A Low Cost Imaging Displacement Measurement System for Spacecraft Thermal Vacuum Testing

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Abstract

A low cost imaging displacement technique suitable for use in thermal vacuum testing was built and tested during thermal vacuum testing of the space infrared telescope facility (SIRTF, later renamed Spitzer infrared telescope facility). The problem was to measure the relative displacement of different portions of the spacecraft due to thermal expansion or contraction. Standard displacement measuring instrumentation could not be used because of the widely varying temperatures on the spacecraft and for fear of invalidating the thermal vacuum testing. The imaging system was conceived, designed, purchased, and installed in approximately 2 months at very low cost. The system performed beyond expectations proving that sub millimeter displacements could be measured from over 2 meters away. Using commercial optics it was possible to make displacement measurements down to 10 μm. An automated image processing tool was used to process the data, which not only speeded up data reduction, but showed that velocities and accelerations could also be measured. Details of the design and capabilities of the system are discussed along with the results of the test on the observatory. Several images from the actual test are presented.

I. Introduction

The Spitzer infrared telescope facility was launched in August, 2003, and after a short check-out period began providing infrared astronomical images of a quality not possible from earth bound telescopes. To achieve these results a unique spacecraft thermal design and orbit were called for, the details of which are discussed in several previous papers [1-4]. The telescope facility was designed to be launched at approximately room temperature, with a 360 liter tank of liquid helium at a temperature of less than 2K. Once on orbit the cryogenic telescope assembly (CTA) outer shell (OS) was allowed to passively cool to about 35K while the cryogenic optics and detectors were cooled with helium vapor to less than 5K. The spacecraft structure, electronics and propulsion system were controlled to about 263K, while the solar panel reached about 340K. The spacecraft is designed such that the solar panel, solar panel shield (SPS), and the CTA are all mounted to the spacecraft structure with gamma-alumina struts as shown in Figs. 1-2. Due to the strut mounting scheme and the large temperature differences across the spacecraft there was concern that a small dimensional distortion caused by the coefficient of thermal expansion in the key structural mounts would cause a large distortions near the top of the telescope facility. Since the solar panel and SPS shade the CTA, large distortions allow direct sun light onto the CTA OS, thus causing the liquid helium to boil off prematurely. Sufficiently large distortions in another direction can cause the relatively warm SPS to touch a hinge mechanism on the CTA again causing the helium to boil off prematurely thus jeopardizing the mission life goal of 5 years. A solar panel extension was designed for the top of the SPS in order to provide shade to the telescope during its full range of attitudes from -10° to +30° relative to the sun pointing vector. The CTA was predicted to contract approximately 1.1cm during thermal vacuum testing due to the change in temperature of the OS. If the OS contracted less than this amount, the telescope was in danger of receiving direct sunlight when tilted toward the sun, and if the OS contracted more than this amount then the solar panel extension would be unnecessarily long thus subjecting the telescope to greater thermal radiation from the relatively warm extension to the cold telescope and again reducing the lifetime of the liquid helium.

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Approximately one month prior to the system level thermal vacuum test, a decision was made to measure the distortions on the space telescope facility. Due to the large temperature differences between various spacecraft assemblies, standard displacement measuring instruments such as linear variable differential transformers (LVDTs) could not be used and instead a unique optical measurement technique that used off-the-shelf CCD cameras, lenses, computer frame grabber card, and image analysis software was proposed. Figure 2 shows the locations and views of the 3 cameras such that each of the important distortions could be observed. Other researchers have developed vacuum chamber camera systems for photogrammetry displacement measurements, infrared optical temperature measurements, or simple vacuum inspection systems [5-7]. These systems have tended to be elaborate and very expensive devices that require environment controlled pressurized canisters, or extensive redesign to make the devices vacuum compatible. For this experiment, a single engineer was able to design the experiment, purchase the necessary equipment (less than $6000), test the technique, and set-up the experiment inside the Lockheed Martin Delta vacuum chamber facility in less than one month without interfering in other spacecraft thermal vacuum test goals or schedule, thus making this technique much more affordable and useful than previously proposed systems. The only environmental control necessary for the cameras was a single heater and thermocouple to maintain the camera temperature. Lighting for the cameras was provided with standard variac controlled flood lights, which could be switched off when not in use. Figure 3 shows the spacecraft installed inside the vacuum chamber with the cameras in place just prior to closing the chamber door. The thermal vacuum test lasted approximately one month, and images were collected on a laptop computer, at the rate of 6 frames per day. The laptop computer contained off-the-shelf image analysis software that provided for rapid processing of several hundred images that were collected during the test. The displacement measurement accuracy is a function of the image magnification with the highest accuracy being achieved when the entire frame is filled with relative distance to be measured. For this application the cameras could detect changes in distance of less than 100µm from a distance of about 1.5m, when configured differently, the same zoom macro lenses were capable of measuring changes in distances of less than 10µm from a distance of over 4m, thus acting as a long distance microscope.

