


# CFD Vision 2030 CFD Study

*A Pathway to Revolutionary Computational Aeroscienes*


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# CFD Vision 2030 Study

- **NASA commissioned a one-year study to develop a comprehensive and enduring vision of future CFD technology:**
  - HPC
  - Numerical Algorithms
  - Physical Modeling
  - Multidisciplinary analysis and optimization
- **Wide community support for the research roadmap:**
  - Aerospace America, Aviation Week & Space Technology
  - AIAA Aviation 2014 Panel Discussion

**NASA CR 2014-218178**



Report (published March 2014) available at:
http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140003093.pdf

# Background - 1: CFD Impacts 3 NASA Mission Directorates

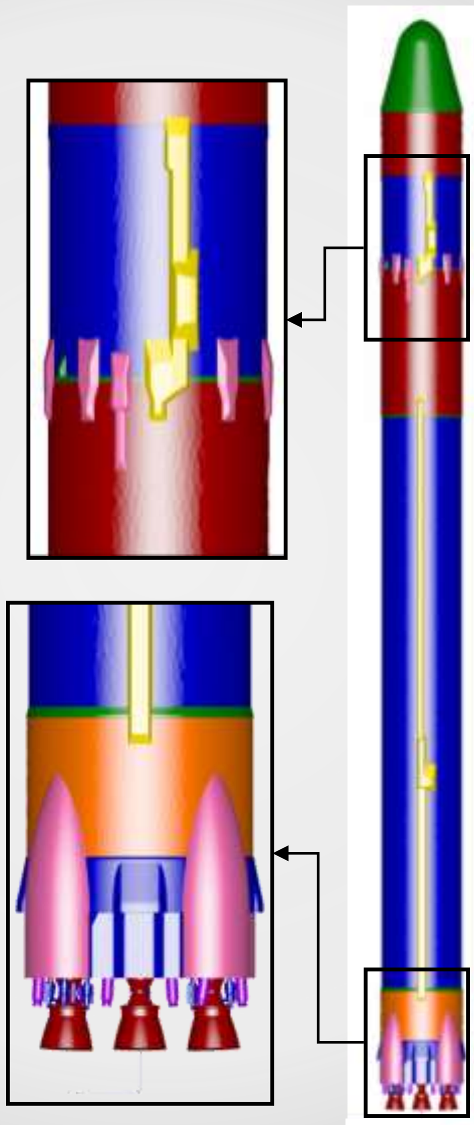
**CFD is a cross-cutting technology**

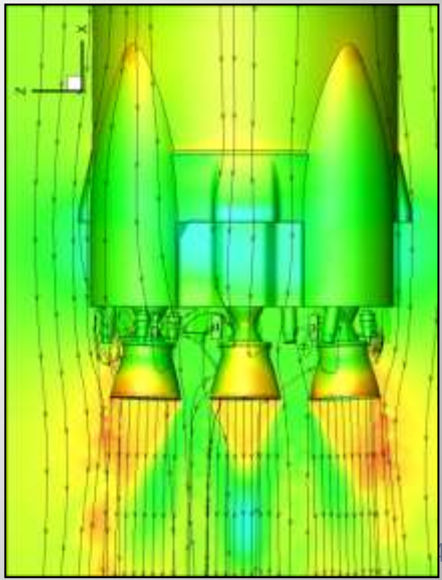
- **Aeronautics Research Mission Directorate (ARMD):**
  - It supports three of the ARMD strategic thrusts, and the associated "outcomes"
  - Plays an important role in subsonic and supersonic civil aircraft and rotorcraft technology development
  - Basic computational tool development
    - OVERFLOW, CFL3D, ARC3D, Wind-US, Vulcan …
    - FUN3D, USM3D, CART3D…
- **Human Exploration and Operations (HEOMD):**
  - Development of Space Launch System, Orion
- **Science (SMD):**
  - Planetary entry systems (MSL/Curiosity)
  - Climate, weather, environment

# Background - 2: CFD Impacts Commercial Space Industry

- Using NASA's FUN3D as primary CFD tool for:
  - Falcon 1 ascent aero
  - Falcon 9 ascent aero
  - Lower speed Dragon reentry aero
- Full, detailed vehicle models, including up to 18 plumes
- Performing hundreds of simulations per vehicle across the flight envelope
- CFD predictions agree very well with all flight and wind tunnel data
- SpaceX developing combustion CFD for rocket engines using GPUs
  - Chemistry-turbulence interaction using grid adaptation

