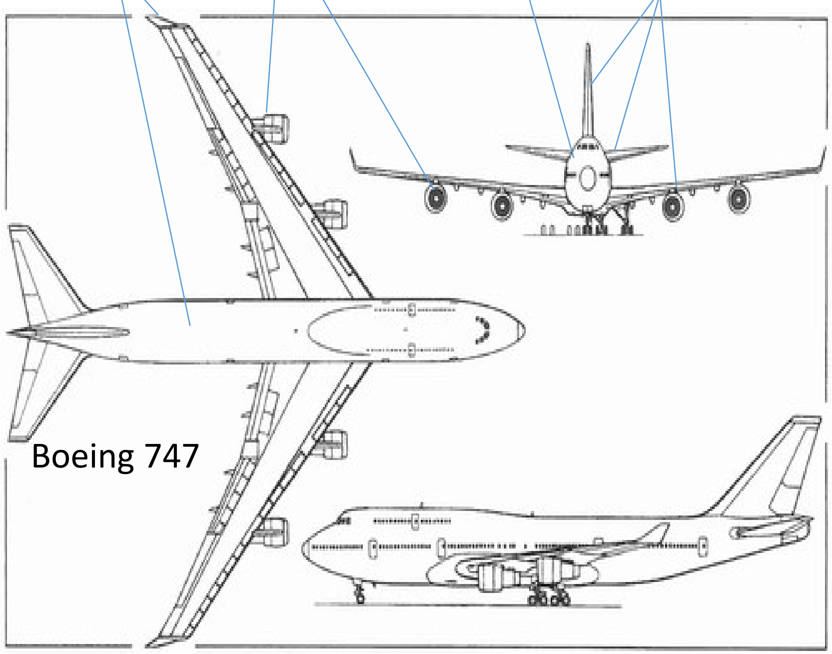
MDAO offers greater performance potential, but significantly increases the complexity in the design process

