Mapping and Correcting the Surface of the GQuEST End Mirrors

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What am I going to talk about?

01.

Introduction

–What is GQuEST

–Noise sources in GQuEST

02.

Objective

–How to reduce classical noise

–Effects on mirror surface

–What am I working on

03.

Approach and Advancements

–Introduction to the modes I focus on

–Mirror surface and deformations

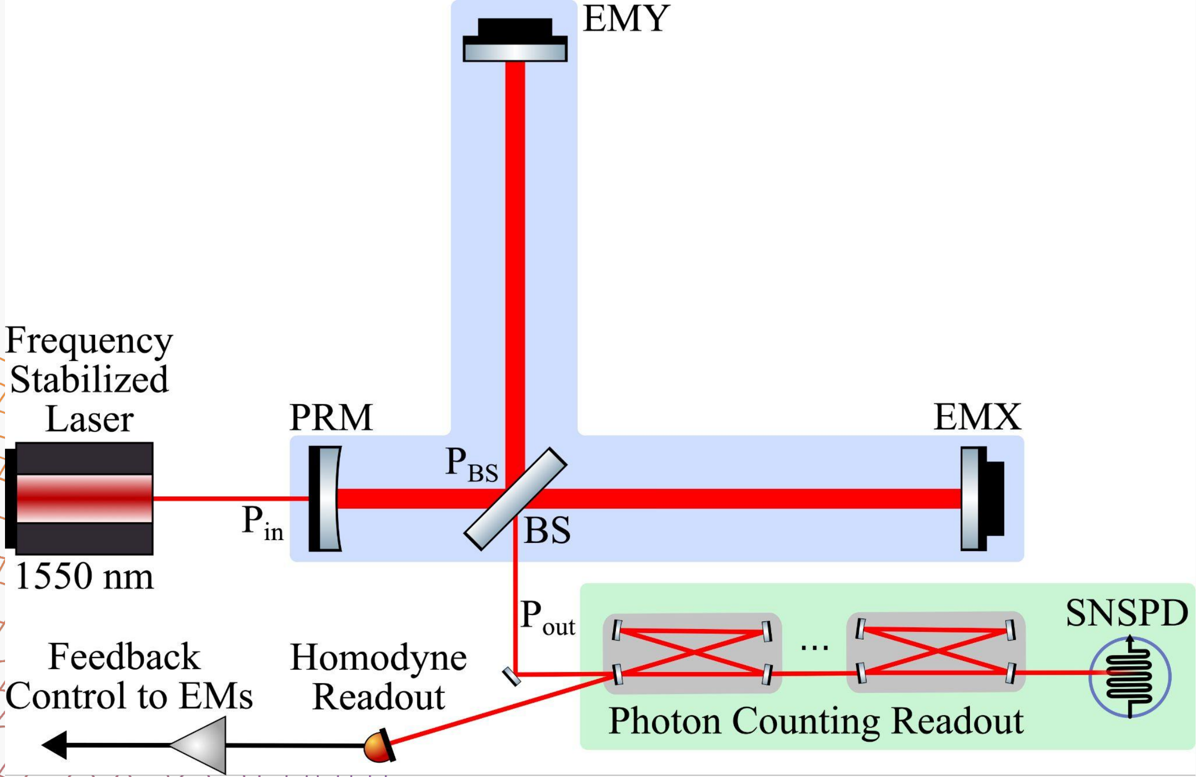
–Coupling coefficients

–The Zernike approach

–The matrix approach

What is GQuEST?

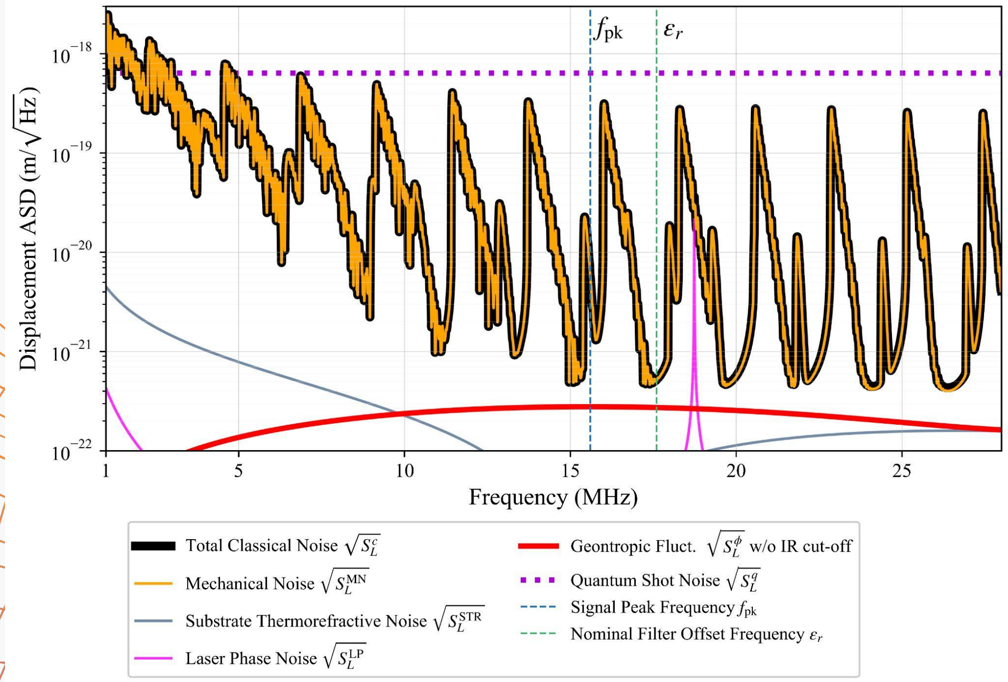
Gravity from the Quantum Entanglement of Space-Time

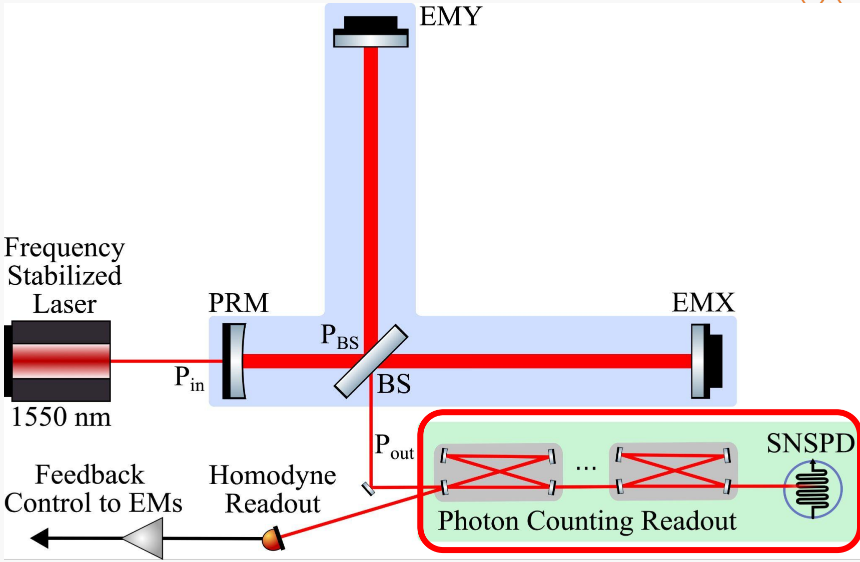


Erik Verlinde and Kathryn Zurek predict 'geontropic' fluctuations, stochastic fluctuations of space-time geometry induced by entropy.

GQuEST is a table top (7m) Michelson Interferometer designed to detect these **quantum gravity fluctuations**.

What are the advantages to GQuEST?