***Images and Information Courtesy of SpaceX***



# Background - 3: CFD Impacts Aeronautical Industry

**Substantial CFD Utilization** **Some CFD Utilization** **Limited CFD Utilization**


**Key Enablers Include High Performance Computing and Physics-based Design/Analysis/Optimization**

**Courtesy of Boeing**

# Background - 4: Impact on Aircraft Efficiency and Wind Tunnel Testing

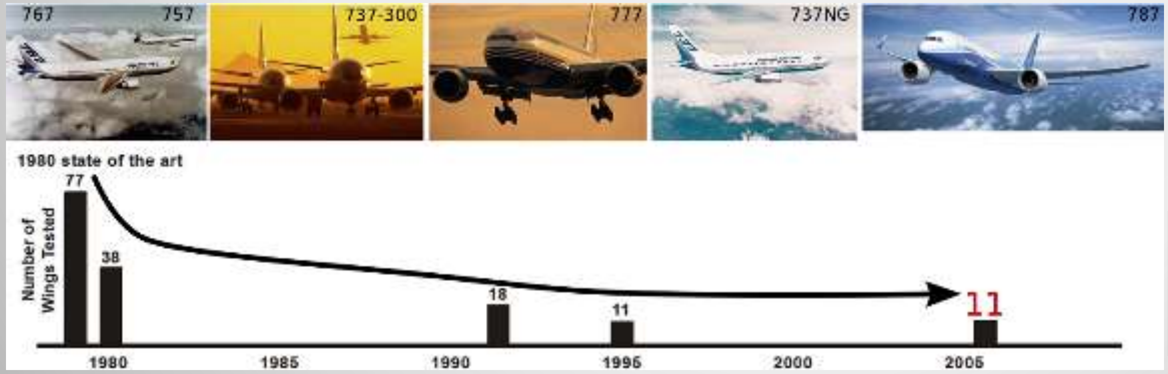
**"Since the first generation of jet airliners, there has been about a 40% improvement in aerodynamic efficiency and a 40% improvement in engine efficiency … about half of that has come from CFD."**

(Robb Gregg, BCA Chief Aerodynamicist)

- Significant (almost 70%) decrease in wind-tunnel testing time since 1980s has reduced cost and enabled faster market readiness
- Reduction in testing time largely enabled by availability of mature and 'calibrated' advanced CFD

# Background – 5: CFD Challenge for Aeronautics

- **CFD has drastically reduced testing for cruise design**
  - Attached flow, well predicted by current turbulence models
- **Testing required for off-design (e.g., high-lift) conditions (for conventional configurations) and for innovative configurations, in general**
  - Flow separation is the key issue, as separation not well predicted by turbulence models
  - First principles simulations a HPC challenge
- **Flow physics challenge highlighted in the Malik-Bushnell study**
  - “Role of Computational Fluid Dynamics and Wind Tunnels in Aeronautics R&D,” NASA-TP-2012-217602
  - Led to Revolutionary Computational Aerosciences (RCA) Initiative




Inability to further reduce number of tests due to deficiency in modeling of turbulent flow physics

# Background – 6: Potential of Advanced CFD

## "Discovery" by High Performance Computing

- Accurate, fast and robust computational tools can fundamentally change the aerospace design space

- Improved simulation capabilities bring:
  - Superior/more capable designs
  - Reduced development cycle time/cost/risk
  - Scientific and industrial competitiveness
  - Lead to innovation

**Decadal Survey of Civil Aeronautics (NAE):** ***"…an important benefit of advances in physics-based analysis tools is the new technology and systems frontiers they open"***

# Vision 2030 Study Charter

- NASA commissioned a one-year study (completed in March 2014) to develop a comprehensive and enduring vision of future CFD technology and capabilities:
  - **"…provide a knowledge-based forecast of the future computational capabilities required for turbulent, transitional, and reacting flow simulations…"**
  - **"…and to lay the foundation for the development of a future framework/environment where physics-based, accurate predictions of complex turbulent flows, including flow separation, can be accomplished routinely and efficiently in cooperation with other physics-based simulations to enable multi-physics analysis and design."**

# Vision 2030 CFD Team Members

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

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**William Gropp**
National Center for Supercomputing Applications

**Elizabeth Lurie**
Pratt & Whitney – United Technologies

**Dimitri Mavriplis**
University of Wyoming

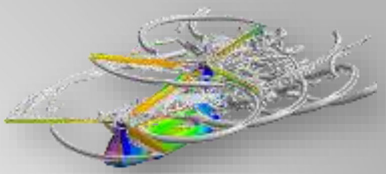
Extended Vision 2030 Team:

