Large High Performance Optics for Spaceborne Missions: L-3 Brashear Experience and Capability

Blaise Canzian[1], George Gardopee[1], Andrew Clarkson[1], Tony Hull[2]
([1]L-3 Communications Integrated Optical Systems, Brashear; [2]L-3 Communications Integrated Optical Systems, Tinsley)

Abstract

Brashear is a division of L-3 Communications, Integrated Optical Systems. Brashear is well known for the ground-based telescopes it has manufactured at its facilities and delivered to satisfied customers. Optics from meter-class up to 8.3 meters diameter have been fabricated in Brashear's facilities. Brashear has demonstrated capabilities for large spaceborne optics. We describe in this paper both legacy and new Brashear capabilities for high performance spaceborne optics.

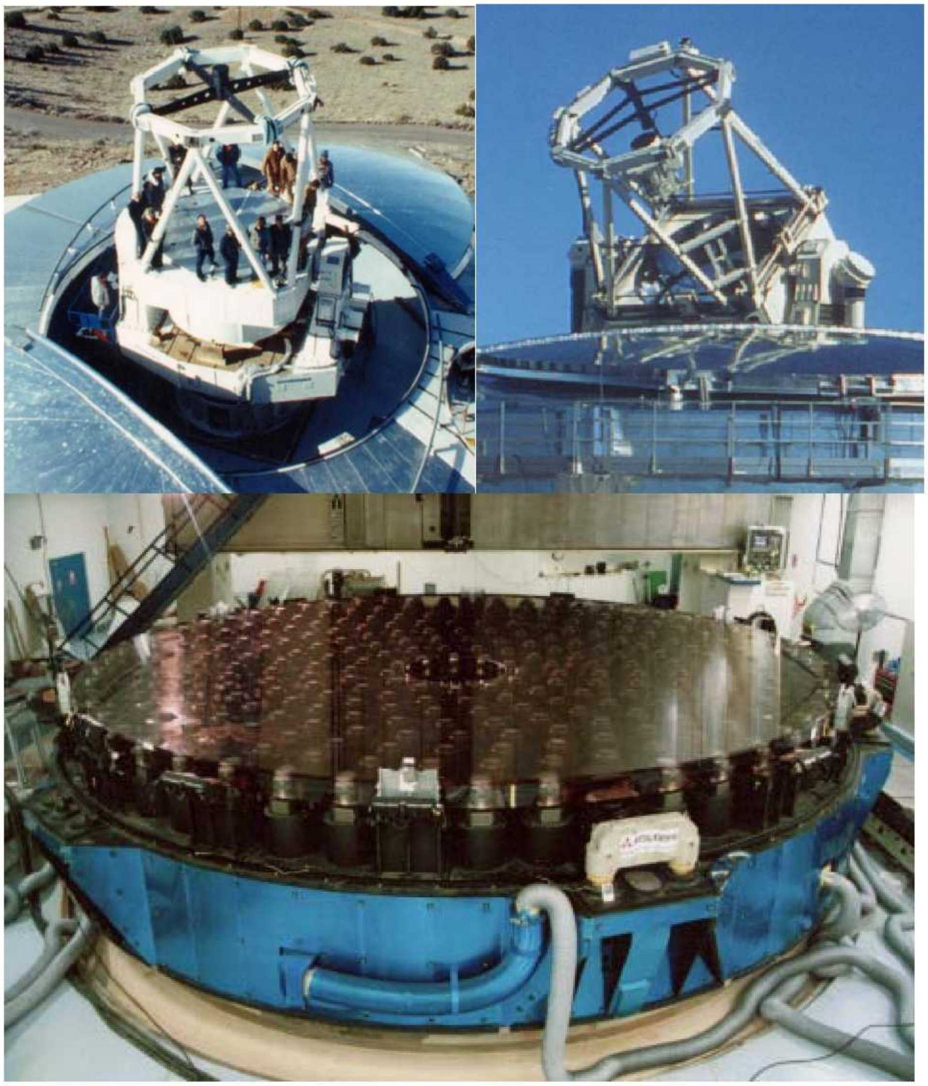


Figure 1 Some large precision optics manufactured by Brashear. (top left) 3.5m Starfire Optical Range telescope. (top right) 3.67m AEOS telescope. (bottom) 8.3m Subaru primary mirror.

