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Assessment and Mission Planning Capability For Quantitative Aerothermodynamic Flight Measurements Using Remote Imaging

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High resolution calibrated infrared imagery of vehicles during hypervelocity atmospheric entry or sustained hypersonic cruise has the potential to provide flight data on the distribution of surface temperature and the state of the airflow over the vehicle. In the early 1980's NASA sought to obtain high spatial resolution infrared imagery of the Shuttle during entry. Despite mission execution with a technically rigorous pre-planning capability, the single airborne optical system for this attempt was considered developmental and the scientific return was marginal. In 2005 the Space Shuttle Program again sponsored an effort to obtain imagery of the Orbiter. Imaging requirements were targeted towards Shuttle ascent; companion requirements for entry did not exist. The engineering community was allowed to define observation goals and incrementally demonstrate key elements of a quantitative spatially resolved measurement capability over a series of flights. These imaging opportunities were extremely beneficial and clearly demonstrated capability to capture infrared imagery with mature and operational assets of the US Navy and the Missile Defense Agency. While successful, the usefulness of the imagery was, from an engineering perspective, limited. These limitations were mainly associated with uncertainties regarding operational aspects of data acquisition. These uncertainties, in turn, came about because of limited pre-flight mission planning capability, a poor understanding of several factors including the infrared signature of the Shuttle, optical hardware limitations, atmospheric effects and detector response characteristics. Operational details of sensor configuration such as detector integration time and tracking system algorithms were carried out ad hoc (best practices) which led to low probability of target acquisition and detector saturation. Leveraging from the qualified success during Return-to-Flight, the NASA Engineering and Safety Center sponsored an assessment study focused on increasing the probability of returning spatially resolved scientific/engineering thermal imagery. This paper provides an overview of the assessment task and the systematic approach designed to establish confidence in the ability of existing assets to reliably acquire, track and return global quantitative surface temperatures of the Shuttle during entry. A discussion of capability demonstration in support of a potential Shuttle boundary layer transition flight test is presented. Successful demonstration of a quantitative, spatially resolved, global temperature measurement on the proposed Shuttle boundary layer transition flight test could lead to potential future applications with hypersonic flight test programs within the USAF and DARPA along with flight test opportunities supporting NASA's project Constellation.

Nomenclature

M	freestream Mach number
Re	freestream Reynolds number
T	surface temperature
α	angle of attack, deg
β	angle of side slip, deg

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Acronyms

BLT	boundary layer transition
CFD	computational fluid dynamics
CEV	Crew Exploration Vehicle
DoD	department of defense
DARPA	Defense Advanced Research Project Agency
HALO	high altitude observatory
HYTHIRM	hypersonic thermodynamic infrared measurements
IR	infrared
ISS	International Space Station
LWIR	long-wave infrared
MDA	missile defense agency
MWIR	mid-wave infrared
NESC	NASA Engineering and Safety Center
NIR	near infrared
NSTTF	National Solar Thermal Test Facility
RCG	reaction cured glass
RCS	reaction control jets
RTF	return to flight
SSP	Space Shuttle Program
SWIR	short-wave infrared
STS	space transportation system
TPS	thermal protection system
ViDI	virtual diagnostics interface
WAVE	WB-57F ascent video experiment

I. Introduction

KKnowledge of the technical motivation to obtain surface temperatures of hypersonic vehicles in flight is critical to understanding recent attempts to demonstrate a global flight thermography capability on the Shuttle. In general, heating augmentations and temperature increases resulting from boundary layer transition to turbulence during hypersonic flight through the atmosphere of Earth (or other planets such as Mars) impose critical requirements on the design of vehicle thermal protection systems (TPS). The onset of laminar-to-turbulent transition and subsequent fully turbulent surface heating determine thermal protection system material selection, placement, and thickness. In terms of vehicle performance, boundary layer transition (BLT) can influence vehicle aerodynamics (i.e., increased drag), landed (or impact) accuracy of autonomously guided spacecraft or delivery systems and scramjet propulsion system performance. The development of numerical tools for the reliable and rapid prediction of BLT on complex vehicle shapes, however, continues to be hindered by the inability to accurately model the complex physics associated with the transition process. During STS-114's Return-to-Flight (RTF) mission, these uncertainties led to a management decision to conduct an unprecedented spacewalk to remove two protruding gap fillers. If the necessity of inherently risky on-orbit repair operations are to be lowered in the future, uncertainties in predicting early (high Mach number) BLT need to be reduced. Looking towards the future, the present heatshield TPS design philosophy from the Crew Exploration Vehicle (CEV) assumes fully turbulent flow in flight at all times. Under this assumption, uncertainties in predicted surface temperature from numerical turbulence models are of more concern. Collectively, uncertainties in both transition onset and turbulent heating can impose unnecessarily large TPS margins that translate to reduced payload capability and degraded mission performance.

Relative to discrete onboard surface instrumentation, the passive nature of infrared thermography makes it a very powerful tool to observe surface flow phenomena from a global perspective. Any flow phenomena that create measurable surface temperature changes such as shock wave interactions, flow separation, and boundary layer transition could be visualized. Quantitatively, if surface temperatures associated with a hypersonic laminar and/or fully turbulent boundary layer flow can be inferred from calibrated in flight imagery they could be used to verify numerical predictive methods and associated turbulence models. While most aerospace applications of infrared thermography have been limited to wind tunnel testing, this measurement technique has been utilized during several Shuttle entries over the past 25 years to obtain flight data[1-7]. The most recent imagery during Shuttle entry[8] was motivated by the desire to reduce uncertainties associated with an empirical strategy to predict BLT onset. This empirical methodology is presently derived from ground-based measurements[9] that are extrapolated to flight using representative (and limited) flight data[10]. During the RTF BLT predictive tool development phase, it was recognized that the level of conservatism imposed by these extrapolation uncertainties could be more clearly established and/or reduced with quality data from a controlled roughness flight experiment. Advocacy from the technical community has resulted in the Space Shuttle Program (SSP) support of a hypersonic boundary layer flight test. In the planned tests, an isolated protuberance located on the Shuttle wing will be used to induce boundary layer transition and turbulence at hypersonic conditions[11]. Global temperature IR images with adequate spatial resolution and dynamic range could non-intrusively complement the discrete thermocouple data on these flight tests by providing spatially continuous surface temperature at targeted Mach number(s). Recognizing the tremendous opportunity of this Shuttle BLT flight tests, the NASA Engineering and Safety Center (NESC) has sponsored the formation of a team of technical experts to assess existing imaging capability within the US and to develop and validate a mission planning tool set. The overall goal of the assessment team is to demonstrate the viability of obtaining global temperature measurements of hypersonic flight vehicles using the nation's existing suite of applicable imaging assets. The near term target of opportunity to demonstrate capability is (but not limited to) the Shuttle BLT flight experiment currently planned for spring 2009.

