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Milestone Report for High NA Optics Development
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Milestone 4a: Specification package for the polished mirror substrate M1

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Executive Summary

The key task in initiating the fabrication of mirror substrates for the new High NA Camera is in preparing the specification package that details the substrate geometry and the specifications for the optical surface. This specification package has been completed for substrate M1, and the vendor has begun optical fabrication. In addition, mounting hardware has been designed and fabricated, and substrates have been bonded to the kinematic mounts. The design of the secondary substrate, M2, is underway, but will depend upon details of the PO Box actuation system and space constraints. Sufficient details of the M2 design to enable the vendor to procure material will be determined during October, while the final details of the mounting surfaces will be completed prior to the end of Q4 1999.

The geometry of the M1 substrate is compatible with our planned approach for fixturing the optic within the PO Box and within metrology tools. The completion of this specification package required detailed consideration of: the mounting approach within the PO Box, degrees of actuation required for PO Box alignment, space constraints imposed by the vendor's metrology, requirements for LLNL metrology, and datum definitions needed for mechanical assembly of the PO Box. In addition, each of the degrees of freedom of the substrate has been properly constrained, and shown to be sufficiently insensitive to disturbance forces for minimizing deformation.

An approach to fixturing has been adopted that extends beyond the approach taken for the Engineering Test Stand (ETS). For the ETS, each substrate, including spares, has dedicated mounting hardware that is used exclusively for each element. In exchange for a reduced risk of mounting-induced deformation, this incurred substantial expense and precluded optics from using interchangeable tooling. For the current High NA camera, we have adopted an approach that employs interchangeable mounting hardware that can be used for any of the substrates. This approach better accommodates a large number of manufacturing spares and the need for different mounting hardware for the PO Box and the metrology tools. This approach was enabled by designing the mounting hardware to

minimize differences in the disturbance forces offered by different fixtures on the optic. An error budget and sensitivity analysis indicates that figure errors induced on the optics due to changes in fixturing are within the required tolerances for high quality imaging.

The specifications for the optical surface on M1 are nominally the same as for the ETS substrates. These impose requirements for 0.25 nm rms for figure, 0.20 nm rms for mid-spatial frequency roughness, and 0.10 nm rms for high spatial frequency roughness. These designations are sufficient for controlling wavefront quality, image contrast, and multilayer reflectivity.

Details

M1 Optic Substrate Design

Status: A formal drawing of the M1 substrate has been completed and is enclosed with this report. To enable the design of the substrate, a system level decision was required on the trade-off between the distance between the back of the substrate and the wafer image plane and thickness of M1. A thicker substrate leads to lower sensitivity to deformation, while a thinner substrate offers greater wafer stage clearance. In addition, definition of the datum surfaces on the substrate required a strategy for fixturing the substrate to the Zeiss interferometer, to the LLNL interferometer, and to the PO Box. All of these decisions have been completed and incorporated into the final design drawing, a portion of which is shown in Figure 1.

The mounting strategy for M1 is similar to the ETS optics with one notable exception to be addressed in the following section. The buttons are made from Super Invar to nearly match the coefficient of thermal expansion (CTE) of the Zerodur substrate. The current plan calls for 14 substrates to be mounted, 11 to produce 2 finished aspheres and 3 reference spheres for the interferometer. Each substrate will have three equally-spaced "buttons" attached to the outside diameter using the same vacuum-qualified epoxy as in the ETS. The buttons are attached prior to final figuring of the optical surface. The gluing fixture has been built, aligned and tested using aluminum mock optics.

A number of substrate/mounting concepts were considered ranging from more elaborate substrates with integral mounting features to the simplest substrate that we finally adopted. The vendor's personnel were actively involved in this decision and strongly supported our final approach. The main complication in the substrate is a center hole required for ray clearance to the wafer. The final figure will be achieved with a partial-depth hole leaving a continuous surface for polishing. Then the thin membrane will be removed and etched to remove grinding stress.

