LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

LIGO-T060285-00-R 12/11/2006

Charging Noise Model Used in Bench 5.0

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Noise from charge buildup on LIGO test masses is an increasing concern, both for initial/enhanced LIGO and for the Advanced LIGO design. The program BENCH, which simulates the limiting noise sources in Advanced LIGO and calculates sensitivities to some gravitational wave sources, includes a model for noise from charge buildup in Versions 5.0 and beyond.

The noise model comes from Rai Weiss [1],

$$S_F(f) = 2 \langle F^2 \rangle / (\pi\, \tau_0\, (1/\tau_0^2 + (2\, \pi\, f)^2)) \qquad (1)$$

where $S_F(f)$ is the spectral density of force, $\langle F^2 \rangle$ is the average squared force between charges on the test mass and a nearby ground plane, and τ_0 is the correlation time of the Markov process that is assumed to describe the charge behavior. The average squared force can be found from the usual Coulomb law, provided the amount of charge and some effective distance between the charge and the nearby ground plane are known. The effective distance is one that includes corrections due to the distribution of the charge and the spatial extent of the ground plane. The LIGO research program on charging [2] is primarily aimed at directly measuring and understanding τ_0. If the value is found to cause the charging noise to be a limiting noise source in Advanced LIGO, further research will be conducted to try to reduce τ_0.

In BENCH 5.0, Eq (1) is used to model the charging noise. The parameter input file to BENCH, IFOModel, includes values for the total charge, the effective distance, the surface conductivity of the test masses, and the test mass dielectric constant. The relaxation time is then calculated from

$$\tau_0 = 4\, \pi\, \varepsilon_0\, \varepsilon/\sigma \qquad (2)$$

where ε_0 is the permittivity of free space, ε is the test mass dielectric constant, and σ is the test mass surface conductivity. These values can be adjusted by the user of BENCH just by changing the values in IFO_Model. The default values for BENCH 5.0 are seen in Table 1. The value for σ is motivated by the observations of Prokhorov et al [3], who saw no detectable decay out to a time of 1000 hours. The effective distance is motivated by the separation between the test mass and the metal in the electrostatic drive.

Table 1.

Charge	$Q = 10^{-12}$ C
Effective distance	$d = 4$ mm
Test mass dielectric constant	$\varepsilon = 3.75$
Test mass surface conductivity	$\sigma = 10^{-17}\ \Omega$ m

Using these values, BENCH 5.0 makes an Advanced LIGO noise spectrum as seen in Figure 1. The charging noise is just visible as a technical noise source at the bottom right corner. This noise spectrum predicts a binary neutron star inspiral range of 180 Mpc, a black hole binary (10 solar mass) inspiral range of 980 Mpc, and a stochastic background sensitivity of 1.2 X 10^{-9}. The inspiral ranges are strongly affected by the choice of coating on the optics.

