Figure testing of 300 mm Zerodur mirrors at cryogenic temperatures

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1. ABSTRACT

Deep Impact is a NASA Discovery Mission to impact and observe the nucleus of Comet Temple 1. The instrumentation includes a 300 mm aperture telescope that will operate at 130K once in deep space. It is critical that the telescope mirrors maintain their figure at the operational temperature. We report on measurements of the surface figure changes of three Zerodur primary mirrors from room temperature to 130K, using a PhaseCam® interferometer from 4D Vision Technologies, Inc. Although the mirror substrates were taken from the same melt and annealing, they did not perform equally, with differential surface figures ranging from 0.014 waves RMS at 633 nm to 0.082 waves.

2. BACKGROUND

There is an extensive history of testing optics under extreme environmental conditions. Among the desired characteristics is the ability of optical elements to maintain their optical figure. This is particularly important for the telescopes of NASA's Deep Impact mission to Comet Temple 1. The entire scientific imaging suite will be passively cooled by exposure to deep space and shielding from the sun. These imagers include 300 and 120 mm aperture reflective telescopes. Thermal modeling predicts that the primary mirror for larger of these telescopes will stabilize at 130 K in deep space.

3. PRIMARY MIRROR DESCRIPTION

Zerodur was selected for the mirror substrates based on its low CTE and the breadth of the temperature range over which this CTE remains low. A single lot of four mirror blanks were purchased from Schott, and light-weighted using CNC machining.

To mount the mirror, small Invar pads will be bonded to its periphery. Structural analysis predicted that significant stress would be induced over the 170K differential from room temperature, even with the small difference in expansion between Zerodur (+0.001% expansion) and Invar (0.031% contraction). Our initial plan was to observe this stress induced figure distortion of a mounted mirror and to correlate it to the FEM predictions. The goal was to confirm that the distortion would not consume a significant fraction of the system wavefront error budget of 70 nm RMS (λ/10 at 700 nm).

Taking an optics to cryogenic temperatures requires the use of a thermal vacuum chamber. The resulting environments are far from those in optical laboratories where mirrors can be tested on vibration isolated equipment. It is possible to isolate the entire chamber from vibration,[1,2] or put vibration isolation within a vacuum chamber. The test equipment must either also go into the vacuum, or be placed on a separate isolation system outside the chamber. Each of these approaches have been done successfully , but they are difficult and expensive.

4. PHASECAM DESCRIPTION

The need for vibration isolation comes from the common method for taking interferograms. An interferometer, commonly of the Fizeau configuration[3], is arranged to produce a null or near-null interferogram. Each interferogram is recorded quickly, but is still of sufficient duration that environmental vibrations blur the fringes. If phase measurement is used to obtain higher precision, the reference plate is then stepped several times, each time moving a fraction of a wavelength, and an interferogram is recorded at each position. If the environment causes the distance between the device under test and the interferometer to change by even a small fraction of a wavelength, the phases of the individual interferograms become decorrelated, and the information is lost

The Deep Impact mirrors were tested using a new interferometer from 4D Vision Inc. called a PhaseCam. The interferometer can be seen in operation in Figure 1. This device records four phase shifted interferograms simultaneously on a single CCD array. A real-time video frame is shown in Figure 2. The PhaseCam includes a fast

CCD that can limit the exposure time to as little as 30 microseconds. This allows the system to record interferograms in a manner insensitive to vibrations below about 10 kHz, and through turbulent air. Multiple interferograms are recorded and their results are averaged. This enables the system to average out time varying effects such as air turbulence. The resulting surface measurement is displayed as shown in Figure 3.

5. TEST CONFIGURATION

Figure 4 illustrates the test configuration. For the initial testing, an Engineering Model mirror was polished with a spherical surface, and held in a sling mount, facing a side port of the vacuum chamber. The port was sealed with a meniscus window. The PhaseCam head, with its diverging F/7 beam, was placed so that its source point was at the center of curvature of the mirror[4]. Interferograms were observed, although each one had up to several waves of random tilt due to the environmental vibration. This was not surprising considering the cantilevered platform on which the interferometer was mounted. The interferograms were taken in ten groups of 16. Despite the environment, the variance of the averaged wavefronts remained below 0.0006 waves RMS.

