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On Errors In Interferometric Measurements: The Presence of the Interferometer

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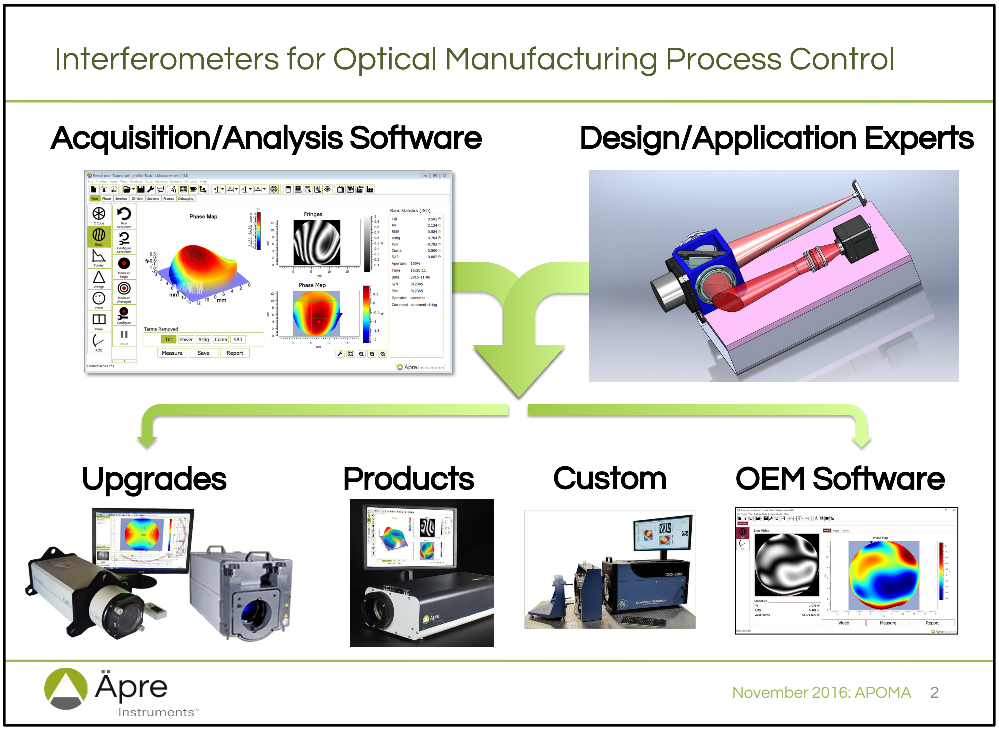
Äpre Instruments is in a unique position to evaluate various designs of interferometers. We upgrade many generation II and III systems (many with designs that are still sold today) and are able to test their performance. This talk refers to our observations.



APRE combines Acquisition and Analysis software with our Interferometer Design and Application Expertise to provide:

- Upgrades to aging interferometers
- State-of-the-art, Generation V, interferometer standard products
- Custom interferometers and systems
- OEM Software

Outline

- Interferometer History
- Retrace Errors
  - With Tilt
  - With Defocus
- Imaging Resolution
  - Optical quality
  - Aperture Stop
  - Zoom?
- S100|HR Performance: Generation V
- Summary

Interferometer History: Basic Technologies

Interferometer Generation	Imaging System	Data Acquisition
Gen I	Zoom with rotating ground glass	Visual or fringe tracking
Gen II	Zoom with rotating ground glass	PSI[†], VTPSI[††]
Gen III	Zoom without rotating ground glass	PSI[†], VTPSI[††]
Gen IV	Discrete magnifications, megapixel camera without rotating ground glass	PSI[†], VTPSI[††], VIPMI[†††]
Gen V	Fixed magnification, multi-megapixel camera with controlled retrace errors	PSI[†], VTPSI[††], VIPMI[†††]

[†] Phase Shifting Interferometry: Multiple camera frames acquired and analyzed for pixel by pixel phase
[††] Vibration Tolerant Phase Shifting Interferometry: PSI with post processing to minimize vibration induced errors
[†††] Vibration Insensitive PSI: Single Camera Frame, rapidly shuttered to freeze vibration. Uses multiple cameras or pixels to extract phase data, therefore typically phase resolution is every 4 pixels acquired.

