Analyzing Mid-Spatial Frequency Figure Error in Monolithic Freeform Telescopes

Product Requirements Document

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Document Number 00005

Revisions Level	Date
E	12/14/2017

Authentication Block

Revision History:

Revision	*Description*	*Date*	*Authorization*
A	Initial PRD	11/01/17	MMP
B	Updated PRD	11/15/17	DHL
C	Updated PRD	11/29/17	MMP
D	Updated PRD	12/10/17	DHL
E	Final PRD	12/14/17	DHL

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This product requirements document has been approved by Optimax Systems Inc. (12/12/17)

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1. Introduction

Monolithic optical systems offer great promise for a variety of applications by eliminating the possibility of most alignment errors; however, fabricating monolithic systems – especially those containing aspheric or even freeform surfaces – remains a challenge. Mid-spatial frequency (MSF) figure errors are unavoidable artifacts imprinted on an optical surface when employing sub-aperture grinding and polishing methods, which are typically used when fabricating aspheric and freeform optics. Although a variety of techniques can be used to mitigate these features, MSF errors can potentially hinder optical performance in a variety of different ways. Measuring and tolerancing these MSF errors introduced during the manufacturing process are key first steps in adequately fabricating these monolithic optical systems. Three monolithic telescope designs being fabricated by Optimax Systems contain multiple freeform surfaces and will be studied for sensitivity to MSF error.

Vision:

The product vision is a thorough design study analyzing the impact of mid-spatial frequency (MSF) figure error on the imaging performance of three monolithic freeform telescopes as well as providing sensitivity analysis as to what MSF error is allowable for desired optical performance. Preliminary testing will also be conducted to empirically verify the results of the design study and sensitivity analysis.

2. Environment

The MSF tolerancing analysis will be performed on proof of concept optical systems that are being fabricated and tested on the Optimax floor and will not be used in practice:

Temperature

69 ± 2°F - temperature controlled in testing facility

Relative Humidity

50% - humidity controlled in testing facility

Spectrum

Monochromatic at 632.8 nm - testing wavelength

3. Regulatory Issues

Appropriate laser safety should be observed for metrology that requires use of a laser. Class IIIa (medium power) HeNe lasers are often used in optical metrology. Class 3R visible-light lasers normally would not harm the human eye during momentary exposure of less than 0.25 seconds; however, one should not deliberately look or stare into the laser beam. Laser protective eyewear is not necessary. These lasers do not present skin or material burn hazards.

4. Fitness for Use

The design study will:

Create a thorough model of how mid-spatial frequency (MSF) figure error affects imaging performance.

Apply the MSF model to one of the monolithic freeform telescope designs to determine how imaging performance is affected.

Empirically test the imaging performance of the examined design and compare with the modeled imaging performance to serve as a form of model verification.

Be used to analyze one or more designs' sensitivity to MSF figure error.

It is desirable to:

Create a convenient model of MSF figure error that can be used again on different projects.

Allow for easy conversion between MSF models in CODE V and Zemax.

Provide a summary listing rules of thumb regarding the effect of MSF error on imaging performance. Examples suggested by Optimax include how does performance change with an increase in MSF ripple frequency? How does performance change with an increase in MSF ripple amplitude?

5. Project Scope

UR Team is responsible for:

Providing a thorough analysis of the effect of MSF figure error on one monolithic freeform telescope design. This will be done using an MSF error model for determining the sensitivity of the design's performance to MSF error.

Conducting measurements of imaging performance on one monolithic freeform telescope design in order to verify the MSF model and sensitivity analysis.

If time permits, UR Team will:

Expand the MSF figure error model to encompass more advanced characteristics including randomly positioned 2D insular Gaussian errors and a superposition of different MSF spatial frequencies.

Create an additional MSF error model to analyze stray light using a non-sequential ray trace software such as LightTools.

Apply the MSF error model(s) to the remaining monolithic telescope designs.

UR Team is not responsible for:

Tolerancing other system parameters (power, thickness, tilt, decenter, etc.) or MSF error on plano window surfaces.

Optimax Systems is responsible for:

Fabricating the monolithic freeform telescopes.

