Testing a Parabolic Mirror with a Compact Interferometer

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Introduction

Parabolic mirrors are well suited to a number of imaging and illumination applications. In the case of an imaging application, the form accuracy of the parabola can introduce significant wavefront error. While reflective optics are free of chromatic aberration, care must also be taken to minimize degradation due to mounting distortion. This paper describes the measurement of a 300 mm diameter f/8 parabolic mirror with a compact, phase-shifting interferometer.

The test set-up

The set-up for testing a parabola is shown below. The numerical aperture of the interferometer objective should be as large as or preferably slightly larger than the parabola under test, in order to measure form over the entire surface. The auto-collimation technique is very efficient in the sense that only the return flat need be as large as the largest parabola to be tested.

The set-up requires a small hole in the return flat in order to pass the convergent beam from the interferometer objective. For the compact interferometer utilized in this test, the hole diameter need only be 5 millimeters or less. For a 300 mm diameter parabola, this represents an area less than 0.03%

By locating the front focus of the interferometer objective coincident with the first surface of the return flat, the effective focal length of the parabola may be determined according to the axial distance between the parabola and return flat. To set the axial position of the interferometer, temporarily place a small mirror over the hole in the return flat to view and adjust the cat-eye condition to null.

The return flat can also be tested ahead time using the same compact interferometer in the Ritchey-Common configuration, with the addition of an adequately large concave mirror. In this case, the concave mirror is qualified directly with a divergent beam from the compact interferometer.

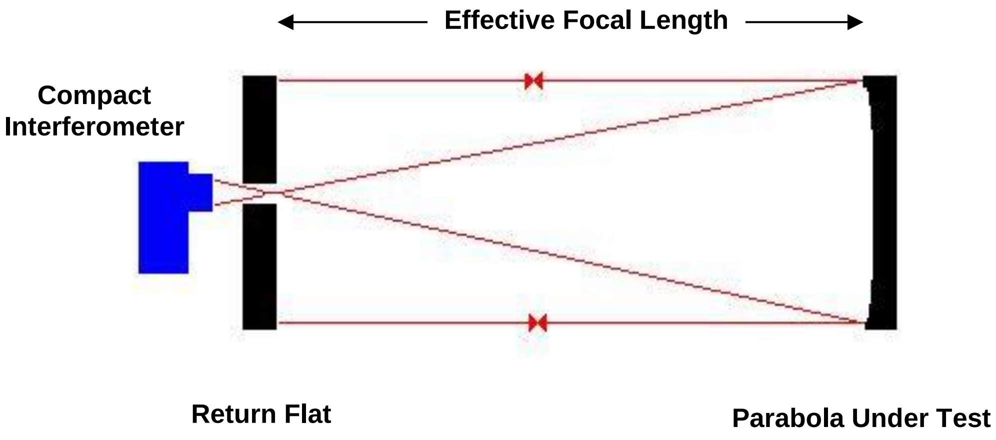


Figure 1
Auto-collimation test for a parabolic mirror

Compact Interferometer

The compact interferometer used in this application was a Fisba Optik μPhase 2 HR. This is a Twyman-Green design, also referred to as a LUPI (laser unequal path interferometer). It utilizes fiber coupling of a frequency-stabilized Helium Neon (HeNe) laser.

Though the coherence length of a typical HeNe laser is ~0.2 meters, stabilized single longitudinal mode HeNe lasers offer coherence lengths on the order of 50 meters. Adequate coherence length is required to ensure suitable fringe contrast over the long test paths associated with large paraboloids.

