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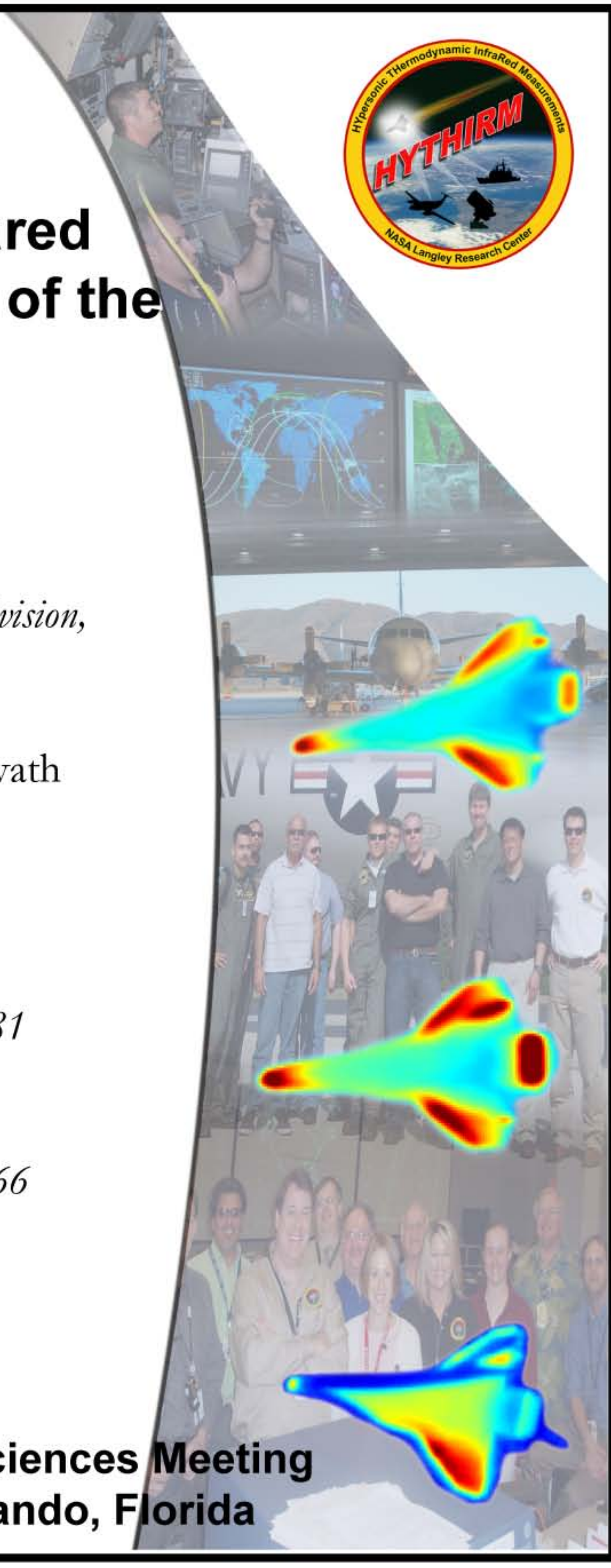

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High resolution calibrated infrared imagery of the Space Shuttle was obtained during hypervelocity atmospheric entries of the STS-119, STS-125 and STS128 missions and has provided information on the distribution of surface temperature and the state of the airflow over the windward surface of the Orbiter during descent. This data collect was initiated by NASA's Hypersonic Thermodynamic Infrared Measurements (HYTHIRM) team and incorporated the use of air- and land-based optical assets to image the Shuttle during atmospheric re-entry. The HYTHIRM objective is to develop and implement a set of mission planning tools designed to establish confidence in the ability of an existing optical asset to reliably acquire, track and return global quantitative surface temperatures of the Shuttle during entry. On Space Shuttle Discovery's STS-119 mission, NASA flew a specially modified thermal protection system tile and instrumentation package to monitor heating effects from boundary layer transition during re-entry. On STS-119, the windward airflow on the port wing was deliberately disrupted by a four-inch wide and quarter-inch tall protuberance built into the modified tile. In coordination with this flight experiment, a US Navy NP-3D Orion aircraft was flown 28 nautical miles below Discovery and remotely monitored surface temperature of the Orbiter at Mach 8.4 using a long-range infrared optical package referred to as Cast Glance. Approximately two months later, the same Navy Cast Glance aircraft successfully monitored the surface temperatures of the Orbiter Atlantis traveling at approximately Mach 14.3 during its return from the successful Hubble repair mission. In contrast to Discovery, Atlantis was not part of the Boundary Layer Transition (BLT) flight experiment, thus the vehicle was not configured with a protuberance on the port wing. In September 2009, Cast Glance was again successful in capturing infrared imagery and monitoring the surface temperatures on Discovery's next flight, STS-128. Again, NASA flew a specially modified thermal protection system tile and instrumentation package to monitor heating effects from boundary layer transition during re-entry. During this mission, Cast Glance was able to image laminar and turbulent flow phenomenology optimizing data collection for Mach 14.7. The purpose of this paper is to describe key elements associated with STS-119/125/128 mission planning and execution from the perspective of the Cast Glance flight crew that obtained the imagery. The paper will emphasize a human element of experience, expertise and adaptability seamlessly coupled with Cast Glance system and sensor technology required to manually collect the required imagery. Specific topics will include a near infrared (NIR) camera upgrade that was implemented just prior to the missions, how pre-flight radiance modeling was utilized to optimize the IR sensor configuration, communications, the development of aircraft test support positions based upon Shuttle trajectory information, support to contingencies such as Shuttle one orbit wave-offs/west coast diversions and then the Cast Glance perspective during an actual Shuttle imaging mission.