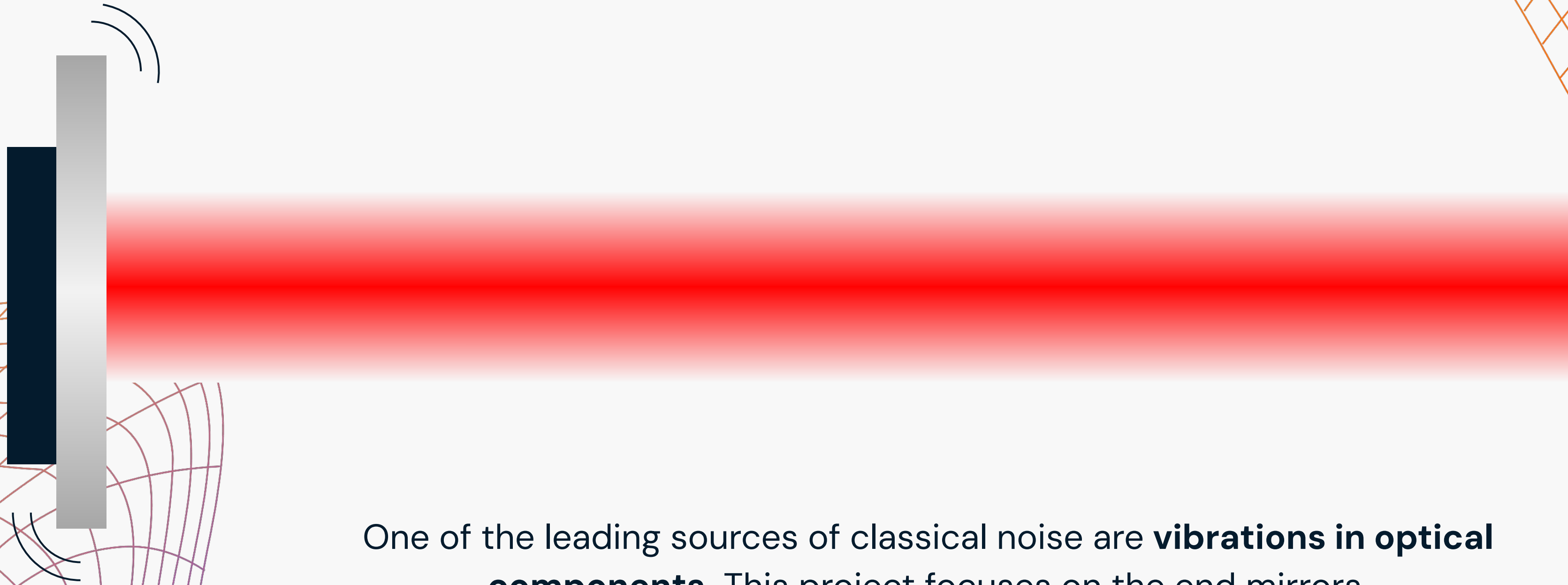




GQuEST filters the output light such that **only photons carrying the signal are detected** (some noise will still pass).

Noise in GQuEST

Because of photon counting, GQuEST is not limited by quantum shot noise but instead **limited by classical noise**.



One of the leading sources of classical noise are **vibrations in optical components.** This project focuses on the end mirrors.

Modeling Noise from End Mirrors

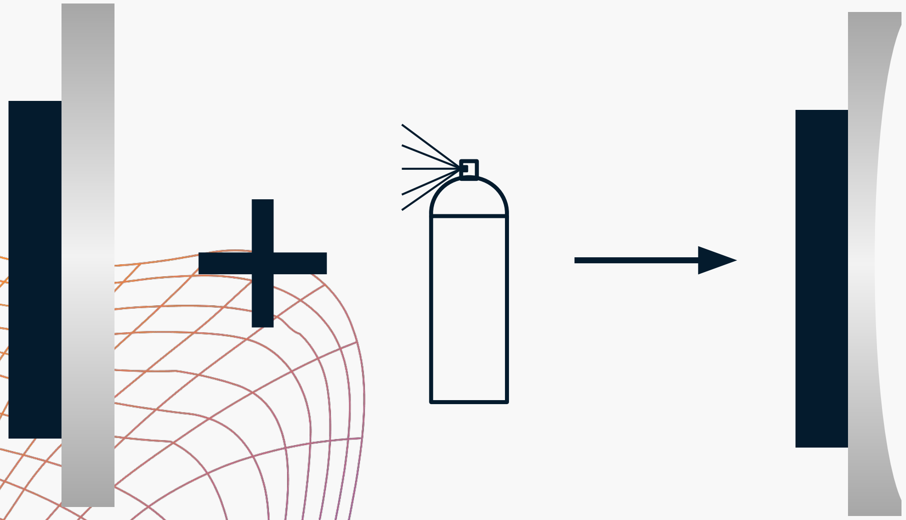
We can approximate the contribution to the noise floor from the substrate of the mirror by the following analytical equation,

$$\bar{S}_L^{SMN}(\Omega) = \frac{16 k_B T h \varphi_s}{\pi^3 M_s w^2 \Omega}$$

The **simplest parameter to modify is the thickness (h) of the mirror**. GQuEST plans to utilize **2 mm silicon mirror**, bringing the noise floor from the substrate below the coating thermal noise floor.

What are the Effects of Skinny Mirrors

Minimizing the mirror thickness causes the mirror to be **more pliable**. This means when the Bragg reflective coating is applied it **curves the face of the mirror**.

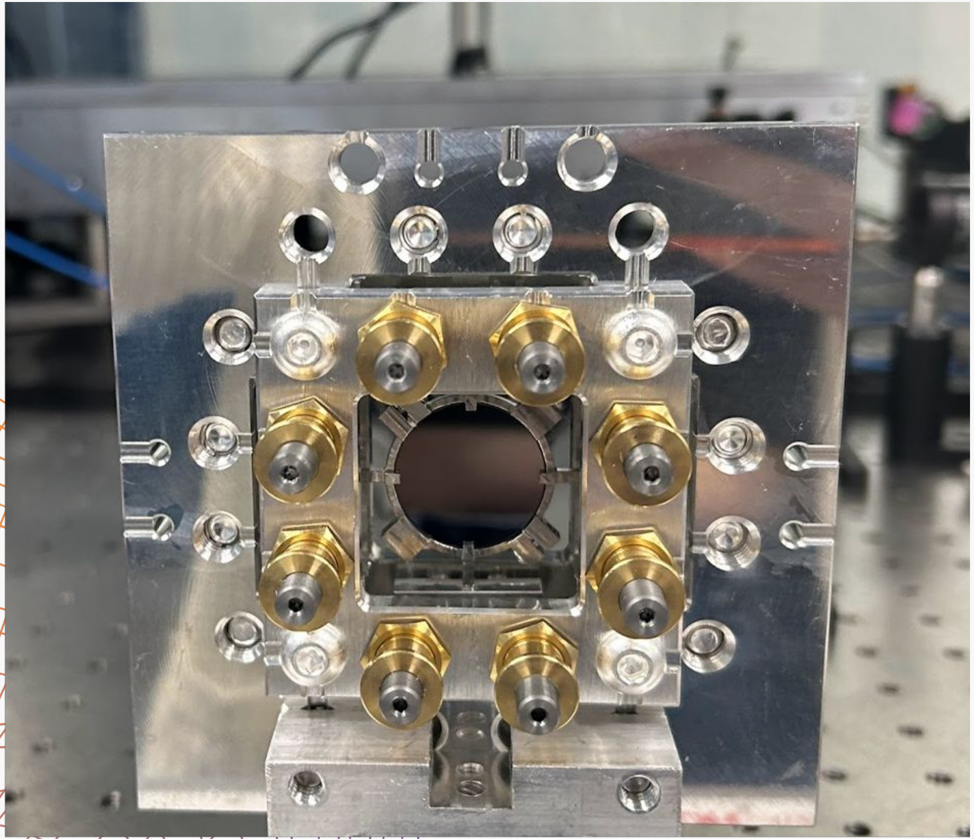


$$r_{curv} \approx \frac{E_s h^2}{6\sigma_c h_c(1-v_s)} = 7.6\mathrm{m}$$

When light reflects off of a curved mirror surface some of the **light is converted into higher-order modes** (HOMs). The optical power loss of these modes,

$$D = 2/r_{curv}$$

How to Reduce Optical Power Loss



1. Apply an anti-reflective coating to the back side of the mirror (expected to reduce power loss by a factor of 10)
2. Utilizing matching pairs (expected to reduce power loss by a factor of 10)
3. Using the adjustable mirror mount to correct for the curvature (remaining mismatch)

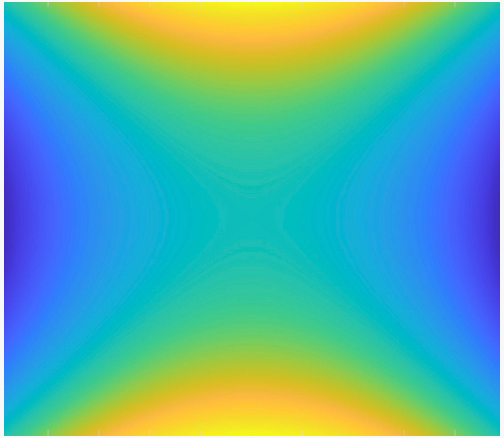
With the current proposed parameters for GQuEST the mirror mismatch is expected to be **roughly 0.26 diopters**. To achieve a significantly low contrast defect (<10ppm) the mirror mismatch must be **<3e-4**.

