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Motivations for Scatter Measurement

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Scattering measurements are one part of an extensive optical testing capability being considered for Ligo. The other aspects of this are

- A facility to measure optical loss in materials.
- Measurement of wavefront distortion of optical components.
- Rudimentary standard test procedures to qualify optical components.

The motivations for having an optical scattering measurement capability are outlined here. They fall into three categories. First is estimation of scattering noise, which would be aided by measurement of the small angle scattering of all optical components. Second is measurement of total scattering loss, which would complement ring-down testing and calorimetric absorption measurement to yield an understanding of mirror loss. Third is evaluation of coatings, which is to be done in conjunction with mirror heating tests. Only large angle or total scattering measurements can be done by industry. If small angle scattering is to be measured well, then we need to develop our own apparatus to measure it.

Thorne has done calculations[1] of the expected noise contribution to scattered light. Of necessity, a number of assumptions were made in these calculations, and the first of them is that the scattering function of an optical surface is of the form

$$\frac{1}{P_{inc}}\frac{dP}{d\Omega} = \frac{\alpha}{\theta^2} \tag{1}$$

where P_{inc} is the power incident on the mirror, P is the power scattered into a solid angle Ω in a direction θ away from specular, and $\alpha = 10^{-6}$.

[1] Kip Thorne, *Light Scattering and Proposed Baffle Configuration for the LIGO*, Second draft, 11 Jan 89.

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This is consistent with the known losses of supermirrors. Michelle Stephens measured scattering which was approximately fit by

$$\frac{1}{P_{inc}}\frac{dP}{d\Omega} = \frac{\alpha}{\theta^{1.75}} \tag{2}$$

over a limited range of angles. However, no measurements of optical scattering have been made at the angular scale relevant to Ligo, roughly the baffle radius divided by the tube length, or 10^{-4} radians. The capability to make these measurements would help us to have more confidence in Kip's estimates if equation (1) holds and to adjust the estimates of it doesn't. Moreover, it would be useful to know the mirror scattering functions as a source term to get optical transfer functions of the Ligo tubes for later modeling when Ligo exists, especially in the diagnostics for interferometer performance and to guide the development of improved interferometers. In addition to measurements of cavity mirrors, the scattering from other optical components will influence Ligo as well, since scattered light in the recombined beam forming optics can cause noise due to scattering. Scattering from Faraday isolators, Pockel cells and beamsplitters is not well known.

The light lost in a cavity is the sum of scattering and absorption. The absorption can be measured calorimetrically or radiometrically, and the total loss can be measured using ring-down techniques. Ideally, one should have access to all three tests, thus ensuring that we understand the mirrors, coatings and substrates. At present, only the ring-down test is done routinely. Total scatter measurements can be done for us by industry, but we may wish to have the capability ourselves.

Measurement of the parameter α in equation (1) and the functional dependence of scattering with angle is needed to evaluate optical coatings. We anticipate a lively interaction with the coating industry in the development of low absorption, low scatter coatings, and the capacity to measure scattering quickly will be needed. Again, this can be taken on by industry if need be.

In summary, the principal motivation for the development of a scatterometer is to have the capability to measure scattering at small angles from specular, because this scattering can cause noise in the gravitational interferometer. Evaluation of optical coatings and understanding of mirror losses are also aided by scatter measurement.

Present status of scatterometer planning

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The development of a design for a Ligo scatterometer has gone slowly. This memo outlines what the outstanding issues are.

The goal is to design an instrument which can measure scattering at any angle relative to the specular direction. Scattered light at small angles is difficult to detect because of the diffracted beam background. Scattered light at large angles is difficult because of its low intensity.

The spatial scale d of imperfections at which a surface will scatter at an angle θ is given by the grating equation

$$\lambda = d \sin\theta \tag{1}$$

where λ is the optical wavelength. Thus, one would like to have a probe beam diameter of roughly one centimeter. The optics which expand the beam to this size, and which contract it for subsequent detection must not scatter so much as to overwhelm the scattered light signal from the surface under test. This is a tough requirement, because there are more surfaces in the expansion/contraction optics than there are under test. One piece of the strategy to do these measurements involves subtraction of the instrument "signature" from the measured waveform.

The injection and collection of light are to be done with optical fibers. The input fiber serves as the source of a single mode beam. The collection fiber should be of larger diameter to collect more light. The design of a low scatter beam expansion/contraction system which does not overwhelm the scattering from a sample under test is the current design problem. Once this is designed and modelled the required arm length of the scatterometer will also be known.

Rayleigh scattering in air may be a noise source. Its contribution is proportional to the scatterometer arm length, and it may dictate that the measurement must be done in vacuum, though calculations show that it does not need to be a very high vacuum.

The reduced scattering intensity at large angles may require a different receiver than the one for small angles. The limiting noise source is the dark current of the photomultiplier.

This summarizes the areas which must be understood in order to design a scatterometer and evaluate its sensitivity. I estimate that it will take three weeks (part-time).