Brashear has along heritage of precision optics and telescope manufacture. Recent high performance ground-based optics and optical systems manufactured by Brashear include the 3.5m Starfire Optical Range telescope (in New Mexico), the 3.67m AEOS (Advanced Electro-Optical System) telescope (on Haleakala, Hawaii), and the 8.3m Subaru telescope primary mirror. Brashear has also produced telescopes and optics for space, the most recent being the primary mirror for Kepler, a current NASA Discovery mission.

Kepler was launched March 6, 2009; first light data were received April 8, 2009. Kepler has a mission to monitor hundreds of thousands of stars photometrically with micro-magnitude accuracy, accumulating light curves that would reveal the transit of planets across the stellar disk.

Figure 2. Photo of the Kepler satellite. *(Source: W.J. Borucki presentation, http://kepler.nasa.gov/ed/ppt/BoruckiPPT/Borucki2009IAUpresentation.ppt)*

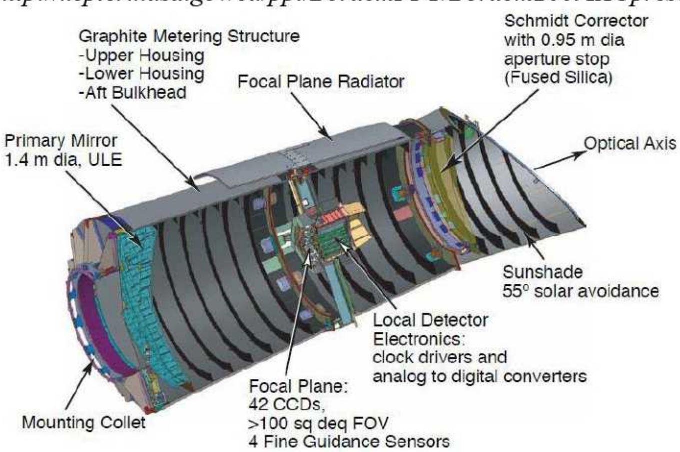


Figure 3 Kepler satellite model cross-section. *(Source: NASA press kit. http://kepler.nasa.gov/pdf_files/314125main_Kepler_presskit_2-19_smfile.pdf)*

The Kepler photometer is a Schmidt-type telescope with 1.4 meter primary mirror polished at Brashear. The primary mirror is a ULE glass face-sheet with underlying supporting honeycomb structure that is 86% lightweighted.

Figure 4 Kepler primary mirror (rear side inspection). *(Source: NASA press kit. ://kepler.nasa.gov/pdf_files/314125main_Kepler_presskit_2-19_smfile.pdf)*

Brashear was contracted by Ball Aerospace to design, fabricate, and test the Kepler primary mirror, including the mirror assembly with its support structure (called the "Primary Mirror Assembly", or PMA). Brashear was responsible for the selection and characterization of all component materials making up the PMA. A lightweight, frit-bonded primary mirror made of Corning ULE (ultra-low expansion glass), including reinforced main and alternative support bonding sites, was designed at Brashear. The lightweighted mirror has only a 50 kg/m2 areal density. Brashear also designed and analyzed the hexapod support structure beneath the primary mirror. The hexapod consisted of carbon fiber struts with titanium cross flexure end fittings. The hexapod attached to the primary mirror at six invar bond pads, which were adhered to the mirror backsheet using an epoxy adhesive bond. The bond design, proof-testing of the PMA bond pads with adhesive, and proof-testing of the hexapod struts were all successfully performed at Brashear. The handling fixtures for the primary mirror and strongback support fixture for the PMA along with other related fabrication and testing tooling were also designed and fabricated by Brashear.

