**LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY**

*LIGO Laboratory / LIGO Scientific Collaboration*

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# Ground Vibration Induced Motion of the Filter Cavity Tube (FCT) Baffles

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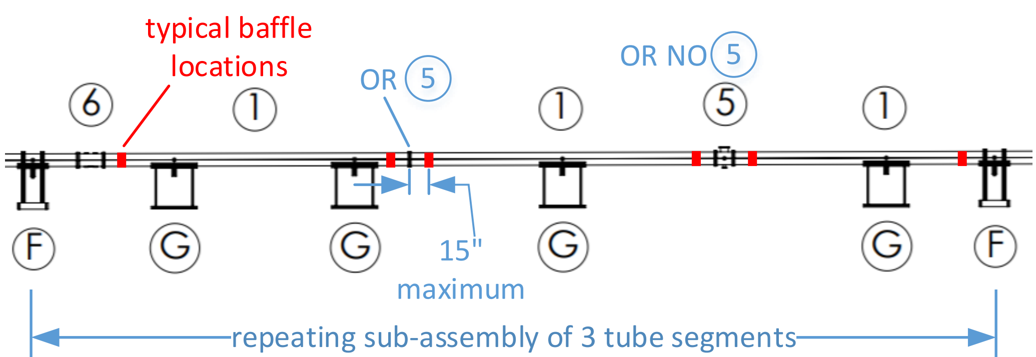
# 1 Introduction

Ground vibrational motion induces motion of the baffles within the filter cavity tube (FCT), which in turn may cause scattered light noise in the frequency dependent squeezed light system. The purpose of this memo is to present a dynamic analysis of the FCT, including its supports and installed baffles, in order to calculate the baffle motion response to ground vibration. The measured ground motion spectrum at the LIGO observatories was used to estimate the motion of the FCT baffles.

This version of the dynamic analysis of the FCT assembly is based on the conceptual design of the baffles (LIGO-E2000177-v1; LIGO-D1900424-v2) and the conceptual design of the FCT supports (LIGO-T2000002). As the designs mature this analysis may be updated.

# 2 Representative Sub-Assembly

The 300 meter long FCT is comprised of 48 flanged tubes (typically 20 ft in length), 20 expansion joints (bellows), 17 6-way crosses, 9 gate valves, 65 guided supports and 16 fixed supports, as shown in the FCT layout drawing (LIGO-D1900456-v7). Rather than attempt to model the entire length of the FCT, a representative repeating sub-assembly was chosen for analysis, as shown in Figure 1. There are 10 of these repeating sub-assemblies with three tube segments within the entire FTC (as indicted in Figure 2). There are also 6 repeating sub-assemblies with two tube segments, and then 2 unique end sub-assemblies. Since the sub-assembly with three tube segments is the most common it was chosen for this analysis.




| PARTS LIST | | |
|---|---|---|
| ITEM NO. | PART NUMBER | DESCRIPTION |
| 1 | D1900443-01 | FC BEAM TUBE, 20' LG. |
| 2 | D1900443-02 | FC BEAM TUBE, 15' LG. |
| 3 | D1900443-03 | FC BEAM TUBE, 14'-2.14" LG. |
| 4 | D1900443-04 | FC BEAM TUBE, 15'-3.75 LG. |
| 5 | D1900485 | 6-WAY CROSS |
| 6 | TBD | BELLOW, 20" LG. |
| 7 | TBD | GATE VALVE 10", 12 CF |
| 8 | D1900443-05 | FC BEAM TUBE, 12' LG. |
| 9 | D1900443-06 | FC BEAM TUBE, 8' LG. |
| 10 | D1900443-07 | FC BEAM TUBE, 7'-6" LG. |
| G | TBD | GUIDED SUPPORTS |
| F | TBD | FIXED SUPPORTS |

**Figure 1 Representative repeating sub-assembly (from D1900456-v7)**

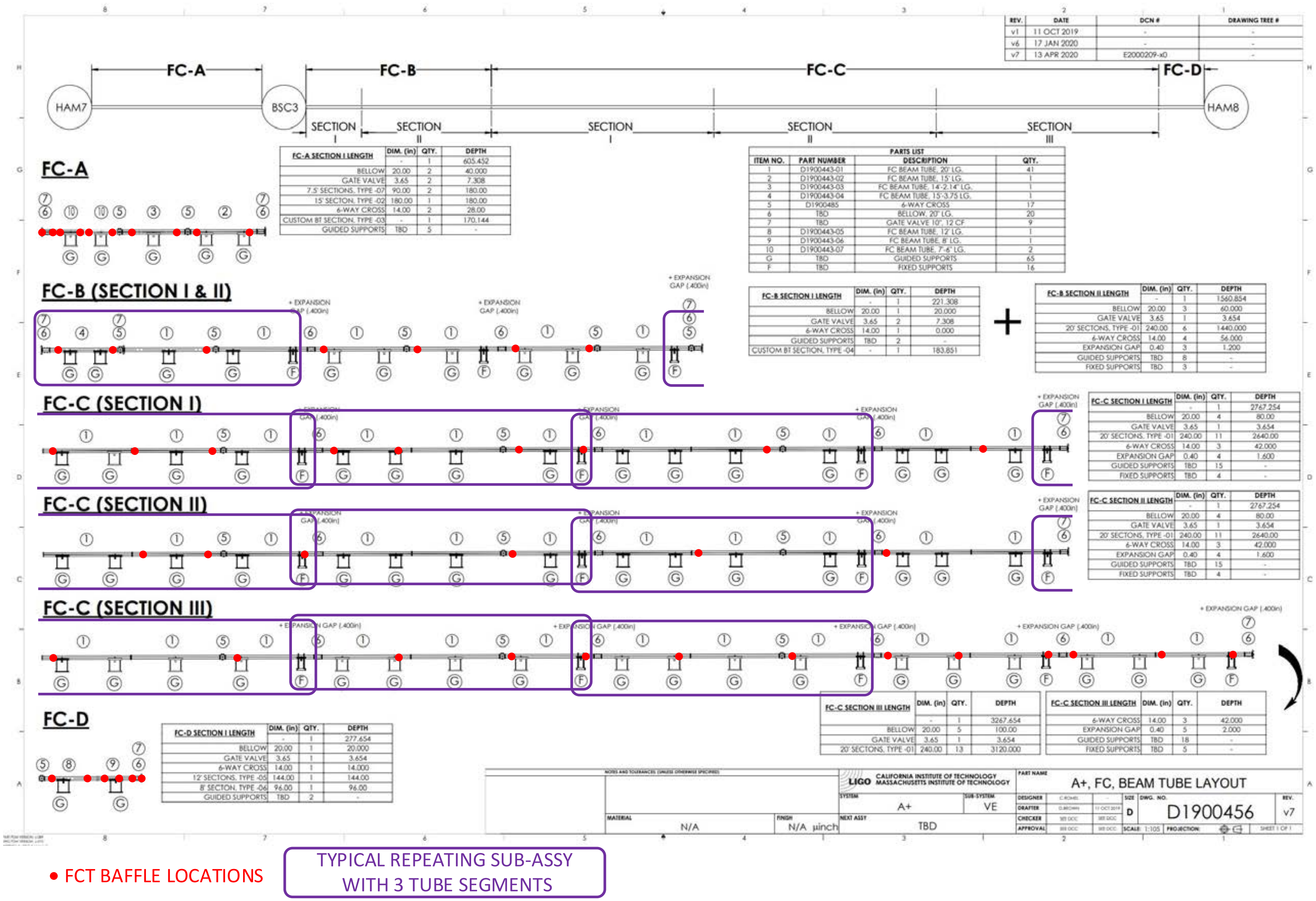



**Figure 2 Typical repeating sub-assemblies of the FCT with Baffle locations (from E2000177-v1)**

Typical dimensions of this repeating sub-assembly are shown in Figure 3.

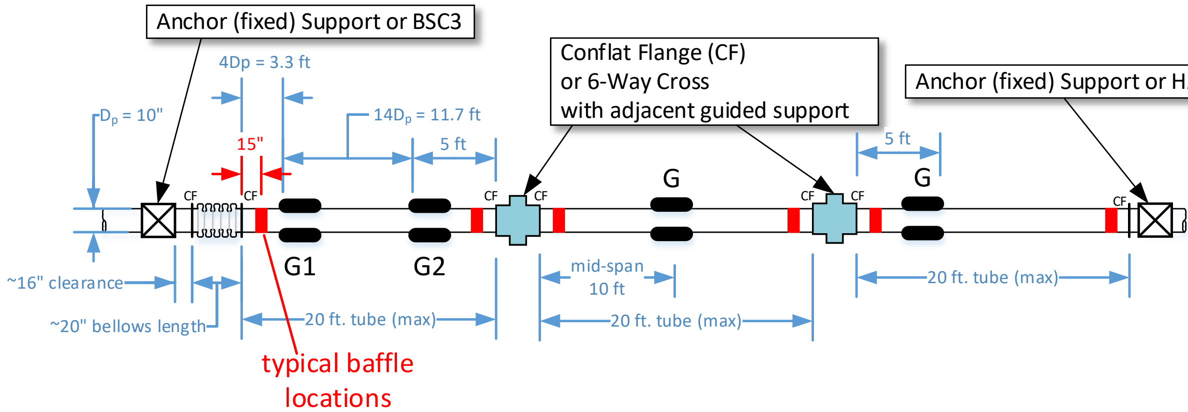



**Figure 3 Approximate dimensions of the repeating sub-assembly (from Figure 6 of T2000002-v1)**

The elevation views in the top-level assembly/layout drawings for the A+ Vacuum Equipment (D1800238-v13 for L1 and D1800241-v10 for H1) show that the support stand height is greatest in the LVEA and the FC End Station, and much less in the FCT enclosure (FCTE). As indicated in D950148-v2:

- the BTE Y-slab is 30.9" (785 mm) higher than the LVEA slab at LHO
- the BTE Y-slab is 29.8" (757 mm) higher than the LVEA slab at LLO

The FCT centerline height above the LVEA floor is:

- LLO: 5'-9.4" (1.8 m) at HAM7 and at HAM8, with a pitch up of .155 deg
- LHO: 5'-10.4" (1.8 m) at HAM7 and 5'-10.3"at HAM8, with a pitch up of .148 deg

Since the structural modes associated with the supports will be reduced with taller supports, the LVEA height for LHO will be used for the representative model, i.e. 5'-10.4" from the floor to the FCT centerline.

The FCT support stand design is currently only at the conceptual level (see T2000002). The simple representation shown in Figure 4 will be used in this dynamic model as a rough approximation of the support stand. Floor anchoring details, height and lateral adjustment details and tube attachment details are missing.

