M1M3 Crow's Feet

Contents

1. Introduction

At the October 2014 M1M3 monthly meeting held at SOML, it was noted that crow's feet had been observed on M1M3, mostly on M3. This technical note describes our effort to evaluate the impact of the crow's feet on M3.

Crows' feet come from bubbles with sharp edges that trap pitch and/or polishing compound, causing streaks of deep removal. They have the characteristic crow's foot pattern because of the direction of motion of the tool across the bubble. They're easily seen in reflected light, such as the fluorescent room lights. Figure 1 shows a picture of two crow's feet taken by SOML. These are among the worst on M3. They were caused by sub-mm bubbles, now chamfered to ~2 mm diameter. Most of the crows' feet come from bubbles so small that it's hard to find them until they cause crows' feet.

Figure 2 shows the M3 surface map we received from SOML. It is the product of a complex interferometric data reduction pipeline (Xin, et al.). This is a 1006 by 1006 pixel image, covering the entire M3 surface, whose outer diameter (clear aperture) is 2508 millimeter. The largest crow's feet can easily be seen on this map, for example, at the 12:30 and 1 o'clock positions. Although the pixel size is about 5mm, the true resolution of the interferometer is worse than that. In Section 2, we will see that the width of the wings of the crow's feet is about 3mm, which is beyond what the interferometer can resolve. Therefore, most of the crow's feet are not visible on this surface map. Even for those that are visible, the features, such as depth and width, are not correctly represented.

In lack of a detailed survey map from SOML, we have come up with a synthetic M3 surface map, where we have used Figure 2 as the starting point, and patched with higher resolution synthetic maps of individual crow's feet. These are based on pictures of Fizeau test fringes of individual crow's foot (Figure 4, no numeric data available), verbal communications with SOML, and a visit to SOML to inspect the mirror (without stepping on). In Section 3 we will describe how we synthesize the M3 surface map. This map is then used in subsequent analysis on structure function, PSF and encircled energy, and scattering, which are described in the rest of this document.

Figure 1 A picture of two crow's feet separated by ~3.5cm.

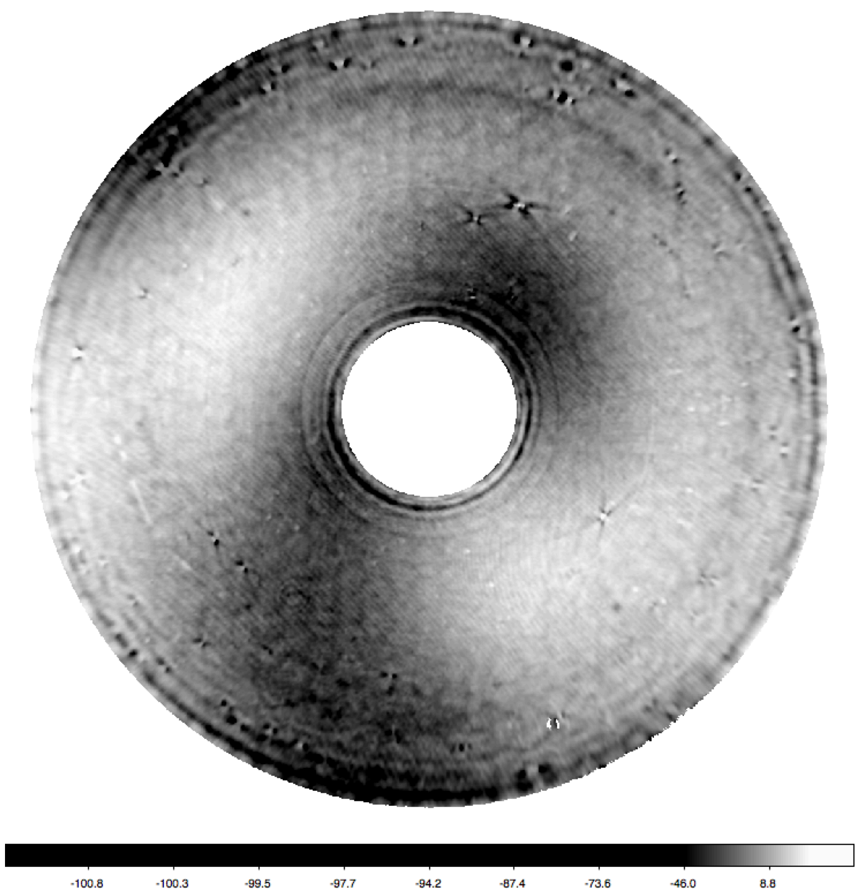

Figure 2. M3 reduced surface map from SOML.