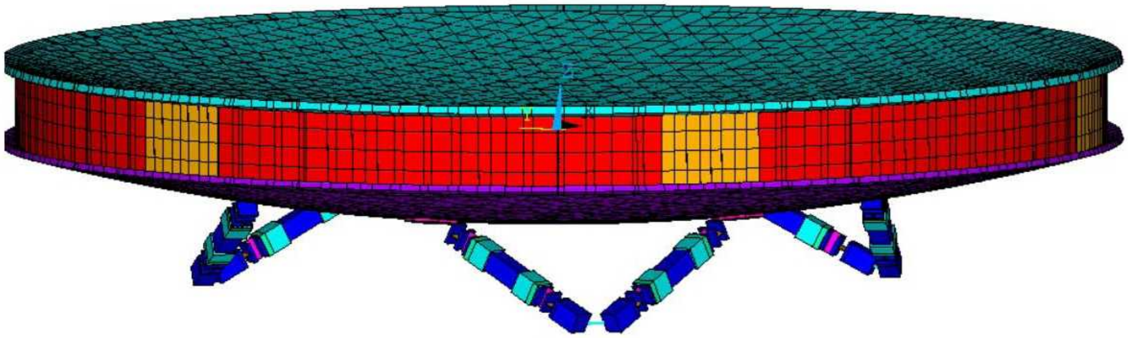


Figure 5 Model of the Kepler primary mirror and strut support assembly (PMA). *(Source: Brashear)*

Brashear performed the finite element analyses (FEA) of the PMA, to include surface figure analyses both for in-process testing and for the final thermal vacuum cryogenic testing. During mirror generation and in-process metrology, the bare mirror was supported to minimize gravity effects. Brashear also worked out the technical and analytical means to combine analytical FEA modeling of the gravity sag (for various support configurations) with interferometric test data to approximate the gravity free surface figure of the mirror. Surface figure is critical to Kepler photometer performance, since the point-spread function size affects achievable photometric precision for a given observing cadence with a sampled imager. Brashear achieved a low 0.0585 waves RMS clear aperture surface manufacturing error for the Kepler primary mirror.

Figure 6 Vertical and horizontal interferometric testing at Brashear of the Kepler primary mirror surface figure. Measurements were both at low resolution (full mirror) and at high resolution (stitched sub-fields in an array covering the mirror). *(Source: Brashear)*

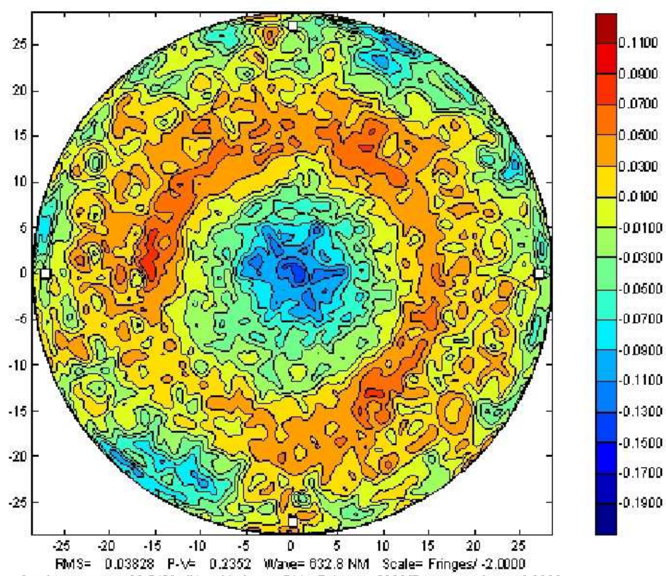


Figure 7 Kepler primary mirror final manufactured clear aperture surface error of 0.0585 waves RMS. *(Source: Brashear)*

Brashear also used FEA analysis to estimate the cryogenic figure with a plan to polish out a portion of the analytical figure prior to cryogenic testing. Due to Brashear's careful modeling with attention to detail and use of prototypes to validate the model, the FEA predicted cryogenic surface figure matched the measured cryogenic surface figure to high accuracy. Implementing a similar measured approach on future projects will permit schedule reductions by enabling more aggressive pre-cryo figuring, which may even circumvent the need for post-cryo figuring.

