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Displacement Noise in Advanced LIGO Triple Suspensions

M. Evans, P. Fritschel

Distribution of this document:

Detector Group

California Institute of Technology
LIGO Project, MS 18-34
Pasadena, CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project, Room NW22-295
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

LIGO Hanford Observatory
Route 10, Mile Marker 2
Richland, WA 99352
Phone (509) 372-8106
Fax (509) 372-8137
E-mail: info@ligo.caltech.edu

LIGO Livingston Observatory
19100 LIGO Lane
Livingston, LA 70754
Phone (225) 686-3100
Fax (225) 686-7189
E-mail: info@ligo.caltech.edu

http://www.ligo.caltech.edu/

1 Summary

This note examines the expected low frequency length noise in the Michelson and signal recycling cavity degrees-of-freedom and their impact on the gravitational wave channel. The current designs of the suspensions for the beamsplitter and the signal recycling cavity optics lead to noise estimates that mostly lie below the limits established by treating these as technical noise sources. The estimates lie above the noise limit for the signal recycling cavity noise, however, in the 10-30 Hz band.

For the small and large triple suspensions, the noise limit shown in Fig. 2 should be taken as the target noise level, but recognizing that seismic noise is expected to exceed this target at very low frequencies. From these modeling results, we can make some recommendations for the design of these suspensions:

- The suspension thermal noise level is acceptable, provided the effective wire loss is close to 2×10^{-4}, so care needs to be taken in the implementation to achieve this.
- Efforts should be made to increase the vertical seismic isolation, particularly in the 10-20 Hz band.
- Consideration should be given to making the highest vertical eigenfrequency (the 'bounce mode') the same for both small and large triples (probably the higher frequency of the current small triple design is preferred).

For the beamsplitter suspension, the noise limit shown in Fig. 2 is more readily achieved across the full band; the following recommendations are made for the BS suspension:

- The suspension thermal noise level is acceptable, provided the effective wire loss is 2×10^{-4} or less, so care needs to be taken in the implementation to achieve this.
- Consideration should be given to increasing the vertical seismic isolation, to provide more margin for potentially higher BSC ISI platform noise in the 10-20 Hz band.

Finally, since coupling of vertical motion to optical path length is shown to be significant, the optical layout of the recycling cavities should be done so as to minimize this coupling; preferrably the coupling determined by the beam path should be smaller than 10^{-3}.

2 Strain Noise Limits

We place limits on the equivalent strain noise due to displacement noise in the signal recycling cavity and Michelson, assuming that these noise sources are dominated by suspension thermal noise in the band of interest. For Michelson noise, the coupling to strain (meters of DARM per meters of MICH) is independent of frequency. Michelson noise due to beamsplitter suspension thermal noise falls as $f^{-5/2}$, essentially the same slope as for the target strain noise spectrum at low frequencies. So we limit Michelson strain noise at 10 times below the interferometer noise for the operating mode that has the best low frequency performance.

For signal recycling cavity noise, the coupling to strain (meters of DARM per meters of SRCL), falls as f^{-2}. Suspension thermal noise of the SRC optics will thus produce an equivalent strain noise that falls as $f^{-9/2}$. The SRC coupling to strain also scales linearly with the stored arm power. Taking these factors into consideration, we limit SRC strain noise at 10 times below the high-power interferometer noise at 20 Hz.

These limits are shown explicitly in Fig. 1. Note that due to the power scaling of the SRCL coupling, in the low-frequency performance modes (*1a* and *3*), SRCL strain noise will be at least 10 times below interferometer noise above 10 Hz.

