SCATTERED LIGHT CONTROL IN ADVANCED LIGO

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The phase shift of the light field scattered from baffles, beam dumps, optical elements, or from the vacuum enclosure walls that have horizontal motion, which is injected into the interferometer (IFO) optical mode, will cause an apparent differential arm signal. The magnitude of the scattered light noise depends upon the particular point in the IFO into which the light is injected; and for small phase angles, the phase noise is proportional to the rms amplitude of the horizontal displacement of the scattering surface and to the electric field amplitude of the scattered light injected into the IFO. Fringe wrapping will occur for large phase angles and will generate noise at odd harmonics of the fundamental motion frequency of the scattering surface. Transfer functions for the scattered light phase noise were used to calculate the apparent displacement noise cause by scattered light. For Advanced LIGO, the total scattered light phase noise, expressed in equivalent displacement noise, must be < 1/10 of the quadrature sum of the suspension thermal noise and the test mass thermal noise.

1 Scattered Light Displacement Noise Theory

1.1. *Scattered Light Noise Requirement*

A signal is received at the dark port of the Laser Interferometer Gravitational Wave Observatory (LIGO) interferometer (IFO) when the differential arm length (DARM) is modulated as a result of a gravity wave strain. The minimum DARM signal is defined by the following expression[1]:

$$V_{signal} = (DARM)Lh_{\min}\sqrt{P_0}$$

Where L is the arm length, h_{min} is the minimum gravity wave strain spectral density requirement—taken as the quadrature sum of the suspension thermal noise and the test mass thermal noise, P_0 is the input laser power into the IFO, and DARM is the signal transfer function.

In a similar manner, an apparent signal (noise) from scattered light occurs when a scattered light field with a phase shift is injected into the IFO at some particular location, e.g. through the back of the end test mass mirror (ETM) in the interferometer arm. The scattered light noise is defined by the following expression:

$$V_{noise} = (SNXXX)\delta_{\mathrm{SN}}\sqrt{P_{SNi}}$$

P_{SNi} is the scattered light power injected into the IFO mode, δ_{SN} is the phase shift of the injected field, and SNXXX is the noise transfer function for that particular injection location.

The phase shift spectral density of the injected field due to the motion of the scattering surface is given by

$$\delta_{\mathrm{SN}} = \frac{4\pi x_s}{\lambda}$$

where x_s is the spectral density of the longitudinal motion of the scattering surface and λ is the wavelength of the light field. In general, the different scattering sources are not coherent and must be added in quadrature. The requirement for total scattered light displacement noise can be stated with the following inequality:

$$\sqrt{\sum_{i=1}^{n}\left(\frac{SNXXX}{DARM}\frac{4\pi x_s}{\lambda}\sqrt{\frac{P_{SNi}}{P_0}}\right)^2} \le \frac{1}{10}Lh_{\min}$$

2. Calculating Scattered Light Displacement Noise

2.1. *Scattered Light Noise Sources*

The severity of the scattered light noise depends upon the injection point in the interferometer; e.g. the noise caused by light scattered into the power recycling side (PR) of the interferometer is reduced by common mode rejection of the arms, whereas the same light power scattered directly into the arm cavity adds to the differential arm signal and causes the greatest amount of noise.

The possible scattered light injection points are summarized in Figure 1. PR is the power recycling side; SR is the signal recycling side and dark port; BS is the beam splitter; ITM is the input test mass; ETM is the end test mass.