Nomenclature

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

Acronyms

ACCB	Aircraft Change Control Board
AOS	Acquisition of Signal
Az	Azimuth
BLT	boundary layer transition
CAPS	Computer Aided Pointing System
CFD	computational fluid dynamics
CPA	Closest Point of Approach
DoD	Department of Defense
DARPA	Defense Advanced Research Project Agency
El	Elevation
EO	Electro-Optical
FoR	Field of Regard
FPA	Focal Plane Array
GMT	Greenwich Mean Time (Zulu time)
HSDI	High Speed Digital Imager
HYTHIRM	hypersonic thermodynamic infrared measurements
ICS	Intercom System
IR	infrared
ISS	International Space Station
LOS	Loss of Signal
MSP	Mission Support Plan
MWIR	mid-wave infrared
NESC	NASA Engineering and Safety Center
NIR	near infrared
RTF	return to flight
SA	Situational Awareness
SRB	Shuttle Rocket Booster
SSP	Space Shuttle Program
SWIR	short-wave infrared
STS	space transportation system
T&E	Test and Evaluation
TIG	Time of Ignition
TPS	thermal protection system
TSP	Test Support Position
ViDI	virtual diagnostics interface
WFOV	Wide Field of View

I. Introduction

Global thermal measurements obtained by the NASA Hypersonic Thermodynamic Infrared Measurements (HYTHIRM) team provided a unique and never before observed perspective on the global distribution of surface temperature and the state of the airflow (i.e., laminar/turbulent) over the entire windward surface of the Shuttle during hypersonic re-entry. The quantitative thermal imagery represented several years of advocacy within the aerothermodynamics technical community, sponsorship by the NASA Engineering Safety Center, the Space Shuttle Program Office and the Hypersonics project within the NASA Aeronautics Research Mission Directorate and careful planning and mission execution by a coalition of NASA, Navy, government labs, and contractor personnel. On Space Shuttle Discovery's Spring 2009 STS-119 mission, NASA flew a specially modified thermal protection system tile and instrumentation package to monitor heating effects from boundary layer transition during re-entry[1]. Boundary layer transition occurs when the smooth, laminar flow of air close to the Shuttle's surface is disturbed and becomes turbulent – resulting in surface temperature increases. On STS-119, the windward airflow on the port wing was deliberately disrupted by a four-inch wide and quarter-inch tall protuberance built into the modified tile - intended to promote transition to turbulent flow near Mach 15. In coordination with this flight experiment, the HYTHIRM team positioned a US Navy NP-3D Orion aircraft 28 nautical miles below Discovery and remotely monitored surface temperature of the Orbiter at Mach 8.4 using a long-range infrared optical platform referred to as Cast Glance.

The imagery from this mission not only captured the expected thermal footprint of the turbulent flow downstream of the wing protuberance but a much larger area of turbulent flow on the opposing wing that was not anticipated, as shown in Fig. 1. The global thermal imagery obtained from the aircraft complemented the data collected with an onboard instrumentation package consisting of 10 surface thermocouples.

Approximately two months later, the same Navy aircraft successfully measured the surface temperatures of the Orbiter Atlantis (not configured with a protuberance) traveling at Mach 14.3 during its return from the successful Hubble repair mission, STS-125 (Fig. 2). Six months after the first flight experiment Discovery, outfitted with a slightly taller protuberance intended to promote transition to turbulent flow near Mach 18, was successfully imaged by the Cast Glance aircraft at Mach 14.7 (Fig. 3). Collectively, the spatially resolved global thermal measurements made during the Shuttle's hypersonic re-entries were intended to demonstrate the capability to collect scientific- quality imagery in a reliable manner using available technology.

It is the intent of the HYTHRIM project to analyze the imagery and provide the technical community critical flight data for reducing the uncertainty associated with present day ground-to-flight extrapolation techniques and current state-of-the-art empirical boundary-layer transition and turbulent heating prediction methods. Laminar and turbulent flight data is considered critical for the validation of physics-based, semi-empirical boundary-layer transition prediction methods and to stimulate the validation of laminar numerical chemistry models and the development of turbulence models supporting NASA's next-generation spacecraft under the Constellation program.

