Optical Distortion Evaluation in Large Area Windows using Interferometry

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Abstract
It is important that imagery seen through large area windows, such as those used on space vehicles, not be substantially distorted. Many approaches are described in the literature for measuring the distortion of an optical window, but most suffer from either poor resolution or processing difficulties. In this paper a new definition of distortion is presented, allowing accurate measurement using an optical interferometer. This new definition is shown to be equivalent to the definitions provided by the military and the standards organizations. In order to determine the advantages and disadvantages of this new approach the distortion of an acrylic window is measured using three different methods; image comparison, Moiré interferometry, and phase-shifting interferometry.

Keywords: Distortion, optical interferometry, optical metrology, optical windows, Schlieren, Moiré

1. Introduction

The primary function of a window is to allow observation of, yet protection from, a potentially hazardous environment. Yet, from the window designer's point of view, ensuring protection from weather conditions in home windows; from wind, temperature, and airborne debris in automotive windows; and from extreme pressures and temperatures in aircraft and spacecraft windows has almost always taken precedence over image quality. This bias was most strikingly borne out in a 1981 Air Force report [1] discussing optical distortion requirements that stated "The F-106, F-111, B-1, T-28, F-5, and F-15 have all exceeded these requirements, and sacrificing pilot visual performance has been justified by the increased aerodynamic performance of the aircraft." Such a design preference is defendable—it is more important to protect an astronaut from the vacuum of space than to provide clear imagery—yet these are not exclusive requirements. Advances in materials and material processing allows the designer to attain better optical performance while not sacrificing important material specifications such as strength. In addition, increased performance demands on spacecraft windows, which are now used for photography and telescope observation, and even for laser communications, requires greater consideration be paid to optical clarity.

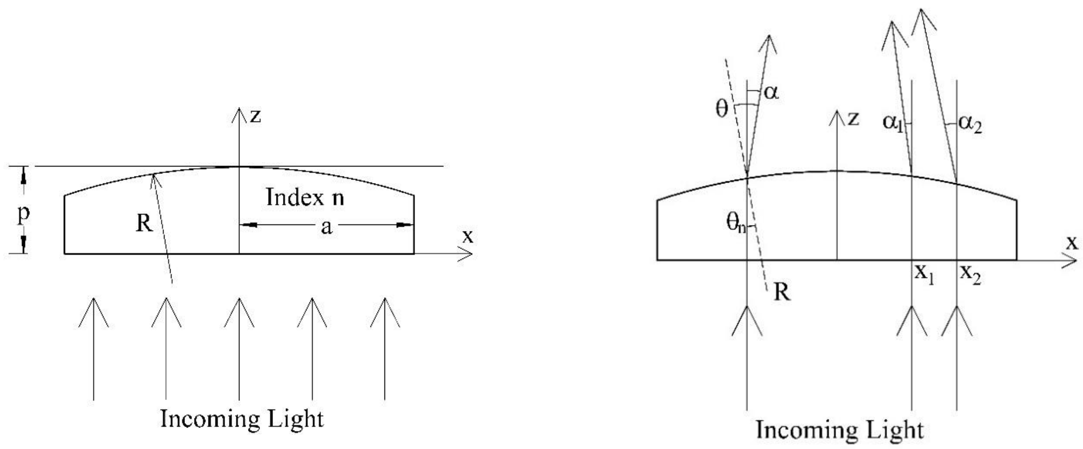
Along with the need for better optical performance comes a corresponding need for improved definition and quantification of the distortion of an optical window. Distortion can be subjectively determined by a viewer looking through the window [1], but this is difficult to quantify and is not repeatable. Consequently, over the last 50 years a wide range of window distortion measurement approaches have been proposed [1, 2]. Some are only applicable to windows with large distortions that can be determined by measuring surface variations [3] and some require specialized components, such as an array of micro-lenses [4]. By far, the most common method for measuring distortion is to photograph an image with and without the window and then compare them [1, 5, 6, 7] but this approach has limited resolution and is not applicable to higher quality windows. A newer approach, based on Moiré Interferometry [8, 9], has higher resolution, but yields imagery that can be difficult to quantify. In this paper we propose a new method for quantifying distortion based on phase-shifting interferometry.