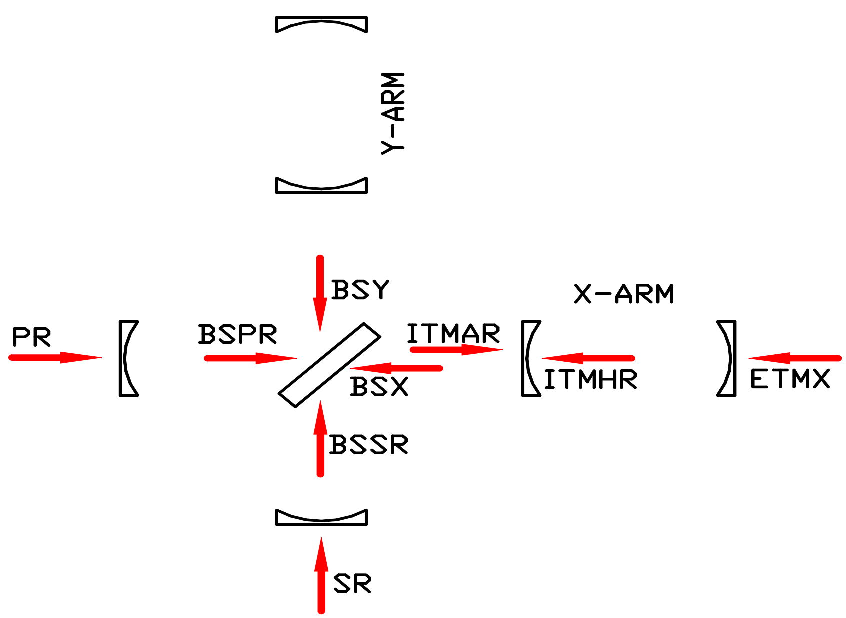

Figure 1: Scattered Light Injection Points

The SNXXX/DARM[1] scattered light noise transfer function ratios for various injection locations within the IFO were calculated using the LIGO FFT E2E model and are shown in Figure 2.

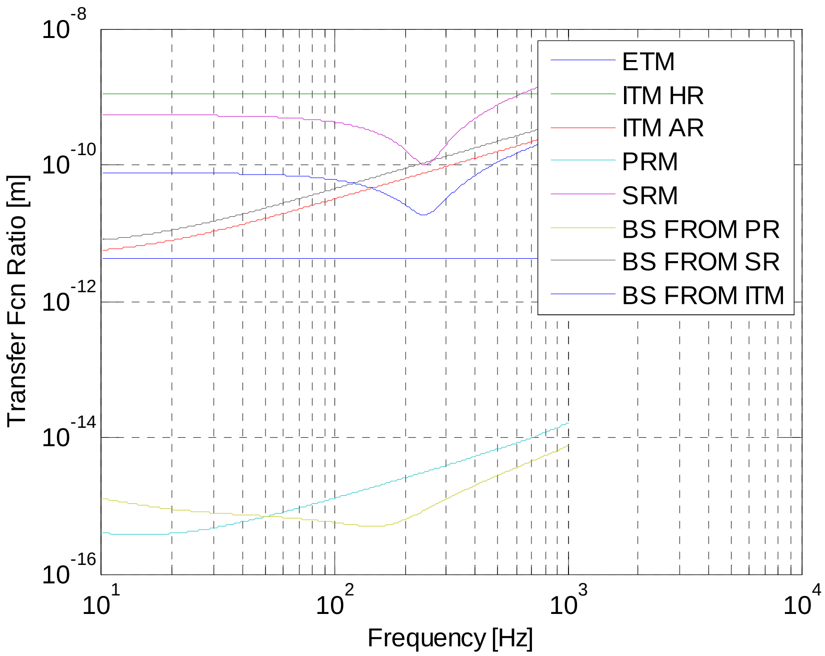

Figure 2: Scattered Light Noise Transfer Functions

2.2. *Scattered Light Power into the IFO*

The light power scattered into the interferometer from the ith source is calculated as follows[2]:

$$P_{SNi} = P_{in}(BRDF)\Delta\Omega \frac{w_{IFO}^{2}}{w_{SN}^{2}} T$$

Where P_{in} is the power incident on the scattering surface, BRDF is the fraction of incident light that is scattered per unit solid angle, $\Delta\Omega$ is the solid angle subtended by the mode inside the IFO arm, w_{IFO} is the beam waist of the mode inside the arm, w_{SN} is the beam waist of the beam incident on the scattering surface, and T is the transmissivity of the path from the scattering surface to the injection point in the IFO.

