© 1999 OSA/FTA 1999

Simulation and optimization for a computer-controlled large-tool polisher

James H. Burge

University of Arizona, Optical Sciences Center
1630 E. University Blvd., Tucson, Arizona 85721

Abstract
Large aspheric mirrors are ground and polished at the Steward Observatory Mirror Lab (SOML) using stressed-lap polishers under computer control.[1] Stressed-lap polishing uses large stiff circular polishing tools, which are actively deformed under computer control so the lap continually fits the aspheric mirror surface.[2,3] The size of the tool is typically one-third to one-sixth the diameter of the mirror. As the lap is translated across the rotating mirror, the lap's horizontal speed and rotation rate, the total force on the lap, and applied moments to the lap are all dynamically controlled. In order to take full advantage of these many degrees of freedom, computer simulation and optimization software has been developed. The simulation is based on Preston's relation (local removal rate proportional to pressure and relative velocity) but allows the inclusion of non-linear effects based on measured results. The optimization of polishing parameters is accomplished by a damped least squares optimization algorithm which varies the polishing parameters to obtain a desired simulated removal profile. This software has been successfully used at SOML to guide grinding and polishing of numerous large primary and secondary telescope mirrors.[4] The software was developed for the stressed lap polishers at the University of Arizona, but it can be used with equal effectiveness for other types of polishers.

Keywords: optical fabrication, large optics, aspheres, telescope mirrors

Introduction
Polishing and grinding machines that use computer-controlled motions are becoming common as the costs for computer control come down and the value of the flexibility is realized. Aspheric mirrors are often ground and polished using machines that drive small tools with orbital motion.[5] The tools and orbits must be either small enough or compliant enough to maintain an accurate fit on the aspheric surfaces. The dwell time, or length of time the lap runs over each area of the mirror, is calculated to give the desired removal based on a measurement of the surface. Since the removal profile of the orbital tool is small and does not depend on position on the mirror, Fourier deconvolution techniques give a solution to the dwell time, except when the tool overhangs the edge. The edges are typically difficult to control with small tool polishers and much work has been done to refine algorithms for improving this.

The stressed lap allows use of a larger tool, which gives natural smoothing of mid-frequency errors. However it is more difficult to target small zones with this large tool. Also, the simulation and optimization of stroke parameters are much more difficult for the large tool because the removal varies as a function of radial position. The computation of the wear function on any point of the mirror must be made by numerically integrating Preston's relation over two variables – lap stroke position and mirror rotation angle.

Computer model of large-tool polisher
The geometry for the large tool computer-controlled polishing machines is shown in Figure 1. The lap is a rotating disk that translates across the mirror, while the mirror rotates under the lap at a fixed rate. The lap rotation, translation, applied pressure, and applied moment are dynamically controlled by computer.

The effects of polishing strokes are simulated by assuming Preston's relation, that glass removal rate is proportional to pressure and velocity between the tool and the optic.

© 1999 OSA/FTA 1999

The total removal is computed by integrating the removal rate. Preston's model for polishing is

$$\Delta z = C\,P\,V\,\Delta t$$

where

$\Delta z(\rho,\alpha)$	Absolute glass removal at mirror position ρ,α
C	Proportionality constant (units µm/hr/psi/(m/s)).
P	Local pressure (this varies across the tool when it overhangs the edge)
V	Instantaneous velocity of tool relative to the mirror surface
Δt	Time

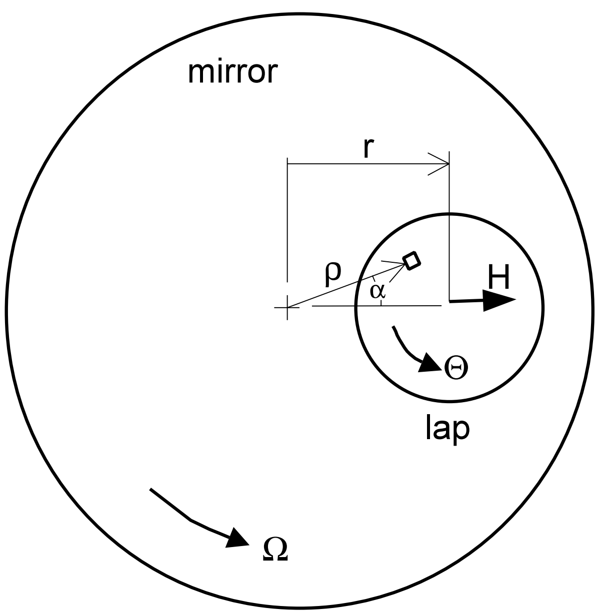

Figure 1. Definition for polishing simulation.
(Reproduced with permission from Ref. 1, Copyright 1998, OSA)

