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- LIGO -
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Derivation of CDS Rack Acoustic Noise Specifications

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1 ABSTRACT

This document derives allowable acoustic noise levels for the LIGO Detector CDS racks. The analysis uses allowed sound pressure levels previously defined and factors in the present CDS and vacuum chamber layout configurations to deduce from the requirement an acoustic noise budget per CDS rack.

2 KEYWORDS

Acoustic noise, CDS racks, LIGO sensitivity.

3 OVERVIEW

The environmental noise budget for LIGO is documented in LIGO-L950238. The vibrational component has been revised in LIGO-T950113-05-O. However, the acoustic requirements, which are the subject of this document, have not been changed. The overall disturbance budget is allocated among the following sources:

- acoustic excitation of facilities equipment (e.g., HVAC systems)
- vibrations of the ground
- acoustic excitation due to electronics hardware racks (CDS)
- acoustic/vibrational excitation from vacuum equipment

The acoustic noise budget for LIGO was worked out by R. Weiss and S. Whitcomb and is documented in LIGO-L950238. The source document for this was written by Weiss and is entitled "Motions Due to Sound Fields," dated 16.02.95.

4 CDS REQUIREMENT

4.1. Model Definition

The top level allowable acoustic noise level allocated to CDS equipment must be subdivided among 50 CDS racks in the LVEA and among 3 racks in the VEAs (mid- and end stations are assumed identical for this analysis). The allowable noise budget is affected by the separation distances among racks and chambers and also by the acoustic properties of the LVEA or VEA. The model developed here accounts for both direct acoustic coupling ("line-of-sight") and indirect coupling due to the acoustic reverberations of the (L)VEA.

Direct coupling uses the layouts within the (L)VEA for the CDS racks and the vacuum chambers which have been developed and are documented in (L)VEA Integrated Layout. This layout provides the location of the components and permits the distances between each rack and each vacuum chamber to be determined. For the purposes of this analysis center-to-center distances (from a 2D plan drawing) are used.

Indirect coupling uses information provided by M. Long at the Parsons Facilities PDR (December, 1995). In this meeting, M. Long presented estimates for the frequency-dependent reverberation times within the (L)VEA. The estimates covered the frequency band 4 Hz < f < 8000 Hz, and this allows calculation of the buildup of acoustic energy within the (L)VEA from a source, such as a rack.

Taken together, these two effects may be used to derive from the top-level acoustic noise level requirement a requirement for an individual CDS electronic rack. It must be noted that this allocation is dependent on both layout geometry and (L)VEA acoustic properties. The derivation is presented in Appendix 1. Diffraction and the presence of other vacuum equipment, such as the large beam manifolds, were not included in this analysis.

4.2. Results for presently planned LVEA and VEAs

:If one source of noise is measured to produce a sound pressure level p_0 measured at a distance r_0, then the total sound pressure level at a chamber at distances r_i from N such sources is given by Eq. [A14]:

$$p_{tot}(r) = p_0 \left(\sum_{i=1}^{N} \left(\frac{r_0}{r_i} \right)^2 + \frac{N 4\pi r_0^2 \tau c_s}{V} \right)^{\frac{1}{2}} \qquad [1]$$

In dB:

$$20\log[p_{tot}] = 20\log[p_0] + 10\log \left(\sum_{i=1}^{N} \left(\frac{1}{r_i} \right)^2 + \frac{N 4\pi\ \tau(f)\ c_s}{V} \right) + 20\log[r_0] \qquad [2]$$

By setting the LHS of this last expression equal to the overall LIGO acoustic noise budget for CDS racks, it is possible to derive the single-rack performance from the overall performance requirement. The last term on the right permits one to scale the requirement curve for different distances at which acoustic emission from a test article may be measured. The geometry of the (L)VEA rack and chamber layout is shown in Figures 1a and 1b. The single-rack performance requirements are indicated in Figure 2 for the LVEA and the VEAs separately. For each building, estimates indicating the acoustic requirements in the vicinity of chambers containing suspended masses are shown for both initial seismic isolation systems and enhanced systems with active isolation. For each case, three curves are indicated: the total requirement is indicated by a dashed line; the single-rack requirement is shown for two different distances to the rack. In all cases, the higher curve corresponds to a measurement performed at 1 m and the lower curve corresponds to a measurement at 3m. The parameters used in Eq. [2] to generate the curves are indicated in Table 1.

