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- LIGO -

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Corner station floor motion and its influence on mode cleaner beam pointing at LLO

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1. Summary

This document describes an analysis we made at LLO to characterize the floor motion of the corner station and to investigate its influence on the beam pointing of mode cleaner's (MC) transmitted beam. We recorded seismic motion at various locations in the corner station and computed the coherence and transfer function between the locations. The coherence data indicates that two points in the corner station apart by up to 5.5 m are correlated very well in a frequency range 0-5 Hz. A phase analysis on the obtained transfer functions indicates that the horizontal floor motion propagating as a transverse-wave forms a standing wave at around 1.5 Hz, whereas it forms traveling waves at other frequencies. Considering that the HAM (horizontally accessible module) isolation stack has resonances near 1.5 Hz, we speculate that the standing wave is a consequence of interference between a floor motion propagating towards a HAM and that coming from the HAM. Here the former is caused by an external source and the latter is reemission of the oscillation energy stored in the HAM stack at the resonance. It seems that this standing wave excites two opposite sides of HAM1 with different amplitude, causing rotational motion of the HAM table on which MC1 and MC3 are placed. This rotational motion of the HAM table in turn causes beam pointing fluctuation of the MC transmitted light. This observation is consistent with our previous observation of horizontal rotational (yaw) motion of HAM1 table [1]. It is also consistent with the fact that coherence between the beam pointing motion of the MC transmitted light and floor motion is much higher than coherence between the beam pointing motion and MC length control. Coherence between floor motion and the dark-port signal shows peaks near the HAM resonances, indicating that floor motion transferred to the MC beam pointing affects the GW signal.

2. Horizontal floor motion of corner station

2.1 Measurement

The purpose of this measurement was to characterize the floor motion of the corner station by investigating the coherence of seismic signals among different locations in the corner station. We measured horizontal floor motions with a portable seismometer at several points along the X and Y arm, and compared them with the signals from a stationary seismometer taken at the same time. The stationary seismometer was placed near the beam splitter chamber, and the portable seismometer was placed as far as 5.5 m from the stationary seismometer with an increment of 2.7 m.

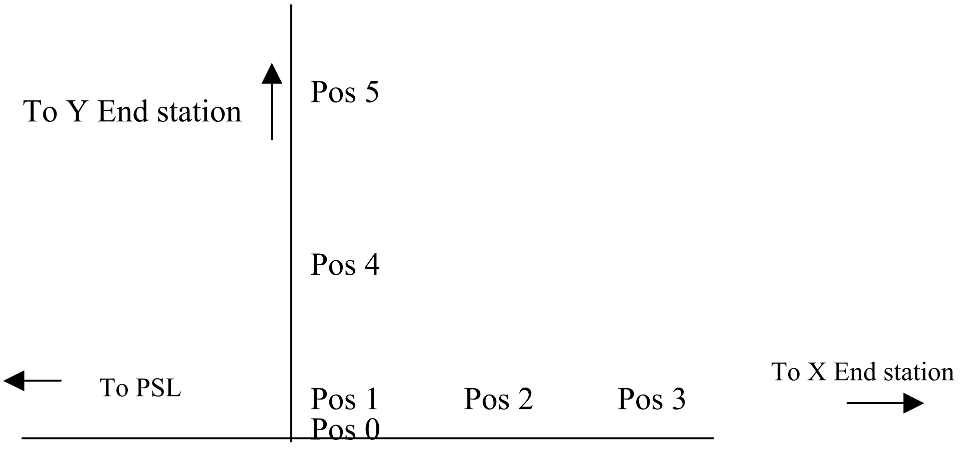


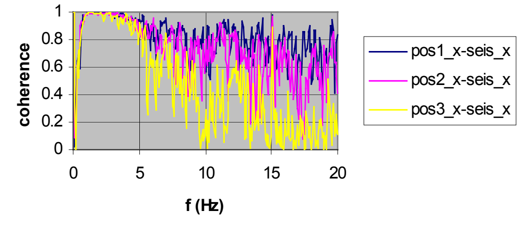
Fig. 1 Locations of measurement with the portable seismometer

