Measuring large optics requires metrology systems that function despite vibration, turbulence and other challenges.

Optical Metrology for Large Telescope Optics

Mike Zecchino

Introduction

In recent years the demand for meter-scale optical elements has increased significantly, driven by growth in terrestrial and satellite-based astronomy, and defense and security applications. 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 is used to control polishing operations, verify dimensional stability of support structures, align mirror segments and complete other critical metrology applications.

Requirements for Meter-Class Metrology

"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 may be monolithic glass structures or may consist 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 more challenging projects are in development.

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 a test optic. In a traditional, "temporal" laser interferometer the reference optic is translated relative to the test surface in known steps, typically quarter-wavelength shifts. The instrument acquires a frame of phase data following each shift. From this phase data the optical path difference (OPD) can be determined, and the surface shape can be extracted. Measurement data is compared after each polishing iteration until final shape is achieved.

As the diameter of optics has grown, several issues have complicated the use of laser interferometry. Since measurement times are on the order of hundreds of milliseconds, vibration can greatly affect measurement quality. Secondly, to measure the entire optical surface, the interferometer must be positioned a significant "stand-off" distance from the test piece—in some cases tens of meters away. Turbulence within such a large cavity can significantly distort the phase data. Vibration isolation and airflow control systems of this scale can prove prohibitively expensive or functionally impractical.

A third 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 designs rely upon non-traditional elements, such as conformable mirrors or aspheric optics. Characterizing these new elements creates yet another challenge for metrology systems.

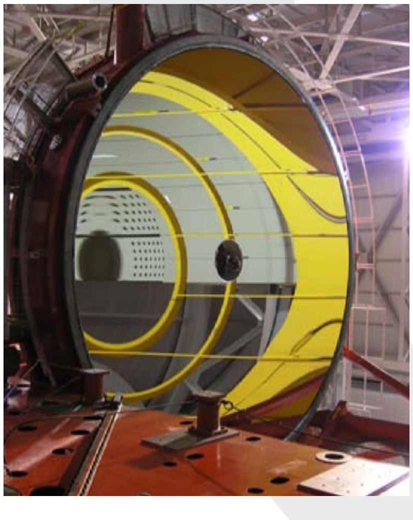

Figure 1. Measurement of large optics, such as this 8 meter primary mirror for the Large Binocular Telescope Observatory, requires metrology systems that can function despite vibration, turbulence and other challenges. (Courtesy R. Bertram and LBTO).

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Dynamic Interferometry

Unlike a temporal interferometer, which acquires phase data frames over hundreds of milliseconds, a “dynamic interferometer” acquires all phase data simultaneously. Short acquisition time (typically several microseconds) enables dynamic interferometers to measure in high noise environments, 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 can also measure 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.

Measuring Large Concave Mirrors

Telescope mirror manufacturers, such as the Steward Observatory Mirror Lab, 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 Steward Labs comments, “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.”

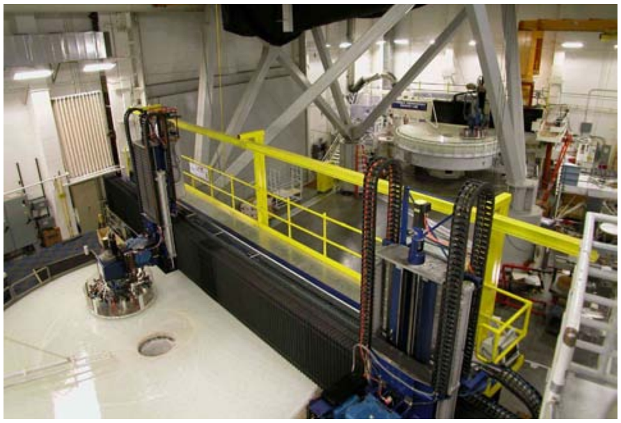


Figure 2. Dynamic interferometry data guides polishing of 8.4 meter and 6.4 meter mirrors (Courtesy Steward Observatory Mirror Lab).

Testing Space Hardware in Actual Use 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 due to space constraints. It proves impossible when the test configuration requires a long measurement path.

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). The method is often the only available option to complete these mission-critical measurements accurately and cost-effectively.

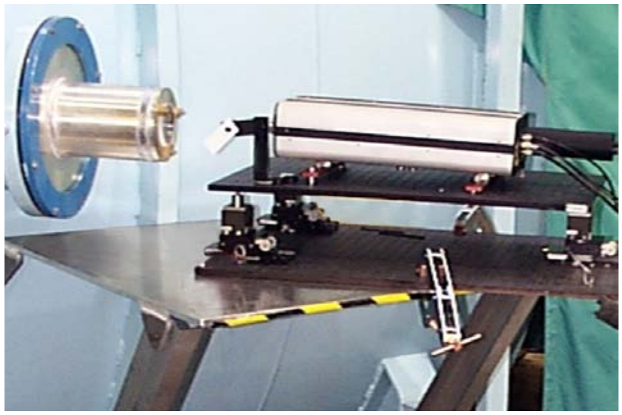


Figure 3. A dynamic interferometer measures a test sample in a vacuum chamber through a view port (Courtesy Ball Aerospace).

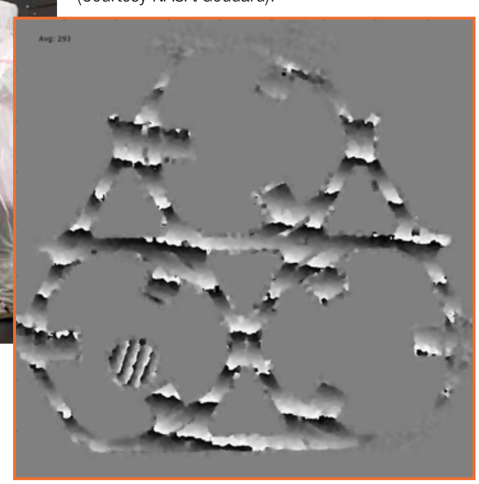
Stability of Support Structures

The James Webb Space Telescope (JWST), scheduled for space deployment in 2013, has presented a number of unique metrology challenges. One of these is the need to control dimensional stability of the primary mirror's support structure over time, at cryogenic temperatures. To verify stability before flight, a representative test structure was built. The test plan called for three weeks of near-continuous measurement of the large, diffuse structure in a cryogenic chamber.

Electronic Speckle Pattern Interferometry (ESPI), a well known method for measuring such diffuse surfaces, was chosen for the measurement. A dynamic phase shifting speckle interferometer was placed outside of the test chamber, several meters from the test article. The instrument simultaneously captures all phase data over the entire structure in the duration of a single laser pulse (9 ns). Figure 4a shows the test article being placed in the cryogenic chamber, while Figure 4b shows the test results from the dynamic interferometer. Out-of-plane deflections of tens of nanometers across 100s of microns can be measured in this way.

Figure 4a. The support structure for the James Webb Space Telescope undergoes cryogenic testing for dimensional stability. (Courtesy Northrop Grumman ATK Space Systems).

Figure 4b. Dynamic ESPI interferometry measurement data for the structure (Courtesy NASA/Goddard).



Mirror Segment Alignment

The JWST project also required a method for verifying that the segments of the primary mirror, which are folded for launch, will align 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.

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 abeam ratio control to balance the test and reference beams and maximize contrast and measurement quality.

CONCLUSION

Advances in astronomy are the result of numerous technological achievements, both in opto-mechanical design and in manufacturing. Dynamic interferometry has been a significant contributor to the development of the current generation of ground and space-based telescopes and will continue to be an enabling technology for projects currently in development.

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