

Global Effect of a Thermal Change on a Mirror Glued to a Metal Substrate

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OPTI 423L

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I. Introduction

This experiment was done to investigate the effect of different configurations of adhesives applied to materials with very different coefficient of thermal expansion.

II. Theory

Different materials have varying coefficients of thermal expansion. When temperature change occurs, different materials expand at different rates. For materials bonded together, this differential expansion can induce stresses in materials. For optical applications one typically occurring material difference is aluminum and glass. Aluminum is an extremely common use material, yet it has a CTE of approximately 23ppm/C. Despite the wide range of different glasses, the common use glasses have CTEs ranging from 5-10ppm/C. When these two materials are bonded together and exposed to some significant thermal change, the increased expansion of aluminum would create stress in the glass. This stress creates a moment in the glass which will distort the surface.

In mirrors angular deflections cause large errors. In this experiment I used a thin glass mirror bonded to an aluminum block. The changes in thermal expansion caused a differential expansion between the block and the mirror. The induced moment on the glass was investigated. For different adhesive configurations there are different surface deflections. In this analysis I investigated a three point configuration, a ring configuration, and compared the two results.

III. Experiment design

The materials tested include several aluminum 6061 plates, thin glass windows probably made of BK7, and an adhesive RTV. Each material is described in more detail below:

Aluminum plates-

Composed of 6061-T6 Aluminum, purchased from the Stewart Mirror Observatory Workshop as 2" x 2" x 0.5" cut blocks. The surface was prepared using sandpaper. This was done by rubbing the blocks on sandpaper in circles until the high points were removed. The blocks were cleaned with water and surface preparation was verified by visual inspection.

Glass-

The glass was purchased from <http://surplussed.com/> and the specific glass type was not specified, but it is probable that the glass is BK7. The glass samples were 50mm diameter with 3mm thickness. There was no surface preparation done to the glass.

Adhesive-

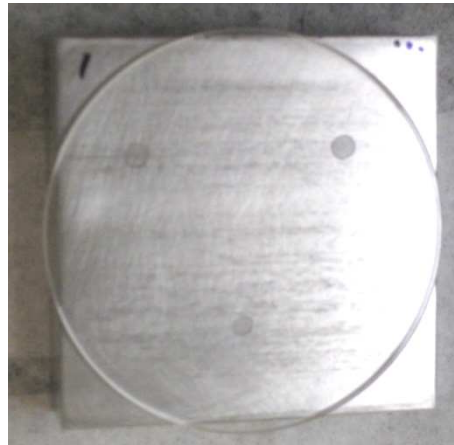
The adhesive used was Dow Corning 732 RTV. This was chosen because of availability in the lab. A typical adhesive thickness is 0.005", as shown in Paul Yoder's book: *Opto-Mechanical Systems Design, Third Edition*. The bond width was chosen to be 2mm, or 0.00787" by a rule of thumb to look at the global effect of the adhesive and not the localized effect.



Adhesive used in experiments

Three point configuration-

The adhesive points were chosen to somewhat relate to expected practical uses. An initial radius of 15mm (normalized radius of 60%) was selected because this is near the optimal position for self-weight deflection when supported by three points, which is 68%. The diameter of the points was chosen to be 2mm by rule of thumb to make small points. The adhesive was applied and 0.005" shims were placed in the middle and edges to define the adhesive thickness.



