ABSTRACT
Manufacturing precision aspheric surfaces is often limited by the availability of surface metrology. Interferometric tests of aspheres have traditionally needed dedicated null lenses, which require significant time and expense to design and fabricate. The costs of null lenses are recurrent because each is specific to one particular asphere prescription. Although sub-wavelength uncertainty is attainable, the accuracy of null tests is often limited by alignment errors and inadequate calibration techniques. Aspheric surfaces can also be tested with scanning instruments and profilometers. These devices are more flexible than null lenses because they are compatible with a variety of geometries and prescriptions. Accuracy, however, is typically limited by errors in the machine axes, and the time required for a full aperture map can be problematic for a manufacturing environment.

In 2004, QED Technologies introduced the Subaperture Stitching Interferometer (SSI®) to automatically stitch large diameter and high numerical aperture spherical surfaces (including hemispheres). This system also boosts accuracy with in-line calibration of systematic errors such as reference wave and imaging distortion. More recently, the system’s aspheric testing capability has been developed, which effectively extends the longitudinal dynamic range of a standard interferometer by an order of magnitude or more.

We present the SSI_a™: a flexible and robust method of stitching non-null aspheric phase measurements. Through the use of novel compensation schemes and in-line system error calibration, our subaperture stitching system can provide high accuracy interferometric measurements of surfaces with tens of microns of departure from the best-fit sphere. This is done without the use of dedicated null lenses, and can be applied to a wide variety of mild aspheric surfaces. The system reports a full-aperture map, which can then be used in conjunction with a deterministic finishing process. An example stitched asphere measurement is shown along with null test data for comparison.

1. PRINCIPLES OF NON-NULL STITCHING
In practice, Fizeau interferometers are typically used in a “null” configuration. This occurs when the test and reference wavefronts closely match each other. One example of a non-null test is measuring a rotationally symmetric aspheric surface against a spherical reference wave. Although a non-null test is simple in principle, it does present some difficult challenges. The most significant constraint is the resolution of the interferometer itself. A non-null aspheric test is effectively limited to only a few microns of aspheric departure, due to the fringe density and resolution of the detector. Other challenges include non-common path effects, and an increased susceptibility to scaling, alignment, and imaging errors. These types of errors can cause inaccurate removal of the aspheric shape, which directly degrades the measurement accuracy.

Subaperture stitching can alleviate many of these issues. One of its biggest advantages is achieved by dividing a wavefront that, measured all at once, is beyond the interferometer’s capability into smaller sections that are measurable individually. This characteristic effectively increases the longitudinal dynamic range of a Fizeau interferometer by an order of magnitude or more. It also significantly improves the lateral resolution of the instrument. By measuring a small section of the surface with the same interferometer and camera that is used for full aperture measurements, the lateral resolution can be improved by 3x or more. These are examples of how the acquisition process associated with stitching can be advantageous for aspheric surfaces. Once the data is collected, however, it must then be properly reconstructed to provide an accurate map of the surface form error.
2. MEASUREMENT DESIGN

The first responsibility of the user is to properly input the prescription of the aspheric surface to be tested. Figure 1 shows two plots calculated based on the prescription of an aspheric surface that was tested on the SSI_A; on top is a plot of the departure from best fit sphere, and the graph on the bottom shows the two principle curvatures of the surface (radial and tangential). Both graphs are plotted as a function of the distance from the center of the surface. Once the aspheric surface to be tested is defined, the location of each subaperture must be determined. The optimal measurement design, termed the “lattice”, is automatically computed for each asphere. An example asphere lattice can be seen in Figure 2. It uses a number of parameters to perform this calculation including, but not limited to; local curvatures, interferometer resolution, magnification available from each transmission sphere, as well as other guidelines that make the stitching process more robust. After the user selects their preferred option, a lattice is automatically calculated. The software has parameters that allow adjustment of the overlap to accommodate varying requirements for relative speed and accuracy.

Previous work in aspheric stitching utilized a method known as “zonal” or “ring null” stitching. Zonal stitching involves acquiring nearly nulled measurements in ring-shaped subapertures (the annular “zones”). A different measurement zone is achieved by adjusting the distance of the aspheric test part from the interferometer (by moving through the optical axis). The size of measurable data from each ring null is relatively small compared to the area of the detector. One of the SSI_A workstation’s capabilities rests in its freedom to move the surface off-axis with respect to the interferometer. This allows the system to acquire subapertures that utilize far more pixels on the detector. Figure 3(a) shows a simulated ring null fringe map, where (b) is an off-axis measurement nulled to a local best fit sphere.

