



"Digital Thread: Turbomachinery Design" Workshop

East Hartford, CT

August 20, 2018

Dr. Michael M. Rogers

Manager, Transformational Tools & Technologies (T³) Project

Transformative Aeronautics Concepts Program

NASA Aeronautics Research Mission Directorate



Outline

- **NASA Motivation**
- **CFD Vision 2030 Study Summary**
 - The Vision
 - Roadmap
 - Validation Experiments
 - CFD 2030 Activities Since Report Release
- **T³ Technical Challenges Supporting CFD Vision 2030**
 - Revolutionary Computational Aerosciences (RCA)
 - Multidisciplinary Design, Analysis, and Optimization (MDAO)
 - Combustion Modeling
 - Innovative Measurements (Proposed)
- **Implementation Plan, Going Forward**
- **Summary**



NASA Aeronautics Strategic Implementation Plan (SIP)

A Living Document



Mega Drivers

Strategic R&D Thrusts

Community Vision

Community Outcomes

Research Themes

System-Level Metrics

Roadmaps

<https://www.nasa.gov/aeroresearch/strategy>



NASA Aeronautics Strategic Implementation Plan

Continues to Guide NASA Aeronautics Investment



Key Trends (Not Exhaustive)

Increasingly Urbanized World

Rising Global Middle Class Driven by Asia-Pacific

Urban Transportation Increasingly Congested

Continuing Pressure to Reduce Noise and Local Air Quality Impacts

Aviation Industry Sets Challenging CO₂ Reduction Goals through Mid-Century

Networked Com and Sensors, Embedded Artificial Intelligence, and Big Data Converging with Traditional Systems and Technologies

On-Demand Service Models
Disrupting Traditional Industries

Aviation Mega-Drivers



Analysis & Community Dialogue



**Industry / Gov't Execs
What's Needed?**



**Industry / Gov't SMEs
What's Possible?**



Systems Analysis

Community Vision



**Safe, Efficient Growth in
Global Operations**



**Innovation in Commercial
Supersonic Aircraft**



**Ultra-Efficient Commercial
Aircraft**



**Transition to Alternative
Propulsion and Energy**



**In-Time System-Wide
Safety Assurance**



**Assured Autonomy for
Aviation Transformation**



NASA Aeronautics Programs and Projects



NASA Mission Directorates

**Aeronautics Research
(ARMD)**

**Human Exploration and Operations
(HEOMD)**

**Science
(SMD)**

**Space Technology
(STMD)**

ARMD PROGRAMS

Jay Dryer: Director

Advanced Air Vehicles

Projects

- Advanced Air Transport Technology
- Advanced Composites
- Revolutionary Vertical Lift Technology
- Commercial Supersonic Technology
- Hypersonic Technology



Aerosciences Evaluation & Test Capability Office



Akbar Sultan: Director

Airspace Operations and Safety

Projects

- Airspace Technology Demonstrations
- UAS Traffic Management
- System-Wide Safety
- ATM-X



Dr. Ed Waggoner: Director

Integrated Aviation Systems

Projects

- Unmanned Aircraft Systems Integration in the National Airspace System
- Flight Demonstrations and Capabilities
- Low Boom Flight Demonstrator



X-planes/test environment



Dr. John Cavolowsky: Director

Transformative Aeronautics Concepts

Projects

- Convergent Aeronautics Solutions
- Transformational Tools and Technologies
- University Innovation



Critical cross-cutting tool development





Needed Prediction Capability for NASA Aeronautics

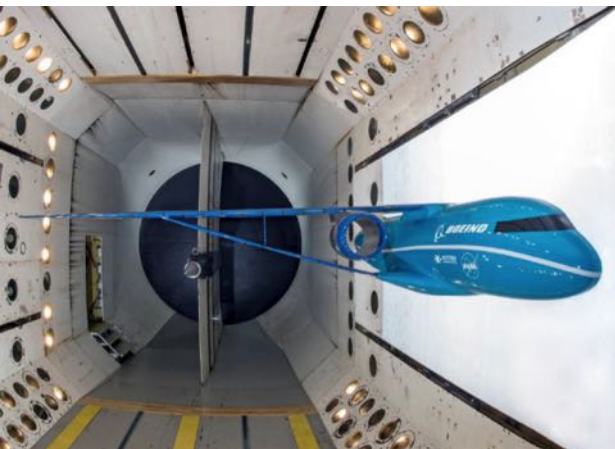




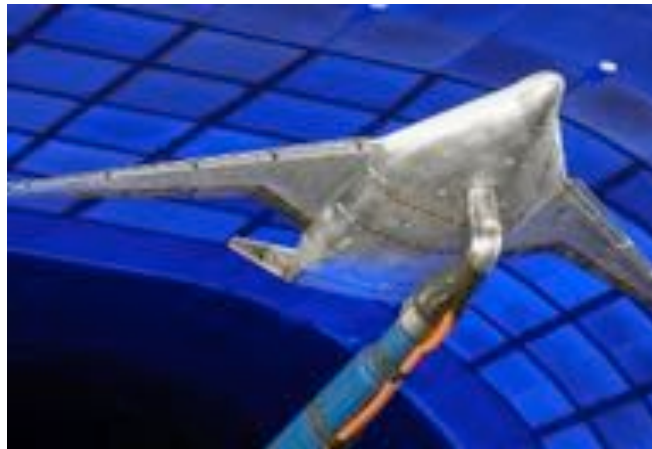
Ultra-Efficient Subsonic Transport (UEST) Concepts



Examples of Progress Through FY16



TTBW Aeroservoelastic • FY14
Langley Transonic Dynamics Tunnel



BWB/UHB Low Speed Operability • FY15
National Full-Scale Aerodynamic Complex at Ames



D8/BLI Integrated Benefit • FY13&14
Langley 14-By 22-Foot Subsonic Tunnel



TTBW Aerodynamic Integration • FY16
Ames 11-Foot Transonic Wind Tunnel



BWB Non-circular Fuselage • FY15
Langley Combined Loads Test System (COLTS)



HWB/OWN Performance • FY15
Langley National Transonic Facility



UEST X-Plane Concepts



Aurora
Double bubble/upper aft BLI



Boeing
Transonic Truss-Braced Wing



Boeing Blended Wing Body



Lockheed Martin
Hybrid Wing Body



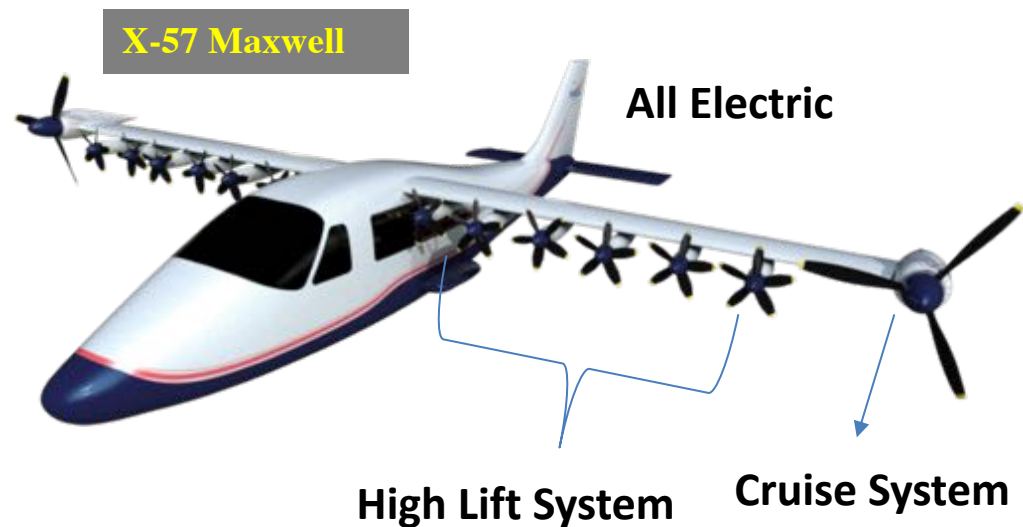
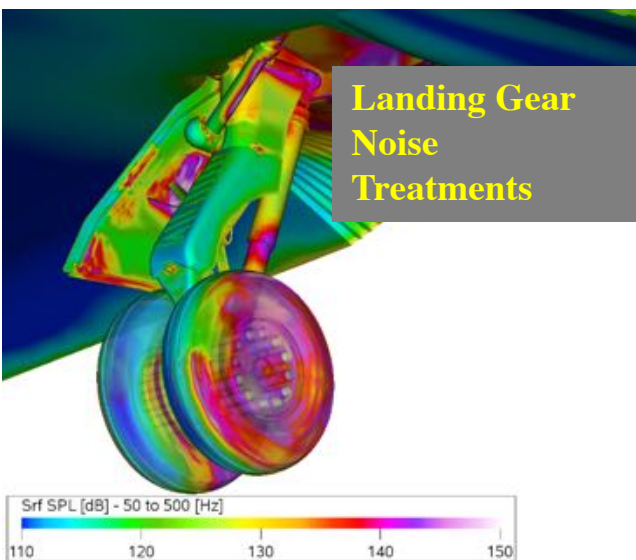
Dzyne Blended Wing Body



X-56 Performance Adaptive Aeroelastic Wing



Adaptive Compliant Trailing Edge II



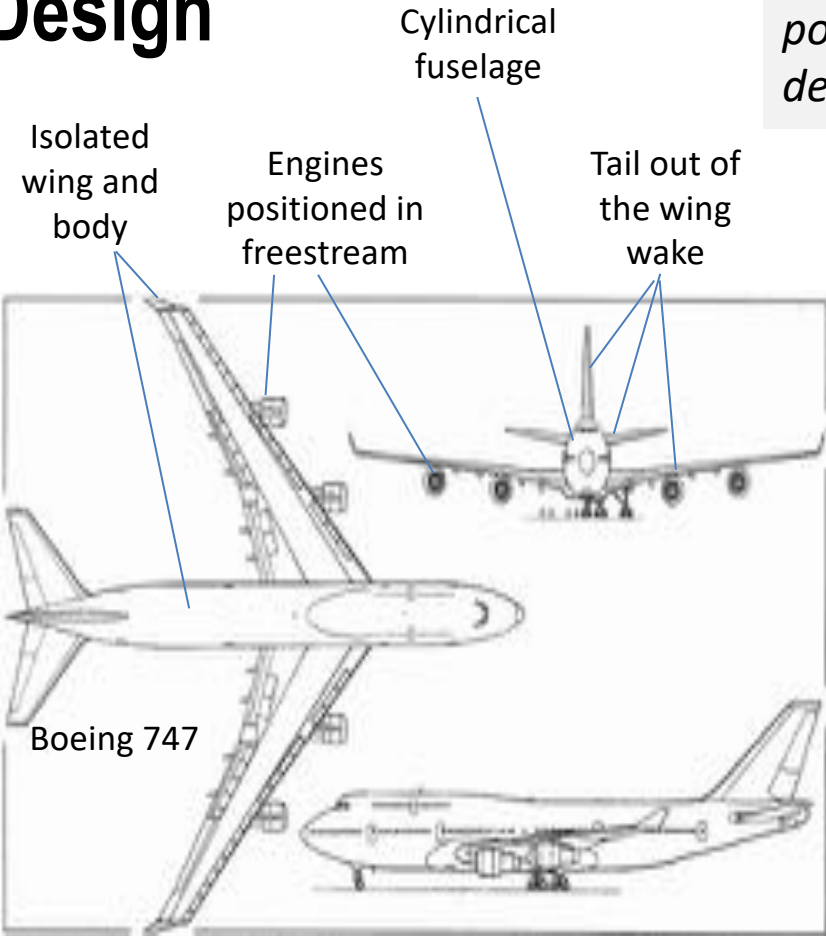


Conventional versus Revolutionary Vehicle Design

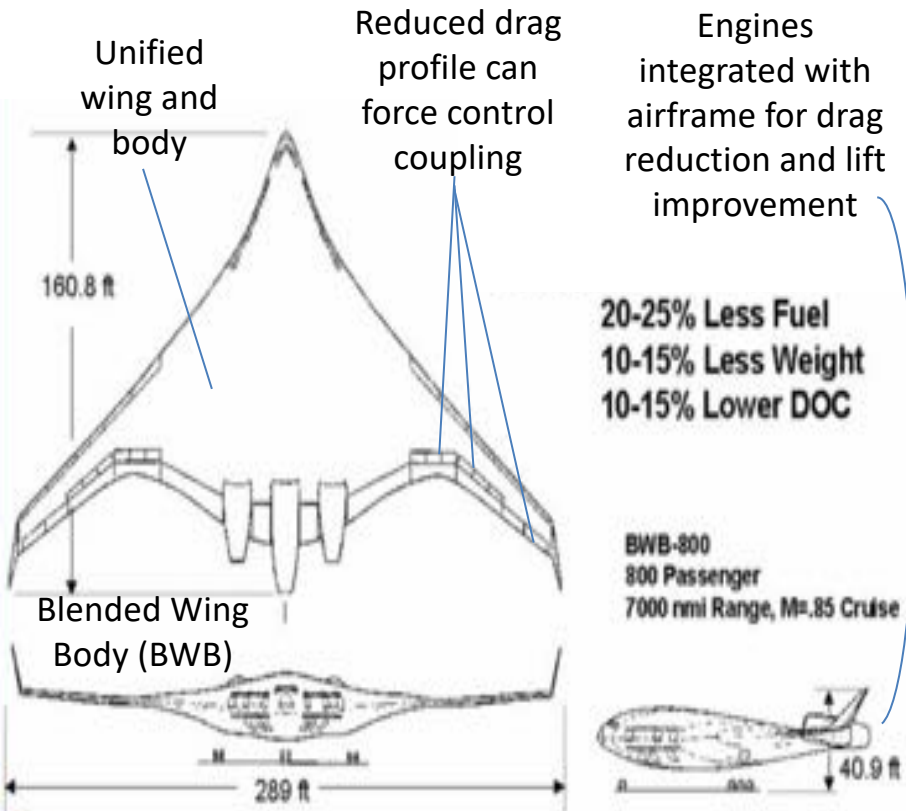
Conventional design of aircraft deliberately decoupled components to allow each to be considered independently

This simplifies the analysis, but limits the design choices

Integrated designs offer greater performance potential, but significantly increase complexity of the design process, requiring more capable analysis tools



Conventional “tube-and-wing” design



Unconventional design

Emerging Urban Air Mobility (UAM) Market

- **Key Applications**

- Highways in the sky → Personal travel/taxi service in and around cities to avoid congestion
- Point-to-point air mobility without going through a hub
- Cargo delivery services
- Huge emerging market



An artist's concept of UAM

- **CFD Challenges:**

- **Aeroacoustics** – Community noise and its control, a huge issue
- **Unsteady Flow** – Maneuvering vehicles will have unsteady flow separation and will benefit from flow control
- **Boundary Layer Transition** – Smaller vehicles will have both laminar and turbulent flow
- **Flow/structure interaction**



Cora, an electric air taxi designed by Kitty Hawk

UAM companies have used NASA codes FUN3D and OVERFLOW for aerodynamic design



Transformative Aeronautics Concepts Program



MISSION: Pursue rapid, proof-of-concept ideas in a high-risk and reward environment in order to inspire new solution paths, promote innovative design, and enable technology breakthroughs

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** across disciplines and advanced methods

APPROACH:

- Fostering innovative solutions
- **Explore never-done-before tools**
- Investing in advanced technologies
- **Challenging internal and 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 (T³) 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 (UI) 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.

