

STUDY OF OPTICAL SCATTERERS IN COATING LAYERS OF
GRAVITATIONAL WAVE DETECTOR
TEST-MASS MIRRORS

A Thesis

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Master of Science
in
Physics

By

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ABSTRACT

Study of optical scatterers in coating layers of gravitational wave detector test-mass mirrors

By

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Similar in appearance to images of star clusters, photographs of the LIGO Gravitational Wave detector mirrors illuminated by the standing beam were analyzed with DAOPHOT, an astronomical software tool designed to identify stars within images and extract information about the structure of light point sources. DAOPHOT found hundreds of thousands of weaker, point-like scatterers, uniformly distributed across the mirror surface, ignoring the smear of actual dirt on the mirror. The amplitude distribution of the observed scatterers implies that they extend through the depth of the coating while their sheer number implies a fundamental, thermodynamic origin. Theoretical material science considerations indicate that these scatterers are a likely source of the mirror dissipation and thermal noise, perhaps pointing the way towards a mitigation strategy, improved sensitivity of Gravitational Wave observatories and increased Gravitational Wave detection radius into the Universe.

ACKNOWLEDGMENTS

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CHAPTER 1

What is the LIGO-Virgo Collaboration?

The LIGO-Virgo Collaboratio (LVC) presently comprises three main gravitational wave detectors, Virgo in Italy and the two LIGO detectors in the USA. The candidate is an active member of the collaboration and author of the collaboration publicationsⁱ, as well as of two topical papers that he and his direct collaborators produced, which is currently under review^{ii,iii}.

Founded in 1960s and first breaking ground in 1994, the Laser Interferometer Gravitational Wave Observatory (LIGO) is the first facility to successfully detect and measure gravitational waves from cosmic origin (Table 1 and Figure 1). This achievement, which first took place in September 2015, validates a general relativity theory presented by Albert Einstein nearly a century prior^{iv}. LIGO consists of two widely separated installations within the United States, one in Hanford Washington and the other in Livingston, Louisiana, operated in unison as a single observatory. Virgo, the third site of the LVC, is located near Pisa. The primary interferometer of LIGO consists of a

ⁱ David Tanner and Gianluca Gemme, “February 2017 LSC and February 2017 Virgo author list,” *LIGO Scientific Collaborative Database* LIGO-M1700033-v7 (2017).

ⁱⁱ Lamar Glover et al., “Observation of a Large Population of Optical Scatterers in the Advanced LIGO Mirrors,” *LIGO Scientific Collaborative Database* LIGO-P1600325-v4 (2017).

ⁱⁱⁱ Lamar Glover et al., “Optical scattering measurements and implications on thermal noise in Gravitational Wave Detectors Test-Mass Coatings,” *LIGO Scientific Collaborative Database* LIGO-P1600345-v2 (2017).

^{iv} Albert Einstein, “On Gravitational Waves,” *Königlich Preußische Akademie der Wissenschaften (Berlin). Sitzungsberichte* (1918): 154.

Michelson Interferometer and two arms, which are 4 km in length along with a 1064 nm laser light source that reaches 100 kW in the light cavities. Virgo is similar, but has arms that are 3 km long, and still in its commissioning phase. Since its first detection, there have been at least 3 additional detection events, all of which have detected binary black hole inspirals.^v

Primary black hole mass	$36^{+5}_{-4} M_{\odot}$
Secondary black hole mass	$29^{+4}_{-4} M_{\odot}$
Final black hole mass	$62^{+4}_{-4} M_{\odot}$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	$410^{+160}_{-180} \text{ Mpc}$
Source redshift z	$0.09^{+0.03}_{-0.04}$

Table 1: *Source parameters for GW150914, the historic first gravitational wave detection which consisted of a binary black hole inspiral merger. Data consists of median values with 90% credible intervals that include statistical errors, and systematic errors from averaging the results of different waveform models. Masses are given in the source frame; to convert to the detector frame multiply by $(1+z)$. The source redshift assumes standard cosmology.*^{vi}

^v The LIGO Scientific Collaboration and the Virgo Collaboration, “GW170104: Observation of a 50-solar mass binary black hole coalescence at redshift 0.2,” *LIGO Scientific Collaborative Database* LIGO-P170104-v5 (2017).

^{vi} The LIGO Scientific Collaboration and the Virgo Collaboration, “Observation of Gravitational Waves from a Binary Black Hole Merger,” *Physical Review Letters* 116 (2016): 061102-7.

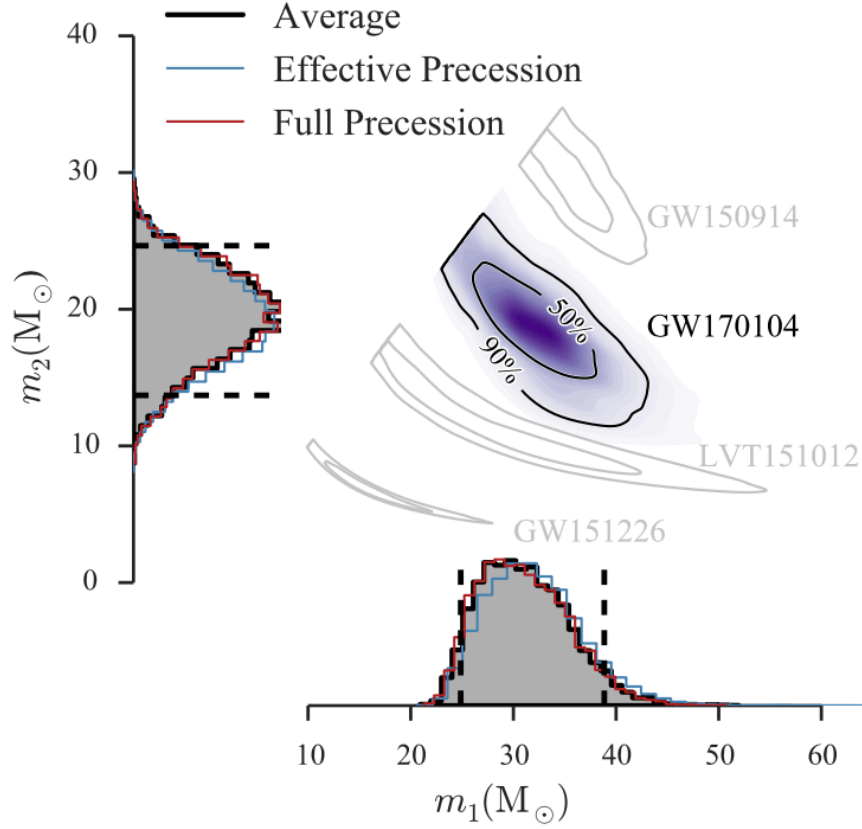


Figure 1: Synopsis of the 4 detected events: the image focuses on the posterior probability density for the source-frame masses m_1 and m_2 (with $m_1 \geq m_2$) related to the most recently detected gravitational wave event on January 4, 2017. The 1-dimensional distributions include the posteriors for the two waveform models and their average (black). The dashed lines mark the 90% credible interval for the average posterior. The 2-dimensional plot shows the contours of the 50% and 90% credible regions plotted over a color-coded posterior density function. For comparison, we also show the 2-dimensional contours for previously detected gravitational wave events, all of which have been binary black hole mergers (For 2-D plot: inner contour = 50% credible region, outer contour = 90% credible region.)^v

While the fundamental structures of the interferometer are congruent with those employed in science since the 19th Century, LIGO has incorporated vastly improved technologies for each of the various components of the device and is currently the most precise tool ever known to mankind. The dramatic increase of precision of many orders of magnitudes achieved has given LIGO the current precision at the 10^{-18} m level, sufficient for detecting gravitational waves.

CHAPTER 2

What is the Problem that we try to address at Cal State LA?

As precision increases, various noises become more prominent in the detected signal of the device. Identifying and eliminating noise sources become vital. At the level of 10^{-18} m, the surfaces of the test mass mirrors move under the effects of thermal excitation, exhibiting what is called mirror thermal noise. Mitigating thermal noise at this level is the next step for detecting weaker gravitational wave signals from farther away in the Universe.

In addition to mirror thermal noise, the scattering of the LIGO stored beam light from the mirror surface also contributes to the noise budget. Light power decreases and the quantum squeezing of the stored beam is affected by the scattering.^{vii} Scattering is attributed to irregularities in the refractive index of the coating layers, caused by either voids or denser crystallites within the coating layers. A reduction of the current levels of scattered light would also increase the current sensitivity of LIGO, by allowing stronger squeezed light in Enhanced LIGO (the 3rd and next stage of improved operations for the LIGO project).^{vii}

^{vii} John Miller et al., “Prospects for doubling the range of Advanced LIGO,” *Physical Review D* 91 (2015): 062005-2.

CHAPTER 3

Thermal noise comes from mechanical losses, sources of which are a mystery

It is known that mechanical losses in the materials composing the coating layers generate thermal noise. Yet, the source of mechanical losses has not been concretely identified. It is possible that the source for the mechanical losses is located on the newly detected subwavelength irregularities within the coating layers. These irregularities, smaller in size than the light wavelength of the LIGO stored beam, 1064 nm,^{vi} can be attributed to either crystallites or nanovoids.

