

BOLT-1B Roughness Side Flight Results

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A series of flight experiments referred to as BOLT (for Boundary Layer Transition or Turbulence) have been underway since 2017 to study hypersonic transition or turbulence on a geometry with concave surfaces and highly swept leading edges. The most recent flight was with BOLT-1B, which successfully flew from Andøya, Norway on September 2nd, 2024. The BOLT geometry provides for two independent surfaces that allow for both smooth and rough wall experiments to be flown at the same time. The present report is focused on the BOLT-1B rough wall flight data which was developed to investigate the effect of nose-joint steps. Details on the as flown size and locations of joint steps are provided. Comparisons of the boundary layer transition onset movement between the smooth and rough sides as a function of flight conditions have shown that the flight results behaved as expected with the rough side having a lower transition Reynolds number than the smooth side. The roughness side flight transition data compares favorably to the original ground-based step correlation used to design the original experiment.

I. Nomenclature

M_∞	Mach number
Re_L	Reynolds numbers based on forebody length (0.866 m)
$St = q_w/(T_0 - T_w)(\rho U_\infty C_p)$	Stanton number
q_w	Heat flux at the surface
t	Time after liftoff (s)
T	Temperature (K)
x, y, z	Body coordinates in the axial, vertical, and spanwise directions
ρ	Density (kg/m ³)
U	Freestream velocity (m/s)
C_p	Specific heat capacity (J/kg K)
α	Angle of attack (degrees)
β	Sideslip angle (degrees)

II. Introduction

The Boundary Layer Transition/Turbulence (BOLT) series of sounding rocket flight experiments was initiated in 2017 by the Air Force Research Laboratory (AFRL) and Air Force Office of Scientific Research (AFOSR) to advance our aerothermodynamic modeling capabilities on complex geometries at hypersonic flight conditions. Previous flight research under the Hypersonic International Flight Research Experimentation (HIFiRE) series (specifically flights 1 and 5) had largely focused on cones, so the BOLT geometry (shown in Fig. 1) was established to be three-dimensional with concave surfaces and swept leading edges. The goal of the BOLT flight program is to expand our knowledge of

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boundary layer transition physics through a comprehensive effort to compare ground-based experiments to computational results and flight data. A review of the formulation and genesis of the BOLT effort is provided in [1]. The basic BOLT geometry provides the capability to simultaneously conduct two separate experiments on either side of the vehicle. Thus, from inception, one side of the flight vehicle was focused on smooth body transition (designated as Side A) while the other side was dedicated to roughness effects (Side B). There have been three attempts to get hypersonic flight data using the basic BOLT geometry.

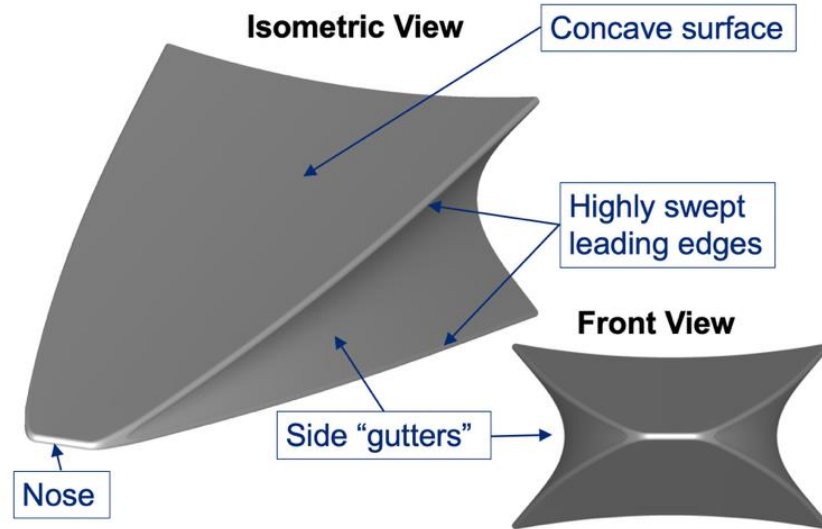


Figure 1. BOLT flight experiments basic geometry.

NASA's Langley Research Center in Hampton, VA has been a contributing partner to the BOLT program from the beginning, providing the initial set of experimental data from the Langley 20-Inch Mach 6 Tunnel. These early contributions to the effort were documented in [2]. NASA's support for BOLT has been provided by the Aeronautics Research Mission Directorate (ARMD), Advanced Air Vehicle Program (AAVP), Hypersonic Technologies Project (HTP). NASA has provided guidance and oversight of the roughness side experiments for all three flights.

The initial flight effort, now retroactively referred to as BOLT-1A, was led by Johns Hopkins Applied Physics Laboratory (APL) and had the German Aerospace Center (DLR) Mobile Rocket Base (MORABA) as the launch partner. This multi-year effort of ground-based experiments matched to computational predictions culminated with a launch at Esrange, Sweden in 2021. The launch vehicle did not reach the desired hypersonic conditions [3]. This initial flight took place on a two-stage system, that included a first stage S31 coupled with a second stage Improved Orion. Shortly after staging, there was an unexpected dynamic instability. Postflight analysis of the BOLT-1A flight behavior helped inform changes leading to improvements and successful subsequent flights.

The second flight, called BOLT-2, was led by a team formed by Texas A&M University and CUBRC with launch services provided by NASA Wallops. This launch was fully successful in 2022, also using a two-stage system, this time a Terrier Improved Malemute. The intent with BOLT-2 was slightly different from the first mission in that the focus was to be more on turbulence and less on the instability mechanisms [4]. Thus, with the success of BOLT-2 based in part on lessons learned from BOLT-1A, a second attempt of the first mission got underway to fulfill the original goals of the BOLT effort.

This third flight was the fully successful BOLT-1B mission in the Fall of 2024 from Andøya Space, Norway. The payload was a revised version of the BOLT-1A experiment, once again led by APL with MORABA as the flight partner. This launch took place utilizing a single-stage Black Brant VC, which provided even higher Mach number conditions than originally planned with BOLT-1A. The prioritized science goals for this flight were to (1) measure smooth wall boundary layer transition, and (2) measure the impact of intentionally added roughness in the form of joint steps. The focus of the present paper will be to review the flight results obtained to satisfy this second objective, largely from measurements on the roughness side of the BOLT-1B vehicle. Initial results from this third flight were discussed in [5].

A. Roughness Side Differences Between Flights

The roughness experiment on Side B (also referred to herein as the roughness or secondary side) has varied with each flight. BOLT-1A was set up to investigate step effects on Side B resulting from joints between parts of the vehicle assembly [6]. The original design called for a nosetip able to absorb the high temperatures of hypersonic heating, an isolator section, and the main body (where most of the flight instrumentation was located), which introduced two joints that were near the front of the vehicle. Thus, the focus of the BOLT-1A roughness experiment was an exaggerated step (purposefully large) at the second of the two joints, between the stainless-steel isolator and the aluminum main frustum. BOLT-2 was established and underway before the BOLT-1A flight attempt, which resulted in the roughness experiment changing to an investigation of discrete roughness effects in the form of boundary layer trips [7, 8]. Once the decision was made to make another attempt at the first flight, Side B of BOLT-1B reverted to looking at step effects again. However, due to some minor variations in the design and fabrication of the parts (to be discussed in greater detail in a later section), both joints had prominent steps on the roughness side.

B. Historical Step Effect Cases

The impact of joint steps on the aerothermal environment of hypersonic flight vehicles is surprisingly not a topic that has been heavily documented over the years. There have been numerous flight programs with joints between assembled sections, but often the impact of the joint steps does not get much coverage in the literature. Three well-known cases that come to mind are the Reentry F, HIFiRE-1, and HIFiRE-5 vehicles.

Reentry F was a boundary layer transition experiment, launched from Wallops in 1968, that provided high Mach number transition data associated with real gas effects and nosetip ablation [9]. The vehicle was a 5° half-angle cone with a graphite nosetip roughly 0.22 m (8.5") long that was expected to ablate and recess during flight, followed by a beryllium heat shield. The target Mach number for this flight was 20, which was achieved by use of a third stage that provided acceleration during descent. The total vehicle length was 3.96 m (156") which was instrumented with in-depth thermocouples. The joint between the graphite and beryllium included both a gap and step to account for thermal effects on the graphite during flight. The preflight gap was 2.54 mm (0.1") wide and the step was rear facing and reported to be 1.02 mm (0.040") high. The gap and step were expected to reduce during flight, but the amount of change was never firmly established postflight. These flight data have been widely studied over the years, but all reviews have largely ignored the possible impact of the nosetip gap and step in the analysis. A recent review of both the preflight contractor reports, that provide insight into the reasons for the selected gap and step, and postflight NASA reports, can be found in [10].

The HIFiRE series of boundary layer transition flight experiments (flights 1 & 5) also were designed utilizing a separate nosetip assembly that ordains nose joints (and thus steps). In fact, much of the initial BOLT design was predicated on heritage derived from HIFiRE-5, such as the use of the similar vehicle materials and approach, and the use of the same launch provider and data acquisition system. The BOLT flights were intended to build upon the research objectives that initially started during the HIFiRE campaign.

The HIFiRE-1 vehicle included a 7° half-angle cone that was 1.1 m long (~43") with a nose radius of 2.5 mm (~0.1") followed by cylindrical and flare sections, with total length of 1914.2 mm (~75"). A solid piece of titanium-zirconium-molybdenum (TZM) was selected as heat-resistant material for the 221.3 mm (8.7") long nosetip. The cone assembly consisted of the TZM, followed by a carbon-steel isolator and stainless-steel joiner that was connected to the aluminum main body, establishing 3 joints near the nose. The steps of the cone assembly were measured prior to flight to be on the order of 0.2 mm (0.008") or less and rear facing, with the expectation that thermal heating would result in these joints all being flush late during reentry [11]. This flight, which occurred in 2010 at Woomera, Australia, provided approximately Mach 7 flight conditions during both ascent and descent. The flight results indicated that the steps did have an influence on the transition behavior during ascent, but detailed analysis of the connection of the actual circumferential distribution of step heights during flight to the transition onset has not yet been firmly established. Postflight analysis of the flight data has been performed based on the worst-case assumption of a 0.2 mm rear facing step based on preflight measurements [12], which does not account for any thermal step changes during flight.

The HIFiRE-5 vehicle was a three-dimensional body derived from a 2:1 elliptic cone to incrementally include boundary layer phenomena atypical of axisymmetric cones, such as leading-edge effects and crossflow instability. The minor axis provides the same 7° half-angle as before with the same 2.5 mm nose radius. The length of the elliptic cone section was 0.86 m (~33.8"), comprised of a similar cone assembly as HIFiRE-1 (TZM to carbon steel to stainless steel to aluminum), requiring 3 joints to contend with. Again, all joint steps were designed to be rear facing and to thermally reduce during flight. The maximum preflight values measured were on the same order as before 0.2 mm

(or $\sim 0.008''$), with the largest steps found along the leading edge (or major axis) [13]. There were two flights associated with this effort (like the BOLT-1 case which were retroactively designated with A and B). The first launch, at Andoya, Norway in 2012, did not go according to plans, reaching only supersonic flight conditions ($\sim$ Mach 3). There were step effects in the transition data for this flight, as reported in [14]. The second flight was back at Woomera in 2016, which provided the desired Mach 7.5 conditions. The HIFiRE-5b flight data did not seem to suggest any step effects, as concluded due to the gradual movement of transition during flight (no “flashing” of transition movement that had been seen on previous flights) [15]. The HIFiRE-5b steps were reported as slightly smaller than the ones measured on HIFiRE-5a (200 microns vs. 250 microns).

These three prominent historical hypersonic boundary layer transition flight cases all had joint steps to contend with. In all three cases, there was a concerted preflight effort to minimize the impact of the steps by determining a roughness threshold for design purposes and then hope for the best. In all instances, any postflight analysis of the flight data largely ignored the joint steps or bounded the step height by the preflight values. The present effort associated with BOLT-1B is to provide a thorough review of the preflight measurements of the circumferential variance of the steps and then account for the thermal environment during flight to come up with the best assessment of the actual step heights during flight to clearly establish cause and effect.

C. Leading Edge and Step Effects

The unique shape of BOLT provides an opportunity to derive clear sensitivities of the impact of step effects on hypersonic boundary layer transition. This is because the BOLT swept leading edges represent the region at which the steps are most pronounced while also being the location at which the boundary layer is the thinnest. Figure 2 provides a sample flight computation showing boundary layer thickness on one quadrant of BOLT-1B for an actual flight condition corresponding to Mach 7.1 with a freestream unit Reynolds number of $4.2 \times 10^6/\text{m}$ at 27.6 km altitude with nominal attitude, e.g., angle of attack (α) and sideslip angle (β) of zero. The black lines indicate the placement of the two nose assembly joints. The boundary layer is shown to be the thinnest on the nose and along the swept leading edge. Thus, expectations are that roughness in the form of exaggerated steps along the leading edges will dominate the transition behavior observed in flight. In contrast, the variation of step height around the circumference of the HIFiRE-5 joints are less likely to correspond to the specific location where the boundary layer is thinnest, which makes interpretation of any flight data trends a little harder. For this reason, the flight instrumentation on the roughness side of BOLT-1B was concentrated to be along the surface streamlines emanating from the location of the joints at the leading edge. The leading edges were the locations designated as informational “aim points” during the design and fabrication process providing acceptable step heights for all four quadrants for both the smooth and rough sides.

