

Design Considerations of Polishing Lap for Computer-Controlled Cylindrical Polishing Process

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This paper presents the development a deterministic computer-controlled polishing process to minimise the mid-spatial-frequency axial figure errors on cylindrical shaped mandrels. We discuss the design considerations of large size polishing lap and report our first experiments performed using a newly developed computer-controlled polishing machine.

1 Introduction

Replicated grazing-incidence full shell optics for hard X-ray telescopes are under development at Marshall Space Flight Center [1-2]. The angular resolution of mirror shells depends on the quality of the mandrel from which they are being replicated. Mid-spatial-frequency axial figure error arises from the mandrel fabrication process and is a dominant contributor in the error budget of the mandrel. We presented our efforts in developing a polishing process whereby a computer-controlled polishing machine and the simulation software to optimize the mandrel figuring process were developed [3].

In this paper, we present further investigations on the optimisation of the polishing process. The process variables, such as the material removal rate, and the shape and size of the tool's influence function have been determined from the actual polishing runs on a mandrel. Using the extracted information of the process variables, a large size polishing lap has been designed.

2 Determination of process variables

Experiments were designed to determine the material removal rate and the shape and size of the tool's influence function under a set of known polishing parameters as such applied weight, stroke length of the polishing lap, rotational speed of the mandrel, tool distribution on the lap, and the duration of polishing time.

2.1 Determination of material removal rate

To extract the material removal rate, one half of the specimen was polished for two hours under a set of known operational parameters. The other half remained untouched during the experiment. Diamond-shaped tools were selected in the polishing lap configuration. Figure 1 shows the difference between the measurements before and after the polishing. The amount of material removed during

the polishing operation was approximately 0.5 microns which makes material removal rate 0.004 $\mu\text{m}/\text{min}$.

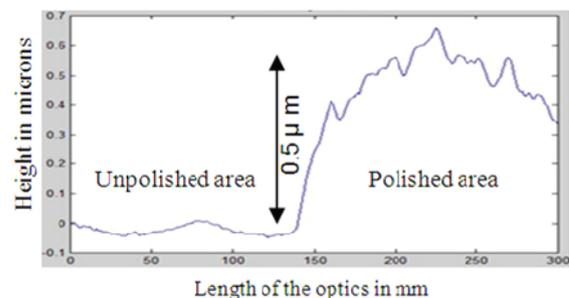


Fig. 1 Difference between height measurements before and after the polishing (before - after).

2.2 Determination of tool influence function

A polishing lap comprising of four square shaped tools was prepared. The tools have enough separation between them so that their polishing contour on the specimen did not overlap. The polishing was performed for two hours with a stroke length of 30 mm. Figure 2a shows the difference between the measurements before and after the polishing run. It has been compared with simulations when a step influence function is considered.

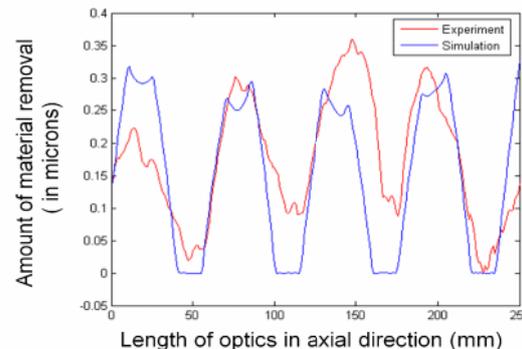


Fig. 2 Difference between height measurements before and after polishing

Figure 3 shows the shape of the average influence function for the selected square tools in axial and azimuthal directions qualitatively. It is observed that the influence functions are not symmetric in shape in azimuthal direction. We believe that the rotational directionality of the mandrel is the main reason for this asymmetry.

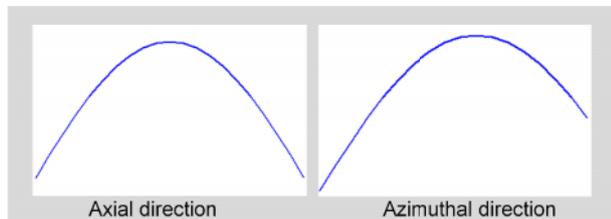


Fig. 3 Experimental influence function in axial and azimuthal directions for the selected square tools

3 Design considerations of large size polishing lap

The experimentally measured values have been fed in to the simulation software to get optimized design of polishing lap and machine operational parameters. It is observed that equal tool to groove ratio with two rows of shifted tool configuration (Fig.4) delivers the least residual mid-spatial frequency deviations. The optimum stroke length is found to be as 30 mm.