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

# Vision 2030 Overview

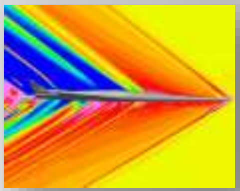
- Elements of the study effort:
  - Define and develop **CFD requirements**
  - Identify the most critical **gaps and impediments**
  - Create the **vision**
  - Develop and execute a **community survey** and **technical workshop** to gain consensus and refine the vision
    - ➢ Input from Government, Academia and Industry
  - Develop a detailed **technology development roadmap** to
    - capture anticipated technology **trends** and future technological **challenges**,
    - guide **investments** for long-term research activities
    - provide **focus** to the broader CFD community for future research activities

# Vision of CFD in 2030



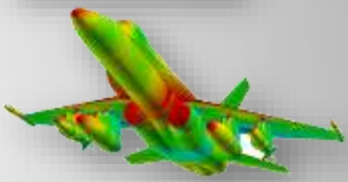
**Emphasis on physics-based, predictive modeling**

Transition, turbulence, separation, chemically-reacting flows, radiation, heat transfer, and constitutive models, among others



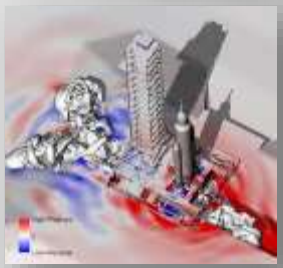
**Management of errors and uncertainties**

From physical modeling, mesh and discretization inadequacies, natural variability (aleatory), lack of knowledge in the parameters of a particular fluid flow problem (epistemic), etc.



**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

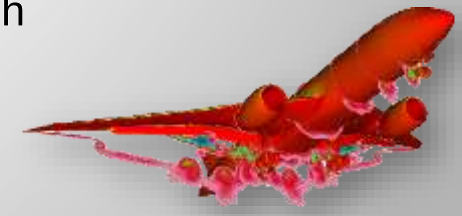


**Effective utilization of massively parallel, heterogeneous, and fault-tolerant HPC architectures available in the 2030 time frame**

Multiple memory hierarchies, latencies, bandwidths, etc.

**Flexible use of HPC systems**

Capability- and capacity-computing tasks in both industrial and research environments



**Seamless integration with multi-disciplinary analyses**

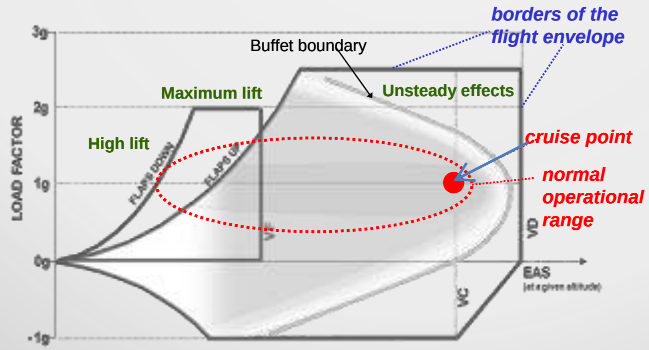
High fidelity CFD tools, interfaces, coupling approaches, etc.

# Findings

1. Investment in technology development for simulation-based analysis and design has declined significantly in the last decade and must be reinvigorated if substantial advances in simulation capability are to be achieved.

2. High Performance Computing (HPC) hardware is progressing rapidly
   - Many CFD codes and processes do not scale well on petaflops systems
   - CFD codes achieve only 3-5% of peak theoretical machine performance
   - NASA poorly prepared for exaflops ($10^{18}$ flops) revolution

3. 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




*CFD accurate only near cruise point*

# Findings CONTINUED

4. Mesh generation and adaptivity continue to be significant bottlenecks in the CFD workflow, and very little government investment has been targeted in these areas
   - Goal: **Make grid generation invisible to the CFD analysis process →** Robust and optimal **mesh adaptation methods** need to become the norm
5. Algorithmic improvements will be required to enable future advances in simulation capability
   - Robust solution convergence for complex geometries/flows is lacking
   - Improved scalability on current and emerging HPC hardware needed
   - Develop "optimal" solvers, improve discretizations (e.g., high-order)
6. Managing the vast amounts of large-scale simulations data will become increasingly complex due to changing HPC hardware
7. In order to enable multidisciplinary simulations, for both analysis and design optimization purposes, several advances are required: CFD solver robustness/automation, standards for coupling, computing and propagating sensitivities and uncertainties

