

The BOLT Experiments: Outcomes from a Decade of Fundamental Science in Hypersonic Flight

Bradley M. Wheaton*

Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723

Ivett A. Leyva[†]

Texas A&M University, Fort Worth, TX 76102

Rodney W. Bowersox[‡]

Texas A&M University, College Station, TX 77843

Graham V. Candler[§]

University of Minnesota, Minneapolis, MN 55455

Scott A. Berry[¶]

NASA Langley Research Center, Hampton, VA 23681

Aaron T. Dufrene^{||}

CUBRC, Buffalo, NY 14225

Steven P. Schneider^{**}

Purdue University, West Lafayette, IN 47907

Sarah H. Popkin^{††}

Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723

The paper highlights major accomplishments, outcomes, new knowledge, and lessons learned from nearly a decade of research surrounding the three BOLT flight experiments (BOLT-1A, BOLT-2, and BOLT-1B) as well as associated preflight and postflight research surrounding the flights. It is hoped that the documentation of the BOLT program outcomes will highlight the progress made in fundamental understanding of transition and turbulence from the flights. Major topics addressed include outcomes from wind-tunnel testing of this common geometry in many facilities over the years, the key advancements in numerical simulation techniques motivated by the need to model physics on the complex BOLT geometry, progress in flight experimentation methodologies, the value of combining hypersonic flight test with atmospheric measurements, and the value of programs like BOLT for accelerating workforce experience.

I. Introduction

The BOLT flight experiment program was initiated in 2017 by the Air Force Research Laboratory (AFRL) Air Force Office of Scientific Research (AFOSR) and aimed to challenge and energize the basic research community to better understand boundary-layer transition and turbulent flow in the flight environment. A new geometry with low-curvature concave surfaces and highly-swept leading edges (Fig. 1) was created to have significantly more geometric complexity than standard conical geometries. This complexity was intentional, as the flow induced by the geometry was

*Principal Professional Staff, Force Projection Sector, 11100 Johns Hopkins Rd., Laurel, MD, 20723, Associate Fellow AIAA

[†]Associate Dean for Research, College of Engineering, 801 Cherry St., Fellow AIAA

[‡]Senior Associate Dean for Research, Regents Professor, Department of Aerospace Engineering, Fellow AIAA

[§]McKnight Presidential Endowed Professor, Department of Aerospace and Engineering Mechanics, Fellow AIAA

[¶]Senior Researcher, Aerothermodynamics Branch, M/S 408A, Associate Fellow AIAA.

^{||} Aerospace Engineer, Aerothermal/Aero-Optics Evaluation Center, 4455 Genesee Street, Suite 106, Associate Fellow AIAA

^{**}Professor, School of Aeronautics and Astronautics, Fellow AIAA

^{††}Senior Professional Staff, Force Projection Sector, 11100 Johns Hopkins Rd., Laurel, MD, 20723

intended to stress existing computational tools as well as the research community's knowledge of transition physics [1]. Symmetry in the geometry was also intentional with two identical concave surfaces that would enable separate studies of boundary-layer transition on smooth and roughened/stepped surfaces. The two main surfaces were isolated from each other by high-curvature side regions such that flow from the top surface would not cross-contaminate onto the lower surface.

The program began with a flight experiment focused primarily on boundary-layer transition physics, initially named “BOLT” but retroactively referred to as the “BOLT-1” flight experiment [1]. BOLT-1 was led by the Johns Hopkins Applied Physics Laboratory (APL) and consisted of a large international team of organizations that span academia, government, and industry. The team conducted a fast-paced and widespread preflight research campaign with ground testing and computational analysis to predict transition mechanisms in this new geometry [2–8]. At the end of the preflight research, a design was finalized for a sounding-rocket flight experiment to make detailed measurements of transition on the BOLT geometry in the hypersonic flight regime [9, 10]. A second flight experiment named “BOLT-2: In Memory of Mike Holden” (led by Texas A&M University and CUBRC) was concurrently established utilizing a lengthened variant of the BOLT geometry to enable measurements of turbulent flow [11]. The original BOLT-1 geometry had a full-scale length of 866 mm, while the BOLT-2 geometry added length to extend the geometry to 1.0 m (shown as the additional blue region in Fig. 1). The BOLT-2 flight further expanded ground test and computational analysis databases for the geometry and designed a new flight article instrumentation layout focused on turbulent flow measurements [12–14].

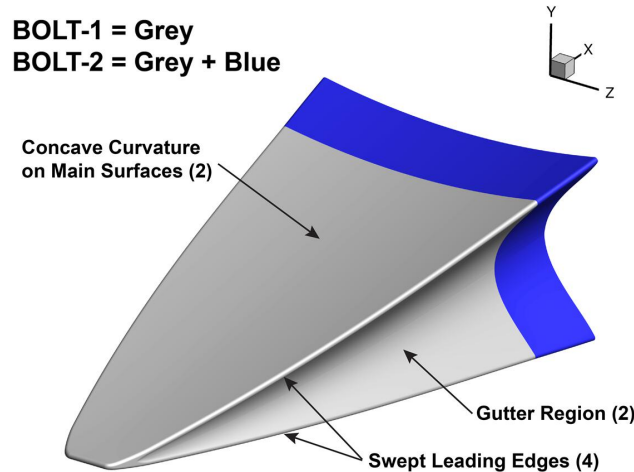


Fig. 1 The BOLT geometry: low-curvature concave surfaces with highly-swept leading edges.

The first flight experiment “BOLT-1A” was built at APL and launched in 2021 from the Esrange Space Center in Sweden. The flight vehicle experienced a dynamic instability and did not reach the planned hypersonic experiment conditions [15, 16]. A postflight investigation and analysis campaign identified the flight instability as pitch-roll coupling [17, 18]. The BOLT-2 flight experiment manufactured by CUBRC flew successfully in 2022 from the NASA Wallops Flight Facility and generated a wealth of new flight results for both transitional and fully-turbulent flow at Mach numbers near 6.0 [19–22]. Motivated by obtaining the originally-envisioned transition-focused flight measurements to complement the new BOLT-2 data, the BOLT-1 experimental forebody was re-designed and re-built by APL with additional instrumentation and design enhancements [23]. The new flight, BOLT-1B, launched aboard a German Aerospace Center (DLR) Black Brant VC vehicle from Andøya Space in 2024 reaching a peak Mach number of 7.2 and obtaining new boundary-layer transition and even turbulent flow measurements [24].

Over the majority of the past decade, the BOLT flight experiment series has brought together teams of different organizations to advance the state of the art in computational simulation approaches, ground test methodologies, and best practices for obtaining high-fidelity aerothermal validation data in the hypersonic flight environment. The co-authors of this paper include both investigators and former program officers from the BOLT flights. The paper will attempt summarize the collective progress and new knowledge gained from all three flight experiments as well as associated preflight and postflight research.

II. Background

Before discussing the outcomes of the BOLT experiments, it is important to understand the state of hypersonic transition and turbulence research in 2017 (when the program began). The understanding and accurate prediction of boundary-layer transition has remained a challenging problem in hypersonics. Historical research over the prior decades focused on understanding transition and heating on conical bodies representative of reentry vehicles (RV's) with major ground and flight test efforts during the 1960's and 1970's [25]. Transition on blunt reentry capsule bodies was a historical focus of NASA during that same time period [26]. In the 1980's, the Space Shuttle program as well as programs such as National Aerospace Plane (NASP) that aimed for "single stage to orbit" vehicles resulted in a robust expansion of transition research to more complex configurations (including winged bodies, high-speed airbreathing engines, and gliding vehicles). Over these decades, much knowledge of the various physical mechanisms important for transition in these types of configurations was gained, but as summarized in Stetson [27] the correlations developed for the prediction of the transition all had serious deficiencies. These early decades of transition research were also primarily limited to testing and observations, as computational power was insufficient to simulate transition physics for entire vehicle flow fields.

After a downturn in hypersonics-related funding in the 1990's, the 2000's saw a renewed interest in the field driven primarily by interest in new hypersonic systems for military applications. Significant advancement in the understanding of boundary-layer transition has been obtained in the past two decades for several reasons: (1) This period saw new investment in modern ground-testing, including new tunnel facilities and improved diagnostics capabilities for measuring transition in wind tunnels (such as temperature-sensitive paint, infrared thermography, and surface-mounted high-frequency pressure transducers). Hypersonic "quiet" tunnels came online in the United States that allowed critical study of transition under low-noise environments more comparable to flight [28]. (2) Advanced computational simulations and numerical techniques for simulating transition physics became more routine after significant new code development efforts alongside the increasing power and accessibility of computational hardware. In recent decades, new boundary-layer stability codes have emerged, and direct numerical simulation (DNS) of hypersonic flowfields has become attainable within the research community. (3) A still limited but renewed funding for hypersonic flight experiments seeking to obtain validation data for complex flow phenomena that cannot be properly simulated in any single wind-tunnel test environment. Hypersonic flight experiments differ in focus from hypersonic flight tests (or demonstration programs) in that they seek only measurements that advance scientific knowledge and are not trying to demonstrate a functional vehicle system or technology. Experiment programs can thus tolerate higher risk, tailor the flight requirements to properly support the scientific outcomes while reducing cost, and more easily try new instrumentation and measurement techniques. The Hypersonic International Flight Research Experimentation (HIFiRE) program [29] was initiated in 2007 and conducted jointly by the United States Air Force Research Laboratory (AFRL) and the Australian Defence Science and Technology (DST) Group. This program significantly advanced methods for the investigation of basic science hypersonics phenomena in the flight environment through the use of the aforementioned experimentation approach over several flights during 15 years. These flight experiments emphasized a combined computational, ground-testing, and flight experiment approach to advancing physical understanding of many phenomena including transition.

Two of the HIFiRE flights specifically focused on hypersonic boundary-layer transition as their primary objective [30]. HIFiRE-1, flown in 2010, demonstrated the use of new instrumentation to measure transition on a 7° half-angle cone (axisymmetric geometry dominated by the second-mode instability). The HIFiRE-5 flight extended the complexity of the experiment body, using a 2:1 cross section elliptical cone as the subject of the experiment. The goal of HIFiRE-5 was to study transition on a three-dimensional body where the crossflow instability was presented. The first flight of HIFiRE-5 occurred in 2012 but did not attain hypersonic conditions because of a problem with ignition of the rocket upper stage, and was repeated successfully as HIFiRE-5B in 2016. That same year, the German Aerospace Center (DLR) flew another hypersonic boundary-layer transition experiment ROTEX-T on a 7° half-angle cone [31]. The influx of new basic research validation data from flight environments energized academic researchers and contributed to new ground tests to correlated the flight results to different facilities, the maturation of stability analysis codes, advanced numerical simulations at ground and flight conditions, and overall a greater understanding of transition physics.

Following HIFiRE-5 and ROTEX-T, AFRL/AFOSR began to conceptualize a new flight experiment program as described in Ref. [1]. The first goal of this new program was to challenge the academic community and allow self-evaluation of the ability of modern computational and diagnostic test tools to predict the transition physics in flight for a brand new geometry significantly more complex than HIFiRE-1 and HIFiRE-5. The second goal was to fly this geometry with as much instrumentation as possible to connect computations, ground testing, and flight data. And last but not least, AFOSR was resolute to involve academia (students and professors) in the design of the flight experiment

from the onset. A small Government team was convened to design the new geometry. The general desired features were swept leading edges and independent surfaces permitting multiple experiments at once. Figure 2 shows some of the early concepts for the BOLT geometry as the design was iterated (infamously, at one point using Play-Doh to mold an approximate shape). A highly-collaborative team consisting of academia, a University Applied Research Center (UARC), key subject matter experts from AFRL with HIFiRE program experience, NASA, and industry would then go on to mature the flight article design. Ultimately, the BOLT program resulted in three flight experiment payloads shown in Fig. 3, with the BOLT-2 flight addressing a primary objective not specifically included in any of the HIFiRE flights: that of fully-turbulent flow physics [11].