- Most interferometers in use today are Gen II

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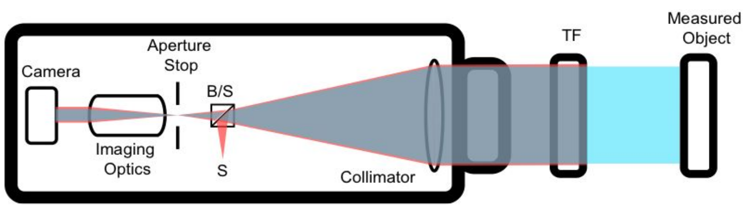
Brief History

Late 1978's: Gen I interferometers were created for VISUAL ONLY data analysis of FLATS and SPHERES, using very low resolution (less than 100 X 100 "pixel") vidicon cameras. Thus the zoom system was needed to SEE small parts and the parts were OBSERVED in a near null condition, less than 5 fringes in the data.
Early 1980's: Phase shifting data acquisition was added to the Gen I interferometers.
Late 1980's, early 1990's: Gen III interferometers (continuous zoom, without the ground glass diffuser) were introduced, the optical error sources and limitations are nearly identical to Gen I and II, so all reported error sources in this presentation apply to Gen III systems
Early 1990's: The first Gen IV introduced the Zeiss Direct 100
2000's: Gen IV become more available – driven by vibration insensitive and mid-spatial frequency (fine surface detail) requirements.
2010's: Gen V become available, driven by the demand for mid-spatial frequency measurements and low retrace errors.

Most interferometers in use today are Generation II and III.

Measurement setup - Fizeau Interferometer



- Measurement of a flat element in a “Nulled” condition (“Almost” common optical path.)
- Instrument induced errors are canceled as test and reference beams traverse the same optical paths

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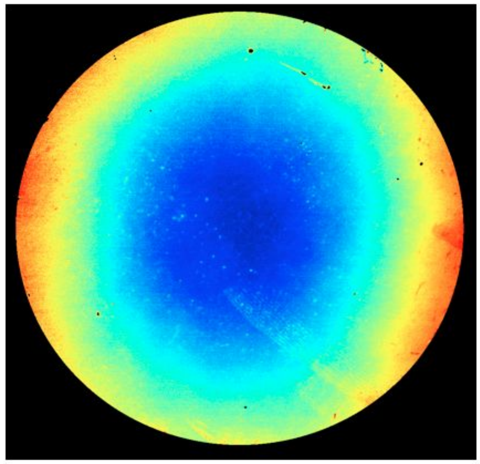
The Generation II and III systems discussed in this talk are designed for measurement with nulled fringes, when they are “almost” common path.

The system induced error at null cancels out if the fringes can be nulled (Measured part is close to perfect).

Measurement of a flat: “Nulled” condition

REFERENCE:
Tilt: Nulled
PV_{36} : < 0.05λ



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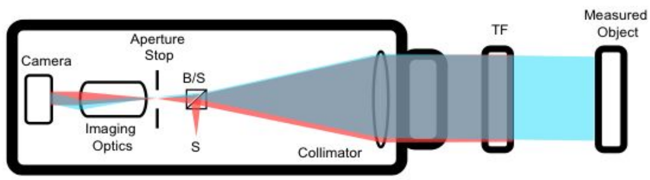
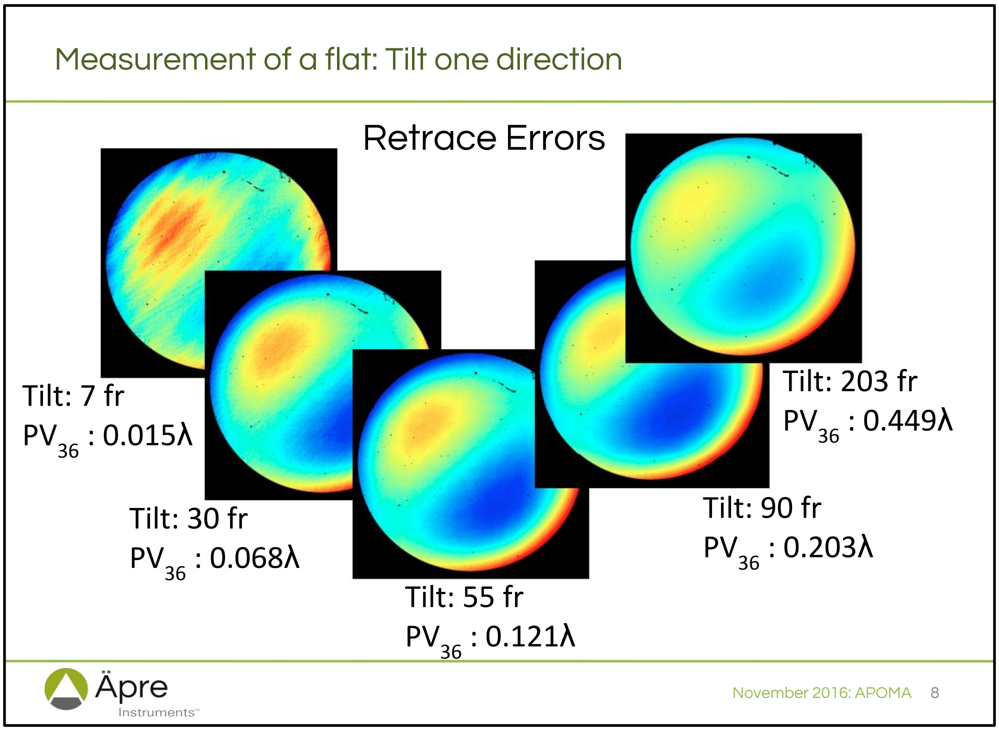
Here is an example of a nice measurement with <1/20th wave of power.
This measurement is used as a reference through the rest of the presentation.