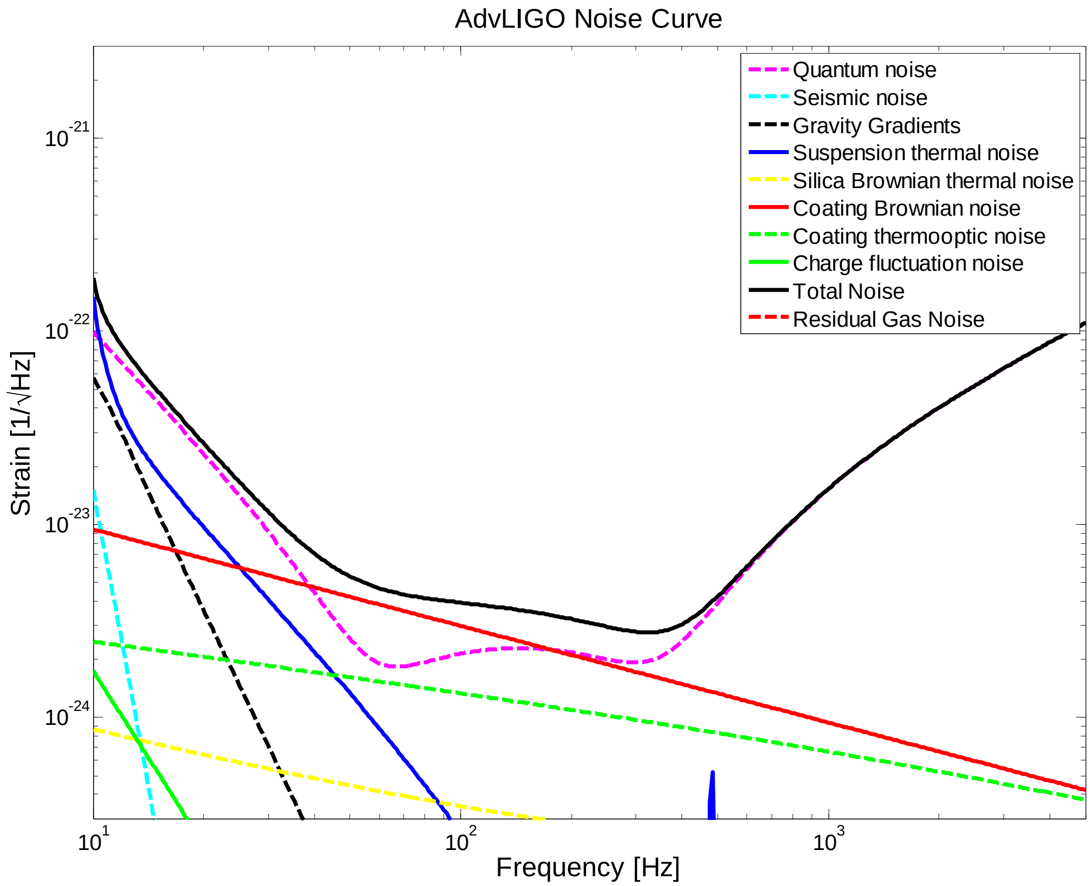

Figure 1 – Advanced LIGO noise spectrum with standard charging parameters from Table 1.

Increasing the amount of charge on the optic to Q = 10^{-11} C results in the noise spectrum shown in Figure 2 with a binary neutron star range of 170 Mpc, a black hole binary range of 860 Mpc, and a stochastic background sensitivity of 1.6 X 10^{-8}. The charging noise is a limiting noise source in the frequency band 10-20 Hz.