Isolated wing and body

Engines positioned in freestream

Cylindrical fuselage

Tail out of the wing wake

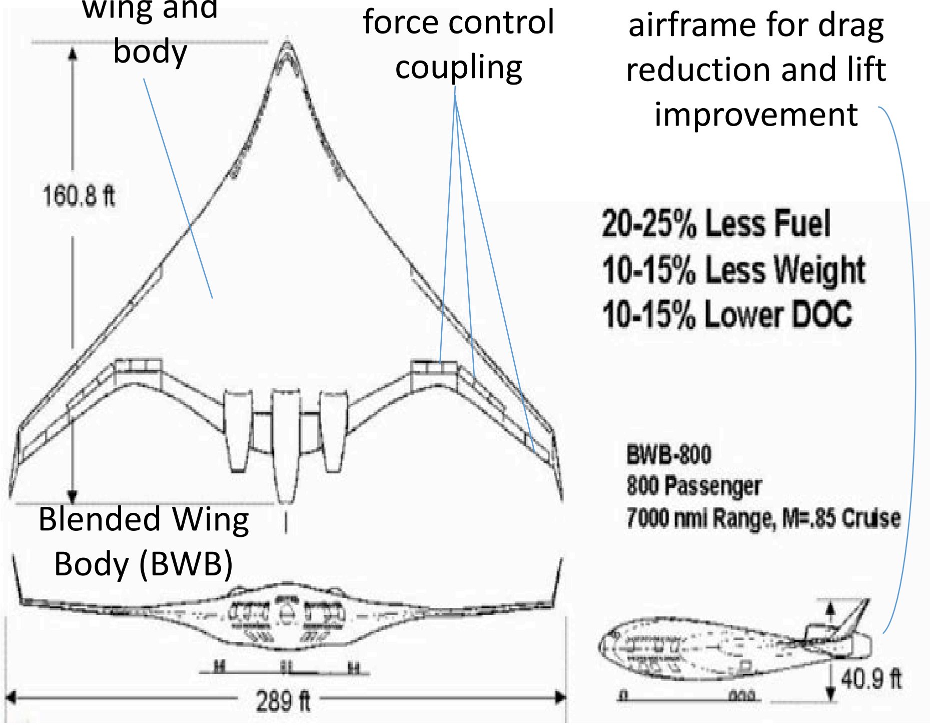


Conventional "tube-and-wing" design

Unified wing and body

Reduced drag profile can force control coupling

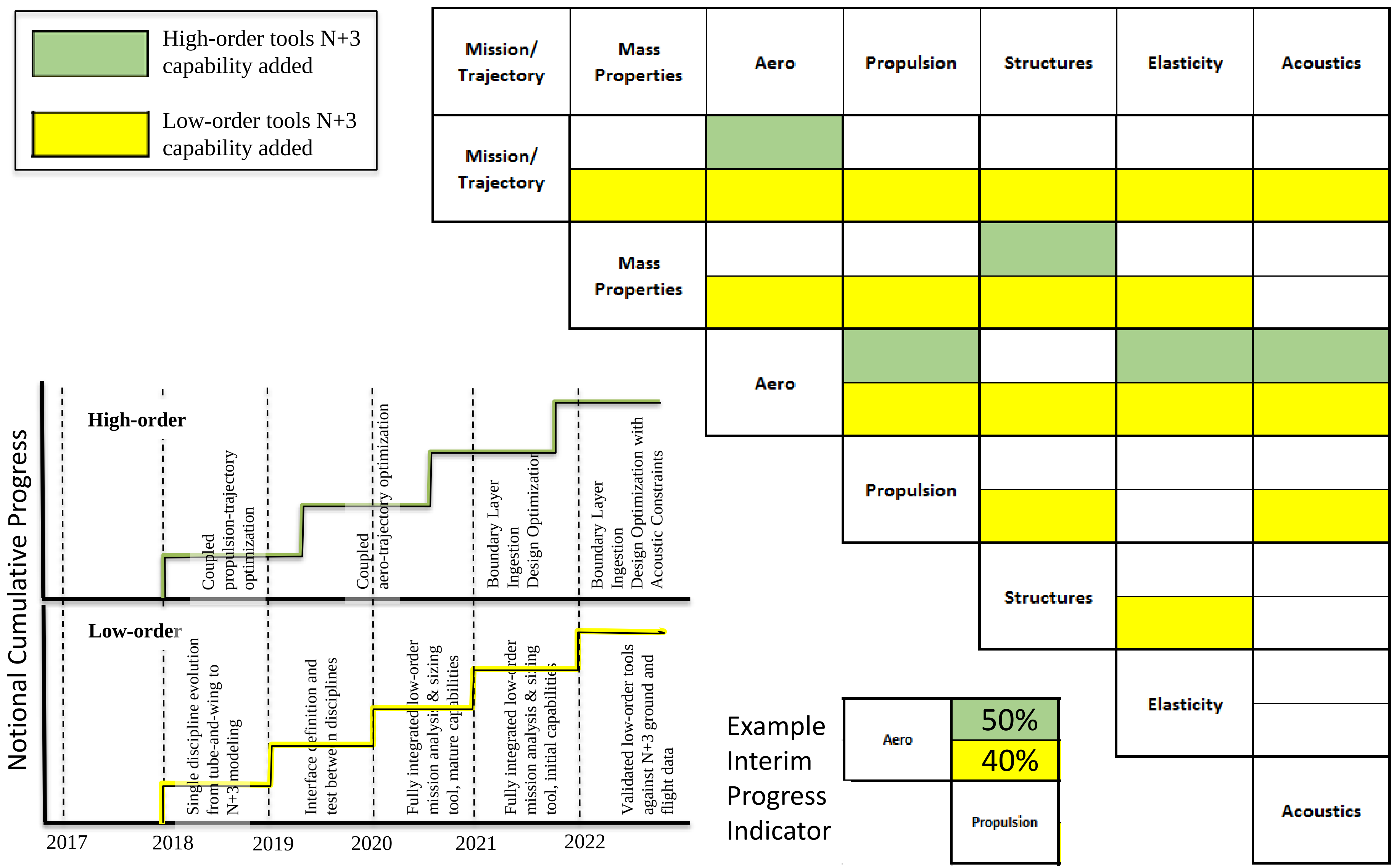
Engines integrated with airframe for drag reduction and lift improvement



Unconventional design

MDAO TC Progress Indicators

Targeted Disciplines for Coupled Analysis/Optimization for N+3 Vehicles



T³ Combustion Modeling

Technical Challenge:

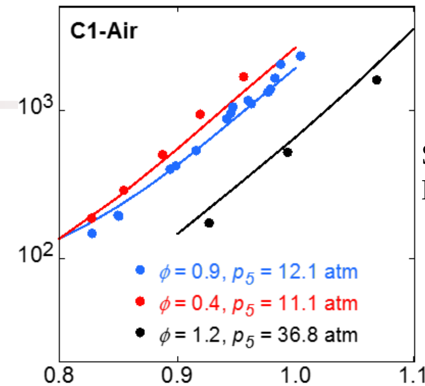
Predict the sensitivity of lean blowout and soot emissions to changes in fuel composition occurring with the use of alternative fuels (or blends) where the relative difference in fuel sensitivity between simulations and experiments is less than 20%.

