SOLAR THERMAL VACUUM TEST OF DEPLOYABLE ASTROMESH REFLECTOR

Matthew D. Stegman
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA

ABSTRACT

On September 10, 2008, a 36-hour Solar Thermal Vacuum Test of a 5m deployable mesh reflector was completed in JPL's 25' Space Simulator by the Advanced Deployable Structures Group at JPL. The testing was performed under NASA's Innovative Partnership Program (IPP) as a risk reduction effort for two JPL Decadal Survey Missions: DESDynI and SMAP. The 5.0 m aperture Astromesh reflector was provided by Northrop Grumman Aerospace Systems (NGAS) Astro Aerospace, our IPP industry partner. The testing utilized a state-of-the-art photogrammetry system to measure deformation of the reflector under LN2 cold soak, 0.25 Earth sun, 0.5 sun and 1.0 sun. An intricate network of thermocouples (approximately 200 in total) was used to determine the localized temperature across the mesh as well as on the perimeter truss of the reflector. Half of the reflector was in a fixed shadow to maximize thermal gradients. A mobility system was built for remotely actuating the cryo-vacuum capable photogrammetry camera around the circumference of the Solar Simulator. Photogrammetric resolution of 0.025 mm RMS (0.001") was achieved over the entire 5 meter aperture for each test case. The data will be used for thermo-elastic model correlation and validation, which will benefit the planned Earth Science Missions.

KEYWORDS

Solar Thermal Vacuum Test, Deployable Astromesh Reflector, Photogrammetry, 25' Space Simulator, Thermal Deformation, Thermo-elastic Model Validation

INTRODUCTION

Earth Science Missions are being considered by JPL in support of the top Earth science needs identified by the most recent Decadal Survey. Two of these Missions, DESDynI and SMAP, are shown in Figures 1(a) and (b) below.

(a) (b)

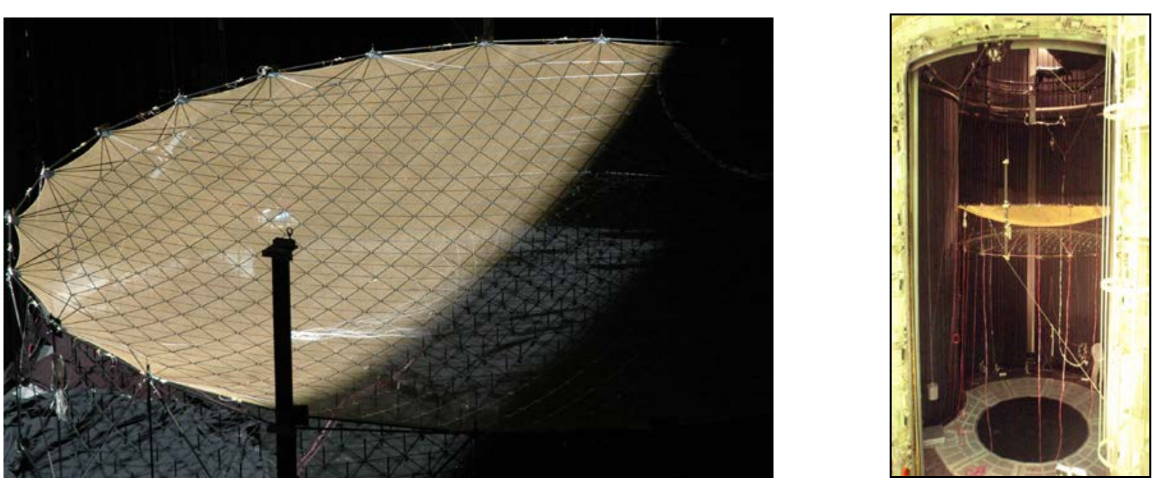
Figure 1. Mission concepts: (a) DESDynI: *http://radar.jpl.nasa.gov/* (b) SMAP: *http://climate.jpl.nasa.gov*

Both DESDynI and SMAP require deployable mesh reflectors for their Mission Instruments, since the required RF apertures are much larger than can be accommodated by available launch vehicles. The Northrop Grumman Aerospace Systems (NGAS, formerly NGST) AstroMesh reflector is considered to be one of the leading candidates for these missions because of its low mass as well as the surface accuracy and beam pointing stability that NGAS claims it provides.