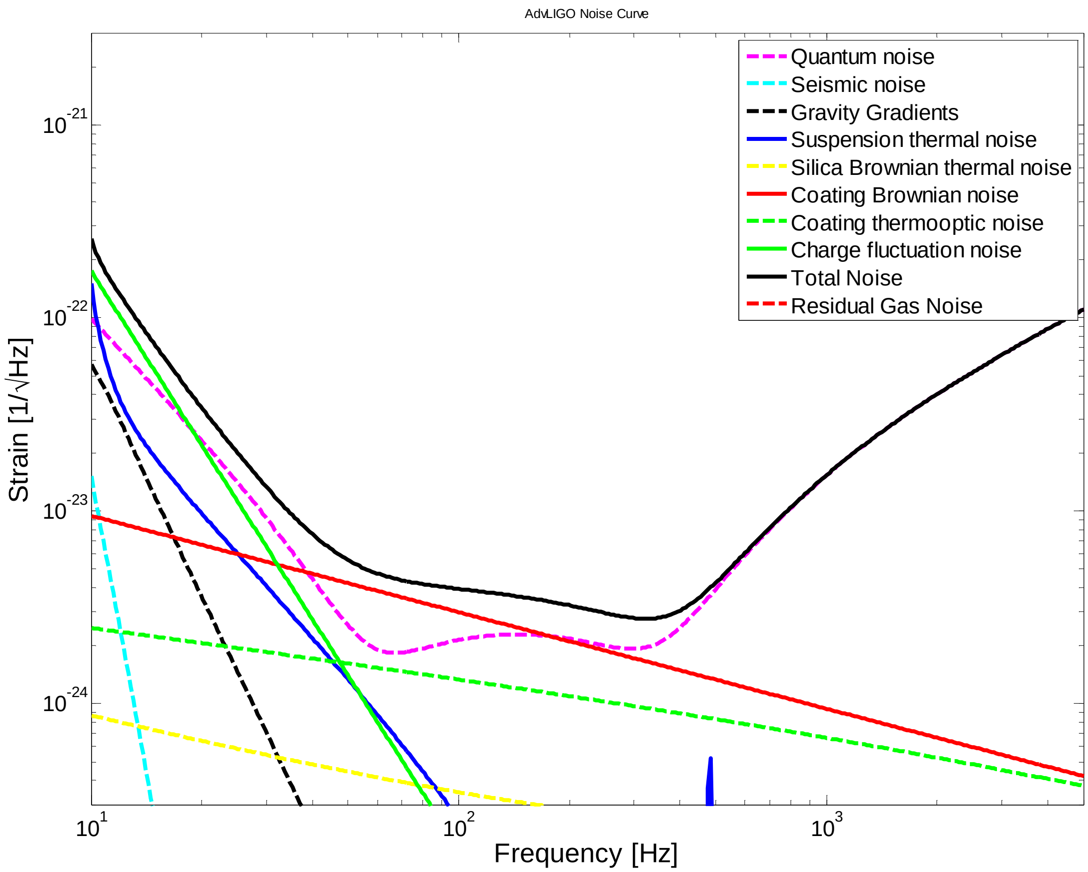

Figure 2 - Advanced LIGO noise spectrum with a charge of Q = 10^{-11} C, otherwise standard charging parameters from Table 1.

Changing the surface conductivity to 10^{-18} Ωm, which is equivalent to a relaxation time of 100X the limit from Prokhorov et al, while holding the charge level at the level of Table 1 results in the noise spectrum shown in Figure 3 with a binary neutron star range of 180 Mpc, a black hole binary range of 980 Mpc, and a stochastic background sensitivity of 1.2 X 10^{-8}.

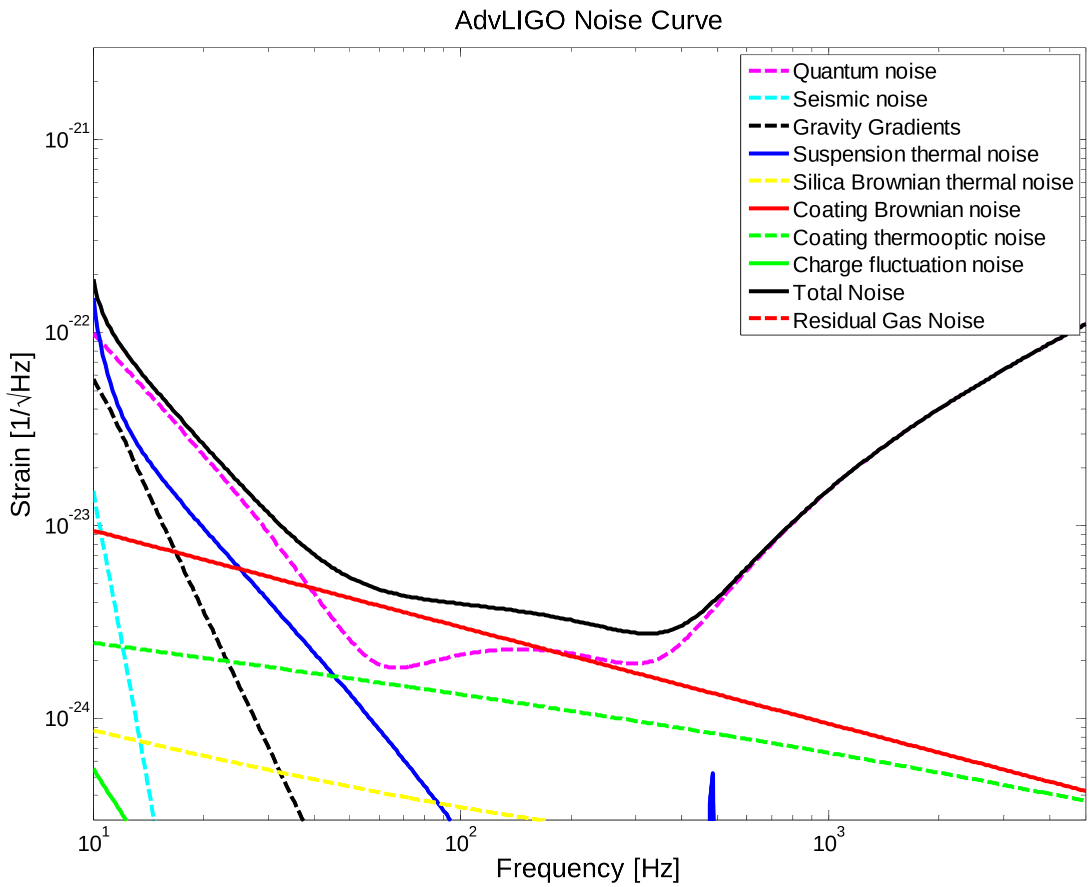

Figure 3 - Advanced LIGO noise spectrum with a surface conductivity of $\sigma = 10^{-18}\ \Omega$ m, otherwise standard charging parameters from Table 1.