T³ 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.

Autonomous Systems

Foundational research to enable increased autonomy in aviation. Currently being planned.

CFD Vision 2030 Study Summary



CFD Vision 2030 Study

RCA's Research Planning Guide



NASA CR 2014-218178



NRA awarded:
9/30/2012

Report published:
3/19/2014

- **The study was conducted:**
 - “...to 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**.”

An industry-universities team led this study with CFD community input

- **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**
- **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.**
- **Report recommendations inform T³ project planning**



NASA CR 2014-218178

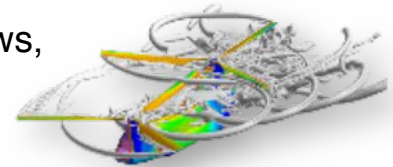
Report available at:

<https://www.nasa.gov/aeroresearch/programs/tacp/ttt/cfd-vision-2030-study>

Vision of CFD in 2030

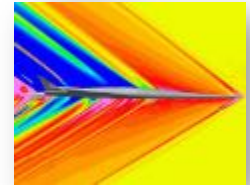
- **Emphasis on physics-based, predictive modeling**

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.



Technology Development Roadmap

TRL ■ LOW
■ MEDIUM
■ HIGH

◇ Technology Milestone

★ Technology Demonstration

⊕ Decision Gate

2015

2020

2025

2030

HPC

CFD on Massively Parallel Systems

PETASCALE

Demonstrate implementation of CFD algorithms for extreme parallelism in NASA CFD codes (e.g., FUN3D)

Demonstrate efficiently scaled CFD simulation capability on an exascale system

30 exaFLOPS, unsteady, maneuvering flight, full engine simulation (with combustion)

CFD on Revolutionary Systems (Quantum, Bio, etc.)

PETASCALE

Demonstrate solution of a representative model problem

NO

YES

NO

YES

EXASCALE

Physical Modeling

RANS

Improved RST models in CFD codes

Highly accurate RST models for flow separation

Hybrid RANS/LES

Unsteady, complex geometry, separated flow at flight Reynolds number (e.g., high lift)

LES

Integrated transition prediction

WMLES/WRLES for complex 3D flows at appropriate Re

Combustion

Chemical kinetics calculation speedup

Chemical kinetics in LES

Unsteady, 3D geometry, separated flow (e.g., rotating turbomachinery with reactions)

Algorithms

Convergence/Robustness

Automated robust solvers

Grid convergence for a complete configuration

Multi-regime turbulence-chemistry interaction model

Production scalable entropy-stable solvers

Uncertainty Quantification (UQ)

Characterization of UQ in aerospace

Reliable error estimates in CFD codes

Uncertainty propagation capabilities in CFD

Large scale stochastic capabilities in CFD

Geometry and Grid Generation

Fixed Grid

Tighter CAD coupling

Large scale parallel mesh generation

Automated in-situ mesh with adaptive control

Adaptive Grid

Production AMR in CFD codes

Knowledge Extraction

Integrated Databases

Simplified data representation

Creation of real-time multi-fidelity database: 1000 unsteady CFD simulations plus test data with complete UQ of all data sources

Visualization

On demand analysis/visualization of a 100B point unsteady CFD simulation

On demand analysis/visualization of a 100B point unsteady CFD simulation

MDAO

Define standard for coupling to other disciplines

High fidelity coupling techniques/frameworks

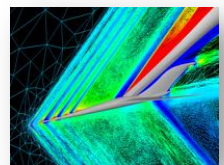
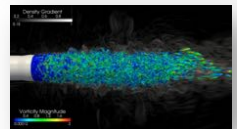
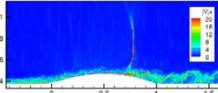
Incorporation of UQ for MDAO

MDAO simulation of an entire aircraft (e.g., aero-acoustics)

UQ-Enabled MDAO

CFD Vision 2030 Study Findings

- The **accuracy of CFD** in the aerospace design process is severely limited by the **inability to reliably predict turbulent flows** with significant regions of **separation**
- **HPC hardware is progressing rapidly** and technologies that will prevail are difficult to predict
- **Revolutionary algorithmic improvements** will be required to enable future advances in simulation capability
- **Mesh generation and adaptivity** continue to be **significant bottlenecks** in the CFD workflow, and very little government investment has been targeted in these areas
- Managing the **vast amounts of data** generated by current and future large-scale simulations will continue to be problematic and will become increasingly complex due to changing HPC hardware
- Technology advances are required to enable increasingly **multidisciplinary simulations**, for both **analysis and design optimization purposes**





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.

T³ CFD Validation Experiments

• 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

• Turbulent Heat Flux (THX) Experiment

- Need experimental data for CFD of turbulent heat transfer

• Shock Wave/Boundary Layer Interaction

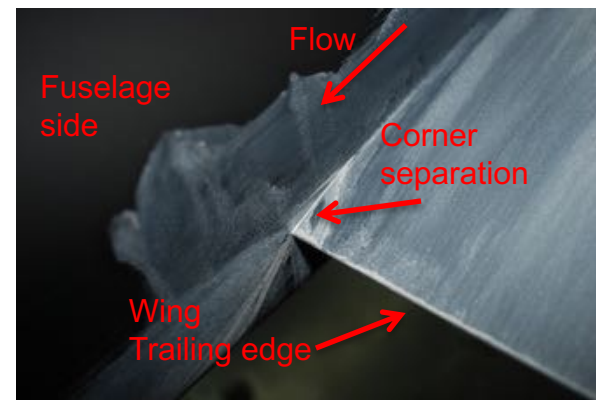
- Mach 2.5 Axisymmetric SBLI (attached and separated)
- Mean and turbulent stress data

• “2D” Separation

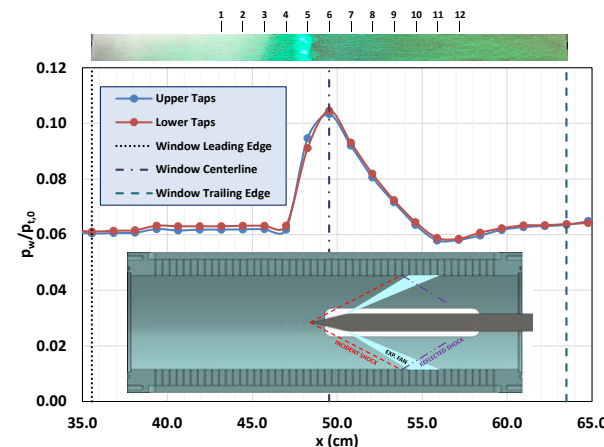
- NRA to Notre Dame (Flint and Corke)
- Data for attached and separated (incipient, small, large) flow

• 2D Compressible Mixing Layer

- NRA to U-Illinois (Dutton and Elliott)
- Full documentation of BC and mean/turbulence data



Experimental surface flow visualization

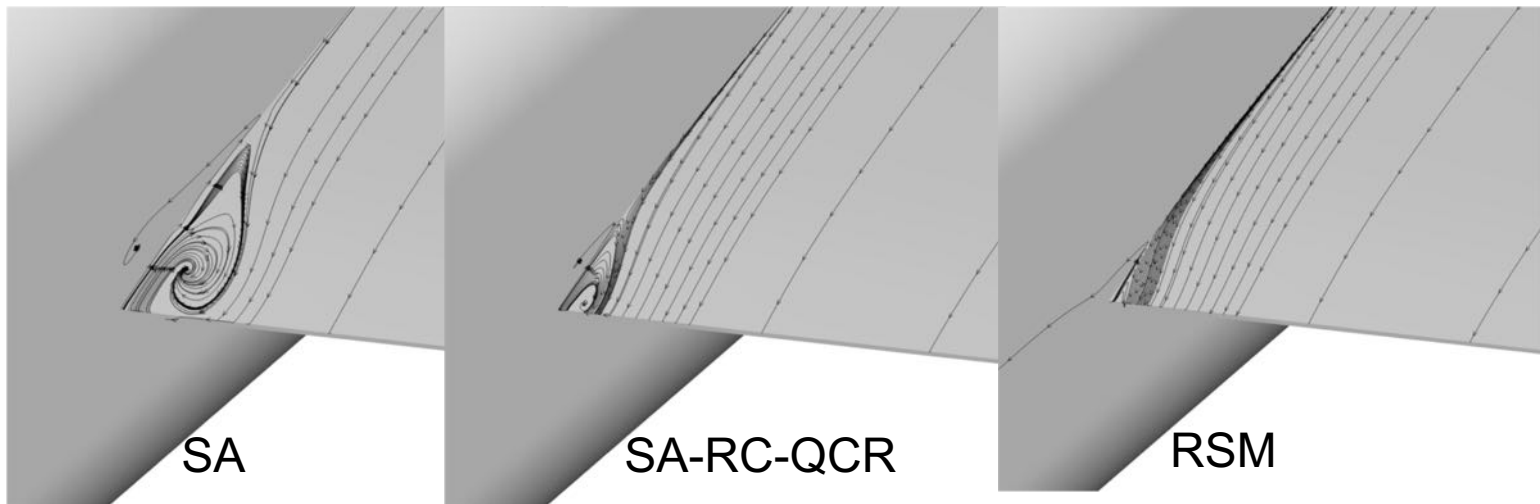


Axisymmetric SWBLI – 13.5° Cone Angle

A CFD Validation Experiment should include the measurement of all information, including boundary conditions, geometry information, and quantification of experimental uncertainties, necessary for a thorough and unambiguous comparison to CFD predictions.

NASA Juncture Flow Experiment

- Geometric junctures (corners) are common on aircraft
 - CFD predictive capability is currently uncertain
 - For example, in Drag Prediction Workshops (DPW), participants predicted a wide range of wing-body corner separation bubble sizes (none to very large)
- Because of the high degree of uncertainty in the CFD predictions, relevant separated corner flow experiments focused specifically on obtaining high-quality data for CFD validation are needed



Example juncture flow computations using 3 different turbulence models

NASA 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



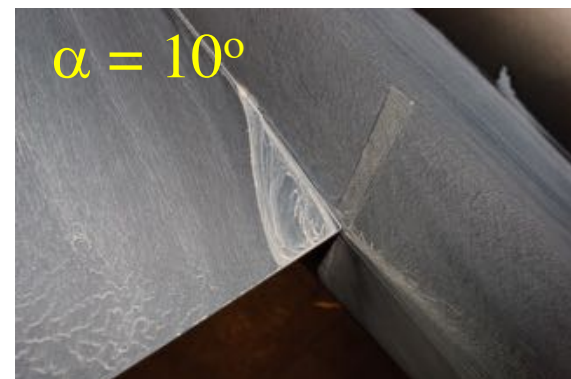
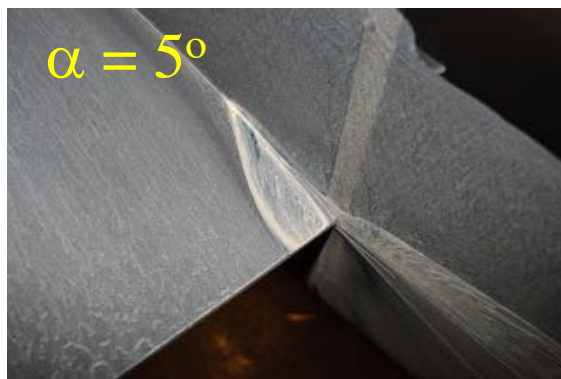
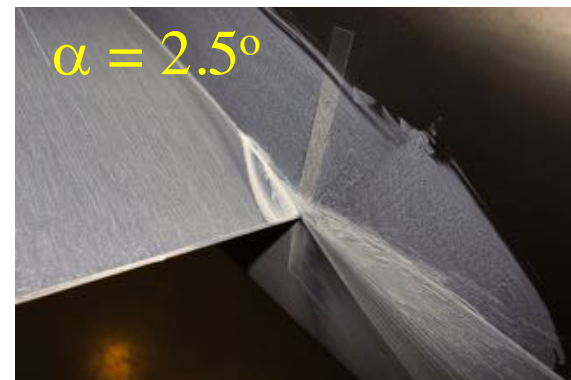
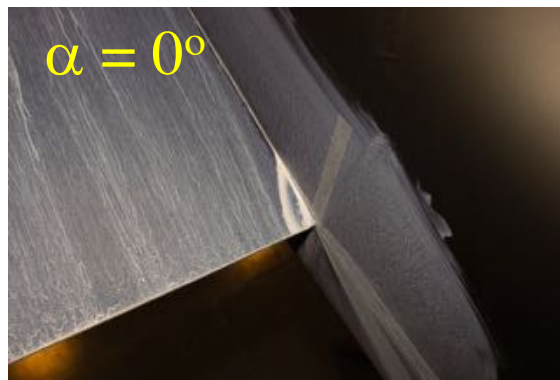
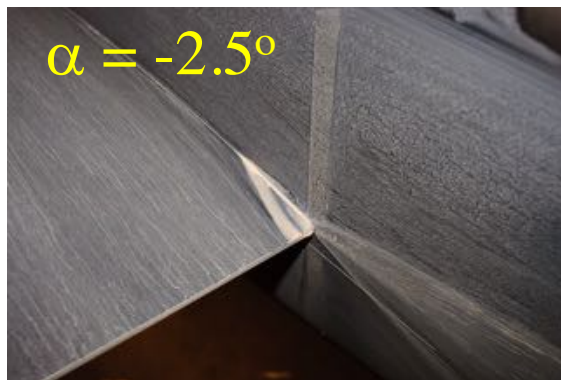
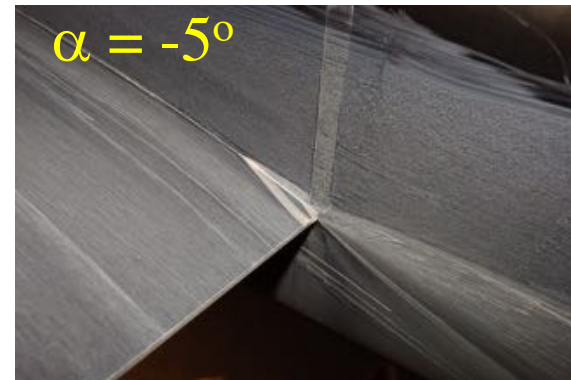
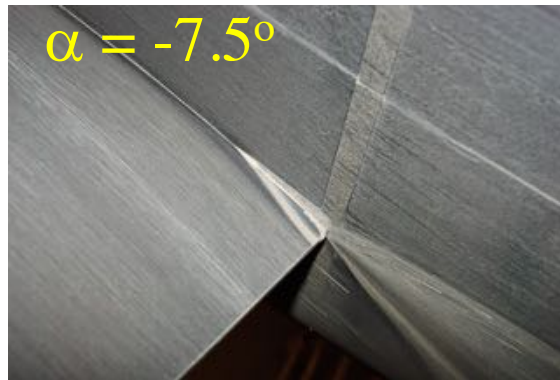
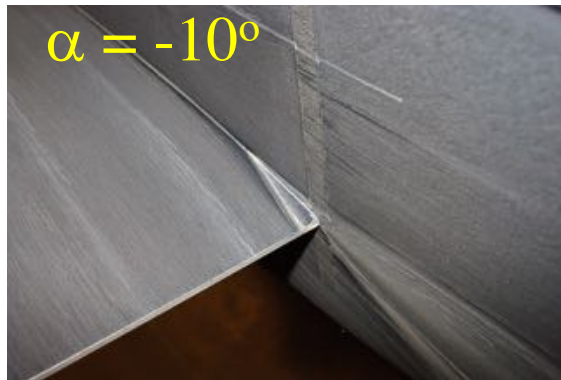
2.5% Juncture Flow Model in the VA Tech 6-foot Stability Wind Tunnel Aug 2015

