

Shuttle Entry Imaging Using Infrared Thermography

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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. After the accident, recommendations were made to NASA management to develop and maintain a state-of-the-art imagery database for Shuttle engineering performance assessments and to improve entry imaging capability to support anomaly and contingency analysis during a mission. As a result, the Space Shuttle Program sponsored an observation campaign to qualitatively characterize a nominal Shuttle entry over the widest possible Mach number range. The initial objectives focused on an assessment of capability to identify/resolve debris liberated from the Shuttle during entry, characterization of potential anomalous events associated with RCS jet firings and unusual phenomenon associated with the plasma trail. The aeroheating technical community viewed the Space Shuttle Program sponsored activity as an opportunity to influence the observation objectives and incrementally demonstrate key elements of a quantitative spatially resolved temperature measurement capability over a series of flights. One long-term desire of the Shuttle engineering community is to calibrate boundary layer transition prediction methodologies that are presently part of the Shuttle damage assessment process using flight data provided by a controlled Shuttle flight experiment. Quantitative global imaging may offer a complementary method of data collection to more traditional methods such as surface thermocouples. This paper reviews the process used by the engineering community to influence data collection methods and analysis of global infrared images of the Shuttle obtained during hypersonic entry. Emphasis is placed upon airborne imaging assets sponsored by the Shuttle program during Return to Flight. Visual and IR entry imagery were obtained with available airborne imaging platforms used within DoD along with agency assets developed and optimized for use during Shuttle ascent to demonstrate capability (i.e., tracking, acquisition of multispectral data, spatial resolution) and identify system limitations (i.e., radiance modeling, saturation) using state-of-the-art imaging instrumentation and communication systems. Global infrared intensity data have been transformed to temperature by comparison to Shuttle flight thermocouple data. Reasonable agreement is found between the flight thermography images and numerical prediction. A discussion of lessons learned and potential application to a potential Shuttle boundary layer transition flight test is presented.

Nomenclature

M	=	freestream Mach number
Re	=	freestream Reynolds number
T	=	surface temperature
x	=	axial location along the Shuttle centerline
α	=	angle of attack

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β = side slip angle

Acronyms

<i>BLT</i>	= boundary layer transition
CAD	= computer aided design
CFD	= computational fluid dynamics
HALO	= high altitude observatory
IFOV	= individual field of view
<i>IR</i>	= infrared
<i>IRIS</i>	= infrared imagery of shuttle
ISTEF	= innovative science and technology experimentation facility
MADS	= modular air data system
MDA	= missile defense agency
OEX	= orbiter experiments
RTF	= return to flight
SILTS	= shuttle infrared leeside temperature sensing
SSP	= space shuttle program
STS	= space transportation system
TPS	= thermal protection system
UTC	= universal time code
ViDi	= virtual diagnostics interface
WAVE	= WB-57F ascent video experiment

I. Introduction

The passive nature of infrared thermography makes it a very powerful tool to observe surface flow phenomena globally. Any flow phenomena that create measurable surface temperature changes such as shock wave interactions, flow separation, and hypersonic boundary layer transition can potentially be visualized. While most aerospace applications of infrared thermography have been limited to wind tunnel applications, the Space Shuttle Program (SSP) has utilized this measurement technique several times over the past 25 years to obtain flight data¹⁻⁷. Early infrared (IR) imaging attempts of the Shuttle during hypersonic entry were motivated by substantial design uncertainties associated with extrapolating ground test aeroheating results to the prediction of flight aeroheating environments. Supported by the surface thermocouple measurements from the Development Flight Instrumentation (DFI) package, the first IR imaging attempts⁶ were conducted remotely during STS 1-5 to provide flight data necessary to verify new computational methods and extrapolation methods being developed at that time to support possible TPS block changes. Later, as part of a series of Orbiter Experiments (OEX), global temperature images of the Shuttle leeside surface during hypersonic entry were obtained by an IR detector flying on the Shuttle⁴. Characterized by a complex, separated, three-dimensional vortical flow, the Shuttle leeside flow was not amenable to

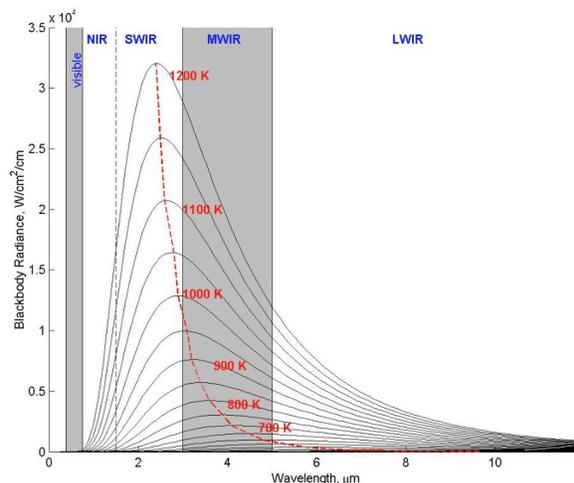


Fig. 1. Black body radiance characteristics

analysis by computational methods of the time. Uncertainties with extrapolation methods led to substantial conservatism in the design of the Shuttle's thermal protection system (TPS). The OEX IR measurements were intended to reduce design conservatism of the Shuttle leeside TPS and that of future entry vehicles. Another series of remote global IR imaging attempts¹⁻³ used the Shuttle as a test-bed to validate collection and analysis techniques of infrared images obtained at hypersonic speeds. The methods developed during this test series were to support NASA's Reusable Launch Vehicle program by obtaining hypersonic boundary layer transition flight data on the proposed Lockheed Martin X-33. This paper highlights a series of recent Shuttle entry IR observations that were conducted during Shuttle Return-to-Flight and could influence future support to a proposed Shuttle hypersonic boundary layer transition flight test.

The basic principle behind infrared thermography is the measurement of surface emissions in the infrared radiation band, which are then related to surface temperature. The Infrared (IR) radiation spectrum is classically divided into several bands: Near Infrared (NIR; 0.8-1.5 μm), Shortwave Infrared (SWIR; 1.5-3.0 μm), Midwave Infrared (MWIR; 3.0-5.0 μm), Longwave Infrared (LWIR; 5-15 μm), and Far Infrared (FIR; 15-300 μm). Temperatures on the Shuttle windward surface (excluding nose and wing leading edge) during entry are generally in the range of 600 to 1100 deg K. For these temperatures, a black body radiation source will have its radiation peak between 2.5 and 4.8 micrometers as shown, Fig. 1. In general, mid Wavelength Infrared (MWIR) imaging system wavelengths are well suited for quantitative imaging of the Shuttle during entry, particularly for surface temperatures associated with boundary layer transition (700-1000 K). Imagery associated with the other spectrums can be useful, but sensitivity and signal power from data obtained at these wavebands present certain challenges (discussed in section VIII).

II. Historical Background of Shuttle Entry Infrared Imaging

A. IRIS STS-3 (1982)

In 1973, a study sponsored by NASA ARC and performed by Martin Marietta Corporation⁵ concluded that it was feasible to obtain high spatial resolution infrared imagery of the Shuttle lower surface during entry to determine accurate measurements of aerodynamic heating. NASA sought to reduce weight and cost of future space transportation vehicles by providing flight data to validate design methodologies of the time. The technical objectives were to provide windward surface temperature distributions, the location of boundary layer transition, and the extent of flow separation in front of the Shuttle control surfaces. The platform used for this experiment, which came to be known as the IRIS (Infrared Imagery of Shuttle) experiment⁶, was the Kuiper Astronomical Observatory (KAO). The KAO was a modified C-141 aircraft that was operated by NASA ARC and used an astronomical telescope on a stabilized platform to obtain the Shuttle imagery during entry. The goal of IRIS was to use an airborne platform to obtain imagery with a temperature resolution of 75 deg F (at 2960 deg F) and a linear spatial resolution of approximately 40-in per pixel or better. For maximum sensitivity to the expected temperature range, a MWIR detector was utilized and it was recommended that the aircraft fly at or above 45kft to mitigate water vapor absorption of the radiation in the wavelength band 1.5 to 2.5 micrometers. Filters were selected to avoid atmospheric absorption bands and to limit the dynamic range of the incident radiation. The IRIS program sought to mitigate technical risks through rigorous system analysis and test flights with an SR-71 serving as the target aircraft. The first attempts to obtain imagery during STS-1 and STS-2 failed primarily due to ground communication issues between ground control and the C-141. Partial success was achieved during STS-3 and one image was obtained at approximately Mach 13. Because of a small misalignment between the tracking telescope and the acquisition telescope, only 60% of the Shuttle was actually imaged, Fig. 2. Extensive analysis was performed on this image⁷. Because the Shuttle was banked at an angle relative to the observation aircraft, a rigorous analytical image registration method was developed post-flight to remove geometric effects of a non-orthogonal projection on the image plane. That is, IRIS pixel coordinates were projected onto the lower surface of the Shuttle using flight orientation information from both the Shuttle and the C-141 at the time of image acquisition. Shuttle mid-fuselage surface temperatures inferred from IRIS measurements were shown to be within 75-100 deg F of the surface thermocouple measurements from the DFI thermocouples. Image distortion effects (blurring) were encountered and early speculation suggested focusing problems. Despite the distortion effects, targeted resolution was achieved and a quantitative temperature map obtained⁶. Subsequent analysis ruled out focus, optical refraction from Shuttle shock wave density gradients (the Shuttle shock envelope is relatively smooth with the exception of the wing/bow shock interaction zone), and mechanical vibrations from aircraft feedback as distortion contributors for the C-141/KAO system. Ultimately, degraded optical performance during the STS-3 observation was attributed to aircraft induced flow separation near the telescope. Refraction from unsteady flow structures in the telescope cavity was believed to be responsible for the image blurring. The IRIS system was flown in support of STS-4 but unspecified equipment problems prevented image acquisition. The project was discontinued after STS-4. Due to Shuttle cross range uncertainties, it was concluded that one of the biggest challenges included preflight planning, communication between the

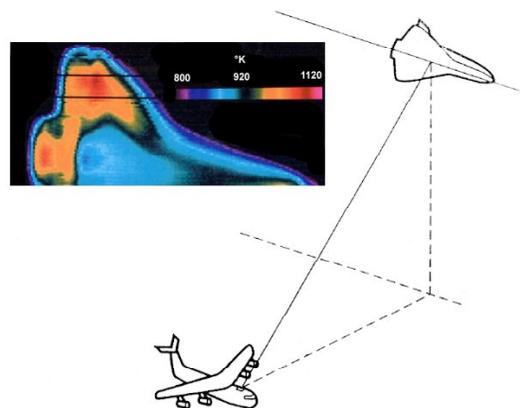


Fig. 2. IRIS MWIR Infrared Image from STS-3.