2. Distortion

The window attribute that causes image distortion is curvature, either introduced through a variation in the window thickness or by a localized variation in the index of refraction of the window. It is assumed that these curvatures are very gradual relative to the wavelength of light and that the window surfaces are very smooth, i.e. polished. This is important. Window variations on the order of wavelengths will scatter light and cause image aberrations such as light streaks and diffracted images. These are not attributes of distortion and are ignored in the present discussion. So it is assumed that all window imperfections are very large compared to an optical wavelength and smoothly varying.

Figure 1 shows an idealization of a section of a window. One side of the window is assumed to be perfectly flat while the other side is slightly curved with a radius of curvature, R, that is very large compared to size of this window segment, i.e. $R >> 2a$. Also, assume that the window has a uniform index of refraction, n. Using a set of coordinate axes on the segment as shown the curved surface can be expressed by the equation

$$z[x] = p - x^2/(2R) . \tag{1}$$



(a) (b)

Figure 1. This sketch shows a small section of a window with one planar surface and one constant curvature surface. Figure (a) provides the descriptive parameters for this window section and (b) shows how rays of light are refracted by the curved surface.

2.1 Distortion Definition 1

The most common definition of distortion is based on tracking rays of light that pass through the mirror. Referring to Figure 1(b), a beam of light that passes through the window at location x_1 is deflected by an angle α_1, while a parallel beam, a short distance away at location x_2 is deflected by an angle α_2. This change in the deflection of light versus position leads to the first definition of distortion, D, namely

$$D \equiv \frac{\alpha_2 - \alpha_1}{x_2 - x_1} . \tag{2}$$

If the surface curvature is gradual and the sampling distances small this expression becomes the derivative of the angular deviation with respect to location, i.e.

$$D \equiv \frac{d\alpha[x]}{dx}\,. \tag{3}$$

This definition is used by the military in specifying distortion, for example an optical flat should have less that 1 minute of arc per inch distortion [1] and is the basis of the International Organization for Standardization (ISO) standard [6].

Using Snell's Law this definition can be related to the surface curvature and the index of refraction of the window. Looking at Figure 1(b), an incoming ray of light hits the curved surface at an angle, θ_n, to the normal, shown by the dashed line that leads back to center of the radius of curvature, R. This ray of light is refracted by an angle, θ, towards the y axis. The goal is to find the deviation angle, α as a function of x, so its derivative can be calculated. Start with Snell's Law $n\sin[\theta_n] = \sin[\theta]$, which, since the curvatures are all very gradual, can be converted into a small angle form, i.e. $n\theta_n = \theta$. Now, note that the slope of the window's curved surface is equal to θ_n and that this slope is also equal to the derivative of Equation 1. Finally, looking at the figure it is seen that $\alpha = \theta - \theta_n$. Combining these yields

$$\alpha[x] = \theta - \theta_n = (n-1)\theta_n = (n-1)\frac{d}{dx}\left(p - x^2/(2R)\right) = -\frac{(n-1)}{R}x\,. \tag{4}$$

So from Equation 3 the distortion is found to be

$$D = \frac{d\alpha[x]}{dx} = -\frac{(n-1)}{R}\,. \tag{5}$$

This agrees with our initial requirement that a planar surface, i.e. one with infinite radius of curvature, has zero distortion. It also indicates that as the curvature becomes smaller the distortion becomes larger, a reasonable result.

2.2 Distortion Definition 2

A second definition of distortion is given by the American Society for Testing and Materials (ASTM) [5] and states that distortion is equal to one over the focal length, F, of the lens formed by the curvature of the window, i.e.

$$D \equiv (1/F)\,. \tag{6}$$

This definition describes distortion in terms of local curvature as described by the resulting focusing, or defocusing, of the window. In order to find the focal length of the lens formed by the curved window surface in Figure 1(b) we need to ask, where on the z axis do the refracted rays converge? Using a small angle approximation, we see that $\alpha[x] \approx x/F$. Using this result and Equation 4 the second definition of distortion yields

$$D = (1/F) = \alpha[x]/x = -(n-1)/R\,. \tag{7}$$

As expected these two definitions yield the same result, though they start with very different physical intuition.

