The mask designs for Space Interferometer Mission (SIM)

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ABSTRACT

The Space Interferometer Mission (SIM) consists of three interferometers (science, guide1, and guide2) and two optical paths (metrology and starlight). The system requirements for each interferometer/optical path combination are different and sometimes work against each other. A diffraction model is developed to design and optimize various masks to simultaneously meet the system requirements of three interferometers. In this paper, the details of this diffraction model will be described first. Later, the mask design for each interferometer will be presented to demonstrate the system performance compliance. In the end, a tolerance sensitivity study on the geometrical dimension, shape, and the alignment of these masks will be discussed.

Key words: Diffraction, metrology, interferometry

1. INTRODUCTION

The Space Interferometer Mission (SIM) [1] consists of three interferometers (science, guide1, and guide2) and two optical paths (metrology and starlight). It involves large propagation distances, which means that the diffraction model is needed to analyze the optical performance. Here we mainly discuss the internal metrology mask designs that are optimized to meet the system requirement. For each interferometer, diffraction model uses scalar diffraction theory to simulate 4 optical propagation paths. Two of the paths begin from the launcher, then propagate 8.8 meters to a corner cube and back through the same path. One of these two paths includes an additional optical delay line path. The other two paths include two local oscillators that are used as reference paths. The corner cubes are articulated to look at different points in the sky and the optical delay line moves with respect to the corner cube articulation. Three system requirements are OPD as a function of corner cube articulation (grid error and narrow angle error), cross-talk between the two corner cube paths (cyclic error), and the power loss of the beam at the detectors (heterodyne power).

2. MODEL DESCRIPTION

The model applies scalar diffraction theory to simulate the internal metrology system. Two major assumptions are made. The first is that a scalar model of the electric field is sufficient. This assumption implies that the vector effects of the electric field are small enough that they can be ignored. The second assumption is that the paraxial approximation can be made to the Fresnel equation. This approximation assumes that the optical rays from the wavefront normal are small ($\sin\vartheta \approx \vartheta$). The code breaks the Fresnel equation into two forms, near and far field equations. It decides when to use either equation based on propagation distances and system inputs. The code also applies common scalar diffraction techniques such as edge

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tapering to minimize Gibbs phenomena, and storing the wavefront curvature separately from the actual wavefront to prevent aliasing. So, Benson's Code is able to implement the scalar diffraction theory to the internal model to pm accuracy [2].

For the model implementation, it uses a library of functions created in FORTRAN by R. Benson [3] and analyzes their outputs using Matlab. Figure 1 shows detailed calculation flow.