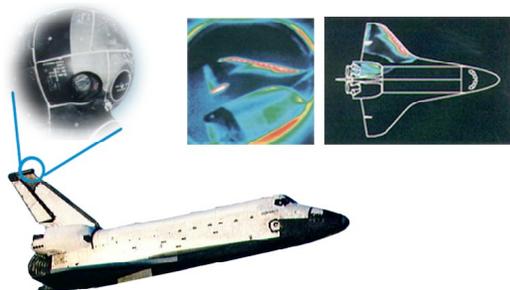


Fig. 3. Shuttle Infrared Leeside Temperature Sensing (SILTS) Experiment

proximately 20 minutes of data after entry interface (~Mach 25 to 6). On one flight, laminar/turbulent transition on the leeward surface was observed near Mach 16. Resolution was sufficient to resolve features along the wing leading edge, the gap between the inboard and outboard elevons, and the Orbital Maneuvering System Pod and nozzle as shown, Fig. 3. While the IR imagery was not obtained remotely, several hardware and image registration challenges were identified that would be of general value with regard to future entry observations. Comprehensive analysis of the SILTS thermography required accurate consideration of several factors such as geometry of the observed surfaces, local surface emissivity, solar radiation, and other potential sources of image degradation. As the relative positions of the viewing camera and the imaged surface were fixed, it was relatively straight forward to establish pixel location relative to position on the Shuttle surface permitting orthogonal projection of the IR imagery onto an Shuttle planview. While the proximity of the detector to the imaged surface significantly increased spatial resolution, it also created field of view of restrictions that limited the external surface areas that could be studied.

C. MDA/ISTEF STS-96 and STS-103 (1999)

To support the NASA Reusable Launch Vehicle Technology demonstrator program, a ground-based infrared imagery experiment was proposed to obtain global temperatures on the surface of the X-33 at the time of boundary-layer transition. The experiment, referred to as ISAFE (Infrared Sensing Aeroheating Flight Experiment), was designed to acquire infrared images at hypersonic speeds in order to ultimately develop the capability of measuring hypersonic boundary layer transition¹⁻³. To demonstrate capability, several Shuttle missions were chosen and land based tracking sites were selected on the West coast of Florida. In contrast to the remote imaging provided by the airborne platform IRIS over a decade earlier, IR data were collected using the Missile Defense Agency/Innovative Science and Technology Experimentation Facility (MDA/ISTEF) mobile platform. Similar to IRIS, MWIR detectors were employed to maximize temperature sensitivity. In support of STS-103, the detector array located at Cedar Key, FL was successful in obtaining surface infrared data of the Shuttle during hypersonic flight as it appeared at horizon break on its descent into the NASA-KSC landing complex. Data were collected from approximately Mach 6 down to Mach 3. Given the slant range and optical properties of the telescope, linear spatial resolution was estimated to be approximately 21 in per pixel at Mach 5. The STS-103 data complemented an earlier subsonic data set of the Shuttle windward surface during STS-96¹. In support of STS-96, the mobile imaging platforms were located south of the runway at KSC. An STS-96 global IR image calibrated from field methods is provided in Fig. 4. Thermocouple measurements are shown for comparison.

The infrared images from STS-103 were transformed to global quantitative temperatures using two different techniques. The first technique relied upon Shuttle surface thermocouple measurements taken during flight. The thermocouple calibration technique required no atmosphere correction factors, minimal laboratory and field calibration activities, and no surface emissivity considerations. However, there were challenges introduced by this process. Specifically, matching of the thermocouple location on the infrared image without registration points can introduce large errors, especially when viewing at large distances with limited spatial resolution. In addition, the limited thermo-

ground and the aircraft, and tracking and image acquisition of the Shuttle. In addition, the project provided valuable experience should the agency decide to build another airborne platform for remote entry imaging.

B. OEX SILTS STS-61C, STS-28, STS-32, STS-35 and STS-40 (1984-1991)

As part of the OEX program, the Shuttle Infrared Leeside Temperature Sensing (SILTS) experiment⁴ was designed to obtain spatially resolved infrared images of the leeside of the Space Shuttle Orbiter during atmospheric entry by means of a scanning infrared radiometer located in a pod atop the Shuttle's vertical stabilizer. The experiment was flown on five flights and collectively, obtained ap-

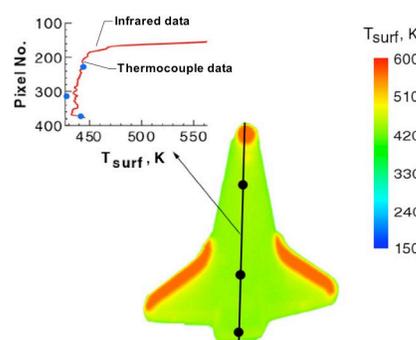


Fig. 4. Shuttle (STS-96) Global Temperature Using Calibration Constants Derived from Field Methods

couple placement and the range of the measurements could influence the overall calibration and its extrapolation over the surface. The other technique for generating global temperatures relies upon calibration factors (e.g., atmospheric path transmittance, atmospheric radiance, optics, radiance, and surface emissivity) developed from measurements in the laboratory and in the field. Differences between Shuttle surface thermocouples and that inferred from this standard field calibration methodology were within 50 deg F. Comparison between the two different calibration methods showed good overall qualitative results.

Some of the vulnerabilities associated with land-based imaging systems were exposed during the ISTEf test series. Due to weather restrictions at the primary landing site, the STS-103 de-orbit burn was delayed by one orbit. This one orbit wave-off resulted in a significant displacement of the entry ground track from that originally assumed and increased slant range. Locations of the imaging platforms dictated by advance knowledge of Shuttle energy management (roll) maneuvers during descent were no longer optimal. As a result, side views of the Shuttle were obtained rather than windward views as desired. Inherent to land-based systems, clouds (or as with the STS-103, tree-lines) near horizon break did impede target acquisition.

III. Motivation in Support of Return-to-Flight (RTF) and Shuttle Flight Testing

The most recent global IR imaging attempts on the Shuttle have been in support of Shuttle Return-to-Flight (RTF). Prior to STS-114, several engineering tools were developed to ascertain tile damage⁸. One such tool⁹ predicts hypersonic boundary layer transition (BLT) onset from damage (e.g., tile impact, gap fillers). Lack of quality flight data to calibrate this tool has resulted in uncertainties when BLT occurs and to what extent the turbulent flow spreads along the windward surface. These uncertainties resulted in a unprecedented spacewalk during STS-114 to remove a protruding gap filler¹⁰. If a spacewalk and its inherent risks are to be avoided in the future, uncertainties in predicting early BLT need to be reduced. Current hypersonic BLT predictive methods implemented during RTF rely on correlations derived from wind tunnel tests extrapolated to flight conditions using limited flight data. This limited flight data consists of thermocouple measurements made in the presence of flow turbulence introduced by protruding tile gap fillers. Unfortunately, these historical occurrences of Shuttle BLT did not occur under controlled conditions, so the extrapolation methodology possesses inherent uncertainties. During the BLT predictive tool development phase, it was recognized that the level of conservatism imposed by these 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) assessing the feasibility of performing a series of hypersonic boundary layer flight tests to be conducted before retirement of the fleet. During these test flights, surface temperature on the Shuttle would be obtained from a limited number of existing thermocouples on the windward surface that are located downstream of a controlled protuberance. Limited surface instrumentation will impose challenges in determining the area affected by turbulent flow (i.e., a turbulent wedge). When assessing Shuttle TPS damage, the global spreading characteristics of the boundary layer transition front is important as it determines the areas on the windward surface of the Shuttle that experience higher heating and consequently higher temperatures from turbulent flow. Determination of the actual turbulent spreading angle in flight could reduce uncertainties and avoid risky repair options. For the proposed flight tests, options are presently being considered to relocate the existing thermocouples (spaced tens of feet apart) to more optimum locations (the use of temperature sensitive paints to assess turbulent spreading are being considered but flight recertification issues may arise). Global temperature IR images with adequate spatial resolution could non-intrusively complement the discrete thermocouple data by providing spatially continuous surface temperature at targeted Mach number(s).

In anticipation of a BLT flight test program, an effort was made prior to first re-flight (STS-114) to establish 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. This effort was leveraged from post STS-107 recommendations made to NASA management^{11,12} 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 an entry observation campaign to qualitatively characterize a nominal Shuttle entry over a wide Mach number range ($25 > M > 3$). The initial objectives of the entry observations focused on an assessment of capability to identify/resolve debris liberated from the Shuttle during entry and characterization of potential anomalous events associated with RCS jet 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 measurement capability over a series of flights. Within the budget constraints of the SSP observations, visual and IR entry imagery was obtained by several existing airborne sensor platforms in an effort to demonstrate capability (i.e., tracking, acquisition

of multispectral data, spatial resolution) and identify system limitations using state-of-the-art imaging instrumentation and communication systems between the aircraft and the Shuttle entry flight dynamics personnel in mission control.

IV. Imaging During Shuttle Return-to-Flight

For the present entry observations, airborne IR detector platforms were selected over the land-based systems utilized during the ISTEf program 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. Tables 1 and 2 summarize the aircraft performance and imaging detector specifications, respectively. The three aircraft, depicted in Fig. 5, consisted of an MDA Gulfstream High altitude Observatory (HALO II) aircraft (observation results not discussed in this paper), a NAVY P-3 Orion (CAST GLANCE), and a NASA WB-57F Ascent Video Experiment (WAVE) aircraft. The Navy and NASA 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. The CAST GLANCE aircraft is equipped with detectors for imaging in the SWIR, NIR and the visible. The CAST GLANCE (and WAVE) measurement systems are not configured to provide calibrated imagery via a relative intensity method, thus, temperature data must be inferred from surface thermocouples (or field methods). The CAST GLANCE tracking system uses a gimbaled gyro-stabilized mirror to direct radiation to the detector rather than moving the camera and lens itself. The optical systems for the WB-57F are located in a removable nose-mounted pod. Optimized for ascent imaging using high definition zoom camera and a NIR detector, the WB-57F aircraft did not successfully acquire useful entry data; the WB-57F performance characteristics are included in Tables 1-2 for comparative purposes.