Measuring the surface profile of any of these designs and providing data and information to support analysis.

UR Team deliverables will be provided by the end of the spring 2018 semester.

6. Project Details

a) Monolithic Freeform Telescope Designs

There are three different stages of monolithic freeform telescope designs.

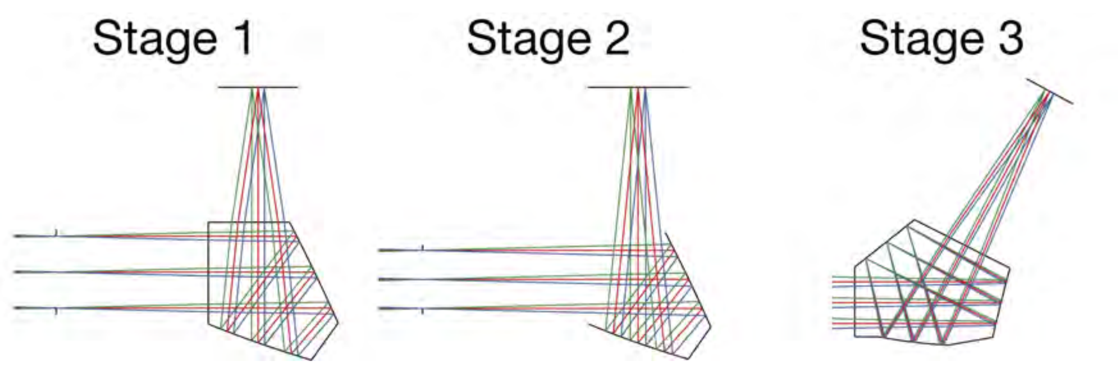

Figure 1: Three monolithic freeform telescope designs.

Design Specifications:

	Stage 1	Stage 2	Stage 3
Half field of view, Y (°)	4.365	4.365	4.365
Half field of view, X (°)	1.431	1.431	1.431
Entrance pupil diameter (mm)	50	50	50
Design wavelength (nm)	633	633	633
Effective focal length (mm)	168.338	248.732	227.082
Material	Silica	Silica	Silica
Number of freeform surfaces	2	2	3
Design style	Prism	C shape	Prism
Diffraction limited performance?	No	No	Yes
Fabrication complete?	Yes	Yes	No

Table 1: System specifications for three monolithic freeform telescope designs. *The fabrication of Stage 3 is in process and is expected to be complete early in the summer of 2018.*

b) Fabrication Methods Employed

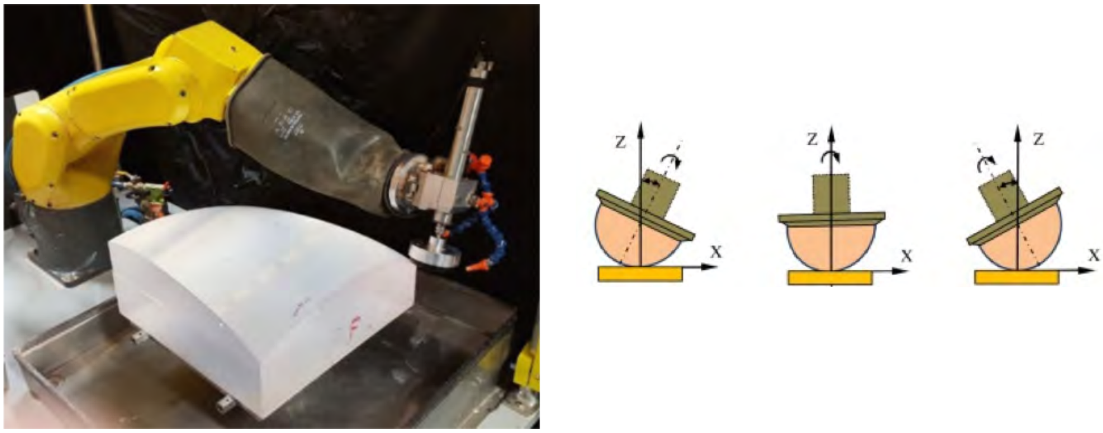

Figure 2: Grinding and polishing methods for monolithic telescope designs. Left: contour grinding. Right: bonnet polishing.[4]