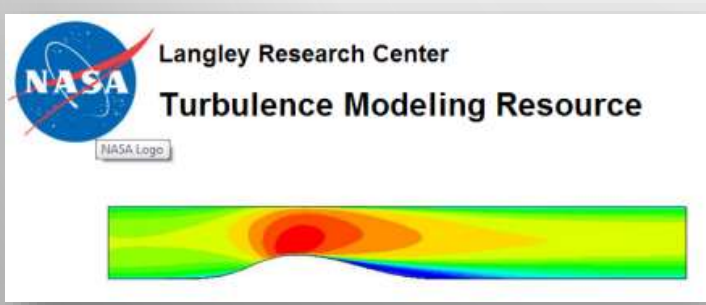
# Recommendations

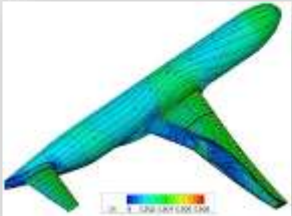
1. **NASA should develop, fund and sustain a technology development program for simulation-based analysis and design.**
   - Success will require **collaboration** with experts in computer science, mathematics, and other aerospace disciplines
2. **NASA should develop and maintain an integrated simulation and software development infrastructure to enable rapid CFD technology maturation.**
   - **Maintain a world-class in-house simulation capability**
     – Critical for understanding principal technical issues, driving development of new techniques, and demonstrating capabilities
3. **HPC systems should be made available and utilized for large-scale CFD development and testing.**
   - **Acquire HPC system access for both throughput (capacity) to support programs and development (capability)**
     – *improved software development, implementation, and testing is needed*
   - **Leverage national HPC resources**

# Recommendations CONTINUED

## 4. NASA should lead efforts to develop and execute **integrated experimental testing and computational validation campaigns**

- High quality experimental test data for both **fundamental, building-block** *and* **complex, realistic configurations**, coupled with careful computational assessment and validation, is needed to advance CFD towards the Vision 2030 goals
  - Experiments to provide data for development of advanced turbulence models/prediction capability
- **NASA is uniquely positioned** to provide key efforts in this area due to the availability of world-class experimental test facilities and experience, as well as key expertise in benchmarking CFD capabilities