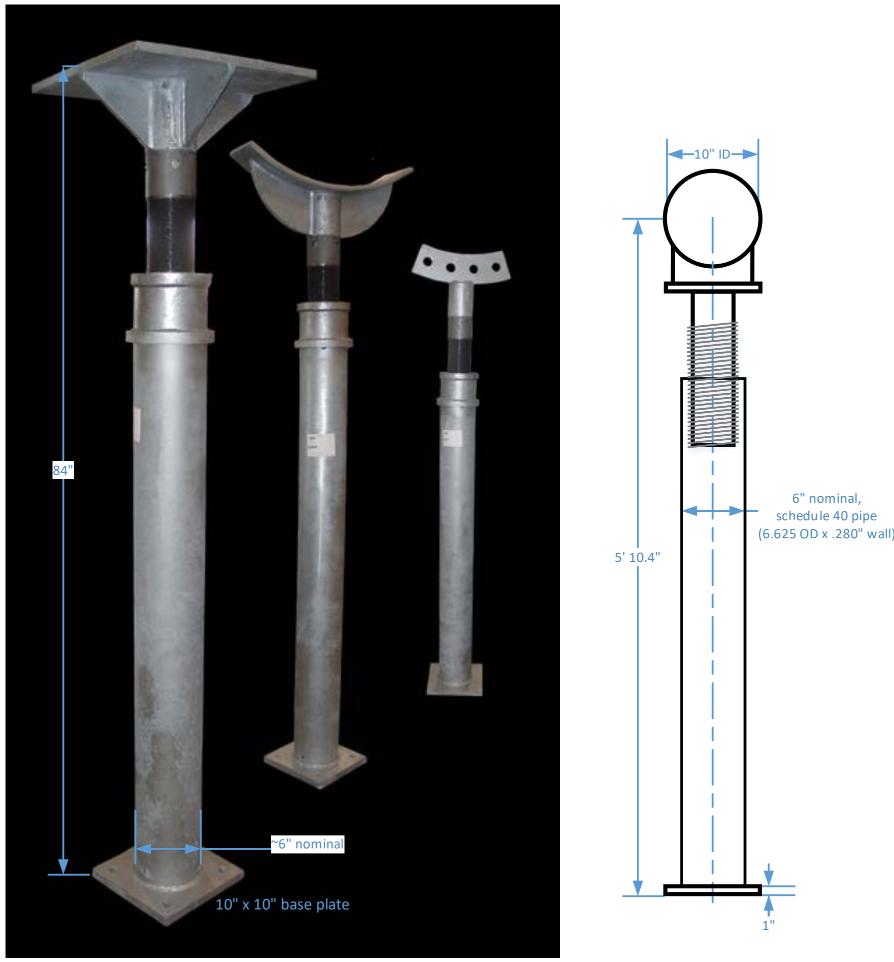



**Figure 4 Very approximate model of a FCT Support based on a Piping Technology & Products Inc design**

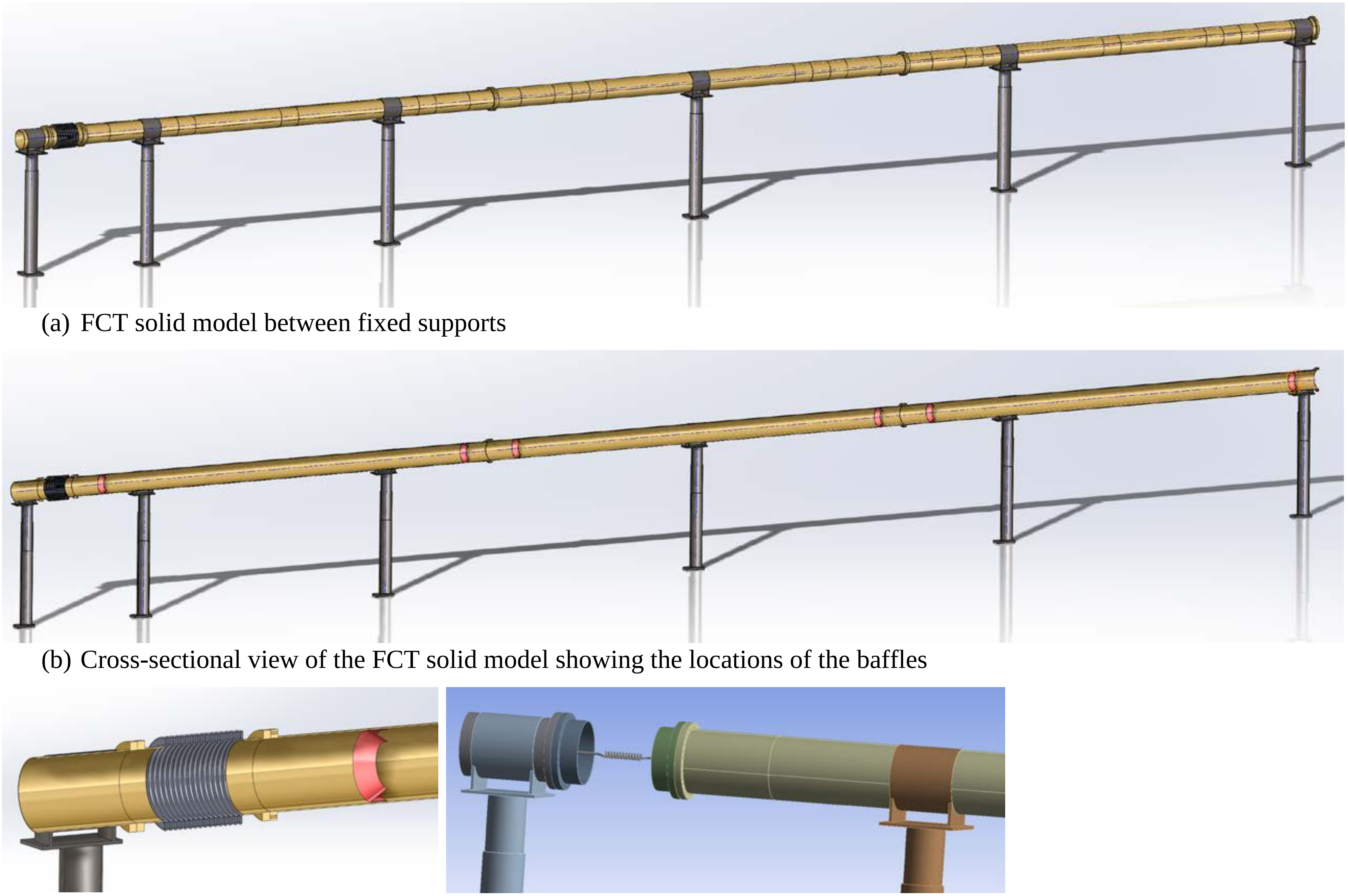
(https://pipingtech.com/resources/ptp-blog/adjustable-pipe-stands-to-support-ductile-iron-pipe/)

## 3 Solid Model of the representative sub-assembly

In the solid model () used for the analysis:

- conflat flanges are used instead of 6-way crosses. This reduces the length a little and there is some more bending compliance for a 6-way cross versus just two conflat flanges, but the differences should be negligible for this analysis.
- A solid model of the formed bellows was prohibitive for the scale of this analysis. As an alternative, the bellows are approximated as 4-dof springs using calculated spring rates for the bellows (see the spreadsheet "T2000002-v2 A+ FC bellows EJMA calculations.xlsx" at LIGO-T2000002). The calculations are approximate but likely as accurate as a 3D FEM of the presumed parameters of the expansion joint at this point in time. (The expansion joint detailed design and fabrication are currently under contract.) The 4 degrees of freedom and corresponding spring rates are:
    - o Longitudinal: 17,161 N/m
    - o two lateral directions: 39,003 N/m
    - o torsional: 350,299 N-m/rad

- The fixed support stand connections to the filter cavity tube are modeled as bonded (aka welded) with no relative motion permitted between the tube and the support stand.
- The guided support stands are modeled as a frictionless interface between inter-nested cylinders.
- The baffles don't include the mechanism used to expand them outward against the inner diameter of the filter cavity tube; The interface is modeled as bonded.
- No damping has been added to the model, although there is provision for damping in the baffle attachment mechanism, and they may be damping added to the FCT supports.



(a) FCT solid model between fixed supports

(b) Cross-sectional view of the FCT solid model showing the locations of the baffles

(c) Formed bellows (left) and idealized spring representation (right)

**Figure 5 Solid model of a representative, repeating, sub-assembly of the FCT**

# 4 Modal analysis

The first 30 modes span 16 Hz to 188 Hz, as shown in Figure 6. The first 11 modes are within the span of the measured base excitation frequency range (to 50 Hz), and are depicted in Table 1.