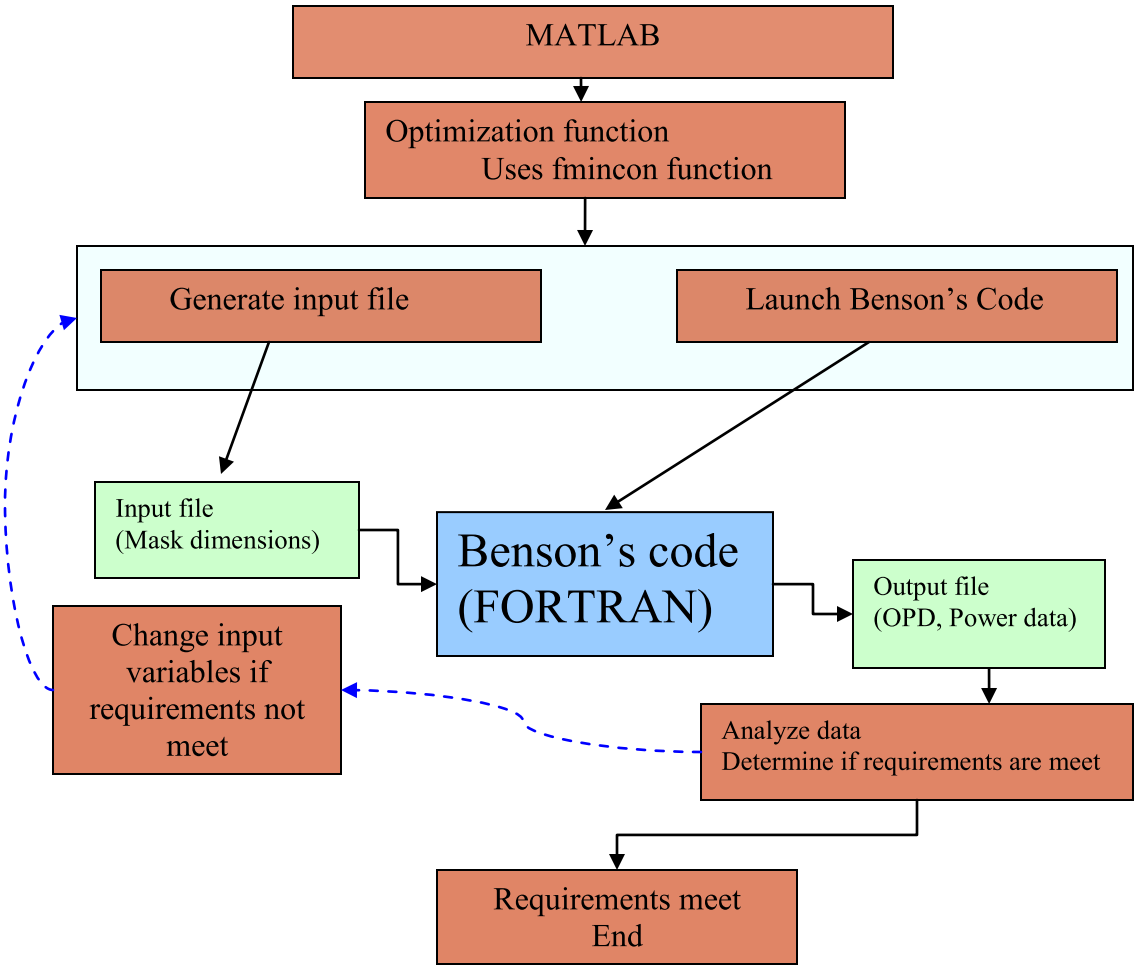

Figure 1 Diffraction model calculation flow chart.

The internal diffraction model has several masks which affect the diffracted wavefront for the different corner cube articulations and different optical delay line lengths (Figure 2). The local oscillator paths begin with a Gaussian beam that has a 16.7mm 1/e beam diameter at the beam waist. The source wavelength is 1319nm. It propagates 850mm, and is then clipped by a field separator mask (FS). It propagates 60 mm to an ideal lens where it is focused down onto a 300 μm detector. The two corner cube paths begin with the same Gaussian beam and propagate 850 mm to a beam splitter mask (BS). The first corner cube distance is 8.8m plus the optical delay line which increases or decreases according to: $9 \times \sin \vartheta$ (1)

From the equation, θ corresponds to the articulation of the corner cube in the x direction. However, for the second corner cube path the distance it propagates after the BS is always 8.8m. After the beam propagates the 8.8m plus the delay line, it is clipped by a second mask. The mask is called the fast steering mirror mask (FSM). The beam propagates through the corner

cube and back through the path it came from. After the beam goes back through the BS it propagates 800mm. Next the beam is clipped by the FS and is focused down to a detector. Each corner cube path is heterodyned with its corresponding reference beam. The OPD, cross-talk and power loss are all calculated at the detector.