As in Figure 2, the surfaces of the monolith freeform telescopes are being ground with a robotic arm using a contour bound-abrasive diamond tool. The surfaces are being polished using a sub-aperture bonnet technique typical of Zeeko polishers. Both of these methods are sub-aperture optical fabrication methods and, therefore, leave residual MSF error. Qualitative evidence of this MSF error can be seen in Figure 3 where nonhomogeneity is evident in the out of focus image spot for the Stage 1 design. This could be attributed to the MSF errors on either or both of the freeform surfaces.

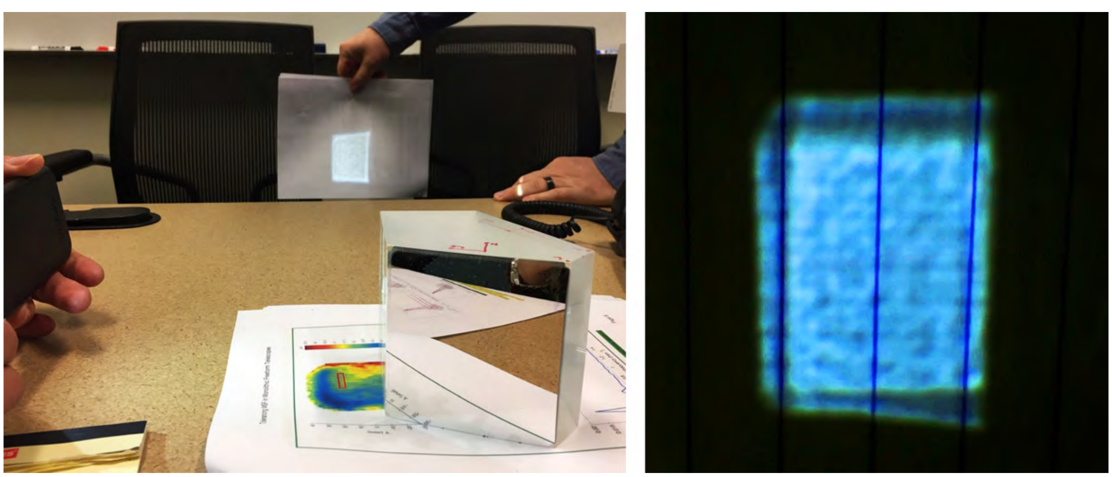

Figure 3: Visible mid-spatial frequency (MSF) error. Left: fabricated Stage 1 design forming a defocused image point by shining point source through optical system. Right: close up of out of focus point containing nonhomogeneity due to MSF.

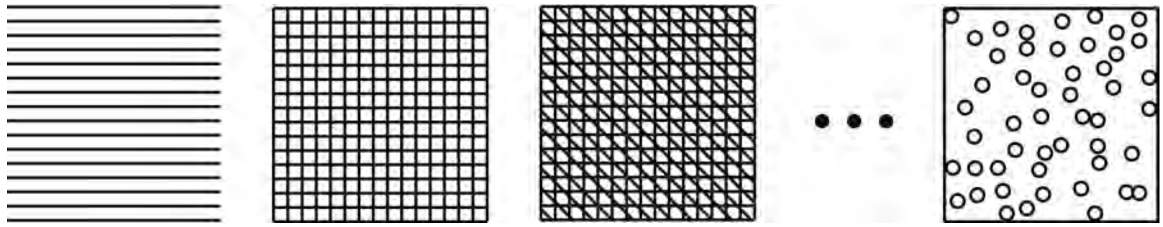

Figure 4: Different number of overlaps of linear MSF patterns, ultimately yielding a randomized surface pattern.