Three point configuration sample

Ring configuration-

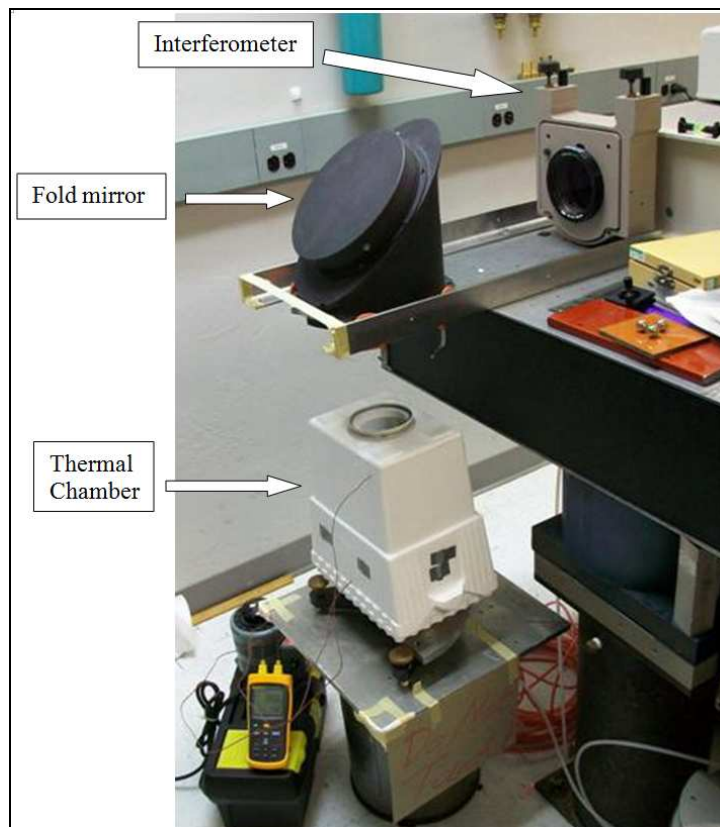
A smooth ring would be difficult to create and control, so I chose to use many points of adhesive to approximate a ring. When I was applying the adhesive, I chose to make each point similar to each point in the three point configuration. Again, the same radius was chosen as the other configuration. To guide the application of adhesive, I drew a circle of radius 13mm, and then applied the adhesive approximately 2mm away from the line. I placed shims of 0.005" thickness around the outside to define the adhesive thickness.



Ring configuration

IV. Test configuration

The testing setup used an interferometer on a vibration isolated table, with a fold mirror to redirect the light down into a thermal chamber, as shown in the figure below.



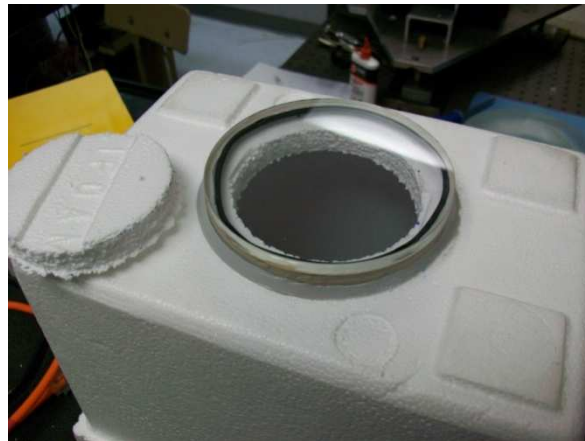
Total test setup

The thermal chamber was used to create a temperature change from room temperature (24C) to 40C. The chamber was constructed from a foam cooler with a heating wire coiled inside, a Variac voltage controller to adjust the temperature, temperature sensors to measure the chamber temperature, and a mounted optical window. The heating wire was