6. FIRST TEST

Interferograms were recorded at each step of the test. This included the initial set-up before the window was installed. Additional interferograms were recorded through the window, after the vacuum was established, and at various temperatures during the two day cool-down. Corresponding measurements were made as the mirror was warmed, and as the chamber was returned to room temperature and ambient pressure, and with the window removed. Using fiducials placed on the mirror surface, the interferograms were precisely overlayed, and numerically subtracted. The room temperature measurements before and after cooling and heating differed by <<0.01 waves RMS.

However, during cooldown, a significant amount of distortion was observed. The RMS surface figure error was recorded at several temperatures. These values are plotted in Figure 5. The thermo-mechanical distortion was best seen by taking the differences between the surface profile at a reduced temperature and at ambient temperature. This difference peaked at 0.075 waves RMS. A map of the differential figure is shown in Figure 6.

7. ROTATED MIRROR

To discern whether this effect was inherent to the mirror or an artifact of the test, the mirror was rotated 120°, which matched its internal symmetry, and the test repeated. Figure 6 includes the RMS figure error measurements for both runs, where the second data set is distinguished as “Rotated”. The figure irregularity repeats quite precisely. When these irregularities were quantified as third order aberrations, their magnitudes and orientations were seen to remain the same, and to remain in the same physical relation to the mirror substrate. That is, the axes of the apparent coma and astigmatism rotated 120° with the mirror to a precision of ~5°.

8. PARABOLIC MIRROR TESTING

When the thermo-mechanical distortion of the Engineering Model mirror was discovered, plans were made to test the Flight and Flight Spare mirrors in the same manner. This was more difficult because these mirrors had already been finished with parabolic profiles. Position errors that displace the source from the center of curvature of the parabolic mirrors will generate coma and astigmatism. In addition, testing a parabola as a sphere results in spherical aberration of third and higher orders.

Despite the additional opto-mechanical sensitivity of parabolas, good data was still obtained. The stability of the measurements can be quantified by comparing repeated measurements. While each displayed surface profile is the average of many individual interferograms, multiple profiles can be obtained in a short time. To quantify the repeatability, we plot in Figure 7 the standard deviation of the surface irregularity. With the exception of one case with higher than average irregularity, the repeatability values remain below 1/1000 of a wave RMS, or about 4% of the irregularity being measured.

Figure 8 is a plot of the surface irregularity vs. temperature. The lack of trend in the measured figure irregularity proves that both of these mirrors exhibited no more than a small fraction of the temperature dependent distortion seen in the Engineering Model mirror. It should be noted that few intermediate measurements were taken. One reason was that the interferometer source point has to follow the center of curvature of the mirror to avoid inducing aberrations, and this is particularly difficult when the mirror and all of its surrounding hardware are contracting with changing temperatures. However, the primary conclusion can be drawn that the irregularity is roughly the same at the two stable temperatures, even with a difference of 170 K.

All three mirror substrates were machined and processed following identical procedures, with the exception of the parabolic figures, which removed extremely small amounts of material. The pedigree of all three substrates were examined and discussed with Schott[5]. All were cut from the same melt and annealing. However, there is no information on their relative locations within the original boule. No explanation has been found for the differences between the mirror substrates.

9. MOUNTED MIRROR TESTING

Having shown that the flight and flight spare substrates will maintain their optical figures when cooled to the operational temperature, testing returned to the original goal of assessing the mirror mounts. For programmatic reasons, at this point the Engineering Model mirror had also been figured as a parabola. It was suspended in the chamber by three flexures, each of which was attached to one of the Invar mounting pads which were bonded to the mirror's edge.

The bulk distortion seen in the first two tests was reproduced in this third test, in the same magnitude and orientation as expected. This allowed us to subtract this distortion from the new data. Figure 9 is a map of the remaining surface figure difference between ambient and operational temperature. Spherical aberration has been removed by the software. The bulk distortion of the unmounted mirror tests has also been removed using a point by point subtraction.