In the world of optical fabrication, MSF error is a looming grey area where not much is well defined about its effect on performance, yet a variety of techniques exist to mitigate the presence of MSF. The technique being used by Optimax to mitigate the MSF features on the monolithic freeform surfaces consists of repeatedly raster polishing the same surface but with the raster path oriented at different angles, as in Figure 4. The result of repeatedly overlapped linear patterns is a pattern of pseudo-random clusters of 2D Gaussian "islands." This effect can be seen in the preliminary surface measurements in Figure 7. This island effect complicates the modeling process significantly since it would involve a different modeling technique using Fast Gauss Transforms for decomposition, for example. For simplicity, this may be approximated using a 2D grid of linear sinusoidal gratings being applied to a surface.

c) Mid-Spatial Frequency Error (MSF) Characteristics

A variety of different MSF parameters can affect imaging performance, as listed in Table 2 and depicted in Figure 5.

Parameter	*Description*
Frequency	The number of ripple cycles per unit length on a surface
Amplitude	The ripple height and depth
Style	Linear, concentric ripples, or 2D Gaussian "islands"
Relative orientation	Angular orientation of ripples on surface
Surface number	The location of surface within a system

Table 2: Five parameters defining the effect mid-spatial frequency figure error has on imaging performance.

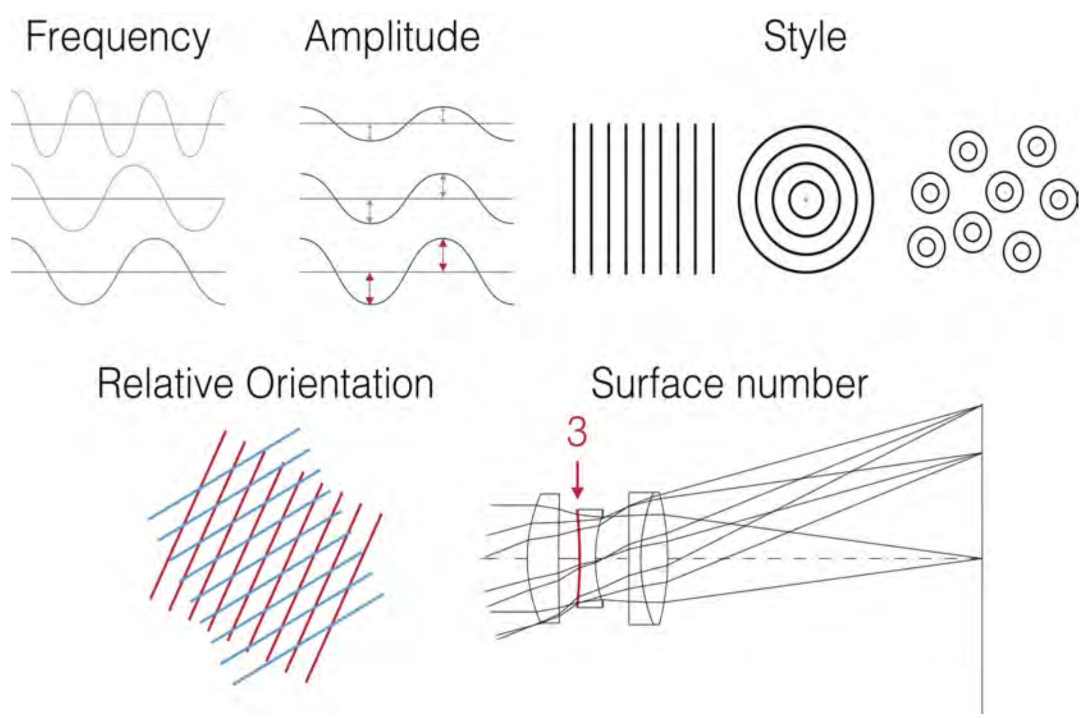

Figure 5: Depiction of five parameters defining the effect mid-spatial frequency figure error has on imaging performance.

d) Possible Modeling Techniques

Mid-spatial frequency figure error consists of sinusoidal ripples; thus, one method for modeling MSF error is using sinusoidal gratings with the same amplitude and frequency as the MSF error. It is known from preliminary measurements (see Figure 7) that the wavelength of the MSF ripples is on the scale of centimeters. This is an important distinction since the grating spacing is not on the scale of the wavelength of visible light. This means that error introduced by MSF will be reflective in nature (since the ripples are on a coated mirror surface), *not* diffractive.