Although current mesh reflectors themselves are a mature space-qualified technology, their thermoelastic properties have not been demonstrated. Neither the AstroMesh nor any other state-of-the-art deployable reflector has been validated by test for deployed thermoelastic deformations in an appropriate environment. In fact, the last empirical measurements of thermo-elastic deformation of a deployable reflector occurred during the development of TDRS several decades ago. The two aforementioned Missions will make science measurements of unprecedented sensitivity; however, thermal deformations will introduce errors that could limit sensitivity. Thus, a very accurate *test-validated* thermoelastic model will either show that such losses are negligible or, at a minimum, allow the predicted pointing errors to be backed out analytically to regain the required sensitivity. In order to validate the reflector's thermoelastic model, a Solar Thermal Vacuum (STV) test was performed in JPL's 25' Space Simulator.

The intent of this paper is to describe the rationale and methodology behind the aforementioned STV test. Prior to the subject STV Testing, all aspects of the AstroMesh design, except thermoelastic behavior, were either at TRL 9 or will be TRL 6-7 after routine pre-flight hardware qualification programs. This STV test has raised our deformation analysis capability from TRL 3 to TRL 6, which enables us to confidently pursue the intended missions. NGAS provided a 5-meter AM-Lite test article, instrumentation, and personnel (both test and analytical). The DESDynI and SMAP Projects also contributed generously to the IPP Task in a total amount in-kind with NASA's IPP funding level. NASA and JPL funds provided all test Mechanical Ground Support Equipment (MGSE) and Electrical Ground Support Equipment (EGSE), technician and engineering personnel, most of the required instrumentation, plus operation of the 25' Space Simulator.

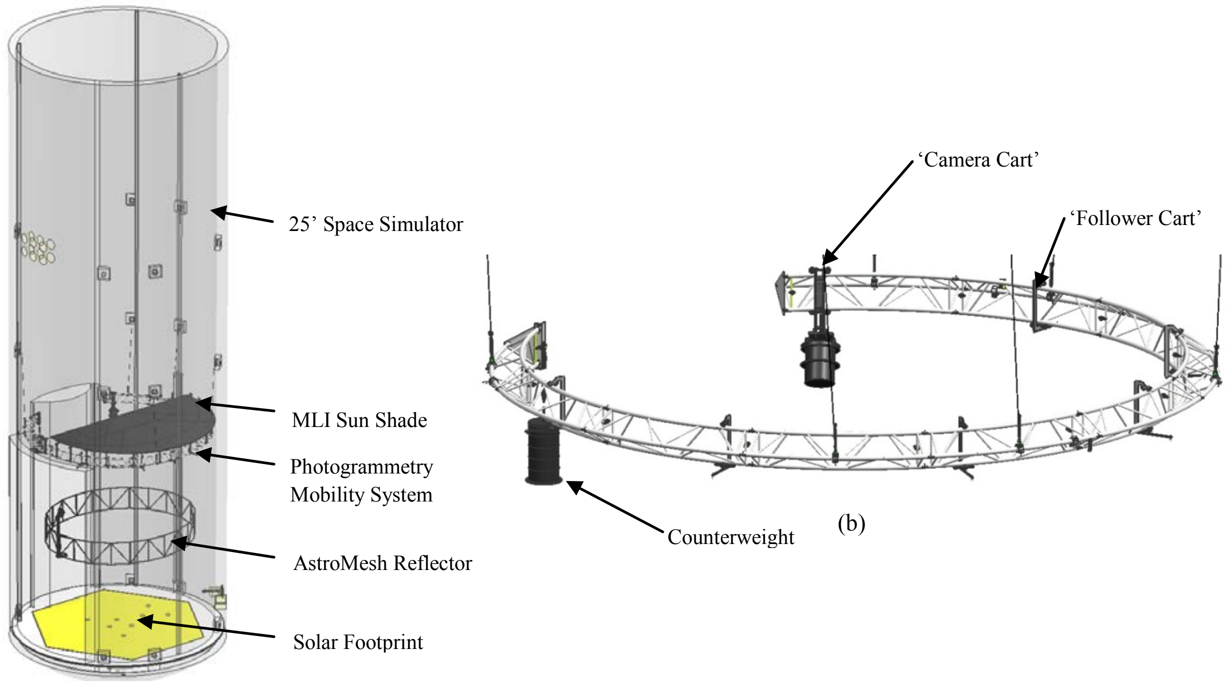
SOLAR THERMAL VACUUM TEST OVERVIEW



(a) (b)

