HTP

Hypersonic Technology Project

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Joint AFOSR/ONR/NASA HTP Boundary Layer Transition Workshop Summary for RAeS

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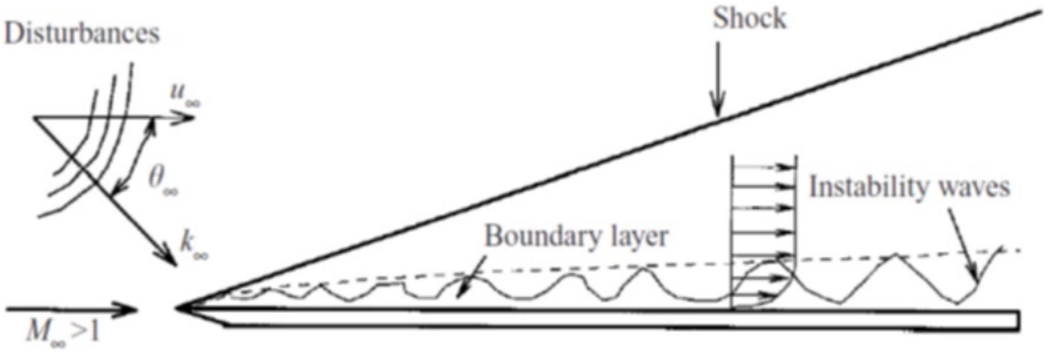
Overview of Joint Boundary Layer Workshop

- Why boundary layer transition?
- Objectives and participant makeup
- Overview and History of the National Hypersonic Foundational Research Plan (NHFRP)
- Assessment of NHFRP Roadmap
- Highlights of “pre-work” discussions
- Subjects of interest for new notional roadmaps

Why Boundary Layer Transition



[credit: NASA]

- Difficult problem: need to account for initial conditions, boundary conditions
- Laminar vs. turbulent BL state has implications
    - Transitional and turbulent BL has higher surface heating (3-8x higher), increased viscous drag (10% laminar to 30% turbulent), increased aerooptical distortion
    - Laminar separation over control surfaces reduces effectiveness, increases pressure drag
    - Laminar flow reduces engine performance: unstart or reduced mixing

Why boundary layer transition?

Objectives and Participants

Overview and History of the National Hypersonic Foundational Research Plan

Assessment of NHFRP Roadmap

Highlights of “pre-work” discussions

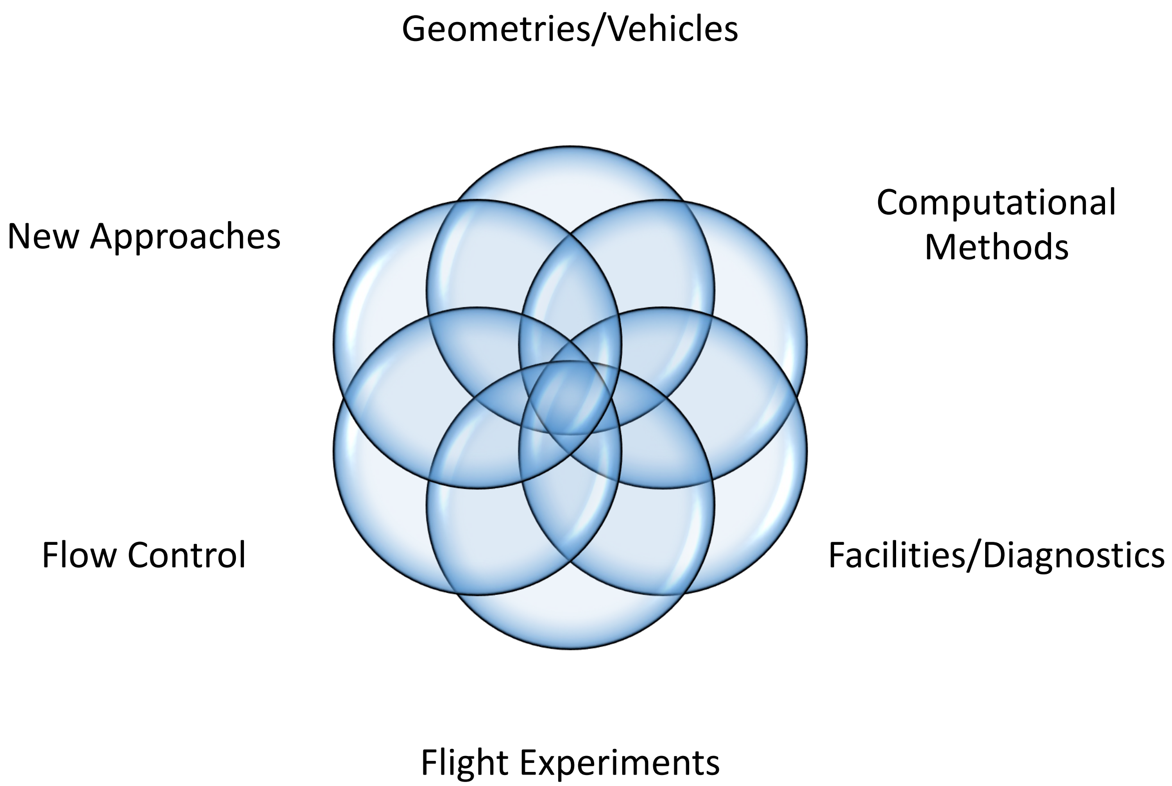
Subjects of interest for new notional roadmaps

Overview: Objectives

Assemble SMEs in high-speed boundary layer transition to assess the current state of research

Develop roadmap of high-speed boundary layer transition research

Areas within Boundary Layer Transition



- Participants were mix of academia, industry, government agencies – split into teams
- Limited capacity in room
  - Helped foster discussion
  - Produced actual end products
- Members contributed information for discussion via “pre-work” questions
- Team “captains” organized responses:
  - **Geometries:** Lindsay Kirk, NASA Commercial Crew Program
  - **Computational Methods:** Pedro Paredes, NIA
  - **Facilities/Diagnostics:** Matthew Borg, AFRL RQHF
  - **Flight Experiments:** Bradley Wheaton, JHU/APL
  - **Flow Control:** Thomas Corke, University of Notre Dame
  - **New Approaches**: Joseph Nichols, University of Minnesota

Why boundary layer transition?

Objectives and participant makeup

A look back

Overview and History of the National Hypersonic Foundational Research Plan

Assessment of NHFRP Roadmap

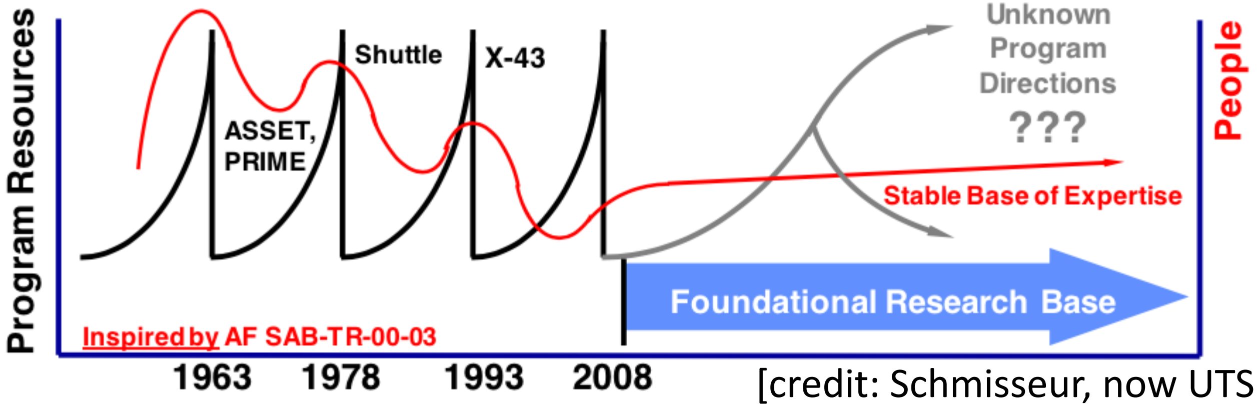
Highlights of “pre-work” discussions

Subjects of interest for new notional roadmaps

History

- Past efforts at coordinating national focus of hypersonics research were to be guided by the National Hypersonic Foundational Research Plan (NHFRP)
  - Participation included: NASA, Sandia, AFRL
  - Established in 2007, Hypersonic Academic Research Partnership (HARP) in 2009
- Effort was meant to sustain national hypersonic capabilities
  - Build a stable base of expertise to counteract decline of skill level due to volatile nature of hypersonic funding
  - Facilitate coordination of foundational research efforts across agencies supporting hypersonic research
  - Support national planning efforts and simulate investments from other agencies

The volatile history of hypersonic system development has resulted in a long-term erosion of the hypersonic skill base



[credit: Schmisseur, now UTSI]

Why boundary layer transition?

Objectives and participant makeup

Overview and History of the National Hypersonic Foundational Research Plan

What have we accomplished?

Assessment of NHFRP Roadmap

Highlights of “pre-work” discussions

Subjects of interest for new notional roadmaps

NHFRP Roadmap Assessment

- Question of "what have we accomplished" is mixed
  - Defining what "accomplished" means: someone has a solution vs. the solution is used in standard practice
  - Many items have been studied, but not in full, and adoption into standard practice takes time
    - Defining how well-understood a phenomenon is has different meanings to different people: airframers may only care up to a certain degree, physicists will want to know the mechanisms responsible
  - What is accomplished may always be improved upon
    - Refinement of modeling
    - Creating tools and diagnostics that are turn-key or able to be used by outsiders to the BLT community *accurately*
- Gaps in our current knowledge are primarily in: chemistry/ablation effects, surface feature characterization and modeling, receptivity, viable flow control

Why boundary layer transition?

Objectives and participant makeup

Overview and History of the National Hypersonic Foundational Research Plan

Assessment of NHFRP Roadmap

What do we need to know?

Highlights of “pre-work” discussions

Subjects of interest for new notional roadmaps

Geometries/Vehicles Team

- Focus was meant to be on big-picture systems-level impacts
- Team was to consist of airframers, program officers, vehicle designers

- What geometries are relevant to the community?
- How does boundary layer transition affect them?