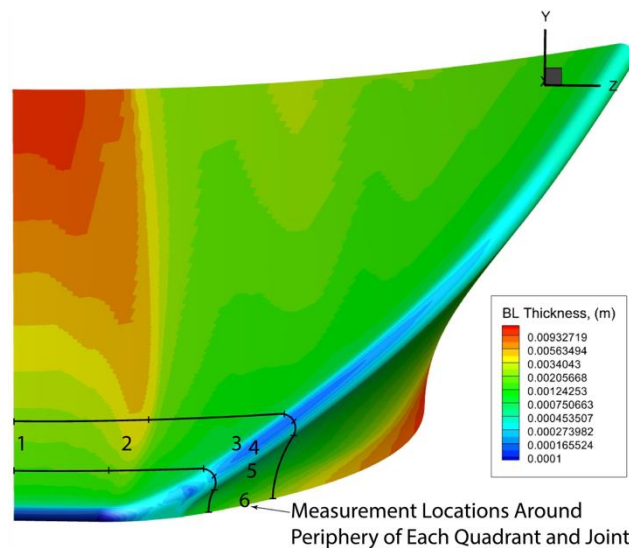


Figure 2. Sample BOLT-1B calculation of boundary layer thickness for one quadrant. (Mach 7.1, $Re_\infty=4.2$ million/m, and $\alpha=\beta=0$)

In reference to the joints shown in the above figure, there are six key locations designated for measurement and analysis on each quadrant and joint. Locations 1 and 6 are defined as the centerlines of the experimental surfaces and

gutters, respectively. Location 2 is the midpoint between the experimental surface centerline and the leading edge. Locations 3 and 5 are the transition points between the experimental surfaces or gutters and the leading edge. Lastly, location 4 is the leading-edge midpoint, represented by a 45° angle between the perpendiculars of the experimental surface and gutter. Location 4 has been shown through analysis to be the critical location where thermal expansion provides the most pronounced change in step height.

III. Flight Configuration and Trajectory

A. Vehicle Details

The BOLT-1B vehicle is largely consistent with the previous BOLT-1A vehicle except for a few modifications to improve performance and ease of assembly [5]. The entire BOLT-1B rocket stack is shown in Fig. 3, identifying the main components and organizations responsible for each section. The BOLT-1B flight geometry is shown at the front end of the rocket stack and has a total length of 0.866 m. The flight geometry has two separate sides allowing independent transition experiments to be conducted during flight. One side, designated as Side A, is intended for smooth body transition measurements, while Side B is focused on roughness transition, in this case based on intentionally large nose-joint steps. Downstream of the flight geometry is the Transition Support Module (TSM) and Payload Support Module (PSM), which have been redesigned with a new one-piece contour that also allows easier adaption of the payload ballast. The flight geometry, TSM and PSM were all fabricated by APL in partnership with the Air Force Research Laboratories Aerospace Systems Directorate (AFRL/RQ). Next, the Cold Gas System Module (CGSM) and Attitude Control System Modules (ACSM) are located downstream of the TSM/PSM. These sections, fabricated by DLR MORABA, provide for the exo-atmospheric re-orienting, descent attitude control, and telemetry. The entire stack was completed with the addition of a single-stage Magellan Aerospace Black Brant VC Mark IV motor, that was selected to provide Mach 7 ascent and descent flight conditions.

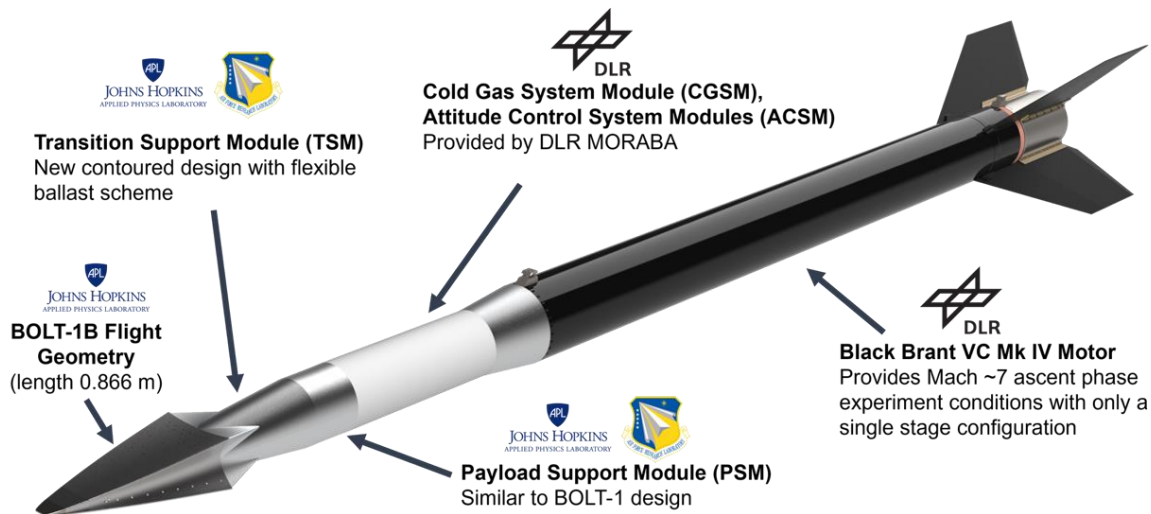


Figure 3. BOLT-1B Flight Research Vehicle.

Several key modifications utilized for BOLT-1B are identified in Fig. 4, including changes in material selection, instrumentation coverage, and structural design. These adjustments were made to accommodate some fabrication lessons learned from previous flights and the higher temperatures predicted for this flight. The nose was fabricated from TZM but featured a ruthenium coating instead of the iridium coating on BOLT-1A. Different materials were selected for the frustum sections, as the higher Mach flight conditions meant higher temperatures than allowable with the use of aluminum. Instead, BOLT-1B utilized 410 stainless-steel for the isolator and main body, which had also successfully been used as part of the BOLT-2 flight. There were some changes to the instrumentation, including increased coverage, which will be discussed in greater detail later. Finally, the TSM was redesigned to fully integrate the fairings as part of the structure to allow more efficient packaging of the sensor electronics and vehicle ballast.

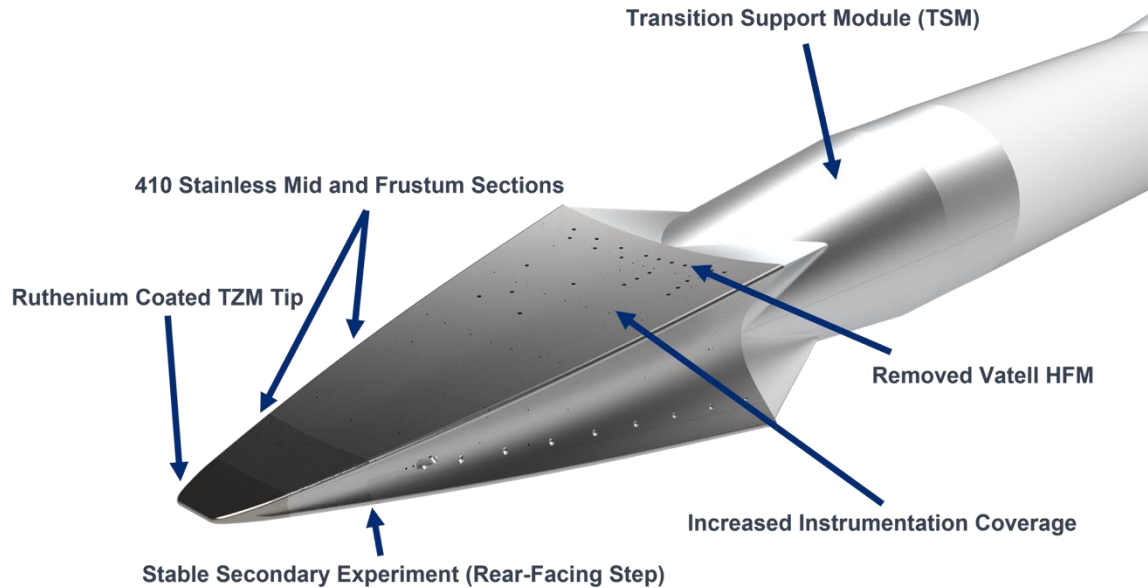


Figure 4. Changes made to BOLT-1B vehicle based on lessons learned from past flights.

The use of new materials on BOLT-1B required additional preflight analysis to ensure the Side A would remain smooth enough throughout flight while the Side B would provide the expected step heights required for the roughness experiment. As shown in Fig. 4, there are three distinct sections to the experimental body (nositip, isolator, main frustum), necessitating 2 joint locations (herein described as the upstream and downstream joints). These joints are located at 0.082 m and 0.184 m from the nositip. Since the isolator and frustum were now the same material, with the same coefficient of thermal expansion, there was less concern about the step heights changing significantly at the downstream joint location. Thus, for the smooth side, the step height at the downstream location was chosen to be the smallest rearward facing step possible. On the roughness side, the target was rearward facing steps at the downstream joint of 0.36 mm (0.014”), which would be roughly consistent with the original “3x bigger” step over the smooth side based on the BOLT-1A plans [6]. The downstream joint for the roughness experiment was intended to be the focus here based on the original plan, as the use of consistent materials across the joint meant that the steps were not expected to change appreciably due to thermal effects. The preflight thermal growth analysis for the upstream joint was completed, using conservative heating assumptions, to indicate that a rear facing step on the order of 0.1 mm (0.004”) tall at the leading edges should avoid roughness effects in flight for the smooth side. This value was initially selected as the aim point for both sides to minimize any influence of the upstream joint. However, in the final buildup of hardware for flight, with multiple iterations of the isolator design due to uncertainties with the Ruthenium coating, the roughness side ended up with a larger rear-facing step at the upstream joint location. This was based on the nositip being purposefully biased in final assembly to ensure any excess material would be absorbed by the rough side joint. Again, the desire was to keep both the upstream and downstream joints on the smooth side joints as rear facing steps on the order of 0.1 mm or less. This led to a less-than-ideal scenario of having both joints on the roughness side with steps that could significantly influence the transition behavior. The upstream joint would be expected to vary during flight, while the downstream one should remain relatively consistent in time.

Various measurements were taken preflight to ensure that the aim points on the smooth side matched requirements, which is discussed in detail in [16]. Figure 5 provides representative photos, taken just prior to launch, that indicate the range of rear facing steps for both the upstream (top row of images) and downstream (bottom row) joints for both Side A (Fig. 5a) and Side B (Fig. 5b). As can be seen in those photos, Side B featured larger rear-facing joint steps at the upstream joint (due to the nonuniformities in the nositip coating), which will be shown later to be on the order of 4 times large than on the smooth side. The downstream joints on Side B were thought to be close to the intended step size based on the original aim point of 0.36 mm (0.014”). Note that in the images provided in Figure 5, which were taken a day or so before launch and at the time of last set of preflight molds, there were black ink marks placed on the surface as a way of anchoring the mold locations to the photos taken. The marks were removed before flight. A subsequent section will discuss the analysis of the various measurements. \

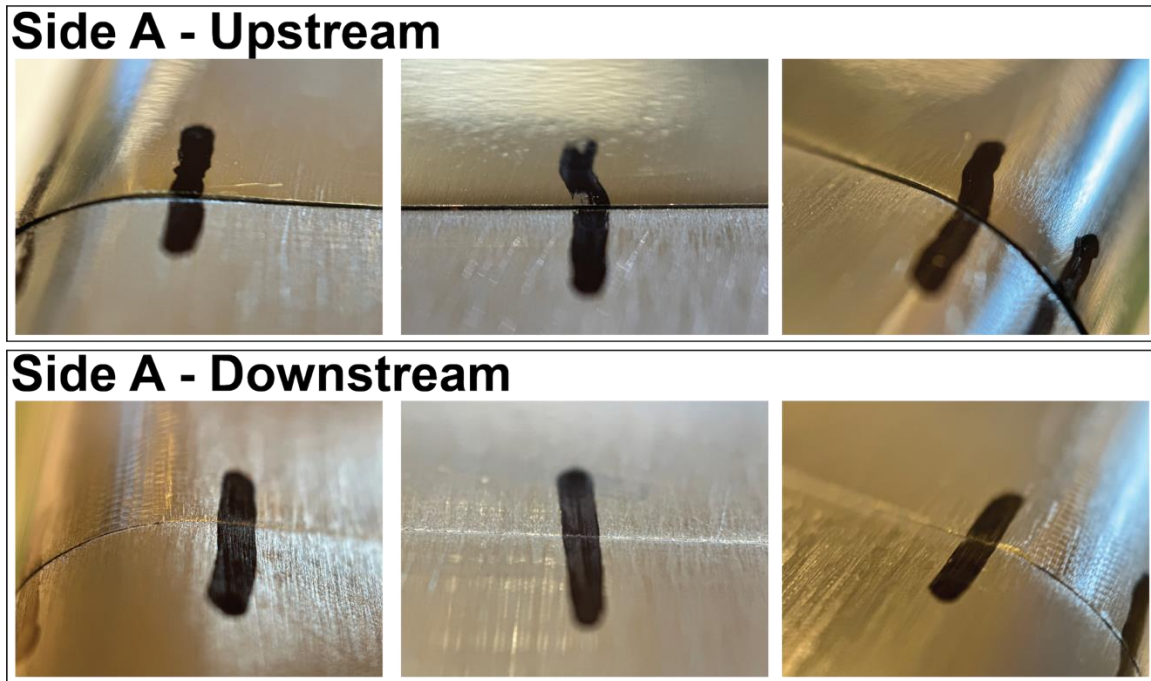


Figure 5a. Side A nose joint step photos, view looking forward [Source: APL].