Table 1: Parameters values used in Eq. [14]

Parameters	LVEA	VEA
N, number of CDS racks	50	3
Inverse-square RSS distance, $\left(\sqrt{\sum_i \frac{1}{r_i^2}}\right)^{-1}$	6.3 m	5.5 m
r_0, scale distance for measurements	1 m and 3 m	
c_s, speed of sound in air	330 m/s	
Volume, V (m^3)	3.19×10^4	9.42×10^3
Surface Area, S (m^2)	3.5×10^3	1.45×10^3
$\tau(f)$	Per Fig. A2.	

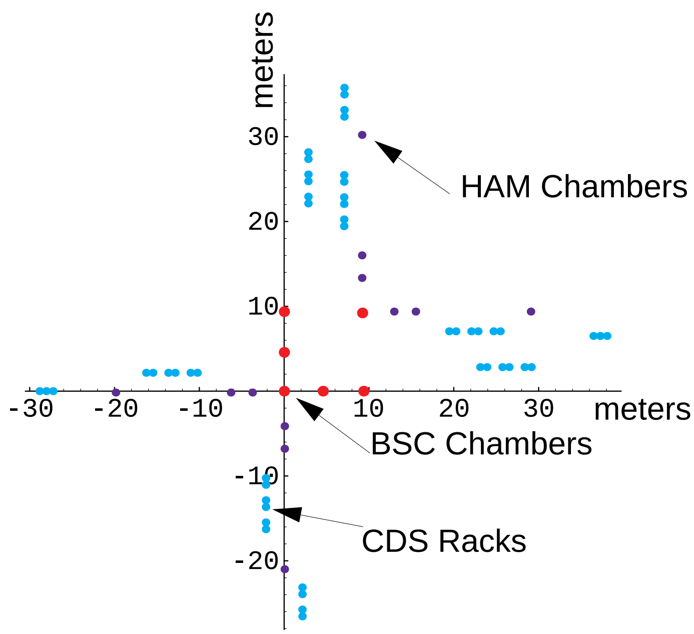

Figure 1a: Configuration of Chambers and Racks in LVEA.