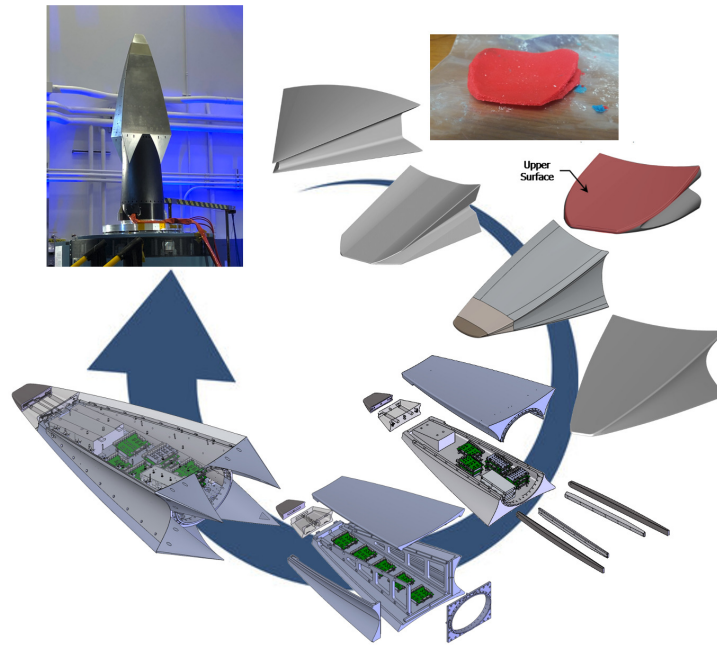


Fig. 2 From concept to flight experiment - early designs for the BOLT-1A flight geometry.

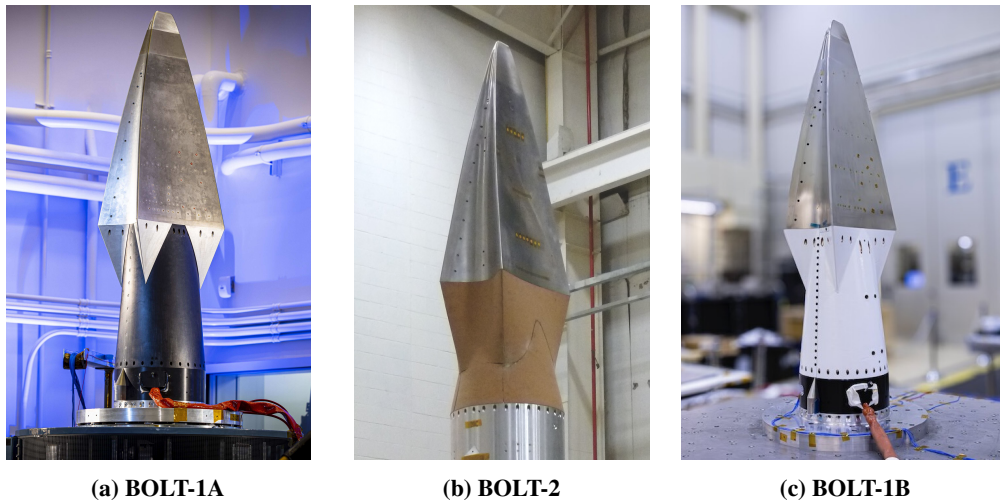


Fig. 3 Preflight photographs of each of the three BOLT flight experiments.

III. Outcomes from the BOLT Experiments

This section summarizes accomplishments, outcomes, and major lessons learned under the BOLT series of flight experiments. The authors sought to summarize responses to several questions: What was accomplished over the past decade? What have we learned? What challenges remain? How can the data acquired from these flights be best utilized to advance the state of the art in hypersonic flight predictions?

A. Deep Understanding of the BOLT Flow Features

The main objectives of the BOLT experiments were to investigate flow features, boundary-layer transition mechanisms, and turbulence on the new complex geometry, where the details of the flow were not known a priori at the onset of the research. Given this goal, and the project's extensive testing and computational analysis work, the program indeed produced new knowledge of the flow physics induced by this geometry. This section summarizes knowledge gained about the flow physics on the BOLT geometry from the combined approach of ground testing, numerical simulation, and flight experimentation. Section III.B and Section III.C will focus more specifically on unique advancements in ground testing and numerical simulations, respectively, during the research. For summaries of the results and insights from the flight experiments, readers are referred to Refs. [19–21] for BOLT-2 and Refs. [32, 33] for BOLT-1B. Additional supersonic transition measurements from BOLT-1A are shown in Ref. [16].

The flow features and transition mechanisms discovered on the BOLT geometry over the years are summarized in Fig. 4. The image is from a computational simulation of BOLT-1B at flight conditions in Johnston et al. [34], with surface contours of heat flux and spanwise slices of streamwise velocity component to highlight flow structures. The geometry induces an extremely complex laminar flow field, as intended for the purpose of the research.

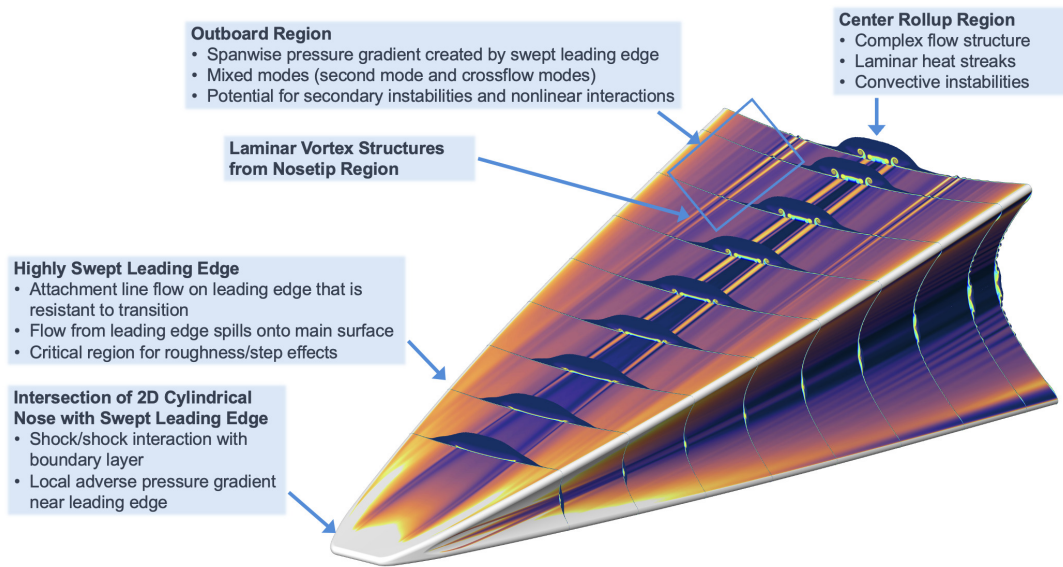


Fig. 4 Dominant features of the BOLT laminar flow field.

One of the most surprising initial outcomes of the BOLT research was the discovery of a flow field dominated by streamwise vortex structures. Within the first months of preflight research in preparation for the BOLT-1A flight, direct numerical simulations and quiet-tunnel experiments began observing these streak structures. The streaks were primarily seen in two regions: (1) a center rollup region, where flow structures roll up into vortices due to the spanwise pressure gradient driving the flow together here, and (2) within an outboard region where smaller and more numerous streak structures are seen in test and simulations. Transition fronts were initially observed in conventional facilities, showing that independent boundary-layer transition mechanisms were likely occurring within each region [35, 36]. The near-centerline vortex structure was found to contain convective instabilities while the outboard region contains nonlinear interactions of crossflow and second-mode type instabilities [7, 8]. These vortex structures were found to be potentially enhanced or altered by surface roughness [37] or steps [38, 39], and were shown to move with angle of attack and sideslip angle [5]. The abrupt nosetip curvature change from the two-dimensional cylindrical nosetip to

the swept leading edge introduces vorticity, causing the vortex structures to be inherent features of the laminar mean flow [40]. Knowledge of these streak structures informed significant decisions on flight instrumentation for the BOLT flights (Fig. 5), requiring analysis to precisely place sensors in regions of interest, and analysis proving that flight instrumentation could resolve the transient movement of these structures during flight.

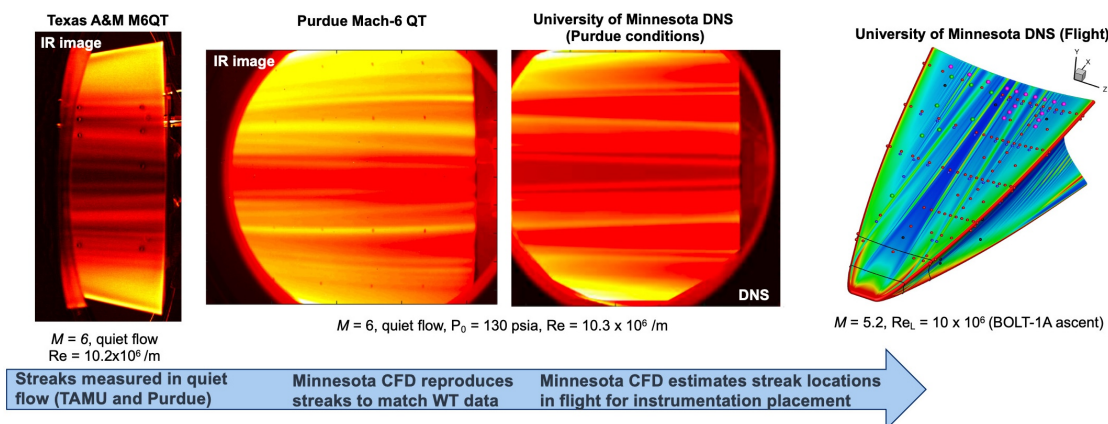


Fig. 5 Discovery of laminar streak structures and combined quiet-tunnel and computational approach to flight instrumentation for BOLT-1A.

B. Ground Testing

The BOLT experiments involved an extensive series of wind-tunnel test campaigns to gather data that would inform instrumentation suites on the flight articles and other associated tests to better understand the transition behavior in different facilities (Fig. 6). Some of the test facilities included the Purdue and Texas A&M Mach-6 quiet tunnels, the NASA Langley 20-Inch Mach-6 tunnel, the Texas A&M Actively Controlled Expansion (ACE) tunnel, CUBRC's LENS II facility, the Mach-6 Ludwig Tube at the U.S. Air Force Academy, and at the University of Queensland's T4 free-piston driven shock tunnel and X3R expansion tube. The major preflight testing was followed by additional testing performed by other researchers at the Hypersonic Test Section (H2K) at DLR in Cologne [41], the R2Ch blow-down facility at the French Aerospace Lab (ONERA) with the French Alternative Energies and Atomic Energy Commission (CEA), the AFRL Mach-6 Ludwig Tube, and additional testing performed by RTX Inc. on geometric excursions from the BOLT geometry [42]. The authors believe that the BOLT program has collectively produced the most extensive set of published ground test results of hypersonic transition and turbulence on a non-conical body.

When considering some of the lessons learned from the HIFiRE program, Kimmel et al. [43] recommended that "ideally in a hypersonic boundary layer transition flight test, the actual flight article would be ground-tested before flight, soft-recovered and post-flight tested" in order to "directly compare wind-tunnel transition to flight, and also to test the flight instrumentation." Ultimately, none of the HIFiRE boundary-layer transition experiments conducted any preflight wind-tunnel testing in the flight article, nor did they recover the payload in a state conducive to any postflight testing. The BOLT-2 flight was, however, able to perform several ground tests of the final flight payload in the CUBRC LENS II facility prior to flight. Most of flight instrumentation responded quickly enough for the short-duration tests, but in an effort to maximize data output global IR imaging was used covering half of the secondary side and one gutter region with a thin vinyl film, following a similar procedure outlined in Ref. [44] for film installation. Quantitative heat-flux measurements are possible, but only qualitative assessments were made for this test campaign. Tripped vs. natural transition transition were observed at the the lowest Reynolds Number condition along with other interesting features observed in other sub-scale tests. The film can be applied directly over flight sensors and easily removed after testing in preparation for flight activities. Though a limited number of runs, these tests are the first known time that a full-scale hypersonic flight test article has been tested in a wind tunnel before flight [14]. The as-flown BOLT-2 trajectory was at a higher Mach number than anticipated, and thus the preflight test points (based on the nominal trajectory) did not precisely match the flown conditions. Soft recovery of any of the BOLT flights was not attempted so the flight hardware is not available for any postflight wind-tunnel testing, however the authors believe that new tests at conditions more closely matching the flown flight conditions should be pursued in the future.

