The Boundary Layer Transition (BOLT) Flight Experiment

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ABSTRACT

The Boundary Layer Transition (BOLT) flight experiment, a unique collaboration spanning academia, government, and industry, sought to obtain flight data on a critical phenomenon affecting hypersonic vehicle design. The project aimed to further understanding of the physics of boundary-layer laminar-turbulent transition on a complex geometry, a process that can significantly increase heating and can affect hypersonic vehicle drag, controllability, and engine performance. The Johns Hopkins University Applied Physics Laboratory (APL), the project's principal investigator, led a large team of external collaborators to design a sounding rocket flight experiment over an 18-month period, while conducting an extensive campaign of wind-tunnel experiments and computational simulations to predict the flow physics on the BOLT geometry. The final flight experiment was built and instrumented at APL using Laboratory expertise in designing and prototyping hardware for extreme environments. The BOLT experiment was delivered to the US Air Force for the flight experiment, designed to gather critical validation data on BOLT's boundary-layer transition from over 340 sensors in the hypersonic flight regime. Although the flight test ultimately did not achieve the desired experimental conditions, the BOLT research resulted in new experimental databases, new computational tool development for complicated hypersonic flows, and significant new workforce development through the inclusion of students in the program. APL's efforts to develop BOLT led to a follow-on flight experiment focused on turbulence (BOLT2: The Holden Mission), which flew successfully in March 2022.

INTRODUCTION

Hypersonic vehicles fly faster than five times the speed of sound, a regime in which the vehicle's high velocity introduces complex physics and extreme temperatures, especially as the Mach number increases. As a hypersonic vehicle's velocity increases, the kinetic energy of the airflow surrounding the vehicle increases with the velocity squared. The high energy of the surrounding airflow is transferred into the vehicle skin as heat through a thin region of air called the boundary layer. The boundary layer exists as the result of the slowing of velocity near the wall because of friction, and it begins as "laminar" (or uniform), eventually transitioning to a "turbulent" state in which the boundary-layer flow is chaotic and dominated by swirling eddies. The transition of the boundary layer is initiated by extremely small disturbances that interact with the vehicle flow field and grow exponentially within the laminar boundary layer until they eventually reach large enough levels to cause turbulent flow.

Understanding this transition process has been one of the greatest challenges in fluid dynamics since the beginning of the 20th century. Not only understanding this process, but also predicting the onset of transition, is incredibly important to designing hypersonic vehicles because of the extreme heat transfer rates in this regime. The swirling eddies within a turbulent boundary layer more effectively transfer energy from the surrounding airflow into the vehicle surface, and can increase the heat transfer rates by as much as a factor of 3 to 8. In many scenarios, a conservative design for a vehicle's thermal protection system can account for the increased heating to avoid the challenge of predicting the boundary-layer state. However, an overly conservative design increases the thermal protection system's thickness and thus the vehicle's weight, impacting performance and range. In addition, the state of the boundary layer also increases drag (impacting range) and can affect flow fields around vehicle control surfaces (impacting controllability) as well as optical access through the boundary layer (impacting onboard sensors).

As the US Department of Defense strives to design and field a wide range of new hypersonic systems, the ability to more accurately predict the onset of transition will improve the performance and survivability of these systems. More accurate prediction requires rapidly transitioning scientific knowledge into deployable prediction tools based on our understanding of the physics of this process. It is important that these tools be anchored and validated with a wide range of data sets on vehicle geometries of increasing complexity, particularly in the actual hypersonic flight environment.

PREDICTION OF HYPERSONIC BOUNDARY-LAYER TRANSITION AND THE NEED FOR FLIGHT-TEST DATA

Boundary-layer transition is difficult to predict because it is affected by a wide variety of factors, including vehicle geometry, vehicle orientation, Mach number, Reynolds number (a scaling parameter based on the ratio of inertial forces to viscous forces), freestream disturbance environment, enthalpy, surface temperature distribution, pressure gradient, surface roughness, chemical reactions, and the introduction of by-products from ablation into the boundary layer. No single wind-tunnel (ground-test) facility can reproduce the proper combination of these parameters expected in flight. Thus, complete flight-test data are desired but are often unavailable, requiring that parameters from data in these ground-test facilities be extrapolated to flight conditions, creating large uncertainty.

Historically, transition has been predicted by estimating some properties of the flow or boundary layer and developing empirical correlations based on those parameters and available ground-test or flight-test data. Often, parameters such as the Mach number at the interface between the boundary-layer edge and the freestream flow, as well as the Reynolds number based on a boundary layer's momentum thickness, have been used. While these empirical parameters are useful in the absence of a more advanced method, particularly early in the design process, they contain large uncertainties—so much uncertainty, in fact, that they often are not trusted, and designers will assume the flow is turbulent more often than not. The geometries and data sets for which these correlations were developed are usually significantly different from the vehicle geometry and flight conditions for which they are used. Also, it is not practical to gather test data across a wide range of ground-test facilities for every new hypersonic vehicle design to attempt to reduce those uncertainties. Thus, it is desired to develop some method that can rapidly predict transition with minimal computational expense, using what we know about the physics of the process for a particular case.