The effective solid angle increases whenever the IFO beam waist has been transformed to a smaller waist by a beam-reducing telescope or some other focusing element, because the product of solid angle and beam waist cross-sectional area is proportional to the total radiant flux, which is an optical invariant. Therefore, as the area of the beam waist decreases the effective solid angle increases proportionally.

2.3. *Bidirectional Reflection Distribution Function (BRDF)*

The BRDF is an empirical parameter that describes analytically the scattering properties of a surface, and in general depends both upon the incident angle and the scattering angle. However, for the purposes of the scattering calculations described above, we are interested only in the back-scatter BRDF, in which the scattered light returns directly back onto the incident ray direction. The BRDF depends upon the incident angle and on the polarization of the incident light beam.

We will use the "cosine corrected" definition of BRDF in which the effective reduction of the scattering surface area due to the obliqueness of the incidence beam is included in the BRDF value. With this definition, BRDF is simply the fractional scattered light per unit scattering solid angle.

$$BRDF = \frac{P_{scat}}{P_{in}} \frac{1}{\Delta\Omega}$$

The back-scatter BRDF of selected baffle materials was measured[3] with the apparatus shown schematically in Figure 3. The laser source creates a laser beam that is reflected from two steering mirrors. The beam passes through the "Beam Focus," a telescope with a pair of lenses to create a beam waist at the sample location. A rotatable half-wave plate sets the plane of polarization at the sample. The chopper wheel modulates the beam signal to discriminate against ambient light scattered from the sample. The beam passes through an aperture and then through a hole in a mirror before hitting the sample. The aperture ensures that no light is scattered from the inside of the hole in the mirror. This is crucial because the surface of the mirror is in direct line of sight of the photodiode. A beam dump on a rotatable arm is positioned to catch the specular reflection from the sample. The backscattered light is reflected around the edges of the hole in the "Splitter Mirror" through an adjustable aperture, which is used to set the solid angle for the BRDF calculation. The backscattered light is then focused onto a photodiode to form an image of the scattering spot at the sample. The signal from the photodiode is sent to a lock-in amplifier which uses the modulation frequency set by the chopper wheel to reject any ambient light signals. The 50/50 beam splitter enables us to view the surface of the sample with a camera and ensure there are no dust particles causing erroneous scatter data, such as are shown in Figure 4.

The measured BRDF of polished stainless steel samples with various amounts of oxidation to reduce the reflectivity are shown in Figure 5.