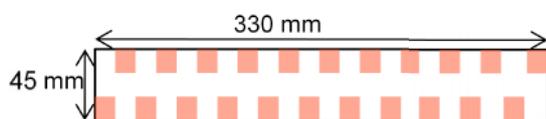


Fig. 4 Optimum lap configuration while using square tool

4 Results and Discussion

Using the inputs from the mathematical model, a mandrel having conical approximated Wolter-1 geometry, has been polished using the computer-controlled cylindrical polishing machine recently developed at MSFC. The same polishing run is simulated using the developed mathematical model. Figure 5 compares the amount of material removal during actual polishing with that of the simulated one.

The experimental results agree with the predictions in broad terms but there are disagreements in the localised regions. At present we believe that they arise due to the non-uniformity in polishing lap compliance. Certain areas of tools are either not in contact with the surface or are not applying the same pressure on the surface. Investigations are in progress to determine the level of non-uniformity. This information will also be fed into the simulations to be able make more accurate predictions.

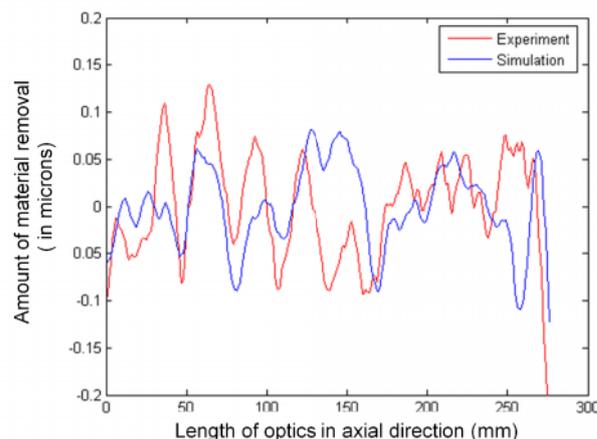


Fig. 5 Optimum lap configuration while using square tool

5 Conclusions

In summary, we have presented design considerations of large size polishing lap where the experimentally determined process variables have been used for optimising the lap configuration and the machine operational parameters. The first experimental results have been found in qualitative agreement with the predictions of the simulated model. Further investigations are under way to make the process quantitatively deterministic. One of the goals of developing the model is to find out the achievable limits in terms of angular resolution of the developed replicated optics at Marshall Space Flight Center, NASA. Additionally, the ability to simulate the polishing process is an important contribution to extend automation further and thus increase the cost effectiveness of mandrel production

6 References

- 1 Brian D. Ramsey, "Replicated nickel optics for the hard-x-ray region," *Experimental Astronomy* 20, 85-92 (2005).
- 2 Mikhail Gubarev, B. D. Ramsey, D. Engelhaupt, W. Arnold, "Technology Development for Nickel X-Ray Optics Enhancement," *Proc. SPIE 7011*, 7701133-7 (2008).
- 3 Gufran S. Khan, M. Gubarev, W. Arnold and B. Ramsey, "Development of a Computer-Controlled Polishing Process for X-Ray Optics", *Proc SPIE 7437*, (2009) 74371

Acknowledgements

This research work was supported by an appointment to NASA Postdoctoral Program at the Marshall Space Flight Center, administered by Oak Ridge Associated Universities through a contract with NASA



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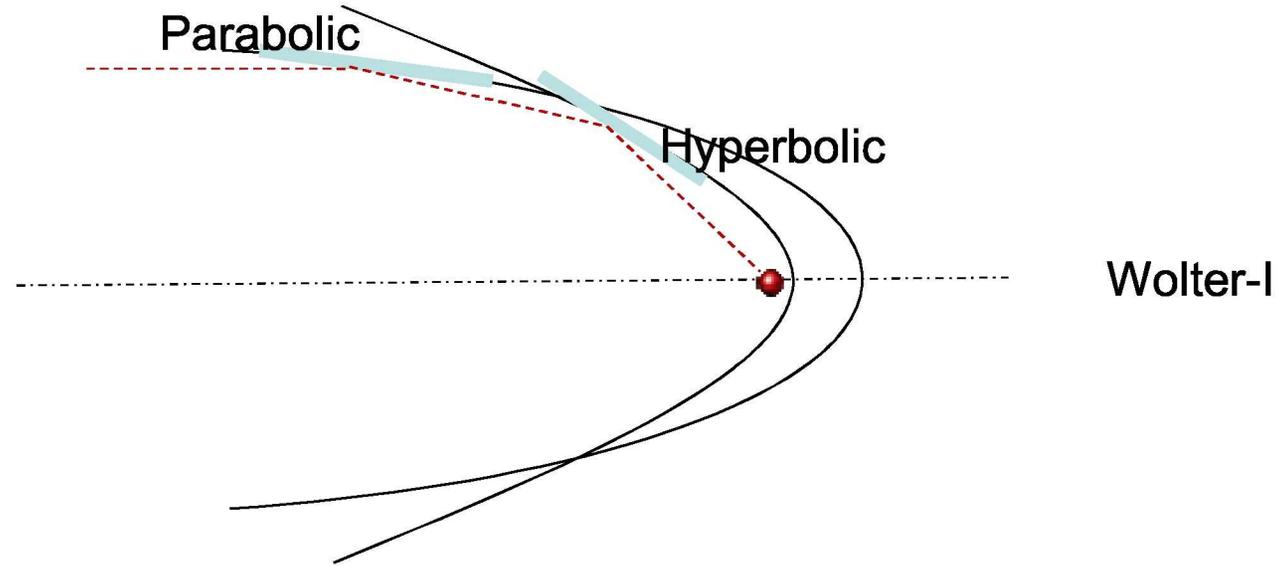
Design Considerations of Polishing Lap for Computer-Controlled Cylindrical Polishing Process