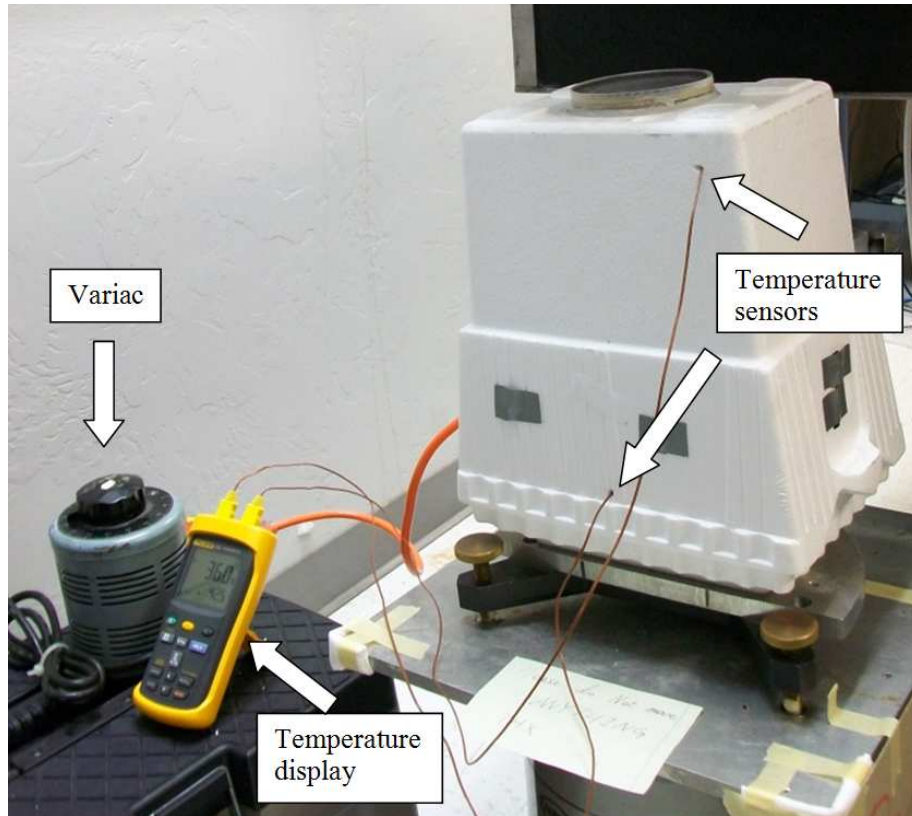
held up by twist-ties, and the end of the wire that exited the chamber was covered with duct tape to minimize losses.



Inside of chamber showing coiled heating wire



Window on top of chamber with cut piece shown at left



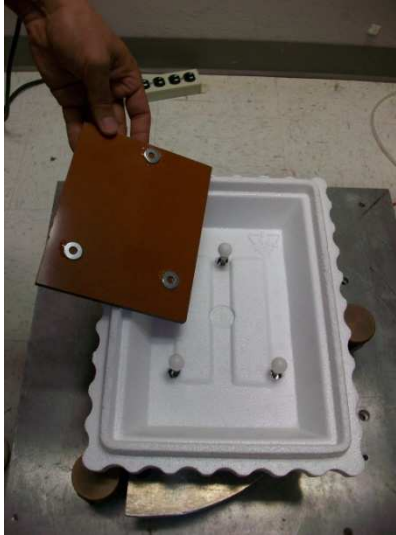
Chamber with temperature sensors and Variac

To minimize vibrations, the load path for the samples needed to be well defined. Rather than setting the samples onto the foam of the chamber, a special support base was created. The design was to mount three balls on posts to the tip-tilt stage on the vibration isolator.



Three ball support base

Three holes were cut into the foam bottom and placed over the posts so that the balls would stick up into the chamber. Three washers were glued to a plate to give repeatability when removing and replacing the plate.



