Revised HAM-ISI Performance Targets for Advanced LIGO Signal Recycling Cavity Chambers

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1 Summary

We present new performance ‘targets’ for the optical tables in HAMs 4, 5, 10, and 11 for Advanced LIGO. These new targets have improved performance around 10 Hz to reduce the noise in the Signal Recycling Cavity Length (SRCL). This is in response to the calculations by Peter Fritschel and Matt Evans in T080192 ‘Displacement Noise in Advanced LIGO Triple Suspensions’. In that document, they present a target motion for the SRCL of 3e-17 m/$\sqrt{\text{Hz}}$ at 10 Hz. Based on that number, both SEI and SUS have looked for additional opportunities to improve isolation from the ground, resulting in the addition of feedforward sensors on stage 0 of the HAM-ISI platforms for HAMs 4, 5, 10 and 11 (and LASTI), and improved vertical isolation for the triple suspensions.

As of this writing, the HAM and BSC targets below 0.2 Hz are still in discussion. This document describes the targets around 10 Hz.

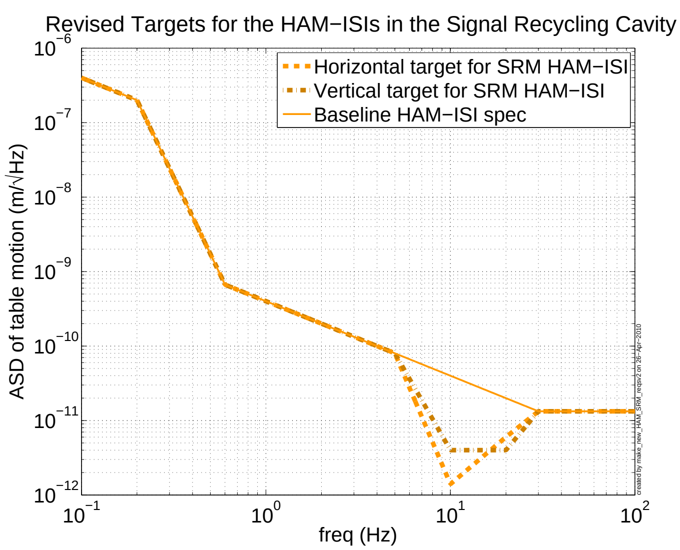

Figure 1: Suggested target for HAM-ISI performance at 10 Hz for the chambers in the signal recycling cavity. At 10 Hz, the horizontal target is 1.4e-12 m/$\sqrt{\text{Hz}}$ and the vertical target is 4e-12 m/$\sqrt{\text{Hz}}$. Table 2 details the new target.

Given the models for the suspension systems, reaching a SRCL motion of 3e-17 m/$\sqrt{\text{Hz}}$ at 10 Hz would require a horizontal motion of the HAM-ISI of 6e-13 m/$\sqrt{\text{Hz}}$ at 10 Hz, a goal which does not seem possible with the current design.

The original target left some margin between the SRCL length and the quantum limited noise of the LIGO interferometer at 10 Hz. If we set the seismic noise at 10 Hz to be equal to the quantum noise of the detector at 10 Hz, then the SRCL length at 10 Hz is roughly 5.9e-19 m/$\sqrt{\text{Hz}}$ at 10 Hz. If the horizontal motion of the HAM-ISI is 1.4e-12 m/$\sqrt{\text{Hz}}$ at 10 Hz, then SRCL will be just below the quantum noise, and this is a level which we may be able to achieve. The new targets are shown in figure 1.

We believe that we can probably achieve 1.4e-12 m/$\sqrt{\text{Hz}}$ at 10 Hz in the horizontal direction, or at least come close. We have reached performance of about 1e-11 m/$\sqrt{\text{Hz}}$ at 10 Hz in the Y direction of HAM6-ISI, slightly below the frequency of the gullwing resonance. We have seen performance improvements from sensor correction at 10 Hz of about a factor of 10, although typically this has been done without the high performance isolation loops in operation. The sensor noise of the L-4C used for feedforward is about 8.5e-13 m/$\sqrt{\text{Hz}}$ at 10 Hz (in the high-gain mode).

