Substrates, Prisms, Flat Optics and Windows Interferometer Measurements Made Easy

by: Robert Smythe, rsmythe@apre-inst.com

Abstract: Substrates, Flats, Prisms and Windows[1] are essential optical components enabling modern technologies. Interferometric level accuracy is required, but difficult to achieve due to limitations in available interferometers. New Technology, Spectrally Controlled Interferometry (SCI) combined with high resolution interferometers removes all the limitations of the alternatives making these optics easy and fast to measure. SCI plus alternative technologies will be reviewed.

Flat Optics and Prisms Are Hard to Measure

When measuring plano optics, the parallel surfaces of the object all return overlapping fringes. An example of a typical plano object's overlapping fringes is illustrated in figure 1. Because this is a property of the part, the only way to successfully measure a surface of the part is to eliminate one of the surface's fringes. Once an interfering surface's fringes have been subdued, the part can be measured then rotated to allow the previously subdued fringes to be measured. This paper will discuss various approaches to eliminating these interfering fringes and the benefits and limitations of each. We examine Laser Fizeau interferometry, grazing incidence interferometry, delay line interferometry, wavelength shifting Fourier transform interferometry, and finally spectrally controlled interferometry.
Another topic worthy of note in any discussion of interferometric measurements is the issue of image resolution. Increasing image resolution means a larger range of part sizes can be measured by the system, leading to a more efficient and cost-effective setup. Image resolution is not to be confused with pixel sampling. The optical resolution and camera pixel sampling must be matched. We will address relevant limits on image resolution with the various interferometry approaches.

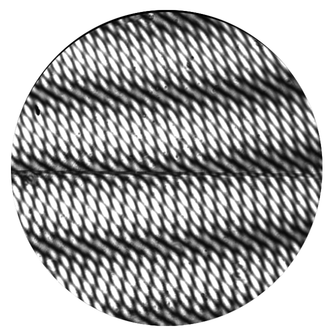


Figure 1: Confused interference fringes caused by back reflections off several surfaces in a laser Fizeau interferometer

Laser Fizeau Interferometry

Laser Coherence Problems

In many cases, measurements using a laser Fizeau interferometer are easy to set up. The long-coherence source produces fringes over all optical path lengths[2] (OPL). While this makes for easy measurements of most objects, it presents a challenge for plano objects as all of the parallel surfaces produce overlapping fringes. An example interferogram of these confused fringes can be seen in figure 1.

[1] Substrates, glass wafers, prisms, windows and domes will be called plano optics in this paper
[2] OPL = index of refraction of the glass * physical distance

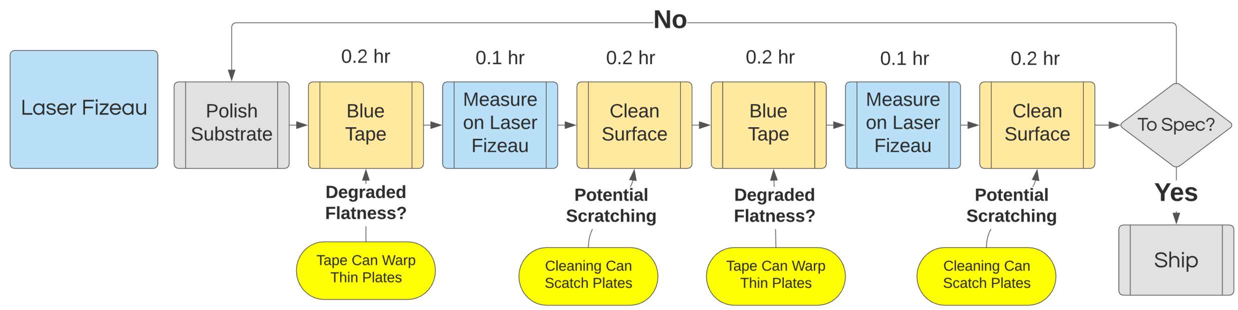


Figure 3: Flow Chart of the process of taping the substrate surfaces to measure with a laser Fizeau interferometer. The labor costs of this process can cost $50 per part, If only 4 parts are measured a day that's $50,000! For painting the surface the cost can be double this due the cleaning difficulties

The industry has developed techniques to avoid the unwanted back reflections. These include painting, taping and greasing the back surface. The concept is to "index match" and absorb the light off the surface to suppress its fringes. The techniques work though not without costing time and labor. Manipulating the part extensively creates potential for surface damage, and reduced accuracy as the applied material will warp the part, especially with thinner parts which might simply break in response to handling.