Technical Areas and Approaches:

- Develop chemistry, spray, soot, and turbulent combustion models
- Advance large eddy simulation methods for combustion
- Leverage fuels and test data from National Jet Fuels Combustion Program (NJFCP) and AFRL experiments
- Validation Experiments (GRC, NRAs, and NJFCP partners) with multiple fuels (or surrogates)

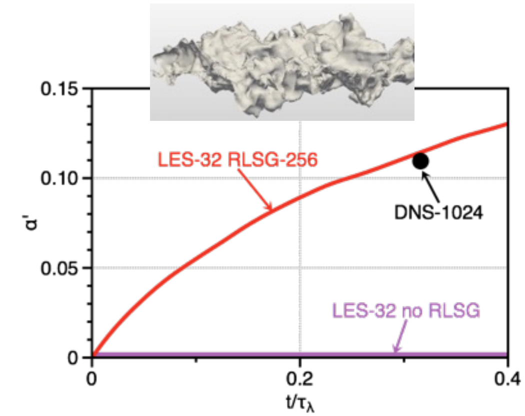
Benefit/Pay-off:

- Streamline ASTM fuel certification process (NJFCP)
- Accelerated use of lower life-cycle carbon alternative jet fuels and increased blend ratios (ARMD Thrust 4a)
- Tools to optimize combustor to fuel (or fuel to combustor)
- Development of chemistry, spray, and turbulent combustion models for LBO and soot also likely to improve NOx emission prediction capabilities (ARMD Thrust 2 and 3)

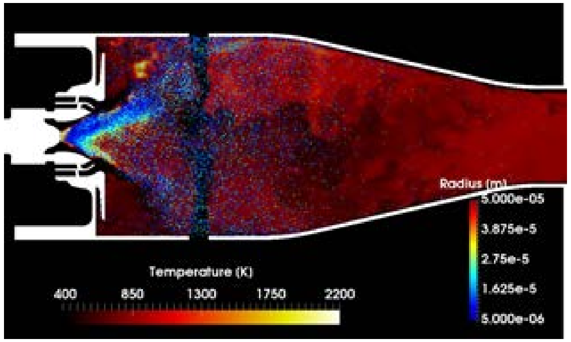


Symbols = exp
Lines = model

Ignition delay (μs) vs 1000K/T for NJFCP alternative fuel C-1 (Gevo)



Liquid breakup (LES vs DNS)



NJFCP Referee Rig LES Temp & spray

T^3 Combustion Modeling Technical Challenge (TC)

- **Develop physics-based combustion models for the prediction of aircraft combustor operability, dynamics, and emissions (gaseous and particulate) over a wide range of potential fuels, operating conditions. and combustor designs.**
- **Inherently multi-disciplinary, requiring modeling of spray atomization and evaporation, chemical kinetics, soot formation and evolution, radiation heat transfer, and the interaction of turbulence with all of these complex physical processes.**
- **Proposed TC will address one key operability process (lean blowout) and one key emissions component (soot).**
- **Models developed under this TC will likely also improve the modeling of NOx, CO, and particulate emissions, combustion dynamics, and ignition processes.**

Design tools are needed to support the increased use of alternative jet fuels with wider variations in composition (relative to Jet-A) and the potential for increased blend ratios, while maintaining combustor operability and meeting more stringent aviation emissions standards.

TC Success Criteria

$\Delta\varphi_{\text{fuel}}$ = Change in value of φ from Jet-A to alternative fuel (or blend)

= $\varphi_{\text{fuel}} - \varphi_{\text{JetA}}$

$\Delta\varphi_{\text{fuel}}^{S}$ = Change in value of φ predicted by **S**imulation for Jet-A and for alternative fuel (or blend)

$\Delta\varphi_{\text{fuel}}^{E}$ = Change in value of φ measured by **E**xperiment for Jet-A and for alternative fuel (or blend)