Model loaned to VA Tech for further testing and educational use



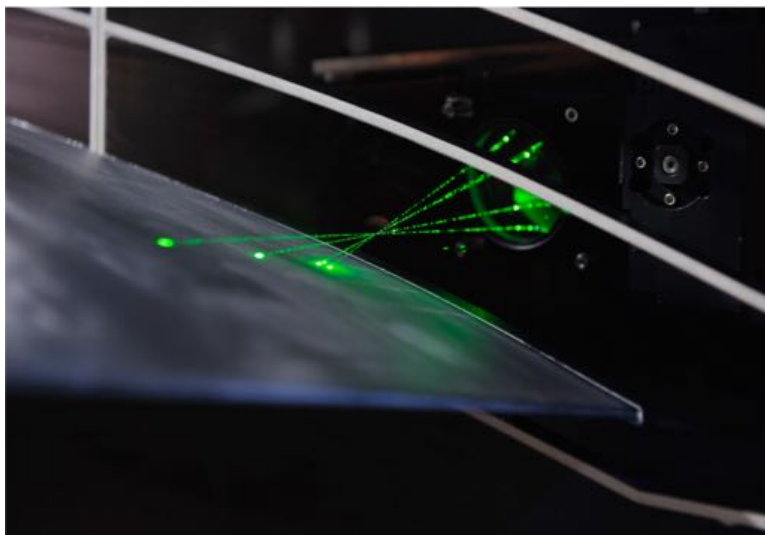
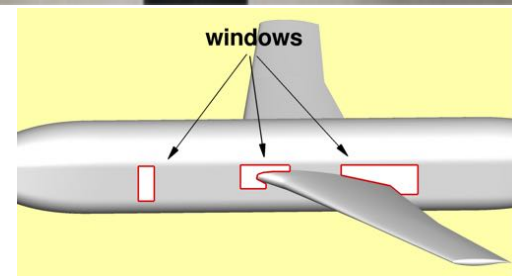
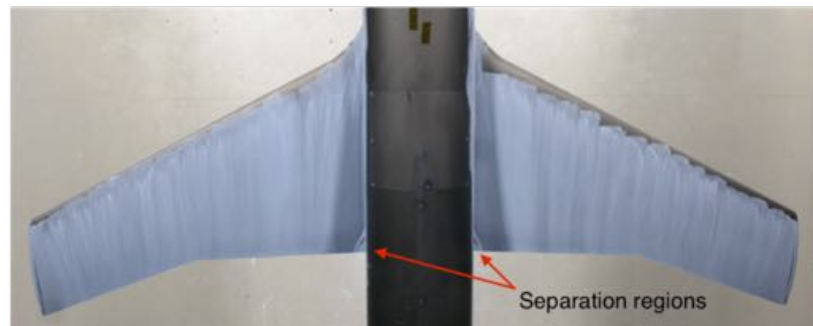
6% Juncture Flow Model in the LaRC 14'X22' Wind Tunnel Nov/Dec 2015







NASA Juncture Flow Experiment

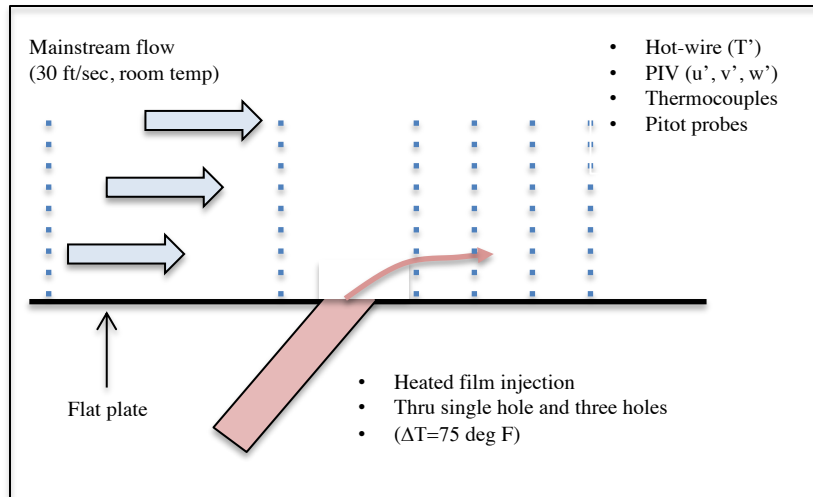


Turbulent Heat Flux (THX) Experiments

Data for improving models for turbulent heat flux and cooling hole boundary conditions. High-quality flow field data includes: Mean velocities and temperatures, turbulent statistics – using PIV and Raman; surface temperatures using TCs and IR imagery. Well documented inflow conditions for CFD modeling. Experimentalists and CFD modelers involved in all aspects of experiments from test planning through experimentation.

TESTING

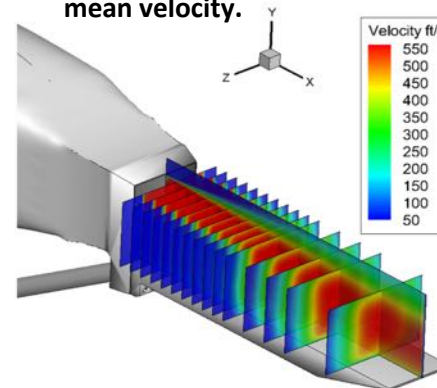
- Phase 1 experiments: low speed/temperature cooling flow
- Phase 2 round jet experiments: Maximum $T_t=1000$ K and jet Mach = 0.9 - NASA GRC Acoustic reference nozzle (ARN)
- Phase 3 square nozzle with plate having single cooling injector (similar flow conditions as step 2, multiple blowing ratios)
- Phase 4 same nozzle as Phase 3, 3 arrays of 45 cooling holes - hardware fabrication completed; tests scheduled in AAPL May-June 2018.



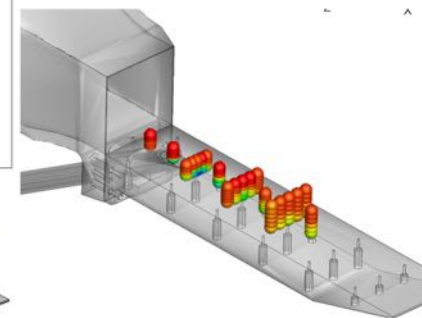
THX Phase 3 nozzle and plate (single injector hole) installed in NASA GRC AAPL facility.



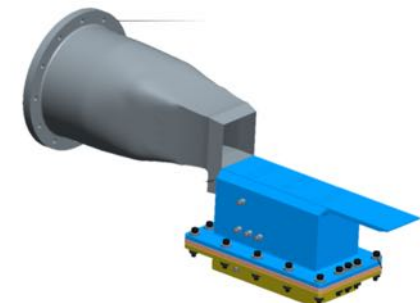
PIV measurements of mean velocity.



Raman measurements of mean temperature.



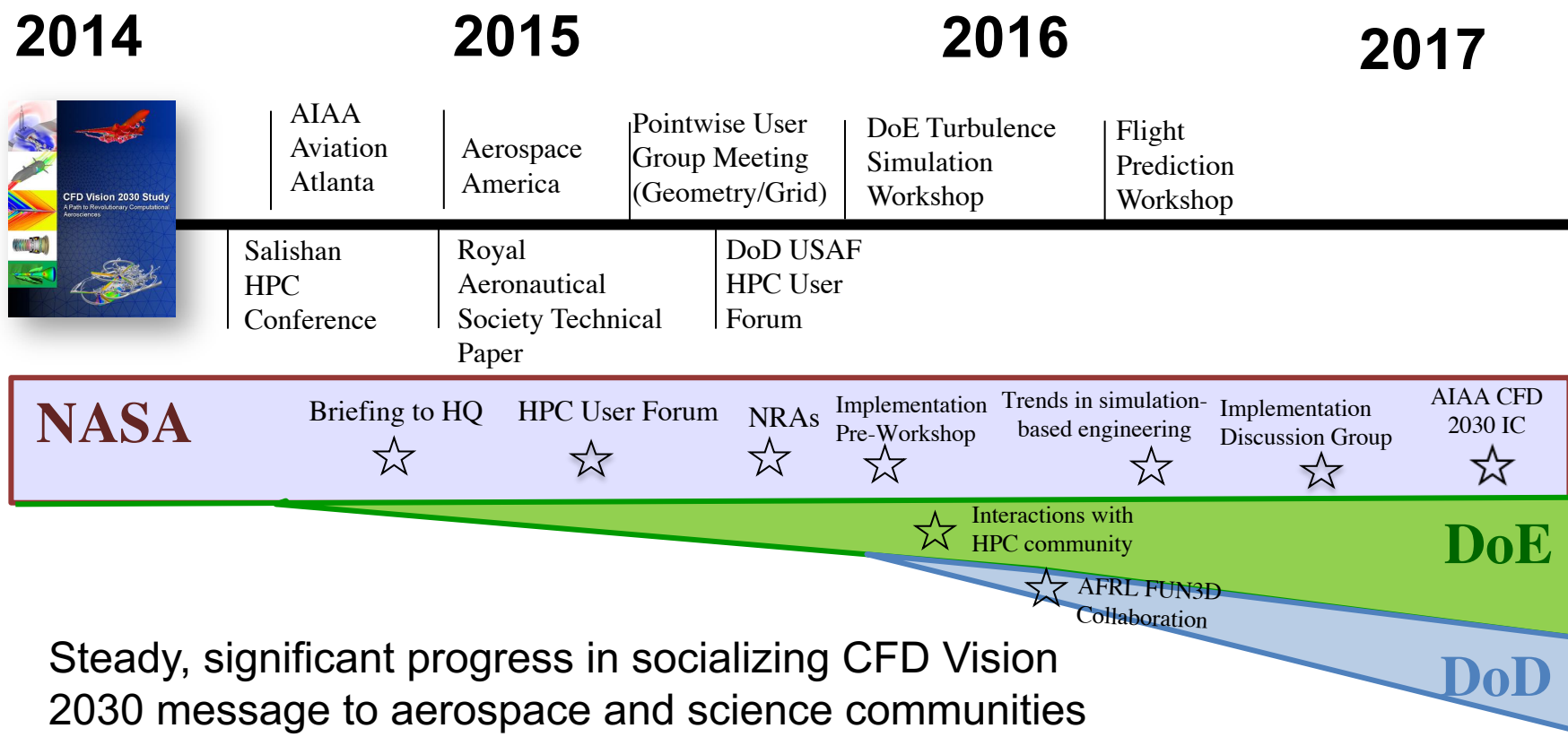
THX Phase 4 plate concept (3 arrays of cooling holes).



POC: Nick Georgiadis (GRC), Mark Wernet (GRC), and Randy Locke (GRC/VPL).



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



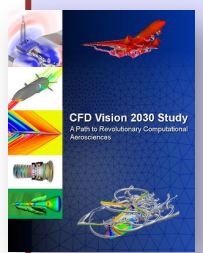
CFD 2030 Activities Since Report Release



2014

2016

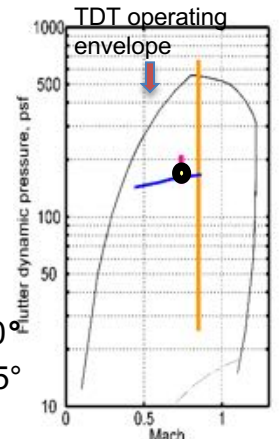
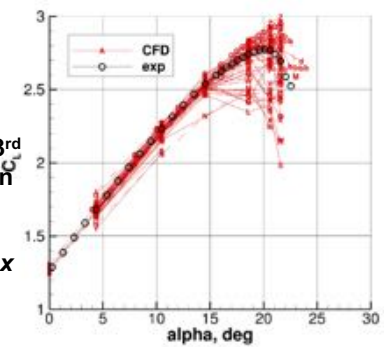
2018



Flight Prediction Workshop May 2016	Symposium on "Advances in Turbulence Modeling" July 2017	AIAA CQbA Community of Interest meeting January 2018	CFD Prediction Error Assessment Workshop March 2018	AIAA CQbA Community of Interest kickoff June 2018
Invited sessions AIAA Aviation June 2016, 2017, 2018	Transition Prediction Workshop September 2017	NASA/Boeing CbA Workshop April 2018	NASA/PW/UTRC virtual meeting May 2018	

Technology areas requiring research and development:

- Accurate prediction of CL_{max} , buffet and flutter
- Accurate prediction of complex flows:
 - Thermal shear layers
 - Corner flows
 - Inlet distortion/BLI
 - Turbomachinery
- Reduce start to finish analysis time/increase HPC efficiency
- Uncertainty quantification/data fusion/ROM
- Aeroelastic/aeroacoustics predictions



- Results from AePW-2, showing large scatter at transonic conditions:
- Experiment
 - Linear Analysis
 - CFD Mach 0.74, $\alpha = 0^\circ$
 - CFD Mach 0.85, $\alpha = 5^\circ$

Use of CFD at corners of the flight envelope will require more use of unsteady analysis and improved physical models

T³ Technical Challenges (TCs) Supporting CFD Vision 2030



Revolutionary Tools & Methods TCs

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.	<u>Physical Modeling:</u> 1. Advanced RANS 2. Large eddy simulation (LES) 3. Hybrid RANS/LES approaches 4. Validation experiments for turbulence and transition <u>Algorithms:</u> 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.	<u>MDAO:</u> 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%.	<u>Physical Modeling:</u> 1. Develop turbulent combustion models, including chemistry, spray, soot 2. Large eddy simulation methods for combustion 3. Validation experiments, with multiple fuels



CFD Prediction Error Assessment Workshop

March 2018



An external peer review panel, consisting of experts from academia and industry, assessed the progress of the completed TC and provided a report

Was the 40% challenge successful?