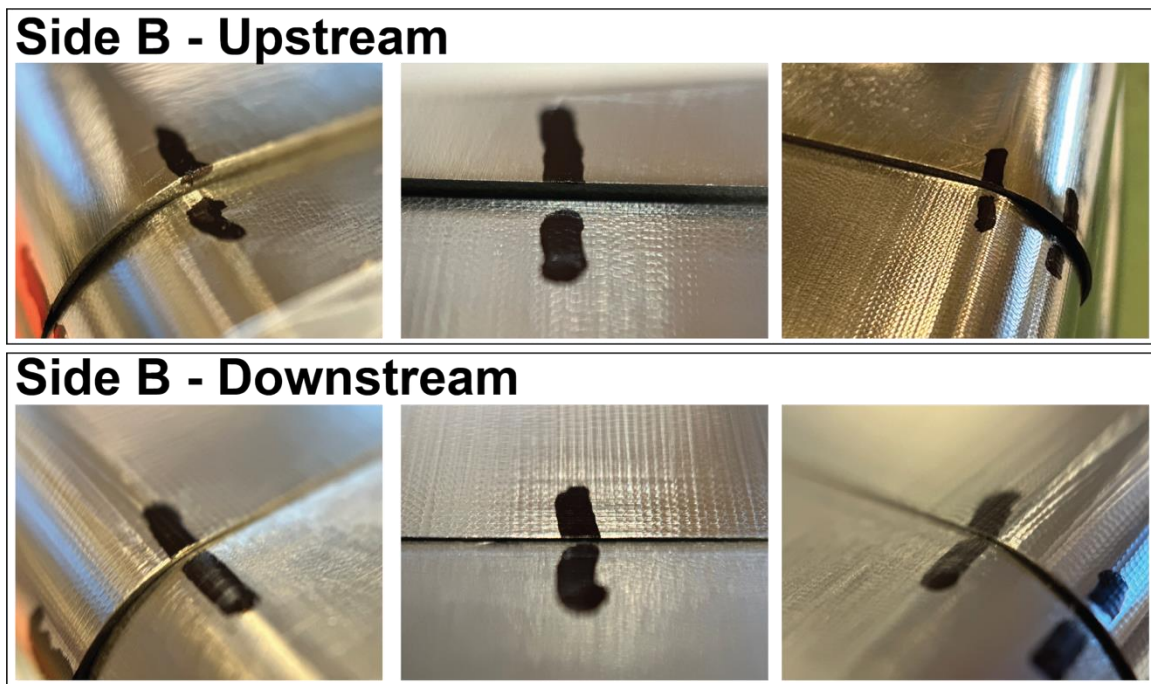


Figure 5b. Side B nose joint step photos, view looking forward [Source: APL].

B. Instrumentation Layout

The instrumentation totals for BOLT-1B were 282 discrete surface sensor locations with over 400 channels of data. Figure 6 provides a sketch showing the layout of the various sensor types, predominately focused on surface temperatures and pressures. Lessons learned from previous flights (BOLT-1A and BOLT-2) were factored into the chosen layout and selection of sensor types utilized for this flight. To track the movement of boundary layer transition, 212 Medtherm Type-E coaxial thermocouples were included to measure surface temperatures, which could then be

converted to surface heating. This number of discrete surface locations provided improved spatial coverage over previous flights. There were an additional 14 subsurface thermocouples (Type K) that were included to provide internal temperatures of the joints during flight. The vehicle included 16 low-frequency pressure sensors (Kulite XCEL-100-5A and -15A) to monitor attitude (α and β) variations in flight. An additional 40 high-frequency pressure sensors (Kulite XCEL-100-5A and PCB 132B38) were placed to measure boundary layer spectral content throughout flight. Additional details about the instrumentation can be found in [5]. Figure 6 also introduces that the two sides can be further divided by quadrants, where Side A has quadrants A and B and Side B has quadrants C and D, as shown. Quadrants A and D were the more heavily instrumented regions of the two sides as can be seen in the figure.

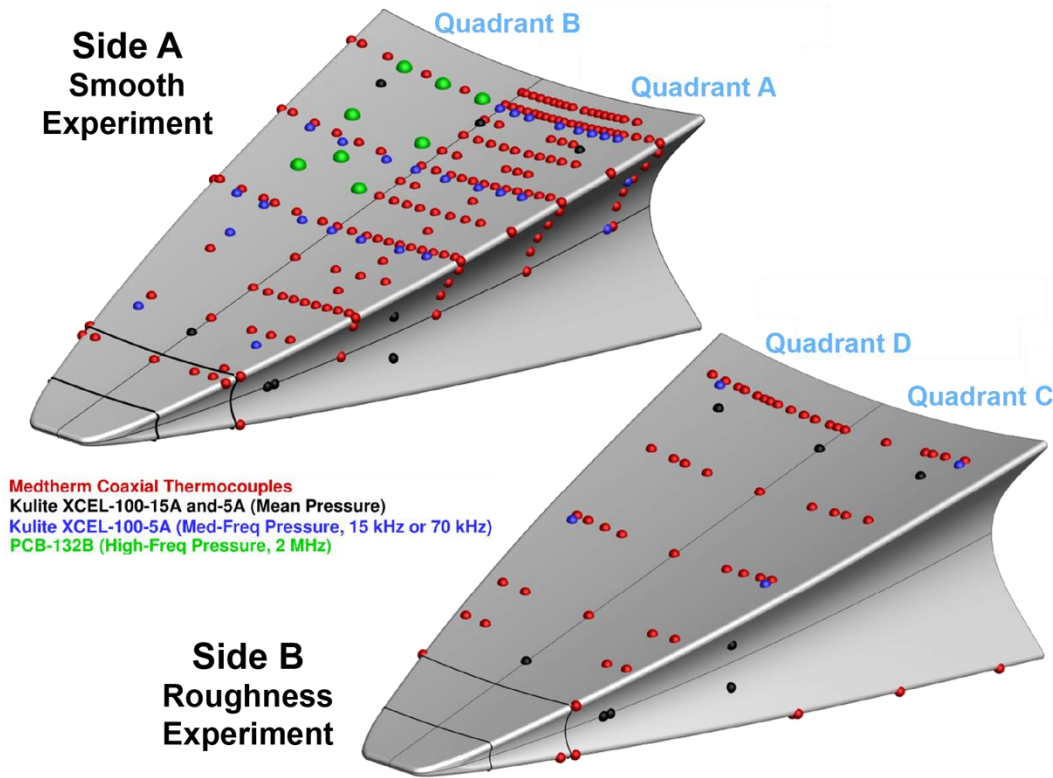


Figure 6. BOLT-1B flight instrumentation layout.

C. Trajectory and Attitude

BOLT-1B was successfully launched from Andøya Space in northern Norway on September 2, 2024, at 0941 UTC, using a single-stage Black Brant VC Mark IV vehicle operated by DLR MORABA. Figure 7 provides multiple views of the launch, taken from several locations. Atmospheric conditions at the time of launch were ideal with clear skies and low winds. The ground temperature was 17°C (or 63°F). The vehicle was spin-stabilized and launched on a ballistic trajectory to provide scientific measurements during both ascent and descent phases of flight. Range telemetry captured all data up until loss of signal at 5.7 km altitude (18.7 kft) above the impact point in the Norwegian Sea 185 km downrange (607 kft). Splashdown occurred within less than one standard deviation from the nominal aim point.

The research vehicle included various redundant sources of flight data for reconstruction of the trajectory with accurate estimates of vehicle position, attitude, and velocity. There were two onboard Global Positioning System (GPS) receivers that provided position and velocity in close agreement throughout flight, indicating a maximum velocity of 2140 m/s and apogee of 254 km. Both receivers operated continuously throughout flight providing higher confidence in the measured results. There were also Inertial Measurement Units (IMUs) onboard to provide additional checks on position and velocity, while also providing vehicle attitude data. The IMUs included DMARS-R and Memsense 3050 units allowing for independent attitude solutions. The DMARS-R is an autonomous inertial guidance, navigation and control sensor specifically designed for use in spin-stabilized sounding rocket flights. Together, these four independent strings of flight data provide the means to back out a more accurate solution of the time history of vehicle position, velocity and attitude.



Figure 7. BOLT-1B launch photographs [Source: APL, DLR, Amanda Chou].

The second important part of determining the final Best Estimated Trajectory (BET) is to also develop an improved understanding of the atmospheric conditions that the vehicle flew through. To support this aspect, four radiosonde balloon soundings were conducted, three preflight (at 0645, 0741, and 0858 UTC) and one postflight (at 0953 UTC). The radiosonde data provided atmospheric temperatures, pressures, humidity, wind speeds, and wind direction up to 26-32 km altitude. These data, as well as publicly available local and global weather modeling data, were combined for a Best Estimated Atmosphere (BEA) that includes some measure of uncertainties along the flight path of the experiment.

The BOLT-1B flight was designed to obtain boundary layer transition measurements at hypersonic conditions within ascent and descent science windows defined by a length-based Reynolds number (Re_L) range of 1-20 million. The overall vehicle length ($L = 0.866$ m) was used as a reference value. The peak Mach number (M_∞) during flight was 7.2 but there was some variation during the ascent science window (low of 5.6). Details about the BEA, BET, and the specific scientific conditions achieved in reference to the goals of the mission can be found in [16]. This report also provides insight into the ongoing analysis regarding estimates of the vehicle attitude with time, specifically an accurate accounting of the angle of attack and sideslip.

D. Determination of Preflight Joint Steps

At various points along the fabrication process, several different methods were utilized for documenting the measurements of the steps around the periphery of both joints and both sides. The methods included the use of structured-light scans to capture the global and continuous nature of the three-dimensional joint steps, to compare against discrete tactile values obtained using feeler gauges and X-ray computer tomography (CT) of discrete molds. The surface scans were acquired after final assembly, just prior to shipment of the payload to the launch site. The tactile measurements and molds were gathered at various times, including prior to payload shipment and just before launch. The X-ray CT measurements of the molds are the more precise measurements, although only at discrete points along the joints. The white light scans provide for continuous variation along the joints, although they are less precise especially for small step heights. A full discussion of the postflight analysis of the various step height measurements is provided in [16].

E. Postflight Analysis of Joint Step Thermal Growth

As part of the postflight analysis of the BOLT-1B flight data, a comprehensive computational database has been generated that allows calculation of the aerothermal heat load during flight. These results were used to estimate the thermal-mechanical response of the payload during flight using finite element modeling. Thermal contact resistance across the nosetip joints were analyzed and validated against thermocouple data. This analysis was also used to estimate the step height change throughout the ascent and descent test windows due to differential thermal expansion

across the joints. Surprisingly, the preflight “cold wall” steps were found to be relatively stable throughout much of the ascent and descent test windows, in contrast to preflight predictions that were built on conservative assumptions using all turbulent heating profiles. The details of this thermal and structural analysis can be found in [17]. The resulting values (in English units only) estimated from both the assessment of the various preflight measurements and the post flight heating are captured in Tables 1(a-d) for the joint locations pertinent to the smooth and rough surfaces for both the upstream and downstream joints. The joint step locations are identified by a three-character designation, where the first identifies the joint (U or D for upstream or downstream), the second identifies the quadrant (A, B, C or D), and the last identifies the location (1-4 where 1 is on centerline and 4 corresponds to the LE). Not listed in the tables below are locations 5 and 6, which are relevant to the gutter region only. Note that the largest rear facing steps are found on Side B at the upstream joint, at either location 3 in quadrant C or location 4 in quadrant D.

Table 1a. Estimation of step variation for Side A upstream joint.

Side A	UA4 (in)	UA3 (in)	UA2 (in)	UAB1 (in)	UB2 (in)	UB3 (in)	UB4 (in)
Upstream	LE			CL			LE
Preflight	0.0058	0.0039	0.0028	0.0031	0.0039	0.0039	0.0056
Ascent Estimate	0.0057	0.0038	0.0028	0.0031	0.0039	0.0038	0.0055
Descent Estimate	0.0040	0.0035	0.0025	0.0028	0.0037	0.0035	0.0038

Table 1b. Estimation of step variation for Side B upstream joint.

Side B	UC4 (in)	UC3 (in)	UC2 (in)	UCD1 (in)	UD2 (in)	UD3 (in)	UD4 (in)
Upstream	LE			CL			LE
Preflight	0.0159	0.0229	0.0233	0.0242	0.0227	0.0206	0.0219
Ascent Estimate	0.0158	0.0228	0.0233	0.0242	0.0227	0.0205	0.0218
Descent Estimate	0.0141	0.0225	0.0231	0.0239	0.0225	0.0202	0.0201

Table 1c. Estimation of step variation for Side A downstream joint.

Side A	DA4 (in)	DA3 (in)	DA2 (in)	DAB1 (in)	DB2 (in)	DB3 (in)	DB4 (in)
Downstream	LE			CL			LE
Preflight	0.0019	0.0007	0.0014	0.0007	0.0012	0.0009	0.0005
Ascent Estimate	0.0023	0.0010	0.0014	0.0009	0.0012	0.0012	0.0009
Descent Estimate	0.0025	0.0008	0.0015	0.0009	0.0013	0.0011	0.0011

Table 1d. Estimation of step variation for Side B downstream joint.

Side B	DC4 (in)	DC3 (in)	DC2 (in)	DCD1 (in)	DD2 (in)	DD3 (in)	DD4 (in)
Downstream	LE			CL			LE
Preflight	0.0126	0.0076	0.0060	0.0065	0.0048	0.0045	0.0072
Ascent Estimate	0.0130	0.0079	0.0060	0.0067	0.0048	0.0048	0.0076
Descent Estimate	0.0132	0.0078	0.0061	0.0067	0.0049	0.0047	0.0078

IV. Flight Data Analysis and Results

An initial assessment of boundary layer transition trends was discussed in [5], although with more of a focus on the smooth side data. Those results showed that in some cases the transition onset behavior seemed sensitive to small alpha/beta variations that occurred as the vehicle spun. For the present discussion, the intent is to focus on the roughness side results while bringing in any differences between the sides for context, and to develop an approach to account for the alpha/beta sensitivities. The results will be presented as Stanton number derived from the previously reported heat flux values obtained from the thermocouple measurements. Details of the approximated equations and material properties used for that analysis are provided in [16].

The roughness side sensor layout was developed preflight to allow tracking the onset of transition along streamlines that develop from the leading edges near the joint locations. Figure 8 provides the Side B sensor locations compared to the nominal (alpha/beta equal to zero) streamlines derived from solutions at a Mach 7.3 flight condition. Subsets of sensors were aligned behind either the downstream joint (the outboard array that stretches the length of the main body) or the upstream joint (the more inboard array). There were also a handful of sensors placed in the center region. All roughness side sensors were strategically located with counterparts in the other quadrants (or on the other side, if

on centerline). Tables 2(a-d) provide a listing of these counterpart thermocouples, identified by location (metric units only) and sensor number. Any sensor number shown in red font is meant to convey a thermocouple that failed to provide useful information during flight.

The data analysis to be presented subsequently can be summarized as follows: (1) examine the global trends to establish data credibility by comparing the observed transition behavior between the two sides, (2) extract the incipient and effective conditions by quadrants, if possible, and then (3) investigate any appropriate correlations based on boundary layer properties derived from available computational databases. The incipient condition is defined as the flight case at which transition is just starting to occur at a distance (at the back of the vehicle), while the effective case corresponds to transition occurring as close as can be measured to the disturbance source. The database of solutions available for this last goal presently provides only “as flown” flight conditions computed with nominal flight attitudes (alpha and beta of zero).