NASA

Office of Naval Research ONR Science & Technology

DARPA

United States Navy

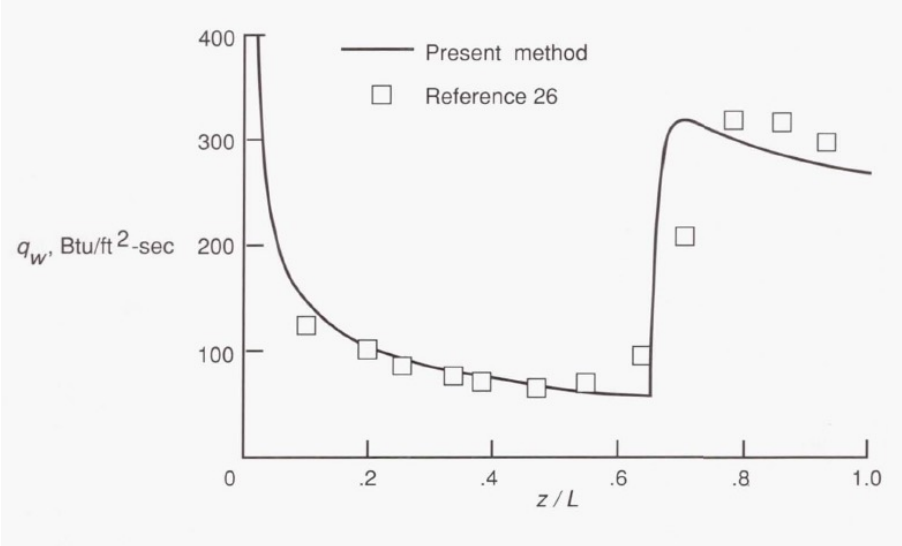
Johns Hopkins Applied Physics Laboratory

Raytheon Technologies

Lockheed Martin

Highlights from Geometries/Vehicles Team Pre-Work

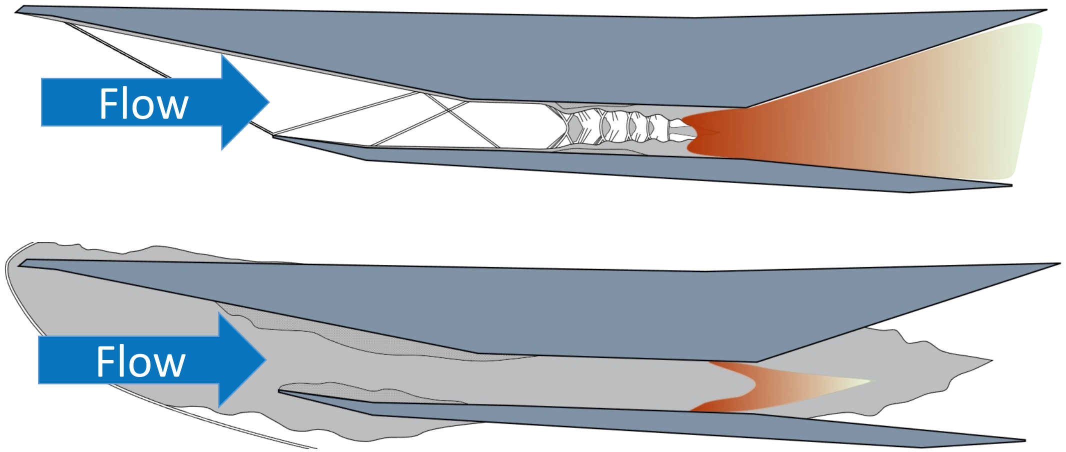
- Why do we care about transition on these classes of vehicles? What parts of the vehicle are more sensitive and which mechanisms are relevant?
  - Vehicle performance and controllability: minimize total heat load and overall drag
  - Flow state preferences:
    - Turbulent flow is preferred over control surfaces for effectiveness, in airbreathing engines (promote mixing, avoid inlet/isolator separation: unstart)
    - Laminar flow is preferred over sensor apertures (less aero-optical distortion)



(b) Altitude = 80 000 ft. $M_\infty = 19.97$; $\alpha = -0.15°$.

Figure 8. Heating-rate distribution along cone for Reentry F.

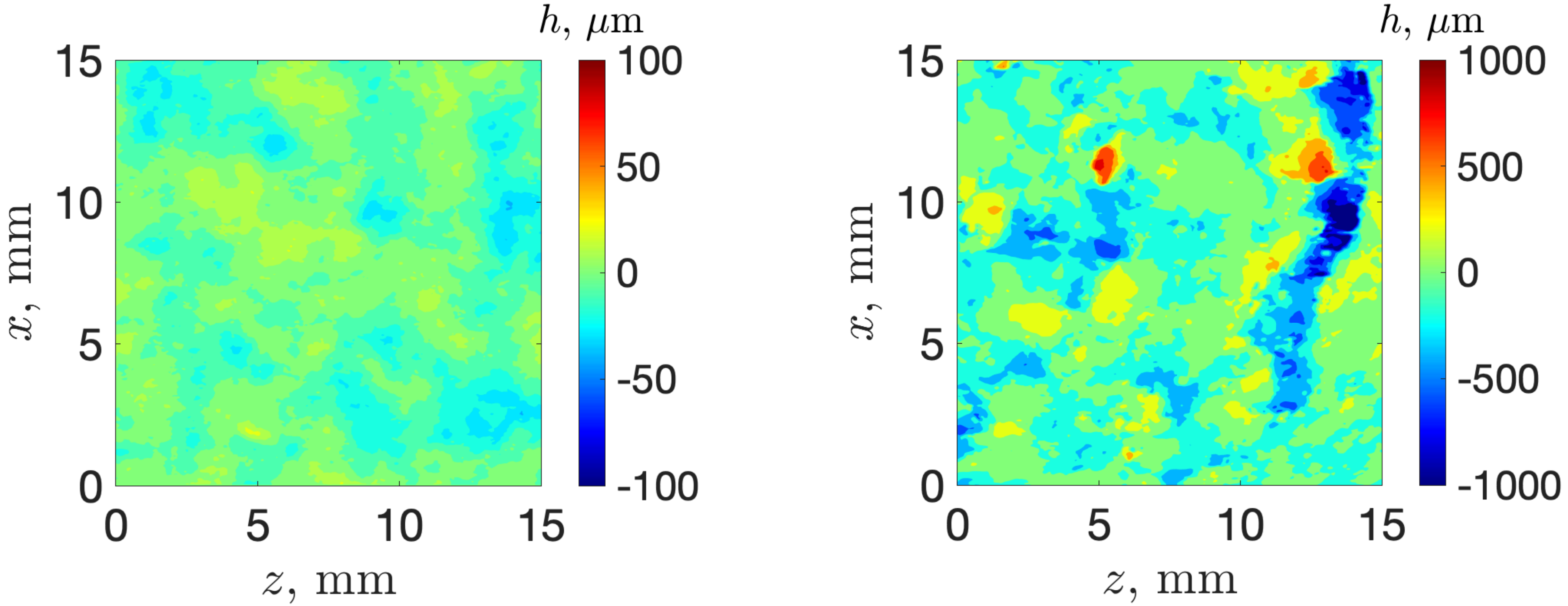
[credit: H. Hamilton et al., NASA-TP-3271]



[credit: L. Edelman, NASA]

Highlights from Geometries/Vehicles Team Pre-Work

- How are the effects of in-flight surface roughness and geometric features on boundary layer transition currently assessed?
  - Look at before and after flown roughness, still no way to quantify changes in flight
  - Defined as RMS or tallest peak or deepest valley

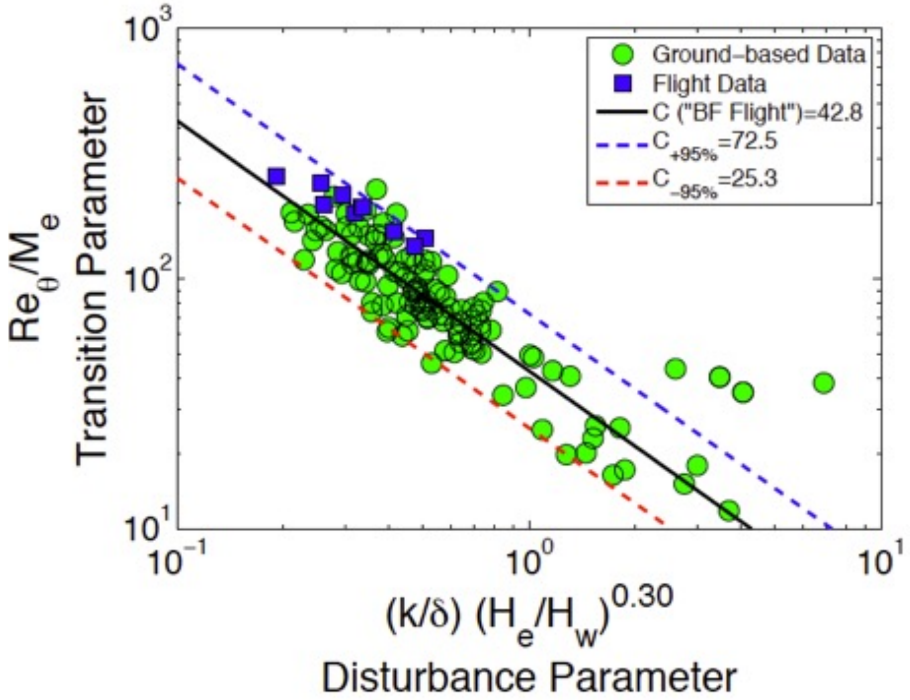


Measurements of surface topography on TPS: not flown (left) and after damage (right)

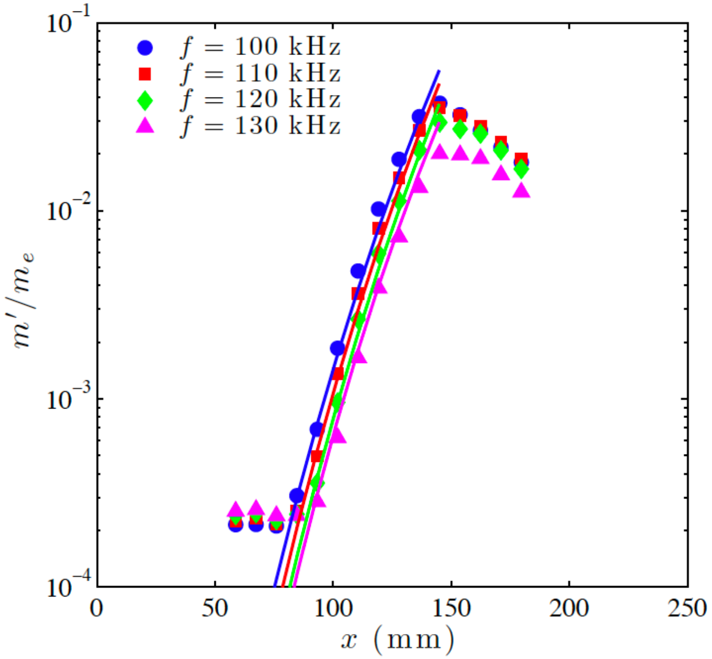
[credit: Chou, NASA]

Highlights from Geometries/Vehicles Team Pre-Work

- Why are correlations still used in practice?
  - Implementation of higher-fidelity tools still has too large an entry barrier or are too slow to use in the design process



[credit: King et al., NASA TP- 2009-215951]



[credit: Kegerise et al. AIAA 2014-2501, NASA]

Computational Methods Team

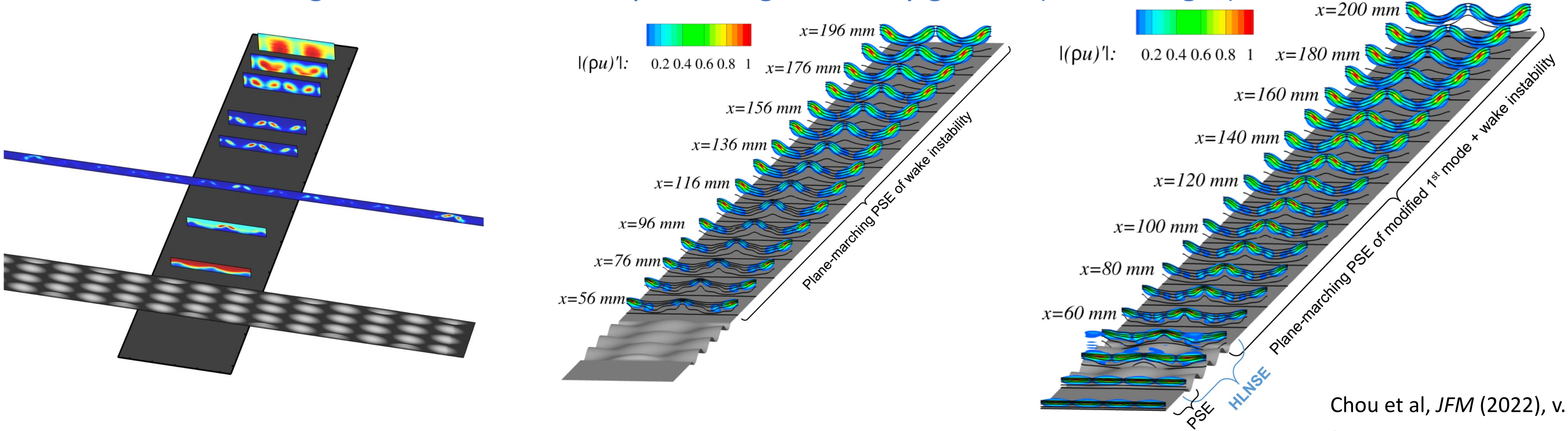
- Industry, academia, OGAs – probably biggest team

- What tools do we have?
- What is missing from our knowledge?
- What is our way of accounting for what is not known?