Support base inside chamber without lid



Three washer plate up close

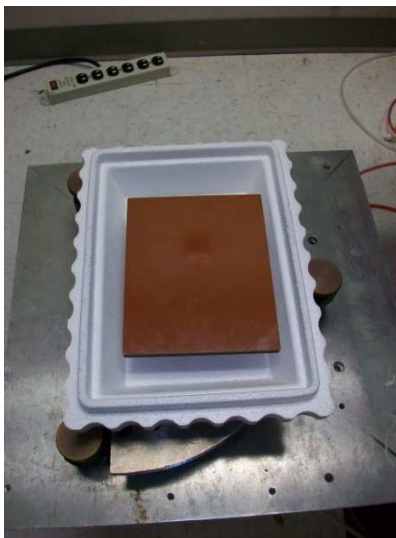


Plate set on balls in chamber without lid

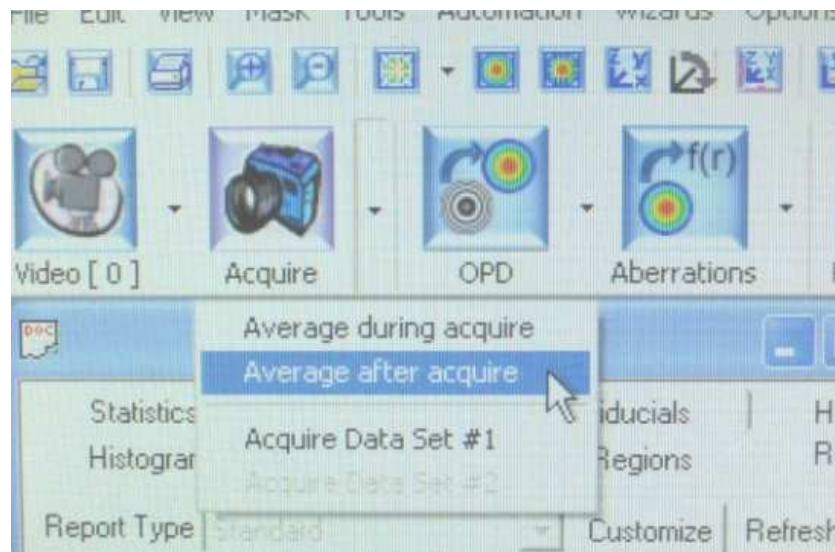
V. Interferometer

The interferometer used was a Zygo, Mark GPI-XPS, Laser Interferometer with Intelliware software. For alignment we matched the bright spot from the reference flat to the dim spot of the sample being tested. This was done because the interferometer uses polarization phase shifting, which takes pictures of the light after applying different amounts of phase shifts, then combines the data together to get the surface data. The dim light is the correct polarization of light to create the phase shifts, but the bright spot is not phase shifted which creates additional errors. The phase shifting reduced errors in the measurements because any static fringes are eliminated when the different pictures are analyzed together. When the bright spot does not change with applied phase shifts, the software considers the fringes to be static and subtracts them out.



Side of interferometer

When the program is initiated to take data I chose to average the readings after acquiring the data because the vibrations in the system were significant enough to cause errors. I chose to not average the fringes before acquiring because it might average out some of the fringes.

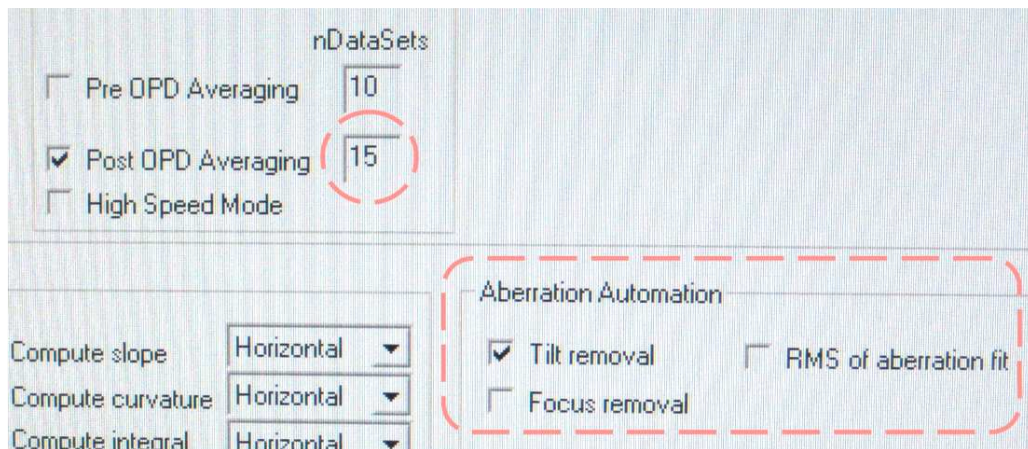


Taking data with "Average after acquire"

To take measurements, a custom configuration was used because the default setting removed tilt, defocus, and an RMS aberration fit. The custom configuration I used only

removed tilt. The defocus and RMS aberration fit values were not subtracted from the data because I wanted to look at the bending of the mirror surface, which is composed mostly of a defocus term. I chose to still remove tilt to decrease alignment errors.

The custom configuration was also different because it averaged fifteen readings instead of the default value of five. I chose this because I wanted to increase the measured accuracy. When I took data for a specific temperature I chose to take data five different times, of which each is an average of fifteen measurements, to give a total of 75 measurements. I used the software to average all five measurements taken and give the complete reading.