Physics-Based Approaches to Transition Prediction

It is helpful to incorporate known physics of transition to improve the accuracy of transition prediction.[1] Over the past decade, significant progress has been made in research toward better understanding of the physical mechanisms responsible for transition for a variety of flows, as well as the effect of the freestream environment on the growth of instabilities within the boundary layer leading to transition. While it is theoretically possible to simulate the entire transition process with computational fluid dynamics (CFD) techniques such as direct numerical simulation (DNS), these techniques have historically remained computationally expensive for most flight conditions of interest and would require precisely modeling freestream disturbances for various tunnel and flight environments, many of which are at present poorly characterized, into the simulation's inflow boundary conditions.

Using a simpler approach to estimate the physics of the transition process, boundary-layer stability methods have been developed and incorporated into tools to predict the growth of disturbances within a laminar "mean" flow. These instabilities can be modeled by applying a perturbation method to the Navier–Stokes equations using a previously simulated laminar flow over the configuration of interest. Some simplifying assumptions are usually necessary to make finding a solution to the perturbation governing equations feasible. These potential assumptions include the following: (1) different instability modes do not interact with each other; (2) locally, the disturbance is temporally and spanwise periodic; and (3) gradients in certain directions can be neglected.

The most simplified form of the stability equations is linear stability theory (LST), in which changes in the mean flow are assumed to be negligible along both the streamwise and spanwise directions when compared with the surface-normal direction. Only the local mean flow properties along the disturbance path direction are necessary to solve the stability equations and identify the most important instability, its frequencies or spatial periodicity, and its growth or decay rates. Solutions are found quickly with LST, and thus it is currently the most commonly used method to characterize the second-mode/acoustic-type instability that often dominates the transition process for hypersonic flows.

For certain flows, however, increased accuracy in the calculation of instability growth can be obtained when nonparallel effects within the boundary layer are included in the stability equations. Extra terms are included, resulting in the linear parabolized stability equations, or often just referred to as the parabolized stability equations (PSE). These equations are still linearized (products of small terms ignored), but the streamwise variation is accounted for with a slowly varying shape function (d/dx << d/dy). Nonlinear PSE take into account both the initial disturbance amplitudes and the interactions between different instability modes; however, these methods are usually only applied to academic problems since the initial disturbance amplitudes are often not known.

The stability methods discussed thus far generally assume that the flow is inhomogeneous in the wall-normal direction when compared with the streamwise and spanwise spatial directions. Another class of stability methods solve the eigenvalue problem in multiple dimensions when the spanwise or streamwise gradients are large enough that they cannot be neglected. The BiGlobal stability method incorporates two inhomogeneous spatial directions into the eigenvalue problem. Including the additional spatial direction adds complexity to the analysis, but combined with planar marching PSE, the method shows promise for analyzing flow fields in which the underlying assumptions of standard LST or PSE are not valid (e.g., complex corner flows, protuberance wake flows, and separated flows). For these more complex flows, more advanced stability methods, such as input/output (I/O) methods, are in development; these methods attempt to utilize the fully three-dimensional flow field, with no approximations to flow homogeneity, treating the entire flow field as a complete linear system.

Numerical boundary-layer stability methods have been applied to a wide range of wind-tunnel data, mainly for conical and ogive body shapes. When combined with ongoing detailed characterizations of wind-tunnel freestream environments, many of these methods show promise for improving estimates of transition location in flight. First, however, appropriate correlations must be developed based on databases of observed instability and transition in ground- and flight-test experiments.

Stability methods typically use an e^N approach for correlation of boundary-layer transition whereby the N-factor describes the relative growth of a disturbance mode for the instability mechanism of interest. The N-factor is defined as

$$\boldsymbol{N(f,s) = ln\left(\frac{A}{A_0}\right) = \int_{s_0}^{s} \sigma ds},$$

where A_0 is the initial amplitude of some disturbance mode occurring at a particular frequency f in the boundary layer at the location s_0, where the disturbance first becomes unstable. The amplitude A is the amplitude of the disturbance mode at some location (s) downstream. The N-factor can be calculated by integrating the local growth rate σ along the disturbance path from s_0 to s. Provided that the disturbance path is known or can be estimated, stability codes will calculate the growth rate along that path in order to calculate an N-factor for a variety of frequency and spanwise wavenumber combinations of interest. When growth rates and N-factors from individual frequencies and spanwise wavenumbers have been calculated, the overall “envelope” of the individual N-factors can be created.

The boundary-layer transition location can then be correlated to a particular N-factor from the overall N-factor envelope. The physics of the transition process can thus be incorporated into the prediction process. Linear stability methods incorporate only the initial linear growth of the instabilities, which is a large portion of the relevant physics. However, it is still semi-empirical because many important physical influences are ignored. The actual values of the initial amplitudes of the relevant disturbance frequencies are generally not known and are not taken into account, nor are the actual values of the final breakdown amplitudes. Various factors can influence both the initial and breakdown amplitudes, such as surface roughness and the freestream noise environment. Additionally, for some instability types (e.g., stationary crossflow), the transition onset location does not correlate well with the primary disturbance (e.g., stationary crossflow vortices) reaching a critical amplitude level. Rather, transition is caused by secondary instabilities that result from distortion of the mean flow by the primary instability. The N-factor therefore can serve only as a measure of strength of the primary instability mechanism, and only with further analyses can the secondary instabilities be predicted.