The present paper provides an overview of the NESC **H**ypersonic **TH**ermodynamic **I**nfra**R**ed **M**easurement (HYTHIRM) assessment team and the integrated effort that was involved with identification and cataloging of relevant optical imaging assets and the development, maturation, and validation of simulation and modeling tools for assessment and mission planning purposes. It is intended as part of a series of four papers on the viability of quantitative spatially resolved flight thermography. Reference 12 provides the results of a system trade study using the simulation modeling tools[13] developed during the initial HYTHIRM effort. The results from the trade study will be used to evaluate the technology readiness of multiple systems and determine their relative priority for deployment in support of the Shuttle flight experiment. Reference 14 documents a semi-remote field deployment of optical assets at Sandia National Laboratories' National Solar Thermal Test Facility (NSTTF) whereby radiometric data was collected on a shuttle tile array heated to surface temperatures typical of a Shuttle re-entry. The objective of this test was the validation of a suite of mission planning tools including a radiance prediction methodology and the characterization of atmospheric effects. And finally, Reference 15 provides an update on the Shuttle flight experiment and the synergy with a HYTHIRM ancillary global data collection. Recent wind tunnel results are discussed that characterize the turbulent footprint from a protuberance placed at the location desired for the actual flight experiment. In addition, the Shuttle BLT predictive capability as currently implemented in the damage assessment process for each mission is reviewed.

II. Shuttle Entry Infrared Imaging during Return-to-Flight

A. STS-114 (2005), STS-121 (2006), STS-115 (2006), STS-116 (2006)

Reference 8 provides a complete historical perspective regarding IR thermography applied to Shuttle. The following section briefly summarizes motivations and data associated with the most recent attempts during Return-to-Flight. In anticipation of a Shuttle BLT flight test program, interest developed in determining whether or not remote imaging could provide quantitative global surface temperature on the windward surface of the Shuttle during boundary layer transition at high Mach number. The ensuing effort leveraged from post STS-107 recommendations made to NASA management[16,17] to improve imaging capability during ascent and entry. During the Columbia Accident Investigation, imaging teams supporting debris shedding analysis were hampered by poor entry image quality and the general lack of information on optical signatures associated with a nominal Shuttle entry. As a result, the SSP sponsored entry observations to qualitatively characterize a nominal Shuttle entry over a wide Mach number range (25>M>3). Visual and IR

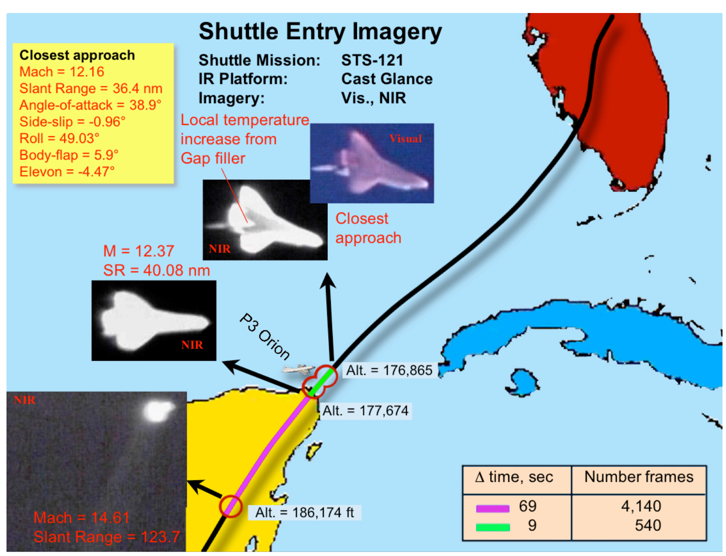

Fig. 1. Cast Glance Entry Imaging in Support of STS-121

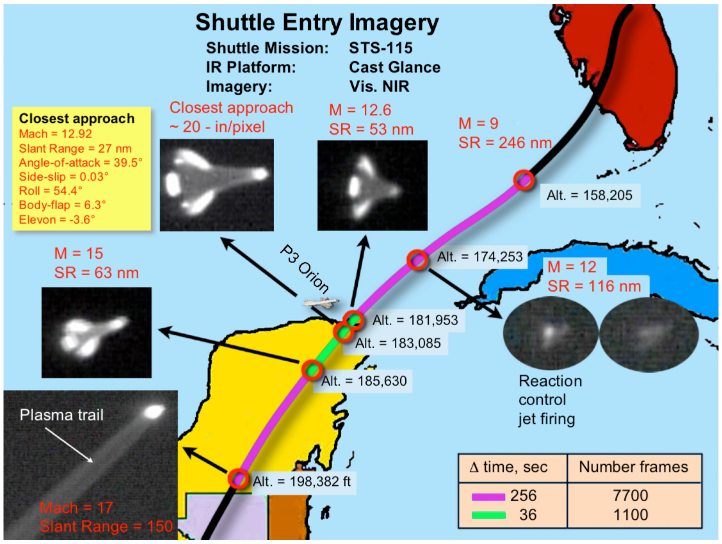

Fig. 2. Cast Glance Entry Imaging in Support of STS-115

entry imagery was obtained by several existing airborne sensor platforms. These missions involving operationally mature assets, were flown ad-hoc, that is, with very minimal pre-flight mission planning. Initial objectives of these entry observations focused on the potential to identify/resolve debris liberated from the Shuttle during entry and characterization of potential anomalous events associated with Reaction Control Jet (RCS) firings or unusual phenomenon associated with the plasma trail. The aeroheating technical community viewed the SSP sponsored activity as an opportunity to influence the observation objectives and incrementally demonstrate key elements of a quantitative spatially resolved surface temperature measurement capability over a series of flights. (i.e., tracking, acquisition of multispectral data, spatial resolution on target etc.).

