The Infrared Multi-Object Spectrograph (IRMOS) is a facility instrument for the Kitt Peak National Observatory’s 3.8 m Mayall Telescope and an engineering prototype for a possible design of the Next Generation Space Telescope/Multi-Object Spectrograph. IRMOS requires a toroidal, off-axis, biconic camera mirror ("M4") on an aluminum substrate for near-IR imaging and spectroscopy. This mirror (shown in Figure 1) presents significant fabrication difficulties due to its non-rotationally symmetric (NRS) form and tight tolerances [1]. Combining the capabilities of a long range fast tool servo (FTS) with a 400 μm maximum excursion and a diamond turning machine (DTM) with a 600 mm diameter part capacity has made it possible to fabricate large, free-form optics for demanding scientific applications.

Novel surfaces like M4 pose unique challenges for measuring figure error (i.e., surface error at spatial periods of 2 mm). Several methods are applied and evaluated for their merits and drawbacks. The use of computer-generated holographic (CGH) null elements in interferometry allow high-resolution measurements; however, alignment of the test setup can be time-consuming since the alignment tolerances are tight. We address this issue with a set of custom alignment fiducials built-in to the CGH and the M4 mirror. Additionally, CGH masks normally cannot be directly verified with a known standard. Stylus profilometry, on the other hand, is traceable since the instrument can be calibrated using known standards. Even with minimal probing forces the contact process can be destructive if local contact stresses leave witness marks on the surface. Depending on the system, profilometry data may also be time consuming and difficult to assemble and interpret.
M4 Biconic

M4 defies conventional fabrication and metrology methods by virtue of the fact that it has no rotational axis of symmetry. As shown in Figure 2, M4 is an off-axis, 94 mm by 76 mm aperture of a concave, oblate ellipsoid. It is decentered by -2.01 mm and 227.41 mm in $x$ and $y$, and has shape parameters,

$$k_x = 0.0778,$$
$$k_y = 0.1265,$$

$$R_x = 377.3939 \text{ mm}$$
and $$R_y = 406.8829 \text{ mm}.$$

The surface of M4 was separated into a rotationally symmetric 4th order asphere that can be machined on a DTM and an NRS component (Figure 3) to be machined simultaneously with an FTS. Machining was performed off-axis, although not in the parent orientation [1]. Accurate metrology of the mirror surface is an essential aspect of mirror fabrication since it allows troubleshooting of this complex machining process.

CGH Interferometry

While the idea of using a tailored diffractive element to measure non-standard surface shapes in an interferometer is certainly not new [2], the degree of sophistication for CGH metrology has dramatically improved with in the last few years. Now commercially available, the CGH masks are equipped with alignment fiducials essential in setting up a measurement [3]. This aids in both aligning the mask to the interferometer as well as aligning the sample to the mask. Since traditional methods of finding fringes often do not apply for free-form surfaces, such tools are indispensable for CGH metrology. Unfortunately, this also means that fiducials must be applied to the sample and other alignment tools such as theodolites are required. In the case of M4, a diamond flycut back surface was used to align tip and tilt and several crosshairs were used to align translation. The fiducials do, however, serve another function in that they will later be used to align the mirror in a complex optical system.
CGH Results
Initial alignment of the CGH and mirror using fiducials immediately showed fringes and allowed data collection. However, translation of the sample was required to minimize the error. This known translation was later correlated with a phase shift present in the FTS system. The residual error on the optimally aligned sample, shown in Figure 4, revealed a trefoil pattern identical to that of the servo excursion shown in Figure 3. While the amplitude of the measured error was about 8% of the servo excursion, the shape correlation led to the discovery of a scaling error in the FTS output that had to be corrected. A numerically generated reference surface confirmed these CGH results. A distorted (i.e., phase shifted and scaled) NRS component was added to the least squares aspheric component and compared with the interferometer data. These results show clearly that through the use of a CGH and proper alignment fiducials, one can troubleshoot a machining system in much the same way it would be done with a spherical or flat surface.

Profilometry
Since the CGH cannot be directly tested against a known standard, it is generally prudent to perform additional measurements with a method that can. While ultraprecision CMM’s or multiaxis profilometers would be expertly suited to this task, they are not commonly available. Three-dimensional surface data can, however, be acquired by assembling multiple linear traces from a standard profilometer. One method, called the Union Jack [4], allows this assembly to be performed without the use of multiple axes. Fiducials placed on the surface of the part are used to relate the positions of the traces to each other. All of the intersections of the traces are then joined to assemble the data, as shown in Figure 5. Since each trace has multiple intersections, the redundant intersections can be used to test for alignment and measurement errors.
**Data Manipulation and Surface Fitting**

Matlab™ software for automating 3D surface evaluation is being developed. Two data sets are input for comparison. One is a measurement, presumably either a profilometer or interferometer data set and the other is a reference datum. The reference may be an analytic function (e.g., a biconic equation) or an\([x,y,z]\) point cloud. The Levenberg-Marquardt unconstrained nonlinear optimization algorithm is used to align the two surfaces. The optimization merit function is the residual sum of squares error in either the parent \(z\) direction or the normal direction of the measurement. Parameters are the elements of a homogeneous transformation matrix (HTM) that is used to locate the measurement data set with 6 degrees of freedom. The measurement is translated in the reference coordinate system and rotated about a coordinate system whose origin is the geometric moment of the data set and whose \(z\) axis is normal to the surface. This was done to enhance the sensitivity of rotations for far off-axis data sets such as M4; otherwise small angle rotations are difficult to distinguish from translations. To speed up the alignment process and reduce the probability of convergence to a local minimum, a preliminary coarse alignment is done. The measurement is translated so that its center is coincident with the center of the reference and then rotated about that center point so that it has the same normal vector as the reference. Throughout the process, the reference surface remains at its original location in the parent coordinate system.

If an analytic function is not available as a reference datum, then the residual must be formed by interpolation. Either the reference surface can be triangulated onto the \((x,y)\) grid of the measured data or vice versa or both data sets can be interpolated onto a common grid. This must be done on each evaluation of the merit function since parameter adjustments necessarily misalign the data. For widely spaced, irregular data such as that from a *Union Jack* process, a closely spaced reference grid is triangulated onto the measurement grid to minimize interpolation errors. The results of this process are, 1) a residual error surface and the accompanying metrology statistics and 2) the composite HTM that aligns the measurement data.

**Conclusions**

The expanded use of free-form surfaces in optical systems is inevitable. As demonstrated in the case of the biconic mirror M4, figure metrology of these surfaces presents some unique challenges. While tools are available for measuring these surfaces, the techniques for doing so expeditiously and economically are not yet mature. CGH reference masks may take weeks to design and fabricate and 3-D profilometer measurements require an arduous process of data manipulation before meaningful results are available. Nevertheless, once results are obtained, they can be used in much the same way as standard ones for quality control, troubleshooting and performance assessment.

**References**


