Revolutionary Computational Aerosciences (RCA)
Research Portfolio and CFD 2030

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HiFi-TURB Project Kick-Off Meeting
Brussels, Belgium
July 2nd, 2019
Outline

• NASA Aeronautics Organization Structure
  – ARMD → TACP → TTT → RCA

• CFD Vision 2030

• Revolutionary Computational Aerosciences (RCA) Research Portfolio

• Example Highlights

• Foundational Research in RCA → ARMD and other Mission Directorates

• Summary
NASA Aeronautics Programs and Projects

NASA Mission Directorates

**Aeronautics Research (ARMD)**
Dr. Jaiwon Shinn, AA
- Advanced Air Transport Technology
- Revolutionary Vertical Lift Technology
- Commercial Supersonic Technology
- Hypersonic Technology

**Human Exploration and Operations (HEOMD)**

**Science (SMD)**

**Space Technology (STMD)**

**ARMD PROGRAMS**

**Advanced Air Vehicles**
Dr. James Kenyon: Director
- Projects
  - Advanced Air Transport Technology
  - Revolutionary Vertical Lift Technology
  - Commercial Supersonic Technology
  - Hypersonic Technology

**Airspace Operations and Safety**
Akbar Sultan: Director
- Projects
  - Airspace Technology Demonstrations
  - UAS Traffic Management
  - System-Wide Safety
  - ATM-X

**Integrated Aviation Systems**
Dr. Ed Waggoner: Director
- Projects
  - Unmanned Aircraft Systems Integration in the National Airspace System
  - Flight Demonstrations and Capabilities
  - Low Boom Flight Demonstrator

**Transformative Aeronautics Concepts**
Dr. John Cavolowsky: Director
- Projects
  - Convergent Aeronautics Solutions
  - Transformational Tools and Technologies
  - University Innovation

**Aerosciences Evaluation & Test Capability Office**

X-planes/test environment

Critical cross-cutting tool development

www.nasa.gov
T³ project performs deep-discipline research and engages in 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 enable design of advanced aeronautics systems.

- Revolutionary Computational Aerosciences (RCA)
- Innovative measurements
- Multi-disciplinary analysis and optimization (MDAO)
- Combustion modeling and technologies
- Propulsion and flight controls
- Materials and structures for next generation aerospace systems
- Autonomous systems

RCA develops high-fidelity, physics-based computational analysis capability informed by CFD Vision 2030 study recommendations
RCA Research Portfolio Guided by:
CFD 2030 Technology Development Roadmap

<table>
<thead>
<tr>
<th>TRL</th>
<th>LOW</th>
<th>MEDIUM</th>
<th>HIGH</th>
</tr>
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<tbody>
<tr>
<td>2015</td>
<td>Technology Milestone</td>
<td>Technology Demonstration</td>
<td>Decision Gate</td>
</tr>
<tr>
<td>2015</td>
<td>Demonstrate implementation of CFD algorithms for extreme parallelism in NASA CFD codes (e.g., FUN3D)</td>
<td>YES</td>
<td>NO</td>
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<tr>
<td>2020</td>
<td>PETASCALE</td>
<td>Demonstrate solution of a representative model problem</td>
<td>YES</td>
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<tr>
<td>2025</td>
<td>EXASCALE</td>
<td>YES</td>
<td>NO</td>
</tr>
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**HPC**
- **CFD on Massively Parallel Systems**
  - Demonstrate implementation of CFD algorithms for extreme parallelism in NASA CFD codes (e.g., FUN3D)
- **CFD on Revolutionary Systems (Quantum, Bio, etc.)**
  - Demonstrate efficiently scaled CFD simulation capability on an exascale system

**Physical Modeling**
- **RANS**
  - Improved RST models in CFD codes
- **Hybrid RANS/LES**
  - Integrated transition prediction
  - WMLES/WRLES for complex 3D flows at appropriate Re
- **LES**
  - Chemical kinetics calculation speedup
  - Chemical kinetics in LES
  - Grid convergence for a complete configuration
- **Combustion**
  - Multi-regime turbulence-chemistry interaction model

**Algorithms**
- **Convergence/Robustness**
  - Automated robust solvers
- **Uncertainty Quantification (UQ)**
  - Reliable error estimates in CFD codes
  - Large scale stochastic capabilities in CFD

**Geometry and Grid Generation**
- **Fixed Grid**
  - Production AMR in CFD codes
- **Adaptive Grid**
  - Simplified data representation
  - Production AMR in CFD codes