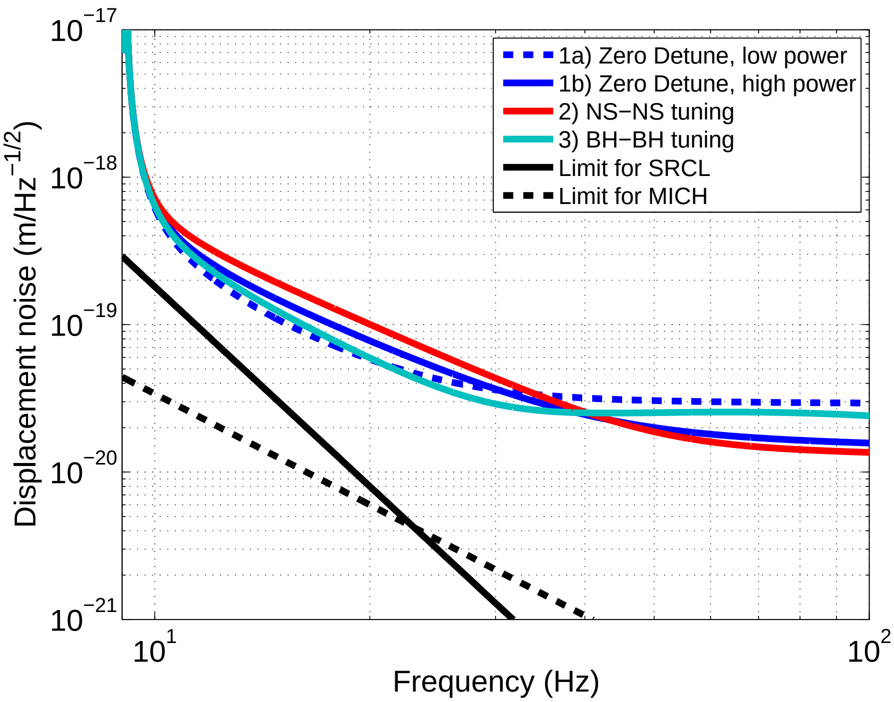

Figure 1: DARM (differential arm) displacement noise for the interferometer in its different modes of operation (colored curves), and the limits for the equivalent DARM noise due to noise in the Michelson (MICH) and signal recycling cavity length (SRCL) degrees-of-freedom. For SRCL, the limit is set at 10 times below the mode 1b noise at 20 Hz. For MICH, the limit is 10 times below the mode 3 noise at 20 Hz.

To turn these equivalent strain noise limits into limits on the signal recycling cavity optics and the beamsplitter, we divide by the coupling factors. For the beamsplitter, the factor is:

$$x_{DARM}/x_{BS} = \pi/\sqrt{2}F\,,$$

where F is the arm cavity finesse and x refers to motion along the normal to an optic's HR surface. For the signal recycling cavity, the coupling is:

$$\frac{x_{DARM}}{x_{BS}} = 6\times10^{-3}\left(\frac{10\,\mathrm{Hz}}{f}\right)^2\left(\frac{P_{arm}}{750\,\mathrm{kW}}\right)\left(\frac{0.014}{T_{ITM}}\right)\left(\frac{\mathrm{DARM_{off}}}{5\,\mathrm{pm}}\right).$$

While the full parameter dependence is shown above, at high power the only parameter that is really open is the DARM offset, which we take to be 5 pm. This looks to be large enough to provide full sensitivity (see the ISC conceptual design, T070247-00), but there is certainly some uncertainty in this parameter.

The displacement noise limits for the signal recycling cavity optics and beamsplitter are shown in Fig. 2. Note that we have also leveled off the noise limits above 30 Hz for SRCL and above 40 Hz for the BS, given their lower impact on interferometer noise at higher frequencies.

