White Paper

Interferometer Optical Design:

Image Quality and Data Accuracy

Abstract

A common assumption is interferometers are inherently accurate. High quality reference surfaces, Fizeau common path designs, and powerful software give this impression. Unfortunately life is not so simple. The interferometer optical design, though often ignored, determines much of the quality of particular interferometer measurement. In this paper three performance parameters are discussed: Image resolution, image distortion and retrace error. Data from ÄPRE S-Series, Fizeau and LUPI interferometers, demonstrates state-of-the-art design performance.

Image quality is increasingly important as deterministic polishing methods are nearly ubiquitous. These polishers can leave mid-spatial frequency surface defects that degrade optical performance via scatter in incoherent systems and diffraction patterns in coherent systems. Mid spatial frequency features are loosely defined as frequencies higher than 36 Zernike polynomial features and lower than roughness in the micrometer length scale. For 10's of millimeter sized optics between 0.5 c/mm and 12 c/mm.

A common misconception is resolution is driven by camera pixel count. A 1.2 Megapixel camera is thought to image finer detail than a 1 Megapixel camera. This is only true if the camera sampling resolution matches the optical system design. Three parameters determine imaging performance regarding resolution, distortion and retrace errors:

1. High quality optical design with camera matching imaging goals
2. Manufactured optical assemblies that meet the optical design goals
3. An aperture stop accommodating the desired imaging resolution

1. Optical Design

There are two basic optical designs in interferometers, be they Fizeau or Twyman-Green configurations. Type-1, see figure 1, have an intermediate image on a ground glass that is relayed through a zoom lens to the camera. Type-2, see figure 5, directly images onto the camera with a fixed magnification.

Type-1 Interferometer Optical Design

The type-1 interferometer design was created in the late 1970's. These systems were visual only and used vidicon cameras. The image on the camera had to be large enough to see the fringes therefore a zoom was required. Prohibitively a zoom lens for use in a coherent laser based interferometer would be expensive. Placing the intermediate image on a rotating ground glass created spatially incoherent light through the zoom and camera lenses allowing a very low cost commercial zoom to be used. This design became the standard for 30 years and has remained virtually unchanged, even today.

As noted the aperture stop is a limiter regarding image resolution. In the type-1 system the aperture stop was originally set to limit the maximum tilt fringes to ~75 fringes so that "when the operator saw fringes they would get a good measurement". In the mid-1990's the fixed aperture stop was opened to allow ~150 fringes to enable more applications without regard to other error sources like retrace errors (see section below). Today's designs combine these same optics with a 1 Megapixel camera.

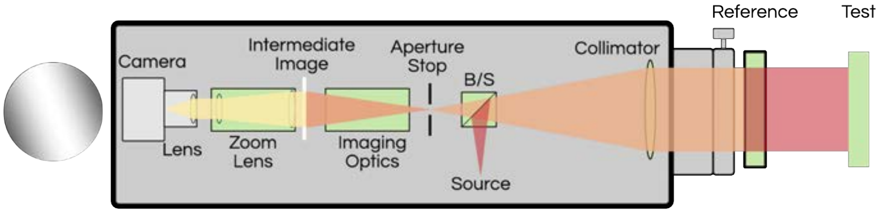

Figure 1: Type-1 interferometer optical design has an intermediate image that is then relayed through a zoom optical system to the camera. These were the earliest interferometer designs necessary when interferometers were used for visual only measurements and initially with 100 X 100 pixel CCD camera pixel sampling.

Type-1 Imaging Resolution Tests

Since the aperture stop limits the imaging resolution, and being fixed, at some point increased zooming will not improve resolution. Tests were run to determine a the limits of Type-1 imaging system imaging. In figure 2b a simple incoherent resolution test is shown. This test is similar to an Modulation Transfer Function (MTF) test.

Testing interferometer resolution in coherent light has physics limitations. An interferometer is a non-linear coherent optical instrument. The resolution depends not only on the interferometer design, but also on the test optic being measured, the heights and frequencies of the test optic surface features and the distance of the test optic from the interferometer. “The transfer function is unique to each test set-up; it must be determined for each test configuration. Experimental variables, such as cavity length, test component location, and working distance, all contribute, along with the physical principles of diffraction, to effect image formation at the detector.”[1] Therefore a reasonable characterization of imaging performance is still an MTF type of test.