Relative difference in simulation and experimental value for the **change** in LBO or soot emission from Jet-A to an alternative fuel (or blend) is less than 20%

$$\text{Fuel Sensitivity Error} = \frac{\Delta\varphi_{\text{fuel}}^{S} - \Delta\varphi_{\text{fuel}}^{E}}{\Delta\varphi_{\text{fuel}}^{E}} < 20\%$$

where

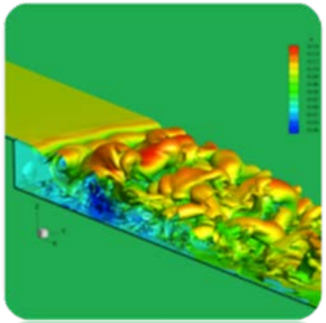
- φ = Fuel/Air ratio for LBO
- φ = Soot mass at flametube exit or combustor exit

Implementation Plan, Going Forward

- **Review/update roadmap every 5 years**
  - Current T^3 priorities encapsulated in the 3 Technical Challenges
  - Review progress and adjust research portfolio periodically to maximize impact on CFD Vision 2030 objectives
- **Explore collaborative opportunities with OGAs more aggressively**
  - Order of magnitude more DOD and DOE investment in HPC
- **Leverage CFD community activities through AIAA**
  - Focused workshops, special sessions
- **Seek opportunities to interact with international experts**
  - European institutions leading in certain areas
- **Reevaluate use of Collaborative Centers of Excellence when additional funds are available**
  - First Priorities: (1) Geometry and Grid Generation, (2) HPC and Knowledge Extraction
- **Consider use of prizes and challenges**

Summary

- Exciting suite of **fundamental, cross-cutting research**
- Developing and validating **critical computational models and tools** for application to NASA projects and the broader aeronautics community
- T^3 has paid special attention to the CFD Vision 2030 recommendation for acquisition of quality **data for CFD validation**
- Leveraging **external expertise** to augment and complement in-house research efforts via NRAs/SBIRs
- Focus on **collaborations** with DOD and DOE to make progress in the currently *un-funded* roadmap swim lanes
  - HPC



Development of Computational Tools will Enable Aircraft Certification by Analysis and Design of New Aerospace Configurations

Current RCA NRAs - 1

INSTITUTIONS	NRA TITLE	PROGRESS
Stanford University	Validation of wall models for LES with application to the NASA Common Research Model	EQWM for CRM. Comparison of EQWM and NEQWM for RCA standard separation test cases.
University of Texas - Austin	Novel Hybrid RANS/LES Models for Aerodynamic Flows	New hybrid model used to compute NASA hump case.
University of Colorado	Spatio-Temporally Adaptive Variable Fidelity Approach to Modeling and Simulation of Complex Turbulent Flows	Wavelet-based approach to capture turbulent structures.
Notre Dame University	Benchmark Smooth Body Flow Separation Experiments For CFD Validation	Model designed/fabricated. Two-dimensionality being assured. Data acquisition underway.
University of Illinois - UC	Benchmark Experimental Measurements of Turbulent, Compressible Mixing Layers for CFD Validation	Facility fab complete. SPIV shows 30% reduction in growth rate at Mc = 0.53. Normal stresses dominate.

Current RCA NRAs - 2

INSTITUTIONS	NRA TITLE	PROGRESS
University of Wyoming	Development of Scalable Solvers for Current and Emerging Steady-state and Time-dependent Discretizations	Several approaches to reduce time to solution. Parallel time spectral method yields up to two orders reduction in compute time.
MIT	Swept time-space domain decomposition rule for breaking the latency barrier	Try to break latency barrier using swept decomposition. Factor of 3 achieved for 2D Euler.
Old Dominion University	Extreme-Scale Parallel Mesh Generation: CFD 2030 Vision	A Multi-Layered Runtime System to implement guaranteed quality mesh generation and error-metric based adaptivity.
Syracuse University	Distributed Multi-processor Geometry Environment to Support Design and Analysis on Extreme-scale Grids	Unified framework for grid generation, adaptation, and sensitivities as well as flow analysis.

