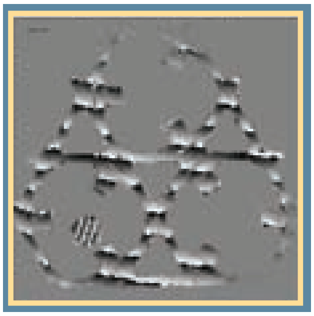
Northrop Grumman ATK Space Systems



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Improved Interferometric Optical Testing

James C. Wyant

While the basic principles of interferometry have been well known for more than 100 years, this powerful measurement tool is continually evolving. Indeed, modern electronics, computers and software are changing the ways that interferometry can be used and broadening its metrology applications in industrial and research labs.

Facing page: Engineers inspect the backplane stability test article (BSTA), the prototype structure that holds and supports the primary mirrors of the James Webb Space Telescope. Above: Electronic speckle pattern interferometry fringes obtained testing the BSTA.

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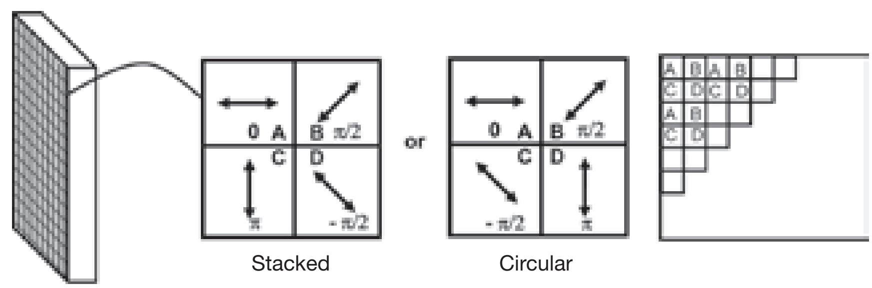
Interferometry is used for testing optical components and optical systems as well as the metrology of many other components, such as the flatness and roughness of hard disk drive platters and the shape of magnetic recording heads and machined parts.

This article describes three recent advances that are broadening the applications of interferometric metrology: a new technique for reducing the sensitivity of interferometry to vibration; an interferometric method for measuring deformations and vibrations of diffuse surfaces; and a method for reducing the sensitivity to vibration and coherent noise and enabling measurement of parallel glass surfaces.

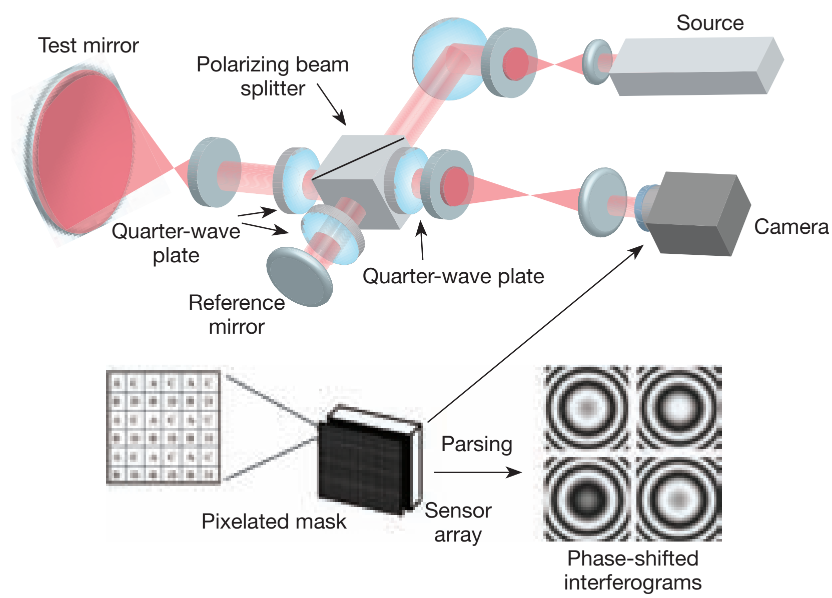
Before delving into these new techniques, I will first describe phase-shifting interferometry, which is critical to all three advances. Moreover, the phase-shifting technique has greatly increased the popularity and the usefulness of interferometry in industrial and research applications.

[Array of oriented micropolarizers]



The polarizer array is matched to the detector array pixels.

[Twyman-Green interferometer]



This schematic shows a Twyman-Green interferometer that uses the micropolarizer phase-shifting array. Proc. SPIE **5531**, 304-14.

Phase-shifting interferometry

Phase-shifting interferometry is an excellent way to get interferometric data into computers. With interferometric data, there are three unknowns: the amplitude of the reference beam, the amplitude of the test beam and the phase difference between the two interfering beams. Of these, the quantity of most interest is the phase difference between the two interfering beams. This is because the phase difference gives the optical path difference, which tells us both what needs to be done to correct the optics and how well the optics will perform if they are not corrected.

