Characterization of Dielectric Mirrors

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Introduction:

Now that Gravitational Waves (GW) have been detected, the effort is towards reducing the noise that limits the sensitivity of GW from deeper in the Universe.

The performance of the mirrors used in GW detectors is limited by thermal noise and light scattering, a result of the manufacturing process. A large number of scatterers were detected in mirror coatings at Cal State LA [ref]. They may be the locus of both scattering and thermal noise.

We attempt to map the distribution of these scatterers within the layers of coating witness samples, both depth-wise and laterally using microscopy and fitting procedures.

If successful, we will be able to provide a tool to guide the development of better performance mirrors and thus extend the detection range of GW detector, contributing to a better understanding of the Universe.

Feasibility Study:

The aim is to identify the size and location of scatterers within the thickness of coatings. We show that the position and depth of sub-wavelength features within a coating can be determined with a few nm precision.

If successful, this may become a standard inspection technique to monitor and guide the development of lower scattering and thermal noise, leading to detection of gravitational waves deeper in the Universe.

Methodology:

1. Using a CCD microscope camera and a stepper motor we scan the focal plane through the position of a scatterer. Images are captured at half micron steps. The scatterers show up as Airy functions, narrowest when the feature crosses the focal plane. The Airy distribution is fit with a Gaussian. A scatterer's depth is determined by fitting the point of smaller size.
2. With a resolution of 50 nm we can determine the host layer of each scatterer.

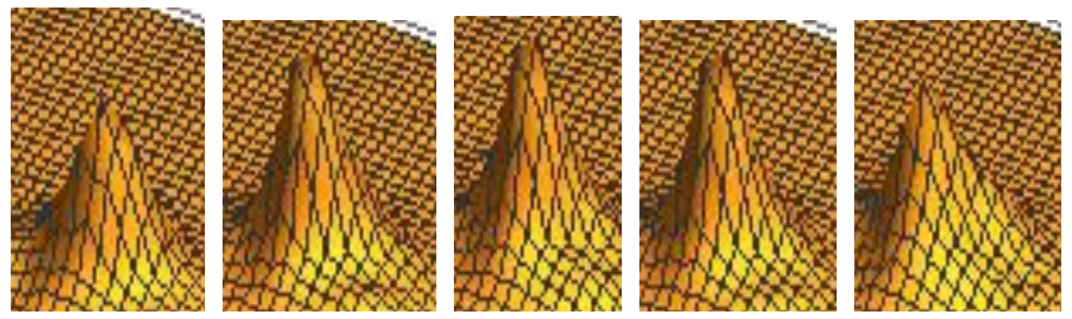
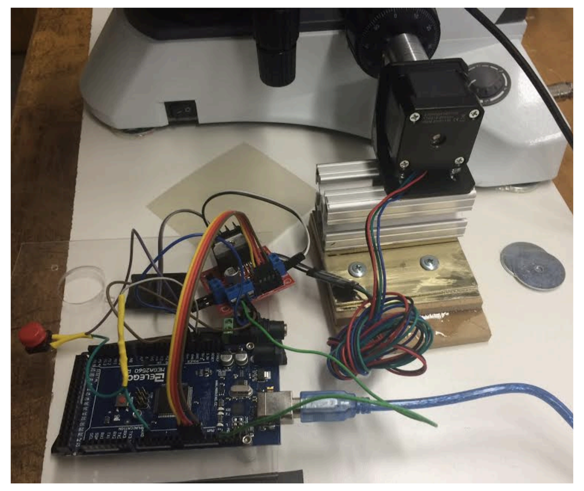


Figure 1: *Scatterer as the focal plane is scanned through.*

Depth Measurement:

Dark Field Test

We built an Arduino-controlled stepper motor drive for the microscope focus, capable of 0.5 µm steps.



We took a sequence of photos at 0.5 µm steps. From each photo we extracted pixel index and brightness values. Each scatterer is identified and a Region Of Interest defined. ROI data is fit with a simple Gaussian ignoring the Airy rings and extracting only amplitude using KaleidaGraph.

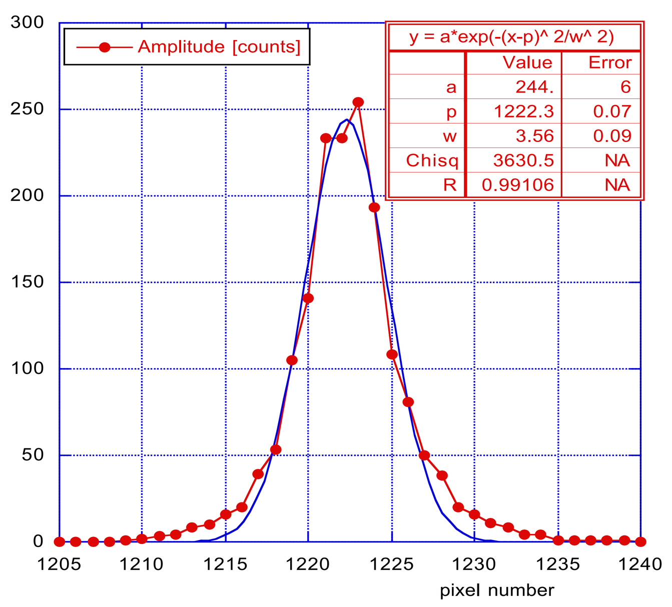


Figure 2: *Fit to the Airy function of one of the images of a scatterer. The fit ignores the outer rings of the Airy function, visible here as small shoulders. (These image is close to focus)*

We used the Gaussian amplitude vs. depth to find the best focus. We demonstrated ~ 70 nm depth resolution with actual scatterers using the microscope with 20x magnification and dark field.

