Global Infrared Observations of Roughness Induced Transition on the Space Shuttle Orbiter

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ABSTRACT

High resolution infrared observations made from a mobile ground based optical system captured the laminar-to-turbulent boundary layer transition process as it occurred during Space Shuttle Endeavour's return to earth following its final mission in 2011. The STS-134 imagery was part of a larger effort to demonstrate an emerging and reliable non-intrusive global thermal measurement capability and to complement a series of boundary layer transition flight experiments that were flown on the Shuttle. The STS-134 observations are believed to be the first time that the development and movement of a hypersonic boundary layer transition front has been witnessed in flight over the entire vehicle surface and in particular, at unprecedented spatial resolution. Additionally, benchmark surface temperature maps of the Orbiter lower surface collected over multiple flights and spanning a Mach range of 18 to 6 are now available and represent an opportunity for collaborative comparison with computational techniques focused on hypersonic transition and turbulence modeling. The synergy of the global temperature maps with the companion in-situ thermocouple measurements serve as an example of the effective leveraging of resources to achieve a common goal of advancing our understanding of the complex nature of high Mach number transition. It is shown that quantitative imaging can open the door to a multitude of national and international opportunities for partnership associated with flight-testing and subsequent validation of numerical simulation techniques. The quantitative imaging applications highlighted in this paper offer unique and complementary flight measurement alternatives and suggest collaborative instrumentation opportunities to advance the state of the art in transition prediction and maximize the return on investment in terms of developmental flight tests for future vehicle designs.

1.0 INTRODUCTION

The purpose of this paper is to encourage the consideration of quantitative high spatial resolution imaging measurement techniques to complement more traditional discrete surface instrumentation methods supporting the needs of the hypersonic flight test community – with an emphasis on the engineering community involved with the prediction of hypersonic boundary layer transition (BLT). The benefits of high-resolution observations go beyond simple photo documentation and include correlation of critical flight events with on board instrumentation and flight anomaly reconstruction. In terms of hypersonic transition, a brief synopsis of transition and the impact on vehicle design is first presented. The role of flight test in the vehicle design process is then discussed. A recently demonstrated capability for obtaining global heating measurements on the U.S. Space Shuttle Orbiter lower surface during hypersonic re-entry is introduced. A high spatial resolution thermal observation of the Orbiter during the Space Transportation System (STS)-134 re-entry is then presented to highlight existing capability to globally detect the onset of hypersonic transition along with the measurement of surface temperatures corresponding to turbulent heating. To advance our understanding of the hypersonic BLT process, collaborative opportunities for data sharing, development of a next generation imaging system and/or the application of quantitative imaging to future flight tests are offered.

1.1 Boundary Layer Transition & Vehicle Design

Whether supporting the development of advanced space transportation concepts, hypersonic cruise vehicles, or planetary spacecraft, the aerothermodynamic design process starts at the system analysis level whereby trade and packaging studies directed at achieving mission requirements dictate the initial shape of the proposed vehicle. Successful aerothermodynamic vehicle design closure is achieved by balancing aerodynamic performance against management of heat rates and loads. Heat rates determine peak temperature and drive material temperature capability requirements; heat loads determine insulation (mass) requirements for backface temperature constraints. Heat rates and loads from BLT during hypersonic ascent, cruise, or entry thus represent an important thermal protection system (TPS) design constraint;[1-2] hence, the accurate prediction of transition onset and associated heating augmentation levels is generally of vital importance to the successful design and flight of agency advanced transportation system concepts. The successful and economical operation of any future space transportation or payload delivery system will be largely dependent on the ability to accurately predict when, where and how hypersonic boundary layer transition will occur during atmospheric flight. The accurate prediction and/or control of BLT is essential from the perspective of (1) economics (e.g., vehicle weight reduction, simplified mission operations/maintenance), (2) risk reduction/crew safety (e.g., TPS performance under abort conditions or TPS tolerances to damage and repair), and (3) enhanced mission flexibility (e.g., scramjet propulsion system robustness, precise aerodynamic control and cross range capability). Despite these first order design impacts, diverse mission requirements make a robust generalized predictive methodology difficult to achieve. Development of numerical tools for the reliable and rapid prediction of BLT on 3-dimensional vehicle shapes has progressed[3] but continues to be hindered by the lack of a practical capability to accurately model the complex physics associated with the transition process in flight. As noted by Berry et. al.,[4] the basis of modern day research and scientific method dictates that observable, empirical and measurable evidence of behavior must be utilized for acquiring knowledge and revising theories. While ground testing will most certainly be required for the further development and validation of physics based predictive models for hypersonic BLT, it is commonly accepted that testing at scaled conditions in conventional or low disturbance wind tunnels cannot truly replicate all conditions representative of hypersonic flight. Thus, measurement in flight is ultimately required to provide the insights necessary to truly evaluate design assumptions, assess performance margins and ultimately better characterize the nature of the weaknesses of database design tools (including BLT predictive capabilities).

1.2 Flight Testing

Generally speaking, aircraft, spacecraft and weapons systems are fundamentally designed within a framework of analytical tools, wind tunnel testing, material testing, computational simulation and more often than not, end with flight testing.[5-7] Flight-testing represents a critical phase in the development process and ultimately in the validation and certification of technologies destined for future civilian and military operational capabilities. Nowhere is this more evident than for vehicles operating in or traversing through the hypersonic speed regime. As is commonly recognized, hypersonic vehicles operate at flight conditions very different from their counterparts at subsonic or supersonic conditions. This poses additional challenges to the designer in the sense that material response, surface phenomenon and gas characteristics around the vehicle cannot necessarily be duplicated in any one laboratory or wind tunnel or necessarily simulated by numerical means. Flight testing is therefore imperative to engineers working the design of hypersonic vehicles. It provides the first set of insights from which to truly evaluate design assumptions, assess performance margins and ultimately better understand the nature of the weaknesses of database design tools. Measurements obtained in relevant flight environments also provide unique opportunities to observe flow phenomenon that represent the "unknown" unknowns. Historically, flight-testing spacecraft has required de-orbiting or flying the vehicle to be evaluated into a predetermined test area and either recovering the test vehicle or recording data during re-entry for subsequent recovery, or both. Precise targeting and de-orbiting of the re-entry vehicle is required to assure safe return to the desired location. For example, the first five flights of the U.S. Space Shuttle were heavily instrumented with sensors and equipped with multiple data recorders to collect information on the heating environment and the performance of the Orbiter's thermal protection system under laminar, transitional and turbulent conditions.[8] This type of instrumentation package, often referred to as Developmental Flight Instrumentation (DFI) naturally comes at the expense of added internal complexity, cost and schedule risk to the project. After the five developmental flights were completed, most of this extensive DFI sensor suite was removed from the Shuttle Columbia to mitigate cost and weight penalties.

Berry et. al.,[4] conclude the only viable method for allowing fundamental breakthroughs in our understanding of the transition process at hypersonic flight conditions is flight-testing. The authors indicate that executing such an endeavour would involve overcoming formidable challenges in the design and instrumentation of a test vehicle to yield the desired test conditions and high frequency transition data. Coupled to high frequency surface instrumentation, it is suggested in this paper that an affordable thermal observation capability could potentially provide an unparalleled insights of the global development and spatial progression of BLT in a high enthalpy flight environment free of disturbances that contaminate such measurements in ground-based wind tunnels. While nothing will completely replace the value of in-situ instrumentation – and in particular, high frequency sensors, the challenges of minimizing DFI impacts to vehicle weight and internal complexity as well as inherent instrument bandwidth limitations will always restrict the ability to make high spatial density in-situ measurements. Thus, imaging conducted remotely can provide a synergistic opportunity to noninvasively obtain unique and critical flight data without interfering with nominal vehicle operations, weight, performance and project scheduling.

2.0 HYTHIRM PROJECT

The genesis of NASA Langley Hypersonic Thermodynamic Infrared Measurements (HYTHIRM) project is linked to the Columbia Accident Investigation (CAI) and the subsequent Return-to-Flight (RTF). Until recent events associated with the Shuttle RTF effort, NASA imaging was often relegated to supporting public affairs interests. The lack of definitive quantitative imaging requirements left CAI image analysts with data of insufficient quality (or no data) to meet the needs of the engineering community. For example, engineers supporting launch debris shedding analysis were hampered by poor image quality and CAI breakup analysts lacked general information on optical signatures associated with a nominal Shuttle entry. After the accident, recommendations were made to NASA management to improve imaging capability/data to support anomaly and contingency analysis during a mission.[9-10] One such contingency analysis tool predicts hypersonic BLT onset from damage (e.g., tile impact, gap fillers).[11-12] Lack of quality flight data to initially calibrate this tool resulted in large uncertainties in terms of when BLT occurs and to what extent the turbulent flow spreads along the windward surface of the Orbiter during descent. These uncertainties resulted in an unprecedented decision to perform a spacewalk during STS-114 to remove a protruding gap filler.[13] Post STS-114, it was recognized that the level of conservatism imposed by the BLT tool uncertainties could be more clearly established and/or reduced with quality data from a controlled roughness flight experiment. Advocacy from the technical community resulted in the Space Shuttle Program (SSP) approving a series of hypersonic boundary layer flight tests that were conducted before retirement of the fleet.[14-15] During these test flights, surface temperature on the Shuttle was to be obtained from a limited number of thermocouples on the windward surface that were located downstream of a controlled protuberance on the wing (i.e., the BLT Flight Experiment). Limited surface instrumentation was expected to impose challenges in determining the area affected by turbulent flow (i.e., a turbulent wedge). To augment the discrete temperature data obtained during the BLT flight experiment and to honor the commitment to improve overall imaging capability, the HYTHIRM project was formulated in 2007 to demonstrate capability to provide non-intrusive spatially continuous Infrared (IR) derived surface temperature at targeted Mach number(s) with adequate spatial resolution.[16-17]