“The metric was quantitatively specific, making the challenge quite ambitious. Our assessment of whether the goal was achieved is a qualified **yes**: the results have identified a clear need to further refine and pursue these goals.

- i) RANS models have shown the potential to be more accurate when suitably tailored, but most of the improvements remain problem-specific,
- ii) The potential of intermediate level fidelity (WMLES and HRLES) was demonstrated, but model sensitivity needs extensive further assessment,
- iii) High-fidelity methods (WRLES) of impressive size were shown to be clearly capable, but grid convergence and expense considerations require more work even for moderate Reynolds numbers.”

Proposed Technical Challenge: Develop, implement, and validate computationally efficient physics-based methods and tools that reduce error in predicting aerodynamic stall, buffet, flutter and propulsion system performance, to enable novel efficient aircraft designs and aircraft certification by analysis.

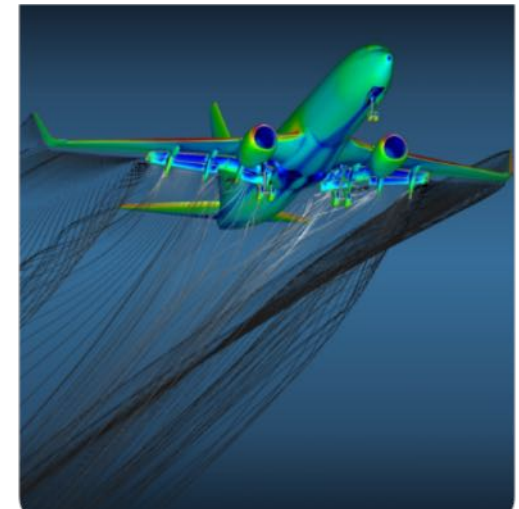
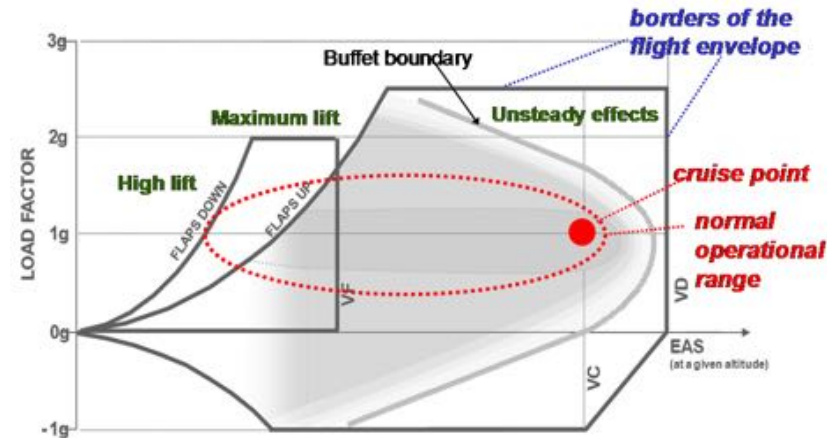
- Directly supports new Design and Development Methods Critical Commitment
- Expands capability of CFD to predict unsteady phenomena such as stall, buffet, and flutter
- Includes focus on low-speed, high-lift flight, a multidisciplinary challenge that accounts for up to two-thirds of flight certification test points

Technical Areas and Approaches

- LES and RANS/LES hybrid approaches for unsteady flows
- Data-driven turbulence modeling, using machine learning tools
- Accurate, efficient, and robust higher-order computational methods
- Effective utilization of emerging HPC hardware
- Reliable and effective grid generation and adaptation
- Reliable uncertainty quantification and error estimation
- Laminar-turbulent transition modeling
- CFD Validation Experiments
- Demonstration of new computational methods for CL_{max} , buffet, flutter and aeropropulsion predictions

Benefit/Pay-off

- Enables improved and accelerated multidisciplinary designs, reduced certification flight test, and substantial cost savings.





Issues with Certification by Analysis (CbA)

White Paper on “Establishing Comprehensive Recommended Practices on the Use of Certification/Qualification by Analysis to Reduce Verification Flight Testing,” March 2018

- **Issues that prevent larger scale use of computational simulation data for certification include:**
 - Numerical simulation, especially CFD, still has accuracy limitations, particularly near the edges and off-nominal areas of the flight envelope. Limited validation of current-generation tools has been performed away from nominal flight conditions.
 - There is a general lack of robustness and consistency of the computational analysis process. Numerical accuracy, especially in the application of CFD, is often dependent on the expertise of the specific user and method or process being utilized.
 - Varying levels of geometric simplification often result in the potential loss of modeling fidelity required to capture the essential physics in CFD simulations of real aircraft and/or engine configurations. Accurate modeling of all relevant geometric features is critical in using numerical simulation to correctly predict flight characteristics.
 - There is a general lack of trust and understanding of the use of analysis tools specifically for regulatory certification and compliance.

RCA's Technical Challenge is designed to overcome these issues, enabling computational simulations to provide data for Certification by Analysis rather than by flight testing.

Technical Challenge:

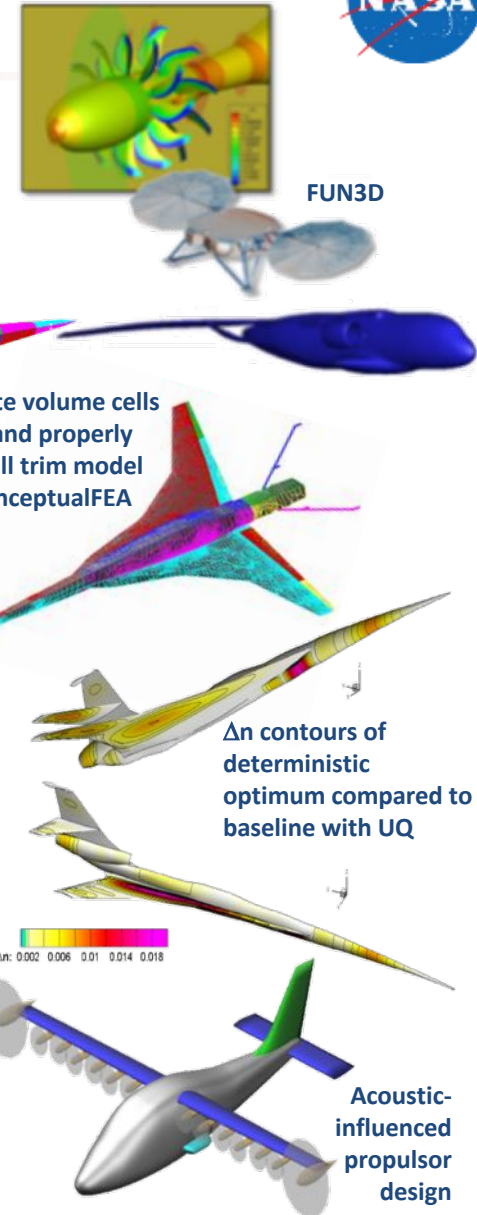
Develop advanced design and optimization tools for coupled multidisciplinary analysis with a range of fidelities to shorten the design cycle of revolutionary new vehicles. Use X-Plane ground and flight test data to validate the implementation of critical physics required to model new concept aircraft.

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.





Progress Indicator Chart: Multi-disciplinary Design, Analysis, and Optimization (MDAO)

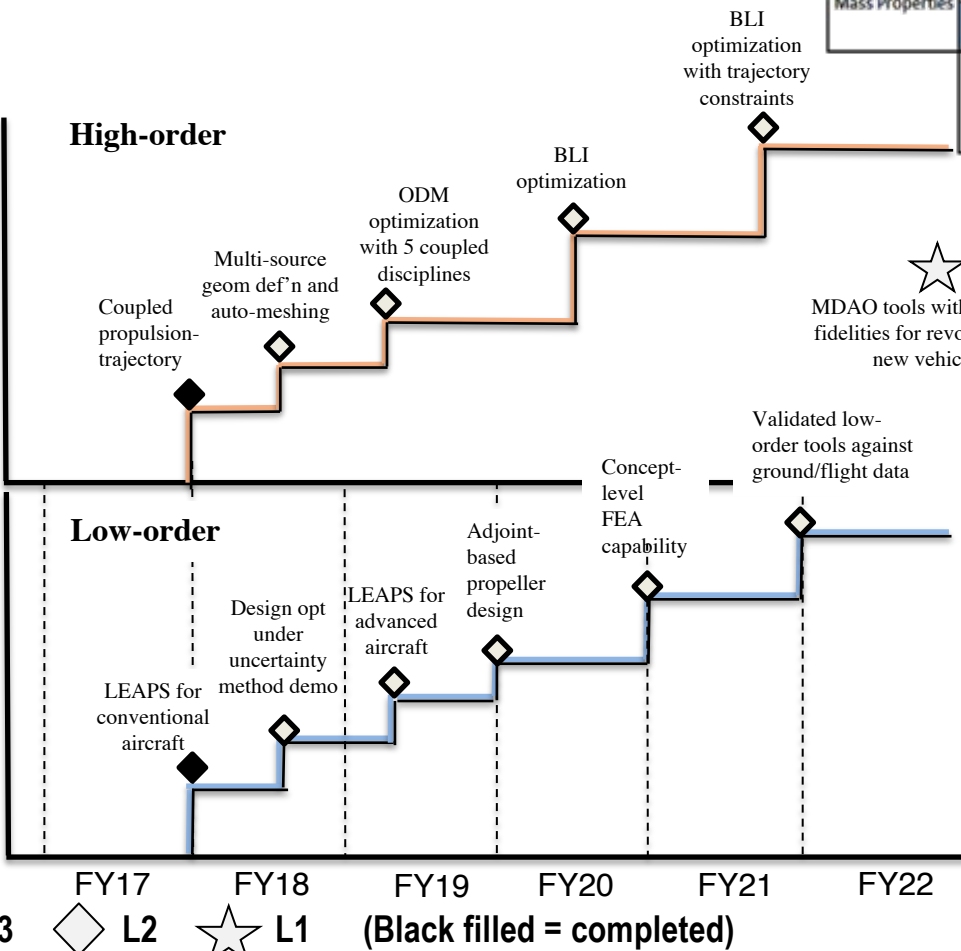


Targeted Disciplines for Coupled Analysis/Optimization for N+3 Vehicles

Notional Cumulative Progress

High-order tools N+3 capability added

Low-order tools N+3 capability added



Mission/ Trajectory	Mass Properties	Aero	Propulsion	Structures	Elasticity	Acoustics	Thermal
Mission/ Trajectory		70%					
	40%	30%	20%			10%	
Mass Properties				50%			20%
	30%	30%	30%				
Aero		50%			10%	20%	10%
	30%	30%				10%	
Propulsion							20%
			20%			10%	
Structures					30%		
Elasticity							
Acoustics							
Thermal							

	Progress	Criteria
Formulation	10%	Early design/formulation
	20%	Mature design/formulation
	30%	Stand-alone/unit testing
Integration	40%	Early toolset integration
	50%	Mid toolset integration
	60%	Mature toolset integration
Testing	70%	Early verification testing
	80%	Mature verification testing
	90%	Early validation testing
	100%	Completed validation testing

T³ Combustion Modeling

Technical Challenge TACP04:

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

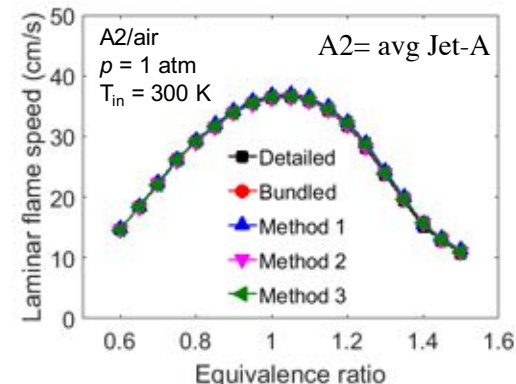
Technical Areas and Approaches:

- Develop chemistry, spray, soot, 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
- Conduct experiments (GRC, NRAs, and NJFCP partners) with multiple fuels (or surrogates) to provide validation data
- Develop combustor-turbine LES capability addressing compact engine core challenges for high OPR or hybrid-electric

Benefit/Pay-off:

- Streamline ASTM fuel certification process (NJFCP)
- Accelerate use of alternative fuels and increased blend ratios of alternative fuels with conventional Jet-A (ARMD Thrust 4)
- Tools to optimize combustor to fuels (or fuels to combustor)
- Advances in chemistry, spray, and turbulent combustion models expected to improve NO_x emission prediction capabilities (ARMD Thrust 2 and 3)

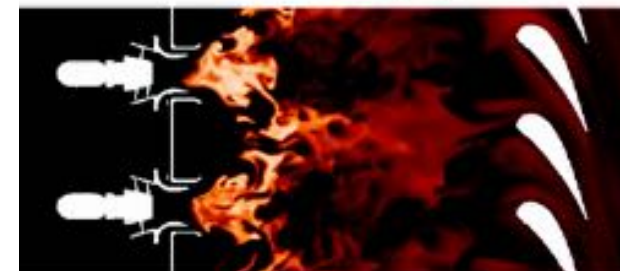
Validate up to 56x speedup of transport property evaluations for reduced chemistry



Premixed stretch-stabilized flames doped with Jet A or distillate fractions



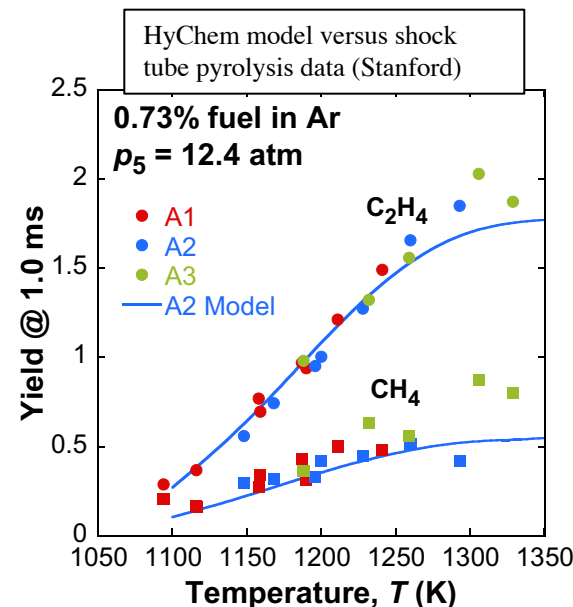
Time-Filtered OpenNCC simulation of
 EEE combustor and 1st stage HPT vanes



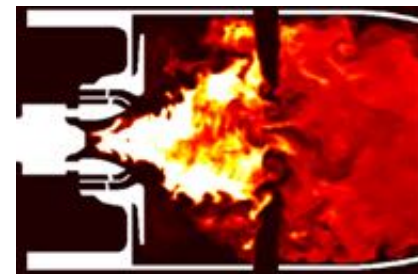
Combustion Modeling – Highlights

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

- **Chemistry Modeling:** Validated that Hybrid Chemistry approach can predict fuel sensitivity of fuel pyrolysis and ignition delay time. HyChem models created for conventional and alternative fuels were reduced to 26 – 31 species, and transferred to GRC and NRA CFD teams for LBO simulations.
- **Soot Modeling:** Completed experiments quantifying impact of light and heavy end of Jet-A distillation species on soot production and demonstrating need for multi-component spray evaporation models to accurate soot nucleation predictions.
- **CFD Modeling:** Achieved coordination of four teams (GRC, Stanford, GTech, UTRC) to use same grid, boundary conditions and spray injection for simulating LBO experiments in NJFCP referee rig for Jet-A and two alternative fuels. Provides consistent basis to evaluate impact of chemistry and turbulent-chemistry modeling on LBO predictions. Simulations are underway.
- **Spray Modeling:** Validated key components of LES spray atomization sub-grid turbulence modeling and dense spray region of atomization process.