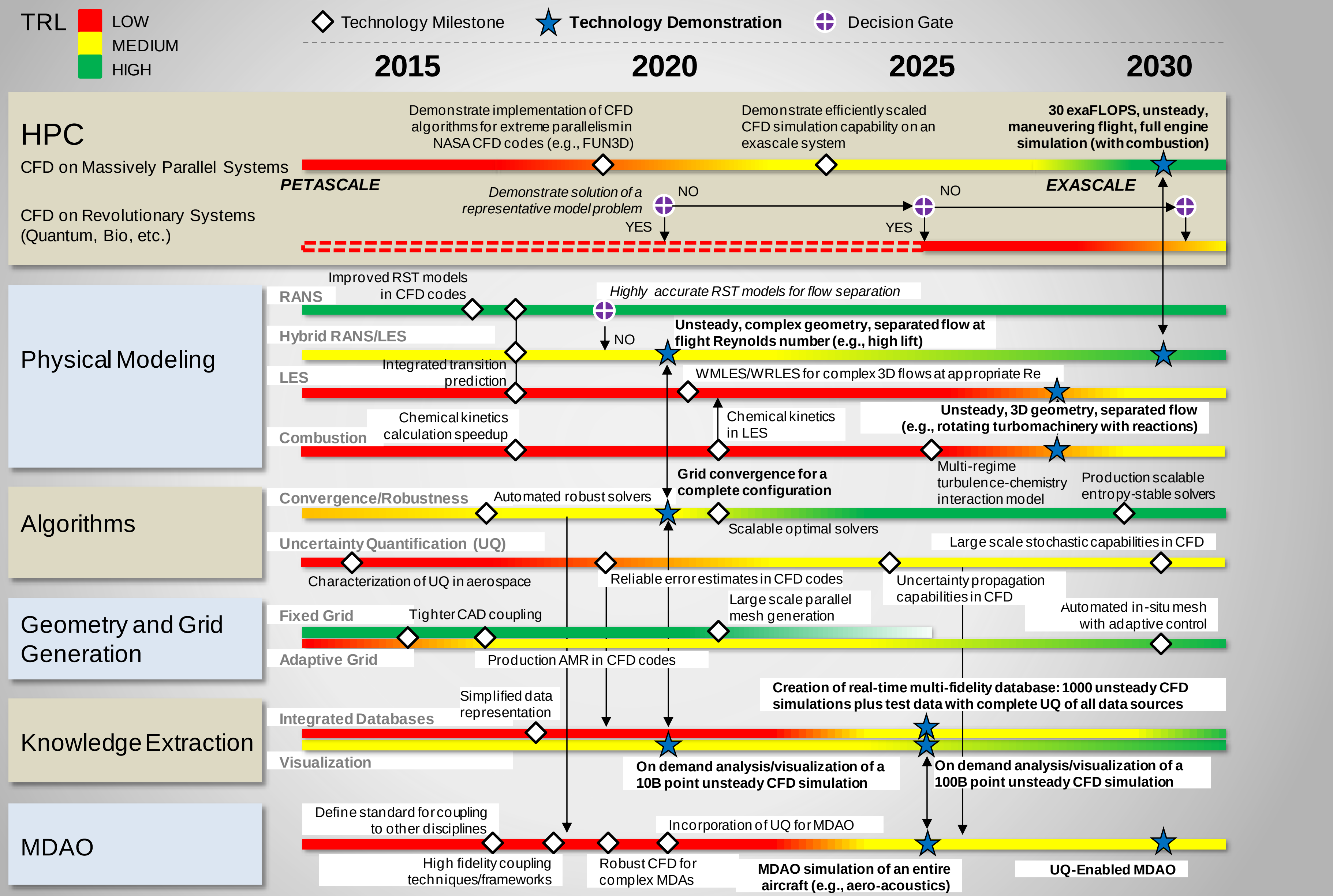
# Recommendations CONTINUED

5. **NASA should develop, foster, and leverage improved collaborations with key research partners across disciplines within the broader scientific and engineering communities**
   - Emphasize funding in **computer science and applied mathematics**
   - Embrace and establish **sponsored research institutes** → provides centralized development of cross-cutting disciplines.

CTR

6. **NASA should attract world-class engineers and scientists.**
   - **Success in achieving the Vision 2030 CFD capabilities is highly dependent on obtaining, training, and nurturing a highly educated and effective workforce**
     - Expand **fellowship programs** in key computational areas
     - Encourage and fund long-term **visiting research programs**

# Notional Technology Roadmap



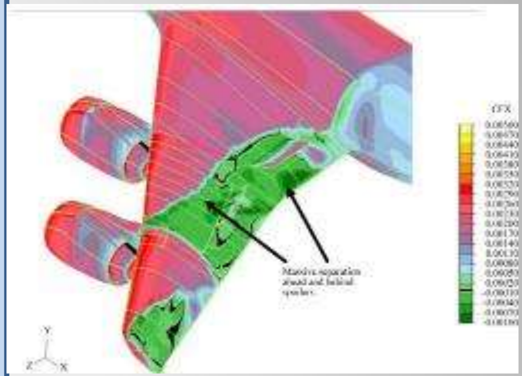
# Grand Challenge Problems

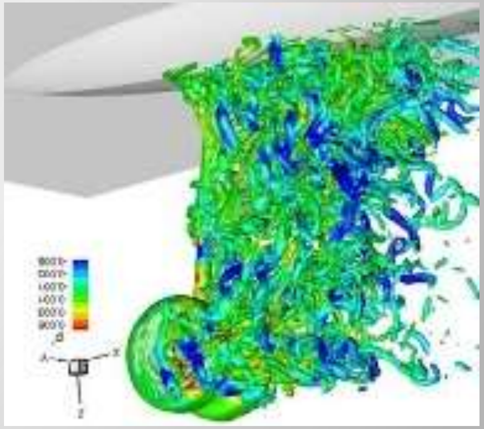
- Represent critical step changes in engineering design capability
- May not be routinely achievable by 2030
- Representative of key elements of major NASA missions

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

# LES of a Powered Aircraft Configuration Across the Full Flight Envelope

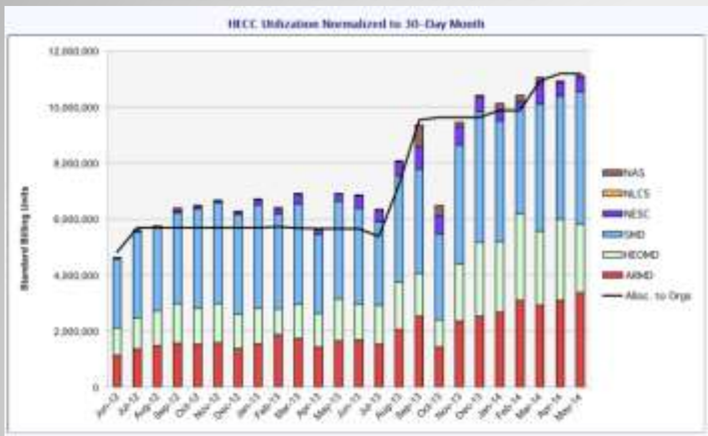
- **Assess the ability to use CFD over the entire flight envelope, including dynamic maneuvers**
- **Assess the ability of CFD to accurately predict separated turbulent flows**
  - Monitor increasing LES region for hybrid RANS-LES simulations
  - Evaluate success of wall-modeled LES (WMLES)
  - Determine future feasibility of wall-resolved LES (WRLES)
- **Assess the ability to model or simulate transition effects**
- **Enable future reductions in wind tunnel testing**