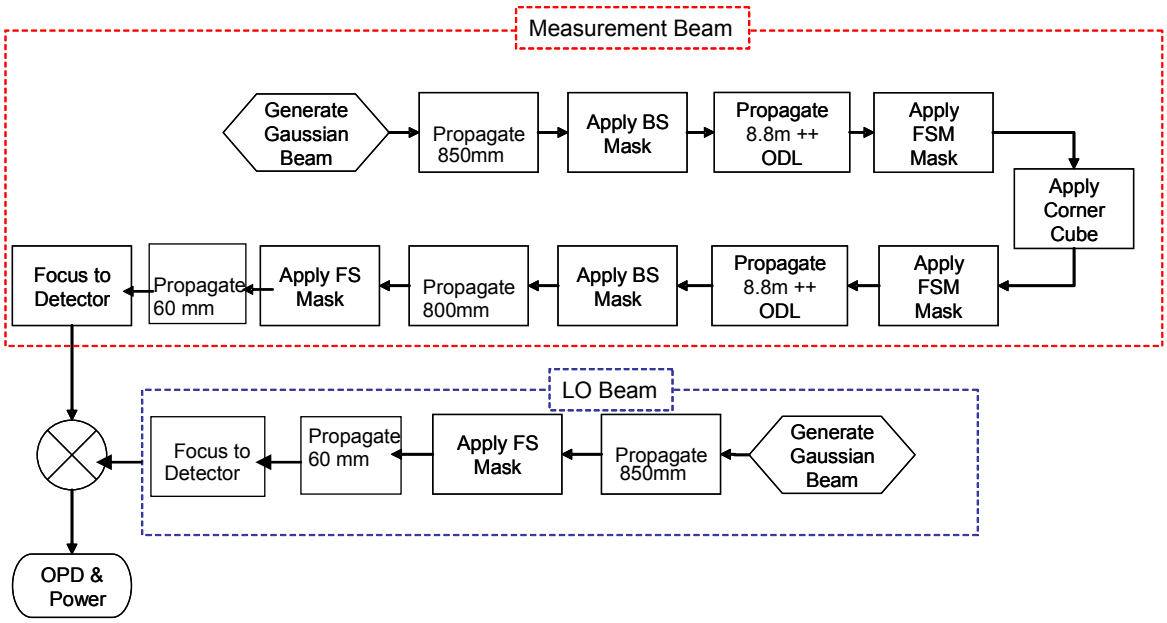

Figure 2 Mask configuration

A Matlab script is written to find the limiting aperture after rotating the corner cube aperture through its outer articulation angles. That limiting corner cube aperture is passed to the internal metrology model so that the FSM masks can be designed in a way that for maximum corner cube articulation the corner cube does not clip the beam, or the rooflines (Figure 3).

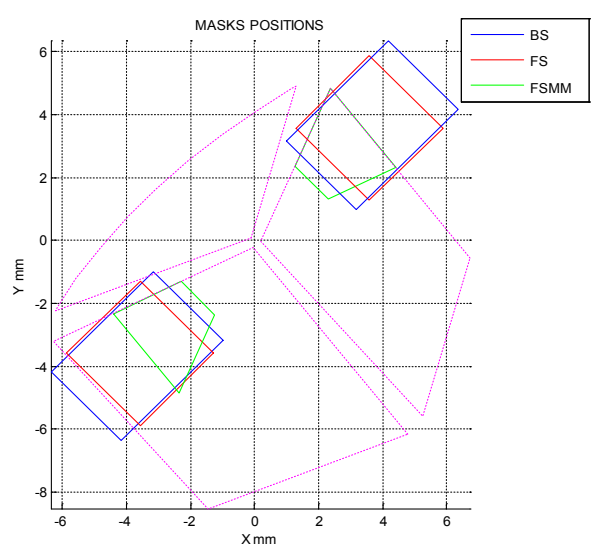

Figure 3 masks and corner cube limiting aperture

There are some relevant assumptions made in the model that should be noted. One is that the model does not include the beam compressor. The corner cube is actually 8.7 times larger

than what is implemented in the model. The beam compressor is assumed to perfectly image the corner cube down to the FSM mask. Another assumption is that there is zero dihedral error in the corner cubes. Lastly, there are no fold mirrors molded in the simulation, and it is assumed that the system is aligned perfectly during the mask optimization.

3. REQUIREMENTS

The metric to evaluate whether the model is meeting its performance requirements is the OPD as a function of corner cube articulation, cross-talk (cyclic error), and power loss. The model adjusts the free parameters (the masks dimensions) until the requirements are meet. Also, there are three interferometers: Science, Guide1, and Guide2 in our system. For guides, their FORs are limited so that their requirements are on crosstalk error and heterodyne power only.

The OPD metric is broken into two components: Grid error (GE) and narrow angle (NA) error. A Matlab routine [4] is developed to use the Zernikes that were fit to the calculated OPD and predict the GE and NA (SIM will actually calculate these numbers during mission operation). The requirement for GE and NA is 115pm and 3pm, respectively.

The cross-talk or cyclic error results from the coherent crosstalk between two metrology beams. The cyclic error in arm #1 due to leakage from the beam in arm #2 is defined as:

$$\varepsilon_1 = \frac{1}{2k\sqrt{2}}\frac{P_2}{P_1} \tag{2}$$

Where P_1 is the heterodyne power of arm#1 at detector #1, P_2 is the heterodyne power of arm#2 at detector #1 (the crosstalk), and k is $2\pi / \lambda$. The requirement for this metric is ≤ 14.425pm RSS (root sum square) of the two detectors. Because the different paths are separated spatially, optimization of the masks dramatically affects the cyclic error. Notice that guide2 can handle larger cyclic error so its requirement is set larger at 42.425pm.