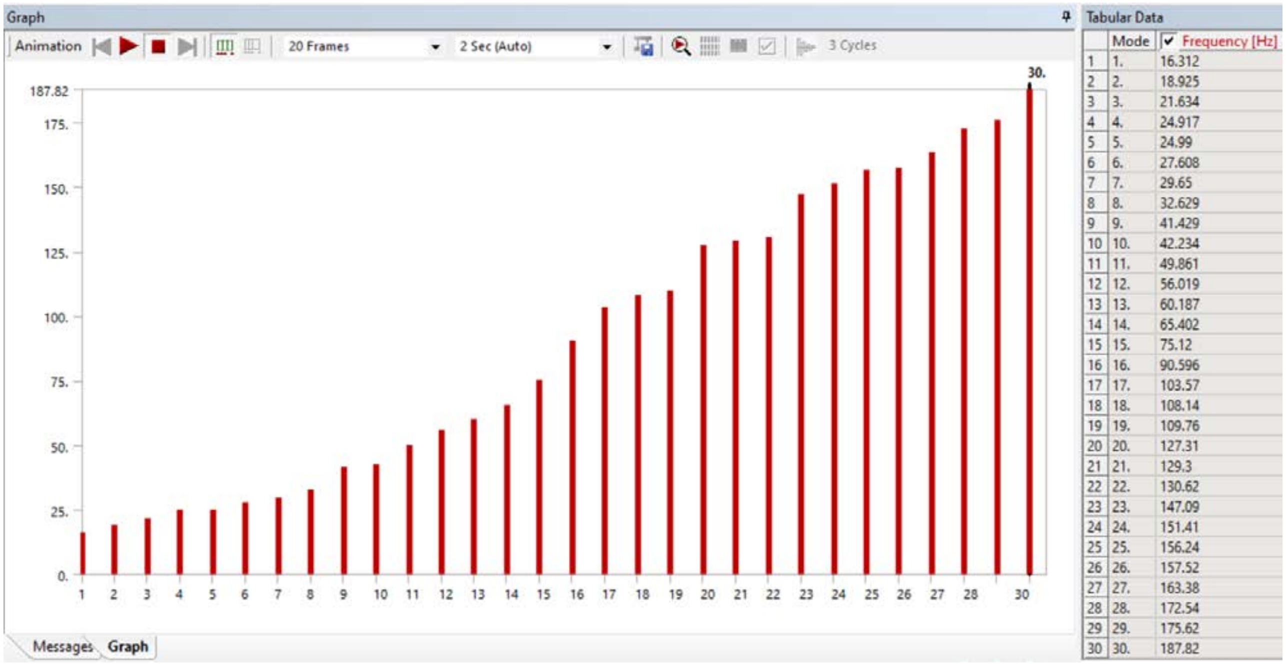
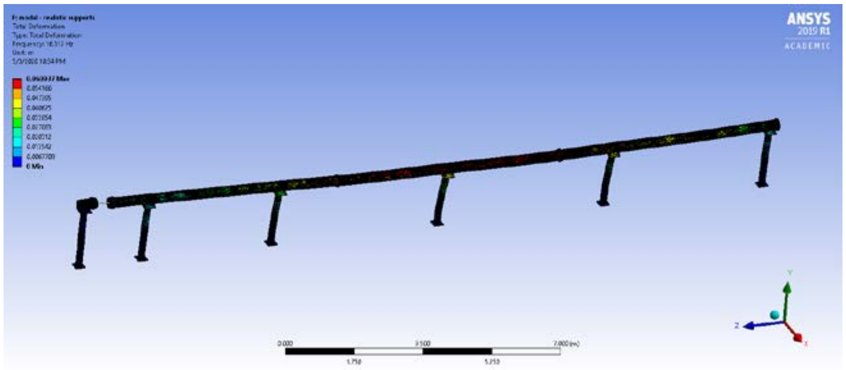
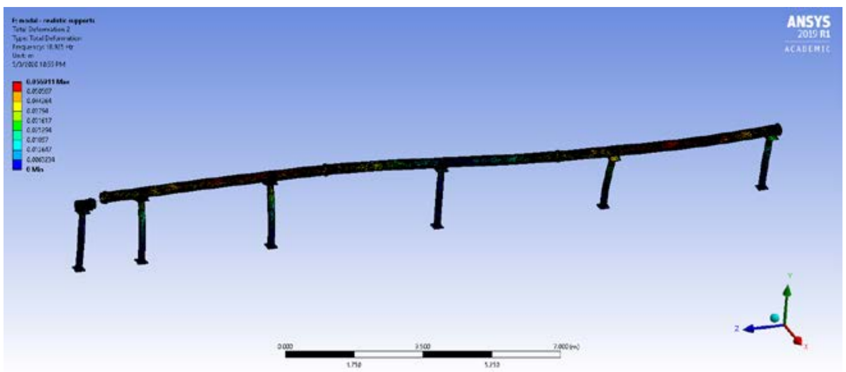
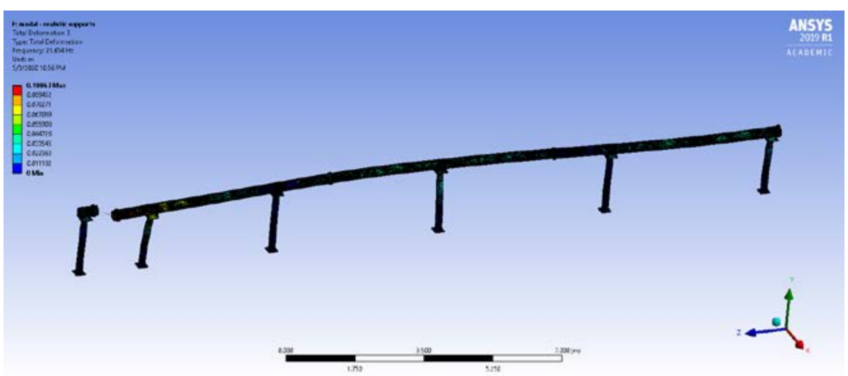
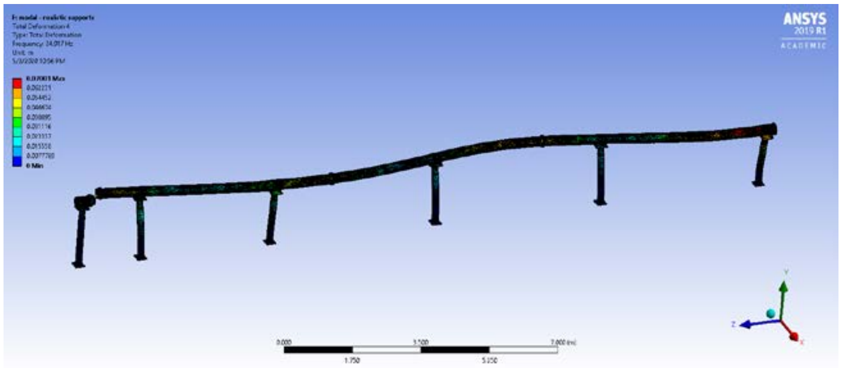
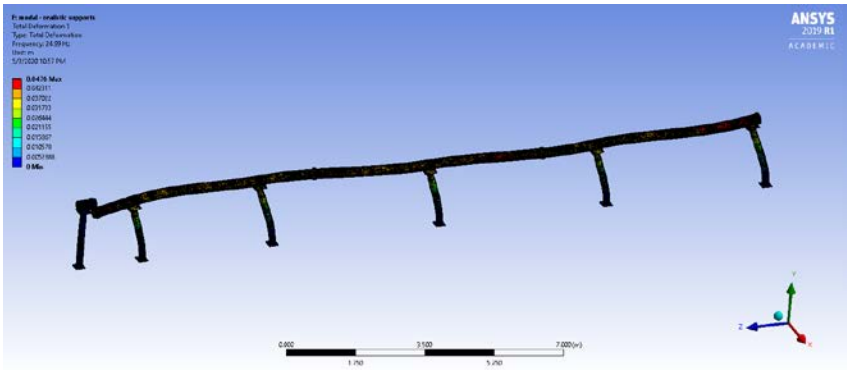
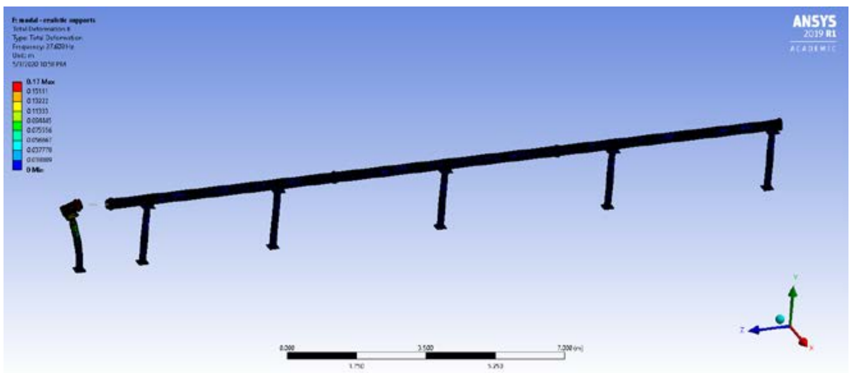
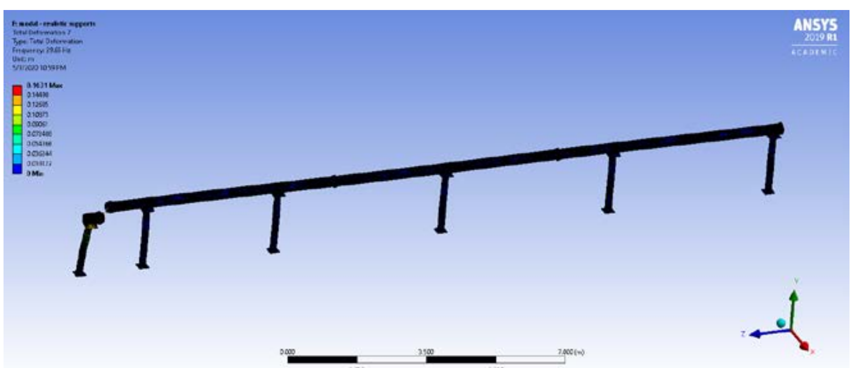
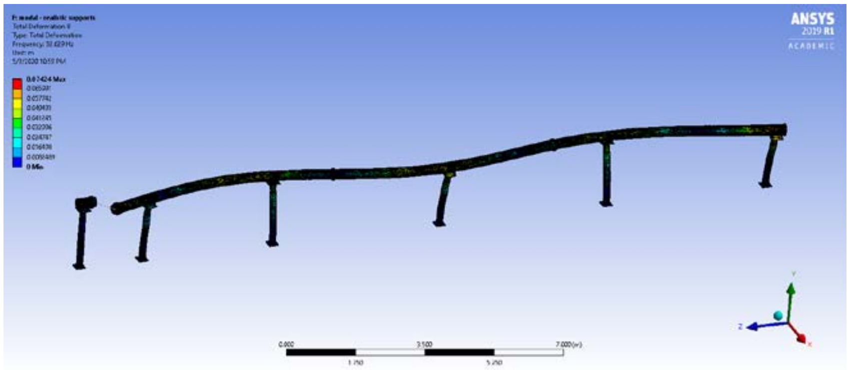
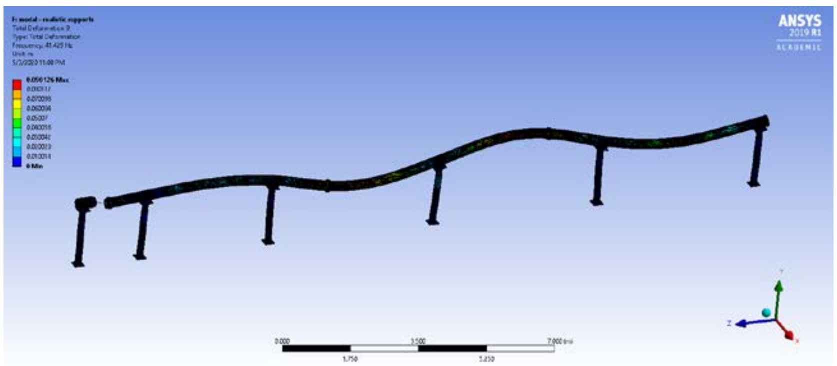
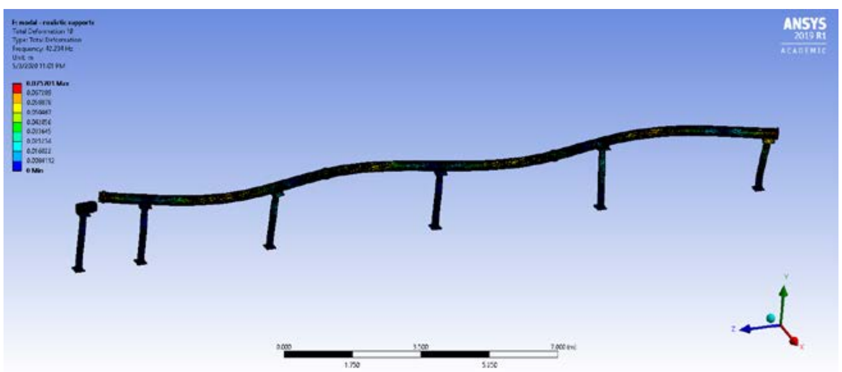
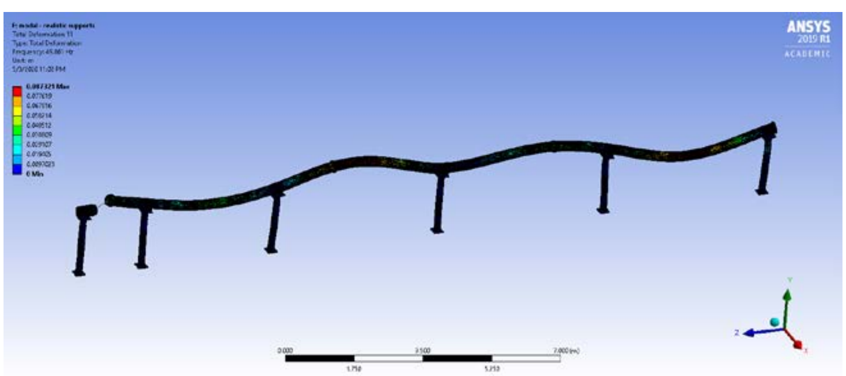