The focus of this summer will be to generate pure and combinations of HOMs under the assumption that if we learn how to generate HOMs in a consistent fashion then we will be able to make an inverse adjustment to remove them in the future.

HOMs and their Production

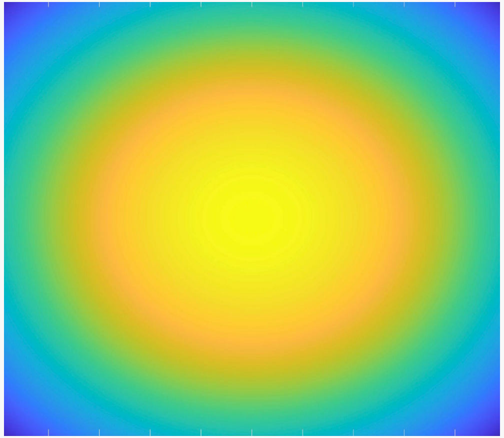
There are three main mirror deformations that we are concerned about.

XMode



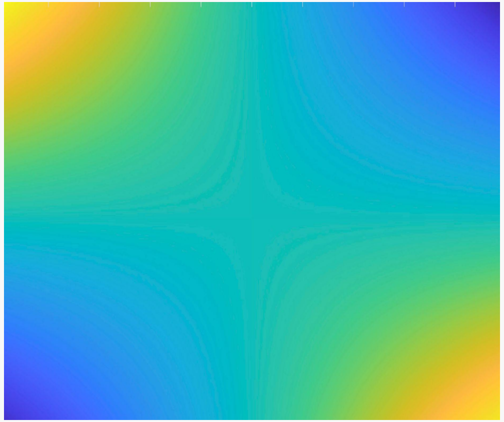
Leads to coupling into the HG_02 and HG_20

OMode



Leads to coupling into the HG_02 and HG_20

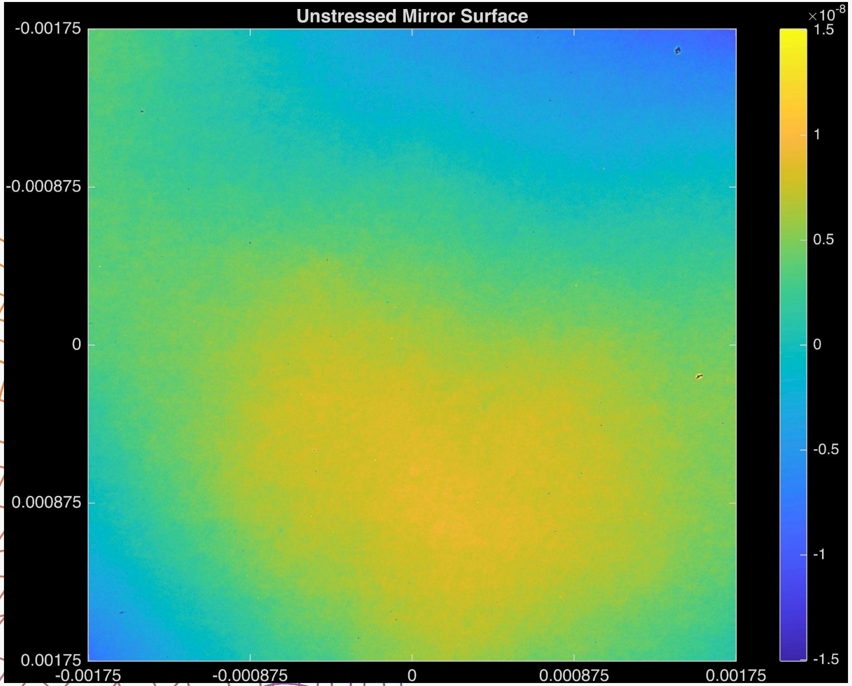
Twist Mode

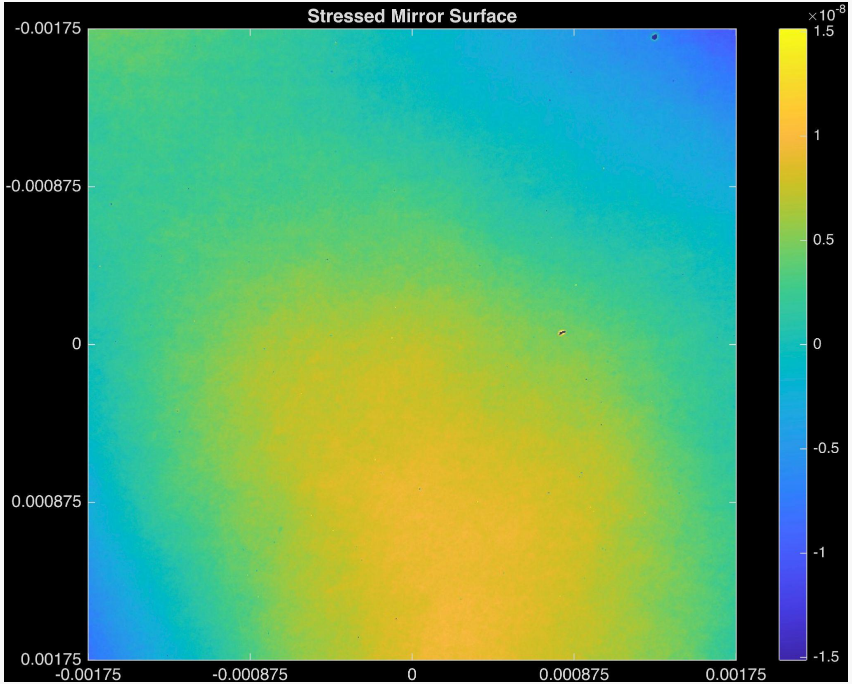


Leads to coupling into the HG_11

Mirror Surface and Deformations

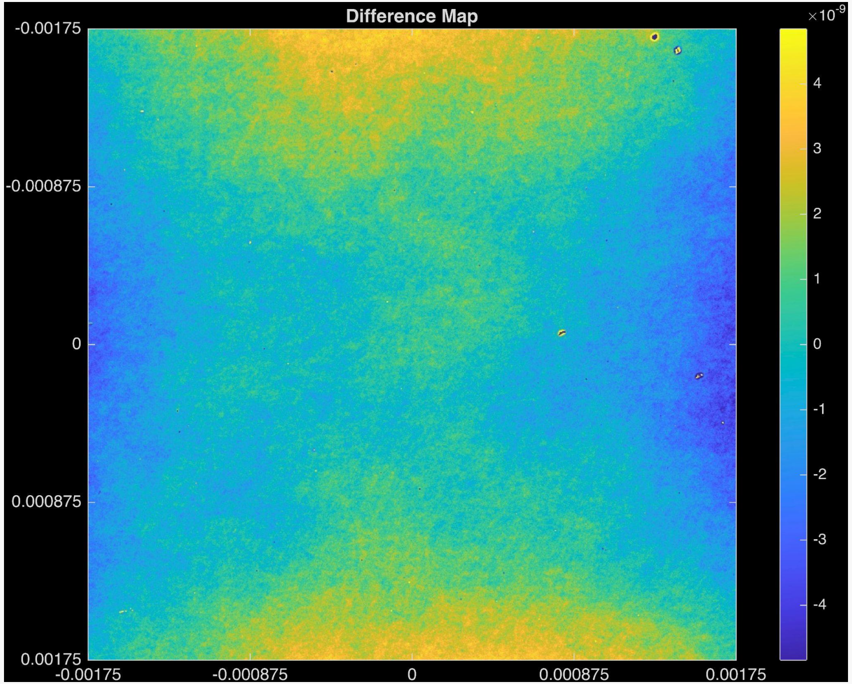
This project uses a NanoCam HD, a small scale optical profiler. This allows us to calculate the curvature of the unstressed mirror and observe how the mirror surface reacts to adjustments from the mount.