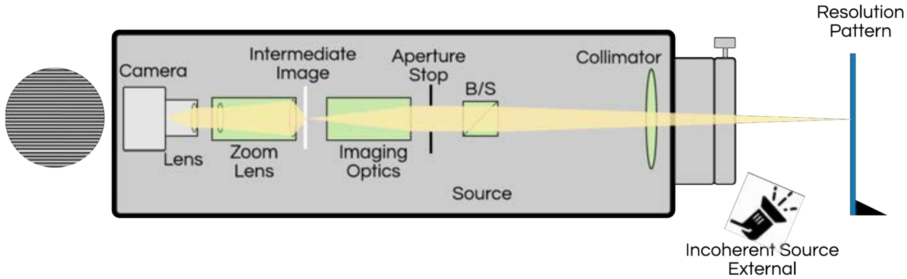

Figure 2a: Image resolution test setup. An incoherent test of the imaging optics

Figure 2b: Test Target

Type-1 Test Results

Test targets of 1.0 mm^{-1} and 2.0 mm^{-1} were used with several 4 inch, Type-1 interferometers. The results shown are typical and varied little. Figure 3 shows the results with a 4 inch, 1 Megapixel camera Type-1 system set at 1X zoom. Note the 1.0 mm^{-1} image is fully resolved yet the 2.0 mm^{-1} image is not. This sets the finest resolvable feature between 1,000 μm and 500 μm. Also the resolution is not uniform across the image. The resolution decreases as the edge of the field of view is approached.

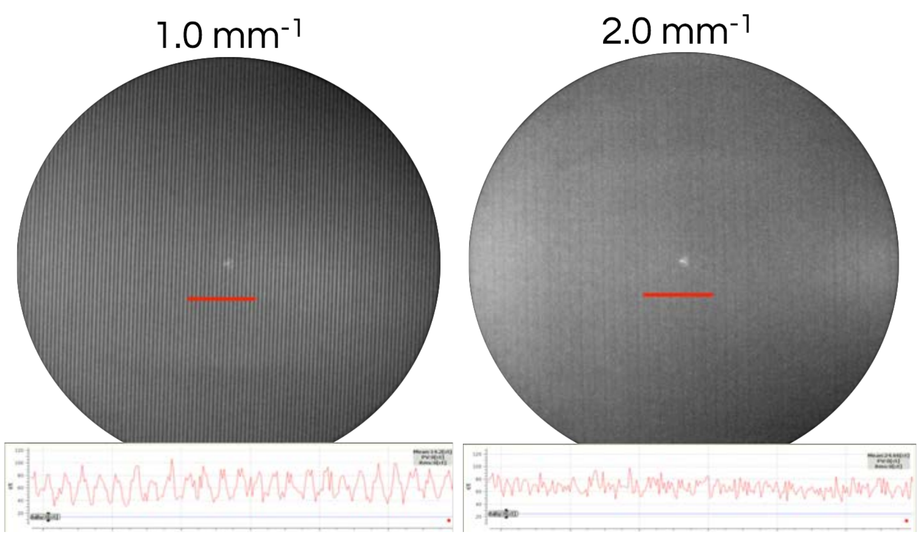

Figure 3: Incoherent imaging of 4 inch Type 1 interferometer. Note 1.0mm^{-1} if fully resolved. Yet 2.0 mm^{-1} is not. Therefore the limit of resolution <2.0 mm^{-1}.

Zoom Resolution in a Type-1

If a zoom is used the resolution decreases as shown in figure 4. The same incoherent test is used on the 1 mm^{-1} line test target. As the zoom is increased the contrast fails indicating loss of resolution. This is because the aperture stop is fixed and the commercial lens optical performance degrades with increased zoom settings.

The image resolution is limited by the aperture stop and the optical system quality when matched with a 1 Megapixel camera. Therefore for a type-1 it is recommended to set the zoom magnification at 1X to achieve the best optical performance. When zoom must be used for a small optic understand the optical resolution will decrease.