To determine the phase difference between the two interfering beams, one must measure the intensity of the interference fringes while the phase difference between the two interfering beams is changed in a known manner. Typically, the phase is changed by 90 degrees between consecutive intensity measurements. Since there are three unknowns, at least three intensity measurements must be made. Ninety-degree phase steps are generally used to simplify the calculations, since the sine and cosines of the phase difference are being measured.

A solid-state detector array should be used to detect interference fringes. The output of the detector is digitized, and the digitized data are read directly into computer memory. A phase shifter, such as a moving reference mirror or an electro-optic modulator, will vary the phase difference between the two interfering beams. The phase change between detector readouts can be either discrete steps

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(phase-stepping) or continuously varying (phase-shifting).

As the detector output is read into the computer, the computer controls the phase difference between the two interfering beams. From these three or more measurements, the phase difference can be calculated using a wide variety of algorithms. Taking measurements with phase-shifting techniques can be both fast and accurate. The environment in which the measurements are made is critical to ensuring accuracy, because vibration or air turbulence can change the phase difference between the two beams in unknown ways and hence introduce large errors. To reduce the effects of vibration, all of the phase-shifting frames should be taken at once.

Phase-shifting single-shot interferometer

The phase-shifting single-shot technique can significantly reduce sensitivity to vibration and enable complete data acquisition in a single laser pulse. There are several types of phase-shifting single-shot interferometers. An approach that works well over a large spectral bandwidth involves the use of a quarter-wave plate followed by linear polarizers at different angles to get the phase shifts (Opt. Comm. **154**, 249). In this method, the test and reference beams have circular polarization of the opposite sense.

If these circularly polarized beams are transmitted through a linear polarizer, the result is a phase shift between the two interfering beams proportional to twice the rotation angle of the polarizer. Thus, if a phase mask is made of an array of four linear polarizer elements having their transmission axes at 0, 45, 90 and 135 degrees, as shown in the top figure on the facing page, where a polarizer element is placed over each detector element, the mask will produce an array of four 0, 90, 180 and 270 degree phase-shifted interferograms. A phase shifter of this type is often called a geometrical phase shifter, since the phase shift is independent of wavelength.

The bottom figure on the facing page is a schematic of a Twyman-Green interferometer that uses the micropolarizer phase-shifting array (Proc. SPIE **5531**, 304-14). The figure below shows the results for measuring a 300-mm diameter, 2-m radius-of-curvature mirror, where the mirror and interferometer are on separate tables. The micropolarizer phase-shifting array interferometer works very well in the presence of vibration and with a wide range of source wavelengths. Because the interferometer makes short exposures, the vibration and the air turbulence are frozen. The effects of air turbulence can be reduced by taking many sets of data, arranging for the time between taking the data sets to be long compared to the time it takes for the turbulence to change, and then averaging the data.

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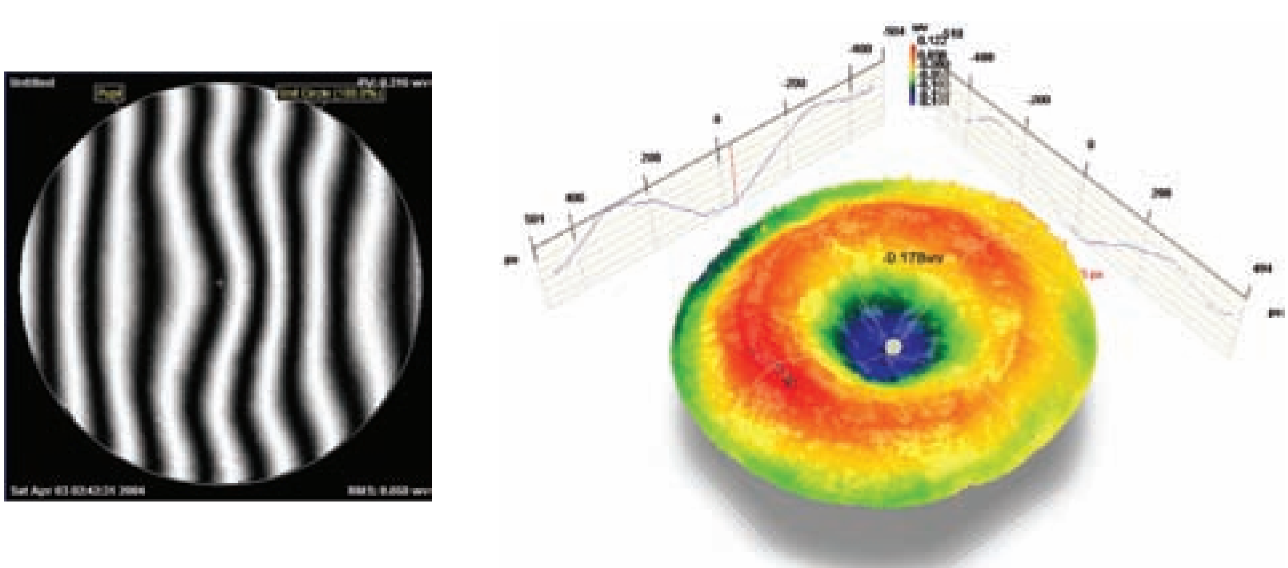
[Measuring a 300-mm diameter, 2-m ROC mirror]