OUTLINE

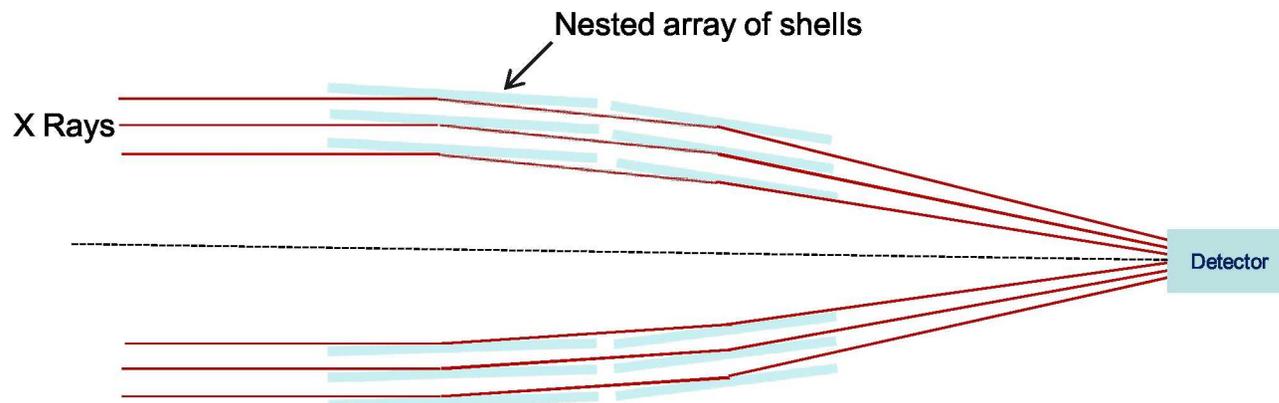
- Grazing Incidence X-Ray optics
- Motivation and challenges
- Mid spatial frequency generation in Cylindrical Polishing
- Design Considerations for Polishing Lap
- Simulation Studies and Experimental Results
- Future Scope
- Summary

Grazing Incidence X-Ray Imaging Optics

Grazing incidence optics provide high resolution Imaging at X-ray energy levels



Concentrically nested to build up collection area

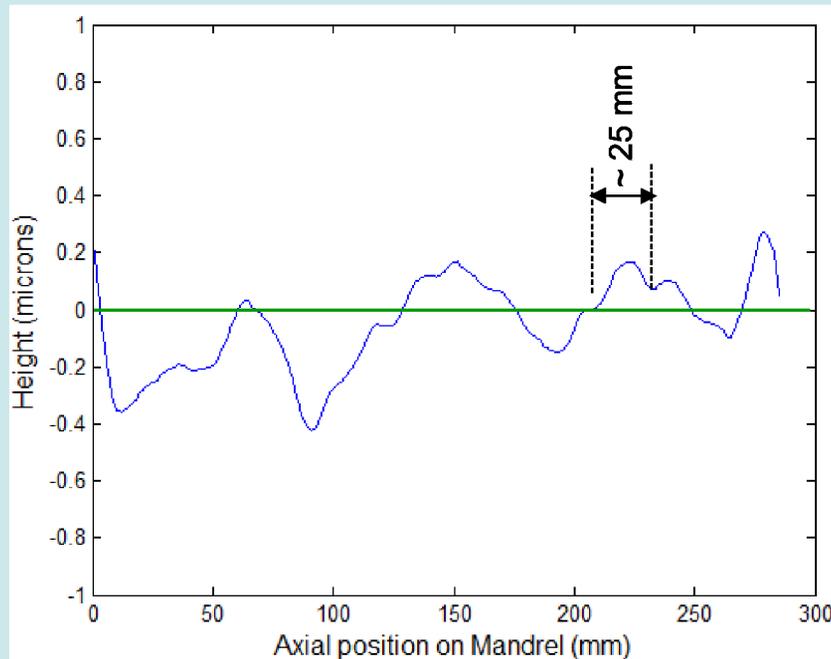


Shells are developed by using replication approach

Motivation

- Typical mirror shells fabricated at MSFC
 - angular resolution 13-15 arcsec HPD
Mandrel ~ 10 arcsec HPD
- Future optics requirement (*such as in IXO*)
 - angular resolution < 5 arcsec HPD
Mandrel ~ 2 arcsec HPD
- Quality of the mandrel is the limiting factor
- Mid-spatial-frequency range errors are dominant source of error on mandrel