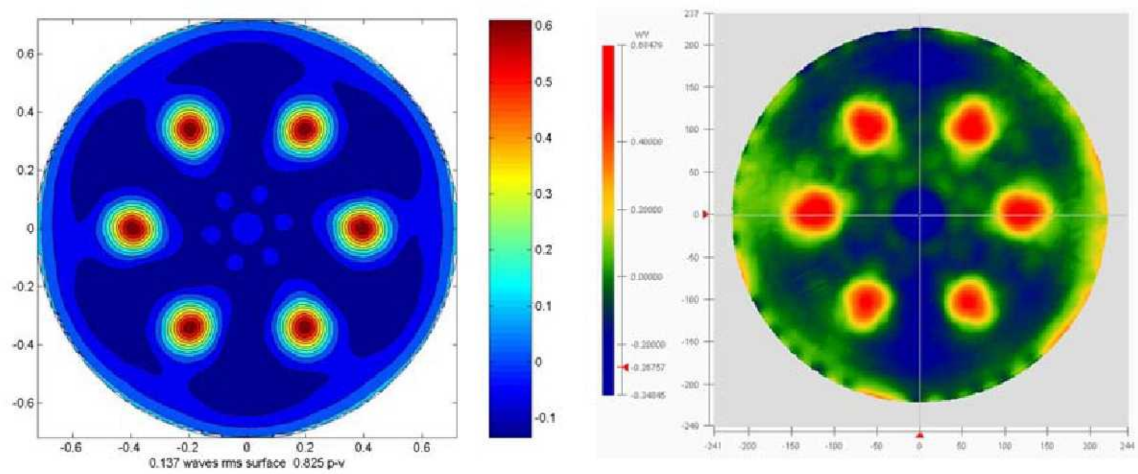


Figure 8 Kepler primary mirror at –60°C, showing expected "print-through" of support structure. (left) FEA model <u>prediction</u> of 0.137 waves RMS surface; (right) <u>measured</u> at 0.143 waves RMS surface, within 8% of the model prediction. *(Source: Brashear)*

Final figuring and polishing of the Kepler primary mirror at Brashear resulted in an excellent mirror, with correct figure and low surface roughness (0.94nm average). Surface roughness is critical to photometric performance because of its contribution to scattered light, which raises the background and wings of the point-spread function, thus affecting photometric accuracy for a planned observing cadence. The quality of the Kepler primary mirror delivered by Brashear is a key factor enabling Kepler to achieve its mission-critical photometric precision.