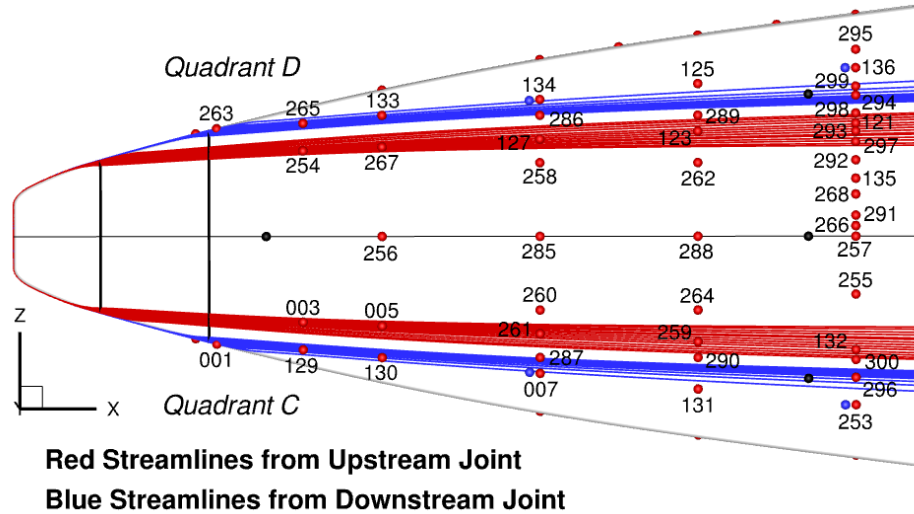


Figure 8. Roughness side sensors in relation to predicted streamlines at nominal alpha and beta.

Table 2a. Thermocouple locations on centerline with corresponding counterparts.

Side A (+y z=0)	Side B (-y z=0)	x (mm)	y (mm)	z (mm)
49	256	349	±46	0
237	285	499	±67	0
105	288	649	±83	0
181	257	799	±101	0

Table 2b. Sensor counterparts along streamline from downstream joint identified by quadrant.

Quadrant A (+y +z)	Quadrant B (+y -z)	Quadrant C (-y -z)	Quadrant D (-y +z)	x (mm)	y (mm)	z (mm)
043	027	001	263	192	±29	±102
045		129	265	274	±42	±107
095		130	133	349	±52	±115
195		287	286	499	±70	±115
137	187	007	134	499	±72	±130
	223	131	125	649	±91	±145
270		296	294	799	±108	±134
159			299	799	±109	±142

Table 2c. Sensor counterparts along streamline from upstream joint identified by quadrant.

<i>Quadrant A</i> (+y +z)	<i>Quadrant B</i> (+y -z)	<i>Quadrant C</i> (-y -z)	<i>Quadrant D</i> (-y +z)	<i>x (mm)</i>	<i>y (mm)</i>	<i>z (mm)</i>
101	031	003	254	274	±40	±81
093		005	267	349	±50	±85
		261	127	499	±68	±92
111		259	123	649	±87	±100
071		290	289	649	±88	±115
081			297	799	±104	±90
302			293	799	±105	±100
157	183	132	121	799	±106	±107
310		300	298	799	±106	±117

Table 2d. Sensor counterparts in other locations identified by quadrant.

<i>Quadrant A</i> (+y +z)	<i>Quadrant B</i> (+y -z)	<i>Quadrant C</i> (-y -z)	<i>Quadrant D</i> (-y +z)	<i>x (mm)</i>	<i>y (mm)</i>	<i>z (mm)</i>
141		260	258	499	±67	±70
109		264	262	649	±845	±70
301			266	799	±101	±10
201			291	799	±101	±20
153		255	268	799	±101	±40
203	236		135	799	±102	±55
155			292	799	±103	±72
009	087	253	136	799	±111	±160
161			295	799	±114	±177

A. Ascent Transition Maps

The flight thermocouple data have been converted from temperature measurements to heating in the form of the laminar scaling parameter of Stanton number multiplied by the square root of Reynolds number ($St \cdot Re^{0.5}$). To first examine the global trends, these results were plotted spatially according to sensor location in Fig. 9 to visualize the changing heating patterns at discrete times (or Reynolds number). In these images, BOLT is pointing to the left and flow is left to right. When plotted in this manner, consistently low heating levels should identify where the boundary layer remains laminar, especially in regions of planar flow (away from the leading edges). Regions of nonlaminar flow tend to easily stand out against the background values, providing an approximate threshold for visualizing the transition front behavior with time. Figure 9 provides several images comparing the two sides at key times along the ascent trajectory. The focus here is with the transition trends associated with the Side B, to identify the range of conditions for which transition has moved from one extreme (all laminar) to the other (all turbulent). The Side A comparisons provide additional insight and context, allowing a first order sanity check for whether the observations seem reasonable. During ascent, these key points are presented in terms of increasing time, which corresponds to decreasing Reynolds number. To these global images, solid black lines have been added manually to illuminate and demark the points of higher heating. The solid lines are only captured in the quadrants that are highly populated with sensors (quadrant A on the Side A and quadrant D for Side B), such that the line locations can be easily traced and verified. In the less populated quadrants, dashed lines are shown that are mirrored version of the solid ones. Since the sensor coverage is less in quadrants B and C, symmetry across quadrants is harder to verify. Thus, the dashed lines are offered as an indicator to check if symmetry is observed. Anomalous results in reference to the dashed lines can be attributed to slight differences in the joint roughness or due to any trajectory maneuvers. These global transition maps are considered qualitative, primarily to indicate approximate incipient and effective times to consider in

subsequent analysis. The time selection is not precise here; these are just representative points to show the global behavior and trends.

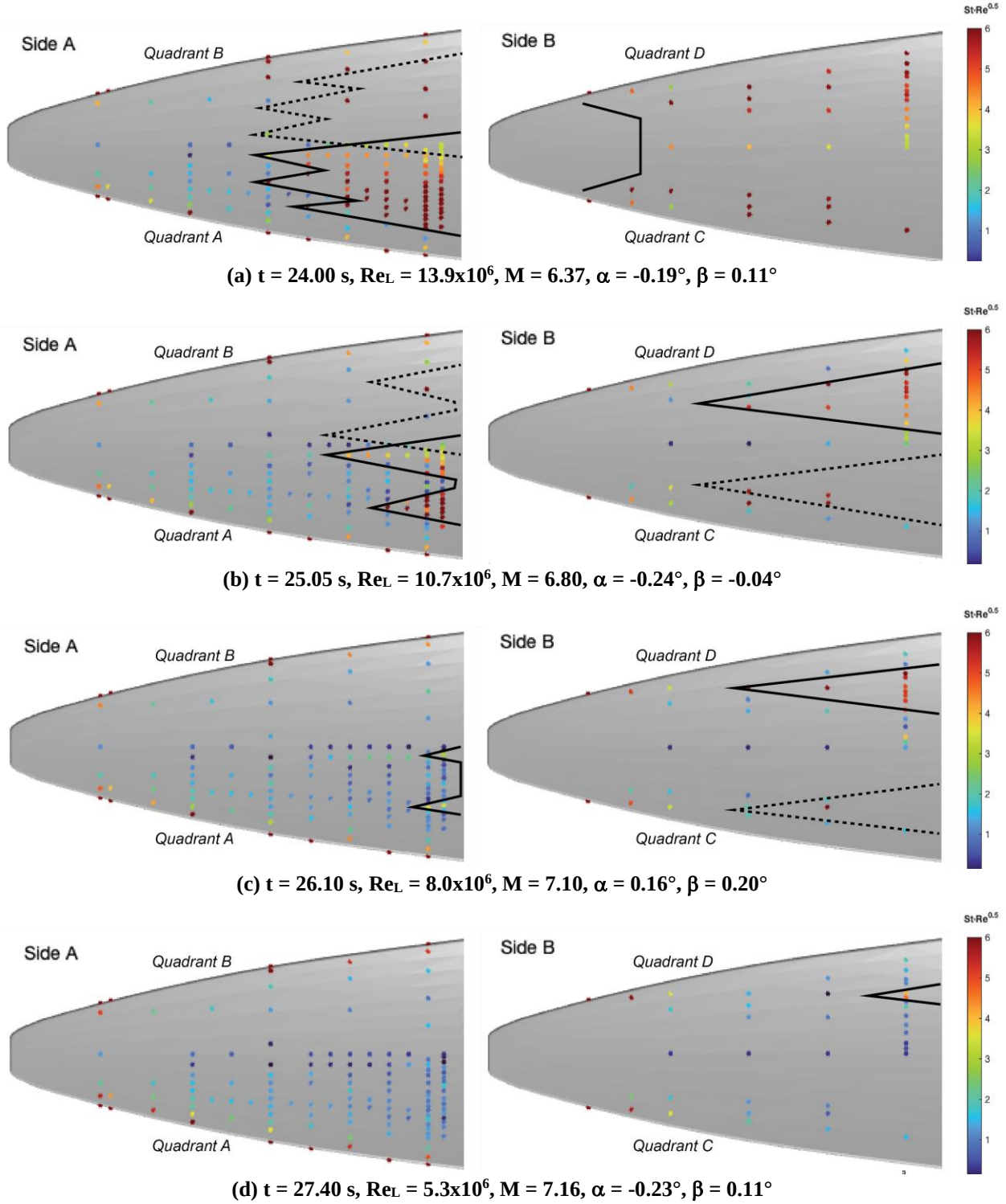


Figure 9. Transition front movement comparison between sides during ascent.

Figure 9a provides a side-by-side comparison at an early trajectory point during ascent ($t=24.0$ s) with a relatively high Reynolds number, $Re_L = 13.9$ million. For this comparison, all the sensors on Side B are shown to have elevated heating levels, whereas only some of the sensors on Side A are similarly elevated. The demarcation line on Side A

where the elevated heating starts is approximately halfway back on the frustum. In quadrant A, from the denser coverage of sensors, the elevated heating seems to coalesce into a series of streaks, represented by the jagged solid line that is shown. The quadrant A data suggests three wedges, one close to the centerline region, one in the outboard region, and one in between, although increased sensor density would be necessary to confirm this heating structure. Similar smooth wall streaks have been observed in ground testing at quiet flow conditions. The dashed line shown on quadrant B mostly supports a mirrored version of this same transition front, although the spatial coverage is not sufficient to claim or refute symmetry with certainty. There are, however, two quadrant B sensors that are not in family with the dashed line. This discrepancy on the smooth side map could be due to the slight alpha/beta conditions shown of that trajectory point ($\alpha = -0.19^\circ$ and $\beta = -0.11^\circ$). The significance of this case is that it shows the relative difference between the sides at sufficiently high Reynolds number indicating the roughness side is fully turbulent while the smooth side is transitional.

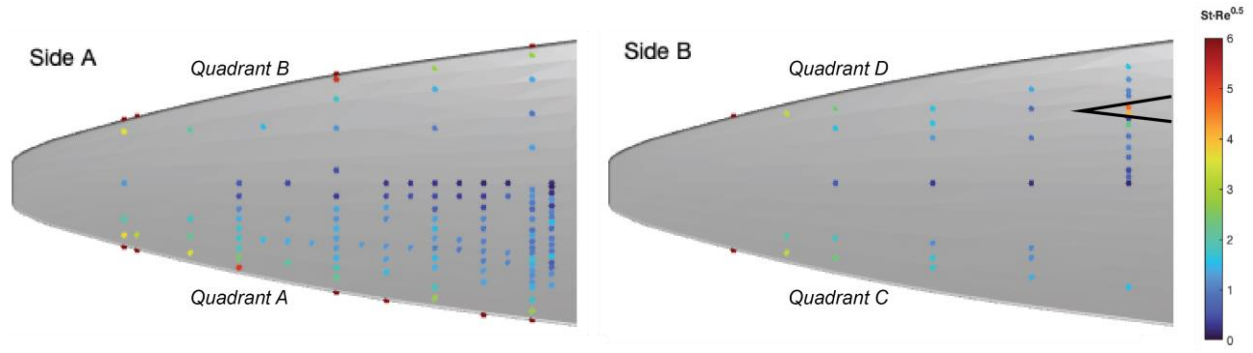
Figure 9b provides the same comparison, slightly later in time ($t=25.05s$), when the Reynolds number has decreased to $Re_L = 10.7$ million. The Side A sensors with elevated heating levels are seen to be receding, now closer to the end of the vehicle. The solid line contains all the elevated heating locations that now reflects only two prominent wedges in quadrant A. One heating streak is near centerline, and the other is roughly midway between the center region and the leading edge. The mirrored dashed line does capture all the quadrant B high heating locations except for one sensor that is just outside (or in front of) the symmetrically placed transition front. Again, this discrepancy may be due to the nonzero alpha/beta for this trajectory point ($\alpha = -0.24^\circ$ and $\beta = -0.04^\circ$). On Side B, all the sensors in the center region and some towards the leading edge show reduced heating relative to the previous Side B image. The remaining elevated heating sensor locations are contained by a wedge, drawn with a solid line in quadrant D. The mirrored dashed line does contain the few quadrant C sensors that are elevated. From the size of the wedge, and the forward extension of higher heating to near the first row of sensors, this would suggest that this Side B trajectory point is close to an effective case with the wedge seeming to emanate downstream of a nosetip joint from the leading edge.

The next condition of interest corresponds to $Re_L = 8.0$ million ($t = 26.1s$), shown in Fig. 9c. Here all Side A sensors have dropped to low heating levels except for two small areas towards the back of the forebody (near centerline and at the midpoint of quadrant A). This could be interpreted as being near an incipient case on ascent for the smooth side. A mirrored dashed line was not included in this case as there are no sensors in quadrant B that indicate higher heating. On Side B, the wedge of higher heating in quadrant D is observed to be receding a little in comparison to the previous case. The mirrored dashed line on Side B captures one elevated heating location and one with low heating, which again could be due to the nonzero alpha/beta values. This roughness side case is significant for showing the progression of transition as the Reynolds number decreases. The systematic behavior of the transition front moving in accordance with Reynolds number provides confidence in the flight measurements and interpretation of trends as they relate to the roughness experiment.

