Estimates of the scattering from hot spots on the LIGO vacuum envelope

R Weiss July 15, 2007

Abstract: The dominant scattering phase noise in the interferometers comes from paths that involve the cavity mirrors and surfaces near the edge of the beams, the so called small angle scattering and recombination paths. The large angle scattering due to point scatterers on the mirrors contribute to the loss but are not important, at current levels, in making scattering phase noise. Paths with combined small and large angle scattering and recombination are not important, in part, because recombination outside the cavities is reduced in equivalent displacement noise by the cavity finesse.

The dominant paths involve scattering and reflecting surfaces at the etm endcaps which use the itm as scatterers and recombiners and at the reducing rings at HAM 2 and 5 which face the etm. The reducing rings have smoother surfaces than the endcaps and have a higher probability of making specular reflection glints than the endcaps. The ring surfaces need to modelled as both specular reflectors and scatterers. The phase noise from the specular part depends critically on the geometry and orientation of the rings and is found to be capable of making even larger contributions to the phase noise than has been measured if oriented in unfortunate directions.

The fix for both the end cap and reducing ring scattering are simple sheet metal baffles. The baffle to reduce the phase noise from the reducing ring is similar in concept to the beamtube conical baffle while the baffle to reduce the noise from the endcap can be a set of “Venetian” blind louvers spot welded to a ring held in the recess of the dished head. Both baffle designs can be constructed from light weight polished 304 SS sheet which does not need to be hydrogen free as the entire vacuum system in the LVEA is made from standard stainless steel. The baffles will eliminate the reflection paths and will present lower BRDF surfaces to the scattered mirror light. They also will not partake in the acoustically driven resonances that are causing us to worry that the ambient motions will cause noise in the enhanced interferometer. The same baffles will be useful in reducing the scattering intensities in advanced LIGO but more will be needed to deal with the low frequency seismic noise driven motions of any of the baffles. The baffles do not require a separate test pumpdown and evaluation as they are in places that can only reduce the existing scattering intensities and will not produce new paths that have to be evaluated.

The appropriate scattering and recombination relations for the large optics: The scattering relations for the mirrors at small angles is given by

$$\frac{\left(\frac{dP_{scat}}{P}(\theta)\right)}{d\Omega} = \frac{3\times10^{-7}}{\theta^2}$$

due to large scale surface fluctuations and at large angles by

$$\frac{\left(\frac{dP_{scat}}{P}(\theta)\right)}{d\Omega} = \frac{1\times10^{-5}}{\pi}$$

due to point scatterers in the mirror coating and on the surface. The crossing point between the scattering mechanisms occurs at angle of 0.3 radians (17 degrees).

Scattering paths: All the hot spots are within the small angle regime. I have looked at various paths that would involve scattering at larger angles, then reflection or scattering by a surface into the small angle regime for recombination with the main beam. All these paths give smaller phase fluctuations than the simple scattering by the mirror, followed by scattering or reflection by a surface near the main beam and then recombination on the same mirror. The paths I had suspected could be serious such as, say, an ITM scattering to its chamber (large angle scatter) followed by a scattering to a reducing ring (simple BRDF calculation), a reflection to an etm and final recombination on the etm (small angle recombination) produce much smaller phase noise.

Almost smooth surfaces: The almost smooth surfaces of the machined reducing rings in the LVEA are likely to be both reflectors and scatterers. The BRDF only applies to that part of the light power scattered. The reflected part obeys the standard rules of physical optics. The reflectivity of an almost smooth surfaces is given by

$$R = R_{smooth} e^{-\left(4\pi\left(\frac{\sigma}{\lambda}\right)\cos\theta_{incident}\right)^2}$$