Flight Data: The Ultimate Validation of Prediction Methods

Ultimately, the objective of ground testing and computational prediction tools is to estimate the onset of boundary-layer transition in the flight environment. Thus, high-quality flight data sets are desired for validation and "constitute the final basis for evaluating transition-estimation techniques," as noted in Schneider's 1999 review article of publicly available flight data.[2] This article summarizes approximately 20 supersonic and hypersonic flight tests taken throughout the 20th century in which transition was observed. Many of these tests, although documented well, were performed with limited instrumentation and carried uncertainties in vehicle orientation, atmospheric conditions, etc. Although some data from these flights are worthy of analysis with modern transition prediction tools, a need for modern flight data sets with well-characterized boundary conditions and heavy instrumentation suites is evident. Most importantly, experiments such as these must be executed with a focus on minimizing complexity and cost since hypersonic flight testing has historically been prohibitively expensive, at costs of tens of millions of dollars for a single flight.

A new paradigm for low-cost hypersonic flight testing for fundamental scientific research purposes was pioneered by the US Air Force Research Laboratory (AFRL) in an international partnership with the Australia Defence Science and Technology Group and various other partners under a program called HIFiRE (the Hypersonic International Flight Research Experimentation program).[3] The HIFiRE program, initiated in 2006, sought to launch nine flight experiments to gather high-fidelity design databases for various critical hypersonic phenomena in the flight environment and to do so with an emphasis on getting to flight with less time and cost than traditionally possible.

Two of the HIFiRE program flights focused on boundary-layer transition: HIFiRE-1 and HIFiRE-5.[4] HIFiRE-1 was a heavily instrumented circular cone with a 7° half angle and launched in March 2010 from the Woomera Range Complex in Australia. Although the vehicle was originally intended to fly at an angle of attack close to zero during the transition experiment, the vehicle reorientation maneuver failed to position the vehicle upon reentry, and transition data were gathered at angles of attack from 5° to 13°. HIFiRE-5 was a 2:1 ratio elliptic cone designed to excite the crossflow instability mechanism of transition. An initial launch of HIFiRE-5 was attempted at the Andøya Rocket Range, now Andøya Space, in Norway in April 2012; however, in this flight the second-stage ignition failed and the vehicle did not achieve hypersonic flight. This initial attempt was retroactively designated HIFiRE-5a, and a second attempt designated HIFiRE-5b was successfully conducted at Woomera in May 2016, providing a high-quality validation data set on transition in Mach 7 to Mach 7.8 conditions. Although only one of the three flights reached its intended experiment conditions, data gathered on all three flights (including off-experiment conditions) have been used in academic research to improve knowledge of transition and as validation for computations.

Both the HIFiRE-1 and HIFiRE-5 geometries were conical in nature, designed to excite known instability modes previously studied in research by the community. Following these successful research flights, AFRL and its Air Force Office of Scientific Research (AFOSR) began to formulate a concept for a new flight experiment to build on the successful HIFiRE flights.[5] This new flight experiment was to feature a significantly more complicated geometry, in which the dominant mechanisms of transition would not necessarily be known a priori. Leveraging experience, operations concepts, and hardware from the HIFiRE program, this new flight experiment would also be unique in its early and heavy involvement of academia in its design and execution.

BOLT: AN APL-LED COLLABORATION

In early 2017, AFOSR announced the Boundary-Layer Transition (BOLT) flight experiment. The BOLT geometry, created to generate a complex hypersonic flow field that would challenge existing transition prediction tools, features low-curvature concave experiment surfaces and highly swept leading edges (Figure 1). APL competed to be, and was selected as, the principal investigator of the flight experiment and the lead

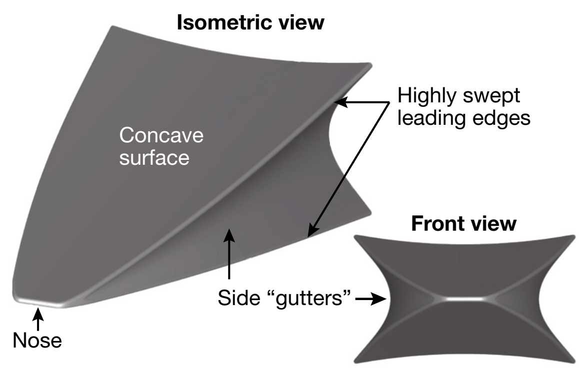

Figure 1. The BOLT geometry. The BOLT geometry, created to generate a complex hypersonic flow field that would challenge existing transition prediction tools, features low-curvature concave experiment surfaces and highly swept leading edges. (From Wheaton et al.[6]; reprinted by permission of the American Institute of Aeronautics and Astronautics, Inc.)