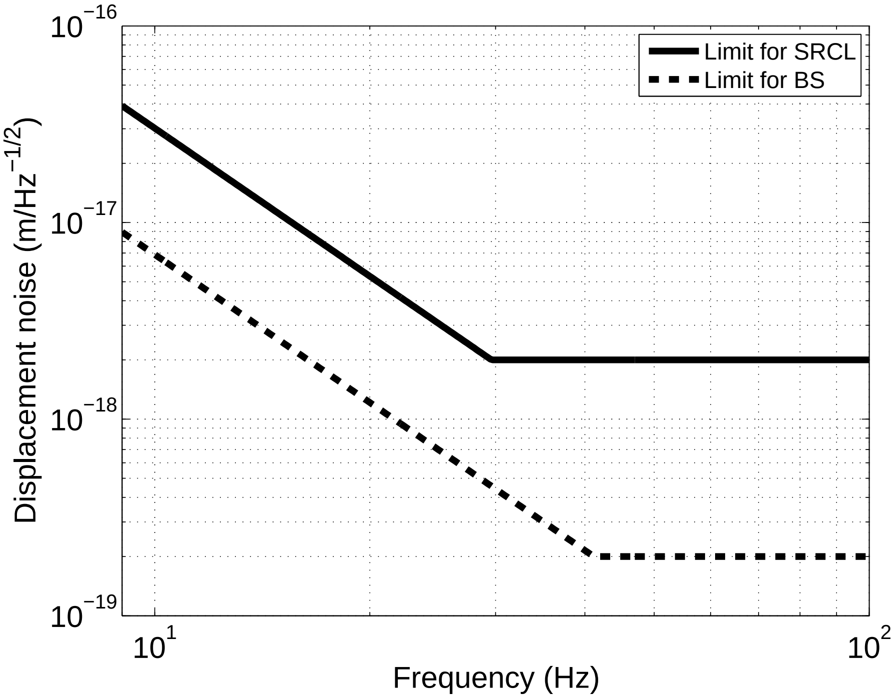

Figure 2: Displacement noise limits for the signal recycling cavity length (SRCL) and the beamsplitter (BS) longitudinal motion, as derived from Fig. 1 and the coupling factors. These limits do not (cannot) apply to suspension vertical mode peaks that would be expected to lie above these curves. The limits are leveled off at higher frequencies, where these noise sources become less significant in the interferometer strain noise.

3 Displacement Noise Estimates

3.1 Signal recycling cavity

The signal recycling cavity contains two small triple suspensions (HSTS) and one large triple suspensions (HLTS). Of course the SRC also contains the two ITMs and the BS, both of which contribute in principle to SRC length noise, but their contributions are much smaller than the HAM triple suspensions so we neglect them.

The SRC length noise estimate includes seismic platform noise and suspension thermal noise, and in particular the longitudinal and vertical components of each. For the seismic platform input, we have made a model based on the performance of the LHO HAM ISI built up in HAM6 for Enhanced LIGO. This is shown in Sec. 4 (Fig. 6). The suspension transfer functions are calculated from the matlab models of the HSTS and HLTS as defined at the end of July 2008. These are shown in Sec. 4 (Fig. 7).

The thermal noise is calculated using the matlab code developed for the quad suspension, specifically the function 'suspR.m' found in the GWINC package. The parameters are suitably altered for the wire suspensions, and to mock a triple suspensions. The main parameters that determine the suspension thermal noise are the assumed loss and dimensions of the final stage suspension wires. These are:

Type	*Wire diameter*	*Wire loss*	*Wire length*
HSTS	120μm	2×10^{-4}	22.0 cm
HLTS	240μm	2×10^{-4}	25.7 cm

The seismic and thermal noise estimates for a single HSTS and HLTS are shown in Fig. 3. The total SRC length noise, due to the triple suspensions, is shown in Fig. 4. SRC length noise is calculated according to: $x_{\mathrm{SRCL}} = (x_{\mathrm{HSTS}}^2 + (2x_{\mathrm{HSTS}})^2 + (2x_{\mathrm{HLTS}})^2)^{1/2}$.