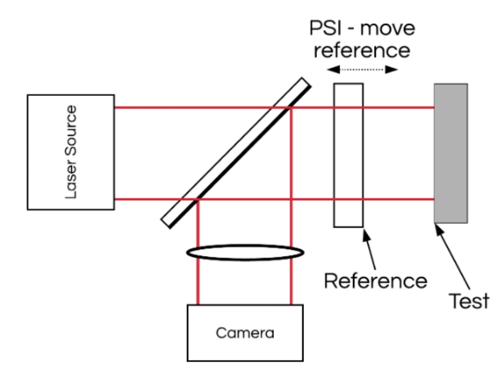


Figure 2: Classic Laser Fizeau: Simple design enabled by laser's long coherence length, unfortunately limiting plano optics measurement by producing fringes anywhere along the OPL.

Taping is one of the "fastest" processes available. The part is taped, measured, then the tape removed and part cleaned. The same process is repeated for each surface. If the part passes it is shipped; if it fails to meet specifications the part is sent back for further processing. This time and labor intensive system is illustrated in figure 3 on page 2. The process can take up to an hour per part, depending on size and shape. At typical labor plus overhead rates this can translate to $50 per part, or $50,000 per year at only 4 parts measured daily. Therefore the annual cost of the techniques to overcome back reflections can be equal to an interferometer cost itself, and $250,000 over the amortization period of the interferometer.

Optical Resolution Limitations

Three factors determine optical resolution in an interferometer: Optical design, manufactured quality and the field stop.[3] Most laser Fizeau interferometers in use today are zoom systems. The zoom was included in a 1978 design to accommodate visual fringe interpretation and later very low resolution cameras (100 X 100 pixels). The zoom enabled measuring optics to approximately 1/6th the full aperture or about 20 mm on a 4" system. Imaging resolution of 100 X 100 is sufficient to measure form of the surface up to 36 Zernike polynomials at typical measurement criteria. Of the three factors determining optical resolution the aperture stop is the limiter in the resolution, as the optics were matched to this.

As camera resolution increased the optical design and aperture stop have remained the same. Therefore the inherent resolution has not changed, only the useful zoom range without empty magnification has decreased. With a 1-Megapixel

[3] Interferometer Optical Design: Image Quality and Data Accuracy, Download White Paper, *Interferometer Optical Design: Image Quality and Data Accuracy*

camera, zoom is not needed as the system is now optically limited at 1X, therefore zooming spreads the image out without any gain in resolution.

Laser Fizeau Interferometer	
Strengths	**Weaknesses**
• Easy to Align	• Confused fringes require supression • Taping/Painting required to suppress • Slow processing time - up to 1 hour front & back • Potential damage due to supression techniques • Zoom system: 5:1 part size range per aperture • Suppression costs ~$50,000/yr @ 4 parts/day • Cannot measure prism faces

Grazing Incidence Interferometry

The grazing incidence interferometer with prism was developed primarily to desensitize the fringes from 0.633 nm to an effective 5μm. This enabled measuring industrial parts with ground and machined surfaces. It is also useful to measure the front surfaces of substrates as the spatial coherence can be adjusted to eliminate the back surface.

The optics require a large prism which limits the aperture to <200 mm square, making this instrument impractical for larger parts. Another limitation is image resolution. The image resolution is unequal due to the smearing in the grazing direction and the unchanged image resolution across the image. Mathematically this can be compensated, but the limit of resolution is the grazed direction. In a 5 μm equivalent wavelength system and 1-Mega-pixel camera the smallest part measurable is approximately 20% smaller than the full aperture.

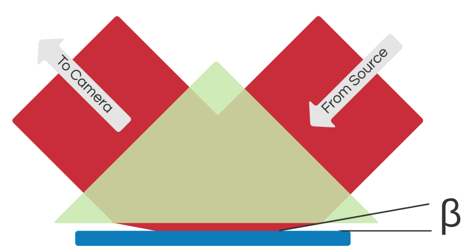


Figure 4: The Grazing Incidence interferometer is a Fizeau that uses a prism to bend the collimated light at a steep angle β up to 80° to desensitize the fringes. The spatial coherence is adjusted to eliminate back reflections.