Mid-spatial-frequency errors on mandrel

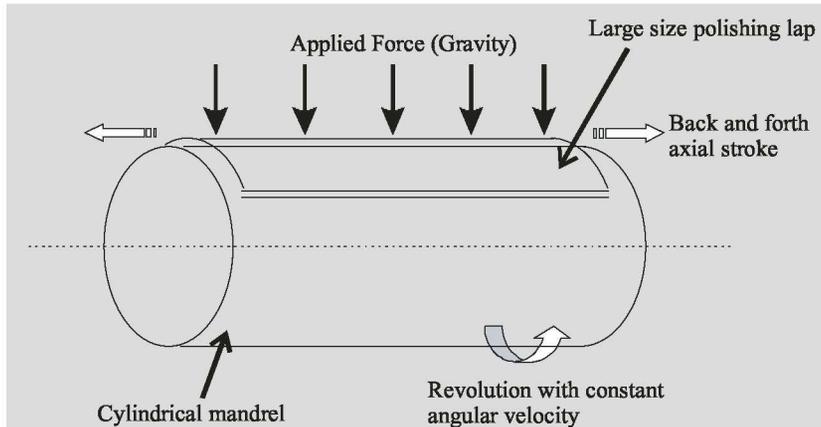


- ▶ These are 1-50 mm size (wavelength)
- ▶ Typically the amplitude of these errors are of ~ 100 nm scale
- ▶ Mid-frequency errors are *inherent* to the polishing process

Cylindrical polishing process using large size polishing lap



Polishing process



Polishing lap configuration



groove
(for slurry flow)

tool

Mid-spatial-frequency range errors generation

Operating parameters

- Mandrel rotational speed
- Lap axial speed
- Stroke length

Lap configuration

- Tool size
- Tool shape
- Tool-to-groove ratio
- Distribution of tools

Non-conformance of lap to the specimen

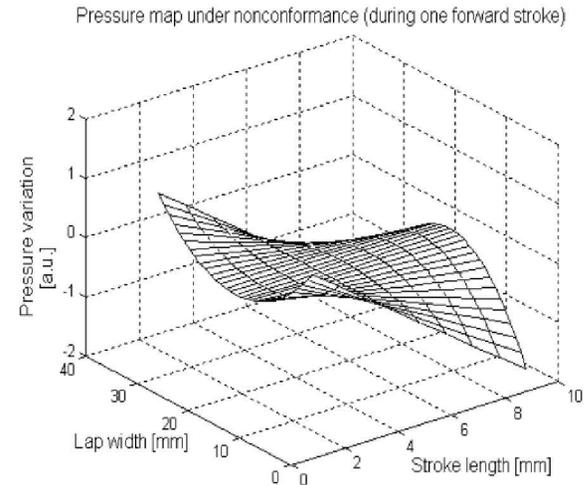
- Pressure variation between the tool and the specimen

Non-Conformance of Polishing Lap to the Optics

(A) Non-conformance due to the mismatch of the shape of lap to the optics during stroke

Depends on

- Design of the optics
- Width of the polishing lap
- Stroke length during polishing



(B) Non-conformance due to the surface error profile

Depends on

Amplitude and the slope error of surface profile

(C) Non-conformance during lap preparation (*Practical non-conformance*)

Depends on

Environmental effects



- ▶ Developed a software to simulate cylindrical polishing process



Simulation studies

Helps us

Establishing a relationship between the polishing process parameters and the generation of mid spatial-frequency error

Optimization of the process (speeds, stroke, etc.) to keep the residual mid spatial-frequency error to a minimum

