HAM Seismic Isolation Requirements (By Peter Fritschel, T060075-00-D)
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This page examines some considerations regarding the desired seismic isolation for the HAM optics platforms. For starters, we look at the effect of HAM platform motion on a triple suspension, specifically the mode cleaner (MC) triple (transfer functions for the recycling mirror triples are quite similar to the MC triple, so the analysis should apply fairly well to the RM triples as well).

MC Triple Suspension with modal control

For the model of the MC triple suspension, we'll use mechanical model under modal control (T050197, L. Ruet), because this gives generally better performance than the more traditional non-modal control. The transfer functions from the suspension point (platform) motion to the motion of the bottom mass (MC mirror) are shown in the figure below. Most of the modal control gains have been increased compared to the gains given in T050197 to get higher modal damping. Note that in the X direction, modal damping can give higher damping at the lowest-frequency mode *and* better isolation at 10 Hz than non-modal damping.

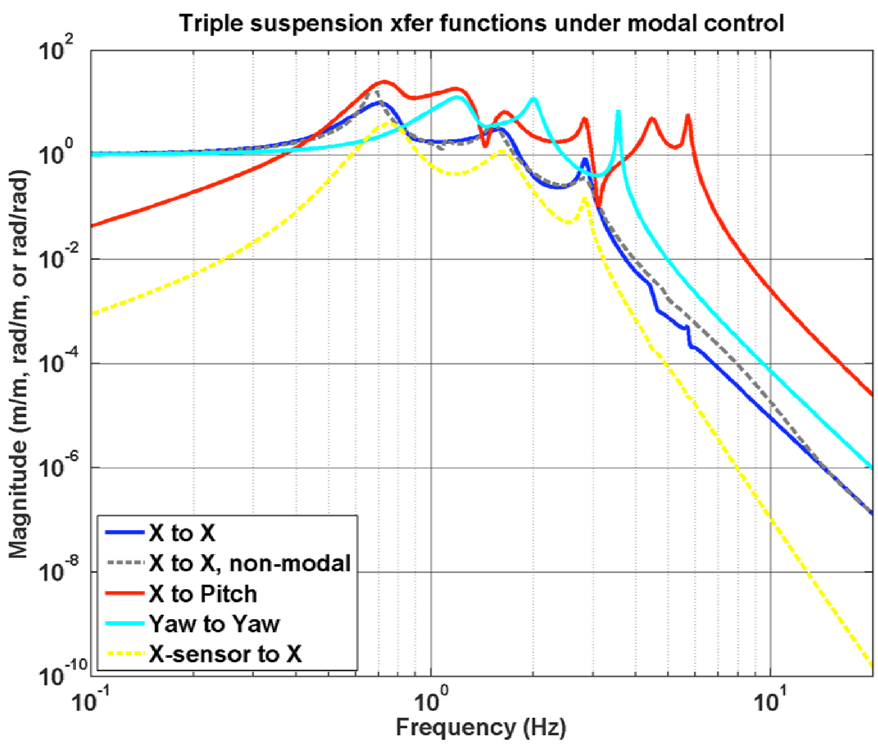


Figure 1. X is along optic axis. X-sensor refers to the local damping sensor.

Local sensor noise

The noise in the local damping sensors impose a limit to the MC mirror noise: even with no HAM platform noise the mirror will be driven by local sensor noise. So we can ask the question: what HAM platform noise spectrum would produce MC mirror noise equal to that produced by the local sensors? This would give a limiting HAM noise level, for which there would be little payoff in improving upon. This calculation is shown in the figure below (fig. 2). The sensor noise used in the calculation is that of the lensed sensor being developed in the UK; the curve shown is model of data provided by N. Lockerbie, Feb 2006.