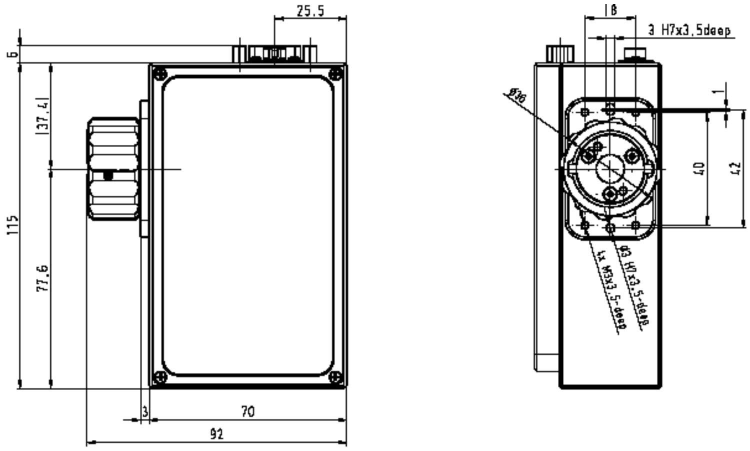


Figure 2
Outline dimensions of the Fisba μPhase 2 interferometer

The interferometer is roughly palm-size; measuring about 2” x 4” x 6.” Mounting features are shown above while a photo of the interferometer is included below. A simple locking ring allows one to mount and dismount auxiliary optics. The interferometer emits a 5 millimeter collimated beam when no focusing objective installed; which is helpful for coarse angular alignment of the parabola and return flat.

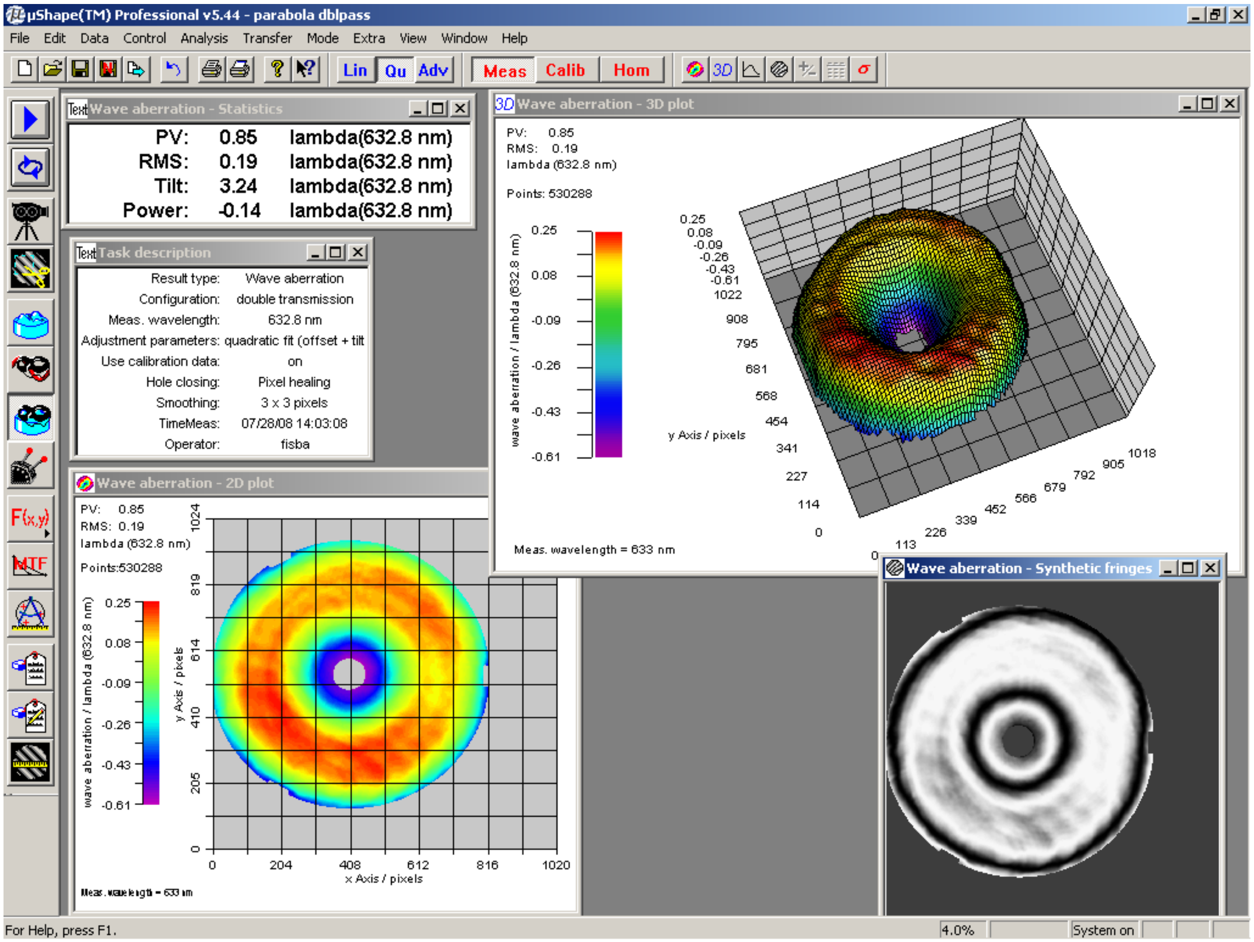
Figure 3
Compact interferometer on 3 axis translation stage