Fig. 1 shows the arrangement of the measurement. Position 0 indicates where the stationary seismometer was located. Positions 1 through 5 indicate the locations where measurement with the portable seismometer (Model L-4 Seismometer, Sercel Inc.) took place. At each location, we recorded horizontal seismic signals in the x and y direction, one at a time. Here x is the coordinate axis in the direction of the X arm and y is the axis in the direction of the Y arm. The signal from the portable seismometer was sent to a temporary DAQ channel L1:ASC-WFSS_DCP (Figs. 2-4). Simultaneously, we recorded the signal from the stationary seismometer through DAQ channels L0:PEM-LVEA_SEISX and L0:PEM-LVEA_SEISY.

2.2 Correlation of floor motion

Figs. 2 – 5 show coherence between signals from the stationary seismometer and portable seismometer. Fig. 2 and Fig. 5 show how the coherence decreases when the distance between the permanent and portable seismometer is increased in the longitudinal direction (changes in the coherence of the x [y] seismic components when the distance between the two seismometer is increased in x [y] direction). Hence these two figures represent how the seismic motion decays when it propagates longitudinally. Fig. 3 and Fig. 4 show how the coherence decreases when the distance between the permanent and portable seismometer is increased in the transverse direction (changes in the coherence of the x [y] seismic components when the distance between the two seismometer is increased in y [x] direction). Hence these two figures represent how the seismic motion decays when it propagates transversely.

In the frequency range of 0 – 5 Hz, all cases show high coherence (>0.9), indicating that the floor motion well propagates both in the transverse and longitudinal direction in this low frequency range. In the frequency range higher than 5 Hz, the following feature is observed. In Figs. 2 and Fig. 5, the coherence patterns at the first two positions are quite similar to each other while the coherence pattern at the farthest position is different from them. In Fig. 3 and Fig. 4, in contrary, the coherence patterns at the farther two positions are similar to each other and the coherence pattern at the closest position is different from them. This indicates that the floor motion decays more quickly in the transverse component than the longitudinal component in this higher frequency range.


Fig, 2 coherence in x when moved along x arm (8-19-02 data)

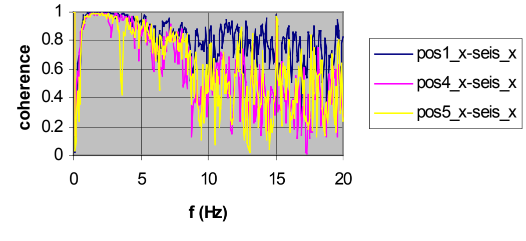


Fig. 4 coherence in x when move along y arm (8-19-02 data)

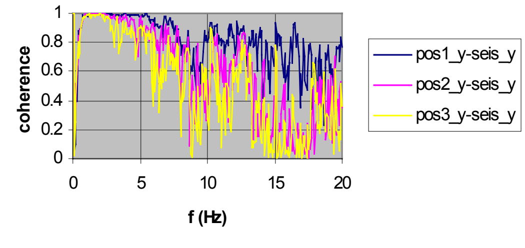


Fig. 3 coherence in y when move along x arm (8-19-02 data)

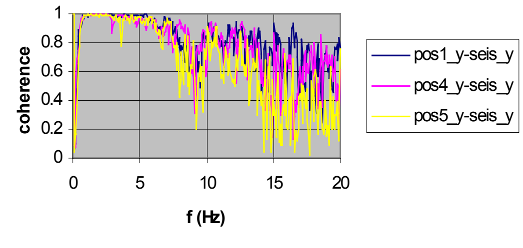


Fig. 5 coherence in y when move along y arm (8-19-02 data)

2.3 Phase delay

Fig. 6 shows the phase delay between the stationary and portable seismometer in the x seismic component when the portable seismometer moves in the x direction, i.e., it represents the phase delay of the floor motion when it propagates as a longitudinal wave in x the direction. Fig. 7 shows the phase delay in the y seismic component when the portable seismometer moves in the x direction, i.e., it represents the phase delay of the floor motion when it propagates as a transverse wave in the x direction. Similarly, Figs. 8 and 9 represent the phase delay of the floor motion when it propagates as a transverse and longitudinal wave in the y direction, respectively. Clearly seen is that while the longitudinal wave shows unidirectional phase delay in both cases, the transverse waves show a crossover around 1.5 Hz. The meaning of this observation will be interpreted in the following section.