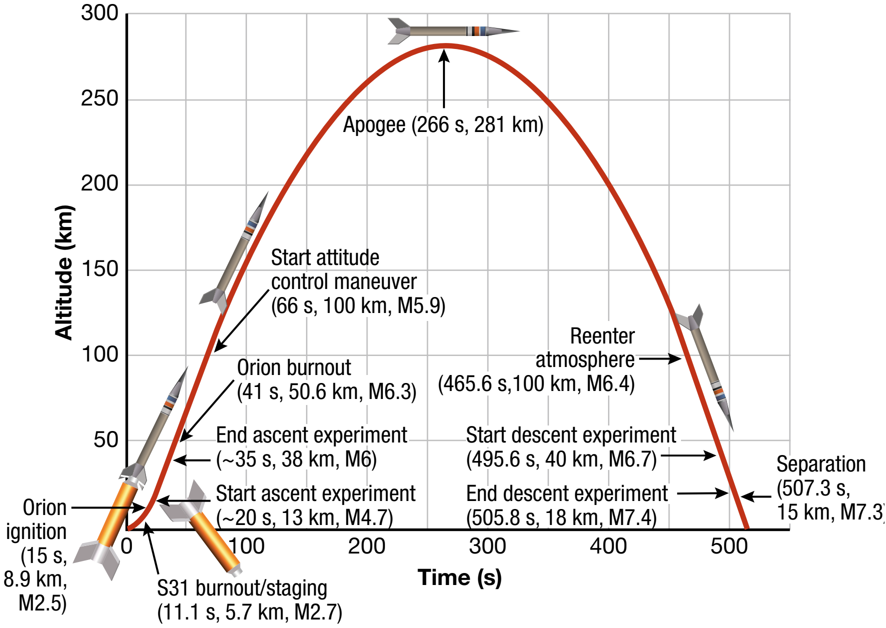

Figure 2. Flight experiment planned mission events. During the flight test, the two-stage sounding rocket would travel through the critical portion of the atmosphere twice during its ballistic trajectory. On the ascent, the flow would change from turbulent to laminar as the atmosphere became thinner. After a several-minute exoatmospheric phase and de-spin/reorientation maneuver, the vehicle would reenter the atmosphere and travel through a laminar to turbulent transition at Mach 7 to Mach 7.5. (From Wheaton et al.[6]; reprinted by permission of the American Institute of Aeronautics and Astronautics, Inc.)

organization to design and fabricate the experiment hardware. According to AFOSR's vision, APL would lead a unique collaboration of top organizations across academia, government, and industry. These organizations would work together to execute a rapid-paced scientific simulation and ground-testing campaign to move from initial concept to flight test in a 3-year period. The team would involve professors and students from the University of Minnesota, Purdue University, and Texas A&M University working alongside APL researchers and conducting advanced ground testing and simulations to explore the transition physics of the BOLT geometry. AFRL would provide its extensive flight-testing capabilities and experience from the HIFiRE program, as well as flight-vehicle components. APL partnerships with the NASA Langley Research Center, CUBRC, and VirtusAero LLC would bring additional testing and simulation to the experiment campaign. The German Aerospace Center (DLR) Mobile Rocket Base (MORABA) was selected by AFOSR to provide flight-vehicle systems and a two-stage sounding rocket vehicle, and to execute the flight experiment launch campaign.[7] The team chose the Esrange Space Center in northern Sweden as the launch range.

The culmination of the project would be the flight test via a two-stage sounding rocket that was designed to travel through the critical portion of the atmosphere twice during its ballistic trajectory. On the ascent, the flow would change from turbulent to laminar as the atmosphere became thinner. Following a several-minute exoatmospheric phase and de-spin/reorientation maneuver, the flight was designed to reenter the atmosphere and travel through a laminar to turbulent transition at Mach 7 to Mach 7.5. Figure 2 illustrates the experiment's phases. A vast array of instrumentation would measure detailed temperatures, heat transfer rates, and pressures on the surface to characterize the boundary-layer transition onset during the entire flight.[6]

The team met at APL for a kickoff meeting in September 2017, with only a concept for the initial BOLT geometry and an initial data set of NASA Langley Mach 6 wind-tunnel results obtained just weeks before. To meet the scheduled flight campaign date in May 2020, the team would have just 18 months to gather as much simulation and test data as possible to understand the transition physics on the BOLT geometry in order to design and instrument the flight experiment payload such that fabrication could commence in early 2019. Most of the wind-tunnel data would have to be obtained within the 12 months following the project kickoff, so the work promptly began.

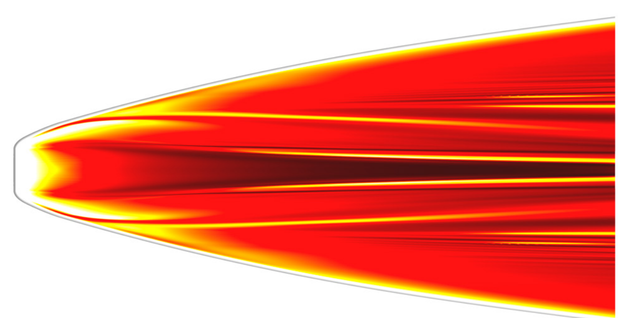

Figure 3. University of Minnesota DNS simulations of heat transfer, showing streamwise streaks from vortex structures in the complex flow (solution provided by John Thome). Team members at the university were able to perform simulations at expected flight conditions to show that vortex structures were likely also to be present in flight, heavily influencing the strategy for the flight instrumentation suite.