The last requirement is the heterodyne power at each detector. The heterodyne power requirement for detector with the optical delay line at the center of the field, and is defined as:

$$P_{dB} = 10\log_{10}(\frac{P}{P_o}) \tag{3}$$

Where P_o is the sum of the power for the corner cube and local reference paths, and P is the power for the corner cube path. The requirement for the heterodyne power is > -20dB.

4. MASK DESIGN AND PERFORMANCE

It has been found that the system requirement for each interferometer is different and sometimes they are working against each other. An optimization routine is developed to optimize three interferometers to meet their respectively requirements in the same time. It applies essentially three loops of optimization subroutine that was initially developed for Science interferometer. To make it work correctly, the boundary conditions of each interferometer have to be carefully defined before routine starts. We will discuss each interferometer design with more details in the following sections.

4.1 Science Internal metrology

The deliverables from this model are the mask dimensions, system performance, and

Zernike coefficients used to calculate the OPD requirements. There are 4 masks that were designed, the BS, FS, and two FSM masks. Additionally, there is a clean up mask for ghost paths and for stray light in the path. Both the BS and FS are simply four rectangular apertures which are separated by 90 degrees. For the two FSM, there are two polygons apertures, and each FSM has mirror symmetry of each other. Cleanup mask has some freedom in its exact position and dimensions, which made it an ideal optimization parameter rather than changing the FSM mask, which was undesirable due to fact that it would require running new Corner Cube model [5]. The dimensions of the masks are defined in the tables below along with their layout in Figure 4:

Masks	**dy**	**dx**	**ro**	**Rotation (degree)**
BS-path1	3.265mm	2.503mm	4.919mm	45
BS-path 2	3.265mm	2.503mm	4.919mm	-45
FS-path1	4.106mm	3.91mm	4.536mm	45
FS-path 2	4.106mm	3.91mm	4.536mm	-45

Table 1 BS/FS mask dimensions

FSM path 1

x mm	**y mm**	**x mm**	**y mm**
5.0784	2.6709	-5.0784	-2.6709
2.7329	5.5717	-2.7329	-5.5717
1.4393	2.7062	-1.4393	-2.7062
2.6413	1.5043	-2.6413	-1.5043

FSM Path 2

x mm	**y mm**	**x mm**	**y mm**
-5.0784	2.6709	5.0784	-2.6709
-2.7329	5.5717	2.7329	-5.5717
-1.4393	2.7062	1.4393	-2.7062
-2.6413	1.5043	2.6413	-1.5043

Table 2 FSM dimensions

If any of the mask designs or propagation distances are changed the system performance will also change. With those mask dimension, the predicted system performance is listed in Table 3:

Metric	**Performance**
Grid Error, NA At the Detector	GE: 42.93pm NA: 2.7pm
Cyclic Error	0.3pm
Heterodyne Power	-19.75 dB

Table 3 performance requirements for nominal case

Notice that there is an addition 5pm/-3dB trade off in the heterodyne power. This means that, for every -3dB of power that the heterodyne power measurement is below the design goal, extra 5pm can be tolerated in the cyclic error measurement.

