

A Summary of the 2023 Joint High-Speed Boundary Layer Transition Workshop

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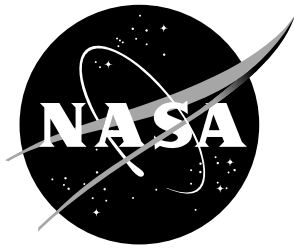
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Abstract

A joint workshop between the Air Force Office of Scientific Research, the Office of Naval Research, and the NASA Hypersonic Technology Project was held in June 2023 on the topic of high-speed boundary-layer transition. The purpose of this workshop was to gather subject matter experts in the areas of supersonic and hypersonic boundary-layer transition and to discuss the current state of the art in the field in the areas of Geometries of Interest, Computational Methods, Facilities and Diagnostics, Flight Experiments, Flow Control, and New Approaches. As accomplishments and gaps were identified, roadmaps were also created to guide future investments in these areas. The top recommendations are (1) to define relevant common geometries of interest that can be worked by multiple research groups; (2) improve modeling of high-enthalpy flows affected by chemistry and ablation, studies of receptivity of freestream disturbances and atmospheric particulates into the boundary layer, surface feature characterization and modeling of changes to geometry; (3) design and determine viable flow control methods; and (4) move towards incorporating boundary layer transition prediction into a standard practice for design of high-speed vehicles. To execute this last recommendation successfully, investments beyond fundamental (basic and early applied) research are needed.

1 Introduction

Historically, high-speed boundary layer transition has been known to affect vehicle performance, from the National Aerospace Plane (NASP) to the Shuttle Orbiter. Laminar boundary layers are known to have less skin friction drag, and thus, lower heating. Turbulent boundary layers are known to have higher kinetic energy, and thus, are less likely to separate across extreme pressure gradients. Standard rules for conservative vehicle design may call for assuming that the flow is fully turbulent or avoiding trajectories where transition may be a factor. However, fully turbulent flow is not necessarily a conservative estimate, as in the cases of separated flow, reattachment heating, etc. As such, investment in this field may be critical to optimize vehicle performance and safety of crewed vehicles.

Several efforts over the years to identify key areas of research in the field of boundary-layer transition have been conducted via workshops of subject matter experts in the field. The most recent event prior to this workshop was the high-speed boundary layer transition workshop at the High-Speed Vehicle Science and Technology (HiSST) conference in 2022 [143]. In that discussion, the following topics were identified as urgent needs to support high-speed boundary layer transition research:

- freestream characterization in ground and flight experiments
- quiet tunnels and flight opportunities
- basic research and physical understanding of real gas and wall temperature effects, outgassing vs. ablation roughness, boundary layer receptivity and global instabilities linked to freestream perturbations and in combination with separation and shock instabilities, mechanism-based approaches for transition

- prediction
- vehicle applications

These discussions likely also influenced the workshop described in this publication, but the planned product of the two workshops was significantly different.

The purpose of this workshop was to bring together subject matter experts in the field of high-speed boundary layer transition to discuss some of the unsolved problems in this field in order to develop a notional roadmap for national research efforts. The attendees of the workshop were split into six teams to assess past research efforts, the current state of our research efforts, and possible future efforts. These teams focused on the following topics:

1. Geometries of interest
2. Computational methods and tools
3. Facilities and diagnostic capabilities
4. Flight experiments and testing
5. Flow control for boundary layers
6. New approaches for studying boundary-layer transition

Prior to the workshop, a questionnaire of 5–11 questions was provided to each team to spark discussion. The responses to the questions were compiled by a “team captain” who presented the results at the two-day workshop in Arlington, VA. The team captains for each of the areas listed above were Lindsay Kirk, Pedro Paredes, Matthew Borg, Bradley Wheaton, Thomas Corke, and Joseph Nichols, respectively.

2 The National Hypersonics Foundational Research Plan Roadmap

A national roadmap was compiled previously in 2007 and involved the Air Force Office of Scientific Research (AFOSR), Sandia National Laboratories (SNL), and the National Aeronautics and Space Administration (NASA) Langley and Ames Research Centers. This roadmap was a part of the National Hypersonics Foundational Research Plan (NHFRP) and was spearheaded by Dr. John D. Schmisser, who provided a look back at the formation of the different roadmaps for hypersonic research.

In the early 2000s, a need was identified to provide a consistent foundation of fundamental research to ensure the long-term availability of experts in the field regardless of the direction of future funding. Due to the cyclical nature of funding in hypersonics, there was a fear that the available subject matter expertise and skill level would erode over time (Fig. 1). This foundation would help enable the development of future hypersonic capabilities envisioned in the national plans among the different federal agencies investing in this area. The NHFRP served two primary purposes:

1. To facilitate the coordination of foundational research across agencies investing in hypersonics

2. To support national planning efforts and stimulate investments from other government agencies.

The original plans were drafted by over 40 government subject matter experts in six different thrust areas, of which “Boundary Layer Physics” was one. Later, plans were reviewed by representatives from the academic community.

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

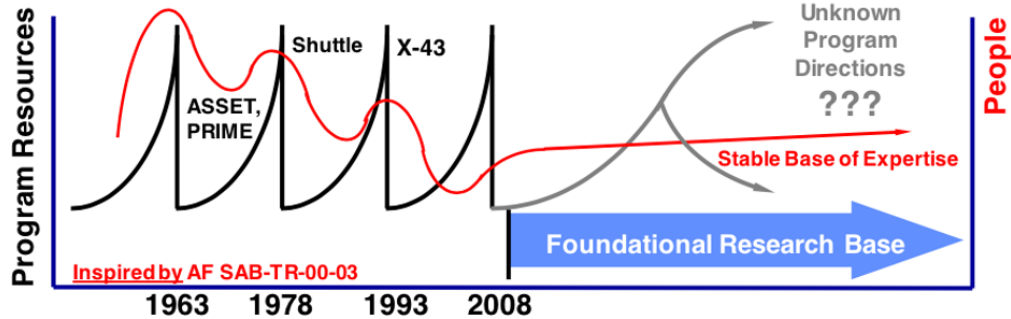


Figure 1: The cyclical nature of funding in hypersonics and the resultant decline in the hypersonic skill base (Credit: J. D. Schmisser [146]).

The top level of each of the thrust areas was intended for use in national planning, and in fact, contributed to the Joint Technology Office for Hypersonics Report to Congress [146]. The detailed plan under each thrust area contained a description of the scientific challenge and was intended for cross-agency collaboration and summarized near-, mid-, and far-term objectives. For example, under the “Boundary Layer Physics” category, the near-, mid-, and far-term goals for laminar-turbulent transition prediction were:

- Near Term (2010): Semi-empirical transition estimation for mild three-dimensional flows
- Mid Term (2020): Semi-empirical transition estimation for realistic flows and surfaces
- Far Term (2030): Physics-based numerical estimation for actual systems

The next level of detail targeted specific aspects of laminar-turbulent transition and the full chart is displayed in Fig. 2. This level of detail was provided to aid in coordinating efforts of the different government agencies involved.

Hypersonics research is often criticized as being too applied to be able to find enough fundamental research that can be supported by organizations such as the AFOSR. [147] Regardless, an argument could be made that the establishment of a strong foundation in boundary layer transition research can provide a stable base of understanding in multiple areas of hypersonics. Several of the benefactors of the NHFRP, such as past performers (students, faculty, civil servants, etc.), are current contributors to multiple areas of hypersonics even outside of the area of boundary layer transition.

Comprehensive Technical Objectives: Laminar-Turbulent Transition



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/re-laminarization - Expand range of application of transient growth	Integrated numerical models for entire transition process, including laminar flow control methods
Receptivity	- 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
Modeling and Experiments	- 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
Material/Surface Influence			
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., CO₂)
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

Figure 2: Laminar-Turbulent Transition technical objectives from the NHFRP Roadmap [Credit: J. D. Schmisser] [146].

Some of the major gaps that were identified in Schmisser's remarks were as follows:

- We must identify where the largest uncertainties in hypersonics are coming from, and know how that does or does not relate to boundary layer transition.
- More collaboration between different disciplines should be included, i.e., through Multidisciplinary University Research Initiative (MURI) topics, to have a better understanding of the effects of transition with respect to material and manufacturing tolerances, impacts on vehicle control, and structural dynamics, etc. as in the ONR topic "Understanding and Tailoring the Interactions between Metamaterials and Hypersonic Flows" in Ref. [124]

A significant point emphasized was that the greatest advancements are expected to occur at the intersection of different disciplines. As technological advances progress in adjacent fields, the focus in the study of boundary layer transition should be able to adapt accordingly.

2.1 Assessment of the NHFRP Roadmap

The different teams were given the opportunity to comment on the status of the roadmap given the current capabilities and research efforts. Had the NHFRP

roadmap been followed, the capabilities and efforts should have accomplished the near-term goals and be close to accomplishing the midterm goals by the time of the current joint boundary layer transition workshop. In the discussion, different levels of accomplishment were identified, including

- the practice or research topic is more or less routine or well-understood by a majority of subject matter experts.
- the practice or research topic is only partially understood by a few subject matter experts.
- the practice or research topic is only understood by one or two subject matter experts or is not at all used or studied.

Based on the NHFRP roadmap, the overall near-term goals should have been accomplished by the time that this workshop was held. The near-term goals included semi-empirical estimation for mildly three-dimensional flows, characterized impact of single discrete roughness elements, and transition estimation for idealized surface conditions. Within these categories, there were more detailed items under physics-based numerical models, receptivity, modeling and experiments, material/surface influence, facilities and instrumentation, and flight experiments. The same roadmap also expected that the following subjects would be in the process of being worked at the time of this workshop: semi-empirical estimation for large bluntness and cones at angle of attack, estimated impacts of realistic roughness and quasi-random distributed roughness, and the exploration of flow control.

An overall assessment of the elements of laminar-turbulent boundary layer transition is provided in Fig. 3. Color-coding of the roadmap corresponds to assessments of accomplishments in the area. Green indicates that this area has been mostly accomplished and is in standard practice for experienced users. Yellow indicates that some work has been done but is not well-understood or is not in standard practice across even the boundary layer transition community. Red indicates that the phenomenon is not well-understood and may only be worked by one or two groups. Consensus as to the state of these topics was not achieved for some of the topics during the workshop, but these disagreements led to further discussion on whether the topics were accessible by the broader engineering community.