2.4 Interpretation on observed phase delay

Noting that the HAM stack has resonances in the U-U and V-V transfer at 1.5 Hz and 1.6 Hz [2] (Table 1), respectively, we can explain the above-mentioned crossover in the phase delay as follows. Here U and V are the translational displacement in the x and y direction, respectively. Consider that disturbance generated by an external source such as people's activity propagates through the floor of the corner station as a transverse wave. When this wave reaches a HAM, some part of the energy will be transferred to the HAM table through the isolation stack. When the frequency of the wave is close to a stack resonance at f_0, the energy transfer is most efficient, making the HAM stack a secondary source of oscillation at f_0. This motion will be reemitted to the floor and will interfere with subsequent wave coming from the external source.

Table 1 HAM stack resonances [2]

mode	Resonance (Hz)
U-U transfer	1.5, 2.3
V-V transfer	1.6, 2.8
V-Yaw transfer	7.2, 8.0

In a simple model, this situation can be expressed as follows. The overall floor motion propagating towards the HAM can be represented by a superposition of sine waves at various frequencies. The frequency of the wave reemitted from the HAM stack to the floor by the above mechanism is dominantly distributed around the stack resonance frequency f_0, and can be approximated by a sine wave oscillating at f_0. Assuming that the energy transfer at the resonance is in equilibrium, the amplitude of this returning wave can be put to be equal to the incident wave at f_0. Thus, the interference between the incident wave component at frequency f and returning wave can be expressed by following equation. Here f is the frequency of the incident wave, f_0 is the stack resonance frequency, and A is the amplitude of the component of the incident wave at f_0. Since the floor motion is considered to be a white noise in the present frequency range, it is a good approximation that the amplitude A is a constant.

$$A\sin(2\pi ft - kx) + A\sin(2\pi f_0 t + kx) = 2\sin\frac{2\pi(f+f_0)t}{2}\cos\frac{2\pi(f-f_0)t-2kx}{2} \tag{1}$$

The second term of the right-hand side of eq. (1) indicates that the overall floor motion resulting from this interference represents a forward-going wave when $f < f_0$ Hz, a backward-going wave when $f > f_0$ Hz, and a standing wave when $f = f_0$ Hz. This explains the crossover observed in Figs. 7 and 8 qualitatively.