**Figure 6 Natural vibration frequencies of the FCT**

**Table 1 Images and videos of the FCT modes up to 50 Hz**

| # | Freq (Hz) | image | video |
|---|---|---|---|
| 1 | 16.312 |   | FCT mode 1.mp4 |
| 2 | 18.929 |   | FCT mode 2.mp4 |
| 3 | 21.634 |   | FCT mode 3.mp4 |

| # | Freq (Hz) | image | video |
|---|---|---|---|
| 4 | 24.917 |  | FCT mode 4.mp4 |
| 5 | |  | FCT mode 5.mp4 |
| 6 | |  | FCT mode 6.mp4 |
| 7 | |  | FCT mode 7.mp4 |

| # | Freq (Hz) | image | video |
|---|---|---|---|
| 8 | |   | FCT mode 8.mp4 |
| 9 | |   | FCT mode 9.mp4 |
| 10 | |   | FCT mode 10.mp4 |
| 11 | |   | FCT mode 11.mp4 |

# 5 LVEA ground vibration

Ground vibration measurements (from 8 mHz to 50 Hz), in the Laser & Vacuum Equipment Areas (LVEA) of both the LHO and LLO observatories, for a one year period (from 8/2009 through 7/2010) were analyzed to establish the monthly percentile levels of the amplitude spectral densities, and reported in LIGO-T1500224. I extracted the maximum Amplitude Spectral Density (ASD) level at the $95^{th}$ percentile for each month, at each frequency, as the basis of a “design” excitation spectrum for the FCT, as shown in Figure 7 (LHO) and Figure 8 (LLO). These ASDs have a large number of points (6400), too large for practical/efficient use as base excitation in a finite element analysis. Consequently I used a peak envelope function in Matlab, followed by spline interpolation, in order to “down sample” the ASD to a more management vector size (~300 points) while retaining the peak amplitudes; An example is shown in Figure 9. These ASD were then squared to obtain the Power Spectral Density (PSD) and imported into the Ansys Workbench, Random Vibration response analysis, using an xml file. The resulting “design peak envelope ASDs” for the X, Y and Z directions in the are shown in Figure 10 (LHO) and Figure 11 (LLO). A comparison of the LHO and LLO “design peak envelope ASDs” is shown in Figure 12.

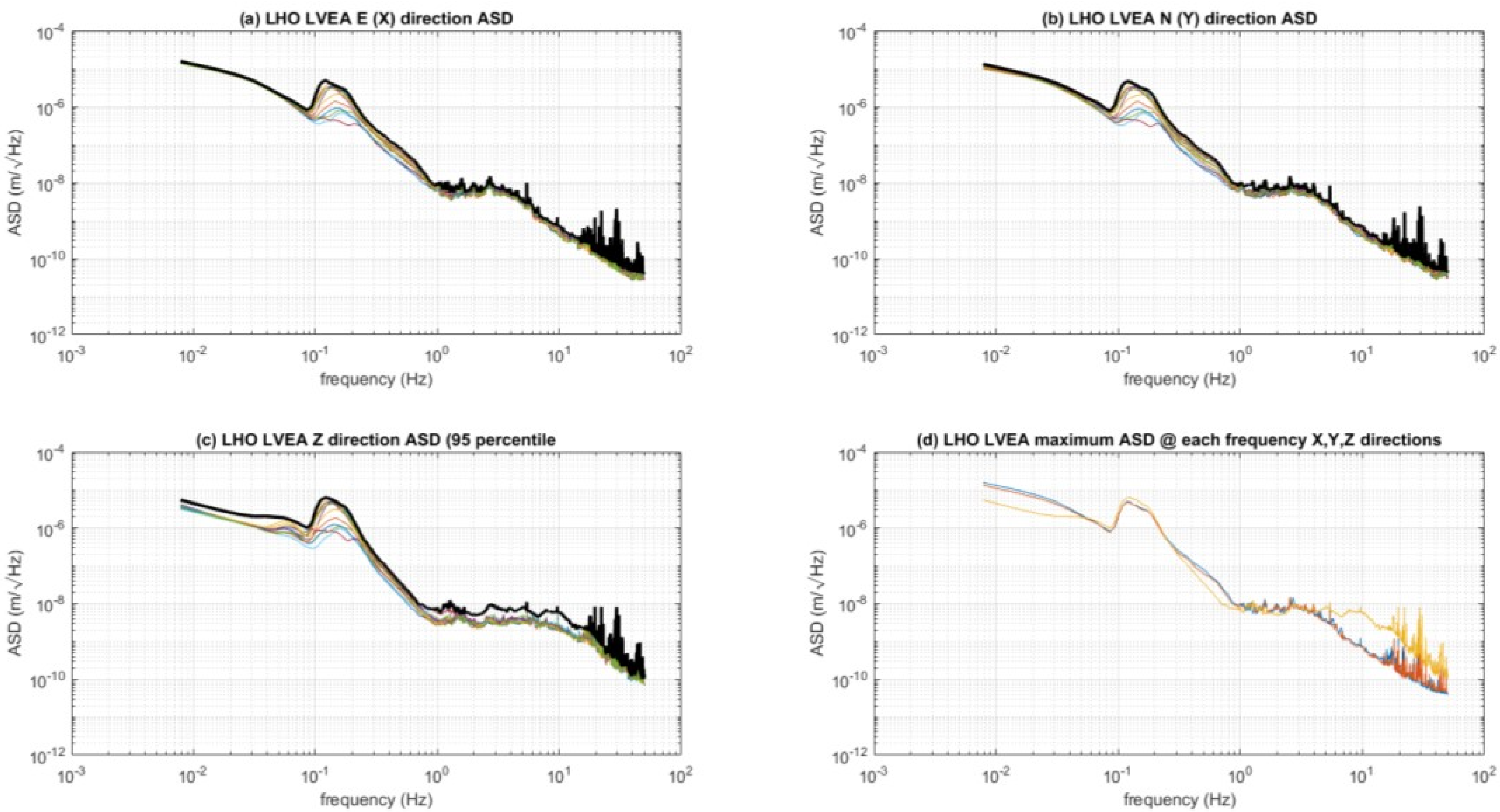



**Figure 7 LHO LVEA Ground Vibration "design" ASD (derived from T1500224)**

*Subplots a, b and c show the 95th percentiles for each of 12 months from 8/2009 through 7/2010. In each of these subplots the bold black line is the maximum ASD at each frequency for each of the 12 months. Subplot (a) is in the East (X) direction, (b) is in the North (Y) direction and (c) is in the Vertical (Z) direction. Subplot (d) shows the maximum ASD at each frequency for the X, Y and Z directions.*

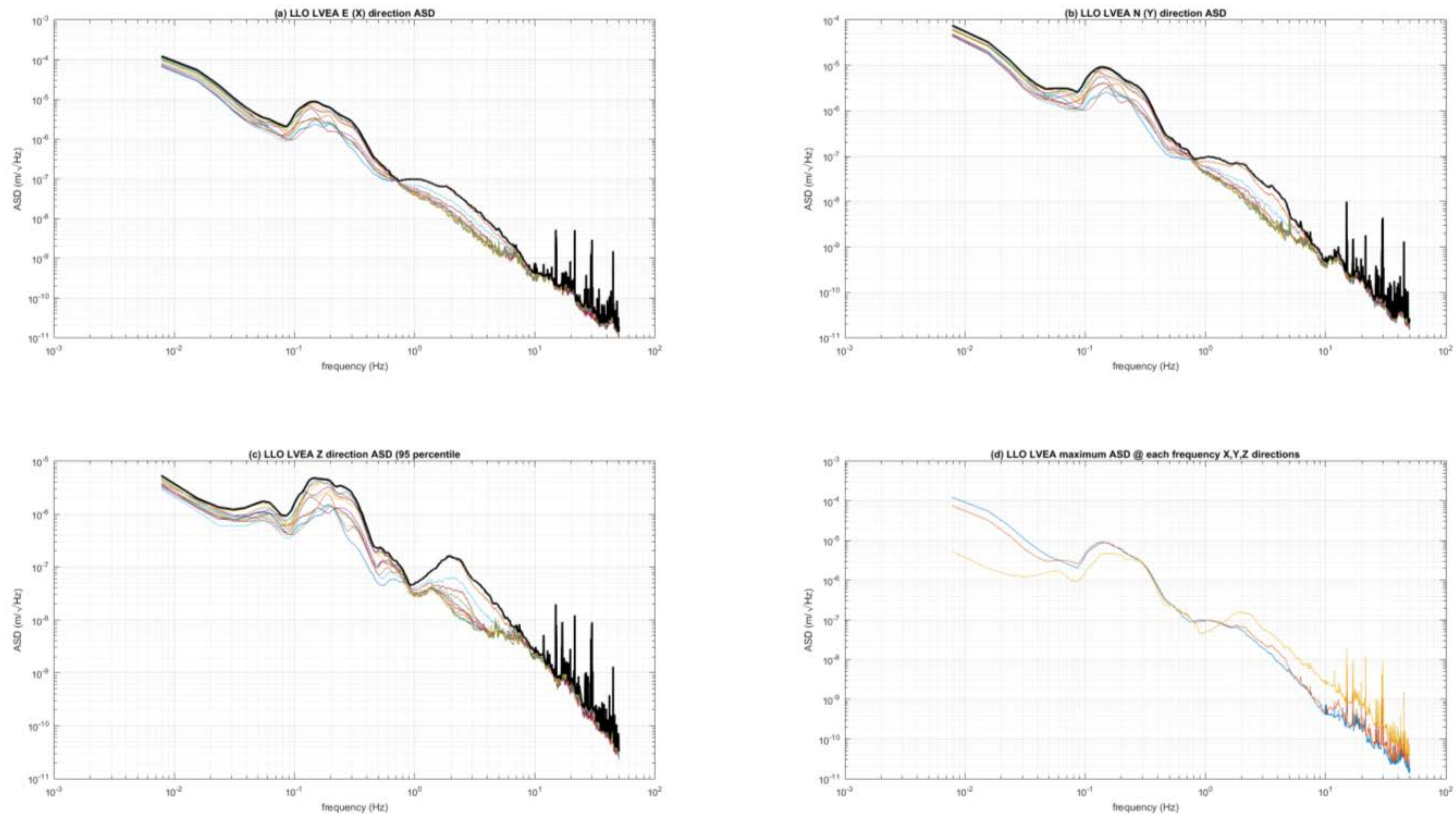
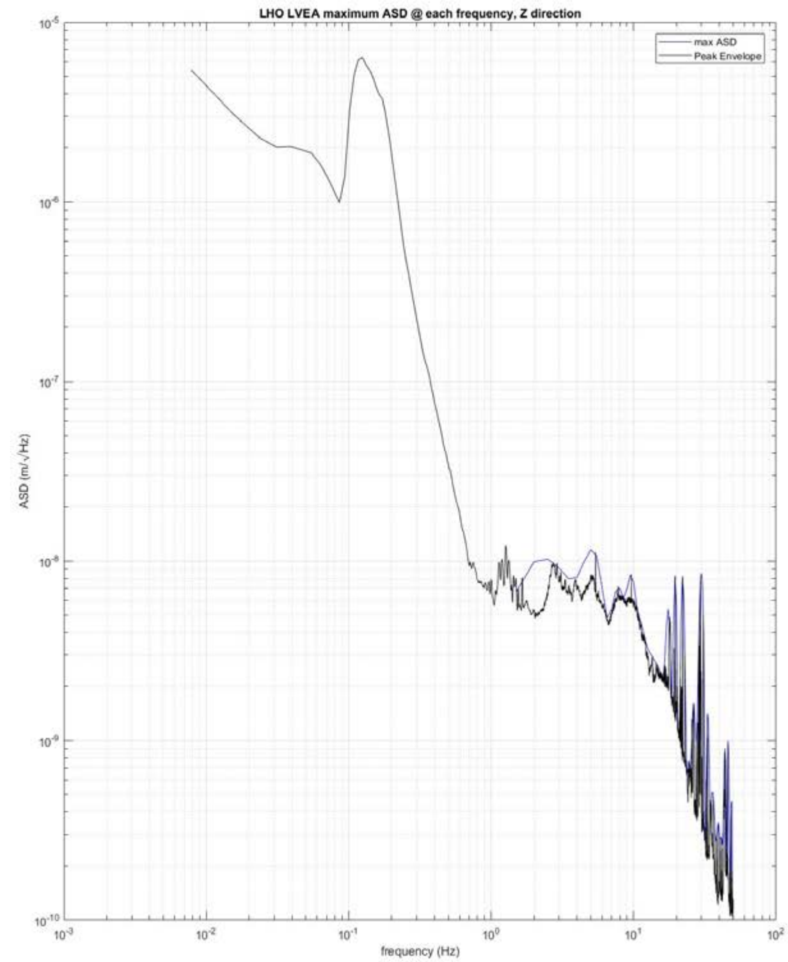