The overall assessment of the near- and mid-term roadmaps is that several of the topics of interest in the near-term NHFRP roadmap have been worked to a level where subject matter experts are able to use the research and tools. However, they have not been widely adopted beyond the boundary-layer transition community and, in some cases, there is not consensus on the level of understanding or depth that has been achieved in research in some of these areas. The ultimate goal of the development of “state of the art” tools should be to eventually incorporate these tools into a “state of the practice” for engineers who are not subject-matter experts. Areas from the NHFRP roadmap where very little has been accomplished include chemistry and ablation effects, surface feature characterization and modeling, receptivity, and viable flow control.

Some areas that are color-coded with yellow, or partially yellow, may be areas where an overall objective was achieved but still requires work to enhance the technology to where the community desires. For example, high-frequency pressure,

Comprehensive Technical Objectives: Laminar-Turbulent Transition



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/re-laminarization - Expand range of application of transient growth	Integrated numerical models for entire transition process, including laminar flow control methods
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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

Figure 3: Laminar-Turbulent Transition technical objectives from the NHFRP Roadmap with applied color-coding to indicate assessments of the state of the field.

high-frequency heat transfer, and skin friction sensors now exist and have been used in some studies for validation of second-mode growth rates [5, 104] or state of the boundary layer in ground and flight [113–115]. However, they may not be the ideal sensors for use in all boundary-layer transition studies, as there are several issues with the packaging (size) of the sensors and issues with calibration of these sensors for use in direct quantitative comparison [173]. While characterization of the facility environments has also become standard practice [52], the measurement of freestream disturbance level is typically concentrated at a limited number of locations and only made with pitot probes. Directionality of freestream disturbances is typically not measured. Probes are sensitive to multiple disturbance types due to the presence of the bow shock in front of the probe [32]. Optical measurements of an empty tunnel, such as focused laser differential interferometry [11] or Doppler global velocimetry [26], are not standard due to limited optical access in some facilities and the difficulty in making these measurements. Likewise, the Hypersonic Flight in the Turbulent Stratosphere (HYFLITS) [1] team has developed balloon systems for freestream turbulence measurements [137] and partnered with the BOLT II flight experiment team to characterize freestream disturbance and particulate environment experienced by BOLT II [95, 96]. This type of measurement, however, is not standard practice before, during, or after a flight test.

One of the biggest challenges to this area of research is its applicability to vehicle

design and analysis. For example, the expertise required to implement stability calculations and apply an N -factor is currently inaccessible in the design phase due to the constantly evolving geometry and a lack of detailed information about the boundary layer. These methods need to be made easy and accessible enough that they will actually be used outside the transition community. If transition prediction is not made simpler and faster, then vehicle designers will continue to use old correlations that may not be relevant to the vehicle that they are designing and/or design around the problem [181]. This methodology could lead to penalties in performance. While high-fidelity analyses are needed occasionally during design or post-flight analysis, there is seldom a use for these types of analyses during the conceptual design phase of a vehicle, where the actual physical geometry may still be in flux.

Although the NHFRP roadmap is no longer in use, an integration plan is desired to coordinate all of the individual focus areas. New numerical approaches such as input-output analysis [83, 121], One-Way Navier Stokes (OWNS) [84, 85], and Adaptive Mesh Refinement Wavepacket Tracking (AMR-WPT) [22, 65] have also emerged and been applied to relevant unit problems like the finned cone [4, 5] but were not developed at the time of the first roadmaps. Considerable effort is being dedicated to addressing various individual aspects of the transition problem, including receptivity, three-dimensional flows, physics-based modeling, surface roughness, and laminar flow control. However, there is currently a lack of coherence in understanding how these different topics integrate with each other within a predictive framework.

3 Geometries of Interest

The focus of the Geometries of Interest Team was to better understand how the research in boundary layer transition could be used to affect hypersonic systems. Currently, there is a vague understanding from outsiders of the community that boundary layer transition can have some impact on vehicle performance via effects on drag, control surface effectiveness, and engine performance, but the communication of how the basic research comes together to produce useful tools for the benefit of system needs is lacking. Empirical and algebraic correlations have long been used because semi-empirical computational tools have too high an entry barrier to be able to be used by a non-expert in the design phase.

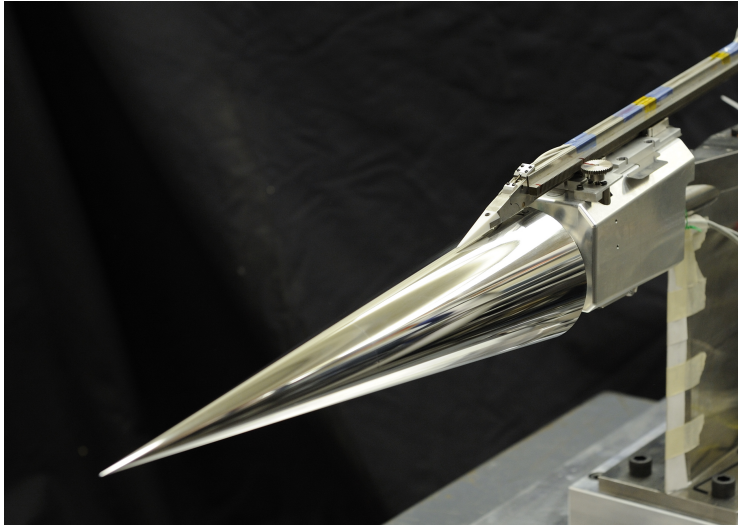
This team looked at defining relevant geometries that the entire community could work on – from fully-open geometries to controlled, unclassified geometries. Several geometries were identified as already having a wealth of experimental, computational, and theoretical research. These included blunt and sharp 7-degree cones [104, 128, 129] (Fig. 4a), ogives [60, 61, 66, 72, 120, 150], elliptic cones [17, 20, 35, 36, 47, 80–82, 89, 166], the BOUNDARY Layer Transition (BOLT) vehicle (Fig. 4b) [175], cones with fins (Fig. 4c) [4, 5, 118, 169, 176] or flaps [58, 59, 109, 126, 127, 142], cones with flare sections [43, 140], and cones with cylindrical sections and flares [14, 29, 130]. Several more geometries were discussed as having little-to-no data, including inlets, realistic control surfaces, relevant jet interactions, surface gaps, and lifting bodies.

Participants of the workshop agreed that common geometries benefit the community the most, allowing for the same problem to be worked on by multiple groups to compare where the deficiencies and agreements occur across different facilities or computational tools. Some follow-on discussion occurred at a later conference, where a few of the participants on the team started plans for a working group [6] with a variety of common geometries that could be used.

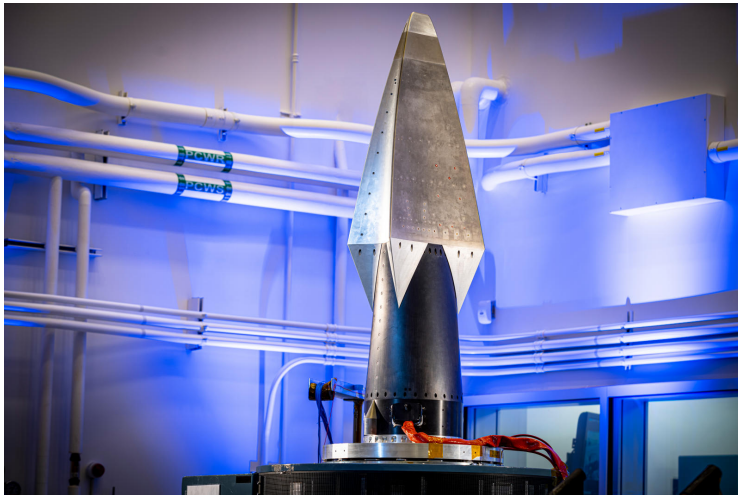
Representative surface roughness was also an area that had little work, but illustrates the difficulty in using some of the higher-fidelity work in reduced-order modeling and production codes. Much of the work that remains also lies in the characterization of distributed roughness such as the one in Fig. 5. The current methods of roughness characterization involve using a statistical representation: the tallest roughness, deepest cavity, the RMS, or the average roughness. Currently, algebraic correlations such as LORN [101, 133, 157], PANT [179, 180], the Shuttle Orbiter Tool [18, 90], and others are used to estimate transition location based on a single roughness parameter and edge quantities [149]. Despite that edge quantities can be challenging to extract on complex geometries, this type of correlation is more straightforward to incorporate into a design cycle than a semi-empirical correlation. However, few details of the physics are considered in the use of these simpler models, and as such, they may be used inappropriately and extrapolated to situations that are not represented in the original data set used to create and to calibrate these tools. To illustrate this example, consider the prediction of roughness-induced transition using the Shuttle Orbiter Tool which compares a transition parameter to some disturbance parameter and a log-log fit to the experimental data (Fig. 6a) and the use of linear stability theory that is used to predict the growth of boundary layer instabilities to determine possible transition locations (Fig. 6b). The Shuttle Orbiter tool does not require the same depth of knowledge of the flow physics that cause transition and may be more appropriate for a design tool while the use of linear stability analysis may require more subject-matter expertise to be able to determine the details of the transition process, namely an understanding of the dominant instability modes. Most of the higher-fidelity experimental work has been done at low speed [50, 51, 93, 154, 162, 163] and moderate supersonic speeds [33, 34, 44, 86] with a little work done at hypersonic speeds [45, 64], and much of it remains pertinent to only higher-fidelity modeling. The connection between these higher-fidelity models and the engineering-level tools are still tenuously defined, and more mid-fidelity modeling may be necessary.

4 Computational Methods

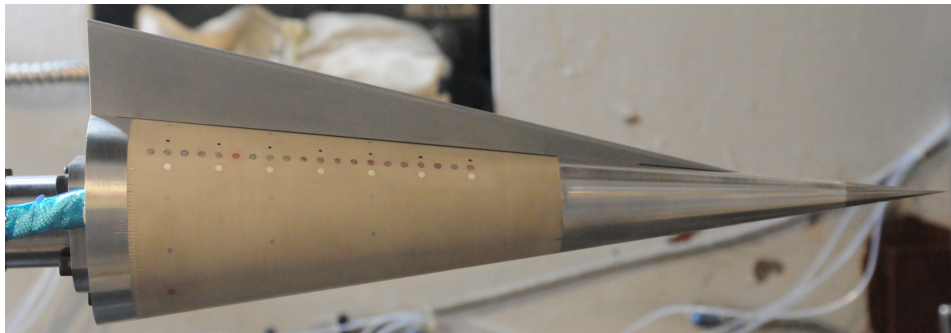
The computational methods team examined recent advances in computational methods and identified remaining gaps. Over the past two decades, advancements have been made in numerical simulation of boundary-layer instabilities for smooth-wall geometries under well-defined freestream disturbances [7, 188], for isolated roughness elements [9, 30, 160], and for arrays of roughness elements [155]. Direct numerical simulation (DNS) has been used to predict the acoustic noise field produced in conventional hypersonic wind tunnels [52, 71] and compute the effect of freestream noise



(a) 7° Half-Angle Cone [Credit: NASA].