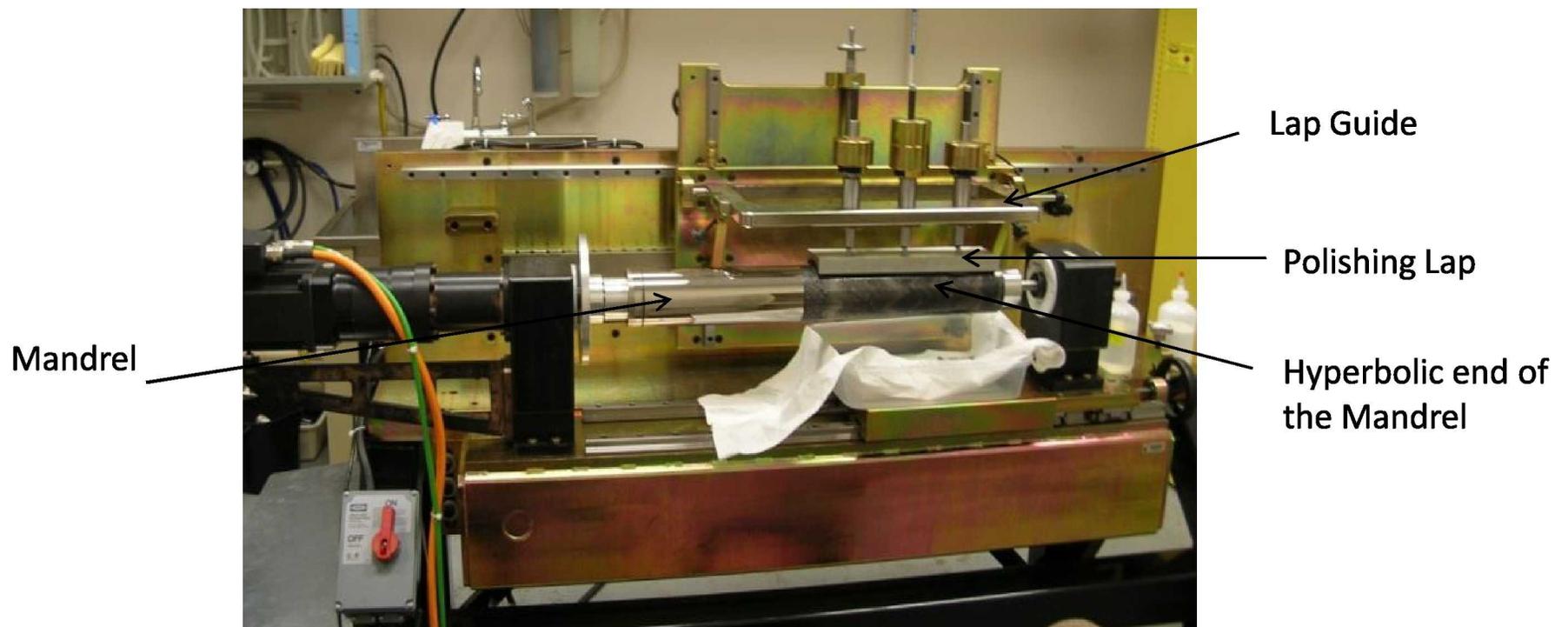
Used in

Consideration of the polishing lap design in optimizing the process to minimize the residual errors

Computer-controlled polishing machine developed at NSSTC

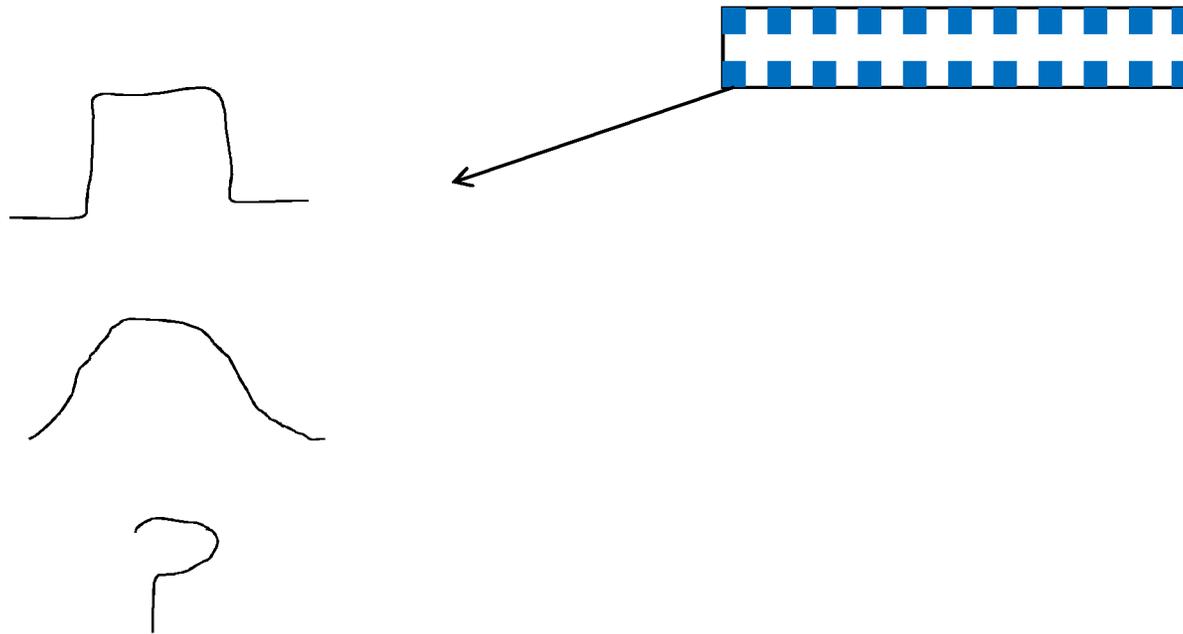


- Capabilities:**
- Accommodates specimen of length from 300 mm to 700 mm
diameter ranging from 40 to 300 mm
 - Precise rotational and axial motion
 - Linear motor – provides a possibility of constant as well as variable axial velocities
 - Designed to make it stable (vibration free)