The mirror and interferometer were on separate tables.

Electronic speckle pattern interferometry

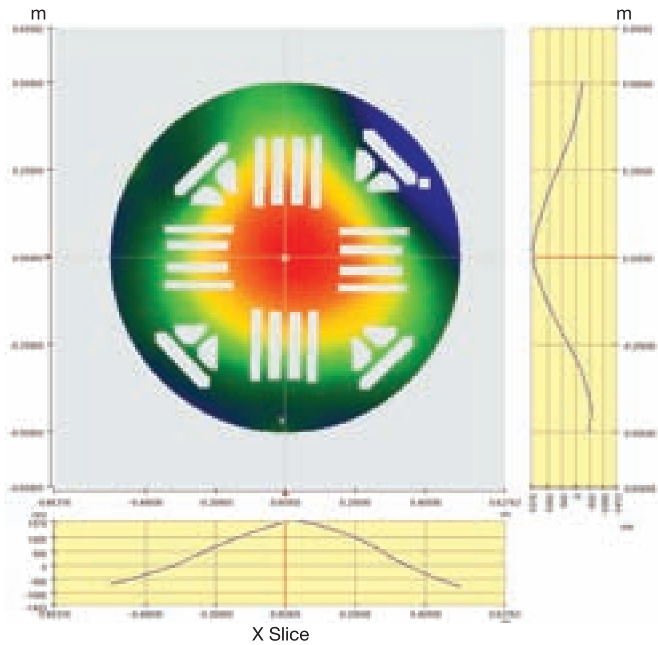
The technique for measuring changes in diffuse surfaces using electronic speckle pattern interferometry (ESPI) is well known. A dynamic phase-shifting electronic speckle pattern interferometer was designed to measure the stability of the James Webb Space Telescope (JWST) backplane (Proc. SPIE **5869**, 58691B-1). During each measurement, the laser produces a 9-ns pulse. Four phase-shifted interferograms are captured during the single pulse. Due to the short single pulse, the measurements do not suffer from the fringe contrast reduction and measurement errors that plague temporal phase-shifting interferometers in the presence of vibration.

Changes in the shape of the backplane are detected by making two phase-shifted ESPI measurements, one before and one after the surface is perturbed, and subtracting the phases. When considering the desired speckle size at the camera, two competing factors govern the selection: throughput and speckle decorrelation between the spatially offset pixels. The small spatial offset between the pixels that are used to calculate the phase leads to a difference in irradiance and phase between neighboring pixels. The larger the average speckle size relative to the offset in the pixels, the smaller the differences.

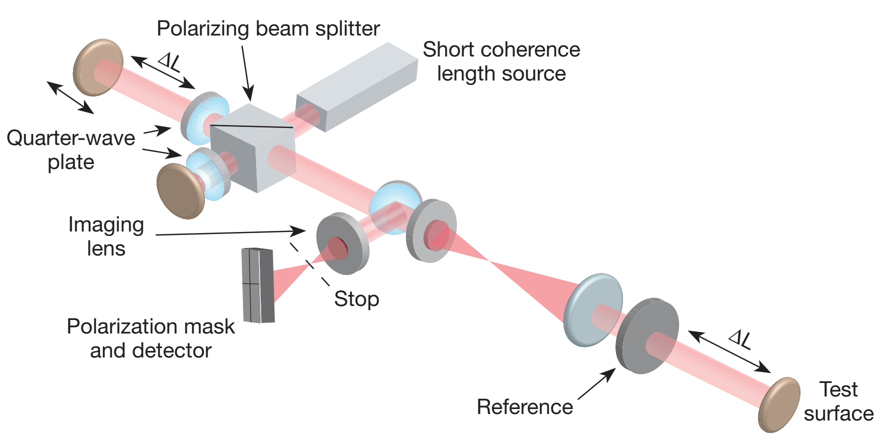
The obvious solution is to stop down the imaging aperture to enlarge the speckle size; however, doing so has the adverse consequence of reducing the amount of light reaching the detector. When one is measuring large structures, light is at a premium and must be conserved whenever possible. A good compromise between these two competing factors is to match the mean speckle size to the "unit cell" (the 2 × 2 set of elements used for a single phase measurement).

