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A System Trade Study of Remote Infrared Imaging for Space Shuttle Reentry

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A trade study reviewing the primary operational parameters concerning the deployment of imaging assets in support of the Hypersonic Thermodynamic Infrared Measurements (HYTHIRM) project was undertaken. The objective was to determine key variables and constraints for obtaining thermal images of the Space Shuttle orbiter during reentry. The trade study investigated the performance characteristics and operating environment of optical instrumentation that may be deployed during a HYTHIRM data collection mission, and specified contributions to the Point Spread Function. It also investigated the constraints that have to be considered in order to optimize deployment through the use of mission planning tools. These tools simulate the radiance modeling of the vehicle as well as the expected spatial resolution based on the Orbiter trajectory and placement of land based or airborne optical sensors for given Mach numbers. Lastly, this report focused on the tools and methodology that have to be in place for real-time mission planning in order to handle the myriad of variables such as trajectory ground track, weather, and instrumentation availability that may only be known in the hours prior to landing.

Nomenclature

BET = Best Estimated Trajectory
BLT = Boundary Layer Transition
CFD = Computational Fluid Dynamics
EAFB = Edwards Air Force Base
FDO = Flight Dynamics Office
HST = Hubble Space Telescope
HYTHIRM = Hypersonic Thermodynamic Infrared Measurements
IR = Infrared
ISS = International Space Station
JSC = Johnson Space Center
KSC = Kennedy Space Center
NESC = NASA Engineering Safety Center
PSF = Point Spread Function
RTF = Return to Flight

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I. Introduction

The ability to comprehend the fundamental physics of hypersonic boundary layer transition and accurately model the process is a critical yet under-developed realm of the aerothermodynamic science. Predictions on when and how a boundary layer will transition from laminar to turbulent flow and potentially back to a laminar state directly affect the ability to predict vehicle drag, thermal loads, and ultimately the mass of the vehicle. The result of this lack of knowledge is a perpetual tendency to over-engineer flight hardware and/or place operational restrictions on vehicles designed to operate in this extreme environment. One of the key sources of information required to unlock the hidden physics of hypersonic boundary layer transition is to obtain the spatially resolved temperature distribution across the surface of the hypersonic vehicle in flight. In order to obtain such data from a vehicle in hypersonic flight, the NASA Engineering and Safety Center (NESC) has established an assessment team working on the Hypersonic Thermodynamic Infrared Measurement (HYTHIRM) project. The vehicle chosen for this study is the Space Shuttle, and the technique will be remote sensing using infrared imaging sensors mounted on airborne and land based platforms (referred to as imaging assets.)

A limited series of experiments have been conducted in the past[1-6], dating back to STS-3 (the third Space Shuttle flight) in the early 1980's that have attempted to acquire infrared imagery of the orbiter during descent. More recently, airborne assets developed to image the orbiter on ascent were utilized in an "ad-hoc" fashion to obtain infrared imagery during reentry. The results were mixed in terms of successful data collection, but the lessons learned were invaluable to gaining insight into how to proceed with preparations for a rigorous series of highly planned out experiments to acquire engineering quality infrared imagery of the Space Shuttle during descent. Those experiences have shown that it is possible to obtain high quality engineering data from air and land based imaging platforms. This trade study will review the primary variables that have to be considered when attempting to acquire remote infrared imagery of the Space Shuttle. This includes the performance of optics, infrared sensors, modes of sensor deployment, reentry trajectories and weather considerations. The goal of the trade study is to develop a methodology to develop optimum data acquisition strategies in near real time, based on a variety of highly variable parameters.

II. HYTHIRM Trade Study

The HYTHIRM trade study has looked at a number of variables that have a significant affect on how the Space Shuttle can be imaged remotely using infrared sensors, and how best to determine optimum solutions. It became evident that a clear cut analysis that states one imaging asset of one type of mode of deployment is better than another is not realistic. What evolved from this study is the development of a methodology of how best to implement a deployment strategy of the imaging assets available given the large number of uncertainties that may be encountered throughout the data acquisition mission. To understand the deployment methodology, there must first be a review of the imaging requirements and operational constraints.

A. Space Shuttle Operational Environment

The Space Shuttle flies an un-powered descent through the atmosphere, entering at Mach 25 and decelerating rapidly to subsonic speeds shortly prior to touchdown. Under nominal conditions, the flow over the vehicle is laminar from entry interface (the portion of flight where the effects of entering the upper atmosphere from space are first appreciable) to the time the vehicle has slowed to about Mach 8. At this point the turbulent flow, which has formed on the aft portion of the vehicle, quickly travels upstream within the boundary layer. This transition results in higher heating loads and aerodynamic drag as compared to the laminar flow, and plays a significant role in the behavior of the vehicle in flight. The behavior of Boundary Layer Transition (BLT) is both critical to the design and operation of hypersonic vehicles, and is little understood from a fundamental physics point of view. The HYTHIRM project can increase the understanding of BLT, shock wave interactions and flow separations by providing global thermography of the Space Shuttle. In addition, this capability can help support a separate flight experiment planned for the Space Shuttle.

A 2009 boundary layer transition flight experiment is being planned at the Johnson Space Center. This experiment will place a "trip" or a small rectangular protuberance on the underside of the right wing of the Space Shuttle. This trip, which is sized to cause transition from laminar to turbulent flow on the Space Shuttle at Mach 15, will be integrated into a specially manufactured heat shield tile. The trip is located such that the extended duration (and thus significantly higher heat load) of the turbulent flow is in a location where there is adequate safety margin. As part of the flight experiment, a series of about ten thermocouples have been added or relocated in an attempt to determine the time history and approximate shape of the turbulent wedge expected to occur. A detailed discussion of the flight experiment can be found in reference 7.

The HYTHIRM project is being run independently but in a complimentary fashion to the flight experiment. Both the flight experiment and the HYTHIRM project can operate in a stand alone mode, but there is significant advantage between combining efforts to obtain the maximum amount of information from the flight experiment and provide HYTHIRM with a well defined and stable geometry that will cause transition of the flow to better understand the boundary layer transition.

B. Imaging Requirements

The ultimate requirement for the HYTHIRM project is to obtain imagery of sufficient thermal and spatial resolution so as to determine the detailed behavior of the turbulent boundary layer[8, 9]. This will require careful consideration of a number or parameters such as the wavelength of the radiation measured, optical characteristics and placement of the sensors and the physical environment within which the measurements will be taken. There are many factors that will place constraints upon the implementation of this experiment, including technical, financial and political considerations. In order to accomplish the project's goals, it will be critical that a thorough understanding of the relationships between these factors be taken into account. The scope of this paper will be limited to the technical considerations with a brief mention of the inevitable financial and political constraints.

1. Thermal Resolution Considerations

The choice of an Infrared (IR) imaging system is dependent upon the portion of the spectrum that is to be analyzed, which is typically divided into four bands (Table 1). Choosing the optimal bandpass for global quantitative surface temperature mapping of the Orbiter during reentry is not trivial, and depends on factors such as thermal sensitivity, optical resolution, and atmospheric attenuation.