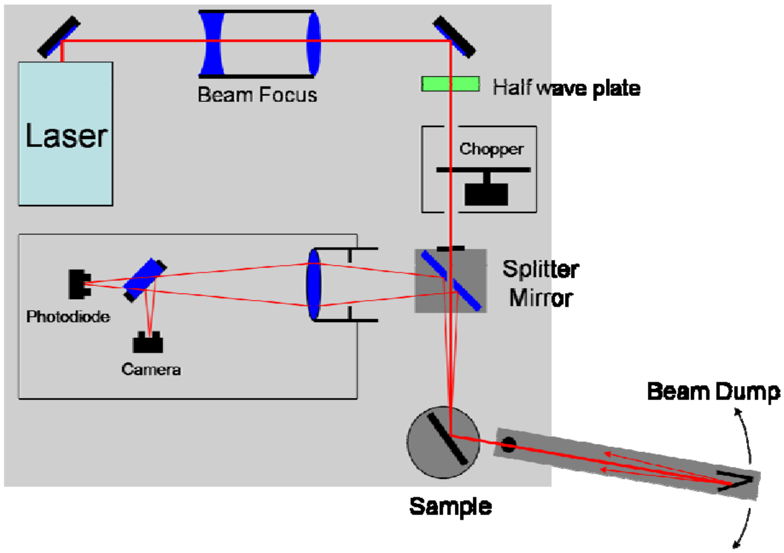

Figure 3: Scatterometer Layout

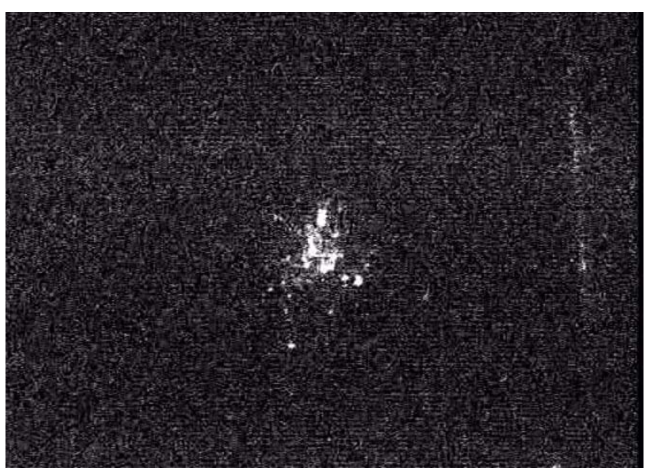

Figure 4: Scattered Light from Dust Particles on the Sample

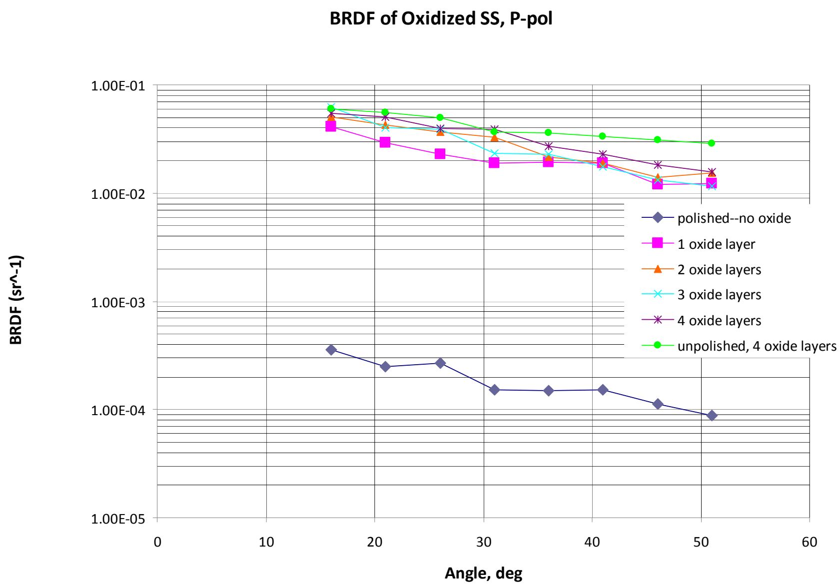

Figure 5: BRDF of Oxidized Polished Stainless Steel

2.4. *Motion of the Scattering Surface*

The motion of the scattering surface is measured using accelerometers and seismometers. The motion data is presented as the amplitude spectral density of the surface motion for a range of motion frequencies of interest, in units of meter/square root Hertz. The data shown in Figure 6 is typical of the motion of one of the large vacuum manifold tubes of the interferometer to which some of the baffles are attached.