Retrace Errors: Tilted wavefronts



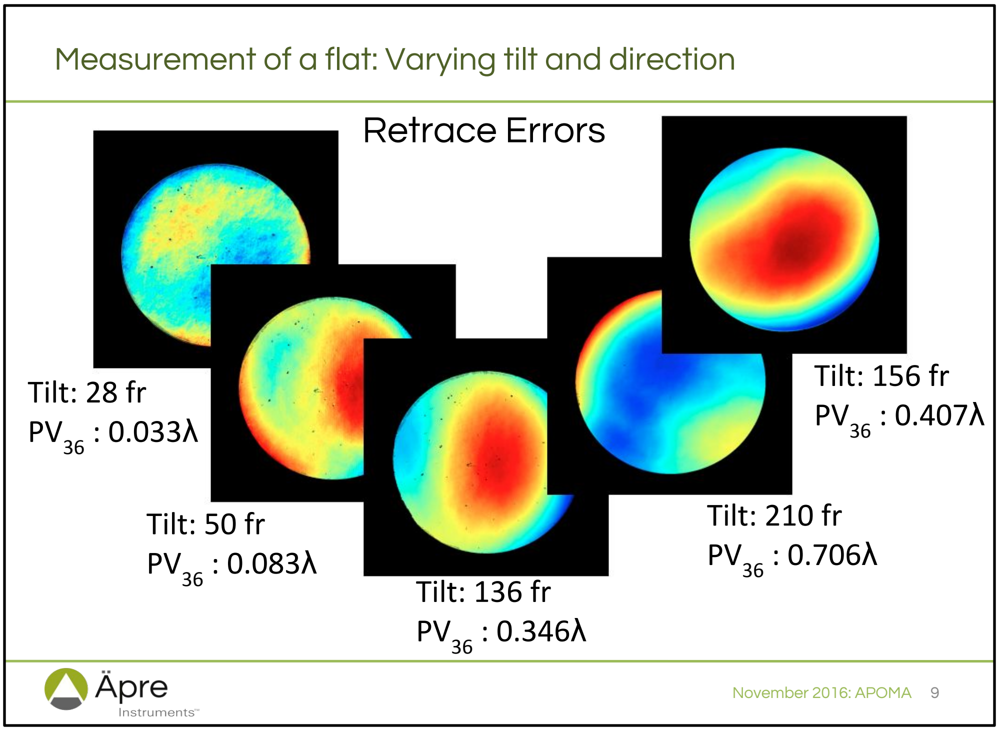
- Measurement of a flat element with a tilt between reference and test beams.
- Instrument induced errors are not canceled as the test and reference beams traverse slightly different optical paths.
- **Problem**: The error amount is unknown and difficult to predict.

When the part is tilted or there are local slopes on the surface under test, errors are induced in the measurement. These errors are not cancelled as the test and reference beam paths are different. The magnitude and distribution of these errors is difficult to predict and thus hard to correct or account for.



Here are some examples of the magnitude of these error. These results show the difference between the measurement of a tilted pair of flats and the reference measurement shown previously.

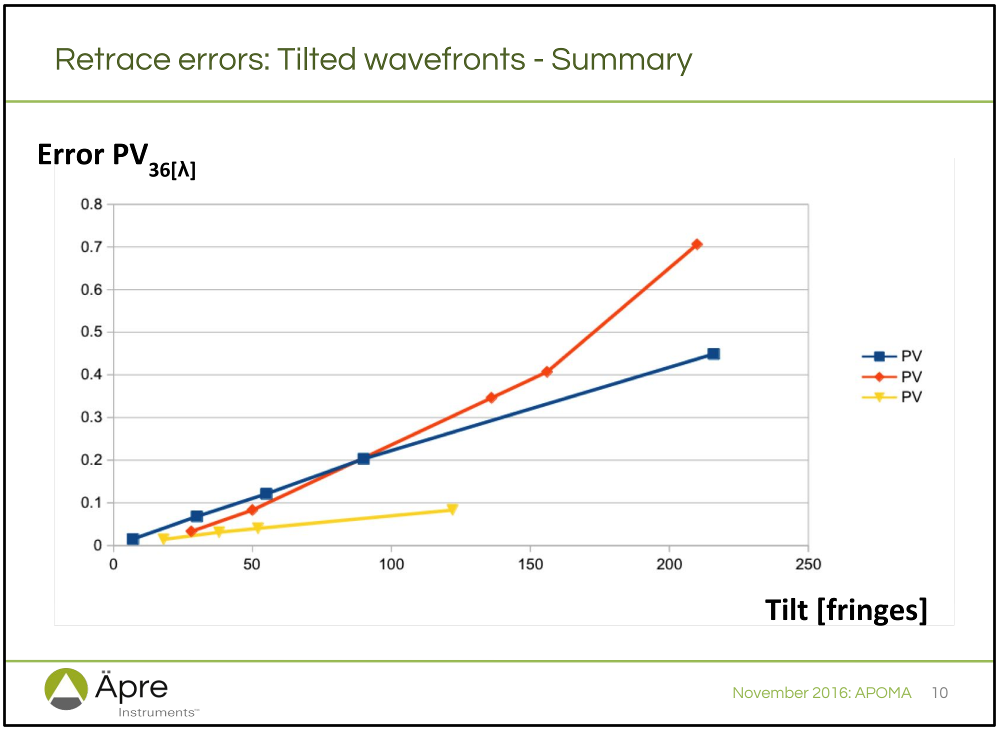
Please note that the error introduced is much greater than 1/20th wave and increases quickly with the tilt.