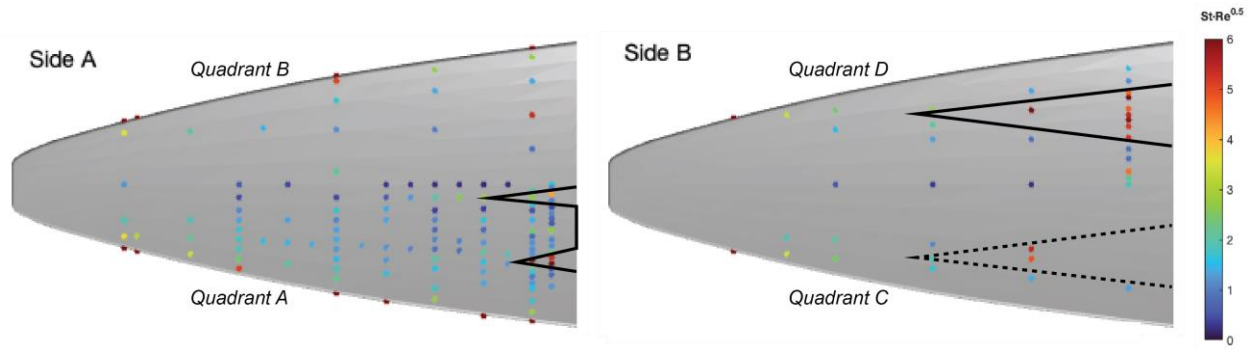
The final ascent condition of interest to the roughness experiment is shown in Fig. 9d, which corresponds to $Re_L = 5.3$ million (for $t = 27.4s$). For this case, all Side A sensors are showing relatively low heating, while only two sensors on Side B (near the end of the frustum on quadrant D) aligned with the upstream leading-edge joints. The small wedge shown by the solid line on Side B is not mirrored as a dashed line for this case, as there are no sensors on the less dense quadrant indicating higher heating. This last case is indicative of an incipient condition for the roughness experiment. Note that a threshold of two sensors in near proximity being at an elevated condition provides a convenient way to filter out random jumps in heating for this qualitative assessment of the boundary layer state. Variations in flight conditions are seen to produce momentary jumps, or dynamic behavior (to be discussed in more detail later), in the heating values if every instance was plotted and shown. In reference to the other flow parameters listed in Fig. 9, these ascent cases correspond to a range of Mach numbers of 6.4 to 7.1, while the vehicle attitude varies somewhat (angles of attack and sideslip within roughly $\pm 0.5^\circ$ based on the data shown in [5]).

B. Descent Transition Maps

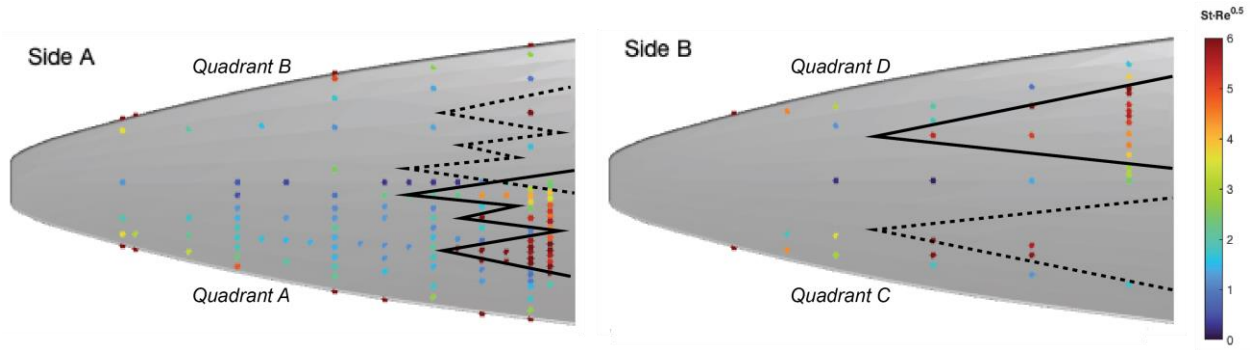
Turning attention to the descent data, Fig. 10 provides a similar set of global images using the same approach to track the development of boundary layer transition. The order of presentation is again with increasing time, which for descent corresponds to increasing Reynolds number. Thus, the general observations provided by these descent case over time will be in reverse order to the previous results. Again, flow is left to right across the surface of BOLT. As before, a solid black line is used in the more densely populated quadrants (A and D) to visualize the transition front as identified by the elevated heating above the background laminar level. The solid line is then reflected as a dashed line on the opposite quadrant (when applicable) to check symmetry. The dashed lines allow assessment of any anomalous results attributable to either trajectory maneuvering or differences across the joint steps.



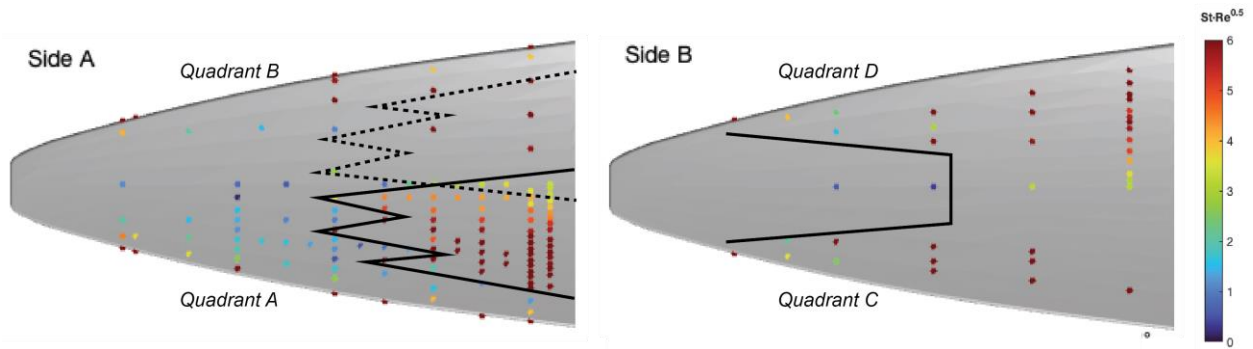
(a) $t = 473.95$ s, $Re_L = 5.4 \times 10^6$, $M = 7.00$, $\alpha = -0.26^\circ$, $\beta = 0.10^\circ$



(b) $t = 475.15$ s, $Re_L = 8.0 \times 10^6$, $M = 7.03$, $\alpha = -0.10^\circ$, $\beta = 0.35^\circ$



(c) $t = 476.10$ s, $Re_L = 10.8 \times 10^6$, $M = 7.03$, $\alpha = -0.03^\circ$, $\beta = 0.15^\circ$



(d) $t = 476.90$ s, $Re_L = 13.9 \times 10^6$, $M = 7.02$, $\alpha = 0.07^\circ$, $\beta = -0.08^\circ$

Figure 10. Transition front movement comparison between sides during descent.

The first descent case, shown in Fig. 10a, corresponds to a Reynolds number of $Re_L = 5.4$ million ($t = 473.95s$). Resembling the last case presented on ascent (Fig. 9d), where almost all sensors (on both sides) indicate lower heating levels, except for two locations on Side B towards the back end of quadrant D. Again, two sensors in proximity with elevated heating was the selection criteria providing an approximate filter for momentary variations in conditions. For Side B, this case likely signifies an approximate incipient condition for descent. There is no mirrored dashed line for this case as there are no sensors within quadrant C that indicate higher heating. Interestingly, both the ascent and descent cases chosen to represent an incipient condition are at nearly identical Reynolds numbers.

Figure 10b provides the descent transition map for $Re_L = 8.0$ million ($t = 475.15s$), which also aligns with the corresponding case identified on ascent (shown in Fig. 9c). With nearly identical flight conditions, similar patterns are observed when comparing Fig. 10b to 9c. For Side A, most of the sensors of quadrant A indicate low heating levels. The exception being two regions towards the back of quadrant A with elevated heating sensors clustered together, one near centerline and the other midway in the quadrant. The dashed line was not mirrored here as none of the quadrant B sensors provide any indication of symmetry across centerline. However, there is one anomalous higher heating sensor on the last row of sensors in quadrant B that could be an indication of asymmetric behavior. Aside from this anomalous result, this case likely reflects close to an incipient condition for Side A. Looking at the Side B results, the small wedge shown previously in quadrant D is now seen to have grown to capture even more elevated heating locations. The mirrored dashed line is supported by a limited set of sensors in quadrant C, with one additional location just outside the reflected wedge. This anomaly is likely a result of the nonzero attitude for this trajectory point (here $\alpha = -0.10^\circ$ and $\beta = 0.35^\circ$), although step size differences between quadrants C and D could also be playing a part. Considering the slight differences in the ascent and descent flight conditions, the consistency observed in the transition maps of Figs. 9c and 10b reflect positively on the quality of the flight data and interpretation of trends.

Figure 10c provides the comparison between the sides during descent for $Re_L = 10.8$ million (at $t = 476.1s$). On both sides, transition is seen to be moving forward on the frustum based on the growing number of higher heating sensor locations (in comparison to the previous images). The Side A transition front shown for quadrant A seems to support three distinct wedges toward the end of the body, which is slightly different from the comparative ascent case shown in Fig. 9b. The significance of three streaks vs. two streaks is not known currently. The mirrored dashed line is only partially supported by the quadrant B data, as one sensor location supports and a second does not. The Side B transition front, shown as a wedge in quadrant D, is seen to be growing larger than the previous case, with more sensor locations indicating elevated heating. The mirrored dashed line shown in quadrant C is mostly supported by the limited set of sensor locations, although there are elevated sensors outside the dashed wedge. Like the ascent case, shown in Fig. 9b, this case is nearly an effective roughness condition during descent, based on the turbulent wedge extending close to the first row of sensors.

The last descent case to be presented is shown in Fig. 10d, for $Re_L = 13.9$ million (at $t = 476.90s$). These results are comparable to the first case from ascent (Fig. 9a), which was at a similar Reynolds number. Most of the Side B sensors are shown to have elevated heating rates, while roughly half of Side A are similarly elevated. The Side A transition front shown in quadrant A, which suggests three heating wedges, is nearly identical to the results shown in Fig. 9a. The quadrant B results tend to support the mirrored dashed line, although additional high heating sensors are outside of the wedge. The general consistency in trends between ascent and descent, both in terms of the matching Reynolds number at key trajectory points and the similar looking transition maps for each case, provides an initial assessment of data credibility with the BOLT-1B flight results.

C. Comparison of Measured to Predicted

As a second assessment of the credibility of the flight data and analysis, Fig. 11 provides comparisons of heating traces (based on Stanton number), during the ascent and descent test windows for four symmetric thermocouples (in all four quadrants), against the corresponding computed results. The location for these thermocouples is far downstream and nearer to the leading edges, where roughness differences between quadrants are less important. The computational predictions were based on the nominal flight trajectory, assuming no α and β variations. The measured results initially follow near the trends of the turbulent predictions during ascent (Fig. 11a), as expected, then all four sensors indicate a switch to the laminar trace at roughly the same time (~ 25 s). Similarly, during descent (Fig. 11b), the measured values are initially aligned with the laminar trace and then all jump to the turbulent trendline also at a nearly consistent time (~ 476 s). The close agreement between measured (all at counterpart locations) and predicted heating values further validates the quality of the BOLT-1B flight data. The sinusoidal variations during the late stages of the turbulent portion of ascent data reflect the minor variations in α and β during flight. Also, the relatively close agreement in the time of transition between all four of these sensors would suggest that this location (which is far back

and outboard) is not one highly influenced by the roughness differences between the two sides, consistent with the nominal streamlines shown in Fig. 8.

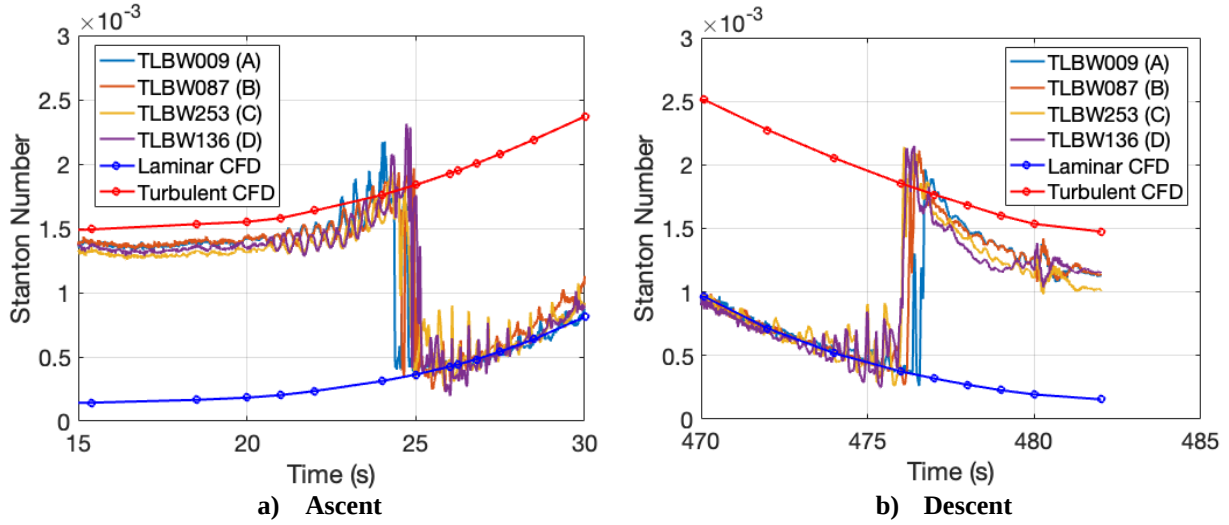


Figure 11. Comparison of heating at symmetric locations across quadrants to nominal predictions.

D. Roughness Side Transition Trends

Having established the general trends in comparison of the global transition maps from both sides anchored to computational results, the next step is to extract the key conditions relatable to the BOLT-1B roughness experiment. The goal is a more precise determination of the incipient and effective points from the movement of transition directly behind the roughness source, driven by the exaggerated steps on the secondary side joints. The previous discussion revealed the existence of turbulent wedges on the roughness side that were produced at lower Reynolds numbers than required for streak heating on the smooth side, suggesting disturbances aligned with the leading-edge steps predominate any naturally generated instabilities. The data will now be presented below not based on time, but instead as a function of length Reynolds number. The incipient condition is found from the onset of transition at the furthest thermocouple along the sensor array, while the effective condition is found from the thermocouple closest to the roughness source. In a general correlative sense, the incipient and effective points can be used to establish the minimum local conditions required at the roughness source to initially induce transition onset in the far field and the maximum conditions required to move the transition front as far forward as possible, respectively.