Ongoing MDAO NRA Awards

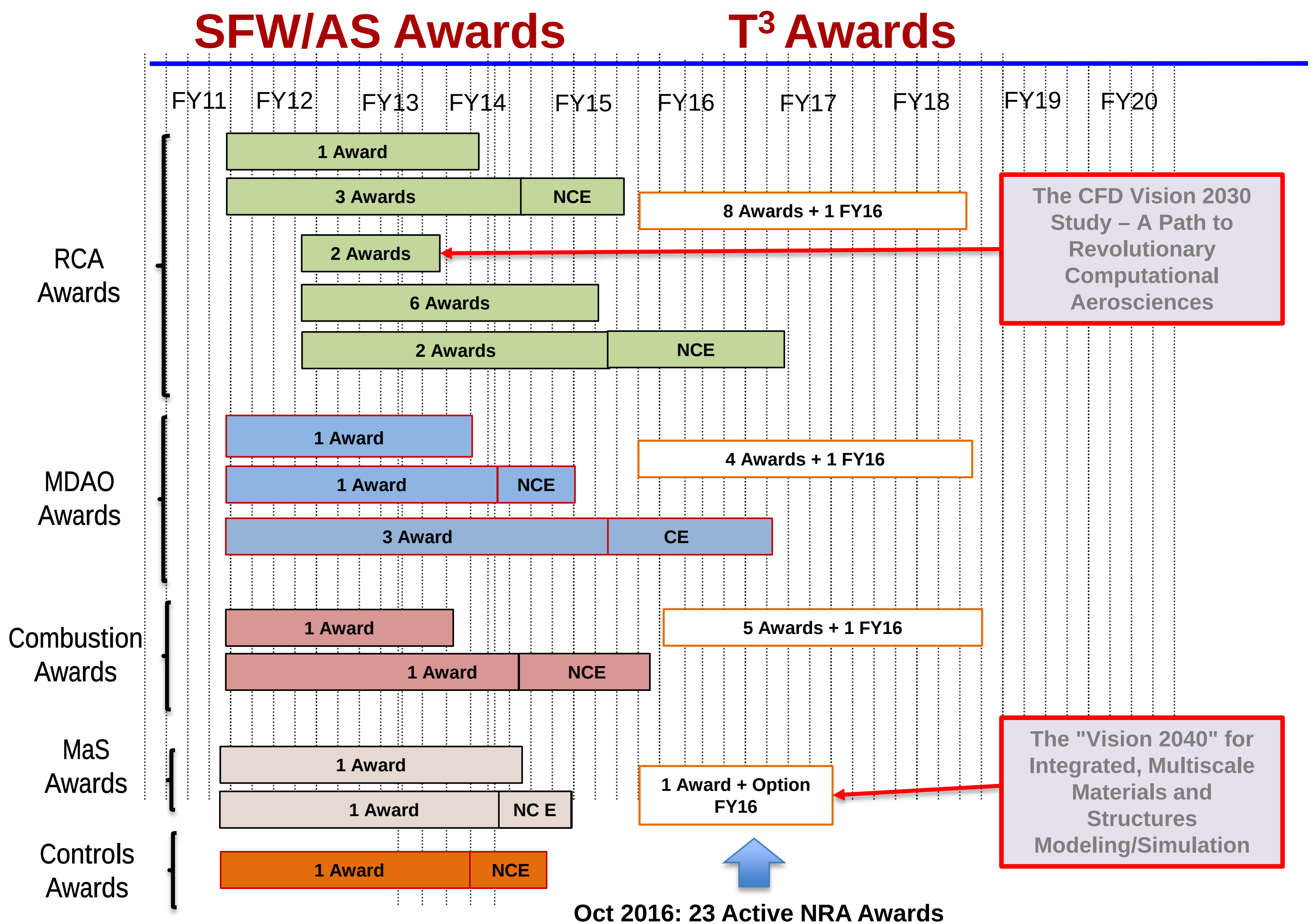
Start Date	PI	Title	Institution/Company
October 2015	Steven Allmaras	Rapid Viscous Aerodynamic Analysis/Design Methodology Utilizing Inviscid Coupling with a 3D Integral Boundary Layer	Massachusetts Institute of Technology
October 2015	Dimitri Mavris	Development and Integration of Tools and Methods for Multi-fidelity Structural Modeling and Analysis for Conceptual Design and Optimization of Aerospace Vehicles	Georgia Tech Research
October 2015	Weihua Su	Enhanced Multi-Fidelity Aeroelastic Models for Efficient Airplane Preliminary Design and Optimization	University of Alabama
September 2015	Graeme Kennedy	An Efficient Scalable Framework for Aeroelastic Analysis and Adjoint-based Sensitivities Using FUN3D and TACS	Georgia Tech Research
September 2016	Per-Olof Persson	High-Order Methods for Fluid Structure Interaction	University of California Berkeley

These MDAO NRAs are advantaged by the Air Force Research Lab (AFRL) and NASA LaRC project entitled Sensitivity Analysis for Multidisciplinary Systems (SAMS), initiated in December 2015. As part of this Space Act Agreement, AFRL is providing ~$200K/year to the Computational Aero Sciences Branch to make FUN3D more modular to enable coupling with nonlinear finite element codes. The RVLT project is making similar investments via a contract with the National Institute of Aerospace (NIA) to couple FUN3D with the multi-body code DYMORE for rotorcraft analysis. The T^3/NRA and RVLT/NIA PIs are collaborating with the SAMS team.