Instantaneous temperature contours from LES of Referee Rig at near LBO condition

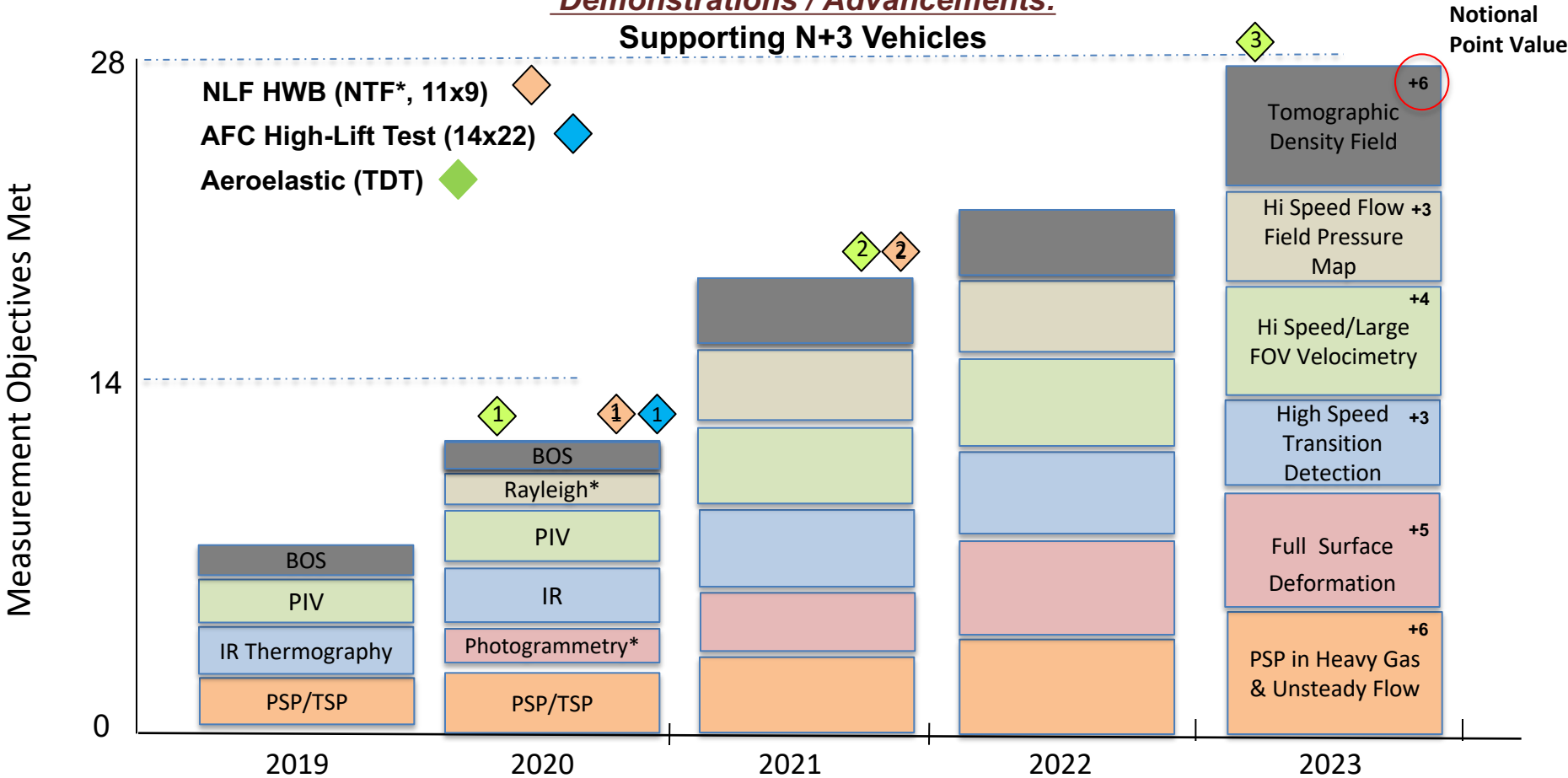




Progress Indicator Chart: Innovative Measurements Technical Challenge

Technical Challenge: Develop new and improved non-intrusive measurement technologies to support and validate flowfield and structural measurements of velocity, temperature, density, pressure, and deflection. Demonstrate new or fivefold improvement in existing techniques in terms of accuracy, precision, efficiency, bandwidth, spatial resolution, or temporal resolution over the current state-of-the-art** supporting planned ARMD unsteady flowfield validation experiments.

Technology
Demonstrations / Advancements:
Supporting N+3 Vehicles



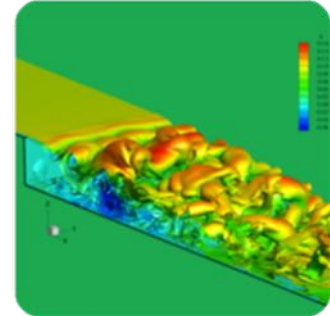


Implementation Plan, Going Forward

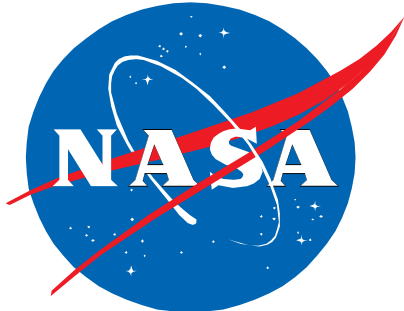
- **Review/update CFD Vision 2030 roadmap every 5 years**
 - Current T³ priorities encapsulated in the 4 Technical Challenges
 - Review progress and adjust research portfolio periodically to maximize impact on CFD Vision 2030 objectives
- **Explore collaborative opportunities with OGAs more aggressively**
 - Order of magnitude more DOD and DOE investment in HPC
- **Leverage CFD community activities through AIAA**
 - Focused workshops, special sessions, Integration Committees, Communities of Interest
- **Seek opportunities to interact with international experts**
 - European institutions leading in certain areas
- **Awarding additional NRA awards in CFD Vision 2030 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

Summary

- **Working towards Certification by Analysis, to significantly reduce flight testing**
 - Accurate prediction of smooth body flow separation, CL_{max} , buffet, and aeropropulsion performance
 - Orders of magnitude speed up, with algorithms and hardware
 - *Needed for eddy resolving simulations, aero database generation, high-fidelity MDAO, and uncertainty quantification*
- **New, high-quality CFD validation data is critical for development of physics-based prediction tools**
 - NASA generated data will be shared with CFD community at large
 - Encourage others to conduct CFD validation experiments
- For more information:
 - <https://www.nasa.gov/aeroresearch/programs/tacp/ttt>
 - michael.m.rogers@nasa.gov

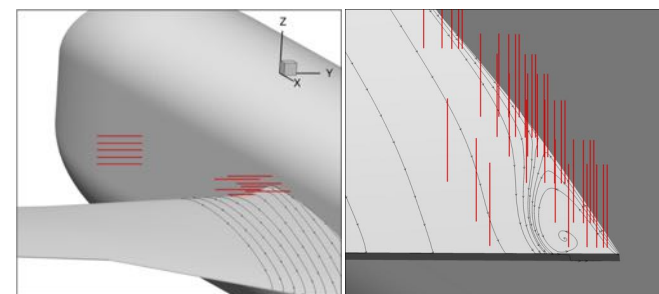
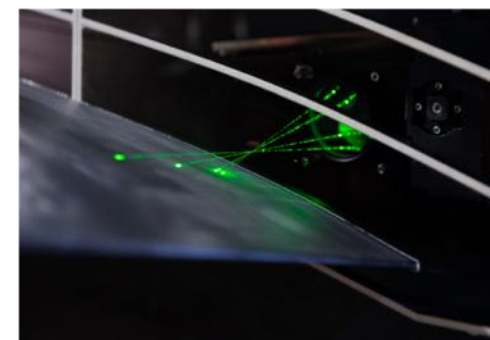
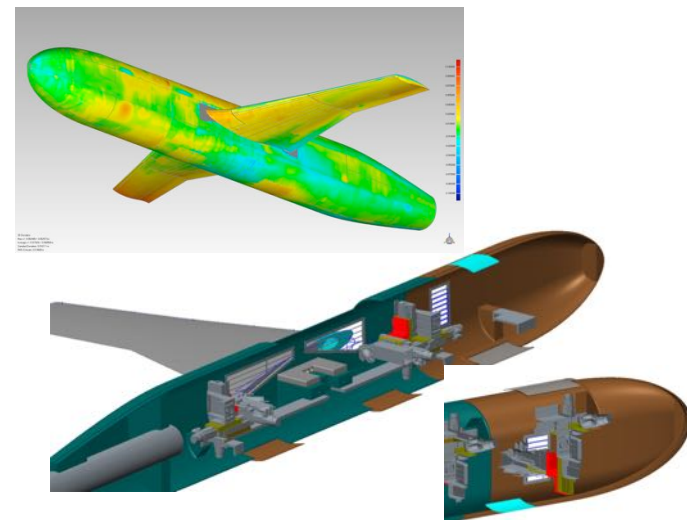


Development of Computational Tools will Enable Aircraft Certification by Analysis and Design of New Aerospace Configurations



Juncture Flow Experiment - 2

- Unique on-board Laser-Doppler Velocimetry (LDV) system specifically designed for measuring the near-wall juncture region flow field through windows
- Consistent CFD and wind tunnel experiment
- Data
 - Off-body velocities and moments (LDV and some PIV)
 - Model surface pressures, unsteady surface pressures and surface shear stress measurements
- Boundary conditions
 - Over the body: measurements at front window
 - Test section wall pressures/wall rakes
 - Infrared thermography for transition detection/trip effectiveness
 - Tunnel inflow (measured with Boeing's QWSS in separate tests)
- Geometry
 - Laser scans of tunnel walls, model, and mast/sting/cabling details
 - Photogrammetry to document wing deflections
- Documentation
 - Special session at AIAA SciTech 2019



Notional Measurement Locations



Other RCA Research

- **Turbulence Modeling and Simulations**
 - Modified k-kL model(s) for wall-bounded and free shear flows
 - Lattice-Boltzmann method for unsteady flow simulation
 - Several hybrid RANS/LES approaches (e.g., PANS)
 - Turbulent hot jets
- **Numerical Methods**
 - Stabilized finite-elements (SUPG)
 - Hyperbolic Navier-Stokes (HNS)
 - Space-time flux reconstruction
 - HANIM for convergence acceleration
 - Uncertainty quantification
- **Transition Prediction and Modeling**
 - LASTRAC: Langley Stability and Transition Analysis Code
 - Analysis and control of hypersonic boundary layer transition
 - Supersonic transition experiments with effect of roughness
 - Crossflow transition experiments to study the effect of steps



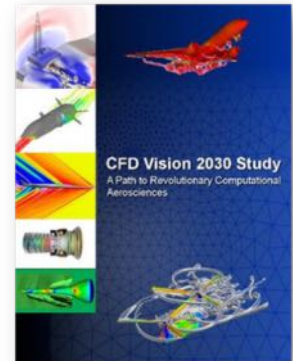
AIAA CFD Vision 2030 Integration Committee



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.

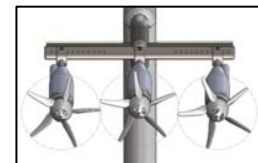
MDAO – FY17 Highlights



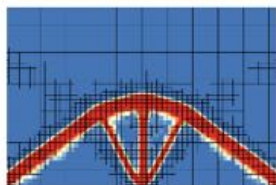
5-bladed high-lift propeller in LSAWT

Acoustics:

- Prediction of Distributed Electric Propulsion (DEP) propeller noise characteristics in software; Wind tunnel test in LSAWT completed for validation data. Work in progress now for multi-prop and prop-wing configurations.
- Integration of human annoyance metrics in coupled ANOPP2-NAF framework.



Virtual rendering of three-propeller rig for LSAWT test



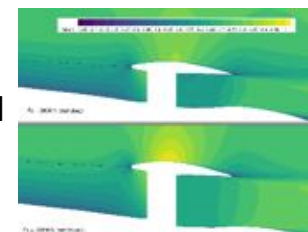
Coupled structural-thermal solution using TACS.



Beam problem solved with new topology optimization natively in OpenMDAO

High-Order-Capable, Multi-fidelity MDAO Tools

- OpenMDAO modeling capability enhancements -- Coupling of key disciplines (Aero-Propulsion, Trajectory-Propulsion, Trajectory-Aero-Thermal, Structural-Thermal) accomplished for high-order-capable MDAO tools targeting eventual coupling of 5 disciplines for conceptual design and optimization.
- Multi-functional structure modeling -- Initial integration of topology optimization methods into OpenMDAO completed to enable generation of multi-functional structures (load-bearing and heat dissipating) lightweight structures.



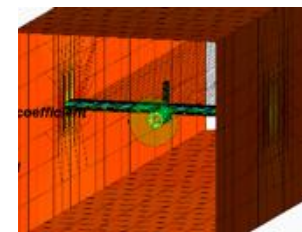
Multi-discipline coupling solution using OpenMDAO

Low-Order Conceptual Design MDAO Tools

- LEAPS Next Generation Aircraft Systems Analysis Software – First results generated using new low-order weight prediction methodology in LEAPS architecture. OpenVSP framework integration architecture design completed and tested in stand-alone environment.
- Distributed Propulsion Design Tool -- Developed a rapid aerodynamic analysis of distributed propulsion interaction with lifting surfaces suitable for parametric analysis capable of modeling arbitrary installation locations of propulsors with respect to the lifting surfaces.



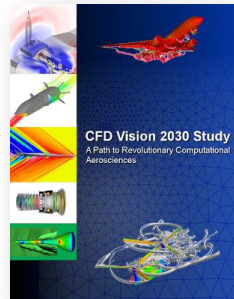
Sample of aircraft that LEAPS will be able to model for rapid concept analysis



Modeling of wing with propeller for comparison with tunnel test.