2. Synthetic M3 surface map

Figure 3 shows the largest crow's foot we have simulated. It is representative of all the features we are including in the current model. In our synthetic model, each crow's foot consists of three distinct components: (1) wings that span up to ±20 centimeters, about 3 millimeters wide, and about 300 nanometers deep; (2) center holes that are about 1 centimeter in diameter, and 1-3 microns deep; and (3) air bubbles with sub-millimeter diameter and depth.

In our model, each crow's foot has four wings. Each pair of wings opposite to each other are represented by two elliptical Gaussians whose centers have the same (x,y) coordinates, with their semi-major and semi-minor axes also aligned. The more elliptical Gaussian that describes the long wings of a crow's foot can be written as

$$z_1 = A_1 \exp[- 0.5 * (r^2 / \sigma^2_{1,major} + r^2 / \sigma^2_{1,minor})]$$

The relatively round 2D Gaussian that represents the center part of a crow's foot can be written as

$$z_2 = A_2 \exp[- 0.5 * (r^2 / \sigma^2_{2,major} + r^2 / \sigma^2_{2,minor})]$$

In addition, there are air bubbles at the center of the crow's feet. There are sub-millimeter bubbles that will act like light traps. Most likely they can be safely ignored for all practical purposes. Therefore they are not included in our current baseline crow's foot model. But we'd like to check the possible scattering caused by these bubbles as an additional check.

Table 1 shows all the parameters used in the current baseline model, with the exception that the air bubbles are actually not included for now. We categorize the crow's feet into two groups based on their size: big and small. Basically "big" refers to those that are visible on SOML reduced M3 surface map (Figure 2), and "small" is for those that are visible upon visual inspection of the mirror, and also show up in the Fizeau tests. The 2nd column of Table 1 gives brief descriptions of what each parameter is, and the last column of Table 1 explains the choice of numerical values of each parameter.

Note that the wings in Figure 3 look much longer than those in Figure 1, because shallower parts of the wings are mostly not visible by eye.

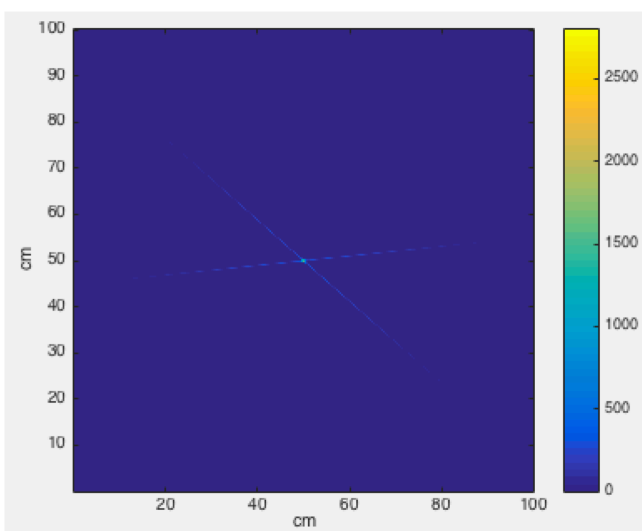

Figure 3 synthetic map of the largest crow's foot with wings spanning ±20cm. The pixel size in this map is 0.5mm.

Table 1 Parameters for current crow's foot baseline model (air bubbles not included for now). Rows are color-coded to group parameters that describe the two elliptical Gaussians.