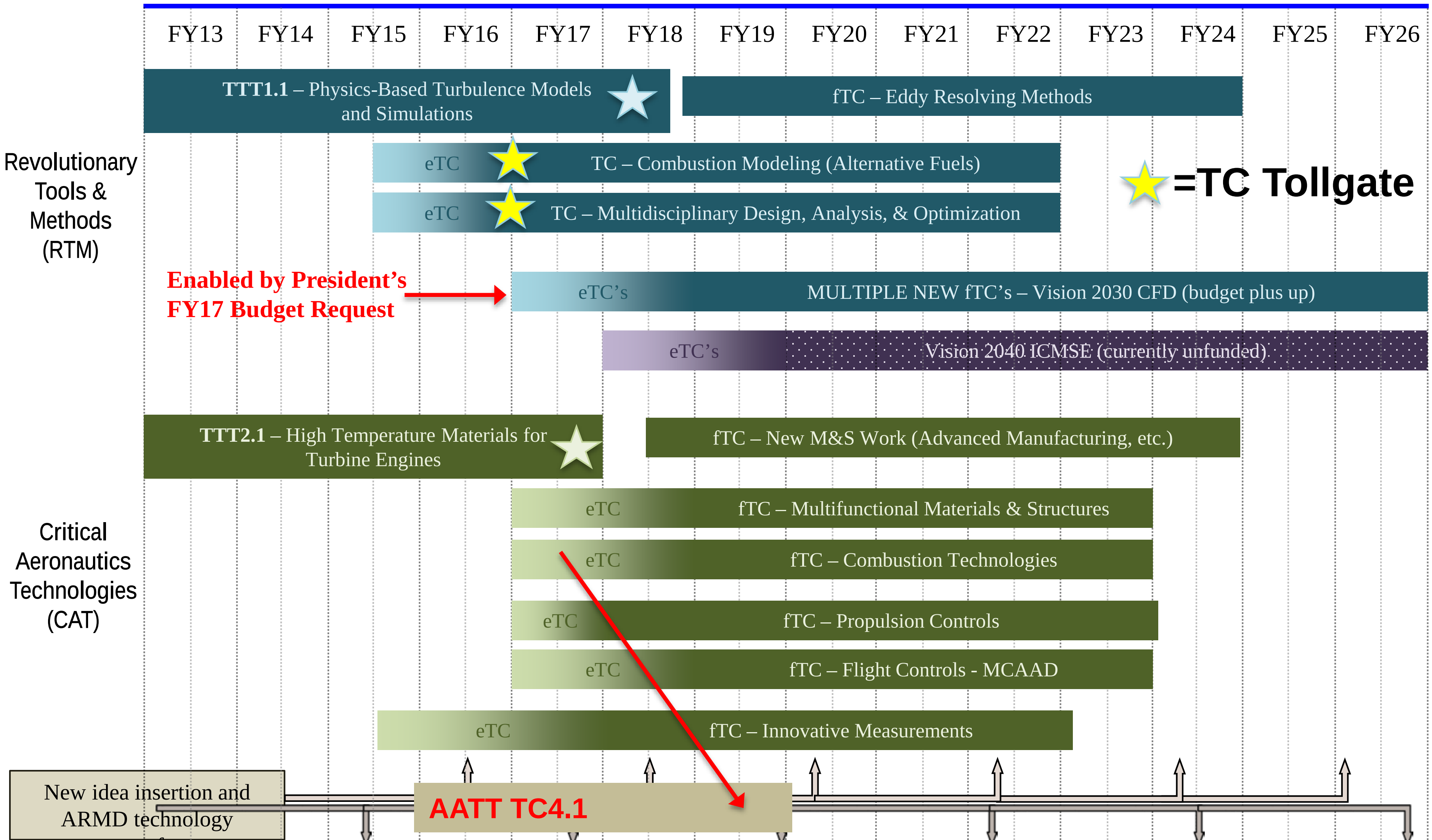
Ongoing Combustion Modeling NRA Awards

Start Date	PI	Title	Institution/Company
January 2016	Marcus Herrmann	A novel hybrid Eulerian/Lagrangian dual scale LES model for predicting atomization in realistic aircraft combustor fuel injectors	Arizona State University
December 2015	Hai Wang	Hybrid Modeling of Jet Fuel Combustion Chemistry	Stanford University
December 2015	Tianfeng Lu	Reduced kinetic models with fuel sensitivity for turbulent combustion simulations	University of Connecticut
