Optical Metrology for Large Space and Terrestrial Telescope Optics

A WHITE PAPER

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Table of Contents

On the cover: Photo courtesy of Ball Aerospace.

The HiRISE space telescope was sent to Mars to take detailed pictures of the Mars surface as part of the Mars Reconnaissance Orbiter mission. Its imaging camera is supported by a telescopic mirror assembly that produces images at resolutions never before seen in planetary exploration missions. The primary mirror, at half a meter diameter, is the largest imaging optic ever sent outside of Earth orbit. High-resolution images from the telescope enable scientists to distinguish 1-meter-size objects on Mars and to study the morphology (surface structure) in a much more comprehensive manner than ever before.

To verify the performance of the optics, the HiRISE engineers used Twyman Green dynamic interferometers from 4D Technology.

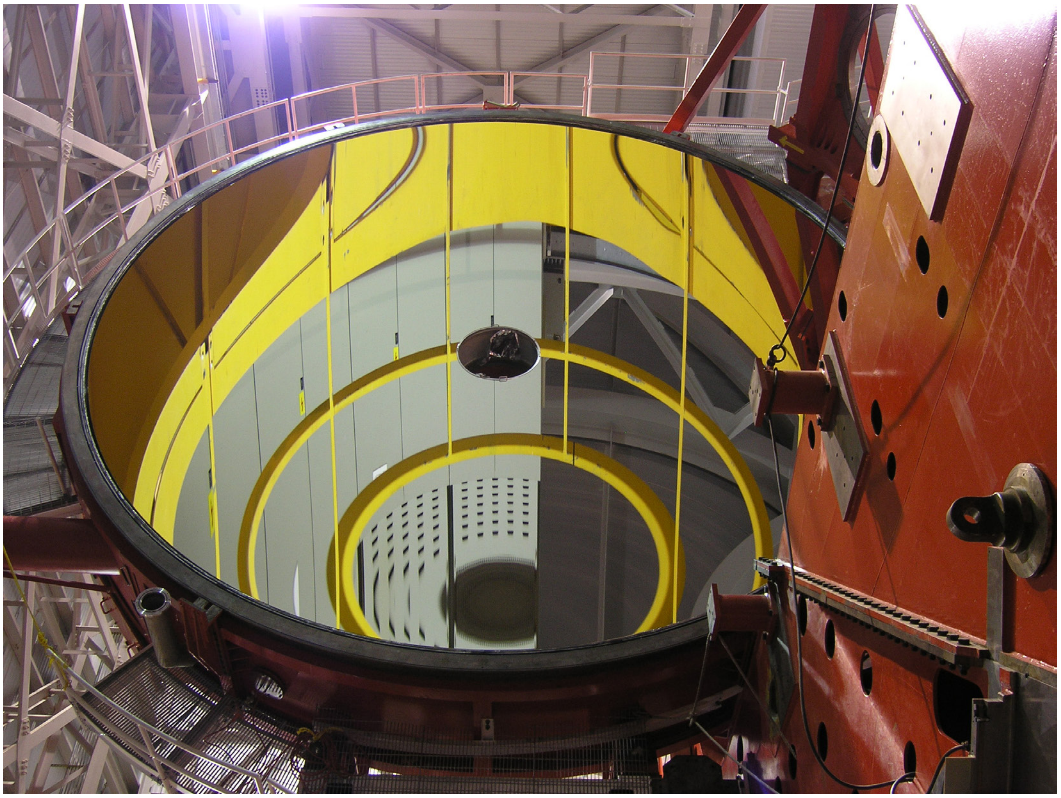
At the time of this writing, HiRISE is transmitting back astonishing images of the Mars surface regularly. These high-resolution images are providing unprecedented views of layered materials, gullies, channels, and other science targets.

Dynamic Interferometry® measures in adverse conditions, providing in-situ feedback, and that allows for faster, more confident production of large mirrors and space-based optics

Optical Metrology for Space and Terrestrial Telescope Optics

Edgar Schrock, Editor

Introduction



8.4 meter primary mirror for the Large Binocular Telescope Observatory.
Photo courtesy of John Hill and the Large Binocular Telescope Observatory.

Measurement of large optics, such as the primary mirror for the Large Binocular Telescope Observatory above, and the space-based HiRISE telescope pictured on the cover, require metrology systems that can function despite vibration, turbulence and other challenges. Laser interferometry is used throughout the manufacturing of large optics to ensure conformance to demanding design specifications. More recently, "dynamic interferometry" has been implemented for vibration-insensitive measurement of large optics. The data are used to control polishing operations, verify dimensional stability of support structures, align mirror segments and complete other critical metrology applications.

To support new manufacturing methods, advanced metrology systems have been developed to provide quality assurance throughout the process. Laser interferometry is the most widely used technique for verifying surface quality of large optics. A laser interferometer measures the phase difference between beams reflecting from a high quality reference optic and from an optic under test. In a traditional "temporal" laser interferometer, the optical path difference is altered in discrete steps, typically quarter-wavelength shifts. The instrument acquires a frame of intensity data with each shift. From these frames, the optical path difference (OPD) can be determined, and the surface shape extracted. Temporal measurements are an inherently frame-rate limited technique. In polishing, measurement data is compared after each polishing iteration, until final shape is achieved.

The necessity and difficulties of testing optical assemblies and structures under simulated spaceflight conditions requires the use dynamic interferometry to achieve the needed precision and robustness. Testing the full range of optics and structures encountered—such as convex, concave, afocal, plane-parallel, and diffuse structures—requires several different interferometer configurations. Table 1 summarizes the applications described in this document and the recommended imaging interferometer type for testing each.[1]

Application	Test Parameter(s)	Recommended Interferometer Type	Special Considerations/notes
End-to-End telescope (auto-collimation)	Transmitted Wavefront	Twyman-Green	At design wavelength
Concave Primary Mirror	Surface Figure	Twyman-Green	Null optics typically required, *e.g.,* CGH. CGH require a well-defined wavelength, *i.e.,* HeNe
	Surface Roughness, Mid-Spatial Frequency	Linnik, Michelson	
Convex Secondary Mirror	Surface Figure	Twyman-Green, Fizeau	Twyman-Green for transmitted wavefront. Fizeau may require aspheric test plate or stitching.
	Mid-Spatial Frequency	Twyman-Green, Fizeau	
	Surface Roughness	Linnik, Michelson	
Segmented Mirrors	Surface Figure, step height	Twyman-Green	Multi-wavelength
Structural	Cryo stability	ESPI Twyman-Green	High power
	Vibrational response	ESPI Twyman-Green	High speed camera

Table 1. Applications and configuration recommendations

No one configuration is capable of testing all types of components and each configuration has its limitations and tradeoffs. Nevertheless, though proper matching of a configuration to an application, Dynamic Interferometry has and will continue to play a major role in the production of state-of-the-art space-based optical instruments, achieving sub-nanometer resolution over vibrational timescales of microseconds to thermal timescales of days.