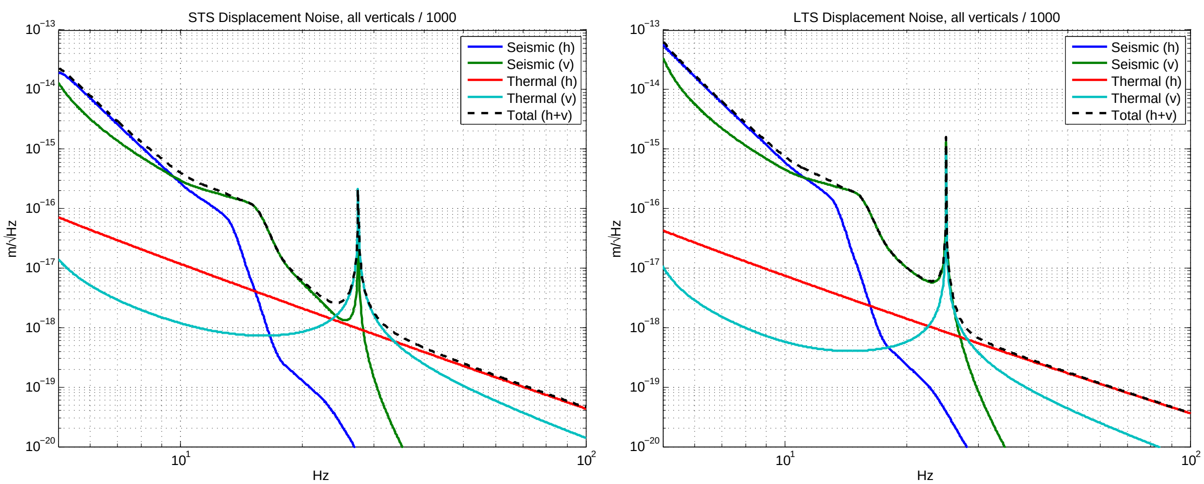

Figure 3: Seismic and suspension thermal noise estimates for the small (STS) and large (LTS) triple suspensions, mounted on HAM ISI platforms.

3.2 Beamsplitter

The Michelson noise is dominated by that of the beamsplitter, since the ITMs are better isolated in their quad suspensions. The BS longitudinal noise estimate, shown in Fig. 5 includes seismic platform noise and suspension thermal noise (longitudinal and vertical components of each). The seismic platform input is shown in Sec. 4 (Fig. 6). The suspension transfer functions are calculated from the matlab models of the BS as defined at the end of July 2008. These are shown in Sec. 4 (Fig. 7).

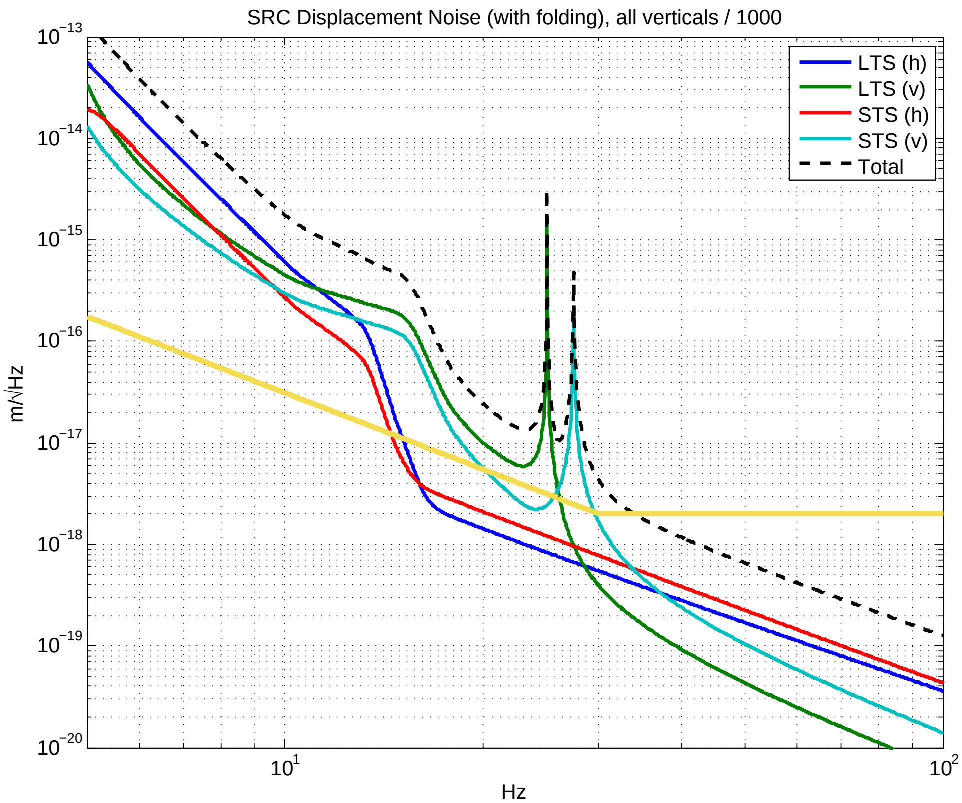

Figure 4: Estimate of the total SRC length noise due to seismic and suspension thermal noise in the three SRC triple suspensions. The gold line is the SRCL noise limit from Fig. 2. The estimate exceeds the limit below about 20 Hz; the excess is due to vertical seismic noise in the 15-20 Hz band, and due to horizontal seismic noise in the 10-15 Hz band.