Finally, if both the charge is changed to $Q = 10^{-11}$ C and the surface conductivity is changed to $\sigma = 10^{-18}\ \Omega$ m, the noise spectrum looks as it does in Figure 4. Here the neutron star inspiral range is 180 Mpc, the black hole inspiral range is 960 Mpc, and the stochastic background sensitivity is 1.3 X 10^{-9}.

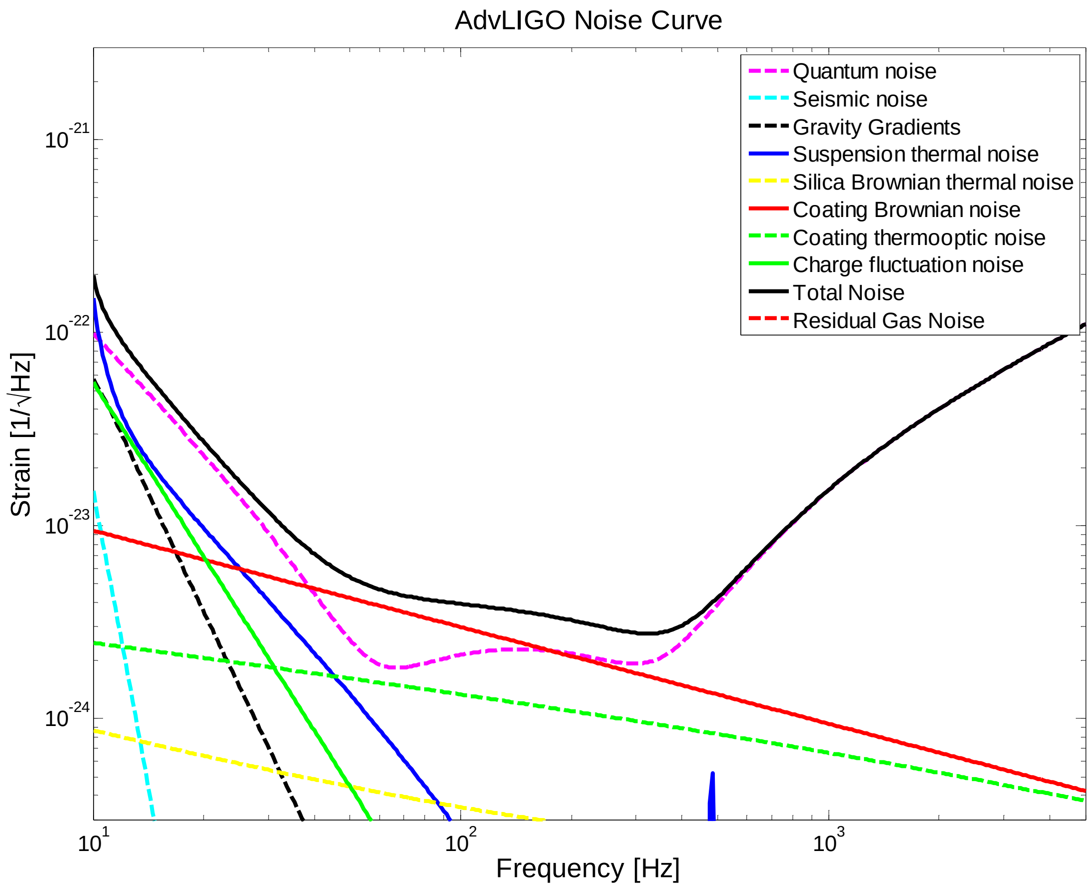

Figure 4 - Advanced LIGO noise spectrum with a surface conductivity of $\sigma = 10^{-18}\ \Omega$ m and charge level of $Q = 10^{-11}$ C.

The importance of the amount of charge Q is evident from these graphs. Research may need to look at what Q level is realistic to expect in addition to measuring and understanding τ_0. The appropriate value of the effective distance d also needs consideration, especially in regards to the role the electrostatic drive might play.

Bibliography

[1] R Weiss "Note on Electrostatics in the LIGO Suspensions" LIGO-T960137-00-E (1996).

[2] G Harry "Research Plan on Noise Effects of Electric Charge on Advanced LIGO" LIGO-T040070-00-R (2004).

[3] L. G. Prokhorov, P. E. Khramchenkov, V. P. Mitrofanov "Measurement of relaxation of electrical charge distribution on fused silica sample", submitted to Phys. Lett. A.