The other preflight ground tests were critical to better understanding transition behavior and confirming results from

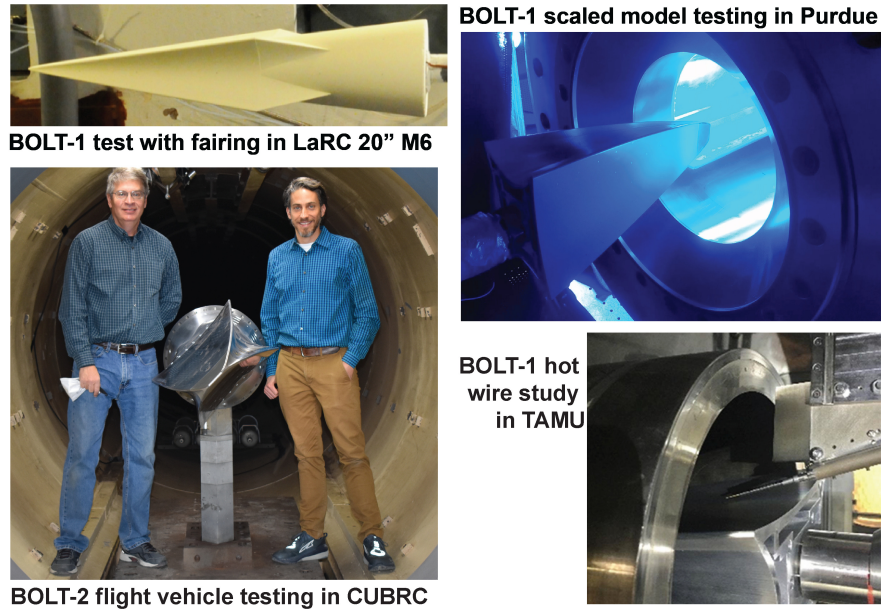


Fig. 6 Several subscale models of the BOLT geometry tested over the years, as well as the actual BOLT-2 flight article in CUBRC LENS II.

supporting computations, directly informing placement of instrumentation on the flight articles. For example, surface pressure fluctuations were measured in quiet flow underneath the near-centerline vortex structure at both Purdue [5] and Texas A&M [6]. A further effort compared detailed off-body hot-wire anemometry measurements (in Ref. [6]) to computations at the University of Minnesota. [8, 40], reproducing the mode shape and frequency of this disturbance. Minnesota Direct Numerical Simulation (DNS) with forcing, conducted at expected flight conditions, confirmed that the PCB132B sensors near the center region were placed in the optimal location to potentially measure instabilities in flight. Sensors in this region were maintained for BOLT-2 and BOLT-1B, ultimately confirming the presence of a convective instabilities in flight [19, 32, 34].

The availability of tests in two quiet tunnels (Purdue and Texas A&M) were extremely valuable to planning flight instrumentation for BOLT. As mentioned earlier, the flow was dominated by streak structures primarily only seen in quiet flow conditions. Aside from the aforementioned quiet-flow measurements of the centerline vortex instability, tests under quiet flow also characterized the expected movement of the BOLT laminar vortex structures with angle of attack and sideslip angle. In fact, results of streak movement in McKiernan et al. [5] would later inspire the use of sideslip angle in flight to reconstruct laminar heating on BOLT-1B [32]. Quiet-tunnel tests were also used to explore joint step effects, resulting in some usable correlations for sizing appropriate step heights on the flight articles [3]. Recently, natural (smooth-wall) boundary-layer transition was observed under quiet flow on the BOLT geometry for the first time in the Purdue Mach-6 Quiet Tunnel [45]. The new quiet flow measurements showed that transition Reynolds numbers under quiet flow ($Re_x \approx 4 \times 10^6$ to 5×10^6) was closer to the flight-observed transition number of BOLT-2 ($Re_x \approx 5 \times 10^6$) than typical transition Reynolds numbers at conventional noise facilities ($Re_x \approx 0.5 \times 10^6$ to 2.5×10^6).

The BOLT program also utilized ground testing to guide engineering decisions, such as transition and heating on the swept leading edge, and heating on the payload transition sections with “fairings” behind the forebody [4]. In general, the breadth of available ground testing data confirmed many of the computational predictions and guided understanding of likely transition behavior in flight. The wide available database at multiple facilities also allows for calibration of effects such as tunnel noise, enthalpy, and wall temperature ratio to compare to the eventual flight experiment results.

C. Computational Fluid Dynamics

The BOLT geometry provided the basic research community with the challenge of assessing predictive capabilities for hypersonic transition and turbulence on a complex new geometry. In particular, the geometry was meant to stress the existing computational analysis capabilities. BOLT provided the community with opportunities to advance understanding and modeling through collaborative linkages across modeling, ground testing, and flight experimentation.

The program afforded new opportunities to evaluate the assumptions of (and results from) boundary-layer stability techniques on the complex flow field. At Texas A&M, application of stability techniques in the EPIC code on the BOLT geometry ranged from Linear Stability Theory (LST), LPSE/NPSE analysis, Spatial BiGlobal, and PSE-3D analysis [7]. APL also performed stability analysis in the BOLT-1A preflight phase using the NASA Langley Stability and Transition Analysis Code (LASTRAC) [46]. Additional stability calculations on common ground test cases were compared as part of a NATO working group [41]. At NASA Langley, a number of new computational results have been generated on the BOLT geometry for a wide variety of ground and flight cases with stability analysis methods, including study of streak instabilities and effects of roughness [47–50].

At the University of Minnesota, the BOLT geometry was used as a testbed to advance several new numerical techniques towards the ultimate goal of routine, large-scale time-resolved computations of hypersonic flight vehicles. Among these advancements were new methods for carefully controlling numerical dissipation to reduce solution noise and increase accuracy, described as “quiet DNS” in Knutson et al. [8]. Figure 7 demonstrates the ability of these numerical techniques to better resolve the important laminar flow structures on the BOLT geometry, which are dissipated when using coarser grids with typical 2nd-order dissipation schemes in typical/standard CFD. The numerical simulations identified the domination of the BOLT flowfield by streamwise vortex structures, predicted by high-fidelity CFD with quiet DNS, measured under quiet flow conditions on subscale wind-tunnel models, and confirmed by data from both the BOLT-2 and BOLT-1B flight. The quiet DNS methodology, when combined with stochastic forcing of disturbances, was used to predict complex boundary-layer instability predictions that directly informed placement of BOLT-1A flight instrumentation and was successfully compared to off-body measurements at wind-tunnel conditions [51, 52].

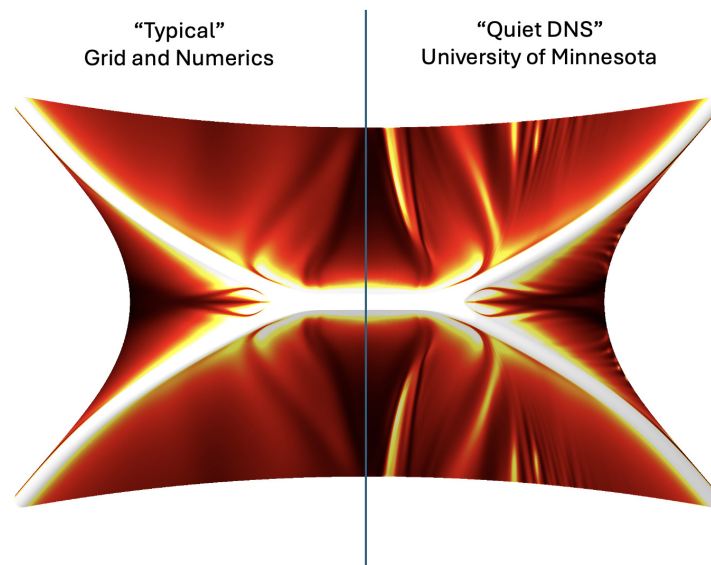


Fig. 7 Comparison of a typical standard 2nd-order heat flux solution, compared to low-dissipation numerics and higher-order fluxes necessary to resolve laminar vortex structures on BOLT.

The BOLT geometry was used to advance prediction of instabilities via the Input/Output analysis technique [53]. Advanced numerical techniques have also been applied in an attempt to better understand step-height effects on transition on the BOLT geometry [39] and advancing toward the goal of demonstrating a resolved laminar mean flow at flight-relevant Reynolds numbers [34, 54].

The BOLT flight experiments motivated significant improvements in CFD methods for complex-geometry hypersonic flows, and helped mature the use of direct numerical simulations (DNSs) for the analysis of multi-modal transition mechanisms. BOLT also further demonstrated the value of high-order, low-dissipation flux schemes and time-accurate implicit time-integration methods. An accurate DNS can be used to quantify the response of the flow field to physical noise (turbulence, particulates and roughness) and to predict instability growth and transition to turbulence.

Most importantly, BOLT showed that obtaining a grid-converged laminar CFD solution is a significant challenge. This is due to the steady-state streamwise vortices and other boundary layer distortion effects present in the BOLT flow field. As the Reynolds number approaches flight transitional conditions, the range of length scales increases, further

increasing the resolution requirements. For example, recent simulations of the BOLT-2 transitional flight data are using a 1.4 billion element grid to resolve the steady-state boundary layer features [54]. A much larger grid would be required if a conventional second-order upwind method was used.

The extreme resolution requirements for steady-state laminar solutions has implications for linear stability analysis methods. In order to obtain an accurate mean flow for stability analysis, a DNS-level grid is required. Furthermore, the stability analysis approach must scale to large, multi-dimensional problems in order to represent the complex transition mechanisms present in the BOLT flow field.

BOLT motivated significant improvements in DNS methods for the prediction of instability growth and transition to turbulence for complex-geometry hypersonic flows. Accurately simulating instability growth requires very low levels of spatial and temporal dissipation and phase error. In addition, all sources of numerical noise must be eliminated. For example, high-frequency noise can be generated by grid imperfections and flickering of shock sensors and limiters. Dissipation must be added only where needed so that physical flow instabilities are not damped, while controlling numerical instabilities.

Over the course of the BOLT programs, the approach for performing reliable, low-noise DNS was improved. The lessons learned include:

- 1) The grid must be generated with a minimum number of singularities, and they must be located so that they do not corrupt the flow in regions of interest.
- 2) The grid must be carefully shock-aligned, and the grid should be orthogonal to the bow shock wave to minimize shock-capturing error.
- 3) The dissipative and phase error depends on the numerical flux scheme and the time-integration method. The modified wave number properties of the numerical method should be optimized to enable accurate large-scale simulations. The temporal error is not important for steady-state simulations, but it is critical for unsteady forced DNS.
- 4) The means of controlling dissipation at shock waves is critical, and it is necessary to tune the shock sensor to minimize error and prevent numerical noise.
- 5) Multiple levels of grid refinements are required to optimize the grid and establish grid convergence. This is a tedious process, but is required for reliable results.
- 6) Unsteady or forcing of the DNS to initiate instability growth may be done inside the shock layer or in the free-stream. However, with free-stream forcing, free-stream forcing may activate numerical instabilities at the shock which can corrupt the simulation. Shock-fitting is known to greatly improve this problem, but it has not been demonstrated on complex geometries such as BOLT.

At this time, performing an accurate low-noise DNS remains a challenge, and requires significant human time and compute cycles. Most of the difficulty is associated with the generation of large high-quality shock-aligned grids. Currently this requires significant effort, especially for flight Reynolds number conditions. Improved numerical methods that are less sensitive to grid imperfections could significantly reduce the difficulty of these simulations.

Figure 8 illustrates the importance of grid resolution and grid design on the predicted laminar steady-state flow field. The surface heat flux at a BOLT-2 flight condition is computed on three grids – on the left is a 680 million element grid with 11 grid singularities near the nose, in the center is a 173 million element grid with one singularity located away from the nose, and on the right is a 1.4 billion element grid with one singularity. These results correspond to a flight Reynolds number of 8.1 million, which is just prior to transition onset. Note that the singularities on the nose cause noise which initiates transition on the centerline (left). Removing the nose-region grid singularities eliminates this spurious effect, but insufficient resolution initiates transition in the outboard vortices (center). There is also early transition on the leading edge for this case. Finally, the large one-singularity grid produces a fully laminar flow with early transitional flow at the trailing edge. See Ref. [54] for additional details.