First looking at the vehicle centerline, Fig. 12 provides a series of heating traces on the roughness side during both the ascent and descent test windows, which can be used to identify and track the movement of transition. For consistency, the point of departure from the laminar trendline is taken as the onset point of interest during both ascent and descent. In some cases, the onset point can be tough to determine, likely due to a sensitivity of transition to vehicle maneuvers, thus the present interpretation will be marked on the figures with arrowheads. As shown in Fig. 12a (ascent), the marks and Re_L values at the point of transition onset for each sensor location reveals systematic movement along centerline. The two most upstream sensors in the centerline series indicated transition onset at the same time (an abrupt jump on the surface) and thus have the same value of onset Reynolds numbers, but then transition is seen to incrementally move past the next two sensors in the series. For ascent, the incipient point is established by sensor 257 (shown by the purple trace) and occurs at $Re_L = 7.4$ million. The corresponding effective point is determined by sensor 256 (blue trace), which indicates transition onset at $Re_L = 12.4$ million. During descent (Fig. 12b), a similar behavior of transition moving abruptly across the two most upstream sensors is seen, although there's enough of a delay in time as indicated by the small delta in Re_L . The rest of the transition onset movement is incremental along centerline. Here, the incipient point (again, identified by sensor 257) is at $Re_L = 7.2$ million, while the effective point (sensor 256) is at $Re_L = 15.3$ million. The reason for a larger value of an effective Re_L during descent is not presently known, but it could be related to the step height reduction during flight (noted in Table 1). The timing of the movement of transition across sensor 257 corresponds to the widest amount of time possible, with onset occurring at that location at the beginning of ascent and then at the end of descent. This duration would allow the most change in the step height to occur based on thermal effects. These incipient and effective points for both ascent and descent provide target conditions applicable for investigating trip correlations for the centerline joint step (2D).

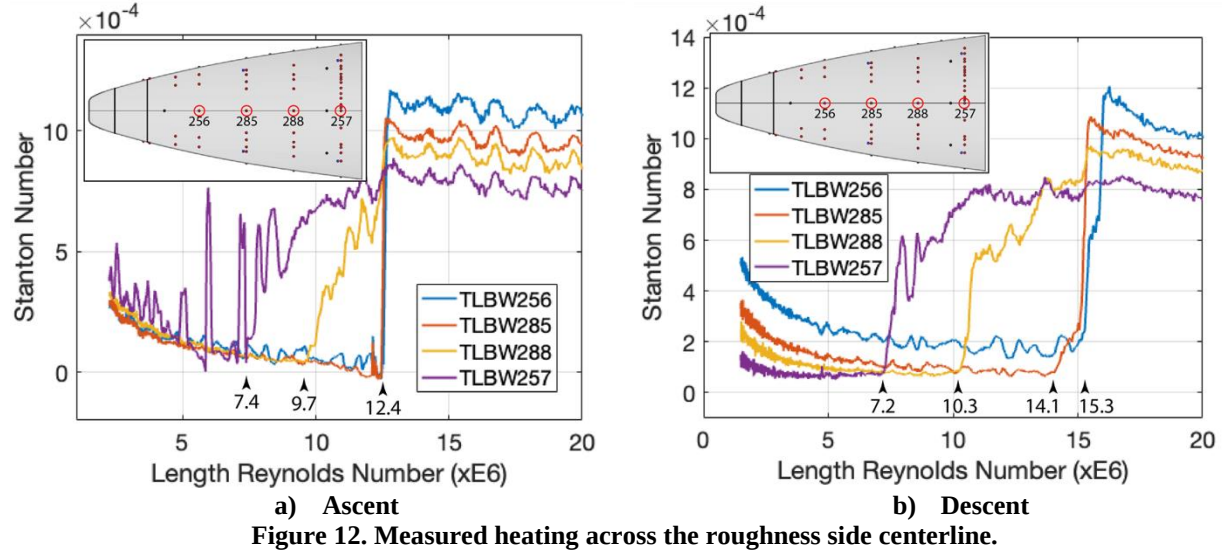
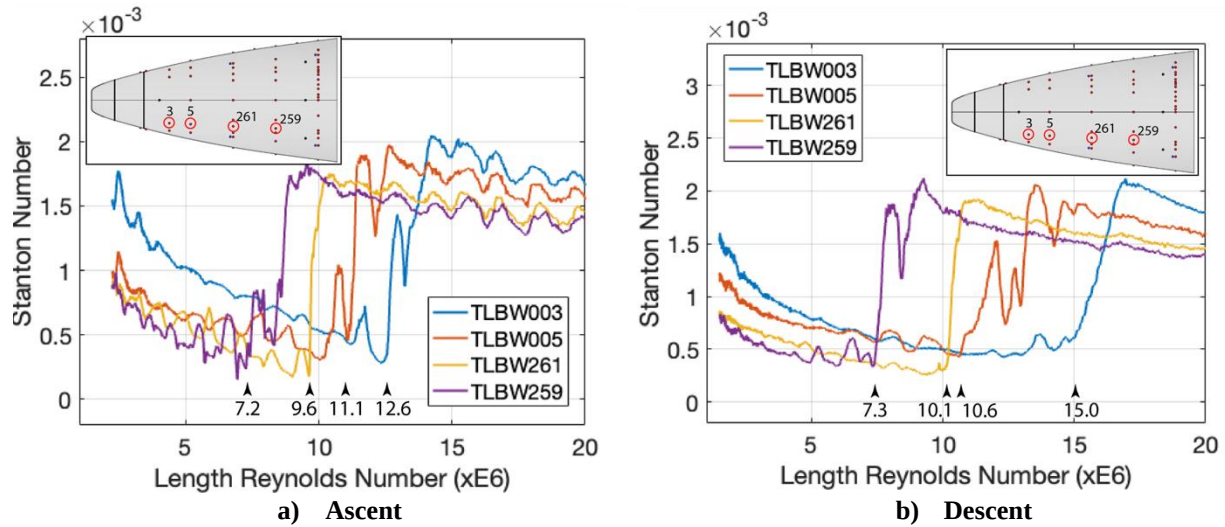


Figure 13 provides a similar set of plots for ascent and descent showing the heating trends along an array of sensors aligned along streamlines propagated from the upstream step in quadrant C. Transition onset is seen to incrementally move along this sensor array as a function of Reynolds number, as would be expected. Note, this array had two potential sensors in the last row (132 or 300) that were nonfunctional during flight. Thus, the nearest working sensor at the backend of this array is 259 (from the row earlier). Using this location provides an incipient point of $Re_L = 7.2$ million during ascent and $Re_L = 7.3$ million during descent. For the effective cases, the sensor closest to the disturbance source is 003, which indicates $Re_L = 12.6$ million during ascent and $Re_L = 15.0$ million during descent. Functionally, the set of four sensors that represent this array have shifted forward in comparison to the set of four sensors on centerline, as is seen by comparing the inset images of Figs. 12 and 13. Thus, the derived incipient and effective cases are not directly relatable. The nearly identical values of transition onset derived from these first two arrays are incidental and misleading due to the shift in axial locations of the available measurements. If you consider the conditions at sensor 288 (Fig. 12) in comparison to sensor 259 (Fig. 13), which are in the same row, the Re_L at the point of transition onset is lower for the quadrant C array (9.7 vs. 7.2 and 10.3 vs. 7.3 for ascent and descent, respectively). A similar conclusion is found looking at the comparative sensors near the front (for the effective case), sensor 256 (Fig. 12) and sensor 5 (Fig. 13) provide a lower transition Reynolds number behind quadrant C than on centerline (12.4 vs. 9.6 and 15.3 vs. 10.6 for ascent and descent, respectively). The inference is that if one of the sensors had worked in the last row, the incipient Re_L based on a measured point of transition onset would be lower than that provided by sensor 259.



For comparison, Fig. 14 provides similar figures (heating vs. Re_L for ascent and descent) from the sensor array aligned with the streamlines propagated from the upstream nosetip step of quadrant D. Once again, transition onset is seen to incrementally move along this sensor array, as expected. Here, the available sensors are comparable in streamwise location to those shown on centerline (compare the inset images of Figs. 12 and 14). The sensor from the last row (298) of this array identified an incipient condition at $Re_L = 5.0$ million during ascent and at $Re_L = 4.9$ million for descent. This array, however, had a nonfunctional sensor in the first row (254). Thus, the next sensor (267) was used to identify effective conditions, which provided $Re_L = 12.8$ million during ascent and at $Re_L = 16.8$ million for descent. Again, this shift in sensor locations between quadrants C and D muddles any direct comparison of incipient and effective conditions between them. The quadrant D sensor array is aligned with the centerline array, which makes comparisons of onset trends between these two locations more meaningful. Comparing quadrant D to centerline, the incipient conditions correspond to $Re_L = 5.0$ million and 4.9 million compared to $Re_L = 7.4$ million and 7.2 million, for ascent and descent, respectively. The effective comparisons between them are $Re_L = 12.8$ million during ascent and 16.8 million during descent, in quadrant D versus $Re_L = 12.4$ million during ascent and 15.3 million during descent, along centerline. Since the incipient condition of quadrant D occurs at a significantly lower Reynolds numbers than obtained on centerline, this supports the earlier hypothesis of the leading-edge steps steering the transition process for the roughness experiment. Thus, the missing quadrant C sensor on the back row would have likely provided a similar increment in transition onset to that found in quadrant D.

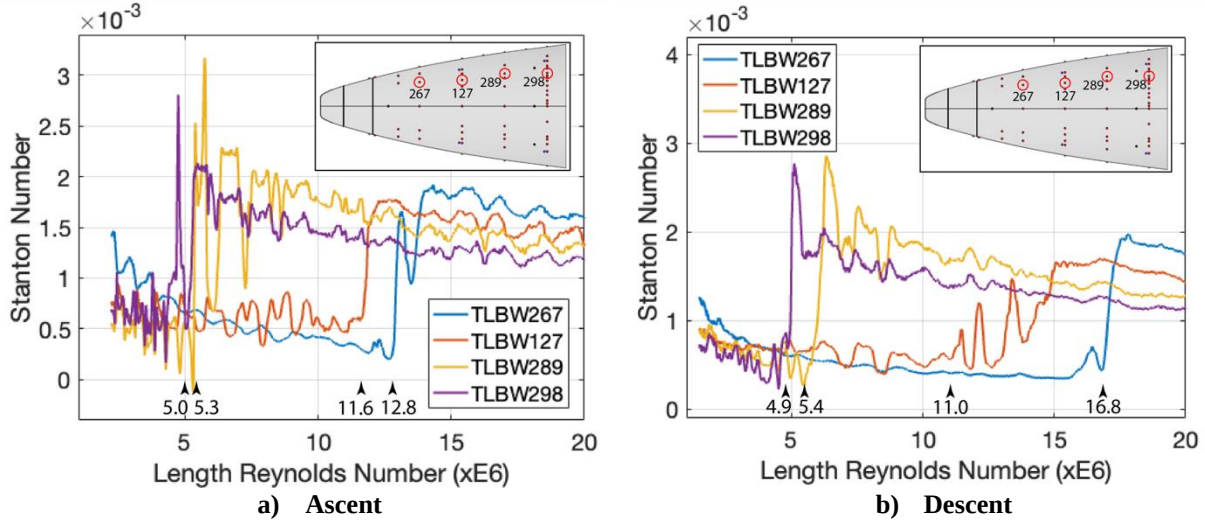


Figure 14. Measured heating along inboard sensor array of quadrant D.

Functionally, the flight measurements have been shown to provide well behaved trends showing transition on the roughness side linked to the region of the leading edges near the joint steps. However, due to damaged sensors in critical locations, meaningful comparisons between quadrants are harder to establish. Further analysis (for instance, perhaps machine learning approaches could fill in missing details) may be required to develop better (or more accurate) extrapolation to fill in for the missing data points. To that end, the next section will provide direct comparisons between symmetric sensor locations within quadrants allowing estimation of differences to establish sensitivities.

E. Symmetric Sensor Comparisons

This section will present direct comparisons between counterpart sensors in the various quadrants to more accurately ascertain the flight measurement differences with linkage to established step height dimensions. Perhaps the following measured results at locations in vicinity to the missing sensors can also be used to improve the assessment of relevant incipient and effective values across all quadrants. These comparisons will start at the back row of sensors, providing insight first on the incipient results between quadrants, and then increment forward station by station to reflect on the effective results.

Figure 15 provides the comparison of heating versus length Reynolds number (both ascent and descent) for counterpart locations of sensor 121 in quadrant D. There were two measurements on the smooth side (157 in quadrant A and 183 in quadrant B) that were located symmetric to sensor 121. The other roughness side sensor (132 in quadrant C) was nonfunctional during flight. From these comparisons, a difference between the smooth and rough sides is established for quadrant D only. The two smooth side sensors are shown to indicate transition onset at similar Reynolds numbers

of ~ 7.5 million during ascent. Quadrant B indicates a slightly lower value of 7.2 million versus quadrant A at 7.6 million, but both Side A sensors oscillate between laminar and turbulent heating levels, perhaps due to alpha/beta maneuvering. During descent, the values of transition onset shift slightly to higher values, with 7.6 million for quadrant B and 8 million for quadrant A. Again, the smooth side data suggests that transition onset may be sensitive to small changes in alpha/beta. For the roughness experiment, the quadrant D sensor indicates transition at a lower Reynolds number of 4.8 million during ascent and 5.0 million during descent. The differences seen between ascent and descent for all three sensors would be consistent with the noted decrease in step heights due to thermal effects (in Table 1b). The missing measurements in quadrant C can only be speculated to have been like the results observed for quadrant D. Thus, the subsequent counterpart comparisons at nearby sensor locations are provided for consideration.