Specifics of aircraft positioning and image acquisition as related to each of the four missions supported during

Fig. 5. Aircraft Collectively Used for Shuttle RTF Entry Observations



DESCRIPTION	HALO II	CAST GLANCE	WAVE
Aircraft	Gulfstream IIB	P-3 Orion	WB-57F
Ceiling (ft)	51,000	30,000	60,000
Endurance (hrs)	7	11	6.5
Cruise speed (knots)	430	200-350	410
Range (n.m.)	3,500	3,500	2,500

Table 1. Nominal Aircraft Flight Characteristics

DESCRIPTION	HALO II	CAST GLANCE	WAVE
Imaging system	n/a	SWIR, NIR, Visible	NIR, Visible
Filter	n/a	Kodak 87A	n/a
Filter wavelength (μm)	n/a	NIR: (0.7-1.1) SWIR: (1.1. -1.7)	NIR: (0.9-1.7)
Aperture (in)	n/a	7 (window)	11 (window)
View area (pixels) (n.m.)	n/a	768 x 494	640 x 480
IFOV ($\mu\text{rad/pixel}$)	n/a	9.75 (4.9 interlaced)	7
Frame rate (Hz)	n/a	60 (interlaced)	19
Data Acquisition	n/a	DVCAM	12-bit digital
Integration time	n/a	100 μs to 10ms	25ms to 34ms

Table 2. Nominal Instrument Characteristics

the SSP sponsored entry imaging are discussed in detailed in the next section. In general, the Shuttle was first detected as a point source (at horizon break) several hundred nautical miles from the observing aircraft. At this point, the plasma wake trailing behind the Shuttle was often readily observed. Given the relative velocity between the aircraft and the Shuttle, the slant range between the two reached a minimum within minutes. The Shuttle appeared at useful spatial resolution 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 nm below the Shuttle. As the shuttle performs energy management maneuvers during entry (roll/bank), pre-flight planning must accurately predict the Shuttle ground track and vehicle orientation to place the observing aircraft in an optimal position to view the windward surface. Sun exclusion angles must be computed (if daylight entry) so as to avoid image degradation or loss. The aircraft are 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 (CAST GLANCE- windows on side of aircraft; WAVE – on the nose of aircraft) each aircraft flies a different terminal maneuver to optimize pointing control of their respective telescopes/mirrors. Aggressive maneuvers can be used to reduce slant range and maximize spatial resolution, but these maneuvers generally incur more risk with maintaining image acquisition. As the Shuttle passed overhead and continued toward the targeted landing site, spatial resolution decreased rapidly and vehicle orientation was no longer optimal. The intermittent firing of the RCS thrusters was often observed during this period of time. In the event of a successful acquisition, between 10,000 and 30,000 frames of visible and infrared images of Shuttle Orbiter during entry are captured. Of these images, only a small number are useful for potentially extracting spatially resolved quantitative surface temperature. Section V details four entry-imaging attempts made during STS-114 (July 2005) thru STS-116 (December 2006). Section VI provides an overview of the processes associated with mapping the 2-D image data to a 3-D representation of the Shuttle windward surface and converting the global intensity data to surface temperature.

V. Flight Experience

A. STS-114 (Landing August 9, 2005)

Approximately one year prior to the first RTF mission, the SSP imaging strategy to support entry called for the use of assets under modification to assess the performance of the Shuttle configuration (Orbiter/tank/solid rockets) during ascent. During launch, two NASA high altitude weather aircraft (WB-57F) were to be utilized to provide additional observation coverage to mitigate situations where clouds or the rocket plumes could obscure the views from land-based cameras. These aircraft were under modification to replace an old ball turret with an updated system capable of housing both HDTV and an IR camera. As such, the NIR systems aboard these two aircraft were primarily intended to support potential night launch operations - *and not entry*. The proposed SSP STS-114 observation plan during descent consisted of locating these two aircraft along a “picket line” under the Shuttle ground-track. A third observation aircraft was under consideration to potentially extend the Mach coverage. The aeroheating technical community sought to influence the selection of this third asset and advocated for the MDA’s HALO II.

Conceptually shown in Fig. 6, one WAVE aircraft was to be co-located with HALO II to insure benchmarking of the uncalibrated WAVE NIR detector with HALO II (possessing an Iridium satellite phone, HALO II also served as a communication relay to WAVE). The second WAVE aircraft was to be located further west to characterize optical signatures of the Shuttle closer to entry interface as recommended by the STS-107 Starfire Image Analysis Team¹¹. Two ground tracks into the primary landing site (NASA KSC) are shown in Fig. 6 and illustrate the challenges of supporting entry imaging; namely: over water operations, diplomatic clearances associated with over-flight of non US territory, crew fatigue, and adequate fuel margins to support a one orbit wave off contingency. Adequately resolved surface temperature were not a requirement of the SSP entry observations. At the suggestion of the technical community, WAVE and HALO II flight paths were selected to reduce slant range and thus optimize image resolution. An initial linear spatial resolution goal of three tiles (approximately 18-in/pixel) was specified. If a Shuttle flight experiment was approved in the future, it was felt this was a reasonable estimate with regard

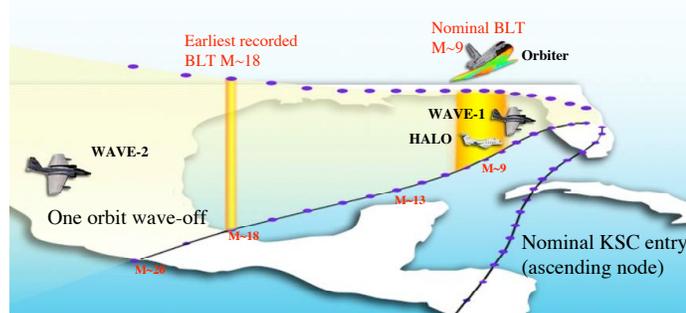


Fig. 6. Conceptual location of WAVE and HALO II aircraft in support of STS-114

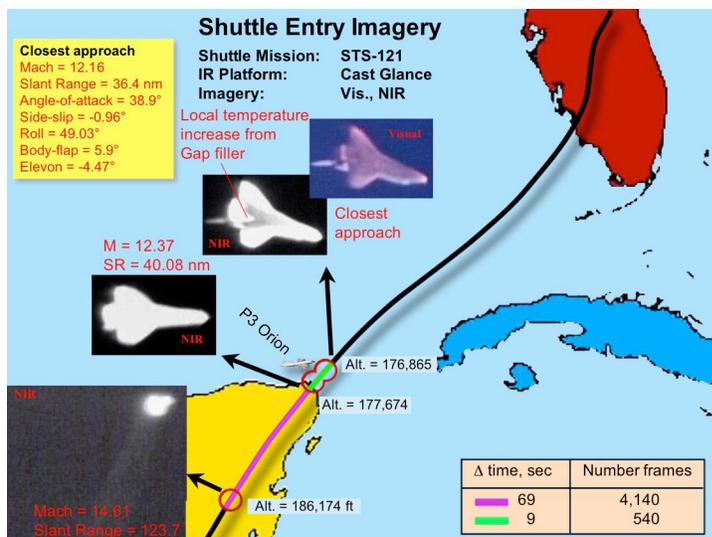


Fig. 7. CAST GLANCE Entry Imaging in support of STS-121

craft were dispatched in the early morning hours of Sept 8, 2005 to image the Shuttle during entry. One of the WAVE aircraft staged from Costa Rica while the second WAVE and HALO II deployed from Ellington Field and Tulsa Oklahoma, respectively. As planned, trajectory updates were provided to the flight crews just 2 hours from entry interface to permit minor corrections to observation staging points and aircraft maneuvers during closest approach. The weather into KSC was questionable for entry. Just minutes away from the de-orbit burn, Discovery was waved off for one orbit due to weather restrictions at the Cape. The utility of an aircraft as an observation platform was effectively demonstrated during this mission, as the aircraft were re-deployed to new observation locations hundreds of miles west of the original ground-track. The weather did not improve and the entry was postponed until the next day. On the following day, a similar scenario unfolded and after two deployments of the three aircraft to support Discovery's entry into KSC (nominal entry + a one orbit wave-off), the Shuttle landed at Edwards AFB. Moving the aircraft to support a west coast diversion was not possible given the observation locations over the Gulf of Mexico. To support a contingency landing at a second site would most likely require another aircraft. While no STS-114 imagery data was collected, the logistics involved with communicating ground track updates and re-deploying the aircraft to support one orbit wave-offs was successfully achieved. Mach numbers targeted for this observation attempt ranged from Mach 7 to 15. Deployment of one of the WB-57F's from a non-US territory was also demonstrated.

B. STS-121 (Landing July 17, 2006)

During launch support to STS-114 on July 26, 2005, the NASA WAVE aircraft experienced imaging challenges associated with support to ascent imaging (primary function). Consequently, resources for STS-121 entry imaging provided for only one WB-57F (the second WAVE aircraft was deployed overseas). To retain the services of the HALO II aircraft to support STS-121, the Hypersonics Initiative of the Fundamental Aeronautics Test Program under the NASA Aeronautics Research Mission Directorate (ARMD)¹³ and the NASA Engineering Safety Center (NESC) provided additional funding to attempt another data collect with the MDA asset.

Post STS-114 process changes to gap filler installation resulted in no protruding gap fillers in critical areas. However, on-orbit TPS inspections of Discovery during STS-121 revealed several protruding tile gap fillers in non-critical areas. After real time engineering assessment, the gap fillers were not considered a flight safety issue and no spacewalk was performed to remove them. Some viewed the decision to enter "as-is" as an opportunity to obtain engineering data regarding potential off nominal Mach number boundary layer transition ($M > 8$). In reality, the uncertainty of the gap filler heights precluded any information with the rigor of a controlled flight experiment (i.e., the gap fillers could bend during entry). However, the location of the protruding gap fillers were in areas being considered for the proposed boundary layer transition flight tests and thus provided a unique opportunity to collect relevant global imagery. During the mission, the SSP secured the services of a Navy P-3 Orion (CAST GLANCE) to obtain additional coverage during entry. A Mach 15 observation point was desired but Mexican over-flight permission was not secured in time. CAST GLANCE was deployed from the Naval Air Station in Jacksonville, FL. thus permitting provisional coverage for a one orbit wave-off. Responding within 72 hours from the initial SSP request, CAST

to the ability to delineate the higher surface temperature boundary associated with boundary layer transition. A best effort was specified on temperature resolution. Because requirements for a radiance model did not exist under the SSP observation plan, Shuttle surface temperatures typical of entry were supplied to the observation teams to guide IR exposure times, required dynamic range, etc. Preflight coordination with Shuttle entry flight dynamics personnel was required to properly locate the aircraft north/south of the Shuttle ground track to account for Shuttle roll/bank maneuvers executed during descent.