Here is the same pair of flats but the tilt magnitude AND direction are changed.

Note the magnitude is a function of both!

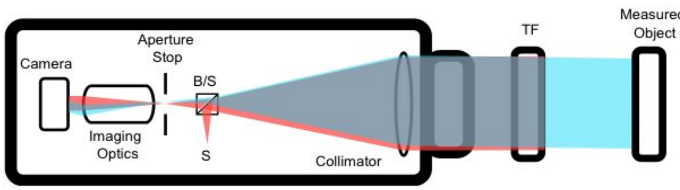
Therefore when surface slopes are present the measurement uncertainty (accuracy) varies across the surface in an unpredictable manner



Plotted magnitudes of the retrace errors due to tilted wavefronts for three different Gen II & III interferometers.

Note ÄPRE's S100|HR Gen V exhibits less than 0.05 waves retrace error at >650 fringes tilt

Retrace Errors: Tilt + Defocus



- Measurement of a flat element with a tilt between reference and test beams and defocused camera
- Instrument induced errors are augmented by the test and reference beams being mutually translated (“sheared”) on the camera detector

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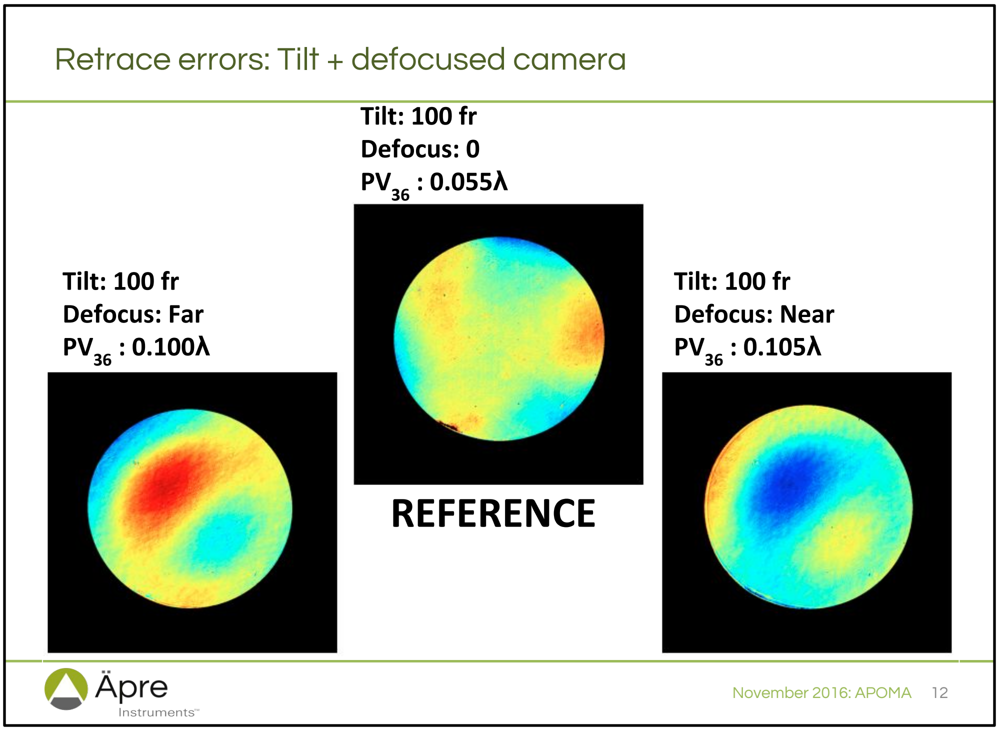
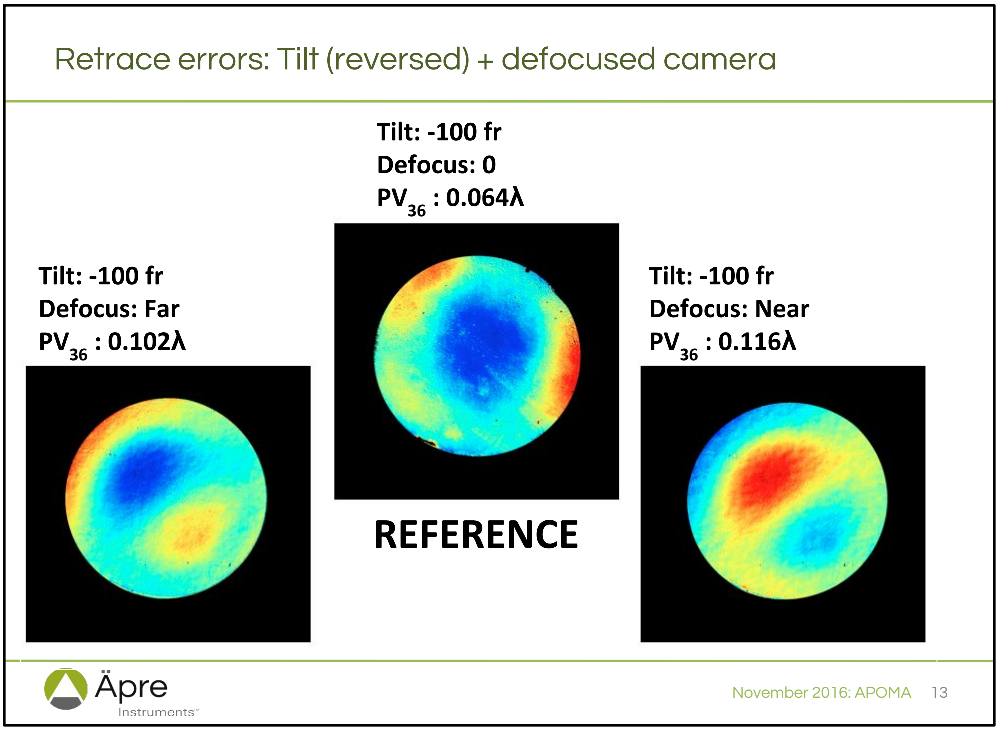
When tilt or slopes are present on the part under test and the interferometer is not focused correctly errors are also created due to the test and reference beams being sheared at the camera detector