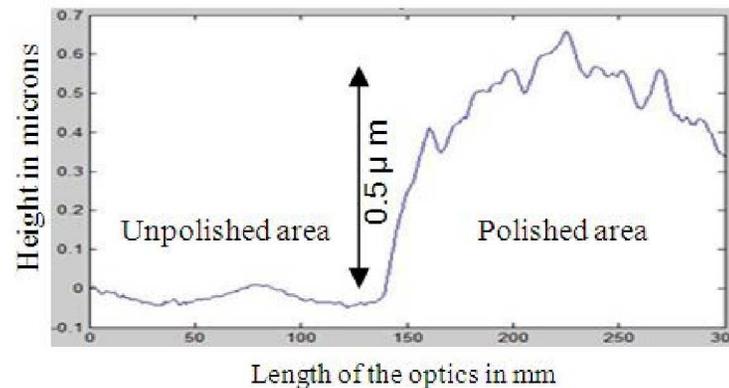
Deterministic prediction of Polishing

- A. Determination of material removal rate
- B. Determination of tool's influence function



Determination of Material Removal Rate

- One half of the hyperbolic section of the mandrel was polished
- Known set of operating parameters
- Polishing time ~ 2 hrs
- Diamond shape tools on the polishing lap



Material removal rate 0.004 $\mu\text{m}/\text{min}$.

Determination of Tool Influence Function

For square tool

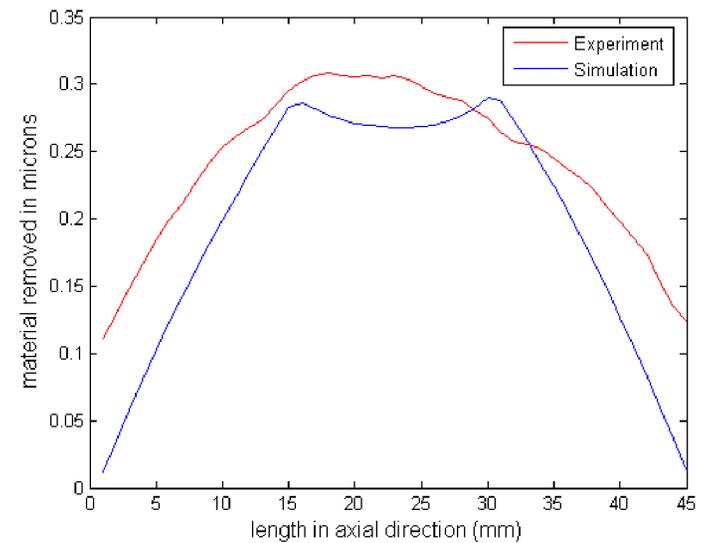
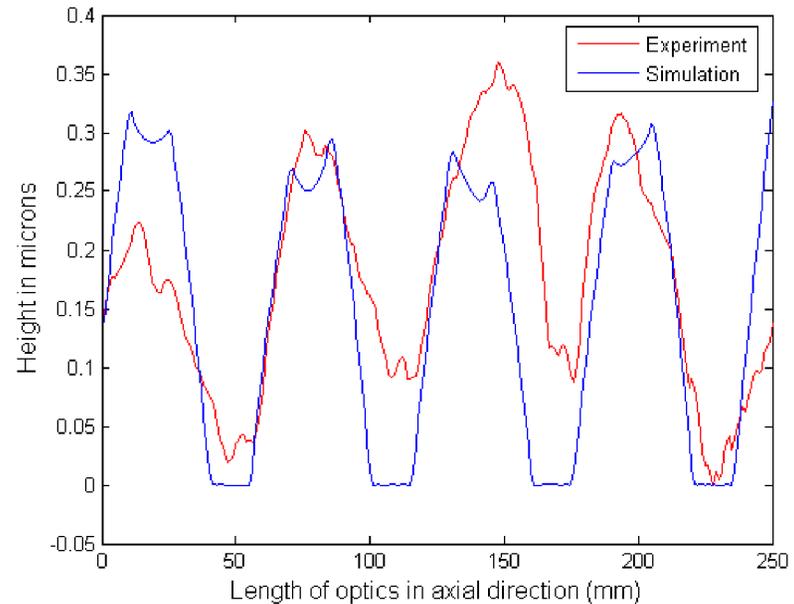
Lap Configuration ?