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

**Visualization**
- **Integrated Databases**
  - On demand analysis/visualization of 10B point unsteady CFD simulation

**MDAO**
- **Define standard for coupling to other disciplines**
- **High fidelity coupling techniques/frameworks**
- **Robust CFD for complex MDAs**
- **MDAO simulation of an entire aircraft (e.g., aero-acoustics)**
- **UQ-Enabled MDAO**

CFD Vision 2030 Study report published in 2014
Progress Towards CFD 2030 Vision

Special Session at AIAA Aviation 2019

- John Cavolowsky (NASA): NASA Aeronautics and CFD 2030
- Jeffrey Slotnick (Boeing): Progress Towards CFD Vision 2030 – An Industrial Perspective for Air and Space Vehicle Applications
- John Chawner (Pointwise): Progress in Geometry Modeling and Mesh Generation Toward the CFD Vision 2030
- Philippe Spalart (Boeing): Turbulence Prediction in Aerospace CFD: Reality and the Vision 2030 Roadmap

Session Sponsored by AIAA CFD Vision 2030 Integration Committee (IC)
The newly formed IC was approved by AIAA in 2018
Three Pillars” of RCA Research
Revolutionary Computational Aerosciences (RCA)

• Robustness/Reliability
  – Ability to generate results with error bounds on every try, by a nonexpert user
    ➢ Robust solver technology/nonlinear stability
    ➢ Uncertainty quantification

• Cost/Efficiency
  – Ability to compute faster by orders of magnitude compared to the current practice
    ➢ Exploit emerging HPC hardware capability
    ➢ Numerical algorithms (e.g., solvers, adaptive grids)

• ACCURACY
  – Ability to accurately compute complex turbulent flows (e.g., transition, flow separation, free shear flows, shock/boundary-layer interaction)
    ➢ Numerical methods (e.g., HOMs), grids, boundary/initial conditions, etc.
    ➢ Improved physical modeling and simulations
      ▪ CFD validation experiments (including physics experiment for model development) a critical need

CFD technology with above attributes will enable “Simulation-Based Engineering”:
  ➢ Application to novel configurations, with confidence, for all NASA missions
    – Airplanes (fixed-wing, vertical lift, manned/unmanned)
    – Launch vehicles, airbreathing propulsion
    – Entry, Descent, Landing
  ➢ Aircraft certification by analysis
Technical Areas and Approaches

• Physical Modeling and Simulations
  § LES/WMLES, hybrid RANS/LES and Lattice-Boltzmann Method
  § Laminar-turbulent transition modeling
  § Data driven modeling

• HPC Tools and Methods
  § Effective utilization of emerging HPC hardware
  § Accurate, efficient, and robust computational methods
  § Grid adaptation
  § Uncertainty quantification

• CFD Validation Experiments
  § Juncture flow
  § Flow separation (wall bump)
  § Turbulent heat flux
  § Shock/boundary-layer interaction
  § Supersonic jet flow
  § High-speed mixing layer
  § TDT aeroelastic experiment

Outcome: Accurate, fully validated CFD capability

Foundational research aimed at solving technical challenges
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 Challenge (TC) completed in 2018
Efficient High-Fidelity Computational Tools for Predicting Maximum Lift on Transport Aircraft

Develop and demonstrate computationally-efficient, eddy-resolving modeling tools that predict maximum lift coefficient ($C_{L_{\text{max}}}$) for transport aircraft with equal or better accuracy than certification flight tests.

Eddy-resolving methods could enable reliable prediction throughout the flight envelope, but will be validated specifically for $C_{L_{\text{max}}}$ prediction.
Propulsion-related challenges include inlet/distortion-tolerant fan aerodynamics and aeromechanics

• Scale resolving simulations of inlet-fan interaction
• Enhanced CFD fan aeromechanics
Research Products

- Advancements in numerical methods and modeling implemented in NASA CFD codes
  - FUN3D
  - OVERFLOW
  - LAVA (NS + LBM)
  - EDDY (high-order spectral element)
  - GFR (flux reconstruction scheme)

Multiple NASA projects fund capability developments in CFD codes
RCA Research Execution Strategy

• **Foundational Research in Computational Fluid Dynamics (CFD)**
  – Breakthroughs cannot be predicted
    ▪ Requires innovative thinking and a lot of trial and error
    ▪ Find and challenge the best people available, let them learn from failures/false starts
      ➢ Success will follow, but it cannot be scheduled