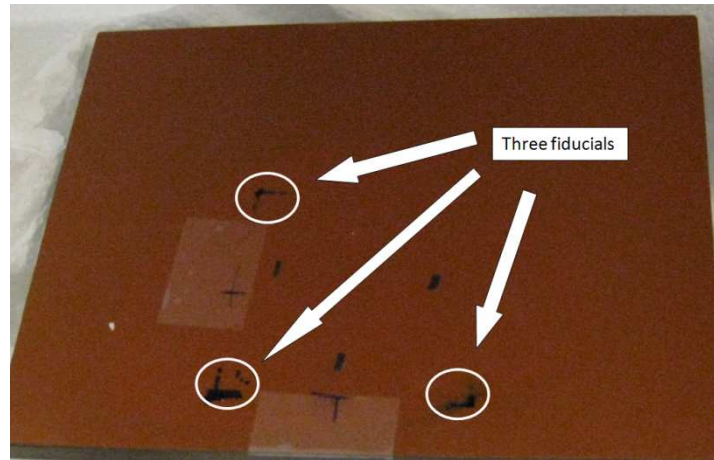
Custom configuration

I used a circular mask to limit the aperture and only take measurements over the portion that included the sample. It was important to make sure that the interferogram slightly overfilled the mask because there were some defects at the edge of the interferogram that caused errors.

VI. Testing procedure

Here are the steps taken during testing:

1. The sample was placed on the plate and aligned with the fiducials. I drew three right angles on the mounting plate to correspond with the aluminum blocks of the samples.



Fiducial marks on plate

2. The interferometer was turned on and put into alignment mode.
3. The tip-tilt stage was adjusted to align the dim spot from the glass surface reflection with the center.
4. The interferometer was changed to measure mode which displays the fringes and a final adjustment was made to center the fringes in the window.
5. A circular mask was applied to fit the size of the sample interferogram.
6. Five measurements were taken to give the ambient temperature reading.
7. The thermal chamber would be heated by setting the Variac to 120 volts for 20 minutes to heat the chamber quickly.
8. After that the Variac was turned down to 90 volts which is the setting for 40C for about 25 minutes until the temperature was stabilized.
9. A final adjustment was made to align the center of the fringes with the center of the mask.
10. Five more measurements were taken to give the warm measurements.
11. Once complete I used software to average the five ambient temperature readings and then set that as the reference.
12. Then I averaged the five warm temperature readings.
13. I then subtracted the reference (which was the ambient temperature) from the warm average. The resultant interferogram and values showed the change between the two temperatures.

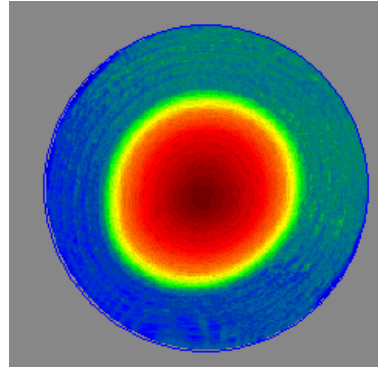
VII. Data

The following data was taken as screenshots from the Intelliwave software. Blue is low and red is high.

Ring Configuration:

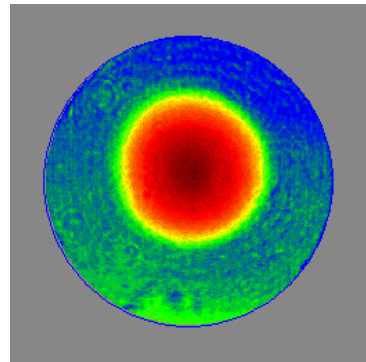
Ambient measurement average (24.6 C):

IntelliWave Report Summary		
Parameter	Value	Units
PV 98.00%	1.2348	waves
RMS	0.3565	waves
4) Focus	-0.5072	waves
5) X Astig	-0.0012	waves
6) Y Astig	-0.0215	waves
7) X Coma	0.0692	waves
8) Y Coma	-0.0626	waves
9) Spherical	0.4057	waves