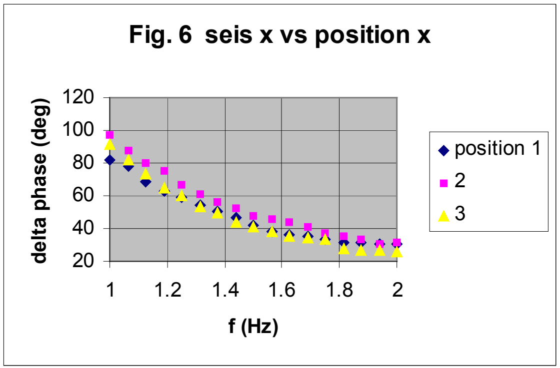


Fig. 6 seis x vs position x

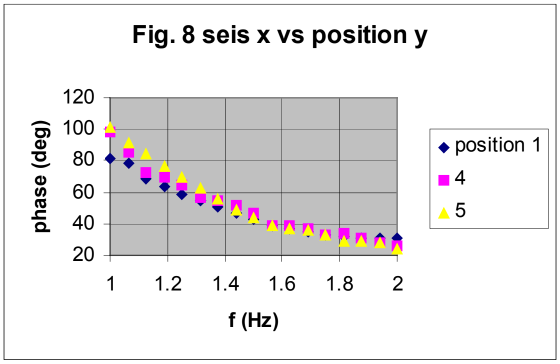


Fig. 8 seis x vs position y

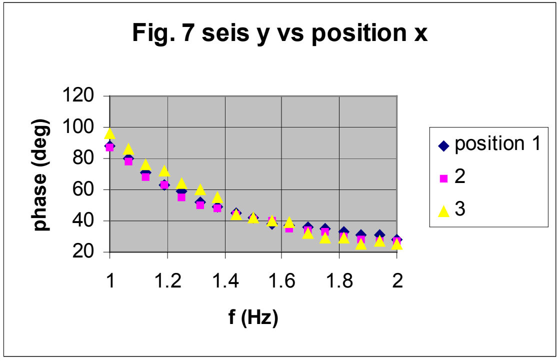


Fig. 7 seis y vs position x

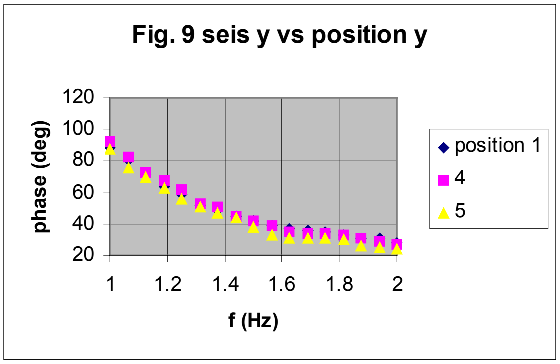


Fig. 9 seis y vs position y

3. Influence of floor motion on optics on HAM1

3.1 HAM table yaw motion

The above interpretation indicates that the floor of the corner station is constantly moving as a standing wave around f_0 Hz. Consequently, depending on the distance from the node of the standing wave, different points of the floor move at different amplitude in a synchronized fashion. This means that legs of the same HAM table, whose separation is less than 5.5 m over which two points on the floor has been observed highly correlated in Figs 2 - 5, will oscillate around f_0 Hz with different amplitude, causing the HAM table to experience horizontal, rotational oscillation. This speculation is consistent with our previous observation that HAM1 table rotates horizontally (yaw motion) at 1.5 Hz and 1.6 Hz [1] (Fig. 10).

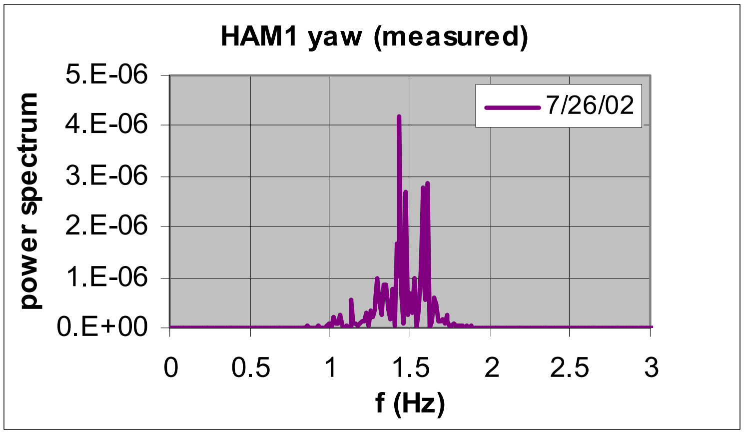


Fig. 10 HAM1 YAW motion

3.2 Beam pointing of MC transmitted light

The HAM table yaw motion mentioned above will cause yaw motions of suspension towers on the table. On HAM1, MC 1 and MC3 are placed close to each other near a corner of the table. This indicates that these two mirrors tend to move commonly as a pair, causing the MC's triangular, intra-cavity beam path to rotate accordingly. To investigate this effect, we measured coherence between the MC's transmitted light and the seismic motion detected by the permanent seismometer placed near the beam splitter chamber.

Fig. 11 shows the measured coherence between the seismic signal and the beam pointing of MC transmitted light. The top left graph indicates that the pitch and yaw motion of the MC transmitted light has strong coherence with the seismic signal in the x direction in the frequency ranges of 0.2–1 Hz, 1-1.5 Hz, and 2.2–2.4 Hz. The frequency range of 0.2–1 Hz contains resonance frequencies of the suspended mirrors (i.e., the resonance in pendular, pitch and yaw degree of freedoms of the mirror motion relative to the suspension tower). The observed high coherence in this frequency range indicates that when the table moves in the x direction, the resultant mirror's swinging motion affects the beam pointing strongly. This is contrastive to the left bottom graph of Fig. 11 that shows low coherence between the beam pointing of the MC transmitted light and the seismic signal in the y direction (see below).