Following the unprecedented spacewalk to remove two protruding tile gap fillers during STS-114¹⁰, Discovery was cleared for entry. For the first time since the 1982 attempt under the IRIS program, three air-

GLANCE was successfully deployed and stationed under the Shuttle ground track near a point in the entry where the Mach number was approximately 12. There was no preflight opportunity to optimize exposure times associated with their NIR detector. To maintain co-location benefits, both the HALO-II and the WAVE aircraft were positioned to collect images further along the ground-track near Mach 8. WAVE and HALO II deployed from Ellington Field in Texas and Tulsa, OK., respectively (deployment from non US territory as was performed for STS-114 was not pursued).

Imagery data were successfully collected by CAST GLANCE (Visual, SWIR, NIR) and HALO II (not presented) during entry. The observation was conducted in the early morning so the issues associated with sun exclusion were not present (the Shuttle was approaching KSC from the southwest). The CAST GLANCE aircraft was positioned for a near normal view of the Shuttle and the resulting NIR data captured the high temperature footprint of what is presumably turbulent flow from the protruding gap filler located just upstream of the body flap as shown in Fig. 7. Because no advance planning was possible, CAST GLANCE was not provided the trajectory update normally received two hours before landing. Consequently, the Shuttle flew almost directly overhead causing telescope gimbal lock and loss of signal. Optimized for ascent imagery with its relatively narrow field-of-view tracker camera, the WAVE aircraft was not able to discern and acquire the Shuttle at horizon break; hence no data was collected.

C. STS-115 (Landing September 21, 2006)

Imaging support to STS-115 provided for two aircraft (WAVE and CAST GLANCE). HALO II was not flown during this entry. On-orbit TPS inspections of the Shuttle during STS-115 revealed no significant tile damage or protruding tile gap fillers. In the absence of damage and any high Mach number transition event, the SSP recommended a Mach 15 observation point, but once again, Mexican over-flight permission was not secured in time. As a result, CAST GLANCE was stationed just off the coast of the Yucatan Peninsula as shown in Fig. 8. No weather constraints existed at KSC and the option for an orbital wave-off was not exercised. As the Shuttle approached during this night entry, the flight crews reported that the Shuttle was easily discerned against the black sky. Imagery was collected (Visual, SWIR, NIR). As discussed pre-flight, exposure times associated with the NIR detector were input manually and were stepped down as the Shuttle approached. Comparison of the STS-121 closest approach intensity image (Fig. 7) with that obtained during STS-115 (Fig. 8) clearly highlights the temperature augmentation just forward of the body flap from a protruding gap filler. Slant range relative to STS-121 was improved (from 36 to 27 nm); the resulting spatial resolution showed expected increased heating at the inboard/outboard elevon interface (mid-span, wing trailing edge), Fig. 8. The data also show the incremental improvements made in reducing image saturation (white areas) between these two missions. Note that intensity “hot spots” are the result of higher surface temperature, and in the case of the wing leading edge and nosecone, differences in emissivity between these Carbon-Carbon components and the acreage tiles. From the perspective of a future BLT flight test, mitigation of saturation on the Shuttle wing is of utmost importance as this location is most likely for placement of a controlled surface roughness element if a flight test is flown. In addition, the large temperature variations near the nosecone, wing leading edges, and control surfaces underscore the challenges to accurately and simultaneously record the radiation intensity of “hot” and “cold” regions in proximity. That is, if the primary test objective of a global, spatially resolved entry observation is the measurement of a locally hot zone (i.e., turbulent flow) embedded in a relatively cool area, it may only be measurable by having a detector of sufficient dynamic temperature range or by exceeding an instrument-dependent floor or ceiling temperature.

WAVE, positioned in proximity to collect images near Mach 13, was equipped with a newly installed satellite phone and a new NIR wide field of view camera to mitigate communication and acquisition problems experienced during STS-121. Unfortunately, image acquisition at horizon

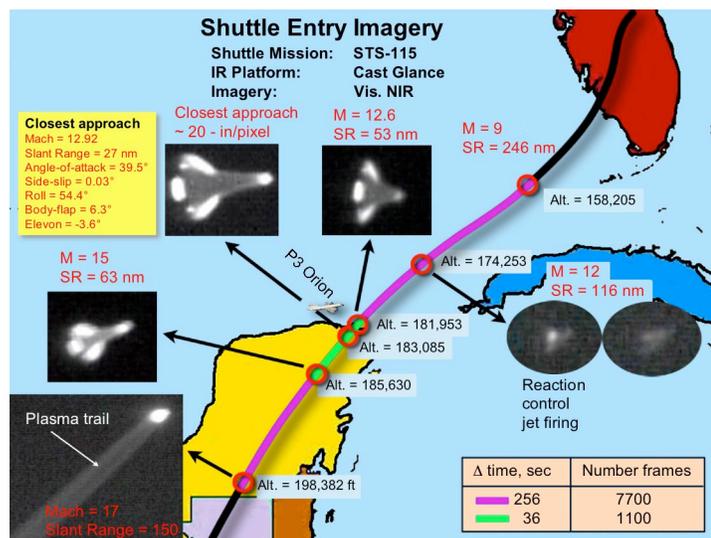


Fig. 8. CAST GLANCE Entry Imaging in support of STS-115

break was again not achieved; it was later determined that the predicted Shuttle ground track file uploaded to the aircraft was in error. Image acquisition was ultimately made just after closest approach but it was intermittent and optimum focus and exposure settings were not achieved. WAVE NIR imagery was saturated.

D. STS-116 (Landing December 22, 2006)

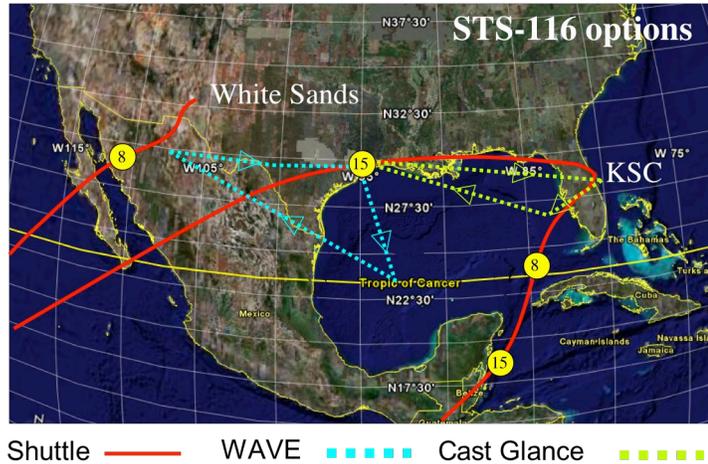
Similar to STS-115, imaging support for STS-116 was two aircraft (WAVE and CAST GLANCE). On-orbit TPS inspections of the Shuttle during STS-116 revealed an extremely clean vehicle, and in the absence of damage, the SSP again recommended observation points of Mach 15 and 8 for the WB-57F and the P-3 Orion, respectively. In contrast to the previous missions, these observation points did not present over-flight issues with Mexico, Costa Rica, or Cuba for both the primary and secondary entry opportunities as shown in Fig. 9. The two ascending entry opportunities into KSC along with dynamically changing weather conditions did present certain logistical challenges not experienced during the previous missions. For example, the provision to support a one orbit wave-off by both aircraft was not possible because of the extreme distances between the respective ground-tracks into KSC. With marginal weather at KSC, entry planning also included a west coast diversion into White Sands as depicted in Fig. 10. For the first de-orbit opportunity into KSC, the Navy P-3 Orion was dispatched from Patrick AFB, FL, and the NASA WB-57F deployed from Ellington Field, TX. Both aircraft were in route to the targeted observation points when the decision was made to remain in orbit and attempt a landing on the second opportunity into KSC. As depicted in Fig. 10, the aircraft were redirected to different mission support points – the WB-57F protecting against a west coast diversion to White Sands (Mach 8) and the Navy aircraft to attempt a Mach 15 observation with the Shuttle over Houston. With minutes remaining to commit to either the primary or secondary landing site, the weather improved and the decision made to land at KSC. Consequently, the NASA WB-57F made an attempt to reposition for an unscripted Mach 19 observation as the Shuttle entered over Texas. Unfortunately, real-time calculation of telescope pointing instructions proved challenging and the Shuttle was never observed visually by the crew or with the wide field of view tracker.

CAST GLANCE was properly positioned at its targeted Mach 15 mission support point. The flight crew reported the presence of a significant amount of illuminated haze in the direction of predicted acquisition. As this was an evening landing at KSC (~5:30 pm EST) the sun was in close proximity to the Shuttle at the anticipated horizon break location. CAST GLANCE was unable to locate and track the Shuttle. It is presumed that the small angle between the sun and the low solar elevation angle of the Shuttle as it appeared over the horizon resulted in a bright and thick NIR haze layer such that from the Cast Glance perspective, the Shuttle could not be distinguished from the horizon background with adequate time to acquire and track the Shuttle. In addition, the Shuttle aspect angle relative to the aircraft presented a minimum cross section of the Shuttle offering the least advantageous geometric radiation signature. Collectively, it is clear that entry imaging conducted at night provide the highest probability of early target acquisition. All these issues can be considered as contributing factors to non-detection. Until an accurate radiance model prediction capability is developed, these factors will remain speculative.

VI. IR Image Processing and Analysis

A. Spatial Mapping of 2-D Intensity Images into a 3-D Virtual Environment

Using technologies developed under the Virtual Diagnostics Interface (ViDI) project^{14,15}, the video imagery obtained from the visual and IR systems of CAST GLANCE and HALO II was mapped to a 3-D Computer Aided Design (CAD) representation of the Shuttle. The objective was to demonstrate a qualitative quick look capability. Two mapping techniques were applied depending upon the amount of perspective distortion present in the original image. The mapping process was conducted as a proof-of-concept exercise, conceived after the flights were concluded. As such, certain desirable elements of data concerning spatial registration were not available, so estimations



Shuttle ——— WAVE - - - - - Cast Glance - - - - -
Fig. 9. Shuttle Ground-tracks and Aircraft Flight Paths Supporting STS-116 Entry Imaging Attempt.