**Figure 8 LLO LVEA Ground Vibration "design" ASD (derived from T1500224)**

*Subplots a, b and c show the 95th percentiles for each of 12 months from 8/2009 through 7/2010. In each of these subplots the bold black line is the maximum ASD at each frequency for each of the 12 months. Subplot (a) is in the East (X) direction, (b) is in the North (Y) direction and (c) is in the Vertical (Z) direction. Subplot (d) shows the maximum ASD at each frequency for the X, Y and Z directions.*



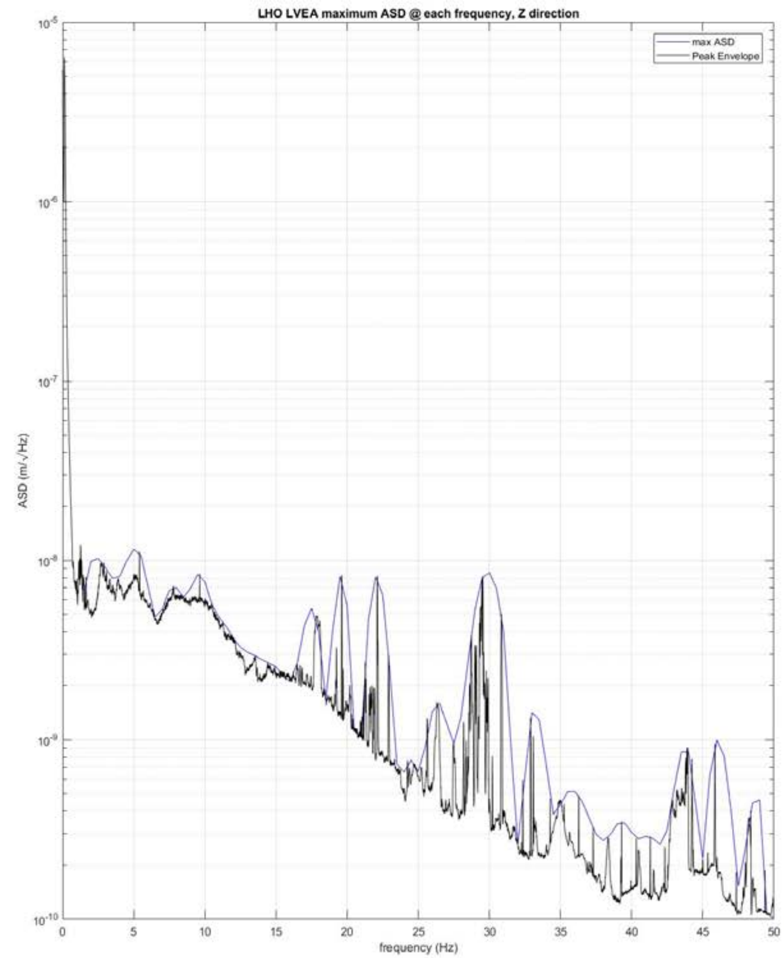




**Figure 9 Example use of peak enveloping function and spline fitting to 'down sample' the LHO Z ASD to fewer points**

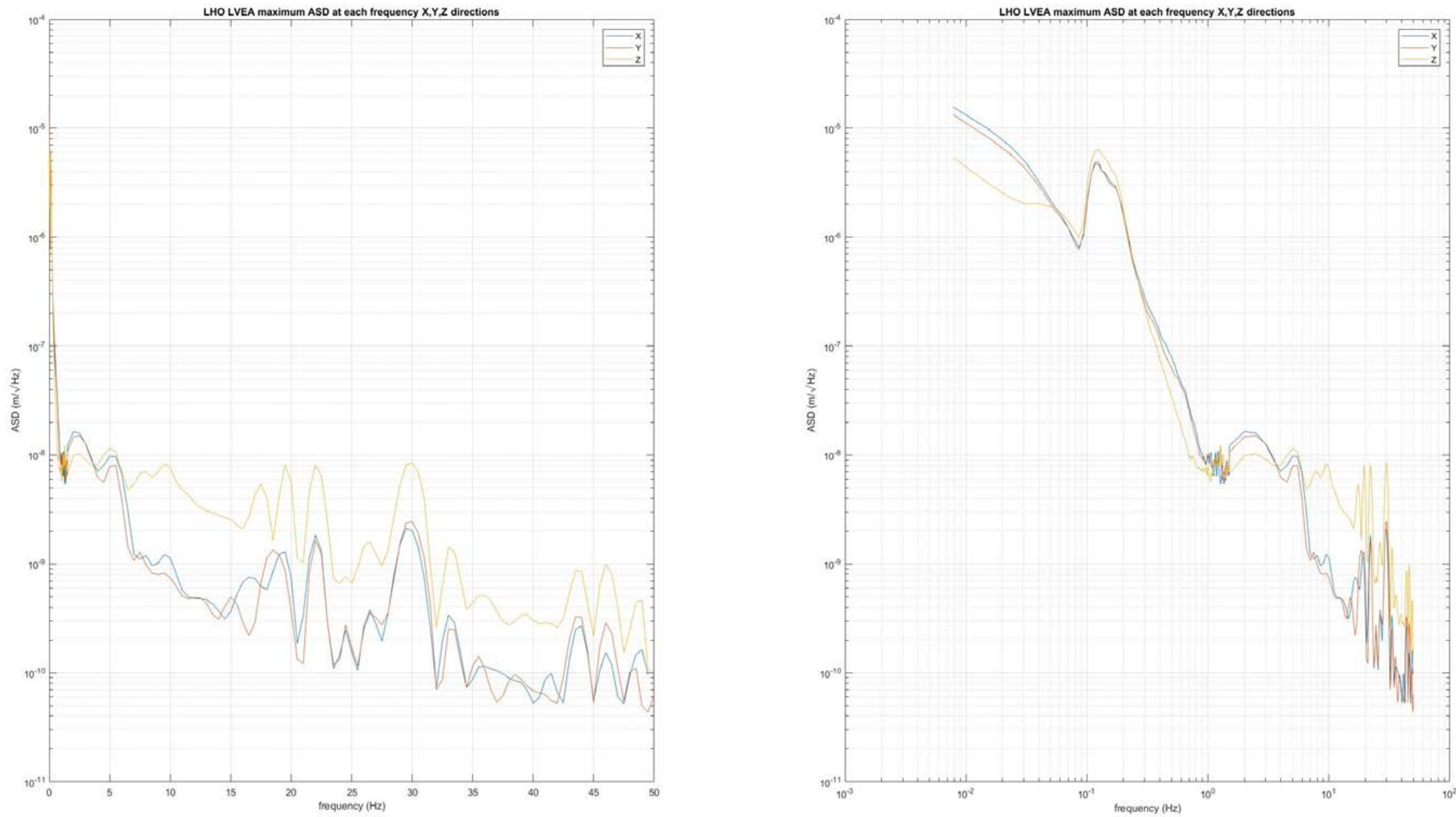



**Figure 10 LHO LVEA Ground Vibration "Peak Envelope" ASD at 95th Percentile**

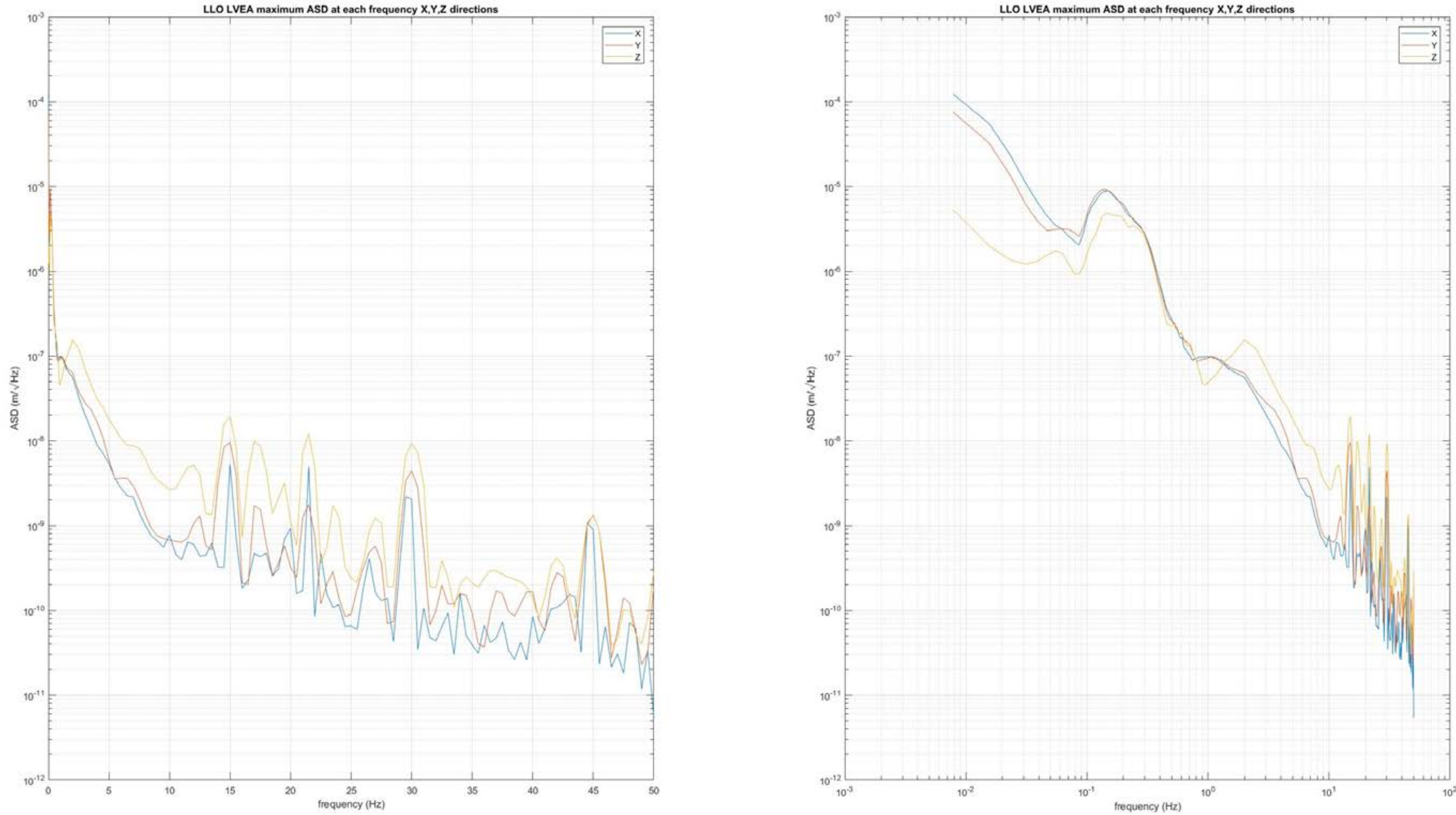



**Figure 11 LLO LVEA Ground Vibration "Peak Envelope" ASD at 95th Percentile**

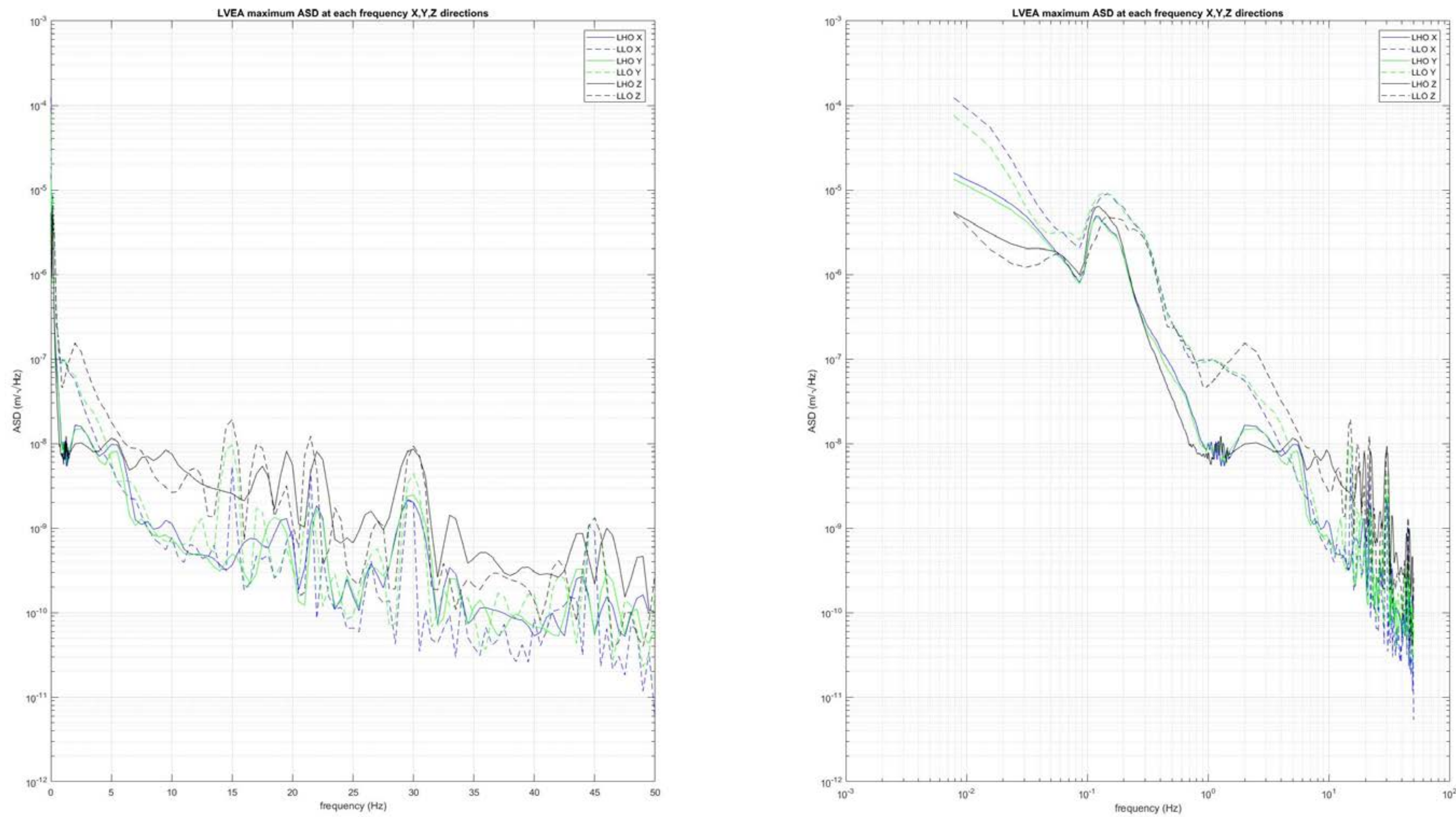