Highlights from Computational Methods Team Pre-Work

- How well do we need to model something to understand or predict transition?
  - Case dependency: even for canonical geometries, some configurations are more sensitive to different surface or freestream conditions
  - More sensitivity studies are required
  - Conventional (not quiet) tunnels have limited value for transition studies. Flight data are sparse, limited.

Hot wire measurements (left) in the wake of sinusoidal “egg crate” roughness in a quiet tunnel validated against two methods of predicting instability growth (middle, right)



Chou et al, *JFM* (2022), v. 948, A27

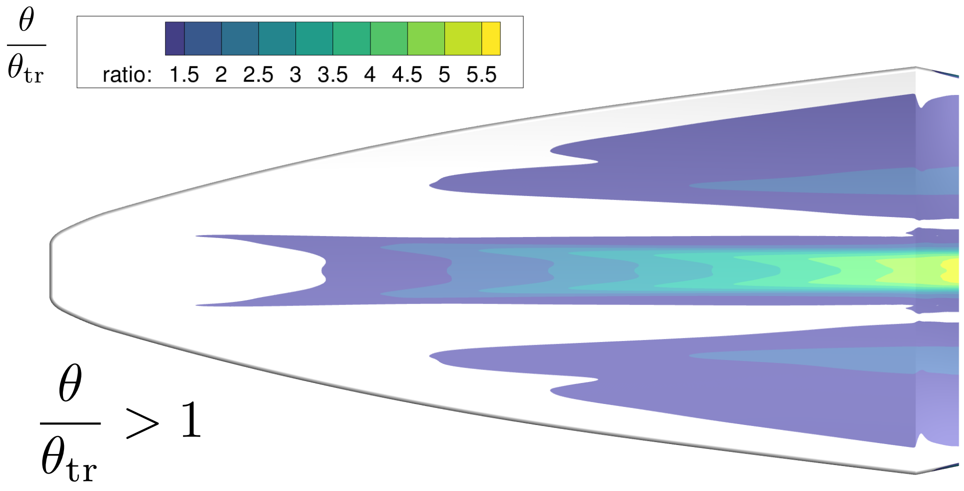
[credit: Chou et al., NASA]

Highlights from Computational Methods Team Pre-Work

- How can low- and high-fidelity tools be used synergistically?
  - High-fidelity tools are used for detailed analysis to help develop low-fidelity tools
  - New work in the Data Assimilation community, Machine Learning models to help build these bridges
  - Need to learn from the MDAO community to use high-fidelity tools to build ROMs

Consider BOLT-II at t = 399.6 sec
$M = 5.924$, $Re_L = 3.09 \times 10^6$

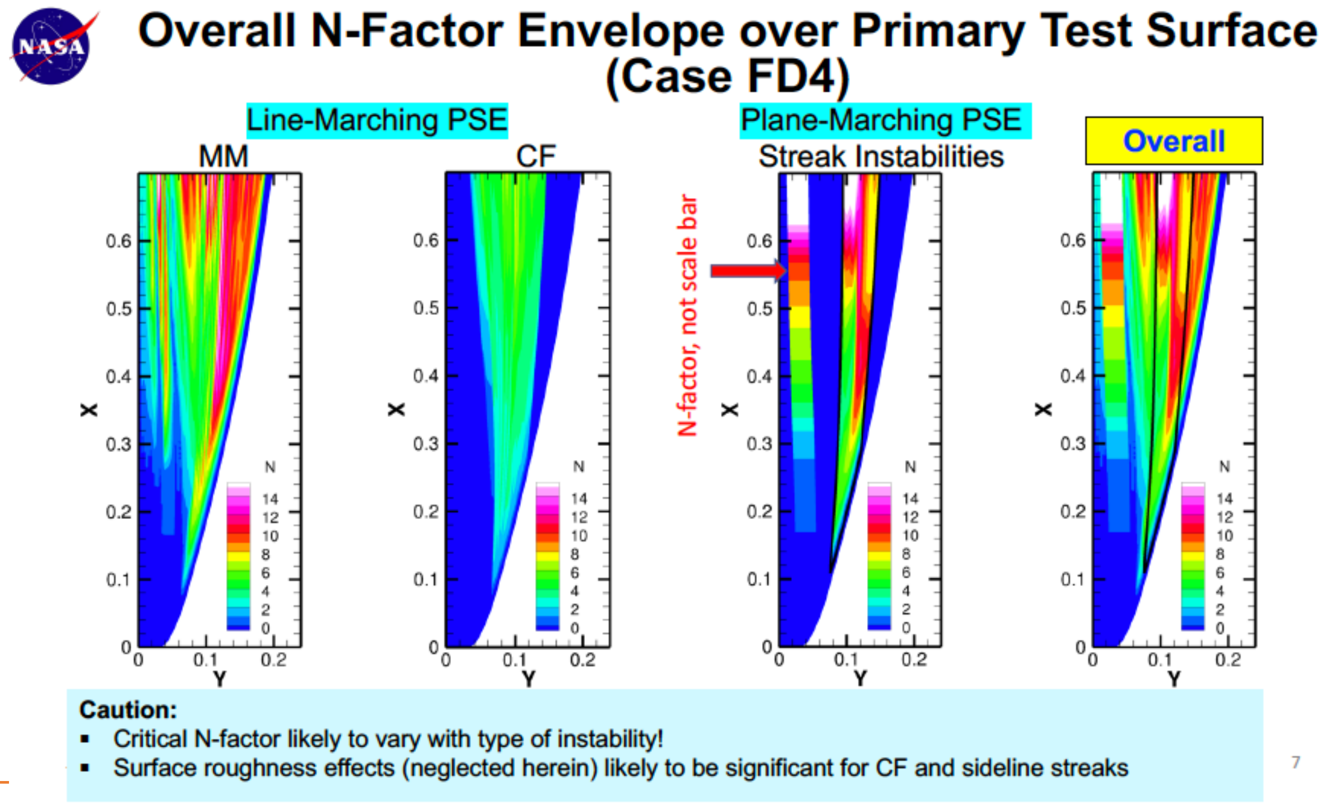
Flight data show **fully laminar flow** at this condition but **LORN Transition Criterion** expects turbulent flow



Predicted Regions of Turbulent Flow

[credit: G. Candler, University of Minnesota]

BOLT-II at Highest Re case: $M = 7.36$, $Re_L = 11.53 \times 10^6$



Overall N-Factor Envelope over Primary Test Surface (Case FD4)

Caution:
- Critical N-factor likely to vary with type of instability!
- Surface roughness effects (neglected herein) likely to be significant for CF and sideline streaks

7

[credit: Li et al., NASA]

Facilities/Diagnostics Team

- OGAs and academia
  - Owners of hypersonic/high-speed facilities
  - Development of diagnostic tools

- Facilities are generally smaller/cheaper to operate for university tunnels

NASA

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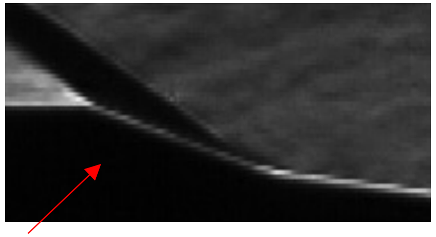
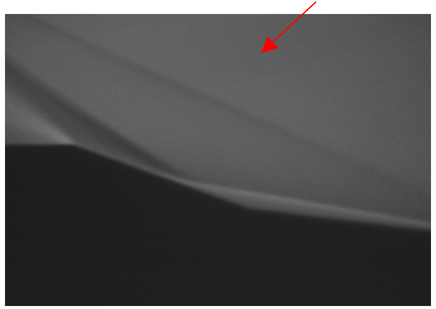
Highlights from Facilities/Diagnostics Team Pre-Work

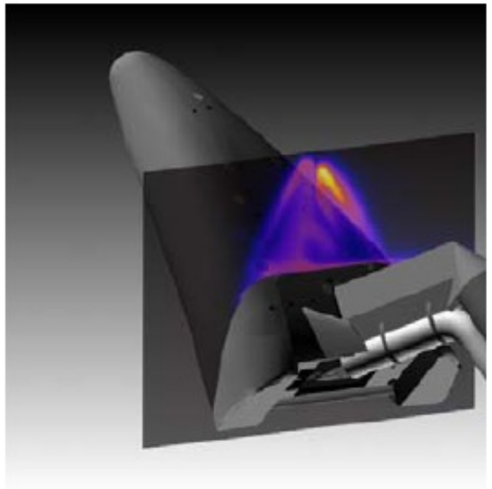
- What measurement techniques do we have and are they sufficient?
  - High-bandwidth pressure, one high-bandwidth heat transfer, shear
  - Optical techniques: schlieren, PLIF, FLDI, etc.
  - Computational team was asked – the types of measurements they want are global measurements of velocity, temperature, and pressure, etc. to a known uncertainty – difficult to achieve, so current capabilities are not sufficient



Conventional vs. focusing schlieren

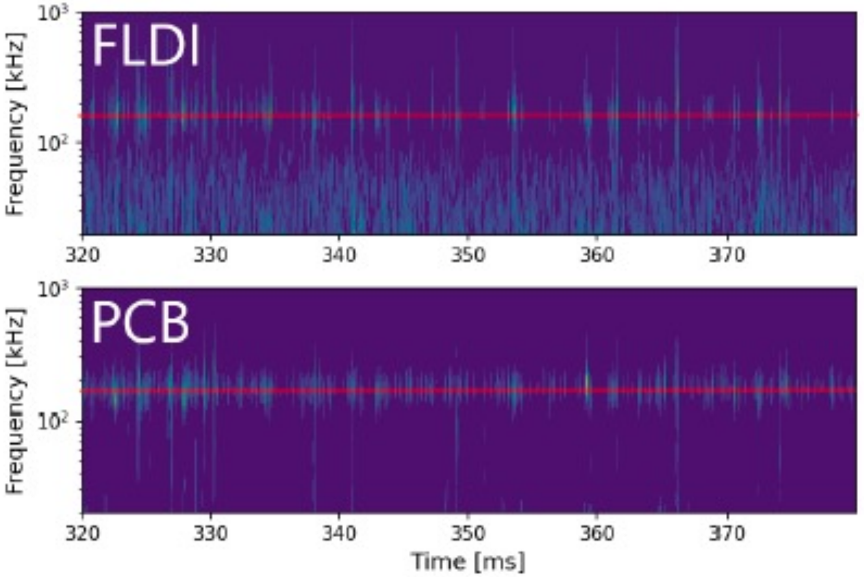


[credit: J. Weisberger, NASA]