Table 1. Infrared Spectrum Nomenclature

Bandpass	Wavelength, μm
Near IR - NIR	0.75 – 1.4
Short wave IR (SWIR)	1.4 – 3.0
Mid wave IR (MWIR)	3.0 – 5.0
Long Wave IR (LWIR)	8.0 – 15.0

During a nominal reentry the temperatures on the underside of the Space Shuttle may vary from between 800 and 1800°F (700- 1250 K) for the hypersonic portion of the flight (Mach numbers greater than 5), as shown in Fig 1. The temperature will spike at approximately the 1250 second mark on the timeline, which is when the flow transitions from laminar to turbulent. Should an anomalous irregularity on the windward surface of the vehicle, such as a protruding gap filler (a small piece of felt placed in gaps between tiles), cause the flow to transition to turbulence earlier in the descent, localized portions of the vehicle could experience temperatures in excess of 2100 °F (1530 °K).

Figure 2 depicts the variation of blackbody radiance (spectral emissive power) with wavelength for various target temperatures in the range of 600 to 1400 K (620 to 2060°F). As the target surface temperature increases, most of the infrared radiation shifts to shorter wavelengths. The in-band integrated radiance over wavelength

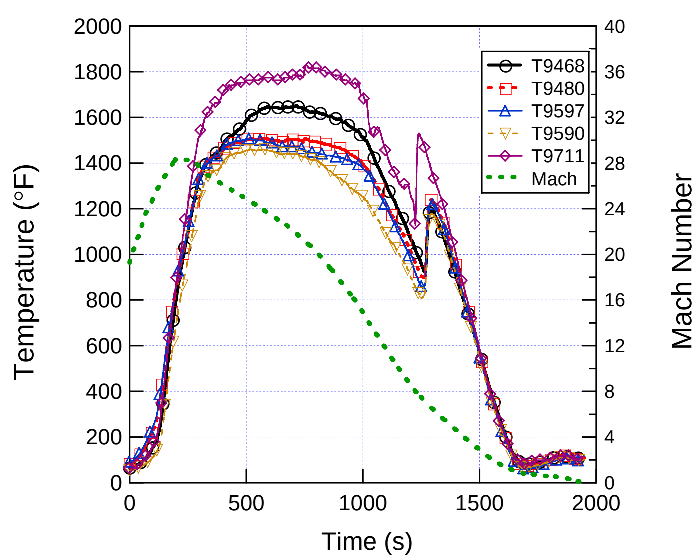


Figure 1. Temperature and Mach number vs. Time from vehicle entry interface to touchdown for thermocouples located underneath Orbiter TPS tiles. The Mach number was obtained from the best estimated trajectory (BET) data. Spike in temperature seen at 1250 seconds is due to transition from laminar to turbulent flow. Data is from the STS-114 mission, and represents nominal behavior.

for the four IR bandpasses as a function of target temperature is shown in Fig. 3. The in-band integrated radiance is extremely low in the NIR bandpass; with thermal sensitivity being extremely low below 1000 K. The LWIR has slightly higher in-band integrated radiance with an almost linear variation of integrated radiance with temperature. The SWIR and MWIR have distinctly higher in-band integrated radiance and higher temperature sensitivity above 1000 K. At the same time the amount of integrated radiance in these bandpasses is so high that saturation of the infrared imaging system becomes an issue and use of neutral density filters and/or higher dynamic range detectors and digitizers may be necessary. At first glance it may seem that the SWIR and MWIR are superior, but additional considerations such as spatial resolution have to be taken into consideration as well (see *Spatial Resolution Performance – Point Spread Function*, Section 5.

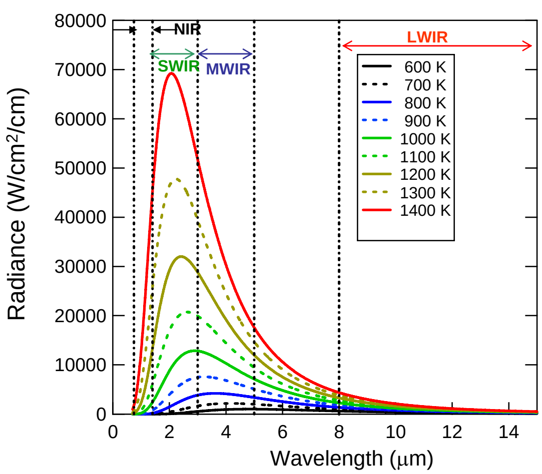


Figure 2. Blackbody radiance as a function of wavelength for different target temperatures.

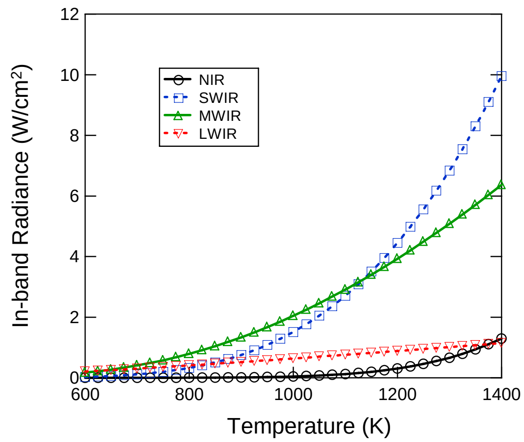


Figure 3. Blackbody in-band integrated radiance for the four IR bandpasses as a function of target temperature

2. Irradiance Modeling for Exposure and Dynamic Range Considerations

A detailed effort has been undertaken to carefully model the response of imaging sensors to the radiance of the Orbiter during reentry. This study has been based upon CFD derived surface temperature data of the Orbiter (due to lack of flight data with sufficient spatial resolution and global coverage), which has been converted to the radiance emitted. The next step in the simulation takes the radiance and computes the response to a sensor sensitive to a particular wavelength. A detailed discussion of this modeling work is given in reference 10. Besides the overall utility of having a reliable predictive tool for the irradiance on the sensor there were several interesting conclusions from a trade study perspective. This includes the ability to compute the optimum exposure time of the sensors as well as an understanding of the required data acquisition digitization resolution.