The present paper is part a series of 5 papers on the viability of obtaining

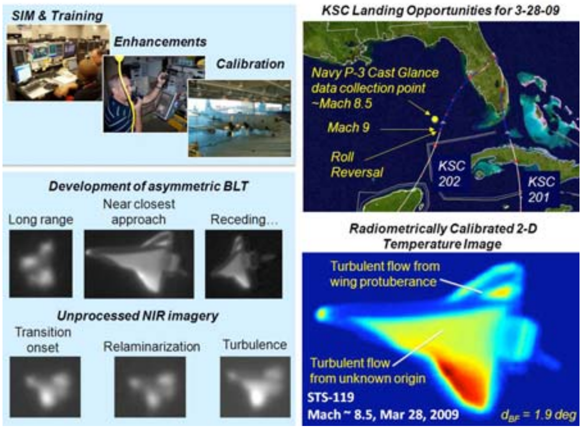

Fig. 1. Summary of Cast Glance Imaging in Support of STS-119

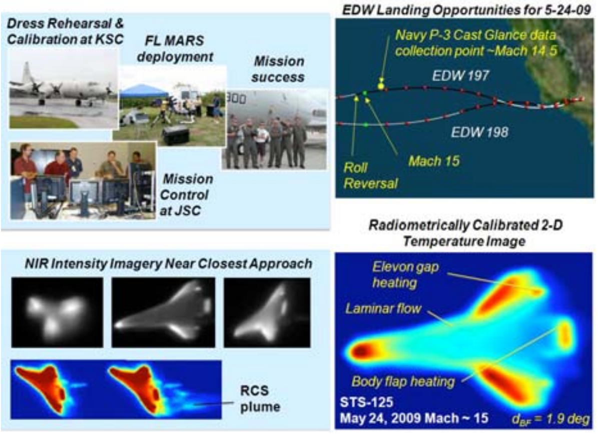

Fig. 2. Summary of Cast Glance Imaging in Support of STS-125

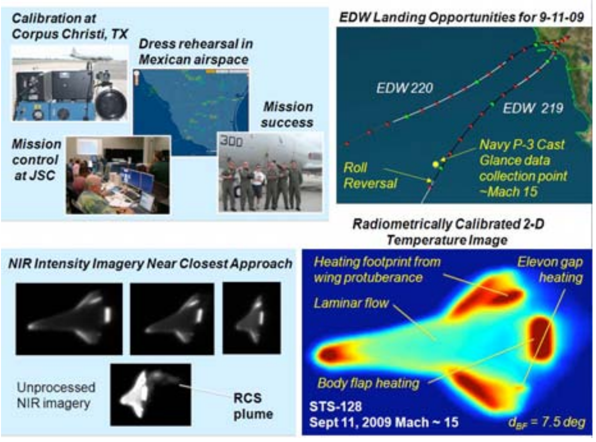

Fig. 3. Summary of Cast Glance Imaging in Support of STS-128

and application of quantitative spatially resolved flight thermography[2-5]. Reference 2 provides a general overview of the HYTHIRM project. The present paper describes key elements associated with mission planning and execution from the perspective of the Navy flight crew that obtained the thermal imagery from onboard a NP-3D Orion aircraft. A summary of a near infrared (NIR) sensor upgrade that was implemented just prior to the HYTHIRM missions is also provided. The formulation of strategies to develop aircraft Test Support Positions (TSP) that will handle contingencies such as Shuttle one orbit wave-offs/west coast diversions is discussed (TSPs are the locations of aircraft holding patterns from which imagery collection begins). Topics such as optimal IR sensor configuration, image acquisition, and the complexity and importance of team communications during a imaging mission are addressed. Reference 3 contrasts the legacy Cast Glance analog IR system to the new digital near infrared (NIR) imaging system (i.e., dynamic range, signal-to-noise) used onboard the Navy Cast Glance aircraft. A description of the calibration strategy and process to characterize this new digital camera is detailed in this reference and focuses on radiometric, spatial and spectral aspects of the NIR imaging system that permitted conversion of captured radiant intensity to temperature values. Reference 4 describes the application of a code that was used to generate high-fidelity synthetic infrared (IR) signatures to characterize Shuttle radiance during reentry and how the output from this model was used pre-flight to configure the infrared sensor to optimize dynamic range and mitigate saturation. Image registration, frame averaging and other processes and algorithms used to reduce atmospheric and optical bench blurring effects and improve image quality are discussed. Finally, in Reference 5 initial comparisons of the NIR derived global surface temperature to numerical turbulent prediction is presented.

II. Cast Glance Background

A. What is Cast Glance?

The term Cast Glance refers to a host of gyro-stabilized electro-optical (EO) platforms mounted in Air Test and Evaluation Squadron Three Zero (VX-30) NP-3D Orion aircraft, at the Naval Air Warfare Center Weapons Division located at Pt. Mugu, CA. The primary Cast Glance aircraft houses two autonomous starboard-looking Cast Glance optical systems, one in the forward observer station and one in the aft observer station. The Cast Glance optical suite provides a stable line of sight for a variety of airborne optical sensors. Typical applications include long-range stabilized photo documentation of air-to-air, air-to-ground, ground-to-air missile systems, rocket launches, imaging reentering objects and surface target impacts. The heart of the Cast Glance system is a gyro-stabilized gimbaled mirror which collects light and directs it into a 7 inch aperture telescope. This system utilizes a concept of controlling the movement of a gyro-stabilized mirror to point a camera, rather than moving the camera and lens itself. Through a series of beam splitters and pick off mirrors, light is diverted to several video, digital and high-speed imaging sensors. Manual tracking of the gimbaled mirror produces the optical data recorded by these fixed cameras. Spectral wavelengths of the Cast Glance systems include visible (0.4μm to 0.7μm), near infra-red (0.7μm to 1.1μm), short wave IR (.9μm to 1.7μm) and mid-wave IR (3.4μm to 4.9 μm). Additional instrumentation includes the Computer Aided Pointing System (CAPS) which supplies aircraft flight data and target position information, which can be embedded into the video fields. Instrumentation cueing is internal to the aircraft and provided by the CAPS to the forward Cast Glance system. The pointing information required for acquisition is then relayed to the aft system.

The Cast Glance optical systems were originally developed at Naval Air Warfare Center Weapons Division, Pt. Mugu (formerly the Pacific Missile Test Center – PMTC), and were employed to overcome the challenges of obtaining documentation-quality imagery of weapons test events over the largest Sea Test Range in the hemisphere. Stabilized tracking and long range optics are both required for high resolution results in the Test and Evaluation (T&E) community, yet this is difficult to achieve over the ocean, without a land mass to accommodate suitable tracking mounts. Hence, the need to develop an airborne gyro-stabilized photometric optics platform became apparent. With its ability to stand-off over water at great distances and provide exceptional stabilized tracking, Cast Glance has been a primary source for electro-optical data gathering at the Sea Test Range for over 30 years. Cast Glance has supported every major DoD missile program and has been utilized on test ranges and over the open ocean, worldwide. Further, Cast Glance has supported programs from every branch of the service, as well as other government agencies and commercial entities, both domestic and foreign. Of additional significant note, Cast Glance and its variants were among the very first airborne gyro-stabilized EO systems - from which most other airborne optical systems find some degree of heritage. Because of the uniqueness, quality, and visibility of the data collected, programs on a national level began to take note and utilize Cast Glance for support. Due to the 12-hour endurance and ability to deploy anywhere in the world, Cast Glance was able to set new standards for remote imaging objectives.