NO PLIF at Mach 10

[credit: P. Danehy, NASA]



FLDI (off-body) and PCB (surface) measurement comparison

[credit: A. Berger, AFRL]

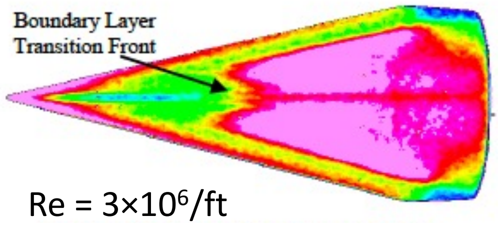
Highlights from Facilities/Diagnostics Team Pre-Work

- How can all classes of ground test facilities and flight testing increase the understanding of BLT and improve/validate modeling?
  - Continue using intentionally-coordinated common geometries that can be tested in multiple facilities, flight tested, and computed with several codes
  - Need a good way of sharing data across organizations

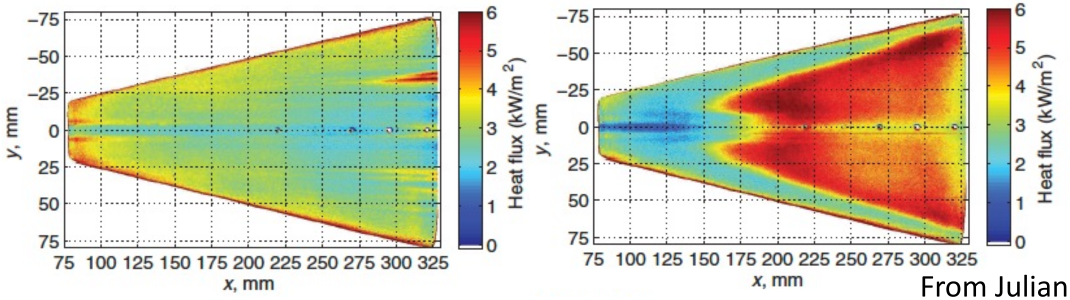
NASA LaRC 20-Inch Mach 6 Air Tunnel

Purdue University BAM6QT (Mach-6 Quiet Tunnel) 10.2×10⁶/m

HIFiRE-5

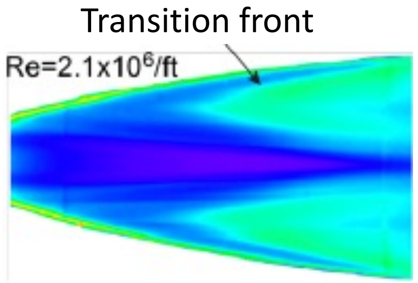


From Berger et al, NASA

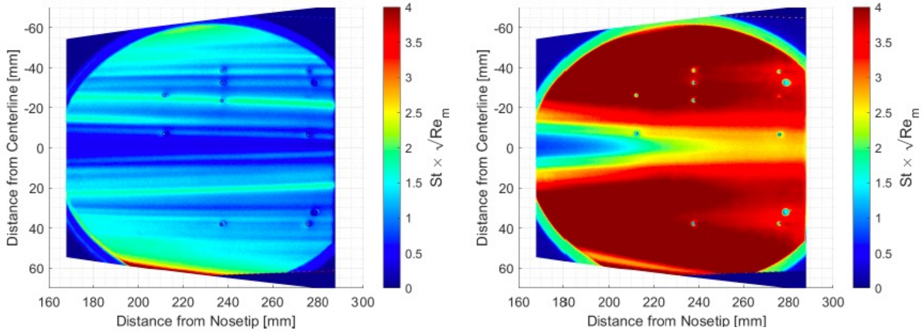


From Juliano et al, *AIAA J*, v. 53, n.4, AFRL

BOLT



From Berry et al., NASA



Quiet Flow

Noisy Flow

From Yam et al., NASA

Flight Experiments Team

- OGAs, UARC, and Academia
- PIs for recent flight experiments

Highlights from Flight Test Team Pre-Work

- What are the current operational limitations in flight testing?
  - Instrumentation, lead times, telemetry bandwidth
  - Recovery is not always available, encryption of TM data can increase chances of data loss
  - Costs and funding for boundary layer transition-specific flight testing

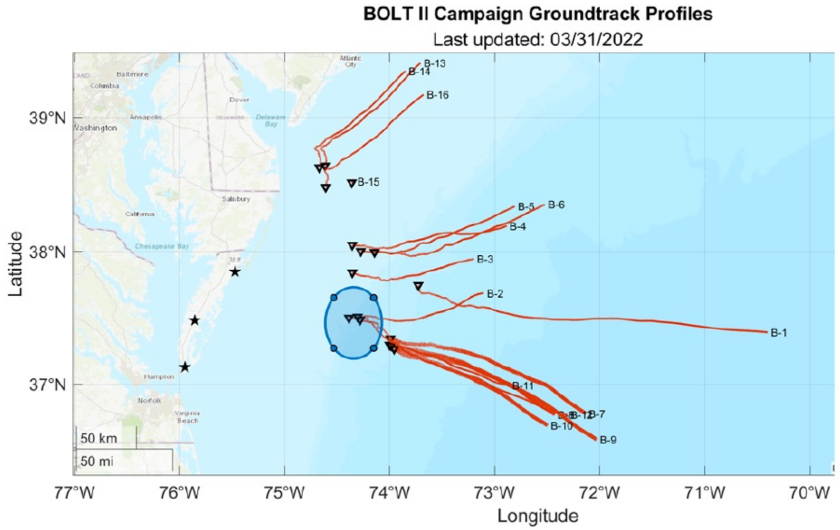
[credit: Bradley Wheaton, JHU/APL]

Highlights from Flight Test Team Pre-Work

- How do we account for the fact that we will never know the initial and boundary conditions of the vehicle in flight to a high fidelity?
  - We can measure pre and post flight boundary conditions
  - AFOSR MURI showed we can measure pre-flight, during flight, and post-flight freestream disturbances
  - Need to identify parameters that most affect transition for various geometries, trajectories and assess/specify maximum uncertainties for those parameters

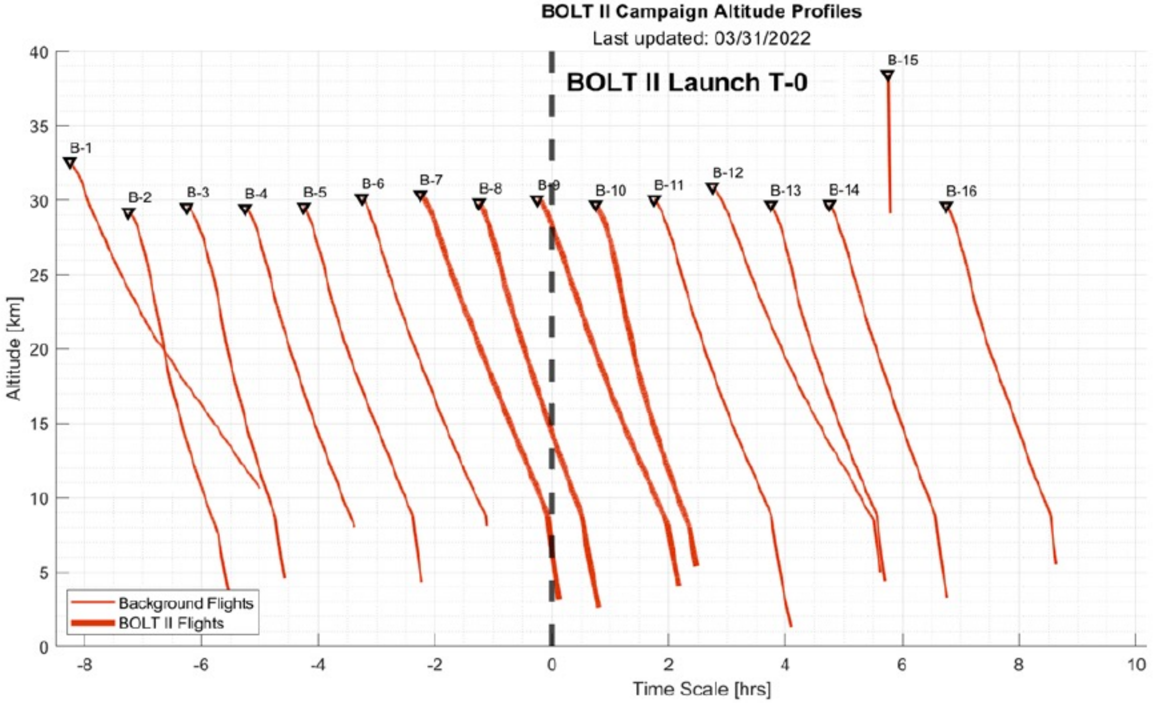
HYFLITS measurements before, during, and after BOLT-II campaign

From Lawrence et al., AIAA 2023-480



BOLT II Campaign Groundtrack Profiles

Last updated: 03/31/2022



BOLT II Campaign Altitude Profiles

Last updated: 03/31/2022

Flow Control Team

- This is an area that historically has not had a lot of funding for the high-speed community

- Primarily, work has been done in passive flow control, optimized for single condition
- Some active flow control has been done with plasma actuators

- Work would benefit from collaboration with materials, systems (e.g., FY24 ONR MURI “Understanding and Tailoring the Interactions between Metamaterials and Hypersonic Flows”)

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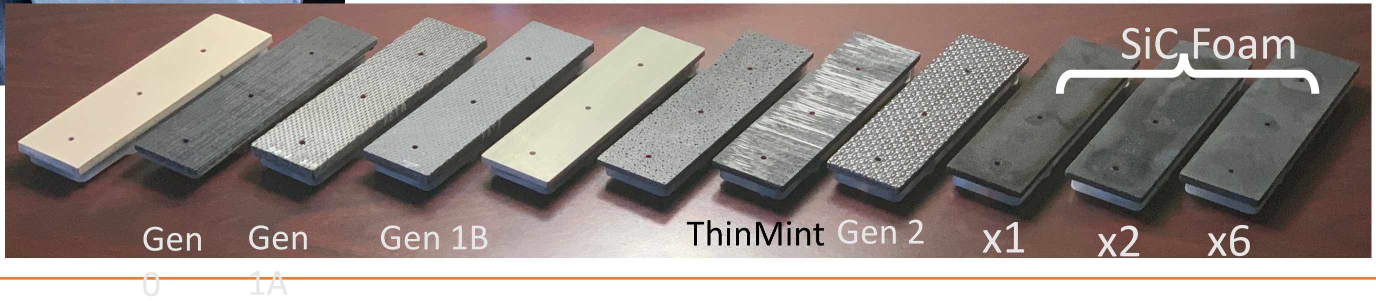
Highlights from Flow Control Team Pre-Work

- What are methods that we have to promote or delay transition based on the knowledge we have of boundary layer instabilities?
  - First mode (typically oblique supersonic dominant instability): wall cooling stabilizes, introduce 3D waves to delay/promote transition
  - Second mode (typically 2D/axisymmetric hypersonic instability): wall cooling destabilizes, ultrasonic absorptive coatings to delay, 2D roughness trips to delay, CO_2 injection to delay
  - Crossflow instability (typically on swept leading edges and angle of attack): discrete roughness elements (DREs) or plasma actuators spaced at a stabilizing or destabilizing “wavelength”

HySonic “boat” at AFRL

Running et al. *Exp. In Fluids* (2023), v. 64:79



[Credit: L. Owens, NASA]

Highlights from New Approaches Team Pre-Work

- Academia
  - Mostly computational, but incorporate experimental work
  - New research efforts, developmental