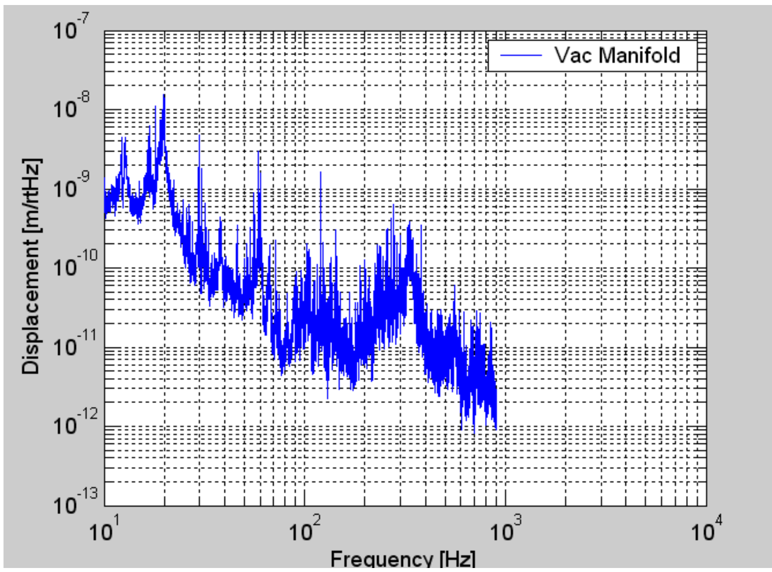

Figure 6: Seismic Motion of a LIGO Vacuum Manifold Surface

3. Mitigating Scattered Light Displacement Noise

3.1. *Output Faraday Isolator*

A typical example of mitigating the scattered light noise is the suspension of the output Faraday isolator, whose purpose is to attenuate scattered light from re-entering the interferometer from the dark port. The optical surfaces of the output Faraday isolator are themselves a serious source of scattered light displacement noise, and the noise from those surfaces is mitigated by suspending the output Faraday isolator and thereby reducing the displacement amplitude of the surfaces.

A 3D graphical model of the Advanced LIGO suspended output Faraday isolator is shown in Figure 7. Horizontal motion attenuation is accomplished by suspending the Faraday isolator with vertical wires that provide a horizontal pendulum frequency of < 1 Hz, with a motion transfer function that falls off above the resonant frequency with a frequency dependence of 1/f or $1/f^2$, depending upon the damping attachment. Vertical motion isolation is provided by the two blade springs that are designed to also have a resonant frequency of < 1 Hz. The Faraday isolator is mounted to an optical table inside the vacuum chamber that provides passive vibration isolation from the ground seismic motion.

The calculated horizontal displacement noise caused by scattering from the suspended optical surfaces of the Faraday isolator is shown in Figure 8 for two different damping attachments—with the eddy-current damping magnets attached to the mounting frame, and with self-damping within the wire suspension and blade springs themselves. The requirement for scattered light displacement noise, as discussed in 1.1 is shown in Figure 8 for reference. The requirement is met for operational frequencies between 10 and 1000 Hz.