Crystallites, the locus from which crystals start and then grow in size, continuously form during the deposition of the glassy coating layers. The crystallite, although made of the same material, is closely packed and has a slightly different refractive index that causes some diffraction. It is important to note that while the volume of the crystallite is more ordered than that of the surrounding liquid glassy matrix, the surface that lies between the crystallite and glass matrix is much more disordered than the glass itself. This is due to the many strained and frustrated bonds between the two different phases of material. There is an energy gain associated with the optimal atomic bonds within the volume of the crystallite and an energy loss associated with frustrated bonds on the surface of the crystallite. The sum of the two energies indicates whether or not it is energetic beneficial for the crystallite to increase in size. The balance between energetic gains and losses defines a critical radius, above which the crystallite will tend to grow.

An idea that we propose to mitigate both the thermal noise and the scattered light problems is that by creating coating sub-layers that are thinner than the critical radius (r^*

from Figure 1 and Table 2), crystallite formation can be decreased and possibly eliminated. Yet, first, the scatterers in present mirrors should be characterized.

Nanovoids are another potential source of thermal noise within the test mass coating layers. These voids that are smaller in size than the wavelength form as a by-product of the coating layer deposition process. Voids trap gas such as argon used in the deposition process. The surface between the void and the surrounding glassy matrix, just like between the crystallite and the glassy matrix, is a likely locus of losses. Previous studies have shown that the surface of fused silica has a much lower Q factor than its interior, which can be attributed to strained and frustrated bonds producing the surface tension of the material.^{viii} Therefore, gas voids would also have significantly higher losses than the surrounding glass matrix. These higher losses produce thermal noise in a similar fashion as the crystallites. With adjustments to the deposition and annealing process, void formation could potentially be decreased.

Both crystallites and voids may serve as sources of thermal noise and quantum noise, both directly by wasting light in scattering and indirectly by degrading the squeezing of injected light. Unfortunately, crystallites and voids would equally produce the scattering we observe and are indistinguishable in our study.

A very important aim of our study is to provide feedback to the coating manufacturers to find ways to stop the formation of crystallites or voids within coating layers. Successfully identifying the scatterers within the coating layers is a crucial step in this process.

^{viii} Steven D. Penn et al., “High quality factor measured in fused silica,” *Review of Scientific Instruments* 72 (2001): 3671.

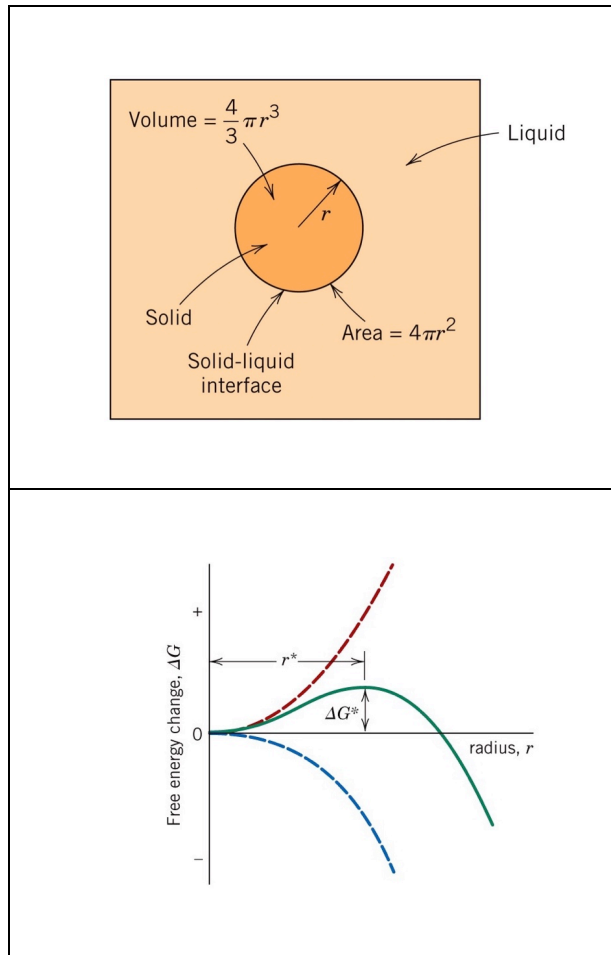


Figure 2: (TOP) Representation of Crystallite surrounded by glassy matrix.

(BOTTOM) The energy gain/loss of the system is determined by the relationship of the surface area energy (red dashed line) and the volume energy (blue dashed line) of the material in crystalline form. Once the radius of the crystallite becomes larger than the critical length (r^*), it becomes increasingly energetically beneficial for the crystallite to grow^{ix}.

^{ix} William D. Callister, Jr. and David G. Rethwisch, *Fundamentals of Materials Science and Engineering: An Integrated Approach* (4th Edition) Hoboken: Wiley Press, 2012.

$\Delta G_s = -4\pi r^2 \Delta G_s$	$\Delta G_v = \frac{4}{3}\pi r^3 \Delta G_v$
$\Delta G = \frac{4}{3}\pi r^3 \Delta G_v + 4\pi r^2 \Delta G_s$	

Table 2: (TOP LEFT) Energy loss associated with the crystallite surface area, (TOP RIGHT) Energy gain associated with the crystallite volume, (BOTTOM) Summation of Energy Gain and Loss^{ix}

$\Delta G^* = \frac{16\pi(\Delta G_s)^3 T_m^2}{3\Delta H_f^2 (T_m - T)^2}$	$r^* = \frac{-2\Delta G_s T_m}{\Delta H_f (T_m - T)}$
--	---

Table 3: Equations for net energy (LEFT) and critical radius (RIGHT) where it becomes energetically beneficial for the crystallite to increase in size^{ix}.

CHAPTER 4

Implications of solving problem

The implications of identifying and subsequently reducing or eliminating light scatterers within the coating layers are significant. The detection sensitivity of LIGO continues to improve as “technical” (not fundamental) sources of noise are further decreased or eliminated, thereby increasing the LIGO detection radius. The source of some of the technical noise is scattered light. Soon, as LIGO continues to implement technical noise reductions at the observatories, the limit will become the mirror thermal noise.

Perhaps more importantly, if it can be proven that the scatterers are also the source of dissipation, their reduction or elimination would reduce the mirror thermal noise.

The reduction or potential elimination of light scatterers, will result in an increase in strain sensitivity and higher detection rate than the current strain sensitivity of LIGO.^{vii} As explained by D.V. Martynov et al in the paper “The Sensitivity of the Advanced LIGO Detectors at the Beginning of Gravitational Wave Astronomy”:

“In general relativity, a gravitational wave far away from the source can be approximated as a linear disturbance of the Minkowski metric, $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ with the space- time deformation expressed as a dimensionless strain, $h_{\mu\nu}$. In a Michelson interferometer, we define the differential displacement as $L = L_{\parallel} - L_{\perp}$, where $L_{\parallel}$ and $L_{\perp}$ are the lengths of the inline arm and the perpendicular arm, respectively, as shown in Fig. 1. With equal macroscopic arm lengths, $L_0 \simeq L_{\parallel} \simeq L_{\perp}$, the gravitational wave strain and the differential arm length are related

through the simple equation $L(f) = L_{\parallel} - L_{\perp} = h(f)L_0$, where h is the average differential strain induced into both arms at frequency f .^x

By solving the problem of light scatterers within the test mass coating layers, the strain sensitivity of LIGO and, consequentially, its detection range could increase significantly.

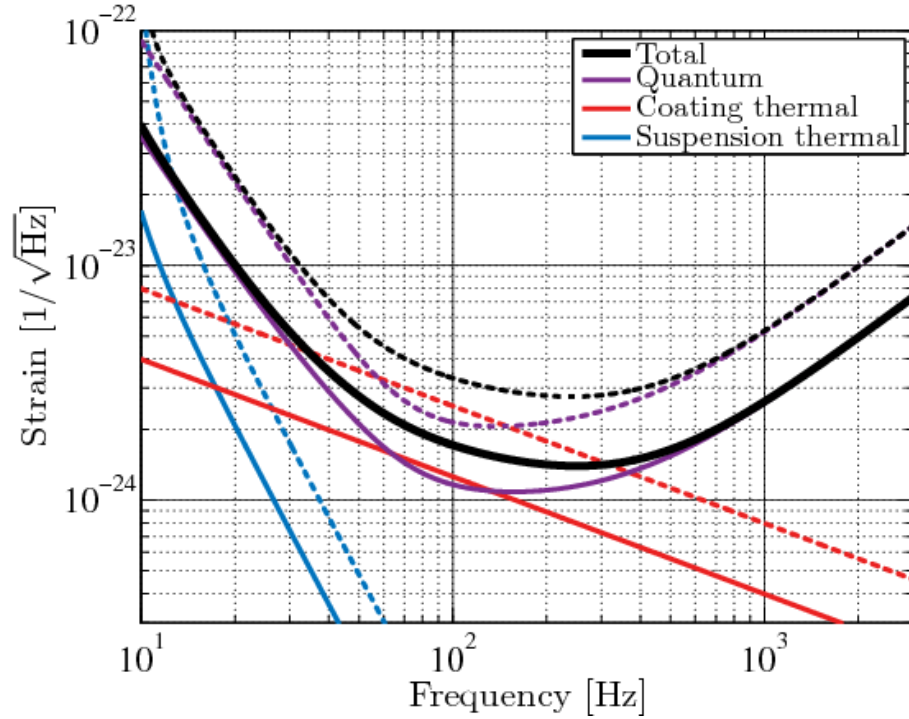


Figure 3: Strain sensitivity of a possible upgraded Advanced LIGO interferometer. The equivalent Advanced LIGO curves are shown using dashed lines.^x

^x D.V. Martynov et al. “The Sensitivity of the Advanced LIGO Detectors at the Beginning of Gravitational Wave Astronomy,” *Physical Review D* 93 (2016): 112004-4.