Nurturing and Growing CFD Vision 2030: Activities in FY 2017



- **Implementation Discussion Meetings (AIAA SciTech 2017; AIAA Aviation 2017)**
 - Group recommended formation of AIAA CFD 2030 Integration Committee (**CFD2030 IC**)
 - Draws members from government, industry, and academia
 - Engages 10 AIAA Technical Committees
 - Proposal submitted to AIAA for approval
- **AIAA Aviation 2017 Special Session** “Capabilities and Challenges in CFD, Academia, Government, and Industry Perspective”
 - 200+ standing room only during presentation on “CFD Vision 2030 and its Implementation”
- **CFD Validation Experiments**
 - Juncture Flow, THX, SWBLI, NRA: separation, compressible free shear layer
- **Computational Aerosciences Framework**
 - Define interfaces for common functionality (Study recommendation #2)
 - Independently developed simulation technologies can be deployed by adhering to defined interfaces → Boeing plans to integrate BCFD into the framework



Nurturing and Growing CFD Vision 2030: Activities in FY 2017 (continued)



- **Transition Prediction Workshop, September 13-14, 2017**
 - Integrated transition prediction capability recommended by the study
 - Over 90 participants from government, industry, academia and international organizations (DLR, ONERA, JAXA)
- **University of Michigan/NASA Symposium on “Advances in Turbulence Modeling”**
 - About 90 attendees from government, industry, and academia, representing modelers, CFD developers/users, and experimentalists
 - Discussed state of the art and the way forward
- **2017 AFOSR High Speed Aerodynamics Portfolio/ONR Hypersonic Portfolio Review**
 - Participated for awareness and leveraging common portfolio
- **Northrop-Grumman Corporation (NGC) Visit**
 - Technical interchange and explored ideas for collaboration
 - Planned collaborative activities in adjoint-based shape optimization
- **Visit by JAXA for Collaborative Activities under CFD Vision 2030**
 - Interested in juncture flow experiment and transition modeling

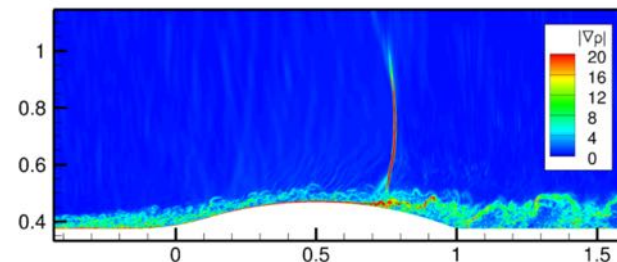
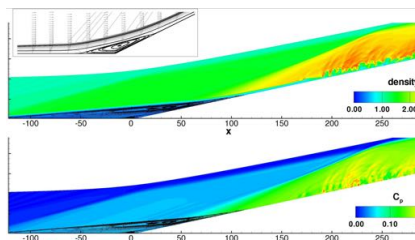
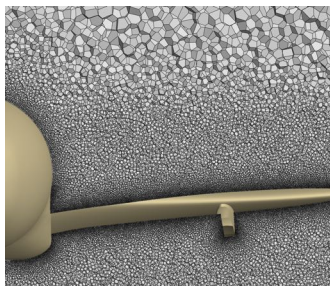


RTM NASA Research Announcements (NRAs)



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





Vision 2040 for Integrated, Multiscale Materials and Structures Modeling/Simulation NRA



Key Element Domains

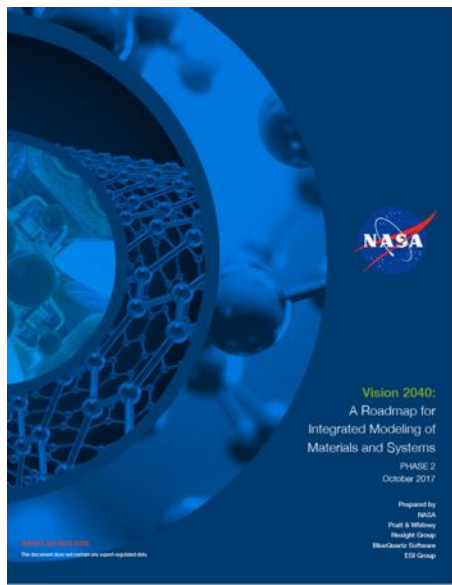
- | | |
|--|---|
| 1. Models and Methodologies | 6. Data, Informatics, & Visualization |
| 2. Multiscale Measurement & Characterization Tools and Methods | 7. Workflows & Collaboration Frameworks |
| 3. Optimization & Optimization Methodologies | 8. Education & Training |
| 4. Decision Making and UQ | 9. Computational Infrastructure |
| 5. Verification & Validation | |

Needed to overcome various gaps and challenges to achieve the fully integrated 2040 Vision end state

Report available at: <https://ntrs.nasa.gov/>

2040 Vision State

A cyber-physical-social ecosystem that impacts the supply chain to **accelerate** model-based concurrent design, development, and deployment of materials and systems throughout the product lifecycle for **affordable, producible** aerospace applications



Pratt & Whitney
A United Technologies Company

NEXIGHT GROUP

esi
get it right®

BlueQuartz
Software

BOEING

Rolls-Royce®

UCSB
UNIVERSITY OF CALIFORNIA
SANTA BARBARA

United Technologies
Research Center

Phase II

Phase I



Vision 2040 for Integrated, Multiscale Materials and Structures Modeling/Simulation NRA



NRA Phase 2 Awarded Sept 2016 – Completion Jan 2018

OBJECTIVE:

Seeking community input to develop *a knowledge-based forecast of the future*:

- Computationally assisted design and certification environment
- **Integrated, multiscale materials and structures modeling**
- Applicable to advanced materials (functional, metallic, ceramic, and polymer matrix composites)
- With a focus on emerging aeronautical vehicle applications
- Achievable by 2040.

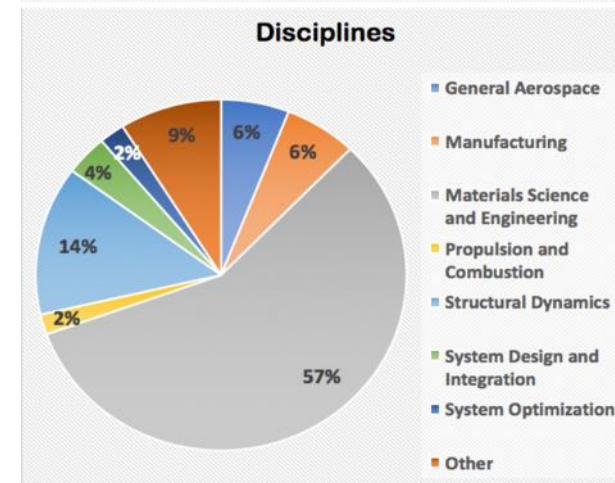
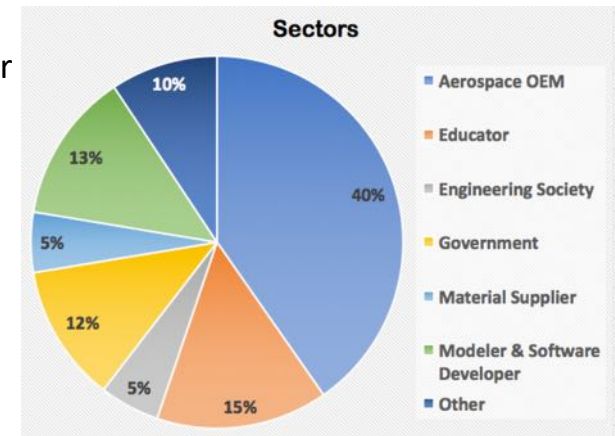
APPROACH:

- Identify core discipline areas, technology gaps, and recommend actions to enable multiscale **coupled material and system** design and analysis
- Study engages *the entire “supply chain” and considers the need for acceptance by regulatory bodies.*

FY 17 NRA PHASE II TASK PROGRESS:

- Established 9 Expert Panels to finalize gaps/actions and obtain consensus
- Held 3 Workshops to gain community consensus on 2040 Vision:
 - AIAA SciTech (Jan 2017)
 - NAFEMS Workshop (March 2017)
 - TMS ICME World Congress (May 2017)
- More than 450 professionals participated in the development of 2040 Vision
- Publication of 2040 report Jan/Feb 2018

2040 Vision Contributor Demographics



Vision 2040 Provides A Community Consensus Viewpoint On Technologies Required To Perform Integrated Multiscale Materials And Structures Modeling in year 2040

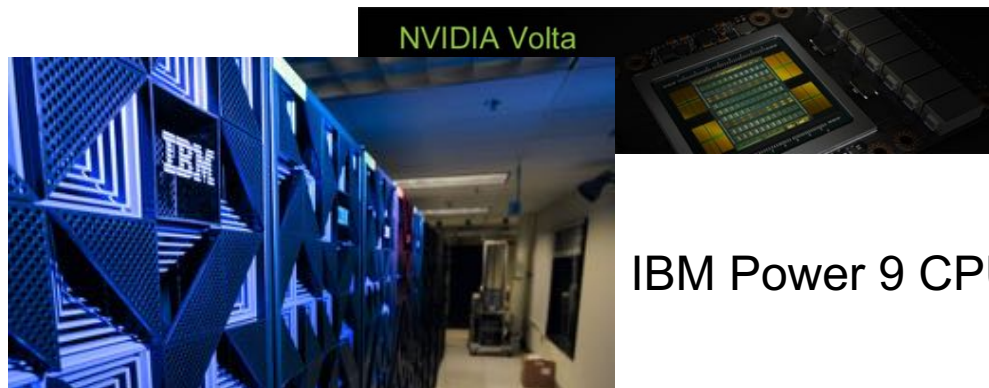


RCA Standard Test Cases

- **Selected after discussions within NASA and with AIAA Turbulence Modeling Benchmark Working Group**
 - Test cases possess the relevant flow physics
 - Simple enough to be useful (avoid complex geometries/additional uncertainties)
 - RANS fail to provide accurate solution
- **“Best” available test cases, but in no way “ideal”**
 - Case 1: “2D” NASA hump
 - Case 2: Axisymmetric transonic bump
 - Case 3: Compressible mixing layer
 - Case 4: Round jets (cold and hot)
 - Case 5: Axisymmetric compression corner
- **Issues**
 - Not necessarily free of WT/facility effects
 - Scale-resolving simulations require more detailed boundary info than RANS
 - Some cases too old → Exercise caution on level of trust put in the results
 - What quantitative metrics for progress assessment?
 - Define some relevant metrics, but allow some leeway and use judgement
 - Note: No test case for BL transition specified
- **Case for new standard/benchmark experiments**
 - Leverage advances in measurement techniques

High Performance Computing (HPC)

- HPC hardware is changing rapidly, exascale in next 3-5 years
 - Improve performance of existing CFD solvers (e.g., FUN3D) on the new hardware
 - New solvers (e.g., GFR, *Eddy*) that more efficiently exploit emerging hardware capabilities



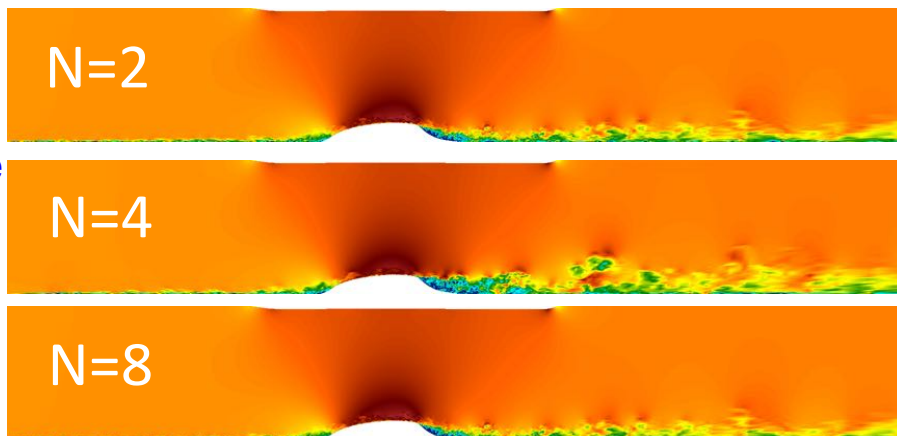
IBM Power 9 CPUs + NVIDIA V100

- Summit at ORNL: 122 PFlop/s on Linpack
 - No. 1 on Top 500 list, as of June 2018
 - 4096 nodes = 24,576 GPUs $\approx$ 20 Pleiades
 - 95% of Summit's compute is on the GPUs

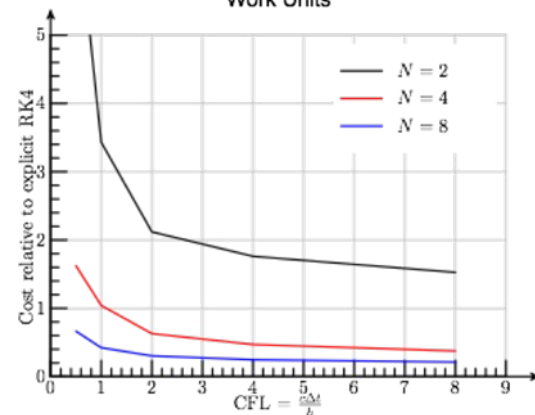
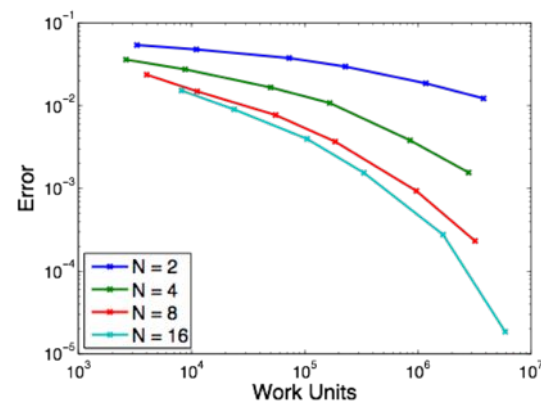
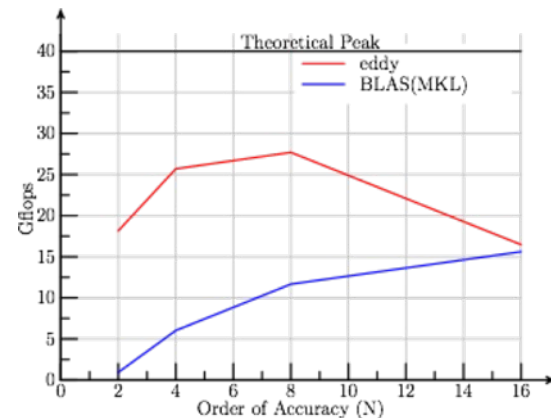
Eddy Solver

- **Eddy is an infrastructure based on the spectral-element method for scale resolving simulations**

- Fully implicit space-time, entropy stable formulation
- 70% of machine theoretical peak on Intel hardware
- Better match for emerging HPC hardware
 - Less data movement, more flops for the same level of accuracy
- For high order, same error as low order, for orders of magnitude less CPU time
- Same memory usage and better efficiency than explicit schemes



More fine scale structures with increasing N





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 RCA NRAs

NASA Research Announcements (NRAs) provide a mechanism to collaborate with academia and industry, a recommendation of the CFD Vision 2030 Study
(9 NRAs awarded in response to the 2015 solicitation)

Turbulence Modeling/Simulations:

- Validation of Wall Models for LES with Application to NASA Common Research Model; [Stanford U \(Parviz Moin\)](#)
- Novel Hybrid RANS/LES Models for Aerodynamic Flows; [UT Austin \(Rober Moser\)](#).
- Spatiotemporally Adaptive Variable Fidelity Approach to Modeling and Simulation of Complex Turbulent Flows; [U Colorado \(Peter Hamlington\)](#)

Numerical Methods/Grid Generation:

- Development of Scalable Solvers for Current and Emerging Steady-State and Time-Dependent Discretizations; [U Wyoming \(Dimitri Mavriplis\)](#)
- Swept Time-Space Domain Decomposition Rule for Breaking the Latency Barrier; [MIT \(Qiqi Wang\)](#).
- Extreme-scale parallel mesh generation: CFD 2030 vision; [ODU \(Nikos Chrisochides\)](#).
- Distributed Multi-processor Geometry Environment to Support Design and Analysis on Extreme-scale Grids; [Syracuse U \(John Dannenhoffer\)](#).