1) Exposure. One of the difficulties in previous data collections using airborne assets has been saturation of the image due to overexposure. This was primarily due to a lack of in-depth mission planning and the fact that the airborne imaging assets are usually tracking smaller, cooler targets than the Space Shuttle. A detailed analysis was done for a particular sensor, and will ultimately be repeated for all of the other imaging sensors (Fig. 4). Here, an

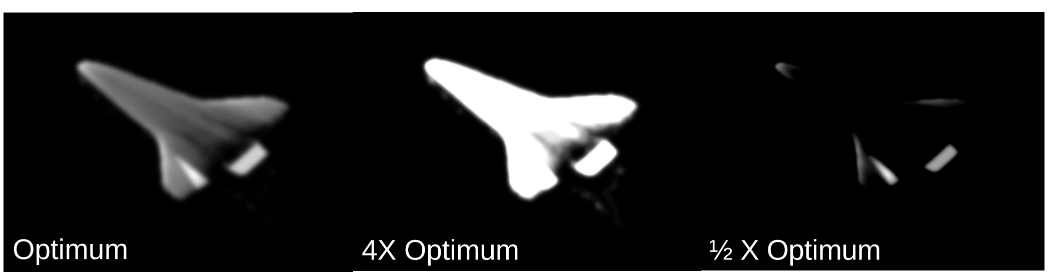
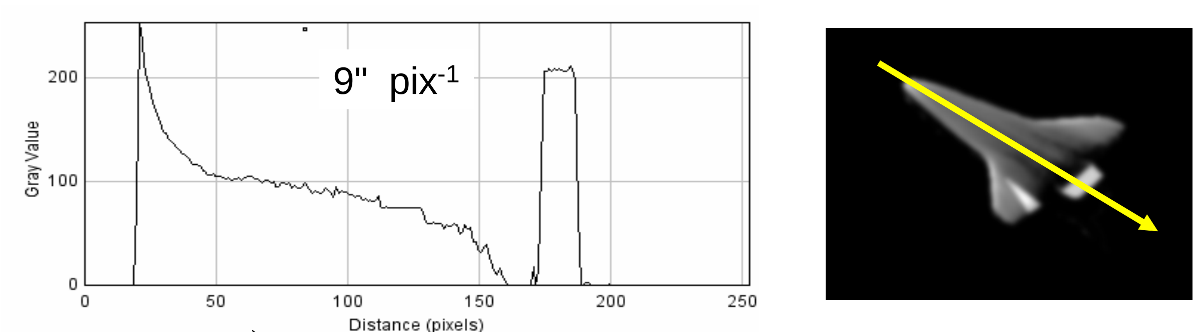


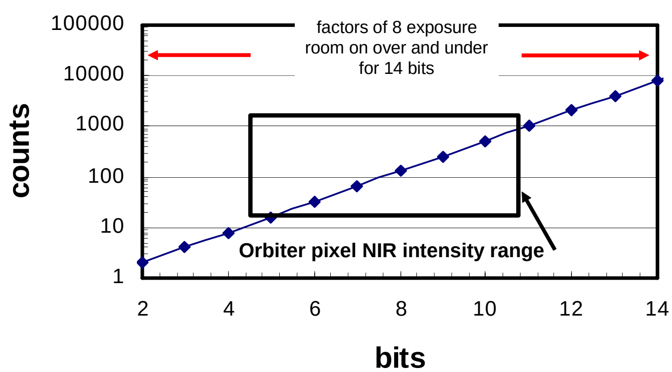
Figure 4. Simulation of variation of exposure setting for a given sensor. Left image shows optimal setting, center image shows a 4 times overexposure and right shows one half underexposure. High temperature laminar flow depicted on right wing in this series of images. Note that turbulent wedge is depicted on lef side here. Whiel flight experiment will have it on the right side (as seen from this angle).

optimum exposure was determined using the radiance modeling. The exposure was then multiplied by 4 and halved in order to gain an understanding of how sensitive a given focal plain array will be to variations from the optimal setting. This information will be used to inform the crews how best to set up the imaging systems and to be certain that the imaging hardware will be able to operate in the correct exposure range.

2) Dynamic Range. The dynamic range of an image is defined as the number of steps between the minimum noise level of a pixel to the point where the pixel becomes fully saturated. The greater the bit depth of the digitizer (an 8 bit system results in 2^8 or 256 values, a 12 bit system is 2^{12} or 4096, and such), the greater the dynamic range of the system. The analysis has shown that if an 8 bit system is used, the exposure will have to be just about perfect in order to obtain an acceptable response along the entire surface of the vehicle without saturation. This has a high risk associated with it. As Fig 5 shows, it would be best to have a 12 to 14 bit system in place to obtain the best quality data.



a) b)



c)

Figure 5. Plot a) depicts the pixel intensity along a line down the center of the orbiter, as shown in b). This simulation was done with 8 bit (256 levels) dynamic range, which is barely adequate to cover the variations from zero signal level to saturation. c) Plots the number of bits to the count levels, and shows that a 12 or fourteen bit system will adequately cover the expected dynamic range of the Shuttle radiance.

3. Spatial Resolution Considerations

A study was conducted using the visualization capabilities of the Virtual Diagnostics Interface (ViDI)[11] to determine the effect of spatial resolution to the information content of the image. For this study, a false color contour mapping of temperature on the underside of the space shuttle was used. The colors represent the temperature distribution of laminar flow of the Space Shuttle at Mach 15 as computed using Computational Fluid Dynamics, with a turbulent wedge imposed by the trip planned for use on the flight experiment described above (Fig 1). These images do not include any blurring or image degradation due to other influences such as diffraction limited optics or atmospheric distortions. These renderings were obtained using a simulated camera with differing field of view, and thus represent a simulation of the optical path of a standard (optically perfect) camera with differing lenses. The top image of Fig 6 depicts the entire underside of the vehicle, and is rendered such that each pixel in the image represents a square two inches on a side. This image clearly shows the high temperature wedge and the temperature distribution within the wedge, and represents an ideal case. In reality, it will be almost impossible to obtain imagery with such high overall spatial resolution. The four inset images shown at the bottom of fig 6 depict how information is lost as the spatial resolution decreases. After a subjective analysis, it was concluded that a spatial resolution of better that 18 inches per pixel is highly desirable.