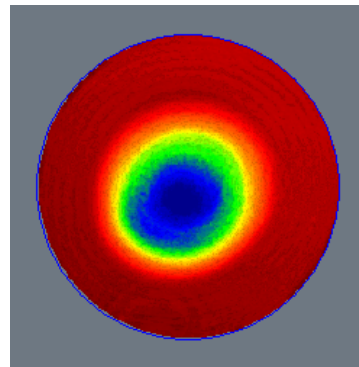
Warm measurement average (39.8 C):

IntelliWave Report Summary		
Parameter	Value	Units
PV 98.00%	0.3614	waves
RMS	0.0945	waves
4) Focus	-0.1199	waves
5) X Astig	-0.0049	waves
6) Y Astig	0.0023	waves
7) X Coma	-0.0100	waves
8) Y Coma	0.0561	waves
9) Spherical	0.1172	waves



Difference between warm and ambient:

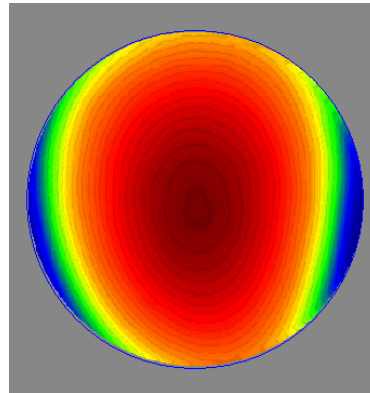
IntelliWave Report Summary		
Parameter	Value	Units
PV 98.00%	0.9498	waves
RMS	0.2731	waves
4) Focus	0.3873	waves
5) X Astig	-0.0037	waves
6) Y Astig	0.0238	waves
7) X Coma	-0.0792	waves
8) Y Coma	0.1187	waves
9) Spherical	-0.2885	waves



Three point configuration:

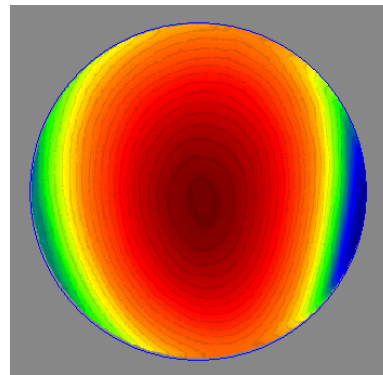
Ambient measurement average (24.6 C):

IntelliWave Report Summary		
Parameter	Value	Units
PV 98.00%	3.6689	waves
RMS	0.9361	waves
4) Focus	-1.4972	waves
5) X Astig	-0.8911	waves
6) Y Astig	0.0652	waves
7) X Coma	-0.0108	waves
8) Y Coma	-0.0894	waves
9) Spherical	0.0993	waves



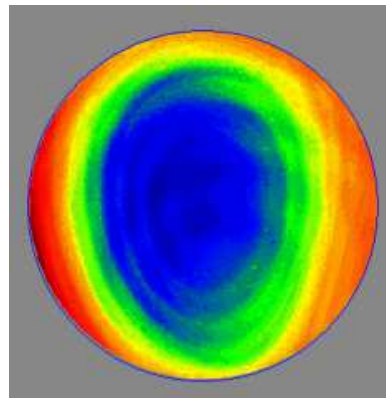
Warm measurement average (38.9 C):

IntelliWave Report Summary		
Parameter	Value	Units
PV 98.00%	3.1400	waves
RMS	0.7797	waves
4) Focus	-1.2338	waves
5) X Astig	-0.7392	waves
6) Y Astig	0.0314	waves
7) X Coma	-0.1217	waves
8) Y Coma	-0.1043	waves
9) Spherical	0.1523	waves



Difference between warm and ambient:

IntelliWave Report Summary		
Parameter	Value	Units
PV 98.00%	0.7399	waves
RMS	0.1705	waves
4) Focus	0.2634	waves
5) X Astig	0.1519	waves
6) Y Astig	-0.0338	waves
7) X Coma	-0.1109	waves
8) Y Coma	-0.0149	waves
9) Spherical	0.0531	waves



VIII. Analysis

The ring configuration caused a larger surface deflection than the three point. The three point configuration was more compliant than the ring, which makes sense with my expectation because more adhesive should create a larger moment on the glass.