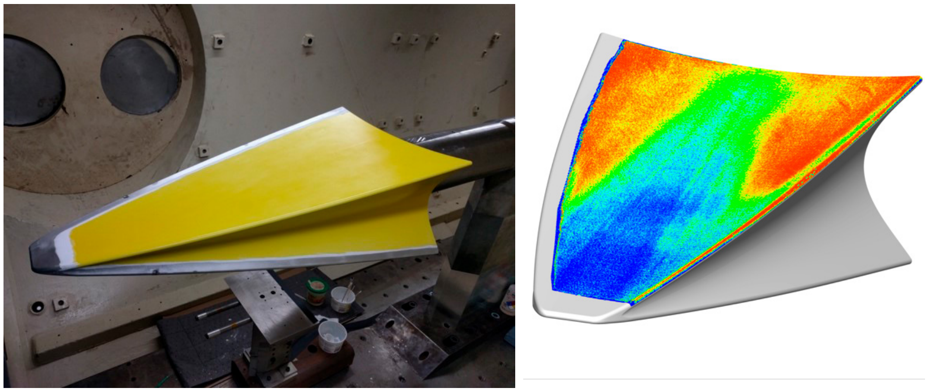

Figure 4. A full-scale wind-tunnel model. The model in the CUBRC Large Enthalpy National Shock (LENS) II shock tunnel (left) and temperature-sensitive paint imaging (right), both showing transition.

APL, Texas A&M, and VirtusAero LLC began performing exploratory CFD simulations to understand the BOLT flow field.[8,9] The flow proved to be extremely complex, with a spanwise pressure gradient on the main experiment surface driving flow into a central vortex structure on the centerline. Boundary-layer stability calculations performed using the NASA Langley Stability and Transition Analysis Code (LASTRAC) and the Texas A&M EPIC code showed that the flow was at least dominated by both the second mode and crossflow instabilities, and a new challenge to the BOLT flow field was that both of these modes are predicted to occur in the same region of the experiment. The modes would presumably interact in a nonlinear fashion, meaning existing tools based on LST may not accurately predict the growth of disturbances on the experiment.

During the month after the project kickoff, APL staff worked on-site at Purdue University's Mach-6 Quiet Tunnel obtaining initial data by using infrared (IR) thermography to visualize surface heating on rapidly prototyped models.[10] The Mach-6 Quiet Tunnel is unique in that it simulates the low-disturbance atmosphere of flight. Using the initial results, APL designed and fabricated a 1:3-scale model of BOLT, which was then tested at facilities across the team members' locations, including two more entries at the Purdue Mach-6 Quiet Tunnel, as well as one at the NASA Langley 20-Inch Mach-6 tunnel[11] and multiple entries at the Texas A&M University Actively Controlled Expansion (ACE) and Mach-6 Quiet Tunnel (M6QT) facilities.[12] The onset of transition was inferred via increases in surface heating from visualization techniques such as temperature-sensitive paint and IR thermography. The data also provided insight on the behavior of transition behind forward-facing and rear-facing steps on the BOLT geometry; these data informed design of a secondary experiment in the flight test to measure step-induced transition in flight.[13]

Although the quiet tunnel facilities were unable to produce a high enough Reynolds number to induce transition on the BOLT geometry in a low-disturbance environment, the absence of tunnel disturbances showed a vastly different flow field than in the conventional noisy tunnel facilities: a laminar flow field dominated by streamwise heating streaks all along the body. Researchers at the University of Minnesota developed and used new computational algorithms to significantly reduce numerical noise in their simulations and were able to show that these streamwise structures were vortices that appeared to be a laminar feature of the complex BOLT flow field. They were then able to perform simulations at expected flight conditions to show that these vortex structures were likely also to be present in flight (Figure 3), heavily influencing the strategy for the flight instrumentation suite. The flight instrumentation would need to have sufficient response to resolve these heat structures and to differentiate heating from them versus heating caused by transition.

Working with APL, the team at CUBRC in Buffalo, New York, began constructing a full-scale model of BOLT for testing in early 2018 in its Large Enthalpy National Shock (LENS) II facility (Figure 4). The CUBRC LENS II facility has the ability to accommodate

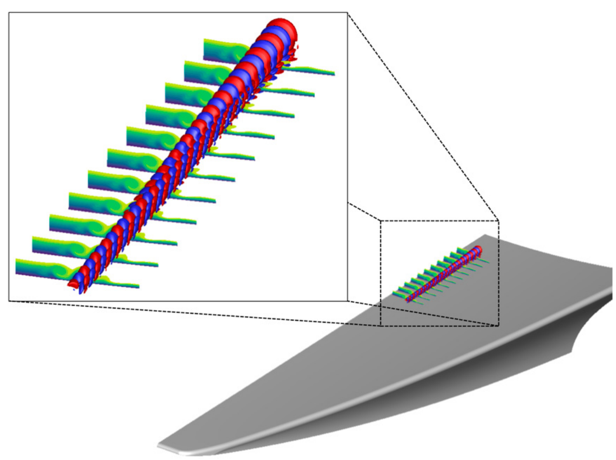

Figure 5. Spatial BiGlobal simulations of an unstable mode in the center vortex structure on BOLT (provided by Neal Bitter). University of Minnesota team members demonstrated that the predicted frequencies of the center vortex mode matched those measured by APL and Purdue in the subscale model experiments under quiet flow. APL was later able to simulate this center vortex mode with spatial BiGlobal stability calculations.

large-scale models and reproduce representative flight enthalpies (a measure of the flow's energy). It can also easily operate at different Mach numbers that more closely match the expected Mach numbers BOLT will experience in flight. Eight runs at CUBRC provided additional valuable data to help APL design the flight experiment.[14,15] Tiny thin-film heat flux sensors embedded in the swept leading edge provided critical heating data to anchor APL's thermal modeling used to predict flight temperatures in this region and to select appropriate materials for the flight experiment payload.