Using the geometry shown above, the strokes are defined by specifying the following:

Ω	mirror rotation rate
r	position of the center of the lap on the mirror
r_{in}	inside limit of lap travel
r_{out}	outside limit of lap travel
$\Theta(r)$	lap rotation rate (as function of r)
$H(r)$	linear velocity of lap (as function of r)
(ρ,α)	polar coordinates of location on mirror

As the rates do not depend on the mirror angular position, the strokes only affect the radially symmetric component of the figure errors. The azimuthally varying errors are addressed by applying dynamic force and moment variations to the lap to increase the pressure over regions that show up high in the phase map.

The typical implementation of computer controlled polishing uses small tools that maintain a constant removal function across the part. The computer simulation convolves the removal profile with the "hit map" which gives dwell time as a function of position on the mirror. However, the removal of the large tool polisher varies strongly with position, so a complete simulation is required.

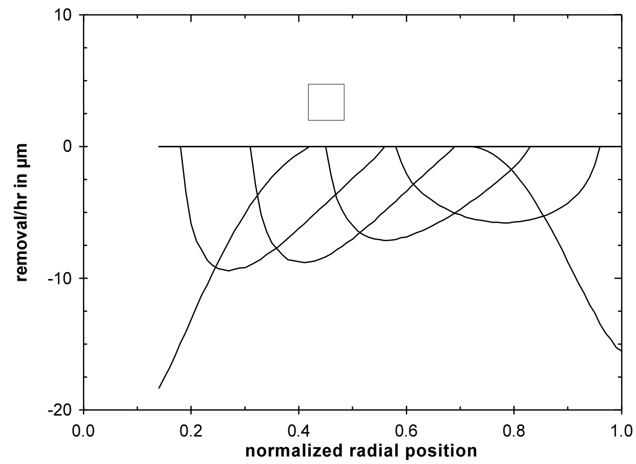

Figure 2. Instantaneous removal profiles, showing how the removal profile varies strongly as a function of lap position.

To calculate the effect of a stroke on the mirror at radial position ρ, a double integral is performed

Integrate over lap positions

Integrate over mirror area under lap

$$\Delta z(\rho) = C \cdot t \cdot \int_r D(r) \cdot \int_\alpha P(r,\rho,\alpha) \cdot V(r,\rho,\alpha)\,dr\,d\alpha$$

The function $D(r)dr$ is defined as a normalized dwell time for the lap to be at position r to $r+dr$, calculated from the velocity function $H(r)$. The simulation has evolved to include non-linear effects by making C a function of velocity and pressure and moving it inside the integral.

A single stroke is defined by entering the mirror turntable rate Ω, stroke extents r_{in} and r_{out} and the lap rotation rate $\Theta(r)$ and the horizontal lap linear velocity $H(r)$, as functions of lap position. These can be entered as polynomial coefficients, or by defining values at specific points and using a cubic spline. The calculation of the effect of this stroke is made by numerically performing the above integrations.

An additional useful degree of freedom is the pitch pattern on the lap. Most tools are uniformly covered with pitch over circular or annular areas. It is also useful to vary the density of the pitch squares on the lap, especially for aspherizing with large tools.[6] The polishing simulation allows this function to be entered and optimized using a cubic spline to define the areal density of the pitch.

When the lap overhangs the edge of the part, a pressure gradient results that has the tendency to roll the edge. This is modeled as a linear gradient, with magnitude chosen to balance the forces and moments on the lap.

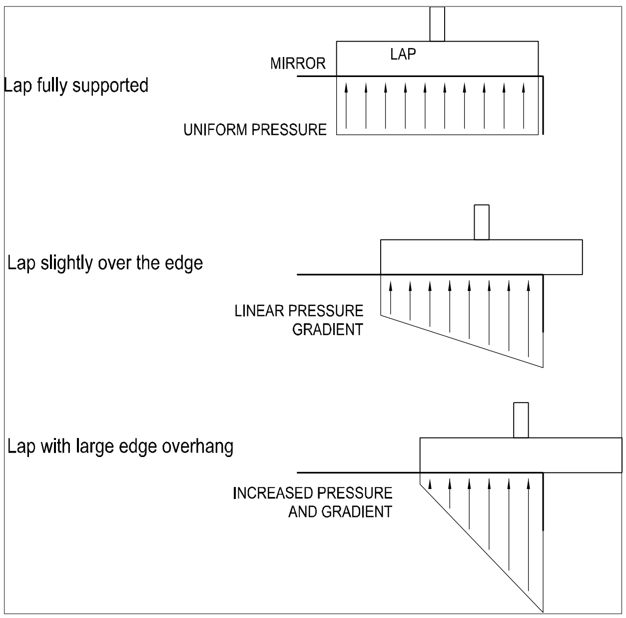

Figure 3. Linear model for pressure gradient when the lap goes over the edge of the mirror.