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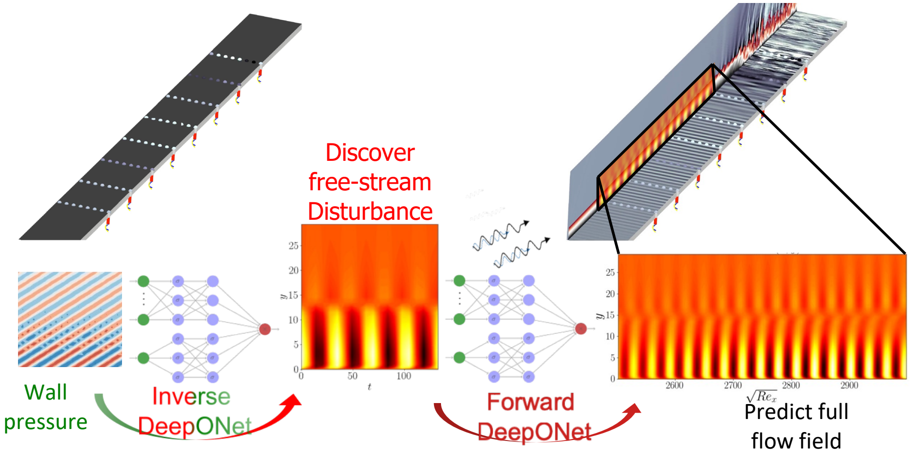
Highlights from New Approaches Team Pre-Work

- What are some new approaches toward predicting or understanding boundary layer transition?
  - **Data Assimilation (DA):** augment physical measurements and predict the flow field from limited data, provides sensitivity of measurements to unknown parameters
  - **Uncertainty Quantification (UQ):** is part of some DA strategies and provides important info regarding sensitivities
  - **Machine Learning (ML):** can be integrated within existing tools. Neural networks can learn functions and operators to work towards reduced order modeling, acceleration of existing optimization/DA, grid-free/automatic refinement solver of PDEs
  - **Hierarchical I/O analysis** for 3D receptivity of realistic freestream disturbances
  - Bayesian approaches dealing with the stochastic nature of transition

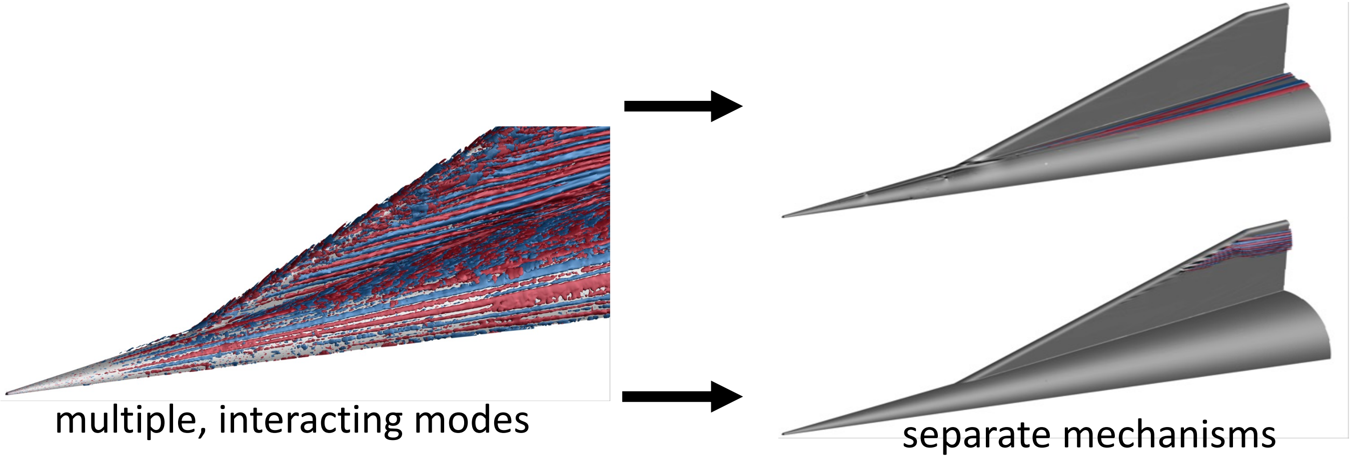
Machine learning to predict possible flow fields/missing data



De Leoni et al., *J Comp Phys, v.* 474 (2023) 111793

[credit: T. Zaki, Johns Hopkins Univ.]

I/O analysis to decompose complex physics into separate modes



AIAA 2020-1820

[credit: J. Nichols, U Minnesota]

Why boundary layer transition?

Objectives and participant makeup

Overview and History of the National Hypersonic Foundational Research Plan

Assessment of NHFRP Roadmap

Highlights of “pre-work” discussions

Subjects of interest for new notional roadmaps

What to focus on in the future?

Geometries/Vehicles

- Common Geometries
  - Identify community geometries
  - Database of relevant mechanisms
- Engineering-Level Tools
  - Incorporation of current understanding into tools
  - Incorporation into the design cycle
- Roughness and Shape Changes
  - Identify parameters and statistics to characterize
  - Incorporation of roughness and shape change models into prediction tools
  - Systematic shape optimization robust to changes

Computational Methods

- Integration into CFD
  - Stability analysis tools available to non-expert engineers
  - Faster tools for the design process
  - Transition assessment integrated with MDAO tools
- Implementation of new approaches
  - Uncertainty quantification as standard practice
  - Sensitivity analysis incorporated in UQ
  - Machine-learning/data-driven approaches for prediction
- Calibration and validation data
  - Use existing flight/ground experiments and DNS, including transition zone
  - Obtain detailedoff-body measurements in large quiet tunnels or flight
  - Modeling of dynamic geometry changes and high-enthalpy in flight

Facilities/Diagnostics

Facility Characterization

- Characterization with existing techniques (E.g., NATO STO AVT-240 effort)
- Correlate data between facilities and digital wind tunnels for common geometries
- Use new time-resolved, off-body planar/volumetric techniques in facility characterization

Measurement/Diagnostic Development

- Development of more high-bandwidth, well-characterized COTS sensors
- Development and refinement of time-resolved off-body planar/volumetric techniques
- Incorporation of validated UQ in measurements

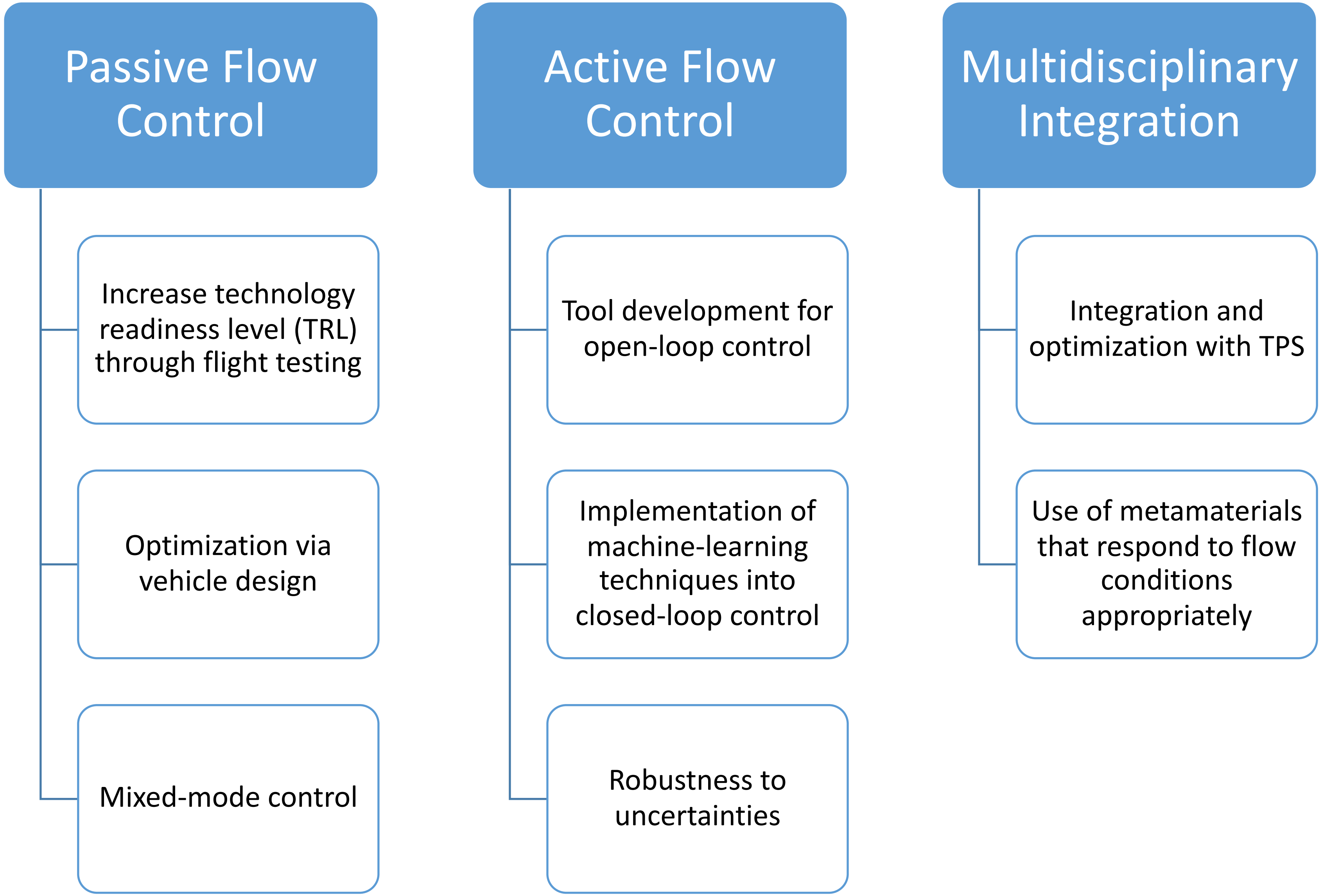
Model Fabrication Techniques

- Higher accuracy additive manufacturing techniques
- Ability to print dense sensors into additively manufactured models

Flight Experiments

- Trajectories
  - Controlled and depressed trajectories
  - Reusable large-scale flight platforms
- Instrumentation & Data Systems
  - Next-gen global measurements integrated with TPS, high-frame rate IR, deformation sensing
  - Higher-bandwidth testing, possible space-based TM systems or routine recovery
  - Implementation of high-res, high-bandwidth sensing in T&E flights/programs
- Atmospheric Characterization
  - Atmospheric characterization via balloon + LIDAR (AFOSR MURI)
  - Routine, in situ standard atmospheric characterization (mean and fluctuating components)

Flow Control



Passive Flow Control

- Increase technology readiness level (TRL) through flight testing
- Optimization via vehicle design
- Mixed-mode control

Active Flow Control

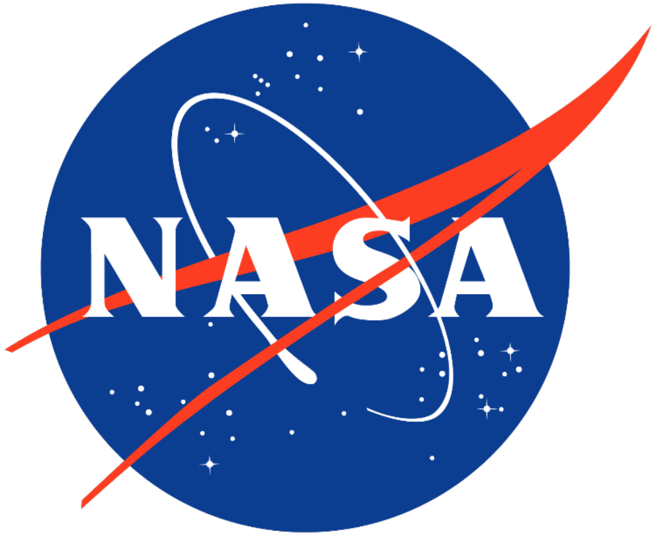
- Tool development for open-loop control
- Implementation of machine-learning techniques into closed-loop control
- Robustness to uncertainties