Grazing Incidence Interferometer	
Strengths	**Weaknesses**
• Isolate front surface • Fast alignment if fixtured	• Front surface only • Unequal X-Y image resolution • 2:1 part size range per aperture • <200 mm aperture due to large prism size • Cannot measure prisms

Delay Line Interferometer

Short coherence source interferometry narrows the coherence to a short micrometer range. When white light fringes are placed on the surface only that surface will be measured so the troublesome backside interference is eliminated. A delay line interferometer design, figure 5, has a coupled internal interferometer that "pushes" the interference fringes away from the Fizeau flat making them usable.

As with all white light interferometers finding the fringes in a system >30 mm in aperture is **very** difficult.

There are two configurations: Fixed or movable fringe position. With the fixed position the test part is moved to the position via stages. In a downward looking system a Z stage moves the part into position and repeated parts are placed on the table. This setup does not allow for measurement of total thickness variation or wedge, as the part must be physically moved to the fringe position, and Z-stage motion errors hinder such measurements. Plus the fixed delay line system is not able to measure prisms

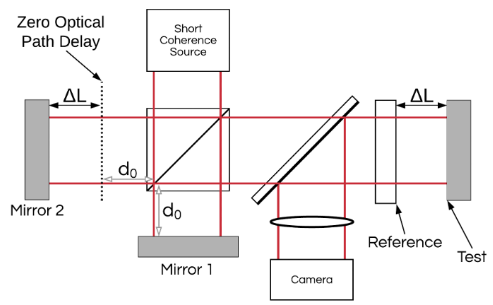


Figure 5: The delay line interferometer couples two interferometers together causing a set of interference fringes to be distant from the Fizeau flat. The delay line can be fixed or movable

The movable fringe position system adjusts the delay line interferometer to move the fringes - so the Z-Stage is not needed. In this case front and back surface can be measured as well, but errors in the stage that adjusts the delay line make the measurement of TTV inaccurate. .

White Light Delay Line Interferometer	
Strengths	**Weaknesses**
• Isolate surfaces to 150 nm OPL	• Difficult to find fringes and align • Special purchase interferometer - one use • Fixed Delay Line cannot measure TTV/Wedge • Fixed Delay Line Cannot meaure prisms

Wavelength Shifting Fourier Interferometry (WSFI)

WSFI replaces the laser of a laser Fizeau (figure 2) with a scanning laser diode and uses Fourier mathematics to calculate the cavity locations in the interferometer. The single frequency laser diode makes alignment easy, like a laser Fizeau. Data acquisition is achieved by wavelength shifting the laser diode. As the laser diode scans short cavity fringes modulate (pulse) slowly and long cavity fringes modulate (pulse) rapidly. A Fourier analysis of the camera intensity over the time of acquisition separates the cavities based on pulse rate. This process is illustrated in figure 6.

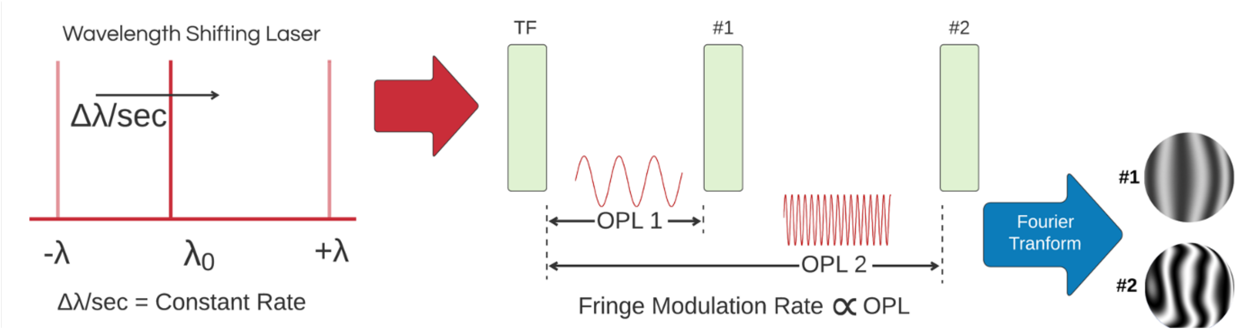


Figure 6: Wavelength shifting Fourier interferometry modulates the laser diode at constant rates and records the intensity pulses in the cavities. After acquisition a Fourier transform identifies separate cavities and reports the measurement results

There are several limitations to this approach:

- A minute long data acquisition can be required for short cavities to achieve the large wavelength shifts to fully modulate the fringes for a phase measurement.
- Long acquisition times expose the interferometer to environmental variations during measurement, therefore repeatability can be poor unless the environment is stable.
- The minimum cavity OPL measurable is approximate 1 mm due to limitations in laser diode scan range
- There is no visual feedback that the measurement was correctly done, or that the correct cavity was measured.[4] You must depend on the algorithm and that you chose the correct cavity representing the surface of interest.