Figure 1. Diagram of the Spitzer telescope facility showing the location of mounting struts
Figure 2. Diagram of the Spitzer telescope facility showing the location of mounting struts, and the locations and views of the displacement measurement cameras.
II. The Experimental Rig

The primary objective of this experiment was to verify that a misalignment due to thermal expansion or contraction would not cause increased heat leak into the CTA thus causing diminished lifetime of the observatory. Mechanical instruments such as LVDT's to accurately measure displacement were considered but not used because the supporting mounts wires and control heaters would have cause an unacceptable thermal change to the thermal vacuum test. The optical technique was selected due its ease of set-up low cost and noninterference with the main objectives of the thermal vacuum test. This technique involves using a standard analog (or digital) video camera connected to a computer controlled frame grabber card. The hardware selected for this experiment was the Pulnix model 6204 and the National Instruments 1409 frame grabber card. Illumination for the cameras is provided by standard flood lights mounted near the cameras and controlled by variacs mounted external to the chamber. The lights were activated when an image was captured and digitally stored in the computer then turned off when not needed. Using the stored images it is possible to measure the relative distance between 2 spacecraft assemblies in units of pixels. If the actual size of a part in the same image is known then a conversion factor between units of pixels and a physical unit such as centimeters can be determined.

This type of optical displacement measurement is most accurate when the entire CCD frame is completely filled with the area of interest. Since the set-up for a thermal vacuum test often requires several areas near the spacecraft be closed off with thermal radiation shields or infrared light sources, the camera must be optically flexible enough to be mounted in less than optimum locations. If the camera is mounted a few meters away from the measurement of interest it must have an adjustable focal length lens, which is typically not available on standard C-mount video cameras. For this experiment the C-mount video cameras were converted to a more flexible F-mount (Nikon) with a C to F converter available many camera stores. For this experiment a 70-300mm F-mount Sigma zoom macro lens was selected to magnify the image such that displacements of about 100µm could be detected at a distance of 2m. Although it was not necessary for this experiment, the same lens is capable of measuring changes in distances of less than 10µm from a distance of over 4m, thus acting as a long distance microscope.

Figure 3. Cameras in position just prior to test
III. The Experiment

After a final walk-through of the experimental set-up, the chamber doors were closed and the pump down was started. The spacecraft and all instrumentation are powered off until the chamber pressure is below 10^{-4} Torr. At that point the necessary spacecraft hardware and ground support hardware is powered on. Some hardware including the cameras and lights remain powered off because they rely on the presence of the liquid nitrogen cold wall to provide thermal radiation cooling. The cold wall begins flooding when the pressure reaches 10^{-5} Torr. After approximately 12 hours the chamber reaches a steady pressure of 10^{-6} Torr and the cold wall reaches a steady temperature of about 85K. The cameras were turned on about ½ way through cold wall cool down, and both the lights and cameras were tested.

As soon as the cold wall reached steady state the first images were recorded. The procedure for recording the images was that the engineer on duty would adjust the voltage supply to a prescribed setting and manually “grab” an image. After the image was saved, the voltage supply for the light was turned backed to zero in order to avoid depositing additional energy into the spacecraft thus disturbing the thermal test results. This procedure was repeated 2 times per shift for a total of 6 frames per day from each of the 3 cameras. The chamber vacuum pumps caused some vibration in the cameras, which caused a slightly different image to be captured each time. Due to the thermal contraction in the camera mounting structure there was a small change in alignment when the chamber reached its steady cold condition; therefore the field of view is slightly different for all images.

IV. Data Reduction

Analyzing image data for displacement (velocity or acceleration) obviously involves measuring the distance between the objects of interest on each frame. The simplest choice was to make hand measurements of the distance of interest on every image. Because of the relatively small amount of data this tedious technique could have been used for this experiment, but would render this experimental technique nearly useless for many other applications. Fortunately there several excellent off-the-shelf image analysis software tools available to handle a wide range of image measurements. For this application National Instruments Vision Builder was used. The image set from each camera presented several different analysis problems for the software.