D. Progress in Flight Experimentation for Hypersonic Aerothermodynamics

Over the course of three flights, the BOLT program made advancements in flight test development and data analysis methods used for scientific flight experiments focused on aerothermodynamics. A review of historical flight measurements of hypersonic boundary-layer transition (BLT) was presented in a 1999 review article by Schneider [55] identifying typical limitations inherent to flight testing. The investigators of the BOLT flights ensured that these limitations were addressed wherever possible. The BOLT flights leveraged expertise and flight systems developed under the U.S./Australia Hypersonic Flight Research and Experimentation (HIFiRE) program, which developed “an affordable, accessible, prototype, experimentation strategy to acquire high quality hypersonic data in a relevant flight

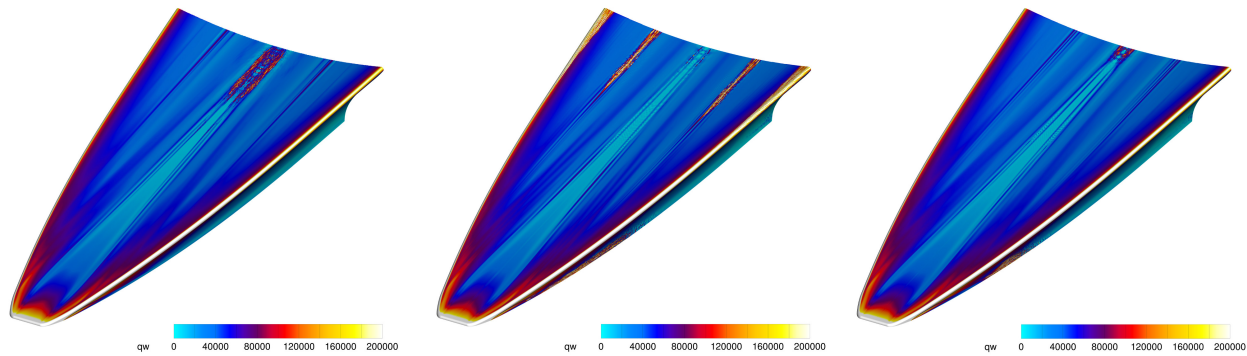


Fig. 8 Laminar heat flux on BOLT-2 at conditions just prior to flight transition using a 680 million element grid with 11 grid singularities near the nose (left), 173 million element grid with one singularity (center) and 1.4 billion element grid with one singularity (right). Note premature transition due to singularities and insufficient resolution. From Ref. [54].

environment” [29]. Three of the HIFiRE flights were specifically focused on boundary-layer transition measurements, and the lessons learned from the development of these flights [43] were leveraged and adapted for the complex BOLT geometry. Berry et al. [56] also provided recommendations for flight BLT testing that were leveraged in the development of the BOLT effort. These suggestions included testing in multiple facilities, selecting a geometry that promoted multiple instability modes, utilizing sounding rockets to keep costs low, using both qualified and newer instrumentation to improve the state of the art, careful consideration of the vehicle surface condition before flight, redundant capability for monitoring of flight conditions and attitude, and sufficient funding to allow adequate postflight analysis. Collectively, the BOLT flights adhered to these recommendations allowing a prolonged, multi-flight test campaign.

E. Thermal and Structural Design

On previous HIFiRE flights much of the preflight thermal modeling had been performed with a fully-turbulent flow assumption during the entire trajectory (along with an additional factor of safety on the heating). Early in the BOLT-1A design phase, test data at CUBRC showed that the swept leading edge of the BOLT geometry remains laminar even at high Reynolds numbers [35]. The BOLT-1A design did not close with the fully turbulent assumption [2]. Flight data from both BOLT-2 and BOLT-1B confirmed the predominance of laminar flow on the swept leading edges, with transition Reynolds numbers of $12.5\text{--}15.0 \times 10^6$ for BOLT-2 [19] and around $14\text{--}15 \times 10^6$ for BOLT-1B (in each case, about double the transition Reynolds number compared to the main surface).

There were major lessons learned in the preflight selection of materials for the BOLT flights and in the overall structural design of the experiments. Each experiment ended up with a slightly different set of materials used for the design of the forebody (Fig. 9), and lessons learned from each flight were carried forward and incorporated into following designs. The flights operated in a regime where metallic materials were available, but where the necessity for nosetip oxidation barrier coatings was questionable. Ultimately, the BOLT-1A/B flights utilized coatings on the nosetip. Due to the lower Mach number of BOLT-2, an uncoated nickel tip was used. Preflight correlation-based heating codes were found to perform poorly in predicting heating on the highly-swept leading edges requiring viscous CFD predictions to be used instead. The program spent extended time analyzing behavior of loaded joint interfaces under transient thermal loads, particularly in the selection of aim points for preflight bolt torque values. An impactful material decision starting with the BOLT-2 flight was a switch of the frustum material to 410 stainless steel, whose thermal properties were well matched to the Type E thermocouples, and this decision was made possible by a larger mass budget for the payload. Ultimately, the 410 stainless steel produced temperature response measurements of exceptional quality on BOLT-2 via increasing the signal difference between the front and back face measurements of the Medtherms, and this material was utilized for the BOLT-1B flight as well.

By performing detailed postflight thermal and structural modeling, using the actual flown trajectory, the effect of over-conservatism in preflight design has been demonstrated in the BOLT program. On BOLT-2, the inclusion of accurate transition behavior and removal of the safety factor reduced modeled temperatures significantly (from a peak frustum temperature of more than 650 K in the preflight modeling, to 475 K in the measured BOLT-2 data) [2]. It was also found on both flights that the nosetip region remains laminar for most of the entire flight, a significant reduction in

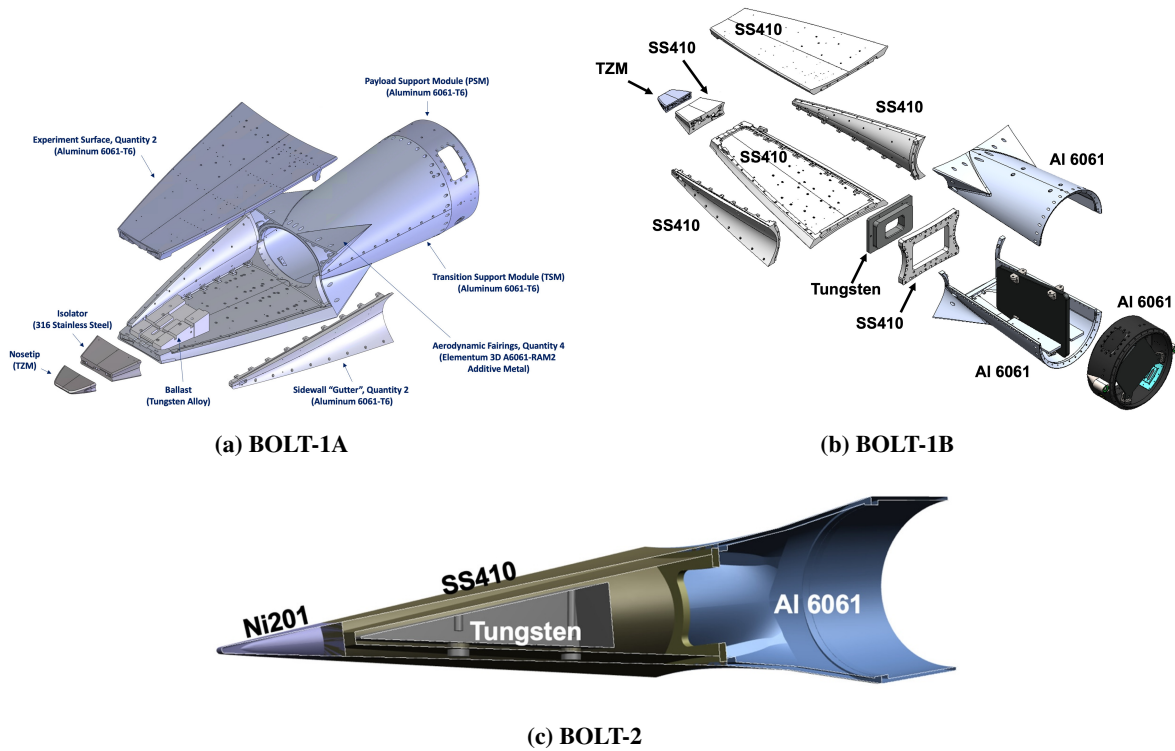


Fig. 9 Structural components of each BOLT flight experiment design.

heating from the conservative preflight models. This lower-than-anticipated flight heating reduces expected temperatures considerably, and reduces the expected differential thermal expansion of the joint interface (almost 50% lower thermal expansion realized on the BOLT-2 joint interface). In retrospect, for the actual nosetip temperatures of the BOLT-1B flight, it may have been possible to forgo the expensive nosetip oxidation barrier coating. The BOLT flights provided specific examples of over-conservatism in thermal modeling by marrying high quality flight data with detailed postflight thermal modeling.

F. Influence of Joint Steps on Boundary-Layer Transition

The design of hardware that survives in the hypersonic flight regime necessarily involves the use of different materials in regions of the vehicle that experience high heating (such as the nosetip). Different coefficients of thermal expansion at material interfaces thus create the risk that steps will occur at these interfaces during the flight experiment and alter the mean flow or promote transition. In the HIFiRE-1 and HIFiRE-5 flights, the nosetips of the flight experiment were machined with a rear-facing step to attempt to account for expected differential thermal expansion in flight [43]. The hope was that by the time the vehicle reached the boundary-layer transition experiment window, the nosetip would expand to a nearly smooth-wall condition at the interface.

The complexity of the BOLT geometry made the design and fabrication of joint interfaces, which would minimize risk of unintended step effects, a challenging issue for all three flights. Because the BOLT geometry is highly three-dimensional, the differential thermal expansion of the nosetip is nonuniform about the azimuth. The risk of unintended joint step effects was identified early in the BOLT-1A design phase, motivating a new set of wind-tunnel experiments to attempt to quantify allowable step tolerances on the BOLT geometry [5, 38] and the selection of intentionally added rear-facing joint steps as the main focus of the BOLT-1 “Side B” roughness experiment [3]. Preflight research identified the swept leading edge itself as the most critical part of the BOLT geometry for risk of unintended step effects, as this region has the thinnest boundary layer. Preflight quiet tunnel experiments and associated computations discovered that the location of the onset of transition due to leading-edge joint steps could be traced along a streamline defined with boundary-layer edge velocities [5]. This discovery would later aid in placement of specific instrumentation to observe step-induced transition [3], as well as the interpretation of flight results [33].

Preflight transient thermal/structural analysis for all three flights attempted to predict the expected differential thermal expansion of the nosetip joints [2, 57] but uncertainty in the ultimate flight trajectory, laminar/turbulent flow state, material properties, and achievable manufacturing tolerances typically required conservatism in selecting the desired preflight joint step. In most cases, the preflight step was selected to provide a bias towards rear-facing steps in flight (avoiding forward steps at all cost, which were thought to be more likely to promote early transition). The challenges were compounded on both BOLT-1A and BOLT-1B which utilized oxidation-resistant coatings that created additional nonuniformity in the nosetip outer mold line to account for when manufacturing the parts for desired preflight steps [58]. Inspecting and characterizing the preflight steps was also a challenge due to the small magnitude of the steps (on the order of thousandths of an inch) and the complexity of the geometry. The BOLT team found that existing transition correlations of roughness parameters all had poor scaling from ground to flight making prediction of joint-induced transition an unknown [3].

Despite the challenges, the BOLT flights spent extensive effort and made considerable progress on developing methods to analyze joint step growth to manufacture and inspect the flight article joint steps. The program advanced the regular use and analysis of Struers Repliset-T3 mold material to quantify joint steps on subscale wind tunnel models [38] as well as the flight articles. Postflight thermal and structural analysis for BOLT-2 [57] and BOLT-1B [59] sought to reduce modeling uncertainties and produce estimated joint step magnitudes throughout flight. On BOLT-1B, the use of in-depth thermocouples within either side of the joint interfaces was used to anchor postflight modeling and results show good postflight modeling comparisons to these data. Combining the preflight measurements of joint steps with a rigorous postflight thermal/structural analysis is critical to produce these estimated step magnitudes throughout flight to aid in interpretation of the resulting flight transition data.

An even better approach would be some method of in-situ optical measurement of the step during flight. There was an attempt to develop an in-situ optical step height measurement capability to be used during the BOLT flights to monitor and record the changing step dimensions during flight [60]. The desire was an ability to observe during flight the changing step heights along the nose joints to an accuracy of greater than $10\mu\text{m}$. Development of this capability for use on BOLT was slowed for various reasons but continues in hopes of providing this capability for a future flight project. Downselect of various optical approaches based on bench testing to provide the desired visual resolution has been completed. Thermal and vibration testing of a representative flight ready design is scheduled to be completed soon. For any future application, the approach adopted thus far would likely have to be adjusted to suit any new hardware application requirements.

The influence of joint step effects on the resulting flight transition data is difficult to fully quantify and should be a topic of continued study in the future. Both BOLT-2 and BOLT-1B report the expected preflight step heights at the nosetip joints as well as analysis of expected growth during the flight [22, 33, 58, 59, 61]. Any small step is likely to have some effect on the flow, but determining whether that effect was significant enough to induce vastly different transition behavior than a nominal “smooth” geometry is challenging. It is particularly challenging to assess step impacts, when the vehicle angle of attack and sideslip angles continuously oscillate during the flights.