The shapes of the two different deformations make sense. In the three point configuration, the two points were at the top and the single point was at the bottom, which creates a triangle-like shape in the interferogram, the hole is wider at the top than the bottom. The ring configuration created a circular shape in the interferogram, which fits because the adhesive was a symmetric circle.

The table below shows the quantitative results from the experiments:

	PP Deflection	RMS Deflection
Three Point	0.7399 waves	0.1705 waves
Ring	0.9498 waves	0.2731 waves
% Difference	28.4%	60.2%

Comparison of complete results

The two surface figures are different, and it is reflected in the deflection measurements. The peak to peak deflections are fairly similar with the ring configuration being 28% higher. The RMS deflection shows the major difference. The reason for this is that the three point interferogram has a much larger hole in the center than the ring.

Often RMS surface distortion is used for wavefront error calculations and a 60% increase in surface distortion is significant. Although the ring is significantly larger, both values are still quite small for such a large temperature change. For a mirror at normal incidence, the surface deflection equals the wavefront deflection, and for many applications wavefront distortions less than 1/3 wave would be acceptable.

The overall small change can be attributed to the high compliance of RTV, but the percent differences between the two configurations is due to the geometric differences of the configurations.

IX. Problems encountered

Interferometer-

Initially when data was taken, the resulting surface was shown to be flat to about 0.001 waves. This was an error from aligning the bright spot from the surface with the bright spot of the reference surface. During the phase shifting, the interferogram was not shifting because it was the incorrect polarization, which caused the entire surface to be removed, and only noise showed surface changes.

Another problem came from inaccuracies in the testing equipment. On the interferometer there was a small interferogram that was always present during testing. Even though we used phase shifting interferometry, the error interferogram was slowly moving, which created an apparent shift while the measurement was being taken.

Thermal chamber-

A thermal gradient was present in the thermal chamber after it was heated up. The temperature was measured at two points, one below the sample and one slightly above. After waiting for the temperature to stabilize about 30 minutes, the thermal gradient was approximately nine degrees Celsius.

X. Lessons learned

One of the most important lessons that I learned was that it is very important to double check that the setup is correct, because it wastes a lot of time to have to redo an experiment that takes an hour for a measurement. At different points I forgot to take out the shims, didn't apply the correct mask, started heating the chamber without recording ambient measurements, or wasn't aligned with the correct polarization image.

I also learned about adhesives. I did some initial testing with some five-minute epoxy, and I learned that it is important to have the entire sample completely prepared because there is only about two minutes of work time before the epoxy starts to harden. With the RTV I used, I learned how to put a high viscosity material into a syringe. It was more difficult than I thought, but even with the ring configuration it doesn't take a lot of adhesive to cover a 15mm radius ring of 2mm width. I always extremely overestimated the amount of adhesive that I thought I would need.

I learned how to use an interferometer to take measurements and change the settings for my specific application. I hadn't aligned or used an interferometer in a real experiment, and it was good to troubleshoot different problems and realize the delicacy of interferometry. If someone is near the path of light, or is leaning on the table, it completely changes the measurement.

I learned that adhesive configurations actually do matter. Similar to designing different constraints, the geometry of the adhesive very directly affects the surface distortions. I did not expect a significant difference between the two configurations.

XI. Conclusion

I learned a lot from doing this experiment. I learned that it is always more difficult to take readings than just putting something down and measuring it. Even with an advanced interferometer and software it still takes a while to set things up and verify that the result from the computer is correct.

From the experiment it was shown that RTV is very compliant and causes surface distortions less than 1/3 wave for a temperature change as large as 20C. For some applications, the 1/3 wave RMS distortion would be too large, so a different design would be needed.

As to the differences between the two configurations, the ring configuration causes significantly larger distortions. Even though there was only a 28% difference between the

peak to peak distortion, the 60% increase in RMS surface distortion is significant. These results are significant enough to justify investigating further between placing a ring of adhesive to make sure a mirror is held securely and using a smaller amount to decrease surface deflections.

The overall small change can be attributed to the high compliance of RTV, but the percent differences between the two configurations is due to the geometric differences of the configurations.