Airborne IR detector platforms were selected over land-based systems because of their inherent flexibility and the fact that post STS-107, Shuttle entry ground tracks were largely over water (the aircraft also fly above most of the water vapor in the atmosphere which tends to absorb the infrared radiation). Crew timelines and orbital mechanics favor ascending approaches (south to north) into KSC or Edwards landing sites for ISS (51.6 deg inclination) missions. With the Shuttle's cross-range capability, entry into KSC generally has the Shuttle flying over Mexico and subsequently the Gulf of Mexico. The initial entry observation strategy was focused on agency assets originally developed for use during Shuttle ascent. Ultimately, the observation strategy was expanded to include state-of-the-art airborne imaging platforms used by the Missile Defense Agency (MDA) and the U.S. Navy. The three aircraft, consisted of an MDA Gulfstream High altitude Observatory (HALO II) aircraft, a NAVY P-3 Orion (Cast Glance), and a NASA WB-57F Ascent Video Experiment (WAVE) aircraft. These aircraft are specially equipped with imaging systems in several wavelength bands that have the potential to provide information on entry aerothermodynamics, and in particular, surface heating.

In general, the Shuttle was first detected as a point source several hundred nautical miles from the observing aircraft. Given the relative velocity between the aircraft and the Shuttle, the slant range (distance between the Shuttle and observing aircraft) reached a minimum within minutes. The Shuttle imagery was acquired at a linear spatial resolution approaching 20 inches per pixel for tens of seconds before it receded back to a point source. For a few seconds near closest approach, the aircraft were approximately 25-50 nmi below the Shuttle. Shuttle ground track and orientation associated with roll/bank energy management maneuvers during entry were accurately predicted pre-entry to place the observing aircraft in optimal positions to view the windward surface. Sun exclusion angles were assessed (if daylight entry) so as to avoid image degradation or loss. The aircraft were generally not placed directly under the ground track so as to preclude gimbal lock (loss of pointing control) of the telescopes. Based upon the differences in observation methods, each aircraft generally flies a different terminal maneuver to optimize pointing control of its respective telescopes/mirrors. Successful acquisition during STS-121 and STS-115 entry (Figs 1 and 2) resulted in 10,000 to 30,000 frames of visible and infrared images. Of these images, only a small number were used to extract spatially resolved quantitative surface temperature. The reader is referred to Ref. 8 for complete details of the four entry-imaging attempts made during STS-114 (July 2005) thru STS-116 (December 2006) including aircraft performance and imaging detector specifications and a discussion of the processes associated with converting global intensity data to surface temperatures.

The intensity image obtained at closest approach (Fig.1) revealed the high temperature footprint of what is presumably turbulent flow from the protruding gap filler located just upstream of the body flap. Had it not been for the global measurement, this off-nominal BLT event would have gone undocumented as on Shuttle Discovery, there were no surface thermocouples located in the vicinity of the expected turbulence. Although the area of high heating downstream of the protruding gap filler on STS-121 is clearly evident in this intensity image, quantitative information regarding temperature or the angular spreading of disturbed flow cannot be determined because of significant saturation (white areas). Figure 2 highlights the incremental improvements made in reducing image saturation during STS-115 entry with Shuttle Atlantis approximately two months later. Although promising, these improvements were made in-situ by arbitrarily reducing the detector integration time. Lack of a radiance model precluded any pre-flight sensor simulation to estimate resolution, characterize atmospheric effects, quantify dynamic range and optimize integration times.

Conversion of a spatially resolved intensity image acquired under optimum acquisition parameters to global temperature is the metric of success for HYTHIRM. Conversion of the STS-115 imagery obtained under ad-hoc circumstances was discussed in Ref. 8 and a calibrated image is shown, Fig. 3. While this temperature mapping derived from calibration verses limited thermocouples on the Shuttle Atlantis was considered a success, it should be remembered that acquisition was performed in non-optimal conditions (no significant pre-flight planning). In terms of analysis, the global data presented in Fig. 3 has not been frame averaged to improve image stabilization and signal-to-noise. Furthermore, a deconvolution transfer function was not estimated or applied to reduce image blurring. The processes and tools developed under HYTHIRM will significantly improve imaging and analysis capability.

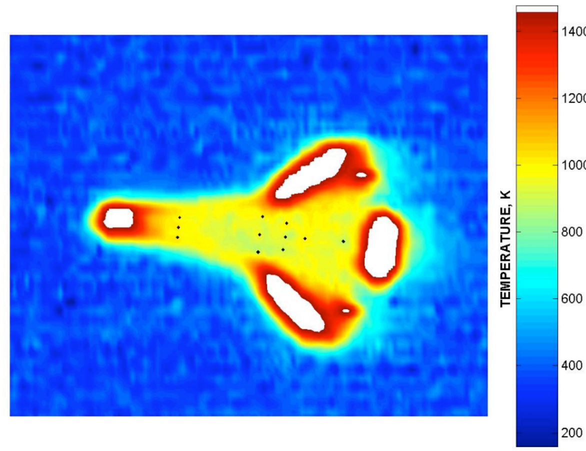

Fig. 3. STS-115 Cast Glance NIR Global Temperature Image with Shuttle Atlantis Thermocouple Locations (exaggerated for emphasis).

III. HYTHIRM: Overview of Assessment and Mission Planning Capability

A. Asset Database

Under HYTHIRM, an unclassified database of available IR imaging assets has been compiled. This information was initially obtained from multiple sources and later, from the individual asset owners. While only aircraft were considered pre-HYTHIRM, an understanding of multiple types of platforms has now been considered as part of a risk reduction strategy. Presently, the optical assets are cataloged by their deployment as a land, sea, or air based platform. Satellite-based systems have been considered but their potential inclusion into the database has been deferred to the future. Many of these optical systems support specific range operations and as such, only a select few are actually viable in support of a Shuttle imaging mission. However, the database was not compiled exclusively for an assessment against a Shuttle data collect. There are a number of other DoD, DARPA, or commercial sector missions on the near term horizon that could potentially benefit from the type of thermal imaging capability to be demonstrated with the Shuttle.

The database of airborne, land-based and sea-based platforms lists pertinent information on existing capability to rapidly assess optical performance/capability and system mobility. Some of the more relevant system parameters include detector waveband, dynamic range, pixel and array size, instantaneous field of view, integration time, analog or digital format, optical resolution, telescope optical diffraction limits, and aperture/focal length. The information, listed in spreadsheet format, is updated periodically and is readily accessible by the simulation and mission planning tools. The database also includes information on aircraft performance metrics such as ceiling, endurance, cruise speed and range so that consideration of timely asset relocation can be determined. The reader is referred to Ref. 12 for a summary of the asset database.