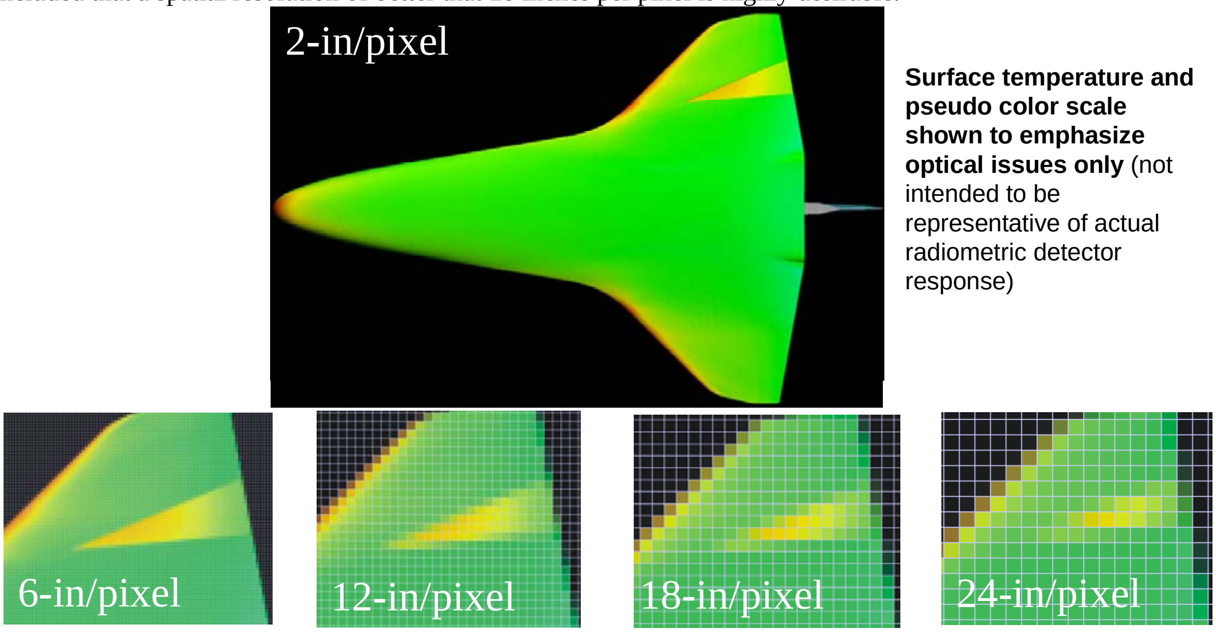


Figure 6. Renditions of differing spatial resolution of the temperature as depicted by a false color scale on the underside of the Space Shuttle orbiter. The high temperature wedge on the right wing is from the proposed Mach 15 trip to be placed on the vehicle as a flight experiment. The spatial resolution was obtained by modeling differing lenses on a virtual camera.

4. Spatial Resolution Performance - Geometry

There are several variables that contribute to the overall optical performance of the imaging system. These include the optics being used, the distance from the target, diffraction limitations and the effects of the operating environment. Each of these contributes to a portion of the point spread function, which is a description of the magnitude of blurring that occurs in the image. Effects from electronic noise, crosstalk and detector non-uniformity can often be calibrated, and are not discussed in detail here.

1) Distance to Target. The most important parameter in determining the spatial resolution is also the most straight forward. This is the distance between the imaging optics and the target. This relationship can be considered linear, thus by halving the distance between the camera and the target, the spatial resolution doubles. Thus, the rule of thumb here is to get as close as possible. However, there are limitations to this based on the optical configuration. If the image provides too high of a magnification, only a portion of the vehicle will be imaged, and this will make it more difficult to ensure that the entire region of interest stays in the frame. Subjectively, in an idealized situation, the image of the Orbiter would fill just about two-thirds of the overall field of view. However, obtaining coverage over this large a portion of the frame may be difficult with the available imaging assets.

2) Angle to Target. The imaging system has to be placed such that it has as close to an orthogonal view to the underside of the Orbiter as possible. This will minimize the foreshortening caused by obtaining an oblique view. Fig. 7 demonstrates this by relating the Watts acquired per pixel in the region of the turbulent wedge for a pass of the space shuttle, if the position of two different sensors is set to view the vehicle optimally at Mach 15. This analysis was conducted in conjunction with the radiance modeling described in Section 2.

5. Spatial Resolution Performance – Point Spread Function. In a perfect world a portion of radiation that is focused directly onto a single pixel of a FPA (Focal Plane Array) would elicit a response from just that one pixel. However, real world effects spread out that energy not just onto the primary pixel, but to a region of neighboring pixels as well. The integrated effect of this phenomenon is described by the Point Spread Function (PSF). Mathematically, it can be defined as a Gaussian distribution in two dimensions, with its magnitude demarked by a number that describes how many neighboring pixels are affected. The larger the number, the greater the spreading of the incoming energy, and the more blurred the resulting image. The overall image PSF is the sum of different physical processes, and these are discussed below. An example of this is given in Fig. 8. The left image is a rendering of the space shuttle as seen by a hypothetical imaging system at some distance from the vehicle. This

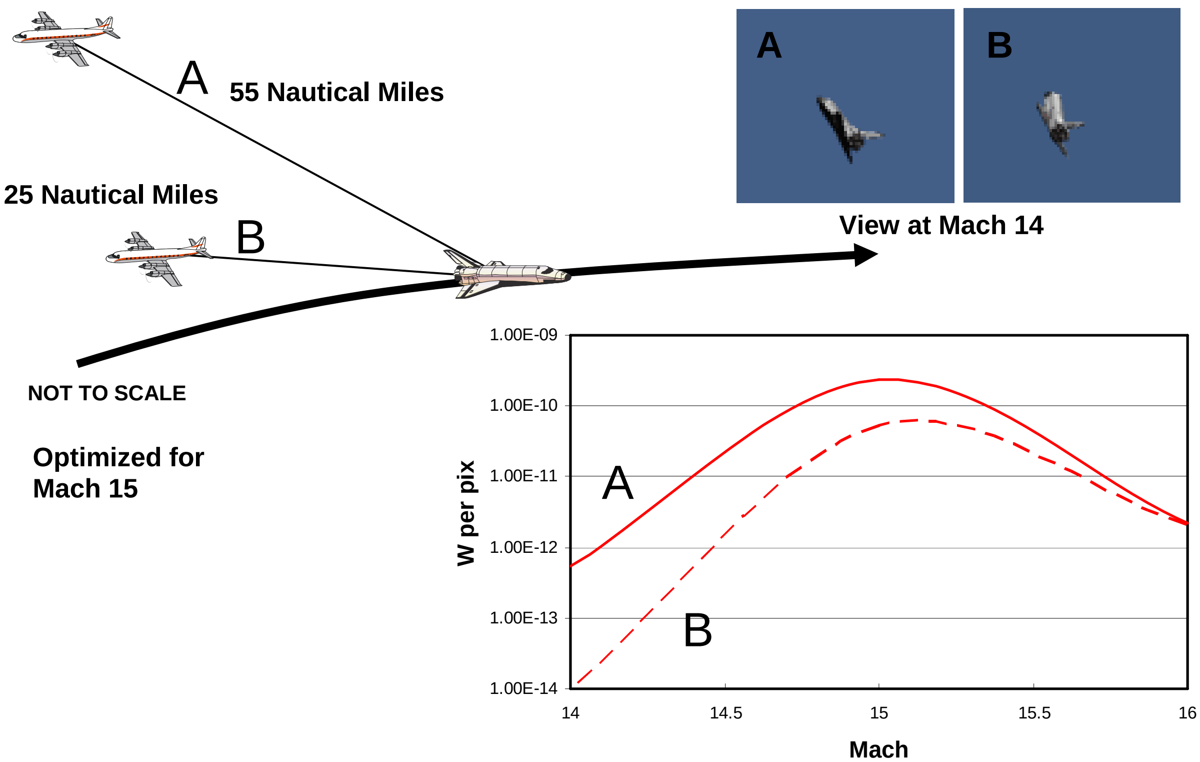


Figure 7. Plot of Watts per pixel vs. Mach number for focal plane arrays at differing distances and angles for a flyby of the Space Shuttle, optimized for Mach 15. Sensor A is placed 55 nautical miles from the Shuttle, and has less spatial resolution than sensor B, placed at 25 nautical miles from the shuttle, but Sensor A can obtain a better view of the vehicle underside than sensor B. This highlights the need to plan carefully using the best predictions available (typically not available until a few hours prior to landing) in order to maximize data return.

computer rendering depicts the absolute perfect image, defined by the perfect focus of perfect optics. Of course, this is a simplification that is impossible to reach in the real world. In reality, any image will possess a certain level of blur as defined by the point spread function (PSF). It is typical to consider a Gaussian PSF, which takes the radiation that should be focused upon a single primary pixel element of a FPA array and distributes it among a region of pixels centered on the primary pixel. The PSF number pertains to the radius of pixels that the primary pixel contributes too, so the larger the PSF, the more blurred the image becomes. The right image of Fig 8 has a Gaussian PSF of 10, resulting in a significant amount of blur.