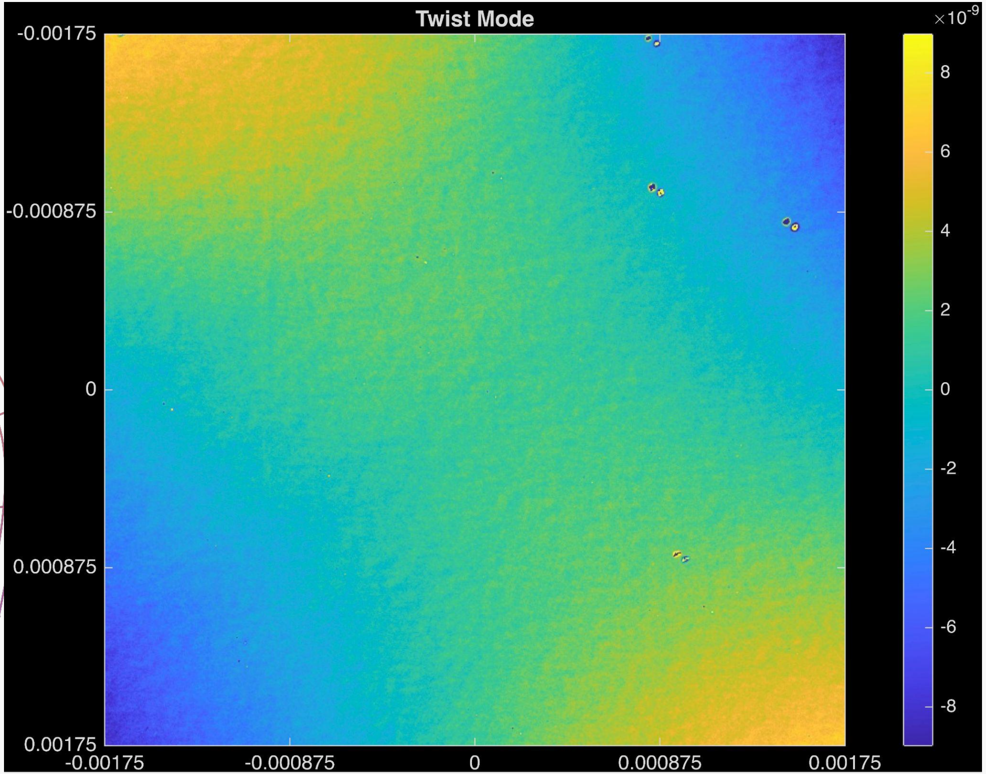
Creating the Xmode

By looking at the **difference between the stressed and unstressed mirror** we are able to more clearly see what modes we are generating.



Creating the Twist Mode

Again, looking at the **difference between the stressed and unstressed mirror** we can observe the twist mode.



We care about coupling to HOMs

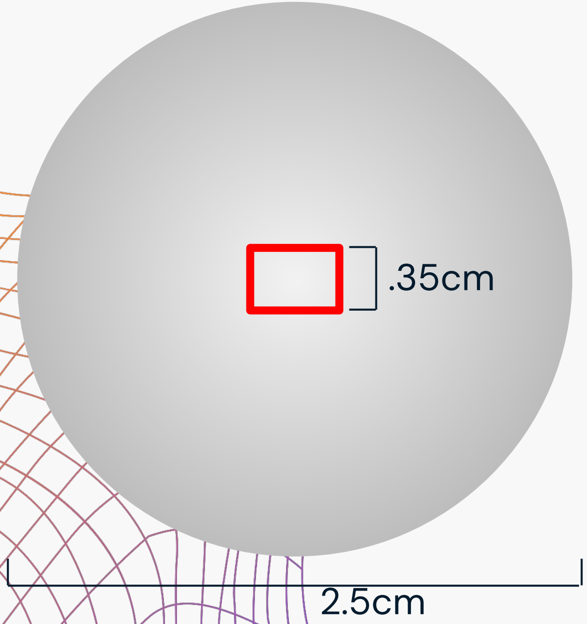
I have also developed a simulation in MATLAB which takes the data from the optical profiler and calculates the coupling coefficients to higher order modes.

$$k_{nmn'm'} = \int\int u^*_{n'm'} e^{2ikz(x,y)} u_{nm}(x,y)\,dx\,dy$$

$$u_{nm}(x,y) = \left(\frac{1}{2^{n+m-1}n!m!\pi}\right)^{1/2}\left(\frac{1}{w_0}\right)\left(\frac{q_0}{q(z)}\right)\left(\frac{q_0 q^*(z)}{q^* q(z)}\right)^{(n+m)/2} H_n\left(\frac{\sqrt{2}x}{w(z)}\right) H_m\left(\frac{\sqrt{2}y}{w(z)}\right) e^{-ik\frac{(x^2+y^2)}{2q(z)}}$$

Limited FOV with the NanoCam

There is a major limitation with the NanoCam, with the current set of objectives we are only able to capture a **3.5mm by 4.5mm area**. The 2σ power radius of the laser on the mirror is expected to be around 3mm which means the area the NanoCam images **does not fully encompass the laser beam.**

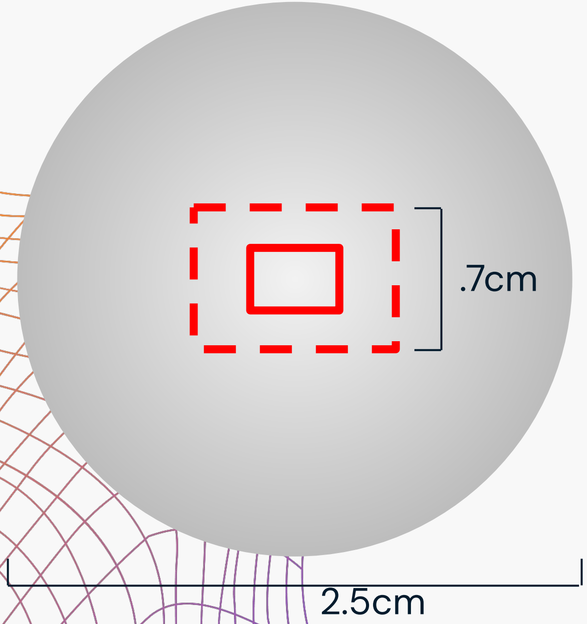


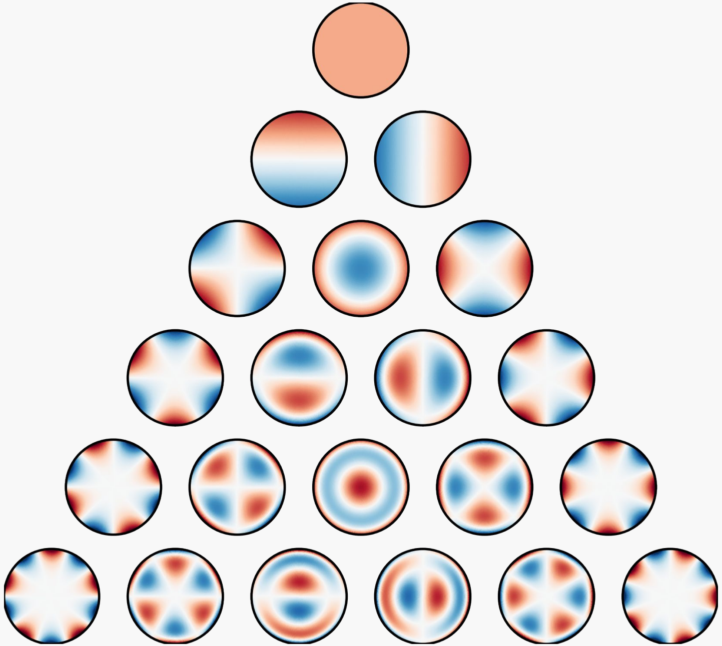
1. We are missing power
2. Hermite Polynomials are not orthogonal

This means that the coupling coefficients calculated will overlap and can't just be scaled up to full power.

The Zernike Approach

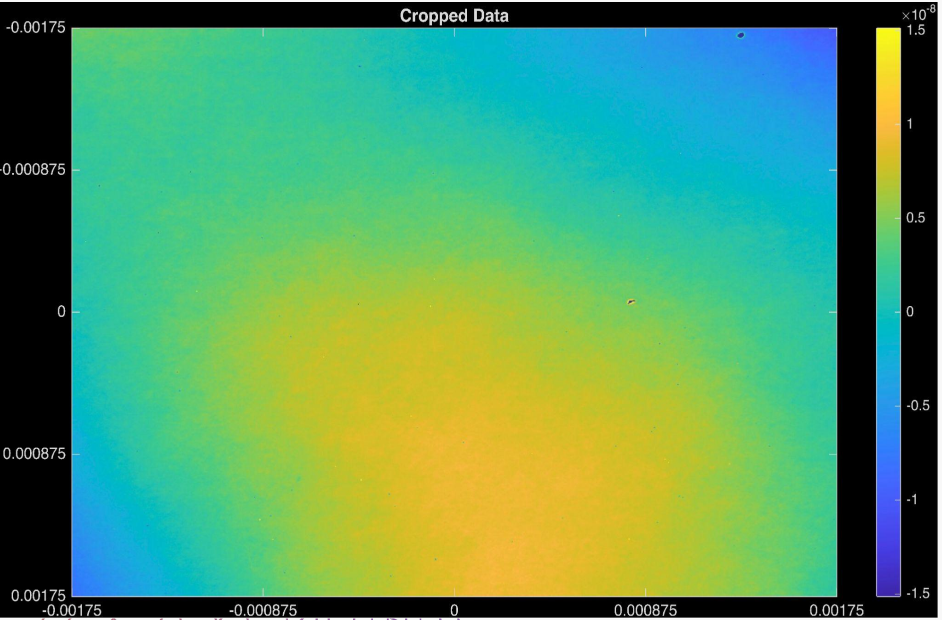
The first approach I took was to approximate more of the mirror area using the Zernike Polynomials. I fit a restricted domain of the Zernike Polynomials to the NanoCam data and then plot those coefficients on the full unit circle.