The outside diameter was driven primarily by the amount of freeboard around the clear aperture desired by the vendor. The inner diameter was dictated by the optical design. The thickness of the optic was made as large as practical within the constraints of the optical design. A preliminary error budget based on finite element analysis (FEA) confirms that the substrate thickness provides sufficient stiffness to minimize fixturing-induced deformation. An FEA analysis of coating stress on the optic showed that there is a small localized coating-induced deformation near the hole. Although it has not been

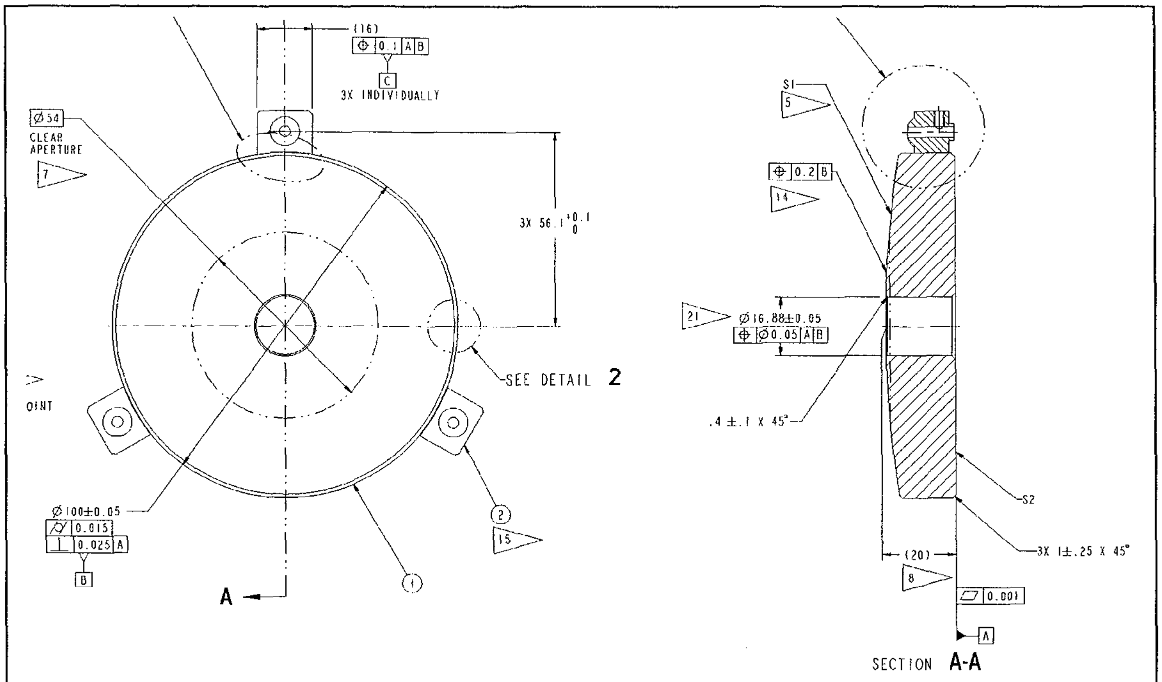

Figure 1. The main views from the M1 optic drawing.

confirmed with our optical design code that this localized effect will be a problem, we have identified methods for minimizing coating stress. Further analysis of coating stress deformation will be included in the report for Milestone 5: Mutlilayer Coating Specifications.

M1 Optic Mount and Metrology Mount Designs

Ideally, an optic should be supported in the same manner and with the same orientation in the projection optics box (PO Box) as in the interferometer. For the ETS optics, this was accomplished by using a dedicated optical mount for each optic in both the PO Box and the interferometer.[1] In this scheme each optic attached only to its mated mount. There are several reasons why a dedicated mount approach was difficult to follow for the MET. Perhaps the most significant are the tight space constraints posed by the wafer near the bottom side of the optic (in the PO Box) and the transmission sphere on the top side of the optic in the interferometer. Therefore, we chose to produce a single metrology mount, different than the PO Box mount, that would work with all the M1 optics and reference spheres (approx. 14 substrates). In addition to meeting the space constraints, this metrology mount could be designed and produced much faster than multiple PO Box mounts. Furthermore, this approach does not constrain the design of the PO Box by forcing a decision on the optical mounting configuration.