	Description	Big	Small	Notes
N	Number of simulated crow's feet in each category (big & small)	~25	~300	We can spot ~25 in Figure 2. 300 is based on SOML survey of one sector of the mirror (6 sectors in total)
P	Distribution of crow's feet along the radial direction	Visually matched to those visible in Figure 2	P= 0.5+0.5/(OR-IR)*(r-IR)	There are more crow's feet toward M3 edge. OR=2508mm, IR=550mm (clear aperture)
A_1	Height of the more elliptical Gaussian. This describes the wings of a crow's foot.	300nm	300nm	The wings are ~300nm deep at a fraction of a σ from the center (Figure 4).
$\sigma_{1,major}$	Standard deviation of the more elliptical Gaussian along semi-major axis.	50-100mm	5-50mm	Big ones have wings spanning ±20cm (Figure 2). We assume ±2σ covers ±20cm.
$\sigma_{1,minor}$	Standard deviation of the more elliptical Gaussian along semi-minor axis.	0.75mm	0.75mm	The width of the wings are ~3mm. We assume ±2σ covers 3mm.
A_2	Height of relatively round 2D Gaussian. This represents the center part of a crow's foot.	2.5 micron	1 micron	There are ~8-10 fringes in the center areas in Figure 4. Each fringe means 300nm difference in depth.
$\sigma_{2,major}$	Standard deviation of the relatively round 2D Gaussian along semi-major axis.	3.3mm	3.3mm	The diameters of the area with steep slopes are ~1.0cm (Figure 4). We assume ±1.5σ covers 1.0cm.
$\sigma_{2,minor}$	Standard deviation of the relatively round 2D Gaussian along semi-minor axis.	1.2mm	1.2mm	The center parts of the wings are ~1.5-2 times wider than the outside.
r_{bubble}	Radii of the air bubbles	100-900 micron	100-900 micron	These are sub-mm bubbles
θ_1	Orientation of the 1st pair of wings	$\theta_0+25^{+10}_{-10}$ degree	$\theta_0+25^{+10}_{-10}$ degree	θ_0 is the circumferential direction
θ_2	Orientation of the 2nd pair of wings	$\theta_0-25^{+10}_{-10}$ degree	$\theta_0-25^{+10}_{-10}$ degree	θ_0 is the circumferential direction

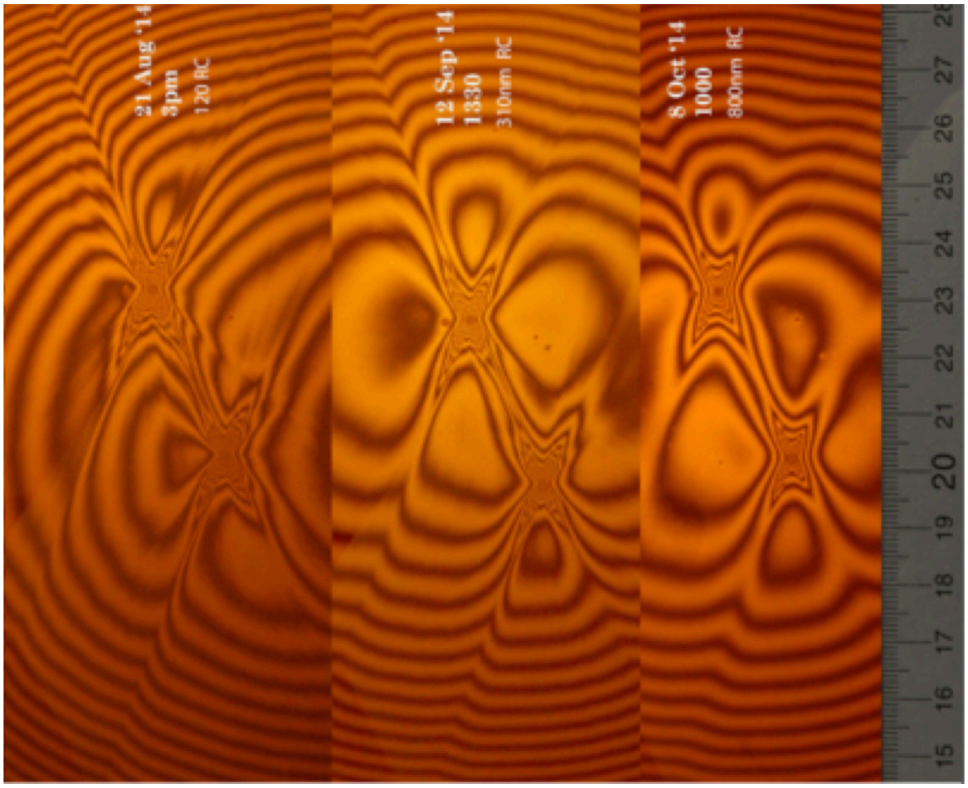

Figure 4 Interference fringes around crow's feet as seen using Fizeau test plates.