An observation made in 2009 by the HYTHIRM team (STS-119) successfully demonstrated the capability to collect scientific quality imagery in a reliable manner using available and accessible technology.[18-22] This emerging quantitative thermal imaging capability represented several years of advocacy within the aerothermodynamics technical community,[23-30] sponsorship by the NASA Engineering and Safety Center (NESC), and the Hypersonics Project within the NASA Aeronautics Research Mission Directorate (ARMD). The partnership resulted in methodical planning and mission execution by a coalition of NASA, Navy, government labs, and contractor personnel. Spanning seven Shuttle missions over a period of approximately 2.5 years since the initial observation in 2009, the HYTHIRM team successfully obtained calibrated thermal imagery[31-32] during Shuttle re-entry over a Mach range from 6.2 to 18.1, Fig 1. The quantitative thermal imagery has provided a unique and never before observed perspective on the global distribution of surface temperature and the state of the boundary layer (i.e., laminar/turbulent) over the entire windward surface of the Shuttle during portions of hypersonic re-entry[31]. To the author's knowledge, the 2011 Shuttle IR observations near Mach 18 (STS-133) represents the highest speed at which calibrated thermal imagery has been obtained on a crewed maneuvering vehicle in the Earth's atmosphere that has sufficient spatial resolution to delineate local temperature differences at various locations on the vehicle surface. Collectively, these thermal observations during Shuttle hypersonic re-entry are intended to provide the technical community with a unique source of flight data for reducing the uncertainty associated with present day ground-to-flight extrapolation techniques and current state-of-the-art

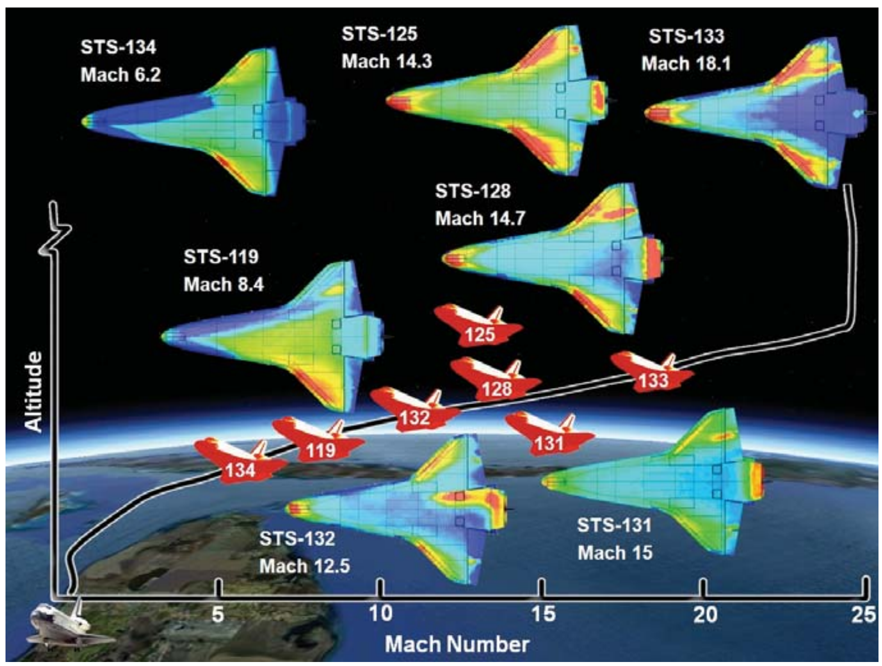

Figure 1: HYTHIRM Shuttle thermal imaging Mach envelope. (color pallet varied to enhance detail on each flight)

computational prediction methods. The imaging capability demonstrated by HYTHIRM suggests a multitude of potential cross cutting applications that could be utilized by the NATO member nations in terms of the assessment, maturation and risk reduction of advanced technologies required for safe and affordable access to and from space including sustained hypersonic cruise. The most recent thermal imagery near Mach 6 (STS-134) captured unique BLT flow phenomenon never before observed in flight on a global scale at unprecedented spatial and thermal resolution.

3.0 THERMAL OBSERVATIONS OF SHUTTLE ENDEAVOUR (STS-134)

The STS-134 mission was the fifth and final flight of the BLT Flight Experiment[15] (and the first on Endeavour). Observations associated with a ground based optical system during Endeavour's final re-entry (June 2011) has provided the engineering community with global surface temperature of a vehicle in hypersonic flight at remarkable spatial resolution. In what is believed to be an unprecedented first, a high-resolution ground based optical system operated by Celestial Computing positioned on the west coast of Florida captured the progressive development and movement of thermal patterns on Endeavour's lower surface resulting from hypersonic laminar BLT during it's night descent and return to KSC, Fig. 2.

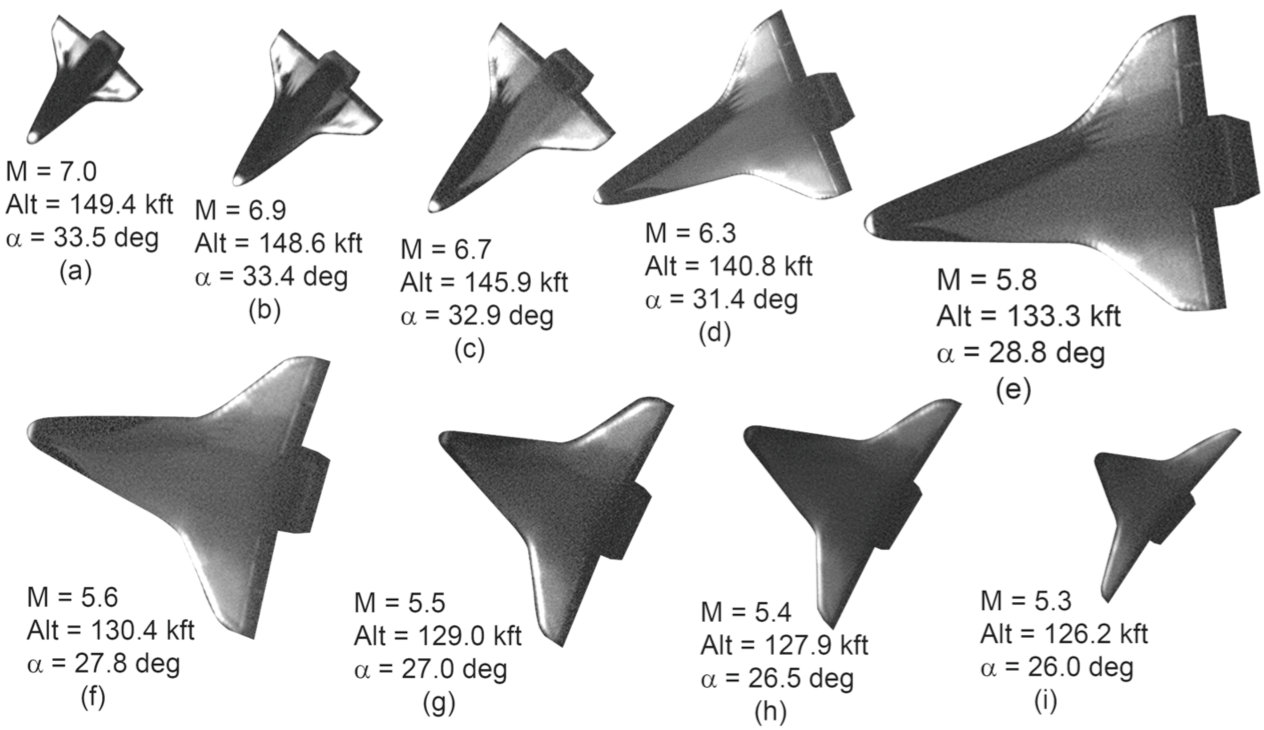

Figure 2: Time sequence of near infrared intensity images showing the evolution of hypersonic boundary layer transition on Shuttle Endeavour's lower surface during STS-134 re-entry. Total elapsed time ~ 2 minutes. Elevated temperatures are shown in lighter gray

Endeavour's re-entry was observed for a period of approximately 6 minutes (Mach 14.3 to Mach 4.5) with a state of the art optical system using a 3050 mm focal length operating at the diffraction limit. A 12 bit uncooled CCD camera with a pixel array size of 1360 x 1024 (individual square pixels of 6.4 microns) permitted an 0.1699 degree instantaneous field of view in the horizontal plane. The spectral response of the camera's silicon sensor is 400 – 1050 nm. A long pass filter with an 850 nm cut on was used to remove the spectral energy in the visible band. The detector frame rate was 30 Hz and the integration time was continuously varied. During the actual observation, integration times were manually selected in real-time to avoid saturation. Based upon these collective parameters and minimal atmospheric turbulence during the night re-entry, the estimated spatial resolution of the Orbiter at the point of closest approach to the imager (~32 nautical miles) was approximately 4 inches per pixel. No image saturation was observed. The sequence of spatially resolved images shown in Fig. 2 spans a period of time of approximately 2 minutes, corresponding to a Mach range from 7 to 5.3. During that time, the Orbiter angle-of-attack decreased from 33.5 deg to 26 deg. At each time interval shown, the relative size of the Orbiter on the sensor focal plane array was preserved so as to convey a sense of the increased spatial resolution as Endeavour approached the ground imaging location. The sequence of images shown in Fig. 2, represent uncalibrated near infrared (NIR) intensity. Image contrast and brightness has been applied to highlight details of the observed thermal features. Because the human eye can readily distinguish subtle contrast changes in gray levels, a gray-scale intensity display pallet was selected to enhance identification of thermal features in this figure (regions of elevated temperature are shown in lighter gray).