The thermal noise is calculated using the matlab code developed for the quad suspension, specifically the function 'suspR.m' found in the GWINC package. The parameters are suitably altered for the wire suspensions, and to mock the BS suspension. The main parameters that determine the suspension thermal are taken to be: wire loss, 2×10^{-4}; wire diameter, $246\,\mu$m; wire length, 0.5 m.

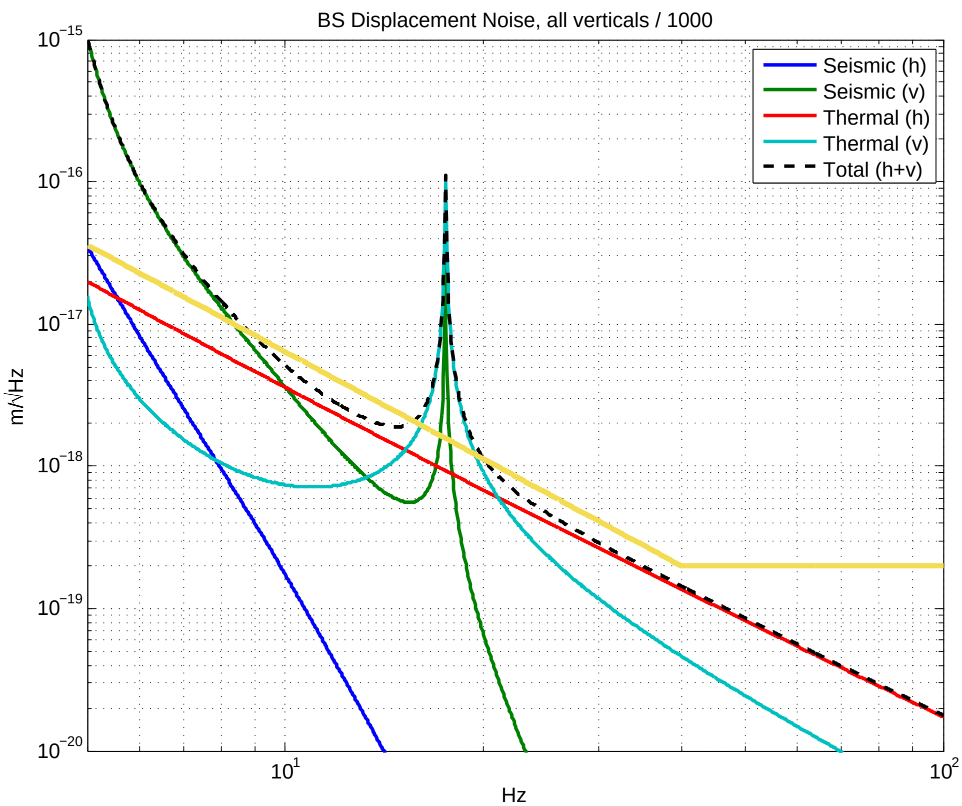

Figure 5: Estimate of the total BS longitudinal noise due to seismic and suspension thermal noise. The gold line is the BS noise limit from Fig. 2.

4 Reference data

For reference, we show here the model for the seismic platform noise, and the suspension transfer functions.