CHAPTER 5

Introduction

The mirror test masses of the LIGO Gravitational Wave detector^{xi,xii} have been specifically designed and constructed with multilayered interference coatings^{xiii} deposited via ion-beam deposition to minimize optical absorption, mirror thermal noise^{xiv,xv} and light scattering^{xvi}. As such, an ideal mirror would appear black when viewed off axis from a collimated source of illumination. However, photographs of an Advanced LIGO End Test Mass illuminated by the 100 kW interferometer stored beam taken at a 9.8° angle from the stored beam axis (Figure 4) show a large number of light scattering points, which were initially interpreted as dirt. This investigation identified, in addition to dirt, hundreds of thousands of diffraction-limited, weak light scatterers, many per mm^2 . The unexpectedly large number, and uniform dispersal of these scatterers is not compatible

^{xi} The LIGO Scientific Collaboration, "Advanced LIGO," *Classical and Quantum Gravity* 32, no. 7 (2015): 074001-14.

^{xii} The LIGO Scientific Collaboration and the Virgo Collaboration, "GW151226: Observation of gravitational waves from a 22-solar-mass binary black hole coalescence," *Physical Review Letters* 116.24 (2016): 241103.

^{xiii} Gregory Harry, Timothy P. Bodiya, and Riccardo DeSalvo, eds., *Optical coatings and thermal noise in precision measurement*. Cambridge: Cambridge University Press, 2012.

^{xiv} Akira E. Villar et al., "Measurement of thermal noise in multilayer coatings with optimized layer thickness," *Physical Review D* 81, no. 12 (2010): 122001.

^{xv} M. Principe, "Reflective Coating Optimization for Interferometric Detectors of Gravitational Waves," *Optics Express*. 23.9 (2015): 10940.

^{xvi} Gregory M. Harry and LIGO Scientific Collaboration. "Advanced LIGO: the next generation of gravitational wave detectors," *Classical and Quantum Gravity* 27, no. 8 (2010): 084006.

with dirt. Their brightness distribution suggests that they may be uniformly distributed in depth within the approximately 3 μm thickness of the coating layers.

Since the overall absorption, measured by the mirror heating, is less than $\frac{1}{4}$ ppm, the relatively larger scattering must be a result of minuscule fluctuations in the index of refraction that do not absorb energy. These density fluctuations are due to either denser proto-crystal formations or small, localized density deficits (atomic scale void clusters).

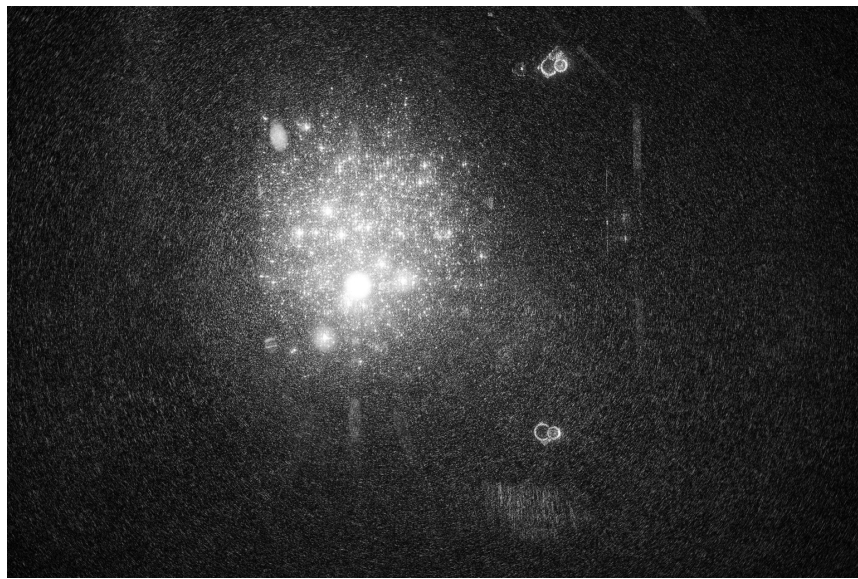


Figure 4: November 2015 Photograph of an End Test Mass at LIGO Hanford with an exposure time of 1.3 seconds. Crowding in the image is solely due to the finite size and nature of the Airy disks^{xvii}. The actual scatterers are expected to be of sub-micron size and widely separated within the actual coating layers of the End Test Mass. (Note: The rings and faint straight lines that appear in the background on the right side of the image are components of the mirror support structure).

^{xvii} G. B Airy, "On the Diffraction of an Object-glass with Circular Aperture," *Transactions of the Cambridge Philosophical Society* 5 (1835): 285

The uniform distribution, and the large number, imply that the scatterer generation happens during the deposition process itself and is likely of a thermodynamic nature. While these defects were observed in ion beam deposited glasses, it is important to note that molten glasses, such as the fused silica mirror substrate of the mirrors, are free of this kind of scatterers.

Ion beam deposited glass layers have been shown to have low quality factors, in the thousands, or tens of thousands, as compared with the many millions, or even billions, quality factors measured in high quality molten glasses^{xviii}. The much larger mechanical losses associated with the lower quality factor of the $\sim 3 \mu\text{m}$ thick coatings cause more excess thermal noise in the mirror than the entire 20 cm thick mirror substrate. The thermal noise in the coatings, therefore is the culprit limiting the sensitivity of gravitational waves detection^{xix}. While recent results have given some indications^{xx}, thus far, there has been no clear identification of the source of the excess dissipation in coating layers. It will be shown that the observed scatterers are a likely locus of the larger than expected coatings mechanical losses. While the exact nature of the light scatterers (crystallite or voids) cannot be identified at this time, their observation is an important diagnostic tool to develop deposition procedures that mitigate optical scattering as well as thermal noise.

^{xviii} Steven D. Penn et al., "Frequency and surface dependence of the mechanical loss in fused silica," *Physics Letters A* 352, no. 1 (2006): 4.

^{xix} Yu Levin, "Internal thermal noise in the LIGO test masses: A direct approach," *Physical Review D* 57.2 (1998): 659.

^{xx} Jonathan P. Trinastic et al., "Molecular dynamics modeling of mechanical loss in amorphous tantala and titania-doped tantala," *Physical Review B* 93, no. 1 (2016): 014105.

While squeezed light has been proven to reduce quantum noise, the effectiveness of the technique is limited by the scattering losses of the stored beam^{xxi}. Every lost photon effectively injects un-squeezed light into the stored beam. The scattering of light, therefore, negatively affects and puts an effective limit on how much squeezed light techniques can reduce quantum noise. Thus, reducing light scatterers within the coating layers would not only directly reduce thermal noise and shot noise (by reducing the cavity finesse and its stored power), but it also would be a key step in optimizing future squeezed light techniques.

^{xxi} J. Aasi et al., “Enhanced sensitivity of the LIGO gravitational wave detector by using squeezed states of light,” *Nature Photonics* 7, no. 8 (2013): 614.

CHAPTER 6

Methods and Procedure

Using Python programming language and DAOPHOT^{xxii}, a software tool included in the IRAF software system written by the National Optical Astronomy Observatory^{xxiii} to count stars in astronomical images, a large number of diffraction limited points, the scatterers, or irregularities in light reflection, have been detected within the mirror coating layers. The search tool is optimized to detect point-like objects, ignoring “nebula-like” objects, which results in ignoring the dirt particles and smears that were initially targeted by previous research efforts^{xxiv}. The camera lens cannot resolve the points extracted by DAOPHOT. These points are compatible with, and are identified by their congruence with, Airy disk profiles generated by the camera lens aperture. Best fit procedure inside DAOPHOT was used to extract the position (in the X,Y plane) and amplitude information of each candidate in 45 images of varying exposure times that were acquired at the LIGO Hanford observatory.

There is a varying degree in scatterer image quality within the images, which can be attributed to either pixel saturation or scatterer crowding. The scatterer Airy disk size on the CCD corresponds to $\sim 80\mu\text{m}$ wide spots on the mirror surface, which produces

^{xxii} Peter B. Stetson, “DAOPHOT: A Computer Program for Crowded-Field Stellar Photometry,” *The Astronomical Society of the Pacific* 99, no. 613 (1987): 195.

^{xxiii} “National Optical Astronomy Observatory”, NOAO Home Page, last modified March 2, 2017, last accessed March 13, 2017, <https://www.noao.edu/>.

^{xxiv} William Kells, “Scattered Light Loss from LIGO Arm Cavity Mirrors,” *LIGO Scientific Collaborative Database* LIGO-T0900128 (2009).

crowding in high exposure images. The actual scatterers must be sub-micron in size to generate large angle scatter, thus they are actually widely separated within the coating layers of the coating.

It is observed that the shapes of Airy disks at larger exposure times are amplitude-dependent, mostly due to CCD saturation. The effects of saturation are illustrated in Figure 5.

The 45 images analyzed varied in exposure times from 1.25×10^{-4} to 1.3 seconds. The numbers of detected scatterers per image were tabulated and graphed as a function of exposure times in Figure 6. The growth of the number of detected points is compatible with a linear function, with a saturation occurring above 0.2 s exposure. The count saturation was attributed, by manual observation, to crowding of saturated airy disks, rather than an actual amplitude cutoff of weaker scatterers. It appears that a population of even weaker Airy disks exists, they likely correspond to progressively less illuminated scatterers in deeper and deeper mirror layers. An entire population may lie below the detected ones.