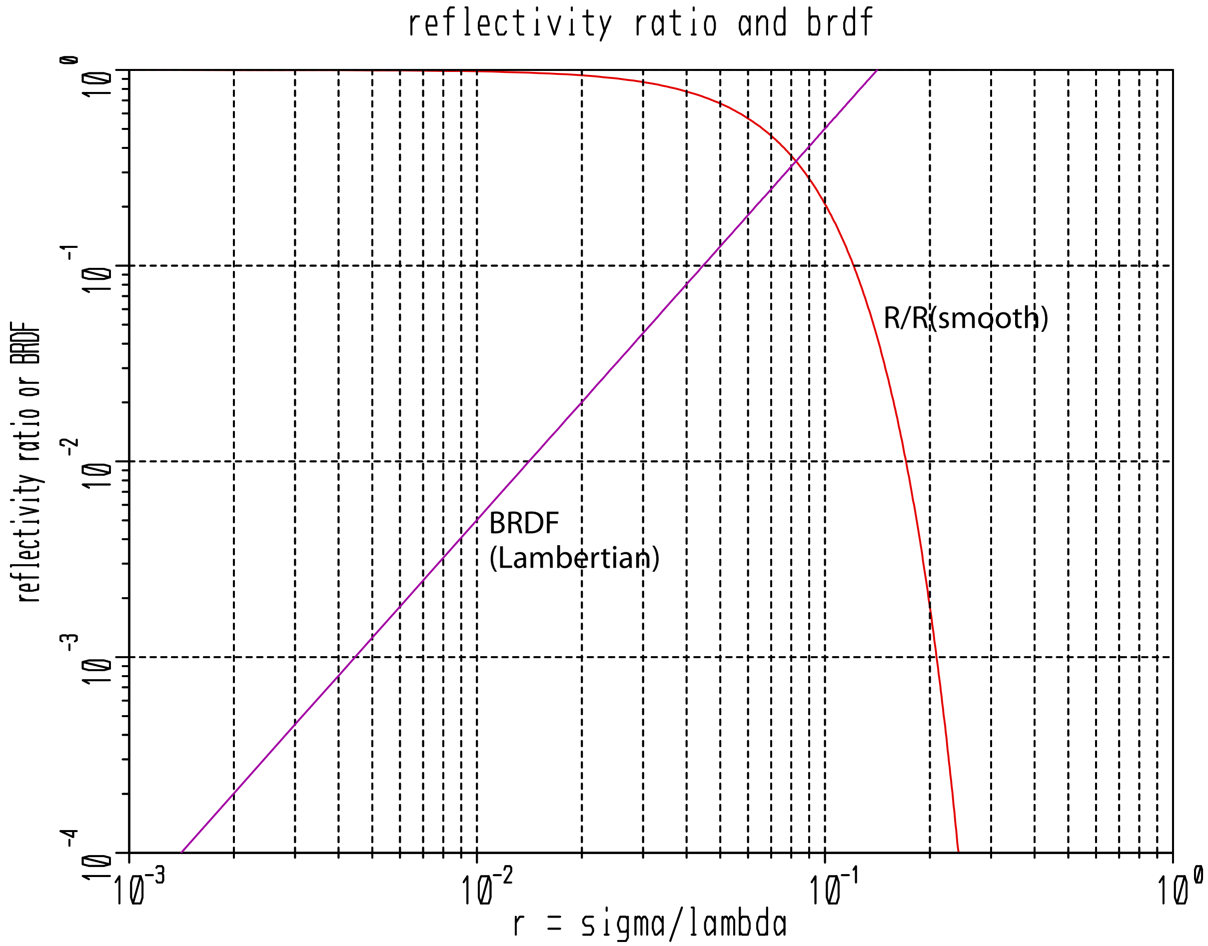
where σ is the surface height roughness, λ the light wavelength and $\theta_{incident}$ the angle of incidence. R_{smooth} is the reflectivity of a smooth surface of the same material. For small roughness the total power scattered by the surface (stolen from the reflection) relative to the incident power is the exponent of the exponential. On normal incidence, a surface with a roughness/wavelength ratio of 0.1 reflects only 0.2 of the light that would be reflected by a smooth surface, scatterring the rest with an angular distribution determined by the surface power spectrum. I suspect the best we would have on the hot spots is a surface roughness to wavelength ratio of 0.03, which gives a reflectivity of about 0.87 that of the smooth surface. The angular distribution of the reflected light is determined by the geometry of the incident light but has to be larger than that associated with coherent diffraction. The area of the light times the solid angle it subtends needs to be of the order of the wavelength squared. The angular size of a beam leaving a region of dimension 2a is at minimum $\theta \sim \frac{\lambda}{\pi a}$. In the estimates where reflection is assumed, I will use this relation to determine the minimum angular size of the beam and ratio it to the angular size of the recombining optic.

Estimate for the phase noise from the scattered light reflected by the reducing rings: The hunch is that the large values of scattering phase noise observed in both the LLO and LHO systems when vibrating the reducing rings at HAM 5 (and I would expect at HAM2 if that ring were accessible) is due to scattering by the ETM, reflection by the ring, and recombination by the same ETM. The large though smaller values of the phase noise due motions by the dished heads behind the ETM are from analogous paths that involve scattering by the ITM, backscatter from the rougher surfaces of the dished heads behind the ETM and then recombination on the ITM. I have looked at paths outside the cavity that would be recombined at the beam splitter or at the photodetector and find that they are less noisy in terms of meter/meter by the finesse of the cavity. Scattering into the 4km cavity dominates.

It is easy to get values of 10^{-9} meters/meter or larger by invoking reflection from the ring rather than scattering. The value depends in detail on the orientation of the ring surface normal and if optimally oriented can even give values as large as 10^{-8}. The calculation is similar to those done previously for the small angle case except that in treating the return power from the ring to the ETM, the reflection coefficient is used and and an upper limit is established from the diffraction angle due to the finite size of the ring. The diffraction angle is ten times smaller than the angular size of the ETM mirror so that in principle all the scattered power on the ring could be recombined at the ETM if only the surface of the ring were so directed. To achieve the value measured at both LLO and LHO of between 2×10^{-10} to 4×10^{-10} meters/meters requires that only about 1 percent of the light on the ring is returned to the ETM which is plausible.

The estimates for the scattering by the dished heads to and from the ITM have been made before and are about the same at both sites, approximately 5×10^{-11} meters/meter. The surface needs no more than a (reasonable) BRDF of 0.1 at normal incidence.

The rings are a machined surface while the dished heads have a rougher finish. I believe the difference between the dished head noise and the ring noise is explained by the direct reflection by the rings. The dished heads are just rough enough to suppress the reflection so that the scattering dominates. There is no reason from the current data to invoke the large angle scattering from the point scatterers.



reflectivity ratio and brdf
reflectivity ratio or BRDF
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
r = sigma/lambda
R/R(smooth)
BRDF
(Lambertian)