The rich data set initially captures the vehicle at approximately Mach 7 when the windward surface boundary layer was largely laminar. Even at extreme range, the complex thermal patterns associated with shock-shock interactions along the wing leading edge are apparent (Fig. 2a). As expected, the spatial resolution at this range is insufficient to reveal details associated with the interaction but the resulting elevated temperatures along the outboard span of both wings is apparent. The thermal footprints of several transition events are observed during this 2-minute time span. First, a small turbulent wedge near the main landing gear door is observed (lower wing, Fig. 2b) near Mach 6.9, and then more notably - a large-scale asymmetric turbulent wedge emanating from the nose region of the Orbiter (Fig. 2c-e) near Mach 6.7. Near the point of maximum spatial resolution, the small-scale thermal features associated with the wing leading edge Reinforced Carbon Carbon (RCC) panels are observed (Fig 2e). As Endeavour passes over the observation site and recedes in the distance, the entire windward surface progresses to a fully turbulent state (Fig. f-i).

Because the Orbiters generally flew a very repeatable entry profile mission-to-mission, surface roughness of each individual Orbiter ultimately determined when and where BLT occurred. Surface roughness of the vehicles was inherently defined by the placement and installation of the individual ceramic tiles and by any in-flight damage that altered the surface.[33] For example, tile gaps and misalignments result in discrete roughness that was distributed over the windward surface. The vehicle roughness can be further increased by post launch damage in the form of tile cavities produced by debris impacts (or protruding gap fillers between individual tiles). In the absence of large-scale isolated surface roughness from damage, the historical average for the onset of BLT on Endeavour corresponded to a freestream Mach number of approximately 6.5.[34] Based upon the limited surface thermocouple data, BLT on STS-134 generally occurred late in the entry timeline (~Mach 8-5.7) depending upon the location the measurement was made, suggesting a relatively smooth vehicle. With this context in mind, the most interesting (and dominant) thermal feature in the time sequence is the appearance of the large and asymmetric wedge-like area of elevated surface temperature on the starboard (lower) wing at approximately Mach 6.7 (Fig. 2c). The imagery revealed that this region of elevated surface temperature appeared rather abruptly over a period of approximately 6 seconds (fully turbulent by Mach 6.7, Fig. 2c) and was interpreted as BLT occurring in an asymmetric manner. The appearance and rapid development to a fully turbulent flow would be expected at this relatively late (low) Mach number. Thermocouple temperature time traces (not shown) show a rapid increase in surface temperature at this point in time and corroborate this interpretation of the thermal feature. An enlarged image of the asymmetric boundary layer transition (ABLT) is shown near the point of maximum spatial resolution, Fig. 3 at Mach 5.8. Image registration and frame averaging have been applied to improve overall image quality by increasing the signal-to-noise (S/N) ratio. The lateral spreading (half angle) of the observed ABLT wedge was found to be approximately 6.5 deg and is within the uncertainty of the correlation derived by Fischer[35] based upon ground-based wind tunnel measurements from isolated roughness. Based upon a computed local edge Mach number of 1.6 at the origin of the turbulence, Fischer's correlation suggests a spreading angle between 6-8 deg. During the actual mission, the Shuttle engineering team that assessed damage and it's downstream influence assumed a conservative lateral spreading half angle value of 7.5 deg.

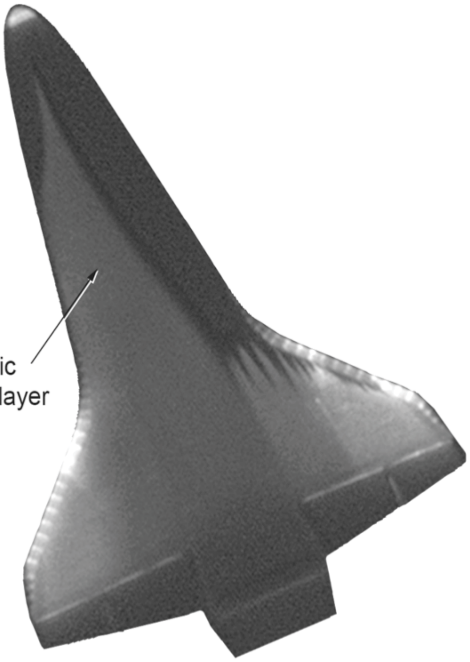

Figure 3: Thermal image of Endeavour during STS-134 re-entry near the point of closest approach, Mach 5.8, AOA = 28.8 deg, Slant Range ~32 nautical miles.

Based upon the initial 2-D intensity images alone, the physical location of the ABLT event cannot be precisely determined. Thus the origin was initially assumed to be located in the general area of the nose and/or forward gear door. During inspections on orbit, several areas of isolated surface roughness were identified. However, these surface defects were located in the opposing plane of symmetry thus placing any turbulent wedge on the port side of the Orbiter – which was not consistent with the observation. Furthermore, detailed surface inspection (post landing) did not reveal any one particular surface defect that could have been exclusively responsible for triggering this event. Based upon the lack of precise information from the initial 2-D imagery as to the exact location of the turbulent wedge, it was initially concluded that some form of distributed roughness was likely responsible for the ABLT. This initial conclusion was reasonable given that there are numerous hardware and thermal protection system interfaces present in this forward nose region (e.g., RCC nosecap and chin panel are surrounded by an array of tiles with a flexible thermal seal closing out the transition between the two TPS systems) that can be populated with numerous small steps and gaps. Any of these hardware interfaces would be highly likely candidates to cause BLT and/or show localized effects at these late (low) Mach numbers. Precisely mapped global temperature data (discussed later) performed months after the initial data collect now suggest that some form of isolated roughness near the rear starboard corner nose landing gear door was likely responsible for the ABLT event. The ABLT thermal footprint observed during STS-134 at Mach 6.7 is remarkably similar to that observed on Discovery (STS-119/March 2009) by a Navy P-3 Orion imaging aircraft (Cast Glance)[18], Fig. 1. During STS-119, an ABLT event was initially captured at long range on Discovery's starboard side but at a much higher Mach number (~Mach 11). During the STS-119 reentry, the Orbiter's flight control system responded to roll and yaw increments from ABLT (differential skin friction between a laminar and turbulent boundary layer induces a yawing moment if the laminar and turbulent zones occur asymmetrically). While not a safety of flight issue, numerous firings of the reaction control jets along with coordinated deflections of the wing elevons were required to return Discovery to a more nominal attitude. In contrast, no measurable aerodynamic increments were detected by Endeavour's flight control system during the Mach 6.7 ABLT event of STS-134. This would be expected as viscous effects (i.e., larger viscous interaction parameter) associated with the higher Mach number ABLT event would generally increase the overall skin friction and drag relative to increments induced at lower Mach numbers.

Post STS-134 launch, several windward surface tile impact sites were identified from photographs taken as the Orbiter approached the Space Station, Fig 4. Engineers using standard assessment tools developed during Shuttle RTF assessed the damage. Based upon this analysis, no safety of flight issues were identified and Endeavour was cleared for re-entry. A cluster of tile damage locations on or downstream of the starboard main landing gear door suggested that early BLT might be observed during re-entry. Upon inspection of the imagery, a small area of flow turbulence was indeed observed in the general location of these damage sites, Fig. 5, just prior to the appearance of the large ABLT thermal footprint. Superimposed upon this intensity image are the general locations of the reported tile damage sites. While not necessarily conclusive, it is reasonable to suspect that a specific tile damage site (cavity) located on the starboard main landing gear door might have been responsible for inducing BLT near Mach 6.9. The general cavity dimensions inferred from on orbit photogrammetric analyses were in excellent agreement with direct measurements obtained post flight (length 6.0-in x width 1.0-in. x depth 0.15-in.) suggesting a stable geometry during re-entry. The orientation of this particular cavity was generally aligned with the local flow direction. As there were no thermocouples in the vicinity of this particular damage site, the presence of BLT during re-entry could not be ascertained with surface instrumentation. The STS-134 imagery provided the only indication that BLT had occurred. Based upon a BLT predictive tool capability,[12] fully effective turbulent flow for this particular damage site was expected by Mach 8.4, suggesting a level of conservatism in the tool. The spreading of the thermal footprint shown in Fig. 5 suggests that the cavity damage was sufficient to promote turbulent flow to the actual site location (i.e., fully effective) to as early as Mach 6.9. The lateral spreading (half angle) of the observed turbulent wedge was found to be approximately 12.5 deg and is well outside the uncertainty of the correlation derived by Fischer[35]. Interestingly, global thermography methods used in the wind tunnel during Shuttle RTF BLT tool development[36] suggested that the turbulent spreading half angle associated with cavities was larger than that observed with protuberances and was more sensitive to Reynolds number.