(b) Boundary Layer Transition (BOLT) Flight Experiment [Credit: Johns Hopkins APL].



(c) ONR Finned Cone [Credit: NASA].

Figure 4: Examples of common geometries that have been used by the community.

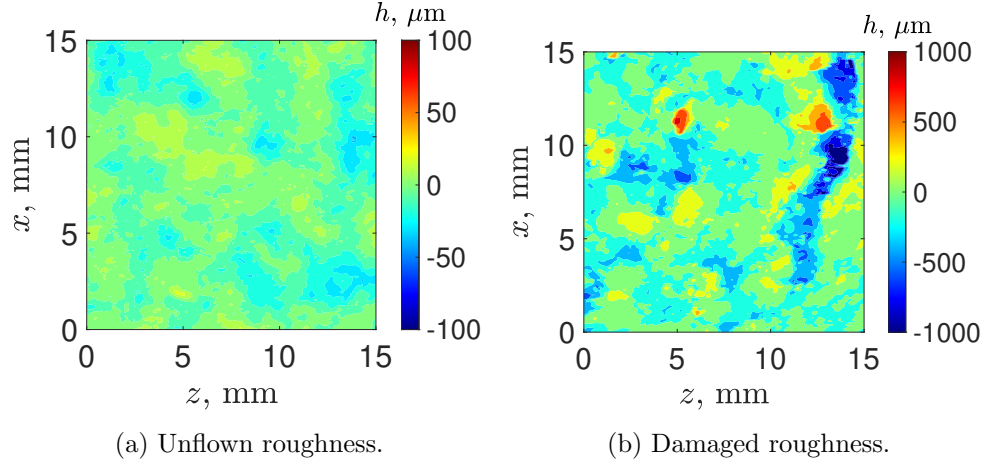


Figure 5: Examples of measured distributed roughness topography of thermal protection materials.

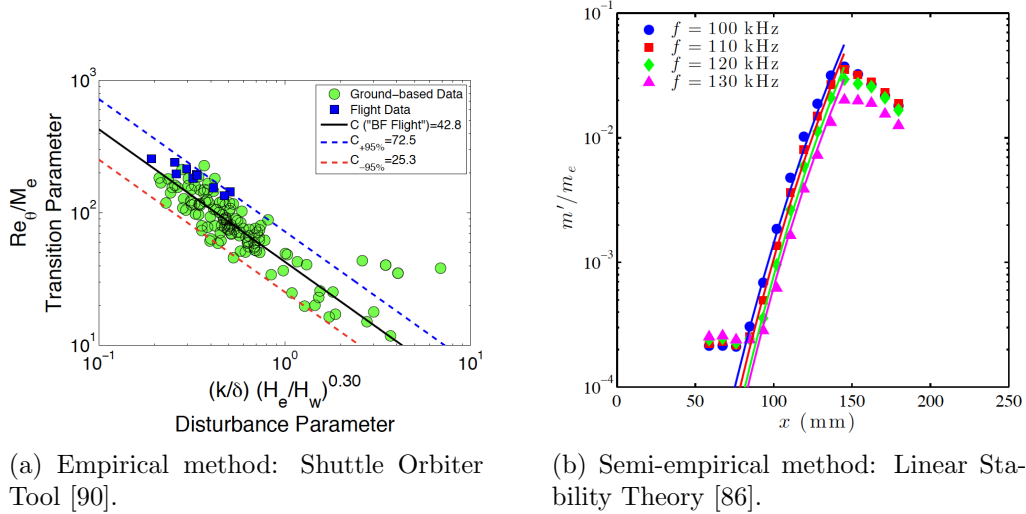


Figure 6: Examples of methods used to predict transition due to isolated roughness. Symbols represent wind tunnel or flight measurements and solid lines represent prediction curves.

on boundary layer transition with “digital wind tunnel” simulations [151].

Initial, but insufficient calibrations for the semi-empirical e^N method have been performed against flight experiments (HIFiRE-1 and -5b) involving second mode [97, 167], stationary crossflow [167], and streak instabilities [36]. Transition onset N -factors for second mode and streak instabilities were determined to be in the range of 14 to 18, in contrast to a lower bound of approximately 10 observed for stationary crossflow. The recent success of the BOLT-II flight experiment [178] and improvement in simulation methodologies for complex geometries [5, 78] show promise in how we extend existing calibrations to complex geometries with multiple interacting instability mechanisms. Advancements have also been made for in situ stratospheric

turbulence and particulate measurements [95,96]. Such measurements along with recent improvements in the simulation of receptivity to particulates [3] and freestream disturbances [37,112] are key to enable amplitude-based methods [8,55,103] for improved hypersonic boundary-layer transition flight predictions.

Despite the significant progress, numerous challenges and gaps still need to be addressed. Grid generation stands out as a critical gap, demanding specialized expertise and substantial time and effort to produce high-quality grids that are smooth, shock-aligned, and boundary-layer adapted, essential for precise high-order solutions. Although grid generation challenges are ubiquitous in hypersonic computational fluid dynamics (CFD), simulations of boundary-layer transition impose especially rigorous demands on both basic-state solutions (base flows) and DNS. Stability analyses demand base flows with finely resolved flow gradients, while in DNS, grid imperfections can introduce numerical noise that competes with instability physics. Promising approaches under consideration to address grid generation challenges include hybrid Cartesian/body-fitted solvers with adaptive mesh refinement (AMR) [110] and AMR with hexahedral “hanging-node” grid [30]. Current challenges in grid generation and the absence of integration of stability analysis tools with CFD tools hinder their utilization by hypersonic vehicle designers. Instead, designers often rely on empirical correlations such as LORN [157], which are frequently applied to conditions and geometries beyond their region of applicability. Figure 7b shows the inadequacy of LORN in predicting boundary layer transition for the BOLT-II flight experiment. Unlike the laminar flight data, LORN predicts predominantly turbulent flow, as depicted by the colored region in Fig. 7a.

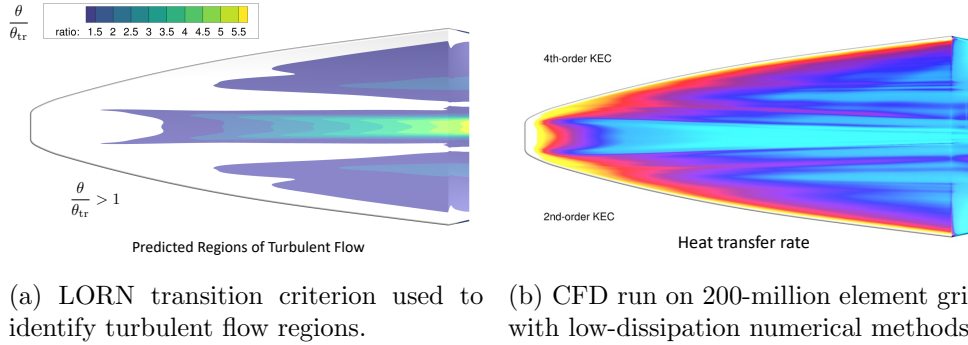


Figure 7: Comparison of BOLT-II computations using LORN transition criterion versus high-fidelity CFD solutions. Flight data at these conditions show fully laminar flow [Credit: Graham Candler, University of Minnesota].

Aside from grid generation challenges, the excessively high computational costs associated with current high-fidelity simulation tools render them unsuitable for Multidisciplinary-Design Analysis and Optimization (MDAO) as well as Monte Carlo trajectory analyses. Therefore, there is a need for the development of reduced order models (ROM). Linear stability and high-fidelity modeling tools used in conjunction with Artificial Neural Networks (ANN) show promise in generating surrogate models for practical transition prediction [122,131]. Partial-differential-equation (PDE)-based transition models suitable for Reynolds-averaged Navier-

Stokes (RANS) CFD are being developed and evaluated [41, 98, 99, 170] (Fig. 8), and while their application to subsonic flows has shown relative success, additional improvements are required before these models can offer more reliable estimates of hypersonic boundary-layer transition.

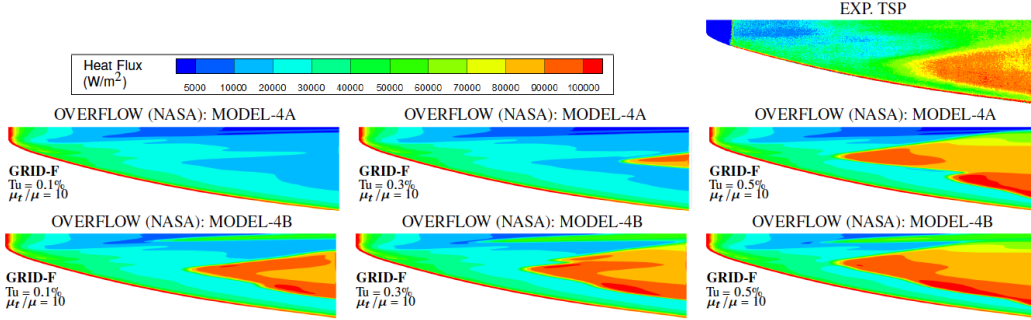


Figure 8: Comparison of the Liu [98] PDE-based transition model with varying freestream turbulence intensities and measurements in the CUBRC LENS II facility for the BOLT II geometry [Credit: Cutrone et al. [41]].

Significant efforts toward characterizing freestream disturbance levels in facilities [52] were made to provide inputs as well as to advance the understanding of receptivity for wind tunnel experiments. Similar efforts of the flight environment have been initiated with the 2017 AFOSR MURI grant for “Integrated Measurement and Modeling Characterization of Stratospheric Turbulence” [1]. Because of the significant variability and uncertainty in stratospheric turbulence and particulates [2, 95, 96], the exact transition location cannot be exactly predicted. Therefore, a statistical framework is needed to quantify probability of transition and predict bounds by connecting freestream variations to the transition process.