2.3 Distortion Definition 3

The third definition of distortion—presented for the first time in this paper—is based on a fundamental window attribute, namely the window's optical path length function, $\sigma[x]$. This function describes the distance, as seen by the light, as it travels through the window and the air, from one plane to a second plane. So calculate the optical path length in Figure 1 as light moves from the lower, planar, window surface at $z = 0$, to the $z = p$ plane. For each value of x the light passes through an amount of glass given by $y[x]$ in Equation 1 and then passes through an amount of air given by $p - z[x]$. So the optical path length function is given by

$$\sigma[x] = n(z[x]) + (p - z[x]) = (n-1)(p - x^2/(2R)) + p\,. \tag{8}$$

The derivative of this function describes the direction that the light takes after passing through the window and air, i.e.

$$d\sigma[x]/dx = -(n-1)x/R = \alpha[x]\,. \tag{9}$$

The second derivative of this function provides the third definition of window distortion

$$D \equiv \frac{d^2\sigma[x]}{dx^2} = -\frac{(n-1)}{R} = \frac{d\alpha[x]}{dx} \tag{10}$$

showing that the distortion of a window can be expressed as the second derivative of the optical path length function. This is important because equipment now exists, namely phase-shifting interferometers, that can easily and quickly provide the optical path length function of a window, both accurately and with high resolution.

2.4 *Component and Total Distortion*

Real world windows extend in two dimensions and the definitions given above for distortion are only one dimensional. The ASTM [5] resolves this by defining three different distortions, D_x, D_y, and D. D_x and D_y are defined in terms of the angular deviation of light when scanning the window in the x and y directions, but no relation between these component distortions and the distortion, D, is provided. The ISO standard [6] states that optical distortion on a window is equal to the maximum distortion found by measuring in all directions. This is better than ASTM, but is still unclear because distortion can change sign.

Our new definition of distortion removes this confusion by the following straightforward extensions of the one dimensional definition given above in Equation 10:

$$D_x \equiv \frac{d^2\sigma[x,y]}{dx^2}, \qquad D_y \equiv \frac{d^2\sigma[x,y]}{dy^2}, \qquad D = D_x + D_y = \nabla^2\sigma[x,y] \tag{11}$$

This states that the total distortion, D, is the sum of the two component distortions and is represented by the Laplacian of the optical path length. This definition is mathematically consistent with the intuition that the distortion should be related to the window curvature, but it should be stressed that window pass-fail criteria must be carefully written. For example, if the window is saddle-shaped, $\sigma[x, y] \propto xy$, then D_x, D_y, and D in Equation 11 are all zero, yet the window is not flat.

3. Measuring Distortion

Having the various equivalent definitions of distortion, we can now compare three different methods for measuring distortion. We will start with a straightforward technique where a test pattern is photographed at some distance with and without the window and the two images compared. Then a newer technique using Moiré interferometry will be tried and the third approach will be to use a phase-shifting interferometer. In all three cases we will examine the same window, a roughly 6 inch diameter section of acrylic sheet that has appreciable distortion. This is of interest because future spacecraft are being designed with plastic windows instead of fused silica in order to save weight even though plastics typically have greater window distortion than the fused silica windows they are replacing.

3.1 Measuring Distortion Using Image Comparison

A distortion measurement system was constructed as described in the ASTM standard [5] and is shown in Figure 2. An image was created of a set of parallel dark lines spaced by 1 cm. This image was located a distance 3.6 m (distance $2L$ in Figure 2) from a focusing lens with focal length, f. A camera was used to take a picture of this reference image and then the acrylic window was placed between the image and the lens and a second photo taken. The acrylic window was then rotated by 90 degrees and a third photo taken. The presence of the acrylic window causes the photographed lines to be shifted and deformed. By measuring the amount of shift in the line segments the distortion in the corresponding section of the window can be calculated.

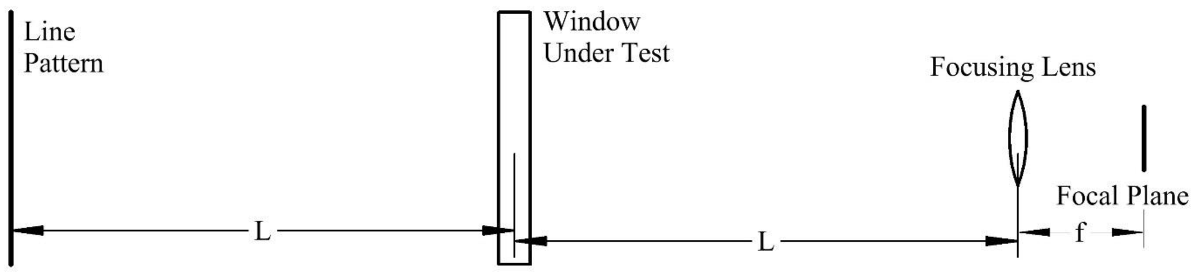


Figure 2. This is a sketch of the distortion measurement system using image comparison.