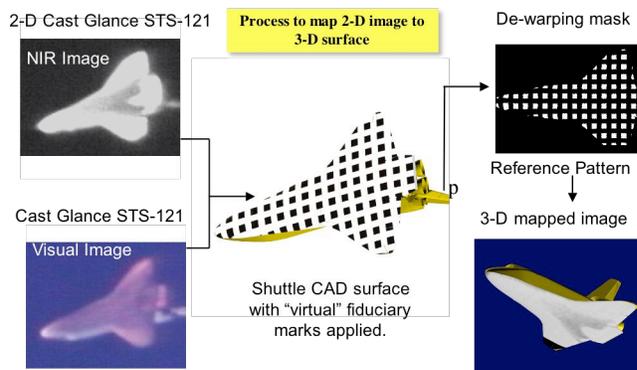


Fig. 10. Mapping technique for Non-Orthogonal Image Views.

adjusted to see patterns and edges (not to gain surface temperature information). In order to further minimize the effects of the perspective distortion and foreshortening of the image (because of the location of the airborne telescope with respect to the Shuttle), the projection of the 2-D image onto the 3-D Shuttle CAD model was adjusted to match the vehicle length and wing-span symmetrically. After the intensity data was mapped to the 3-D Shuttle geometry, Discovery's thermocouple locations were identified and tagged with recorded surface temperature at the time the image. While not attempted during this analysis, a series of mapped images could be used to create a movie rendition of the Shuttle entry. Additionally, the virtual diagnostic environment could be utilized preflight to provide spatially and temporally accurate simulated views from the aircraft permitting assessment of data acquisition and image processing algorithms and procedures.

CAST GLANCE STS-121 NIR data had significant perspective distortion and intensity saturation, Fig. 7. The simple image processing techniques described earlier could not be applied and a more complex image processing technique was developed for 3-D mapping. A custom bi-linear image de-warping algorithm that had originally been developed for wind tunnel test applications was employed.¹⁶ This technique has previously been used by a number of camera-based wind tunnel instrumentation systems in order to eliminate perspective and optical distortions in image based data. The wind tunnel application required a spatial calibration obtained by imaging of equidistant fiducial marks (grid pattern) on the model¹⁷. As applied to Shuttle flight imaging, a virtual environment was used to simulate the NIR camera view and generate the required spatial calibration grid pattern on the Shuttle CAD geometry, Fig. 10. Using this process, the resulting mapped CAST GLANCE image data for STS-121 is presented in Fig. 11. Although the area of high heating associated with the STS-121 protruding gap filler is clearly evident in this intensity image (Fig. 11), quantitative information regarding temperature or the angular spreading of disturbed flow cannot be determined because of significant NIR saturation. Mapped STS-115 intensity data along with the corresponding flight thermocouple measurements are shown in Fig. 12. Imagery resolution during STS-115 was sufficient to reveal intensity gradients associated with expected temperature increases in proximity to the gap of the wing elevons.

B. Global Temperature and Mapping Technique

Conversion of intensity images to global temperature was performed by calibration with thermocouple measurements made during entry. This section describes the processing technique of locating Atlantis' eleven thermocouples on the STS-115 NIR measurement image obtained by CAST GLANCE. The method of using the surface thermocouples as a calibration source is then briefly outlined. This method is largely derived from previous techniques developed and demonstrated with Shuttle IR imagery obtained with land-based systems¹. A comparison is then made between a computational fluid dynamics (CFD) generated global thermal image at nominally similar conditions and the thermocouple data obtained during STS-115 entry.

were made. The data acquired by the IR cameras for STS-121 and STS-115 were provided as computer movie files on CD-ROM. The time stamped movies were played back, and at desired temporal increments, the video image was written as a bitmap image. Then the image would be mapped to the three-dimensional model of the Shuttle. Prior to mapping of the 2-D image to the CAD model, the image had to be prepared for the transformation from a two-dimensional collection of pixels to a pattern that would cover a three-dimensional surface.

Commercial off-the-shelf image processing software was used to qualitatively process selected images from STS-121 and STS-115. A smoothing filter was applied and the contrast and brightness

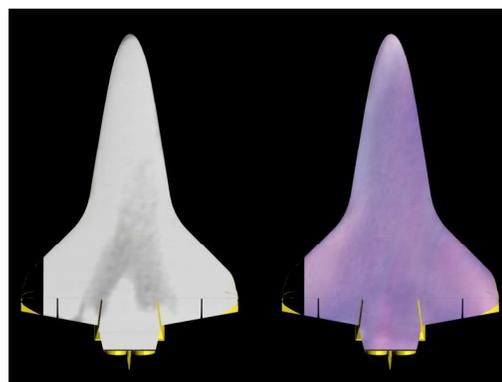


Fig. 11. STS-121 NIR intensity and visual images mapped to 3-D Shuttle CAD model.

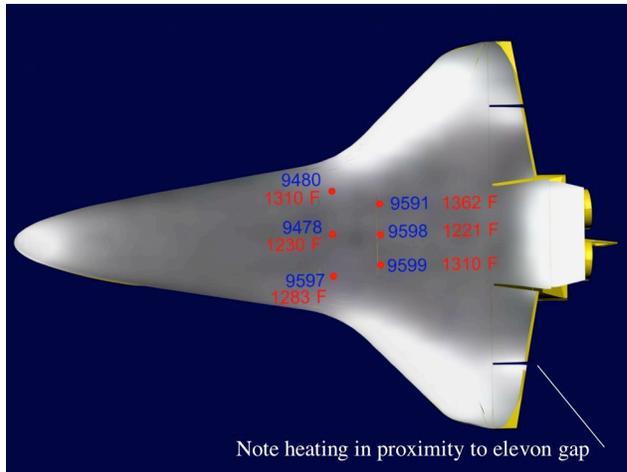


Fig. 12. STS-115 NIR intensity image mapped to 3-D Shuttle CAD model with corresponding surface thermocouple position and temperature.

the “horseshoe” P-3 Orion ground track be on the northerly side of the Shuttle’s ground track. That is, the northerly side of the Shuttle ground track was pre-selected because the Shuttle roll angle is large (right-wing down), which presents an excellent viewing angle. The red line connecting the aircraft and the Shuttle locations on the figure is the “line-of-sight” during the collection of the images.

Image Resolution: Fig. 14 shows a time-history estimate of the Cast Glance NIR slant range and image linear resolution during the STS-115 entry along with the time of the selected NIR image (shown as a vertical dashed line). The computed resolution is given in inches/pixel. The estimate of resolution was determined by knowledge of the pixel length of the image and the image actual physical size. A best estimate of the resolution as a function of slant range was computed from the as-flown navigation files from the aircraft and the Shuttle along with the NIR detector IFOV (see table 2). Theoretically, the best linear image resolution (e.g., no atmospheric distortion) during the data collection process was about 12 in/pixel. The acquisition time (shown on the figure as a dashed-black vertical line) for the image under investigation is about 20 in/pixel. That is, each pixel on the Shuttle image is spaced by approximately 20 in. This resolution functional behavior with time, as shown in Fig. 14 is typical for imaging the Shuttle at high Mach numbers. For example, to acquire a linear spatial resolution of less than 36 in. between pixels, the time interval for imaging is approximately 60 sec. This implies a significant amount of infrared data, about 1800 frames, but not corresponding large changes in Mach number. When trying to resolve features or boundaries (i.e., temperature gradients from boundary layer transition), it is recognized that the theoretical pixel resolution of 20-in/pixel should not necessarily be used to imply that it is possible to discern differences down to 20 inches (or correlate imagery through registration down to a zone comprising approximately 3 tiles). This is because one generally cannot resolve image features below a signature change across 2-3 pixels. So, effective resolution would be lower. Furthermore, resolution of imagery in proximity to saturated intensity data are complicated by “blooming” whereby pixels are essentially polluted by neighboring saturated pixels.

Image Orientation: Conceptually, the process of thermocouple spatial registration was similar to that developed for the 2-D to 3-D mapping technique presented previously. That is, by orienting a scaled 3-D model (in this instance the surface grid used for CFD simulations) to both the NIR and visual images and transferring the thermocouple locations to the NIR

Flight Plan: The STS-115 NIR image selected was taken on Sep. 21, 2006 at 10h 07m 17.89s based upon Coordinated Universal Time (UTC). A sketch of the location of the Cast Glance aircraft relative to the Shuttle and the NIR image, is given in Fig. 13. The black line shown on the figure is the ground track of Atlantis. Motion of the Shuttle is from the Yucatan peninsula (shown in yellow) towards the right. The P-3 Orion aircraft ground track is shown in approximately half-minute intervals (blue dots). The aircraft altitude at image acquisition was 25,508 ft. The location of the Shuttle when the image was taken is shown as a red-circled asterisk on the associated ground track. The slant range, as well as the aerodynamic and freestream conditions of Atlantis when the image was acquired are given in Table 3. The Cast Glance flight plan strategy was to image the Shuttle windside at a predetermined Mach number while at a minimum slant range. This dictated that

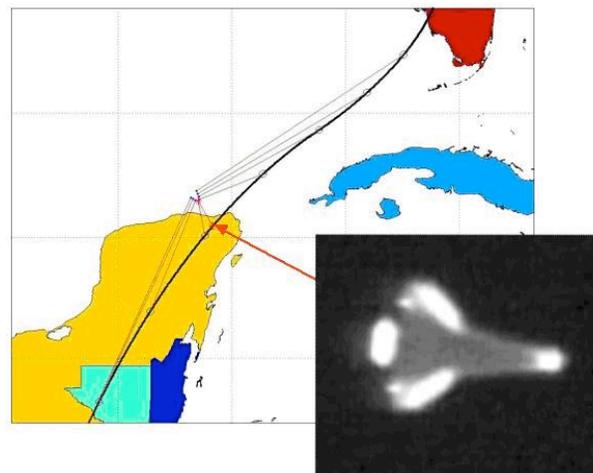


Fig. 13. STS-115 entry ground track and Cast Glance aircraft locations with selected NIR image.