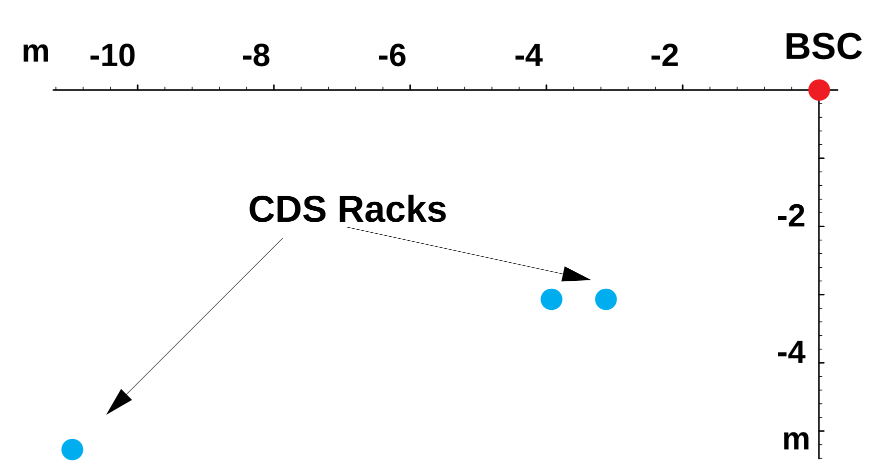

Figure 1b: Configuration in VEAs

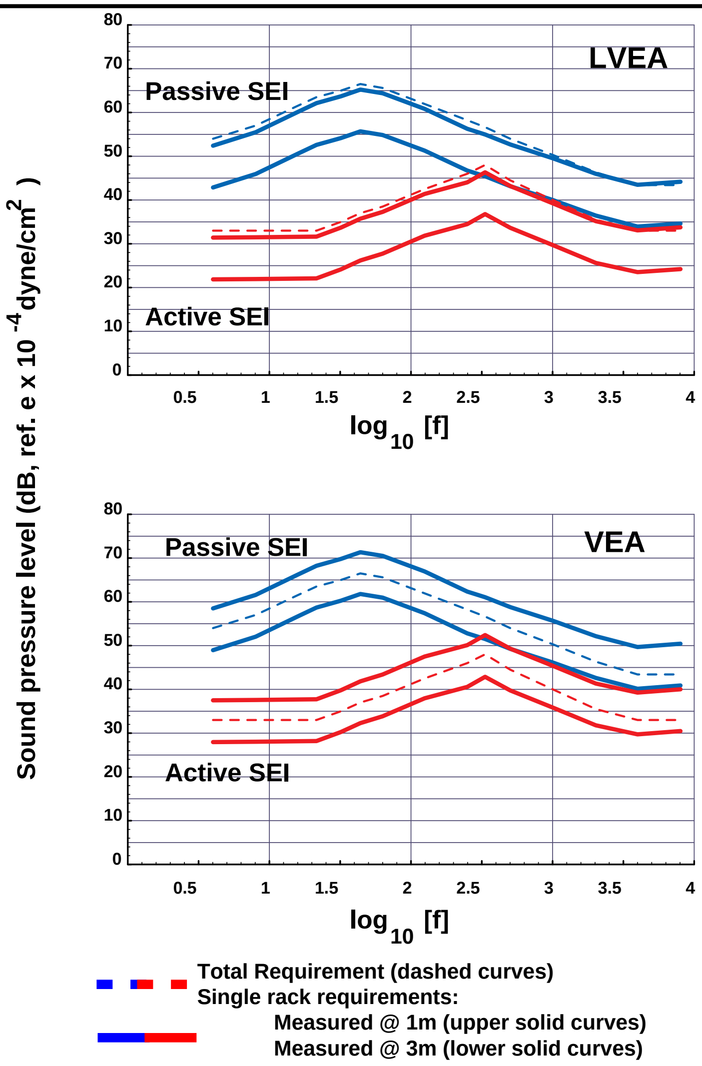

Figure 2

4.3. Conclusion

The net effect of an increased number of CDS racks within the LVEA and VEAs does not significantly alter the per-rack requirement above the total budget. This fact is due to the large dimensions of the LVEA and VEAs. The large dimension has several concomitant effects which mitigate the situation: racks are located rather far from chambers with sensitive components; the large volume of the rooms keeps the acoustic energy at low levels for given rack power outputs and reverberation times; the relative numbers of racks is rather low compared to the rooms sizes.

Active SEI requirements were shown in the figures for comparison purposes only. Their increased sensitivity to acoustic ambient noise levels will be accommodated by providing suitable acoustic shielding for the active system.

<u>For initial LIGO, the most stressing requirement on allowed single-rack noise levels occurs within the LVEA.</u>

APPENDIX 1 CALCULATION OF THE MODEL

Figure A1 shows a schematic of a source of sound at the center of a spherical shell of radius r_0.

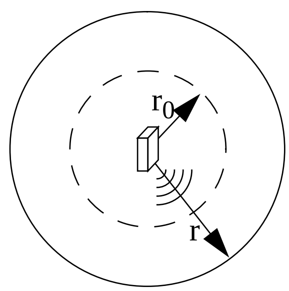

Figure A1

Referred to the surface r_0, the acoustic pressure and intensity on a shell of radius r are related by:

$$p(r) = p(r_0)\left[\frac{r_0}{r}\right] \text{; p in dyne/cm}^2 \qquad \text{[A1]}$$

$$i(r) = i(r_0)\left[\frac{r_0}{r}\right]^2 \text{; i in W/cm}^2 \qquad \text{[A2]}$$

The pressure and intensity are related through the acoustic impedance for sound: $Z_s = \rho_0 c_s$. Here ρ_0 is the density of air and c_s is the speed of sound. Then, we have:

$$i(r) = \frac{p(r)^2}{2Z_s} = \frac{p(r)^2}{2\rho_0 c_s} \qquad \text{[A3]}$$

In an isotropic (“diffuse”) geometry, acoustic intensity (W/m^2) and energy density (J/m^3) are related:

$$i(r) = \hat{E}(r)\, c_s \qquad [A4]$$

The reverberation time estimated by M. Long is related to the characteristic decay time of sound energy within the enclosed (L)VEA. The reverberation time is the time taken for the sound intensity level (or equivalently, energy density) to drop by 60dB:

$$\frac{\hat{E}(T_{rev})}{\hat{E}_0} = \frac{i(T_{rev})}{i_0} = 10^{-6} = e^{-T_{rev}/\tau} \qquad [A5]$$

$$\tau = \frac{T_{rev}}{6\log[e]} \qquad [A6]$$

Figure A2 shows the decay time derived from the reverberation time for both the LVEA and VEAs. The reverberation time for the VEA was derived from that for Long's estimate for the LVEA using the formula (APS Physics Vade Mecum, 2nd Ed., pp 53f, APS 1989):

$$\frac{TS}{V} \propto \frac{1}{c_s \cdot loss} \qquad [A7]$$

This relationship holds for acoustic losses dominated by absorption at the interior surfaces of an enclosed volume having volume V and surface area S.