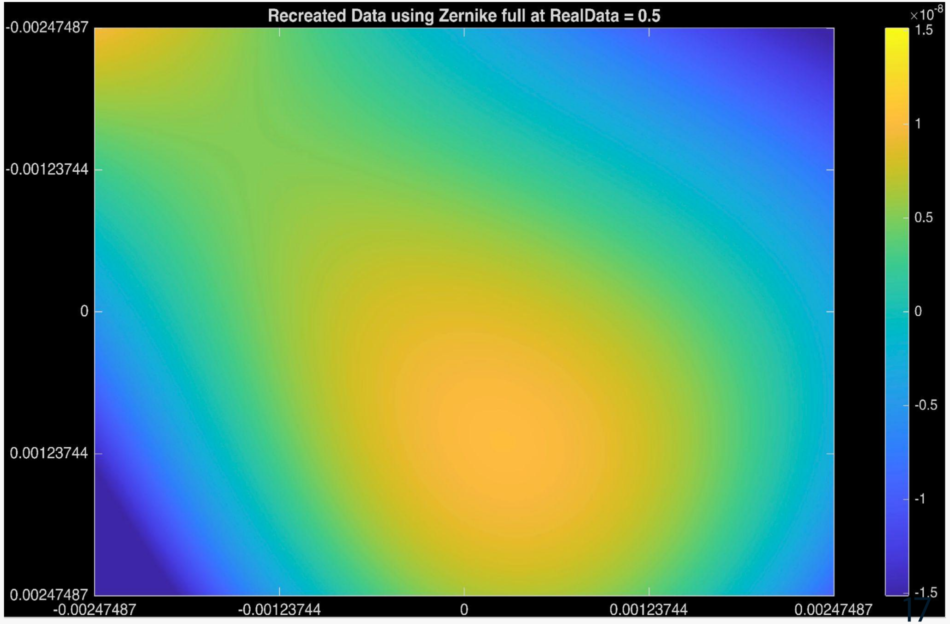




Results from the Zernike Approach

The Zernike polynomials are no longer orthogonal on such small domains. I looked at the difference between the overlapping region of the expanded and raw data to calculate error. The **rms of this difference map was greater than than the rms of the raw data with any expansions greater than 2x**.





The Matrix Approach

The current approach to work around the limited domain of the NanoCam is to **work in two Hermite Gauss bases: HG clipped basis and the HG full basis.**

$$\begin{bmatrix} \mathrm{HG}_{\text{clipped},1} \\ \mathrm{HG}_{\text{clipped},2} \\ \vdots \\ \mathrm{HG}_{\text{clipped},n} \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} & \cdots & m_{1m} \\ m_{21} & m_{22} & \cdots & m_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ m_{n1} & m_{n2} & \cdots & m_{nm} \end{bmatrix} \cdot \begin{bmatrix} \mathrm{HG}_{\text{full},1} \\ \mathrm{HG}_{\text{full},2} \\ \vdots \\ \mathrm{HG}_{\text{full},m} \end{bmatrix}$$

$$M^{-1} HG_{\text{clipped}} = HG_{\text{full}}$$

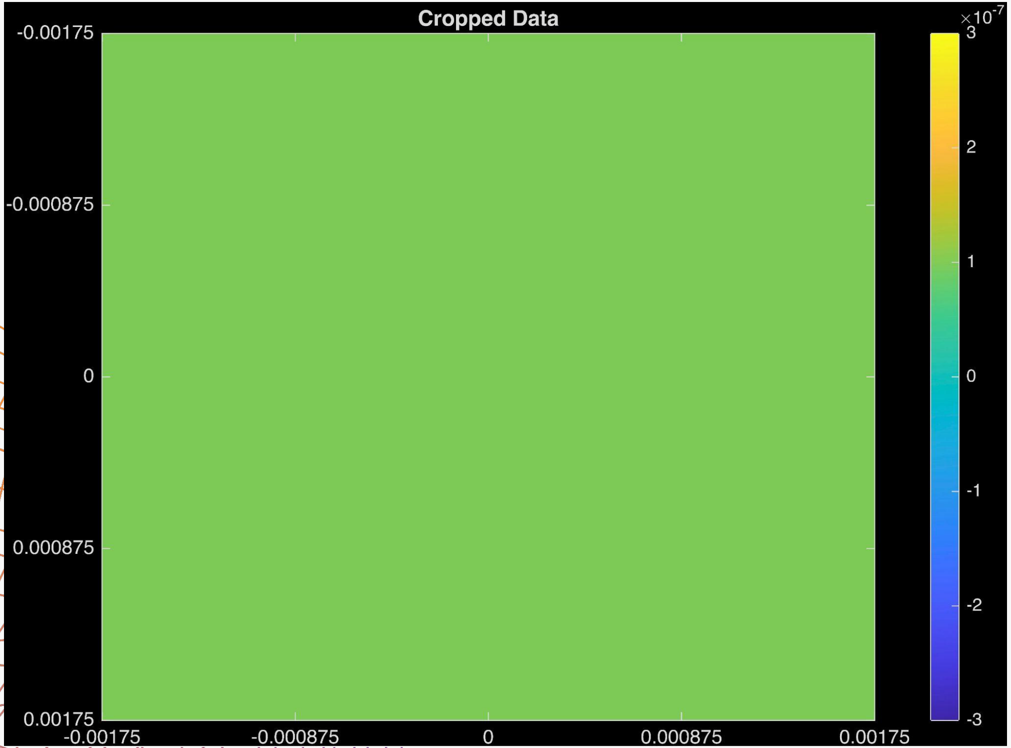
The Matrix Approach cont.

Index	Hermite Gauss Mode
HG_1	HG_{00}
HG_2	HG_{10}
HG_3	HG_{01}
HG_4	HG_{20}
HG_5	HG_{11}
HG_6	HG_{02}
HG_7	HG_{30}
HG_8	HG_{21}
HG_9	HG_{12}
HG_{10}	HG_{03}

$$m_{ij} = \int\int u_i^*(x,y)u_j(x,y)dxdy$$

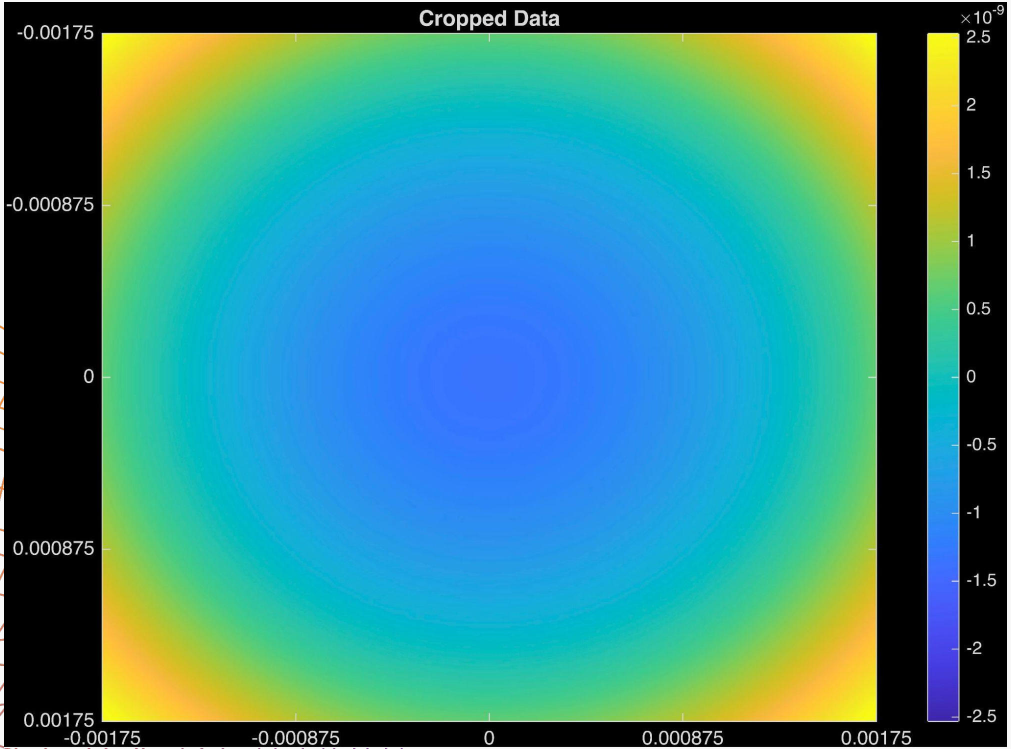
$$\begin{bmatrix} m_{11} & m_{12} & \cdots & m_{1m} \\ m_{21} & m_{22} & \cdots & m_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ m_{n1} & m_{n2} & \cdots & m_{nm} \end{bmatrix}$$