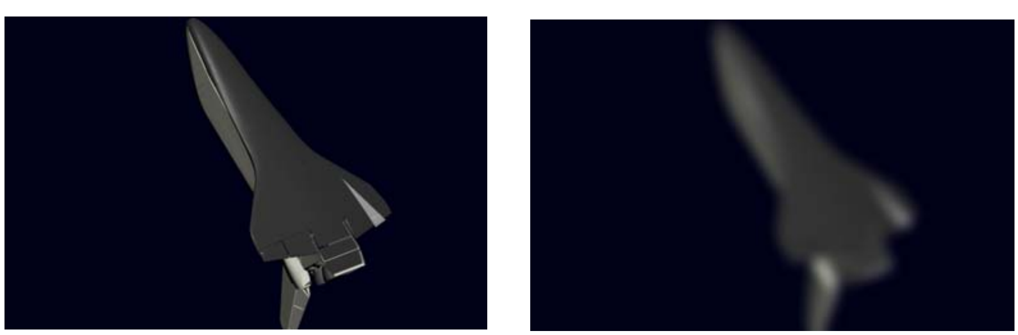


Figure 8. Left image is a "perfect" rendering with no blur, right image has a 10 pixel Gaussian point spread function applied to it.

Factors affecting the PSF are;

1) Diffraction limits due to optics. An important parameter for describing an optical system is the f/number of the optics:

$$f\ /\ no = \frac{f}{D}$$

where f is the equivalent focal length and D is the diameter of the aperture stop. The impinging radiant flux collected by the optical system is inversely proportional to the f/number.. The smaller the f/number the greater the radiant flux collected and the higher the speed of the optics. One of the most important factors affecting image quality is diffraction. Diffraction occurs at the edges of optical elements and at the diaphragms used for limiting the incoming beam. The image of a point source formed by diffraction-limited optics consists of a bright central disk, called an Airy disk, surrounded by rings with significantly lower amplitude. Eighty four percent of the radiant flux is contained in the central disk, with the rest contained in the surrounding rings. The linear diameter of the Airy disk is given by:

$$d = 2.44\lambda(f\ /\ no)$$

where d is the linear diameter of the Airy disk and λ is wavelength. The diameter of the Airy disk varies linearly with wavelength. For IR systems with equivalent f/numbers, the longer the wavelength of the system the larger the Airy disk. Optical system designers size the detectors of focal plane arrays to minimize diffraction effects. Despite this, the lower the wavelength band pass, the smaller the diffraction affects are, and therefore the smaller the detector size, therefore resulting in better optical resolution. Generally speaking the optical resolution of NIR and SWIR imagers is better than MWIR and LWIR imagers.

2) Operating environment. The PSF is also a function of the operational environment of the imaging system. A main environmental contributor is vibration. This is especially critical for the airborne assets considered by HYTHIRM. The imaging systems are located on optical benches that are mounted to the airframe of the vehicle. Thus, the vibratory environment is composed of the high frequency from aircraft engines and systems operation, as well as the lower frequency of turbulence. To date a detailed analysis of the vibration environment on the airborne platforms considered for HYTHIRM has not been fully investigated, but there are large differences between some of the airborne platforms, and vibration mitigation is being implemented for a particular asset, partially in order to help support the HYTHIRM project.

Another contribution to the PSF for airborne platforms is the turbulence of the boundary layer over the aircraft in flight. The light reaching the optics must pass through the beam steering caused by disturbed flow of the boundary layer, and potentially turbulent flow from structures upstream of the optical cavity. This also assumes the line of sight does not include regions of engine exhaust or any other sources of aircraft venting.

From past flight experience it is a reasonable to predict that the contribution to the PSF from disturbances due to the aircraft operating environment will have to be taken into consideration. The overall effects of these contributions to the PSF are not insurmountable in terms of ultimately obtaining the desired spatial resolution.

3) Atmospheric effects. The PSF will definitely be affected by the Earth's atmosphere. Variations in temperature, aerosol and particulate contents and humidity will all play into the magnitude of the atmospheric scintillation that can affect the PSF. This variation is dependent on the season, time of day, location on the planet, and the slant range between the imaging hardware and the target. For airborne platforms, this will be less of an issue, as they will fly above a large percentage of the atmosphere, thus mitigating the problems. However, the land based systems will have to face the issues of the atmospheric blurring. This can be mitigated to some extent by having rapid data collection using short integration times, and by minimizing the slant range. If adaptive optics are utilized, the atmospheric contributions can be significantly reduced. However, implementing a system that contains adaptive optics is currently beyond the scope of resources available to the HYTHIRM team.

C. Operational Constraints

It will be critical for the HYTHIRM project to utilize technology with the proper mix of capabilities as described above to obtain the appropriate measurements. However, it will be just as important to deploy that technology in the field in an appropriate manner if the desired results are to be obtained. This involves choosing the correct platform, placing the asset appropriately, and having suitable contingency plans for one-orbit or one-day Space Shuttle landing wave-offs.

1. Image Asset Database

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

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

2. Shuttle Reentry Trajectories

1) Best Estimated Trajectories. A review of Space Shuttle reentry trajectories was conducted in order to gain an appreciation for where the most likely locations would be to deploy imaging assets. Trajectories from all of the missions to the International Space Station (51.6 degrees orbital inclination) as well as to the Hubble Space Telescope (28.5 degrees orbital inclination) were analyzed. Following a Space Shuttle mission the reentry data are carefully reviewed by the Flight Dynamics Office (FDO) at JSC in order to create the Best Estimated Trajectories (or BETs). The BETs are placed in a thorough database of mission data which is accessible through the JSC JMEWS, or Java Mission Evaluation Workstation System. JMEWS is a set of software applications written in Java that allow user to access a very in-depth database of space shuttle and ISS records, as well as allowing streaming data to be displayed. The system is highly configurable, and can produce customized reports on mission data dating back to STS-1. For HYTHIRM purposes, a custom report was created to retrieve the descent BET from entry interface to wheel-stop on the runway. The reports included the mission time, geodetic latitude and longitude, altitude, roll pitch and yaw, and Mach number. The reports were translated from a binary to a text file format for incorporation into a spreadsheet as well as a graphical representation in the ViDI[10, 11] visualization environment (Fig. 9).