• **Cross Centers Research Effort**
  – NASA Ames Research Center (ARC)
  – NASA Glenn Research Center (GRC)
  – NASA Langley Research Center (LaRC)
    ▪ Additional Postdoctoral Fellows/Research Associates, where needed

• **Leverage Expertise Available at Universities and Industry through NASA Research Announcements (NRAs)**
  – Critical for training future workforce
Currently Funded RCA NRAs

NASA Research Announcements (NRAs) provide a mechanism to collaborate with academia and industry, a recommendation of the CFD Vision 2030 Study

Physical Modeling & Simulations:
• Improving the accuracy and efficiency of scale resolving simulations for favorable and adverse pressure gradient flows; U Colorado (Kenneth Jansen)
• Adaptivity in wall-modeled large eddy simulations of complex three-dimensional flows; U Maryland (Johan Larsson).
• Assessment of wall-modeled LES in nonequilibrium flows with emphasis on grid independency; U Pennsylvania (George Park)
• Scale-resolving turbulent simulations through adaptive high-order discretizations and data-enabled model refinements; U Michigan (Krzysztof Fidkowski)
• Validation of wall models for LES with application to the NASA Common Research Model; Stanford (Parviz Moin)

HPC Tools & Methods:
• Scalable hierarchical CFD solvers for future exascale architectures; Stanford (Juan Alonso)
• Efficient and robust CFD solvers for exascale architectures; U Wyoming (Dimitri Mavriplis)
• A stochastic framework for computation of sensitivities in chaotic flows; U Pittsburgh (Hessam Babaee)
• Parallel geometry for design and analysis; Syracuse U (John Dannehoffer)

CFD Validation Experiments:
• Smooth wall separation over bumps: Benchmark experiments for CFD validation; VA Tech (Kevin Lowe).
• Benchmark experimental measurements of turbulent, compressible mixing layers for CFD validation; U-Illinois (Craig Dutton)

Certification by Analysis:
• Requirements for aircraft certification by analysis; Boeing (Dinesh Naik)
Some Technical Highlights
CFD Validation Experiments
A critical element of the RCA research portfolio

• Recommendation of CFD Vision 2030 Study: NASA should lead efforts to develop and execute integrated experimental testing and computational validation campaigns
  – Experiments to provide data for development of advanced turbulence models/prediction capability is a critical need

• 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

• All data sets made available to interested parties for analysis
Juncture Flow Experiment

- Unique on-board Laser-Doppler Velocimetry (LDV) system specifically designed for measuring the near-wall juncture region flow field through windows
  - Off-body velocities and moments (LDV and some PIV)
  - Model surface pressures (steady/unsteady)

- Experiment performed in NASA 14x22 ft wind tunnel
  - With careful attention to measuring flow-field BC

- Comparisons made using OVERFLOW and FUN3D
  - Nonlinear turbulence modeling (e.g., quadratic constitutive relations or a full Reynolds stress model) necessary to predict size of corner separation
  - Some disagreement between the RANS models and the measured Reynolds stresses in the corner region

POC: Chris Rumsey (LaRC), Mike Kegerise (LaRC), and Dan Neuhart (LaRC).
Juncture Flow Experiment

Wealth of detailed flow physics data acquired in the juncture flow experiment at multiple locations

POC: Chris Rumsey (LaRC), Mike Kegerise (LaRC), and Dan Neuhart (LaRC).
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, turbulence/thermal 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

Computational analysis is underway

POC: Nick Georgiadis (GRC), Mark Wernet (GRC), and Randy Locke (GRC/VPL).
Smooth Wall Separation Experiments over Bumps (NRA to Virginia Tech)

- **Pressure gradients imposed with wall-mounted hump**
  - Attached flow, incipient separation and massive separation
  - Rotation provides parameters for data-driven modeling
  - Geometric symmetries provide key UQ information about geometry uncertainties and flow non-uniformities
  - Instrumentation: Optical (LDV, PIV), pressure rake, hot-wire, temperature, skin-friction (indirect)

- **Document uncertainties**
  - Rotated bump, same location in the tunnel (quantifies geometric nonuniformity)
  - Rotated bump mounted on other side of the tunnel (quantifies flowfield nonuniformity)

POC: Todd Lowe et al. (Virginia Tech)
Compressible Mixing Layer Experiments (NRA to U-Illinois)