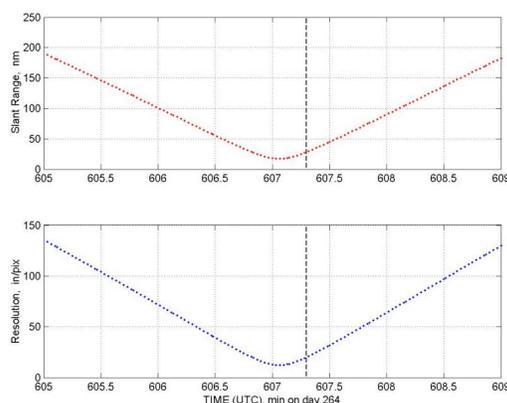


Fig. 14. Cast Glance Slant Range and Image Resolution During STS-115 Entry.

with the 3-D Shuttle as shown in Fig. 15.

Thermocouple data: During entry, the modular auxiliary data system (MADS) records the output of eleven thermocouple locations on the underside of Atlantis, the Shuttle used for the STS-115 mission. Utilization of this thermocouple data as an in-flight calibration of radiance requires the accurate placement (x,y image position) of the thermocouples on the image. Once their position was determined (as discussed above), the radiance-to-temperature transformation is a relatively straightforward process.

Image Calibration: The calibration curve that allows the radiance counts to be transformed into temperature values is shown, Fig. 16. That is, given the radiance count values from the STS-115 NIR image, the corresponding temperatures can be inferred from the curve shown. The curve used in this case is a form of Plank's blackbody radiation law. With 11 thermocouples it is possible to perform a least square process to solve for the three unknown coefficients. The function coefficient values are shown on Fig. 16. It is evident from this figure, that the temperatures differences between the eleven existing flight thermocouples are relatively small (approximately 250K) with only one thermocouple "out of family" from the other ten. This thermocouple, located just upstream of the body flap hingeline, may have been influenced by body flap flow induced separation at the higher Mach numbers. Temperatures outside the range of 750 to 1000 K are extrapolated. As noted earlier, NIR wavelengths are less than ideal for temperature sensitivity and as anticipated, the STS-115 flight temperatures as registered by the thermocouples correlates to approximately 25 counts. To check on the reasonability of the extrapolation, the background sky temperature inferred from the imagery is approximately 160 K. This compares to the molecular-scale temperature of 180 K at the base of the thermosphere (about 90 km) as inferred from the 1976 U.S. Standard Atmosphere model. Based upon the extrapolation, image saturation occurs at 1480 K, although there is no immediate way to confirm this value.

Global Temperature: Fig. 17 shows the STS-115 NIR global temperature contours based upon the calibration curve developed from the surface thermocouples. The color bar shows the temperature (K) up to saturation (white). For reference, all eleven thermocouples are shown in the global temperature image as black dots. The edge around the image is an infrared artifact and the associated temperatures are to be ignored (this "halo" effect has been seen on earlier infrared images¹ most probably a combination of both signal "roll off" as well as detector and image process averaging with the sky background).

Comparison to Prediction: To provide confidence in the temperature measurements calibrated the intensity image, the flight measurements were compared with an existing numerical simulation provided by the Langley Aerothermodynamic Upwind Relaxation Algorithm (LAURA) flow solver¹⁸ (LAURA). The grid used for this

measurement image. Determining the thermocouple location is complicated by the fact that the Shuttle lower surface is not necessarily parallel to the imaging plane of the IR camera's detector array. Because of the non-ideal viewing angle, adjustments are typically required to account for the Shuttle's orientation with respect to camera. This requires post flight navigation files from the aircraft and the Shuttle best estimate trajectory. First, the 3-D Shuttle CFD model is rotated through Euler angles to match the orientation of the 2-D Cast Glance image. It is then scaled and translated to match the size and location in pixels of the 2-D image and the thermocouple locations superimposed to the flight NIR image. Finally, the intensity values of the pixels in the Cast Glance NIR image at the locations of the thermocouples are interpolated using a bilinear scheme to obtain radiance values at these locations. The end result, CAST CLANCE STS-115 NIR intensity image with corresponding thermocouple locations is scaled and properly orientated

Slant Range, nm	27.1
Freestream Mach	12.92
Angle-of-Attack, deg.	39.5
Side-Slip, deg.	0.03
Yaw, deg.	24.5
Pitch, deg.	21.6
Roll, deg.	54.4
Body-Flap deflection, deg	6.3
Elevon deflection, deg.	-3.6
Altitude, ft	183,085
Velocity, ft/s	13,800
Density, slugs/ft ³	1.0283e-06
Freestream Temperature, K	264

Table 3. Shuttle State Corresponding to STS-115 Cast Glance NIR Image Near Closest Approach (264 day 10 hr 7 min 17.890 sec UTC).

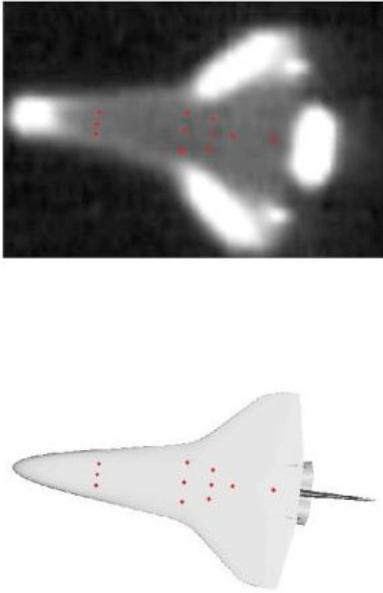


Fig. 15. CFD Surface Model Scaled and Oriented to Match STS-115 CAST GLANCE NIR Image (Flight TC locations shown in red).

seen probably due to the “roll-off” of the radiance due the physical spherical shape of the nose region. That is, most of the radiation signal is directed away from the camera near the edge of the rounded nose section, but the camera is picking up a component of the signal. At the rear of the Shuttle, this “roll-off” is not seen because of the relatively sharp edge of the body flap.

Qualitative agreement of the discrete thermocouple and global NIR data with the laminar CFD simulation is evident, particularly in the mid-section of the Shuttle. Naturally, the temperatures inferred from the global NIR imagery will match the discrete thermocouple temperatures since these measurements are the principle image calibration source. Because the numerical simulation performed in support of the Columbia Accident Investigation did not include the body-flap, the predicted heating near the aft end of the Shuttle ($X/L > 0.8$) is not expected to match the flight measurements (at the time of image acquisition, the body-flap was deflected down about 6.3 deg).

The other discrepancy obvious in Fig. 20 is associated with comparison of NIR measurement with prediction near the nose of the Shuttle. NIR data suggests significantly higher temperatures from X/L 0.02 to 0.2 (excluding image saturation between X/L 0.02 and 0.12). The reason for this large disparity is unknown at the present time and additional analysis of the NIR data would be required to fully explain the differences. The reinforced carbon-carbon (RCC) material (typically on the leading edges) will have a slightly different emissivity over the temperature ranges experienced during flight and would probably require a slight adjustment. As noted earlier, extraction of Shuttle temperatures from NIR wavelengths is not optimal, and near saturation levels, no infrared instrument at any wavelength is well defined.

Similar analysis of closest approach NIR imagery from STS-121 CAST GLANCE (see Fig. 7) and imagery from HALO II were performed

computation was the RTF common baseline grid; one that is used to support all Shuttle missions since STS-107. Fig. 18 shows a CFD simulated global temperature (radiation equilibrium) image at Mach 13.5 and an angle-of-attack of 39.7 deg generated during the Columbia Accident Investigation. The STS-115 NIR image was taken at Mach 12.92, close to the Mach number and angle of attack condition of the laminar numerical prediction. Trajectory differences between CFD solution and the actual flight were small. It should be noted that the numerical simulation assumes no roll or yaw. Fig. 19 compares the predicted centerline temperatures as a function of body length location along with the centerline thermocouple measurements from STS-115 used to calibrate the NIR image. In general, the difference between the flight thermocouple data and the CFD simulation is less than about 6 %, except for the thermocouple located forward of the body flap, which was approximately 16% lower than prediction.

The centerline temperature inferred from the NIR measurements along with the thermocouple measurements used to calibrate the NIR image data is presented in Fig. 20. For comparative purposes, the laminar CFD prediction is included. As noted earlier, saturation of the NIR data occurred at approximately 1500 K. Towards the nose region of the Shuttle, a small region of unsaturated data is

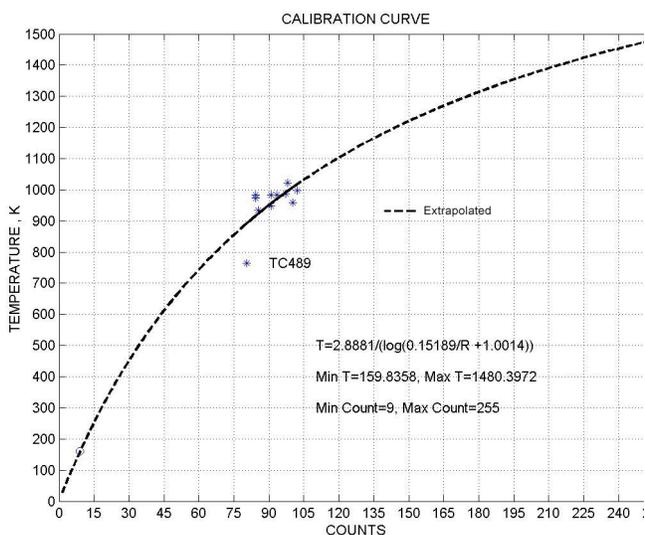


Fig. 16. STS-115 Cast Glance NIR Calibration Curve Based on Thermocouple Data.

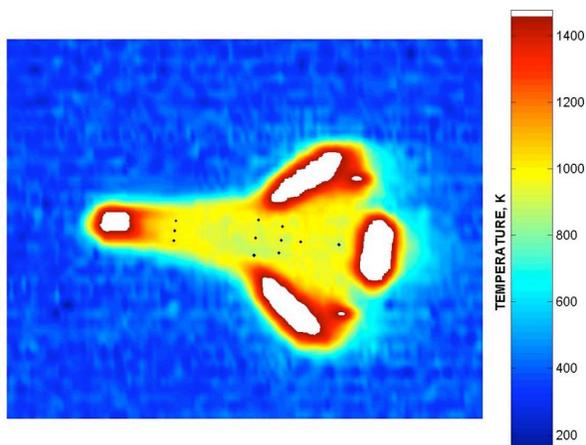


Fig. 17. STS-115 Cast Glance NIR Global Temperature Image with Thermocouple Locations (exaggerated for emphasis).

sored activity. Even with the limitations associated with the SSP requirements, the entry data collected during the STS-114, STS-121, STS-115, and STS-116 imagery attempts are considered to have been a qualified success and present a clear path forward to increasing the fidelity and application of further data collects.