To validate our modeling of the crow's feet, we take part of the synthetic M3 surface and calculate its Fizeau test fringes. This is shown in Figure 5 left. The Fizeau test fringes from SOML is shown in Figure 5 right. This is the same plot as shown in Figure 4 right. The height departure between the ideal mirror surface and the test plate is assumed to be of the form $\Delta z = a(r/r_{max})^2$, where the coefficient a is fine-tuned to make distance between the neighboring outer fringes resemble the SOML fringes. The agreement between the calculated and real fringes is seen to be good enough for the synthetic map to be used for structure function, image quality, and scattering evaluations.

The final synthetic M3 surface map in 1006x1006 resolution is shown in Figure 6. For image quality analysis performed in ZEMAX, we will use a 4021x4021 synthetic surface map. Both 4021x4021 and 8041x8041 surface maps have been made available to Scott Ellis at Photon Engineering for scattering analysis.

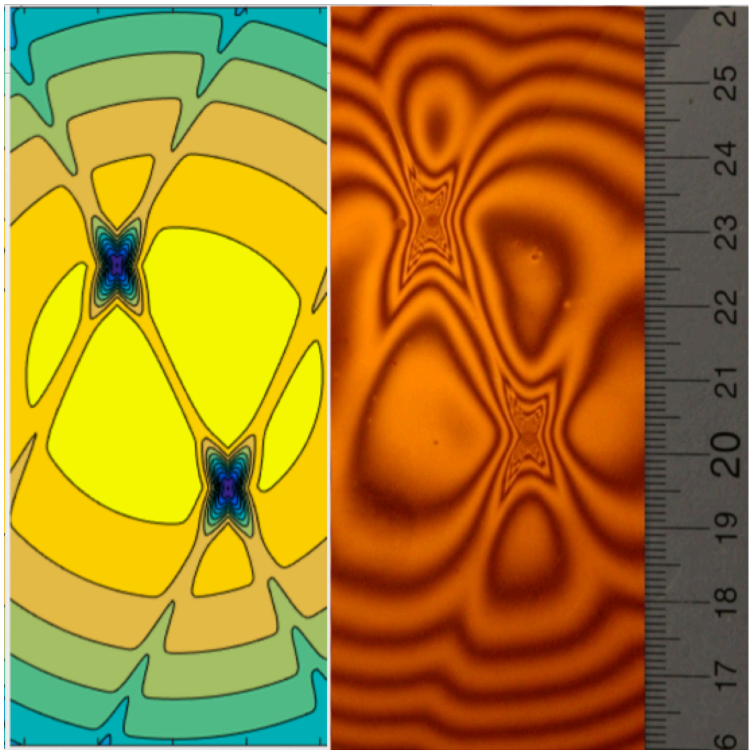

Figure 5 Fizeau test fringes of two crow's feet from the synthetic map (left), as compared to the fringes from a real test performed by SOML (right). The SOML plot is the same one as shown in Figure 4 right.