Figure 2. (a) Astromesh Reflector Partially Illuminated (b) Reflector in Test Configuration

In order to correlate and validate the NGAS thermo-elastic model for the AstroMesh Reflector, a 36-hour Solar Thermal Vacuum Test of a 5m deployable reflector was completed in JPL's 25' Space Simulator on September 10th, 2008. The testing consisted of three primary components: the 25' Space Simulator, a 5m AstroMesh Reflector, and a photogrammetry and mobility system. Figure 2 displays the reflector under partial shadow as well as the reflector in the testing configuration within the 25' Space Simulator. Similarly, Figure 3 displays a CAD image of the test configuration within the chamber and a representation of the photogrammetry and mobility system.



(a)

Figure 3. (a) Test Setup (b) Photogrammetry Mobility System

As is notionally depicted in Figure 3, the photogrammetry system was positioned approximately 26' from the chamber floor. Additionally, the reflector was elevated approximately 12' from the floor of the chamber to minimize the effect of reflected radiation on the reflector from the floor of the chamber. Furthermore, half of the reflector was placed in a fixed shadow to maximize the thermal gradients across the reflector. This was achieved by configuring a MLI blanket in a semi-circular shape, and then positioning it above the photogrammetry system as can be seen in Figure 3. Fortunately for the project, we were able to re-use a MLI blanket that was fabricated for previous STV testing of Pathfinder and MER, which saved the project an estimated $25,000. The thermal deformation of the reflector was measured via a state-of-the-art cryo-vacuum capable photogrammetry system, which was integrated with a remotely controllable mobility system. As a result, distortion measurements were obtained for various environmental test cases which included: LN_2 cold soak, 0.25 Earth sun (355 W/m^2), 0.5 Earth sun (710 W/m^2), and 1.0 Earth sun (1420 W/m^2).

PRIMARY TEST COMPONENTS OVERVIEW

As was previously discussed, the test was conducted by utilizing three primary systems: the 25' Space Simulator, a 5m deployable AstroMesh Reflector, and a mobile photogrammetry system. Each of these components will be discussed in greater detail in the following section.

25' SPACE SIMULATOR

JPL's historic 25' Space Simulator, which is shown schematically in Figure 4, was designed for environmental testing of spacecraft in a simulated interplanetary setting. The chamber is capable of subjecting a test article to high vacuum while maintaining the surroundings at LN_2 temperatures and providing intense solar irradiation. The stainless steel chamber is roughly 27' in diameter and 85' tall. The operating pressure of the chamber is on the order of 1×10^{-6} Torr, which is roughly equivalent to an orbiting altitude of 125 nautical miles. The walls and floor of the chamber are lined with cryogenic shrouds that can be controlled over a temperature range of -185 to +125 degrees Celsius. Solar illumination is provided by thirty-seven 25kW Ushio arc lamps. The test article is then irradiated by reflecting light upon a 23' diameter single pane collimating mirror.

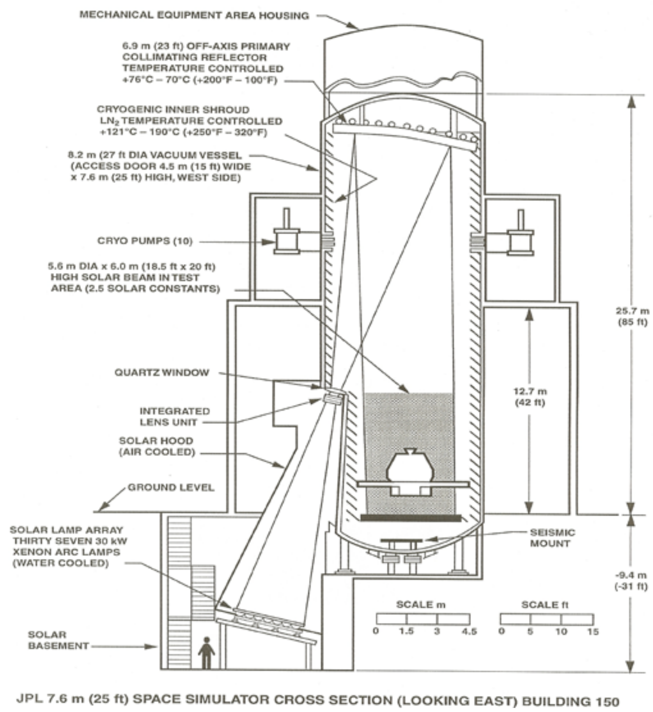


Figure 4. Schematic Representation of 25' Space Simulator
JPL Environmental Testing Laboratory (ETL) Brochure