The absence of ROMs for receptivity and breakdown analysis represents a significant gap. Receptivity remains primarily in the realm of basic research and requires a transition towards practical application. Consequently, urgent attention is needed to further investigate and develop ROMs capable of effectively addressing receptivity across various hypersonic vehicle geometries and conditions including separated flow. While existing research predominantly concentrates on two-dimensional or axisymmetric geometries, exploration of three-dimensional configurations has been limited. Accurate shock perturbation models are pivotal for precisely capturing receptivity to freestream disturbances. Receptivity modeling for three-dimensional configurations, incorporating atmospheric disturbances, particulates, and surface roughness, is crucial for relating ground experiments to free-flight conditions. Integrating ROMs designed for receptivity and breakdown into stability analysis, utilizing methodologies such as the Mack amplitude method [8, 55, 103] or other innovative approaches, is imperative. Enhancing ROMs through correlating measurable disturbance environments requires obtaining quantitative measurements of freestream disturbances and instability waves both in ground facilities and during flight. Furthermore, there is a critical need to develop ROMs for freestream noise in conventional wind tunnels, leveraging existing DNS databases [52, 70, 71, 151] and RANS CFD simulations for

nozzle geometries, to enable accurate and computationally efficient freestream noise models for receptivity studies.

Another set of identified gaps pertains to the incorporation of gas-material interactions, chemistry, and ablation effects, which have the potential to modify surface roughness, steps, and gaps. The team noted a lack of established best practices for incorporating these effects. Some capabilities are currently available for incorporating chemistry, ablation and shape change effects in laminar flow solutions and stability analysis such as parabolized stability equations (PSE) [136]. High-fidelity, fully-coupled solutions are unlikely to be computationally achievable in the foreseeable future due to the wide range of length and time scales involved. Real-time changes to geometry due to ablation or fluid-thermal-structure interactions are typically not taken into account, whether at a macroscopic or microscopic level. Replicating all these effects simultaneously in wind tunnel facilities is improbable. Nevertheless, validation experiments that isolate pertinent physics, such as gas injection, chemistry, surface roughness, step and gaps should be feasible. Currently, there is a scarcity of studies examining the impact of distributed roughness, steps, and gaps on hypersonic boundary-layer transition. Modeling these effects has been recognized as a top priority.

There is a necessity to devise robust methodologies for assessing the sensitivity of boundary-layer transition to surface roughness, chemistry, and ablation effects. This can help identify key phenomena where resources should be allocated to achieve the most significant impact. For validation purposes, flight experiments may offer some information, but they are typically sparse, restricted to discrete surface-based measurements, and may not occur under the desired conditions, necessitating extrapolation for application. More comprehensive measurements are desired, both surface-based and off-body, with off-body measurements enabling a more direct comparison to computed values.

5 Facilities and Diagnostics

Multiple classes of ground test facilities in the Mach 2 and higher range exist all over the United States [144]. The large-scale facilities tend to be housed at government and federally-funded research and development centers (FFRDCs), while smaller-scale facilities are typically housed at universities. These facilities are not necessarily in competition with each other, due to the different capabilities that may be offered at each one, such as high-enthalpy, high Reynolds number, or quiet facilities. In fact, the current facilities appear to be beyond capacity to accommodate all the testing desired for high-speed programs and research in the nation. Many of these facilities have long wait-times, which requires customers to find alternative facilities which may require sacrifices in model scaling, optical access, run duration, and measurement techniques available. Particularly for quiet tunnels, the only three existing operational facilities with proven quiet flow operate at Mach numbers of 3.5 [13] and 6 [73,102]. This limited set of facilities means that quiet tunnels cannot simulate the full range of Mach numbers that may be required for a given trajectory. Improvements can be made to increase the Reynolds numbers [58], but these

university and/or pilot facilities are still size-limited.

Several projects over the years have included intentionally-coordinated common geometries (e.g., seven-degree half-angle sharp and blunt cones [16,31,62,79,87,103,105–108,138,171], HIFiRE-5 [89] (Fig. 9), BOLT [92,109,135] (Fig. 10), and a finned cone [118,168,169,176]) tested across these different facilities to better understand boundary-layer transition in the different environments. Measurements and research on common geometries in multiple ground test facilities should continue to help in reducing uncertainty in the flow physics discoveries made on these geometries. Even within each class of facility, there may be a difference in optical access, available instrumentation, run times, etc., but these can be used to the benefit of different programs (of record, or research). The use of different measurement techniques to show the same quantity on the same geometry is shown in Fig. 9. Figure 9a, which uses phosphor thermography, shows qualitatively similar results to the results of Fig. 9c, which uses temperature-sensitive paint. As an example of similar measurement techniques being used in different types of facilities, Fig. 10 shows three examples of IR thermography measurements on the BOLT geometry. Fig. 10a is only qualitative IR in the NASA Langley 20-Inch Mach 6 Tunnel, but shows the full length of the model. Figs. 10c and 10b show quantitative measurements of heat transfer on the BOLT geometry in different freestream noise environments, but only a small section of the model is in the field of view.

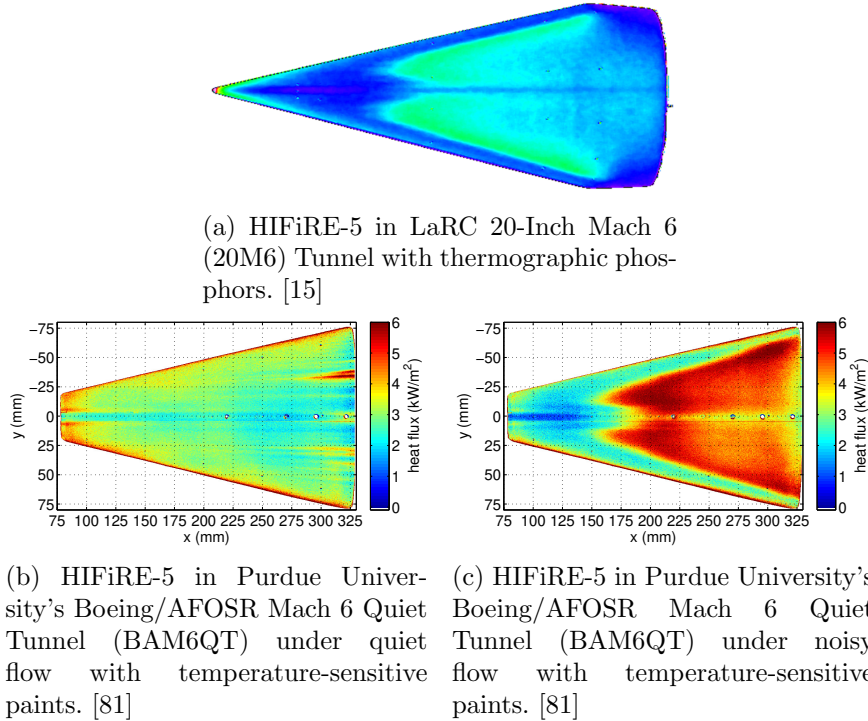


Figure 9: Comparison of HIFiRE-5 geometries in different Mach-6 wind tunnels, using different global heat transfer measurement techniques.

Many of the survey responses from this team on available measurement capabil-

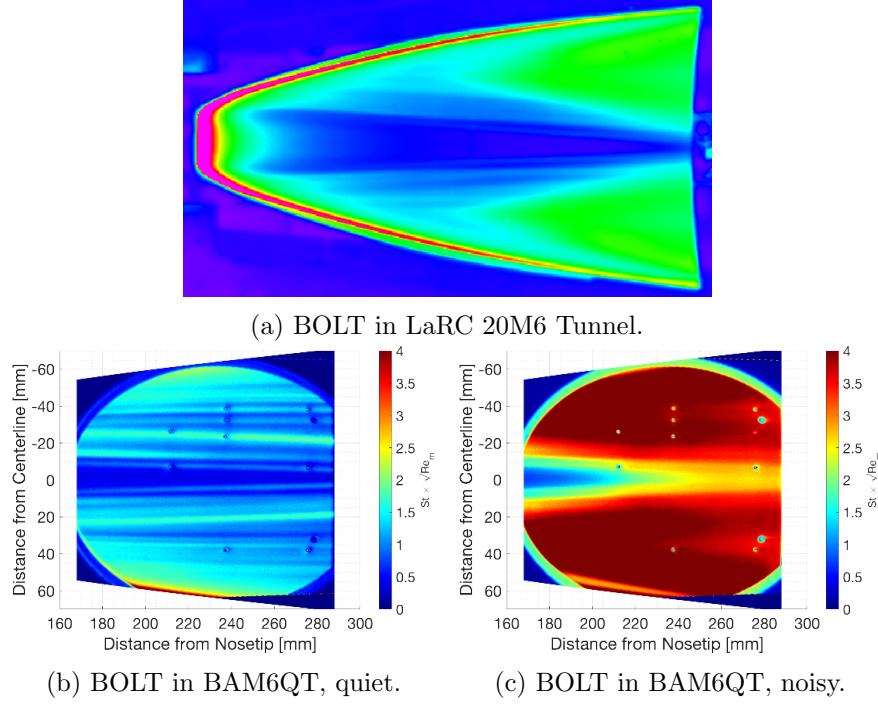


Figure 10: Comparison of BOLT geometry in different Mach-6 wind tunnels, $Re_L \approx 3.0 \times 10^6$, using the same global heat transfer measurement technique.

ities were mixed. A variety of both high-speed and low-speed instrumentation exist for ground test facilities, and each have their benefits and deficits. Many of the community’s desires for measurement techniques require high-frequency methods with quantifiable uncertainties. However, many measurement techniques for high-frequency phenomena do not have a straightforward calibration method, much less a NIST-traceable calibration method, or are nonlinear across the spectral response range. In the measurement of the laminar-turbulent transition process, the sensitivity of the measurement technique may also need to be able to resolve disturbance amplitudes that span many orders of magnitude. Measurements of particulates in the wind tunnel freestream are also not typical.

A majority of the available sensors are also discrete, which is useful, but not necessarily sufficient, particularly when considering the needs of computational tool development. Computational tool development prefers more global measurements of velocity, temperature, and pressure to a known uncertainty, which at its current state is very difficult to achieve. Global surface-based measurements of heat transfer have been performed using phosphor thermography [25, 116], infrared thermography [141, 156], and temperature sensitive paints [94, 161]. Some of these techniques can involve two-color or dual-band implementations, which account for non-uniform emissivity changes to improve uncertainties in global heat-transfer methods [75, 94, 117]. Some of these methods are applied to materials with unknown emissivities, non-uniform lighting, or changes in model position/deformation. Pressure-based measurements have also been performed for some wind tunnel testing with

pressure-sensitive paints [140, 161]. Real-time measurements of model deformation are also still lacking. For heating-driven deformation, most high-speed facilities do not operate for long enough to be able to simulate any thermal growth. Aeroelastic measurements using digital image correlation may be limited to direct line-of-sight [158].