Results from the Matrix Method



n	m	Coupling Coefficient
0	0	1.
1	0	0.
0	1	0.
2	0	0.
1	1	0.
0	2	0.

Results from the Matrix Method



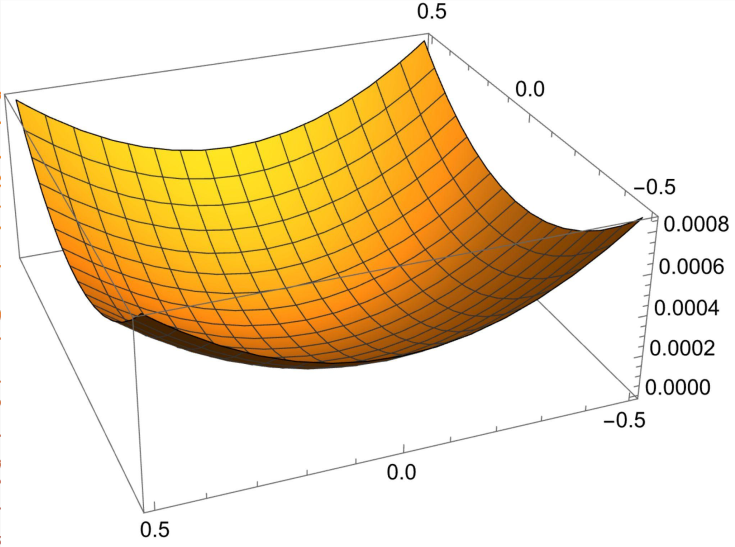
n	m	Coupling Coefficient
0	0	.9997
1	0	0.
0	1	0.
2	0	0.0002
1	1	0.
0	2	0.0002

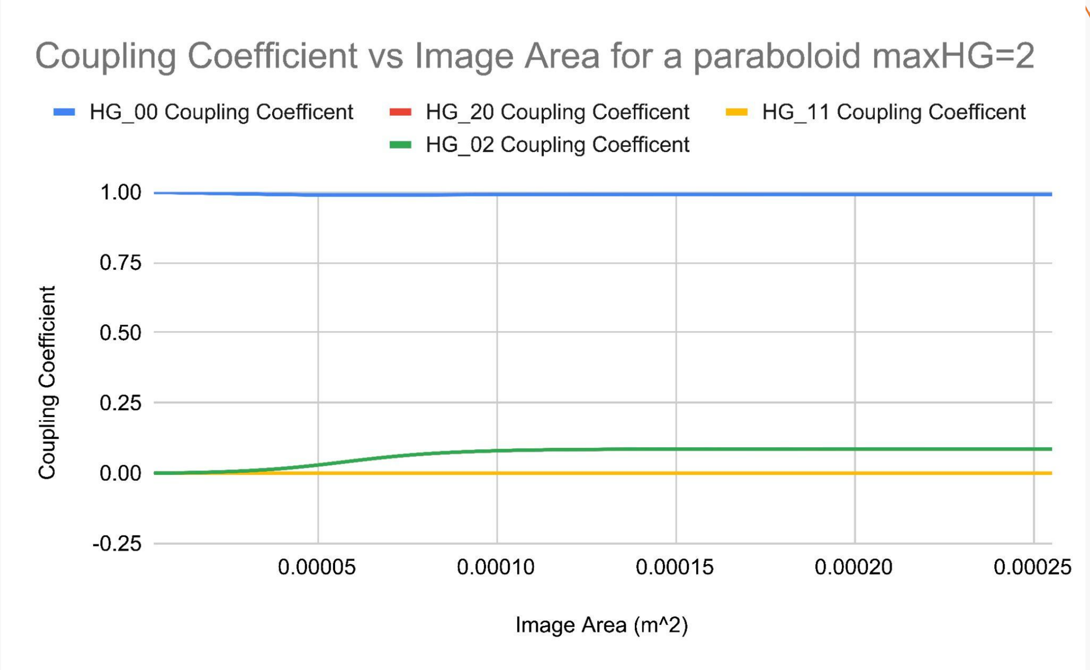
Analytically we **should be getting .02**

Results from the Matrix Method

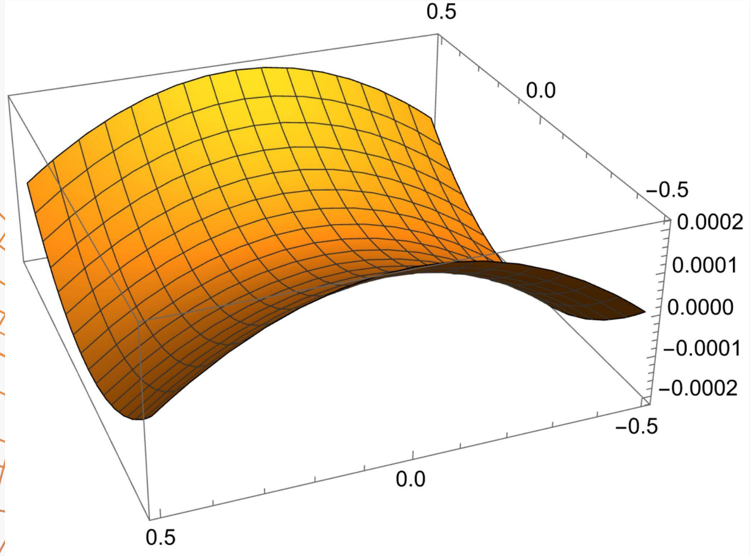
Approximated the Omode with a paraboloid and ran simulations on the **accuracy of the Matrix Method in relation to imaging area.**

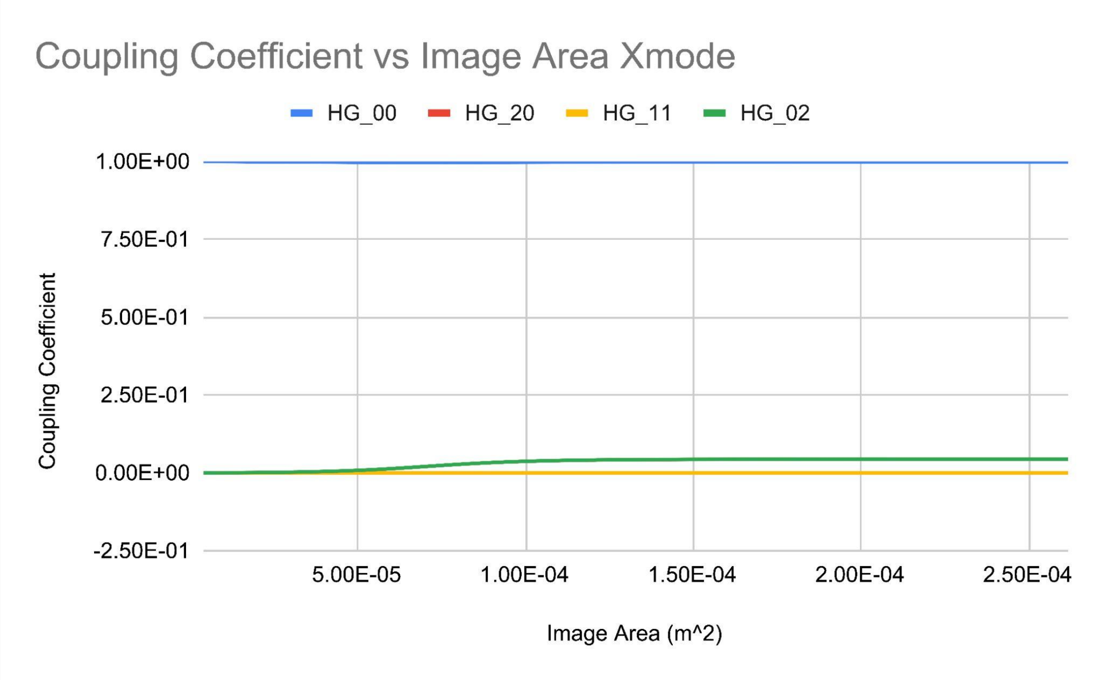
maxHG refers to the maximum value of m,n in the conversion matrix.