• CFD validation-quality measurements of compressible mixing layer to document effects on growth rate, Reynolds stress field, turbulent large-scale structure, mixing (including thermal mixing)
  – Convective Mach numbers, $M_c = 0.19, 0.37, 0.54, 0.74, 0.86$ and $1.0$
  – Schlieren and planar laser-sheet visualizations, static and pitot pressure measurements, with emphasis on stereo PIV measurements of mean and turbulent velocity fields
  – Complete documentation of the inflow conditions/boundary conditions for each case, especially the boundary layers on all incoming walls to the mixing layer
  – Complete uncertainty analysis of entire spatial fields of pressure and SPIV mean and turbulence velocity measurements

POCs: Craig Dutton, Greg Elliott (UIUC)
Wall-resolved LES for Axisymmetric Transonic Bump

- Experimental set up
  - $M = 0.875$
  - $Re_c = 2.763 \times 10^6$
  - $Re_\theta = 6600$

- Flow simulation
  - 4th-order compact scheme, with 10th-order filter
  - 24 billion grid points to cover 120 degree azimuth
  - Free air assumption (tunnel wall effect ignored)
  - Reasonable agreement with measured wall pressure and separation length

POCs: Ali Uzun (NIA), Mujeeb Malik (LaRC)
LAVA: NASA Wall-Mounted Hump

- LAVA curvilinear Navier-Stokes as well as Lattice-Boltzmann Method has been successfully applied to NASA’s wall-mounted hump. Improvement of 96% in reattachment location.

<table>
<thead>
<tr>
<th>Reattachment Location</th>
<th>x/c [-]</th>
<th>Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greenblatt</td>
<td>1.105</td>
<td>-</td>
</tr>
<tr>
<td>RANS from TMR</td>
<td>1.26</td>
<td>14.02</td>
</tr>
<tr>
<td>DDES</td>
<td>1.34</td>
<td>21.26</td>
</tr>
<tr>
<td>ZDES + SEM</td>
<td>1.11</td>
<td>0.45</td>
</tr>
<tr>
<td>LBM + SEM</td>
<td>1.12</td>
<td>0.54</td>
</tr>
</tbody>
</table>

96 % improvement compared to RANS

POC: Cetin Kiris et al. (ARC)
Lesson Learned from RCA’s Completed TC

- Reynolds-Averaged Navier-Stokes (RANS) failed to accurately predict complex flow physics (e.g., RCA standard test cases; CL_{max})
- Wall-modeled large eddy simulation (WMLES), emerged as a promising approach for prediction of CL_{max}, which is critical for aircraft certification by analysis.

Eddy resolving methods development and validation will be the main thrust of the RCA’s new TC
### FUN3D Node-Level Performance Relative to Broadwell (BWL)

<table>
<thead>
<tr>
<th>Hardware</th>
<th>Cores</th>
<th>Baseline Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>BWL: 2× Xeon E5-2680v4</td>
<td>28</td>
<td>MPI Fortran</td>
</tr>
<tr>
<td>SKY: 2× Xeon Gold 6148</td>
<td>40</td>
<td>MPI Fortran</td>
</tr>
<tr>
<td>KNL: Intel Xeon Phi 7230</td>
<td>64</td>
<td>OpenMP Fortran (coloring)</td>
</tr>
<tr>
<td>P100: NVIDIA Pascal</td>
<td>--</td>
<td>CUDA C++ (atomics)</td>
</tr>
<tr>
<td>V100: NVIDIA Volta</td>
<td>--</td>
<td>CUDA C++ (atomics)</td>
</tr>
</tbody>
</table>

**Meanflow Relative Performance**

- **BWL:** 6.8
- **SKY:** 5.4
- **KNL:** 3.0
- **P100:** 2.3
- **V100:** 2.2

POC: Eric Nielsen (LaRC)
FUN3D Performance on Summit

- Plot captures weak scaling on new ORNL Summit system (IBM Power9 + V100)
- Each node solves ~12.8M grid points
  - 5 nodes: 60M pts/267M elms
  - 1,024 nodes: 13.2B pts/58B elms
- **CPU curve** is MPI+OpenMP with 3 ranks/socket (total of 6 per node) with 168 total OpenMP threads per node (smt4)
- **GPU curve** is MPI+CUDA: 3 ranks/socket shepherding 1 GPU each (total of 6 per node); all MPI via GPU Direct
- Nearly linear performance for both
- GPU performance is 23x-37x faster, depending on data point (generally around 25x)

A potential 25-100x speedup in sight for CFD codes, from both hardware and algorithms

POC: Eric Nielsen (LaRC)
Foundational research in RCA impacts focused applications in ARMD and other mission directorates
LAVA Hybrid RANS/LES: Jet-Noise Predictions

- Demonstrated jet noise prediction capabilities within LAVA curvilinear solver utilizing ZDES on unheated axisymmetric round jet.
  - Excellent Comparison between near-field CFD and experiments achieved
  - Far-field predictions utilizing the permeable Ffowcs-Williams Hawkins (FWH) agree very well with experiments. Improvements to previous simulations demonstrated.