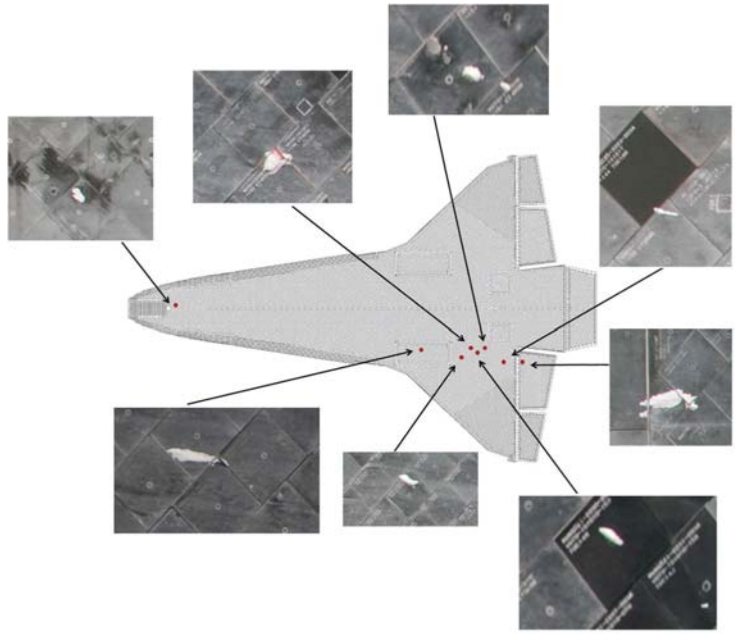

Figure 4: STS-134 tile impact damage observed on orbit as Endeavour approached the space station.

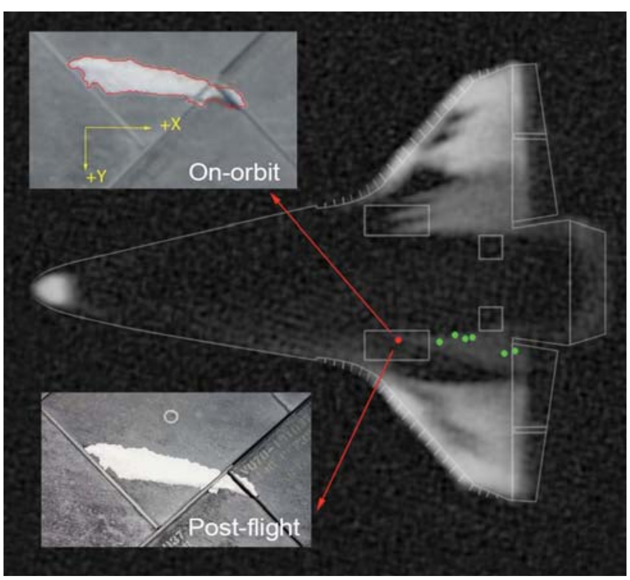

Figure 5: Boundary layer transition induced by a tile cavity. STS-134, Mach = 6.9, AOA = 33.4 deg.

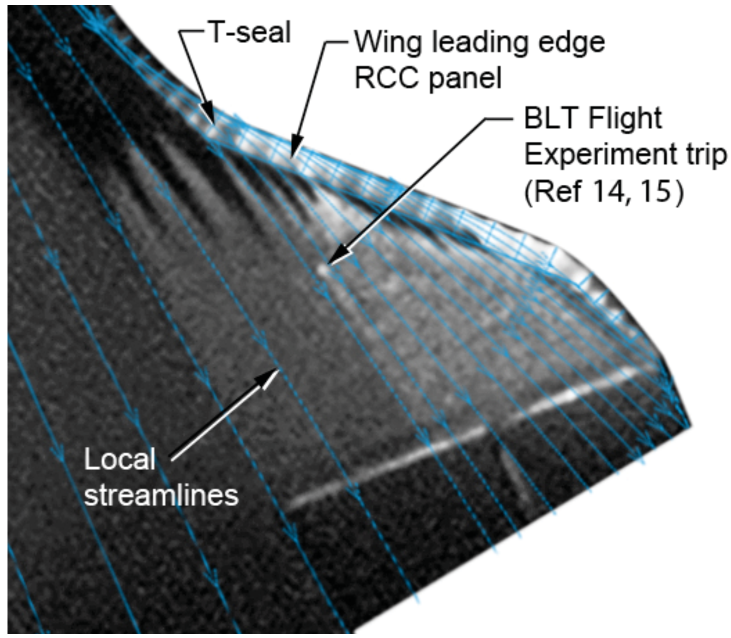

Figure 6: Transition patterns on Port wing. Turbulent wedges appear aligned with RCC panel T-seals. Mach = 5.8, AOA = 28.8 deg.

At the point of closest approach and an estimated spatial resolution of approximately 4 inches per pixel, the near infrared imagery obtained by the ground system was sufficient to reveal thermal gradients associated with the 22 individual RCC panels along the Shuttle wing leading edge. While speculative, it is interesting to note that the transition wedges on the most outboard portion of the port wing, Fig. 6, appear to spatially correlate with the interfaces (T-seals) between the individual RCC panels. Predicted local surface streamlines "seeded" from the rear corners of the RCC panels align with the observed individual turbulent wedges. In these locations, known rearward facing steps from RCC/T-seal interfaces and small cavities from recessed carrier panel attachment screws are present. The presence of such small "roughness" located near attachment lines where cross flow disturbances first begin are known to initiate stationary streamwise vortices leading to transition. The small darker region in Fig. 6, mid span on and just behind the wing leading edge RCC panels and outboard of the bow shock-wing shock interaction, is indicative of relatively lower temperatures and suggests the presence of a small laminar region. This is consistent with the expectation that turbulence in the vicinity of the leading edge attachment line is difficult to sustain.[37] Streamline tracing associated with the more inboard thermal gradients on this port wing indicates the BLT wedges are induced (presumably) from the upstream distributed tile-to-tile step/gap roughness. Insights into BLT phenomenology of this global nature are enabled by the quantitative, spatially resolved imagery. Given the inherent surface irregularities on real flight vehicles, interpretation of transition data from discrete point measurements alone will most certainly possess a degree of uncertainty resulting from potential unintended (and undocumented) "contamination" from transition mechanisms such as roughness.

In order to quantify the observed thermal features, the STS-134 intensity imagery is converted to surface temperature via radiometric calibration.[38,39] In addition to the sensor characterization, the conversion to accurate surface temperature requires an assessment of surface optical properties of the Orbiter tile and RCC components and atmospheric transmission characteristics at the time the observation was made. Lastly, perspective distortion and foreshortening of the image are mitigated by first re-registering the 2-D temperature map onto a 3-D Shuttle surface. This mapping process ultimately enables a more precise determination of the spatial location of pertinent thermal features. The radiometric calibration method, the correction methodology for atmospheric attenuation and the general process of removing geometric effects of non-orthogonal projection on the image plane are described in Refs. 20, 21, and 22. STS-134 surface temperature mappings derived from infrared imaging of the Orbiter windward surface near the point of closest approach is shown, Fig. 7. Figure 7a corresponds to the 2-D mapping. The 2-D temperature information has been projected to a 3-D surface in Fig. 7b.