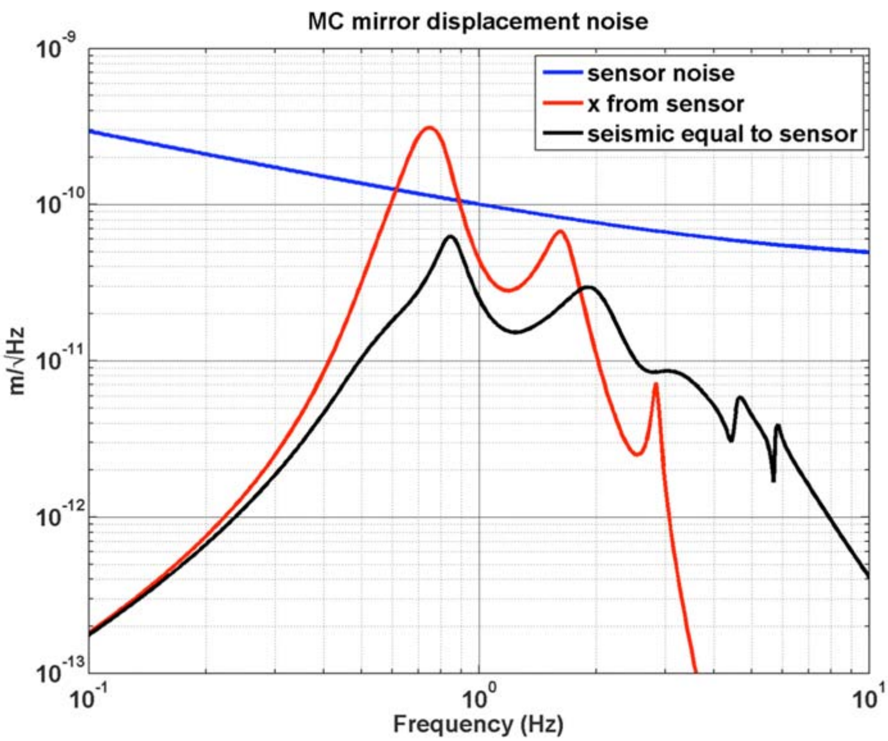
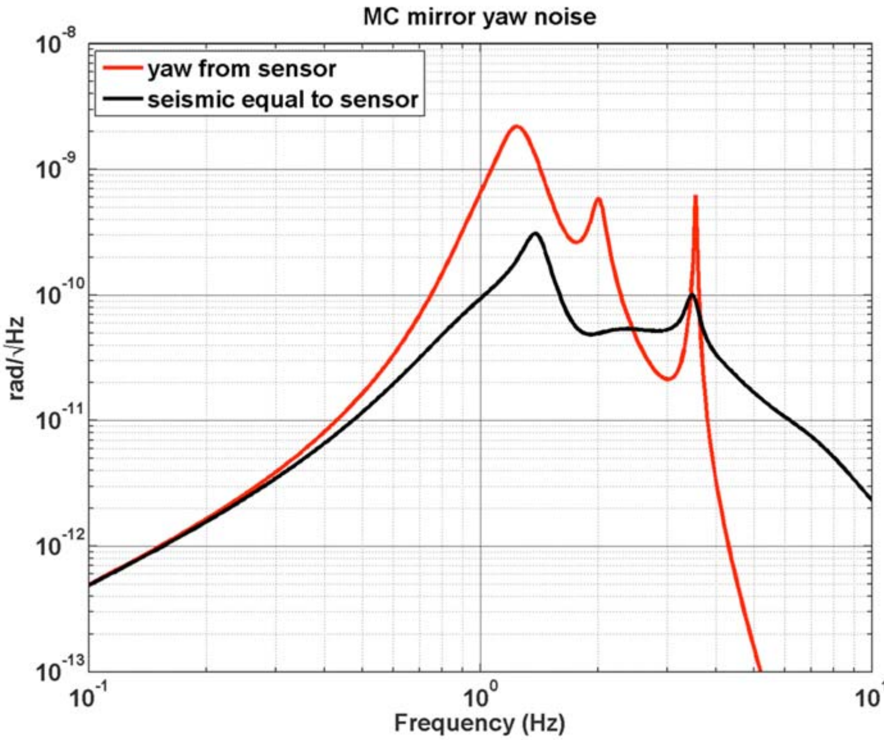
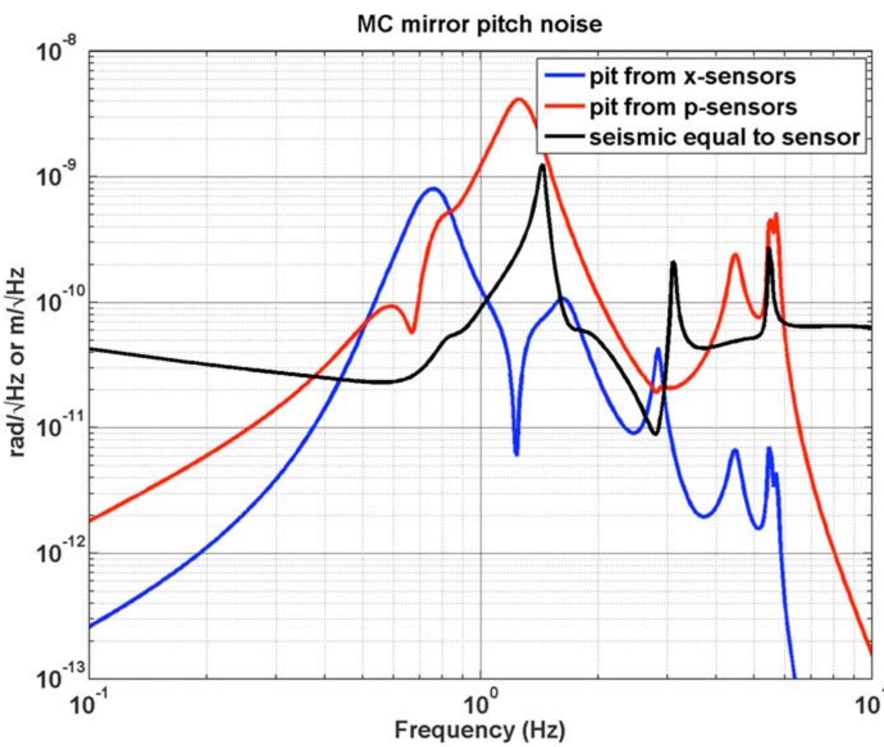