- Demonstrated **improvement in prediction of length of potential core** by 90% (RCA requirement 40%)
- Results published in AIAA/CEAS Aeroacoustics Conference [AIAA 2019-2475]

(a) TKE centerline

(b) PSD at 100D from nozzle exit

POC: Cetin Kiris et al. (ARC)
LAVA Hybrid RANS/LES : Jet-Surface Interaction Noise

- LAVA has demonstrated capabilities to capture noise shielding effects of an inserted plate in close proximity to a jet. This is an important step towards predicting full airframe jet noise.

(a) Lipline velocity

(b) PSD at 100D from nozzle exit

POC: Cetin Kiris et al. (ARC)
LAVA Lattice Boltzmann Simulations of Propeller Noise

APPROACH:
• The Lattice Boltzmann Method
• Solver extended with robust in-house boundary treatment for moving blades which do not violate strict realizability of the density distribution functions (The algorithm development was supported by the TTT project and the systematic validation using far-field noise measurements from NASA Langley Research Center was supported by the RVLT project.)

RESULTS:
• Predicted both the performance and the aerodynamic noise generated by the propeller with unprecedented accuracy and turnaround times

SIGNIFICANCE:
• First step towards predicting Urban Air Mobility Noise from first principles using the Lattice Boltzmann solver
• Completely automated workflow without labor intensive mesh generation
• Quick turnaround time - approximately 4000 core hours for 25 revolutions of isolated propeller (10% chord resolution)
• General formulation – Valid for arbitrarily moving (and deforming) geometry

POC: Cetin Kiris et al. (ARC)
LAVA Lattice-Boltzmann: Landing Gear

• Demonstrated the LBM approach on the AIAA BANC III Workshop Landing Gear problem IV.
  • Computed results compare well with the experimental data
  • 12-15 times speed-up was observed between LBM and NS calculations.

• LBM has better memory access and significantly lower floating point operations relative to WENO+RK4

• LBM has minimal numerical dissipation

• Cartesian methods are very successful for the right problems

POC: Cetin Kiris et al. (ARC)
Grid Sensitivity for PSD: Channel 5: Upper Drag Link

Near Field PSD

- LB: 90 Million
- LB: 260 Million
- LB: 1.6 Billion
- EXP-UFAFF

Surface Pressure Spectra at Sensor Locations

POC: Cetin Kiris et al. (ARC)
Orion Launch Abort Acoustics Simulations

- CFD Vision 2030 Study recommends development of “capability” computing and necessary algorithm improvements to reach exa-scale

- Added a layer of fine-grain parallelism to the Launch, Ascent, and Vehicle Aerodynamics Cartesian solver to scale to 16,000+ cores

- Ongoing efforts target many-core machines with an eye towards GPUs

- New capability used successfully for space vehicles (HEOMD) to predict surface fluctuating pressures over Orion launch abort vehicle (LAV) for a range of abort scenarios

- Demonstrated excellent agreement with experimental validation data from wind tunnel, ground and flight tests

- Short enough turnaround time to affect design of Orion Launch Abort System: completed 400,000 time steps on 630 million cell AMR mesh with accelerating LAV in 30 days on 16,000 cores

POC: Cetin Kiris et al. (ARC)
Orion Launch Abort Acoustics Simulations

Transonic ascent abort at moderate angle of attack and side slip

-- Wind Tunnel Measurements
- LAVA Predictions

Shaded gray area is +/- 2 dB because of uncertainty in simulation results due to short integration time (0.02 s) vs experiment (5.00 s)

Volume rendering of pressure fluctuations

POC: Cetin Kiris et al. (ARC)
Pressure on the vertical plane (white is high, black is low) for LAV transonic ascent abort at high angle of attack

POC: Cetin Kiris et al. (ARC)
Summary

• RCA research portfolio is aimed at making progress towards CFD Vision 2030 and meeting the challenge of predicting aircraft $CL_{\text{max}}$
  – Physical modeling
  – HPC
  – Numerical algorithms
  – Grid adaptation
  – CFD validation experiments

• Explore potential collaborations with HiFi-TURB project
  – Leverage available expertise and data, for accelerated progress toward CFD 2030 goals

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