# Comparison of HPC at NASA and DoE

## *HPC Resource Allocation to NASA Mission Directorates*




## DOE and NASA HPC Systems Among the Top 100 Worldwide

| Machine / Agency | | Speed |
|---|---|---|
| 2. Titan | | 3.3 |
| 3. Sequoia | | 3.3 |
| 5. Mira | | 1.6 |
| 9. Vulcan | | 0.8 |
| 11. Pleiades | | 1.0 |

**NASA**
*1 system, 211 thousand cores capable of 5.3 petaflops.*

**Department of Energy**
*Several systems.*

## *Pleiades Divided Among More than a Hundred Users, generally allowing "capacity" computing only (Typical simulation: 1000's of cores)*

*Pleiades, NASA Ames*

## *Hierarchical Approach at DOE*


*Titan, Oak Ridge*

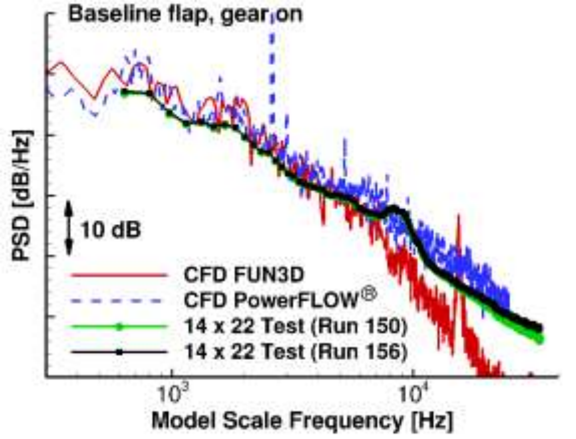
# Simulation-Based Airframe Noise Predictions
## (Model Scale Results) – Example of "Hybrid RANS/LES"

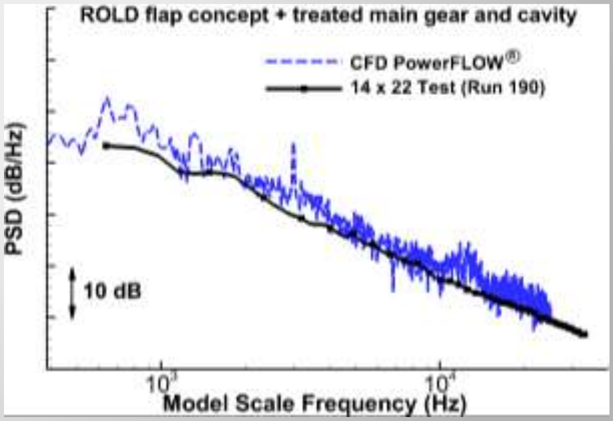
**<u>Simulation Characteristics</u>**

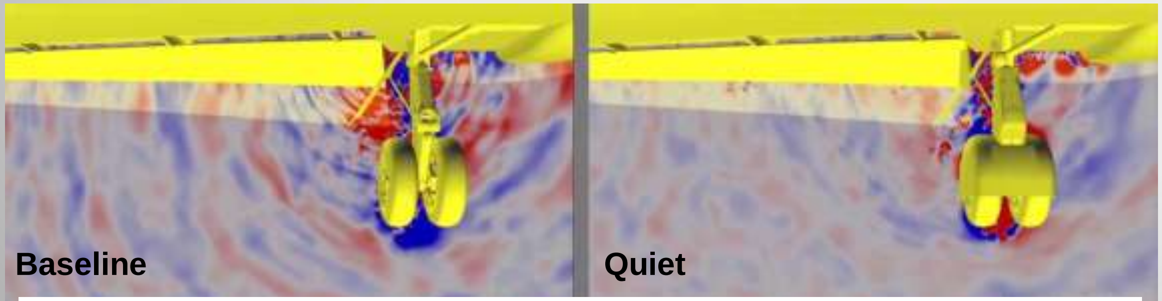
- Simulated geometry
  - ➢ As–built 18% scale high-fidelity Gulfstream model
  - ➢ Re = 3.47 x $10^6$ based on MAC
  - ➢ Finest resolution: 3x$10^9$ cells, 4000 cores, 1x$10^6$ CPU hours (NASA Pleiades)
- Baseline configurations
  - ➢ 39º flap deflection, main gear removed
  - ➢ 39º flap deflection, main gear deployed
- Quiet configurations
  - ➢ Various flap tip noise reduction concepts (main gear off)
  - ➢ Treatment applied to flap tips and main landing gear