Figure 2. Local sensor noise (individual sensor) for the MC triple; MC mirror displacement due to the local sensor noise; seismic (platform) noise that would produce MC mirror displacement noise equal to the local sensor noise contribution.

The same question can be asked for the pitch and yaw degrees-of-freedom of the MC mirror. The pitch DOF is driven by: x-direction displacement of the platform; both the pitch and longitudinal (x) DOF local sensors. The yaw DOF is driven by: yaw motion of the platform; the yaw DOF local sensors. These calculations are shown in the figures below. The lever arms used for the local sensors are those of the MC triple controls prototype.





Noise at 10 Hz and above

The historical noise target for the MC mirrors at 10 Hz is 3e-17 m/rtHz. This was always rather arbitrary, and was simply set so that the MC frequency stability would be somewhere between the reference cavity stability and the ultimate frequency stability needed in the interferometer. There is a lot of freedom to allow higher MC noise at low frequencies, because the common mode servo that provides the final level of frequency stability can provide lots of gain here; the MC noise limit at 10 Hz could be increased 1-2 orders of magnitude with no problem. The recycling mirrors probably provide a firmer noise limit for the triple suspensions. The present requirement for the recycling mirrors (signal and power) is 4e-16 m/rtHz at 10 Hz, though this is being re-examined, and may become further relaxed with DC readout of the GW channel. For now, we stick with the 4e-16 m/rtHz limit. Assuming the RM triple suspension has the same transfer function as the MC triple at 10 Hz (1e-5 for x-to-x), this would impose a platform displacement noise limit of 4e-11 m/rtHz at 10 Hz.

Sub-10 Hz noise and RMS motion

To establish the level of allowed platform noise below 10 Hz, we'd like to think of all the ways that mirror motion in this band impacts interferometer operation, and decide what is tolerable. Here is what has been considered so far:

RMS mode cleaner fluctuations and lock acquisition: for acquiring lock, the residual MC length/frequency fluctuations, translated to an equivalent arm velocity, should be smaller than the predicted arm velocity

RMS fluctuations of the controlled recycling cavities: it should be possible to suppress the RC length fluctuations (PRC & SRC) to the estimated required level, with a straightforward global length control loop

RMS fluctuations of the mirror angles: these should be 'small', with the rms dominated by low frequencies, where it will be easier to further suppress with the wavefront sensor loops; what is 'small'? 1e-8 rad seems small enough (approx. 0.001 of the divergence angle of the arm mode)

Trial HAM platform displacement noise spectrum

To make some headway, we analyze the MC/triple mirror motion for the trial HAM platform motion shown in the figure below. This curve was arrived at with the following considerations:

Set the 10 Hz motion to be 2e-11 m/rtHz, a factor of 2 below the RM limit mentioned above

Some roll-off above 10 Hz, not very critical

1/f increase in motion below 10 Hz, down to a frequency which includes the lowest eigenmode of the suspension, which is 0.65 Hz

Faster increase below 0.6 Hz, similar to the BSC platform noise

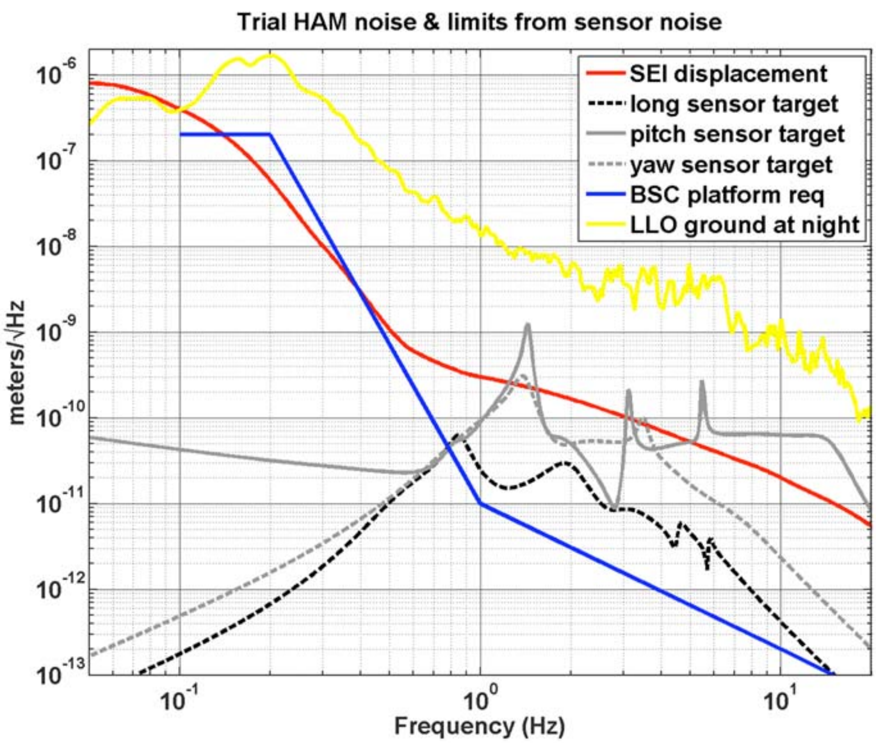


Figure 3. Trial HAM platform motion, compared to other noise levels.

Mirror motion under local damping

The figure below shows the mirror motion of a MC triple suspension, driven by the above trial HAM platform motion and local sensor noise. For the yaw DOF, the HAM platform motion is taken to be the same as the displacement, with radians substituted for meters (i.e., 2e-11 rad/rtHz at 10 Hz, etc). For pitch, the rms motion is 1e-8 radians, the target suggested above. For yaw, the rms is below 1e-8 rad for frequencies above 0.2 Hz, but then increases another factor of 10 when including lower frequencies.