Metrology issues for meter-class optics

"Meter-class" describes a category of telescopes with optical elements larger than one meter in diameter, typically operating within the infrared through visible spectra. The primary and secondary optics in an imaging system may be monolithic glass structures or may be composed of multiple segments that can be actively aligned. Mirror size is only bounded by current manufacturing methods. At present more than a dozen telescopes are in operation with primary mirrors larger than eight meters, and several even more challenging projects are in development.

Measuring a large optic in a shop-floor environment presents multiple difficulties. Figure 1 shows a typical setup for measuring a large, aspheric optic. The size and curvature of the optic dictate that it must be located many meters from the measurement system.

This measurement poses difficult challenges for a temporal phase-shifting laser interferometer. Because a temporal phase-shifting system acquires data over a sequence of frames, its acquisition time is long—on the order of hundreds of thousands of microseconds. Over the duration of the measurement, vibration and air flow would hinder, or more likely prevent, the acquisition of data. To overcome this challenge, vibration would need to be tightly controlled, which would involve coupling the instrument and optic through a single, vibration-isolated pad or stand, as well as carefully controlling turbulence from air flow and temperature differentials. All of these measures add expense and complexity, and would require significant alterations to a facility.

Sidebar

IN REVIEW: Dynamic interferometry methods

Phase-shifting interferometry is a well-established method for measuring optical wavefront phase to λ/200 or better.[14] In this technique, three or more interferogram intensity profiles are recorded. For each recording, there is a different relative phase between the test and reference beams. The phase distribution of the test wavefront is then calculated using the recorded interferogram intensities. **Temporal phase-shifting** can be accomplished by mechanical motion of the reference flat or through tuning of the source wavelength,[15] however, any relative motion between frames, *e.g.,* caused from vibration, introduces an error and may preclude measurement altogether. This is due to the method's frame-rate-dependent basis, resulting in acquition times commonly 0.2 to 0.5 seconds long.

Three different methods have emerged over the last several decades for single-exposure interferometry: spatial carrier, multi-camera, and polarization mask.[16, 17, 18] The three methods are shown in Figure A. The **spatial carrier** method is perhaps the simplest, requiring only a known angle to be introduced between the reference and test beams. Although this is easy to accomplish (typically by tilting the reference surface) it has two unintended consequences: 1) the beams are sheared at the detector and 2) the beams often travel different paths through the imaging and/or illumination system. Both of these introduce a systematic error that must be measured and accounted for to properly calibrate the system under every use case (i.e. if the instrument focus is changed the residual errors also change).

Spatial phase measurement utilizes a single interferogram to extract phase information. In this technique, a spatial carrier, typically in the form of high frequency tilt fringes, is applied to the interferogram. The intensity profile of the modulated spatial carrier interferogram is recorded and then analyzed to determine the phase. The primary advantage of the spatial phase measurement technique over temporal phase measurement is that only one image is required, allowing acquisition times several orders of magnitude smaller than in temporal phase shifting. Rapid acquisition offers significant vibration immunity, the ability to measure dynamic events, and the characterization of systematic vibrational behavior of surfaces.

The use of polarization is another method used to encode reference and test beams with orthogonal polarization states and provide for simultaneous capture of phase-shifted interferograms. One approach is to use multiple cameras and polarization elements to present a different interferogram to each camera.[5] A more compact approach has been developed by 4D Technology Corporation called the pixelated mask spatial carrier method.[6] In this technique, the relative phase between reference and test wavefront is modified on a pixel-by-pixel basis by a micro-polarizer phase shifting array placed just prior to detection. In this manner a single exposure acquires a multiplexed interferogram. The advantage of the polarization based methods is that illumination and imaging can be made "common path," where at a null-fringe both beams travel the same path. A drawback of this approach is that it is sensitive to polarization aberrations in the optical measurement path; however, this can be calibrated without the need of artifacts or multiple alignments.[19]

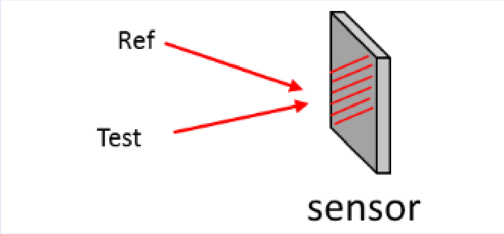


Figure Aa. Spatial carrier

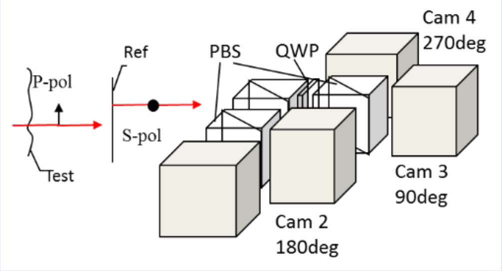


Figure Ab. Polarization method using multiple cameras.

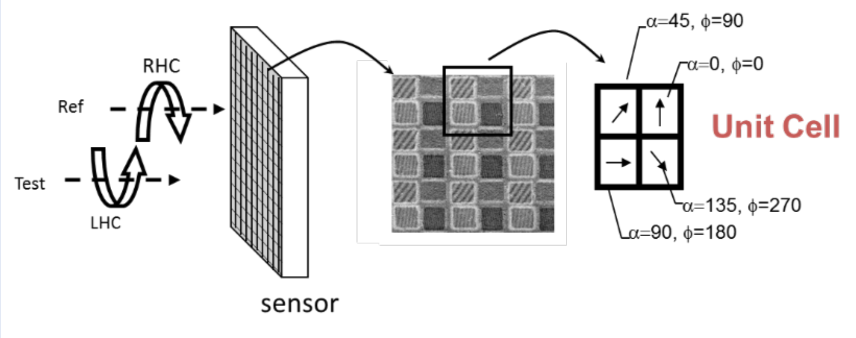


Figure Ac. Pixelated mask spatial carrier method

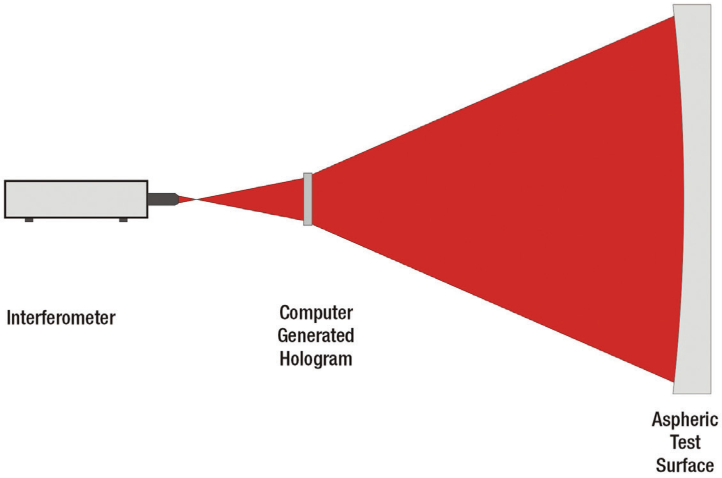


Figure 1. Setup for measuring a large, aspheric optic.