The figure clearly shows expected distortion of the mirror surface in the immediate vicinity of the three mounting pads. The Peak-to-Valley range is 0.43 waves, with much of this outside the clear aperture. By masking the three regions of distortion, it was possible to estimate the contribution to surface figure within the clear aperture to be 0.011 waves RMS.

10. CONCLUSION

Interferometric testing of optics in rugged environments can be readily conducted using the PhaseCam Interferometer. We employed this device for measuring the figure of 300 mm diameter mirrors at cryogenic temperatures. The repeatability of the measurements was below 0.01 waves, despite the high vibration environment. Testing the parabolic mirrors is more difficult than testing spheres, because displacements of the interferometer or mirror introduces aberrations, but was also successful. This testing clearly measured the mounting induced distortion of 0.011 waves RMS magnitude.

One of our Zerodur mirror exhibited 0.075 waves RMS distortion at 130K due to substrate irregularities. This distortion was shown to be inherent to the substrate and not an artifact of testing. Two other mirrors from same melt did not exhibit significant distortion. These mirrors remained at or below 0.035 waves RMS figure irregularity over the 170 K cool-down from room to operational temperature.

11. ACKNOWLEDGEMENTS

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12. REFERENCES

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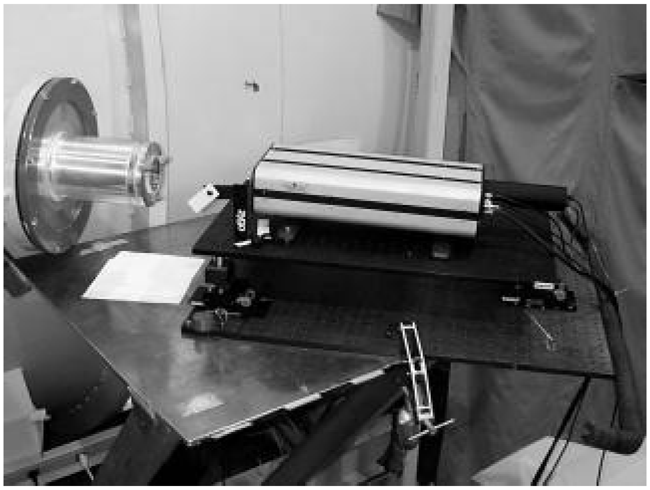