ASTROMESH REFLECTOR

Northrop Grumman Aerospace Systems (NGAS, formerly NGST) provided a 5 meter AM-Lite reflector for the STV test, which is shown in Figure 5. The reflector consists of a deployable circumferential pretensioned truss with dual geodesic domes formed through tensioned Kevlar and/or Carbon-fiber webbing. The antenna utilizes a highly reflective mesh with a mesh count of approximately 40 openings per inch. The weight of the 5m AM-Lite reflector is on the order of 20 lbs (without the spacecraft interface baton). In order to capture the local

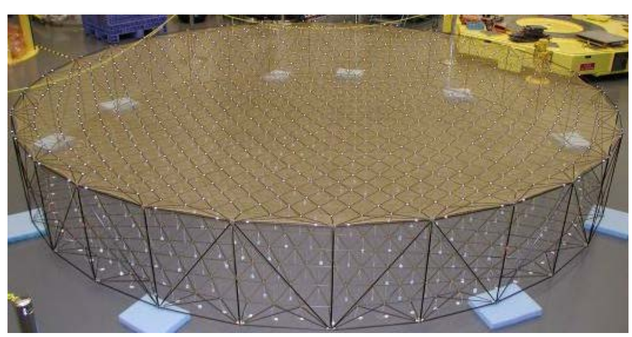


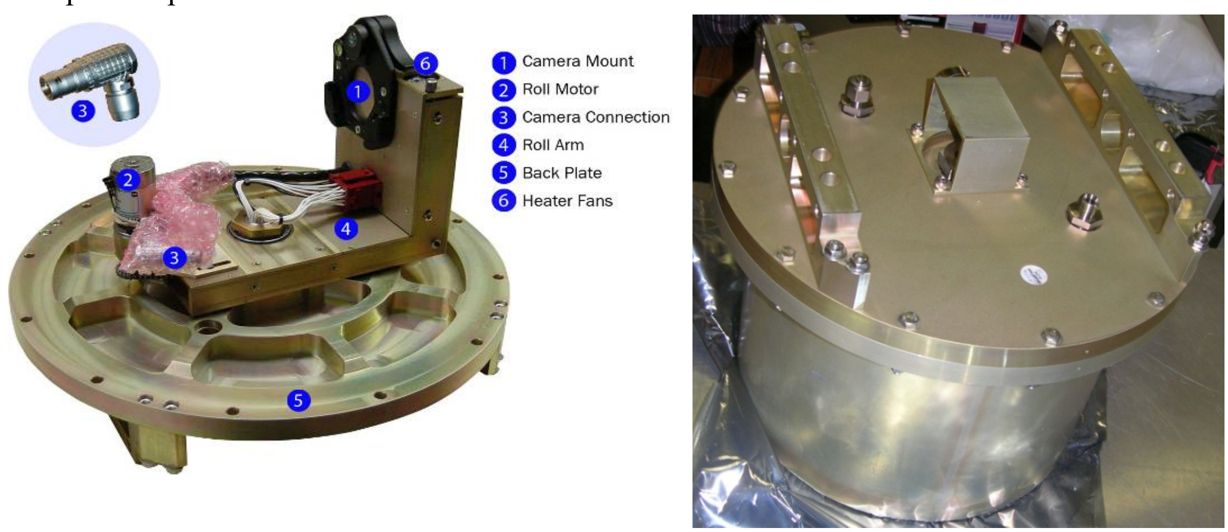
Figure 5. AstroMesh Reflector
NGAS

temperatures of the reflector throughout the test, an intricate network of approximately 200 thermocouples were installed on the periphery of the reflector as well as on the webs on the reflector's mesh surface. Roughly one-half of the thermocouples monitor temperatures of the reflector components in the shaded area, while the other half monitors temperatures in the illuminated area.