Multidisciplinary Integration

- Integration and optimization with TPS
- Use of metamaterials that respond to flow conditions appropriately

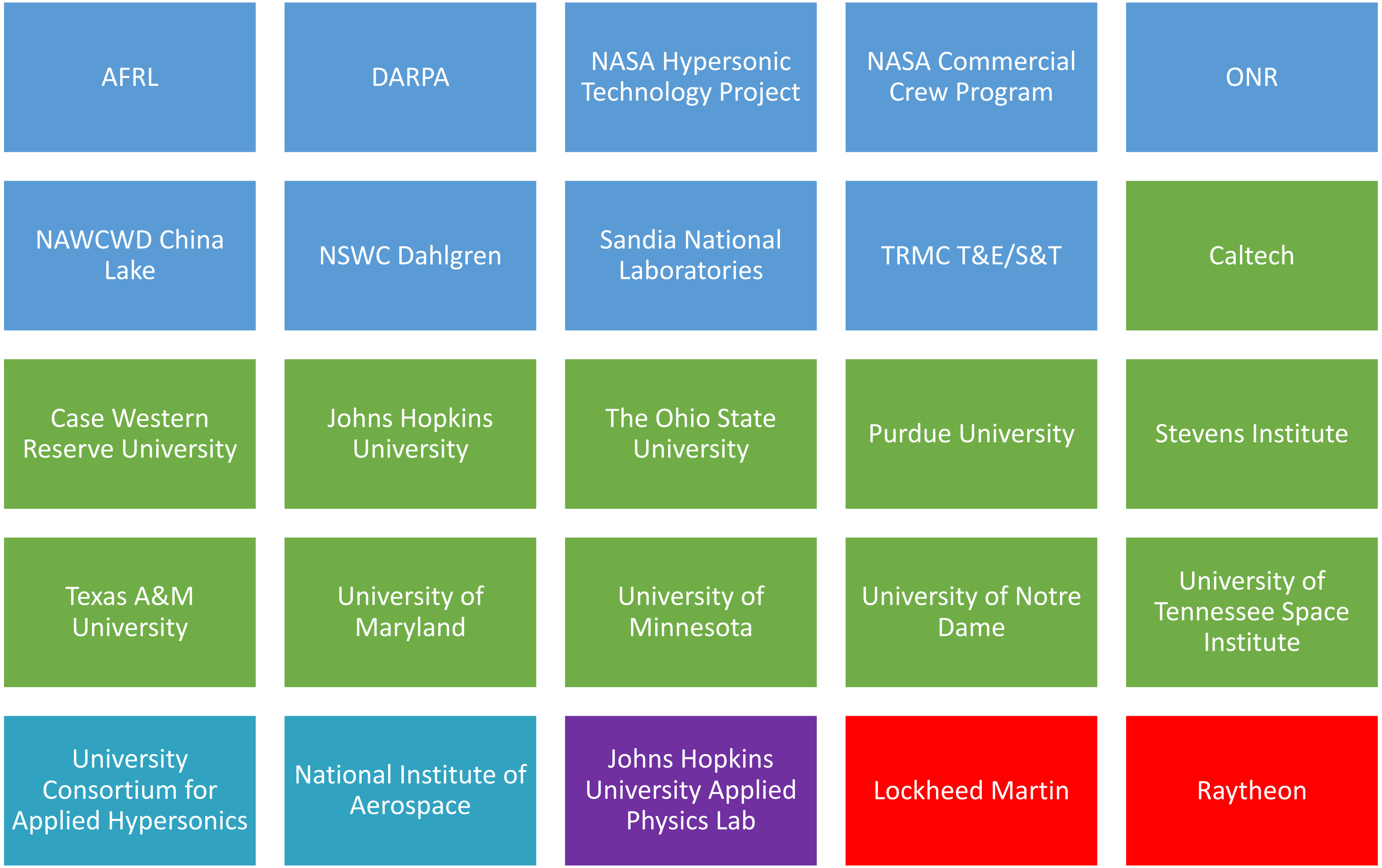
Summary

- New roadmaps demonstrate a pivot, incorporating new technologies
- Need to define a set of realistic common geometries to work toward
  - AIAA working groups and discussion groups need to have a fully-open geometry
  - Need to have a smaller community working CUI
    - Some universities can work this (e.g., some UCAH guidelines limit openness)
    - NASA and OGAs could work, but may lose diversity/expertise of outside
- In-flight conditions are still a large unknown: atmospheric characterization, surface conditions, geometry changes, chemistry
  - These are not unique to boundary layer transition
  - Flow control is an area that has not historically been greatly funded at this speed regime – need for more key players, investigation into robust methods of control
- Incorporate new methods and approaches as they evolve into computations and flight/ground experiments


NASA

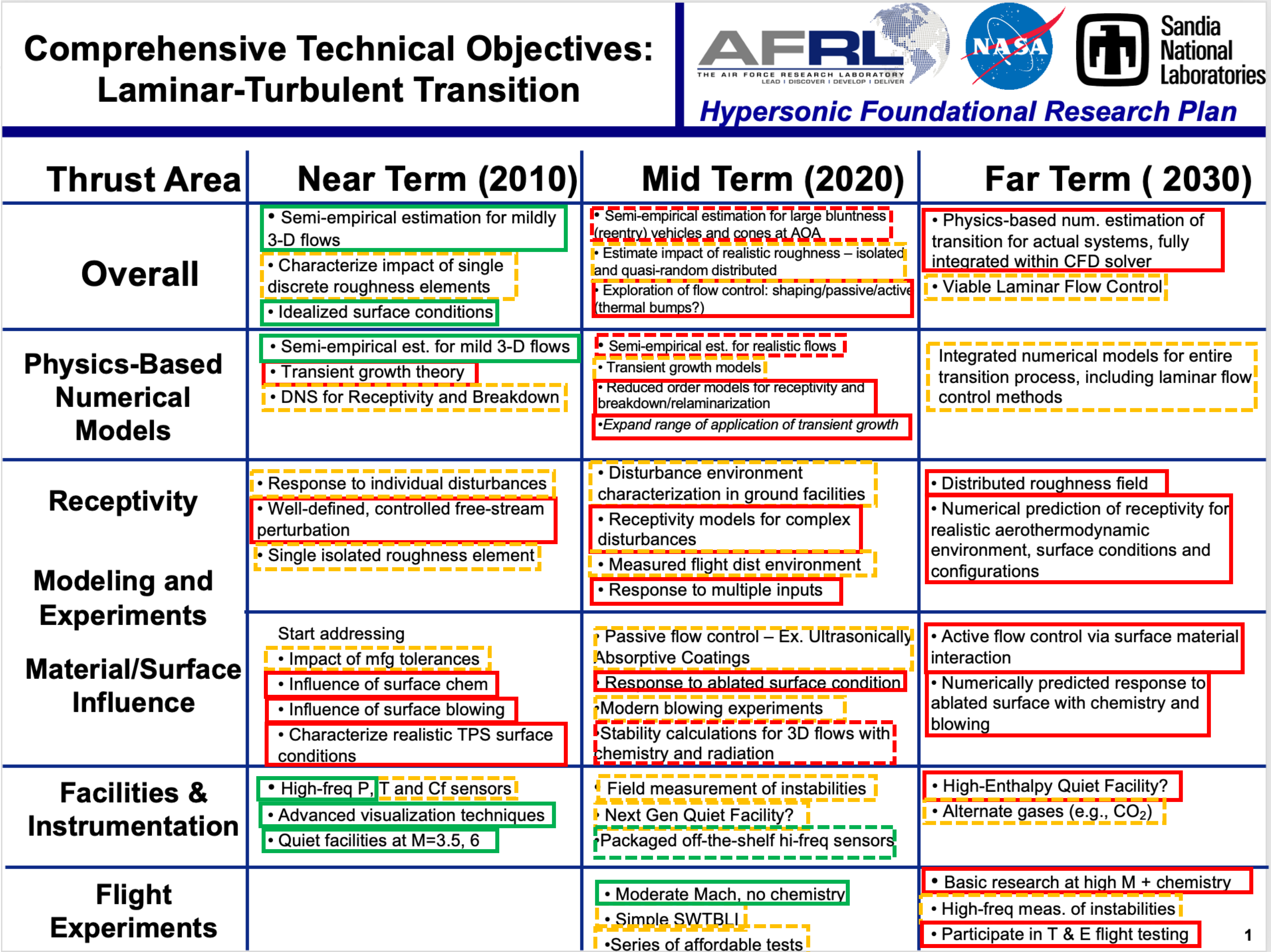
Participants of the Workshop

- Organized by
  - Douglas Smith, AFOSR International Program Officer, Aeronautical Sciences
  - Eric Marineau, ONR Hypersonics Program Officer,
  - Amanda Chou, NASA HTP Vehicle Technologies Lead
- Participants were mix of academia, industry, government agencies
- Limited capacity in room
  - Helped foster discussion
  - Produced actual end products



- AFRL
- DARPA
- NASA Hypersonic Technology Project
- NASA Commercial Crew Program
- ONR
- NAWCWD China Lake
- NSWC Dahlgren
- Sandia National Laboratories
- TRMC T&E/S&T
- Caltech
- Case Western Reserve University
- Johns Hopkins University
- The Ohio State University
- Purdue University
- Stevens Institute
- Texas A&M University
- University of Maryland
- University of Minnesota
- University of Notre Dame
- University of Tennessee Space Institute
- University Consortium for Applied Hypersonics
- National Institute of Aerospace
- Johns Hopkins University Applied Physics Lab
- Lockheed Martin
- Raytheon

NHFRP Ro



Comprehensive Technical Objectives: Laminar-Turbulent Transition

Hypersonic Foundational Research Plan

Thrust Area	Near Term (2010)	Mid Term (2020)	Far Term (2030)
Overall	• Semi-empirical estimation for mildly 3-D flows • Characterize impact of single discrete roughness elements • Idealized surface conditions	• Semi-empirical estimation for large bluntness (reentry) vehicles and cones at AOA • Estimate impact of realistic roughness – isolated and quasi-random distributed • Exploration of flow control: shaping/passive/active (thermal bumps?)	• Physics-based num. estimation of transition for actual systems, fully integrated within CFD solver • Viable Laminar Flow Control
Physics-Based Numerical Models	• Semi-empirical est. for mild 3-D flows • Transient growth theory • DNS for Receptivity and Breakdown	• Semi-empirical est. for realistic flows • Transient growth models • Reduced order models for receptivity and breakdown/relaminarization •*Expand range of application of transient growth*	Integrated numerical models for entire transition process, including laminar flow control methods
Receptivity Modeling and Experiments	• Response to individual disturbances • Well-defined, controlled free-stream perturbation • Single isolated roughness element	• Disturbance environment characterization in ground facilities • Receptivity models for complex disturbances • Measured flight dist environment • Response to multiple inputs	• Distributed roughness field • Numerical prediction of receptivity for realistic aerothermodynamic environment, surface conditions and configurations
Material/Surface Influence	Start addressing • Impact of mfg tolerances • Influence of surface chem • Influence of surface blowing • Characterize realistic TPS surface conditions	• Passive flow control – Ex. Ultrasonically Absorptive Coatings • Response to ablated surface condition •Modern blowing experiments •Stability calculations for 3D flows with chemistry and radiation	• Active flow control via surface material interaction • Numerically predicted response to ablated surface with chemistry and blowing
Facilities & Instrumentation	• High-freq P, T and Cf sensors • Advanced visualization techniques • Quiet facilities at M=3.5, 6	• Field measurement of instabilities • Next Gen Quiet Facility? •Packaged off-the-shelf hi-freq sensors	• High-Enthalpy Quiet Facility? • Alternate gases (e.g., CO_2)
Flight Experiments		• Moderate Mach, no chemistry • Simple SWTBLI •Series of affordable tests	• Basic research at high M + chemistry • High-freq meas. of instabilities • Participate in T & E flight testing