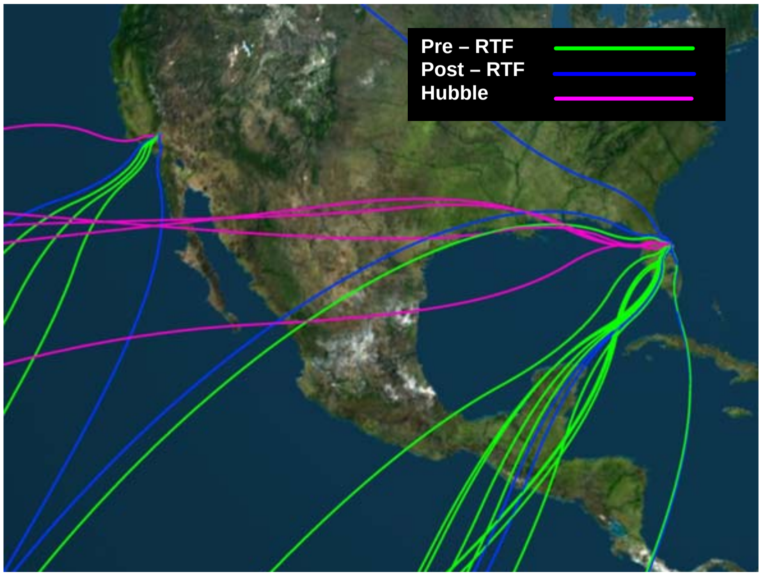


Figure 9. Best Estimated Trajectories for reentry of the Space Shuttle for missions returning form the ISS prior to and after the RTF flight as well as the Hubble Space telescope missions.

Several key points were derived from analysis of the trajectories. First is that almost all of the missions were flown on an ascending node, which meant that the vehicle approached from the south flying to the north. This is primarily to minimize the time the Orbiter is over-flying populated areas. The data was segregated between pre- and post Return To Flight missions, since certain flight rules were changed following the loss of the Columbia. There was no noticeable difference in the landing tracks taken, and to date only one mission returning from the ISS has flown a descending node, which brought the vehicle in over Canada and the continental United States. The HYTHIRM project is considering a "dress rehearsal" of mission planning and potentially a limited deployment of imaging assets during the STS-119 Hubble Space Telescope repair Mission, so trajectories to all of the previous HST missions were included as well.

A key parameter to analyze during descent is the roll angle of the vehicle. While the Space Shuttle flies at a relatively constant 40 degrees angle of attack for a good portion of the hypersonic flight, it undergoes several roll reversals to dissipate energy during descent. The vehicle can maintain roll angles of 40 to 60 degrees for sustained periods, followed by rapid reversals to equivalent bank angles in the other direction. Fig 10 depicts typical timelines of roll angle behavior for reentry for a number of missions. Thus, it is critical that the imaging asset be located on the correct side of the ground track in order to view the underside of the vehicle. Should the wrong side be chosen, the distance needed to travel to correct this error could be over 100 miles, possible in an aircraft but most likely not with a land based asset.

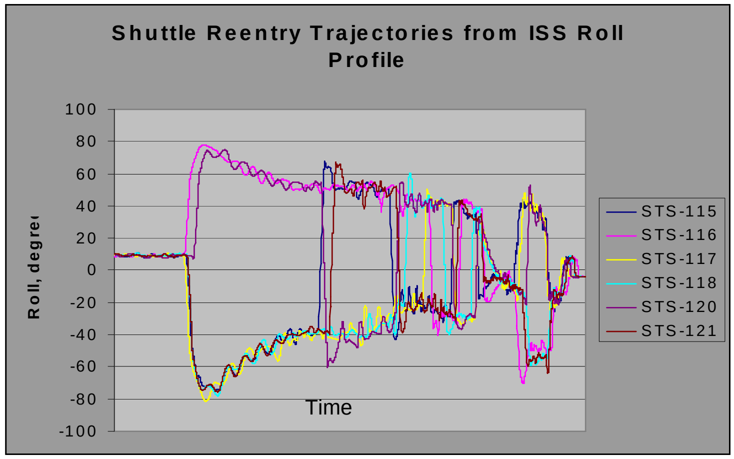


Figure 10. Roll Angle vs. Time for post-RTF ISS missions. The key factors in this plot are that the roll angles are large and stay fairly consistent until the roll direction is changed.

2) Predicted trajectories. As the mission proceeds, the Flight Dynamics office at JSC publishes predicted trajectories for landing. The predicted trajectories are typically produced at L-10 (read as L minus 10) days, L-2 days, L-24 Hours and L-2 Hours ("L" referring to landing time). These include the primary approaches and potential diversions. At the L-2 day point, which is when the Orbiter undocks from the ISS, the landing trajectory predictions are updated to represent a high probability of what the planned descent will be, barring any wave-offs. The L-2 data will be critical to the HYTHIRM project. It is at this point that detailed mission planning can commence, using the full suite of mission planning tools.

3. Analysis of Historical Mission Landing Delays

A review of a NASA published web site listing the history in detail of each space shuttle mission was undertaken in order to determine the likelihood of landing delays on missions that flew to the ISS and the HST. This data was derived from 23 flights to the ISS and from 5 flights to the HST. There is a better than one in three chances that a space shuttle landing will be postponed for some reason (Table 2) When a delay does occur, it usually results in a one or more day delay, as only a small percentage (about 10%) result in use of the one-orbit wave-off, even on the second or third day of delay. Almost all of the flights (over 80%) have been able to make it to the primary landing site (KSC). However, this data does not capture the potential hectic time just prior to making a reentry decision. An example was STS-116. In the final hours of the mission the orbiter was slated for a KSC landing, then changed to an EAFB landing, then changed to a White Sands landing, only to be changed with minutes before the de-orbit burn back to KSC, where they ultimately made an uneventful landing .

The conclusion from this data is that the Space Shuttle is not likely to land as first predicted, and flexibility must be built into the system to accommodate real-time changes. It is also less likely that a landing on a one orbit wave-off than on the first attempt after a 24 hour delay.

Table 2. Summary of Shuttle re-entry delays and diversions

	ISS Missions	Hubble Missions
Missions with any form of wave-offs	35%	40%
Missions with 1 orbit wave-offs	9 %	40 %
Missions with 1 or more days delayed reentry	22%	0%
Missions landing at Primary Site (KSC)	83%	100%

4. Weather

A detailed analysis of the historic weather patterns over Mexico, Central America and the Gulf of Mexico was undertaken by the National Weather Service Spaceflight Meteorology Group at the NASA Johnson Space Center in support of the HYTHIRM project. The primary condition analyzed was the mean cloud cover, which represents the percent of the area covered with clouds occurring at any altitude. The mean total cloud cover for December – February is shown in Fig. 11. From this analysis, it appears that the most favorable areas for imaging the Shuttle during re-entry appear to be along the Pacific coast of Central America and along the Caribbean coast from the

Yucatan Peninsula to Nicaragua. There is a strong gradient in the cloud coverage on the Pacific coast with average cloud cover during the winter season of about 25 percent over the ocean increasing to 55 percent over the land. Clouds typically cover about 45-50 of the area over the Yucatan during the same time period. The resolution of the satellite climatology may not be able to adequately represent the extreme gradient along the Pacific coast.