Global off-body measurements are typically done with optical techniques, such as schlieren, planar laser-induced fluorescence (PLIF), molecular tagging velocimetry (MTV), particle image velocimetry (PIV), and Doppler global velocimetry (DGV) [10, 21, 26, 42]. The current state of the art does not have a suitable commercial-off-the-shelf three-dimensional measurement technique that is high-frequency, quantitative, and calibrated to known uncertainty. Point measurements have a tendency to be better characterized in calibration, uncertainty, and frequency response than global measurement techniques, as most global techniques are calibrated in situ with a point measurement to anchor the flow field. This form of in situ calibration makes gross assumptions of the uniformity of emissivity of materials or uniform application and illumination. However, few high-speed facilities have long enough run time to make single-point, probe-based off-body measurements reasonable, although some work has been done with hot-wire anemometry [34, 40, 86, 91, 92]. Furthermore, the sensor size of most point sensors is too large to make useful measurements, and recessing sensors in hypodermic tubing increases lag time, affecting the frequency response of the sensor.

While the ideal situation would be to build facilities to accommodate all testing needs, there is a general lack of high-enthalpy facilities and an operational, large-scale quiet tunnel. Since the NHFRP, there have been several planned quiet tunnels in addition to the Texas A & M University Mach 6 Quiet Tunnel, the Purdue University Boeing/AFOSR Mach 6 Quiet Tunnel, and the NASA Langley Research Center Supersonic Low Disturbance Tunnel, although none of the new facilities have operated as quiet facilities as of the writing of this report. In reference to the NHFRP, however, it does not seem feasible nor desirable at this point to invest in a high-enthalpy quiet facility. New facilities should also be built with diagnostic capabilities in mind. Several of the older facilities and pilot facilities were not built with optical access, and many of the new diagnostic techniques require this capability.

6 Flight Experiments

A survey of historic flight data for boundary-layer transition are provided in Reference [148] and a more recent holistic review for specific testing related to hypersonic boundary-layer transition has been provided in Reference [19]. After successful flight tests of the HIFiRE-1 and -5 geometries [89], the computational predictions appear to be good at resolving hypersonic transition on a straight circular cone and an elliptic cone. This particular feat addresses some of the roadmap specified in the NHFRP goal in developing semi-empirical models for mildly three-dimensional geometries. Using these data, N factors from these flights have been used to calibrate models that use e^N theory for boundary-layer transition prediction [36, 88, 136, 167].

Other successful hypersonic flight programs include the Boundary Layer Turbulence Flight Experiment in Memory of Mike Holden (BOLT-II) [53,177], and the Rocket Technology Flight Experiment (ROTEX-T) [63,164].

There also appear to be a wealth of supersonic data from the flight program (HIFiRE-1 ascent, HIFiRE-5a and -5b) but this has never been looked at in detail. The first Boundary Layer Transition (BOLT) flight test also contains some supersonic transition data, but it is at extreme yaw and angle of attack [27]. The HIFiRE-5a and BOLT flights were considered “failed” flights, since the target Mach numbers were not achieved, but may still contain some useful information that has not been processed in great detail.

The type of data that can be taken as part of a test campaign have progressed significantly since the early days of the HIFiRE program. Appropriate data acquisition systems still lag, as many of the systems must be custom-built or lack adjustable gains. Furthermore, the high bandwidth required for measurements of the boundary layer instabilities precludes the use of telemetry, so onboard storage and recovery of the onboard system becomes a necessity. Telemetry of these measurements is limited in bandwidth, requiring uneven sample rates, which is unable to capture the boundary layer instabilities [159], or on-board processing of the data and the telemetry of spectral peaks [177,178]. For any flight experiment, recovery is not a guarantee, due to the possibility of a loss of the vehicle. A commercial off-the-shelf (COTS) solution could be a priority for investments, especially with the development of high-cadence flight testing programs. Satellite-based options for collection and relaying of telemetered data may also be a possibility, similar to the NASA Tracking and Data Relay System (TDRS) [49,132].

Appropriate high-frequency instrumentation may be limited by the temperature range at which the sensors can operate, as well as the allowable space on the flight article. At the moment, most boundary-layer transition flight experiments use ballistic trajectories, so temperatures are not necessarily extreme compared to long-duration hypersonic wind tunnels, but future work may desire the use of depressed trajectories, which would produce higher thermal challenges for the instrumentation. The recent BOLT-II flights successfully used surface mounted high-frequency pressure sensors and skin-friction sensors [113] to measure instabilities and transition from laminar to turbulent boundary layer states. Use of rail-launched flight articles may provide cheaper and more suitable alternatives, as these test articles are typically smaller (on the order of the size of typical wind tunnel models) [54].

Limited global measurements that are standard in ground-based facilities are starting to become possible in flight experiments as well. Flow visualization of transition fronts has been critical since the 1950s, where sublimating chemicals were used for in-flight measurements of boundary-layer transition for supersonic speeds up to Mach 2 [111,123]. The ability to make IR measurements of a reentry vehicle in flight has been around since the Hypersonic Thermodynamic Infrared Measurements (HYTHIRM) project in the 2000s [18,74,152,186]. This technology is still in use today via the SCIFLI program for measurements of heating reentry vehicles such as the Hayabusa2 flight by JAXA [153]. Some supersonic flight articles may also be able to use camera pods mounted to the flight vehicle or in a chase plane for imaging in flight [125]. Schlieren imaging in flight has been performed since

the 1980s on supersonic aircraft using the sun as a light source [174]. Background-oriented schlieren of supersonic aircraft has also been performed in flight [68] using an observer craft.

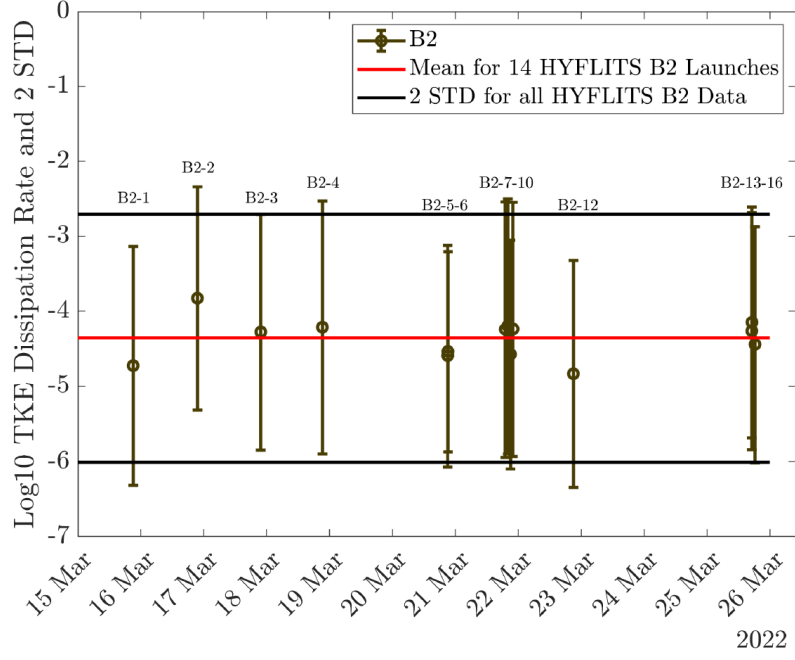
The development of the HYFLITS and HALAS LiDAR program allowed for measurements of the atmospheric disturbance levels prior to, during, and after the BOLT-II flight experiment [48, 95, 96] (Fig. 11). This technology leads to better atmospheric characterization but also a measure of freestream disturbance environment for relevant flight conditions. A step measurement sensor is also currently in development for flight in order to provide real-time changes in two-dimensional roughness (i.e., thermal growth at a nosetip junction) [12]. Typical freestream characterization measurements in ground test facilities and low supersonic flight experiments are already made with probe-based measurements and have only loosely been simulated for comparison to experimental measurements with varying degrees of success [8]. How these flight measurements are incorporated into physics models is not immediately clear, although they should be able to provide a promising approach for estimating initial amplitudes of disturbances when coupled with instability wave amplitude measurements. Work is still required to reduce uncertainty in these measurements. The measured atmospheric conditions may be able to provide a basis for performing Monte Carlo analysis to produce methods of transition prediction on flight articles.

7 Flow Control

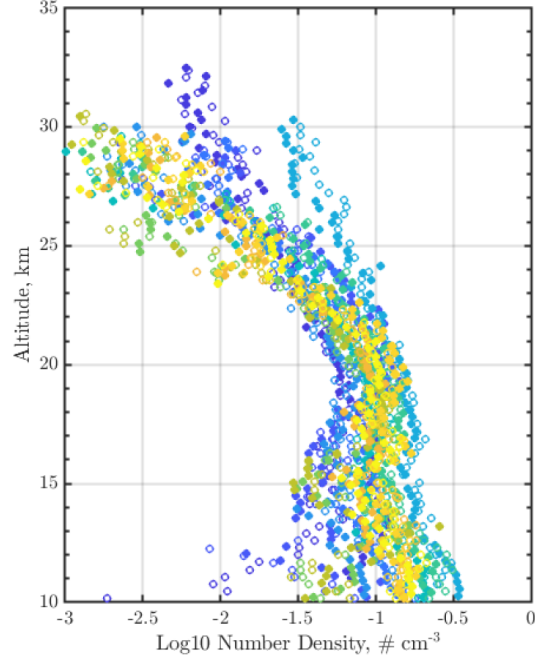
Flow control was identified as an historically underfunded research area for high-speed flows. The current state of the art looks at passive flow control techniques that are often optimized for a single condition. Some active flow control has also been investigated using plasma actuators [182, 183], although these controllers are actuated in a binary off or on position, not necessarily in a sense where varied spacing or amplitudes have been applied across the plasma actuator array.

The current work focuses on promoting and delaying transition as they pertain to first-mode instabilities, second-mode instabilities, and crossflow instabilities. Typically, the first mode instability in supersonic boundary layers manifests as an oblique three-dimensional instability. These instabilities can be stabilized using wall cooling and three-dimensional waves can be used to delay or promote transition. The second mode instability has been controlled via wall heating, ultrasonic absorptive coatings [56, 134, 139, 187] (Fig. 12), two-dimensional roughness strips [57, 67], and carbon dioxide injection [119, 145, 172]. The crossflow instability, which appears typically on swept leading edges and at angles of attack, has been controlled using discrete roughness elements (in ground and flight experiments) [39, 125] and plasma actuators [182, 183] at either stabilizing or destabilizing wavelengths. Several small business innovative research (SBIR) grants have been awarded to work on this problem with varying levels of success, but much of the detail of these projects are both proprietary and export controlled and will not be discussed in this workshop summary.

Some work has been done to investigate the effectiveness of these control tech-



(a) Mean and standard deviation measurements of turbulent kinetic energy dissipation rate over 14 flights.