The polishing process presents additional metrology challenges. Maximizing polishing throughput requires that the measurement process, including setup, alignment, data acquisition and analysis, be as fast as possible.

The surface roughness of an optic in the initial stages of polishing will exceed the measurement capability of most systems. A large optic may have local surface deviations exceeding 40 microns. Such high local slopes are difficult for measurement systems to resolve. Qualitative methods provide some degree of process feedback, but the sooner a manufacturer can acquire quantitative data, the faster and more accurate that polishing can be. This early, quantitative feedback becomes even more critical for guiding automated polishing equipment.

As the diameter of optics has grown, several issues have complicated the use of laser interferometry. Since measurement times are on the order of tenths of a second (100,000 microseconds), vibration can greatly affect measurement quality. Secondly, to measure the entire optical surface, the interferometer typically must be positioned at a substantial “stand-off” distance from the test piece—in some cases tens of meters away. Turbulence within such a large cavity distorts the phase data. Vibration isolation and airflow control systems of this scale can prove prohibitively expensive or functionally impractical.

Another difficulty arises when measuring space-based hardware under actual-use conditions, at extremely low pressure and/or cryogenic temperatures. The demanding environment, as well as the extreme vibration from support equipment, make such real-world testing virtually impossible with traditional interferometers.

Many modern space-based optical imaging designs rely upon non-traditional optical elements, such as conformable mirrors or aspheric optics. Characterizing these new elements creates yet another challenge for metrology systems.

Production issues: Polishing feedback

In an instantaneous interferometric measurement, all data are acquired simultaneously in a single frame, rather than sequentially across several frames. Acquisition time can be only a few millionths of a second (10 microseconds), making the systems virtually insensitive to vibration. This insensitivity enables measurements when the test optic is located far from the instrument—even on a separate concrete pad. Dynamic measurements can also reduce the effect of air flow and turbulence that are unavoidable in a manufacturing environment.

Several commercially available methods for instantaneous phase data acquisition can be found:

1. In the software-based spatial carrier method, high frequency tilt fringes are applied by tilting the reference surface relative to the test beam. The tilt fringes are then filtered out by the software algorithms that determine the phase and thus the surface heights.
2. In an off-axis Fizeau interferometer the test and reference beams pass through separate internal

apertures which select the correct polarization states from the test and reference optics. The apertures also filter the tilt fringes and high spatial frequencies.

3. In a stitching interferometer, multiple data sets covering small portions of an optic are stitched together to provide a full measurement of the total surface.
4. In Dynamic Interferometry, polarization elements separate the test beam into four or more phases. All phase data is recorded simultaneously and analyzed to determine surface heights.

Each of these instantaneous methods may be capable of providing final quality control for large optics. However, most methods are not capable of providing feedback for the early stages of polishing. Only Dynamic Interferometry (4) has proven capable of measuring the full range of spatial frequencies present during polishing, across a large aperture, in the environments typical of a polishing process. In a spatial carrier system (1), the filtering required to remove the tilt fringes limits the spatial resolution and thus the range of slopes that can be resolved. High spatial frequencies are also filtered out by the apertures used in method (2), again resulting in a reduced range of measurable slopes. A stitching interferometer (3) retains high spatial frequencies, but great care must be taken to preserve low frequency data during the stitching process.

Unlike a temporal interferometer, which acquires several phase data frames over tenths of a second, a “dynamic interferometer” acquires all phase data simultaneously. Short acquisition time (typically several millionths of a second) enables dynamic interferometers to measure in high noise environments, and without vibration isolation. This greatly simplifies (and reduces the cost of) the setup, and enables testing in harsh environments, such as those encountered in cryogenic testing.

Dynamic systems measure successfully in the presence of significant air movement. In temporal measurements, turbulence creates relative phase errors between the data frames, rendering the data incorrect or unusable. This frame-to-frame error is not present in dynamic measurement. Averaging several dynamic measurements cancels the effect of turbulence, leaving only the optic’s shape in the measurement data.

Vibrational measurements

One possible successor to the James Webb Space Telescope is an observatory that combines general Ultraviolet-Optical Infrared (UVOIR) astrophysics with the search for life on habitable earth-like exoplanets using a large aperture segmented telescope. The most significant architectural driver beyond the aperture size is the 10^{-10} contrast required to block out the bright stars sufficiently to detect dim earth like planets. Achieving this requires, among other technologies, a very stable telescope that maintains <10 picometer stability during most observations. While measuring this level of stability is very challenging, with the advent of dynamic interferometry and high speed cameras interferometric measurements of dynamic motions are now possible.

Case Study: NASA’s test of mirror array in open lab

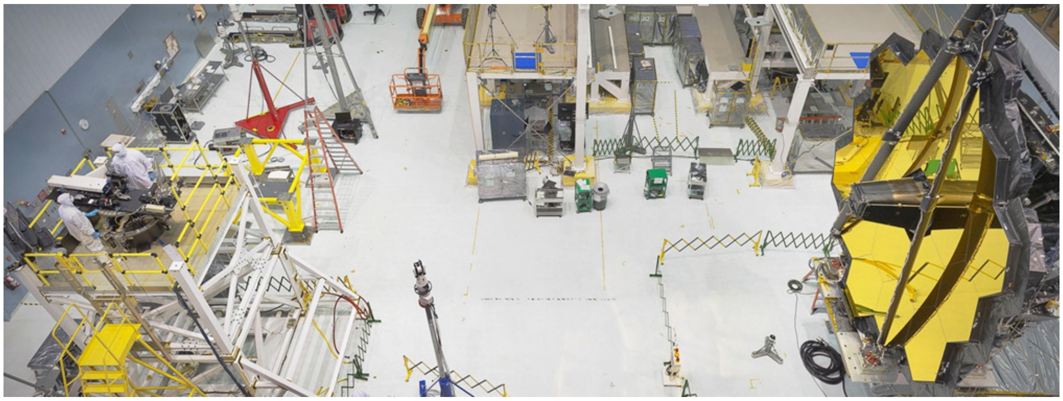
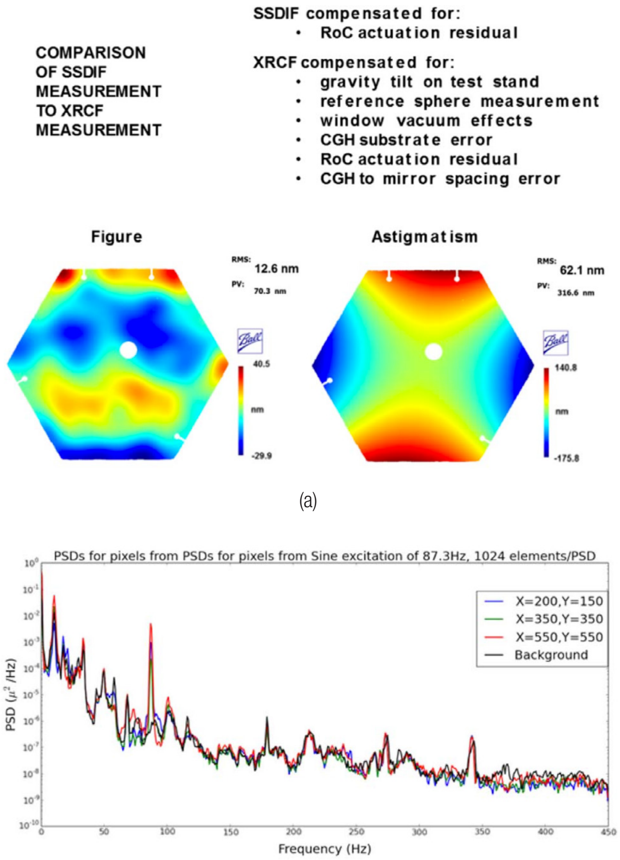