January 2016	Mathias Ihme	Development of a Fidelity-Adaptive LES Combustion Model for Predicting Fuel-Sensitivities on Combustion Stabilization and Ignition	Stanford University
December 2015	Suresh Menon	Multi-Scale Turbulence-Chemistry Closure in Large-Eddy Simulation to Account for Sensitivity to Fuel Composition and Properties	Georgia Tech Research
August 2016	Venkat Raman	Fuel Sensitive Turbulent Combustion Models for Predicting Flame Stability and Emissions from Aircraft Combustors	University of Michigan

NRA Awards (SFW, AS, & T^3 FY15/FY16)



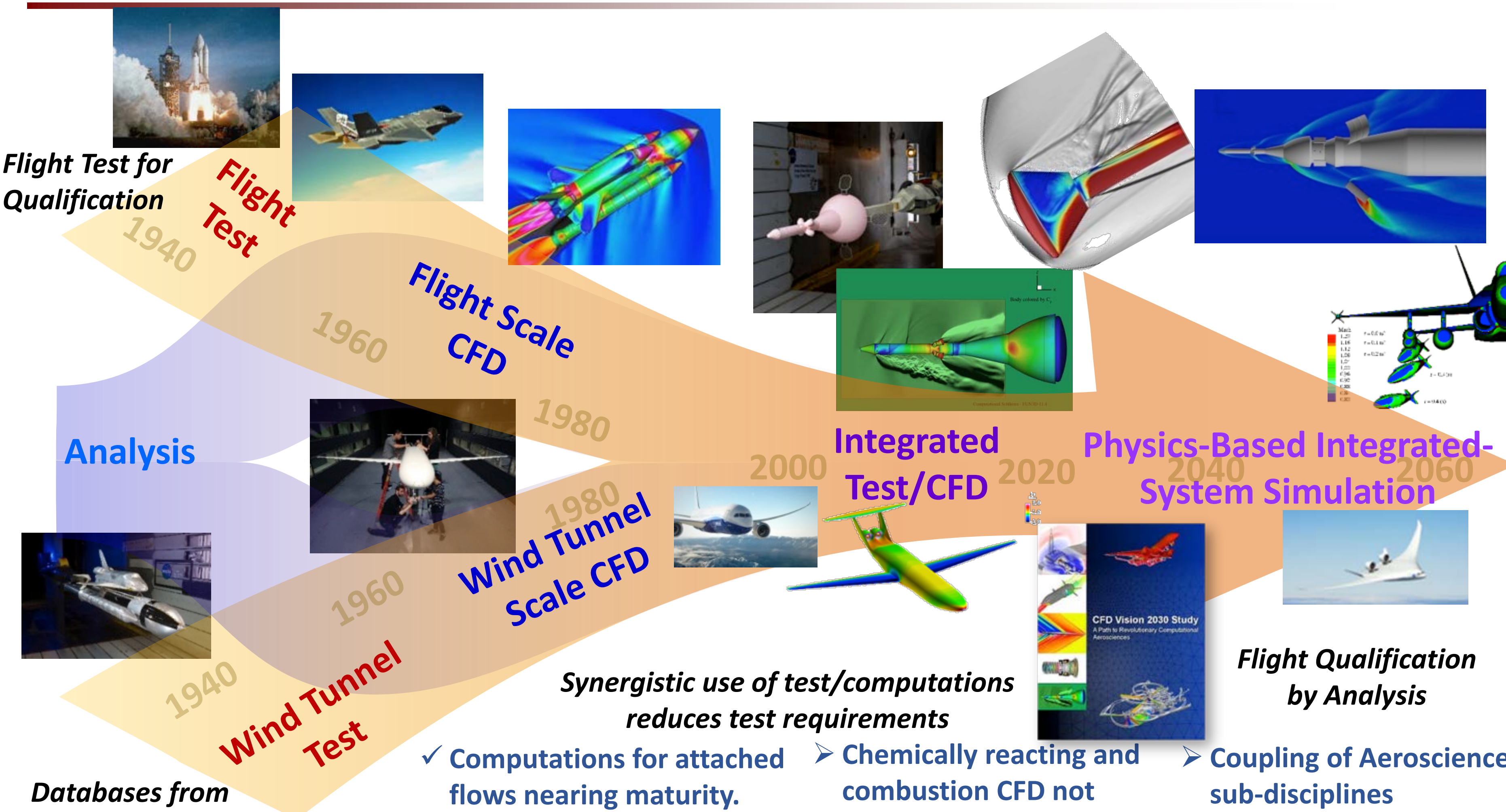
Notional Technical Challenge Activities in T^3