Here are seen the effects of tilt + defocus after subtracting the reference measurement. The magnitude can be up to 1/10th wave error.



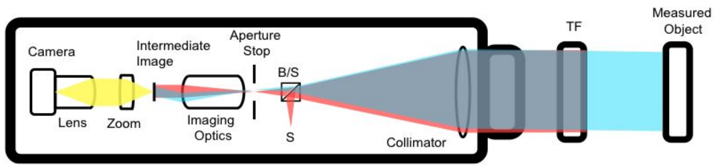
Here are shown the same error but with the tilt reversed.

A common suggestion is to simply null the fringes to minimize these, and the previously discussed retrace errors. This not always possible.

At times the part's final figure creates local slopes of varying magnitude and direction that each induce varying magnitudes of errors. Also with CNC polishing often 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 than 1/20th wave are sought, these errors can quickly overwhelm the part tolerance.

Conclusion: Tilt induced errors need to be understood, minimized in the interferometer design and controlled.

Geometric errors: Imaging Resolution for Mid-Spatial Freq’s.



- Image Quality is defined by the quality of the imaging optics
  - Type 1: Intermediate image on rotating ground glass that is re-imaged on the detector using a zoom and photographic lens
  - Type 2: Direct imagining on the detector
- Aperture Stop – Limits system resolution
  - Aperture stop size sets an upper limit to the number of fringes allowed on the detector

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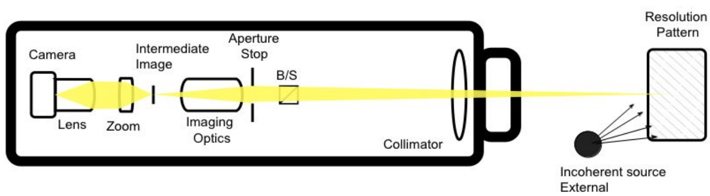
Imaging is the other main function of the interferometer. There are two primary imaging configurations: rotating ground glass with zoom lens (Gen II) and fixed single magnification (Gen V). To obtain good quality imaging the optics in all cases must be of high quality and designed well, but this is not sufficient.

The size of the aperture stop (see drawing in slide) sets the nominal resolution of the system (which can be degraded by the optical design and quality).

The aperture stop often limits resolution because the designers are required to limit the maximum number of fringes to below the Nyquist limit of the detector.