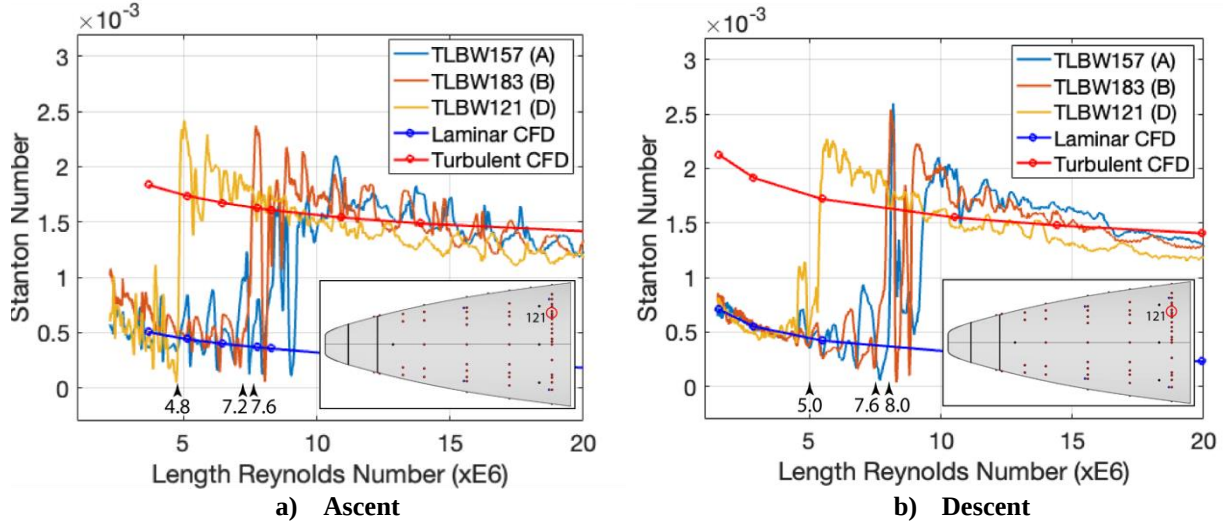


Figure 15. Comparison of counterpart measurements to sensor 121 (quadrant D).

Nearby, sensor 298 in the last row of quadrant D is aligned with 310 in quadrant A. Sensor 300 in quadrant C was nonfunctional during flight. Figure 16 provides the heating profile comparison for both ascent and descent between quadrants A and D. The transition onset observations for this counterpart location are consistent with the previous results with quadrant A jumping from laminar to turbulent heating levels at 7.3-7.6 million and quadrant D at 5.0-4.9 million, with the range indicating ascent and descent, respectively. With consistent observations between the two different locations shown in Figs. 15 and 16, the proximity of these sensors (within 10 mm of each other on the same station) offers some context to the broadness of the disturbances influencing incipient transition. On both sides, onset may be sensitive to the vehicle maneuvers while still providing relatively consistent results. The Side B trace (298) in particular has an oscillation during ascent that increases the uncertainty of the chosen value of transition onset.

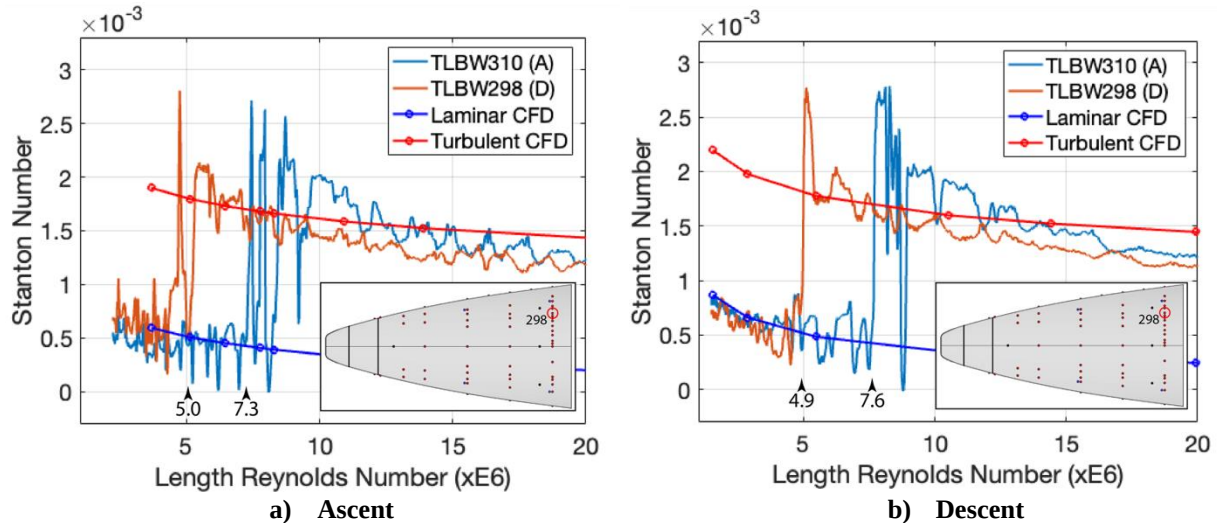


Figure 16. Comparison of counterpart measurements to sensor 298 (quadrant D).

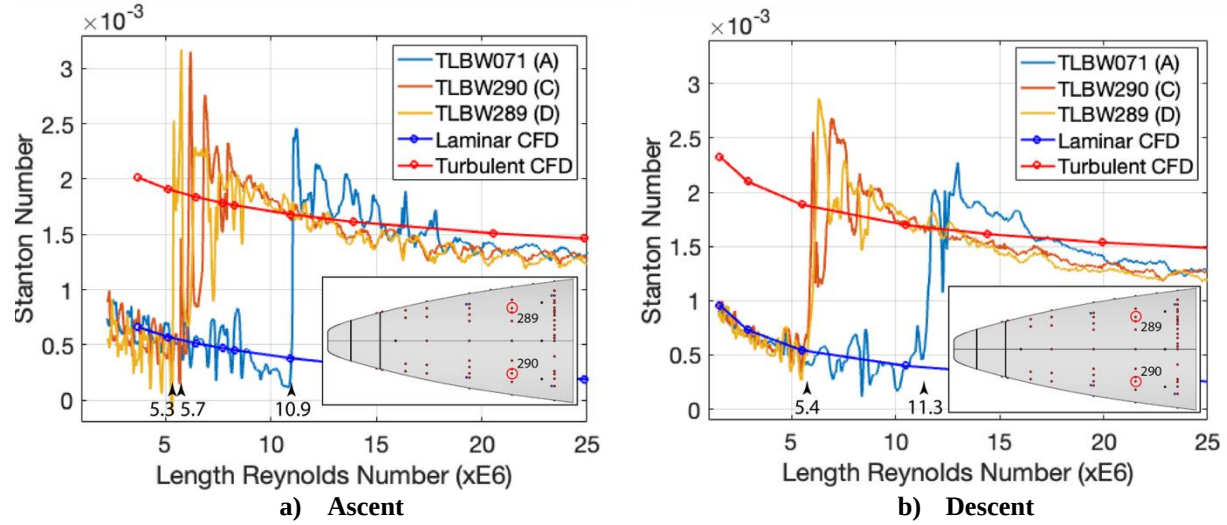


Figure 17. Comparison of counterpart measurements to sensor 290 (quadrant C) and 289 (quadrant D).

The next comparison is for a location on the station ahead of the back row, which provides counterpart measurements in quadrant C (sensor 290), quadrant D (289), and quadrant A (71). Figure 17 provides the heating profile comparisons during both ascent and descent allowing for relative assessment between those three quadrants (A, C, and D). Due to the forward shift in sensor location, the onset Reynolds numbers have shifted somewhat with quadrant A jumping from laminar to turbulent at 10.9 and 11.3 million (ascent and descent, respectively), while quadrants C and D are on the order of 5.5 million. During ascent, quadrant D has a slightly lower Reynolds number than quadrant C (5.3 vs 5.7), but they are both identical values during descent (5.4). A lower onset measurement would imply quadrant D had the bigger step, which is true if we only consider step location 4 as the critical influence. Table 1b reveals the largest rearward facing step at the upstream joint is at location 3 (which is adjacent to the LE) with UC3 having a step of $\sim 0.023''$ in contrast to $\sim 0.016''$ at UC4 and $\sim 0.022''$ at UD4. Since the boundary layer is thinnest at location 4, the two locations may not be on equal footing when considering the incipient condition emanating from the LE step.

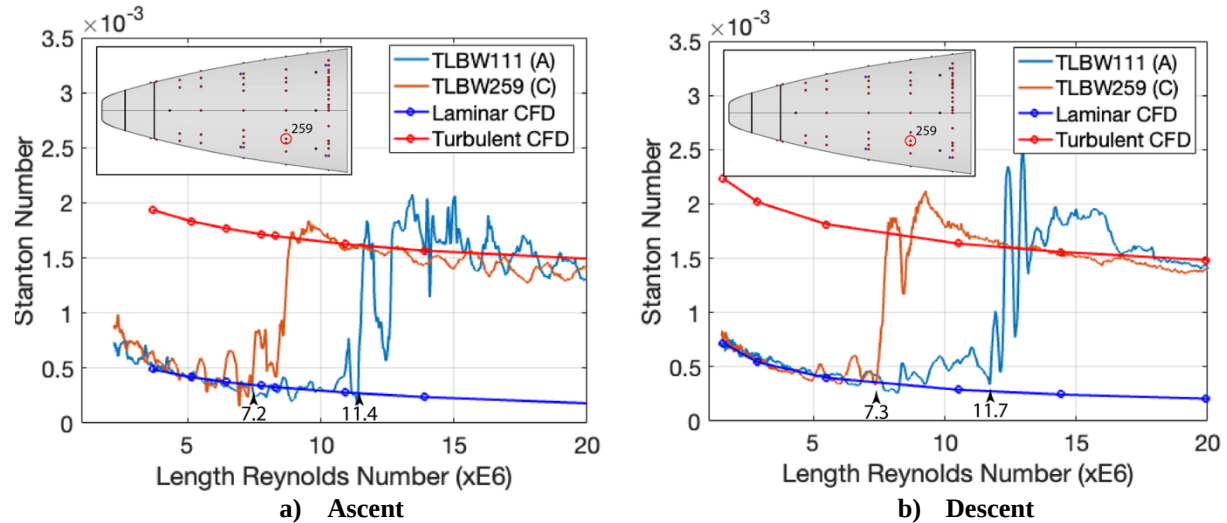


Figure 18. Comparison of counterpart measurements to sensor 259 (quadrant C).

A nearby location on this same second-to-last station is provided in Fig. 18, which shows the ascent and descent heating profiles comparing quadrant C (sensor 259) to quadrant A (111). These results provide a direct assessment of the differences between quadrants A and C. Relative to the previous figure, these transition onset results have shifted to the right slightly, with of 11.4 to 11.7 million (ascent/descent) for quadrant A versus 7.2 million for quadrant C on ascent and 7.3 million on descent. The slightly higher Reynolds number results here (as compared to Fig. 17) could be an indication that this location is outside the critical location of the disturbance path emanating from the LE. The shift in proximity at this station (as indicated in Table 2c) reveals sensor 259 is 15 mm inboard of sensor 290 (both in

quadrant C). Thus, the change in transition onset Reynolds number from ~ 5.7 million (sensor 290 in Fig. 17) to 7.2 million (sensor 259) within this station is likely an indication that the outboard sensor (290) is closer to the critical disturbance path.

Moving ahead one station to the middle row, provides a direct comparison during both ascent and descent between quadrants C and D, shown in Fig. 19 for sensors 261 and 127, respectively. This one is a direct comparison across both quadrants of the rough side. Consistent with the trends already established as ascent/descent differences, there is a similar shift here. Quadrant C provides the lower Reynolds number condition at the point of transition onset with 9.6 million during ascent and 10.1 million during descent. This shift is likely due to the thermal effects during flight reducing the size of rear facing step. Transition onset for quadrant D is observed during ascent at 11.6 million and 11.0 million during descent; however, the end of transition during descent is delayed, perhaps due to some α/β sensitivities. The results at this location are inconsistent with the observation earlier in reference to Fig. 17, where it was suggested that quadrant D might have the bigger step. These results would suggest that quadrant C has the bigger step and by a measurable margin. That is only true if the steps at location 3 (the LE edge) are included as a contributing factor regarding step effects. Speculation for how the two diametrically opposed observations could be compatible is that the incipient condition may be driven more by the thinner boundary layer at location 4, but then as transition starts to move forward on the body, the inboard part of the LE (location 3) could then start to be a factor. The three-dimensional nature of leading edge as it relates to any observation of step effects is a complicating factor in deciphering cause and effect as it relates to the measured results.

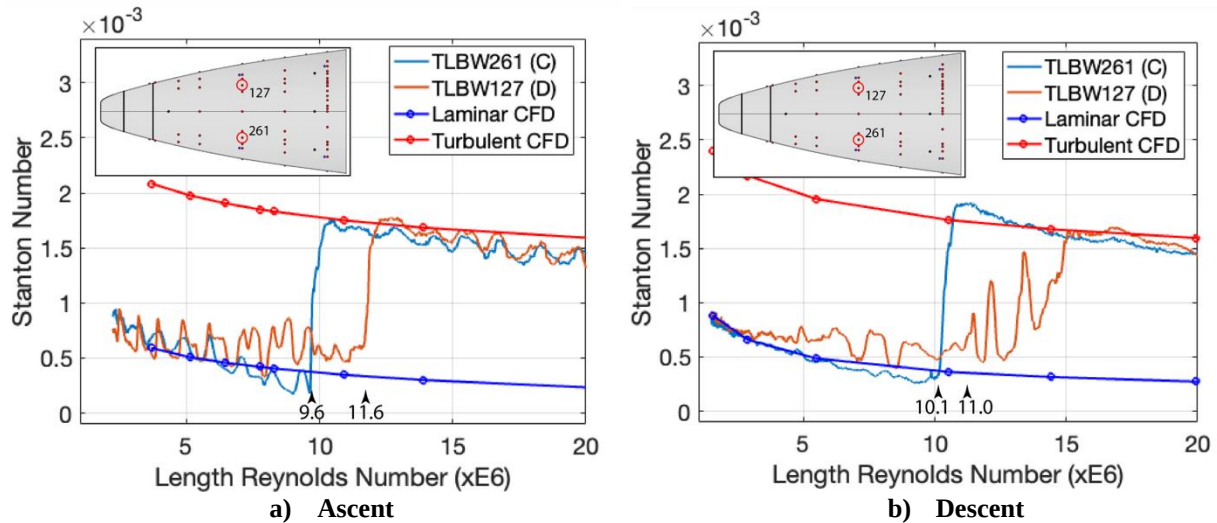


Figure 19. Comparison of counterpart measurements to sensor 261 (quadrant C) and 127 (quadrant D).