2 Calculations

2.1 SRCL Target

The original SRCL target was set forth in T080192-01 as 3e-17 m/$\sqrt{\text{Hz}}$ at 10 Hz. This allowed some margin between the quantum noise and the technical noise. However, given the transmissions of the various triple suspensions, this would require the horizontal motion of the HAM ISI to be 6e-13 m/$\sqrt{\text{Hz}}$ at 10, which is not something we believe can be achieved. Instead, we set the SRCL length contribution at 10 and 11 Hz to match the quantum noise, as shown below in figure 2. At this level, we may be able to achieve the desired performance at 10 Hz. Since the coupling of SRCL to DARM is a function of the power, if we run the IFO in the lower power mode to look for lower frequency sources, the impact of SRCL will be reduced.

The conversion from SRCL to DARM is given in T080192 as

$$\frac{x_{DARM}}{x_{SRCL}} = 6 \times 10^{-3} \left(\frac{10\text{ Hz}}{f}\right)^2 \left(\frac{P_{arm}}{750\text{ kW}}\right) \left(\frac{0.014}{T_{ITM}}\right) \left(\frac{DARM_{offset}}{5\text{pm}}\right) \tag{1}$$

At full power, with the nominal parameters, we can calculate the allowed motion of the cavity length, as shown below in table 1.

2.2 HAM-ISI coupling to SRCL

The layout if the aLIGO detector is shown in figure 3. The signal recycling cavity has optics on both HAM4 and HAM5. Since the cavity is folded, the motion of the SR2 and

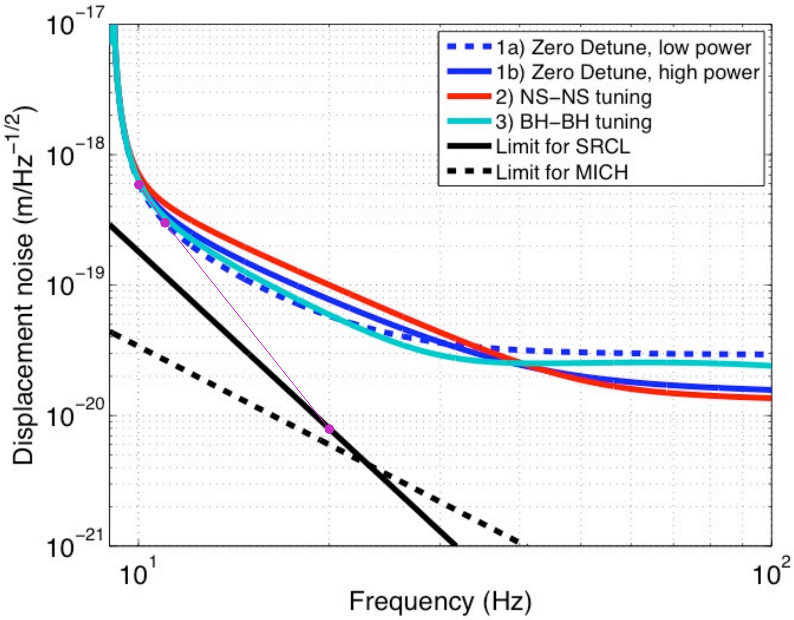

Figure 2: Suggested target for SRCL length in terms of DARM motion at high power, adapted from figure 1 of T080192-01. The original SRCL target is shown as the solid black line, which crosses 10 Hz at 3e-17 m/$\sqrt{\text{Hz}}$. The revised target is shown as the purple curve, which matches the low-power, Zero Detune IFO noise between 10 and 12.1 Hz, then rejoins the original curve at 20 Hz.