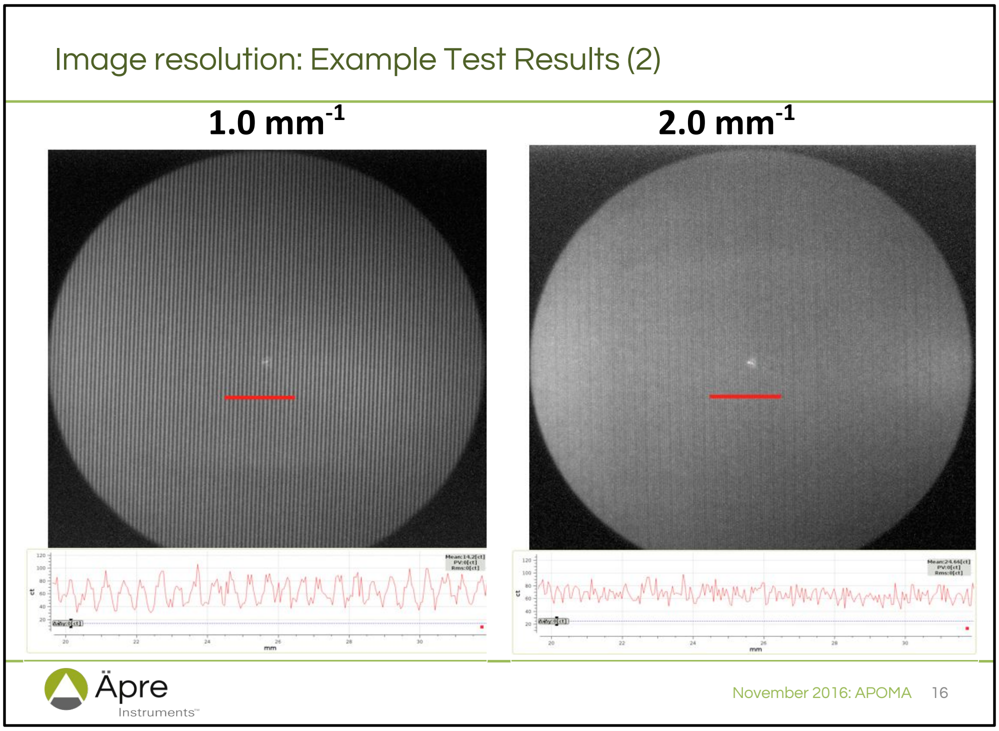
In early 1990’s the Zygo Mark and GPI interferometers aperture stop was doubled in diameter to accommodate greater surface deviations, without improving the optical imaging system, thus increasing the system’s vulnerability to retrace errors and leaving the resolution of the optical system at the previous level - a configuration that was different from the original designers intent.

Image resolution: Simple Test



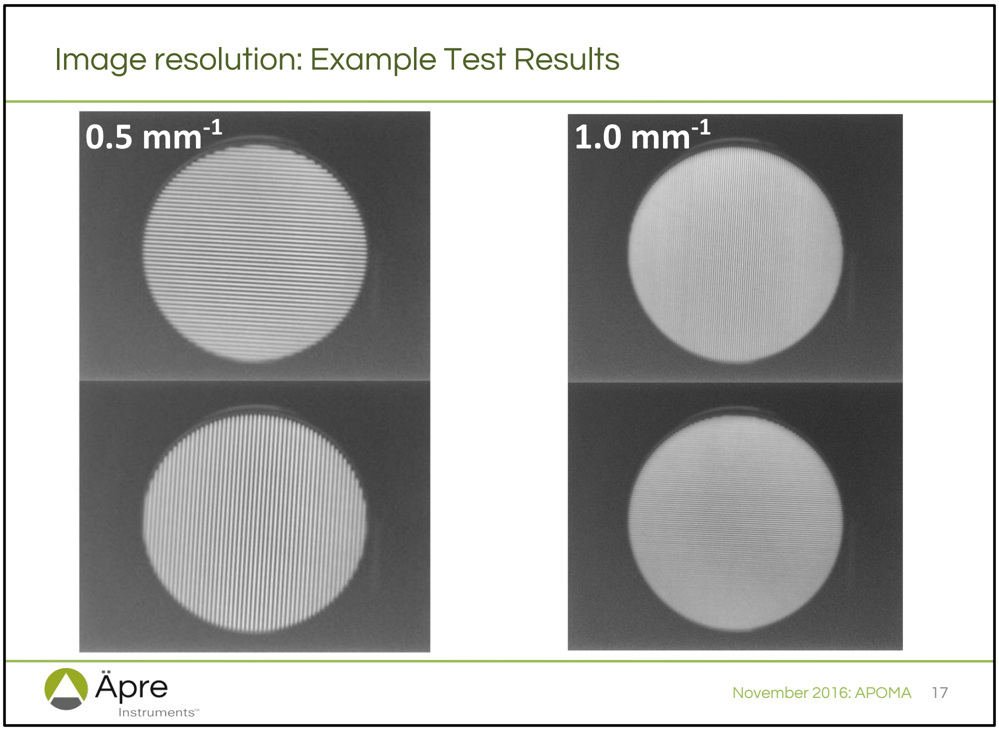
- Test: A simple resolution target is illuminated with an external incoherent source.