In addition to the pressure gradient from the reaction of the lap as it overhangs the mirror, the program simulates explicit control of moment and pressure as functions of lap position. The stressed lap polisher is supported by force actuators to allow this control.

Comparison of predictions with data

The simulation is useful as a tool for guiding the polishing and grinding. It is very accurate for predicting the removal during loose abrasive grinding. For polishing, it accurately predicts the effects of short polishing strokes and it gives a good estimate for the effect of long strokes. It is used effectively by comparing simulated removal with the measured removal of a polishing stroke, then making small modifications to the stroke. Figure 4 shows a comparison of a simulation with measured removal for a long polishing stroke on a 6.5-m mirror.

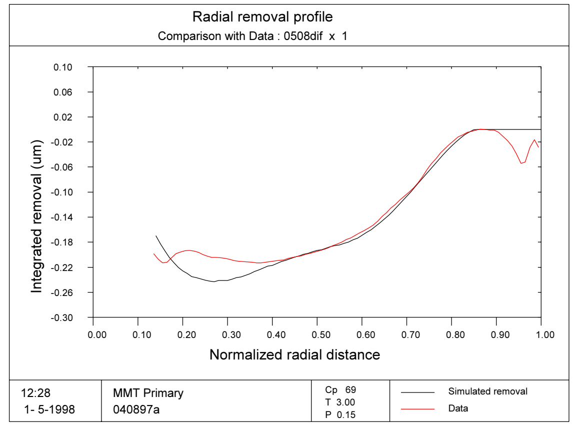

Figure 4. Comparison of simulation and measured removal for a polishing stroke on a 6.5-m mirror.
(Reproduced with permission from Ref. 1, Copyright 1998, OSA)

Optimization of stroke parameters

The functions for defining the strokes can be input directly by the computer operator. They can also be selected by the computer to optimize the simulated removal to give a desired change in figure. A damped least squares gradient search algorithm was built into the computer code so that polishing stroke optimization is done in a similar manner to optical design. The user defines variables to be optimized -- stroke endpoints, spline values for the velocity functions, etc. Then he defines a merit function by entering a target removal. The computer then searches for a polishing stroke that best matches the target. Like designing a lens, the operator must use his experience to guide the computer to give good solutions with realistic functions.

The damped least squares algorithm uses the following definitions:

- Variable Vector (n elements)
  - Variables for the optimization are defined by the user. Parameters such as endpoints, velocity spline coefficients, or empirical "fudge factors" may be used. Limits may be specified.
- Operand or Target Vector (m elements)
  - The operand vector to be minimized is defined as the deviation from desired removal at specified points on the mirror. Piston and focus compensation may be made.
- Damped Least Squares Optimization
  - Numerically Intensive! Each step in the optimization requires (n + 2) simulations at m points and the inversion of an (n x n) highly singular matrix. Adaptive damping is employed.

The computer optimization exploits the fine control of all of the polishing parameters. However, it is only as good as the simulation. The optician must use a caution running strokes that have large changes in rates, or for strokes that are completely different from those run before.

© 1999 OSA/FTA 1999

The optimization is quite useful. It allows long, complex strokes to be run that allow the lap to use its natural smoothing. Also, for loose abrasive grinding, the excellent agreement between the simulation and the measured removals allow excellent use of the optimization.

Figure 5 shows how well a computer-optimized stroke matches the desired removal for aspherizing a 1.2-m mirror. The plot shows only the radial profile of the stroke.

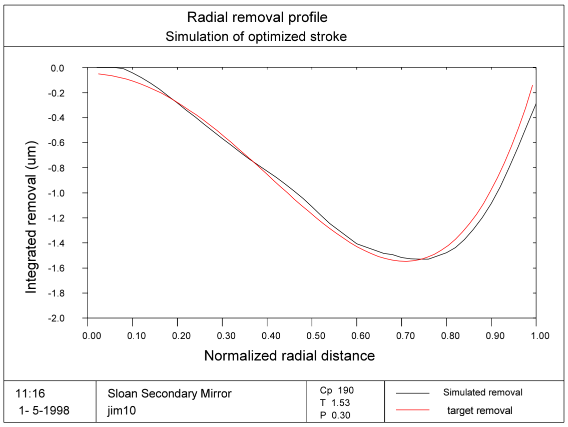

Figure 5. Simulated removal for a computer-optimized polishing stroke designed to give spherical aberration.