Frequency (Hz)	DARM target for SRCL motion ASD (m/$\sqrt{\text{Hz}}$)	SRCL equivalent at full power motion ASD (m/$\sqrt{\text{Hz}}$)
10.0	5.90e-19	9.83e-17
11.0	3.00e-19	6.05e-17
20.0	7.80e-21	5.20e-18

Table 1: Revised SRCL target

SR3 optics is doubled.

The coupling from the seismic tables to the SRCL is estimated by assuming that HAM 4 has a HAM Small Triple Suspension (HSTS) for SR2, and that HAM5 has both a HSTS and a HAM Large Triple Suspension (HLTS), namely SRM and SR3. We assume that the input HAM motion for the 2 optics in HAM5 are the same, so we estimate the length of the cavity to be

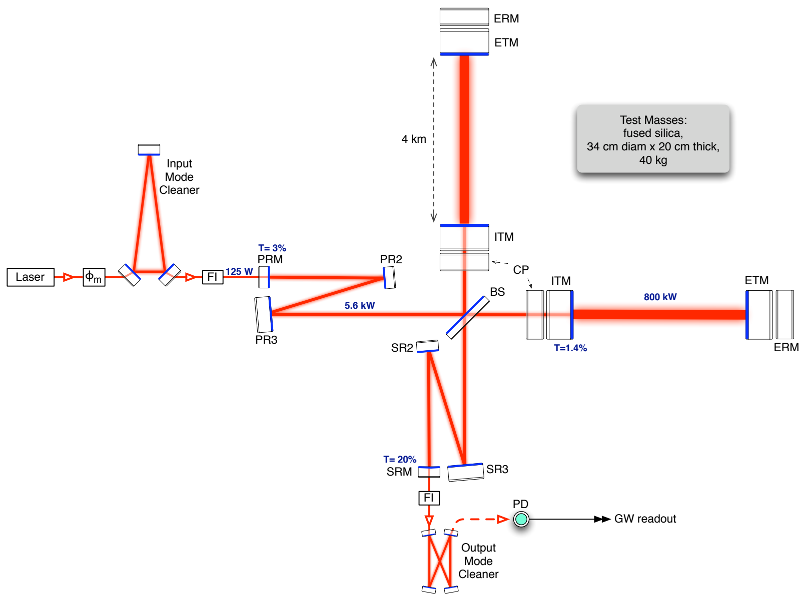

Figure 3: System Layout for Advanced LIGO. SRM and SR3 are in HAM 5 and SR2 is in HAM 4. SR3 is a large triple suspension (HLTS), and SRM and SR2 are small triple suspensions (HSTS).

$$\begin{aligned} x_{SRCL} =& x_{HAM4-ISI} \times 2\, xTF_{HSTS} + x_{HAM5-ISI} \times (2\, xTF_{HLTS} + xTF_{HSTS}) \\ &+ 10^{-3} \times (z_{HAM4-ISI} \times 2\, zTF_{HSTS} + z_{HAM5-ISI} \times (2\, zTF_{HLTS} + zTF_{HSTS})) \end{aligned} \tag{2}$$

where xTF_{HSTS} is the transfer function of the HSTS from longitudinal motion of the table to longitudinal motion of the final optic. For the vertical to horizontal coupling, we use 10^{-3} of zTF_{HSTS} which is the transfer function from vertical table motion to vertical optical motion. The HLTS functions are the analogs for the HLTS. Coherently adding the noise of the table through the SRM and SR3 suspensions gives a more restrictive motion requirement for the ISI than was originally shown. Explicitly considering the vertical coupling allows us to set different requirements for the vertical and horizontal isolation performance. This is important because the required vertical isolation at 10 Hz is not as demanding as the required horizontal isolation.