The analysis of the camera 1 images proceeds as follows: First a small rectangle is drawn around a distinctive feature in the image, in this case a small portion of the telescope dust cover hinge is chosen as shown in Fig. 4. Next another rectangle is drawn around unique pattern of bright spots on the solar panel shield, again shown in Fig. 4. These rectangles will become templates that will be automatically matched in each of the images analyzed. Once the match is found, the centroid of the template is displayed as indicated by the small cross hairs in Fig. 4. At that point it is possible to evaluate the distance, in pixels, between the 2 centroids. To aid in locating the matching pattern, it is necessary to specify a region of interest (ROI) which is shown in Fig. 4 by the larger rectangles. When the search is done, only those areas are considered for finding the match. The software allows the analyst to “script” the measurement steps and then run the analysis in batch mode for all images. The batch processing takes less than 10 seconds for 100 images. The output is a text list of the distances between the centroids given in pixels for every image that can then be plotted. If necessary one can use a known dimension in the image to develop a scale factor that can be applied to the pixel measurement in order to convert into units of distance. In Fig. 4 one pixel equals 0.28mm however since the goal is to determine a change in the distance between the solar panel shield (SPS) and the CTA outer shell it is not necessary to convert into absolute units.
The analysis of the images from camera 2 is slightly different. Like the analysis of the images from camera 1 a ROI is defined by the rectangles shown in Fig. 5. The edge detection tool is then applied to both regions of interest. Figure 5 shows the red line drawn across the edge of the dust cover structural stiffener and the SPS. The outputs of the edge detection tool are the 2 end points of the edge lines as they intersect the ROI. Simple algebraic relationships are used to define several normals to one edge line that intersect the other edge line. Two examples of these normals are shown sketched as white arrows in Fig 5. The length of each normal is evaluated in units of pixels, and then all the lengths are averaged. In this case it is necessary to convert pixel units into length units because the goal of this measurement is to determine how much the CTS contracts with respect to the SPS. The reference length unit in this case is the thickness of the clearly visible dust cover stiffener, which is precisely known. In addition to the edge detection normal measurement, a simpler technique is also used. The line labeled 1,2 normal to the edge lines shown in Fig. 5 is first applied the image. The edge detection algorithm then finds the 2 edges of interest and outputs the distance. Since both techniques were subject to false edge sensing a large amount of over sampling is used to compensate for errors and the results are averaged.
The final measurement (camera 3) is the distance between the SPS and the CTA with a line of site orthogonal to the other 2 cameras as shown in Fig. 2. The distance measurement was sensed by again applying lines between the CTA and the SPS, and then using the edge detection algorithm to measure the distance in units of pixels. Four of the edge detection lines are shown in Fig. 6 with the detected edges labeled 1, 2 on each line. Figure 6 also shows the surfaces of the SPS on the right and the CTA on the left, which are both highly reflective materials in order to minimize radiation heat transfer between the two. These reflective surfaces make edge detection more difficult, but it is not necessary to detect the “actual” edge of the two surfaces only to detect the same point from image to image such that a relative distance can be computed. To compensate for the high reflectivity and the problem of sensing an edge several lines are used to detect edges at different locations, then the distance results are averaged.

Figure 6. Automatic analysis of the CTA outer shell to SPS spacing using Vision Builder software

V. Results

A. Camera 1: The distance between the SPS and the telescope dust cover mechanism.

The results from the centroid measurements that were described in the data reduction section are plotted in Fig. 7. The intension of this measurement is to determine how much the distance between the CTA hinge mechanism and the SPS changed during the course of the test. Given the orientation of the camera it was possible to sense displacement toward or away from the SPS, or side to side movement of either the SPS or CTA. First an average distance is established by averaging all distance measurements throughout the test then dividing each individual measurement by the average. There were several data points that were thrown out due to poor image quality or because in a small number of cases the image analysis software was not able to establish a centroid. In each of these cases the image was inspected to make sure that there were no real problems being missed. The x-axis is simply labeled “sample number” but it roughly corresponds to time from the start of the test through the end of the test approximately 1 month later. Since the distance measurements started before the test fixture and spacecraft had reached steady temperature thermal expansions and contractions caused a few misaligned images, which do not yield good measurement as can be seen from data points 4-7 in Fig. 7. Later in the test, vibrations and thermal contractions of the mounting hardware cause 5 selected ROIs to fall outside the image field of view thus causing bad measurements again seen in Fig. 7 data points 22-27. Three other measurements near the end of the test are also corrupted during warm up and repressurization. Figure 7 shows that a few data points deviate from the average by 2% or about 0.5mm while the rest deviate by less than 1%. In all cases the deviation can be attributed to inconsistencies in the illumination, camera vibration, or image processing. The final conclusion is that no movement is observed.
**B. Camera 2: The height of the SPS relative to the telescope dust cover.**