Wavelength Shifting Fourier Interferometer	
Strengths	**Weaknesses**
• Isolate surfaces when multiple present • Measure fixed & large cavities • Measure ≤2 meter OPL • Measures prisms	• Slow acquisition is vibration and turbulence sensitive, especially for short cavities • No visual confirmation that the surface of interest was measured - must trust the algorithm • Short cavity OPL limit ~1.0 mm • Special purpose Interferometer

Spectrally Controlled Interferometry

Spectrally controlled interferometry, or SCI combines the ease of use of laser Fizeau with the isolation of white light. This combination makes the measurement of plano optics easy. **SCI is an electronically controlled source which connects to any existing Laser Fizeau**. The **SCI has two coherence modes:**

- Long coherence mode for fast alignment
- Short coherence mode to isolate and measure the test surface in milliseconds, regardless of the cavity OPL.

The benefits of the SCI compound with the advanced design of Äpre's S-Series Laser Fizeau design. Because of its modern optical design, the imaging resolution of the instrument has none of the drawbacks of zoom imaging systems. The diffraction limited image resolution of the S-Series enables a part measurement range of 10:1. This means an S100|HR can measure both 100 mm diameter parts and 10 mm parts for form, *anywhere* in the FOV. This is 2X more size range than

[4]When fringes are isolated on a surface there is a visual check of the aberrations to expect. With WSFT no such feedback is possible.

a classic zoom interferometer. Figure 7 graphically shows the range of part sizes measurable with various ÄPRE S-Series interferometers.

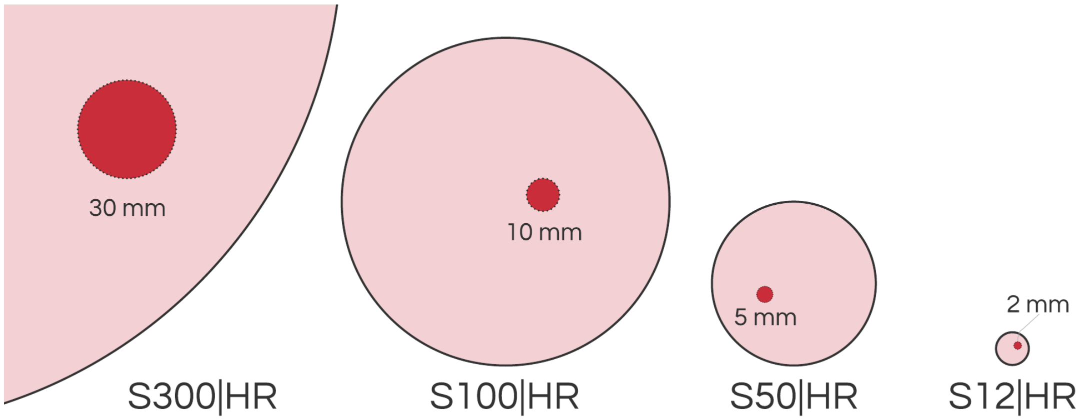


Figure 7: S-Series diffraction limited optics have the greatest measurable size range of any interferometer

When SCI is combined with an S-Series interferometer you now have the fastest, easiest to use, most accurate interferometer with the greatest range of parts sizes you can measure.

Optical Bandwidth, Line Frequency and Phase are Electronically Controlled in SCI

There are three parameters electronically controlled with SCI: The spectrum bandwidth (which controls the isolation and the easy to align laser mode, see figure 8), line frequency (which controls the fringe position, see figure 9), and phase (which controls the fringe phase and data acquisition, see figure 10).