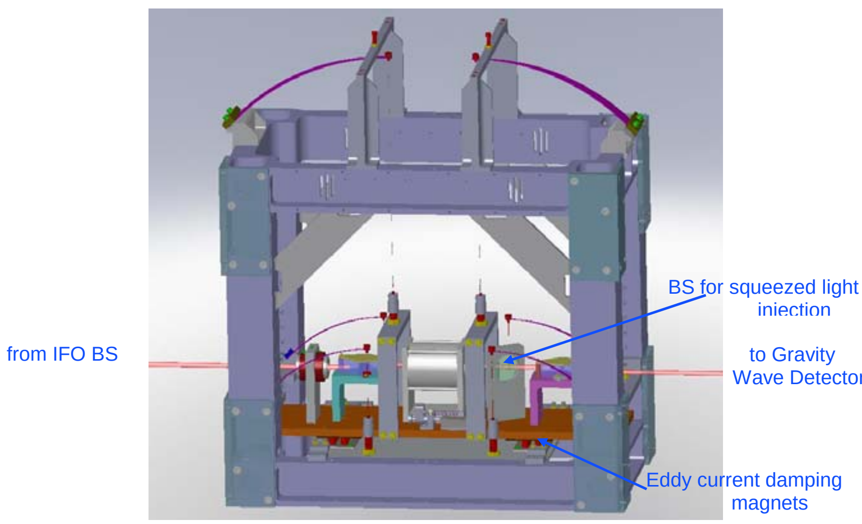

Figure 7: Suspended Output Faraday Isolator

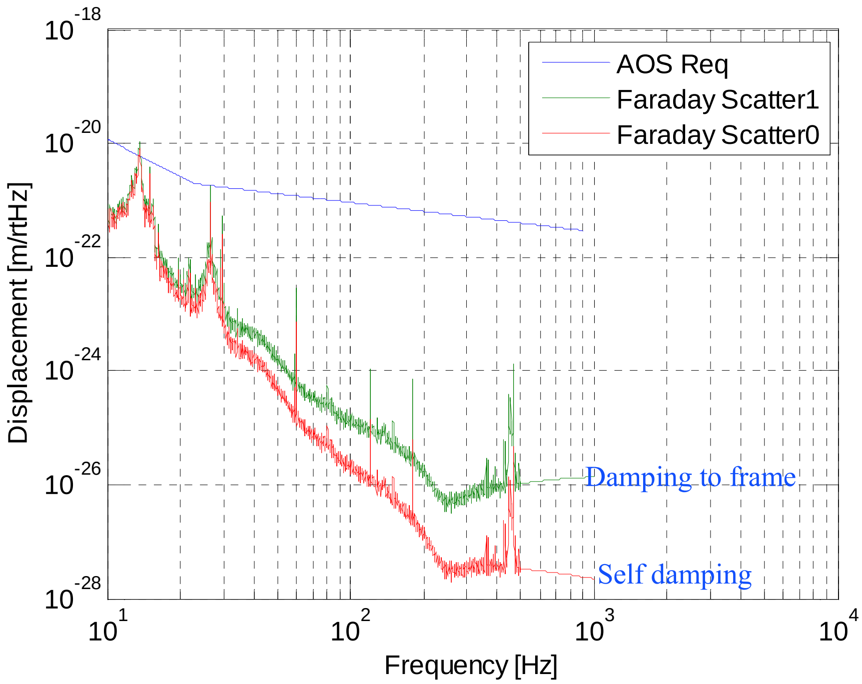

Figure 8: Scattered Light Displacement Noise from Suspended Output Faraday Isolator

3.2. *Other Examples*

Other examples of scattered light mitigation devices used in Advanced LIGO are shown in Figure 9. The Arm Cavity Baffle intercepts the light scattered from each test mass at the opposite ends of the arm cavity. The Wide-angle Baffle intercepts the wide-angle scattered light from the near test mass. The Cavity Beam Dump catches and absorbs the light that transmits through the folding mirror in front of it. These baffles and beam dumps are suspended, and their motion is damped to reduce the scattered light noise from the mitigating devices themselves.

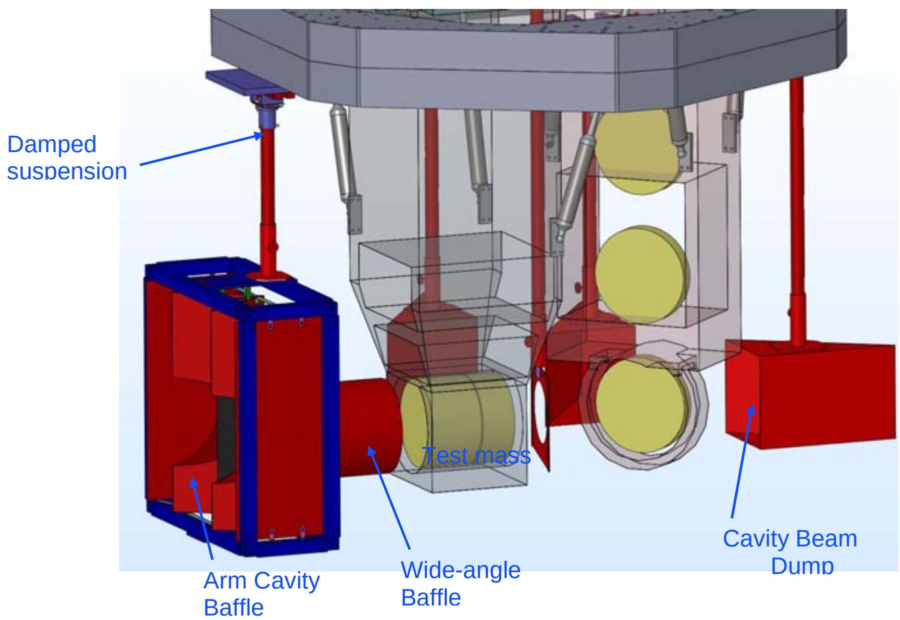

Figure 9: Baffles and Beam Dumps in Advanced LIGO

The ray positions of the various ghost beams and scattered light beams and the locations of the baffles and beam dumps within the interferometer are modeled with an optical design program, ZEMAX, as shown in the ray trace diagram in Figure 10.