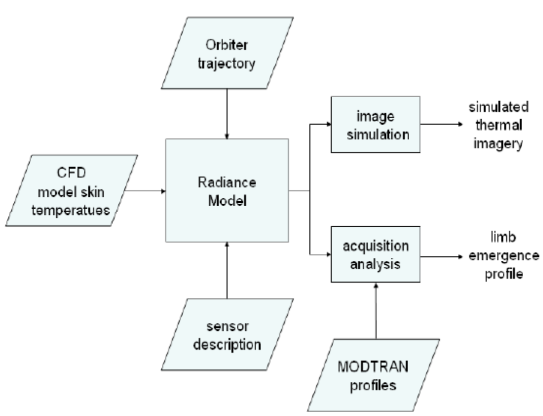

Fig. 4. Radiance Model Methodology

B. Simulation and Radiance Modeling

A more significant lesson learned from the RTF sponsored entry observations (pre-HYTHIRM) was the lack of mission specific planning tools to establish processes and procedures for reliably acquiring and tracking the

Shuttle. That is, the low probability of quantitative imagery obtained under RTF can be directly traced to the inability to quantitatively predict the infrared signature presented by the Shuttle to infrared sensors, and an inability to assess the effects of the atmosphere and subsequent sensor responses. A significant amount of work was performed under HYTHIRM to develop a radiation model to quantify the Shuttle infrared signature during entry[13] and define sensor characteristics (or modifications) needed to meet data requirements. As shown schematically in Fig. 4, the radiance model is fundamentally built around laminar and turbulent CFD surface temperature predictions of the Shuttle over a range of Mach numbers. Trajectory specific radiative equilibrium surface temperatures are assumed along with a surface emissivity appropriate to Reaction Cured Glass (RCG) coated tiles. The reader is referred to Ref. 13 for full details concerning modeling assumptions. When applying this radiation modeling capability to other potential vehicles with TPS systems different than the Shuttle, the assumption of radiation equilibrium wall temperature may not be justified.

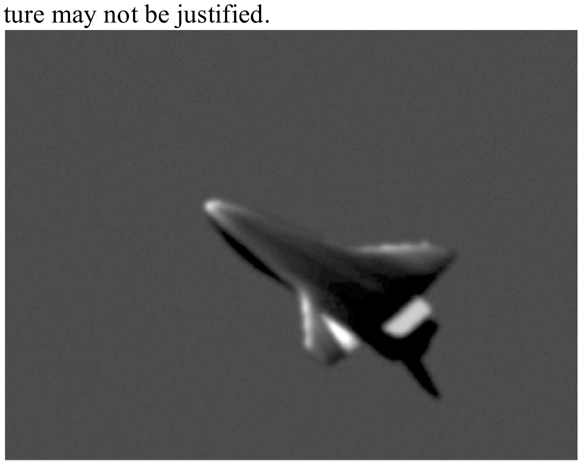

Fig. 5. Simulated NIR Imagery from an Aircraft

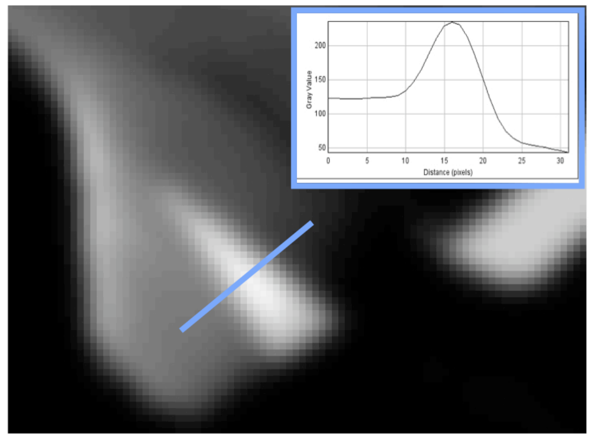

Fig. 6. Pixels on Target from Imagery Simulation

In the waveband of interest, atmospheric radiance and transmittance can be estimated with a widely used radiative transfer code MODTRAN[18] [MODerate resolution atmospheric TRANsmission], a program designed to model the propagation of electromagnetic radiation through the atmosphere. The radiance model is based in a visualization software environment that transforms three dimensional surface temperature input into surface radiant intensity and then projects the three dimensional intensity onto a two dimensional plane that represents a detector array. The projection can be done for arbitrary orientations of the Orbiter. In terms of output, the radiance model also has the ability to graphically represent image quality degradation (i.e., blurring) resulting from atmospheric effects, optical bench motion and/or system optical diffraction limits via a point spread function, if known. In conjunction with the radiance model, a Virtual Diagnostics Interface (ViDI) modeling environment has been used to assist in rapid mission planning, visualization of asset deployment strategies, and a rapid first order determination of spatial resolution on target. The virtual environment was also utilized to assess observation sites associated with a remote field deployment/validation test to be discussed in a subsequent section. Coupled with the use of operationally mature imaging assets, these simulation tools will allow the HYTHIRM team to provide sensor operators with pre-flight simulated imagery and recommended detector configurations thereby increasing the probability of obtaining scientific/engineering quality imagery during an actual deployment.

In a resolved mode, the radiance model can simulate imagery that could be obtained by high-resolution infrared imaging sensors. Recent application of the radiance model to the specific case of the upcoming flight experiment has provided insight for sensors that may be selected to observe local surface temperature increases from boundary layer transition near Mach 15. In Fig. 5, a simulated intensity image from an airborne detector is presented with a 2 pixel guassian point spread function applied. In this simulation, the aircraft was located at minimal slant range approximately 10 nmi from the ground track. The temperature range has been optimized for a 0-255 gray-scale display with the brightest pixel (registering 255) located within the turbulent zone on the wing. Parametric analysis has shown that an 8-bit system would just cover the expected intensity range but would provide no margin for integration time (exposure) errors or uncertainties associated with actual surface temperatures in flight. A 14-bit bit system would provide sufficient margin to protect against saturation. As shown in Fig. 6, the output from the radiance tool is being used to assess pixels on target and estimate resolution capability.

In an unresolved mode, the radiance model has been used to characterize the emergence of a point source representation of the Orbiter from the horizon with both day and night sky radiance. As noted in Ref. 13, the radiance modeling capability has successfully identified the probable root cause of image acquisition failure during the STS-116 daylight entry. Application of the radiance model has also indicated that boundary layer transition events can possibly be inferred in unresolved IR data as a jump in point source intensity. In conclusion, the modeling capability developed under HYTHIRM has quantified improvements in procedures associated with tracking, infrared band selection, dynamic range and estimating spatial resolution.