A. Mission Planning

(1) Uncertainties in aircraft availability: All three platforms (CAST GLANCE/HALO II/WAVE) are susceptible to competing DoD missions. For instance, launch delays can result in entry dates that conflict with DoD mission or tightly scheduled maintenance periods. Support to future Shuttle flight imaging campaigns would require a priority commitment from NASA, Air Force, Navy, and/or the MDA. Aircraft maintenance requirements that involve safety of flight should be addressed well in advance of each mission. Maintenance issues impacted the ability of WAVE to support STS-115 primary de-orbit opportunity. (2) Preflight trajectory definitions from the entry flight dynamics group are essential: Shuttle ground track updates need to be provided to the flight crews as soon as possible to assess implications of wave-offs, Shuttle roll/bank maneuvers, and sun exclusion. In addition, Shuttle ground tracks along with aircraft loiter times and fuel range, determine the allowable Mach coverage for each aircraft. (3) Aircraft base operations outside the continental US (CONUS) are generally required for high Mach number observation locations ($M \sim 18-20$). CONUS locations (e.g., Ellington Field, Patrick AFB) are enabling for most observation locations below Mach 15. (4) Flexibility: For maximum mission flexibility, all airspace restrictions must be addressed well in advance and all over-flight permission protocols associated with each aircraft flight crew satisfied. High Mach number ($M > 15$) data collect will often require Mexican over-flight permission and observation points near nominal BLT Mach numbers ($M \sim 7-8$) will at times not be possible because of Cuban airspace restrictions. The CAST GLANCE STS-115 target observation Mach number was compromised as Mexican over-flight permission was not conveyed to the flight crew prior to departure. Consequently, the observation point was adjusted but the new location resulted in an increased slant range and lower image resolution than was desired. (5) Real time communications: Satellite phone communications from the Aircraft Aux Sensor Coordinator located at JSC are essential. Timing calls for the Shuttle de-orbit burn and entry interface were of high value to the aircraft pilots to set up final aircraft maneuvers for Shuttle

but are not presented herein. The STS-121 NIR data captured by Cast Glance during this flight were largely saturated leaving only one of six available thermocouples in an unsaturated region and one thermocouple in a nearly saturated region (marginally useful for reliable information). The STS-121 data captured by HALO II during this same entry resulting in the availability of four of six thermocouples for calibration.

VII. Lessons Learned

Airborne sensor platforms operated by NASA, the Navy and the MDA were utilized in attempts to visualize the Shuttle entry during STS-114, STS-121, STS-115 and STS-116. While the entry opportunities provided by SSP during STS-114 through STS-116 were extremely beneficial, spatially resolved surface temperature measurements of the Shuttle windward surface was not a primary objective of the SSP spon-

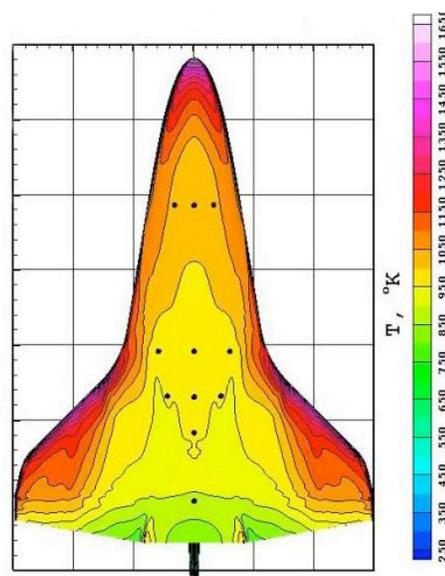


Fig. 18. STS-115 Thermocouple Locations on Laminar CFD Prediction of Global Temperature image

imaging acquisition and tracking. (6) Mechanical/hardware limitations: The slew rate and azimuth/elevation limitations of the observation telescopes can affect image resolution. That is, to reduce azimuth/elevation angles of the telescopes and prevent loss of image, aircraft stand off distances are increased resulting in lower image resolution. More detailed trade studies between slant range and image resolution are required. Aggressive maneuvers of the observation aircraft can decrease slant range and thus improve spatial resolution. (7) Uncertainties in entry date: The actual Shuttle entry de-orbit burn is generally not determined until the midpoint of each mission when consumable margins are assessed, and the entry weight and de-orbit planning are updated. Significant planning and (re-planning) is required to accommodate multiple entry trajectory scenarios. Furthermore, crew fatigue supporting multiple entry delays can arise.

B. Image Acquisition

(1) Image saturation: During SSP entry observations, no attempt was made to develop a Shuttle specific radiance prediction capability; exposures and sensor selection was based on general principals and previous experience with other targets. Despite this shortcoming, the observation opportunities of STS-121 and STS-115 provided valuable knowledge on Shuttle illumination signatures, sensor system settings, slew rates, gimbals limitations, acquisition sequence, aircrew experience, and overall mission operations design and execution. Because of the experience gained by these two diverse missions (e.g., day and night observations), future support promises significant gains in mission success and data value. To mitigate saturation of the CAST GLANCE imagery, a camera with manual shutter speed control was installed prior to the STS-115 mission and the operator adjusted the shutter speed real time during STS-115 engagement to visually control the brightness of the Shuttle image. It is also practical to equip the WB-57F with an automatic NIR exposure control (with a manual over-ride) to mitigate NIR saturation. Preflight assessments with accepted radiance models did not predict image saturation. For large temperature variations with location, it may not be possible to accurately and simultaneously record the temperatures of hot and cold regions. That is, if the primary test objective is a measurement of unusual hot (or cold) spots they may only be measurable as exceeding an instrument-dependent floor or ceiling temperature. (2) Image resolution: A linear resolution goal of 18-in per pixel establishes minimum instrument aperture targets as a function of slant range. Resolving smaller spatial features requires either larger instrument aperture or a smaller slant range. This is a fundamental physical limit on optical spatial resolution, not an instrument quality or focus issue. These considerations initially ruled out other aircraft considered for imaging. For example, a NASA DC-8 was not a viable test platform for STS-121 global thermal imaging as at the minimum slant range, the minimum aperture required substantially exceeded the maximum DC-8 window size. The DC-8 is better suited to missions where spatial resolution is not a required test objective (as with the Stardust entry where spectral measurements in the shock layer were desired). The HALO II, CAST GLANCE and WAVE aircraft are well suited to spatial resolution missions because they carry moderately large optical apertures. (3) Optics personnel: The CAST GLANCE and HALO II observation platforms consist of a large pressurized crew cabin. Multiple crewmembers are present to acquire, track, and optimize sensor system settings. In contrast, the WAVE WB-57F requires a single crewmember to handle all imaging related tasks (tracking, exposure, focus), which may compromise the quality of the data collect. Some WAVE systems could be computer controlled to alleviate operator overload situations. WAVE optical stability was limited by vibrations of the main mirror (“jitter”) and WAVE hardware modifications involving a tie down to the main mirror assembly and related hardware stiffening modifications promised to reduce vibrations. The NASA ARES program under Constellation is evaluating modifications to the WAVE optical bench to improve stability. (3) Solar exclusion: Conservative preflight assessments are made. Further study is required to define realistic sun avoidance requirements for all possible mission scenarios. (4) Sensor suite capabilities and upgrades: The HALO II observation platform is configured to provide optimal viewing of objects such as the Shuttle passing overhead. The CAST GLANCE program is presently adding a MWIR detector to augment the current NIR and SWIR capability. If successfully implemented, MWIR data collection may be available to support future Shuttle entry opportunities. The MWIR band is less susceptible than NIR to atmospheric turbulence and scattering of radiation from haze/water vapor. Finally, it

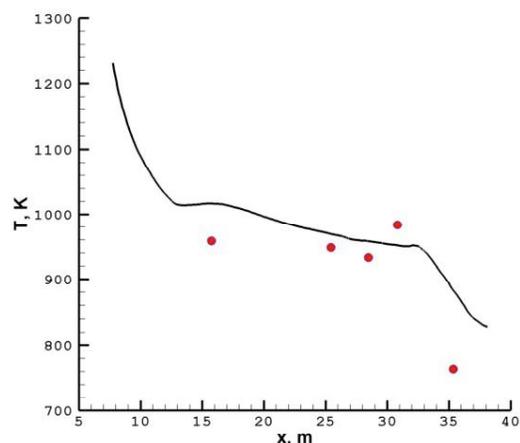


Fig. 19. Comparison of STS-115 Centerline Thermocouple Temperature with Laminar CFD Prediction.