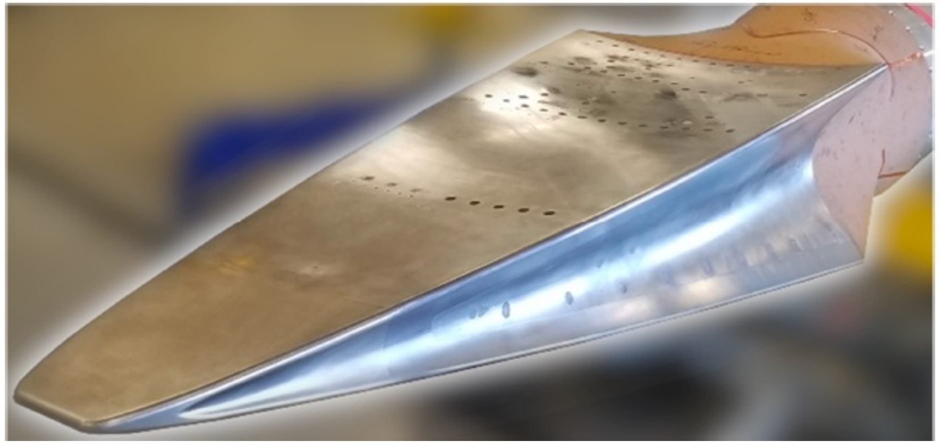
Done for multiple geometries by multiple groups, in standard practice now **for BLT community/experienced users**

Some work has been done, but is not well-understood for multiple applications or is not in standard practice across groups

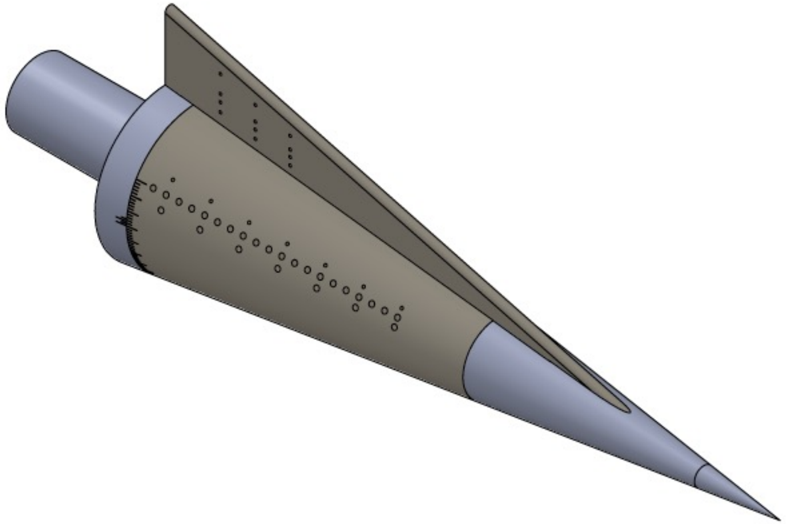
Not well-understood, only being investigated by one or two groups

Highlights from Geometries/Vehicles Team Pre-Work

- What is a suitable process to generate non-sensitive geometries that exhibit relevant geometric complexity and boundary layer transition mechanisms without being directly traceable to sensitive (classified) systems?
  1. Break down the issues to the underlying physics and rebuild something that can provide a study of similar mechanisms: e.g., BOLT, ONR finned cone
  2. Ask someone with no knowledge of systems to propose a new geometry



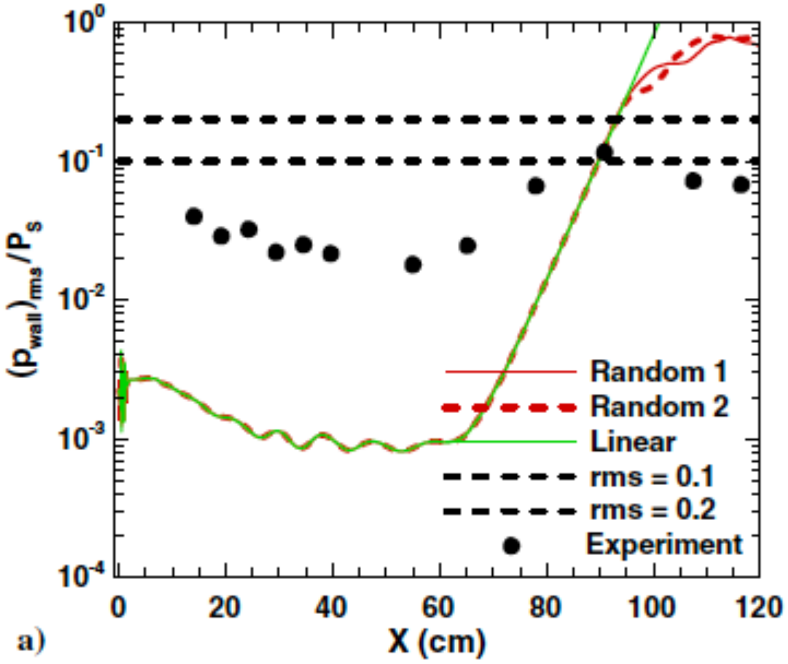
[U] BOLT-II
[credit: Dufrene et al., AIAA 2023-478, AFOSR/AFRL-funded]

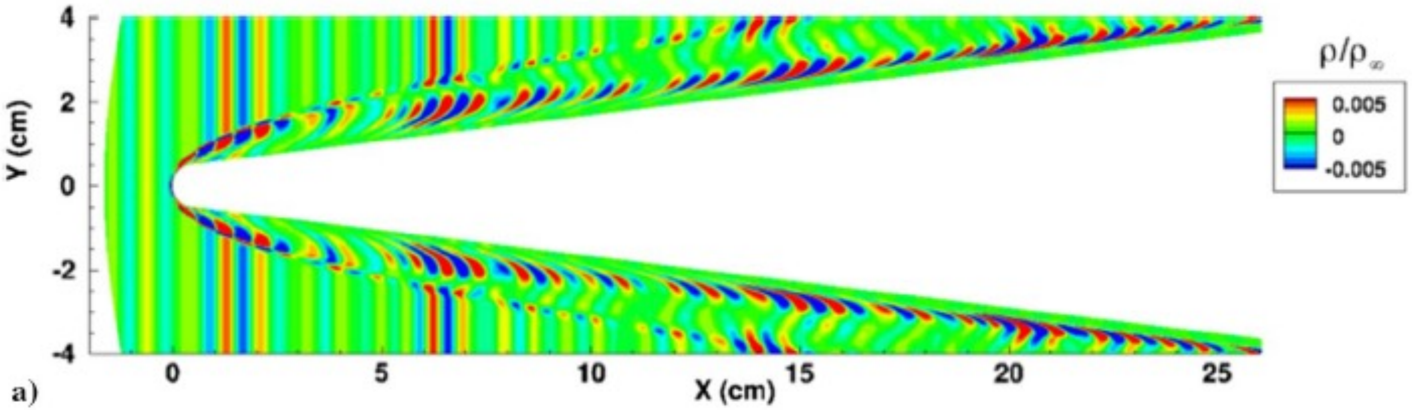


Finned Cone
[credit: F. D. Turbeville, NASA]

Highlights from Computational Methods Team Pre-Work

- Are there gaps in numerical methods and grid generation that need to be assessed?
  - Grid generation is a bottleneck, computing accurate grid-independent laminar solutions for 3D configurations is challenging and needs to be improved
  - Is e^N useful for real geometries that will never be limited by only one instability mode or one flight condition?

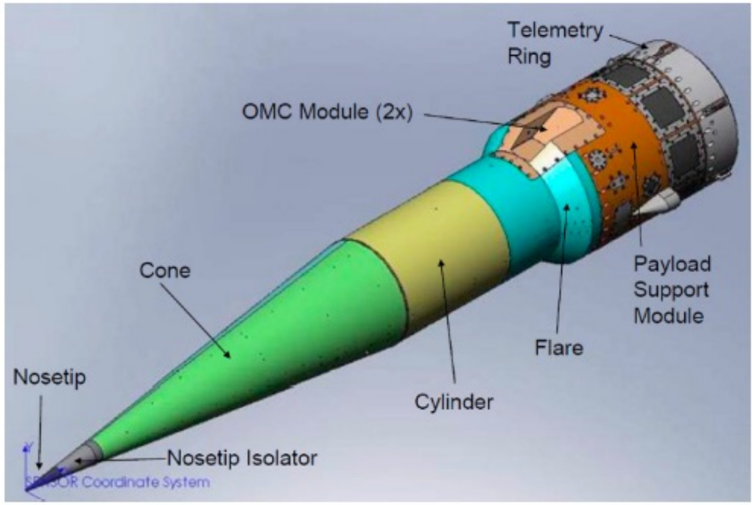




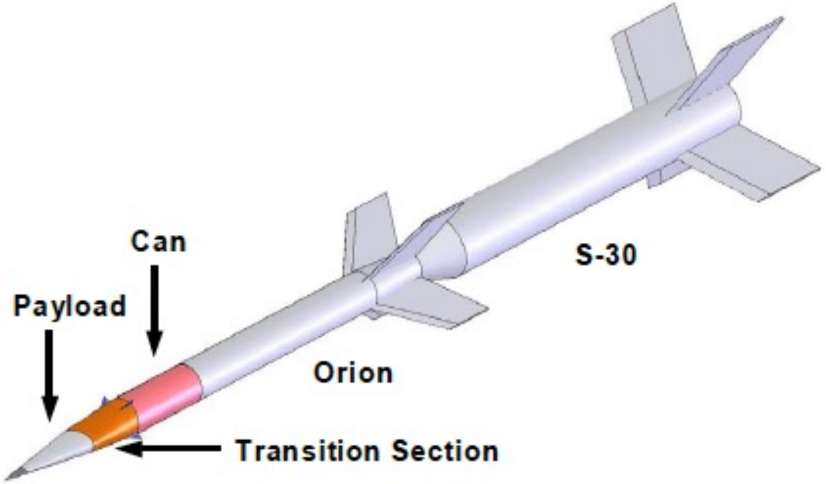
From P. Balakumar et al., *AIAA J*, v. 56, n. 1, 2018. NAS

Highlights from Flight Test Team Pre-Work

- What are the results of unclassified, successful flight programs and how have they advanced our knowledge of boundary layer transition?
  - **HIFiRE**: 1, 5a, 5b pioneered modern instrumentation, hardware, software; second-mode-dominated transition on a cone; leading-edge and centerline transition for non-axisymmetric geometry
  - **BOLT**-II: transition on smooth wall complex geometries, high frequency measurements, concurrent atmospheric characterization
  - **HVP**: aerothermal turbulent heating at high supersonic speeds, transition at low hypersonic speeds
  - Note, some of the “failed” flights have a supersonic transition data in the Mach 2 – 3.5 range