During the busy ground-test campaign, researchers on the team performed advanced CFD to gain a better understanding of the flow on BOLT, while simultaneously debuting and improving new CFD techniques necessitated by the complex geometry. The University of Minnesota team members, having achieved a numerically clean, low-disturbance laminar flow simulation, began introducing stochastic perturbations into the simulation to excite potential transition modes. These forced DNS techniques demonstrated that additional modes not predicted by classic linear stability tools likely existed within the complex vortex structures near the BOLT centerline. They were able to demonstrate that the predicted frequencies of the center vortex mode matched those measured by APL and Purdue in the subscale model experiments under quiet flow. APL was later able to simulate this center vortex mode with spatial BiGlobal stability calculations (Figure 5). With these findings, APL was able to ensure that instrumentation was placed within this region on the flight experiment.

The APL-led BOLT team performed ground testing and numerical simulations rapidly over an 18-month period from kickoff to the flight experiment critical design review. These tests and simulations gave the team the database it needed to understand the likely behavior of the transition physics in flight and to design and implement a flight instrumentation suite to measure those physics. An open, common geometry and combined computational and experimental approach to this research resulted in significant new knowledge and drove critical analysis tool development that can be utilized to assess transition on future complex geometric configurations.

CREATING THE BOLT FLIGHT EXPERIMENT

After the 18-month test and simulation campaign, the BOLT team converged on a scientific instrumentation suite for the eventual flight experiment. (Additional details on the instrumentation approach are provided in Wheaton et al.[6]) The BOLT flight experiment design features more than 340 scientific instrumentation data channels that will measure temperature, heat transfer rates, and mean and fluctuating pressures on the experiment surface during the flight. Having such a large number of sensors is critical for obtaining a high-quality validation data set on transition, and also for capturing the boundary-layer transition's variation with vehicle flight conditions and orientation. APL brought its expertise in designing and prototyping complex hardware for extreme environments to bear on the challenge of integrating all these experimental measurements into a complex hardware design that would survive the thermal and mechanical loads expected during the flight. Although the BOLT principal investigator and core science team primarily comprised members of APL's Force Projection Sector, the project was truly collaborative and leveraged expertise and capabilities from across the Laboratory to design, fabricate, instrument, and test the BOLT flight experiment. This collaboration included contributions from the Air and Missile Defense Sector, the Research and Exploratory Development Department, and the Space Exploration Sector.

A key need early in the project was to understand how various candidate materials affected the BOLT payload's thermal response. Although the HIFiRE-1 and HIFiRE-5 flight payload designs were constructed with aluminum experiment surfaces, it was initially unclear whether the higher heating rates generated by BOLT's highly swept leading edges would necessitate a higher-strength material. APL used its internal suite of aerothermal prediction tools, MSLRAD/ATLAS, early in the project to perform trade studies evaluating different material sets and their resulting temperatures through the flight experiment. Using empirical correlations that could be generated rapidly for heating rates on various portions of the BOLT geometry, MSLRAD/ATLAS gave the BOLT team critical insight into design choices. Data at CUBRC revealed that the swept leading edge was highly resistant to turbulent flow, and a higher-fidelity

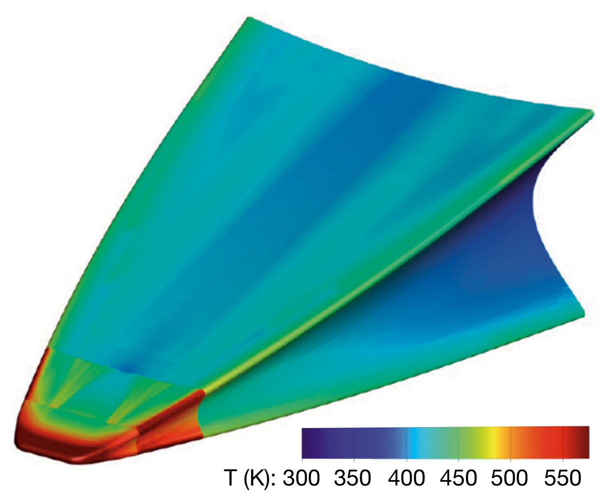

Figure 6. MSLRAD/ATLAS-predicted surface temperatures during the BOLT descent experiment. The APL team used the temperature predictions throughout flight to select materials, verify structural integrity, and design the instrumentation suite.

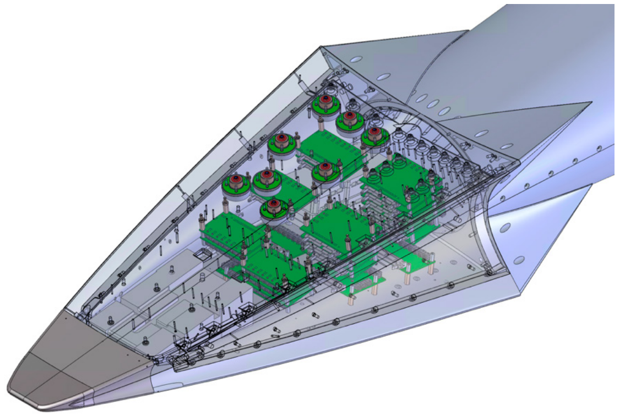

Figure 7. BOLT mechanical design and packaging. The extensive instrumentation suite required a collection of 24 sensor collection boards to be mounted along the inside of the experiment payload. A large tungsten alloy ballast was also required to improve the vehicle's aerodynamic stability. From Wheaton et al.[6]; reprinted by permission of the American Institute of Aeronautics and Astronautics, Inc.)

model of transition was required for more accurate thermal analyses.