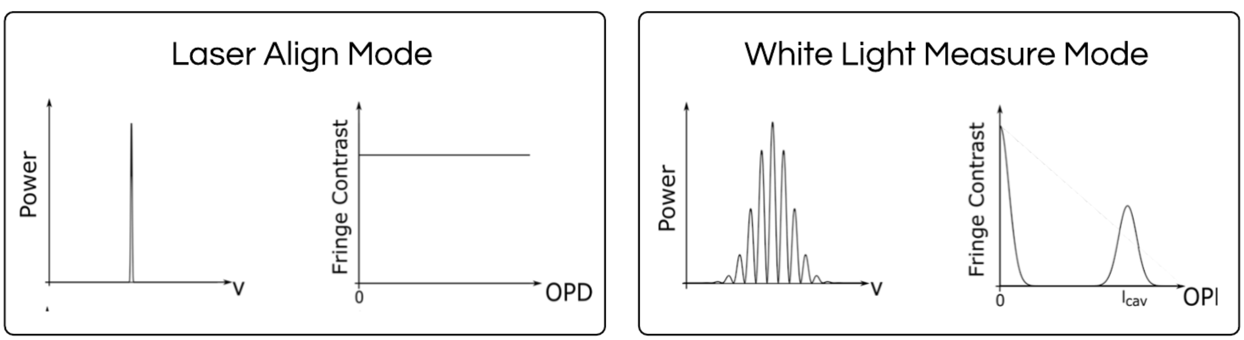


Figure 8: SCI can electronically switch between single line, laser, coherence for alignment (left graph) and a broad spectrum to narrow the coherence for surface measurement (right graph). Switching between the two modes is controlled electronically with a software click

The short coherence fringes are clean and remove all back reflections down to 150 µm OPL in the standard system with special orders down to 75 µm OPL. So measuring almost any sheet of transparent material is possible. Further prisms can be measured, along with homogeneity and wedge and Total Thickness Variations as nothing moves in the cavity and it is this stability that maintains the precision of the angle and thickness measurements.

The process to measure a substrate with SCI is shown in figure 11. Now there is one setup to measure both front and back. Because the part is not moved the front, back, wedge and TTV are measured in one setup. **All faster than other interferometers would measure one surface and no other parameter.**

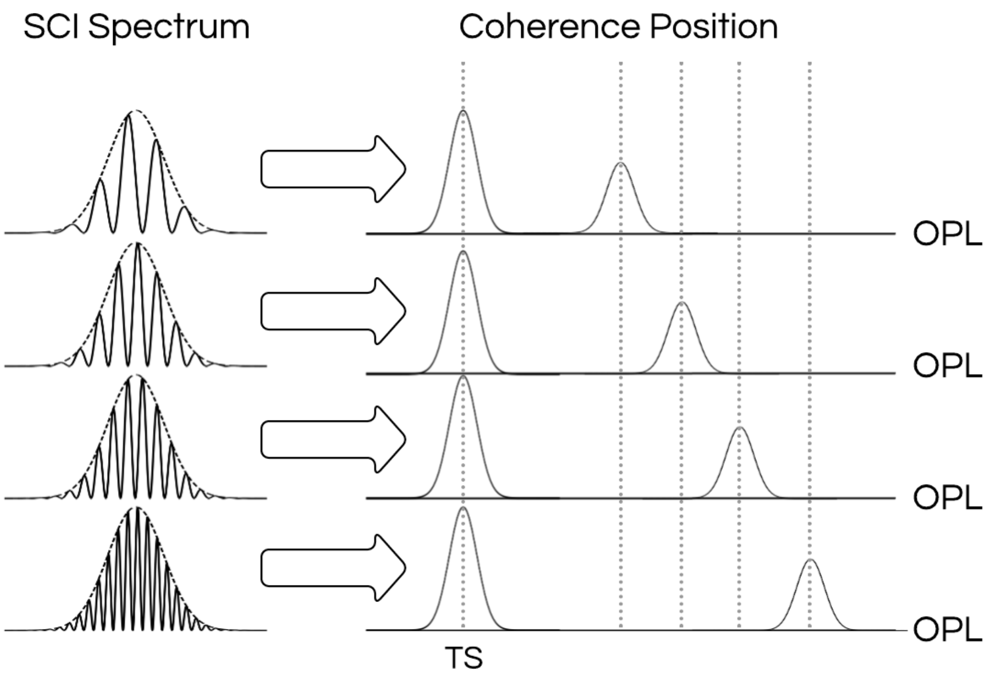


Figure 9: The spectral line frequency controls the selection of the cavity length measured. By electronically adjusting the spectral frequency in ÄPRE's REVEAL™software the surface of interest is selected. Since the coherence is narrow, the surface is isolated. The surface fringes are seen for a quick visual evaluation that can be compared to the phase measured data. Providing a double check of measurement accuracy.