FIgure 2. High Speed interferometer measuring segments of the James Webb Space Telescope
Primary mirror at Goddard Space Flight Center

Saif and his team at NASA used a high-speed dynamic interferometer developed at 4D Technology Corporation to characterize the stability of the JWST optomechanical systems.[2] The interferometer was capable of capturing measurements at a rate up to 5000 frames per second. The testing consisted of synchronously mechanically exciting one of the mounted JWST primary mirror segments and measuring the segment shape, piston and tilt with the high-speed dynamic interferometer. The motions of the segment were tracked by temporally unwrapping the measured phase and calculating a pixel-wise power spectrum of the motion in time. Analysis of the results indicate a nanometer level characterization of the surface motion. Figure 2 shows the high-speed interferometer measuring the James Webb Space Telescope Segment at Goddard Space Flight Center. Figure 3 shows typical measurement results for surface figure and astigmatism from the testing. In addition, Figure 3b contains an example of the resulting PSD calculated at three pixel locations. Experiments where the PSD was calculated for given Zernike term shapes demonstrated picometer level characterization of the structure stability.



(a)

(b)

Figure 3. (a) Typical surface figure and astigmatism measurement of a JWST primary mirror segment using the high-speed interferometer. (b) PSD generated from measurements using the high-speed interferometer on a JWST primary mirror segment.

Measuring large concave mirrors

The heart of the telescope is typically the primary mirror. It is the largest optic in diameter and typically aspheric. Testing of primary mirrors is typically accomplished by focusing the beam at the center of curvature (CoC) as shown in Figure 4. A computer generated hologram (CGH) is often used to compensate for the aspheric departure. Because the CGH has low throughput (typically only 10-30% efficiency) and is used in double pass, the Twyman-Green is a good choice for this type of testing due to its light efficiency and ability to measure high numerical apertures.

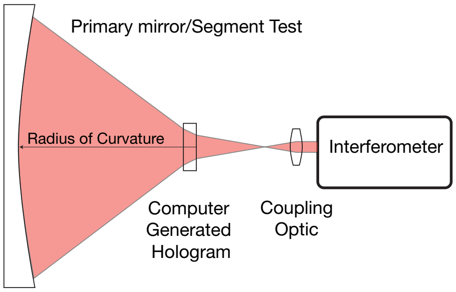


Figure 4. Primary mirror test setup, using a Twyman-Green interferometer and CGH.

Case Study: Steward Mirror Lab

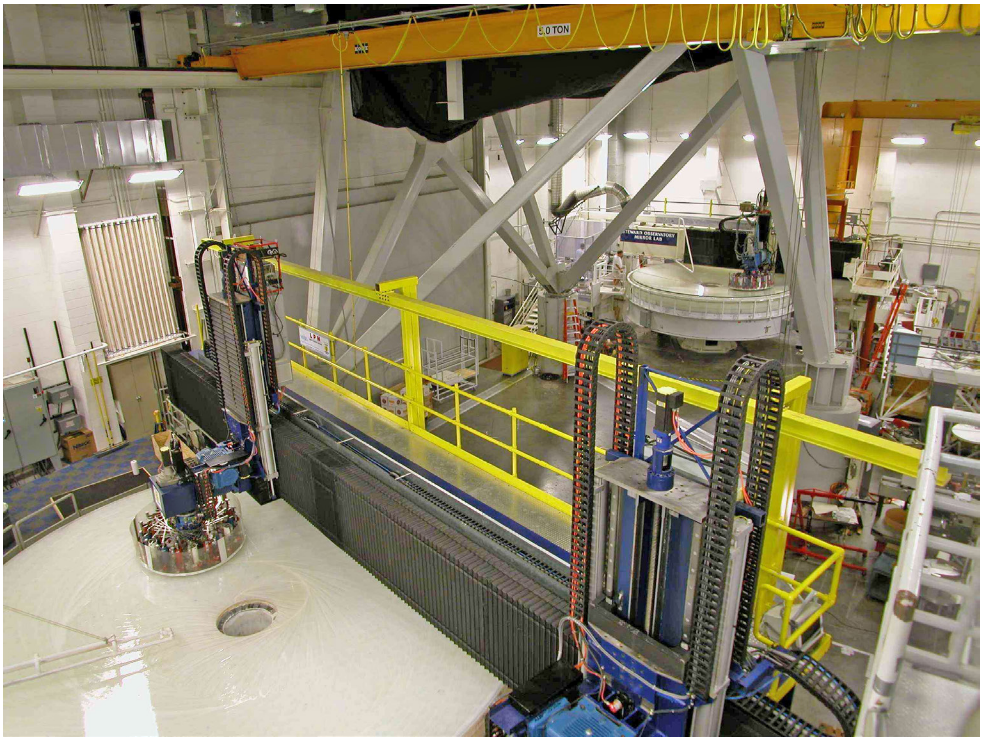


Figure 5. Richard F. Caris Mirror Lab has several large-scale mirror polishing tables.

Telescope mirror manufacturers, such as the Richard F. Caris Mirror Lab (figure 5), have mastered techniques for producing lightweight mirrors exceeding eight meters in diameter. Spin-casting forms the mirror's general curvature during cooling, dramatically reduced the amount of raw material required, as well as the amount of required polishing.

