LIGO Laboratory / LIGO Scientific Collaboration

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Estimate of Noise from Charging in Initial, Enhanced, and Advanced LIGO

Gregory Harry, editor

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LIGO Science Collaboration

This is an internal working note
of the LIGO Project.

California Institute of Technology
LIGO Project - MS 18-34
1200 E. California Blvd.
Pasadena, CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project – NW 22-295
185 Albany St
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

LIGO Hanford Observatory
P.O. Box 1970
Mail Stop S9-02
Richland WA 99352
Phone 509-372-8106
Fax 509-372-8137

LIGO Livingston Observatory
P.O. Box 940
Livingston, LA 70754
Phone 225-686-3100
Fax 225-686-7189

http://www.ligo.caltech.edu/

1. Introduction

Motion of charge buildup on the test masses is a potential source of noise in interferometric gravitational wave detectors. This note gives an estimate of how significant this noise might be in Advanced LIGO based on measurements, observations, and modeling that has been done in the LSC over the last few years.

The primary concern is with Gaussian noise from charge on the dielectric test masses interacting with nearby ground planes. This noise has been modeled in the technical note T960137 as a Markov process, and parameterizes the noise in terms of a correlation time and an amount of charge. Force noise from charge on dielectric interacting with a nearby ground plane is modeled as

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

where $\langle F^2 \rangle$ is the average of the square of the force between the charge and the ground plane. The relaxation time can be estimated from

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

where τ is the correlation time, ε_0 is the permittivity of free space, ε is the permittivity of the mirror material, and σ is the surface conductivity of the test mass. Measurements are being made of τ, by measuring the time it takes for charge levels to drop in a region of a test optic, σ, by measuring surface conductivity directly, and Q, by measuring charge buildup after various charging mechanisms. Figure 1 shows the level of force noise, in arbitrary units, for a high τ and low τ situation. Both graphs scale with the square of the amount of charge on the test mass.

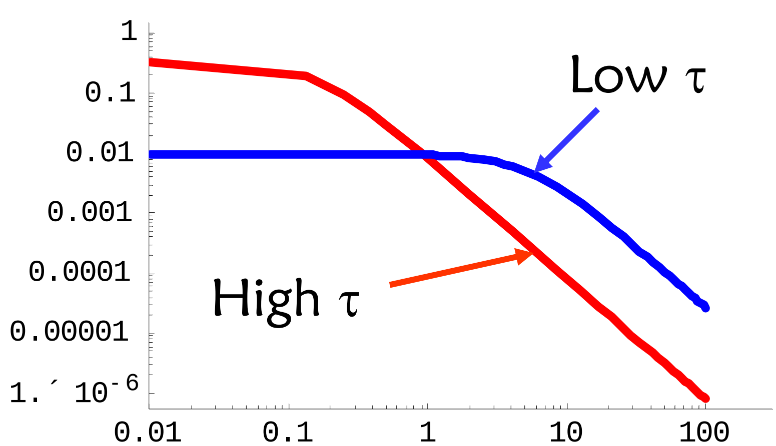

Figure 1 – Force noise for different regimes of the correlation time. The high frequency roll off begins at $f = 1/(2 \pi \tau)$

Measurements at Moscow State University and Trinity University on correlation times and charge levels indicate that they can vary quite a bit depending on the surface properties of the silica optics. The level and type of cleaning that was done and any contact with foreign material (viton earthquake stops, First Contact cleaning preparation, etc.) can change both the correlation times and the amount of charge buildup. Measurements are ongoing, specifically on different cleaning solvents and different preparations of First Contact (red, clear, and carbon nanotube infused), but it seems likely that the Advanced LIGO case will be in the very high τ regime. This means that position noise will be falling as f^3 and as $\sqrt{1/\tau}$ in the Advanced LIGO band

2. Noise Calculations

Using the noise model from T960137, we can estimate the noise from charging in various scenarios using τ and Q parameters as determined by LSC groups doing charging research. The geometry, specifically the distance from the charge on the optic to the nearest ground plane, also plays an important role. Determining the exact values of parameters, especially *in situ* at the LIGO sites, is not a very accurate process. All of the below graphs should be considered as rough estimates of noise levels, primarily useful for determining what charging scenario and/or parameters are important for further study.