BOLT-2 was not focused on steps as part of the roughness experiment. Instead, the desire was to investigate discrete trips on the main roughness surface. The forebody experiment had been redesigned after BOLT-1A to only have a single joint. The manufacturing was also changed by machining the nosetip together with the frustum to minimize likelihood of preflight steps, with a corresponding material change such that any thermal growth of the joint-step would result in a rear-facing step. A small misalignment of the nosetip on BOLT-2 did result in noted preflight steps (as shown in Fig. 10). Refs. [13, 19] note that some likely step effects were seen in the transition data on Side A of BOLT-2. The joint steps were photographed prior to flight and fully characterized in Ref. [61]. A specific joint location nomenclature was used for BOLT-2 and is defined in Ref. [62]. The largest rear facing step, shown in Fig. 10, was found to be in quadrant 4 (Side A) at location C with a measured cold-wall step of 0.0025 in. The postflight assessment of the thermal growth predicted a flush step would become a rear-facing step of approximately 0.0024 in. by the end of flight. Combining those two results, meant that Side A, quadrant 4, location C would have been on the order of 0.0039 in. by end of ascent and 0.0049 in. by the end of flight. These are seemingly small step heights, however this location represents the largest step on the forebody of BOLT-2 in the precise location that experienced early transition onset. This would suggest that even small rear-facing steps can be a factor for transition enhancement.

The equivalent photo for the largest Side A step on BOLT-1B is captured in Fig. 11a, which shows a 0.0058-in. rear-facing step on the upstream joint leading edge (defined as location 4 in Ref. [58]). This step is predicted to shrink to 0.0040 in. by end of flight. The location 3 step at the intersection of the leading edge and main experiment surface was 0.0039 in. and was predicted to shrink to 0.0035 in. Note that the zoom factor between these the photos of Figs. 10 and Fig. 11a are different. The inference here is that the smooth side on both flights may have been influenced by step

effects. Similar transition Reynolds numbers were reported on each symmetric quadrant of Side A of BOLT-1B during both ascent and descent [32], despite an expected difference in step heights between those two phases of flight [59]. This observation highlights the need for additional study to ascertain whether the step effects were either (1) equally present during ascent and descent, or (2) not present or influential on the transition behavior. With the focus of the roughness experiment of BOLT-1B being that of intentionally-added step effects, the corresponding Side B step was as much as four times bigger, as shown in Fig. 11b, for a rear-facing step of 0.0229 in. at location 3 that was predicted to shrink to 0.0225 in. by end of flight. The step height at location 4 was 0.0159 in. predicted to shrink to 0.0141 in.

One cannot assume the effects of joint steps are negligible in any flight transition experiment. While the BOLT flights provided useful new data on joint-step-induced transition, much more work is needed to understand the influence of steps during these flights, and to produce informed design tolerances of allowable joint step magnitudes to avoid premature transition on hypersonic vehicles.

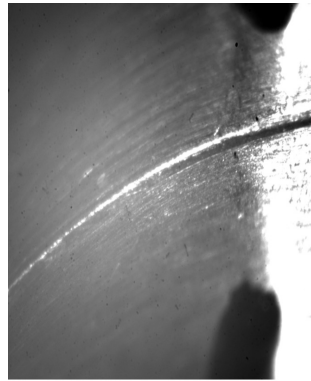
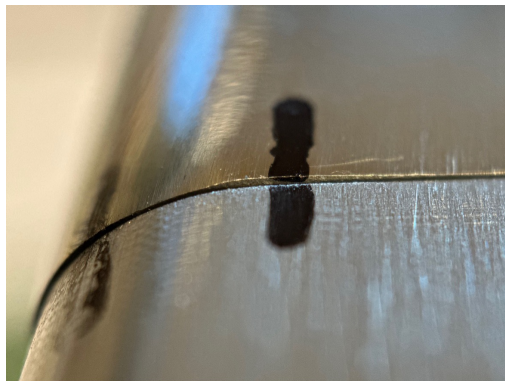


Fig. 10 Photo of rear-facing step on BOLT-2 at location C of quadrant 4 [62].



(a) Side A: location 3 and 4 of quadrant A



(b) Side B: location 3 and 4 of quadrant C

Fig. 11 Photos of preflight rear-facing steps on BOLT-1B leading edges (upstream joint interface).

G. Flight Instrumentation

The BOLT flights primarily leveraged flight article instrumentation previously demonstrated within the HIFiRE program, and used custom data acquisition flight computers developed under that program by the Australian Defence Science and Technology (DST) group [30], which very kindly made them available for the BOLT flights. However, the BOLT flights also demonstrated flight suitability for novel instrumentation.

The BOLT flights were the first U.S. efforts to use PCB Piezotronics 132B pressure sensors to acquire high-frequency surface measurements of pressure, following the first use by the DLR ROTEX-T experiment [31]. The BOLT flights leveraged development of PCB132B sensor heat sink designs and custom data acquisition systems developed by GoHypersonic Inc. (GHI) originally for the HIFLIER flight experiment [63]. Because of delays to the HIFLIER flight,

the GHI systems first flew on the BOLT-1A flight with a capability for onboard storage and onboard processing of low-bandwidth FFT's for the telemetry data. A modified variant of the GHI system to send off a continuous limited set of the highest amplitude FFT components flew on the BOLT-2 flight [19]. BOLT-1B used the HIFLIER variant again. Both BOLT-2 and BOLT-1B measured apparent frequency content in the telemetered FFT's.

The BOLT-1A and BOLT-2 flight developments were heavily affected by the COVID-19 global pandemic and the resulting worldwide supply chain issues. For BOLT-2, the availability and lead times of some instrumentation ultimately affected the specific flight instrumentation choices. BOLT-1B was unable to source the Vatel HFM heat flux sensors originally flown on BOLT-1A. A push towards a greater quantity of sensors on each flight to enhance scientific outcomes also highlighted challenges in limited supply chain for many of these instruments.

On BOLT-2, the team flew with a unique combination of Ahmic Aerospace skin friction sensors, Medtherm thermocouples, Vatel thermogauge heat flux sensors, and pressure gradient sensors that allowed for assessment of modeling approximations such as the Reynolds analogy [20]. BOLT-2 also flew with thin-film heat flux sensors developed by CUBRC for the first time in a flight experiment. The thin-film sensors were previously used by CUBRC extensively in wind-tunnel test articles. A key finding from the BOLT-2 experiments was that the Medtherm sensors performed very well with the stainless steel frustum. Moreover, the spanwise density of sensors was chosen to enable a 2-D conjugate heat transfer analysis to be performed from the data to reconstruct the thermal gradients within the frustum. This step was important for improved accuracy in the heat flux measurement near outer edges of the geometry.

BOLT-1B leveraged instrumentation successes from the prior BOLT-2 flight in consideration of updates to its sensor layout. The switch to stainless steel for the BOLT-2 aeroshell material enhanced the ability of a single surface Medtherm thermocouple channel to provide rapid-response estimated heat flux. This allowed the team to justify adding a significant number of new Medtherm locations for BOLT-1B, including dense spanwise arrays of sensors. These sensors were ultimately able to reproduce laminar spanwise heating during the BOLT-1B flight, correlate movement of laminar vortices over the array, and pinpoint the precise onset location of transition [32].

H. Wall Temperature Distribution

Schneider's flight data review article [55] describes a major limitation of flight data being the "wall temperature distribution is rarely known in great detail". To improve the quality of the BOLT flight validation data, postflight modeling efforts have sought to accurately characterize the wall temperature distribution at transition onset conditions. Postflight modeling of the BOLT-2 flight [57, 64] was completed and wall temperature estimates produced good agreement with measured surface temperatures at transition onset during the descent phase. It was found in postflight BOLT-2 work that accurately modeling transition behavior is critical to matching the flight temperatures [57]. An effort was undertaken following the BOLT-1B flight to further improve the treatment of transition spatially on the body in the transient thermal analysis to match the flight data. Figure 12 shows an example of reconstructed temperature distribution for the BOLT-1B flight at a flight time of 26.8 s (coinciding with the end of turbulent flow during the ascent). The surface contour in the figure is the simulated temperatures while the colored dots represent actual measured temperatures from the flight. From both the BOLT-2 and BOLT-1B flights there are wall temperature distributions available for future study of the effect of wall temperature on boundary-layer transition during these flights.

I. Aerodynamics and Flight Dynamics

Although not originally a research focus of the first BOLT flight (BOLT-1A), the BOLT program produced major lessons learned related to aerodynamics and flight dynamics, particularly surrounding the flight of asymmetric forebodies on unguided sounding rockets. The BOLT geometry is asymmetric and has different aerodynamic properties in the pitch and yaw planes. While previous HIFiRE program flights involved the use of asymmetric forebodies, such as HIFiRE-5 [30], the BOLT-1A flight vehicle was significantly more asymmetric (when comparing the ratio of pitching moment and yawing moment derivatives). Postflight modeling after the BOLT-1A flight showed that this asymmetry (along with aeroelastic effects) enhanced the susceptibility of the vehicle to enter pitch-roll coupling [17, 18]. The mitigation employed successfully for both BOLT-2 and BOLT-1B was to set fin cant to low values to produce near-zero roll rate and delay the crossing of the pitch/yaw critical frequencies [23].

A detailed preflight BOLT-2 flight stability analysis was performed that impacted flight test design decisions. In the pitch plane of the vehicle, the BOLT geometry induces significant lift, which results in lower than typical static margin. For BOLT-2, the need to obtain a minimum static margin requirement for flight impacted the materials choice from a ballast perspective, the test article length, and elimination of recovery of the payload. A key lesson was the importance of sounding rocketry flight experience from NASA Wallops and payload integration from the Air Force Research

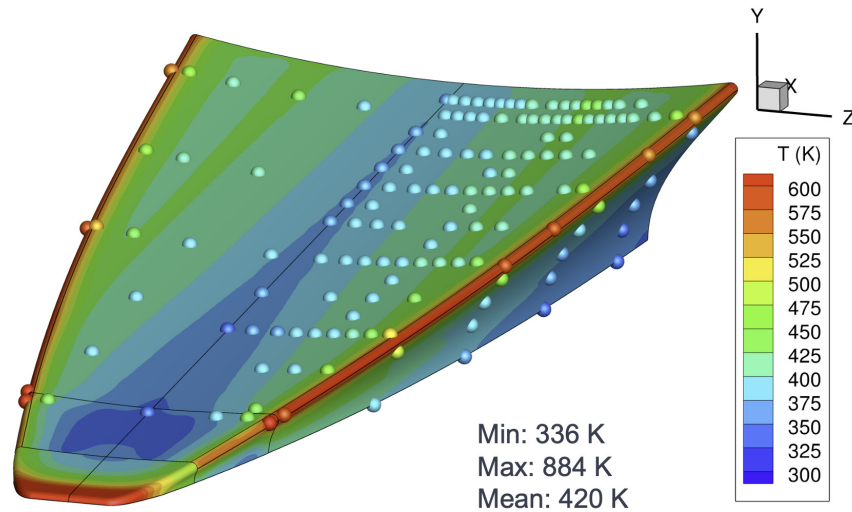


Fig. 12 Postflight reconstruction of the BOLT-1B estimated wall temperature distribution at 26.8 s flight time. The dots represent measured surface temperatures.

Laboratory, which enabled flight stability, payload instrumentation, flight computer integration, payload integration with the rocket stack, and the successful flight. A key advantage of the BOLT program was the unique experiences provided to the student performers by integrating them within this process.

A major lesson learned from the BOLT-1A anomaly and subsequent flight stability work was that sounding rockets with significant asymmetry need to incorporate six degree of freedom (6DOF) modeling with Monte Carlo terms that perturb the trim angle of attack and represent key uncertainties in aerodynamic properties. The BOLT-1B preflight CFD analysis showed that even launch lugs, typically employed only on one side of a sounding rocket vehicle, can be a significant source of causing a vehicle to trim at nonzero angle of attack.

Another lesson learned was that static margin alone is not a sole predictor of flight stability for spinning, asymmetric sounding rockets. The preflight analysis of the BOLT-1B vehicle showed that even a vehicle with significantly high static margin can still be susceptible to dynamic instability as a result of asymmetry, if the spin rate becomes too high during pitch/yaw resonance crossings. Including aeroelastic effects on the vehicle aerodynamics was necessary for BOLT-1B to properly model the reduction in pitch/yaw critical frequencies and the robustness of the vehicle to dynamic instability. The details of these findings are described in Refs. [65, 66].