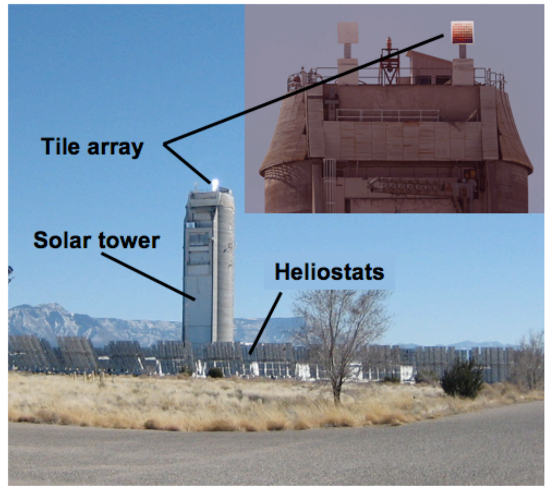

Fig. 7. National Solar Thermal Test Facility

C. Validation Testing

A critical element of the systematic HYTHIRM approach was a semi-remote field deployment of optical assets at Sandia National Laboratory whereby radiometric data was collected on a shuttle tile array heated to surface temperatures typical of a Shuttle re-entry. The objective of the Solar Tower test was the validation of a suite of mission planning tools including a radiance prediction methodology. Subsequent analysis of the imagery will be used to evaluate the performance of the participating sensor systems and associated image processing algorithms. Testing at NSTTF in Albuquerque, NM involved the coordination of infrared imaging assets from five organizations (three land imagers, one airborne and one space-based). The NSTTF consists primarily of a 200 foot tall concrete tower known as the Solar Tower located in close proximity to a field of 212 mirrored solar collectors (heliostats) as shown in Fig. 7. Under a more traditional application, the facility is typically used for material response testing of TPS[19]. That is, ablative material TPS samples are mounted to a test stand on top of the tower and exposed to high heat flux levels to assess material response characteristics. In the HYTHIRM sponsored validation test, the facility was utilized in a more unconventional sense. As shown in Fig. 8, a 4 foot by 4 foot test panel, consisting of an 8 by 8 array of LI 900 ceramic tiles, was constructed. These tiles are similar in construction to tiles used on the windward surface of the Shuttle. The top level of the Solar Tower provided an ideal test bed for the HYTHIRM radiometric calibration and validation tests because of its capability of rapidly heating the tile test panel to spatially uniform and non-uniform elevated temperatures in an unsheltered-open-air environment that was conducive to obtaining unobstructed radiometric data by airborne and land-based IR imaging assets. Illumination of the tile array in the visible spectrum can be seen in the inset of Fig. 7.

The land-based systems were located 5.3, 1.4 and 0.3 nmi away from the Solar Tower tile array while the aircraft flew six test support position profiles with proximities of 30, 25, 20, 15, 10, and 5 nmi from the Tower. Thermocouples installed on the array and an infrared imager located in close proximity to the test target provided surface temperature measurements. Tests were conducted under uniform and non-uniform heating of the tile array to obtain radiometric data of a known radiation source in order to calibrate HYTHIRM systems for resolved and point source images. A view of the tile array from the Cast Glance P-3 Orion aircraft is shown in Fig. 9.

Sensor calibration products from the ensuing analysis will include sensor output digital units as functions of temperature and radiance, true angular resolution and field of view, point spread function, sensor noise floor, focal plane uniformity, and saturation state. Figures 10 a and b show some preliminary results from the on-going Solar Tower data analysis. When the analysis is completed, the results from the Solar Tower tests will be used to evaluate

Fig. 8. Tile Array Test Panel

Fig. 9. Cast Glance NIR View of Partial Tile Array Illumination from approximately 5 nmi

the technology readiness of multiple systems and determine their relative priority for deployment in support of a future hypersonic flight test programs including the Shuttle boundary layer transition flight experiments. The over-all test environment, test article, test approach, and a brief synopsis of test results are discussed in detail in Ref. 14. A preliminary calibration associated with one of the optical assets supporting the Solar Tower Test is shown in Fig. 10a. Detector response is well characterized by a second degree polynomial with a correlation coefficient of 0.996. At this point in the analysis, the data shown in Fig. 10a are uncorrected for a variety of known effects including ra-diant behavior of tile-to-tile gap filler material and the aperture restriction applied to the sensor of approximately 88% (aperture restriction was applied to this particular sensor during the test to mitigate saturation). Figure 10b is a single NIR intensity image from an asset located approximately 5nmi from the heated tile array. The individual tiles are evident despite the atmospheric turbulence. To mitigate turbulence effects and radiation reflected from the frame holding the tile array, only the data from the middle of the tile array was analyzed. Other sample images col-lected during the Solar Tower validation test are presented in Ref.14.

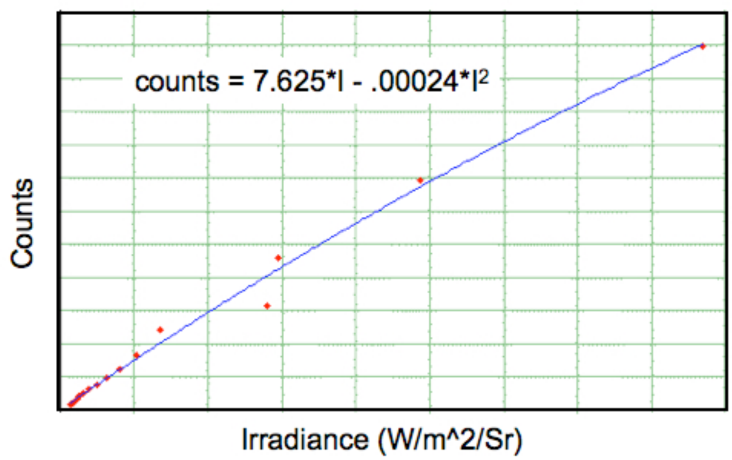

Fig. 10a. Preliminary Calibration Curve for a Uniform Spatial Heating Test (uncorrected for aperture restriction)

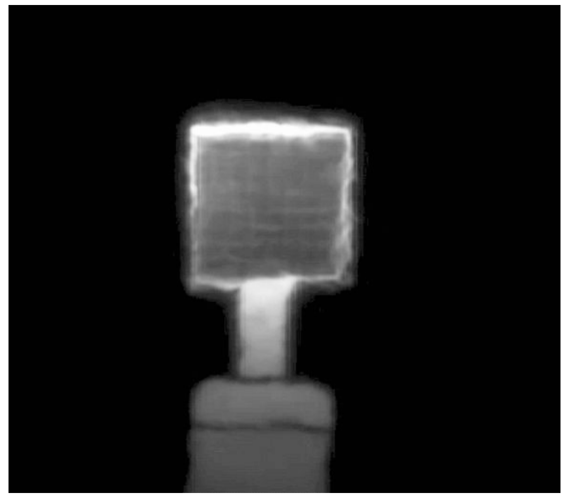

Fig. 10b. Global NIR Image of Tile Array from Land-based Asset Located 5 nmi Distant.