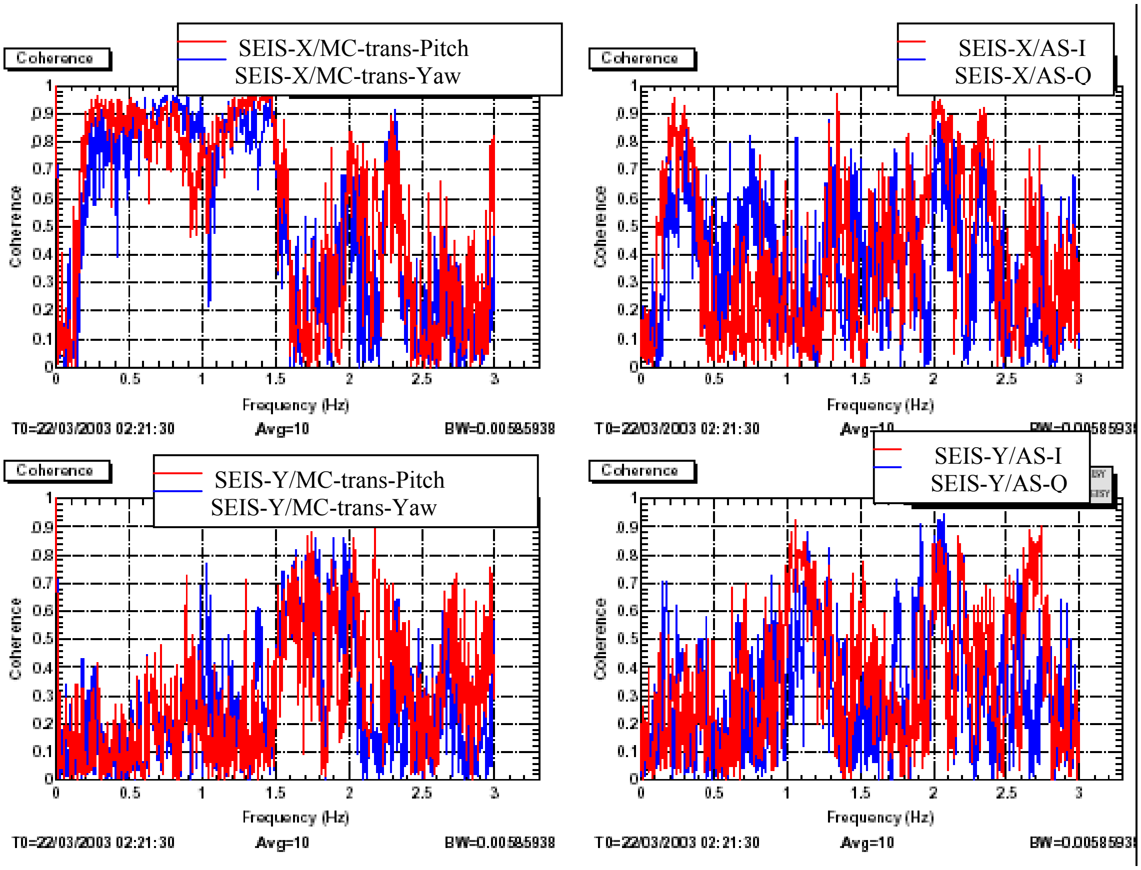


Fig. 11 Coherence of MC transmitted beam pointing and floor motion

The high coherence observed near 1.5 Hz between the yaw motion of the MC transmitted light and x seismic motion indicates that the beam pointing of the MC transmitted light is caused by floor motion via HAM table rotation by the following mechanism. Since the suspended optics do not have a resonance in the pendular, pitch or yaw degree of freedom in this frequency range, it is unlikely that yaw motion of individual MC mirrors due to random noise causes this high coherence. Considering that the HAM stack U-U transfer has a resonance at 1.5 Hz, it is more likely that the translational floor motion rotates the HAM 1 table via the mechanism mentioned in Section 3.1, and this HAM table yaw motion drives MC1 and MC3 yaw motion at the same frequency in a synchronized fashion that in turn causes pointing fluctuation in the MC transmitted light. The high coherence observed in the frequency range of 2.2-2.4 Hz can be explained by HAM yaw motion near the second resonance of the HAM stack U-U transfer by the same mechanism (see Table 1). The two left graphs in Fig. 11 indicate that the pitch motion of the MC transmitted light has basically the same coherence pattern as the yaw motion of the MC transmitted light, indicating that the pitch motion of the MC transmitted light is due to the same mechanism as the yaw motion. Considering that a pure yaw motion of the HAM table cannot cause a pitch motion of the MC transmitted light, it is likely that rotational motion of HAM1 table is not purely horizontal and that causes the pitch motion of the MC transmitted light.

The left bottom graph of Fig. 11 shows that seismic motion in the y direction has high coherence with the beam pointing of MC transmitted light at frequency ranges near 1.6 Hz and 2.8 Hz. These frequencies are HAM table stack's V-V transfer resonance, and therefore this high coherence can be explained by the same mechanism as the case of the seismic motion in the x direction as described in the preceding paragraph.

Comparison between the top left and bottom left graph in Fig. 11 shows that the seismic motion in the y direction has much lower coherence than the x direction with the pitch and yaw motion of the MC transmitted light in the frequency range of 0.5 – 1 Hz where the suspended optic has resonances. This difference can be explained as follows. When MC1 and MC3 commonly swing in the x direction, the distance between the line connecting these two mirrors (two flat MC mirrors on HAM1) and MC2 on HAM2 changes. For example, if these two mirrors swing toward MC2 making the distance