B. Cast Glance Historical Support of Space Shuttle Missions

Early in the Space Shuttle Program (SSP), the unique capabilities of the Cast Glance system were utilized for ascent phase imagery and to document the performance of the Shuttle Rocket Boosters (SRB) parachute recovery systems (Fig. 4). The majority of early STS missions from the 1980's into the early 1990's were supported by Cast Glance, and included additional missions to image the re-entry and break-up of the Shuttle's external tank. More recently, Cast Glance was also called upon to support efforts to image STS-121 during re-entry in July 2006. With just 72 hours notice–Cast Glance was able to deploy and successfully image the Orbiter at approximately Mach 12. This effort was ultimately part of Space Shuttle's Return to Flight (RTF) imagery objectives, which had been initiated prior to Cast Glance involvement. Cast Glance was subsequently tasked to observe re-entry of STS-115 and STS-116. Collectively, these three missions are appropriately referred to as "ad hoc" missions.

Fig. 4. Early Cast Glance Support of the Shuttle Program (circa 1980-90s). Shuttle Rocket Booster (SRB) Parachute Deployment

Cast Glance obtained some very dramatic imagery from these early observations and, in particular, during the STS-121 re-entry. During this mission, on-orbit TPS inspections of Discovery revealed several protruding tile gap fillers. After a real-time engineering assessment, the gap fillers were not considered a safety of flight issue and a spacewalk was not performed to remove them. Cast Glance was successfully deployed and stationed under the Shuttle ground track near a point in the re-entry where the Mach number would be approximately 12. Near the point of closest approach the thermal imagery revealed the high temperature footprint of turbulent flow from a protruding gap filler located just upstream of the body flap (Fig. 5). 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 could not be determined because of significant image saturation (white areas). Although promising, the lack of a radiance model precluded any pre-flight sensor simulation to estimate resolution, characterize atmospheric effects, quantify dynamic range and optimize integration times. Nevertheless, the imagery captured on STS-121, and the demonstrated ability of the Cast Glance crew to deploy, maneuver and collect this data, served as the foundation for a proposal to develop the HYTHIRM team and the tools necessary to increase the probability of returning scientific quality data on the then proposed Shuttle Boundary Layer Transition (BLT) flight experiment.

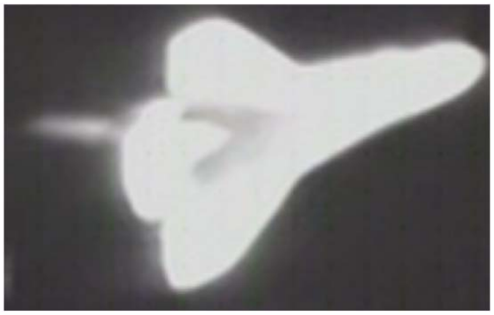

Fig. 5. Saturated Image of STS-121 (2006) at Mach 12

III. HYTHIRM Project Mission Objectives

As also discussed in Ref. 2 the passive nature of infrared thermography makes it a very powerful tool, from a global perspective, to observe flow field phenomena on the surface of a hypersonic re-entry vehicle. This passive data acquisition both compliments and reduces uncertainties of discrete onboard surface instrumentation. Any flow phenomena that create measurable surface temperature changes such as shock wave interactions, flow separation, and boundary layer transition (BLT) could be visualized. Quantitatively, if surface temperatures associated with a hypersonic laminar and/or fully turbulent boundary layer flow could be inferred from calibrated in flight imagery they could be used to verify engineering models or 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 reentries over the past 25 years to obtain flight data[6-15]. These previous attempts, while successful at obtaining images, resulted in limited quantitative data due to sensor saturation and a limited understanding of mission planning. The renewed interest in thermal imagery during Shuttle re-entry was initially motivated by the desire to reduce uncertainties associated with an empirical strategy to predict BLT onset. This empirical methodology, adopted to quickly assess thermal environments induced by damage to the Shuttle's TPS, is derived from ground-based measurements[16,17] that are extrapolated to flight using representative (and limited) flight data[18]. 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 led the Space Shuttle Program (SSP) to support a series of hypersonic boundary layer flight tests. In the initial proposal, an isolated protuberance was to be located on the Shuttle wing to induce boundary layer transition and turbulence at hypersonic conditions[19]. Global temperature IR images with adequate spatial resolution and dynamic range were proposed to non-intrusively complement the discrete thermocouple data on these flight tests by providing spatially continuous surface temperature at targeted Mach number(s).

Applicability of such flight data was not restrictive to Shuttle damage assessment. In general, heating augmentations and temperature increases resulting from hypersonic flight through the atmosphere of Earth (or other planets such as Mars) impose critical requirements on the design and operation of any vehicle thermal protection system (TPS).

Based upon the imagery attempts during the Shuttle RTF, and recognizing the tremendous technical opportunity that the Shuttle BLT flight tests offered, the NASA Engineering and Safety Center (NESC) sponsored the initial formation of HYTHIRM - a team of technical experts to assess existing imaging capability within the US and to develop and validate a mission planning tool set. The success of early proof-of-concept tests to assess the ability to infer temperatures from calibrated imagery provided the necessary fundamentals to execute a Shuttle imaging campaign. The overall goal of the team was to develop validated mission planning tools to demonstrate the viability of obtaining calibrated global temperature measurements on a hypersonic flight vehicle using one or more of the nation's existing suite of applicable imaging assets. The highly demonstrated capabilities of Cast Glance with regard to mission planning and execution during the Shuttle ad hoc observations offered a sensible asset to recruit for the HYTHIRM team.

IV. HYTHIRM Project Technical Objectives

In November of 2008, the HYTHIRM project was given authority to proceed with a March 2009 Shuttle imaging mission. The primary technical concerns identified on previous ad hoc missions flown in 2006 were: 1) the limited dynamic range and over-saturation of the existing Cast Glance NIR tracking sensor, as discussed in Section II; 2) the need to characterize the optical system itself; 3) the lack of fluid critical information exchange between mission control and the Cast Glance aircraft during mission flights; and 4) the inability to fully model imaging parameters pre-mission, both from a radiance and aspect geometry perspective.

The following paragraphs describe the HYTHIRM team's approach to resolving each of these concerns.