(b) Particulate number densities for 0.35–1.0 μm particles over 11 flights.

Figure 11: HYFLITS measurements of atmospheric disturbance measurements before, during, and after the BOLT-II campaign [Credit: Lawrence et al. [96]].

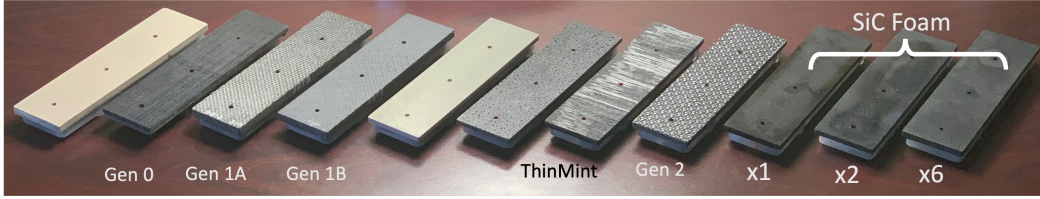


Figure 12: Examples of ultrasonic absorptive coatings created by HySonic [Credit: HySonic [139]].

niques for transition in the presence of multiple instability modes. The work in these areas could benefit from an overall systems analysis of the effectiveness of these techniques across a large enough portion of the vehicle trajectory. In this sense, it may help to define how effective a flow control technique would need to be in order to be useful on a real vehicle. Future work in this area could especially benefit from collaboration with work in materials (e.g., via smart ablators or metamaterials [124]) and close work with systems analysis for active flow control techniques and any structural or material trade-offs that are required for incorporation into a vehicle.

8 New Approaches

The New Approaches team was assigned the task of determining how emerging methods such as data assimilation (DA), machine learning (ML), and uncertainty quantification (UQ) can be utilized to address computational and experimental gaps. Some of the new approaches and techniques available involve close ties with the computational and experimental communities. DA enables the augmentation of physical measurements to predict the complete flow field from limited data. As illustrated in Fig. 13, nonintrusive, nonlinear ensemble-variational data assimilation has proven effective in predicting upstream instability waves and, consequently, the entire flow field, using discrete high-frequency wall pressure measurements [24]. The framework has been used to delay transition through optimized thermal [76] and topographical bumps [77]. DA also offers sensitivity to measurements, boundary/initial conditions, and model parameters, effectively addressing a significant gap identified by the Computational Team.

DA techniques enable the optimization of sensor placement to extract valuable information, such as enhancing the observability of a system based on available sensor measurements. This capability is particularly pertinent for flight experiments, where the number of sensors is often limited. By strategically optimizing sensor placement, DA enables researchers to maximize the information gleaned from measurements, ultimately leading to more insightful analyses of boundary-layer transition phenomena.

Researchers [46] are pursuing ML strategies with DeepONet [100], a neural network-based model that is capable of learning both linear and nonlinear operators, to develop reduced-order models aimed at accelerating DA [69]. ML shows promise to accelerate forward and inverse predictions of instability waves, effect of

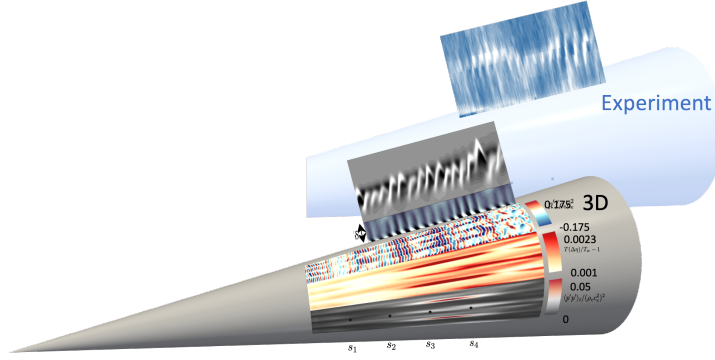


Figure 13: Example data assimilation of reconstructed time-dependent 3D flow. Freestream noise disturbance field in DNS was optimized to match the experimental measurements [Credit: Buchta et al. [24]].

roughness, and transition [46]. One of the most significant challenges with ML is the scarcity and cost of training data. Relying solely on flight test data may not fully satisfy the training data requirements due to the limited availability and infrequency of flight experiments. Additionally, even ground test data may present limitations in terms of quantity. Limitations of ML in the presence of sparse training data sets can produce nonphysical answers when extrapolating outside of the training data [184, 185].

The team also noted the emergence of new approaches for hypersonic boundary layer stability analyses. For instance, One-Way Navier Stokes (OWNS), introduced less than 10 years ago [165], offers a path towards transition prediction that addresses the deficiencies of PSE. Recent applications to hypersonic flow [85] and improvements in computational efficiency [189] make this approach appealing for providing reduced-order models for hypersonic boundary-layer transition.

The importance of inverse problems, such as input-output (I/O) analysis, was noted to uncover the “worst-case” initial and boundary conditions. However, the “worst-case” disturbances need to be constrained by physics to be meaningful. Recent improvements have been made via physically realizable I/O analysis [83], which provides a generic framework for posing physically realizable worst-case free-stream vortical, entropic, and acoustic disturbances. Hierarchical I/O analysis [38] is a new strategy to accelerate I/O for three-dimensional receptivity studies, enabling analysis with systems as large as 300 million degrees of freedom. Representative results from three-dimensional receptivity analyses to acoustic and vortical waves on both sharp and blunt cones at Mach 5.8 are depicted in Fig. 14. These analyses can be used to inform a user on the contribution of how different forcing mechanisms are amplified in the boundary layer. Similar methods to model the effect of roughness are still lacking and should be developed.

Demonstrating the application to complex geometries and addressing the significant computational expenses remain critical challenges. The adaptive mesh refinement wavepacket tracking (AMR-WPT) method [22, 23] is another new approach that has been developed as an efficient alternative to conventional direct

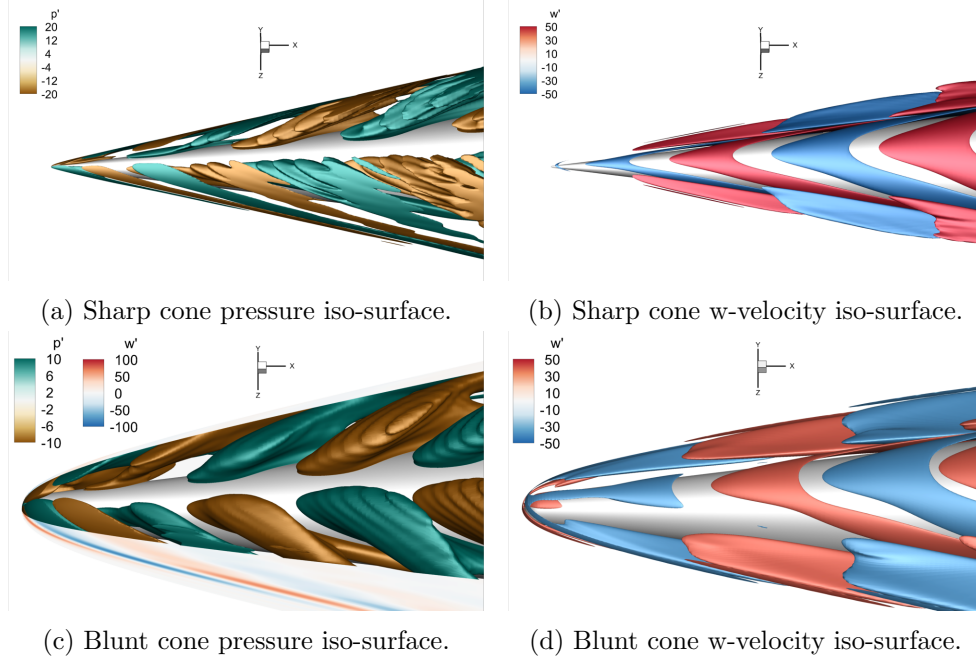


Figure 14: Three-dimensional receptivity on sharp and blunt cones at Mach 5.8 showing pressure and w-velocity generated by incident vortical waves in the near-tip region at 10 kHz [Credit: Cook et al. [38]].

numerical simulations (DNS). The wavepacket tracking method utilizes adaptive mesh refinement with higher-order accuracy to track wavepackets introduced in the boundary layer through pulse disturbances. The progression of these wavepackets is employed to extract boundary-layer stability characteristics, including amplitude curves, growth rates, and N-Factor curves, commonly utilized for transition prediction. The method has been successfully applied to complex geometries such the ONR fin-cone [4] and BOLT [28].

In conclusion, innovative methods like data assimilation (DA), machine learning (ML), and uncertainty quantification (UQ) were emphasized as possibilities to address computational and experimental gaps in hypersonics boundary-layer transition research. These approaches present promising opportunities to deepen our understanding of boundary-layer transition and enhance stability analyses. Figure 15 summarizes the current and envisioned benefits of the new approaches outlined in this section.

9 Closing Comments

Basic research has produced high-fidelity and detailed work in the area of boundary-layer transition. Significant advances have been made in our understanding of and the methods by which we evaluate the phenomenon of high-speed boundary-layer transition through targeted support. If all aspects of the flow field and geometry were known with little uncertainty, it may be possible to predict transition with little

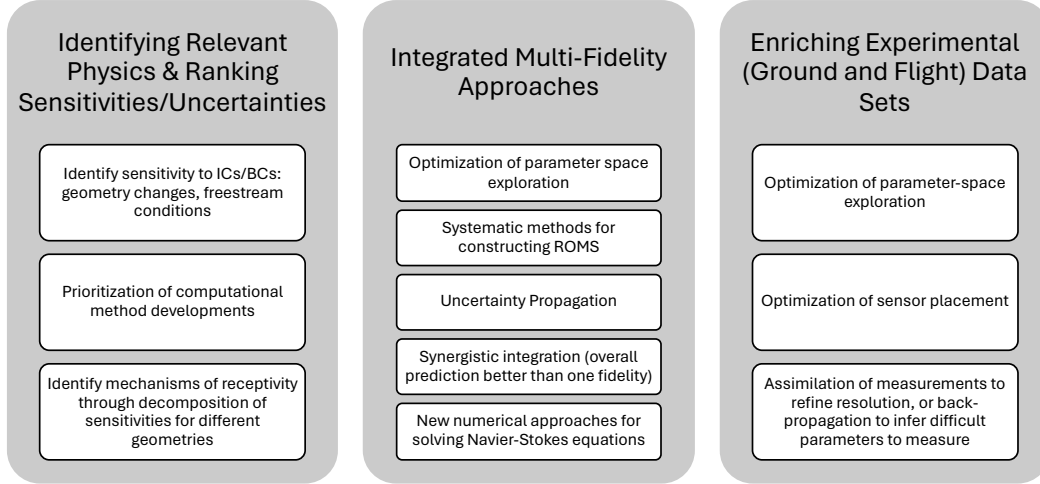


Figure 15: Possible overall impacts of new approaches.

uncertainty. The key is that we will never know everything about the flow field or the geometry at every point in a vehicle's trajectory, so we must understand how all fidelities of analysis can contribute to a manageable uncertainty for transition prediction. However, a shortfall in this area is the lack of understanding on how to bridge or communicate the application of basic research advancements to real systems. Particularly in the area of high supersonic and hypersonic boundary-layer transition, knowledge of how basic research can apply to real systems is limited, due to the sensitive nature of this field. This can create overconfidence in the existing tools and a sense that the fundamental work does not require further investment until closure is not achievable for a design or, in a worst-case scenario, an accident occurs. Due to this shortfall, funding in basic research tends to fluctuate significantly, and this can generate gaps in the ability of the subject matter expertise to address needs of real-world applications. Several of the gaps that have been identified in the area of high-speed boundary-layer transition cannot be addressed with only fundamental and early applied research funding, but support must also come from acquisition programs to have successful tool development, automation, and sustainment of these tools and processes.