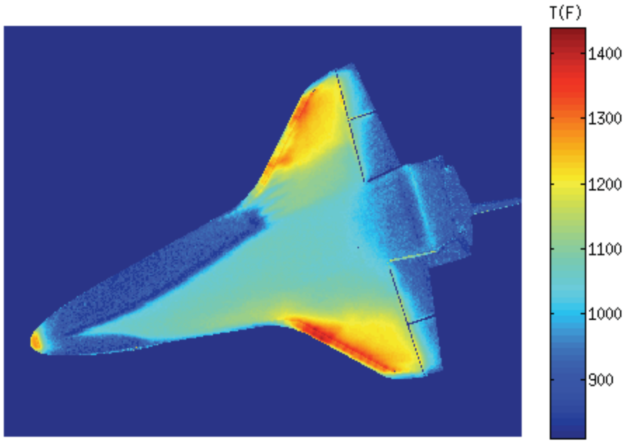

Figure 7a: STS-134 2-D temperature mapping.
Mach = 5.8, AOA = 28.8 deg

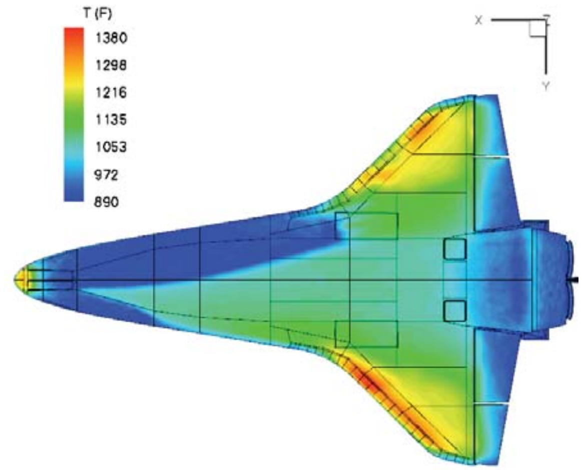

Figure 7b: STS-134 3-D temperature mapping.
Mach = 5.8, AOA = 28.8 deg

The 3-D mapping permits a more accurate assessment of the location of the ABLT footprint relative to known TPS interfaces. The mapping of Fig. 7b provides strong evidence suggesting that the ABLT event was triggered from an isolated roughness located in very close proximity to the starboard rear corner of the nose landing gear door. Because the gear doors are open on the runway, TPS inspections on the ground post flight would likely not have identified any surface irregularity. Temperature accuracies associated with measurements made during Discovery's re-entry during STS-119 have been addressed in Ref. 21. It was determined that in areas exceeding 1300 deg F, near infrared derived surface temperatures generally agreed to within 2-3% of the thermocouple measurement. Acreage surface temperatures associated with the STS-134 observation on Endeavour are near or below this threshold. The accuracies of the acreage thermocouples on Endeavour have not been assessed. Hence, the percent differences between the thermocouples calibrated imagery are presently qualitative. The early analysis of Ref. 38 suggests the percent differences are expected to be a few percentage points higher. In the future, measurements with a detector operating in the longer wavebands (i.e., mid wave or long wave infrared) would yield better accuracy in regions where vehicle surface temperatures are expected to be below 1300 deg F.

4.0 COLLABORATIVE OPPORTUNITIES & RECOMMENDATIONS

Over the last decade, optical methods for extracting surface and flow-field measurements have begun to compliment (or replace) the traditional discrete sensor measurement approach when testing in ground-based wind tunnels. The global nature of the information and the reduced complexity and expense of the instrumentation (installation, wiring, power and recording requirements) are large driving forces behind this trend. The opportunity exists for a similar paradigm shift in terms of how data measured during flight is obtained.[40] Despite the ever present uncertainties in budgets and technology investments in aerospace systems, the near term horizon indicates an abundance of flight test and operational activity – at both the national and international level. Safe, economical and environmentally responsible access to space is a major technological challenge for all nations due to the dependence of the global economy on assured and secure access to space-based services. As NATO member nations embark on supporting the development of new military and/or civilian space launch systems or hypersonic delivery systems with global reach capabilities, an opportunity exists to collaborate on many levels. Possibilities range from the validation/uncertainty assessment of present day design tools by comparisons with global Shuttle flight thermal data to the development and use of affordable cross cutting and game changing imaging technology and instrumentation to support the next generation of hypersonic flight tests including, but not limited to, BLT.

4.1 Global Flight Thermal Data for Model Validation

The NESC and the Space Shuttle Program enabled the acquisition of the landmark global thermal data obtained on the U.S. Space Shuttle during re-entry by the HYTHIRM project. As no significant flight data analyses were intended or performed with Shuttle Program or NESC resources, the Hypersonics Project (NASA Aeronautics Research Mission Directorate) facilitated the development of toolsets to process the 2-D surface temperature into a format more conveniently ported into graphical post processing tools for direct comparison to computational prediction or thermocouple measurement. The global surface temperature data from seven Shuttle re-entries (see Fig. 1) are now available to serve as a benchmark standard for assessing modeling and simulation capability.

In terms of CFD, turbulence models play a crucial role in the simulation of complex flows where separation, shock/boundary layer interaction, and flow reattachment are present. The accurate prediction of surface temperature associated with non-laminar flow depends to a large degree on the nature of the turbulence model employed. Global surface temperature measurements from HYTHIRM provide a rare opportunity to validate, by assessing accuracy, turbulent CFD models for the prediction of radiative-equilibrium surface temperatures on the wind-side acreage of the Shuttle at hypersonic re-entry conditions. As reported by Wood,[41] the STS-119 fight data, acquired by on-board thermocouples and the companion global thermal imagery obtained by HYTHIRM team was used for an initial assessment of two specific algebraic turbulence models implemented in the NASA Ames Data Parallel Line-Relaxation (DPLR) and the NASA Langley Aerothermodynamic Upwind Relaxation Algorithm (LAURA) CFD codes along with a more complex two-equation model implemented in DPLR. It should be noted that elevon/body flap deflection present in the flight imagery was not modelled.

Figures 8 and 9 illustrate the comparison of CFD prediction with measurement (STS-119 global imagery) obtained at a moment in time near maximum spatial resolution (Mach 8.4). For the first time, numerical predictions can be directly compared to hypersonic flight measurement in areas of the Shuttle not instrumented with thermocouples. The first comparison of predicted global surface temperature (upper half) to 3-D mapped STS-119 HYTHIRM flight measurement (lower half) is shown in Fig. 8. Similar comparisons of global HYTHIRM flight data to prediction are possible. Candler,[42] utilized a one-equation turbulence model (with compressibility corrections) coupled with a novel approach for tripping the boundary layer to examine turbulent spreading characteristics. In contrast to more traditional methods that specify turbulent onset at a specified circumferential plane along the vehicle axis, turbulence in the boundary layer was initiated at discrete locations corresponding to locations responsible for the two turbulent footprints associated with STS-119 (ABLT and the BLT flight experiment), Fig. 10. The lateral spreading of the predicted ABLT turbulent flow from the discrete (point source) location display reasonable qualitative agreement with that observed in the corresponding flight thermal imagery (Fig. 11). Differences do exist, particularly associated with the lateral spreading of the turbulent wedge from the BLT flight experiment protuberance found on the port wing. It is suggested that the existing global flight thermal imagery obtained on the U.S. Space Shuttle could serve as invaluable test cases from which to simulate and validate macro characteristics from cutting edge modeling techniques.

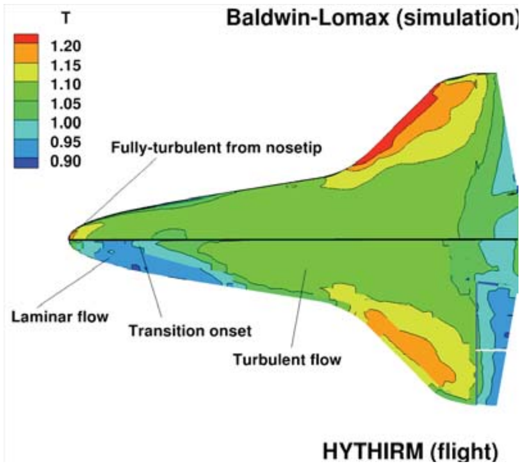

Figure 8: Comparison of Mach 8.4 Fully Turbulent CFD with STS-119 Thermal 3-D Mapping.

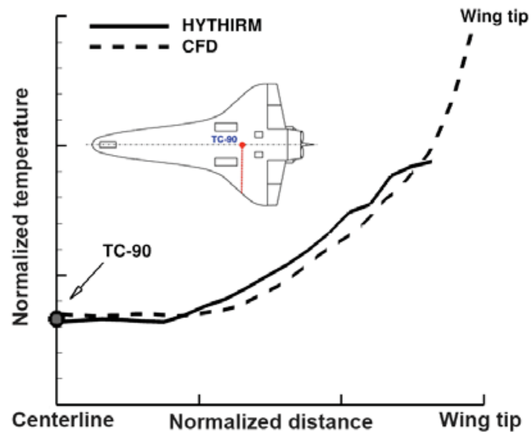

Figure 9: Comparison of Mach 8.4 Surface Temperature Distribution and Fully Turbulent CFD.

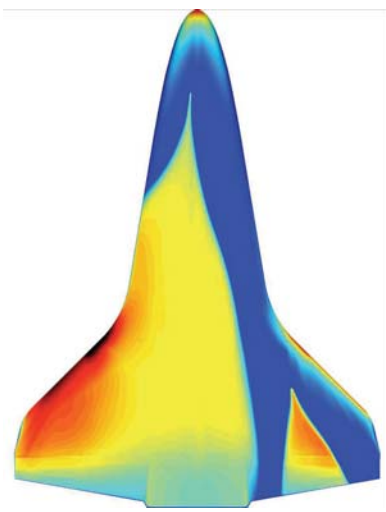

Figure 10: Predicted turbulent spreading from a point source (Ref. 43). Temperature scale on Fig. 11 applies.

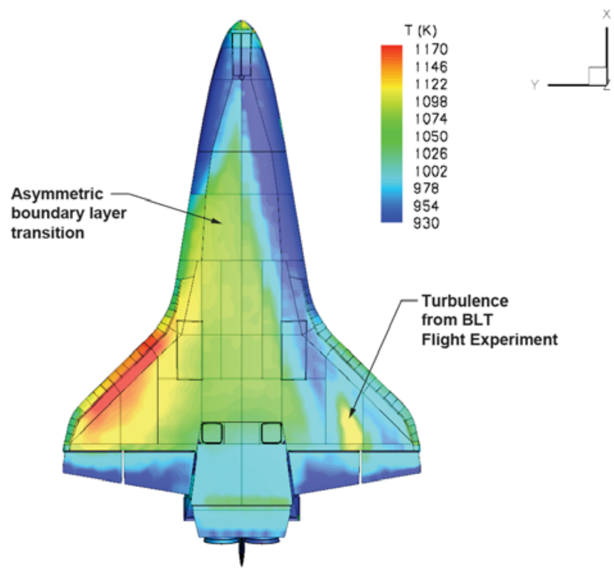

Figure 11: Thermal mapping of STS-119 asymmetric boundary layer transition (ABLT). Mach 8.4.