4. Conclusion

The results of the scattered light mitigation are shown in Figure 11, where the major scattered light sources are plotted. The total scattered light displacement noise requirement shown in the top green trace is 1/10 the thermal displacement noise of the suspension and coatings of the test masses, shown in blue. The quadrature sum of the scattered light displacement noise shown in red meets the Advanced LIGO requirement in the gravity wave detection band between 10 Hz to 600 Hz.

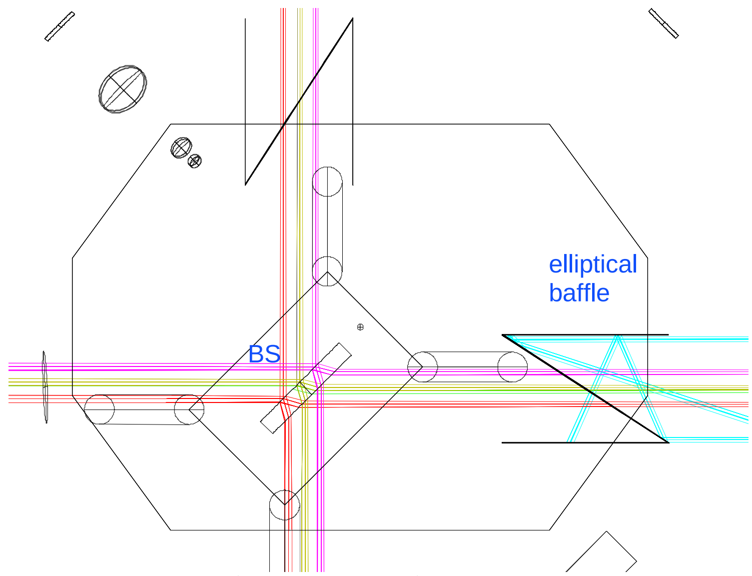

Figure 10: Ray Trace Diagram

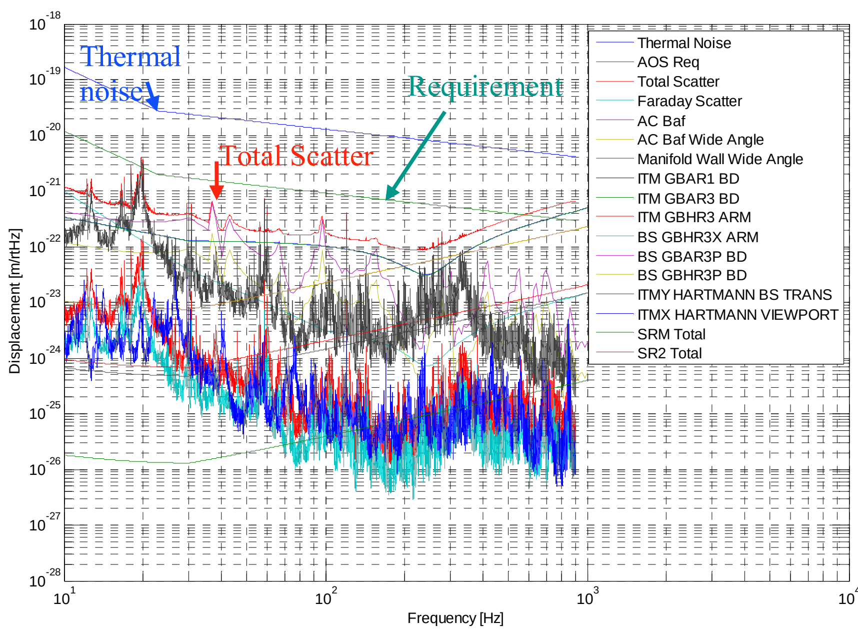

Figure 11: Total Scattered Light Displacement Noise

Acknowledgments

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