Using geometrical arguments it can be shown that the change in location of a line segment image on the focal plane array, Δz, is related to the window deflection angle, $\alpha[x]$, by $\alpha[x] = 2\Delta z / f$. In our configuration the lens focal length was 74 mm. We wrote code (Mathematica) to find the center of each 1 cm long line segment in the reference image and in the two window images. Subtracting these locations then yields two arrays of Δz values from which the angular light ray deviations in the x and y directions can be found, see Figure 3.

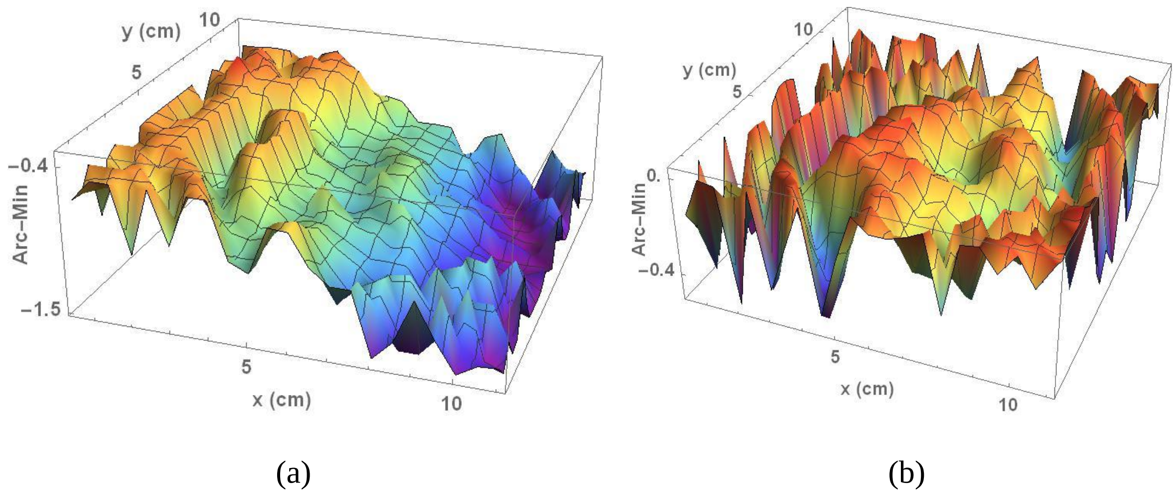


Figure 3. Measured angular deviations seen in the acrylic window as a function of location on the window, for the (a) y -direction and (b) x -direction using the ASTM image comparison approach.

Due to limited resolution it's difficult to determine the distortion of the window. A one pixel shift on the camera corresponds to about 0.4 minutes of arc, so the above images correspond to a less than 3 pixel shift. By averaging data we were able to obtain sub-pixel resolution, but some of the structure seen in these images may be imaging artifacts and not true line segment shifts. Taking the derivative of these two plots amplifies the oscillatory nature and swamps what might be true distortion. For example Figure 3 (a) shows a definite slope across the window corresponding to a large scale, though small, y -directed, distortion across the window, which is many times smaller than the "distortion" seen in smaller regions.

3.2 Measuring Distortion Using Moiré Interferometry

Moiré Interferometry [8, 9], like Schlieren Imagery [10], is an optical technique that amplifies the intensity variations caused by small angular deviations of light rays. The system sketch is shown in Figure 4. Light passes through a transparent lined pattern (i.e. a Ronchi ruling) and travels to a spherical mirror with radius R (48 inches in our system). The light reflects back and passes through the transparent line pattern a second time, and is imaged onto a camera focal plane.