Figure 2. SSI_A lattice design for measuring a concave asphere with ~18 microns of departure. The measurement consists of 33 subapertures.

Figure 3. Simulated fringe patterns for a mild asphere: (a) A ring null subaperture measurement provides a limited area of data. (b) Choosing an off-axis region using a local best-fit sphere dramatically increases the resolvable region.

3. HIGH ACCURACY RESULTS

Adequately sampling the non-null fringes is simply the first step in accurately reconstructing aspheric figure. The common-path property of Fizeau interferometry strictly only applies to null fringe fields; accuracy can degrade rapidly when measuring non-null wavefronts. The SSI_A can estimate and correct for a significant fraction of systematic error present in non-null measurements. This compensation is automatically performed inline with the stitching process, therefore it is a “real-time” calibration.

A mild aspheric mirror with ~ 18 microns of departure from best-fit sphere was measured.
with the SSI\textsubscript{A} system. The departure and curvature plots for this surface can be seen in Figure 1. Figure 4(a) displays the full aperture stitched map computed by the SSI\textsubscript{A} software with the nominal aspheric shape removed. Figure 4(b) and (c) are example interferograms from the central and outer zones, respectively.

Figure 4. (a) Full aperture stitched map of an asphere reported by the SSI\textsubscript{A} software. (b) central subaperture and (c) subaperture from the outer zone.

The same surface was also measured with a null test that required a computer-generated hologram. The results of both measurements are shown in Figure 5, where very good low order agreement can be seen (oblique plots are used to make form comparison possible). Smaller features and surface defects, however, are more evident in the stitched measurement. This difference can be attributed to stitching's inherent increase in resolution over a full aperture measurement\textsuperscript{6}.

4. IMPROVING LEAD TIME

In a manufacturing environment, total lead time is an increasingly important metric. When producing precision aspheres, lead time is often driven by the time required to produce a custom null lens as well as the individual manufacturing steps. Null lenses can take anywhere from weeks to months to produce, and they are specific to one aspheric prescription only.

Another example aspheric surface, this time with ~50 microns of departure, was measured with the SSI\textsubscript{A}. The surface required 35 subapertures in order to provide a high resolution, full aperture map. Under normal conditions, each subaperture takes 20-30 seconds to acquire, therefore this particular measurement was completed in ~15 minutes. A different lattice (measurement design) was then generated with
only 12 subapertures. This measurement was designed to significantly decrease the cycle time by measuring merely a “slice” across the diameter of the surface. Figure 6 shows both the full aperture and faster measurement designs.

Figure 6. (a) is the standard lattice design for providing a full aperture map and consists of 35 subapertures. (b) decreases the measurement time by a factor of 2 by only acquiring data across a slice of the surface.

Figure 7 shows the stitched maps from the full aperture and faster “slice” acquisitions in (a) and (b), respectively. Both maps have the same lateral resolution and nearly identical low order form. Measurement (b) still provides precise data regarding radial (symmetric) errors. The same center feature and astigmatic form can also be identified seen in both maps, however the (b) measurement only required ~7 minutes to complete. The combination of speed and accuracy makes this type of measurement ideal for in-process metrology after, for example, a polishing process that removes the grinding and subsurface damage. The full aperture stitched measurement can then be used for deterministic finishing and final quality testing.

5. CONCLUSION
Subaperture stitching has been able to enhance lateral range and resolution of an interferometer for some time. With QED’s introduction of the SSI, this capability became commercially available for spherical surfaces, with improved accuracy over a conventional test (due to its inline calibration capability). Now with the SSIa software, the system can stitch mild aspheres quickly, automatically and accurately without any dedicated null optics.

QED has demonstrated that the SSIa process is capable of obtaining nanometer-level quality measurements on mild aspheres. Most recently, this instrument successfully measured more aggressive aspheric surfaces with ~ 70 microns of departure. These capabilities are a breakthrough improvement to an interferometer’s lateral and longitudinal dynamic range capability.

REFERENCES