CFD Validation Experiments:

- Benchmark Smooth Body Flow Separation Experiments For CFD Validation; [U Notre Dame \(Flint Thomas\)](#).
- Benchmark Experimental Measurements of Turbulent, Compressible Mixing Layers for CFD Validation; [U Illinois \(Craig Dutton\)](#)



RCA NRAs – 5 New Topics in the 2018 Solicitation

Large number of proposals indicates continued academic community interest in RCA research

- **Requirements for Aircraft Certification by Analysis**
 - Number of proposals = 2
- **Accurate and Efficient Models for Scale Resolving Simulations**
 - 27
- **Sensitivity Derivatives for Chaotic Unsteady Fluid Dynamics**
 - 13
- **Order $N (\ln N)^p$ CFD Solvers for Exascale Architectures**
 - 6
- **Benchmark Experiments for CFD Validation**
 - 9



SBIRs



NASA's Small Business Innovation Research (SBIR) Program provides a mechanism to leverage expertise available at small businesses
(2 Phase II SBIRs to be awarded in the grid generation area)
(Phase I SBIR proposals under review)

- **Leverages Agency SBIR Funds**

- CFD Vision 2030 advocacy helped secure the grid generation subtopic

- **SBIR 2017 Phase II Proposals Selected for Award**

- HeldenSurface: A CAD Tool to Generate High Quality Surfaces ([Helden Aerospace Corporation](#))
- High Order Mesh Curving and geometry Access ([Pointwise, Inc.](#))

- **SBIR 2018 Phase I Solicitation Topics**

- Grid generation for scale resolving simulations
- Multi-fidelity computational and experimental data fusion



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



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 T³/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

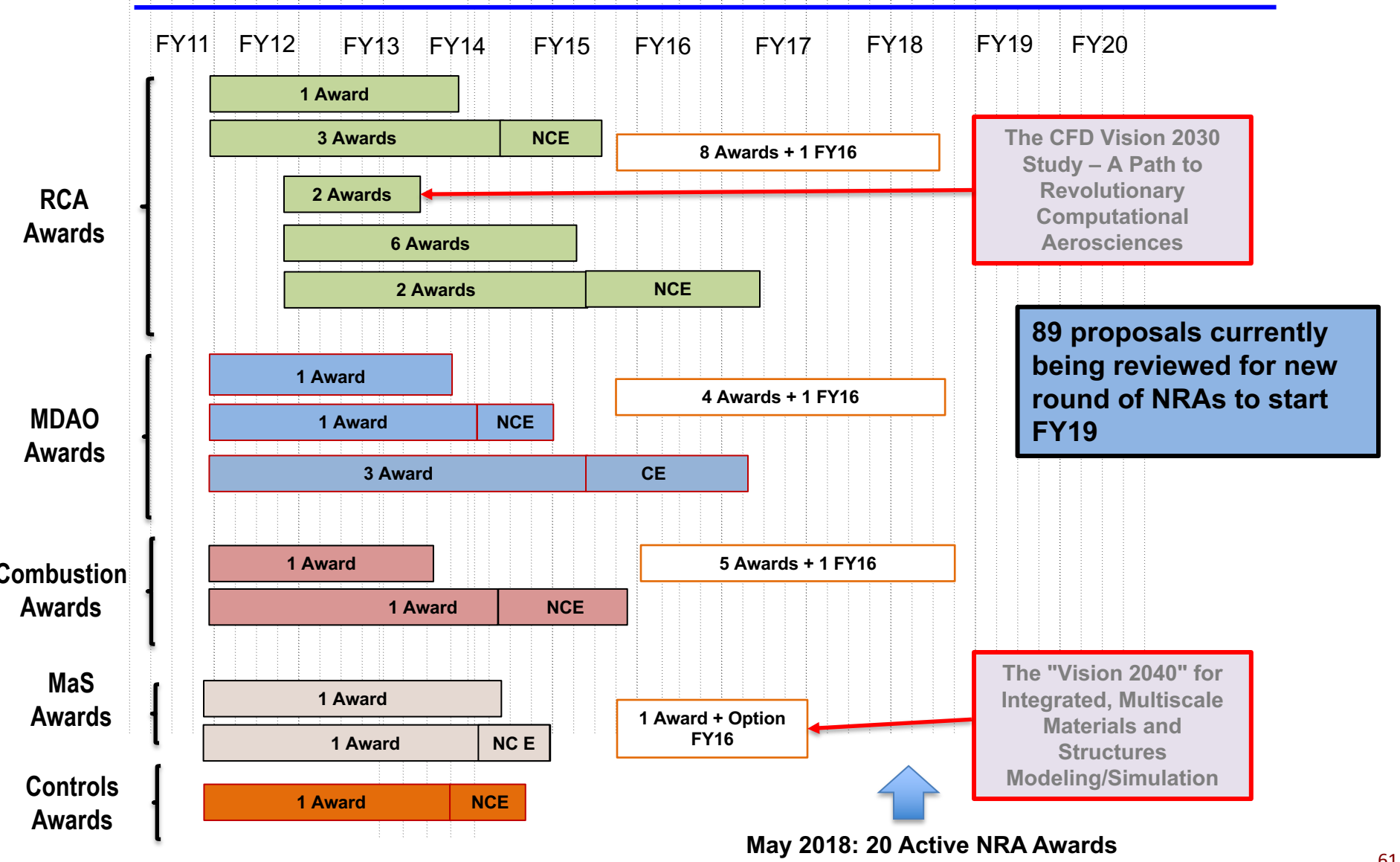


NRA Awards (SFW, AS, & T³)



SFW/AS Awards

T³ Awards

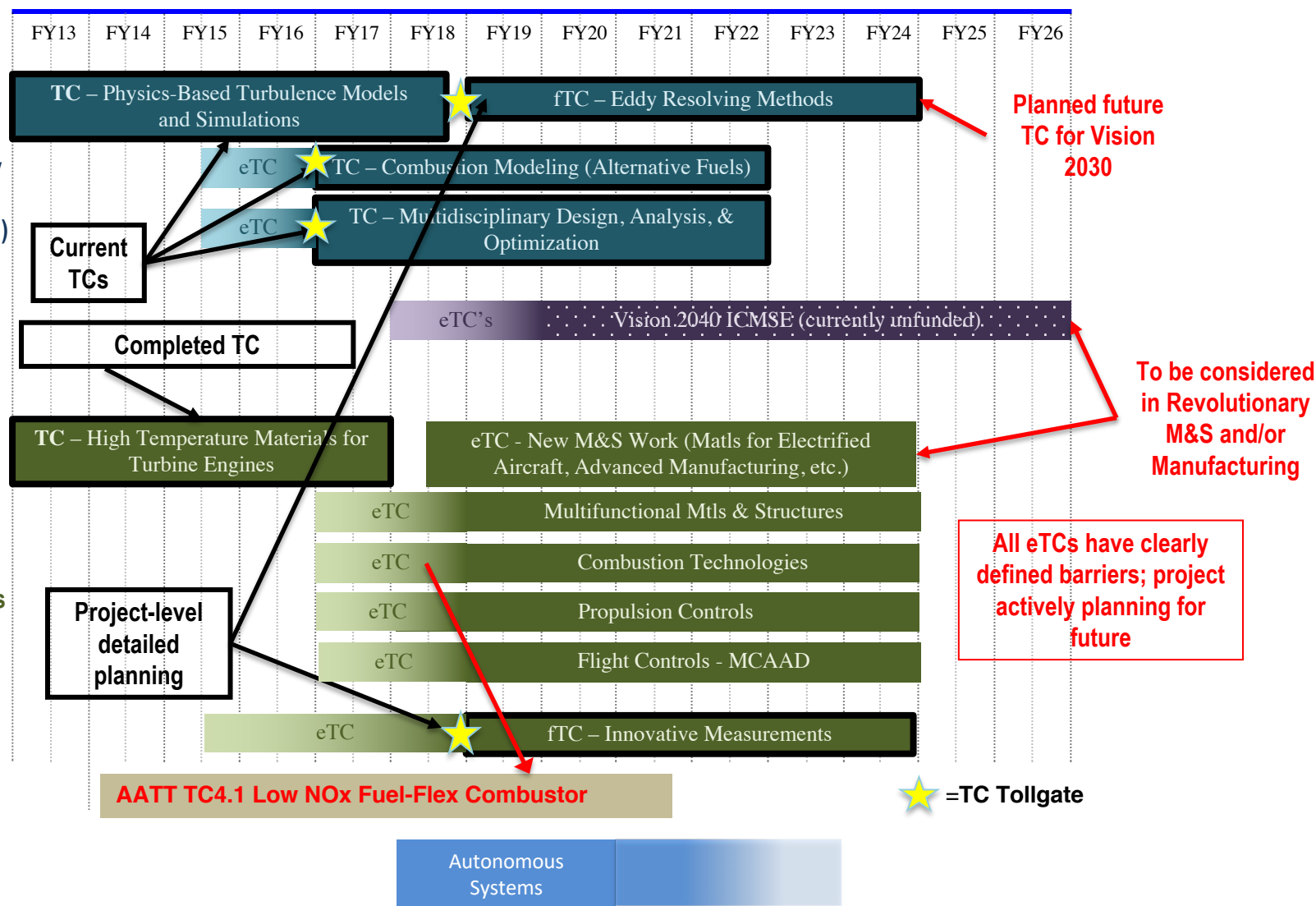




T³ Technical Challenge Planning

Revolutionary
Tools &
Methods (RTM)

Critical
Aeronautics
Technologies (CAT)



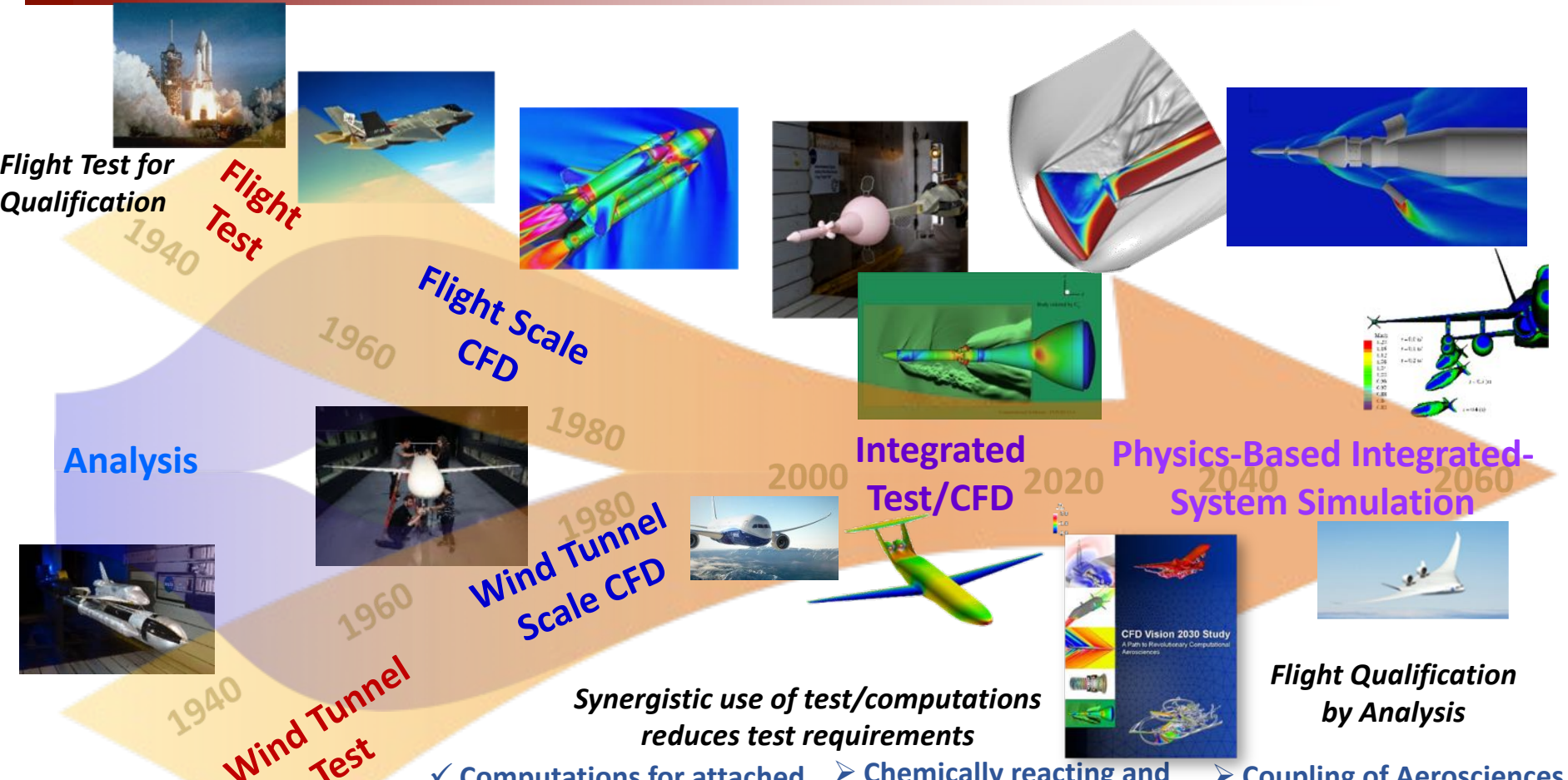
Continual infusion of new ideas - and transition of work to Mission Projects



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 Aerodynamics sub-disciplines
- Integration with complementary disciplines – Flight Mechanics, GN&C, Structures, Materials, Loads & Dynamics, ...