The challenge with this approach is in achieving nearly identical support from two different mounts, the metrology mount and the PO Box mount. The metrology mount is shown in Figure 2. For the optic to be supported identically in any mount, the reaction forces and moments at the constraints must be identical in magnitude and location (w.r.t. the optic) from mount to mount. An ideal kinematic mount provides six constraints that

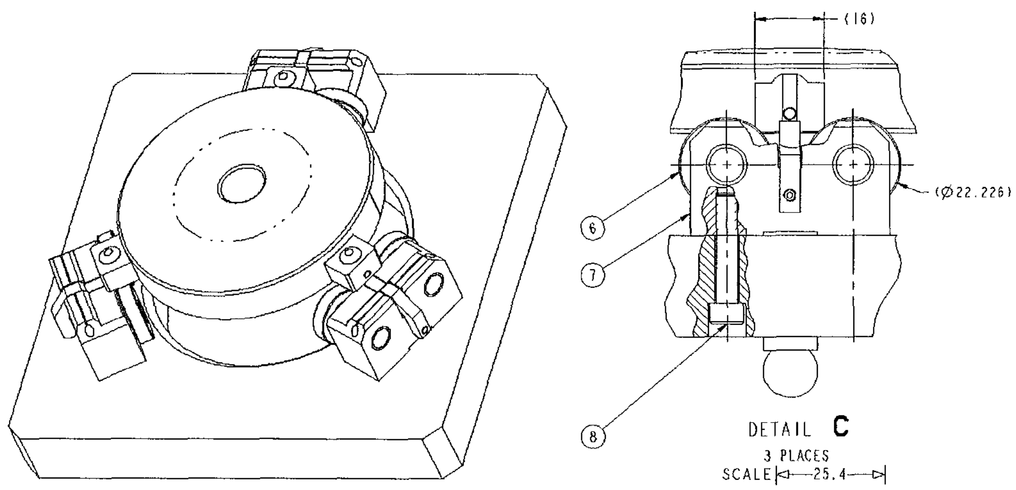

Figure 2. M1 optic supported kinematically in the metrology mount. In Detail C, a partial sphere on each button rests in a vee constraint formed by two anti-friction bearings.

fully arrest the degrees of freedom of the optic without over-constraint. In addition, these constraints must pass through specific points with specific orientations for two kinematic mounts to provide the same support. The degree to which these requirements must be met are analyzed with an error budget.

An error budget of the M1 optic supported in the metrology mount is given in Table 1. It indicates that the error induced by the metrology mount is much smaller than the allowable figure tolerance of the optic. It is based on sensitivities of the optic computed with FEA and disturbance forces and moments as indicated. The various error terms are root-mean-square (RMS) surface deformations for those loads combined in a root-sum-square (RSS) total.[2] A similar analysis will be completed for the PO Box mount as it is designed.

Table 1. Error budget for the M1 metrology mount.

		Budget	Sensitivity	Disturbance	Comments		
Load Type	**Units**	*nm rms*	*nm/load rms*	*load*			
Radial Force	*N*	0.0025	0.0153	0.1650	0.1 coef. of fric. & 45 deg. vee		
Radial Moment	*N-mm*	0.0044	0.0245	0.1815	0.01 coef. of fric. & R11 mm ball		
Tangential Mome	*N-mm*	0.0040	0.0031	1.2833	0.1 coef. of fric. & R11 mm ball		
Axial Moment	*N-mm*	0.0012	0.0009	1.2833	0.1 coef. of fric. & R11 mm ball		
Gravity Load	*g's*	0.0001	0.2232	0.0006	Altitude change of 2 km (6560 ft)		
RSS for 3 mounting points		0.0114					
Fraction of 0.25 nm spec.		0.0456					

The basic mounting approach constrains the optic through the centers of three spheres, one on each button. Since the buttons always remain on the optic, the location where the constraining forces act will not change. Two constraints are required at each button to provide six constraints on the six degrees of freedom. Each constraint pair, i.e. two on each button, forms a plane whose orientation has been chosen to be vertical and tangent to a circle through the three buttons. The orientation of the button's constraint plane can be sufficiently controlled using standard precision manufacturing tolerances.

The four non-constraint directions at each sphere are subject to disturbance forces and moments, such as from friction. Our error analysis identifies two directions with significantly large sensitivities that influence the design of the optic buttons and the metrology mount. The first is a force directed radially from the button to the optic axis. This force also causes tangential reaction forces at the other two buttons. The proper selection of the elevation (vertical height) of the constraint points minimizes the resulting surface deformation. The optimal elevation is approximately 9 mm from the back of the optic. A moment about the same radial axis has the greatest sensitivity as it tends to twist the optic. The use of two anti-friction ball bearings as a constraint pair reduces the radial disturbance moment to an acceptable value. In the other directions, sliding friction limits the disturbance forces and moments to acceptable values.