PHOTOGRAMMETRY (V-STARS) SYSTEM

Photogrammetry, in the most fundamental sense, utilizes the principle of triangulation to determine the position of points in 3D space from images taken at different positions. To obtain the necessary images for the STV test, we utilized the V-STARS photogrammetry system produced by Geodetic. The particular system that was employed consisted of an INCA-3 camera (Figure 6), an ICAN vacuum housing (Figure 7), and the V-STARS software package. V-STARS system is a very capable photogrammetry system, but consequently, the system also carries a heavy price tag. Geodetic advertises the INCA-3 at around $90,000, while the ICAN housing and controller are around $60,000. Thus, sincere thanks are due to Bob Romanovsky of Glenn Research Center who provided JPL with the V-STARS system that was used in the test, and which yielded photogrammetric data of incomparable precision.

Figure 6. INCA-3 Camera
http://www.geodetic.com



(a) (b)

Figure 7. ICAN Vacuum Housing: (a) Internal Mechanism (b) Mating Features
http://www.geodetic.com

MOBILITY SYSTEM: CARTS

To achieve the multiple camera orientations required for accurate photogrammetric measurements, a remotely actuated mobility system was designed to rotate the cryo-vacuum compatible photogrammetry camera around the circumference of the Solar Simulator. The mobility system (Figure 8) consisted of a series of rolling carts that were remotely driven around a circumferential truss by a purely mechanical system consisting of a series of pulleys and a counterweight. One of the carts (appropriately referred to herein as the 'camera cart') was designed to support the photogrammetry system (Figure 9), and to provide the camera with an adjustable view angle. Six additional carts (Figure 10), termed 'follower carts,' were fabricated to trail behind the camera cart and to ensure that the camera cable harness did not shadow the reflector.

Figure 8. Photogrammetry Mobility System in Chamber

Figure 9. Camera Cart

Figure 10. Follower Carts

MOBILITY SYSTEM: TRACK

In order for the carts to circumnavigate the chamber, the design of a circular truss was specified by the engineering team, and the truss was subsequently procured from an outside vendor. The truss consisted of three circumferential Aluminum tubes and a series of cross braces. The circumferential tubes were oriented in such a manner as to create a triangular cross section with the apex pointing out radially. In this manner, the carts were able to roll upon the two innermost tubes, while the track was able to be supported by the outer tube as is shown in Figure 11.

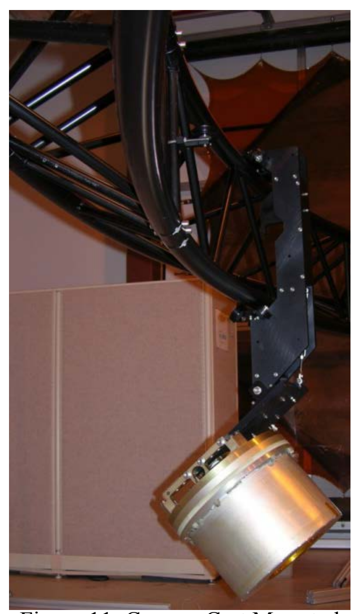


Figure 11. Camera Cart Mounted on Track

MOBILITY SYSTEM: ACTUATION

The carts were driven around the track by means of a counterweight and a network of pulleys. At one end of the track, a large mass was supported by SS wire rope. The wire rope was subsequently distributed through a block and tackle assembly that produced a 4:1 purchase as can be seen in Figure 12. Upon leaving the block and tackle, the wire rope was guided around the track through a series of pulleys as shown in Figure 13.