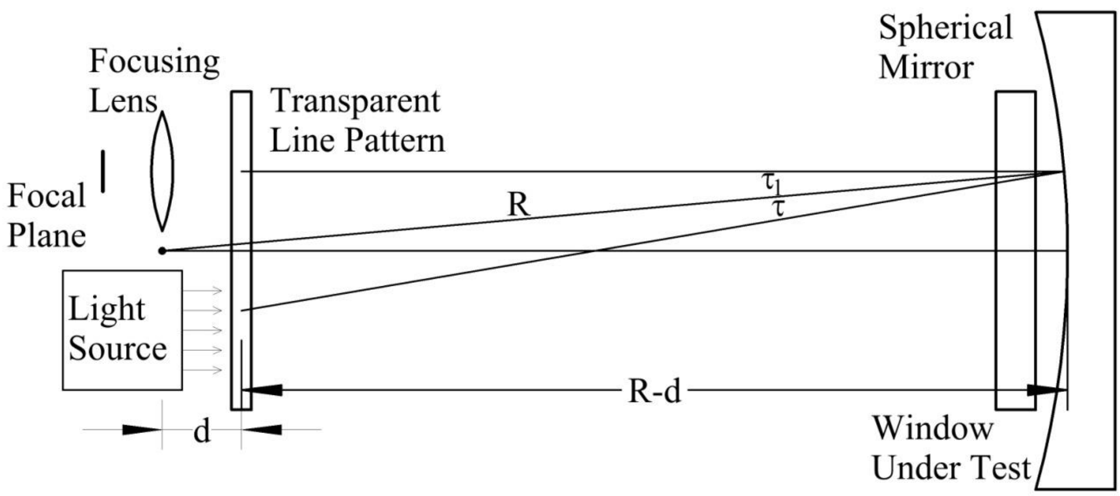


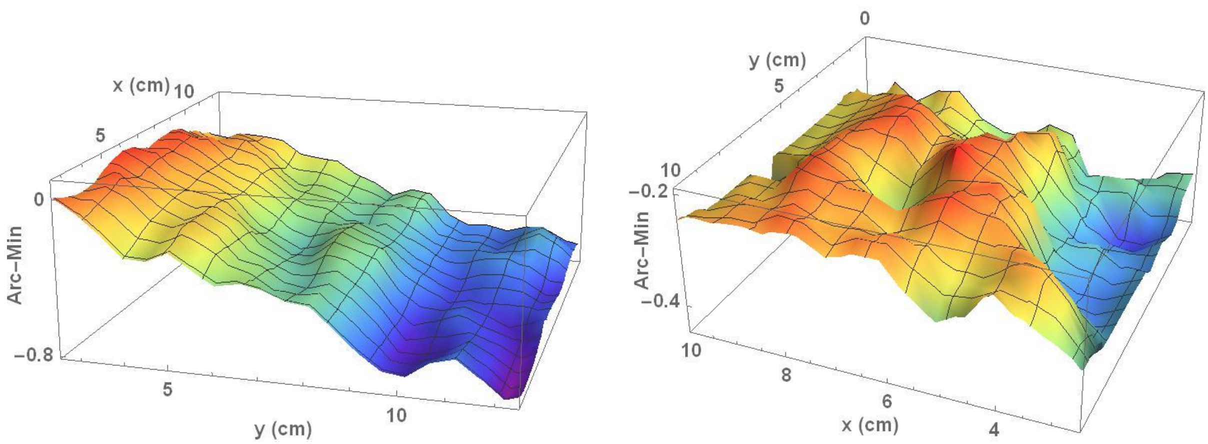
Figure 4. A sketch of the Moiré Interferometry system for measuring window deformation.

The Ronchi ruling is composed of 1/100th inch wide dark lines separated by transparent spaces 1/100th of an inch wide. So in order for the camera to see light, it must look through the gaps between the dark lines and then, looking into the mirror, see light from a gap in front of the light source.

Moving the Ronchi ruling towards the window a distance d causes alternating bands of dark and light to appear on the surface of the mirror, i.e. a Moiré pattern. The spacing of these lines is given by the Ronchi ruling line width times (R/d), which equals 0.2 inches when $d = 2.5$ inches. We took a photograph of this line pattern as a reference and then inserted the acrylic window, as shown in Figure 4. The window causes angular deviations of the light passing through it. Now, if the light returning to the Ronchi ruling is deflected up or down by the window by an angle equal to (1/50th inch)/($R - d$)=1.5 minutes of arc, then the image of the dark and light bands on the mirror will appear to move by one full spacing, i.e. 0.2 inches. So the presence of the window causes the dark and light bands to be shifted and deformed, by amounts much larger than for the ASTM line test described above. Taking into account that the light passes through the window twice, and assuming pixel resolution in tracking the light and dark bands, our system has approximately 0.02 minutes of resolution. This is 20 times better than for the ASTM approach.