Using internal computational resources (a key advantage in this project), APL was able to quickly generate a database of laminar, transitional, and fully turbulent heat transfer rates across the BOLT trajectory using viscous CFD, and to input those results into a higher-fidelity MSLRAD/ATLAS thermal model throughout flight (Figure 6). The viscous CFD results used a model for transitional flow heating rates, which properly modeled the laminar flow on the leading edge itself, but used an approximate transition onset to model the expected higher heating rates from turbulent regions on the experiment surface. The viscous CFD-based transitional simulations were anchored in test data and more accurate than the early correlation-based models. APL rapidly generated more than 100 CFD cases for thermal modeling. With these CFD cases and their implementation into thermal modeling, the team was able to finalize the design: BOLT would use aluminum 6061-T6 material for the majority of the experiment surface, reducing weight and cost and providing ideal initial equilibrium temperature distributions for the descent-phase experiment because of its good thermal conductivity. An iridium-coated titanium–zirconium–molybdenum nose tip was selected for the initial portion of the BOLT flight payload, followed by a 316 stainless steel isolator (used to prevent the extreme temperatures at the nose tip from conducting into the cool aluminum aft portion of the payload). The MSLRAD/ATLAS thermal model results were later fed into a fully transient 3-D structural solver to deem the payload design certified for flight.

With the materials selected, APL used its expertise to develop a complex mechanical design that converged the flight experiment and instrumentation requirements with those for properly integrating the payload with the flight vehicle (Figure 7). Payload packaging proved to be a challenge. The extensive instrumentation suite required a collection of 24 sensor collection boards to be mounted along the inside of the experiment payload. A large tungsten alloy ballast was also required to improve the vehicle's aerodynamic stability. Great care was taken in the BOLT design to ensure that it was machinable, would provide access for installing instrumentation, and accounted for critical dimensions and tolerances.

APL's Advanced Mechanical Fabrication facilities supported BOLT's aggressive schedule. Capitalizing on their expertise in prototyping complex hardware for extreme applications such as undersea and space environments, APL's machinists built the majority of the BOLT flight payload components over just 3 months. The hardware had to be built within critical tolerances without any slack in the schedule for rebuilds. As such, each machining setup and operation was first practiced on test pieces to demonstrate success. Because machinists and mechanical designers were on-site, the BOLT team was able to closely monitor all aspects of the fabrication to ensure a successful outcome.

The fabrication team also needed to creatively solve several challenges. One such challenge was the need for precision-machined rear-facing steps at the interface joints between the nose tip, isolator, and aft portions of the payload. These steps were designed to offset the predicted differential thermal expansion of the different materials on either side of the joint, such that at the experiment conditions of the trajectory there would be no forward-facing step that could artificially trip the flow from laminar to turbulent. Because of BOLT's complex geometry, the design called for a varying initial step to be machined around each joint; this

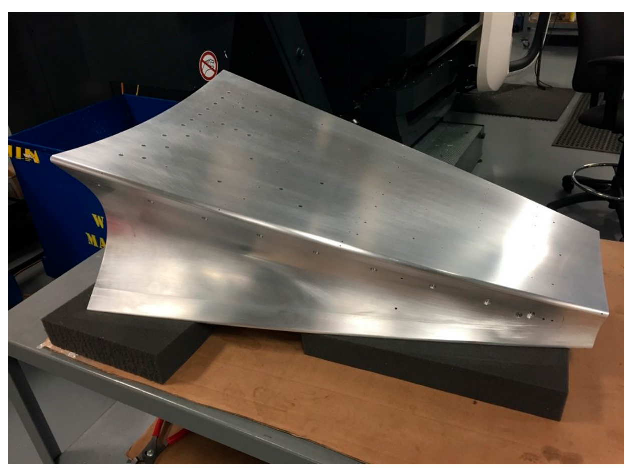

Figure 8. BOLT payload parts after machining. APL's skilled operators accomplished the precision machining using five-axis machining capabilities. (From Wheaton et al.[6]; reprinted by permission of the American Institute of Aeronautics and Astronautics, Inc.)