4.2 Advanced Electro-Optical Sensor Capability

In some sense, the Shuttle served as an ideal candidate from which to demonstrate a quantitative thermal imaging capability. The Orbiter was a relatively large target to image with a well characterized TPS and surface temperature distribution. The operational challenges experienced during the Shuttle missions were ultimately related to adverse local weather at the landing sites that resulted in uncertainties of re-entry timelines and the corresponding return ground track. New aeronautical or aerospace systems tested and eventually operated in flight will likely be much smaller than the Shuttle and hence, will most certainly challenge current remote observation and measurement capability in terms of metrics derived from spatial/spectral/temporal resolution and temperature sensitivity requirements. This is largely due to the fact that a great majority of the airborne electro-optical systems flying today have been tailored to meet the focused needs of the intelligence, surveillance and reconnaissance (ISR) communities – where calibrated spatially resolved thermal imagery is not necessarily a requirement. For example, prior to the collaboration with the HYTHIRM team, the imaging system on board the Navy P-3 Orion[19] was optimized more towards photo documentation needs of the U.S. Department of Defense. That is, target identification, lethality/hit determination and impact intensities, flash decay, debris cloud expansion/trajectories as well as documentation of nominal vehicle performance (i.e., ascent, intercept, staging, parachute recovery etc) and to aid mishap reconstruction. Other airborne assets (e.g., HALO I-II, WASP etc.) operated by the Missile Defense Agency (MDA), require the operation of sensors optimized for the evaluation of Ballistic Missile Defense (BMD) systems and their elements. Several of these assets possess calibrated up-looking Electro-optical/IR sensors. Ironically these sensors were too sensitive in the desired wavebands and lacked capability to mitigate saturation on a target as large and hot as the Shuttle[16,17]. Despite the expanded thermal capability enabled in the P-3, limited aerial capability exists in terms of an electro optical system capable of providing calibrated spatially resolved thermal imagery that is advocated for in this paper.

The design of a next generation optical system would focus on a description of the remote sensing configuration in terms of standard engineering parameters (e.g., primary aperture diameter, effective focal length, focal plane array detector size and pixel grain density, focal plane array waveband sensitivity, etc.). This paper will not attempt to identify a detailed description of such a system in this parameter space. Rather, a graphics-based virtual diagnostic interface (ViDI) simulation tool[43] used during HYTHIRM mission planning was utilized to illustrate potential imaging capability based upon a geometric factor calculated from the detector pixel size and the field of view (FOV) of the optical system, often referred to as the instantaneous field of view (IFOV). IFOV defines the smallest detail that can be detected by an optical system at a given distance based upon the imager size. ViDI analyzes how a given input scene will be viewed by an imaging system. For the purposes of this paper, the tool was used to provide synthetic images with accurate spatial resolution characteristics to highlight imaging performance as a function of IFOV and determine where electro-optical instrumentation investments are desirable. Naturally, the actual system spatial resolution will be influenced by other factors such as the diffraction of the optics (which is a function of the aperture size and wavelength of the light being measured), the time response of the detector, and system integration time relative to the target motion. Radiometric simulation will not be addressed using ViDI in this paper. The interested reader is referred to Ref. 44 for a more detailed description of optical system parameters effecting thermal resolution along with atmospheric effects (haze, humidity, fog etc) that degrade spatial resolution, reduce effective range and introduce uncertainties in radiometric calibration. For the input into ViDI, a fictitious vehicle geometry representative of a hypersonic vehicle in the 15ft (~5 m) class was created, Fig. 12. This notional geometry is dimensionally representative of many active and proposed flight test articles (e.g., SpaceX Dragon, Darpa/Falcon HTV-2, Sandia AHW, Darpa/AF X-37, AFRL/Darpa X-51, NASA/LM EFT-1, NASA IRVE III, DLR SHEFEX, ESA EXPERT, ESA IXV). To visual convey the

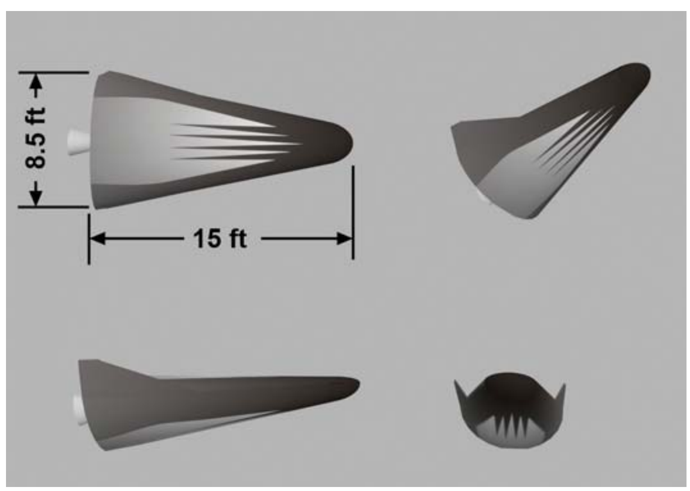

Figure 12: Notional hypersonic flight test vehicle with features mimicking thermal patterns on the lower surface.

effectiveness of an imaging system's ability to resolve thermal features associated with BLT, a series of longitudinal "patterns" were graphically placed on the lower surface of the CAD geometry.

Fig. 13 presents a series of synthetic views of the windward surface of this vehicle at various slant ranges (distance between imager and target) as it would appear to an imaging system under ideal conditions at selected IFOV values. As one would expect, smaller IFOV values yield better spatial resolution.

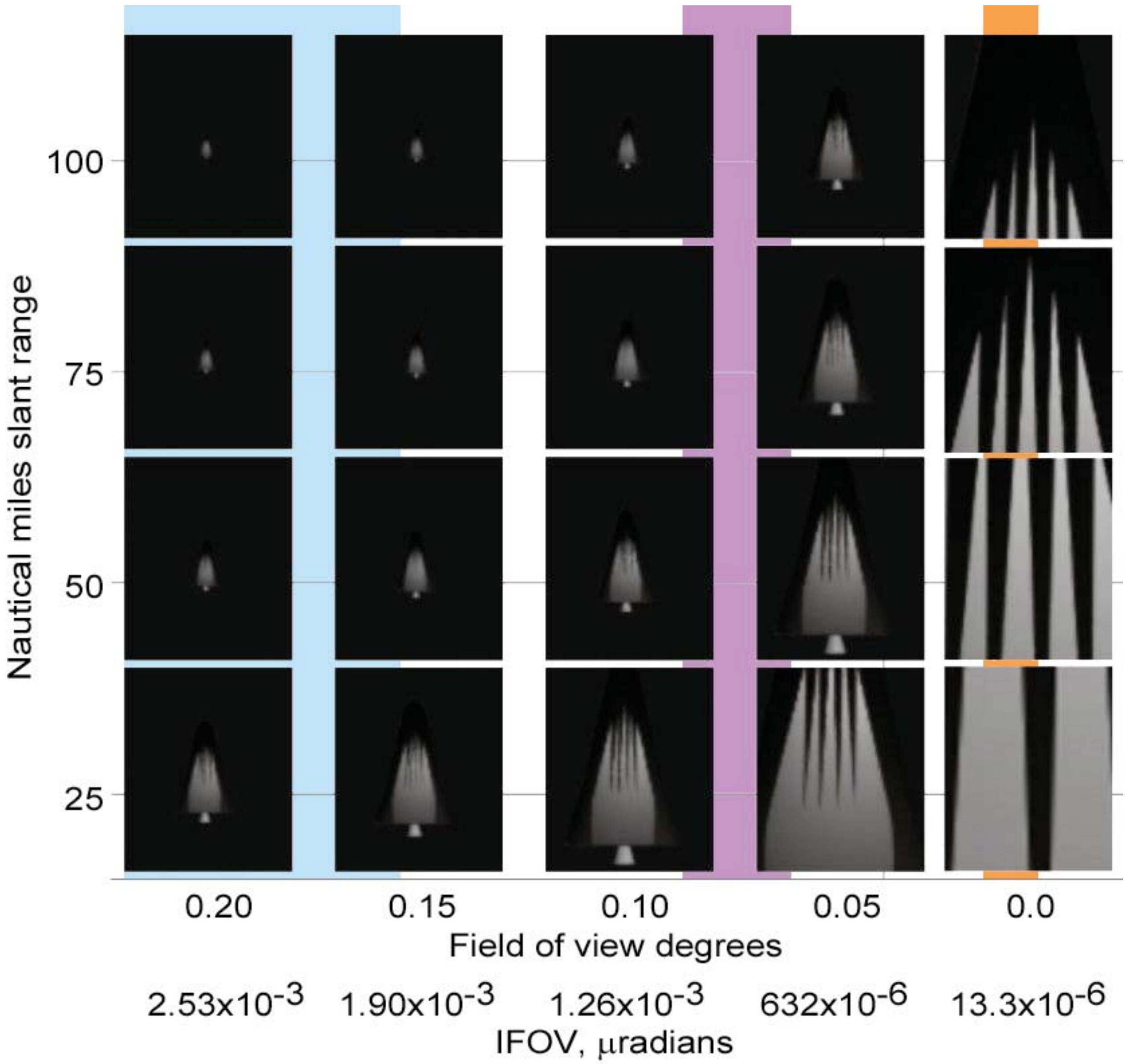

Figure 13: Synthetic images of expected spatial resolution as a function of IFOV and slant range. Blue - capability used by HYTHIRM; Magenta – emerging commercial capability; Tan – existing large aperture (fixed location) ground-based imaging system.