J. Atmospheric Characterization

Improving the characterization of atmospheric conditions during flight experiments enhances interpretation of the resulting flight data, as the uncertainty in critical boundary conditions can be reduced. For aerothermal measurements, these critical parameters include but are not limited to the freestream Mach and Reynolds number. Accurate postflight reconstruction of winds can improve estimates of the vehicle angle of attack as well. Recent research by an AFOSR Multidisciplinary Research Program of the University Research Initiative (MURI) project, HyFLITS, sought to improve knowledge of the turbulence and particulates within the atmosphere. The BOLT-1A and BOLT-2 flights occurred concurrently with the HyFLITS project, and the HyFLITS team supported both campaigns using custom instrumentation to attempt accompanying real-time turbulence and particulate measurements [67]. The team was able to gather data from 9 to 29 km and had 14 successful launches over the launch campaign window for BOLT-2. The balloons got within 20 km of the flight trajectory for altitudes higher than 20 km. They measured turbulent-kinetic-energy dissipation rates and particulate concentrations in the 0.35 to 1.0 μm size. The BOLT-2 flight was also used as an opportunity to demonstrate the Honeywell HALAS system (High Altitude LiDAR Atmospheric Sensing) as an additional source of atmospheric measurements [68]. By including atmospheric physics in the BOLT efforts, this inspired the University of Minnesota to advance methods for simulation of particulates of varying sizes interacting with a hypersonic shape to observe the boundary layer response to the disturbances [69]. All three BOLT flights were supported by postflight

atmospheric reconstruction provided by the U.S. Air Force Weather Agency based on measurements from balloon radiosondes and other available data during the countdowns and have endeavored to produce reasonable estimates of the flight freestream conditions. Significant progress has been made in understanding the potential role of the atmosphere on transition, together from the collective efforts of the HyFLITS MURI project as well as the emphasis of the BOLT flights to prioritize atmosphere characterization in tandem with transition measurements. Similar efforts that pair atmospheric scientists with transition experts should continue to be pursued in the future.

K. Maximizing Captured Flight Data

For hypersonic science in the flight environment the acquisition of high resolution, high sampling rate data is desired. However, there is a limit to the amount of data that can be sent in the telemetry. All three BOLT flights flew with PCB132 high-frequency pressure transducers sampling at 2.5 MHz and all three flights (at least initially) attempted to design a recoverable payload that would store some of the data onboard for potential recovery.

For BOLT-1A, the payload was designed to separate after the conclusion of the descent science window and provide recovery of the entire PCB132 dataset stored onboard from the ascent phase. The data system would send post-processed Fourier transforms of the pressure data as a redundancy in the telemetry. However, the BOLT-1A flight instability caused an early descent, and the payload remained attached to the second stage. While the impact crater was located, the payload was too deep to recover.

The BOLT-2 flight initially desired to add a flotation recovery system for water-based recovery. A flotation system would add weight and cost, increasing the length of the payload as well as the complexity of the flight. Ultimately, due to the need to meet flight static margin minimum requirements, the recovery option was not pursued. The knowledge that the payload could not be recovered impacted data acquisition and telemetry decisions for BOLT-2. The team devised a method to recover post-processed PCB data that were reduced to the top 20 Fourier modes on board, downloaded every 9.2 ms. Recovery would have allowed for the entire time series. BOLT-2, however, was able to operate at the maximum data rate allowable at NASA Wallops and had the largest telemetry rate of all three flights.

BOLT-1B flew over water and for similar reasons to BOLT-2, flotation-based recovery was not pursued. The high-rate PCB132 data was not recovered but instead post-processed Fourier transforms were sent in the telemetry.

There still exists a need to routinely recover high-rate science data from hypersonic flight experiments at rates beyond the limit of existing telemetry systems. Ultimately, none of the three BOLT flights were able to demonstrate successful recovery such data from the payloads.

L. Advancement of Education and Workforce Expertise

An initial primary driver of the BOLT program was to offer students a unique opportunity to gain hands-on experience in the development of hypersonic flight experiments. Indeed, students were involved from the onset and given major roles in the preflight research and development of the flight instrumentation suite. Many students led the preflight ground tests for both BOLT-1 and BOLT-2 flights (Figure 13). Several of the BOLT students did a summer internship at APL to assist in the design work for the BOLT-1A flight. For BOLT-2, the aerodynamic database for the vehicle was developed primarily by students. The students were exposed to fast-paced, schedule-driven, results-oriented scientific test campaigns preparing them for future project work in industry. The BOLT program ultimately produced numerous new graduates with significant hands-on experience, graduates who are now productive professionals in the field of hypersonics.

The authors also highlight the additional benefits of flight experimentation for generating experience and cross-disciplinary expertise for early-, mid-, and even late-career professionals. Joining the scientific pursuit of new knowledge with the development of complex experimental hardware for extreme environments necessitates navigating real-world design constraints and effective planning and communication across many technical disciplines. Additionally, international engagements promoted new skills for collaboration with international partners, leveraging their unique capabilities and engineering mindsets across varied time zones. The BOLT program thus provided enhanced project management experience for professional staff and senior professors alike. Cross-disciplinary collaborations were necessary and often unforeseen, arising due to critical challenges faced during the preflight planning or anomalies in the flights. These collaborations connected researchers and program managers with professional aerodynamicists, mechanical designers, machinists, atmospheric scientists, telemetry experts, flight safety analysts, and range personnel (Fig. 14). These interactions, typically uncommon in an academic setting, promoted a more knowledgeable professional workforce and further expanded the community of hypersonic flight testers.

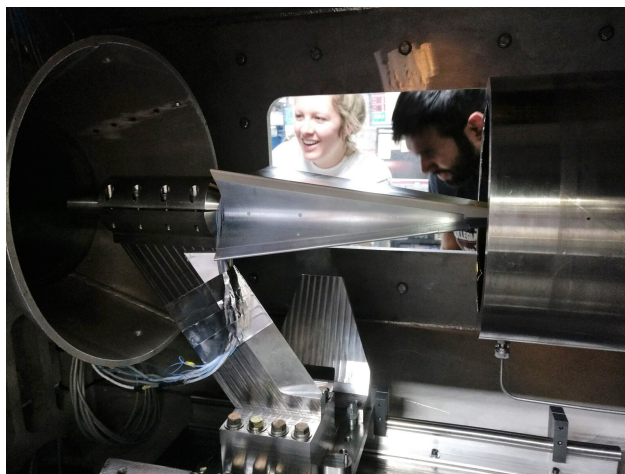


Fig. 13 Graduate students at Texas A&M testing the BOLT-1A wind-tunnel model.



(a) BOLT-1A Preflight Hardware Review



(b) BOLT-2 Team Photo

Fig. 14 Cross-disciplinary teams created new experience for the workforce (students and professionals alike).

IV. Future Work

Major topics addressed in this article include outcomes from wind-tunnel testing of this common geometry in many facilities over the years, key advancements in numerical simulation techniques motivated by the need to model the physics on the complex BOLT geometry, progress in flight experimentation methodologies, the value of combining hypersonic flight test with atmospheric measurements, and the value of programs like BOLT for accelerating student and workforce expertise. Future work should continue to extract knowledge from the collected data from the BOLT experiments, as well as advance scientific flight experimentation methods. This future work includes:

- ***Further Scientific Analysis of the Data.*** It was not a small feat to achieve two high-quality datasets from successful flights under the BOLT program. With the wealth of flight data in hand, there is a unique opportunity for robust postflight simulations and new ground tests. Though initial results from the flight experiments have been published, the authors believe there is much more work to be done. There is a particular need to expand on analysis and modeling of angle of attack and sideslip angle influences on the geometry and understanding how joint steps may have influenced the data. Revisiting the roughness data from the flight Side B experiments in order to compare and update ground-based correlations would be a useful exercise.
- ***Ground Testing at Flight-Matched Conditions.*** None of preflight tests matched flown BOLT conditions. For true comparisons from ground to flight, there is a need to conduct new testing that more closely matches those conditions (simulated or when able, matched in ground facilities). Postflight wind-tunnel testing at as-flown conditions would fill gaps between flight and ground tests that exist now that could be used for improved code validation. Final post-test computations would maximize the impact of these valuable data.
- ***Continue to Pursue New BLT Flight Experiments.*** The BOLT geometry was an evolution of geometric complexity to challenge the basic research community. Two successful flight experiments with this geometry is an achievement, but continued understanding of boundary-layer transition will still require more flight experiments in the future. Future experiments can be a combination of increasing the geometric complexity beyond that of BOLT but also revisiting previous geometries (e.g. conical bodies and HIFiRE-5) as improved diagnostics and flight test experimentation are rapidly advancing. New flight experiments could also be developed specifically for gathering statistical data to support correlation development (and a better understanding of the stochastic nature of hypersonic flow), as this may help balance cost per flight with desired outcomes. Correlation-focused flight experiments would be useful for roughness and step effects, for example. There is a general need for off-body measurements along with in-situ atmospheric characterization in future flights.
- ***Deepen Integration of Atmospheric Measurements.*** Understanding the impact of the freestream environment continues to be critical for improved modeling of transition in flight. There should be a dedicated effort within the transition community to evaluate BOLT-2 and BOLT-1B results alongside available atmospheric measurements, defining requirements to improve future atmospheric measurement capabilities. Future flight experiments focused on transition should prioritize atmospheric measurements of turbulence and particulates into the test design. Furthermore, flights specifically focused on obtaining BLT measurements in tandem with detailed atmospheric characterization should be devised. A number of these flights to begin to assemble a statistically-significant database of measurements and related analysis for understanding of the impact of the freestream atmosphere on transition would be very useful. To move toward this goal, the hypersonics community can continue to engage atmospheric scientists and fund further collaborative research efforts. Capabilities such as those pioneered under the HyFLITS project need to be matured and made permanently available to support flight experiments.
- ***Technologies Enabling Higher Data Rates.*** The BOLT flights demonstrated the scientific value of experiments with a large number of instrumentation locations and increasingly high data sampling rates. Yet, these flights operated with total data rates at the limit of typical telemetry. Technologies that continue to increase the fidelity of flight data, including higher resolution and data rates to support future flight experiments are much needed.
- ***Flight Experiments Focused on Other Disciplines.*** Beyond boundary layer transition and turbulent heating, there are many other engineering-science topics for which flight experiment measurements at relevant conditions are needed to reduce the risk of building new and better hypersonic systems. These topics include (1) effects of weather, (2) aerodynamic control, (3) material performance, and (4) ablation-related effects. A new long-term more encompassing flight program is recommended to enable more sophisticated flights focused on improving knowledge of these phenomena.

V. Final Thoughts

The BOLT flight experiment program (flights 1A, 2, and 1B) successfully advanced the scientific understanding of hypersonic boundary layers for improved prediction. The BOLT program also successfully highlighted the importance of integrating the roles of modeling and simulation, ground test, full system flight mechanics, flight instrumentation, atmospheric measurements, and hands-on student and workforce training. One of the key outcomes of BOLT was the successful integration of academia with applied research institutions, government labs and leaders, industry, and international partners. Unlike other test programs, academia was challenged to be on the critical path for making BOLT since this was a fundamental science flight program. Much remains to be explored with these kinds of carefully designed scientific flight experiments to expose physics in flight that are not fully understood.

Acknowledgments

The BOLT flight experiment program was led by Program Officers at the Air Force Research Laboratory (AFRL) Air Force Office of Scientific Research (AFOSR), including Dr. Ivett Leyva, Dr. Sarah Popkin, Dr. Brett Pokines, and Dr. Amanda Chou. The authors wish to thank the AFRL Aerospace Systems Directorate (AFRL/RQ) for the crucial support of the BOLT flights by providing subject matter expertise and hardware support from David Adamczak. Flight computers were provided by the Australia Defence Science and Technology (DST) group. These flights would not have been possible without this support. The Johns Hopkins Applied Physics Laboratory (APL) was supported by AFRL/AFOSR as the lead for BOLT-1 and a team member for BOLT-2 under award numbers FA9550-17-2-0001, FA9550-20-1-0043, and FA9550-22-1-0357. Texas A&M University and CUBRC were supported by AFRL/AFOSR as the leads for BOLT-2: The Holden Mission and as a team member for BOLT-1 under award numbers FA9550-18-1-0010 and FA9550-19-1-0154, and FA9550-21-1-0105. Additional support to Texas A&M was provided by Lockheed Martin Corporation (Grant S20-003). The University of Minnesota was supported by AFRL/AFOSR under award number FA9550-17-1-0250, with additional BOLT-related research funded by the Office of Naval Research through grant numbers N00014-16-1-2452 and N00014-18-1-2521. Purdue University was supported by AFRL/AFOSR under award numbers FA9550-17-0419 and FA9550-22-1-0110. NASA Langley has been a critical partner to AFRL/AFOSR on the BOLT program as the Principal Investigator for the “Side B” roughness and step experiments on all three flights, and has been supported by the NASA Aeronautics Research Mission Directorate, Advanced Air Vehicle Program, Hypersonic Technology Project. This work was supported in part by high-performance computer time and resources from the Department of Defense (DoD) High Performance Computing Modernization Program. The BOLT program was supported with key contributions from dozens of organizations spanning academia, government, and industry. The authors thank the partners responsible for the flight experiment execution including the German Aerospace Center Mobile Rocket Base (DLR MORABA), NASA Wallops Flight Facility, Swedish Space Corporation (SSC) Esrange Space Center, and Andøya Space. Zach Johnston provided the CFD image in Fig. 4.