(Reproduced with permission from Ref. 1, Copyright 1998, OSA)

The functions defining this stroke are given below. The dwell time is given as a spline and the horizontal velocity is calculated from this. The rotational velocity of the lap is given as a spline. The pressure for this stroke is maintained at 0.3 psi and no moments are applied.

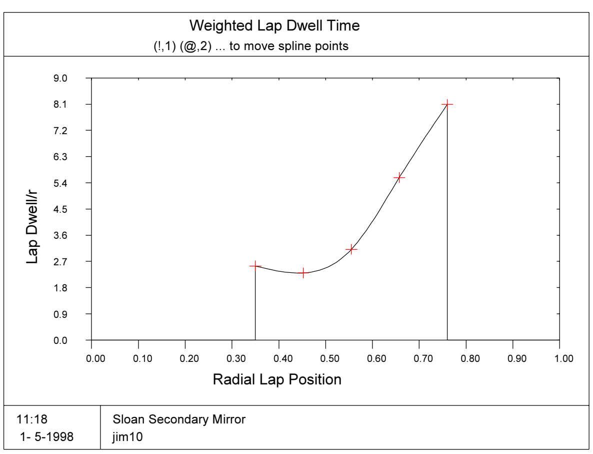

Figure 6. Radial dwell for optimized polishing stroke.

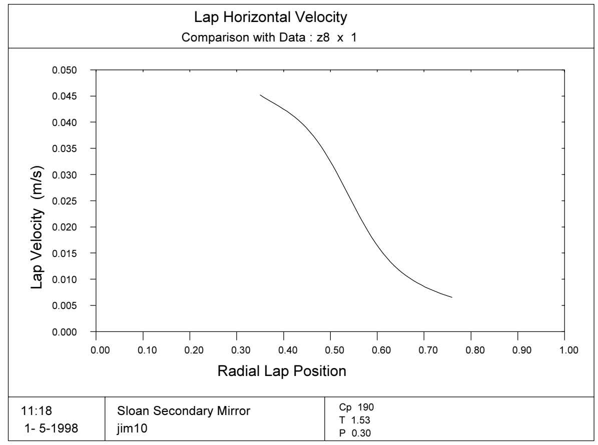

Figure 7. Linear velocity of lap for optimized polishing stroke.

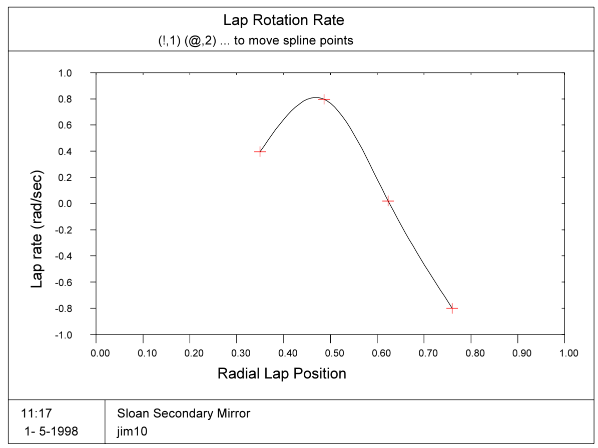

Figure 8. Rotational velocity of lap for optimized polishing stroke.

References

1. J. H. Burge, "Simulation and optimization for a computer-controlled large-tool polisher," in *Optical Fabrication and Testing*, OSA Technical Digest **12**, 43-45 (1998).
2. J. R. P. Angel, "Steps toward 8m honeycomb mirrors V -- A method for polishing aspheres as fast as f/1" in *Very Large Telescopes, Their Instrumentation and Programs,* Proc. IAU **79**, 11-21 (1984).
3. S. C. West, *et al.*, "Practical design and performance of the stress-lap polishing tool," Appl. Opt. **33**, 8094-8100 (1994).
4. H. M. Martin, *et al.,* "Fabrication and measured quality of the MMT primary mirror," Proc. SPIE **3352,** 194-204 (1998).
5. R. A. Jones, "Computer-controlled optical surfacing with orbital tool motion," Opt. Eng. **25**, 785-790 (1986).
6. B. K. Smith, J. H. Burge, H. M. Martin, "Fabrication of large secondary mirrors for astronomical telescopes," Proc. SPIE **3134**, 51-61 (1997).