HIFiRE-1 from AIAA 2011-2358
[credit: Adamczack et al., AFRL]



HIFiRE-5 from AIAA 2010-4985
[credit: Kimmel et al., AFRL]

Hypervelocity Projectile
[credit: US Navy]

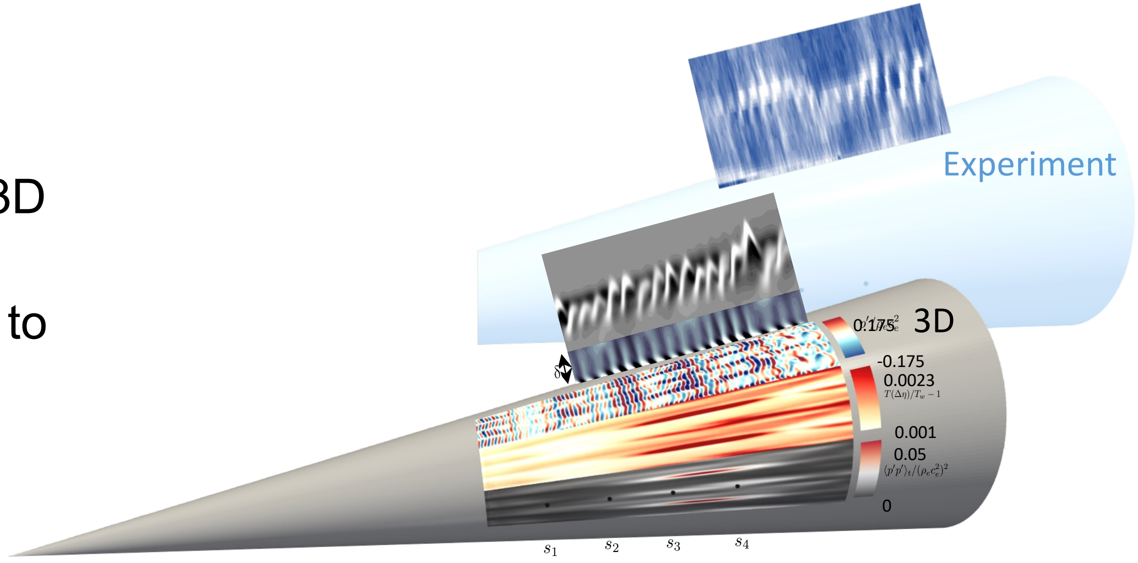
Highlights from New Approaches Team Pre-Work

- How can we use these new approaches to bridge differences between computations and ground/flight test?
  - Data assimilation techniques use a combination of experimental and computational data to ensure that computations predict true conditions (would be a stretch to do this for flight test, given paucity of data)
  - Uncertainty quantification places error bars on predictions to better relate computations to experiments: they are not always “measurement errors” if they are outside computed uncertainty bounds
  - Machine-learning provides a compromise between accuracy and speedup – this may be useful for applications of real-time active flow control

Data Assimilation of reconstructed time-dependent 3D flow:

"optimize" free-stream noise disturbance field in DNS to match the experimental measurements

D. Buchta et al., J. Fluid Mech., v. 947, 2022



	Near (Now)	Mid (+10 Years)	Far (+20 Years)
Geometries /Vehicles	• Define/prioritize common geometries to study in the community, build a database/knowledge capture of existing geometries studied • Work toward engineering-level tool that incorporates current understanding of BLT physics • Define consistent, relevant parameters/ statistics to characterize roughness and shape changes	• Systematic, coordinated characterization of common geometries to define important mechanisms • Engineering-level tools with physics-based understanding of geometric impacts on transition mechanisms • Coordinated characterization of roughness patterns and shape change on real geometries in ground, flight, computations	• Integrate geometric impacts on transition into vehicle design process in early design cycles • Incorporate systematic shape optimization robust to geometric uncertainties: flow control informed by physics-based roughness transition
Computational Methods	• Collaborative efforts to evaluate variable fidelity methods • Transition analysis integrated with CFD available to engineers for analysis and design phase • Obtain calibration/validation data (large quiet tunnel experiments and DNS), including transition zone	• Obtain transition data from large quiet tunnels to build validated models with known error bars • CFD with integrated transition analysis available to engineers with ROMS/ML to combine multifidelity approaches • Fast transition tools for design • Physics-based models for relevant surface geometry	• Understanding/modeling of dynamically evolving surface geometry and high-enthalpy effects in flight • High-fidelity transition assessment integrated with MDAO tools for rabid analysis and design
Facilities /Diagnostics	• Bring online planned facilities and characterization using DA and existing sensors • Develop more high-bandwidth COTS sensors • Develop diagnostics for 2D/3D measurements • Correlate data between facilities and digital wind tunnels for common geometries • Develop additive manufacturing (AM) techniques for models	• Redundancy in high Reynolds number tunnels • Time-resolved global measurements of velocity, density • Validated UQ for common diagnostics • Readily available, well-characterized COTS sensors • AM of models combined with (printed) miniaturized sensors	• Time-resolved global measurements of pressure, temperature, velocity, density, and their fluctuating components with widely-adopted UQ • Turn-key diagnostics capable of implementation in T&E facilities
Flight Experiments	• Use existing platforms for common canonical and representative geometries • Use existing limited point measurements and SCIFLI, develop instrumentation for flight • Develop repository for data preservation, development of higher-bandwidth data systems • Atmospheric characterization with balloon/HALAS system for each BLT experiment	• Fly controlled trajectories, depressed trajectories for common geometries • Next-gen point measurements integrated with real TPS, high framerate IR for ballistic ranges, global measurements, deformation sensing • Utilization of higher-bandwidth testing, space-based TM systems, common high-speed TM and/or recovery. Active repository for flight testing. • In-situ, onboard atmospheric characterization (density, temp., velocity)	• Reusable large-scale flight platforms with high-rate telemetry infrastructure for representative high-speed vehicles • Instrumentation implemented in programs/T&E flights • Routine high-res, high-bandwidth measurements, on-board off-body measurements • Routine, standard atmospheric characterization including p, T, rho, particulates, u, v, w, and their fluctuating components

Notional Roadmap of Geometries/Vehicles Team

- Three main areas: common geometry, engineering-level tools, and how to handle geometric/surface changes (roughness, FTSI, etc.)

Near-Term

Identify common geometries to study in the community

Build a database/knowledge capture of existing geometries studied and important related mechanisms

Work toward **engineering-level tool** that incorporates current understanding of BLT physics

Define consistent, relevant parameters/ statistics to **characterize roughness and shape changes**

Mid-Term

Engineering-level tools with physics-based understanding of geometric impacts on transition mechanisms

Coordinated characterization of **roughness patterns and shape change on real geometries** in ground, flight, computations

Far-Term

Integrate geometric impacts on **transition into vehicle design process** in early design cycles

Incorporate **systematic shape optimization robust to geometric uncertainties**: flow control informed by physics-based roughness transition

Notional Roadmap of Computational Methods Team

- Three main areas: CFD-integrated and multi-fidelity tools, implementation of new approaches, calibration/validation data

Near-Term

Transition analysis integrated with CFD available to engineers for analysis and design phase

Robust, efficient, **automatic generation of base-flow solutions** on complex geometries

Uncertainty quantification of currently available methods

Obtain calibration/validation data (flight/ground experiments and DNS), including transition zone

Mid-Term

Fast transition tools for design

Sensitivity analysis included for UQ

Physics-based models for relevant, real surface geometry/topography

Obtain **detailed transition data from large quiet tunnels or flight to build validated models** with known error bars

Far-Term

Understanding/**modeling of dynamically evolving surface geometry and high-enthalpy effects** in flight

High-fidelity **transition assessment integrated with MDAO tools** for rapid analysis and design

Exploit **data-driven/machine learning approaches for BLT prediction** with sensitivity and UQ

Notional Roadmap of Facilities/Diagnostics Team

- Three main areas: facility characterization and development, measurement techniques/diagnostic development, model fabrication techniques

Near-Term

Bring online planned facilities and characterization using existing measurement capabilities

Develop more high-bandwidth COTS sensors (shear and heat transfer)

Develop diagnostics for 2D/3D measurements

Correlate data between facilities and digital wind tunnels for common geometries (holistic look)

Develop **higher-accuracy additive manufacturing** (AM) techniques for ground test models

Mid-Term

Redundancy in high Reynolds number tunnels

Time-resolved global measurements of velocity, density

Validated UQ for common diagnostics

Readily **available, well-characterized COTS** sensors

AM of models combined **with (printed) miniaturized sensors**

Far-Term

Time-resolved global measurements of pressure, temperature, velocity, density, **and their fluctuating components** with widely-adopted UQ

Turn-key diagnostics capable of implementation in T&E facilities

AM of models and integrated, ultra-dense sensor configurations

Notional Roadmap of Flight Experiments Team

- Three main areas: Ability to fly certain trajectories, development of instrumentation and data systems, atmospheric characterization

Near-Term

Use **existing platforms for common canonical** and representative geometries

Use **existing limited point measurements and flight-based IR/schlieren,** develop instrumentation for flight

Develop repository for data preservation, **development of higher-bandwidth data systems**

Atmospheric characterization with balloon + LiDAR system for each BLT experiment

Mid-Term

Fly **controlled trajectories, depressed trajectories for common geometries**

Next-gen point measurements integrated with real TPS, high framerate IR for ballistic ranges, global measurements, deformation sensing

Utilization of higher-bandwidth testing, space-based TM systems, common high-speed TM and/or recovery. Active repository for flight testing.

In-situ, onboard atmospheric characterization (density

Far-Term

Reusable large-scale flight platforms with high-rate telemetry infrastructure for representative high-speed vehicles

Instrumentation implemented in programs/T&E flights

Routine **high-res, high-bandwidth measurements, on-board off-body measurements**

Routine, standard atmospheric characterization including pressure, temperature, density, particulates, velocity, and their fluctuating components

Notional Roadmap of Flow Control Team

- Goals are aligned with increasing TRL, multi-disciplinary barrier (materials) may arise, may need development of metamaterials

Near-Term

Increase TRL of single-mode control (crossflow, second mode) through flight testing

Develop **mixed-mode control without TPS constraints**

Control of transition via design (vehicle shaping)

Mid-Term

Integrated passive flow control in vehicle design (shaping, porosity, roughness)

Develop tools (e.g., open-loop control and sensors) **for active flow control**

Successful flight experiments to **demonstrate robustness of passive flow control techniques**

Far-Term

Closed-loop active flow control with machine learning, robust to uncertainties

Integrate flow control with metamaterials, smart ablators, osmotic surfaces in TPS that respond to flow conditions appropriately

Possible Overall Impacts of New Approaches

Identifying Relevant Physics & Ranking Sensitivities/Uncertainties

- Identify sensitivity to ICs/BCs: geometry changes, freestream conditions
- Prioritization of computational method developments
- Identify mechanisms of receptivity through decomposition of sensitivities for different geometries

Integrated Multi-Fidelity Approaches

- Optimization of parameter space exploration
- Systematic methods for constructing ROMS
- Uncertainty Propagation
- Synergistic integration (overall prediction better than one fidelity)
- New numerical approaches for solving Navier-Stokes equations

Enriching Experimental (Ground and Flight) Data Sets

- Optimization of parameter-space exploration
- Optimization of sensor placement
- Assimilation of measurements to refine resolution, or back-propagation to infer difficult parameters to measure