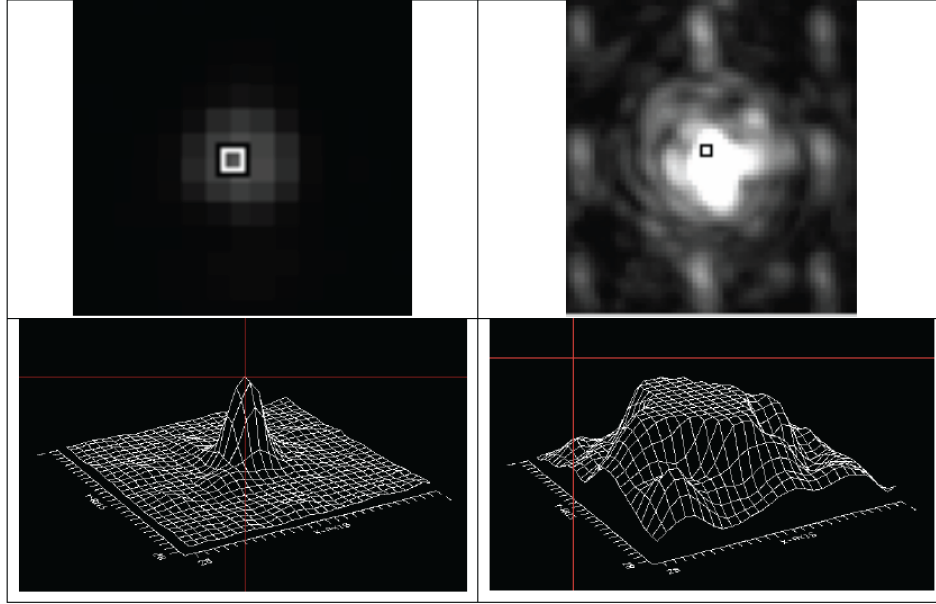


Figure 5: *Images (Top) and Contour Plots (Bottom) of scatterers. A non-saturated Scatterer is shown on the left and an oversaturated one on the right. Saturated scatterers are found with increasing frequency amongst images with longer exposure time. Smaller bumps, only partially recovered by DAOPHOT and visible by eye in both images, they may represent an underlying population.*

CHAPTER 7

Method Limitations

Shorter camera exposure times result in a smaller number of scatterers detected by DAOPHOT, with the less luminous ones fading into the CCD image “dark” pixel count, while the detected scatterers are less saturated, with shapes compatible with Airy disks. Longer exposure times proved to be problematic due to flattened Airy profiles and the fact that when the CCD saturation count of 255 is exceeded, there seems also to be outflow of the excess charge on the neighboring pixels, as illustrated in Figure 2, right panel. To mitigate these shortcomings, it is intended to use a sequence of un-saturated images taken in rapid succession at the same shortened exposure times once more images are available. It is expected that adding the pixel counts of these photos after proper re-centering, to compensate for apparatus movements. This seemingly obvious solution has a limitation. The signal from very weak scatterers in the TIFF images studied is bundled in the dark count and rounded off to zero, and therefore will never appear in the summed up image. To recover the signal hidden in the dark pixel, it will be necessary to use the camera in “raw data” mode with all its 14-bit resolution. This will generate images with much higher-dynamic range, the 14 bits of the raw images, plus one equivalent bit for each doubling of the number of images added up. Theoretically, with 1024 images we should obtain a $14+10 = 24$ -bit resolution. One can expect that with such a resolution a more efficient subtraction of scatterers may be produced by DAOPHOT and a number of fainter scatterers become visible, thus producing a more reliable luminosity distribution curve and reveal a population of weaker scatterers, if they exist, without saturating the bright ones.

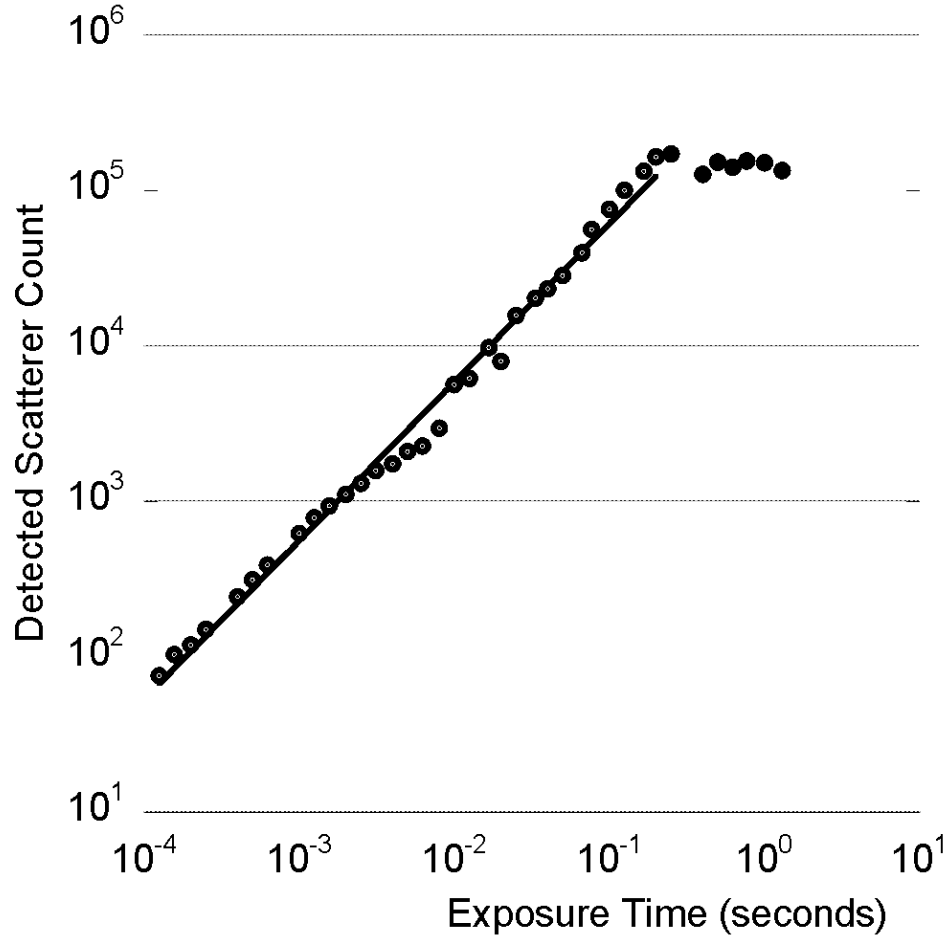


Figure 6: Detected number of scatterers vs. exposure time: the relationship is nearly linear, with slope ~ 1 , until saturation occurs, as shown by the unitary slope line superimposed on the data (the fit is applied only data below the saturation at 0.2 s).

TIFF versus RAW format

The default for the “RAW format” file conversion to TIFF format of 8-bit depth was used initially. It was not anticipated that its limited dynamic pixel range would be a problem. However, the camera can produce “RAW format” images with a 14-bit dynamic range, which will be utilized in future searches. Studies of images with a 14-bit dynamic range show that the dark field forms a narrow peak above zero and, therefore, weak

signals will not pile-up and be rounded off on the zero-count bit. In this condition, even the weakest scatterers will eventually emerge if a sufficient number of images is added up.

At the time this work was written, the two LIGO observatories were offline for service upgrades, and the photos with the desired exposure in order to determine the dark field could not be obtained. This work is therefore limited to the best available images. There is some evidence that light scattered on the relay periscope mirrors through which the camera takes the images may harm the GW detection resolution. For this reason, the cameras have been isolated from the LIGO apparatus, and may not return online until proper seismically isolated supports are designed and built, if they will be built.

It should be noted that these scatterers have already been previously observed^{xxiv},^{xxv}. At that time, it was surmised that the scatterers were laser speckle, which is unlikely because speckle patterns do not mimic well the Airy disk patterns that were observed and the pattern that is observed remains stable even for beam movements over the mirror surface. It is therefore assumed that each Airy disk-like point is the result of actual point-like scatterers. Interestingly, previous scattered light measurements performed from the same viewports on the initial LIGO mirrors (Fig. 3 of reference XII) found scattered intensity levels in excess of what had been estimated using the known mirror substrate roughness measurements. The scatterers studied here may account for some, if not all, of that excess power.

It should also be noted that a data analysis approach similar to that of DAOPHOT

^{xxv} Joshua Hacker, “Distinguishing Points from Glow in Scattering Images,” *LIGO Scientific Collaborative Database* LIGO-G1500772 (2015).

is also used in angular dependence studies of scattering on sample mirrors^{xxv}, finding multiple scatterers throughout the captured images. Angular power information cannot be produced in the measurements described here because all the images were taken from a single location and the camera was not calibrated in light intensity.