Figure 12. Pulley Block Attached to Counterweight

Figure 13. Pulley

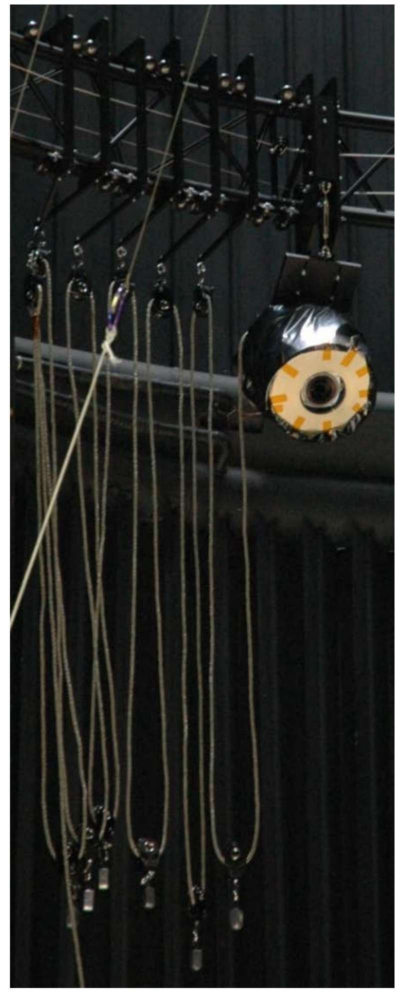


Figure 14. Follower Carts and Camera Wire Harness

After traversing the periphery of the track, the cabling was routed towards the floor of the chamber, and the end of the rope was connected to a spool, which in turn was affixed to a rotary mechanical chamber pass-thru. Thus, one could actuate the rotary pass-thru externally of the chamber, which would cause the wire rope to translate through the network of pulleys and inevitably raise the counterweight at the other end of the track. Due to the fact that the ‘camera cart’ was fastened to the wire rope at a specific location, as the wire rope traversed the track, the ‘camera cart’ travelled with it. Furthermore, since the six ‘follower carts’ were connected to the camera wire harness at fixed locations (see Figure 14), they were pulled around the track behind the ‘camera cart’ with a relatively equal spacing. Once the ‘camera cart’ reached one end of the track, it could begin its return trip by simply allowing the counterweight to slowly lower, which unwound the wire rope from the spool and allowed the cart to return to its starting position.

TESTING

PREPARATIONS

There were a number of preparations that were performed prior to beginning the chamber integration, and before performing the STV testing. Thus, it seems appropriate to briefly mention some of the more important procedures and precautions performed for the sake of historic documentation.

BAKEOUTS AND CLEANING

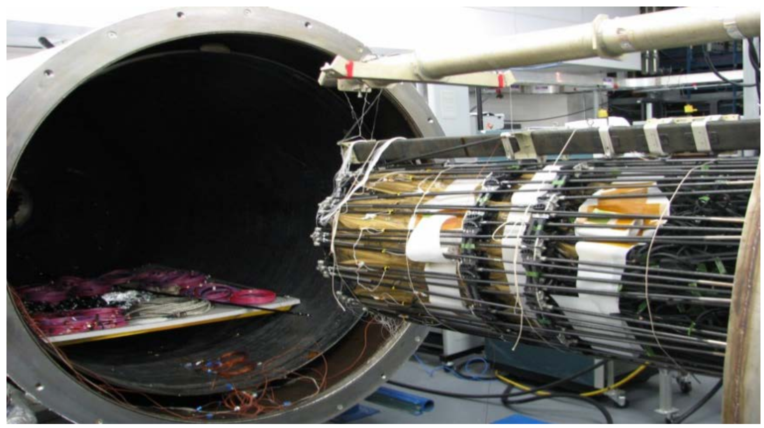


Figure 15. AstroMesh Reflector Outside Bakeout Chamber

Due to the nature of the 25' Space Simulator, and the presence of the 23' diameter optical mirror at the top of the chamber, all hardware that was to be in the chamber during the test had to be baked out or cleaned prior to installation. The project's contamination engineer provided the bakeout and cleaning instructions, and accepted the responsibility of providing general oversight to the contamination control plan. At his recommendation, a total of six bakeouts were performed by NGAS at their facilities in Spacepark (See Figure 15). The required temperature and duration of the bakeouts varied depending on the subject hardware. For instance, the wire rope and photogrammetry coded targets were baked at 100 °C for 120 hrs, while the reflector, pulley blocks, thermocouples, and camera harness were baked at 80 °C for only 72 hrs. By NGAS assuming the responsibility of performing the bakeouts, JPL was able to save an estimated $50k - $100k.

While the test article and select hardware underwent bakeouts, the remaining support hardware went through precision cleaning to ensure that it would not contaminate the chamber. To do so, a small ultrasonic bath was procured, and another larger ultrasonic bath was taken on loan from another internal group. Our contamination engineer provided cleaning instructions for the various material types, and the small hardware was cleaned per his instructions. However, the hardware that was too large to fit within the baths (i.e. the truss segments and MLI shade support structure) was shipped to Astropak for precision cleaning.