NASA engineers used the interferometer to measure a 1-m-diameter target made of carbon fiber. They illuminated the sample and imaged it off-axis with an angle of 5 degrees between the laser and the receiver. The interferometer and the test article were placed on separate unisolated tables with a 4-m standoff between the interferometer and the target. The test article was perturbed between measurements by pushing the center of the carbon fiber target toward the interferometer with a micrometer. The resulting phase for an average of 15 measurements

[Measuring mechanical deformation in 1-m-diameter carbon fiber]



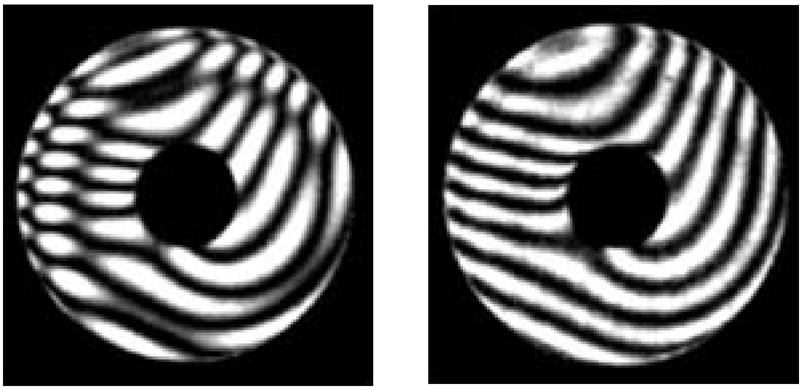
[Simultaneous phase-shifting Fizeau short-coherence-length source]



The interference pattern resulting from long-path-length source beam reflected off reference and short-path-length source beam reflected off test surface. Test and reference beams have orthogonal polarization.

The interferometer designed to measure the stability of the James Webb Space Telescope backplane has a total acquisition time of 9 ns and enough energy in the illumination to measure meter-class structures.

[Interference fringes obtained testing a thin glass plate]



(a) Long coherence length source. (b) Short coherence length source.

is shown in the top figure on the facing page. Averaging was used to mitigate the effect of air turbulence.

Clearly, a dynamic phase-shifting electronic speckle pattern interferometer that uses a single-frame spatial phase-shifting technique to reduce sensitivity to vibration can measure deformations of large objects. The interferometer designed to measure the stability of the JWST backplane has a total acquisition time of 9 ns and enough energy in the illumination to measure meter-class structures.

Single-shot Fizeau interferometer

A single-shot Fizeau interferometer is harder to make than a Twyman-Green interferometer because the Fizeau is more common path and it is difficult to obtain a reference and test beam with orthogonal polarization. In principle, a quarter-wave plate can be placed between the test and reference surfaces to rotate the direction of polarization of the test beam by 90 degrees. In practice, however, this does not work well, especially for the testing of spherical optics. In some techniques, the reference and test beams are tilted with respect to each other. However, a better approach is the on-axis approach.

In this approach, a short coherence light source is used, as shown in the bottom figure on the facing page. The source beam consists of two time-delayed orthogonally polarized beams. The path delay between the two beams is set equal to the path delay in the Fizeau cavity. The desired interference results from the long path source beam reflected off the reference surface and the short path length source beam reflected off the test surface.

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All beams are on-axis, so off-axis aberrations are not a problem. Since both source beams are reflected off both test and reference surfaces and only the two path-length-matched beams give interference, the fringe contrast is reduced, but still more than adequate. Spurious fringes are greatly reduced because a short coherence light source is used. One source that works well is a modulated diode having a coherence length of approximately 300 μm.

Not only will this interferometer work well in the presence of vibration, but it can measure thin glass plates that are virtually impossible to assess with a long-coherence-length laser-based interferometer. Part (a) of the figure on the left shows interference fringes obtained using a long-coherence-length source, while (b) shows the results obtained using the short coherence length source.

When one uses the long coherence light source, the interference fringes resulting from the interference of the light reflected off the two surfaces make the measurements useless. With the short coherence light source, on the other hand, the undesired interference fringes are not present and the measurements are excellent. By adjusting the path delay in the interferometer, fringes can be obtained from either the light reflected off the first surface or the light reflected off the second surface.

It is always exciting to see how the addition of modern electronics, computers and software to old interferometric techniques provides for very powerful measurement capabilities. ◭

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