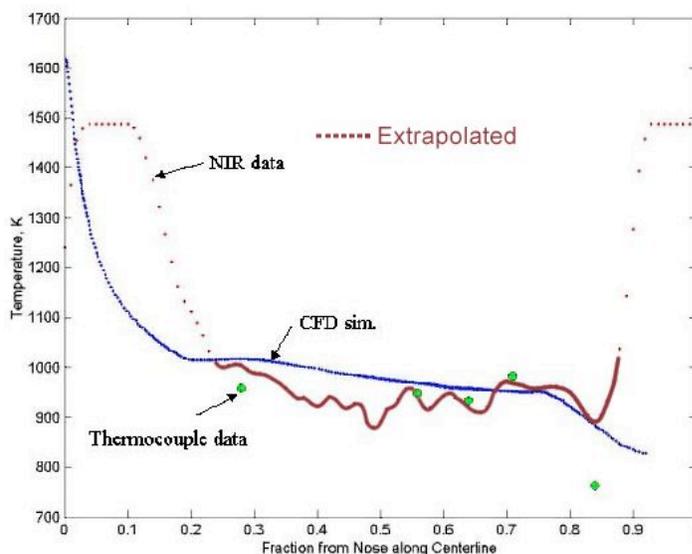


Fig. 20. Comparison of STS-115 Centerline Temperature from Thermocouples and CAST GLANCE NIR Image with Laminar CFD Prediction.

boundaries and consequently introduced uncertainties in calculation of the turbulent wedge spreading angle observed during STS-121. Analytical methods exist to reduce pixel blooming effects in the astronomical community but have not been considered in the present reduction methodology. (2) Image registration: The six week time to deliver a full parameter Best Estimated Trajectory (BET) file post flight continues to drive the analysis timeline. This information is required to translate the 2-D images recorded in flight to the 3-D surface of the Shuttle and precisely locate the reference surface thermocouples. (3) Image resolution: STS-121 and STS-115 measured linear pixel resolution were generally found to be within 10% of preflight prediction at closest approach (approximately 18 and 24-in/pixel along symmetry plane). More rigorous methods need to be developed to assess and communicate image resolution preflight. (4) Changing requirements: Imaging requirements to characterize Shuttle entry optical signatures and demonstrate capability to support proposed Shuttle flight tests (from the perspective of hypersonic boundary layer transition) are presently not consistent with SSP interpretation of visual imaging goals recommended by the Starfire and Imaging teams. Consequently, imaging rationale during STS-114, STS-121, STS-115 and STS-116 were at times inconsistent with the interests of aeroheating community to demonstrate capability to support proposed Shuttle flight tests. For example, only hours before STS-114 de-orbit burn, aircraft observation points desired by the entry aeroheating technical community were changed to accommodate SSP desires for optical signature data collect closer to entry interface. (5) Calibrated imagery: Conversion of CAST GLANCE NIR and HALO II intensity data to global temperature using flight TC measurements has been performed. Surface temperatures derived from flight thermocouples and NIR intensity images is inherently challenging as it requires complex image registration/geometry projection methods. The calibration technique using surface thermocouple data has only been demonstrated on the Shuttle with (more sensitive) MWIR measurements previously obtained with a land-based system.

VIII. Potential Support to Shuttle Flight Experiment

While the entry opportunities provided by SSP during STS-114 through STS-116 were extremely beneficial, spatially resolved surface temperature measurements of the Shuttle windward surface was not a primary objective of the SSP sponsored activity. If ancillary surface temperature measurements from global IR thermography are desired to compliment the proposed Shuttle boundary layer transition flight tests, several recommendations can be made prior to collecting additional imagery. While airborne platforms (HALO II, Cast Glance, and WB-57FF) were used during the last three Shuttle entries, the usefulness of the collected data from an engineering perspective was limited. These limitations were mainly associated with uncertainties regarding operational aspects of data acquisition. These uncertainties, in turn, came about because of a lack of understanding of the infrared signature of the Shuttle and the background atmosphere. Operational details of the aircraft and sensors configuration such as target acquisition at

should be noted that observations out of the side window on CAST GLANCE require that the P-3 Orion perform more aggressive (and higher risk) maneuvers to capture imagery. (5) Shuttle acquisition and tracking: Aircraft sensors need to engage and begin tracking the Shuttle shortly (less than approximately 60 sec) after it emerges over the horizon as the rapidly increasing angular motion decreases the likelihood of successful data acquisition (CAST GLANCE STS-116 for example). The IR appearance of the horizon is variable with a number of factors (wavelength, sun location, season, Shuttle aspect, and others) and a complete understanding of the appearance of the Shuttle near the horizon is required to engage and track with high confidence.

C. Image Analysis

(1) Image saturation: Image saturation was a challenge on all missions and all platforms. Image saturation resulted in pixel “blooming” near saturated/unsaturated

horizon break, integration time and tracking system algorithms for Shuttle acquisition were carried out in ways which led to the limited application of the data such as detector saturation and inability to see the Shuttle as it rose over the horizon. Thus, of highest priority is the development of a radiance model prediction capability specific to Shuttle entry. The model should take as input descriptions of the Shuttle temperature as a function of Mach number, trajectory, and particular sensor and carrier platform characteristics and generate predictions of the detector response to the radiation being emitted by the Shuttle during entry. A higher fidelity understanding of the infrared radiance of the Shuttle during entry and its appearance in the sensor wavebands carried by the aircraft would allow these shortfalls in data collection to be avoided. In addition, improved understanding of the response of these detectors to the Shuttle's radiation emissions could allow the specification of relatively small changes in platform and sensor hardware or software (e.g., changes that could be accommodated at low cost) that could result in significant improvements in data collection. Clear and detailed test objectives from a proposed flight test will assist in defining temperature measurement requirements with sufficient precision to anticipate appropriate instrumental gain and dynamic range settings. Accurately recording a wide range of surface temperatures with IR imagery is difficult because of the sensitivity of radiated power to temperature, the low dynamic range of infrared imagers, and the variation of trajectory issues like slant range and surface aspect with respect to time.

The difficulty using wideband imaging to obtain global thermal imagery of the Shuttle during entry is illustrated in Fig. 21, which presents in-band blackbody radiance as a function of temperature for the four typical IR bands (see Fig. 1). At hypersonic Mach numbers, the surface temperature on the Shuttle ranges from approximately 800 K to 1800 K (see Fig. 18). In the case of a NIR system, the in-band radiances from these correspondingly different areas of the Shuttle vary by nearly four orders of magnitude. This in turn imposes very challenging requirements on the intraframe dynamic range of an electro-optical system in order to avoid saturation at the highest temperatures, often the region of most interest on the Shuttle. A NIR sensor, for example, would require a dynamic range of at least 14 bits in order to capture the full temperature range of the Shuttle windward surface. Fig. 21 also shows that while the longer wavelength bands present a smaller range in radiance, their sensitivity (i.e., slope of the curve) is more non-linear across the temperature range. For example, while the MWIR band presents a smaller radiance dynamic range (8 bits) it is rather insensitive to radiance changes at higher temperatures. The Mach number at which the boundary layer transitions determines the local surface temperature increase. If transition occurs "naturally" near Mach 8, the surface temperature within a turbulent wedge located on the Shuttle centerline is approximately 900-1000 K. Near Mach 18, the surface temperature can increase to approximately 1200 K within the turbulent zone. The trade between dynamic range and good sensitivity across the Shuttle windward surface suggests that a single imaging sensor using traditional IR bands may not be the optimal choice for thermal imaging during entry, particularly if quantification of surface temperatures associated with hypersonic boundary layer transition is desired.

If support of a future Shuttle flight test is undertaken, and calibration information from Shuttle surface thermocouples (as described in the report) are not available to infer surface temperature, bench and field calibrations can be performed and used to interpret flight infrared images. This methodology was not employed in the present analysis and its application to future IR image analysis would require additional planning. For example, local meteorology soundings would be required during the time of entry. In addition, verification checks would be required to measure the radiance of the background sky without the target and by using a calibrated stellar source. A bench calibration establishes the initial relationship between the irradiance and the sensor output and is accomplished in the lab with a calibrated blackbody source. Given the dynamic range for the selected setup, an incident radiance and sensor output relationship can be determined. A field calibration consists of placing a calibrated blackbody source beyond the minimum distance the telescope can focus in the field. Collectively, these calibrations define a complete transfer function that combines the effects of the sensor, optics (including filters), and recording device(s). The reader is referred to Blanchard et. al¹ for further details.

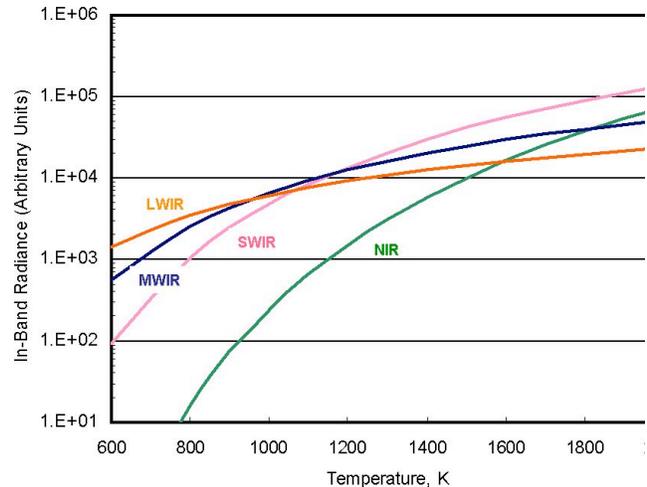


Fig. 21. Comparison of IR-band Radiance

IX. The Summary and Conclusions

Infrared images of the Shuttle windward surface at hypersonic speeds have been obtained during STS-121 and STS-115. Radiant intensity were obtained of the Shuttle at altitudes ranging from 200,000 ft. to about 90,000 ft (Mach number from ~ 17 to ~ 3). While spatially resolved surface temperature measurements of the Shuttle windward surface was not a primary objective of the SSP sponsored entry observations, the engineering community was allowed to influence the observation objectives and incrementally demonstrate key elements of a quantitative spatially resolved measurement capability over a series of flights. The data were obtained from several mature airborne platforms operated by the Navy and the MDA along with developmental aircraft from NASA. Logistics associated with preflight planning and mission execution is discussed. STS-121 imagery was successful at qualitatively capturing surface temperature increases associated with high Mach number boundary layer transition from a protruding gap filler. The global data was of technical value to the engineering community, as Discovery had no thermocouple instrumentation in a position to register the boundary layer transition event. A subset of the STS-115 infrared images based on optimum viewing was selected for detailed quantitative analyses. The data reported herein consists of NIR intensity imagery that has been converted to global surface temperature when the distance between the Shuttle Atlantis and the Navy observation aircraft approached a minimum (about 27 nm). Comparisons of the discrete thermocouple and global NIR data with the laminar CFD simulation show good qualitative agreement.

The calibration technique relied upon thermocouple measurements taken during flight. The thermocouple calibration technique has advantages over more traditional field methods that require atmosphere correction factors, laboratory and field calibration measurements, and vehicle surface emissivity considerations. The thermocouple calibration method does, however, introduce its own set of challenges. The primary obstacle was the determination of the thermocouple location on the infrared image. Without specific registration or anchor points on the Shuttle, larger errors can be introduced especially when viewing at large distances. Further, the number of thermocouples on the Shuttle, where they are located, and the associated temperature range of the measurements can influence the overall calibration and the extrapolation of temperature over the entire surface.

Development of a radiance model prediction capability specific to Shuttle entry is currently being pursued and is considered critical if ancillary support to a Shuttle boundary layer transition flight test is to be considered. Lack of a radiance model was a contributing factor to most of the technical imaging challenges. 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 tests such as the Air Force X-37 and DARPA Falcon programs along with flight test opportunities associated with NASA's project Constellation.

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