The average high cloud (as defined by international standards referencing the pressure at the cloud tops) coverage was also retrieved. The values over the Yucatan and Guatemala range from about 5 to 10 percent during the winter season. Therefore, high cloud does not appear to have the potential to significantly impact the imaging operations of the airborne assets.

In addition to the data derived from satellite imagery, data from ground stations provide additional information on the percentage of cloud coverage. The surface reports, in general, confirm the patterns shown in the satellite imagery and provide some additional information on the strong gradient in cloud coverage on the Pacific coast. Examination of the individual stations indicates that San Jose, Guatemala has the most favorable weather with clear skies 55 to 70 percent of the time. Other locations along the Pacific coast (Acapulco, Mexico and Puntarenas, Costa Rica) also appeared favorable with clear skies between 40 and 60 percent of the time. Cancun, Mexico on the Yucatan peninsula had clear skies about 15-20 percent of the time. The surface observations from eastern Honduras and Panama only report the skies clear less than 5 percent of the time. However, the percent of time with either clear skies or scattered clouds is comparable to the stations in the Yucatan.

D. Real Time Mission Planning

Until the L-2 trajectory data is published, the HYTHIRM team can only be on standby. It is at this point that a predicted trajectory with a high degree of certainty of being flown is known. This will require the preparation of a real-time trade study, taking into account parameters such as the estimated ground track, the weather, available airborne and land based systems, time of day (for sun angles) and the more mundane political issues such as basing of land assets or over-flight rights in foreign countries or airspace, which will require timely State Department clearance.

The predicted shuttle trajectory will be loaded into a virtual environment[12] complete with simulated imaging assets drawn from the imaging asset database described above. The assets will be located in the virtual globe to optimize viewing angle and

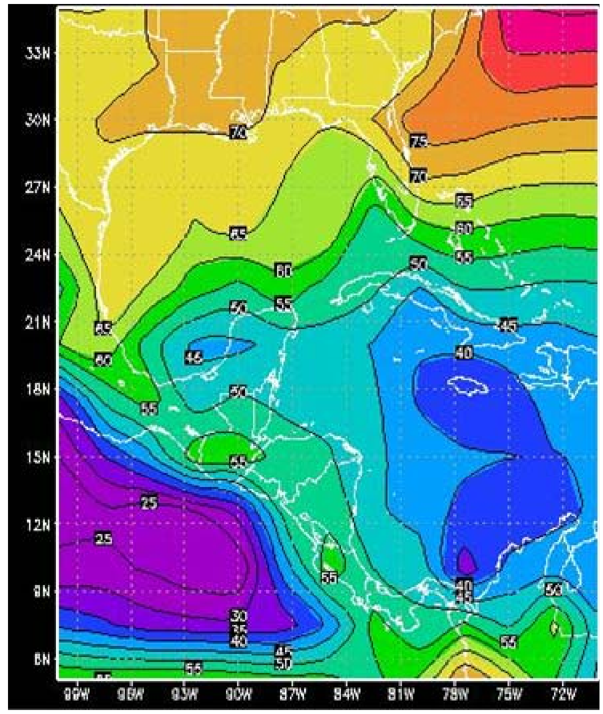


Figure 11. Percentage of low cloud cover over Mexico, Central America, Yucatan Peninsula and Gulf of Mexico. Numbers on the contour lines represent percentage of time there is cloud cover during the December through February time period.

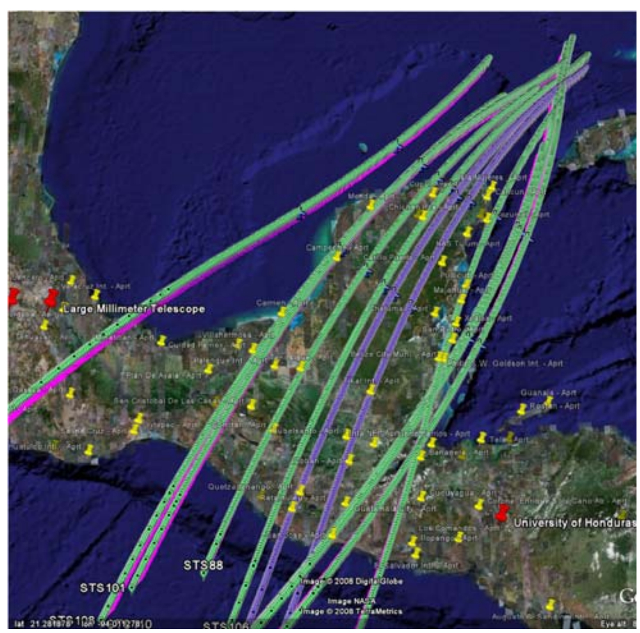


Figure 12. Historical Shuttle trajectories plotted as lines over the Yucatan peninsula. Yellow markers depict general aviation airports capable of handling aircraft that can transport mobile land based systems. Red markers depict fixed observatories.

minimize slant range based on possible land bases (Fig 12) or airborne viewing locations. Then the radiance modeling will be employed to determine the optimum setting for the imaging systems, ensuring that the cameras will not saturate or receive too little signal Finally image degradation due to the PSF will be incorporated, giving the researchers a clear understanding of the quality of the data attainable. From this first evaluation, the imaging assets support crews will be given plans for deployment. As the timeline proceeds toward the reentry burn, many variables can come into play to cause one orbit or a full day or more delay in reentry. As the scenario plays itself out, the simulation work will continue in order to provide the most optimal updates for positioning and operation of the imaging assets.

E. Trade Study Findings to Date

As planning for HYTHIRM has continued, it has become clear that there were many diverse variables, most of which are beyond the control of the HYTHIRM project, that have to be dealt with in order to successfully complete the mission. There is a complex mix of asset capability and cost that will ultimately play into the final deployment strategies. A summary of potential deployment ideas and trades are listed below.

Both the airborne and the land based systems have strengths and weaknesses. These are categorized below.

1) Aircraft

Strengths – Highly mobile, operate above most of the weather, can be deployed over large bodies of water, possible to reconfigure for one-orbit wave-offs. Only available option for EAFB landings and some approaches into KSC.

Weaknesses – Expensive to operate. Scheduling is required in advance, mission delays may exceed window of aircraft availability. Optics will have smaller aperture sizes than land based systems; operate in an area where vibration and optical distortions due to turbulent air over the airframe affect image quality.

2) Land Based Systems

Strengths – High quality large aperture optics can deliver good performance. Systems can be made mobile to redeploy. Much less expensive to field a single ground based unit than a single aircraft.