To measure large, concave mirrors, the interferometer must be positioned several stories above the mirror. Buddy Martin, Project Scientist at Caris Mirror Lab commented, "The path length for our measurements is typically 20 meters, single pass. Even measuring in the middle of the night in an isolated test tower, with all air handlers off, vibration and turbulence limit the accuracy we can get with a temporal interferometer. With our dynamic system we're almost immune to vibration, and we can quickly take enough measurements to average out the effects of turbulence. It saves a lot of time and gives us more accurate data."

Testing hardware in space-like conditions

Verifying the ability of space-based optics to perform to specification after deployment is critical, particularly for systems which will operate beyond the accessibility of the Space Shuttle fleet. Testing at cryogenic temperatures and/or low pressures is the most effective way to ensure that optical systems will perform to specification. Cryo-vac testing is performed within a pressure vessel—an extremely noisy environment, due to vibration from its pumps. Coupling the metrology system to the test sample and isolating both from vibration is difficult because of space constraints. It proves impossible when the test configuration requires a long measurement path.

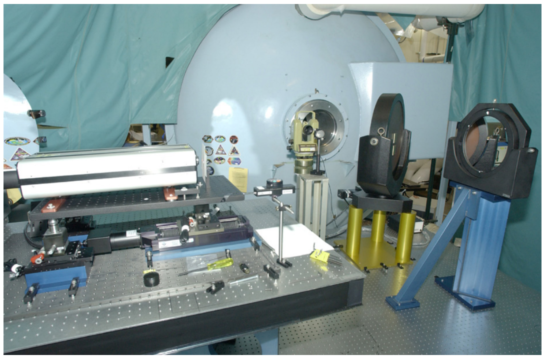


Figure 6. A dynamic interferometer measures a test sample in a vacuum chamber through a view port (Courtesy Ball Aerospace).

Because of its immunity to vibration, dynamic interferometry frees manufacturers from the need to couple the instrument and test optic. This freedom enables test configurations in which the interferometer is located inside the chamber (within its own pressure vessel) or outside the chamber (with the test beam passing through a window into the chamber). Dynamic interferometry is often the only available option to complete these mission-critical measurements accurately and cost-effectively.

Case Study: Cryo-vacuum testing optics at Marshal Space Flight Center

Hadaway et. al. used dynamic interferometry to measure the primary mirror segments for the JWST under both ambient and cryo-vacuum conditions.[3] Measurements are shown in Figure 7. The ambient residual mirror surface figure was 163nm RMS. Cooling to 27K produced a total change of 142nm RMS, mostly in low order astigmatism; however the overall shape remained with the design budget.

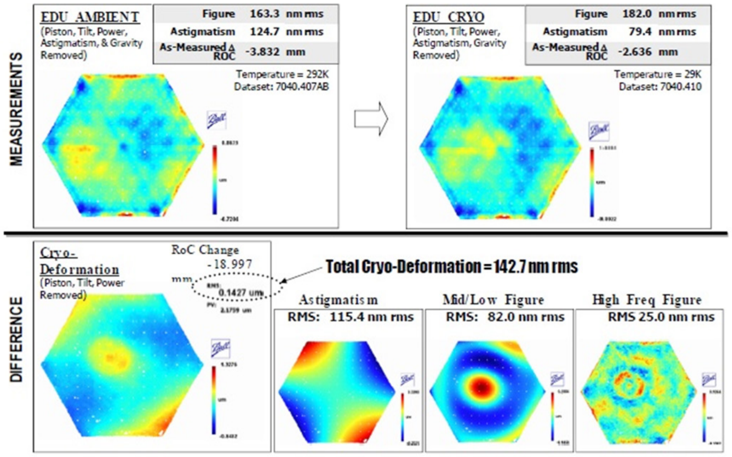


Figure 7. Measurement of primary mirror segment on the JWST under ambient and cryo conditions[3] .

Stability of support structures

In addition to measuring the optical surfaces for space applications it is imperative to measure the stability of the backplane structure on which the mirrors are mounted. Of interest is how the structure shape will change when deployed. In deployment it will routinely undergo large vibrational loads and temperature swings, nominally operating at very cold temperatures. The backplane structures are typically constructed of carbon fiber which is optically rough and the surface shape cannot be directly measured with traditional phase-shifting (*i.e.*, temporal) interferometry. Happily, the change in the structure shape can be accurately measured using electronic speckle pattern interferometry (ESPI).[4]

Electronic speckle pattern interferometry extracts the change in shape of the measured rough surface through the random speckle pattern generated by the interference of coherent light by subtracting a baseline measurement from future measurements. The subtraction largely removes the random pattern exposing the underlying shape change.

Case Study: Space mirror support structure

Saif proposed combining ESPI with a single frame phase-shifting method for application to large space telescope structures.[5] North Morris et al. built an electronic speckle pattern interferometer for measuring the James Webb Space Telescope backplane that utilized a pixelated mask spatial carrier camera and a high energy pulsed laser.[6] The interferometer was capable of measuring 3-meter diameter carbon fiber structures at a 16 meter standoff. The dynamic ESPI system was shown to have an RMS repeatability of 2.1nm and was used to verify the mechanical models of the James Webb Space Telescope backplane.[7, 8] Figure 8 contains a plot of displacement measurement for a single crystal silicon step as a function of temperature. Figure 9 shows the dynamic ESPI interferometer, the JWST backplane sample and a measurement of the JWST backplane sample.

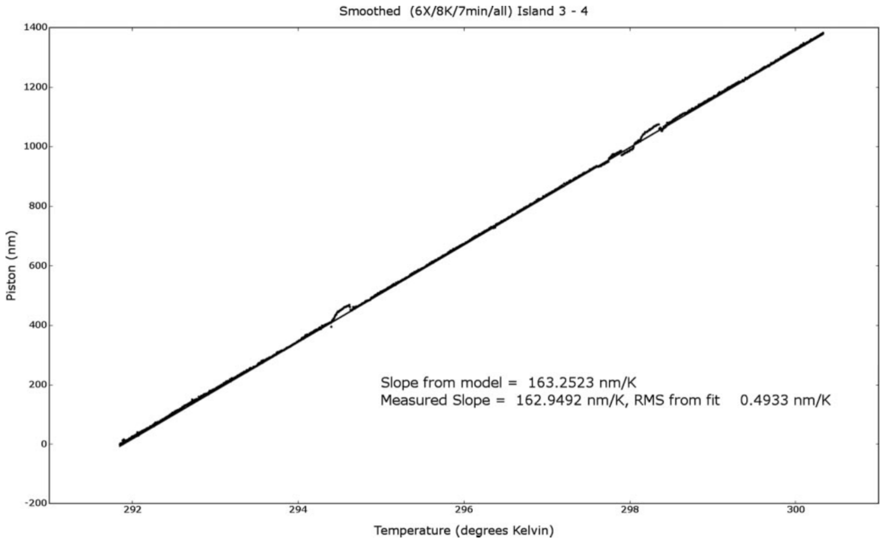


Figure 8. Peak to valley displacement for a single crystal silicon step as a function of temperature as measured with the dynamic electronic speckle pattern interferometer.