References

- [1] Leyva, I. A., and Cummings, R. M., “Introduction to the Special Section on the Boundary Layer Transition (BOLT) Flight Experiment,” *Journal of Spacecraft and Rockets*, Vol. 58, No. 1, 2021, pp. 4–5. doi:10.2514/1.A34872, URL <https://arc.aiaa.org/doi/10.2514/1.A34872>.
- [2] Wheaton, B. M., Berridge, D. C., Wolf, T. D., Araya, D. B., Stevens, R. T., McGrath, B. E., Kemp, B. L., and Adamczak, D. W., “Final Design of the Boundary Layer Transition (BOLT) Flight Experiment,” *Journal of Spacecraft and Rockets*, Vol. 58, No. 1, 2021, pp. 6–17. doi:10.2514/1.A34809, URL <https://arc.aiaa.org/doi/10.2514/1.A34809>.
- [3] Berry, S. A., Wheaton, B. M., and Chynoweth, B. C., “Secondary Side Considerations for Boundary Layer Transition Flight Experiment,” *Journal of Spacecraft and Rockets*, Vol. 58, No. 1, 2021, pp. 18–25. doi:10.2514/1.A34778, URL <https://arc.aiaa.org/doi/10.2514/1.A34778>.
- [4] Rieken, E. F., Berry, S. A., Mason, M. L., and Greene, F. A., “Aerothermodynamic Ground Tests in Support of the Boundary Layer Transition Flight Experiment,” *Journal of Spacecraft and Rockets*, Vol. 58, No. 1, 2021, pp. 38–53. doi:10.2514/1.A34803, URL <https://arc.aiaa.org/doi/10.2514/1.A34803>.
- [5] McKiernan, G. R., Chynoweth, B. C., Schneider, S. P., Berridge, D. C., and Wheaton, B. M., “Boundary Layer Transition Preflight Experiments in a Mach-6 Quiet Tunnel,” *Journal of Spacecraft and Rockets*, Vol. 58, No. 1, 2021, pp. 54–66. doi:10.2514/1.A34772, URL <https://arc.aiaa.org/doi/10.2514/1.A34772>.

- [6] Kostak, H. E., and Bowersox, R. D. W., "Preflight Ground Test Analyses of the Boundary Layer Transition (BOLT) Flight Geometry," *Journal of Spacecraft and Rockets*, Vol. 58, No. 1, 2021, pp. 67–77. doi:10.2514/1.A34858, URL <https://arc.aiaa.org/doi/10.2514/1.A34858>.
- [7] Moyes, A. J., and Reed, H. L., "Preflight Boundary-Layer Stability Analysis of BOLT Geometry," *Journal of Spacecraft and Rockets*, Vol. 58, No. 1, 2021, pp. 78–89. doi:10.2514/1.A34792, URL <https://arc.aiaa.org/doi/10.2514/1.A34792>.
- [8] Knutson, A. L., Thome, J. S., and Candler, G. V., "Numerical Simulation of Instabilities in the Boundary-Layer Transition Experiment Flowfield," *Journal of Spacecraft and Rockets*, Vol. 58, No. 1, 2021, pp. 90–99. doi:10.2514/1.A34599, URL <https://arc.aiaa.org/doi/10.2514/1.A34599>.
- [9] Wheaton, B. M., "The Boundary Layer Transition (BOLT) Flight Experiment," *Johns Hopkins APL Technical Digest (Applied Physics Laboratory)*, Vol. 36, No. 2, 2022, pp. 213–223. URL <https://www.jhuapl.edu/sites/default/files/2024-09/36-02-Wheaton.pdf>.
- [10] Hörschgen-Eggers, M., Kirchhartz, R. M., Jung, W., Schoppmann, K., Ettl, J., and Wittkamp, M., "Boundary Layer Transit Flight Experiment: Mission Overview, Launch Vehicle and Payload Subsystems," *Journal of Spacecraft and Rockets*, Vol. 58, No. 1, 2021, pp. 26–37. doi:10.2514/1.A34877, URL <https://arc.aiaa.org/doi/10.2514/1.A34877>.
- [11] Leyva, I. A., and Popkin, S., "Introduction to the Virtual Collection on the Boundary Layer Turbulence Flight Experiment in Memory of Mike Holden (BOLT II)," *Journal of Spacecraft and Rockets*, Vol. 62, No. 2, 2025, pp. 280–281. doi:10.2514/1.A36401, URL <https://arc.aiaa.org/doi/10.2514/1.A36401>.
- [12] Kostak-Teplicek, H. E., and Bowersox, R. D. W., "Hypersonic Stability and Breakdown Measurements on the AFRL/AFOSR BOLT II Flight Geometry," *Journal of Spacecraft and Rockets*, Vol. 61, No. 6, 2024, pp. 1623–1639. doi:10.2514/1.A36155, URL <https://arc.aiaa.org/doi/10.2514/1.A36155>.
- [13] Berry, S. A., Semper, M. T., Riha, A. K., Mullen, C. D., Reed, H. L., Dufrene, A. T., and Fasel, H. F., "Development of the BOLT-2 Roughness Experiment for Flight," *Journal of Spacecraft and Rockets*, Vol. 61, No. 5, 2024, pp. 1362–1374. doi:10.2514/1.A35960, URL <https://arc.aiaa.org/doi/10.2514/1.A35960>.
- [14] Portoni, P. P., Dufrene, A., Maclean, M., Wadhams, T., Kostak-Teplicek, H., and Bowersox, R. D. W., "BOLT II Vehicle Design, Instrumentation, and Ground Test Comparisons to Flight," *Journal of Spacecraft and Rockets*, Vol. 62, No. 4, 2025, pp. 1278–1293. doi:10.2514/1.A36160, URL <https://arc.aiaa.org/doi/10.2514/1.A36160>.
- [15] Wheaton, B. M., Butler, C. S., McKiernan, G. R., and Berridge, D. C., "Initial Results from the BOLT Flight Experiment," *AIAA Paper 2022-0345*, 2022. doi:10.2514/6.2022-0345, URL <https://arc.aiaa.org/doi/10.2514/6.2022-0345>.
- [16] Butler, C. S., Araya, D. B., McKiernan, G. R., and Wheaton, B. M., "Supersonic Transition Measurements During the BOLT Flight Experiment Descent Phase," *AIAA Paper 2022-4099*, 2022. doi:10.2514/6.2022-4099, URL <https://arc.aiaa.org/doi/10.2514/6.2022-4099>.
- [17] Kutty, P. M., Butler, C. S., Wheaton, B. M., and Fortier, J. B., "6DOF Simulation Analysis for the Post-Flight Investigation of the Boundary Layer Transition (BOLT) Experiment," *AIAA Paper 2022-3884*, 2022. doi:10.2514/6.2022-3884, URL <https://arc.aiaa.org/doi/abs/10.2514/6.2022-3884>.
- [18] Melcher, J. T., Radcliffe, E. J., Butler, C. S., and Wheaton, B. M., "Effects of Aeroelasticity on Flight Stability of the Boundary Layer Transition (BOLT) Experiment," *AIAA Paper 2022-3748*, 2022. doi:10.2514/6.2022-3748, URL <https://arc.aiaa.org/doi/10.2514/6.2022-3748>.
- [19] Wirth, J. M., Morreale, B. J., Bowersox, R. D. W., Dufrene, A. T., and Wadhams, T. P., "Measurements of Natural Transition During the BOLT II Flight Experiment," *Journal of Spacecraft and Rockets*, Vol. 62, No. 2, 2025, pp. 563–578. doi:10.2514/1.A35867, URL <https://arc.aiaa.org/doi/10.2514/1.A35867>.
- [20] Wirth, J. M., Bowersox, R. D. W., Dufrene, A. T., and Wadhams, T. P., "Measurements of Natural Turbulence During the BOLT II Flight Experiment," *Journal of Spacecraft and Rockets*, Vol. 61, No. 5, 2024, pp. 1281–1292. doi:10.2514/1.A35868, URL <https://arc.aiaa.org/doi/10.2514/1.A35868>.
- [21] Berry, S. A., and Wheaton, B. M., "BOLT-II Roughness Side Flight Results," *Journal of Spacecraft and Rockets*, Vol. 62, No. 2, 2025, pp. 548–562. doi:10.2514/1.A36089, URL <https://arc.aiaa.org/doi/10.2514/1.A36089>.
- [22] Wheaton, B. M., and Dufrene, A. T., "Preflight and Postflight Thermal/Structural Analysis of BOLT II: The Holden Mission," *Journal of Spacecraft and Rockets*, Vol. 61, No. 5, 2024, pp. 1204–1218. doi:10.2514/1.A35978, URL <https://arc.aiaa.org/doi/10.2514/1.A35978>.

- [23] Kutty, P. M., Butler, C. S., Melcher, J. T., and Wheaton, B. M., "Flight Dynamics Modeling of the Boundary Layer Transition 1B (BOLT-1B) Experiment," *AIAA Paper 2023-3672*, 2023. doi:10.2514/6.2023-3672, URL <https://arc.aiaa.org/doi/10.2514/6.2023-3672>.
- [24] McKiernan, G., Butler, C., Wolf, T., Kathrotiya, P., Kutty, P., Melcher, J., Wheaton, B. M., and Adamczak, D. W., "Initial Results of the BOLT-1B Flight Experiment," *AIAA Paper 2025-1339*, American Institute of Aeronautics and Astronautics, Orlando, FL, 2025. doi:10.2514/6.2025-1339, URL <https://arc.aiaa.org/doi/10.2514/6.2025-1339>.
- [25] Schneider, S. P., "Hypersonic Laminar-Turbulent Transition on Circular Cones and Scramjet Forebodies," *Progress in Aerospace Sciences*, Vol. 40, No. 1-2, 2004, pp. 1–50. doi:10.1016/j.paerosci.2003.11.001, URL <http://www.sciencedirect.com/science/article/pii/S037604210300112X?via%3Dihub>.
- [26] Horvath, T. J., Berry, S. A., and Merski, N. R., "Hypersonic Boundary/Shear Layer Transition for Blunt to Slender Configurations - A NASA Langley Experimental Perspective," *NATO RTO-RSM-AVT-III*, 2004.
- [27] Stetson, K. F., "On Predicting Hypersonic Boundary Layer Transition," *Air Force Wright Aeronautical Laboratories Technical Memorandum AFWAL-TM-87-160-FIMG*, Flight Dynamics Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio, 1987.
- [28] Schneider, S. P., "Effects of High-Speed Tunnel Noise on Laminar-Turbulent Transition," *Journal of Spacecraft and Rockets*, Vol. 38, No. 3, 2001, pp. 323–333. doi:10.2514/2.3705, URL <https://arc.aiaa.org/doi/10.2514/2.3705>.
- [29] Dolvin, D. J., "Hypersonic International Flight Research and Experimentation (HIFiRE): Fundamental Sciences and Technology Development Strategy," *AIAA Paper 2008-2581*, 2008. doi:10.2514/6.2008-2581, URL <https://arc.aiaa.org/doi/10.2514/6.2008-2581>.
- [30] Kimmel, R. L., Adamczak, D. W., Borg, M. P., Jewell, J. S., Juliano, T. J., Stanfield, S. A., and Berger, K. T., "First and Fifth Hypersonic International Flight Research Experimentation's Flight and Ground Tests," *Journal of Spacecraft and Rockets*, Vol. 56, No. 2, 2019, pp. 421–431. doi:10.2514/1.A34287, URL <https://arc.aiaa.org/doi/10.2514/1.A34287>.
- [31] Thiele, T., Gülhan, A., and Olivier, H., "Instrumentation and Aerothermal Postflight Analysis of the Rocket Technology Flight Experiment ROTEX-T," *Journal of Spacecraft and Rockets*, Vol. 55, No. 5, 2018, pp. 1050–1073. doi:10.2514/1.A34129, URL <https://arc.aiaa.org/doi/10.2514/1.A34129>.
- [32] McKiernan, G. R., Berridge, D. C., Butler, C. S., Johnston, Z. M., and Wheaton, B. M., "Flight Transition Data from the BOLT-1B Flight Experiment," *Paper to Be Presented at AIAA SciTech 2026*, 2026.
- [33] Berry, S. A., Turbeville, F. D., Brown, J. L., Wheaton, B. M., and McKiernan, G. R., "BOLT-1B Roughness Side Flight Results," *Paper to Be Presented at AIAA SciTech 2026*, 2026.
- [34] Johnston, Z. M., and Bitter, N. P., "Hypersonic Boundary Layer Transition of BOLT-1B at Flight Conditions," *Paper to Be Presented at AIAA SciTech 2026*, 2026.
- [35] Berridge, D. C., McKiernan, G., Wadhams, T. P., Holden, M., Wheaton, B. M., Wolf, T. D., and Schneider, S. P., "Hypersonic Ground Tests In Support of the Boundary Layer Transition (BOLT) Flight Experiment," *AIAA Paper 2018-2893*, 2018. doi:10.2514/6.2018-2893, URL <https://arc.aiaa.org/doi/10.2514/6.2018-2893>.
- [36] Berridge, D. C., Kostak, H., McKiernan, G., Wheaton, B. M., Wolf, T. D., and Schneider, S. P., "Hypersonic Ground Tests With High-Frequency Instrumentation In Support of the Boundary Layer Transition (BOLT) Flight Experiment," *AIAA Paper 2019-0090*, American Institute of Aeronautics and Astronautics, Reston, Virginia, 2019. doi:10.2514/6.2019-0090, URL <https://arc.aiaa.org/doi/10.2514/6.2019-0090>.
- [37] Thome, J., Dwivedi, A., Nichols, J. W., and Candler, G. V., "Direct Numerical Simulation of BOLT Hypersonic Flight Vehicle," *AIAA Paper 2018-2894*, 2018. doi:10.2514/6.2018-2894, URL <https://arc.aiaa.org/doi/10.2514/6.2018-2894>.
- [38] Yam, C., Schneider, S. P., and Jewell, J. S., "Effects of Forward-and Backward-Facing Steps on BOLT at Mach 6," *AIAA Paper 2022-0346*, 2022. doi:10.2514/6.2022-0346, URL <https://arc.aiaa.org/doi/10.2514/6.2022-0346>.
- [39] Johnston, Z. M., Butler, C. S., McKiernan, G. R., and Wheaton, B. M., "Numerical Investigation of Backward-Facing Step on BOLT at Hypersonic Conditions," *AIAA Paper 2024-1975*, 2024. doi:10.2514/6.2024-1975, URL <https://arc.aiaa.org/doi/10.2514/6.2024-1975>.
- [40] Thome, J., Knutson, A., and Candler, G. V., "Boundary Layer Instabilities on BoLT Subscale Geometry," *AIAA Paper 2019-0092*, 2019. doi:10.2514/6.2019-0092, URL <https://arc.aiaa.org/doi/abs/10.2514/6.2019-0092>.