Understanding that the resources for funding this area of research may be limited, this document is meant to provide a snapshot of the current state of the art and the current gaps in the field to help guide future investments. The areas of research in which more attention should be directed include

1. high-enthalpy flows involving chemistry and ablation
2. studies of receptivity of freestream disturbances into the boundary layer
3. surface feature characterization and modeling of changes to geometry
4. and viable flow control methods.

These studies can range from basic to applied, but in order to maximize investment across the agencies that are involved in this workshop, should be focused on common geometries and multidisciplinary approaches. There should be some over-

arching connection between the research in each of these areas via the use of common geometries or reference vehicles. The goals of computational approaches should be to either work toward producing a framework of multiple-fidelity modeling approaches or accelerating the prediction process that it can be used toward engineering-level tools in the design cycle. This type of tool development necessitates funding sources beyond what is typically allotted for fundamental work. Some fundamental work in this area should continue, however, as fundamental research often is the catalyst for discovering new methodologies. The goals of diagnostic and facilities should be toward enhanced understanding of the different research topics, and to be able to do so by making more global measurements with known uncertainty. Flight testing should also work toward the standard practice of making measurements of atmospheric characterization (including both turbulence and particulates), and further development may be required to move towards more reliable high-bandwidth data acquisition and recovery.

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Appendix A

Workshop Participants

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- Stefan Wernz, Raytheon Technologies
- Bradley Wheaton, Johns Hopkins University/Applied Physics Lab
- Tamer Zaki, Johns Hopkins University

Appendix B

Pre-Work Questionnaires

All groups had a common set of questions assessing the former NHFRP roadmap:

1. Assessment of roadmap: where are we now, what have we accomplished so far? (Figures and references preferred)
2. What still needs to be accomplished?

The remaining questions were specific to each of the separate teams. For each set of questions, team members were encouraged to cite references and/or include specific examples to support their responses. The team responses were compiled into presentations that were shown on the first day of the workshop. The presentations of the compiled responses can be made available upon request to the authors.

B.1 Geometries of Interest

1. Which geometry classes do we consider of highest importance to the nation's capabilities? (No specifics, but categories only: boost-glide, scramjet-powered, ballistic reentry, etc.) Define these classes if necessary.
2. Why do we care about transition on these classes of vehicles – what parts of the vehicle are more sensitive and which boundary-layer transition mechanisms are relevant? You may draw sketches or include sketches from literature as needed.
3. What is a suitable process to generate nonsensitive geometries that exhibit relevant geometric complexity and boundary-layer transition mechanisms without being directly traceable to sensitive systems?
4. For certain classes of hypersonic systems, can boundary-layer transition be ignored or “worked around?” For which classes of systems and why?
5. How are the effects of surface roughness and geometric features on boundary-layer transition (step, gaps, etc.) currently assessed? Are the current approaches good enough and why/why not?
6. Why are correlations (e.g., LORN, PANT, etc.) still used in practice?

B.2 Computational Methods

1. What tools do we currently have? (Physics-based modeling, numerical methods, ROMs, etc.)
2. How can we best link computational modeling of receptivity to ground or flight experiments?
3. How well do we need to model something to understand or predict transition? (e.g., how sensitive are these models to idealized vs. realistic geometry, boundary conditions, initial conditions)
4. If boundary-layer transition is a deterministic process, how do we account for the fact that we will never know the initial and boundary conditions to a high fidelity?

5. What are some best practices we currently have to model gas-material interaction/chemistry or ablation in computations?
6. How can mechanism-based methods be incorporated in the analysis and design loop?
7. How can low- and high-fidelity tools be used synergistically? Can high-fidelity tools be used to develop fast running tools and if so, how? How general will these tools be (e.g., limited to specific classes of geometries)? How expensive will the generation of these tools be (training, validation, etc.)?
8. Are there gaps in numerical methods and grid generation that need to be assessed? If so, what are the main gaps?

B.3 Facilities and Diagnostics

1. What facilities and capabilities does the nation currently have for studies of boundary-layer transition? Are they sufficient? Why or why not? If not, which investments should be prioritized?
2. How well can we quantify free-stream disturbances, particulates, and receptivity in our ground facilities?
3. If boundary-layer transition is a deterministic process, how do we account for the fact that we will never know the initial and boundary conditions in flight to a high fidelity?
4. What measurement techniques do we currently have? Are they sufficient? Why or why not?
5. How is ablation, gas-material interaction, and chemistry accounted for in ground testing? Can it be modeled and is this method of modeling sufficient?
6. How can we synergistically use noisy, quiet, high-enthalpy tunnels, ballistic ranges and flight to increase the understanding of BLT and improve/validate modeling tools?

B.4 Flight Experiments

1. What are results of successful unclassified flight programs that we have had and how have they advanced our knowledge of boundary-layer transition? (CUI responses allowed)
2. What are some of the current and upcoming unclassified flight experiments and what should the next ones focus on?
3. What kinds of trajectories should we be considering for unclassified flight experiments (e.g., ballistic vs. depressed)?
4. What are the current limitations that we have in flight experiments (e.g., instrumentation capabilities and lead times, telemetry bandwidth)?
5. If boundary-layer transition is a deterministic process, how do we account for the fact that we will never know the initial and boundary conditions in flight to a high fidelity?
6. What do we know about the flight environment in terms of particulates, turbulence, other disturbances, etc.? How is the freestream disturbance environment accounted for in flight experiments to interpret results?

7. How is ablation or gas-material interaction accounted for in flight experiments to interpret results

B.5 Flow Control

1. What methods do we have to promote or delay transition based on the knowledge we have of boundary layer instabilities?
2. Are there methods of flow control that are capable of optimizing a vehicle for more than one flight condition and transition mechanisms? Is one condition sufficient for optimization?
3. Which flow control methodologies are best suitable for different vehicle types (boost glides (with ablating TPS), boost glides (with non-ablating TPS), hypersonic cruise missile (with metallic TPS), etc.)?
4. What is the maturity (TRL level) of various flow control methods? How can the maturity be increased efficiently?

B.6 New Approaches

1. What are some new approaches toward predicting or understanding boundary-layer transition (machine learning, data assimilation, I/O, UQ, etc.) and how does this advance the field?
2. How can we use these new approaches to bridge differences between computations and ground or flight experiment?
3. How do we use these tools to best determine what is important to model and when, knowing that we will never know initial and boundary conditions to a high fidelity?

Appendix C

Proposed Roadmaps

The notional roadmap for the different teams are presented in Figs. C1, C2, C3, C4. Flow control needs to be included in future roadmaps, but as of the conclusion of this workshop, requires more careful coordination before a coherent plan can be formed. New approaches are meant to be incorporated into aspects of each of the near-, mid-, and far-term goals for all of the different roadmaps.

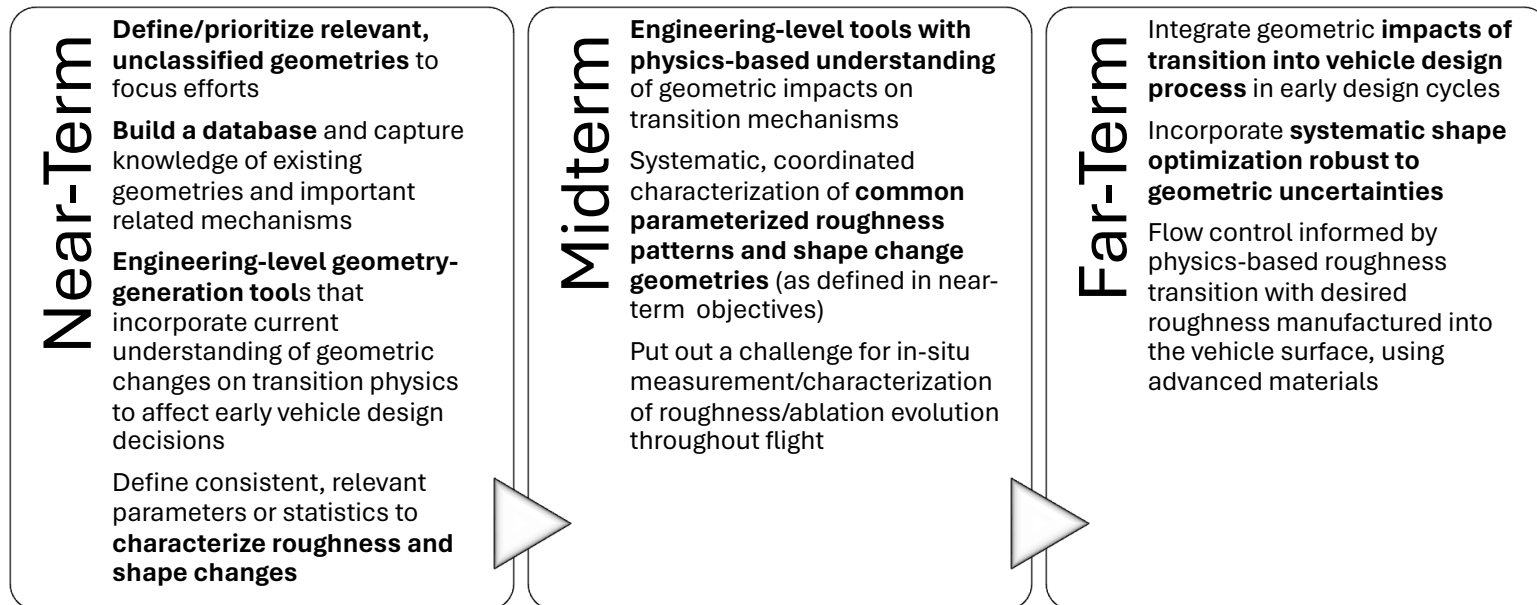


Figure C1: Notional roadmap for high-speed geometries of interest.

