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Optical scattering measurements and implications on thermal noise in Gravitational Wave detectors test-mass coatings

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ABSTRACT

Photographs of the LIGO Gravitational Wave detector mirrors illuminated by the standing beam were analyzed with an astronomical software tool designed to identify stars within images, which extracted hundreds of thousands of point-like scatterers uniformly distributed across the mirror surface, likely distributed through the depth of the coating layers. The sheer number of the observed scatterers implies a fundamental, thermodynamic origin during deposition or processing. These scatterers are a possible source of the mirror dissipation and thermal noise foreseen by V. Braginsky and Y. Levin, which limits the sensitivity of observatories to Gravitational Waves. This study may point the way towards the production of mirrors with reduced thermal noise and an increased detection range.

1. Introduction

Vladimir Braginsky [1,2] and Yuri Levin [3] predicted that thermal noise of coatings would limit the sensitivity of Gravitational Wave detectors. The mirror test masses of LIGO [4,5] have been specifically designed and constructed with multilayered interference coatings [6] via ion-beam deposition to minimize optical absorption, mirror thermal noise [7,8] and light scattering [9]. As such, an ideal mirror would appear black when viewed off axis from a 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 of the stored beam show a large number of light scattering points. The images are similar in appearance to star clusters (Fig. 1). Therefore, they were analyzed with DAOPHOT [10], an astronomical software tool developed by the National Optical Astronomy Observatory [11] to identify stars within galaxies. Initially, it was assumed that the scattering was caused by dirt, which DAOPHOT ignored as nebulae. It identified 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 with actual dirt. (Henceforth, we will call dirt any non-diffraction limited feature, reserving the term scatterer for diffraction limited ones). The scatterers went unnoticed thus far due to their faintness. The few brighter dirt particles in the foreground diffuse only several ppm of the incident power with each of the much more numerous scatterers diffusing parts per trillion of the beam power. Actual scatterers must be sub-micron is size to produce large-angle scattering. Their brightness distribution suggests that they may also be uniformly distributed in depth within all the coating layers.

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

The uniform distribution also implies that the scatterer generation during the deposition process itself is likely of a thermodynamic or statistical nature. While optical defects are observed in deposited glasses, it is important to note that molten glasses, such as the fused silica used in the 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, measured in high quality molten glasses. The mechanical losses associated with the

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lower quality factor of the coatings cause excess thermal noise in the mirror that, in its turn, limits the sensitivity to and detection range of gravitational wave events. Thus far, there has been no clear identification of the source of the excess dissipation in coating layers. It will be shown here that the observed scatterers are the possible locus of the larger than expected coatings mechanical losses. While the exact nature of the light scatterers cannot be identified at this time, their observation may become an important diagnostic tool to develop deposition procedures that mitigate optical scattering as well as thermal noise.

A more detailed analysis will be presented in a companion paper [12].

2. Methods and procedure

Using DAOPHOT, a large number of tiny scatterers, diffraction limited 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” dirt particles, which locally masked the underlying scatterers (see Figs. 1 and 4). The camera lens cannot resolve the points identified by DAOPHOT, which are visible as, and are identified by their congruence with, Airy disk profiles generated by the camera lens aperture. Best fit procedure extracts the position (in the X,Y plane) and amplitude information of each candidate. DAOPHOT identified the positions and relative luminosity of the scatterers in 40 images of varying exposure times that were acquired at the LIGO Hanford observatory in November 2015, when the interferometer was running at about 100 kW of stored power in its Fabry–Perot arm cavities.

There is a varying degree in scatterer 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 ~80 μm wide spots on the mirror surface. The crowding observed in high exposure images is due to the size of the Airy disks. 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, due to CCD saturation. The effects of saturation are illustrated in Fig. 2.

The 40 images analyzed varied in exposure times from 1.25×10^{-4} to 1.3 seconds. The numbers of detected scatterers per image were graphed as a function of their respective exposure times in Fig. 3. The growth of the number of detected points is nearly linear, with a saturation occurring above 0.2 s exposure, which was attributed, by manual observation, to crowding of saturated airy disks rather than an actual cutoff of weaker scatterers. It appears that a population of apparently even weaker scatterers, progressively less illuminated in deeper and deeper mirror layers, lies behind the detected ones.