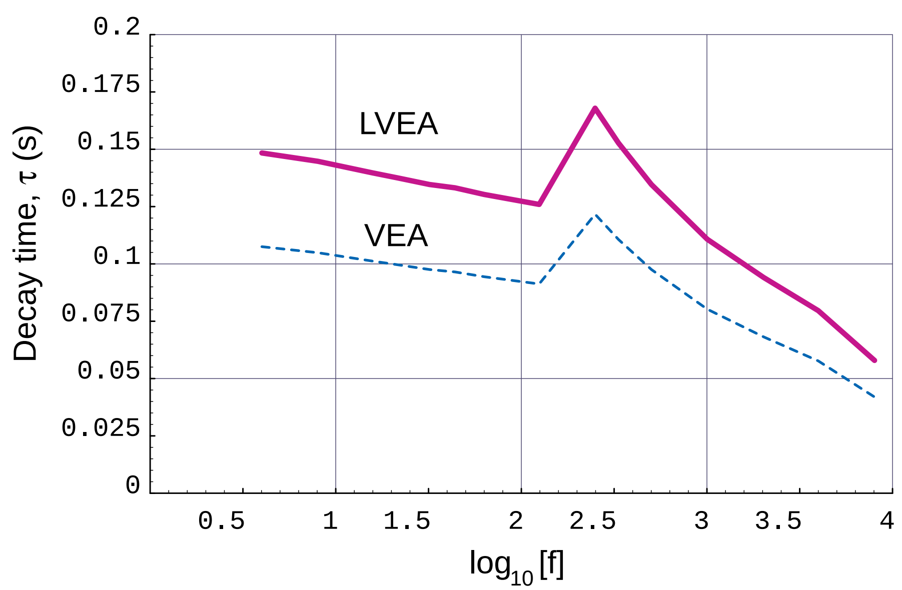

Figure A2

Consider a single source of sound within the (L)VEA, and let the source output power be P_0. The differential equation describing the buildup of acoustic energy, including the loss represented by the reverberation time, is given by:

$$\dot{E} = P_0 - \frac{E}{\tau} \qquad [A8]$$

In the steady state, $\dot{E} = 0$, and $E_{eq} = P_0\tau$. The energy density within the a volume V at equilibrium is:

$$\hat{E}_{eq} = \frac{E_{eq}}{V} = \frac{P_0\tau}{V} \qquad [A9]$$

Using Eq. [A4], the equilibrium acoustic intensity within V is given by:

$$i_{eq} = E_{eq}c_s = \frac{P_0\tau c_s}{V} \qquad [A10]$$

The total intensity produced at a point a distance r from a source of output power P_0 consists of the directly radiated component, which drops off as $1/r^2$, and the reverberating component, which is independent of distance:

$$i_{tot}(r) = \frac{P_0}{4\pi r_0^2}\left(\frac{r_0}{r}\right)^2 + \frac{P_0\tau c_s}{V} \qquad [A11]$$

$$i_{tot}(r) = i_0\left[\left(\frac{r_0}{r}\right)^2 + \frac{4\pi r_0^2\tau c_s}{V}\right] \quad ; \quad i_0 = \frac{P_0}{4\pi r^2{}_0} \qquad [A12]$$

For N such sources, each at position r_i, the total acoustic intensity is a sum over the N sources:

$$i_{tot}(r) = \sum_{i=1}^{N} i_0\left[\left(\frac{r_0}{r_i}\right)^2 + \frac{4\pi r_0^2\tau c_s}{V}\right] = i_0\left(\sum_{i=1}^{N}\left(\frac{r_0}{r_i}\right)^2 + \frac{N4\pi r_0^2\tau c_s}{V}\right) \qquad [A13]$$

Using Eq. [3] one has:

$$p_{tot}(r) = p_0\left(\sum_{i=1}^{N}\left(\frac{r_0}{r_i}\right)^2 + \frac{N4\pi r_0^2\tau c_s}{V}\right)^{\frac{1}{2}} \qquad [A14]$$

Or, in dB:

$$20\log[p_{tot}] = 20\log[p_0] + 10\log\left(\sum_{i=1}^{N}\left(\frac{1}{r_i}\right)^2 + \frac{N4\pi\ \tau(f)\ c_s}{V}\right) + 20\log[r_0] \qquad [A15]$$