We took pictures of the shifted line pattern with the acrylic window oriented along both Cartesian axes and generated the angular deviation functions shown in Figures 5(a) and 5(b). Comparing these to Figure 3 shows the improvement achieved by using Moiré Interferometry over a direct image comparison approach. However, this approach, even though it is very sensitive, has accuracy problems. For example, inserting a perfect window into the system will yield shifts that are not due to distortion, but due to the refraction of light by the window. These refraction effects have to be calculated and numerically removed from the data, which was done in our case, but neglecting this will lead to an offset in the distortion calculation.

When comparing Figures 3 and 5 (as well as Figure 7 below), note each approach generates an angular deviation offset. Also, we did not strive to match the x and y axes, so they are offset in the Figures and in one case, Figure 5b, we inverted the x axis.



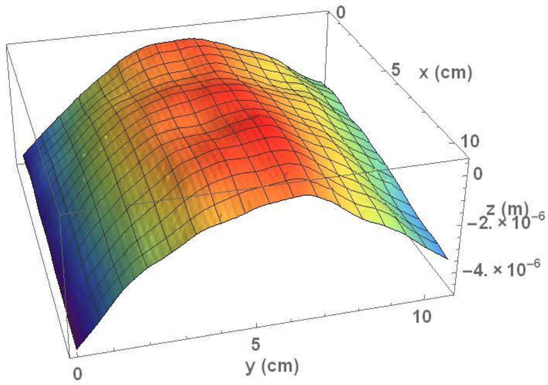
(a) (b)

Figure 5. Measured angular deviations seen in the acrylic window as a function of location on the window, for the (a) y -direction and (b) x -direction using the Moiré interferometry approach.

3.3 *Measuring Distortion Using Phase-Shifting Interferometry*

Phase-shifting interferometry is a standard technique for measuring the optical path length of optical components. Several companies sell complete systems, typically used for optical component evaluation. For our work we used a Zygo Corporation Verifire^{TM} ATZ system [11] as shown in Figure 6(a), with a 6 inch diameter measurement capability. Placing the acrylic window into this system yields the optical path length plot shown in Figure 6(b). This plot shows that the acrylic window has a very slight cylindrical shape.

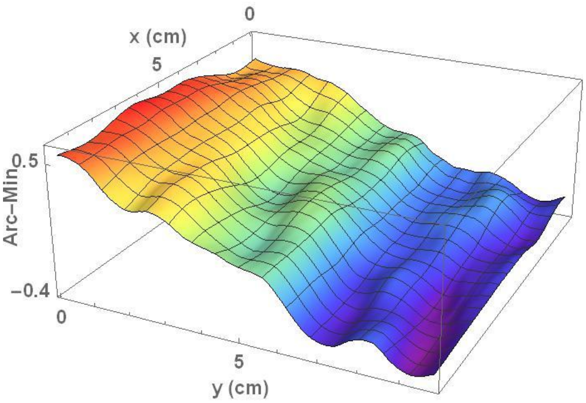
(a)



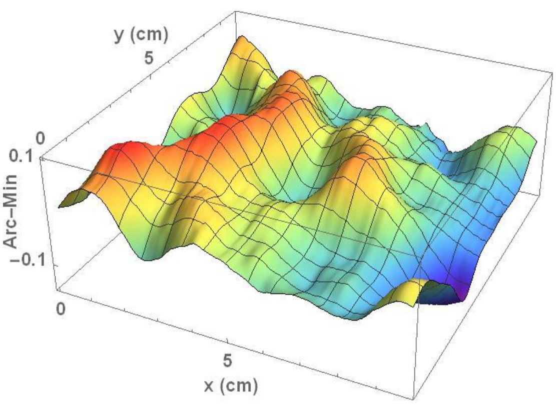
(b)

Figure 6. This is a photo of a Zygo phase-shifting interferometer, the Verifire^{TM} ATZ, alongside the measured optical path length of the acrylic test window.

The Zygo Interferometer supplies high resolution imagery, approximately 60 pixels per cm, allowing the derivatives of this function to be calculated and averaged, yielding the angular deviation functions from Equation 9. These two functions are plotted in Figures 7 (a) and 7 (b). Comparison of these plots with those shown in Figures 3 and 5, provides an immediate visual indication of the quality of data provided by the three distortion measurement methods being compared in this paper.