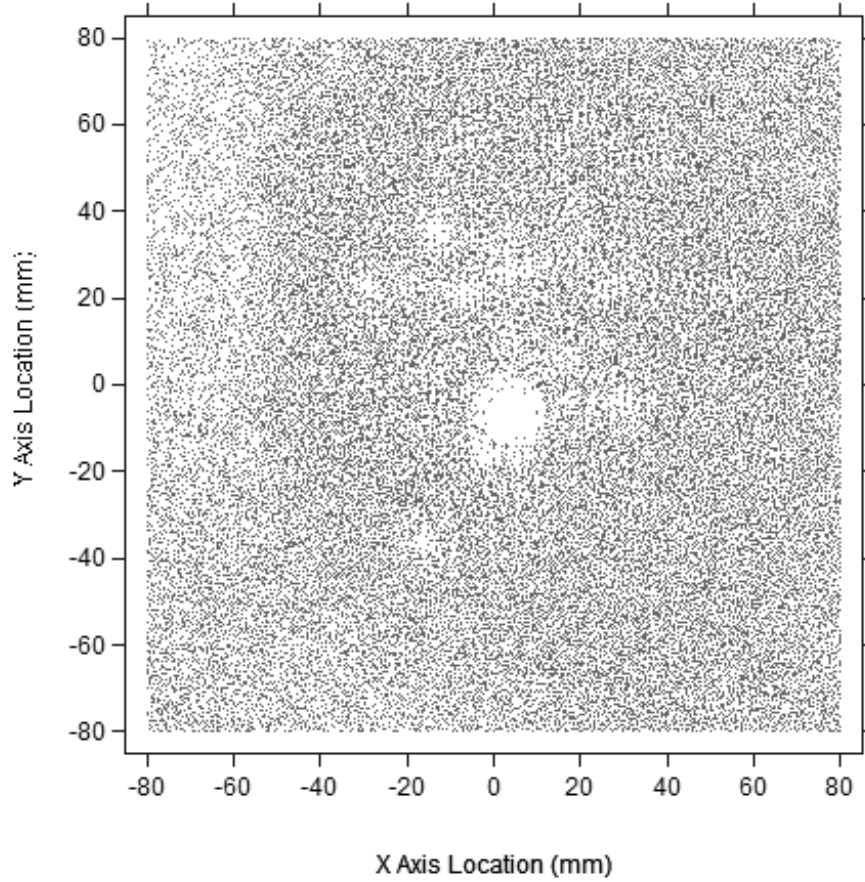


Figure 7: DAOPHOT-detected scatterers with 0.763 second exposure. Smear due to dirt limits DAOPHOT's detection efficiency in some areas that appear blank. The number of counts per square is reported in table 4. The density of detected scatterers is lower on the beam spot tails, due to the rapidly decreasing illumination, but it is otherwise compatible with a constant value. An average scatterer density of $6.5 \text{ scatterer/mm}^2$, $10.7 \text{ scatterer/mm}^2$ at the center, is estimated.

#	1	2	3	4	5	6	7	8	9	10	Sum
1	1952	1493	1025	1160	1425	1640	1699	1241	1171	1278	14084
2	1999	1661	1239	1457	1963	2364	2017	1090	897	1091	15778
3	1885	1651	1665	1836	2246	2366	1808	952	736	812	15957
4	1695	1485	1945	2267	2691	2471	1734	1087	643	790	16808
5	1463	1404	1767	2567	2576	2601	2049	1368	759	812	17366
6	1216	1443	1592	2517	2206	2729	2312	1607	850	1048	17520
7	934	1462	1431	2487	2539	2626	2249	1891	1231	1480	18330
8	977	1444	1270	2502	2645	2286	1629	1731	1593	1888	17965
9	1062	1534	1340	2299	2265	1709	1544	1427	1867	2209	17256
10	1122	1566	1458	1921	1525	1213	1293	1200	1918	2220	15436
Sum	14305	15143	14732	21013	22081	22005	18334	13594	11665	13628	166500

Table 4: number of scatterers detected by DAOPHOT in 1.6 cm x 1.6 cm cells of the image of figure 4. The top line and left column are the column and row number. The bottom line and right column are the row and column sums.

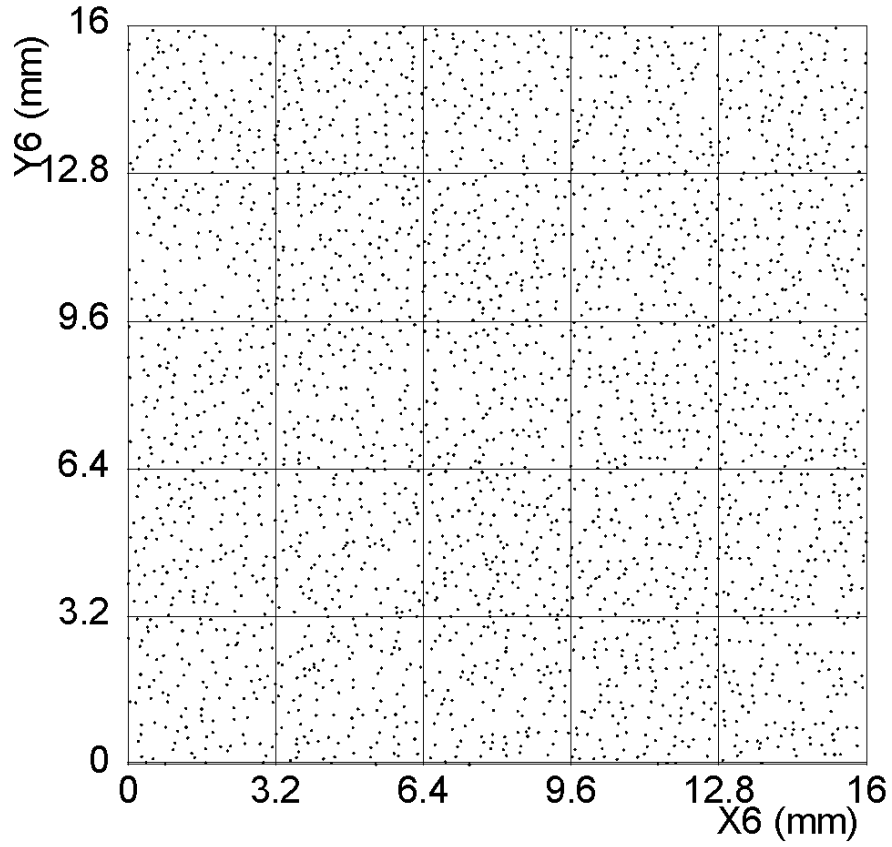


Figure 8: Scatter plot of the detected scatterers of cell 6,6 of table 4. Uniformity in this dirt-free cell is evidenced by the scatterer count uniformity within the expected $\sqrt{n}$ variance.

CHAPTER 8

Results

The photographs were taken with approximately 100 kW stored beam illuminating the test masses. The camera utilized a 240mm lens, set at f/11 and ISO 100 with exposure times varying between 1.25×10^{-4} to 1.3 seconds.

Minimum	643
Maximum	2,729
Sum	166,500
Points	100
Mean	1,665
Std Deviation	539
Std Error	54

Table 5: Statistical analysis of the data of table 4. The standard deviation of 539 is more than ten times larger than the expected statistical fluctuation, $\sqrt{1665}=41$, of the mean value, reflecting the masking effects of dirt, and the changing illumination level.

A pixel size of $\sim 80 \mu\text{m}$ in both the X and Y directions was calibrated using the known size of straight edges of the mirror support structure, visible in figure 4.

The scatter distribution in figure 4 is clearly not uniform, which can be attributed to areas where dirt inhibits DAOPHOT's identification process. This is visible as white patches in figure 4 (bright in figure 1) with a strong deficit of scatterers. The illumination level affects the number of detected scatterers, according to the slope fit in figure 3. The count number is also decreasing on the wings of the stored beam profile, due to lower

illumination. It is clear that the average density of scatterer/mm² obtained by dividing the number of points by the field of view area is merely a lower limit. Excluding the points where there were smears due to dirt particles degrading the DAOPHOT detection efficiency, the scatterer density around the beam center, at the saturation level of figure 4 (with an exposure time of 0.763 s), was approximately 10.7/mm².

The following procedure was implemented to produce a better evaluation of the actual scatterers' density if the illumination was uniform and the dirt absent.

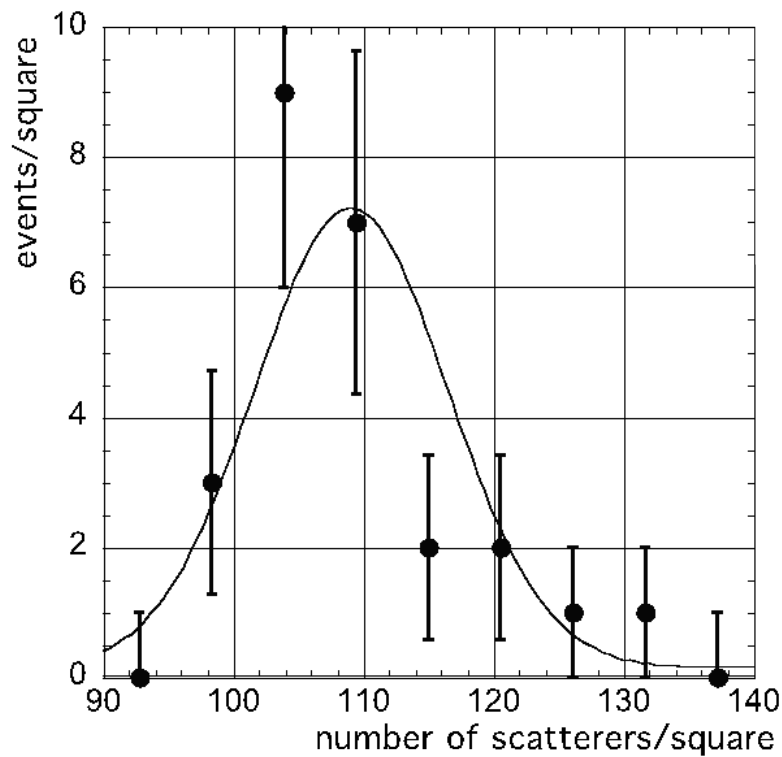


Figure 9: Plot of the data of table 6, the data is in agreement, within statistical error bars, with the Gaussian predicted by a uniform distribution of scatterers of average 109 counts/square (smooth line), 10.7/mm² accounting for the square size.