**<u>Accomplishments</u>**

- Core objectives met
  - ➢ Predicted farfield noise for baseline and quiet configurations in good agreement with measurements obtained in the LaRC 14x22 wind tunnel
  - ➢ Established computational simulations as an accurate predictive tool
  - ➢ Paved the way for application to full-scale


Simulated instantaneous pressure field for baseline and quiet configurations

# Simulation-Based Airframe Noise Predictions
## (“Full” Scale Results) – Example of “Hybrid RANS/LES”

**Simulation Characteristics**

- Simulated geometry
  - Full scale Full Gulfstream Aircraft
  - Re equivalent to 50% of flight: Re = 10.5 x $10^6$ based on MAC
- Baseline configurations
  - 39º flap deflection, main gear removed
  - 39º flap deflection, main gear deployed

**Accomplishments**

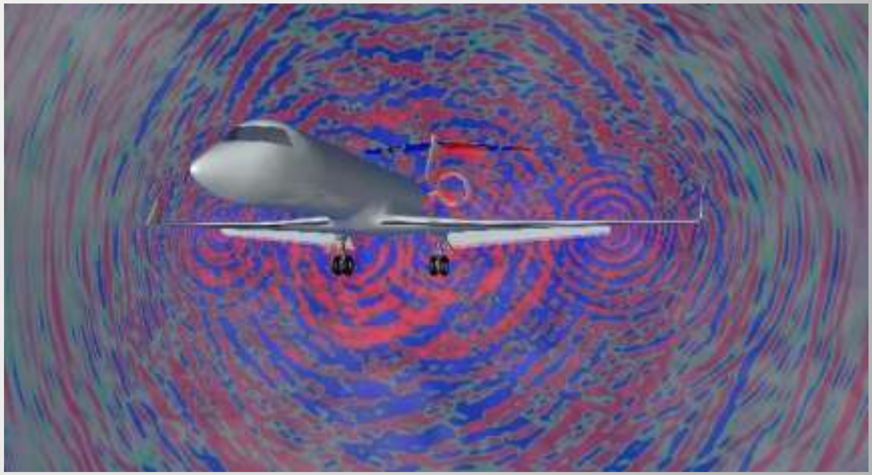
- Predicted farfield noise for baseline configurations in very good agreement with 2006 flight test measurements
  - Establishes CAA simulations as a complementary tool to flight testing
- Evaluation of full-scale noise reduction concepts via simulations has commenced

**Computational Resources**

- All simulations executed on NASA’s Pleiades
- Finest resolution attempted
  - Grid size: 8.4 x$10^9$ cells
  - Cores: 6000 - 12000
  - CPU hours: 7 x $10^6$
  - Physical time: 20 – 25 days per run
  - Main issue: solver scalability for data gathering and I/O operations per time step

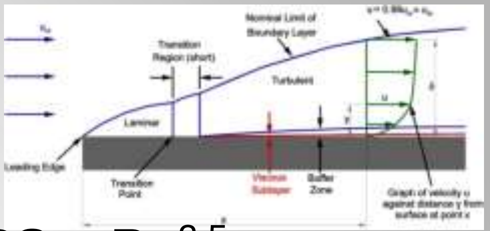


2006 flight test configurations

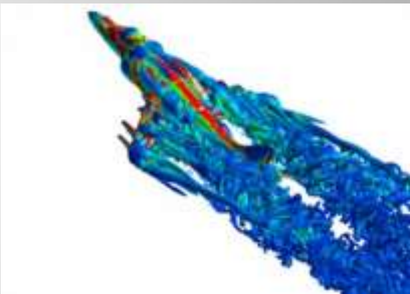


Simulated radiating pressure field for baseline configuration

# Cost Estimates for Full Aircraft LES



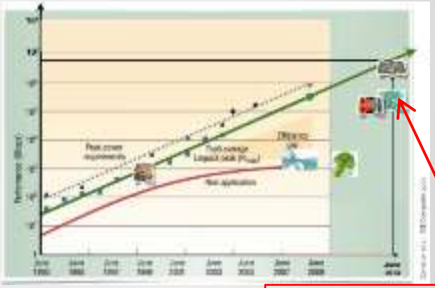

- **Pure LES intractable due to range of scales in Boundary Layer**
  - Large aircraft flight Reynolds number ~ 50M
  - LES* (explicit in time) : grid resolution ~ $Re^{13/7}$, FLOPS ~ $Re^{2.5}$
    - Resolved to $y^+ = 1$
  - Wall Modeled LES* (explicit): grid res. ~ Re, FLOPS ~ $Re^{1.3}$
    - Resolved to $y^+ = 100$
- **Estimates for WMLES for simple wing (AR=10) at flight Re**
  - $10^{11}$ to $10^{12}$ grid points, 500 Pflops for 24hr turnaround
  - Simulating transition adds factor of 10 to 100
  - Feasible on Exaflop machine
- **Full aircraft WMLES not possible on exascale machine**