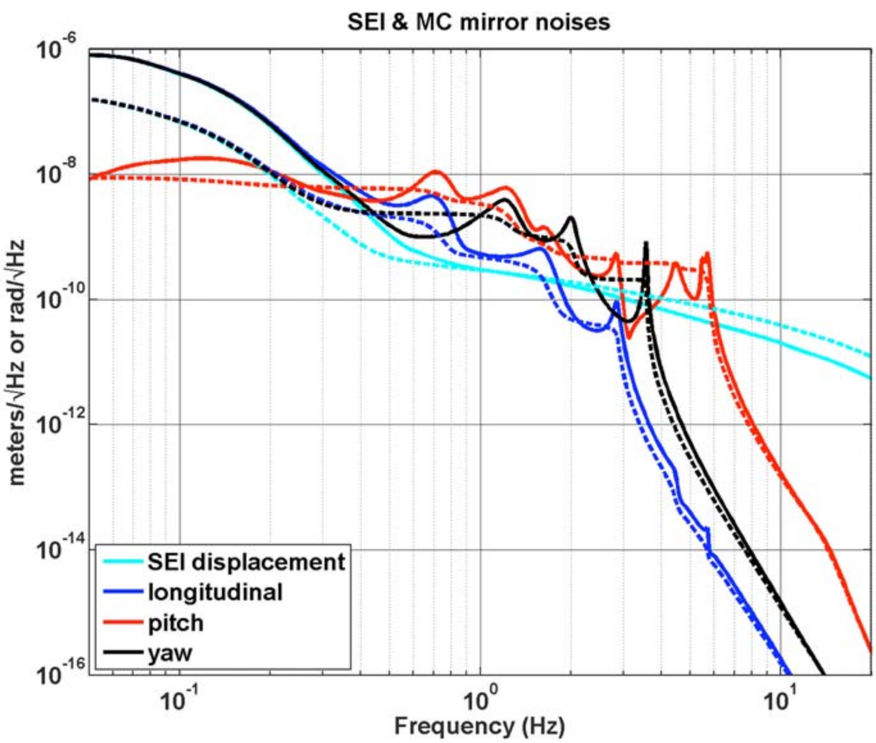


Figure 4. MC mirror noise driven by trial HAM platform noise and local sensor noise. The dashed curves give the rms for each solid curve (same color), integrated from high frequency to f.

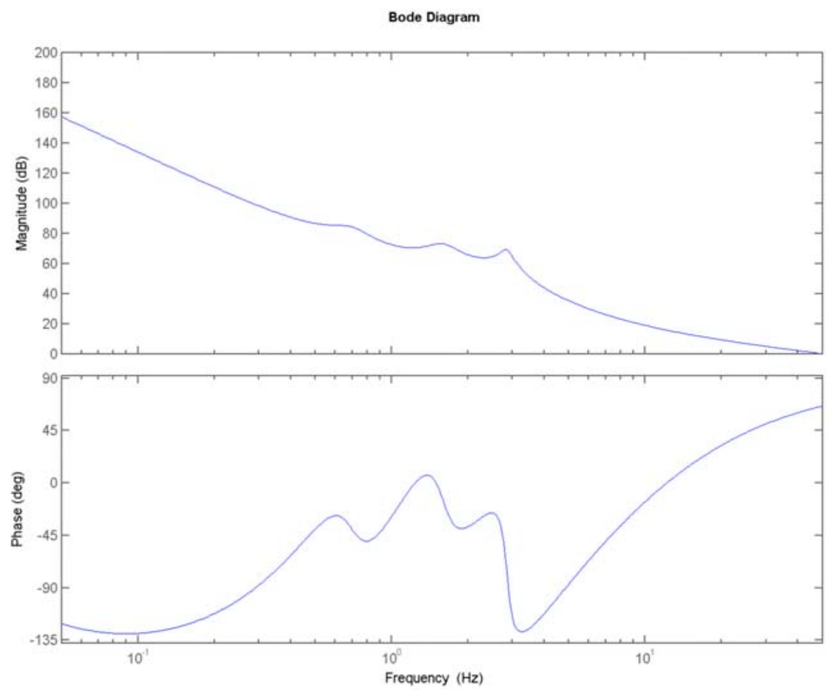
Stabilized MC length noise

For lock acquisition, the MC servo will work as it does for initial LIGO: high frequency feedback to the laser frequency (via the VCO) and low frequency feedback to the MC length. The cross-over of these two paths is at about 50 Hz. The point of this mode is that the MC length fluctuations are reduced, by stabilizing them to the reference cavity. If the laser frequency were instead stabilized to the MC length at all frequencies, the effect of the MC length fluctuations on the locking error signal transient would effectively be multiplied up by the ratio of the arm length to the MC length, i.e. by more than 2 orders of magnitude!

So we need to verify that we can suppress the MC length fluctuations so that they are less than (16/4000) times the arm fluctuations. How big are these? The arm length fluctuations will be dominated by frequencies below 0.3 Hz, and so should be essentially the same as the BSC platform motion, which is about 100 nm-rms for the BSC SEI requirement. We should actually be talking about velocities, and the arm velocity will be about 100 nm/sec-rms, since 2*pi*f ~ 1 at the relevant frequencies. It has been suggested that an SPI (seismic platform interferometer) could reduce the arm fluctuations by a factor of 100, so we should also consider the impact of the MC length noise in this case. So, the residual MC length fluctuations, with the MC servo in lock-acquisition mode, should be:

below 100 nm/sec * (16/4000) = *4e-10 m/sec-rms*, without an SPI
below 1 nm/sec * (16/4000) = *4e-12 m/sec-rms*, to support an SPI