For the spectral densities, we assume that the motions of HAM4 and HAM5 are independent, but, unlike what was assumed in T080192-01, the coupling of the motion through the different suspensions on HAM5 is coherent. Thus, the ASD estimate becomes

$$
\begin{aligned}
\tilde{x}^2_{SRCL} =& \tilde{x}^2_{HAM-ISI} \times \left(abs(2\, xTF_{HSTS})^2 + abs(2\, xTF_{HLTS} + xTF_{HSTS})^2 \right) \\
& 10^{-3*2} \times \tilde{z}^2_{HAM-ISI} \times \left(abs(2\, zTF_{HSTS})^2 + abs(2\, zTF_{HLTS} + zTF_{HSTS})^2 \right).
\end{aligned} \tag{3}
$$

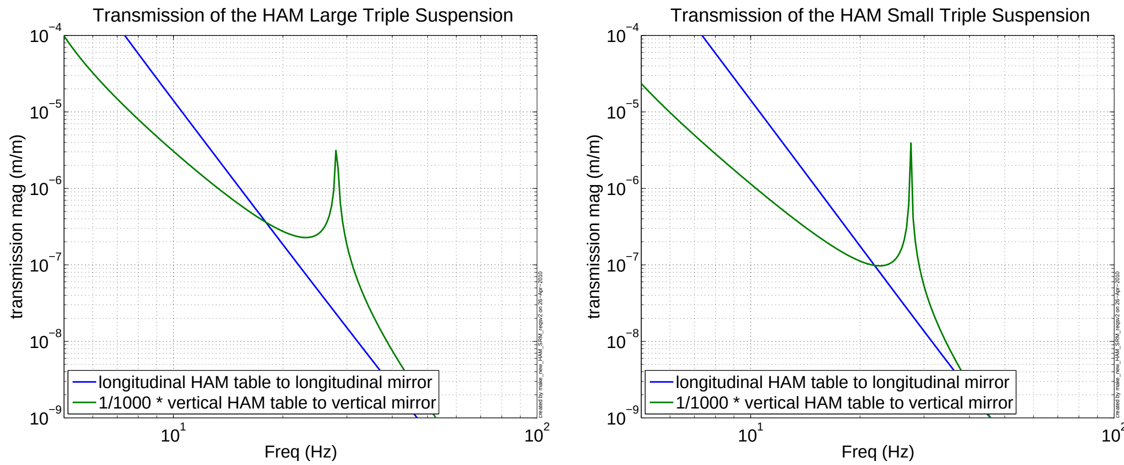

Figure 4: Modeled transmission of the triple pendulums for the HAM chambers with local damping on. On the left is the HLTS, per the FDR, adapted from model in T080310-v3. On the right is the HSTS, per the PDR, adapted from model in T080311-v2.

We can use the models of the HAM triple suspensions to estimate the coupling from the table to SRCL. For this, we use the transfer functions shown in figure 4. For the HLTS, we use the same model used for the FDR, adapted from the Matlab/ Simulink model in T080310-v3. For the HSTS, we use the model used for the PDR, adapted from the Matlab/ Simulink model in T080311-v2. Both models assume that the active damping is on. We also assume that the only vertical to horizontal coupling is the 0.1% coupling of vertical mirror motion to motion in the beam direction.

Since we know the SRCL target, and we know the transfer functions of the mirrors, we can choose a HAM-ISI motion which just meets the new targets. This is not completely deterministic because there is both horizontal and vertical motion to consider. The solution we think can probably be achieved is shown below in figure 5 and table 2.