IV. Support to Shuttle Flight Experiment

A. Trade Study

The NESC sponsored HYTHIRM project has led to the identification and inventory of relevant optical imaging as-sets and the development, maturation, and validation of simulation and modeling tools for assessment and mission planning purposes. The culmination of the imaging assessment was the application of these tools to identify the best hardware configurations and deployment strategies for successful acquisition of quantitative global surface tempera-ture data. In this context, the Shuttle was viewed as a near term target of opportunity to demonstrate HYTHIRM capability. On the surface, the Shuttle would appear to be an ideal candidate for quantitative imaging. That is, a large vehicle with a well characterized thermal environment re-entering along a pre-determined path. In truth, the reality of supporting an actual Shuttle entry is quite complex. For instance, the actual Shuttle entry de-orbit burn is generally not discussed until the midpoint of each mission when consumable margins are assessed, and the entry weight and de-orbit planning metrics are updated. Under a nominal mission to the International Space Station (ISS), the detailed end-of-mission entry ground track is not issued by the flight dynamics group at JSC until the Shuttle undocks with ISS approximately 2 days before entry. To facilitate timely planning, Shuttle ground tracks need to be provided to asset owners as quickly as possible to assess implications of weather or mechanical related wave-offs, Shuttle roll/bank maneuvers, and sun exclusion. Significant planning and re-planning is required to accommodate multiple entry trajectory scenarios. In addition, Shuttle ground tracks along with aircraft loiter times and fuel range, determine the allowable Mach coverage for each aircraft. Furthermore, aircraft base operations outside the conti-nental US may be required for high Mach number observation locations (M~18-20). The reader is referred to Ref. 8 for more details regarding the complexity of mission planning during the RTF entry observations sponsored by the Shuttle program.

Figure 11 summarizes the variability of recent Shuttle flights returning from ISS, with landings at both KSC and Edwards Air Force Base. Based exclusively upon the historical ground-track information shown in Fig. 11, asset deployment strategies favor the flexibility and range of airborne systems. Optical performance metrics such as diffraction limits and atmospheric effects tend to cloud the issue of defining the optimum platform. Optical systems carried aloft by aircraft minimize atmospheric effects. Alternatively, larger aperture, longer focal systems inherent to ground systems are less sensitive to optical diffraction limitations. As detailed in Ref. 8, even airborne systems cannot guarantee protection against a diversion to west coast alternative landing sites. The only way to mitigate the uncertainty of entry into landing sites other than KSC is to consider the use of multiple systems to protect against all contingencies, albeit at increased cost. A mix of land and air assets may preserve asset deployment flexibility and provide wave-off protection at reasonable costs. A significant number of ground tracks associated with the 15<M<20 are in proximity to the Yucatan Peninsula suggesting the logistical viability of land-based systems. The HYTHIRM assessment team approach has been to advocate for the use of operationally mature assets with minimal hardware upgrades to increase the probability of engineering quality data return. Ref. 12 summarizes the status of the current trade study and identifies the relevant parameter space from which to consider deployment strategies. Formal requirements will evolve from the final NESC trade study report. While the final HYTHIRM trade study has not been issued, flexibility appears to be the best strategy from which to ensure a higher probability of obtaining quantitative imagery[12,15]. A clear understanding of strengths and weaknesses of airborne and land-based systems is essential to successful mission support.

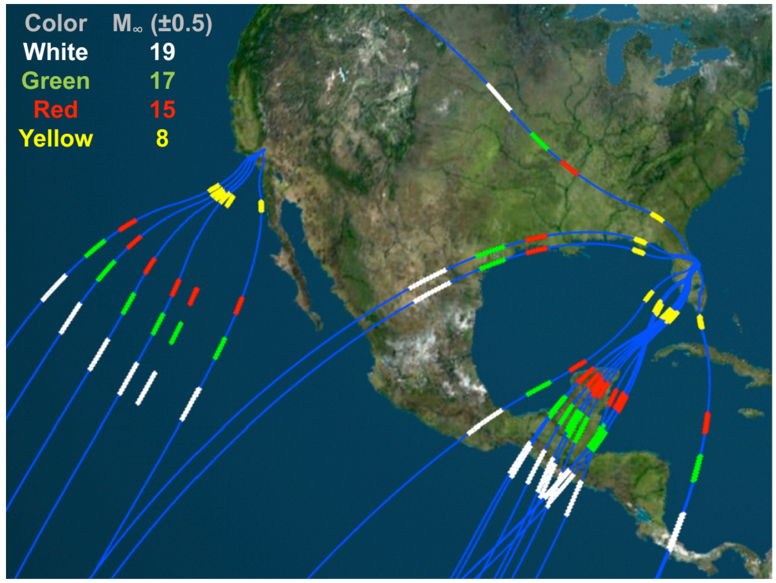

Fig. 11. Recent Shuttle Entry Trajectories into Kennedy or Edwards Returning from the International Space Station

The aircraft strengths are that they operate above weather and significant water vapor in the atmosphere, are positioned closer to the target (looking through less atmosphere), can conduct over water operations, and are typically mobile and thus able to more readily accommodate 90 minute one-orbit wave-offs. Their primary weaknesses include image blurring from optical bench motions from structural resonance and local cavity-induced flow turbulence from optical housing. Other challenges include operational expense and schedule conflicts from other DoD programs. For land-based systems, the strengths include lower per asset operational expense, large aperture/long focal length optics for spatial resolution, and mobility in terms of supporting one-day wave-offs. The land-based imaging systems do not appear to be as susceptible to schedule conflicts. Weaknesses include increased vulnerability to weather (below clouds and moisture), inability to support one-orbit wave-offs with a single system, and logistical considerations (availability of access roads, system security and power generation). Both airborne and land-based systems require long lead times to secure US State Department approval for international deployments. Reference 12 provides additional trade study details and other considerations regarding deployment options.