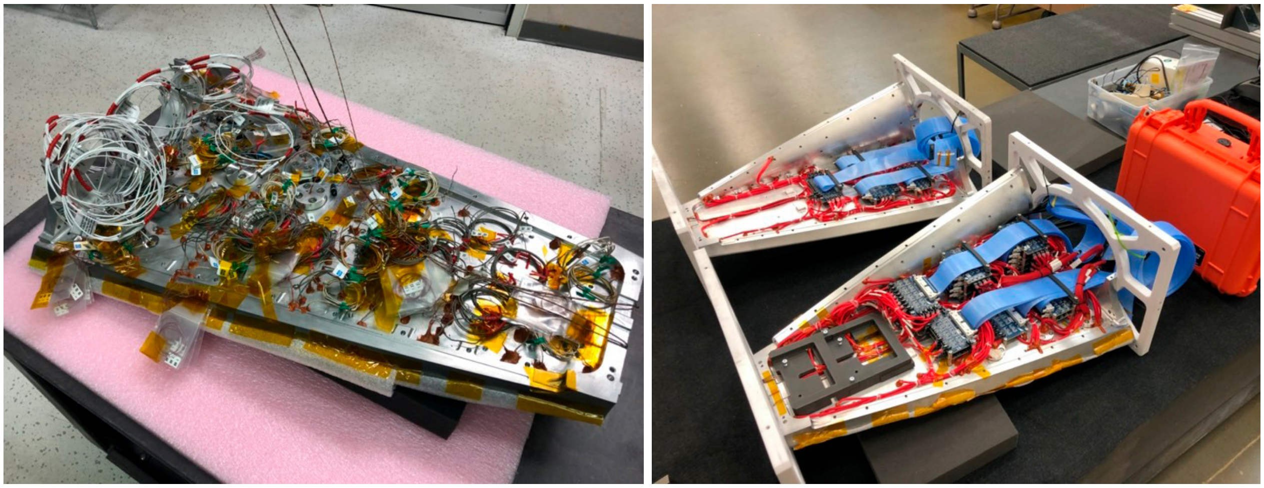

Figure 9. Integration of flight experiment components. Components are shown before (left) and after (right) electrical integration of the instrumentation. (From Wheaton et al.[6]; reprinted by permission of the American Institute of Aeronautics and Astronautics, Inc.)

step would need to be accurately machined to heights of only a few thousandths of an inch. The required step heights were on the order of the diameter of a typical human hair.

APL's skilled operators accomplished the precision machining using five-axis machining capabilities. Computer-controlled machining operations enabled by the five-axis machine, programmed by APL's machinist operators, minimized the number of manual setups and subsequent realignment of the parts. In fact, each separate experiment surface part only required one change of operations, resulting in highly accurate features. Additionally, experimental machining of test pieces that simulated the material interface joints and inspections of the resulting parts produced a final isolator design that matched the design step heights on the experiment surface within the target ±2 thousandths of an inch. Figure 8 shows some of the completed BOLT experiment components during an initial assembly.

Once the hardware components had been machined and their assembly verified, the APL team began the long process of installing and wiring 226 sensors into the experiment payload. Most of the sensors on the surface are coaxial thermocouples, produced by Medtherm Corporation and then installed and finished by hand at APL until they were flush with the surface. Other instruments, such as the pressure transducers and heat flux sensors, needed to be bonded in place with sufficient conformality to avoid any steps or discontinuities in the surface shape that could cause early boundary-layer transition. Most importantly, the wires from all these instruments needed to be tracked to a particular sensor-board channel internal to the BOLT payload (Figure 9). Technicians from APL's Advanced Electrical Fabrication Group worked for several months to sheath, route, connect, and test each wire within a complex assembly of internal sensor boards.

Figure 10. The completed BOLT flight experiment payload undergoing vibration testing at APL's Environmental Test Facilities. During testing, which included vibration and thermal testing over 2 weeks, sensors and electronics performed well during testing. All operational sensors remained responsive after testing.

Just over 8 months after starting to machine the BOLT components, the team completed the instrumentation installation and wiring, and BOLT was ready for assembly. The completed payload was delivered to the Air Force for further integration with additional components of the flight vehicle and then returned to APL's Environmental Test Facilities to undergo flight qualification testing (Figure 10). This testing included vibration and thermal testing over a 2-week period. The sensors and electronics performed well during testing, and all operational sensors remained responsive after testing. BOLT returned to AFRL in Dayton, Ohio, for further hardware testing and remained on track for its planned launch date in May 2020. While the flight was ultimately delayed as a result of the COVID-19 global pandemic, BOLT's aggressive schedule was met thanks to the efforts and capabilities of APL and the entire BOLT team.

The flight test ultimately occurred in June 2021. Because of unexpected behavior, the flight did not achieve the desired experiment conditions. However, the BOLT research resulted in new experimental databases, new computational tool development for complicated hypersonic flows, and significant new workforce development through the inclusion of students in the program. APL's lessons learned from the BOLT flight were instrumental in ensuring the success of a follow-on flight experiment, BOLT2: The Holden Mission, focused on hypersonic turbulence. The BOLT and BOLT2 programs addressed a need for increased flight experimentation access for the hypersonic research and development community.

A BRIDGE BETWEEN SCIENCE AND APPLICATION

A project like BOLT fits within APL's core purpose, as a university-affiliated research center, to organize collaborative activities that promote linkages among the Department of Defense, academia, and industry. APL played a key role in fostering education and mentoring the students who were deeply involved in this unique project from its onset. Several of the BOLT graduate student researchers worked as summer interns alongside staff at APL to help solve critical challenges in the flight experiment's design. These students were exposed to fast-paced, schedule-driven research that aimed to accomplish a complex objective (hypersonic flight test). In response to threats from near-peer adversaries, the nation is in the midst of a revolution in hypersonics, and APL is uniquely positioned, through projects like BOLT, to assist in developing the next-generation hypersonic workforce and in accelerating new scientific knowledge into application for the design of future systems.

Pairing academia with a university-affiliated research center to execute BOLT was beneficial to all parties. APL staff members were able to learn from top researchers via the collaborative relationship with the University of Minnesota, Purdue University, and Texas A&M University. These researchers applied advanced testing and simulation capabilities to BOLT—capabilities that APL's subject-matter experts are now able to apply to other hypersonic programs. BOLT serves as a potential new model for accelerating transition of capabilities, not just in boundary-layer transition, but in other technical disciplines where it remains a challenge to successfully field new hypersonic systems.

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