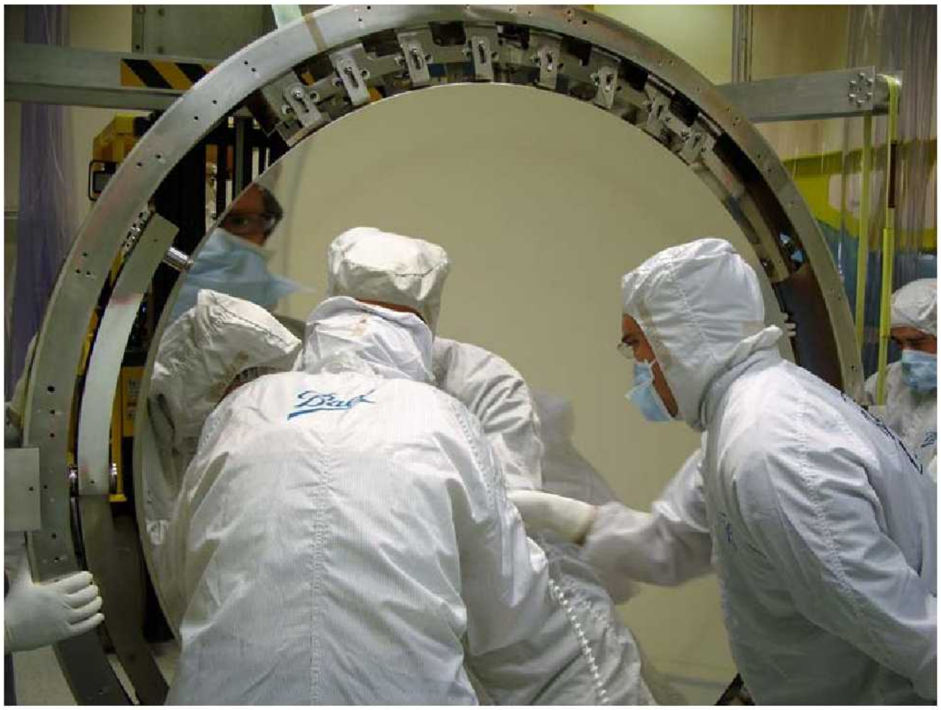


Figure 9 Kepler primary mirror inspection after enhanced silver coating. *(Source: Brashear)*

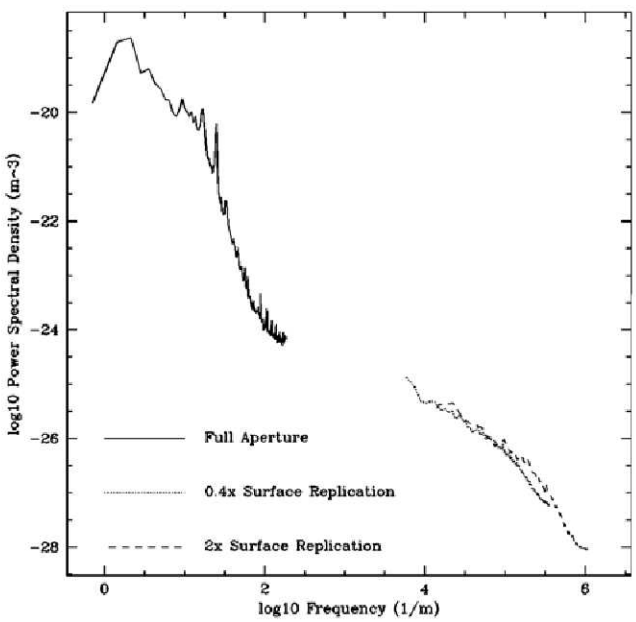


Figure 10 PSD of the Kepler primary mirror surface from interferometric mapping and from surface replication, both measured at Brashear. *(Source: Brashear)*

Brashear engineering and manufacturing departments successfully addressed the following issues in the design and manufacture of the Kepler primary mirror:

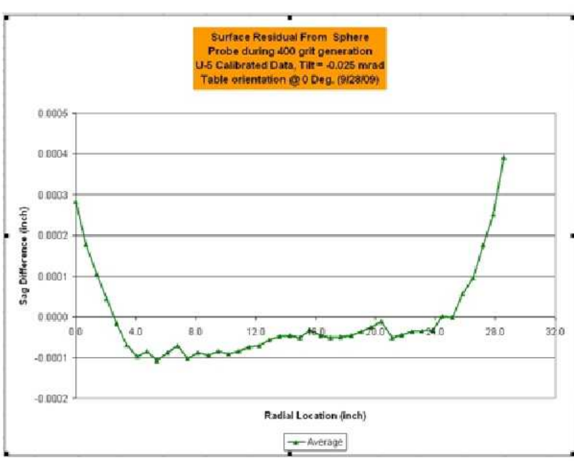
- Safe mirror handling
- Structural lightweighting ensuring survival during launch and injection into orbit