Figure 1 PhaseCam in Operation at the Thermal Vacuum Chamber

Figure 2 Real-time video display

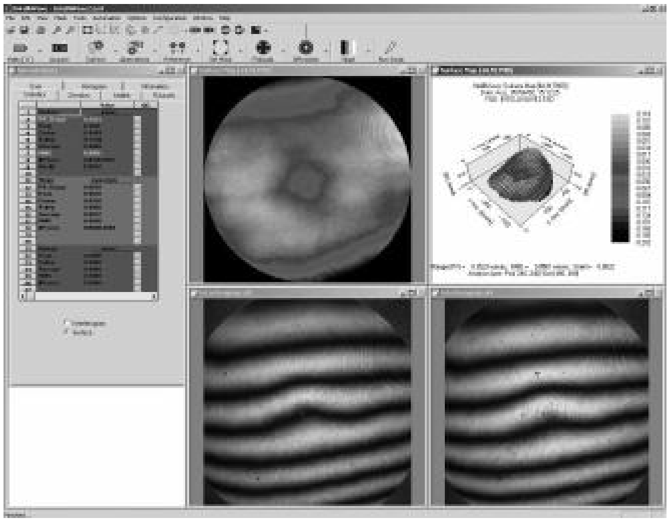


Figure 3 Intelliwave display of raw and processed interferogram and analysis

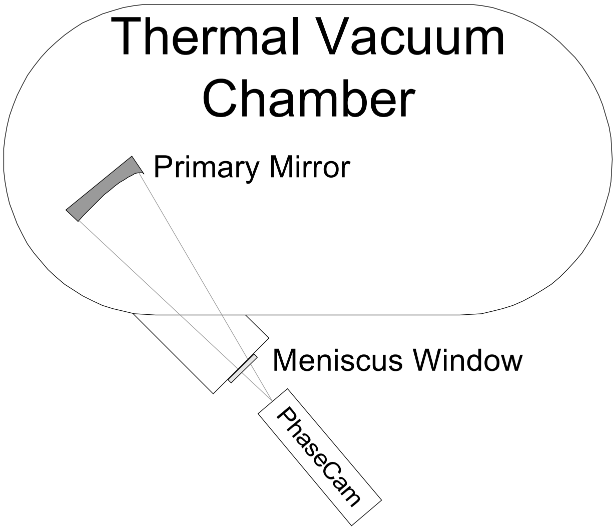


Figure 4 Testing configuration with the Thermal Vacuum Chamber

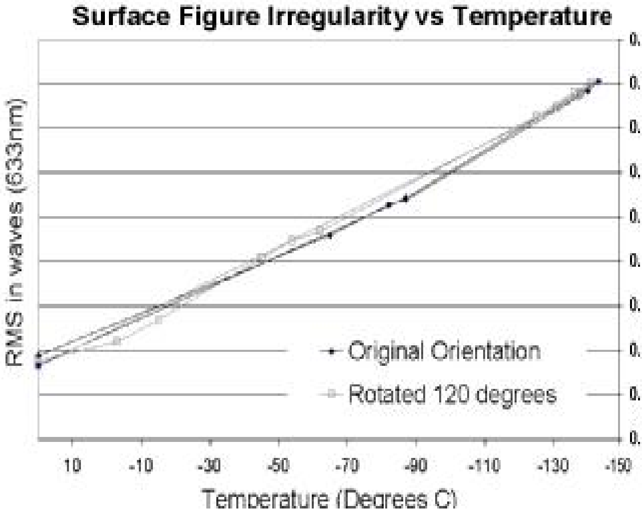


Figure 5 Engineering Model Mirror Irregularity vs temperature

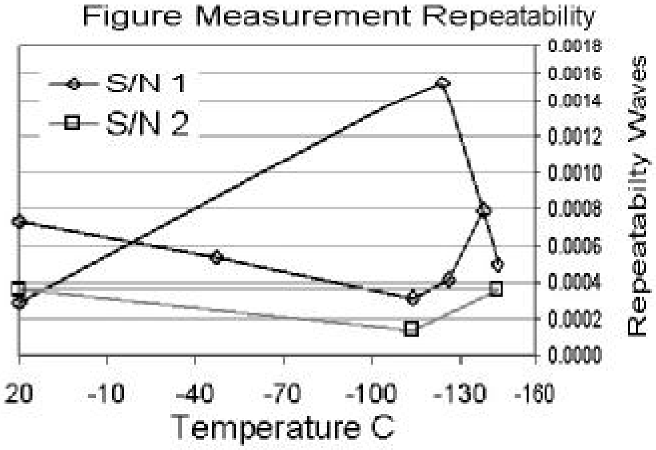


Figure 7 Flight Mirror Figure Measurement Repeatability