(a)



(b)

Figure 7. Measured angular deviations seen in the acrylic window as a function of location on the window, for the (a) y -direction and (b) x -direction using the phase-shifting interferometry approach.

The quality of the data from the phase-shifting interferometer is high enough that the second derivatives can be obtained numerically, i.e. the distortion plots, (Equation 11). These are shown in Figures 8(a) and 8(b). It is interesting to note that the large curvature seen in the optical path length function, which shows up as the slope in Figure 7(a), has little effect on the distortion. It corresponds to roughly a -0.1 min/cm offset in Figure 8(a) which is difficult to see in the presence of the larger, more localized, distortion effects.

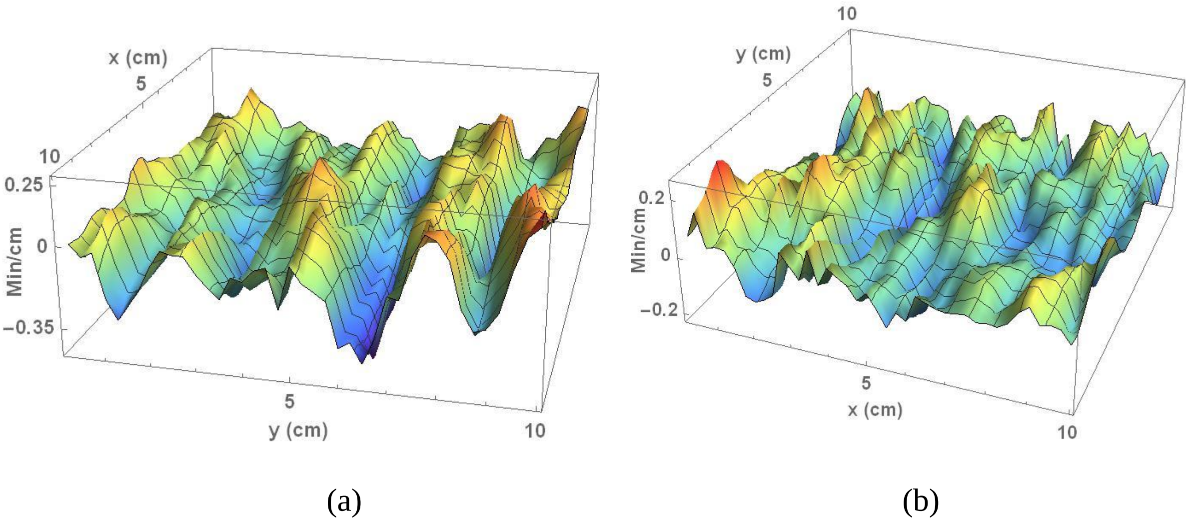


Figure 8. The measured distortion in the acrylic window as a function of location on the window for the (a) y -direction and (b) x -direction using the phase-shifting interferometry approach.

As opposed to the results shown in the image comparison method, the fine structure shown in Figures 7 and 8 are real and are not the result of noise or errors introduced in the derivative process. Phase-shifting interferometers can achieve nanometer optical path length resolution, so distortions much smaller than an arc-second/cm can be measured.

4. Conclusions

We have introduced a new definition of distortion and shown that it allows a phase-shifting interferometer to be used to determine the distortion of an optical window. At first glance this appears to be a preferable technique for measuring distortion over image comparison and Moiré interferometry, however, each has its strengths and weaknesses. Phase-shifting interferometry provides the highest resolution measurements, but the system cost is expensive and the dynamic range is limited to only higher quality windows. Also, scanning large area windows requires making multiple measurements and then stitching the imagery to obtain a complete window map. Moiré Interferometry is inexpensive and sensitive, but quantifying the data can be difficult and requires careful measurement and analysis. Even so, once the algorithm is developed this approach can be scaled to large windows by using a larger spherical mirror and the system sensitivity can be adjusted by changing the spherical mirror’s radius of curvature. So it can be used over a wide range of window qualities. Finally, the image comparison approach is the least expensive and most straightforward and has been the standard method for many years. It is adequate when examining relatively low performance windows, but as shown above, it is limited in performance.

Acknowledgements

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