1. <u>Limited Dynamic Range -</u> The HYTHIRM team proposed the use of a new enhanced, digital NIR sensor to be installed on the Cast Glance system. This enhanced sensor dramatically increased the dynamic range and signal-to-noise ratio over the previous analog sensor, enabling greater thermal resolution during data collection. Further, new software was created for airborne-specific applications to control the sensor during observation of re-entry, thus enabling system operators real-time authority to 'ride' crucial sensor

Fig. 6. Cast Glance Hangar Calibration

settings such as integration time and gain – the key to mitigating image saturation and overcoming tracking challenges. This enhanced sensor was integrated onto the Cast Glance system through the NAVAIR Aircraft Change Control Board (ACCB) flight clearance process, and successfully captured dramatic Shuttle re-entry imagery on STS-119, STS-125 and STS-128.

2. <u>Optical System Characterization -</u> For the thermal imagery produced by the enhanced sensor to have any foundation in truth, a full characterization of the optical system was required and subsequently performed. A lab environment was recreated in the VX-30 hangar (Fig. 6) complete with black-body radiation sources, full-field illumination optics and a host of spectrally delineated filters for band-pass measurements. The characterization of the Cast Glace Optical system is discussed at length in Ref. 3.

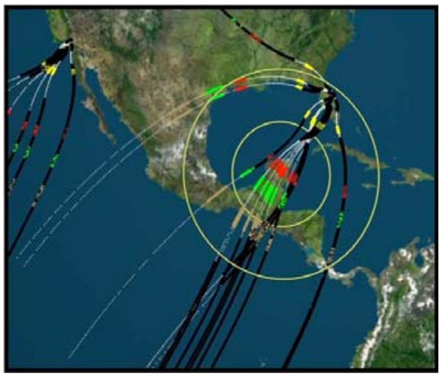

Fig. 7. Historical (post Return-to-Flight) Shuttle Trajectories.

3. <u>Mission-Critical Information Exchange -</u> Successful acquisition and tracking of the Space Shuttle during hypersonic re-entry requires intricate coordination on many levels. To address the dynamically changing situation during this flight regime, the HYTHIRM team developed procedures and equipment to facilitate efficient communications between mission control, Cast Glance personnel, VX-30 aircrew, ground-based imaging assets, and airspace management officials, areas which had been deficient during the ad hoc missions. The improvement of mission communications was felt to be important because re-entry trajectories, Shuttle roll reversal locations, Mach numbers and de-orbit burn times are continually changing right up to the time of ignition (TIG) for the de-orbit burn. As shown in Fig.7 the trajectories of the Shuttle re-entry can vary considerably depending on orbital mechanics variables as well as landing site weather constraints. It is imperative this information be rapidly and concisely conveyed to all parties involved in the data collection process to effectively flex and adjust for orbiter acquisition and acceptable viewing parameters. If re-entry is waved-off to the next orbit, every minute is needed to re-position the aircraft as much as 600nm away from the initial support point, which again requires efficient communication (Fig. 8). Foreign and domestic airspace coordination also became a task of the HYTHIRM team as determinations are made when and where to land the Shuttle. The HYTHIRM team in mission control at JSC provides the Cast Glance aircraft with time-critical support to permit maximum flexibility in covering re-entry path contingencies.

Fig. 8. A sample of aircraft re-positioning based on varying Shuttle trajectories.

4. <u>Pre-Mission Radiance Modeling and Real-Time Aspect Modeling -</u> One of the most significant lessons learned from the Shuttle-sponsored re-entry observations during RTF (2005-2006) was the lack of mission-specific planning tools and corresponding decision making proc-

esses and procedures for reliable acquisition and tracking of the Shuttle. For the Cast Glance NIR data to have the most scientific value, two additional shortcomings needed to be addressed – (1) the anticipated line of site geometry from the optical system to the Orbiter windward side and (2) a pre-mission understanding of the predicted Shuttle radiance. Unlike pre-mission planning for the ad hoc missions, HYTHIRM utilized high fidelity radiance modeling[4] on the 2009 flights to assist Cast Glance personnel in determining proper sensor settings, such as integration times, minimizing the chance of image saturation. Additionally, a graphics-based virtual environment tool was employed for visualization of Cast Glance relative to the Shuttle. The Virtual Diagnostic Interface (ViDI)[20] tool developed at LaRC was adapted for HYTHIRM use. In this software package, surface CAD definition of the vehicle targeted for imaging along with 6 degree of freedom trajectory information is imported in a custom ViDI program tied in with commercial off the shelf graphical software to visualize aspects of the entire trajectory on a virtual three-dimensional Earth. HYTHIRM control was also able to make real-time position recommendations to Cast Glance based on the visual simulations rendered. Based on simulation results, HYTHIRM provided recommendations to the Cast Glance team for TSP design planning, to ensure proper viewing geometry was achieved and mission resolution objectives met.

Cast Glance has now flown against six missions to image the Space Shuttle during re-entry - STS-121, STS-115, STS-116, STS-119, STS-125 and STS-128. From a flight design perspective, support for each STS mission largely builds on experience gained during observations of the previous missions. Armed with the new HYTHIRM pre-mission planning tools, Cast Glance initiates mission support planning months prior to deployment. This is a methodical process that evaluates and fuses observation requirements with aircraft and Cast Glance system performance parameters, then imparts the union onto the widest dispersion of geographical support scenarios.