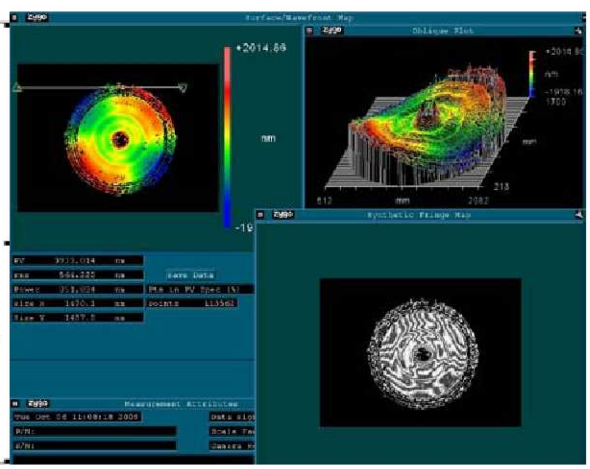
- Hexapod support design and construction
- Correct analysis of mirror and support strain and figure over complete shipment, launch, and cryogenic operation temperature range
- Design for cryogenic vacuum operation with space-qualified materials and techniques
- Design of support fixtures and analysis techniques simulating zero-gravity conditions in earth's gravity field for surface figure measurement and test
- Accurate predictive modeling of the cryogenic surface figure to guide the final polishing at ambient temperature
- Accurate final mirror figure and small surface roughness

Brashear has two large CNC work centers for optical materials generation and optical figuring.

Brashear's CNC optics generator is a six-axis model with a 2-meter rotary table that has a 3.5 × 5.5 meter work area and a 10-ton work capacity. The machine has integral 3D Renishaw-MP700 probing CMM capability. Surface accuracy performance ranges from 1 to 5 microns RMS with specular surface finishes ready for interferometric phase capture.

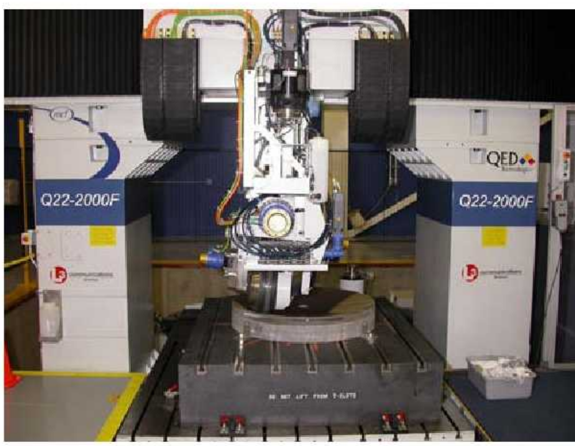
The typical surface accuracy form error below is from a 1.5-meter class optical surface finished with D40-resin. The surface is directly phase measurable before any polish.