SYSTEM CHECKOUTS

Prior to beginning chamber pump-down, a series of full system checkouts were performed to test the functionality of the photogrammetry system. These preliminary tests proved quite fruitful for several reasons, but primarily because they enabled the engineering team to mitigate potential failure modes. For instance, the ambient testing ensured that the camera mobility system functioned properly without interference from the chamber. Also, the checkouts enabled the camera's view angle to be optimized to ensure that the camera was able to capture as much of the reflector's surface as possible. Figure 16 displays an example of V-STARS data recorded during the baseline test runs, and the figure displays how this example camera position was able to detect the majority of the targets on the reflector. Another vital adjustment that was made during the checkout was the tuning of the camera's f-stop to ensure good visibility of the reflector's targets under the extreme solar conditions. As the camera had to have enough sensitivity to concurrently capture targets on the reflector under full shadow as well full sun, an ND filter was installed on the camera and the f-stop was iteratively varied until an amicable setting was determined.

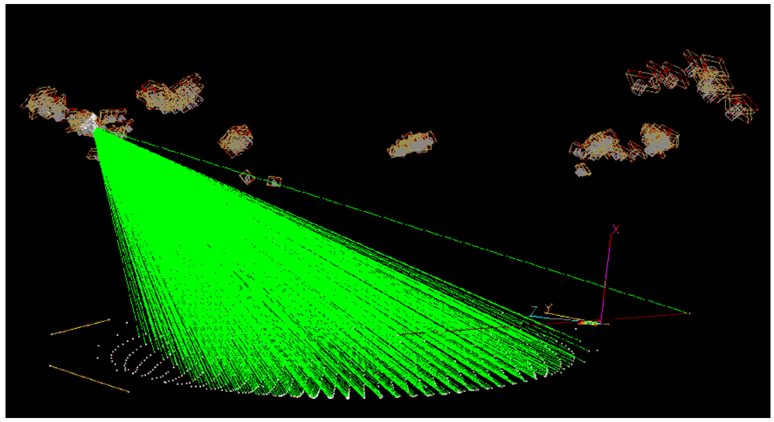


Figure 16. Example of V-STARS Image Processing

SOLAR THERMAL VACUUM TEST

After the test article and MGSE hardware had been integrated into the chamber and all pre-test preparations had been made, the chamber pump-down was initiated around 10:40 am on 9/9/08. By 1:00 pm on the same day, the chamber pressure had reached 1 x 10^{-5} Torr, and the shroud temperatures were ramped down to -180° C. Around 7 pm, the first set of photogrammetry data was captured for the LN_2 cold soak test case. Over the course of the following 24 hours, photogrammetry and thermocouple data were collected for the remaining test cases. Subsequently, the backfill of the chamber began around midnight on the night 9/10/08, which was approximately 36 hours from the start of the test. A plot displaying the temperatures of several locations on the reflector throughout the duration of the STV test is displayed below in Figure 17.