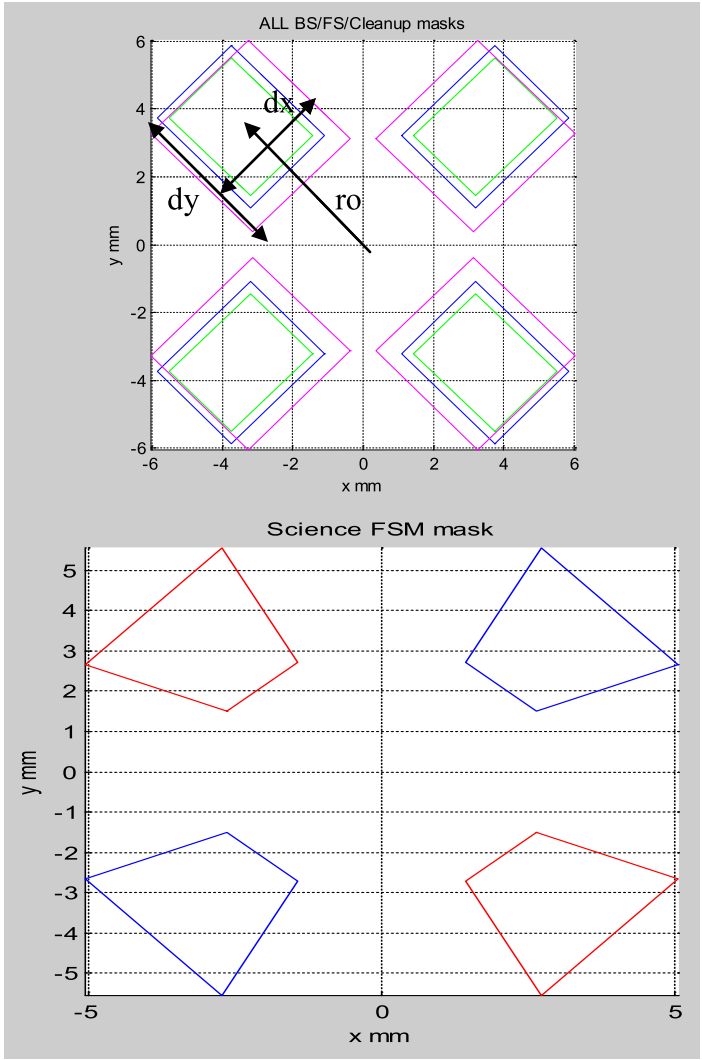

Figure 4 BS/FS/cleanup/FSM masks

4.2 Guide internal metrology

The guide 1 and 2 internal metrology both have different corner cubes, orientations and propagation distances compared to the science interferometer. This means that the science FSM masks will not work for the guide interferometers, because the beam might fall off the Guide Corner cubes. For example, the current Guide corner cubes have a 52.2mm radius base plate and a 46.2mm wedges, while the Science has an 80.5mm base plate and wedge height. It turns out that science mask fall off the corner cube boundary.

Because the Guide 1 and 2 have different orientations, they also have a different clear aperture that is permitted by the TCC. This means that a different FSM mask for each of the guide interferometers is needed. During the guide interferometer mask optimization, only the FSM masks are changed so that we can still apply the same launchers for all the interferometers. The requirements for the guide are the same as the Science except there is no Grid Error or Narrow Angle requirement since the Guides are not field dependent. Figure 5 shows the Guide1 FSM mask design configuration, and Table 4 shows its dimension and performance.

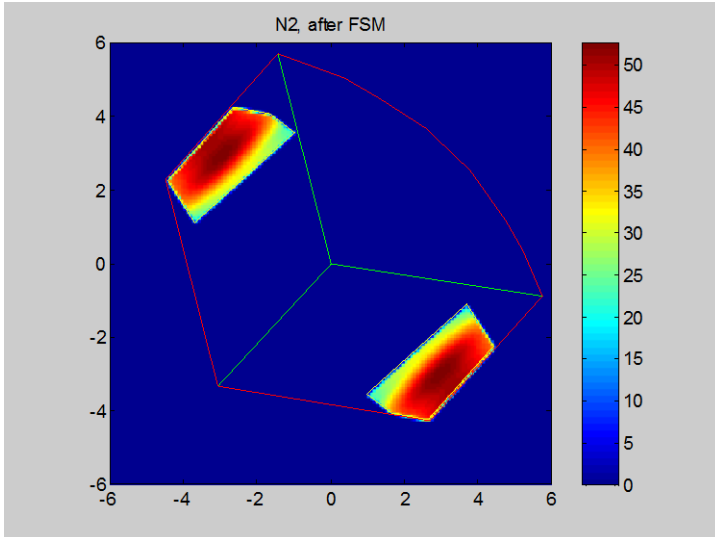

Figure 5 Guide1 FSM design

FSM path 1

x mm	y mm	x mm	y mm
1.6410	4.0630	-1.6410	-4.0630
2.656	4.258	-2.656	-4.258
4.453	2.266	-4.453	-2.266
3.7063	1.1125	-3.7063	-1.1125
0.9792	3.5730	-0.9792	-3.5730

FSM Path 2

x mm	y mm	x mm	y mm
-1.6410	4.0630	1.6410	-4.0630
-2.656	4.258	2.656	-4.258
-4.453	2.266	4.453	-2.266
-3.7063	1.1125	3.7063	-1.1125
-0.9792	3.5730	0.9792	-3.5730

Metric	Performance
Cyclic Error(rms)	3.94 pm
Heterodyne Power	-19.95 dB

Table 4 Guide1 FSM dimension and performance

Guide 2 is different from Guide 1 in the sense that each bay has a different FSM shape,. This is due to the fact that there is a 17.678° ccw rotation, looking down the primary toward the SID, in the pupil. The two Guide IntMet are also different in the sense that the requirements for the Guide 2 are more relaxed due to its tiny field of regard. Figure 6 shows the Guide2 FSM configuration for each arm. Table 5 shows its dimension and performance.