If the HAM-ISI tables in the signal recycling path can meet these targets, then the contributions to the SRCL will be as shown in figure 6. The horizontal HAM-ISI motion is the largest contributor, which means that attention must be paid to both the translation

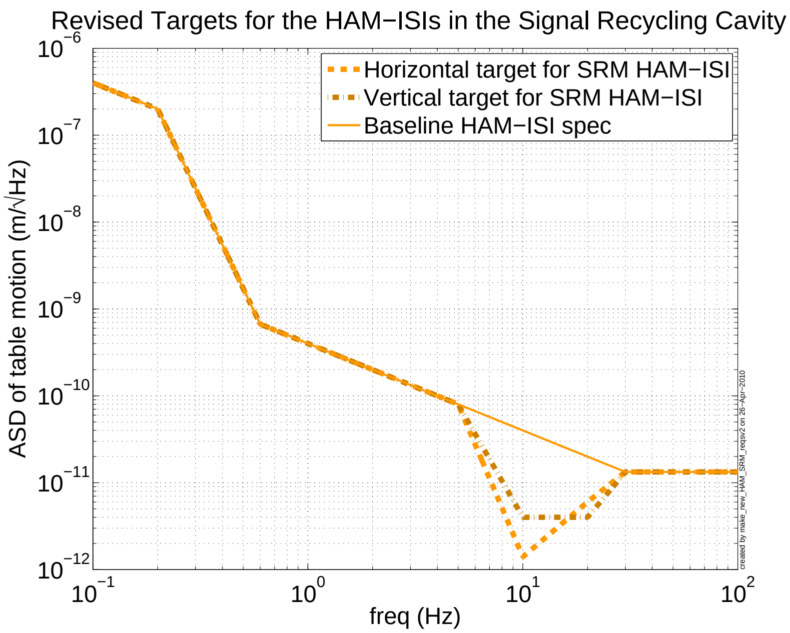

Figure 5: Suggested Target for HAM-ISI performance for the chambers in the signal recycling cavity.

Frequency (Hz)	Original HAM spec motion ASD (m/$\sqrt{\text{Hz}}$)	new Horizontal target for SRM HAM motion ASD (m/$\sqrt{\text{Hz}}$)	new Vertical target for SRM HAM motion ASD (m$\sqrt{\text{Hz}}$)
0.2	2e-7	2e-7	2e-7
0.6	6.67e-10	6.67e-10	6.67e-10
5	8e-11	8e-11	8e-11
10	4e-11	1.4e-12	4e-12
20		6e-12	4e-12
$\geq$ 30	1.33e-11	1.33e-11	1.33e-11

Table 2: Revised SRCL target

and tilt motion relevant to the beam direction (i.e. Y and RX). At 20 Hz, the horizontal and vertical contributions are both important (because of the resonance).

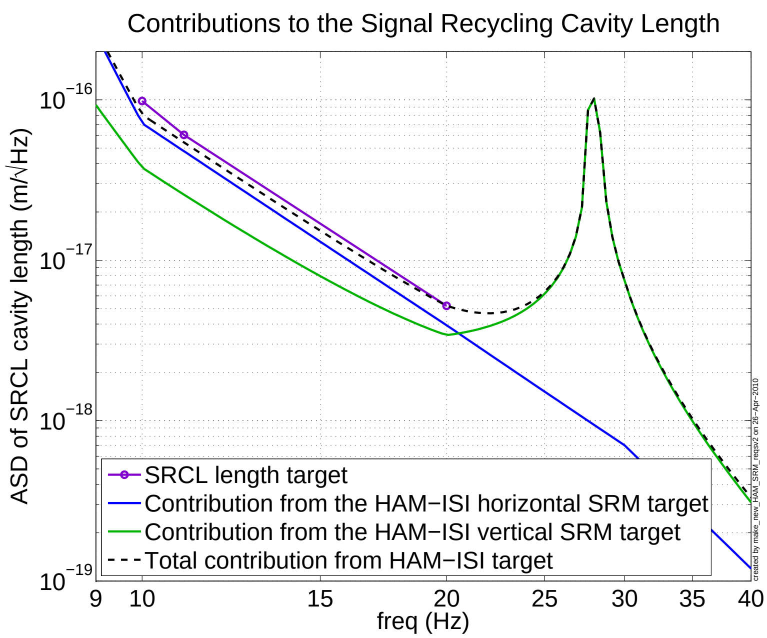

Figure 6: Contributions to SRCL from the HAM-ISI.