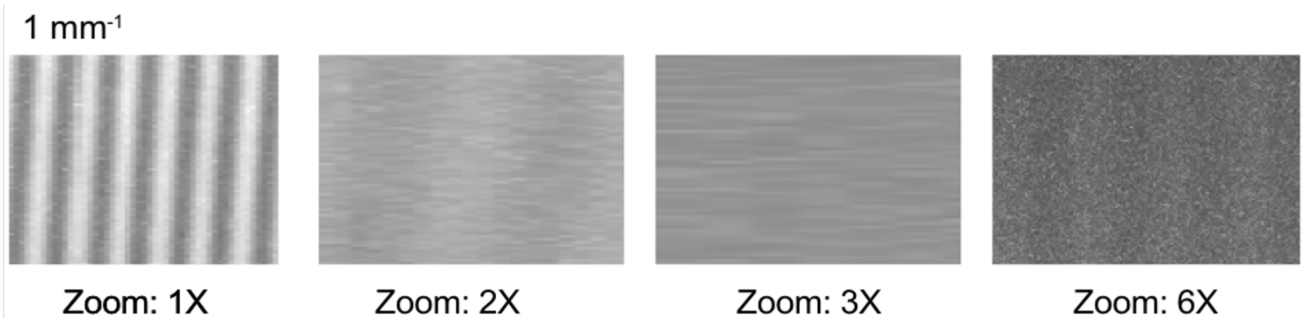

Figure 4: Image resolution with increased zoom magnification. The image resolution decreases as zoom is increased. This is due to the fixed aperture stop and the degrading optical performance of the commercial optical zoom in Type-1 interferometers.

Type-2 Interferometer Optical Design

The Type-2 interferometer directly images the test object unto the camera, see Figure 5 . There is no intermediate image. This enables optimized optical design for resolution, and minimized distortion and retrace errors[2]. The optical system parameters are the same, requiring a well designed optics, matched to the camera sampling, a large enough aperture stop to enable full use of the camera sampling and good manufacturing quality of the optical system.

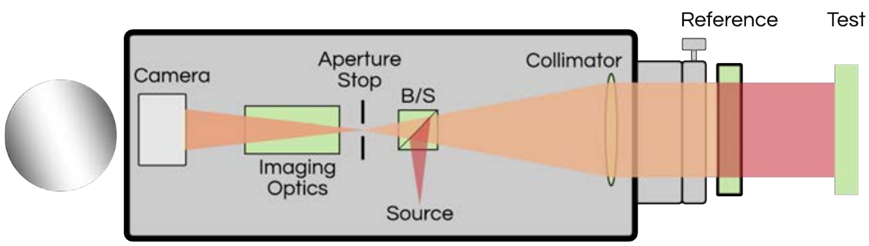

Figure 5: Type 2 interferometer optical design directly images unto the camera. With modern megapixel cameras and matching imaging optics a larger range of optical element sizes can be measured.

Direct Imaging Performance: ÄPRE S-Series Type-2

The image resolution of modern >4 Megapixel interferometers are more difficult to quantify as the resolution is ~100 μm. In figure 6 a phase image of an oil drop on a test plate is measured. This highly magnified image shows a <100 μm droplet imaged as an airy disk as expected at the limits of resolution. This far exceeds the resolution of a Type-1 system.

Imaging Resolution Conclusion

Superior image resolution is possible with a direct imaging interferometer. Thus with a 100 mm Type-2 interferometer a 4 Megapixel camera can measure surface figure of 10 mm diameter surface for an equivalent 10 X zoom imaging system. This far exceeds a Type-1 system in both imaging resolution and "zoom" range.