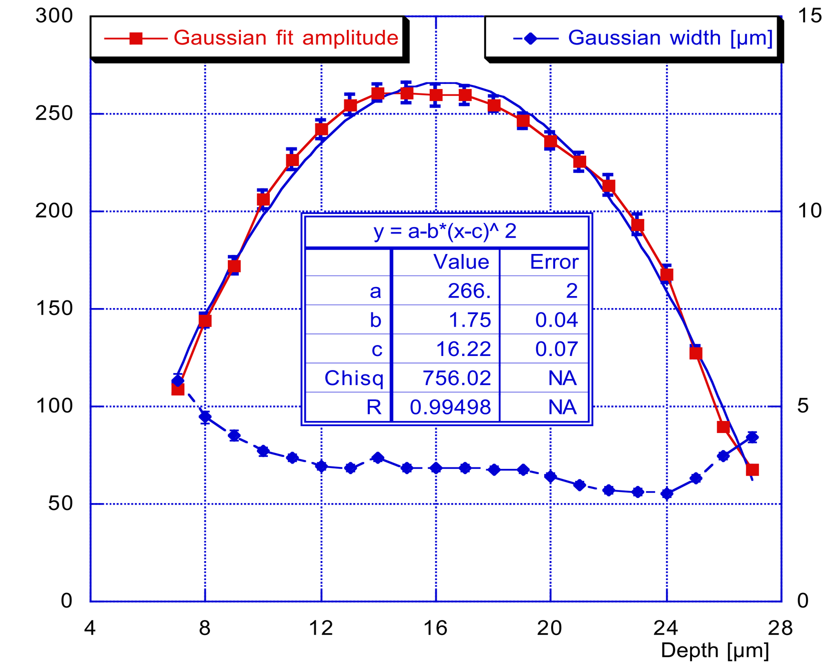
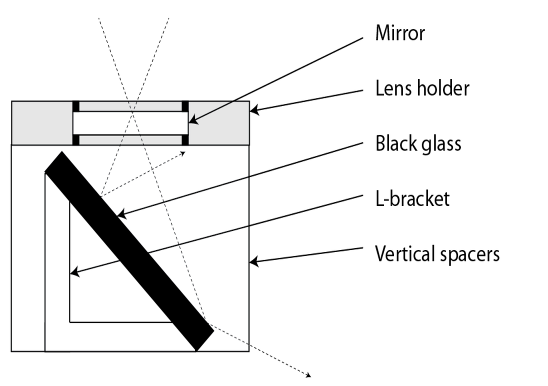


Figure 3: *Amplitude of Gaussian fits as function of image number/depth. The depth error is 70 nm. The blue dots show how the width of the center section of Airy function does not change.*

Bright Field Test

We repeated the experiment with bright field.

A light catcher was built to minimize bright field baseline, the baseline is still hi ~140/256 but flat bright field signal subtracted mean field 144.



We used magnification 50x, which yields a shorter focal depth. Fits on slices gave resolution of 50-70 nm.

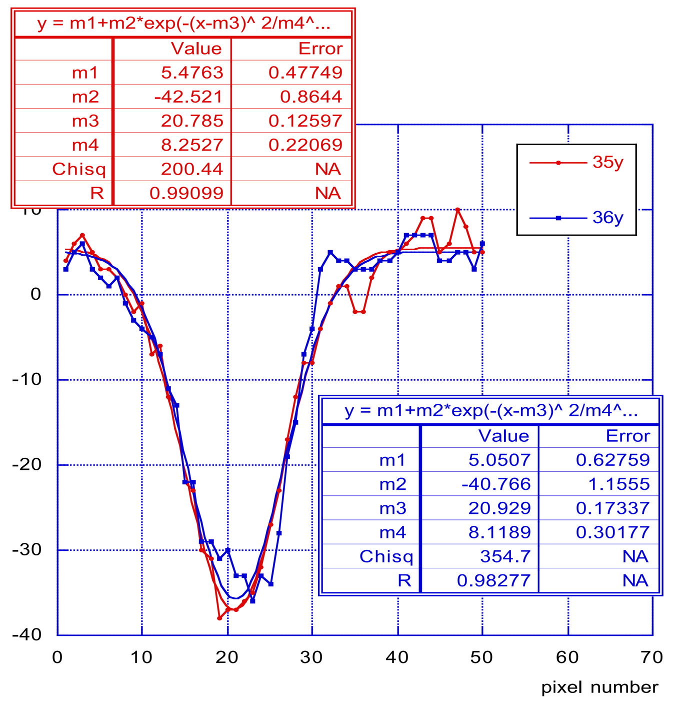


Figure 4: *Gaussian fit to the Airy function of bright field image of a scatterer. The bright background of average 144 count has been subtracted.*

Disagreement between x-slices and y-slices of same scatterer is up to 150 nm. For now we quote a precision of 50 to 100 nm. This problem should disappear with 2D fits that take into account all slices in fit.