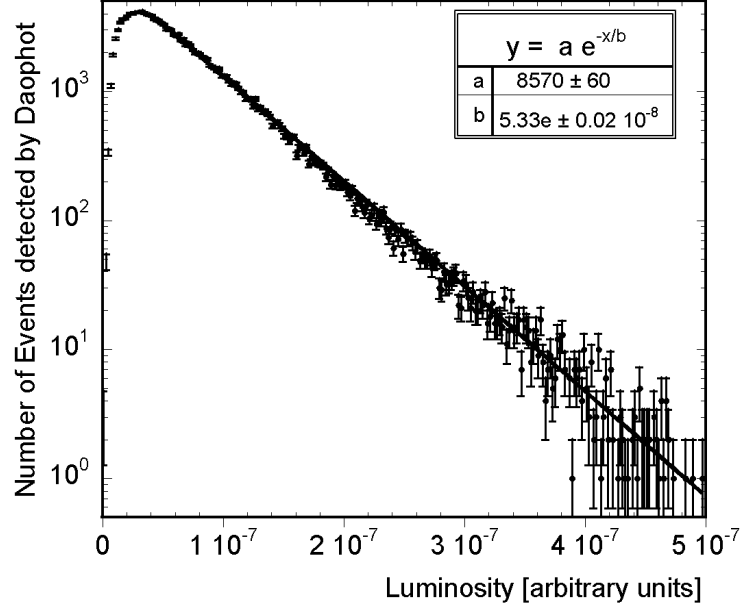


Figure 10: Detected scatterer luminosity distribution. The exponential decay fit is performed only on the points above $Z=0.5 \cdot 10^7$.

Rows / Columns	1	2	3	4	5	Max.	133
1	99	123	99	109	109	Sum	2724
2	99	110	119	103	105	Points	25
3	108	103	105	115	109	Mean	109
4	106	108	133	108	115	Std Dev.	8.5
5	104	104	105	124	102	Std Err.	1.7

Table 6: Left six columns: number of scatterers detected by DAOPHOT in highest count subdivision of cell 6,6. Right two columns: Statistical analysis of the left panel data. The standard deviation of 8.5 counts is in good agreement with the expected statistical fluctuation $\sqrt{109}=10.4$, indicating that dirt is likely absent in this cell, and the scatterer distribution is uniform.

The cell region of interest of figure 4 was first sub-divided into a 10 by 10 matrix of smaller cells. The detected scatterers were counted in each of the 100 cells, and reported in Table 1.

Given the fact that dirt masks out detected scatterers and that the beam profile tapering reduces the number of detected scatterers in the wings, the largest value of table 1 is considered to be the best estimator of the undisturbed scatterer density, i.e. the actual detected scatterer density at this exposure level is at least 64% higher than the gross average estimation of 1658 scatterers per bin in figure 4. It remains to be established if the highest cell count is representative, i.e. unaffected by dirt. It can be considered that, in absence of dirt, the scatterers' distribution should be uniform. If the distribution of scatterers in the bin cell with the highest count is uniform, it is probable that that scatterer is actually unaffected by dirt.

The highest count is in cell 6,6 in table 4, which is close to the beam center. Cell 6,6 was subdivided into a second 5 x 5 matrix of cells as shown in figure 5, and their content counted. The results are reported in table 6 and figure 9, illustrating the uniform distribution of the scatterers in that cell.

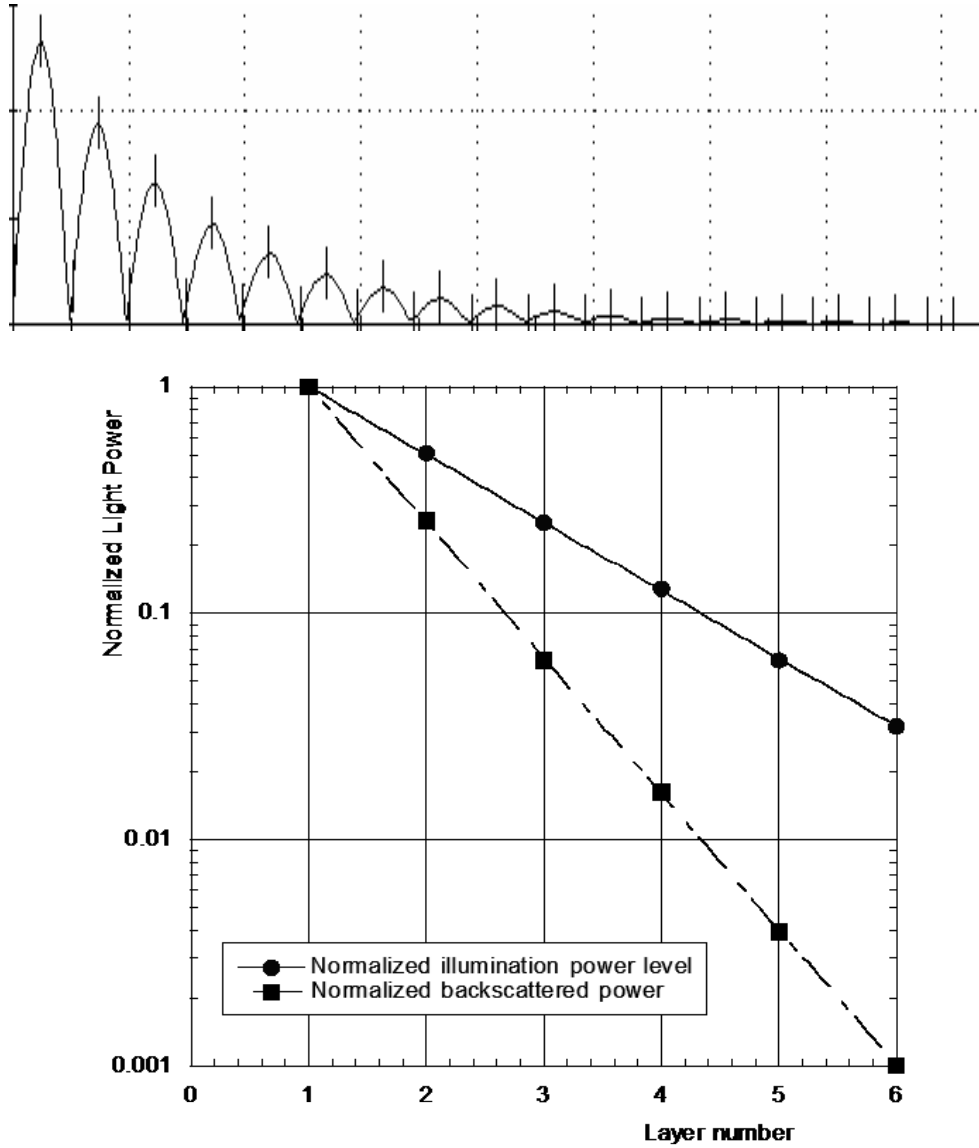


Figure 11: *Top:* Calculated electric field intensity within an optimized dichroic advanced LIGO ETM silica/titania-doped-tantala mirror (as in design provided by UniSannio to LMA). **Bottom:** exponentially decreasing light power as function of layer number (dots). The scattered light is further attenuated on its way back to the surface and the camera. Scatterers beyond the third layer are visible at the percent level or less. Therefore, light that is reflected back by the material layers comes from scatterers located in the uppermost coating layers.

The amplitude distribution of the individual events detected by DAOPHOT in the image of 0.763 second exposure is shown in figure 7. It is important to remind that coating layers near the surface are much more strongly illuminated than deeper layers. To make a rough evaluation of the overall number of scatterers actually present throughout the mirror, one should take into consideration the illumination drop with the coating layer number.

In addition, because the camera observation angle from the beam axis is small (9.8°), the backscattered light from deeper layers is reduced by approximately the same factor as the illumination. The two effects amount to a strong exponential attenuation, which makes that scatterers from the second layer are visible with 25% of luminosity and 6.3% from the third layer^{xxvi}. In practice, assuming that the scatterers are concentrated in the Tantalum layers, only scatterers present in the top layers contribute to figure 4 and 5 while scattering from deeper layers is hardly visible. Because there are 26 layers in a coating, about an order of magnitude of additional scatterers can be expected to exist undetected below the surface, i.e. hundreds per square millimeter.

^{xxvi} Sophocles J. Orfanidis, *Electromagnetic waves and antennas* New Brunswick: Rutgers University Press, 2002.

CHAPTER 9

Detecting Changes in Optical Scatterer Position and Luminosity and Its Implications

Movements amongst the components of the LIGO apparatus (mirror, beam and camera) are a nuisance for scatterer characterization and need to be corrected before adding up sequences of images. We studied a correction mechanism that offers an interesting opportunity. Movements can be precisely determined by comparing the image-to-image changing position of scatterers. It is important that non-saturated images be used in this process.

Using image tracking capabilities in Wolfram Mathematica, the apparent movement of individual detected scatterers were determined.

Figure 9 shows how, when comparing the variations in relative position of detected scatterers of two successive images, one can evaluate the following position sensitivity capabilities.