At the time of this publication, the operating performance of the imaging systems employed by HYTHIRM have IFOV values of $1.9x10^{-3}$ micro radians or greater. With IFOV performance in this range and at slant ranges that exceed 100 nautical miles (nm), the target vehicle would essentially appear as a point source. Depending upon the actual vehicle trajectory and the desired imaging Mach number, slant ranges of 25-50 nm near the point of closest approach with a ground or sea based asset are feasible. An aerial based imager at 25,000 ft or 80,000 ft would reduce the slant range by 4 to 13 miles, respectively. As shown in Fig. 13, imaging systems possessing IFOV values of $632x10^{-6}$ or less have the potential for resolving fine scale surface thermal features from flow structures associated with 3-dimensional BLT mechanisms. Current systems possessing these small values of IFOV do exist but they are inherently constrained to fixed ground locations because of large aperture optics (~9 ft diameter) and hardware weight.

A notable exception is the NASA Stratospheric Observatory for Infrared Astronomy (SOFIA) aircraft (a modified 747) equipped with a 17 ton, 8.2 ft diameter aperture telescope. Presently this powerful imaging system supports astronomical requirements and is currently not configured with a tracking system capable of following a high-speed target with substantial angular velocities (imaging platforms will be discussed in more detail in section 4.3). Based upon the results shown in Fig. 13, electro-optical technology investments to increase focal plane array size and/or reduce pixel grain density thereby decreasing IFOV (and increasing spatial resolution) are desirable in the wave band(s) of interest. For high-speed targets, surface temperatures are likely to exceed 1000 deg F. At these temperatures, basic physical laws governing irradiance from a perfect thermal emitter (i.e., black body) indicate superior thermal sensitivity can be found in the short wave (SWIR) and mid wave (MWIR). Alternatively, increased sensitivities in these wavebands often produce saturation (e.g. insufficient dynamic range). Temperature augmentations associated with BLT would only exacerbate the issue. Detectors with sufficient dynamic range would mitigate this issue. Neutral density filters to attenuate the IR radiation in real time without spectral filtering to prevent detector saturation at these higher levels would be required. In addition, investments in reducing IR detector time constants would permit these imagers to respond much faster. Current IR imaging technology will not permit thermal measurements associated with the physical processes associated with hypersonic instability and transition as the frequencies of interest are simply too high. Material thermal response times of more conductive TPS would further limit resolution of temporally varying thermal features. One of the highest frame rates of commercially available IR imager is 48 kHz. (2x64 pixels) which precludes measurements of the resolution desired by the transition modeling community. Under certain circumstances, two-color IR thermography can improve the accuracy of temperature measurements. This is important in applications where accurate surface temperature is desired and/or the emissivity of the vehicle skin is not well characterized or known. The two-color analysis is complex and to date, the technique has been largely limited to industrial applications.

Despite the current hardware/sensing limitations, the STS-134 observations of the transition “thermal footprint” (Sec 3) clearly illustrate the merits of global observations to support in-flight research pertaining to hypersonic BLT. Any physics based flight experiment will need to address the potential unintended (and undesired) “contamination” from transition by-pass mechanisms related to real world TPS surface roughness. Therefore, opportunities may exist for the exchange of information regarding state-of-the-art electro-optical sensing, data storage and image processing capability that would enable enhanced spatial resolution (and better time resolved) global measurements that would complement traditional discrete[6] (and high frequency) surface instrumentation required for advancements in physics based modeling. Cooperation and application of existing imaging capability towards currently funded flight test programs within the NATO member nations is encouraged (see Sec 4.4). It is suggested that flight instrumentation requirements associated with any future BLT flight experiment should include those derived from imaging experts to permit top-level quantitative observation requirements to be properly integrated into any planning activities. One collaborative possibility would be an active participation of selected BLT experts in the NATO Sensors & Electronics Technology (SET) Panel. The charter of this panel is to advance technology in electronics and passive/active sensors as they pertain to reconnaissance, surveillance, target acquisition, electronic warfare, communications, navigation and to enhance sensor capabilities. The SET focuses on research concerning phenomenology related to target signature, propagation, electro-optics, electro-optical sensors, and signal/image processing techniques. Specific cross cutting technology development in these areas may be applicable to the spatially resolved thermal imaging capability advocated for in this paper. For example advanced image processing techniques such as adaptive optics and advanced de-convolution algorithms for target identification may prove useful in recovering details in the imagery lost due to atmospheric turbulence or motion induced blur.

4.3 Advanced Imaging Platforms & Tracking Systems

Imaging platform strategies tend to favour the flexibility and range of airborne systems. Airborne platforms generally operate above weather and IR attenuating water vapour/CO_2 molecules in the atmosphere, are positioned closer to the target (looking through less atmosphere), can conduct over water operations, and can accommodate reasonable changes in the target vehicle ground track. Primary weaknesses include diffraction limit induced blurring associated with small window apertures, image blurring from optical bench motions from structural resonance and/or local cavity-induced flow turbulence from optical housing. Logistical challenges include operational expense and schedule conflicts from other programs competing for the use of an aerial asset. For land-based systems, the advantages include lower per asset operational expense and large aperture/long focal length optics for improved spatial resolution. Commercially operated land-based imaging systems do not appear to be as susceptible to schedule conflicts. Weaknesses include long atmospheric path lengths, increased vulnerability to weather (below clouds and moisture), inability to support large deviations in the target vehicle flight path (with a single system), and logistical considerations (e.g., system weight, availability of access roads, system security and power generation).

Drones offer one potential path to realize the benefits of an airborne imaging platform at a more affordable cost. The leadership within the NASA Science Mission Directorate (SMD) has recognized that unmanned aircraft systems (UAS) have the potential to transform the way airborne science platforms contribute to earth science related investigations and environmental monitoring. The UAS application of the SMD is presently focused towards enabling the use of autonomous aerial systems and advanced remote sensors for conducting earth science and atmospheric research. Expanding that innovation to include aeronautical research and the acquisition of vehicle performance data associated with future aerospace systems could enable a paradigm shift towards a reliable, flexible, affordable, less evasive process of maximizing the return on investment of NASA flight testing by complementing, enhancing or in limited cases, replacing the traditional in-situ DFI measurement approach. A vehicle health monitoring capability supported by an aerial based remote imaging system traded against a traditional onboard system might

Figure 14: Evolutionary autonomous and robotic imaging system to support requirements of the flight test community.

also be of interest.

As conceptually shown in Fig. 14, a truly affordable next generation system might evolve from the large expensive platforms used today towards a smaller, more versatile system; an up looking "smart sensor payload" with a UAS (or high altitude airship) optimally designed around it. In this long-range vision, sensor and platform are integrally connected. Sensor inputs would permit completely autonomous operations (i.e., no remote pilot) even in GPS-denied environments. Using intelligent flight controls and a payload-directed flight, this next generation imagery system would ultimately permit autonomous long range target acquisition, tracking, image stabilization and enhancement, real-time sensor re-configuration/wave-band selection and aircraft attitude/orientation to optimize the data collect thus significantly increasing mission flexibility while reducing operational costs. Because UAS are capable of long-duration loitering, they are ideal for observations where there is uncertainty in mission timelines (i.e., launch or re-entry delays). Because they are unmanned, UAS are also ideal for conducting operations in remote, dangerous or restricted airspace where there is risk to pilot and aircraft. As noted earlier, a high altitude capability places sensors well above the detrimental effects of the atmosphere. To make optimal use of the platform capabilities to satisfy future science and engineering objectives and most importantly, facilitate and provide direction to this vision, a system trade study has been initiated by NASA to identify gaps between the existing optical and detector technology, new sensor concepts and platform command and control architecture. With the increasing use of unmanned drones for surveillance and reconnaissance missions,[45] cooperation with and inputs from the NATO partners is actively sought to improve this trade study.

On a cost per pixel basis, the development of a small versatile robotic imaging system (e.g., an unmanned aerial system or airship) could enable an affordable imaging system that is competitive to a traditional DFI type temperature data collection architecture. One of the challenges with a remote imaging capability is the limited time the target vehicle is observed at spatially resolved conditions. Traditional in-situ surface or onboard measurements pertaining to BLT can be made continuously during re-entry or sustained flight. Existing capability with a single ground or aerial asset only permits observations of tens of seconds at meaningful spatial resolution. It is suggested that cooperation among multiple autonomous robotic imaging platforms positioned along the expected flight path could effectively extend observation times. This type of strategy would permit extended spatial coverage where uncertainties in the flight path are possible or expected, and enable distributed capability deployment, where vehicles can have varying sensor/manipulator capabilities to better achieve a broad range of objectives (i.e., visual, spectral, thermal). Such an aerial system would autonomously distribute required tasks amongst themselves based upon each vehicle's capabilities/sensor package and adapt to changes in the environment, learned knowledge associated with the phenomenology of the observation and mitigate failures on individual aerial platforms. The time horizon for a UAS based imaging system is imminent as there are significant ongoing national and international efforts to integrate UAS operations into sovereign airspace. It is now an opportune time to work UAS payload integration challenges.