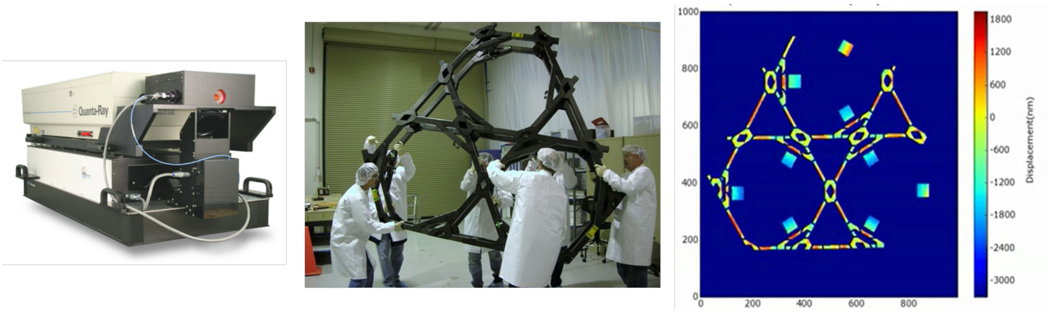


Figure 9. (left) Dynamic ESPI interferometer, (center) JWST backplane sample, (right) ESPI measurement of JWST backplane sample

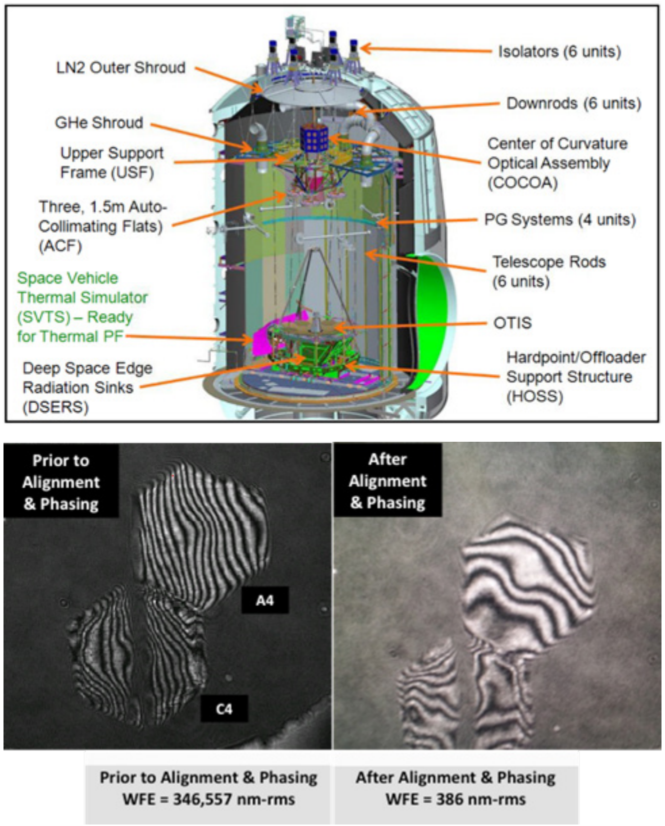
Segmented mirrors

Segmented mirrors, such as the James Webb Space Telescope, pose an additional measurement challenge in that the segments need to be placed in the appropriate Z-plane relative to one another. While phase-shifting interferometry has extremely high resolution, it also has a small dynamic range for measuring step discontinuities. The discontinuity must be less the ¼ the measurement wavelength to be unambiguously resolved. For example, a HeNe laser source (at 632.8) nm has a step discontinuity tolerance of less than 0.16 microns. Fortunately, the dynamic range of an interferometric measurement can by extended through two-wavelength interferometry.[9]

Case Study: the James Webb Space Telescope primary mirror segments

The JWST project also required a method for verifying that the segments of the primary mirror, which are folded for launch, will be aligned by the telescope's active segment mirror control system to within sub-wavelength tolerance upon deployment. The initial misalignment between segments is much greater than the measurement range of a standard interferometer. For this application a multiple wavelength dynamic interferometer was employed. The much longer "synthetic" wavelength generated by the instrument is capable of measuring the initial misalignment. As the segments are brought closer to alignment, the wavelength is stepped down for increasing resolution.

The verification of phasing of large telescope mirrors using a dynamic phase-shifting two-wavelength interferometer was demonstrated on the James Webb Space Telescope path finder mirrors in the large vacuum chamber at Johnson Space Flight Center,[10] and then repeated on the actual JWST telescope. In the testing, the mirror segments were phased by starting at the longest synthetic wavelength, phasing the mirrors segments, and stepping down to the next lower synthetic wavelength where the process was repeated. The mirror segments were phased to within 116 nanometers. Measurements at a 16.7-micron synthetic wavelength and the fundamental wavelength at 687 nanometers agreed to within 13 nanometers. Figure 10 illustrates the measurement setup and data measured at Johnson Space Flight Center where the Two-Wavelength interferometer was used to phase segments on a testbed. The two-wavelength interferometer is enclosed in the COCOA module.



Prior to Alignment & Phasing WFE = 346,557 nm-rms

After Alignment & Phasing WFE = 386 nm-rms

Figure 10. Illustration of JWST test setup at Johnson Space Flight Center that makes use of two-wavelength interferometery to phase the telescope mirrors. The two-wavelength interferometer is located in the COCOA module. Image provided by Conrad Wells

Two-wavelength interferometry extends the dynamic range of the measurement by subtracting two measurements captured using two different wavelengths of light. The resulting difference represents a measurement taken at a much longer synthetic wavelength: $\lambda_s = \frac{\lambda_2 \cdot \lambda_1}{|\lambda_2 - \lambda_1|}$. North-Morris, Millerd, *et al.* combined the two-wavelength approach, the pixelated polarization mask spatial carrier phase shifting technique, and a range of source wavelengths to mitigate the effects of vibration and facilitate its application to large telescope mirrors.[11] The application of two-wavelength interferometry to large segmented telescope mirrors requires some level of immunity to vibrations and the ability to phase the segments to tens of nanometers when the starting position of the mirror segments may be out of phase by as much as a millimeter. Uniting the two-wavelength approach with dynamic interferometry, North-Morris, *et al.,* demonstrated a collective capture time for both measurements of less than 100 microseconds—essentially freezing out the effects of vibrations for most mechanical frequencies.[12] They also used a combination of two fixed lasers and a tunable laser to generate synthetic wavelength ranging from 10 millimeters down to 18 microns. Example measurement taken with a synthetic wavelength of 2mm is shown in Figure 11.

