Modeling of optical scattering using the Bidirectional Reflectance Distribution Functions of Advanced LIGO test masses

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Introduction

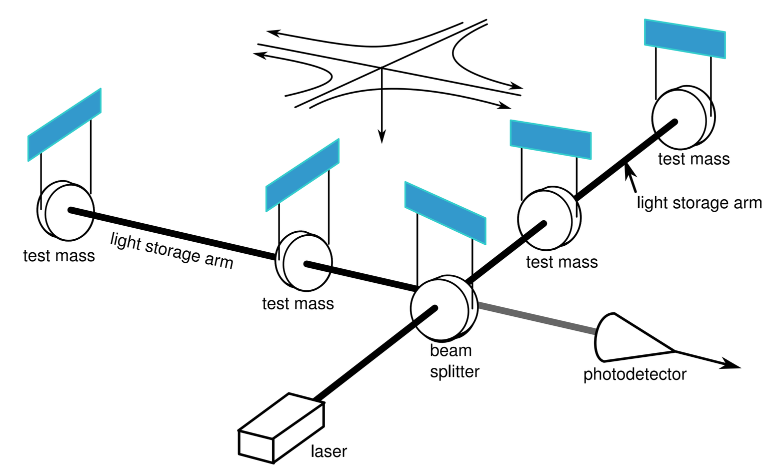

Figure 1: Diagram of a laser interferometer.

The Laser Interferometer Gravitational-Wave Observatory (LIGO) contains two Fabry-Perot cavities as seen in Figure 1. As light reflects between two test masses, a small percentage is scattered in an unintended direction due to surface imperfections. **This scattering results in power loss and noise in the interferometer** (IFO) which must be either accounted for or corrected[1]. Measuring optical scattering requires a power measurement of the light scattered to a known area, distance, and angle. This can be accomplished directly either through the use of a camera with a known conversion from power incident on the lens to intensity of light in the image or with a photodiode (PD). **The scatter is measured by the Bidirectional Reflectance Distribution Function** (BRDF) and is given by[2]:

$$BRDF = \frac{P_s}{\Omega \times P_i \times \cos(\theta_s)} \quad (1)$$

It is a measure of the ratio of power which is scattered (P_s) per solid angle (Ω) to power incident (P_i) on the reflecting surface.

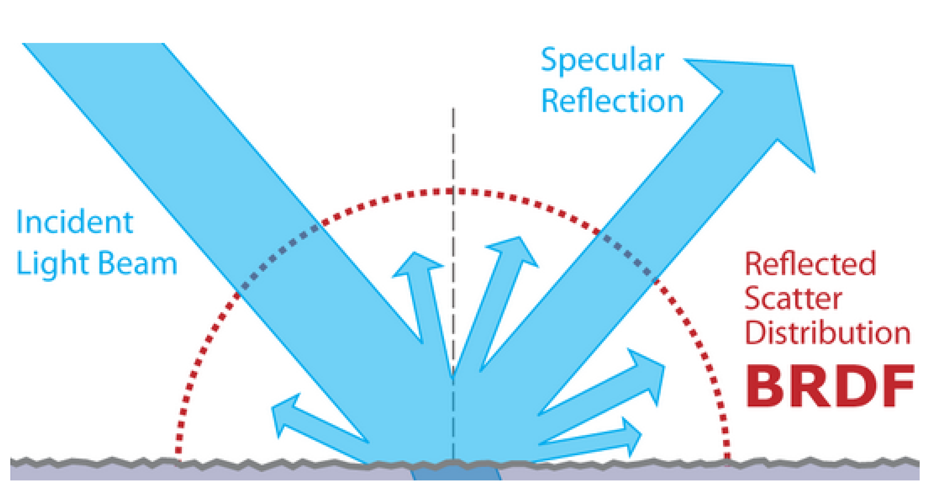

Figure 2: How light scatters from an imperfect surface[3].

LIGO Test Masses

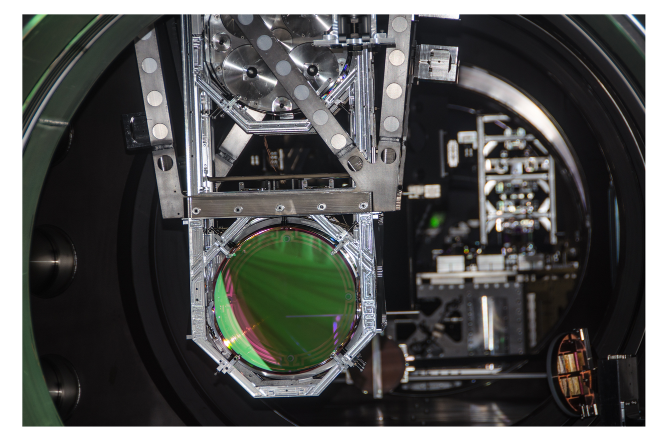

Figure 3: Photograph of installed ITM.

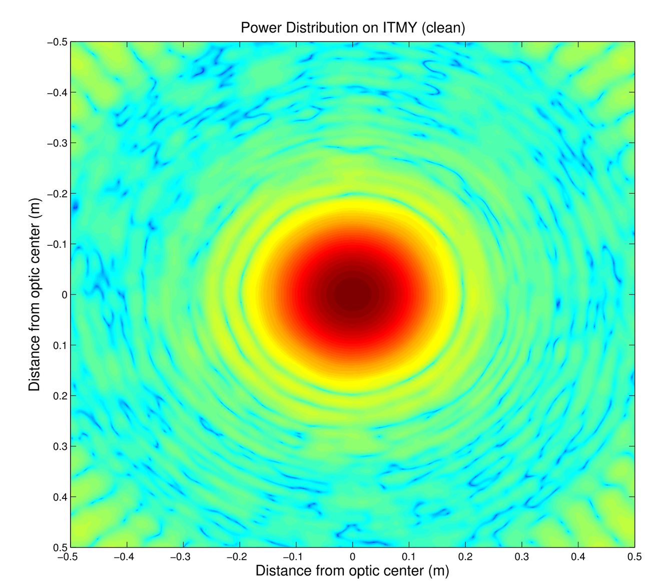

Figure 4: Model of power scattered to ITMY.