Camera 2 was used to make an absolute length measurement of the height of the solar panel shield relative to the dust cover for the CTA. This measurement was necessary to confirm that after the observatory reached its steady state operating temperature the solar panel shield would be high enough to shade the telescope at its minimum tilt orientation of -10°, while at the same time not being too high such that the shield would radiate additional energy to the CTA. Figure 8 shows the change in distance between the solar panel shield and the CTA dust cover. Zero contraction on the y-axis is defined as the number of pixels (converted to centimeters) between points 1 and 2 in Fig. 5 for the image immediately prior to flooding of the liquid nitrogen cold wall. Again the x-axis in Fig. 8 is labeled sample number, but roughly corresponds to time. As expected the CTA shrank with respect to the solar panel shield, with a maximum relative change of approximately 1.23 cm.

**Figure 7. Change of distance between the CTA dust cover mechanism and the SPS**

**Figure 8. Change in height of the CTA dust cover relative to the SPS**
C. Camera 3: Distance between the SPS and the telescope dust outer shell.

Camera 3 was used to make a relative length measurement between the SPS and the OS of the CTA. This measurement is made about 1m from the bottom of the CTA in a location where the gap between the SPS and the CTA is the smallest (about 1.9cm). In some sense this measurement duplicates the measurement of camera 1 and was added to ensure some redundancy in the experiment. The edge detection software had a difficult time locating an edge on the curved, highly reflective surfaces so the measurements first had to be filtered for data that was obviously incorrect. After filtering, the remaining data from each edge detection line was averaged, and then each measurement is divided by the average. When all the data is plotted together in Fig. 9 it is possible to evaluate deviations from the average, and once again the x-axis is labeled “sample number,” which roughly corresponds to time. It is immediately obvious that there is substantial scatter in the data caused by the difficulties in edge detecting. In an attempt to understand the noisy data a 2nd order polynomial is fitted to the data. The curve fit shows a slight expansion of the gap in the middle of the test at the coldest point, with the gap closing towards the end of the test when the spacecraft is warmed up. The curve appears to show that the gap expands about 2% at its coldest point or about 380µm.

Figure 9. Relative spacing between the CTA outer shell and the SPS

VI. Summary

The SIRTF Spacecraft thermal vacuum test offered a unique opportunity to develop and test a low cost imaging displacement system suitable for use in thermal vacuum chambers. Given the short time available to set-up the system, expectations for useful data were low, however the system proved to be more flexible and reliable than anticipated and yielded excellent results. The accuracy of the measurement depends on the field of view, but can approach 10µm. The computer frame grabber and computer image storage system was reliable and easy to use. Having stored the images digitally it was possible to analyze movements automatically using flexible off the shelf image processing software. The software offered much greater capability than was necessary for this experiment, and it was obvious that it was possible to measure velocity and acceleration in addition to displacement.
The data collected on SIRTF showed the expected contraction in the telescope OS and a very small unexpected expansion in the gap between the OS and the SPS. Even with the very small unexpected expansion between the OS and the SPS, all data verified that the telescope met the requirements for the design giving great confidence that the telescope would perform well on-orbit. The key concern was a displacement of the SPS and CTA towards each other, allowing the two to touch and cause a catastrophic heat leak into the liquid helium dewar. The images showed that large displacements were not possible, and analysis showed the only major thermal displacement noted was the expected contraction in the length of the CTA. The experiment showed a contraction of 1.23±0.04cm, which is outside the predicted contraction of 1.102cm. The most probable explanation for this is that the relatively poor quality of the images from this camera combined with a parallax effect caused an error in defining the conversion factor from pixels to centimeters. The gap between the outer shell and the solar panel shield may have expanded by about 380µm at its coldest point. The noisy nature of the data that suggests this expansion casts some doubt on the expansion observation. The observed expansion is so small that regardless of its validity there are no adverse consequences to the spacecraft. The final proof that all displacement design requirements were met is the on-orbit performance of the telescope facility. The Spitzer infrared space telescope facility has been on-orbit for over 2 years and has met or exceeded all requirements for astronomical observations and helium usage. The heat leaks into the CTA have been less than expected, and the cryogenic helium is expected to last well beyond the required lifetime of 2.5 years and also exceed the goal lifetime of 5 years.

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References