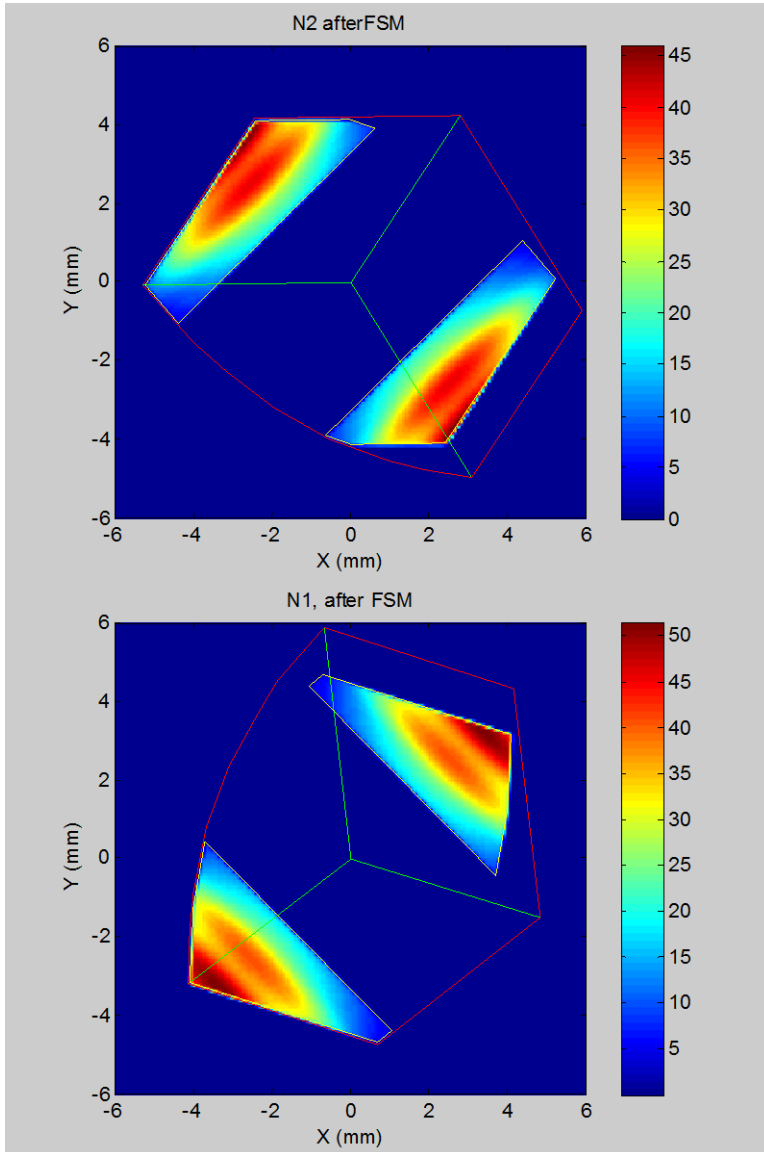

Figure 6 Guide2 FSM mask

From the table, it appears that the Guide 2 internal metrology does not meet its requirement, but actually it does due to the 5pm/-3dB tradeoff conversion. The big margin (~37 pm) in cyclic error gives us ample room to tolerate even more much weaker heterodyne power.

FSM path 1

x mm	y mm
-4.1890	-0.8021
0.6021	4.0833
-0.6667	4.2580
-1.7707	4.4027
-5.1610	0.7698

x mm	y mm
4.1890	0.8021
-0.6021	-4.0833
0.6667	-4.2580
1.7707	-4.4027
5.1610	-0.7698

FSM Path 2			
x mm	**y mm**	**x mm**	**y mm**
-0.8688	4.1890	0.8688	-4.1890
3.7500	-0.4688	-3.7500	0.4688
4.2970	1.0940	-4.2970	-1.0940
4.5083	2.4973	-4.5083	-2.4973
0.1125	4.7033	-0.1125	-4.7033

Metric	Performance
Cyclic Error(rms)	5.35 pm
Heterodyne Power	-22.59dB

Table 5 Guide2 FSM dimension and performance

As an illustration on the features of the model, Figure 7 lists the optical beam pattern at each element along the science interferometer path. The chart turns to be quite useful as a guidance to check the experiment.