The metrology mount has been fabricated and shipped to the vendor. The first sets of M1 substrates have been delivered to LLNL from the vendor, had buttons bonded to their sides, and then returned to the vendor. The LLNL bonding station employs a coordinate measuring machine and can accommodate one element per day.

Specifications for Optical Surface

The specifications for the optical surface for the MET optics address the same functional requirements as for the Engineering Test Stand and include dividing the errors among three categories of surface spatial frequency: figure, Mid-Spatial Frequency Roughness (MSFR), and High-Spatial Frequency Roughness (HSFR). The specification level and definition of each category are nominally the same as for the Engineering Test Stand and are listed in Table 1. In general, figure errors are associated with wavefront aberrations and distortion and are determined by low-spatial frequency errors. Mid-spatial frequency roughness generally determines near-angle scattering and is associated with loss of contrast or flare. High-spatial frequency roughness leads to wide-angle scattering and a loss in multilayer reflectivity.

The surface errors listed in Table 2 represent levels similar to those already attained by the vendor on aspheric test optics but are beyond their current state-of-the-art because the current optics have a larger aspheric departure[3]. Defining the specifications in this manner allows for a convenient comparison with ETS optics regarding the ability of the manufacturing community to simultaneously meet figure and finish specifications on aspheric optics. We are currently modeling dependence of flare for both the ETS and the High NA cameras as a function of spatial frequency of the roughness. Based on these calculations, the spatial frequency definitions listed in Table 1 may be updated at a future date. Conclusions reached during this modeling, and any changes in the spatial frequency definitions given in Table 1, will be discussed in the Q4 1999 Quarterly Report.

Table 2. Nominal specifications for EUVL substrates.

Error term	**Maximum error specification**	**Defined by integrating the PSD of surface errors over the following bandlimits:**
Figure	0.25-nm rms	(Clear Aperture)$^{-1}$ – 1 mm^{-1}
Mid-spatial frequency roughness (MSFR)	0.20-nm rms	1 mm^{-1} – 1 μm^{-1}
High-spatial frequency roughness (HSFR)	0.10-nm rms	1 μm^{-1} – 50 μm^{-1}

An important consideration in defining the specifications according to the enclosed spatial frequency limits is that the different error categories are measured independently by three different types of instruments. Figure measurements are acquired using optical interferometry: e.g. a 1024 pixel camera distributed over a 54 mm clear aperture leads to about 19 pixels per mm, which is sufficient for measuring to 1mm periods. Phase-shifting interferometric microscopes have a resolution of about 1 μm and a scan size up to a few mm, corresponding to the MSFR definition. Note that different microscope magnifications are used to cover the full range of spatial periods. Finally, an atomic force microscope is used to measure periods below a micron. Although an effective upper limit on AFM resolution is determined by the tip radius, our functional specification has a maximum bandlimit of about 50um^{-1} because of smoothing provided by the Mo/Si multilayer coating process at higher spatial frequencies.

Enclosure

M1 substrate drawing

Auspices

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[1] For the ETS, only substrates M2, M3, M4 were tested in the same fixture that would be used for mounting in the PO Box. The M1 substrate had a 3-meter focal length that was better addressed using a horizontal interferometer, as opposed to the vertical orientation it has within the PO Box. At the present time, all indications suggest that the M1 fixturing approach has been successful.

[2] Additional calculations will be carried out during the design of the PO Box to consider different weighting factors among the error terms.

[3] Handschuh, H., Froschke, J., Julich, M., Mayer, M., Weiser, M., and Seitz, G., "EUV Lithography at Carl Zeiss: Manufacturing and metrology of aspheric surfaces with Angstrom accuracy", paper presented at the 43rd International Conference on Electron, Ion, and Photon Beam Technology, June 1-4, 1999, Marco, Island, FL; the aspheric departure on the mirror mentioned in the paper is about 1.8 μm, compared to about 3.8 μm for the current M1 substrate.