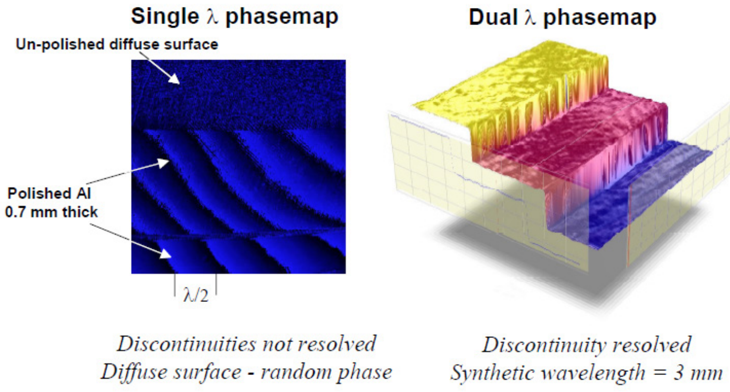


Figure 11. Dynamic Interferometry measurement using two laser sources to generate a synthetic wavelength.

Surface roughness and mid-spatial frequencies

Interference microscopes allow very high magnification necessary to measure surface roughness and mid-spatial frequencies (1cm – 1um) leftover from polishing and potentially detrimental to optical performance. Dynamic capability is particularly important when measuring very large optics (>300mm) where it is difficult to move the optic under a conventional interference microscope and it is desirable to measure the optic directly with portable or scanning system.[13] Several types of interference microscopes are possible including the Linnik, Michelson and Mireau which are shown in Figure 12 a, b, and c respectively. The Linnik and Michelson configurations readily lend themselves to polarization based Dynamic systems owing to the replacement of the beamsplitter with a polarization cube. The Linnik incorporates two objectives; one within the reference arm and one in the test arm to match optical paths traveled by both the reference and test beams. The Linnik configuration achieves very high magnification (50-100X) and long working distance between the objective and the test part. In addition to the portability, Dynamic Interference Microscopes have the advantage of achieving lower noise through averaging over very many measurements whereas temporal based systems typically bottom out at a limit determined by the vibration level.

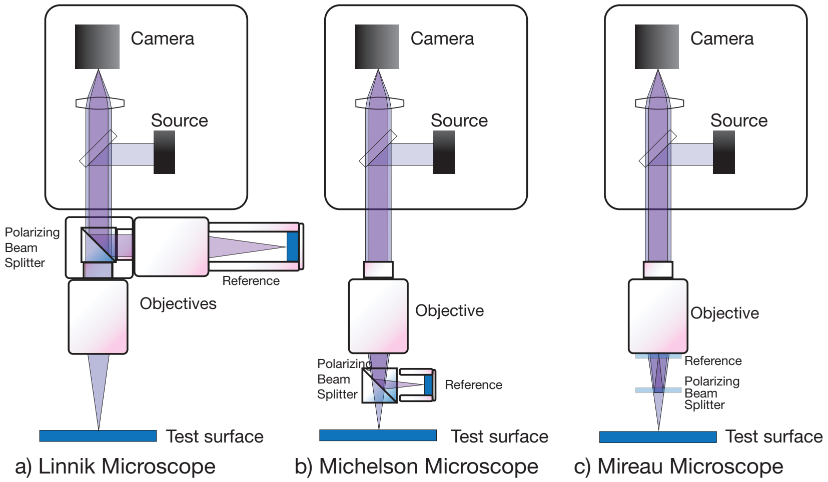


Figure 12. Interference microscope configurations.

On large optics, and especially large active optics—where actuator and anchor points may affect the imaging surface—mid-spatial frequencies in the range of 1-100 cm might be a concern. For these relatively large features, a sub-aperture measurement with a Fizeau or Twyman-Green laser interferometer is advised.

Case Study: Imaging exoplanets

The microscopic surface roughness of optics is becoming increasingly critical to the performance of telescopes and precision optical equipment. For example, in proposed NASA exo-planet detection missions, the electromagnetic radiation reflected from the orbiting planet may be 10 orders of magnitude less than radiation emitted from the star. Surface roughness on the optics of the telescope is currently the limiting factor in direct imaging of exoplanets because the direct star light is scattered outside the stars primary image, obscuring the planet. X-ray telescopes have similar requirements for ultralow surface roughness, but they are further complicated by their complex shape, making inspection with conventional metrology tools impractical. Manufacturing the next generation of telescope optics requires both high quality polishing technologies for complex shapes and metrology tools capable of rapidly measuring surface quality across a very large aperture.

Kimbrough et. al. demonstrated a dynamic Interferometer for measuring surface roughness and mid-spatial frequencies in 2011.[13] A significant advantage of dynamic interferometry is the ability to quickly acquire and average data to reduce the measurement noise, which is typically dominated by shot-noise. Figure 13 shows the NanoCam dynamic surface profiler which can be placed directly on the surface of large optics or machine mounted for scanning of highly aspheric surfaces such as xray mirrors. The measurement noise of the system is plotted as a function of averages (equivalent to time). Figure 14 plots the noise floor over an average: it can be seen that the noise floor can rapidly be reduced below 1 angstrom with only a few seconds of acquisition time.

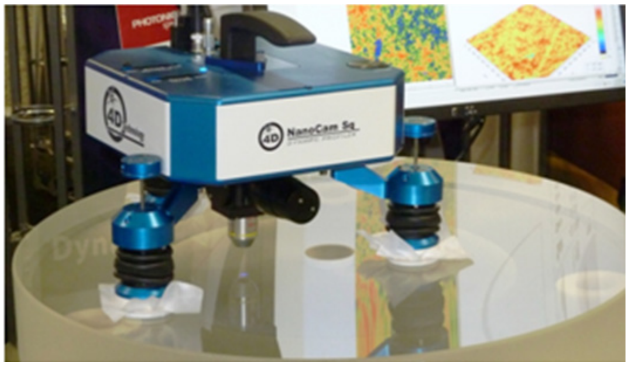


Figure 13. A dynamic intereference microscope is immune to vibration, and can be placed anywhere on a large optic without requiring vibration isolation.

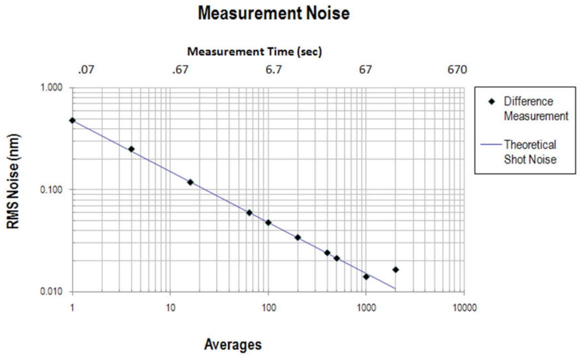


Figure 14. Dynamic surface roughness profiler and measured noise floor as a function of averaging (time).