To check this, the effect of the MC servo is idealized by modeling a single feedback path loop with open loop gain G and a unity gain frequency of 50 Hz, and good phase margin. The open loop gain looks like this:



The above MC mirror noise spectrum is then multiplied by sqrt(3) and divided by (1 + G), to get the stabilized noise spectrum shown below. The red curves in the plot actually show the MC length noise in terms of equivalent arm velocity (MC length times 4000/16), so should be compared to 1 nm/sec-rms.

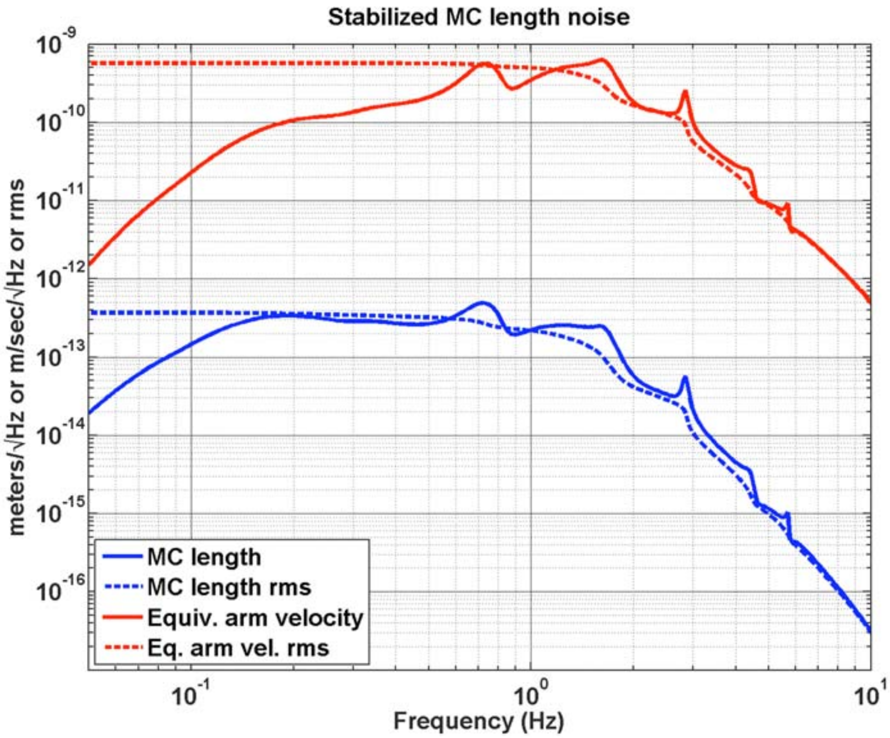


Figure 5. Residual MC length fluctuations under MC servo control, acquisition mode.

Recycling cavity length fluctuations

The result in the preceding figure can also be applied to the recycling cavity (PRC & SRC) degrees-of-freedom, telling us that with a 50 Hz ugf in these loops we could achieve a residual deviation of a bit less than 1 pm. Is this good enough? In initial LIGO, we stabilize PRC (& MICH) to a couple of picometers, with a ugf around 100 Hz. This is a much smaller residual fluctuation than was originally thought to be necessary, and it has been driven by the need to avoid saturation in the photo-detection. It seems likely that this will also be the driving criterion in AdLIGO, where the detection properties of PRC and SRC should be similar to that for PRC in initial LIGO. And so the fact that we estimate a residual deviation of 1 pm or less with a 50 Hz bandwidth loop indicates that the trial HAM platform noise is adequate for control of PRC & SRC.

Considerations not yet studied

Relative HAM platform motion at low frequencies: the seismic isolation system could make the relative motion between two HAM platforms larger than it is when just driven by ground motion at low frequencies (<0.5 Hz); how much relative motion (for the different DOF) do we allow?
Effect of HAM platform motion on the output mode cleaner
Effect of HAM platform motion on (non-suspended) beam reducing telescopes, and implications for signal detection

Analysis for single- or double-suspensions, as might be used within a stable recycling cavity configuration
How much position control is needed for the HAM platforms?