Follow this setup to test the optics. Email Apre Instruments at inquire@apre-inst.com to request a 1 cycle/mm printed test target with instructions.



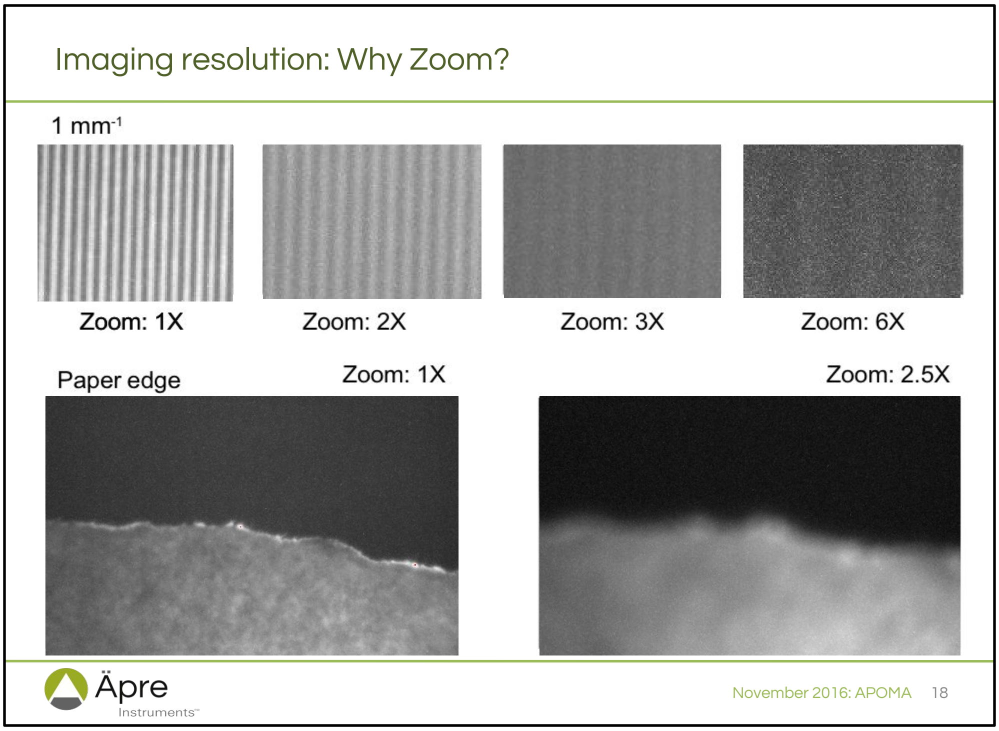
Here is an example from a Generation II ground glass + zoom lens system. On the left is a 1 cycle/mm test target and on the right a 2 cycle/mm test target. Clearly the system cannot resolve details much smaller than 1 mm. This system has a 1K X 1K camera, for a nominal pixel size on the 100 mm aperture of 0.1 mm. So the system is limited by the quality of the optical system or the size of the aperture stop – it does not matter.

Is the resolution the same for vertical and horizontal lines?



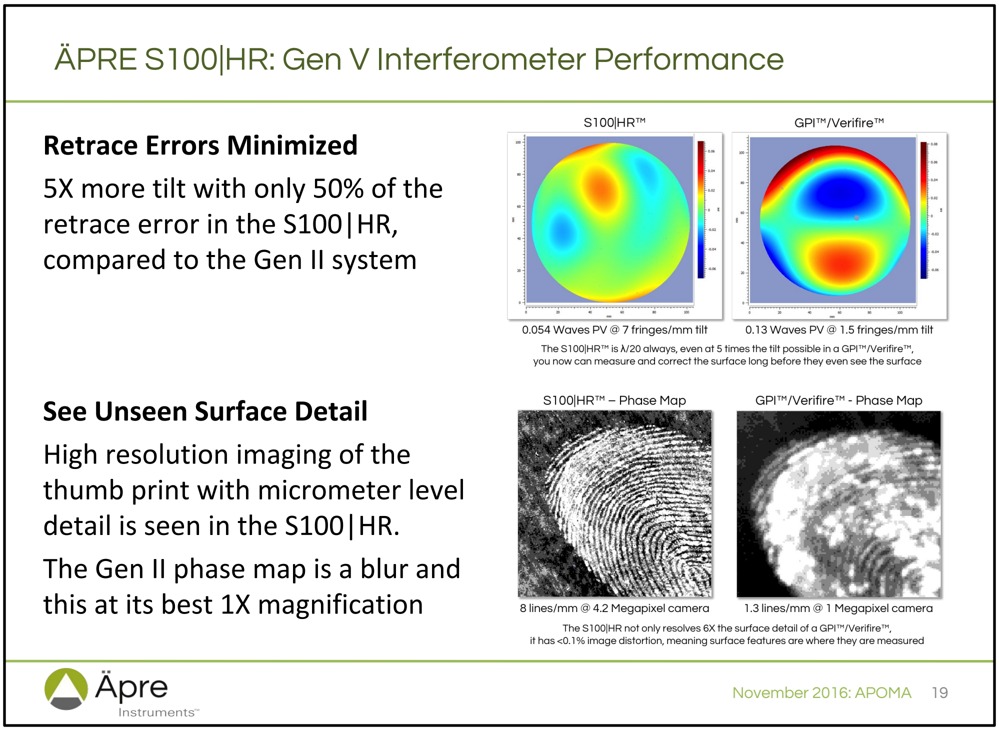
Again the left images 0.5 cycle/mm spaced lines and the right 1 cycle/mm spaced lines. In each case the center shows better resolution than the edges.