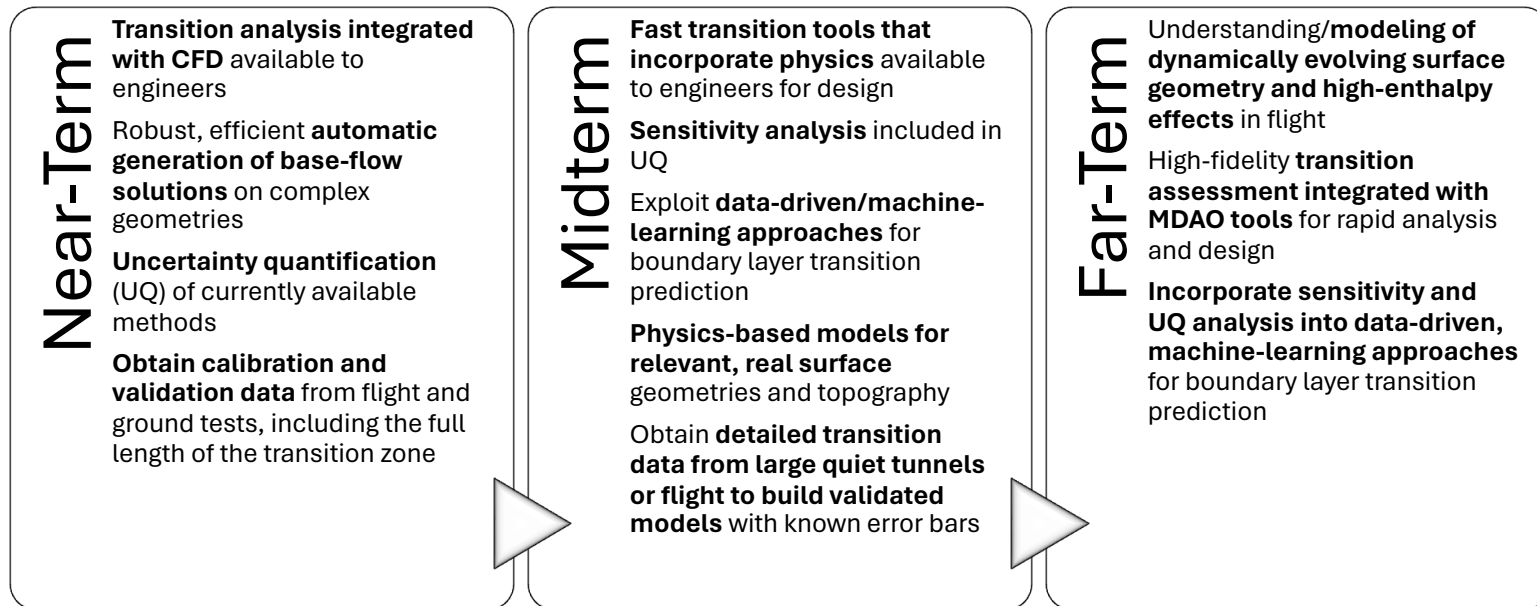


Figure C2: Notional roadmap for computational methods.

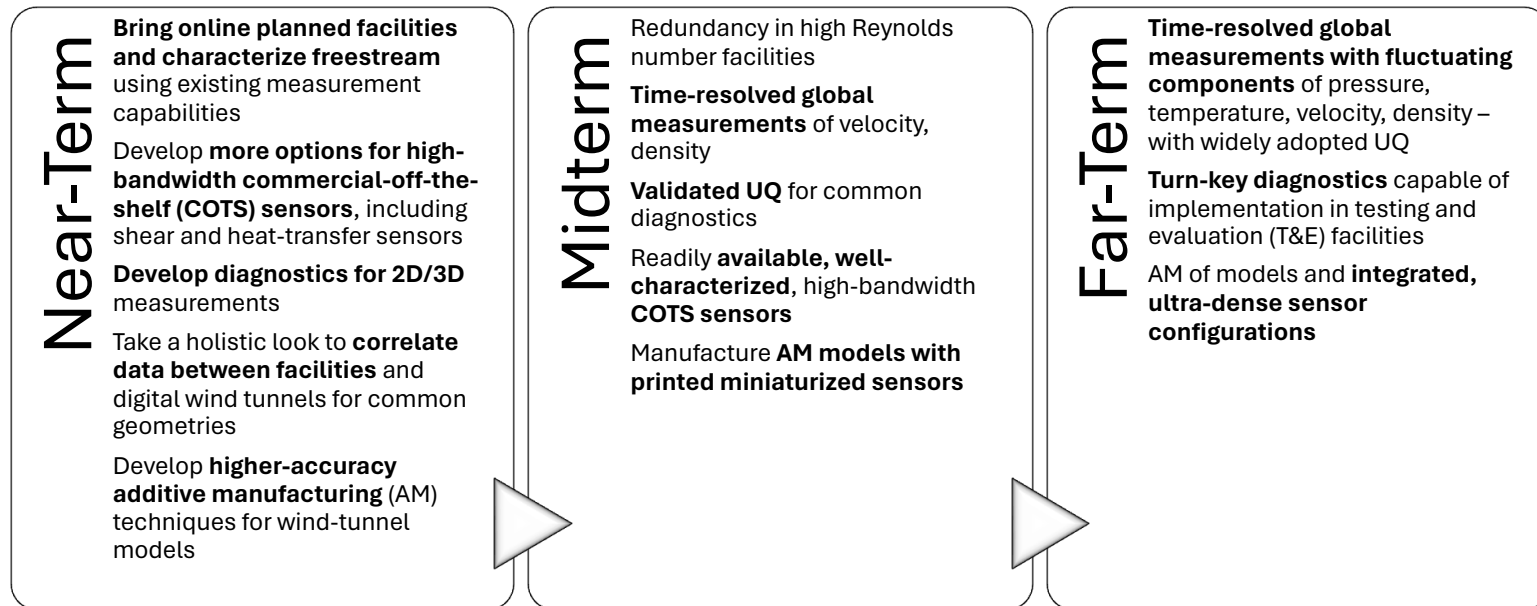


Figure C3: Notional roadmap for facilities and diagnostics.

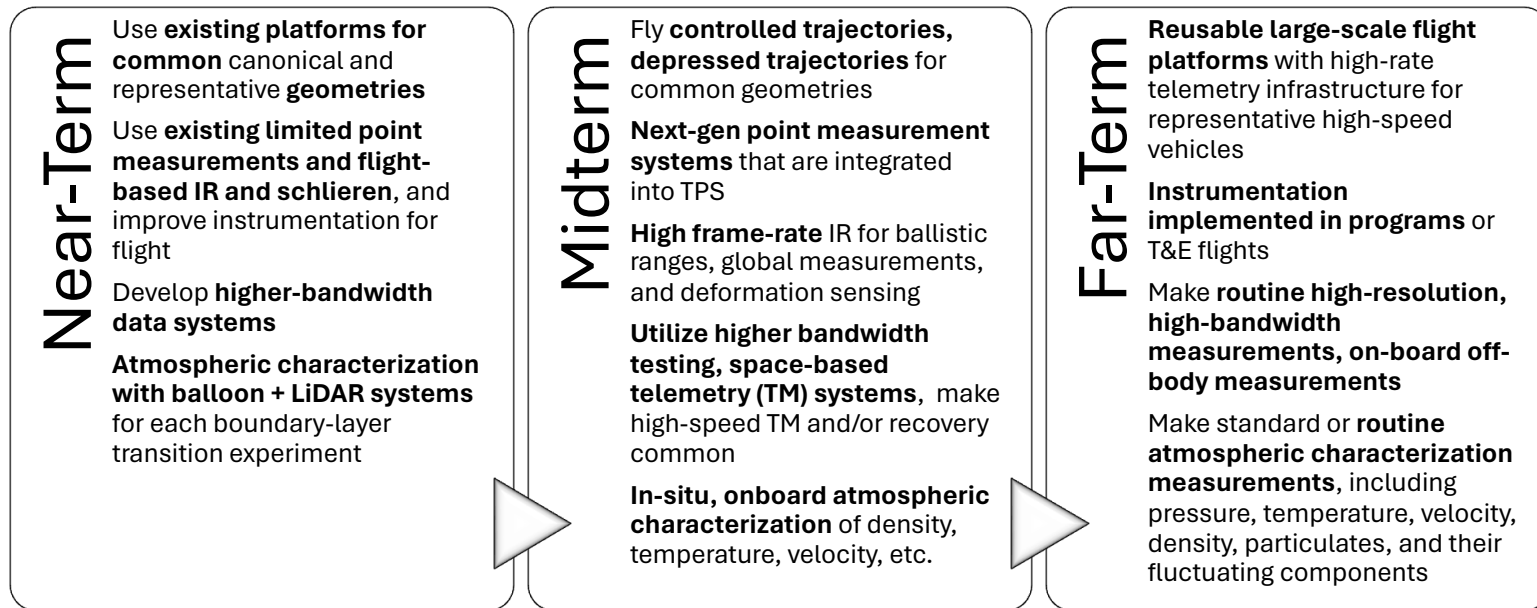


Figure C4: Notional roadmap for flight experiments.

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14. ABSTRACT A joint workshop between the Air Force Office of Scientific Research, the Office of Naval Research, and the NASA Hypersonic Technology Project was held in June 2023 on the topic of high-speed boundary-layer transition. The purpose of this workshop was to gather subject matter experts in the areas of supersonic and hypersonic boundary-layer transition and to discuss the current state of the art in the field in the areas of Geometries of Interest, Computational Methods, Facilities and Diagnostics, Flight Experiments, Flow Control, and New Approaches. As accomplishments and gaps were identified, roadmaps were also created to guide future investments in these areas. The top recommendations are (1) to define relevant common geometries of interest that can be worked by multiple research groups; (2) improve modeling of high-enthalpy flows affected by chemistry and ablation, studies of receptivity of freestream disturbances and atmospheric particulates into the boundary layer, surface feature characterization and modeling of changes to geometry; (3) design and determine viable flow control methods; and (4) move towards incorporating boundary layer transition prediction into a standard practice for design of high-speed vehicles. To execute this last recommendation successfully, investments beyond fundamental (basic and early applied) research are needed.						
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