Weaknesses – At mercy of the weather and local atmospheric conditions such as aerosols and humidity. Even mobile systems cannot redeploy for one-orbit wave-off situations. Requires logistical considerations such as access to roads in Central America or small aircraft to redeploy in short notice. Can not support certain approaches that are far over water.

Conclusion - A mix of both land and airborne platforms should be considered for each mission. There are inherent advantages and disadvantages for each system, but deployment of at least two ground based systems and at least one airborne platform should be considered a minimum (if mission ground track allows ground based system to deploy). This will allow one ground based system to be on the main ground track, and one to be on the one orbit wave-off ground track while the aircraft can reconfigure itself under this condition.

There are several possible deployment strategies to consider for a mixture of aircraft and land based systems. For land based units these include;

1) Placing two ground based systems under the primary ground track, and two ground based systems under the one orbit wave-off area. Separate by one to two hundred miles such that a local weather issue for one asset may not affect the other unit.
   Risk: The more units in the field, the higher the costs and complications with relocating on short notice.
2) Place multiple ground based units in a “picket line” at key Mach number locations in the trajectory to observe development of turbulent boundary layer along the trajectory.
   Risk: If all of the units are placed along a single ground track, a one orbit wave-off would preclude the collection of any data from the land based sensors.
3) Place land based units in trucks that can drive overnight to reposition for 24 hour delays.
   Risk: Fatigue, limited time to set up systems, road travel hazards in foreign countries.
4) Use general aviation class aircraft to reposition land based units for 24 hour delays.
   Risk: Relying on general aviation aircraft for repositioning requires additional reliance on acceptable weather over a longer period of time.
5) Have multiple sets of land based hardware pre-positioned at locations such a general aviation airports so a minimal number of crew can quickly reconfigure for changes in reentry tracks.
   Risk: Pre-positioning hardware requires extra logistical coordination and carries a security risk to the unattended hardware. Consider off-shore oil facilities as possible bases for mobile systems.
   Risks: Off shore oil platforms may offer limited viewing angles and a “thermally polluted” environment for the IR sensors, permission may be difficult to obtain.

For airborne assets there are fewer variables, but given the increased cost of deployment over land based systems, the deployment strategy has to be carefully considered. This includes;

1) Have up to three different aircraft available for data collection. Each aircraft would be positioned at different altitude, and there would be NIR, MWIR and LWIR sensor looking at the Shuttle simultaneously. This may help in obtaining higher fidelity engineering data by being able to compare data acquired
   Risk: Very high cost for a single mission, spatial resolution capabilities for MWIR and LWIR systems are limited, so optimal positioning of aircraft is critical.
2) Locate aircraft along a "picket line" to observe the development and movement of the turbulent boundary layer.
   Risks: Costs of deployment are high, and generally non-refundable should no data be collected for any reason. Higher workload for mission planning in event of last minute changes to ground track

Further risk reduction can be considered through the following options.
Increase available number of land based assets. A maximum of nine mobile land based assets can possibly be fielded, although the cost of such a deployment would be very high, and there would be difficulties in providing manpower for all of the units. However, it is not unrealistic to consider a deployment of up to four units. Also, since several key Mach numbers occur along portions of the flight path that traverse foreign airspace early engagement of the United States State Department for obtaining the required permissions from foreign governments to over-fly with airborne imaging assets and deploy land based imaging assets.

III. Conclusion

A comprehensive review of the issues that will affect the ability to obtain high quality engineering data from the IR images of the Space Shuttle orbiter during reentry have been investigated in a trade study format. The performance of various imaging platforms, both land and airborne, have been studied, as have the parameters that will most directly influence the quality of the imagery that could be acquired. In addition, the historical performance of the Space Shuttle has been investigated to understand patterns in the reentry trajectories as well as weather patterns in the deployment areas surrounding Central America and Mexico. Based on previous flight experience and on the execution of the mission simulation and planning tools available to date, a methodology for arriving at recommendations on options for optimizing the deployment of imaging assets in real time has been developed. The final conclusion of the trade study to date points to an environment for data acquisition that will be challenging and dynamic, but manageable in order to obtain the desired imagery for detailed engineering analysis.

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References

1 Blanchard, R.C., Wilmoth, R.G., Glass, C.E., Merski, N.R., Berry, S.A., Bozung, T.J., Tietjen, A., Wendt, J., and Dawson, D., "Infrared Sensing Aeroheating Flight Experiment: STS-96 Flight Results," *Journal of Spacecraft and Rockets*, Vol. 38, No.4, 2001, pp.465-472.
2 Blanchard, R.C., Anderson, B.A., Welch, S.S., Glass, C.E., Berry, S.A., Merski, N.R., Banks, D.W., Tietjen, A., and Lovern, M., "Shuttle Orbiter Fuselage Global Temperature Measurements from Infrared Images at Hypersonic Speeds," AIAA Paper 2002-4702, August, 2002.
3 Berry, S.A., Merski, N.R., and Blanchard, R.C., "Wind Tunnel Measurements of Shuttle Orbiter Global Heating with Comparison to Flight," AIAA Paper 2002-4701, August, 2002.
4 Throckmorton, D.A., Zoby, E.V., and Kantsios, A.G., "Shuttle Infrared Leeside Temperature Sensing (SILTS) Experiment," AIAA Paper 85-0328, January, 1985.
5 Chocol J. C., "Infrared Imagery of Shuttle (IRIS)," Martin Marietta Corporation Final Report, MCR-76-564, Contract NAS2-9381, August, 1977.
6 "Infrared Imagery of Shuttle (IRIS) Experiment," IRIS/STS-3 Engineering Report, NASA-CR-193052, NASA AMES Research Center, June, 1982.
7 Campbell, C. H., Garske, M. T., Kinder, J., and Berry, S. A., "Orbiter Entry Boundary Layer Flight Testing," AIAA-2008-0635, Jan., 2008.
8 Horvath, T. ., Berry, S. ., Alter, S., Blanchard, R., Schwartz, R., Ross, M., and Tack, S., "Shuttle Entry Imaging Using Infrared Thermography," AIAA-2007-4267, June 2007
9 Berry, S., Horvath, T., Schwartz, R., Ross, M., Campbell, C., Anderson, B., "IR Imaging of Boundary Layer Transition Flight Experiments," AIAA-2008-4026, June 2008.
10 Ross, M., Werner, M., Mazuk, S., Blanchard, R., Horvath, T. ., Berry, S. ., Wood, W., and Schwartz, R., "Infrared Imagery of the Space Shuttle at Hypersonic Entry Conditions," AIAA-2008-0636, Jan., 7-10, 2008.
[11] Schwartz, R.J., "ViDI: Virtual Diagnostics Interface Volume 1-The Future of Wind Tunnel Testing" Contractor Report NASA/CR-2003-212667, December 2003
[12] Schwartz, R.J., Fleming, G.A.,"LiveView3D: Real Time Data Visualization for the Aerospace Testing Environment**",** AIAA-2006-1388, 44th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, Jan. 9-12, 2006.