Measurement Results

A “catalog” parabolic mirror was tested according to the method described above. The f/8 mirror has a nominal effective focal length of 100 inches (2540 mm.) with a 12 ½” diameter (317.5 mm.). We illuminated the parabola with a f/7 objective, in order to view the entire surface of the parabola.

The form accuracy of the parabola is specified as “1/8 wave.” Generally, most manufacturers specify form accuracy in terms of PV (peak to valley). However, the supplier of this parabola does not explicitly state whether the value is in terms of PV or rms (root mean square).

For traditional manufacturing methods, one might expect the ratio of PV to rms to be in the range of 4:1 to 6:1. For diamond-turned surfaces, this ratio tends to be higher due to mid-spatial frequency (waviness) contributions on the surface, due to spindle error and or diamond tool contour issues.



PV:	0.85	lambda(632.8 nm)
RMS:	0.19	lambda(632.8 nm)
Tilt:	3.24	lambda(632.8 nm)
Power:	-0.14	lambda(632.8 nm)

Result type: Wave aberration
Configuration: double transmission
Meas. wavelength: 632.8 nm
Adjustment parameters: quadratic fit (offset + tilt
Use calibration data: on
Hole closing: Pixel healing
Smoothing: 3 x 3 pixels
TimeMeas: 07/28/08 14:03:08
Operator: fisba

Figure 3
Transmitted wavefront measurement of parabola in auto-collimation set-up

The “transmitted” wavefront error was 0.85 waves PV, as measured at the 632.8 nanometer wavelength of the HeNe laser. However, to determine the form error of the mirror we must take into account the number of reflections for the test method as well as the difference between surface form error and the wavefront error as reflected by the mirror.

The first reflection occurs as the divergent wavefront from the interferometer objective is reflected by the parabola. Since surface errors double in reflection, a form error of 10 nanometers on the parabola surface would produce a 20 nanometer wavefront perturbation in air; our first factor of two.

However, the wavefront is reflected from the parabola a second time after it returns from the optical flat. Hence, we must divide the total measured wavefront value by a factor of 4 to arrive at the actual form error of the parabolic mirror. Therefore, the form error of the parabola is 0.21 waves PV, some 1.7 times the specified form accuracy of 0.125 (1/8) wave PV.

While there is long tradition in specifying surface form in terms of PV, it has serious limitations. Whereas we collected some 500,000 data points for this particular measurement, PV is calculated using only two data points. Further, PV does not offer any shape information; rather it only expresses a magnitude.

Specifying rms is statistically a more robust measure, as it uses all the data collected. However, it represents an ‘average’ error from ideal; it still lacks useful shape analysis.

For the parabola tested, one can readily observe a strong rotationally symmetric error in figure 3. Utilizing Seidel analysis allows us to confirm this visual observation, where we find the dominant error to be spherical aberration. In comparison, the magnitude of coma and astigmatism are 9% and 3%, respectively, in relative magnitude to spherical aberration.