V. Cast Glance Shuttle Mission Planning

When initial mission planning begins, broad considerations influence initial Test Support Point (TSP) flight design and Mission Support Plan (MSP) development. Requirements include but are not limited to (1) to image the bottom (windward) side of the orbiter at best possible aspect angle, (2) design multiple TSPs to obtain imaging of the Orbiter at a variety of contingency Mach numbers up to Mach 18, (3) mitigate image saturation, 4) maximize image size of Orbiter, 5) ensure that diplomatic and Special Use Airspace (SUA) clearances are in place for all airspace likely to be used for Cast Glance TSPs and transit paths, and 6) select TSPs and basing locations within aircraft range and endurance capabilities to support two entry opportunities per mission day and/or expedite re-deployment for alternative Shuttle landing site. As mission details and predicted trajectories evolve, further considerations are factored into planning. For example, the Cast Glance aircraft is required to fly a racetrack pattern (Fig. 9) at the TSP at a specific angle to the re-entry trajectory. Relative to the Shuttle position the flight pattern within the TSP is a critical factor in a successful data collect. In detailed planning the, design of the location, size, and shape of that orbit is determined to optimize for the desired Mach number achievable while viewing the underside of the orbiter. It is necessary for the TSP design to allow for a CPA (closest point of approach) nearest that

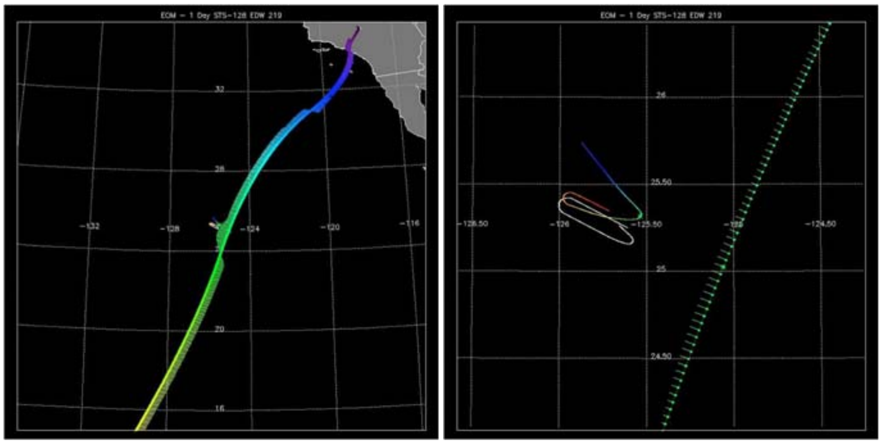

Fig. 9. Racetrack Pattern at a Test Support Position (TSP) for a Shuttle West Coast Re-entry into EDW AFB

particular desired Mach number. An extended inbound (upwind) leg is designed to insure maximum likelihood of orbiter acquisition. Another factor in detailed planning is that the TSP position must be designed to allow enough time for a "one orbit wave off" contingency. The wave-off scenario may require a positional shift of up to 600nm between landing opportunities and, given that the trajectories become further spaced at higher Mach numbers, factors heavily into the maximum Mach number that can be targeted on the first landing opportunity while still protecting the TSP for the second opportunity.

Also a factor in detailed planning is the requirement to maximize spatial resolution. This is accomplished by minimizing the slant range between Cast Glance and the Orbiter at the target Mach number. The Cast Glance aircraft is nominally stationed at an altitude of approximately 25,000 ft during the mission. In contrast, the Shuttle descends thru an altitude of approximately 200,000 ft traveling at hypersonic speeds as it approaches the aircraft. At CPA, the aircraft and its crew observing the Shuttle are approximately 22-40 nautical miles from the orbiter during re-entry, depending on the final relative positioning.

With the frame of reference described above, the Cast Glance team begins the process of flight design. The first step is to plot the initial trajectories and associated Mach numbers. These trajectories change but an estimate of preliminary test support locations is required as a foundation to build the plan. HYTHIRM science goals are communicated to Cast Glance mission planners, who then evaluate the geographic location of desired Mach observation selections along all entry trajectory possibilities. Because of the Shuttle's limited cross range capability there are nominally just two entry trajectories for a given day into KSC, and two associated with an alternate west coast landing site. These initial trajectories into either landing site are evaluated by the Cast Glance team and can be many hundreds of miles apart from one orbit to the next. In the event a wave-off from the first entry opportunity to the second occurs, time is the major driver when deciding upon a secondary TSP. Typically a wave-off call is passed just prior to the planned de-orbit burn time, allowing only 90 minutes plus the time from entry interface at Mach 25 to the desired Mach number, for the Cast Glance aircraft to reposition along the next ensuing orbit trajectory. The first answers returned to HYTHIRM encompass the total Mach science objectives that can be achieved based on the limitations of aircraft transit speed and on-station time, verses the geographic location of said objectives.

Next, Cast Glance planners model the aircraft support racetrack and specific aircraft maneuvers required to acquire and maintain track throughout the Shuttle's fly-by. A closest point of approach (CPA) is established based on desired Mach number and acceptable viewing aspect parameters. More importantly however, CPA selection is also a function of aircraft maneuvering limitations, Cast Glance field of regard manipulation and acceptable Cast Glance system tracking slew rates. The two Cast Glance systems look only out the starboard side of the aircraft and have a conical Field of Regard (FoR) of +/- 40 degrees azimuth and elevation; high fidelity tracking is contained within that FoR at a certain maximum usable track slew rate. In general, Cast Glance TSP design attempts to minimize the distance to a given target, in turn maximizing image size on sensor Focal Plane Array's (FPAs). Aircraft speed, distance, heading, angle of bank and altitude are modeled against Cast Glance system performance and simulated over and over, then further refined and re-simulated until no limitations are exceeded.