between the line connecting the two flat mirrors and MC2 becomes shorter. This means that the intra-cavity beam path under this condition changes in such a way that the beam path between MC1 and MC3 becomes longer so that the total beam path length remains the same (i.e., the light traveling a longer distance between MC1 and MC3 meets the MC resonance condition and comes out from MC as the transmitted light). Consequently, the intra-cavity beam path is forced to miss the center of MC1 and MC3, causing the direction of the transmitted beam more sensitive to yaw and pitch motion of MC1 and MC3 individually.

The right two graphs in Fig. 11 show that AS_I and AS_Q signals have similar coherence pattern to the MC beam pointing, indicating that the beam pointing of MC transmitted light due to the floor motion influences the dark port signal.

Since MC2 sitting on HAM2 is a curved mirror, when MC1 and MC3 on HAM1 experience a HAM table's rotational motion, it is possible that the vertex of the intra-cavity triangular optical path on MC2 moves on its surface in such a way that the total path length is unchanged or changed very slightly. If that is the case, the motion will not be sensed by the MC length control and therefore the beam pointing of MC transmitted light is rather uncontrolled. To investigate if that is the case, we measured the coherence between the pitch/yaw motion of MC transmitted light and the MC length control signal. Fig. 12 summarizes the result. The two graphs on the left indicate that the MC length control has much lower coherence with floor motion than the beam pointing of MC transmitted light. Note that these data were taken on a different day from Fig. 11, but still the coherence pattern between the pitch/yaw motions of the MC transmitted light and the seismic motion is very similar to Fig. 11. The top right graph shows that the coherence between MC length control and the beam pointing of the MC transmitted light is indeed low in the entire frequency range of 0.2-3 Hz. These results support the above-mentioned speculation that the motion of the intra-cavity beam path in MC is not well sensed by the length control, and therefore is rather uncontrolled.

The bottom right graph of Fig. 12 shows the coherence between pitch and yaw motion of the MC transmitted light. Very high coherence (>0.9) is seen in 0.5-1.6 Hz. This is the frequency range in which the seismic motion has high coherence with the beam pointing of the MC transmitted light (left two graphs of Fig. 12). This explicitly indicates that pitch and yaw motion of the MC transmitted light is due to a common cause and that the seismic motion is the common cause.