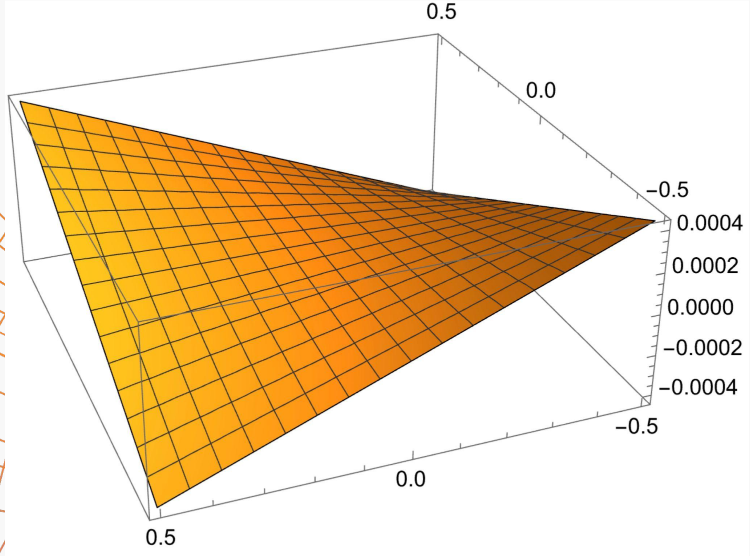


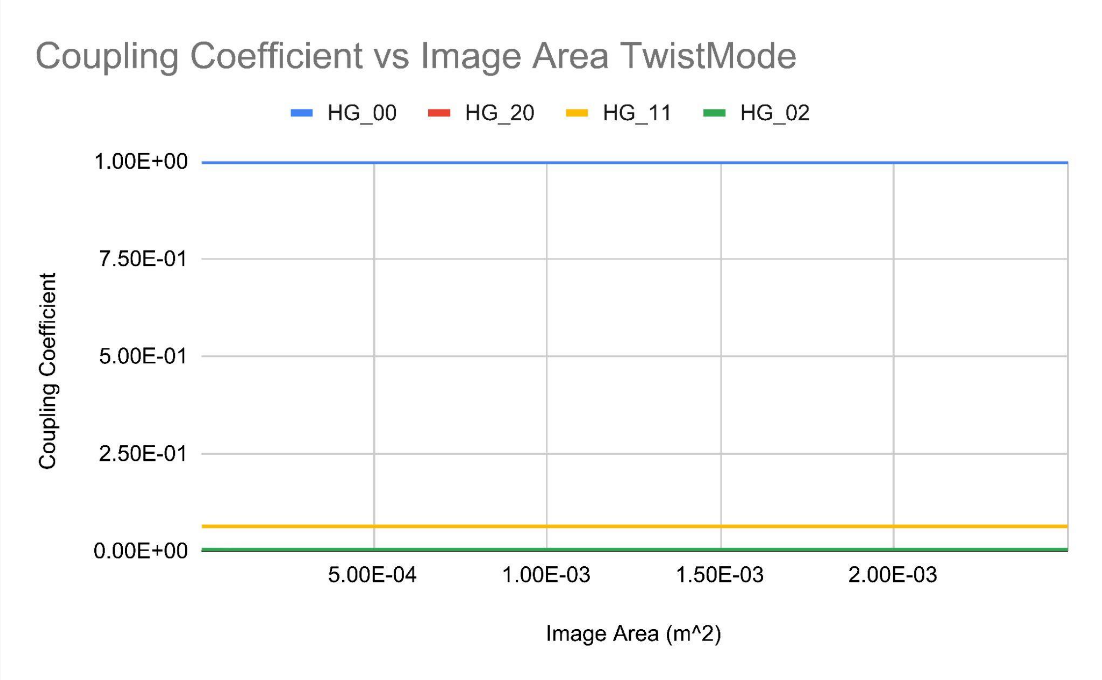
Results from the Matrix Method



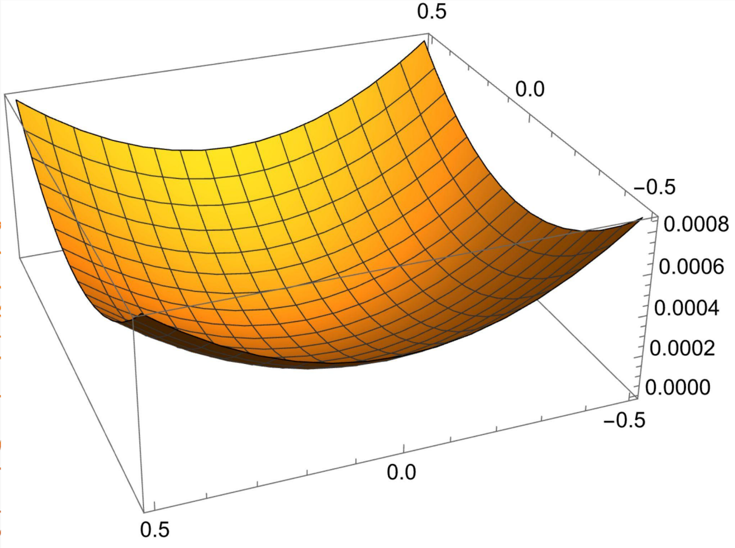


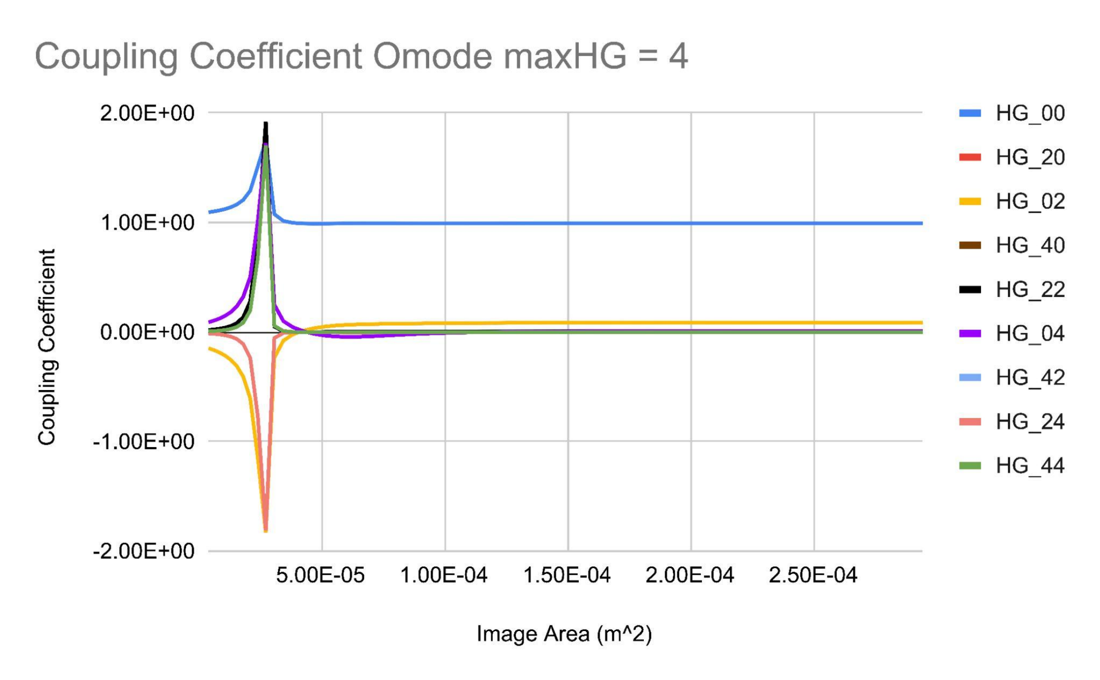
Results from the Matrix Method



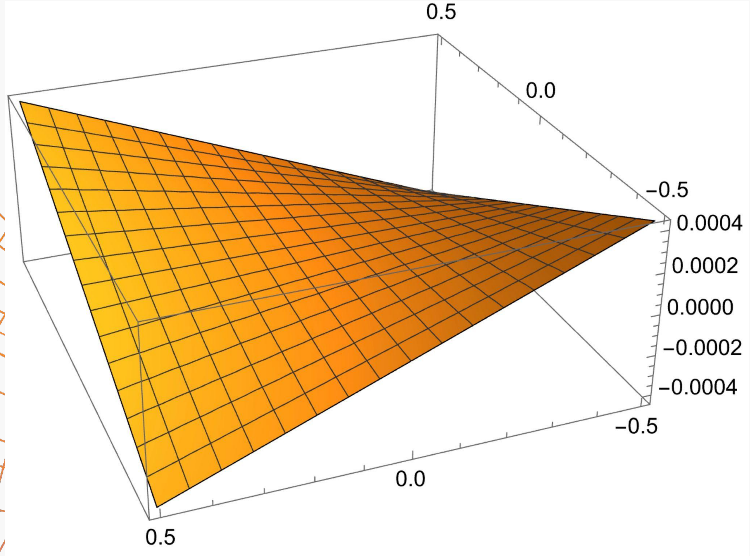


Spiking With Increased Mode Depth

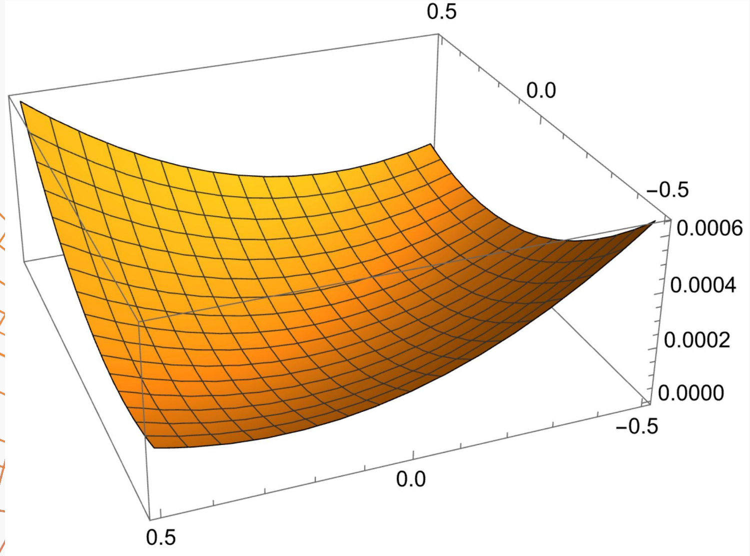


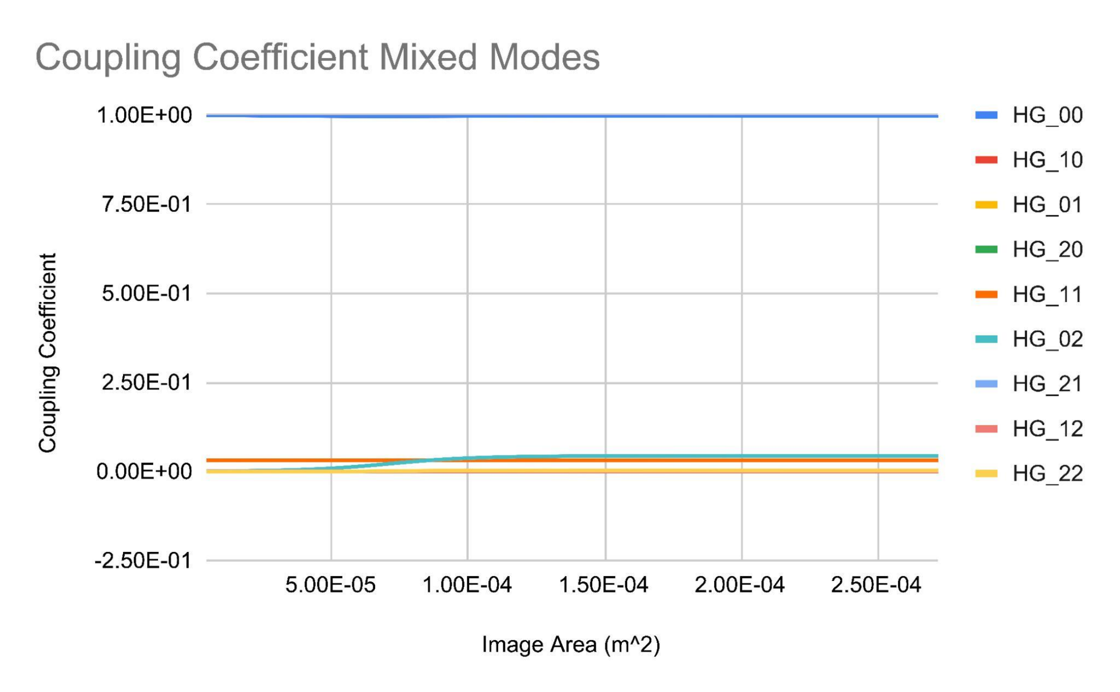


Spiking With Increased Mode Depth