Verifying adaptive optics

Many large telescopes now employ adaptive optics on either their primary or secondary elements to counter the effects of constantly changing atmospheric conditions. The actuators for the adaptive system are typically piezo elements attached to the back of flexible elements. In the past, to understand the modal response of an optic to changes in the actuators, sensors have been used to measure movement at individual points on an optic—a slow, low-resolution solution. Dynamic interferometry, because of its short acquisition time, can be used to image an optic as it is being actuated to verify and calibrate the response of the actuators. The dynamic system shows the 3D response of the entire optic, providing a complete image of control system performance.

Testing aspheric optics

Aspheric optics are now used more frequently in designs to simplify system designs and improve performance. To verify the performance of such a complex-shaped surface, a computer-generated hologram (CGH) is employed to transform the spherical or collimated test beam into the aspheric wavefront required to test the optic.

In addition to the issues of vibration and turbulence, CGHs introduce another challenge, as test setups are very inefficient, returning less than 1% of the laser power to the interferometer. To provide sufficient power to allow measurement, dynamic, Helium-Neon laser interferometers have been developed with output of 7-15 milliwatts (versus 1 -2 milliwatts for standard instruments) These systems typically provide a beam ratio control to balance the test and reference beams and maximize contrast and measurement quality.

Case Study: Measuring a large aspheric optic

Optical Surface Technologies of Albuquerque, NM designs, manufactured and coated custom optical components for specialized applications. In one project, the company polished six 1.4-meter diameter, parabolic mirrors. Stringent requirements dictated that the final surface quality would need to be 29nm RMS, so both large-scale shape and small-scale structure were important to monitor during polishing.

The size and shape of the optic dictated that it be located approximately 3 meters from the interferometer, resulting in the optic being located on a separate concrete slab. As the facility was situated near the intersection of two interstate highways, the measurement environment was also subject to significant background noise and vibration.

The manual polishing process consisted of two phases: first, polishing the blank to a sphere and then polishing in the final shape. Rod Schmell, Optical Fabrication Manager at Optical Surface Technologies, noted that acquiring reliable measurement data early in the process was critical for producing the mirrors on a tight schedule. “If we can see surface deviations when the surface quality is at 33 waves RMS, then we can polish more aggressively and converge on the final shape faster,” he said.

For those measurements, the company first employed an off-axis Fizeau interferometer, but because of the extreme local slopes they were unable to obtain reliable data. A dynamic interferometer was then used (Figure 15) and was found to measure accurately even at the rough blank stage (Figure 16). “We had data we could believe, and we tracked it throughout the polishing run,” said Schmell. “The data gave us confidence to work the part more quickly,” he added.

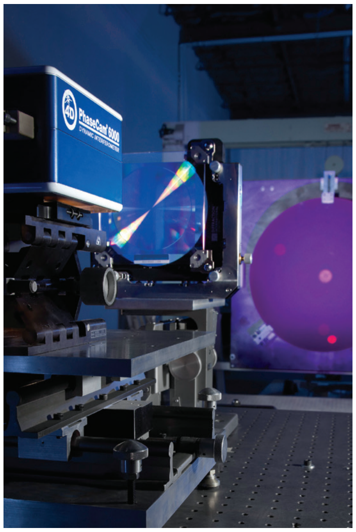


Figure 15. Measurement setup for 1.4-meter parabolic optic, with the interferometer in the foreground, CGH and optic. Courtesy Optical Surface Technologies.

Also important was the dynamic interferometer's ease of use for in-process measurement. Setting up the off-axis Fizeau system required alignment of two spots per optical element; determining which spot was correct required significant additional time and effort. The Twyman-Green type dynamic interferometer did not have this limitation. This advantage, along with minimal system drift and other benefits, enabled the polishing team to reduce the entire measurement cycle to only 15 minutes.

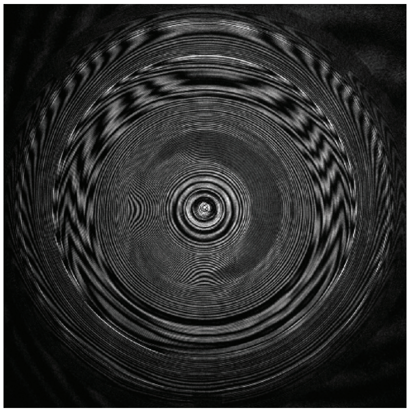


Figure 16. Dynamic interferometric measurement of a large aspheric surface during the early stages of polishing.

End-to-end test

End-to-end optical wavefront testing for telescopes are typically arranged as an auto-collimation test as shown in Figure 17. Due to various coatings and possible refractive elements this type of testing is almost always performed within the designed spectral pass-band for the telescope. A large return flat (RF) is necessary although it is possible to conduct sub-aperture tests. To ensure good performance systems are tested at multiple field points. Both Twyman-Green and Fizeau are good choices for moderately fast systems (~>F/5); for faster (<F/5) the Twyman-Green usually has lower uncalibrated wavefront errors and is preferable. The larger aperture size of the Fizeau results in longer standoff distance for a given f-number which is can be advantageous in situations where the interferometer cannot be placed near the focal plane.

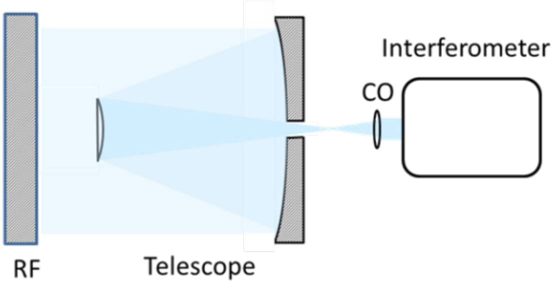


Figure 17. End-to-end test configuration.

Conclusions

1. Dynamic interferometry provides quantitative feedback for manual and automatic polishing operations, from rough polishing to final shaping.
2. Dynamic interferometry has been a significant contributor to the development of the current generation of ground and space-based telescopes through:
    - measurement in situ of materials in extreme settings, whether vibrationally decoupled, over large cavities, or of materials in cryovac and turbulent environments
    - automated metrology that picks and places metrology devices wherever it is required on a large operating platform

- active manufacturing feedback which enables aggressive polishing and less downtime, so manufacturers can deliver high-quality, finished optics in less time
- a broad range of measurement capabilities, from the finest sub-angstrom microscopic surface finish measurement, to macro-scale, rough carbon fiber structures
- measurements not obtainable through traditional means

3. By using dynamic interferometry, large telescope and space-based optics manufacturers are able to make essential measurements of the performance of their systems, without sacrificing the accuracy and vertical resolution desirable in the non-dynamic methodologies.

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