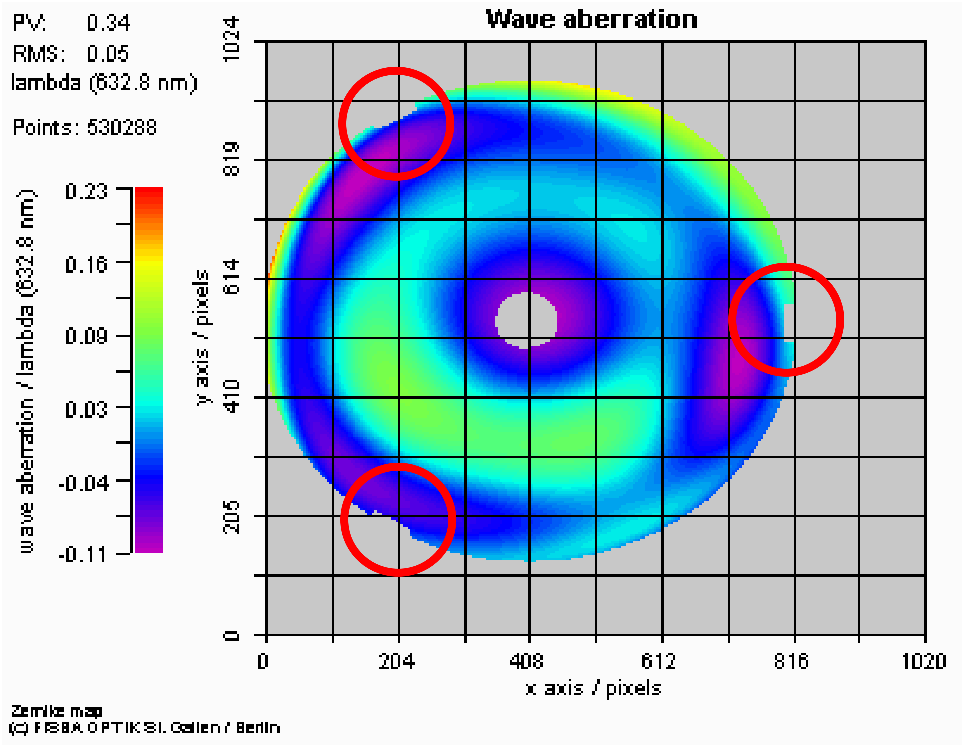


Figure 4
Wavefront analysis reveals mounting distortion

Zernike analysis allows even greater assessment of different error contributions. In the 2D plot above (figure 4), the original wavefront was re-analyzed with the spherical aberration excluded. Please note that the resulting wavefront aberration PV is 0.34 waves; in comparison to the original 0.85 waves.

By mathematically omitting the dominant form error, we can observe the presence of other errors. In this case, it appears there may be mechanically induced surface distortion. That is, one may observe that the three local depressions are in close proximity to the three mounting tabs. Recalling surface error is ¼ the value of the wavefront aberration, the magnitude of this error is less than 1/10 wave PV.