**Figure 12 Comparison of LHO and LLO LVEA Ground Vibration "Peak Envelope" ASD at 95th Percentile**

## 6 Baffle random vibration response

The response ASDs in the X, Y and Z directions, for 4 points on the perimeter of the edge of the baffle aperture, was calculated for each of the 6 baffles in the representative repeating sub-assembly of the FCT for the LHO "peak design, 95$^{th}$ percentile" displacement excitation. These four points are at the 12, 3, 6 and 9 o'clock positions. The baffle response ASDs are shown in the following figures, and given in the spreadsheet file "T2000280-v1 FCT baffle psds.xlsx" uploaded at LIGO-T2000280-v1.

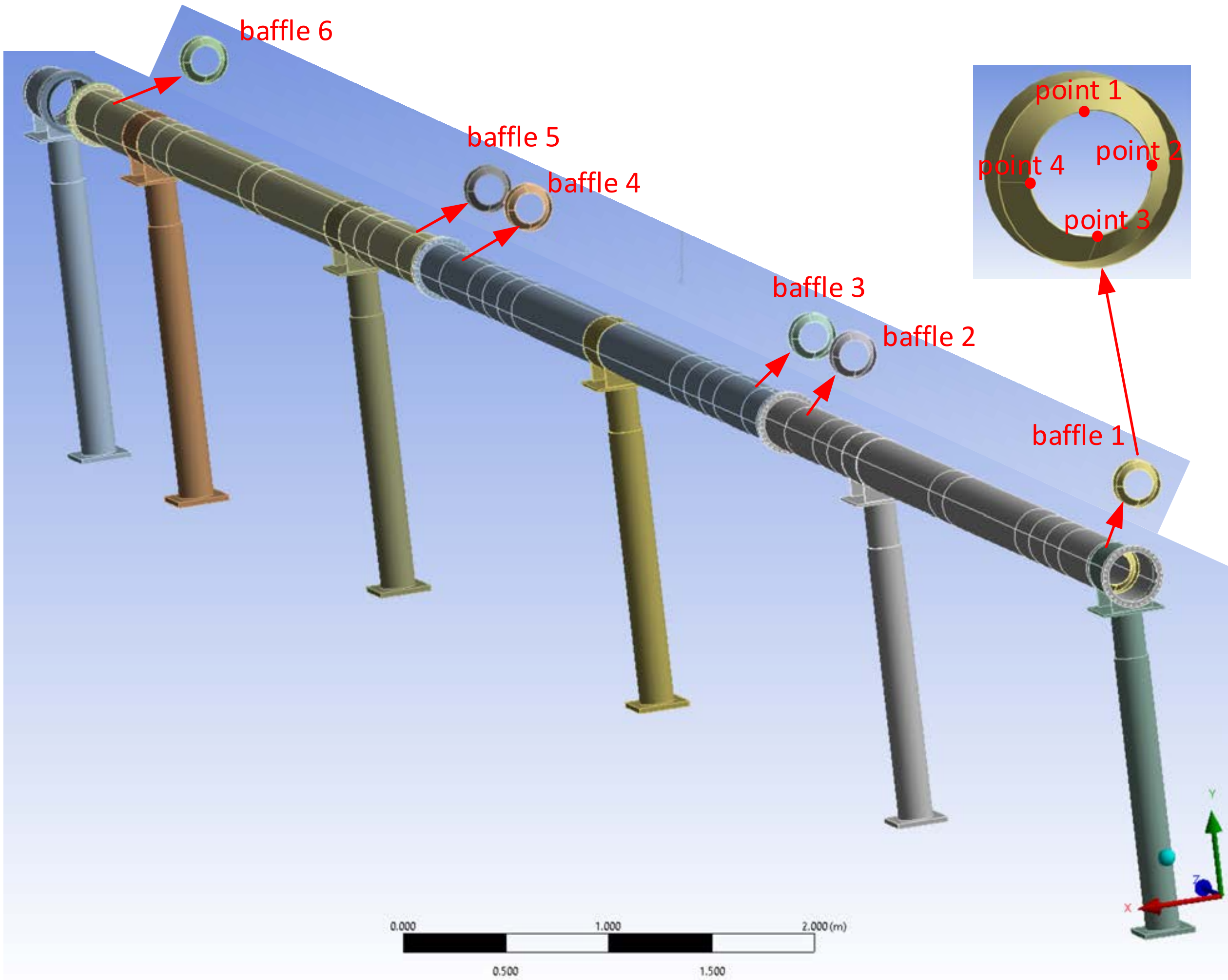



**Figure 13 Baffle response point designations**

In the following response plots the "series n" sequence is:
*{baffle 1, point 1; baffle 1, point 2; baffle 1, point 3; baffle 1, point 4; baffle 2, point 1; baffle 2, point 2; … baffle 6, point 4}*