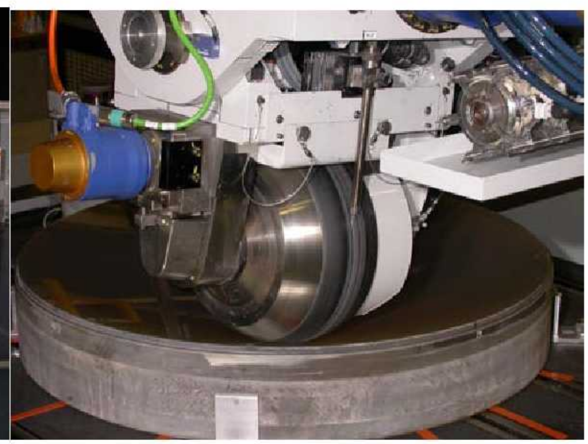


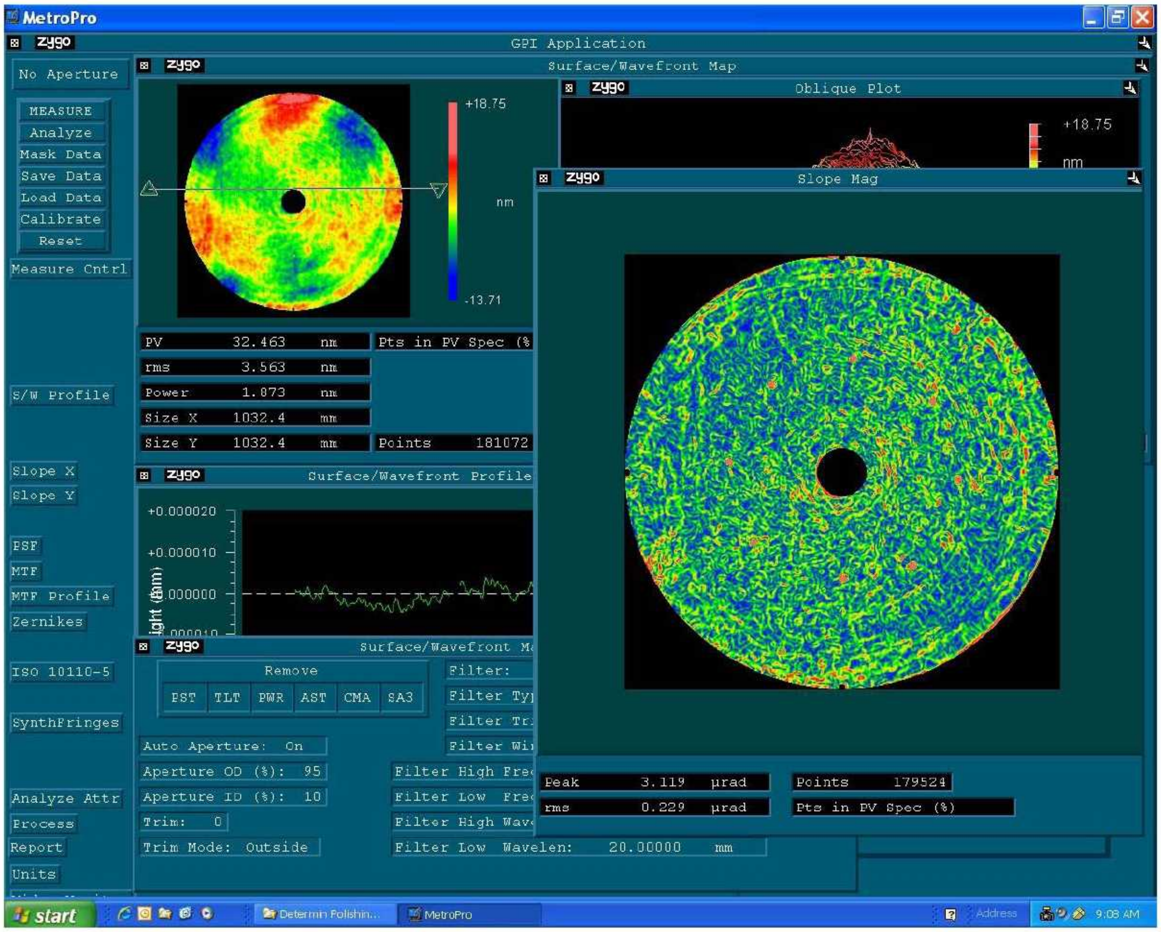


L-3 Brashear and QED Technologies®, Inc. partnered in 2003 for a joint research program to mature Magneto-Rheological Finishing (MRF®) technology for large optics. The world's first 2-meter class MRF® machine became fully operational at L-3 Brashear in 2008 as the 2.3 meter class Q22-2000F platform. The machine is equipped to figure any type of optical surface prescription with a maximum sag angle of ±30 degrees.

The figuring convergence rates typically observed are 80-95% and are mostly dependent on the quality of the metrology solution. Brashear has finished several 1- and 2-meter class optics all below 10nm RMS total surface accuracy. Most of the residual surface errors are low order in nature related to the complexity of obtaining perfect metrology solutions. The typical surface below after subtraction of Zernike terms Z5-Z9 has a surface accuracy well below 5nm RMS.







The figure above shows the interferometric phase map of the surface error on the 1.1 m Cervit test piece after MRF® processing. Low-order Zernike terms (Z5 – Z9) have been removed from this map. Full aperture surface errors are 3.5nm RMS.