A. Acquisition and Tracking Strategy

As referenced above, the Cast Glance racetrack design requires detailed planning and customization to each trajectory and Mach number. After a CPA is selected, upwind and downwind headings are established based upon the most advantageous geometry for sensor acquisition. A 14 minute orbit is designed with 5 minute legs and two minute turns. This is longer than the typical 10 minute Cast Glance racetrack and is intended to maximize the amount of time inbound to "search" and acquire the Shuttle as it ascends above the local horizon. The Cast Glance aircraft does not have any ground cuing uplinks, but does have the Computer Aided Pointing System (CAPS) whereby a nominal trajectory can be uploaded and simulated. CAPS is linked to aircraft inertial reference (INS), GPS and the Cast Glance optical systems. Though it can assist in acquisition, it is limited by several factors most notably the last minute changes to the Shuttle trajectory itself, which cannot be received and uploaded while airborne over remote locations. Initial pointing angles provided by CAPS can be helpful in determining horizon broach, however. Cast Glance operators develop an acquisition scan pattern, anchored to reference pointing angles for a given time. During entry Cast Glance operators will employ four aids for acquisition of the orbiter as it ascends over the local horizon. As acquisition is critical, a dynamic blend of all acquisition devices is used to mitigate the risk of acquisition failure:

1. Nominal Space Shuttle re-entry trajectory files (provided for TSP planning) are uploaded into CAPS as described above. The "track" file will then be synchronized with EOM (end of mission) time. Operators can elect to allow CAPS generated offsets to drive the system mirror for acquisition.

2. A cockpit acquisition sight allows for pilots to slew a pointer onto a target. Operators can elect to allow acquisition sight generated offsets to drive the system mirror for acquisition, however if the Shuttle re-entry occurs in the daytime it is near impossible to see it with the naked eye.

3. Preset 'cage-position' azimuth and elevation predictions based on mission simulations. Operators can elect to allow cage-position generated offsets to drive the system mirror for acquisition.

4. A wide field scope, part of the system optical path, is constantly monitored until the target is acquired and captured in the NFOV tracking monitors, again difficult for daytime operations. Once acquisition of the Space Shuttle is achieved, the operator will take control of gimbal steering manually. Rate-aided signal processing is applied to minimize object movement within the field of view.

B. Sun Exclusion and Weather Contingencies

Cast Glance performs a detailed analysis of optical tracking line of sight plotted against the sun's azimuth and elevation throughout the observation. When a conflict arises, positional shifts are considered to mitigate sun influence. However, repositioning is usually not possible due to the fixed relationship between FoR and acquisition angle. It is still important for Cast Glance operators to be cognizant of sun angle influence to determine proper sensor settings and to anticipate any visual difficulties in maintaining track.

Weather contingencies are another area of Cast Glance detailed planning. The operational ceiling of the NP-3D aircraft is limited to 30,000 feet, which is often lower than variable cloud layers in typical re-entry areas. Alternate TSPs and execution planning are developed and briefed. Weather information is obtained by the Cast Glance team days in advance as a source of situational awareness (SA). During mission pre-flight, VX-30 aircrew are briefed on weather both at the deployment site and in the mission operation areas. Just prior to take off, Cast Glance personnel are provided with the latest predictions and satellite photos from HYTHIRM control. If adverse weather is apparent in any of the planned TSPs, a dynamic decision making process ensues between HYTHIRM, Cast Glance team and VX-30 flight crew as to where to position the aircraft.

VI. Cast Glance Shuttle Mission Execution

The HYTHIRM objectives are challenging; Shuttle trajectories are diverse, dispersed and ever evolving; the Cast Glance aircraft, systems and planning are exhaustively fine tuned and simulated - yet successful data collect all comes down to precise execution. The harmonious interaction between HYTHIRM control, every member of the flight crew and the Cast Glance team is imperative to properly execute the mission design and meet the observation objectives. After take-off, the symphonic process begins, all players synchronized to Greenwich Mean Time (GMT) and scripted to the same sheet of music.

Shifts in time and position of the Shuttle re-entry trajectory are passed from HYTHIRM control, and new support times are generated for all the points of the TSP racetrack. Once on station, pilots and navigators refine the aircraft timing and position, making all necessary adjustments for winds and other atmospheric conditions. Cast Glance operators are busy fine tuning the equipment, assessing lighting conditions, making sensor adjustments, recording star calibration data (when applicable), and exercising acquisition simulations on every lap. If the call is received to wave-off the first entry attempt, the aircraft immediately takes up a heading towards the secondary TSP at best possible speed. Once on station at TSP 2, aircraft timing and synchronization begins anew. All flight crew members work from a predefined mission script – a comprehensive checklist fusing all necessary tasks, radio and Intercom System (ICS) calls and aircraft maneuvering synchronized to GMT. This script is generated by the Cast Glance team and rehearsed continually throughout the entire deployment.

Once confirmation of de-orbit burn is received from HYTHIRM control, activity onboard the Cast Glance aircraft intensifies significantly. Timing is honed, all sensor settings are confirmed and all operators are in place while the aircraft performs its final few racetrack orbits. On the second to last lap, the

“DRY” pass, final conditions of flight are recorded, last minute contingency decisions are made and the call is made to “start recorders” – all data acquisition systems (High Speed Digital Imager , video, NIR, MWIR) are armed and set to record data. As the aircraft begins its final 14 minute lap, recorders and data acquisition systems are double checked for proper functionality, the CAPS acquisition file is started at a precise moment and the Cast Glance team anticipates the impending acquisition.

A. The “HOT” Pass (Hands on Flying and Tracking)

At CPA – 6 minutes, the aircraft rolls onto its final acquisition heading. Sensor acquisition is predicted to be no sooner than CPA-4 minutes, giving operators 2 minutes on heading to ensure flight design headings and predicted angles correspond with those actual flown. At CPA – 4 minutes, NIR and MWIR data acquisition computers begin recording and Cast Glance operators enact the target acquisition plan. CAPS cuing or predicted cage az/el angles are selected by the operator. A scan pattern is manually initiated centered on these angles as the operator searches for the Shuttle ascending above the local horizon. Once the Shuttle is detected on wide field of view (WFOV) sensors, track is achieved and centered, directing light to all bore-sighted sensor focal plane arrays (FPAs). The actual line of sight established between the Cast Glance optical system and the re-entering Shuttle determines all subsequent aircraft maneuvering, based on the true az/el relationship within the FoR. Gimbal angles are called out on ICS for SA, maneuvering is verbalized by Cast Glance operators to the flight station to maintain optimal viewing parameters within the FOR. As the Shuttle and Cast Glance aircraft converge, constant adjustments in heading and angle of bank are required. From the CPA-1 minute waypoint, angular rates increase rapidly and aircraft turning becomes far more aggressive through the CPA. Furthermore, Cast Glance system gimbal slew rates are at the highest usable output, adding a real challenge to manual tracking. After CPA, the aircraft and Shuttle ground tracks diverge; turn rate, angle of bank and Cast Glance system slew rates become more benign. Track is eventually lost as the Shuttle descends over the opposite horizon.