4.4 Flight Testing & Next Generation BLT Flight Experiment

As NASA and the NATO partners embark on new space launch systems or hypersonic cruise systems, an opportunity exists at the Agency and international level to implement a top down requirements approach to designing and developing an imagery system and its supporting infrastructure that provides sufficient flexibility to incorporate changing technology to address the future needs and objectives of the flight test community. Partnerships are encouraged to develop advocacy for next generation hypersonic BLT flight experiments where complementary ground measurements would be obtained to minimize the uncertainties associated with current ground to flight extrapolation methods and synergistic remote imaging would be used to complement advanced high frequency surface instrumentation to advance our understanding of the complex process of flow transition.

A recognized long-term goal of the HYTHIRM project was to seek other opportunities to obtain global IR aerothermal data as possible support for other BLT related flight tests. One program given serious consideration was the NASA hypersonic boundary layer transition (HyBoLT) flight experiment.[46] HyBoLT was proposed for reducing uncertainties with the extrapolation of wind tunnel derived BLT correlations for flight application (and in particular, those derived from the Shuttle RTF effort). In this flight test, an instrumented payload was to be carried aloft on a rocket launched from Wallops Flight Facility. Surface thermocouples and high frequency sensors were to have been utilized for the verification of physics-based models used to design the experiment. As the first step in building an advocacy package for thermal imaging to complement the vehicle instrumentation, the ViDI simulation capability was exercised. Shown in Fig. 15 are two simulated images of instrumented payload atop the rocket launcher based upon the 2008 capabilities of an airborne imaging platform located five miles from the ground track. Global thermal patterns from a wind tunnel test were mapped to CAD geometry to assess the ability of the IR system to spatially resolve anticipated thermal patterns in flight. The graphic on the left of Fig.15 is the synthetic image corresponding to an orientation showing thermal patterns associated with the natural transition experiment (i.e., no BLT trips) at Mach 3.5. The image suggests resolution sufficient to reveal thermal details such as the flow structure from boundary layer flow rakes near the aft end of the payload. On the right side of Fig. 15, thermal patterns associated with turbulence forced from the three BLT trips are shown. Based upon the expected distance from the imaging aircraft to the rocket at Mach 7 (expected BLT Mach number), the spatial resolution was anticipated to be approximately 1.3-in per pixel. As expected, the resulting Mach 7 simulated image is relatively smaller but the three turbulent wedges can still be identified, suggesting adequate resolution was possible. Naturally, these simulations represent just the optical performance of the 2008 imaging system at its best with no blurring due to atmospheric turbulence or aircraft vibration. Additionally, images in Fig. 15 do not actually simulate the expected irradiance from the vehicle, as a radiance model of a copper body payload was not developed. Despite the promise of reasonable spatial resolution, the requirements associated with initiating an undertaking of this nature two months before launch prevented the approval to proceed. Ironically, Ref. 4 pointed out the value of imaging from the perspective of reconstruction in the event of a mishap. On August 22, 2008 range-safety forced destruction of the rocket approximately 27 seconds into the launch after loss of control was determined. High-resolution aerial based imaging was not obtained.

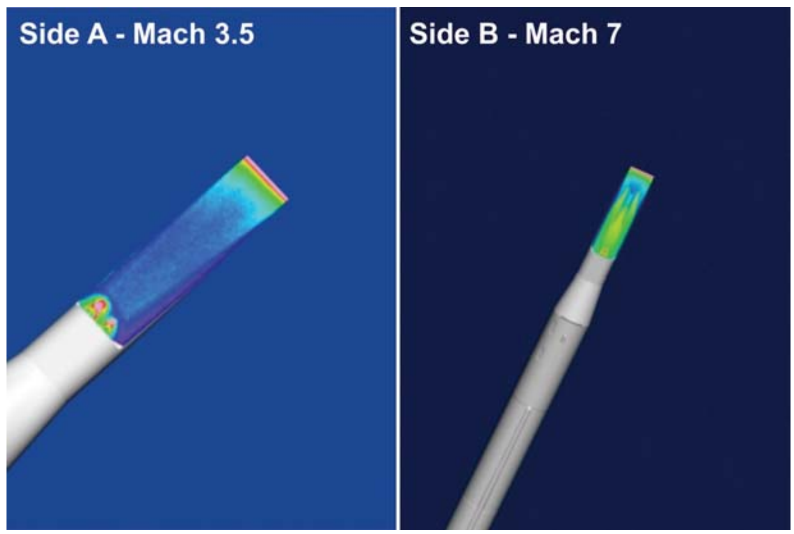

Figure 15: Optical simulation of the HyBoLT launch using an airborne system 5 miles from anticipated ground track.

On the international front, the pace of flight test activity continues to move forward. The European Space Agency's Future Launcher Preparatory Program (FLPP) is embarking on several flight test programs aimed at obtaining high quality aerothermodynamic flight data. An exploratory dialog with the IXV program[47] has been started to determine specific mission requirements and if verification can be achieved or enhanced with quantitative spatially resolved thermal imagery. Initial interest has been expressed for global heatshield surface temperatures derived from calibrated radiometric imagery to complement limited surface thermocouple measurement. In a similar manner, dialog with EXPERT program[48] management is desired. Of interest to the transition community, the EXPERT vehicle will be flown with a surface protuberance similar in nature to that flown on the Shuttle. Imagery could potentially provide useful ancillary information regarding the global nature of BLT. Based upon the size of the IXV and EXPERT test vehicles, current airborne capability will be challenged from a resolution perspective. A commercially available large aperture, long focal length imaging system deployed from any of the planned sea-based ships supporting telemetry or recovery functions appears more promising.

Based upon the initial success of the HYTHIRM team, it is recommended that any future hypersonic flight test consider global thermography as part of the instrumentation suite. After consultation with the hypersonic transition community, Berry et. al.[4] have offered an approach towards advancement of physics based BLT predictive models. A program consisting of ground and flight based measurements to provide fundamental data is ultimately necessary to evaluate stability based analyses techniques. Their recommendations in regards to a flight test program are based upon careful consideration of the current needs of the hypersonic BLT community, with an eye on the goals, approaches, and lessons learned from past flight programs. The recommendation revolves around the use of a series of launch vehicles similar in performance to that used by HyBoLT. Since second mode instabilities are currently not well characterized in flight the proposal advocates the use of current high-frequency sensor technology, such as surface mounted piezoelectric pressure gauges to characterize the in-flight disturbances. In Ref. 4, it was determined that flight conditions in the range of Mach 6 to 10 and altitudes around 80kft should be adequate for an initial flight test effort and will allow for some limited comparisons against ground-based data. These speeds and altitudes represent conditions favourable to provide high-resolution thermal imagery. Global thermography similar in nature to that performed during Shuttle re-entry could provide vital information on the 3-dimensional nature of the transition front resulting from second mode instabilities. In the event of a measurement anomaly, such imagery could be essential.

5.0 SUMMARY

A recently demonstrated flight measurement capability under the NASA Langley HYTHIRM project culminated in a high spatial resolution infrared observation from a mobile ground based optical system capturing Space Shuttle Endeavour's return to earth following its final mission in 2011. The STS-134 observation is believed to be the first time that the development and movement of a hypersonic boundary layer transition front has been witnessed in flight on such a global scale and in particular, at unprecedented spatial resolution. This emerging capability suggests several opportunities for technical collaboration to advance modeling and instrumentation capabilities supporting hypersonic BLT research. The benchmark surface temperature maps of the Orbiter lower surface represent a rare and unique opportunity for collaborative comparison of advanced numerical predictive techniques focused towards high Mach number laminar flow and hypersonic transition and turbulence modeling against in-flight global surface temperature measurement. With targeted investments in optics, infrared sensor and imaging platform technologies suggested in this paper, quantitative imaging applications at the national and international level would offer a unique and complementary flight measurement capability to maximize the scientific return on investment in terms of developmental flight tests for future vehicle designs. Partnerships within the NATO member nations are encouraged to develop advocacy for next generation hypersonic BLT flight experiments where remote imaging would be used collaboratively with advanced high frequency surface instrumentation to advance our understanding of the complex process of flow transition.

6.0 ACKNOWLEDGEMENTS

The authors would like to acknowledge the ambitious and dedicated behind the scenes work of numerous organizations and individuals that were responsible for all the Shuttle thermal imaging missions leading to the STS-134 observation of Endeavour's last flight. Special recognition is extended to Paul Krasa, Debi Tomek and Robert Kerns for their extraordinary leadership throughout the HYTHIRM project that ultimately set the stage for this visionary look forward. A special thank you to Richard Wheless who spent numerous hours in figure preparation. The authors gratefully acknowledge all contributions and behind-the-scenes work.

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