3. Method limitations

Shorter camera exposure times result in less saturated and smaller Airy disk shapes, but also in a smaller number of scatterers detected, with the less luminous ones fading into the CCD image “dark” pixel count. Longer exposure times proved to be problematic due to the fact that when the CCD saturation count of 255 is exceeded, there seems to be outflow of the excess charge on the neighboring pixels, as illustrated in Fig. 2. To mitigate these short-

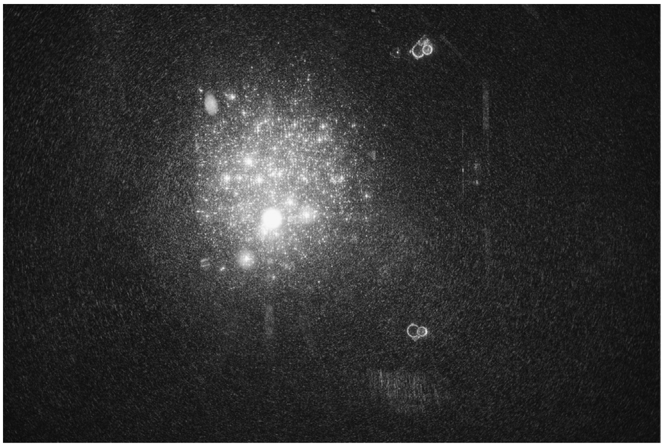

Fig. 1. Photograph of an End Test Mass; Exposure time of 1.3 seconds. Light blobs are interpreted as surface dirt. The rings and faint straight lines on the right side of the image are part of the mirror support structure.

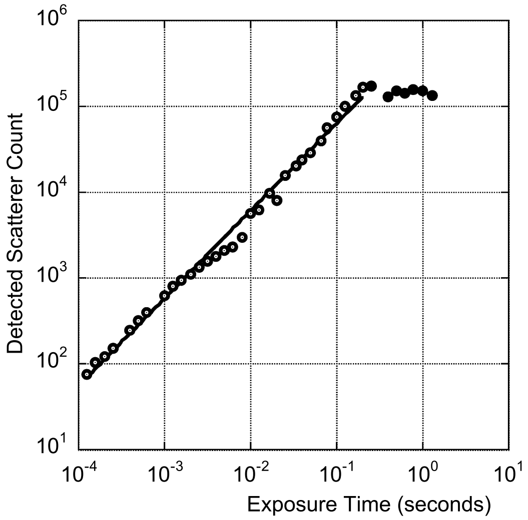

Fig. 3. Detected number of scatterers vs. exposure time: the line is a fit performed with a power law a x^b on the points with a white center. The fit gives an exponent $b = 1.02$, compatible with slope ~1, until saturation occurs.

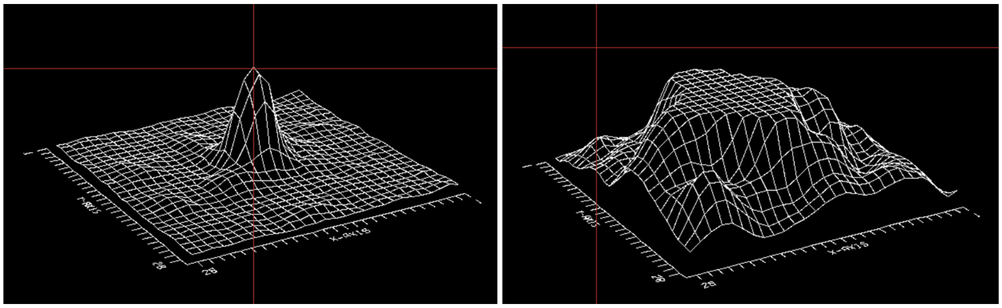

Fig. 2. Contour Plot of a non-saturated Detected Scatterer (left) and of an oversaturated one (right). The latter are found with increasing frequency amongst images with longer exposure time.