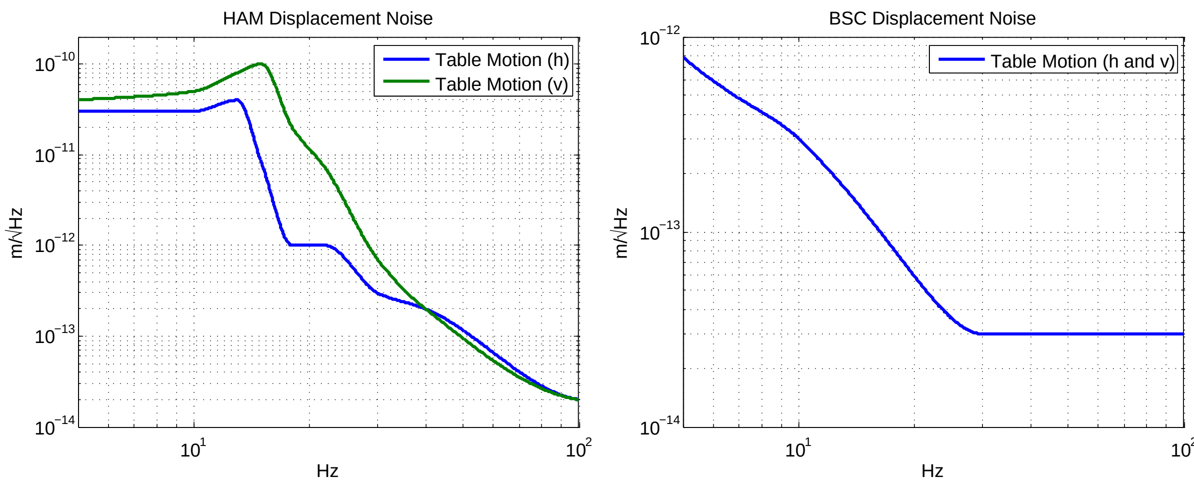

Figure 6: Seismic platform noise models used to calculate the displacement noise estimates in this document. The HAM ISI model derives from the performance data taken on the LHO HAM ISI (installed in HAM6) in July 2008. These are smoothed versions of this; the peaks in the actual data due to resonances of the external 'gull-wing' supports have been smoothed over, as these peaks are expected to be increased in frequency with stiffer supports, and well-damped by the HEPI system they will mount on in Advanced LIGO. Vertical motion is significantly higher than horizontal in the 10-30 Hz region because the vertical ground motion is much higher than the horizontal in this region (the isolation provided by the ISI is about the same in the two directions). The BSC ISI model is the nominal displacement requirement for the BSC platform.

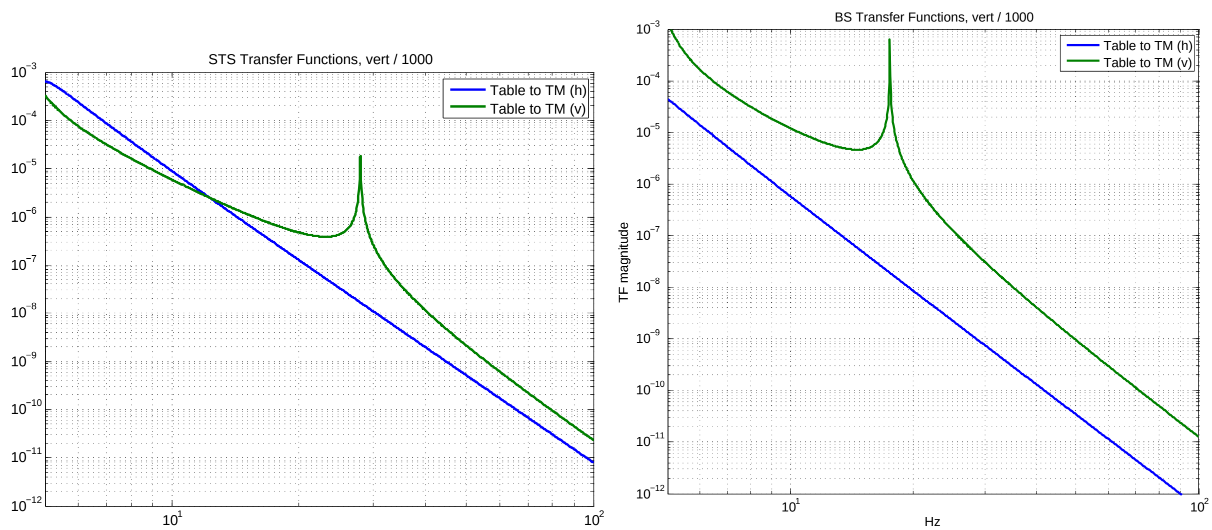

Figure 7: Longitudinal and vertical suspension transfer functions for the small triple suspension (STS) and the beamsplitter suspension, as used in this document. Note that the vertical transfer functions are multiplied by 0.001, for the assumed cross-coupling into the longitudinal degree-of-freedom (even with this factor, the BS vertical transfer function lies significantly above the horizontal!). The LTS transfer functions are very similar to the STS (except that the vertical mode is at about 25 Hz) and so are not shown here.