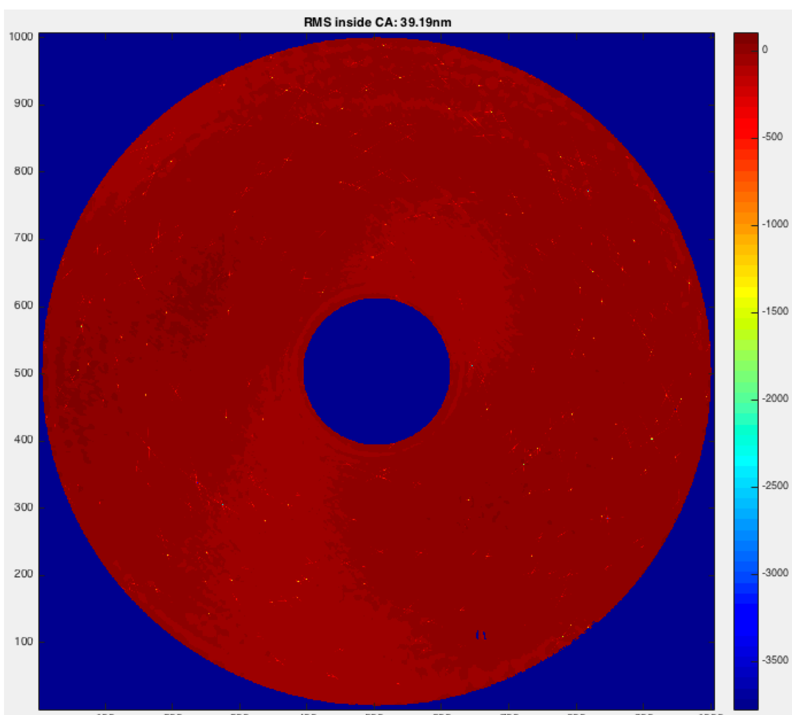

Figure 6 The synthetic M3 surface map from our baseline crow's foot model. (No air bubbles included).

3. Structure function

Figure 7 shows the structure function calculated from the synthetic surface map in Figure 6. It is compared to the LSST M3 structure function specification, and the structure function based on the SOML reduced M3 map. Our structure function calculation routine used here is based on the auto-correlation and cross-correlation functions, therefore, mainly involves FFT operations. It has been validated using the SOML M1 and M3 surface maps (the M3 example is also shown in Figure 7), and by comparing to the brute force calculation that exhausts all combinations of the pixels on a given surface map.

The surface RMS of the synthetic M3 is 39.19nm, which is consistent with saturation level of the structure function. Note that all structure functions are for wavefront phase, which is two times the surface deformation.

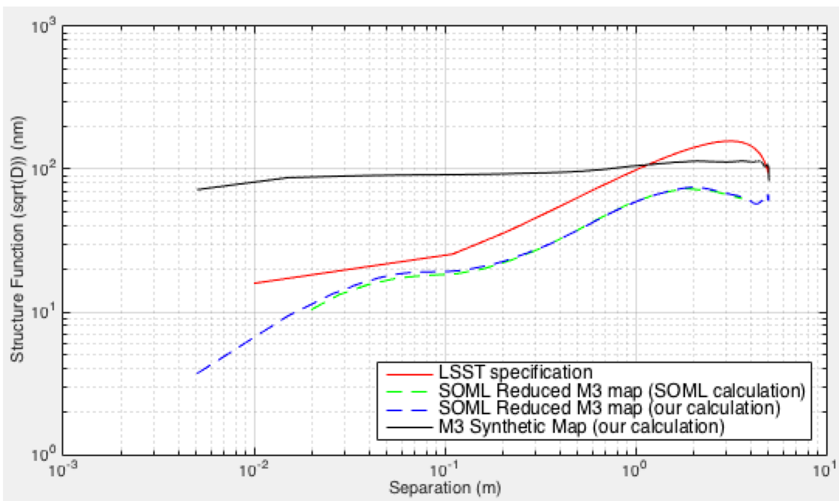

Figure 7 Comparison of the structure functions calculated from the SOML reduced M3 surface map, our synthetic M3 map, and the LSST specification.

4. PSF and Encircled Energy (in progress)

5. Scattering Analysis (in progress)

Bibliography

Seo, B.-J., Nissly, C., Angeli, G., Ellerbroek, B., Nelson, J., Sigrist, N., et al. (2009). Analysis of normalized point source sensitivity as a preformance metric for large telescopes. *48* (31), 5997.

Xin, B., Angeli, G., Liang, M., Sebag, J., Hileman, E., Neil, D., et al. *M1M3 Data Reduction pipeline.*