- [41] Sombaert, L., Lugrin, M., Bur, R., Nicolas, F., Esquieu, S., Butler, C. S., Wheaton, B. M., Li, F., Choudhari, M., Paredes, P., and Willems, S., "Ground Tests on BOLT at Mach 7: Cross-Facility Comparison and Stability Analysis," *AIAA Journal*, Vol. 63, No. 6, 2025, pp. 1–16. doi:10.2514/1.J064242, URL <https://arc.aiaa.org/doi/10.2514/1.J064242>.
- [42] Wernz, S. H., Basore, K., Scott, C. F., Turbeville, F. D., and Berry, S. A., "Experiments on Flat-BOLT Surrogates for Investigating the Impact of the Nose Region on Acreage Heating and Transition to Turbulence," *AIAA SCITECH 2025 Forum*, AIAA SciTech Forum, American Institute of Aeronautics and Astronautics, 2025. doi:10.2514/6.2025-1497, URL <https://arc.aiaa.org/doi/10.2514/6.2025-1497>.
- [43] Kimmel, R.L., and Adamczak, D., "HIFiRE-1 Background and Lessons Learned," *AIAA Paper 2012-1088*, 2012. doi: 10.2514/6.2012-1088, URL <https://arc.aiaa.org/doi/10.2514/6.2012-1088>.
- [44] Running, C. L., Rataczak, J. A., Zaccara, M., Cardone, G., and Juliano, T. J., "A Wrap-Film Technique for Infrared Thermography Heat-Transfer Measurements in High-Speed Wind Tunnels," *Experimental Thermal and Fluid Science*, Vol. 135, 2022, p. 110604. doi:10.1016/j.expthermflusci.2022.110604, URL <https://linkinghub.elsevier.com/retrieve/pii/S089417722000097>.
- [45] Chynoweth, B. C., Lay, A., and Jewell, J. S., "Boundary-Layer Transition on BOLT in High Reynolds Number Mach-6 Quiet Flow," *Journal of Spacecraft and Rockets*, 2025, pp. 1–4. doi:10.2514/1.A36425, URL <https://arc.aiaa.org/doi/10.2514/1.A36425>.
- [46] Wheaton, B. M., Berridge, D. C., Wolf, T. D., Stevens, R. T., and McGrath, B. E., "Boundary Layer Transition (BOLT) Flight Experiment Overview," *AIAA Paper 2018-2892*, 2018. doi:10.2514/6.2018-2892, URL <https://arc.aiaa.org/doi/10.2514/6.2018-2892>.
- [47] Li, F., Choudhari, M. M., and Paredes, P., "Streak Instability Analysis on BOLT Configuration," *AIAA Paper 2020-3028*, 2020. doi:10.2514/6.2020-3028, URL <http://arc.aiaa.org>.
- [48] Li, F., Choudhari, M., and Paredes, P., "Transition Analysis for Isolated Trips on BOLT-II Wind-Tunnel and Flight Configurations," *AIAA Paper 2021-2905*, 2021. doi:10.2514/6.2021-2905, URL <https://arc.aiaa.org/doi/10.2514/6.2021-2905>.
- [49] Choudhari, M. M., Li, F., and Paredes, P., "A Computational Analysis of Boundary Layer Instability over the BOLT Configuration," *AIAA Paper 2021-1207*, 2021. doi:10.2514/6.2021-1207, URL <https://arc.aiaa.org/doi/10.2514/6.2021-1207>.
- [50] Li, F., Choudhari, M. M., and Paredes, P., "Wake Instability behind Isolated Trip Near the Leading Edge of the BOLT-II Configuration," *AIAA Paper 2022-1063*, 2021. doi:10.2514/6.2022-1063, URL <https://arc.aiaa.org/doi/10.2514/6.2022-1063>.
- [51] Johnston, Z. M., and Candler, G. V., "Hypersonic Simulations of the BoLT-II Subscale Geometry," *AIAA Paper 2021-0366*, American Institute of Aeronautics and Astronautics, 2021. doi:10.2514/6.2021-0366, URL <https://arc.aiaa.org/doi/10.2514/6.2021-0366>.
- [52] Johnston, Z. M., Hemati, M. S., and Candler, G. V., "Modal Analysis of Instabilities in the BoLT-2 Flowfield," *AIAA Paper 2022-0346*, 2022. doi:10.2514/6.2022-0348, URL <https://arc.aiaa.org/doi/10.2514/6.2022-0348>.
- [53] Cook, D. A., Thome, J., Nichols, J. W., and Candler, G. V., "Receptivity Analysis of BOLT to Distributed Surface Roughness Using Input-Output Analysis," *AIAA Paper 2019-0089*, 2019. doi:10.2514/6.2019-0089, URL <https://arc.aiaa.org/doi/abs/10.2514/6.2019-0089>.
- [54] Vu, C., and Candler, G., "DNS of Hypersonic Boundary Layer Transition in the BOLT II Side A Descent Trajectory," *Paper to Be Presented at AIAA SciTech 2026*, 2026.
- [55] Schneider, S. P., "Flight Data for Boundary-Layer Transition at Hypersonic and Supersonic Speeds," *Journal of Spacecraft and Rockets*, Vol. 36, No. 1, 1999, pp. 8–20. doi:10.2514/2.3428, URL <https://arc.aiaa.org/doi/abs/10.2514/2.3428>.
- [56] Berry, S. A., Kimmel, R., and Reshotko, E., "Recommendations for Hypersonic Boundary Layer Transition Flight Testing," *AIAA Paper 2011-3415*, 2011. doi:10.2514/6.2011-3415, URL <https://arc.aiaa.org/doi/pdf/10.2514/6.2011-3415>.
- [57] Wheaton, B. M., and Dufrene, A. T., "Thermal and Structural Analysis of BOLT-2: The Holden Mission," *AIAA Paper 2023-0685*, 2023. doi:10.2514/6.2023-0685, URL <https://arc.aiaa.org/doi/10.2514/6.2023-0685>.
- [58] McKiernan, G. R., Wolf, T. D., Warner, J., Wheaton, B. M., Berry, S. A., and Brown, J. L., "Design and Measurements of the BOLT-1B Joint Steps," *Paper to Be Presented at AIAA SciTech 2026*, 2026.

- [59] Luo, C., Stevens, R. T., Wheaton, B. M., and McKiernan, G. R., "Thermal and Structural Analysis of BOLT-1B Flight Geometry Including Joint Step Estimates," *Paper to Be Presented at AIAA SciTech 2026*, 2026.
- [60] Bathel, B. F., Weisberger, J. M., Berry, S. A., and Jones, S. B., "Development of Optical Step Height Measurement Capability for the BOLT Flight Vehicle," *AIAA Paper 2022-1657*, 2022. doi:10.2514/6.2022-1657, URL <https://arc.aiaa.org/doi/10.2514/6.2022-1657>.
- [61] Leidy, A. N., "BOLT II Forebody Surface Measurement Analysis," *NASA TM-20230000169*, 2023. URL <https://ntrs.nasa.gov/citations/20230000169>.
- [62] Berry, S. A., Broslawski, C., Wheaton, B. M., Adamczak, D., Bowersox, R., and Dufrene, A., "BOLT-2 Roughness Side Flight Data Results and Analysis," *NASA TM-20240015600*, 2024. URL <https://ntrs.nasa.gov/citations/20240015600>.
- [63] Borg, M. P., Adamczak, D. W., Culler, A. J., and Kurtz, M. D., "HIFLIER Hypersonic Flight Experiment: Design, Analysis, and Ground Test," *AIAA Paper 2025-0733*, 2025. doi:10.2514/6.2025-0733, URL <https://arc.aiaa.org/doi/10.2514/6.2025-0733>.
- [64] Damm, K. A., Gollan, R., and Veeraragavan, A., "Trajectory-Based Conjugate Heat Transfer Simulation of the BoLT-II Flight Experiment," *AIAA Paper 2023-0292*, 2023. doi:10.2514/6.2023-0292, URL <https://arc.aiaa.org/doi/10.2514/6.2023-0292>.
- [65] Melcher, J. T., Butler, C. S., Kutty, P. M., and Wheaton, B. M., "Overcoming Flight Instability in the Boundary Layer Transition Experiments," *Paper to Be Presented at AIAA SciTech 2026*, 2026.
- [66] Kutty, P. M., Huber, T., Butler, C. S., Melcher, J. T., McKiernan, G. R., and Wheaton, B. M., "Flight Dynamics Design of the BOLT-1B Flight Experiment," *Paper to Be Presented at AIAA SciTech 2026*, 2026.
- [67] Lawrence, D. A., Argrow, B. M., Pointer, J., Roseman, C., Kenny, N., Habeck, J., Flaten, J., Candler, G. V., Barjatya, A., and Guardado, J., "In-Situ Turbulence and Particulate Measurements in Support of the BOLT II Flight Experiment," *Journal of Spacecraft and Rockets*, Vol. 61, No. 6, 2024, pp. 1563–1576. doi:10.2514/1.A36034, URL <https://arc.aiaa.org/doi/10.2514/1.A36034>.
- [68] Dobbins, T. J., Wiebold, M. D., VanKerkhove, J., ArchMiller, M. C., Taylor, L. N., and Horak, E. H., "Atmospheric Measurements with the HALAS LiDAR System Supporting the BOLT II Flight Test," *AIAA Paper 2023-0479*, 2023. doi:10.2514/6.2023-0479, URL <https://arc.aiaa.org/doi/10.2514/6.2023-0479>.
- [69] Habeck, J. B., Kroells, M., Knutson, A., and Candler, G. V., "Numerical Study on the Role of Aerosol Particles in Hypersonic Boundary Layer Transition," *AIAA Paper 2024-0702*, American Institute of Aeronautics and Astronautics, Orlando, FL, 2024. doi:10.2514/6.2024-0702, URL <https://arc.aiaa.org/doi/10.2514/6.2024-0702>.