*Response to the LLO base excitation spectrum has not been calculated (as yet).*

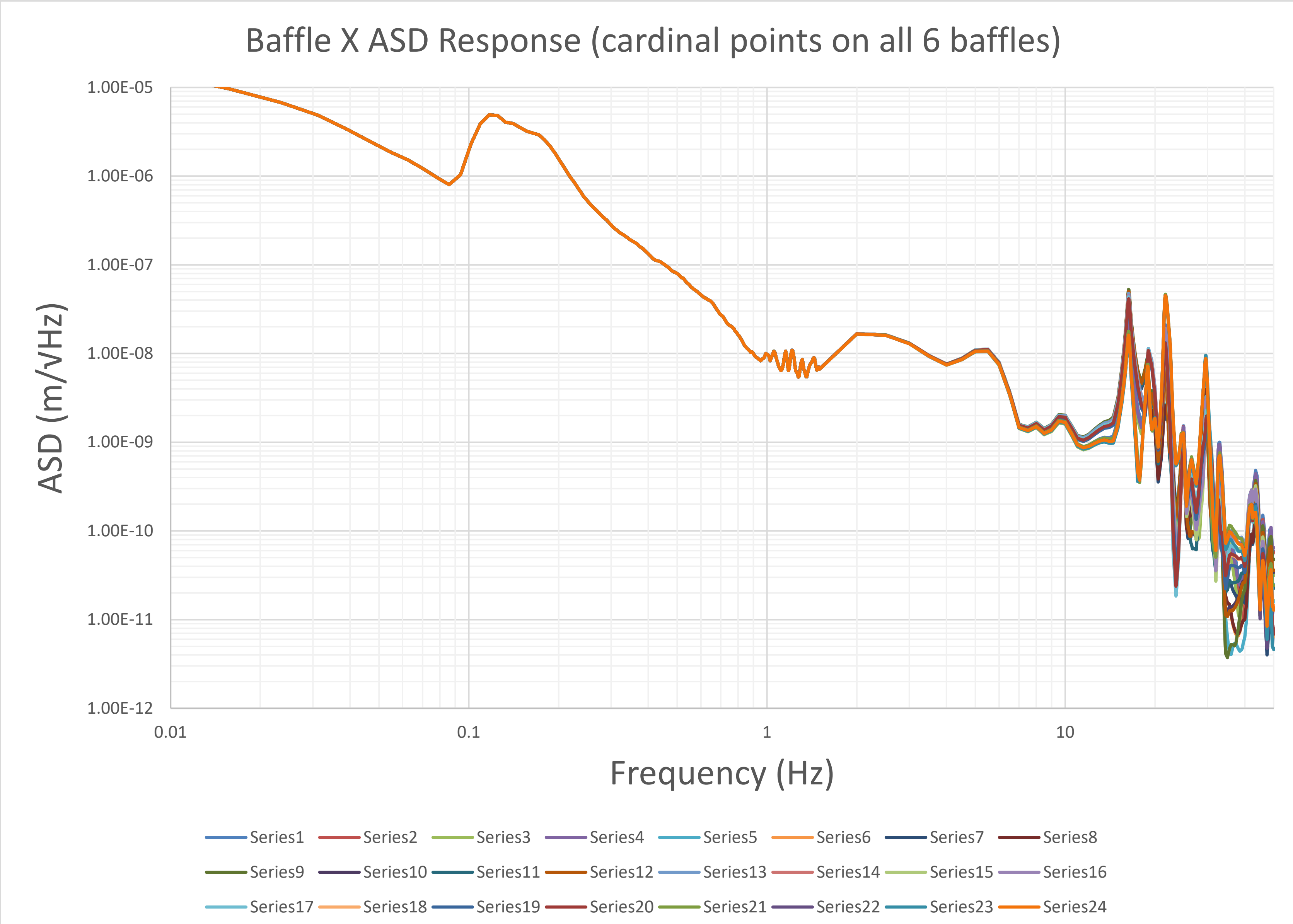



**Figure 14 Baffle X ASD Response (LHO) – loglog**

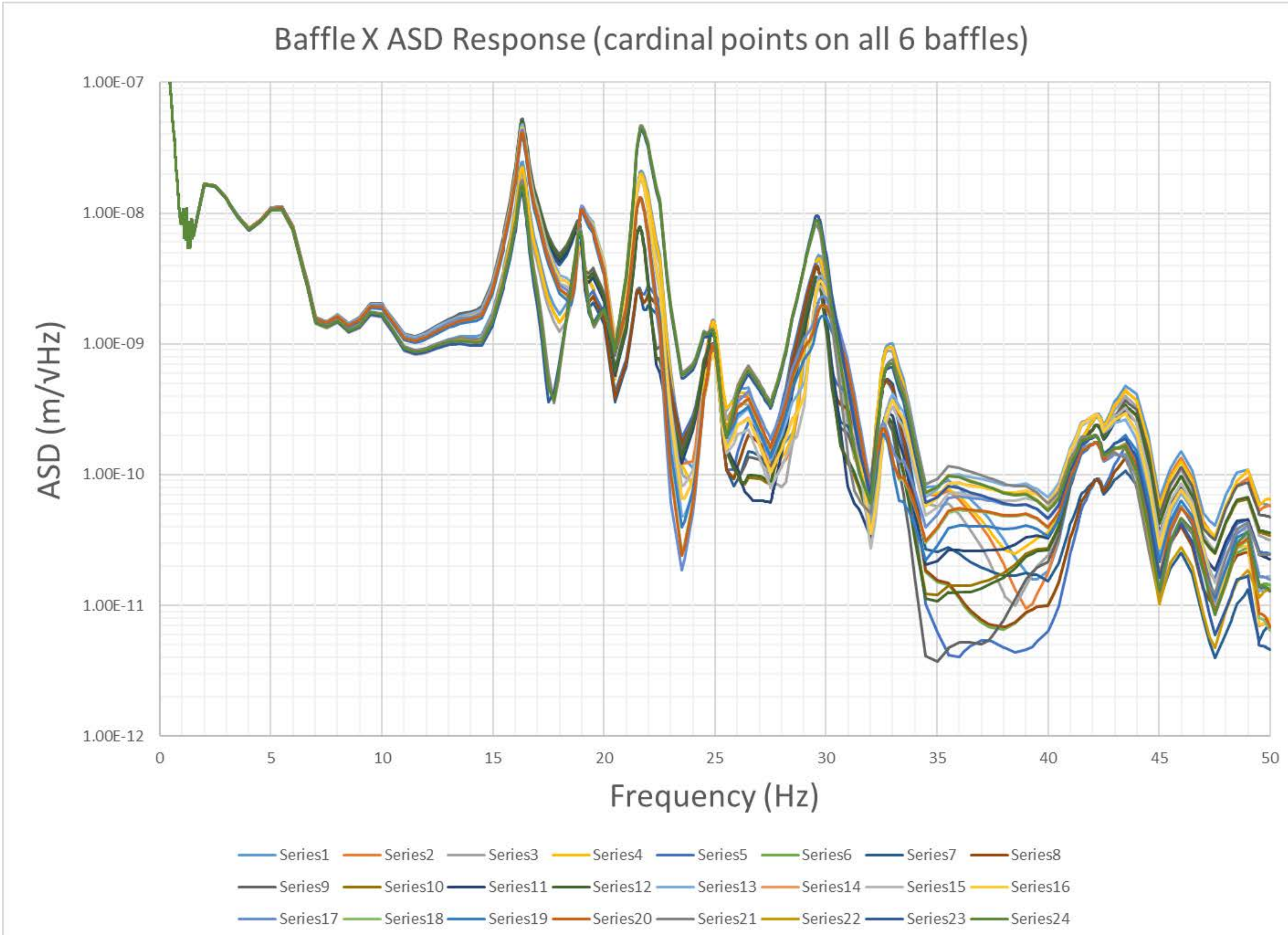



**Figure 15 Baffle X ASD Response (LHO) – semilog**

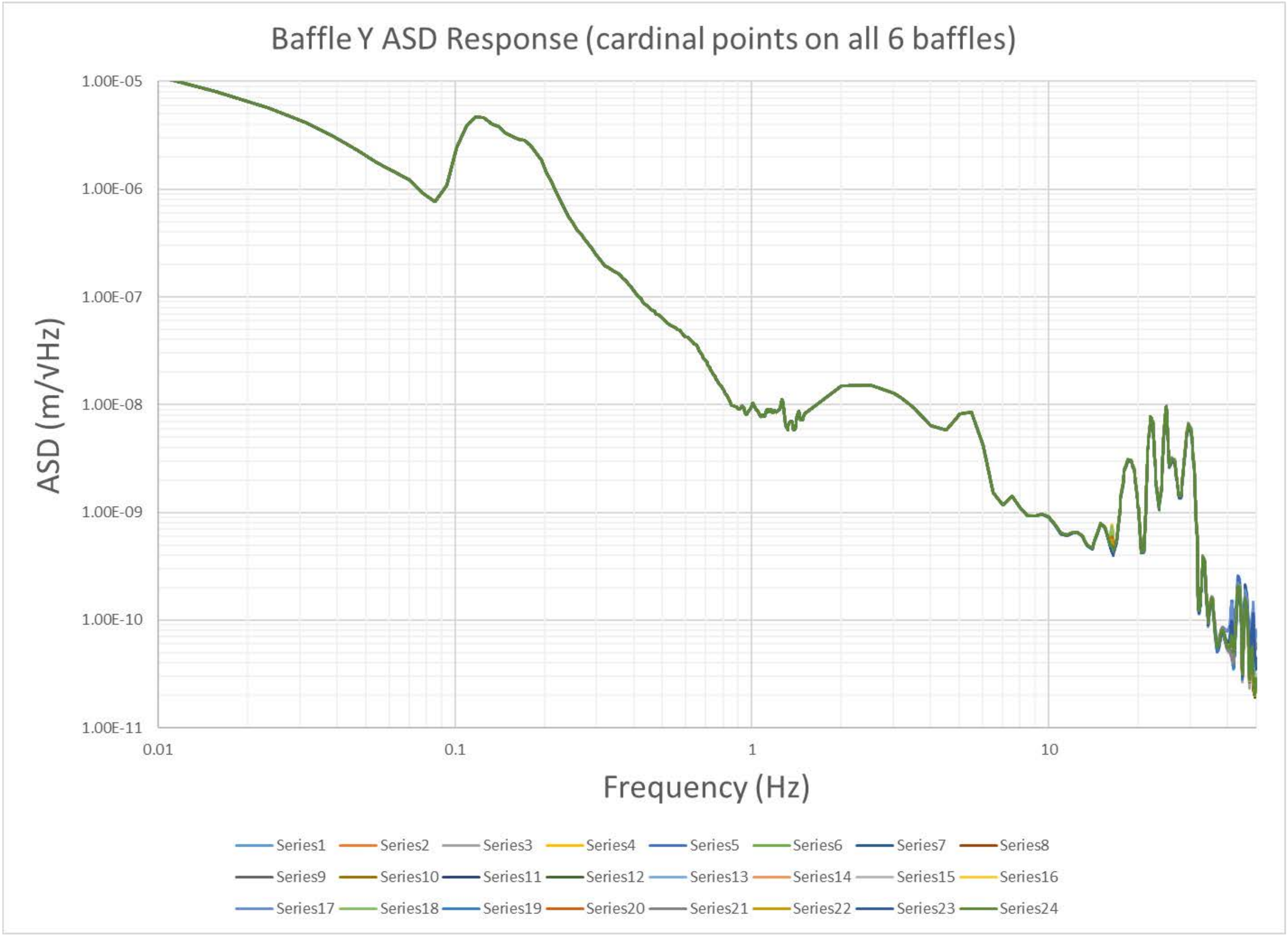