- The lateral scatter of the points (standard deviation), $10.6\text{ }\mu\text{m}$ in x and $10.8\text{ }\mu\text{m}$ in y, i.e. about 1/10 of a pixel, is the best indicator of the precision of DAOPHOT's positioning for individual, unsaturated scatterers.
- The standard error of the distribution indicates that a beam positioning sensitivity better than $1.28\text{ }\mu\text{m}$ can be achieved. In absence of saturation, this precision can be expected to improve by $1/\sqrt{n}$ where n is the number of detected points. This high precision is important because it allows proper corrections for the image shift when adding the pixel counts from many images.
- The change of the mean value measures the apparent movement of the mirror (the combined relative movement of the camera and mirror). A change of -

$58 \pm 10.6 \text{ }\mu\text{m}$ in the x-axis and $31 \pm 10.8 \text{ }\mu\text{m}$ in the y axis was measured between the two images separated by 10 s intervals.

The preliminary results above are limited by the fact that the analyzed photos have all different and far-from-ideal exposures. The best pair of images available to test this task (images with same exposure were not available in our data set) were two images from the Nov. 2015 data set with 0.125 and 0.1563 milliseconds exposure times, taken approximately 10 seconds apart from one another. Having the choice, 10x or longer exposure would be used. The results obtained here should therefore be considered as upper limits of the achievable resolution. The results from the comparison of the two images used are not sufficient to determine the ultimate position sensitivity, but establish that this kind of analysis can track image-to-image movements and sets an upper limit of the achievable sensitivity even with non-optimized exposure times.

Additional beam diagnostic information can be extracted.

Tracking the position of the scatterers does not give information of the beam movements with respect to the mirror surface. In order to accomplish that, one can take advantage of the fact that scatterers are in fixed positions on the mirror surface. Movements of the stored beam with respect to the mirror will produce change of luminosity of the scatterers. Using the luminosity values associated with each detected scatterer, shifts in luminosity within the images were calculated. Dividing the identified scatterers in quadrants, and comparing the four illumination levels integrated over the four quadrants, it is possible to monitor beam movements across the mirror surface. A split along the x axis was used to detect horizontal motion as well as a split along the y axis for vertical motion. In the two images studied, the normalized luminosity changed by

a factor of 0.0008 along the x axis (from an original ratio -0.0070 to a -0.0062), indicating a leftward shift of the stored beam position. Along the y axis, the luminosity changed by 0.0272 (from an original ratio -0.0278 to -0.0550), indicating a larger upward shift in stored beam position. Supposing a Gaussian beam radius of 50 mm, these measurements estimate a “measured” beam to mirror movement of 0.16 and 1.35 mm over a 10 s interval.

These three results represent high-resolution measurements of variables that may be of great interest as feedback signal for improving interferometer controls, or even simply for monitoring.

There is an additional, potentially very important opportunity. It is suspected that some of the interferometer glitches that pollute the signal detection pipeline are due to beam movement. It is therefore important, for debugging and reducing false signal probability, to attempt to correlate either of the movements detected with this method with interferometer glitches.

These arguments may be sufficient cause to justify the expense to develop seismic attenuators for the relay mirrors and cameras, and re-introduce the cameras in future evolutions of the LIGO detector.

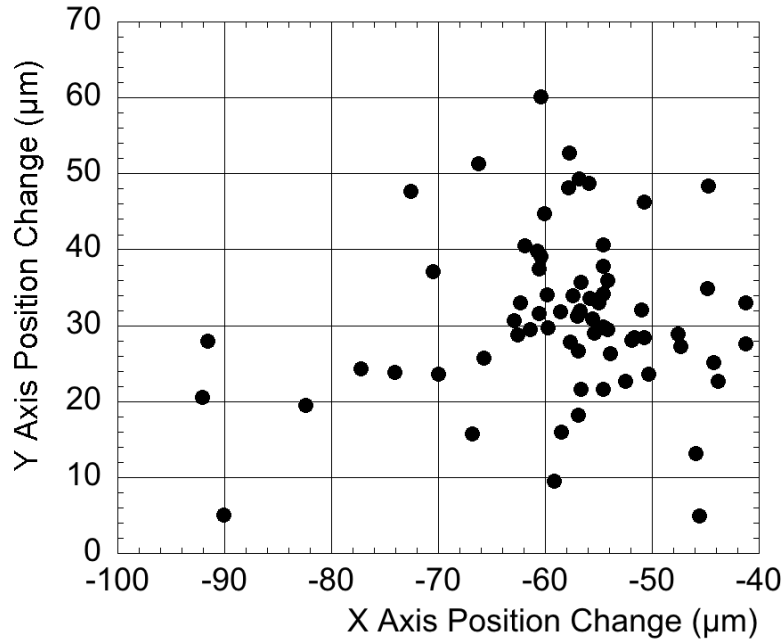


Figure 12: The above shows the small changes in position calculated via Mathematica when comparing two successive ETM images of similar exposure times, taken at a 10 s interval. One pixel is approximately 80 μm in width. Between the two shots, the camera-mirror relative position changed by $\sim 58.48 \pm 10.6 \mu\text{m}$ in the horizontal position and $\sim 31.07 \pm 10.8 \mu\text{m}$ in the vertical. The image-to-image scatter (fitting error) of the beam center position provided by DAOPHOT is $\sim 1.2\text{-}1.3 \mu\text{m}$.

CHAPTER 10

Considerations and Implications for dissipation and thermal noises

It is very unlikely that such a high and uniform scatterer density can be accidental. It requires a fundamental source, probably in the deposition process.

Vladimir Braginsky^{xxvii,xxviii} and Yuri Levin^{xix} predicted that thermal noise of coatings would limit the sensitivity of Gravitational Wave detectors but it has been a puzzle why dissipation and thermal noise in deposited glasses proved to be so high.

One can wonder if the puzzling scatterers detected in this work are also the source of the excess dissipation in deposited glasses.

Large-angle scatter without absorption requires fluctuations of refraction index at sub-wavelength scale. As the chemical composition of the material is uniform, density fluctuations are necessary. Fluctuations of either sign are possible.

(+) Positive refraction index fluctuations are given by crystallites, which are fluctuations with higher molecular order and larger density.

Previous studies have shown evidence of large mechanical losses within the coating layer material.^{xxix} There, materials are observed to evolve into crystal (columnar)

^{xxvii} V. B. Braginsky, V. P. Mitrofanov, and K. V. Tokmakov. "Energy dissipation in the pendulum mode of the test mass suspension of a gravitational wave antenna," *Physics Letters A* 218, no. 3 (1996): 164.

^{xxviii} V. B. Braginsky and S. P. Vyatchanin, "Corner reflectors and quantum-non-demolition measurements in gravitational wave antennae," *Physics Letters A* 324, no. 5-6 (2004): 353.

^{xxix} S. D. Penn et al., "Mechanical loss in tantala/silica dielectric mirror coatings," *Classical and Quantum Gravity* 20, no. 13 (2003): 2917.

growth in thicker film depositions of the same materials, as well as in films that have undergone excessive annealing, which imply the presence of crystallite seeds.^{xxx,xxxix} It is therefore reasonable to suspect that crystallites, that should be present anyhow, may be the observed scatterers. The following argument shows that they may also be the locus of dissipation.

As better discussed below, the interface between glass and crystallite is rich in dangling and frustrated bonds that could be locus of mechanical dissipation.

There are a number of possible improvements suggested by the theory that crystallite may be the source of mechanical dissipation.

The crystallites have a minimum critical size, due to the competition between the high energetic cost of the dangling and frustrated bonds on the surface and the energy gain of crystallization, which is proportional to the volume. Crystallites that are too small tend to dissolve back in the glass during annealing, while larger ones tend to grow.

Crystallite growth can be prevented by nano-layering different materials within each coating layer^{xv, xxxii} with layer thickness smaller than the crystallite minimum size.

Crystallite growth can also be depressed by alloying different materials, which historically was already done to improve coating performance even before this reasoning was developed^{xiv}.

^{xxx} Huang-Wei Pan et al., "Thickness-dependent crystallization on thermal anneal for titania/silica nm-layer composites deposited by ion beam sputter method," *Optics Express* 22, no. 24 (2014): 29853.

^{xxxix} André Anders, "A structure zone diagram including plasma-based deposition and ion etching," *Thin Solid Films* 518, no. 15 (2010): 4088.

(-) While the columnar growth arguments lead us to prefer the crystallite as scatterers, it has to be said that negative refraction index fluctuations can also be effective sources, and cannot be ruled out in this work.

Negative refraction index fluctuations may be due to local fluctuations of the density deficit present in the glass. Glasses are always less dense than their crystalline counterpart, due to a statistically uniform distribution of atomic-size voids, but evaporation-deposited glasses are even less dense than molten glasses and can present larger deviations from uniformity. The coating glass appears optically uniform, but one can expect scattering of light from lower density volumes if the void size distribution has sufficiently large fluctuations, and/or if a sufficient concentration of atomic-size voids happens in the scale of a fraction of a wavelength. The ensuing local refraction index deficit could then produce the observed scattering. Voids also present dangling and frustrated bonds, and could equally well be a locus of mechanical dissipation. It is suggested that low density fluctuations may be mitigated by means of hot substrate deposition, ion assisted deposition, annealing or other production techniques.^{xxxii ,xxxiii}

While it is impossible to distinguish between high and low density fluctuations with the observational methods used here, both lower and higher density zones are expected to have a larger amount of loose or dangling bonds than the rest of the glass. They can be conceptualized as two-level systems represented by asymmetric double-well potentials in some configuration coordinate. The distribution of corresponding double-

^{xxxii} D. R. Queen et al., "Two-level systems in evaporated amorphous silicon," *Journal of Non-Crystalline Solids* 426 (2015): 22.