Step IF ?

With ideal Influence function
Step function

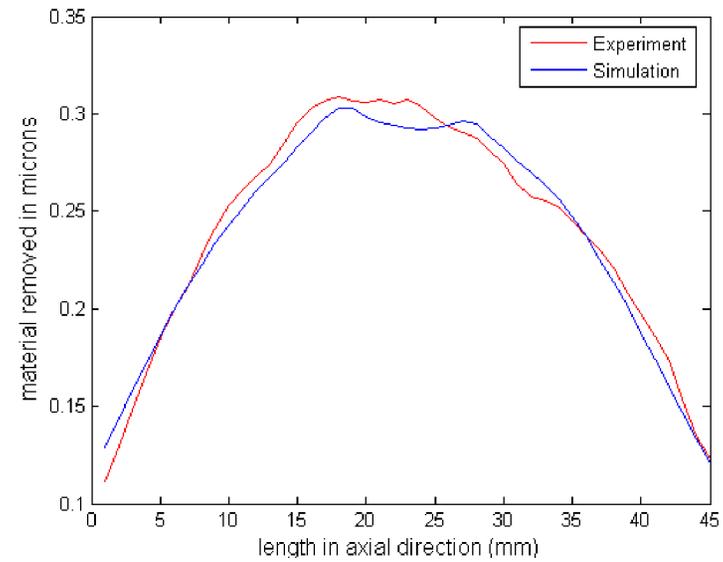
Blue: average of four meridians (sim)

Red : average of four meridians (sim)



Determination of Tool Influence Function

Shape of Extracted IF
1D?
2D?



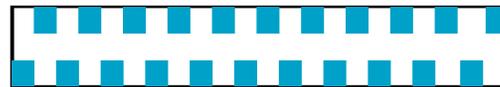
SIMUALTION APPROACH

Variation of Stroke length with different tool shapes and lap configurations

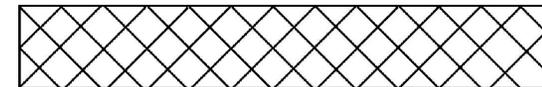
Ideal surface has been selected



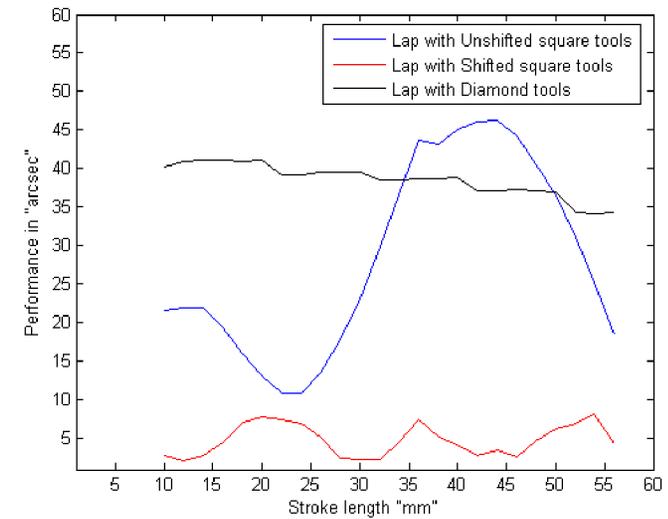
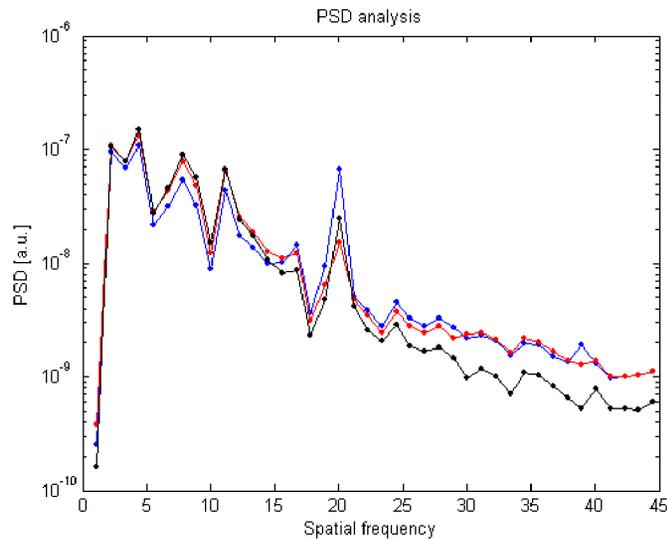
Un-shifted square tools