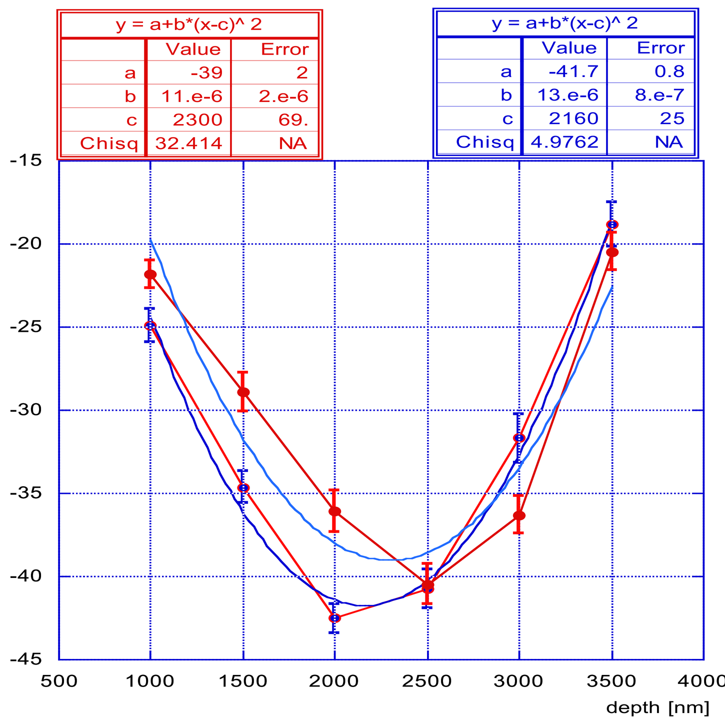


Figure 5: *Scatterer depth calculated with x and y slices of the Airy distribution.*

Results

The worse resolution obtained is ~ 100nm, the best ~ 30 nm. A 30 nm depth resolution appears feasible.

Due to refraction, inside the coating the effective step depth is reduced by 1/n (n=1.46 for silica, n= 2.13 for Tantala, 2.45 for titania). The resolution measured should be reduced by the same 1/n value as the actual ¼ wavelength layer thickness.

Therefore the resolution values obtained can be directly compared with the ¼ wavelength layers (251 nm deep when observed from outside).

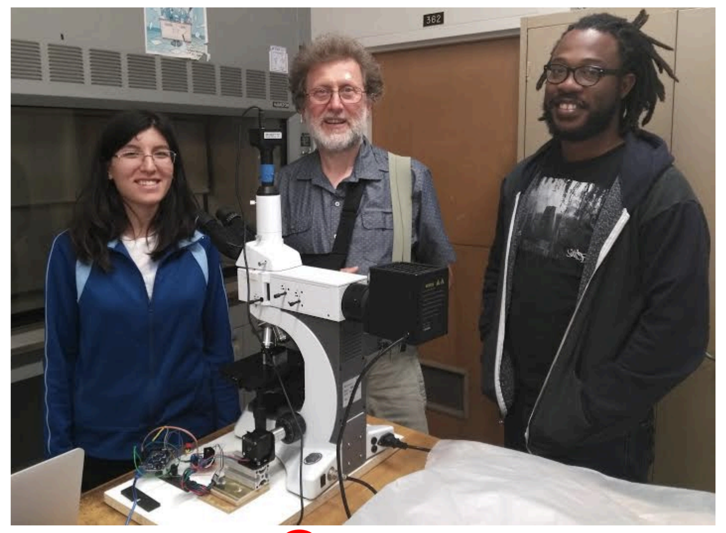
The achieved resolution allows clear identification of the host layer, and even if the scatterers are uniformly distributed or concentrated towards one surface or the other.

To do:

Fully automatize X-Y-Z scanning with three stepper motors, image acquisition, image processing to extract depth, to fully map sample mirrors and produce a powerful diagnostic tool for coating facility test samples.

Conclusions and Next Steps:

The method is designed to be used on coating prototype samples, for fast characterization of new coatings manufactured with new processes, and thus drive the development towards lower thermal noise mirrors, better sensitivity for GW, and detection of Black hole inspiral events much deeper in the Universe. If successful, our knowledge of the Universe will be greatly expanded.



Contacts:

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Glover, Lamar, Eddy Arriaga, Erik Barragan, Riccardo DeSalvo, Eric Do, Cameron Fajardo, Michael Goff, Jignesh Patel, Innocenzo Pinto, Travis Sadecki, Richard Savage, EthanVillarama, "Observation of a Large Population of Optical Scatterers in the Advanced LIGO mirrors", LIGO-P1600325, (2016) submitted for publication in the Journal of Optical Society of America. For a pre-print copy, please contact lglover3@calstatela.edu.