Figure 3 Shows the input test mass (ITM) that the laser passes through to enter a Fabry-Perot cavity. Once the laser enters a cavity it reflects, and scatters, back and forth between the two test masses (TMs) until light exiting the cavity is equal to the entering light[1]. To prevent scattered light from interfering with the main beam, structures, called baffles, are placed between the TMs. These baffles each contain 4 PDs. The final power circulating within the cavity is given by Equation 2[1].

$$P_{cavity} = \frac{2F}{\pi} \times P_{ITM} \quad (2)$$

Here F is the cavity finesse (416 for Advanced LIGO) and P_{ITM} is the power entering the cavity through the ITM. Once the TMs are aligned and the cavity power has stabilized, the IFO is said to be in lock. The path and power distribution ($W \times m^{-2}$) of the light can be modeled using the Static Interferometer Simulation (SIS) package, which uses phase maps of the TMs taken *before installation*. Figure 4 shows a head on view of this power distribution in log scale at the input test mass of the y-arm (ITMY).

Comparing Data with the Model

Data was taken for each set of PDs surrounding each TM to find the power scattered to their solid angles. Power incident on the TMs was calculated with Equation 2. This was done for every lock period of Advanced LIGO. With this data, BRDF values for each individual lock were calculated using Equation 1 and averaged to produce the statistics in Table 1. As can be seen from the large standard deviations, **the BRDF fluctuates significantly from lock to lock**. The features of alternating peaks and troughs in Figure 4 encompass the region where the PDs are located. It is easy to imagine that, with a slight change in alignment, the light seen by a PD could change significantly. The figure to the right shows how the measurements compare to the SIS modeled values for scatter towards ITMY. There are two important points to note from this plot:

- The measurements are comparable with the model
- Scatter from the installed TMs is larger than the model for all angles

The latter indicates that the fine structure of the TMs was altered during installation, likely from accumulation of particles.

PD	BRDF (Ω^{-1})	SD (Ω^{-1})	SEM (Ω^{-1})
1	1160±40	680.57	74.26
2	8.0±0.4	3.33	0.37
3	14.5±0.6	10.65	1.19
4	170±20	75.11	8.56

Table 1: Mean of measured BRDFs from ETMY with standard deviation and standard error of the mean.

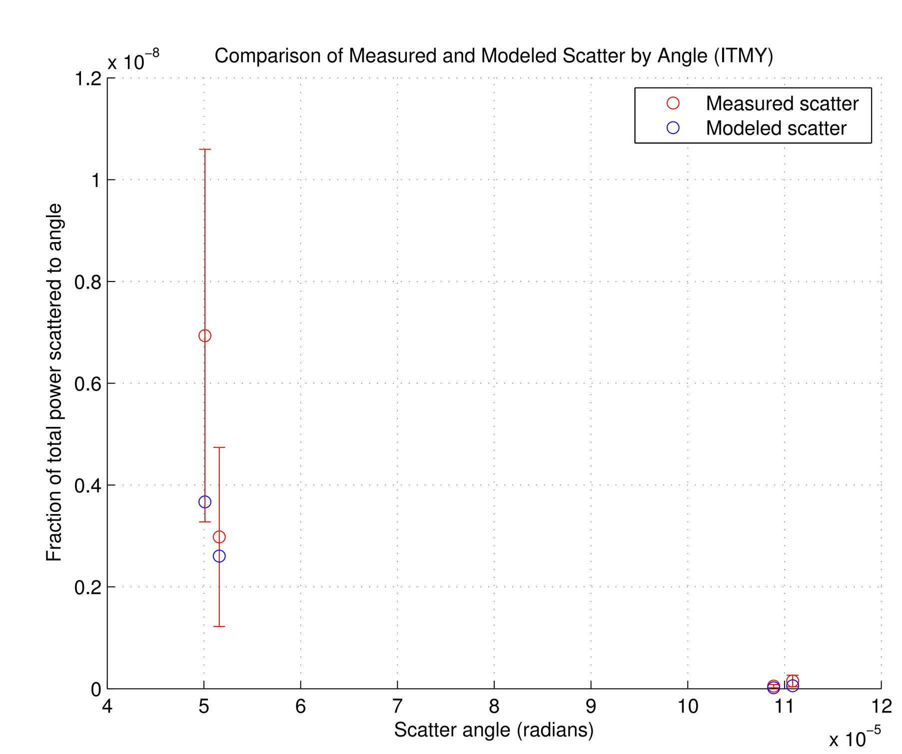

Figure 5: Measured and modeled fraction of power scattered to PDs.

Conclusion

The measured BRDF of each test mass varies significantly from lock to lock. From analyzing models produced by SIS, this variation is likely the result of alignment changes. **We found that the fine structure of the test masses was altered during the process of installation, resulting in larger power losses at all measured angles compared to the model**. More work should be done comparing measurements to the model in order to develop new phase maps which reflect the conditions of the installed test masses.

Additional Information

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References

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[3] Bsdf. `http://en.wikipedia.org/wiki/File:BSDF05_800.png`, 2006. File: `BSDF05 800.png, GNU Free Documentation License.`

Acknowledgements

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