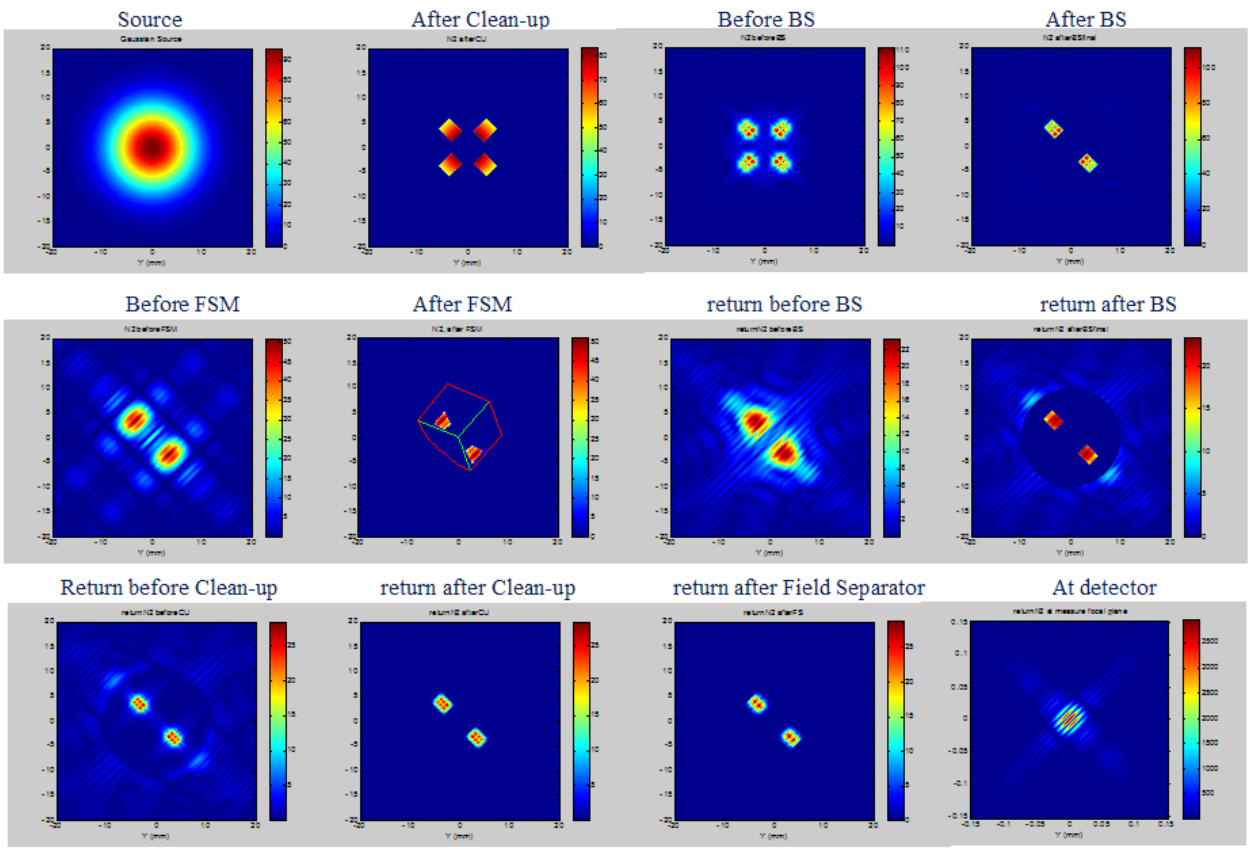

Figure 7 Metrology beam pattern along the optical path for Science interferometer.

5. MASK TOLERANCE ANALYSIS

Once we finalized all the masks for all interferometers, we did some tolerance analysis on their manufacturing errors and package alignment errors, specifically, the mask center alignment offset and mask dimension misshape. On top of that, tolerance variation on each arm is assumed

to be independent. As an example, the tolerance analysis on science interferometer is presented. A Monte-Carlo run is carried out to randomly change tolerance set, and a statistical analysis reveals its pass rate. As long as 70% of the cases meet the requirement, the tolerance set is accepted. Four types of errors that the current analysis covers are FSM mask coordinates (4 variables), BS/FS x/y dimension and y0 separation (3 variables), metrology source center vs FSM mask center (1 variable), packaged FSM center vs designed FSM center (1 variable). Figure 8 shows the statistic result with above four types of errors at following varying boundaries: ±25um, ±25um, ±50um, and ±50um. Notice that those numbers are maximum derivation around its nominal values. The Monte-Carlo runs randomly select values at the uniform distribution pattern.