In terms of optical system performance metrics, several wavebands in the IR spectrum can be considered. The infrared (IR) radiation spectrum can be divided into several bands based upon uses (e.g., astronomical) or detector response characteristics. One commonly used sub-division scheme suggests: Near Infrared (NIR; 0.75-1.4μm), Shortwave Infrared (SWIR; 1.4-3.0μm), Midwave Infrared (MWIR; 3.0-5.0μm), Longwave Infrared (LWIR; 8-15μm), and Far Infrared (FIR; 15-1000μm). The basic principle behind infrared thermography is the measurement of radiation in the IR band(s) of choice, which is then related to surface temperature. Temperatures on the Shuttle windward surface (excluding nose and wing leading edge) during hypersonic entry are generally in the range of 700 to 1250 deg K. For these temperatures, a black body radiation source will have its radiation peak between 2.5 and 4.8 micrometers as discussed in Refs. 5 and 8. The choice of IR imaging system bandpass for global quantitative surface temperature mapping of the Shuttle during reentry is not trivial, and depends on factors such as thermal sensitivity, optical resolution, and atmospheric attenuation. As discussed in Ref. 12, the in-band integrated radiance is low in the NIR bandpass; with thermal sensitivity being extremely low below 1000 K. Reference 12 notes that the

LWIR waveband has slightly higher in-band integrated radiance with an almost linear variation of integrated radiance with temperature. The SWIR and MWIR have distinctly higher in-band integrated radiance and higher temperature sensitivity above 1000 K. At the same time, the amount of integrated radiance in SWIR and MWIR is so high that saturation of infrared imaging system becomes an issue and use of neutral density filters and/or higher dynamic range detectors and digitizers (14 or 16 bit) may be necessary.

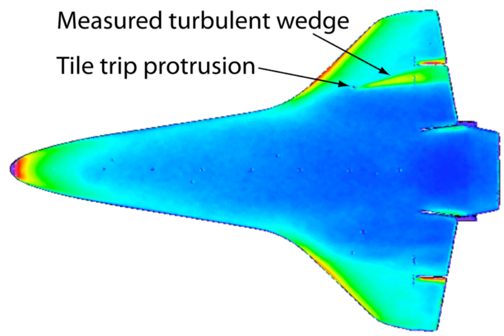

Fig. 12. Mach 6 Wind Tunnel Result Showing Location of Shuttle BLT Flight Experiment Trip and Turbulent Wedge Footprint (α = 40 deg, Re/ft = 3 x 10^6).

B. Ground-based Testing

The TPS design of any re-entry vehicle requires the prediction of its aerothermodynamic characteristics at conditions that cannot be entirely modeled with CFD or duplicated in ground facilities. Current ground-to-flight extrapolation techniques typically involve a complementary process entailing both wind tunnel and numerical prediction. To pre-position the HYTHIRM team with ground-based information, a Mach 6 wind tunnel entry was conducted to assess the measured turbulent wedge shape/orientation against that predicted for flight and to determine sensitivities of the expected turbulent footprint to vehicle angle-of-attack (30, 35, and 40 deg) and sideslip (±2, ±4 deg). In particular, these tests were conducted to quantify the movement of the turbulent footprint relative to Shuttle thermocouple locations on the wing. In addition, limited data was collected to characterize the effect of trip orientation and location on the wedge footprint and to provide site-specific boundary layer transition data to assess the current version of the Shuttle RTF BLT prediction tool. To bridge ground to flight extrapolation, additional tests are tentatively planned for Mach 10 at NASA Langley Research Center and Mach 15 at Calspan-University of Buffalo Research Center for higher Mach and enthalpy conditions.

As discussed in Ref. 15, the Mach 6 perfect gas test qualitatively revealed that the turbulent wedge angle as inferred from the wind tunnel image in Fig. 12 was slightly smaller and directed more inboard than expected at Mach 18 flight conditions. As currently implemented, the tool used to predict the wedge footprint in flight has the wedge passing over the elevon gap). Naturally, some differences between the perfect gas wind tunnel and flight condition were anticipated due to differences in local conditions and pressure gradient at the wing protuberance site. Further analysis is underway to quantify these differences and determine if there are any implications for the placement of the surface thermocouples associated with the flight experiment. A global measurement technique would certainly provide corroborating information regarding the turbulent wedge position in flight and serve as a contingency measurement in the event of thermocouple failure. See Ref. 15 for further discussion on the observed turbulent wedge insensitivity to Shuttle angle-of-attack and sideslip.

The test results also provided qualitative measurements to determine if damage located downstream of the Shuttle BLT Flight Experiment (FE) wing protuberance could further augment the acreage heating above pre-existing turbulent levels. An additional protuberance (simulating a gap filler) placed downstream and within the turbulent footprint did not increase the acreage heating above the already turbulent levels as shown in Fig. 13. Long term, the wind tunnel entry also served to provide limited site-specific boundary layer transition data to assess against the current version of the Shuttle RTF BLT prediction tool.

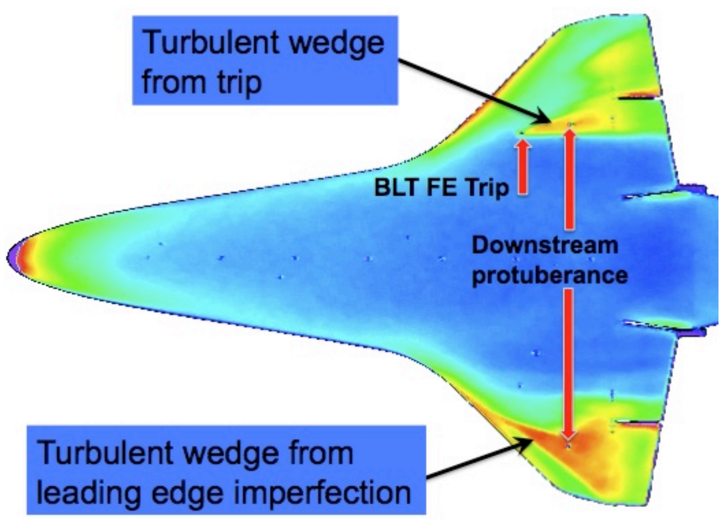

Fig. 13. No Turbulent Heating Augmentation from Protuberance Located Downstream of BLT FE Trip as Inferred from Measurement (α = 40 deg, Re/ft = 4 x 10^6).