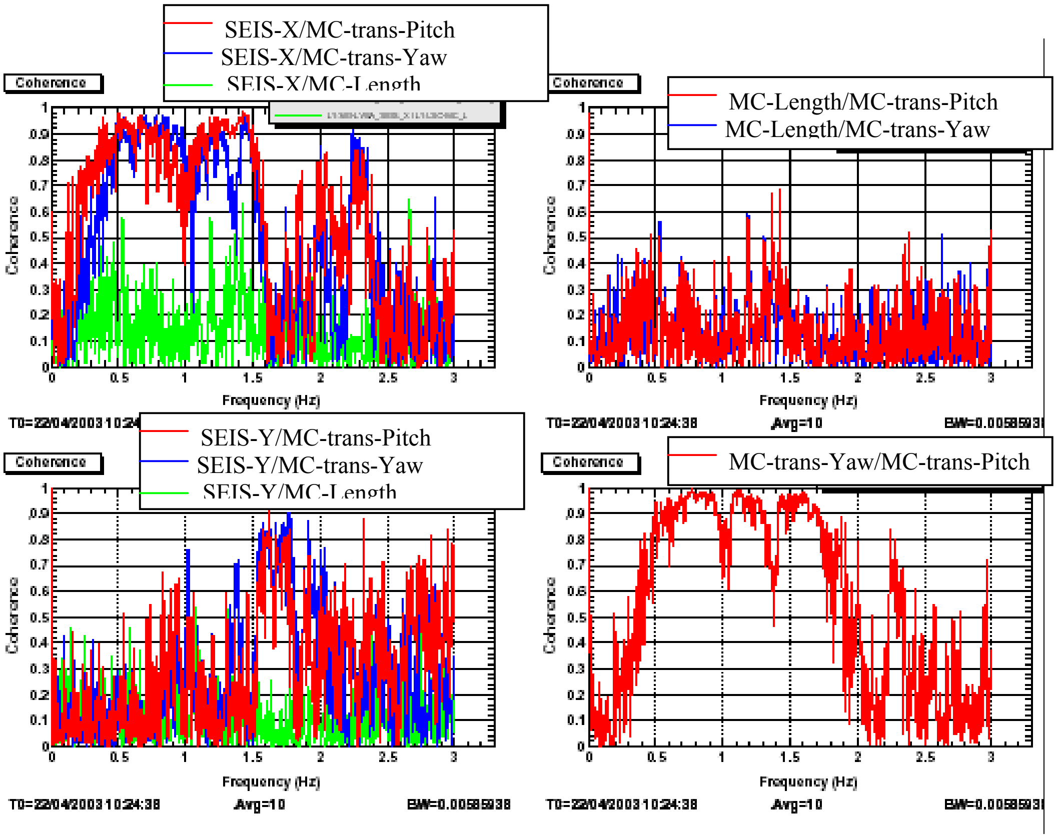


Fig. 12 Coherence of MC transmitted beam pointing and MC length control signal

4. Conclusion

This analysis indicates that two points separated by up to 5.5 m on the floor of the corner station are well correlated. The correlation observed in the frequency range less than 5 Hz is 0.9 or higher both in the transverse and longitudinal component. Since the separation of the HAM table legs is less than 5.5 m, this indicates that two ends of the table are subjected to a correlated floor motion in this frequency range. The analysis on the phase delay in the transfer function between two points indicates that the HAM isolation stack behave as a secondary source of floor motion at its resonance peaks near 1.5 Hz and 1.6 Hz. Interference between transverse waves from this secondary source and primary transverse waves from an external source seems to create standing waves around these frequencies. This observation is consistent with our previous observation that HAM1 table is under constant rotational oscillation (taw) around 1.5 Hz and 1.6 Hz. The seismic signal has high coherence at these frequencies with the beam pointing of the MC transmitted light and the dark-port signal as well. This indicates that the MC transmitted beam pointing caused by floor motion has substantial effect on the interferometer noise.

References

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2. M. Landry and D. Ottaway, “Summary of mechanical resonances in the LIGO Hanford interferometers”, LIGO T000020-00-W (2000)