**Figure 16 Baffle Y ASD Response (LHO) – loglog**

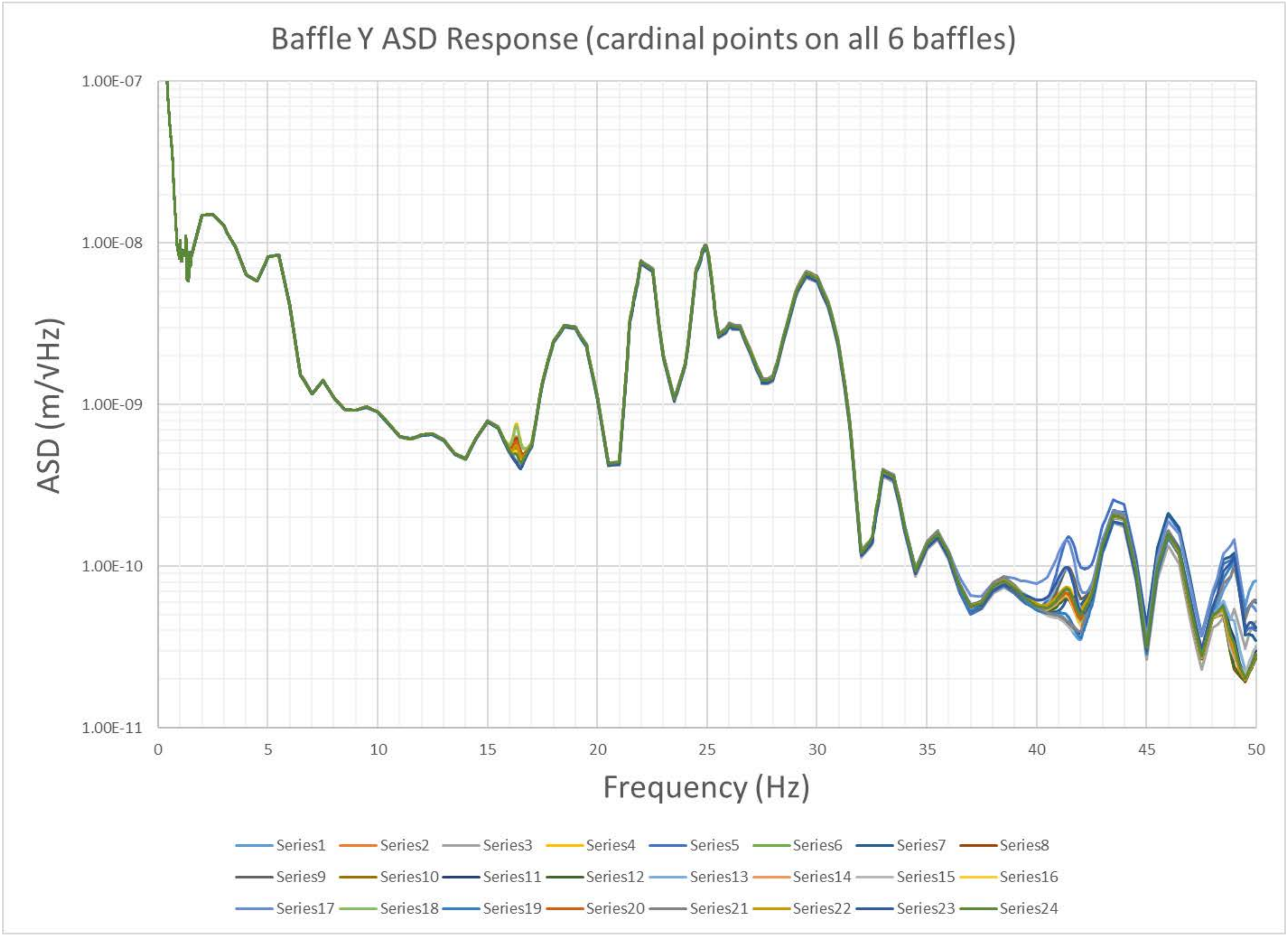



**Figure 17 Baffle Y ASD Response (LHO) – semilog**

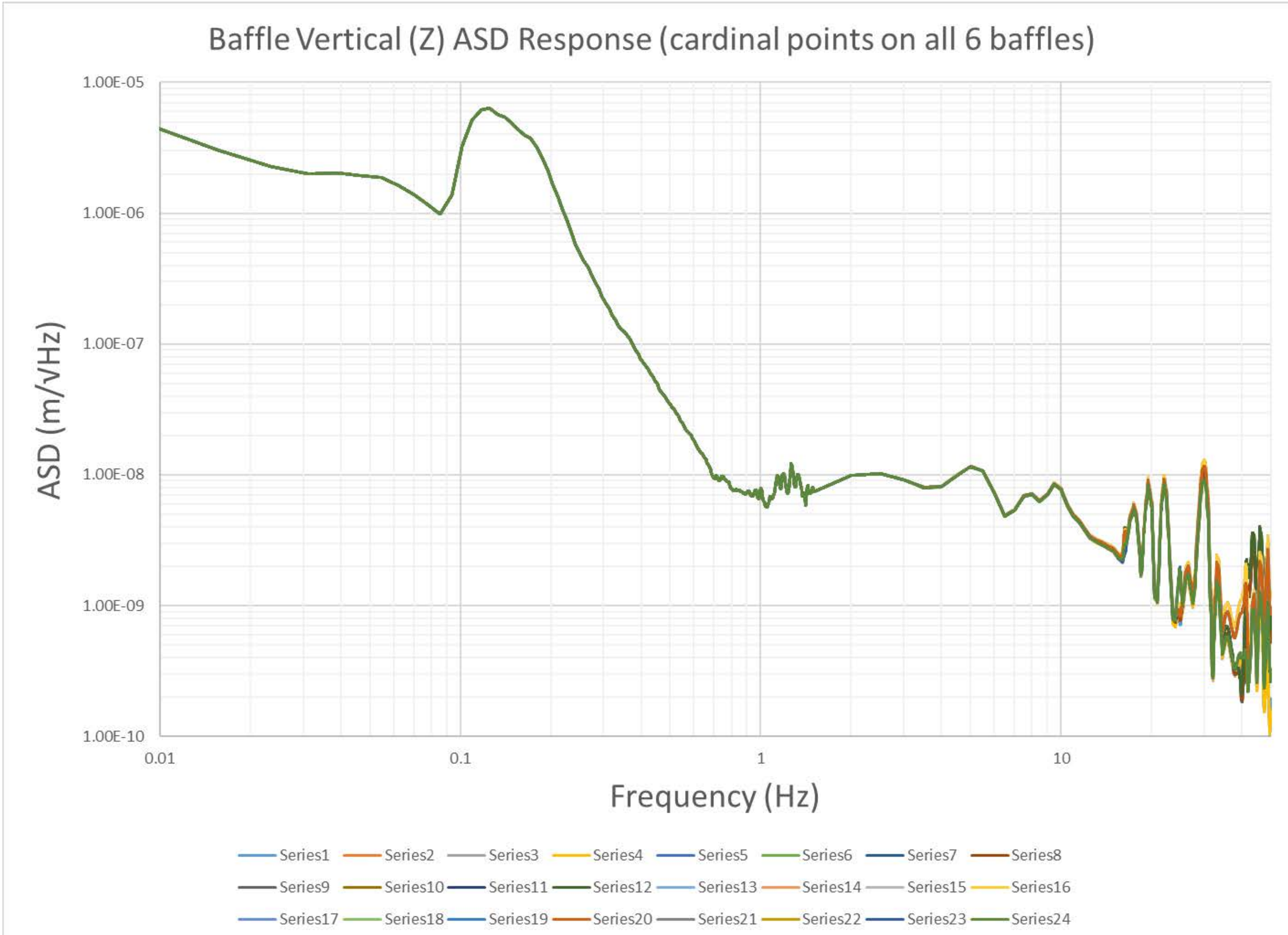



**Figure 18  Baffle Z ASD Response (LHO) – loglog**

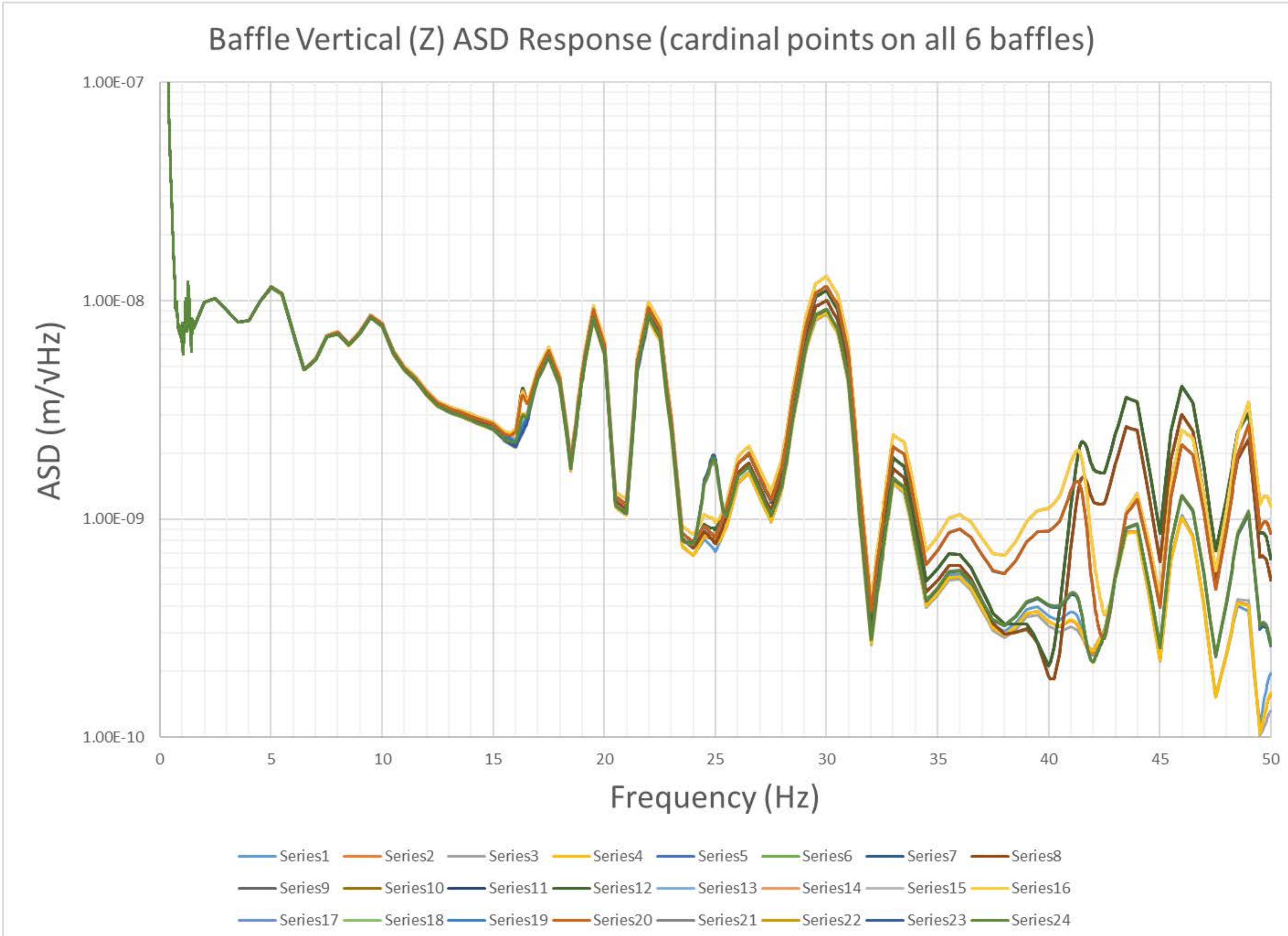



**Figure 19 Baffle Z ASD Response (LHO) – semilog**