V. Applications to Future Flight Test Programs

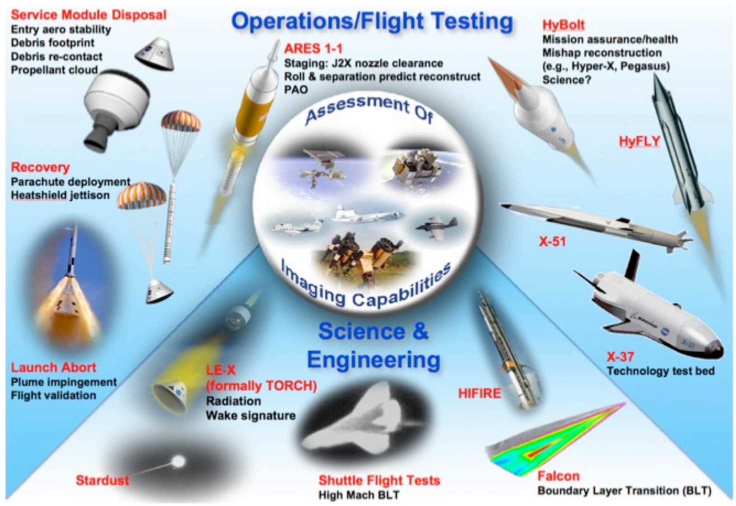

Fig. 14. Programs Potentially Benefiting from a Demonstrated Imaging Capability

Within the next decade, the United States is poised to execute several hypersonic flight test programs. Many of these flight tests will be conducted with little or no surface instrumentation to quantify boundary layer transition, and assess aeroheating environments. Successful demonstration of a remote, non-intrusive quantitative spatially resolved global temperature measurement on the proposed Shuttle boundary layer transition flight test could lead to potential future applications with hypersonic flight tests within the Air Force, DARPA and NASA. HYTHIRM supports a vision of the development of future aerospace systems and critical technologies to enable highly responsive vehicle operations across the aerospace continuum, spanning reusable space lift and global reach and could be extended to include visual/IR imaging of ascent environments. In addition to the traditional objectives supporting the development of methodologies to correlate numerical models, ground, and flight test data, the following programs could leverage the experience gained in the HYTHIRM project (shown notionally in Fig. 14):

1. DARPA/USAF Falcon[20] and Blackswift[21] flight test programs supporting a prompt global strike mission objective. The Falcon program will be coordinating ground-, sea-, air and space-based asset studies along the entire route of flight and in the terminal area to provide radar, optical and thermal imaging for telemetry, tracking and trajectory data. In contrast to Shuttle, a sustained hypersonic cruise capability is required for the prompt global strike mission. Accurate determination of when and where BLT occurs on the vehicle is extremely critical from a TPS and aerodynamic perspective, respectively. For application to this project, the radiation equilibrium wall temperature assumption as an input to the radiance model may not be valid. Alternate material emissivity would need to be quantified for proper image/data reconstruction.
2. Any USAF flight test programs to quantify test and operational performance envelopes associated with a Shuttle-like winged hypersonic entry vehicle.
3. Constellation[22] flight testing to quantify environments from post shock and surface radiative heating during Orion re-entry (similar to unresolved Stardust[23] observations) or ascent convective/plume impingement heating associated with the high altitude launch abort system (LAS). The NASA WAVE aircraft was recently used to provide thermal imagery of the second flight of the new Delta IV Heavy launcher. Visual imaging could potentially be used to assess/verify pyrotechnic system and aerodynamic performance of ARES first stage separation. After burnout and separation, the first stage will use jets to induce a tumbling motion for a controlled deceleration and a reduced landed footprint for recovery operations.
4. Understanding satellite reentry breakup phenomenology is important to NASA for assessing and mitigating the potential risk to people and property on Earth from surviving space vehicle components. NASA has worked with the DoD on several occasions to observe from air-borne platforms the reentry and breakup of spacecraft and launch vehicle stages and document principal breakup altitude, subsequent component explosive events, and debris dispersion characteristics. These airborne observations were at times supplemented with ground-based optical and radar observations. Two recent observations occurred in 1998 and 2000 with the re-entries of Ariane 503 and the Compton Gamma Ray Observatory, respectively. A HYTHIRM team member will be supporting imaging of the European Space Agencies Jules Verne Automated Transfer Vehicle breakup during a guided and controlled scheduled entry over the Pacific Ocean in late 2008.
5. Any flight test program (e.g. NASA HyBoLT,[24] US-Australian sounding rocket program HIFiRE,[25] AFRL/DARPA X-51 Scramjet Engine Demonstrator Waverider Program [26] or the Army Advanced Hypersonic Weapons program[27]) wishing to mitigate challenges associated with general vehicle health monitoring. High quality visual and/or thermal imagery could have potentially lead to a more timely closure of previous mishap reconstruction investigations (e.g. Columbia Accident Investigation[17], Pegasus[28], Hyper-X[29], HYFLY[30]). The

recent Soyuz anomalies experienced during entry[31] underscore the risks associated with returning people from ISS despite the use of a historically highly reliable system.

6. Improvement of space situational awareness. While HYTHIRM is presently not considering space assets to support the Shuttle BLT flight tests, a satellite network such as the Space Based Infrared System (SBIRS)[32] could be used in conjunction with land and air-borne assets to in support of future imaging observations and thus improve the nation's intelligence, surveillance and reconnaissance mission capability.

VI. Summary

An overview of the NASA Engineering and Safety Center Hypersonic THermodynamic InfraRed Measurements (HYTHIRM) assessment activities was presented. HYTHIRM is a coordinated and integrated team effort to determine the viability of obtaining quantitative, spatially resolved, flight thermography of the Shuttle during hypersonic entry. HYTHIRM involves the development, maturation, and validation of a suite of mission planning tools including a radiance prediction methodology for assessment and mission planning purposes. A validation effort consisting of a semi-remote field deployment of optical assets at Sandia National Laboratories' National Solar Thermal Test Facility (NSTTF) was described. In this novel test, radiometric data was collected on a array of Shuttle tiles heated to surface temperatures typical of a Shuttle entry. A trade study using these simulation tools was used to evaluate the technology readiness of multiple systems and determine their relative priority for deployment in support of a Shuttle flight experiment. A brief synopsis on the Shuttle flight experiment and the synergy with a recent wind tunnel are discussed. The ground-based measurements are used to characterize the turbulent footprint from a protuberance placed at the location desired for the actual Shuttle flight experiment. Successful demonstration of a quantitative, spatially resolved, global temperature measurement on the proposed Shuttle boundary layer transition flight test could lead to potential future applications with hypersonic flight test programs within the USAF and DARPA along with flight test opportunities supporting NASA's project Constellation.

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