^{xxxiii} D. R. Queen et al., "Excess specific heat in evaporated amorphous silicon," *Physical Review Letters* 110, no. 13 (2013): 135901.

wells in the atomic displacement depends on the distribution of bond angles and frustrated bonds in the amorphous material.^{xxxiv} As an oversimplified picture, one could imagine an atom “flopping” from one side of a bond to the other during stress propagation, thus absorbing energy and dissipating it in the thermal bath. It is clear that these defects can exist on different length and energy scales, ranging from local, atomic-sized defects such as simple dangling bonds to larger scales such as those that produce two level systems.

The observational method does not allow distinguishing between these two possibilities. Even if one cannot ascertain the exact cause of the fluctuations, they are equally likely sources of the excess of mechanical losses in evaporated glasses. When considering that thermal noise is one of the major sources of noise in gravitational wave detection, the identification of its source has major implications in regards to the optimization of production procedures and ultimately improved reach of the apparatus.^{xxxv}

^{xxxiv} M. D. Ediger, “Vapor-deposited glasses provide clearer view of two-level systems,” *Proceedings of the National Academy of Sciences of the United States of America* 111, no. 31 (2014): 11232.

^{xxxv} M. Pitkin et al., “Gravitational Wave Detection by Interferometry (Ground and Space),” *Living Reviews in Relativity* 14, no. 5 (2011): 5.

CHAPTER 11

Next Steps

As this research continues, it will be necessary to analyze images taken from various test masses or other reflectors that have similar coating layers. Since March 2017, we have begun to receive images from various sites associated with the LIGO Scientific Collaborative (LSC). Figures 13, 14 and 15 showcase some of the recent images from LIGO Hanford, LIGO Livingston and LIGO Caltech 40m Prototype, respectively.

Image quality is very much a concern at this moment. The cameras that are currently being employed to take images at LIGO Hanford and LIGO Livingston are video cameras (GigE and CCTV cameras), and the images provided from these cameras are screen captures of video transmissions. The image size and quality is significantly smaller than what has previously been analyzed. In addition, having the image be properly in focus has been an issue at both LIGO observatories as well as at the LIGO Caltech 40m Prototype. The GigE and CCTV cameras have much less control over focal depth parameters and there are still significant limitations to getting images that are properly in focus. A solution to remedy these challenges at any and all of the sites would be to arrange extended or regular site visits to develop and implement techniques for better image quality.

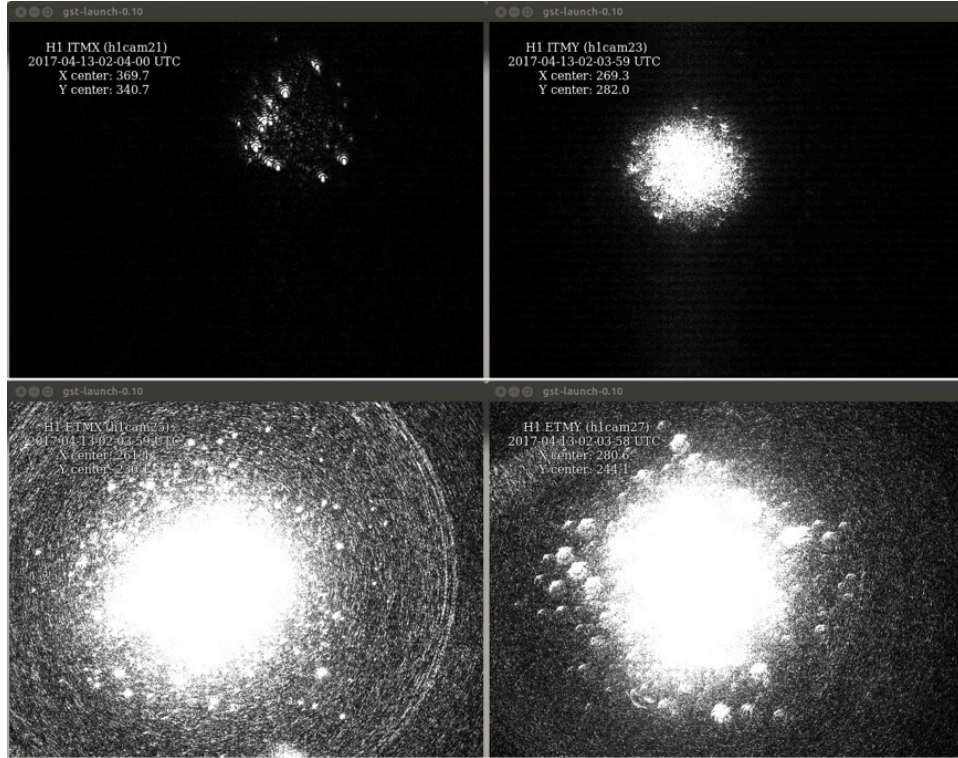


Figure 13: GigE video camera screen capture images of the four different test masses at the LIGO Hanford site.

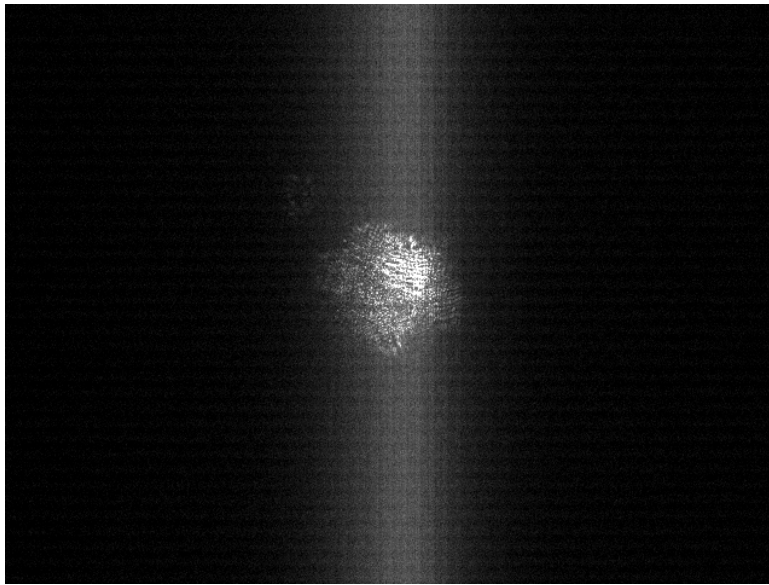


Figure 14: CCTV video camera screen capture image of the X-arm interior test mass (ITM-X) at the LIGO Livingston site. Image streaking is clearly visible.



Figure 15: Image of stored beam interacting with coated reflector at the LIGO Caltech 40 Meter Prototype site.

More refined data analysis from previously obtained LIGO Hanford images is progressing.

Further refinement of both the scatterer detection process as well as the subsequent motion tracking of detected scatterers are also on the docket.

This study has prompted an additional research project here at Cal State LA.

Michael C. Milovich Goff is trying to locate scatterers within the coating layers in witness samples. Fifty images are taken with a microscope CCD while letting the focal plane travel through the coating layers depths of a coating sample. The images are 1 micron apart in depth. Each scatterer is fit with a Gaussian curve in all the 50 images. The width of the Gaussian fits has a minimum when the focal plane passes through the

scatterer. An initial feasibility study^{xxxvi} making a quadratic fit of the width vs. depth has determined a depth resolution of ~50 nm. If the data analysis can show that all the scatterers fall within the first 3 micrometers of the witness sample coating, it demonstrates that the scatterers are located within the coating layers and not on the outer surface or in the substrate.

Measurement of number and depth of scatterers, if successful, will be a precious feedback tool for the production of advanced coatings with lower thermal noise.

^{xxxvi} Eddy Arriaga et al., “Study of depth position resolution of microscopic features, in view of a search for scatterers within the thickness of aLIGO Test Mass Coatings” *LIGO Scientific Collaborative Database* LIGO-T1600276-v1 (2016).

CHAPTER 12

Conclusions

The analysis presented here has shown that a large and unexpected number of optical scatterers is visible within the mirror coating layers when the LIGO test masses are exposed to the ~ 100 kW intensity light from the interferometer stored beam.

Theoretical material science considerations indicate that these scatterers are either nucleation centers, density voids, or a combination of the two, and a likely locus of the anomalous dissipation in the mirror coatings and, therefore, a source of its thermal noise. Observation of these previously overlooked scatterers may point the way towards a mitigation strategy.

The methods developed here allow tracking of the motion of the mirrors and the beams on the mirrors, important diagnostic and feedback tools for the observatories.

The background noise of the GW detectors could be reduced if some of the interferometer glitches were found to correlate with the motions that can be detected with the methods proposed here.

Reduction of thermal noise, reduction of scattering, better alignment, and reduction of glitches are all elements that can potentially increase the detection range of LIGO.

The methods proposed in this thesis do not give depth information of the scatterers and is not practical to provide real time feedback to coating developers. It is important to precisely and systematically locate the scatterers within the mirror coating thickness in sample mirrors. Therefore, this work has spawned a followup thesis work by Michael Goff, trying to identify and characterize the scatterers in mirror samples, and

determine their depth within the $\sim 3\mu\text{m}$ thickness of the coatings, using microscope and white light observations. Together, we have the chance of helping to expand the detection horizons of GW observatories, true to the Cal State LA motto of “pushing the boundaries”.

CHAPTER 13

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