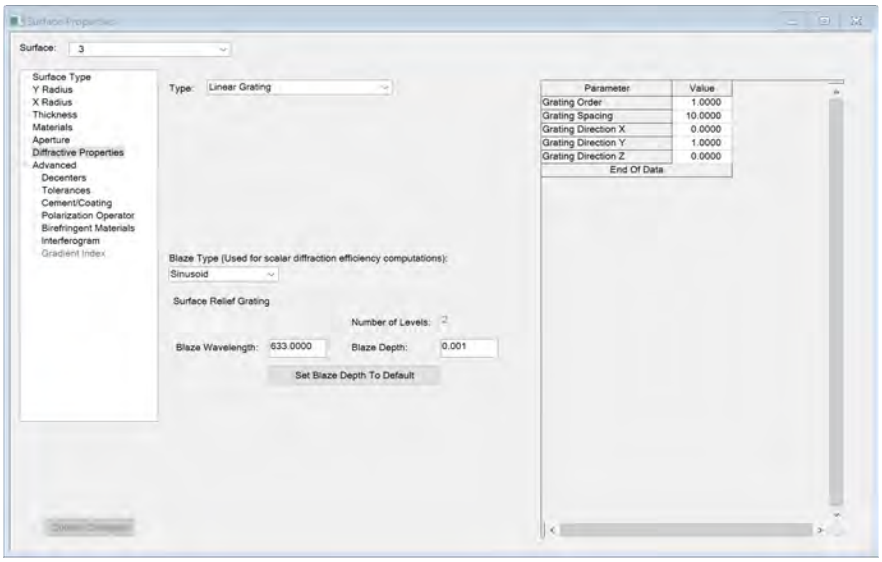

Figure 6: CODE V linear grating user input window.

As in the work of John Tamkin, one method for modeling MSF error is by overlaying multiple linear sinusoidal gratings on a single freeform surface.[1-3] This can be modeled easily using a sequential ray trace program such as CODE V. The linear gratings will match the measured MSF error in accordance with the five parameters in Table 2.

The most important characteristics to identify are the amplitude and frequency of the ripple error. Given the measurement data for a fabricated surface, peak-to-valley (PV) ripple amplitude can be quickly determined from surface height deviation from nominal. Plus, the Fourier Transform of the surface ripple will yield the surface's spatial period distribution along with the predominant ripple spatial frequencies. Preliminary results identifying the frequency and amplitude of MSF figure error can be seen below in Figure 7.

Once the MSF error is appropriately modeled in an optical design software like CODE V, a variety of different imaging performance metrics can be simulated. After performing simulations with our model, empirical measurements could then be performed and compared with the simulation results. Some metrics that could be realistically simulated and measured are:

1. Point spread function (PSF)
2. Line spread function (LSF)
3. Modulation transfer function (MTF)
4. RMS wavefront error
5. Image simulation

e) Other Considerations

Depending on the nominal performance of the monolithic telescope design in question, MSF may have a bigger effect on one design compared to another. For Stage 1, for example, which is far from diffraction limited, the effect of MSF error may be minimal relative to overall performance while prominent MSF may affect the diffraction limited Stage 3 performance greatly.

Furthermore, it should be noted that comparing simulated results from our MSF model with empirically measured results may not yield a direct correlation. Since the realm of our analysis is limited to MSF figure error and ignores other design sensitivities including figure, irregularity, thickness, material, surface tilt, etc., other errors from fabrication will also affect imaging performance. After exhausting all options to reconcile our model with measurements, our backup plan will be to rely on the model since it has received some form of verification through the work of John Tamkin.[1-3]