Notional strategy, including FY17 President's Budget Request

REVOLUTIONARY COMPUTATIONAL AEROSCIENCES

Aerodynamics – Aerothermodynamics – Aerostructures – Aeroacoustics – Propulsion Integration



- ✓ Computations for attached flows nearing maturity.
- ➢ Airframe propulsion integration challenges test and computations.
- ➢ Automated geometry modeling and adaptation require robust investment

- ➢ Chemically reacting and combustion CFD not ready for routine use.
- ➢ Push toward unsteady separated flow CFD requires advanced algorithms and computer technology.

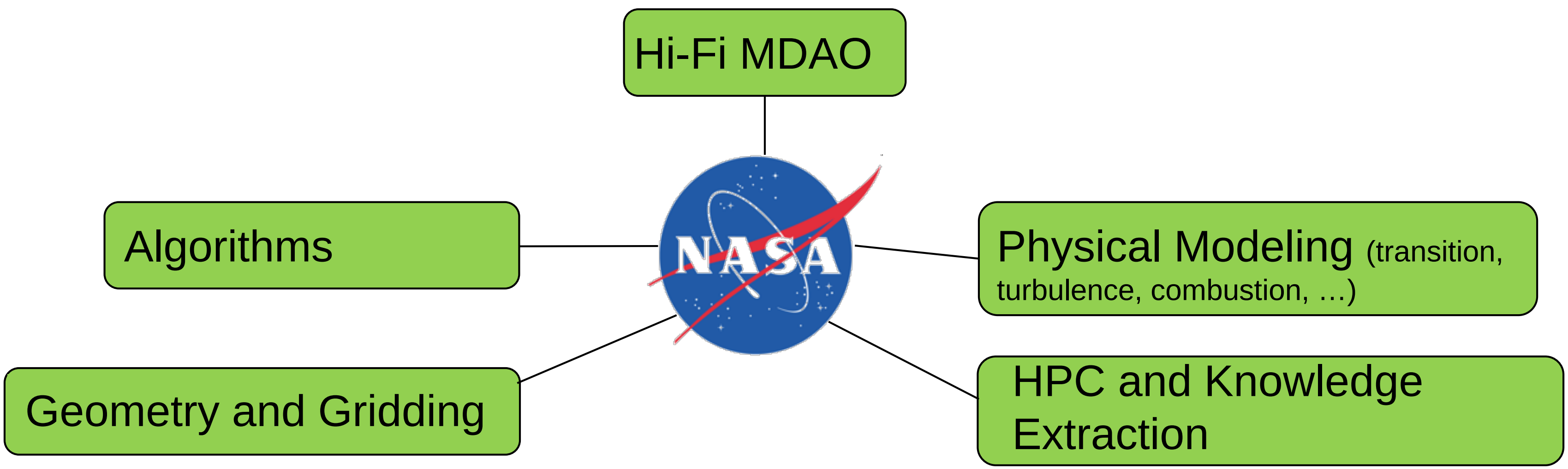
- ➢ Coupling of Aerosciences sub-disciplines
- ➢ Integration with complementary disciplines – Flight Mechanics, GN&C, Structures, Materials, Loads & Dynamics, …

Collaborative Centers of Excellence (CCE)

Key: New Technology Development Requires Concerted, Long-term, Team Effort

Approach: Establish a competed group of "Collaborative Centers" in designated technology areas (roadmap swim lanes), and fund them at sustained level of ~$1-4 Million/year for a period of 5 years.

Idea: Experts across academia/industry/OGAs propose teams to do research in identified areas, but goal is to implement capabilities in NASA computational framework**.**



- Each Center might support up to 4 co-PIs, several post-docs/graduate students
- Teams would work closely with NASA scientists
- Directly supports study recommendations
- *Conduct a series of workshops to develop detailed plans for each area*