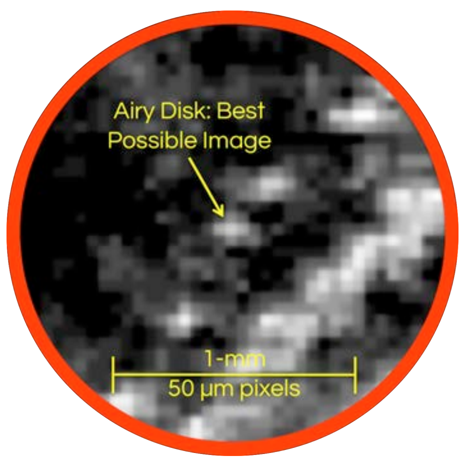

Figure 6: Image resolution on an APRE S100|HR Fizeau inteferometer. Theoretical best phase imaging is 100μm which is demonstrated by the Airy Disk image of the fully resolved small oil droplet. This is a coherent phase image

[1] C. Robert Wolfe, John D. Downie, Janice K. Lawson, "Measuring the spatial frequency transfer function of phase-measuring interferometers for laser optics," Proc. SPIE 2870, Third International Workshop on Laser Beam and Optics Characterization, (20 November 1996); doi: 10.1117/12.259943

[2] A Type-2 Interferometer design enables superior optical performance but does not guarantee superior performance. The optics must be designed properly to achieve the potential benefits.

2. Image Distortion

Image distortion incorrectly maps a test surface location on the camera sensor. The surface height or phase will be correct but the position wrong. For a perfect sphere measured with a perfect transmission sphere and measured at null, distortion does not matter. The created wavefront is planar and a shift in X-Y, in the plane of the wavefront, will not change the result. This is why the old adage is mostly true that a Fizeau interferometer is most accurate when a perfect sphere is measured at null.

Real optics are not perfect nor measured at null and distortion matters. This is especially true with computerized spot polishing. Distortion in the correction map will drive the CNC polisher to the wrong position. Making convergence to specification less deterministic. Also distortion will change the surface map profile depending on the magnitude of the heights and slopes encountered.

Type-1 Interferometer Distortion

Distortion can be created in two sections of the type-1optical system: before the intermediate image and after the intermediate image in the zoom/imaging optics. Distortions before the intermediate image will be added to distortions in the zoom/imaging optics. Anecdotal evidence points to distortion that varies with zoom position and can be up to 2% of the full aperture. For a 1 Megapixel camera that equals 20 pixels of distortion. This is not surprising because the zoom is a commercial grade lens for vidicon cameras and distortion is not tightly controlled.

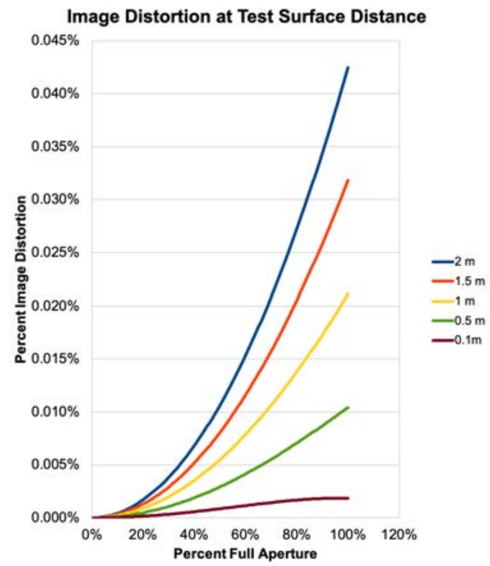

Figure 7: APRE S-Series interferometers (SR, HR and HRx) image distortion as a function of the test surface's distance from the interferometer. Distortion is <0.05% worst case for all ÄPRE interferometers, Fizeau, Twyman-Green, and LUPI

Type-2 Interferometer Distortion

A Type-2 interferometer images directly on the camera sensor enabling an optimized optical design. An example is shown in figure 7 graphing the image distortion present in an ÄPRE S-Series interferometer. Distortion varies with the test object distance. The worst case is >0.05% Distortion at 2 meters test object distance and full field. For a 4 Megapixel camera this is a distortion of <1 pixel worst case.

3. Retrace Error

Retrace errors are a hidden errors. They effect measurement accuracy yet because they are unseen can cause good parts to be scrapped or measurements to vary operator-to-operator. In Figure 8 the cause of retrace errors is shown. When a test surface is tilted, or has local slopes, the test beam follows a different path through the interferometer. Optical aberrations in the interferometer influence the separate paths differently leading to retrace errors. The greater the tilt the greater the errors which are primarily seen as coma.