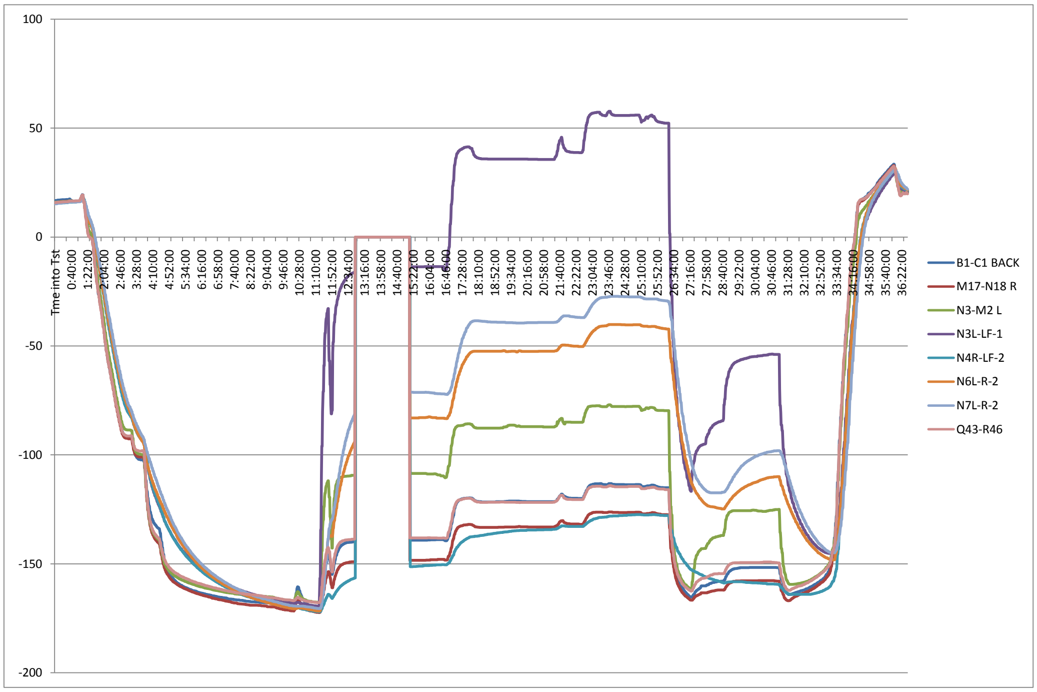


Figure 17. Plot of Several Thermocouples on the Reflector

For all intents and purposes, the test was an overwhelming success! The preparations that the ETL personnel made to the 25' Space Simulator prior to our test were extremely successful as they enabled the chamber to be pumped down to an exceptionally low pressure on the order of 1 x 10^{-7} Torr. The relatively low thermal mass of the test article enabled the transition time between test cases to be minimized, which was a large factor in enabling the team to capture data for four test cases in only a 36 hour period. Furthermore, the mechanical operation of the mobility system, and the remote operation and triggering of the photogrammetry equipment worked as well as could be hoped for.

It should be noted that the entire cost to NASA/JPL for the test was on the order of $500k, which is about half of what the test was initially forecasted to cost. Also of importance to note was the schedule with which the design was engineered, the hardware was built, and the test was completed. Real work on the MGSE design began in January 2008 and a deadline to test by early September was set by the fact that there were other tests scheduled for the 25' chamber for the September/October timeframe.

One major take-away of this test was the ability of the photogrammetry system to achieve resolution on the order of 0.025 mm RMS (0.001") over the whole 5 meter aperture under each extreme environmental condition.

The only unexpected issue that occurred during the test was a condition of poor target illumination during the LN_2 cold soak test case. This phenomenon can likely be attributed to ice forming on the targets during the cold soak, which likely affected their optical properties. The lesson learned from this ordeal is that future photogrammetry tests should bakeout the chamber to remove any trapped water moisture prior to going cold. With that being said, the initial degradation of the resolution of photogrammetry targets during the cold soak test case did not prove detrimental to the data after post processing. With the assistance of individuals from JPL's Hardware Technology Assurance & Electronic Inspection Group (5126), all the data from the cold soak case was able to be retrieved in its entirety.

SUMMARY & CONCLUSIONS

There were a number of distinct conclusions that one could draw from the IPP Solar Thermal Vacuum testing. Likely of most importance was the fact that this testing enabled the deformation analysis of the NGAS Astromesh Reflector to rise from TRL 3 to TRL 6. This will increase the confidence of future Earth science missions to accurately predict and model the behavior of the reflector under specific on-orbit environments.

Of equal importance was the ability of this project to remotely determine the thermal elastic performance of a 5m aperture to an approximate resolution of 0.001," and to achieve this on a relatively shoe-string budget. In fact, the testing was completed for less than half the cost that was estimated for an effort of this scope and magnitude. It is also worth noting that the capability and the required hardware remain at JPL for future projects utilization. Thus, future efforts will be able to utilize the technology and hardware developed herein without having to bear the financial burden of development and procurement. Finally, the lessons learned throughout the preparation and completion of this testing will help to ensure the success of subsequent testing operations.

ACKNOWLEDEMENTS

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

BIOGRAPHY

Matthew Stegman has worked at NASA's Jet Propulsion Laboratory since February 2007 in the Advanced Deployable Structures Group within the Instrument Mechanical Engineering Section. During his time at JPL, Mr. Stegman has worked on numerous research and technical development tasks, which included performing a STV test on a segment of the deployable solar array mast utilized on the International Space Station. Prior to joining JPL, he worked for two years at Delta Air Lines in a Propulsion Engineering group where he authored engineering repair authorizations for unserviceable gas turbine engine components. He obtained a BS in

Mechanical Engineering from the Georgia Institute of Technology, and is currently pursuing his MSME degree remotely through Georgia Tech.