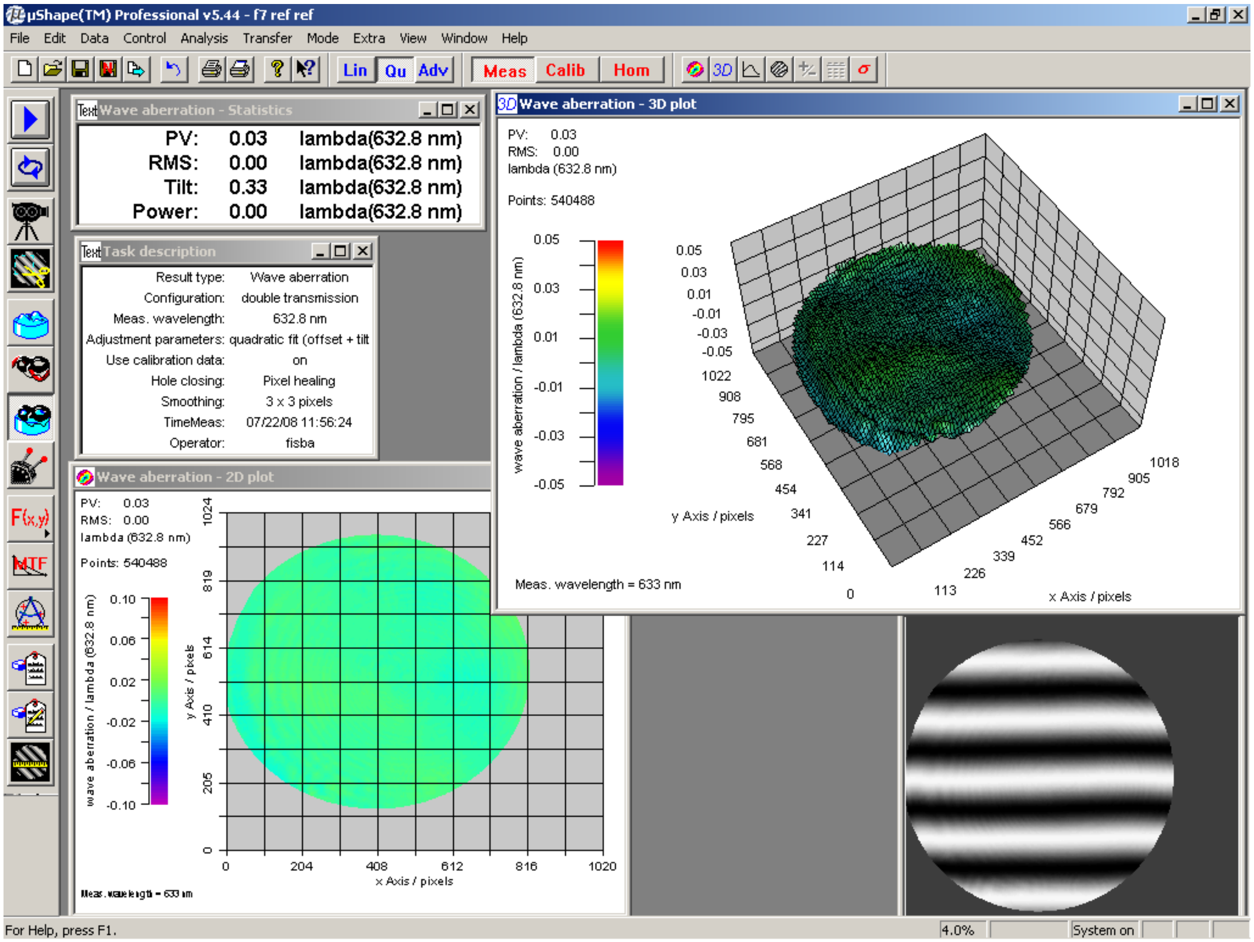
Other Errors

There are several other possible error sources to be considered when performing this type of measurement. Beginning with the LUPI, the beamsplitter and spherical objective have some non-zero error themselves. To address these errors, we used a high quality concave master fabricated from Zerodur to make a reference measurement. The form accuracy of the master was independently verified to have maximum error of 1/20 wave PV (0.03 microns) over the central f/0.70 aperture.

Measuring form accuracy of flats and spheres is easy, with robust adjustment algorithms that reliably separate surface form error from alignment errors. However, testing the parabola requires a bit more care. For instance, a parabola is well corrected only on axis. At increasing incidence angle, one would expect the presence of non-rotational aberrations such as astigmatism. Here again we find the Seidel analysis useful as a means to control this potential error.

Given the long test path, environment can also have some influence on the ability to gather and accurately determine form error. For example, the measurement of this parabola involved an optical path length of ~10 meters. Suitable mechanical vibration isolation and avoidance of thermal gradients/eddy currents is required for this type of measurement.

As long as one can collect the interferometry data, some improvement in measurement precision can be achieved through intensity of phase averaging. The underlying assumption in this approach is that the environmental errors are random in nature.



Wave aberration - Statistics

PV: 0.03 lambda(632.8 nm)
RMS: 0.00 lambda(632.8 nm)
Tilt: 0.33 lambda(632.8 nm)
Power: 0.00 lambda(632.8 nm)

Task description

Result type: Wave aberration
Configuration: double transmission
Meas. wavelength: 632.8 nm
Adjustment parameters: quadratic fit (offset + tilt
Use calibration data: on
Hole closing: Pixel healing
Smoothing: 3 x 3 pixels
TimeMeas: 07/22/08 11:56:24
Operator: fisba

Wave aberration - 3D plot

PV: 0.03
RMS: 0.00
lambda (632.8 nm)
Points: 540488

Wave aberration - 2D plot

PV: 0.03
RMS: 0.00
lambda (632.8 nm)
Points: 540488

Figure 5
Transmitted wavefront measurement repeatability following calibration

As a quick assessment of short-term measurement repeatability, we made measurements immediately following calibration of the interferometer and found the precision to be about 0.03 waves; sufficient for determining the form accuracy for this parabola.

Conclusion

In this paper we present a simply means to measure the form accuracy of large concave parabolic mirrors using a compact interferometer. We found form accuracy of a “catalog” parabola exceeded specification; as well as the possibility of some mechanically induced surface distortion.