7. Preliminary Results

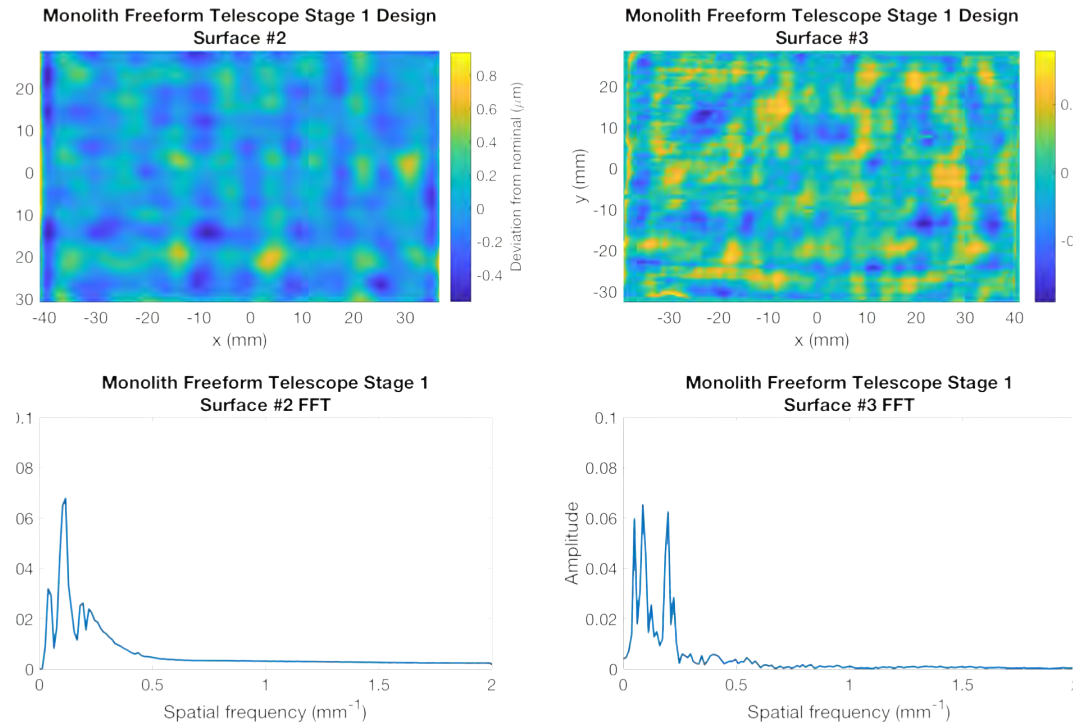

Figure 7: Freeform surface measurements and MSF frequencies. Surface #2 was measured with a 3 μm radius diamond tip. Surface #3 was measured with a 500 μm radius ruby tip.

	Main spatial frequency (mm^{-1})	Amplitude, PV (μm)
Surface 2	0.1157	1.5028
Surface 3	0.0868	1.8514

Table 3: Predominant spatial frequency and peak-to-valley (PV) amplitude by surface.

Using high-density surface measurement data provided by Optimax, the MSF artifacts can be clearly seen and analyzed with a one dimensional Fast Fourier Transform (FFT). The most prevalent frequencies and the peak-to-valley amplitude can be seen in Table 3.

When creating our final model, a two dimensional FFT will most likely be necessary to approximate the 2D Gaussian "island" pattern described previously (see Figure 4).

8. Timeline

Fall semester:

October	Assigned project, held first meeting with customer, gained a basic understanding of project
November	Meet thrice more with customer, gained a more detailed understanding of customer's desires
December	Summarized project in product requirements document

Spring semester:

January	Research how best to implement MSF model
February	Create model
March	Apply model to design under examination and compare simulated and empirical imaging performance
April	Test, tweak, and tune model to verify functionality and use model to analyze MSF sensitivity
May 1st	A completed model that dictates what is the minimum allowable amount of MSF to achieve a certain performance metric

9. Team Member Responsibilities

David	Project coordinator, CODE V modeling, testing
Kevin	Customer liaison, MATLAB data analysis
Matthew	Scribe, testing
Wooyoun	Document handling, CODE V modeling

10. Resources Needed

The following software will be used in the MSF analysis and modeling:

- CODE V/Zemax
- LightTools
- MATLAB

The above software has been acquired and/or is available in the Hopkins Center.

At this time, no materials, intellectual support, or lab space are needed.

11. Acknowledgements

The MSF analysis and tolerancing project is a senior design driven design study. As such its design inputs were derived from our interactions with our project customer, faculty advisor Professor Jannick Rolland, and Professor Wayne Knox.

12 . References

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