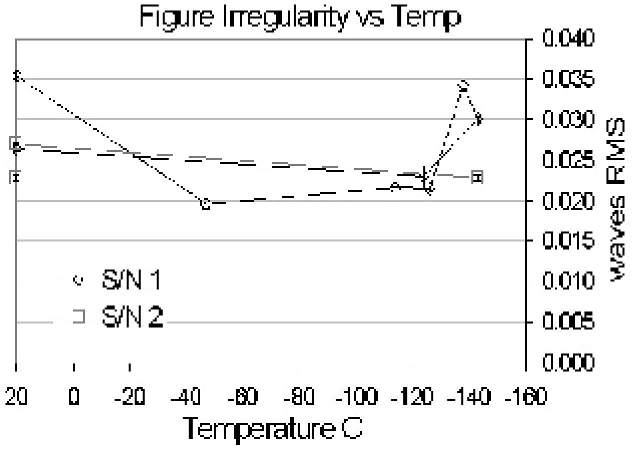
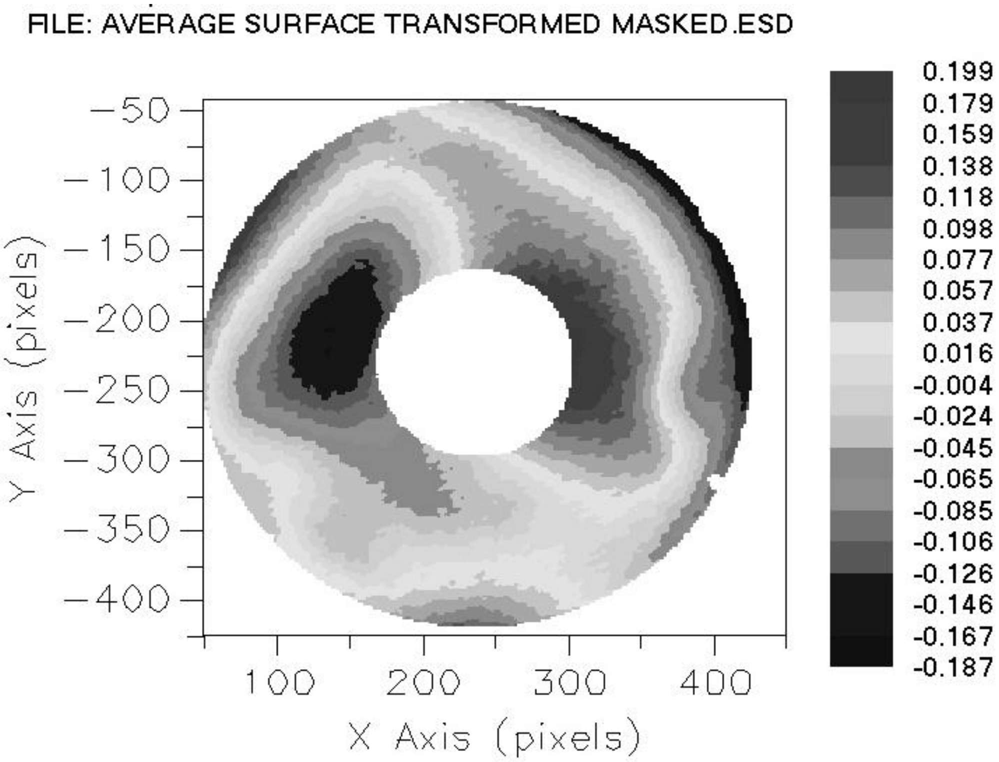


Figure 8 Flight Mirror Surface Irregularity vs Temperature



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Range (PV) =   0.3863 waves,  RMS =   0.0754 waves,  Strehl =   0.7989
Analysis Aper: Pos[ 237, 231] Size[ 379, 379]
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Figure 6 Engineering Model Surface Differential Surface Figure at -141°C

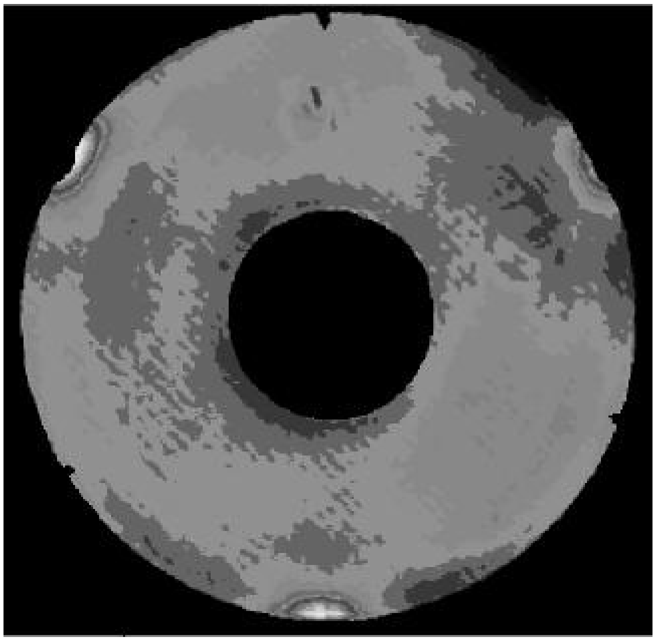

Figure 9 Pinching observed in the mounted EM Mirror at –140 C