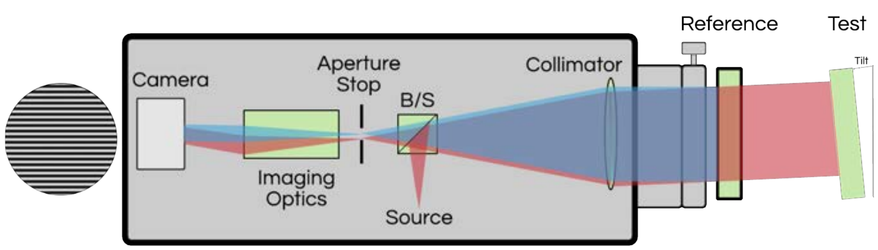

Figure 8: Retrace errors occur when the test object is tilted or by local slopes which cause the test and reference beams to follow different paths through the interferometer; optical aberrations in the optical design cause errors in the measruement.

If retrace errors are controlled to <1/20 wv contributed errors they will be significantly small than the reference surface quality. This increases instrument accuracy. Low retrace errors also simplifies carrier fringe vibration insensitive interferometry minimizing the need to calibrated for these errors when the required many tilt fringes are present.

Interferometer Retrace Errors Measured

To test retrace error first make a reference measurement at the nulled position. Next adjust the test surface to the desired fring number, measure, and then subtract the reference measurement. In Figure 9 retrace errors in a Type-1 interferometer are shown. Here at 150 tilt fringes up to 0.13 wv PVr are recorded.

When measuring a 0.25 wv specified optic, variation of 0.02 can cause a part to be scrapped. One operator might null the fringes, the other leave 5 tilt fringes. The varying retrace errors can cause a part to be scrapped.

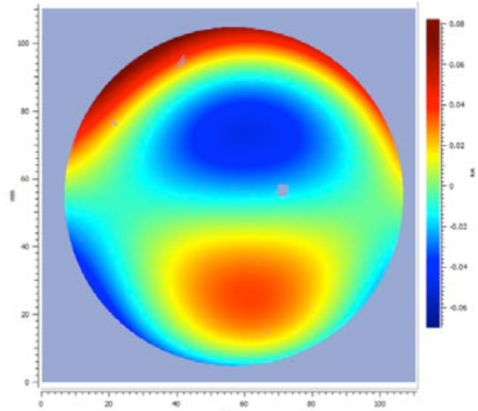

Figure 9: Retrace error in Type-1 interferometer with 150 fringes of tilt on 4 inch system. 0.13 wv PVr error is measured.

Retrace plus Defocus

One parameter often overlooked is focus in an interferometer. Defocus causes diffraction at the test object edge, it also controls the phase of fine surface data on the surface. Less known is the effect on retrace errors. Operator-to-operator variations in focus and tilt magnitude directly induce retrace errors in measurements. In the charts below tilts are exaggerated to demonstrate the effect. In real situations small combinations of tilts and defocus can cause 0.02 wv variations which is 20% of a 1/10 wv (0.1 wv) optical tolerance. When added to other error sources these can be significant errors.

Type-1 Interferometer Retrace Errors and Defocus

Type-1 interferometer designs start with significant retrace errors as shown in Figure 9. Figures 10 and 11 demonstrate how retrace errors grow with defocus. Tilt is induced in all these phase images with focus changed from far to near. Tilt is reversed between the two data sets.

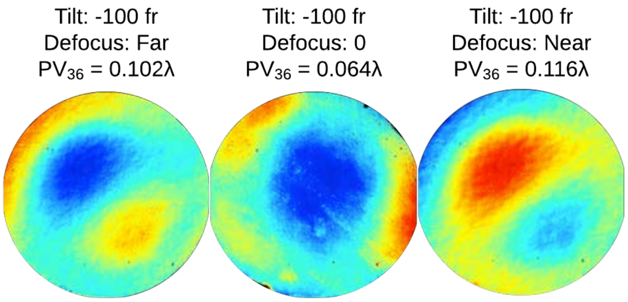

Figure 10: Retrace error plus defocus. -100 fringes of tilt. Increased retrace errors focusing near or far, in the opposite direction to figure 11.