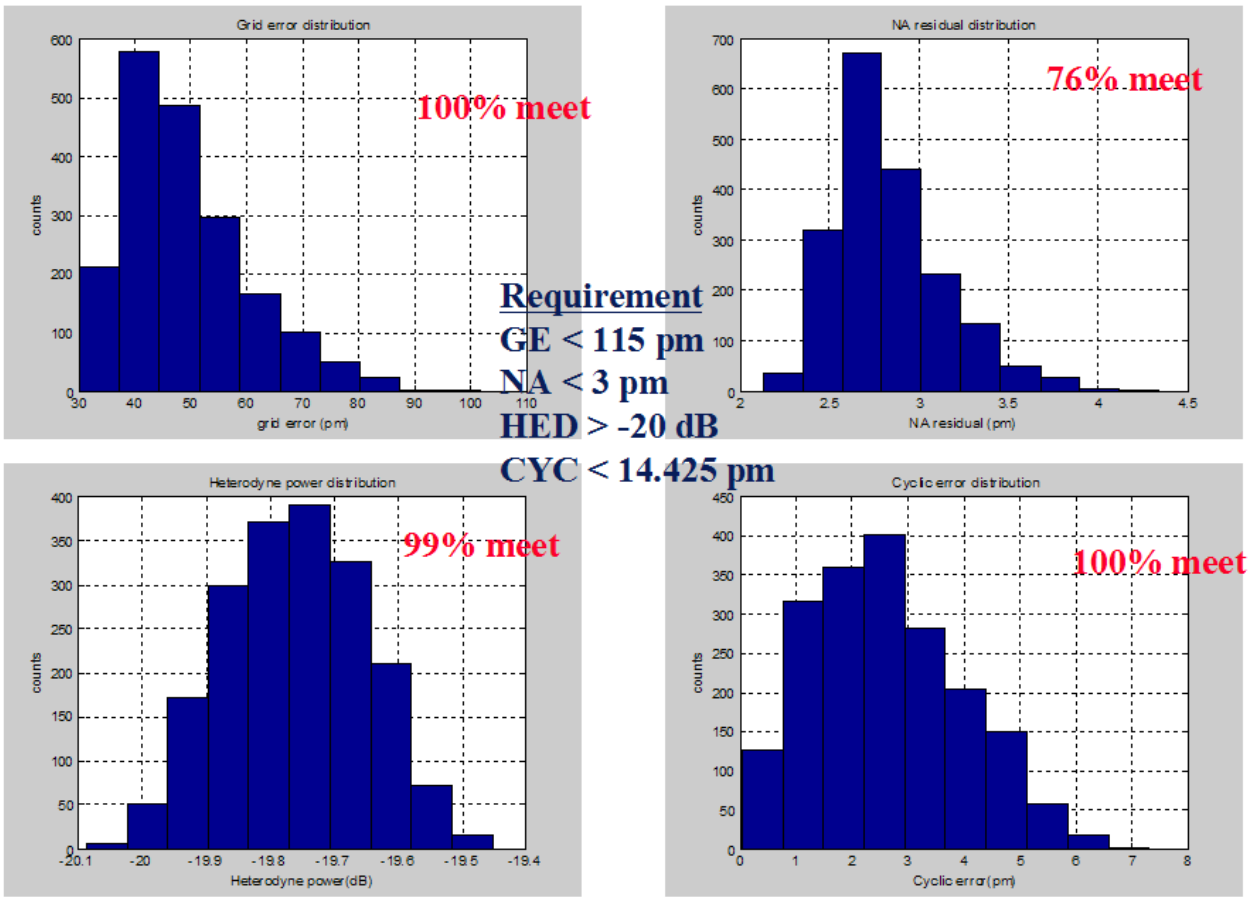

Figure 8 Science interferometer performance distribution with ±25um/±50um tolerance set

6. SUMMARY

A SIM diffraction model is developed to design and optimize various masks to simultaneously meet the system requirements of three interferometers. All the relevant requirements have been checked against with the design performance. To complete design phase, the manufacturing and packaging tolerance analysis on those masks has also been carried out. It should be noted that the optical performance from those masks is very sensitive to the system configuration. Once the optical prescription of the system is modified, the whole design and optimization process has been repeated.

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7. REFERENCES

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