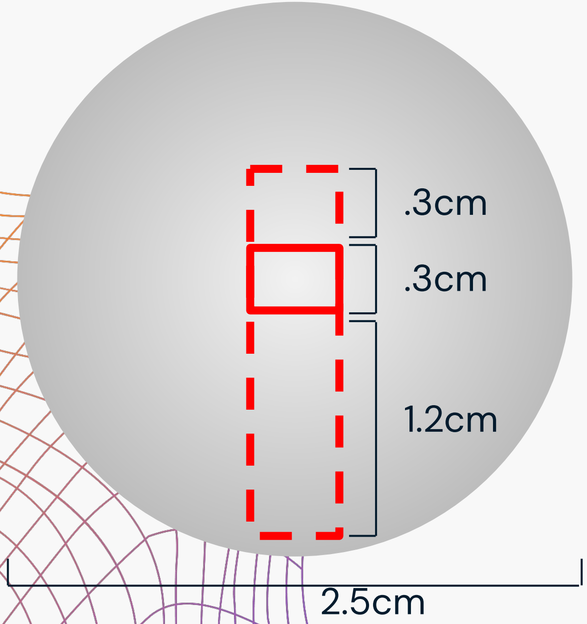
Having Mixed Modes (maxHG = 2)

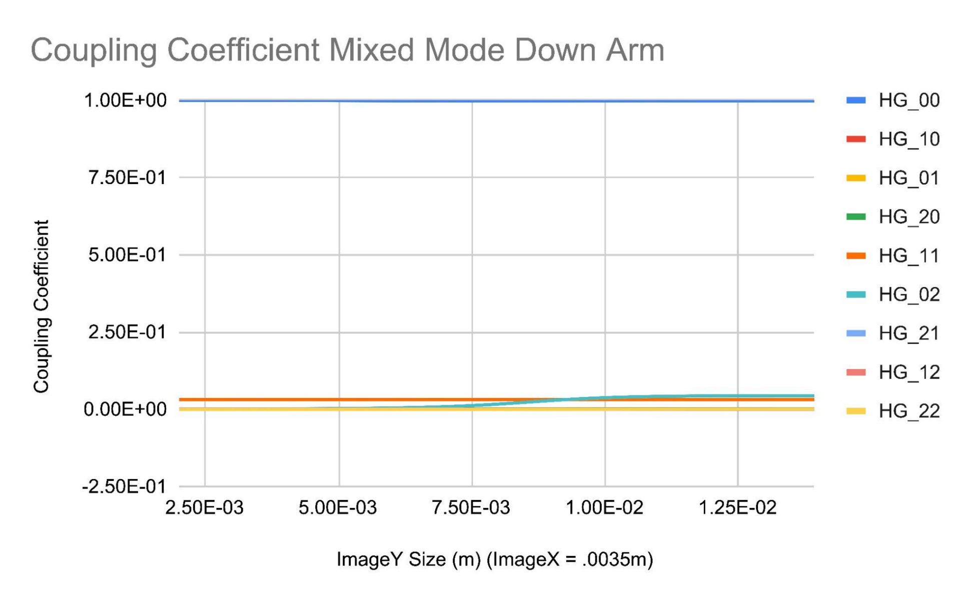




What can we do?

We have the ability to space to move the NanoCam in the **+y direction 3mm and no boundary in the -y direction**. This could be a way to increase our image area.





Accurate at 1cm in 02 mode, can make a symmetry argument for 20 mode.

Questions?

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