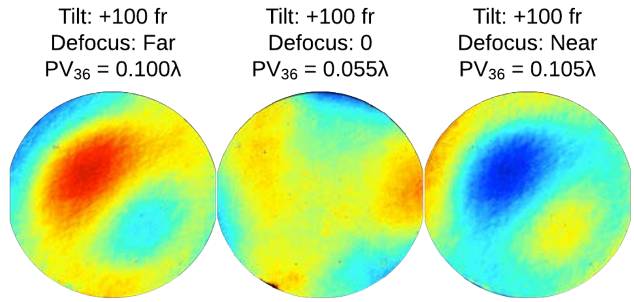

Figure 11: Retrace error plus defocus. +100 fringes tilt. Increased retrace errors focusing near or far, in the opposite direction to figure 10.

With these types of errors present a common suggestion is to null the fringes to minimize these errors. This is not always possible. At times the part's final figure creates local slopes of varying magnitude and direction and due to retrace errors exhibit varying magnitudes of errors. Also with CNC polishing sometimes the part is measured far from final shape and the desire is to quickly converge to the final shape. With the errors due to slopes (out to spec in the case of a sphere) the errors will cause the CNC to incorrectly polish the surface. This iterative process takes time and costs money. Further when measurement uncertainties of better then 1/20 wv are sought, these errors can quickly overwhelm the part tolerance. So tilt induced retrace errors need to be understood, minimized and controlled.

Type-2 Interferometer Retrace Error Performance

A Type-2 interferometer enables optimization for retrace errors. Not only are 4X more fringes, i.e. slopes, able to be measured but retrace errors at those tilts are controled to <1/20 wv magnitudes.

This removes retrace errors as a source of measurement process variation and a source of metrology uncertainty. In figure 12 is shown data from a production S100|HR system, tested for tilt in all four directions. The specification is 1/20 wv (0.05 wv) retrace errors @ 500 fringes. As can be seen this specification has been met.

Vibration Tolerant Measurement & Retrace Errors

In high vibration environments, such as testing long cavities, acquiring data at high speed is required. A common acquisition technique is to use a carrier fringe. Carrier fringes use tilted wavefronts up to 500 fringes to enable this technique. Retrace errors degrade this measurement technique if not well controlled. Common calibration techniques involve multiple measurements with opposing tilts if the retrace errors are too large. When retrace errors are <1/20 wv they become smaller than the reference surface calibration and at times ignorable.

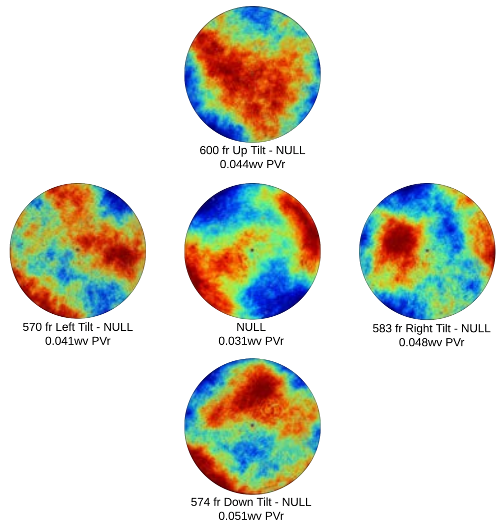

Figure 12: <1/20 wv Retrace Error @ >550 fr tilt on production S-Series interferometer. The Left, Right, Up, Down phase maps have a NULL phase map subtracted (reference subtract) to show the difference between the on-axis null measurement and the minimal contribution of the retrace errors at these large tilts.

4. Summary

Three common though often misunderstood interferometer performance parameters were explored. Type-1 interferometers, the most common interferometer type, have limited performance regarding resolution, distortion and retrace errors. These errors limit the measurement uncertainty and applicability to modern optics.

Type-2 interferometer designs with direct imaging enable the opportunity to minimize these errors and thus enhance performance and applicability to modern optical manufacture. Data from ÄPRE S-Series interferometers was shown to demonstrate state-of-the-are type-2 performance.

5. Äpre Interferometers

All of Äpre interferometers, from 600 mm Fizeau to 6 mm Twyman-Green are based on the same high-performance optical design. Therefore the state-if-the art imaging qualities demonstrated for resolution, distortion and retrace errors are present in all systems.

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