What if the system is zoomed to get a closer look?



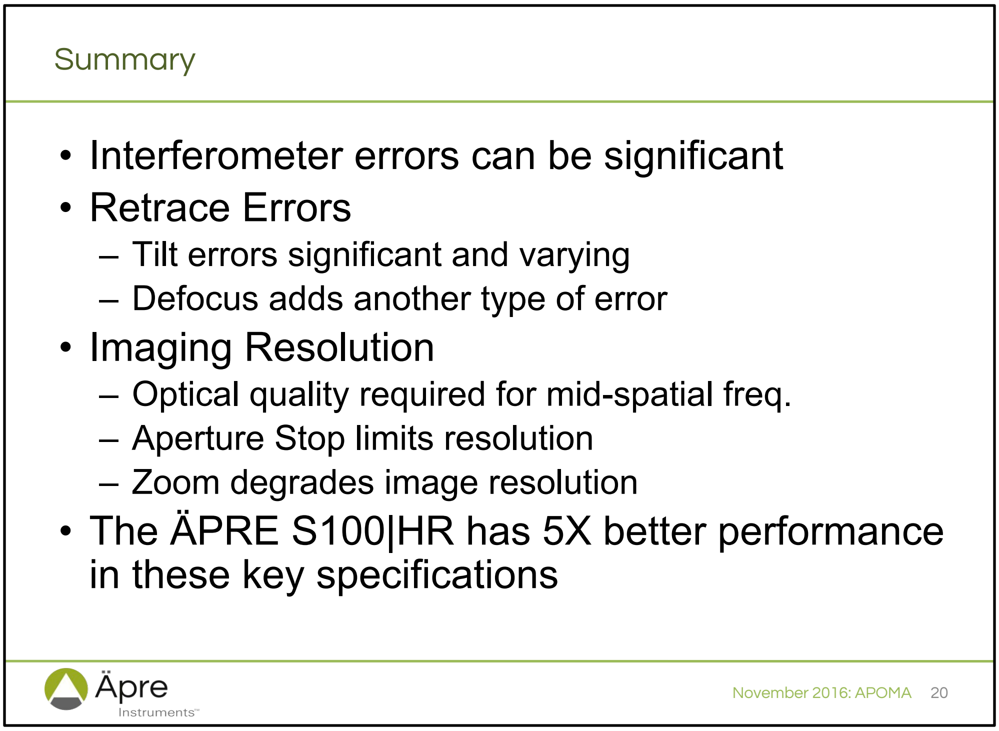
As can be seen in the top row, zooming only makes the situation worse! This system has been lined up and optimized, this system is not out of adjustment. The bottom row demonstrates how the zoom loses resolution, as this is the best focus position.

So the question is why zoom and why build a zoom system? The correctly designed interferometer optical system should have its resolution limited by the size of the aperture stop adjusted to the resolution of the detector - thus zooming the image does not increase the amount of details the system can resolve! Modern Generation IV and V interferometers do not have a zoom system nor ground glass for good reason, they maximize imaging resolution AND minimize retrace errors at the same time.



The Äpre Instruments S100|HR laser Fizeau interferometer exhibits 5X better performance in the key specifications of resolution and retrace errors over the Generation II and III analyzed in this presentation.

This increased performance is important to controlling modern CNC polishing processes and mid-spatial frequencies for all processes.



In summary: Interferometer errors can be significant and an awareness of the errors in the interferometer are important to understand and characterize to confirm that the measurement performance meets your requirements. These come in two main errors source Retrace error and Imaging Resolution errors. Both are easy to test for and quantify.

The Generation V S100|HR from ÄPRE provides 5X better performance in these key specifications.

For more information:

- See our article in Laser Focus World **http://www.laserfocusworld.com/articles/print/volume-52/issue-11/features/interferometry-three-simple-tests-assess-interferometer-performance.html**
- Or contact us at inquire@apre-inst.com