B. Managing the Sensors in Real Time

Finding and tracking the Shuttle during entry is only half the solution to obtaining engineering quality data. Monitoring all sensors throughout the data collection is critical to ensure results are applicable to the HYTHIRM science objectives. The pre-mission radiance modeling provides a baseline for initial settings on the NIR and MWIR sensors, mainly to mitigate the risk of saturation. Adjusting integration time (analogous to shutter speed to a photographer) is the most effective way of controlling proper image exposure while also minimizing the effects of image jitter (blurring). Integration times are recommended by the radiance modeling, but since on-station conditions are highly dynamic it becomes necessary to have real-time control of the integration times. During Shuttle re-entry, an operator monitors the data and makes constant exposure corrections to allow for the maximum amount of energy to strike the FPA while protecting against any pixel saturation. Focus, aperture, and frame rates are also adjusted real-time to accommodate fluctuating conditions. During CPA the operator continues to assess real time the exposure range striving to maximize the signal to noise ratio all while verbally commanding the flight crew on aircraft maneuvers to maintain acquisition. This process continues until the Orbiter recedes and Loss of Signal (LOS) occurs. At the moment of Loss of Signal (LOS) the process of downloading and backing up the data begins. A report of AOS/LOS and total track time is passed over the net to HYTHIRM control.

C. Crew Interaction and Coordination

Pursuant to the complex and dynamic nature of Shuttle re-entry mechanics and hypersonic image acquisition, successful data collection requires harmonic coordination by a multitude of professionals. HYTHIRM team members communicate to Cast Glance personnel, who in turn work closely with VX-30 flight crews in a time critical environment. Man-in-the-loop decisions are made at every level to keep the mission support and Cast Glance platform as flexible as possible, hence meeting the ever changing parameters and satisfying the HYTHIRM science objectives. Sensor enhancements and optical stabilization technologies mean very little without this vibrant blend of expertise to get eyes on target and make sound real-time decisions. The HYTHIRM missions supported by CAST GLANCE illustrate this very interaction, where the end product is a result of peak performance by a unique collaboration of professionals.

VII. Summary

The Cast Glance aircraft, their optical systems and highly experienced crew have demonstrated a long standing tradition of high integrity imagery acquisition in support of NASA and the Space Shuttle Program spanning from the early Shuttle ascent imaging days, the RTF ad hoc missions, to the present day in support of re-entry imaging. This tradition continues with HYTHIRM as the global team effort put forth demonstrated a highly coordinated and integrated effort involving the development, maturation, validation and application of a suite of mission planning tools to obtain quantitative, spatially resolved, flight thermography of the Shuttle during hypersonic entry. In coordination with the HYTHIRM team, the Cast Glance US Navy NP-3D aircraft was flown between 26 to 41 nautical miles below Discovery and remotely monitored surface temperature of the Orbiter at Mach 8.4 (STS-119) and Mach 14.7 (STS-128) using a long-range infrared optical package. This same Navy aircraft successfully monitored the Orbiter Atlantis traveling at approximately Mach 14.3 during its return from the Hubble repair mission (STS-125). A background and an overview of the Cast Glance systems, the mission planning tools and the data acquisition procedures involved that culminated in the acquisition of high resolution calibrated infrared imagery of the Space Shuttle during hypervelocity atmospheric entry has been presented. By maximizing on the experience and lessons learned from historical Cast Glance support, the Cast Glance crew was in a position to greatly contribute to the implementation of well refined mission planning tools in support of HYTHIRM Shuttle imaging campaigns. These refined tools, which led to the success of the HYTHIRM team, included application of a pre-flight capability to predict the infrared signature of the Shuttle to simulate detector response characteristics, installation and optimization of the hardware configuration to increase signal-to-noise and available dynamic range while mitigating the potential for saturation. The mission planning tools also included enhanced ground to air communication tools which contributed to mission success by allowing real time feeds of varying Shuttle trajectories to the Cast Glance crew, thus sharpening deployment positioning and range. All these elements were successfully addressed, implemented and three successful Shuttle missions executed all within a ten-month timeframe in 2009. The successful collection of thermal data on these three Shuttle missions has demonstrated the feasibility of obtaining remote high-resolution infrared imagery during flight for the accurate measurement of surface temperature.

Collectively, the spatially resolved global thermal measurements made by HYTHIRM via Cast Glance during the Shuttle's hypersonic re-entry have demonstrated the capability to collect scientific quality imagery in a reliable manner using available technology. The calibrated imagery captured by the HYTHIRM team represents the first time the entire surface temperature distribution of a hypersonic vehicle has been captured in flight at these Mach numbers. The thermal imagery obtained during STS-119 re-entry represents the first time that hypersonic transition onset to a fully turbulent flow has been observed globally in flight. In addition to the corresponding surface temperature measurements, the global imagery revealed complex flow field phenomena such as wake/contrail formation and RSC thruster firings that will be of scientific interest to specific technical communities. The global temperature measurement obtained on the Shuttle using available technologies suggests potential future applications (thermal, visual, spectral) towards hypersonic flight test programs within NASA, DoD and DARPA along with flight test opportunities supporting NASA's Constellation program. Cast Glance support of the HYTHIRM project will now extend into 2010 with select remaining Shuttle missions as the team works together to further broaden the envelope of this unique flight test data and enhance design and development of future hypersonic flight vehicles.

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