Shock Wave / Boundary Layer Interaction Experiment

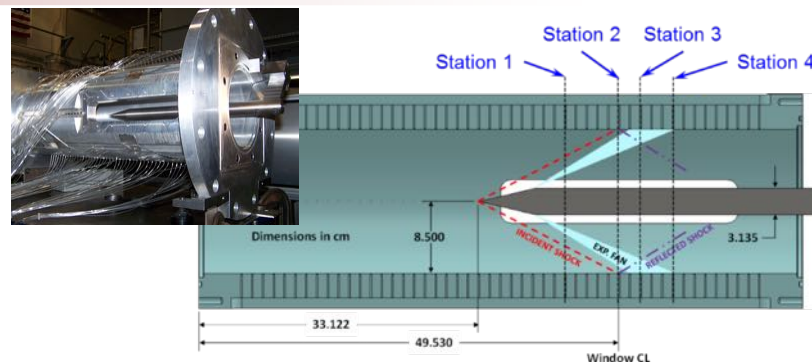
Obtain mean and turbulence quantities through a $M=2.5$ axisymmetric SWBLI of sufficient quantity and quality to be considered a CFD validation dataset. The SWBLI is generated by placing a cone-cylinder in an axisymmetric (pipe) flow. Both 2D and 3D attached and separated flows are considered.

- Simple Geometry:
 - Round pipe with cone-cylinder on centerline.
 - 2D in the mean, but 3D can be created by offsetting cone-cylinder
- Inflow Boundary: Supersonic developing pipe flow (well defined)
- Outflow Boundary: Wholly supersonic
- Redundant measurements:
 - Conventional steady-state and dynamic pressure taps and probes
 - Hot-Wire Anemometry (HWA) (mean and turbulence)
 - Particle Image Velocimetry (PIV)
 - Dynamic Pressure Sensitive Paint (PSP)
 - Dynamic Surface Shear-Stress Film (S3F)
- Comprehensive Uncertainty Analysis

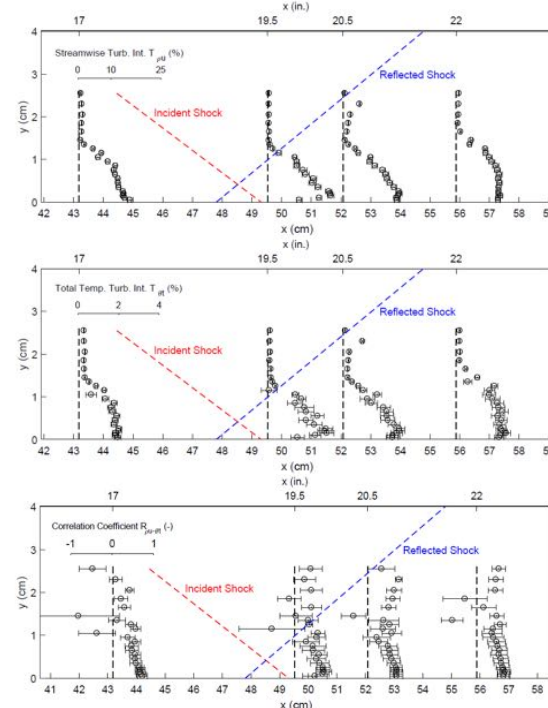
STATUS AND FUTURE WORK:

- Measurements (except PIV) for 2-D configuration are nearing completion.
- Hardware for 3-D configuration is complete and testing has begun.
- A heater has recently been incorporated into the facility for better control of flow conditions (reduced measurement uncertainty).
- Design of PIV system is underway.

POC: David O. Davis (GRC)



Cross-Section Depicting Interaction Region



Resulting quantities of Streamwise Turbulence Intensity (top), Total Temperature Turbulence Intensity (middle) and Correlation Coefficient (bottom)



Heater for better flow control

Benchmark Smooth Body Flow Separation Experiments for CFD Validation

Archival benchmark experiments on smooth body adverse pressure gradient (APG) turbulent boundary layer (TBL) flow separation for the purpose of CFD validation and model development

ACCOMPLISHMENTS:

- Design, fabrication and assembly of all wind tunnel model components.
- Six wind tunnel entries to-date:
 1. 11/15/16 -1/7/17 (23 days - initial model shakedown and troubleshooting)
 2. 1/23/17-1/27/17 (5 days of testing)
 3. 3/20/17– 4/27/17 (31 days of testing, establish APG cases to be investigated; ref *AIAA paper-2017-4128*)
 4. 6/5/17-7/7/17 (24 days of testing; large-scale flow separation)
 5. 9/25/17-10/16/17 (16 days of testing -> ref *AIAA paper 2018-0572*)
 6. 2/2/18-2/23/18 (15 days – side wall boundary layer documentation and corner flow pattern manipulation)

TASKS REMAINING:

- Acquire additional mean velocity and turbulent stress profiles for both the large-scale and small-scale flow separation cases at multiple spanwise locations.
- Perform oil film interferometry measurements in order to determine shear stress distributions and thereby allow inner-variable scaling.
- Characterize the nature of the transition between separation regimes.

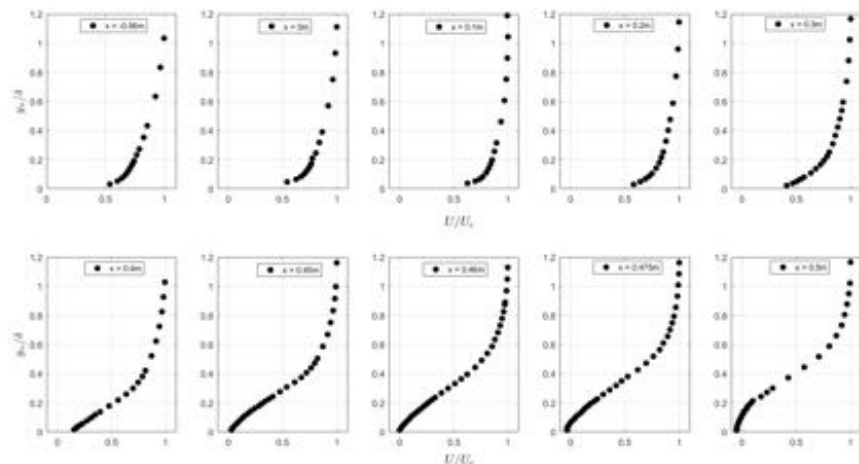
MEASUREMENTS SPECIFIC TO VALIDATION :

- Initial condition TBL profiles obtained at multiple locations.
- Measurement of tunnel side-wall boundary layers.
- Characterization of free stream isotropy and integral macroscales.
- External inviscid velocity boundary condition is measured so that there is no need for mesh modifications for different experiments.
- Measured quantities will be reported at a 95% confidence interval using standard uncertainty propagation methods.

POC: Flint Thomas, Thomas Corke (Notre Dame)



NASA smooth body flow separation experimental geometry installed in the Notre Dame test section with the side door removed.



Sample APG TBL mean velocity profiles measured on the convex ramp.

Compressible Mixing Layer Experiments for CFD Validation

CFD validation-quality measurements of the canonical, two-stream compressible mixing layer over a range of convective Mach numbers (i.e., compressibilities) to document effects on growth rate, Reynolds stress field, turbulent large-scale structure, mixing, etc.

- Work completed or in progress: measurements for four convective Mach number cases, $M_c = 0.19, 0.37, 0.54$, and 0.86
- Measurements to date concentrated on schlieren and planar laser-sheet visualizations, static and pitot pressure measurements, with emphasis on stereo PIV measurements of mean and turbulent velocity fields
- Work to be completed: similar measurements for $M_c \approx 0.74$ and 1.00
- Additional verification measurements of a few cases using hot-wire anemometry (HWA)
- Complete documentation of experimental uncertainty field for all measured quantities

CFD VALIDATION EXPERIMENT DOCUMENTATION:

- Complete documentation of test section as-built geometry through series of drawings posted online
- Complete documentation of the inflow conditions/boundary conditions for each case, especially the boundary layers on all incoming walls to the mixing layer
- Verification of primary SPIV measurements using HWA for a few select cases
- Verification of two-dimensional conditions of mixing layer using end-view visualizations and SPIV measurements at select streamwise locations
- Verification of fully-developed, self-similar conditions of mixing layer using detailed mean flow and turbulence profiles in downstream region
- Complete uncertainty analysis of entire spatial fields of pressure and SPIV mean and turbulence velocity measurements

POCs: Craig Dutton, Greg Elliott (UIUC)

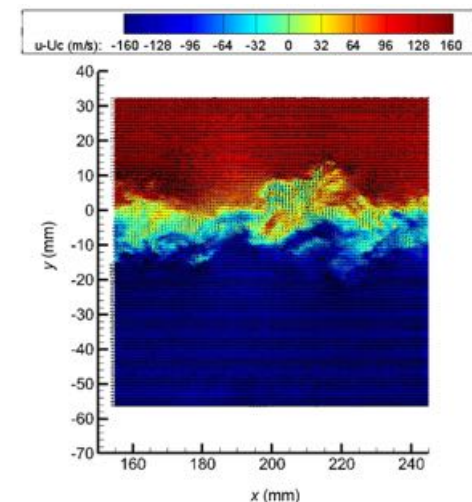


Fig. 1: Typical $(u-U_c)$ instantaneous velocity field measured by SPIV for $M_c = 0.37$

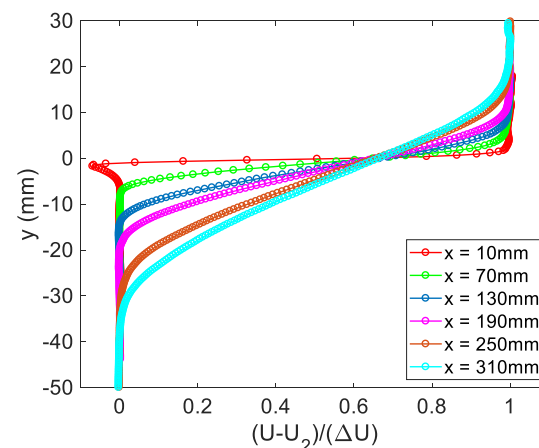


Fig. 2: $M_c = 0.37$ normalized mean streamwise velocity profiles



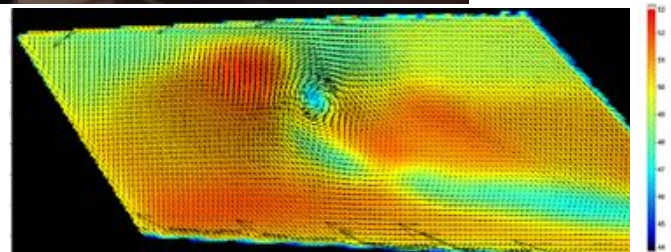
Further Common Research Model (CRM) Testing

- Characterize the on-body and off-body flowfield for a small scale model of a representative commercial aircraft shape.
- Continue ongoing efforts to acquire a variety of experimental flowfield 3D velocity measurements near wingtip and wing/fuselage junction.
- Acquire a variety of wing and fuselage on-body measurements, employing advanced techniques which include Pressure Sensitive Paint (PSP), Fringe Imaging Skin Friction (FISF), and Particle Image Velocimetry(PIV).
- 3% scale model of CRM in 48" x 32" subsonic wind tunnel at NASA ARC Fluid Mechanics Lab
- Acquire measurements at $M \sim 0.15$, at angles of attack of 0, 2, 4 degrees



CRM installed in Test Cell 2 of Fluid Mechanics Lab

PIV
3 wingtips downstream
avg velocity
4 deg AoA

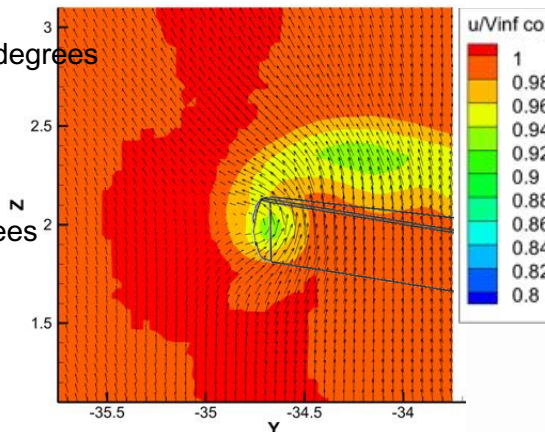


DATA COLLECTED:

- Oil flow on wing and body at 0, 2, 4 degrees
- Skin friction on wing at 2, 4 degrees
- PIV 3 wingtip chords downstream of wingtip at 0, 2, 4 degrees
- Cobra probe matching PIV plane at 0, 2, 4 degrees
- Cobra probe downstream of trailing edge at 0 degrees

REMAINING DATA to COLLECT:

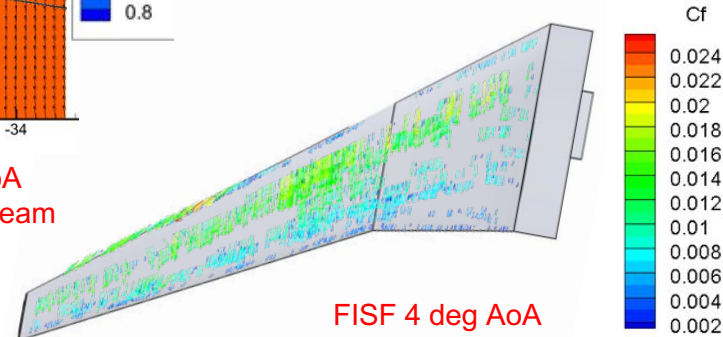
- Cobra probe downstream of trailing edge at 2, 4, degrees
- Inlet conditions of wind tunnel
- Boundary layer measurements upstream of fuselage
- PSP on upper surface of wing at 0, 2, 4 degrees



Cobra Probe 0 deg AoA
3 wingtip chords downstream



Oil Flow downstream TE 4 deg AoA



FISF 4 deg AoA



High Performance Computing

- **NAS at NASA Ames Research Center**

- Pleiades (7.2 PFlops, 245,000 cores); #17 on the Top 500 list
- Electra (4.8 Pflops, 78,000 cores)
 - Due to large number of users, NAS resources allow capacity computing only

- **Department of Energy**

- Gained access to Edison/Cori (NERSC) under ASCR Leadership Computing Challenge Program
 - Parametric studies using up to 42,000 (Edison) and 170,000 (Cori) cores
- Access provided to Theta (ANL), Cori (NERSC), and Stampede-2 (TACC) Knights Landing systems for collaborative CFD developments

- **Department of Defense**

- Access to about 10 different machines for collaborative CFD developments
 - Priority access enables runs up to 85,000 cores with just a few hours queue wait
 - Early access to Knights Landing partition of new Onyx system at ERDC enables extensive Xeon Phi testing
 - Scaling studies performed on DoD machines, using up to ~30,000 cores, for the new higher-order finite element scheme in FUN3D

RCA Exploits NASA and Other National Computing Assets for Capacity and Capability Computing, a Recommendation of CFD 2030 Study