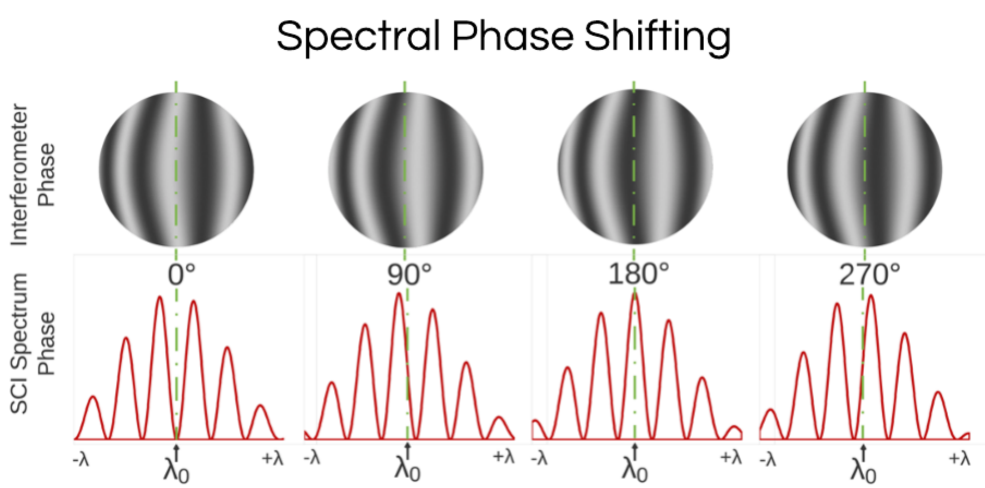


Figure 10: The phase of the spectrum directly controls the phase of the fringes in the cavity. Therefore there is not dependence on cavity length for fast, calibrated measurements.

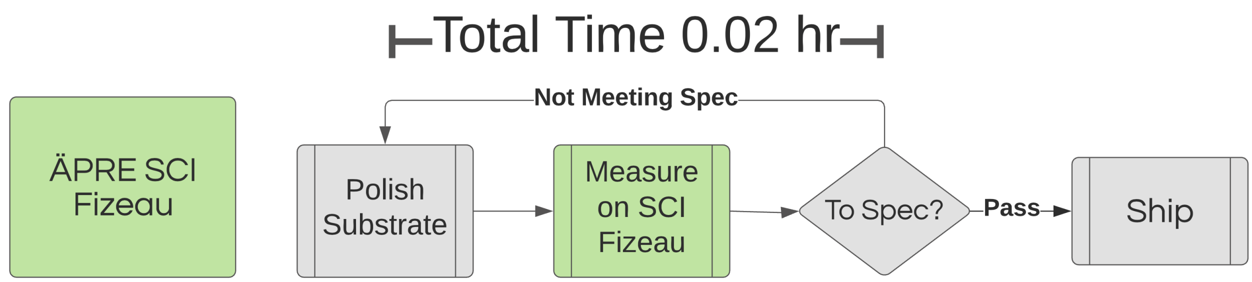


Figure 11: Measuring a substrate with SCI is fast because neither setup preparation nor post measurement part cleaning are required. Plus both surfaces can be measured in the same set up in milliseconds. This translates into a costs saving over a laser Fizeau of >$50,000 per year at only 4 parts measured per day

SCI Fizeau Interferometer	
Strengths	**Weaknesses**
• Easy to Align • Isolate surfaces <150 µm OPL (75 µm special) • Visual fringe confirmation on measured surface • Substrate Front/Back/Wedge/TTV • Measures prism Faces/TWF/Angles • Millisecond data aquisition (regardless of OPL) • S-Series: 20:1 part size range per aperture • Fixed millimeter to meter aperture measurement • Add to any interferometer	• 500 mm cavity length

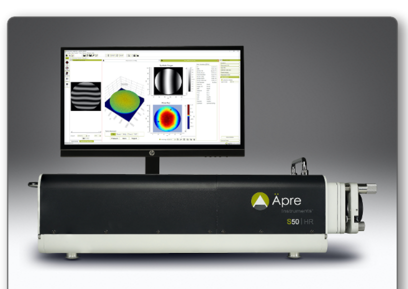
Summary

The combination of SCI + ÄPRE's S-Series interferometers provides the best solution to measure plano optics due to saving 10's of thousands of dollars per year, 2X greater range of part sizes, and ease of use. Click on the link below for a video demonstration measuring a plano optic with SCI.

Click here for a video demonstration

Contact ÄPRE today

Discover what a modern interferometer can do for you



Äpre Instruments™
Tucson, AZ
520.639.8195
sales@apre-inst.com
apre-inst.com