[*]Choi and Moin, "Grid point requirements for LES: Chapman's estimates revisited", Phys. Fluids, 24, 011702 (2012)

# CFD Efficiency Enhancement

- **Orders of magnitude reduction in time to solution is a critical need for analysis and design**
  - Unsteady flow computations for complex configurations
  - Use of high-fidelity CFD in MDAO
- **Approaches for enhancing CFD efficiency**
  - Effective utilization of existing HPC hardware
    - Current CFD codes run at 3-5% of machine peak performance
    - There is potential for 10x improvement
    - 2013 Gordon Bell Prize awarded to ETH team that achieved 55% of theoretical peak performance on IBM Blue Gene
  - Exploitation of future HPC hardware
    - CFD code scalability for exascale architecture
    - GPUs for desktop engineering work stations
  - Grid adaptation (e.g., adjoint-based)
    - Promises significant reduction in grid requirement
    - Automatic viscous grid adaptation remains a challenge
  - High-order methods
    - Significant potential to speed-up unsteady flow simulations (HO accuracy allows coarser grid, both spatially and temporally)
    - Need efficient solvers to overcome numerical stiffness



ETH Team Achieved:
55% of theoretical peak

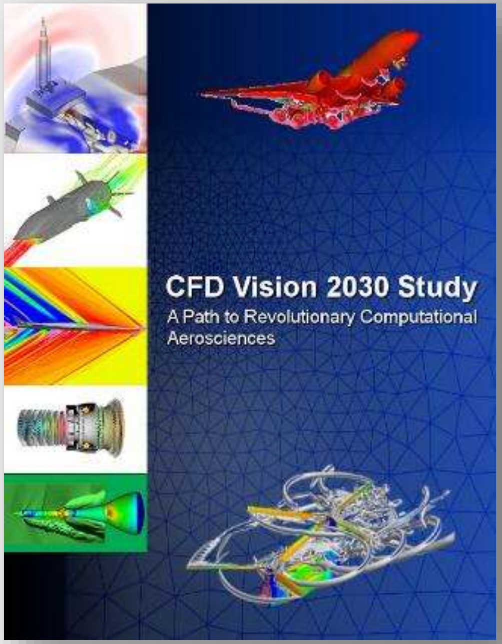
# Conclusions

- **Exascale will enable revolutionary capabilities in aerospace analysis, design, and increased understanding/prediction of complex flows**

- **Improved simulation capabilities bring:**
  - Superior/more capable designs
  - Reduced development cycle time/cost/risk
  - Scientific and industrial competitiveness

- **Achieving exascale for aerospace applications will be challenging**
  - Requires sustained foundational investment
  - Requires strong engagement with national HPC efforts

- **CFD Vision 2030 Study has provided a research roadmap for the CFD community**



NASA

# Case Study: LES Cost Estimates

- **Wall-modeled LES (WMLES) cost estimates**
  - Using explicit, 2nd order accurate finite volume/difference
  - Unit aspect ratio wing, Mach 0.2 flow

| $Re_c$ | $N_{dof}$ | $N_{iter}$ | FLOP | PFLOP/s |
|---|---|---|---|---|
| 1e6 | 9.0e9 | 4.6e7 | 5.2e20 | 6 |
| 1e7 | 8.5e10 | 1.5e8 | 1.6e22 | 180 |
| 1e8 | 7.5e11 | 4.6e8 | 4.3e23 | 5,000 |

24 hour turn-around time

- **Comparison to current HPC #1 system: Tianhe-2**
  - 55 PFLOP/s theoretical peak; 34 PFLOP/s on Linpack benchmark
  - WMLES Re=1e6 feasible today on leadership class machines
- **2030 HPC system estimate**
  - 30 ExaFLOP/s theoretical peak
  - WMLES Re=1e8 feasible on 2030 HPC
  - Wall-resolved LES not possible on 2030 HPC
- **Comments:**
  - These are capability computations (maxing out leadership HPC)
  - Simple geometry (unit aspect ratio; isolated, clean wing; etc.)
  - Algorithmic advances critical for grand challenge problems (hardware advancements alone not sufficient)