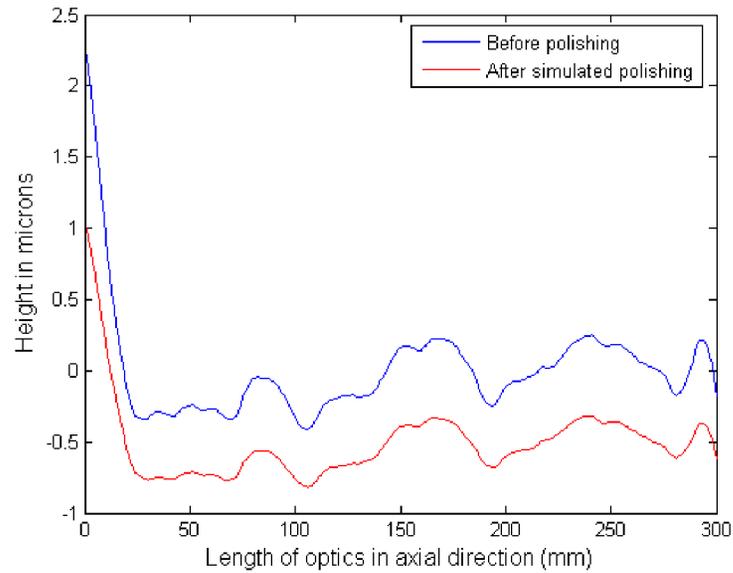
Shifted square tools



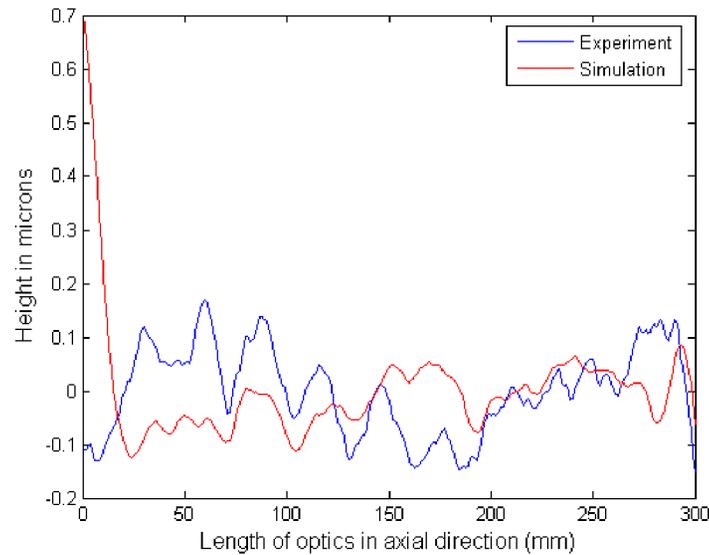
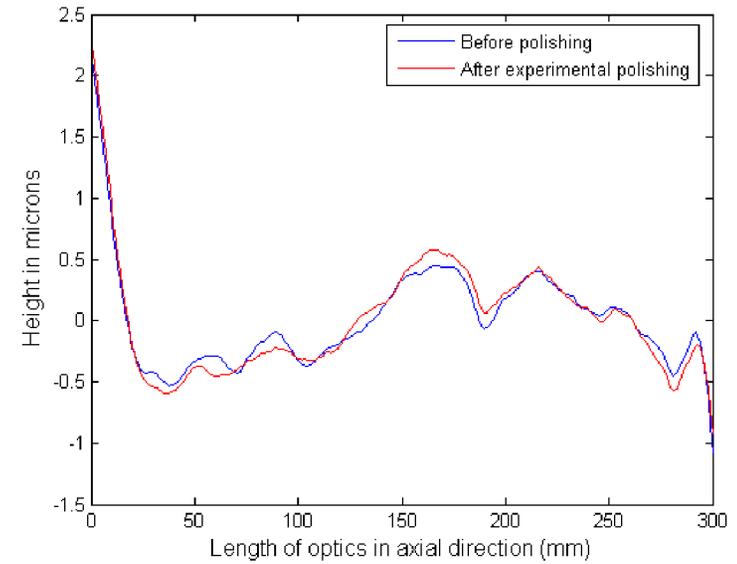
Diamond tools



Simulations with Gaussian Influence Function



Experiment



Comparison of Difference

Conclusions

- Mid-spatial-frequency errors in the polishing process are crucial
 - Improvement in the polishing process is desired
 - Developed a software to simulate cylindrical polishing process
 - Computer-controlled polishing machine
- 

Future plan

- Development of a polishing sequence based on a known error profile of the specimen
- Feasibility study on flexible polishing lap (*pressure variation*)
- In-situ measurement technique for mandrel

It is expected that the study will help us improve the angular resolution of the final electroformed shell X ray optics **close to the 5 arcsec HPD goal**

Thank you