In the next upstream row, symmetric locations are found in quadrants A (sensor 93), C (5), and D (267), shown in Fig. 20 for both ascent and descent. For these plots, the x-axis has been extended to an even higher lengths Reynolds number to allow for Side A transition onset results to be captured. As can be seen in the plots, the transition onset for the smooth side occurs at a higher Reynolds number than what is considered the “test window”. During ascent, onset on the smooth side (with sensor 93) occurs at around 21.1 million, while during descent it occurs closer to 28.7 million. This shift to a higher value of Re_L during descent is consistent with the noted reduction in the step height shown in Table 1a for UA4 ($\sim 34\%$ decrease). For the rough side, the trends observed here are consistent with the observation noted with the previous figure about quadrant C (sensor 5) having the lowest value of transition onset, with a value of roughly 11.1 million during ascent and 10.6 million during descent. Quadrant D (sensor 267), on the other hand, reveals a transition onset Reynolds number of 12.8 million during ascent and 16.8 million during descent. The shift in value between ascent and descent for quadrant D but not C is somewhat surprising. Both rough side quadrants should have experienced a similar percentage of thermal change of the joint-step heights, as can be verified by comparing the values shown in Table 1b.

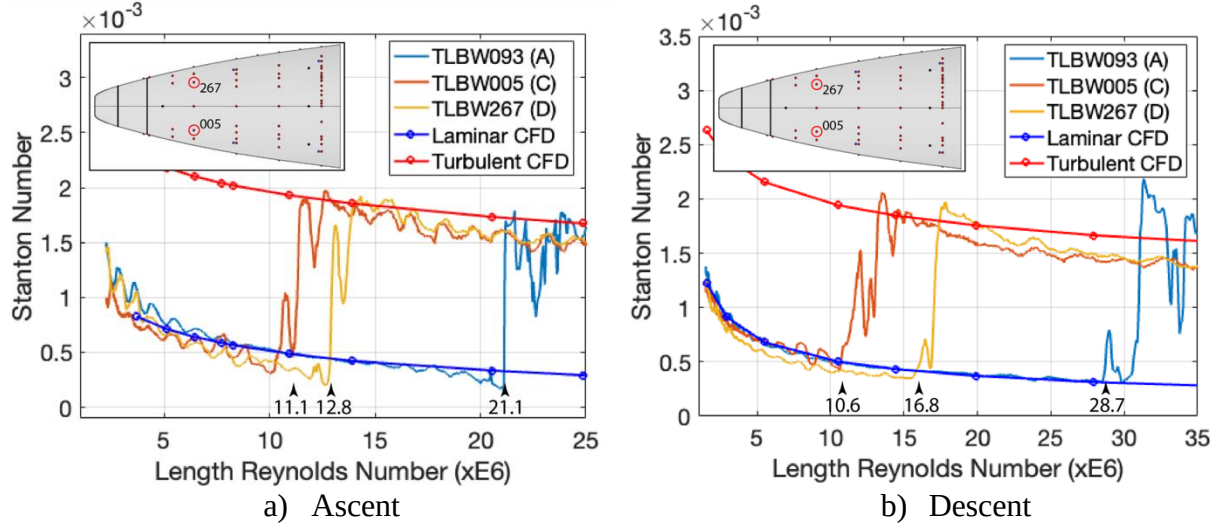


Figure 20. Comparison of counterpart measurements to sensor 5 (quadrant C) and 267 (quadrant D).

The final set of ascent/descent plots are shown in Fig. 21, for a counterpart location on the first row or station, which is most applicable for determining the effective value of transition onset across the quadrants. This comparison of heating traces provide insight into quadrants A (sensor 101), B (31), and C (3). The sensor in quadrant D (254) was nonfunctional during flight. At this location, the smooth side transition onset values can be seen to be quite high, at over 21.1 million for quadrant A and close to 22.4 million for quadrant B during ascent, while both increasing to over 35 million during descent. The ascent traces for the smooth side reflect the oscillatory behavior between laminar and turbulent heating levels, suggesting a sensitivity to alpha/beta maneuvers. For quadrant C, transition onset is observed at around 12.6 million on ascent and at 15.0 million on descent. Based on the previous counterpart results shared, expectations would suggest that a working quadrant D sensor would provide Reynolds numbers just slightly higher than the results for quadrant C.

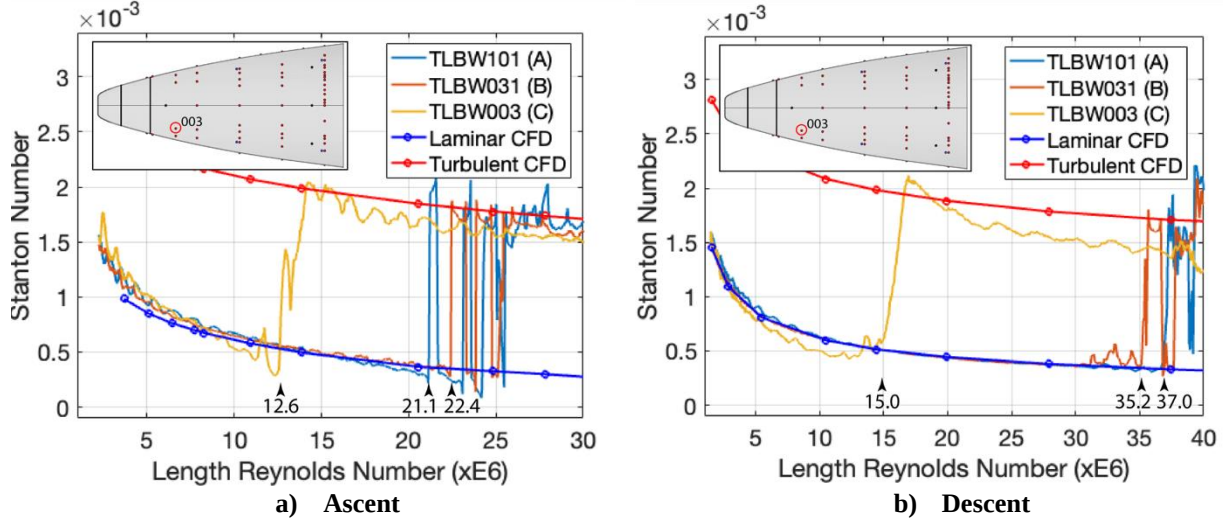


Figure 21. Comparison of counterpart measurements to sensor 3 (quadrant C).

As a general recap to this section, transition onset Reynolds numbers were shown to be consistently lower for the roughness experiment, providing incipient results on the order of 5 million for Side B versus 8 million for Side A. Thus, the Side B joint steps were large enough to influence transition onset at the end of the vehicle before the generation of any naturally occurring instability modes are established on the smooth side. Effective results were observed on Side B at Reynolds numbers ranging from 12.6 to 15.0 million (the difference between ascent and descent, respectively), while requiring ~22 to ~35 million for Side A. The loss of a few key sensor locations blocks the extraction of specific values of incipient and effective conditions across all four quadrants. Other locations were provided in this section for additional context for further analysis (perhaps with the use of machine learning techniques to establish an estimate of the missing results).

F. Comparison to Shuttle Correlation

The design and sizing of the roughness experiment dedicated to studying joint step effects for the original flight (BOLT-1A) was based on correlations developed with step data acquired in the Purdue quiet tunnel [6]. The wind tunnel effort that supported the correlation development was described in [18] where a few correlations were examined based on the ground-based data. One of those correlations utilizes boundary layer edge properties, which is easy to examine here using the computational database already established at actual flight conditions for the heating comparisons. This correlation was developed to support the Shuttle program and was the basis of the Return-to-Flight Boundary Layer Transition Prediction Tool that has previously been shown to compare favorably to test data from a Shuttle flight experiment [19]. From the Purdue results, the basic correlation utilized the momentum thickness Reynolds number (Re_θ), the edge Mach number (M_e), and the boundary layer thickness (δ) along with a curve coefficient ($C=70$ for rear facing steps) to predict the step height threshold (k) for transition onset at the back of the model. The equation used here is:

$$k = C \cdot \delta / (Re_\theta / M_e) \quad (1)$$

This correlation (with $C=70$) based on the boundary properties from the computational database for actual flight conditions (with no α/β), compared against the predicted step height variations for the upstream leading edges of each quadrant, are shown in Fig. 22 for both ascent and descent. Like the original correlation plot in [6], the x-axis reflects increasing time which corresponds to decreasing Reynolds number during ascent and increasing Reynolds number during descent. Note that for each quadrant, the largest step (of either location 3 or 4) is used to compare against the step height prediction, since a predominance of the previous symmetric sensor comparisons revealed lower values of transition onset in quadrant C. As mentioned previously, quadrant C only has the larger rear facing step height value if location 3 near the leading edge is also considered. Using the measured incipient result for quadrant D as our “validation” case, the predicted value of the step height at UD4 crosses the threshold of the Shuttle correlation (based on $C=70$) at a little over 5 million during both ascent and decent. The measured result was 4.8 million for ascent and 4.9 million for descent, likely within any experimental uncertainty (for both the wind tunnel and flight results), all things considered. Thus, the expectation for quadrant C, based on the larger step height at UC3, is that the corresponding incipient result should have been on the order of 5 million if the sensor in the last row had been working. Next, based on the step heights for both quadrants on the smooth side, the correlation would suggest that both quadrant A and B should have been in the vicinity of 16 or 18 million. The fact that both Side A quadrants were measured to be much lower, at closer to 8 million, might suggest that the incipient results on the smooth side are not due to step effects, and instead due to the natural transition modes already at play and shown with the global transition maps to indicate a multi-streaked transition front.

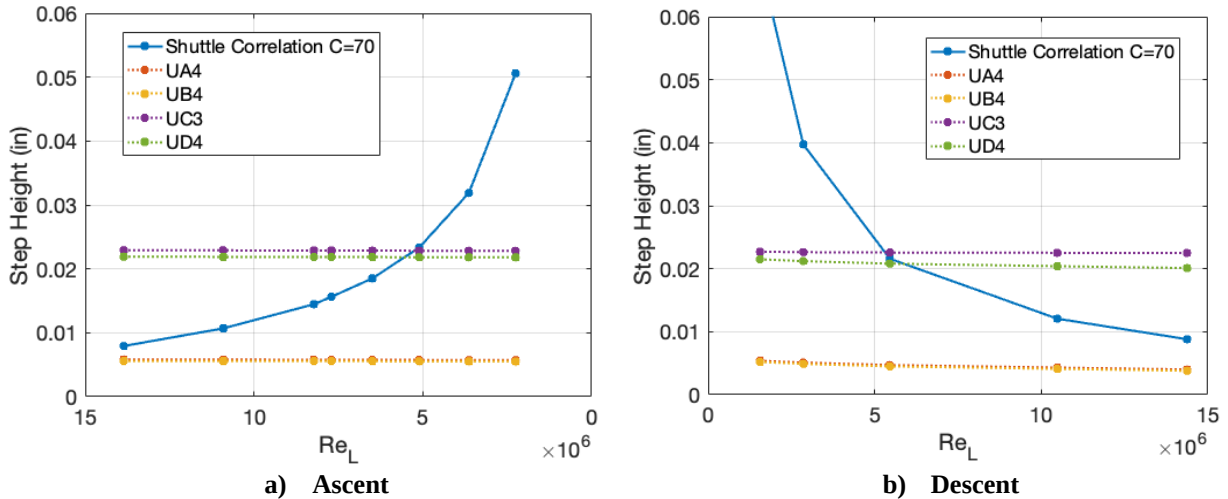


Figure 22. Shuttle correlation based on curve coefficient from Purdue BAM6QT in comparison to largest leading edge step heights in each quadrant.

Having shown that the BOLT-1B flight data compares favorably against the original correlations developed to guide the design of the roughness flight experiment, a postflight numerical investigation of the step effects based on as-flown conditions in a follow up to the initial assessment captured in [20] seems warranted.

V. Summary

The successful launch of BOLT-1B at Andøya, Norway in Sept. 2024 has provided a wealth of flight data requiring in-depth analysis. The vehicle was shown to have performed nearly flawlessly, achieving the desired Mach 7 flight conditions in a ballistic trajectory that provided both ascent and descent science windows. The thermocouple data has been converted to heating, allowing for easy identification of the boundary layer state during flight. The present paper is focused on the Side B roughness experimental data, which was designed to investigate joint step effects. The present analysis has shown that the observed trends of transition behavior in comparison between the two sides (smooth to rough) are well behaved and systematic. Comparisons between the measurement in the four quadrants and two sides have revealed the following observations:

- Global transition maps were provided that reveal the development and movement of transition fronts and turbulent wedges on Side B that trace to the leading edges in the vicinity of the joints.
- The thermocouple measurements, after conversion to surface heating, compare favorably with both laminar and turbulent heating level predictions, thus providing confidence in the overall flight data and the extraction of transition onset results for the roughness experiment.
- The transition onset Reynolds numbers representing an incipient condition are lower on the roughness side, on the order of 5 million for Side B versus 8 million for Side A. The roughness experiment was shown to include steps large enough to force transition onset prior to the generation and breakdown of the naturally occurring instability modes on the smooth side.
- Effective results were observed on Side B at Reynolds number ranging from 13 to 15 million (difference between ascent and descent), while requiring 22 to 35 million for Side A.
- Damaged sensors in key locations makes extraction of direct comparisons of the incipient and effective conditions across all four quadrants more difficult. Other locations were provided for additional context that might warrant further analysis (perhaps machine learning techniques could be utilized to inform on the missing results). Differentiating behind the two joint locations (upstream vs. downstream) was not attempted here due to missing sensors.
- The roughness side flight data compare favorably to the original ground-based step correlation used to design the original experiment.

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