Scenarios:

Initial LIGO circa February 2006

This is to try to explain the noise observed at LLO in spring 2006 as arising from charge that was transferred to the optic by contact with a viton earthquake stop.

Charge – minimum value of $5\ 10^8$ electrons (or $8\ 10^{-11}$ C), from Mitrofanov, G070204. Mitrofanov's measurement was limited by the dynamic range of his instrument.

Distance to ground plane – 4 mm, estimate of distance to metal shaft of earthquake stop from optic when hanging normally, from R. Weiss's LLO ILOG entry, May 10, 2006.

Correlation time – 170 days ($1.5\ 10^6$ seconds) from Ugolini, G070079. This is presumed to be a value for a relatively "dirty" optic, as much higher numbers have been seen in optics cleaned and handled under more strict cleanliness conditions. The *in situ* initial LIGO optics are modeled as relatively dirty based on observations of optical absorption and scatter.

Mass – 10.5 kg

Using the noise model in T960137, these parameters predict a noise level of

$x(f) = 7.2\ 10^{-14} / f^3\ \mathrm{m}/\sqrt{\mathrm{Hz}}$, or graphically as

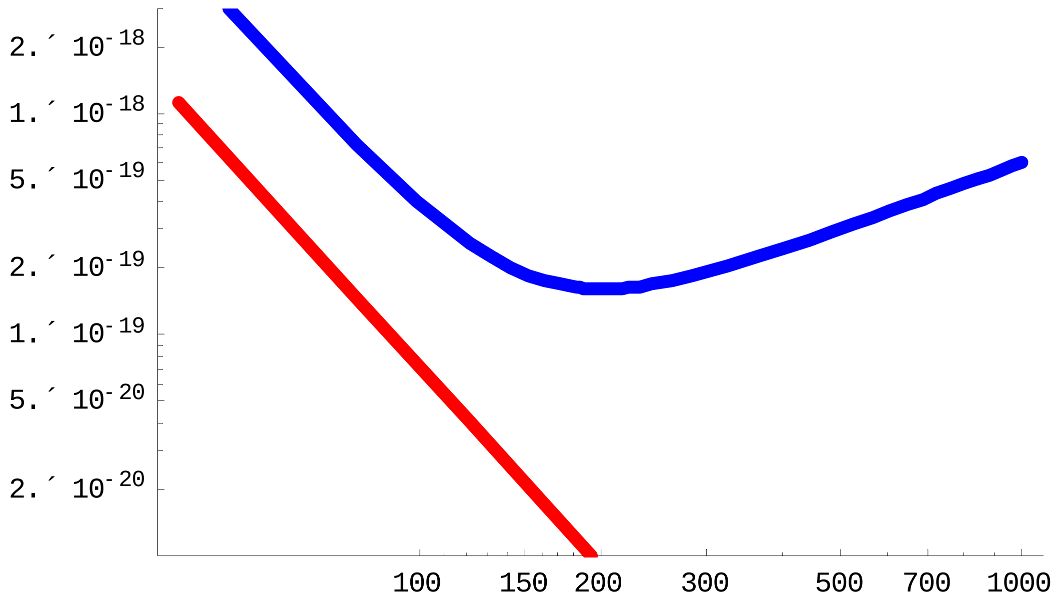

Figure 2. Position noise in Initial LIGO at LLO circa February 1, 2006 (blue) with an estimate of noise from charge transferred from an earthquake stop (red).

Red curves are consistently noise due to charge, while blue curves represent the actual or planned total noise curves. Here the blue is the noise at LLO on February 1, 2006.

The predicted noise from charging is about a factor of 5 below the LLO noise between 40 Hz and 150 H. Noise in m/√Hz goes as charge squared, so a factor of 2 higher charge would agree well with the observed noise. Since Mitrofanov's measured charge was a lower limit, a factor of 2 is quite plausible.

The following graph compares the same charging noise to S5 sensitivity at LHO circa March 2007.

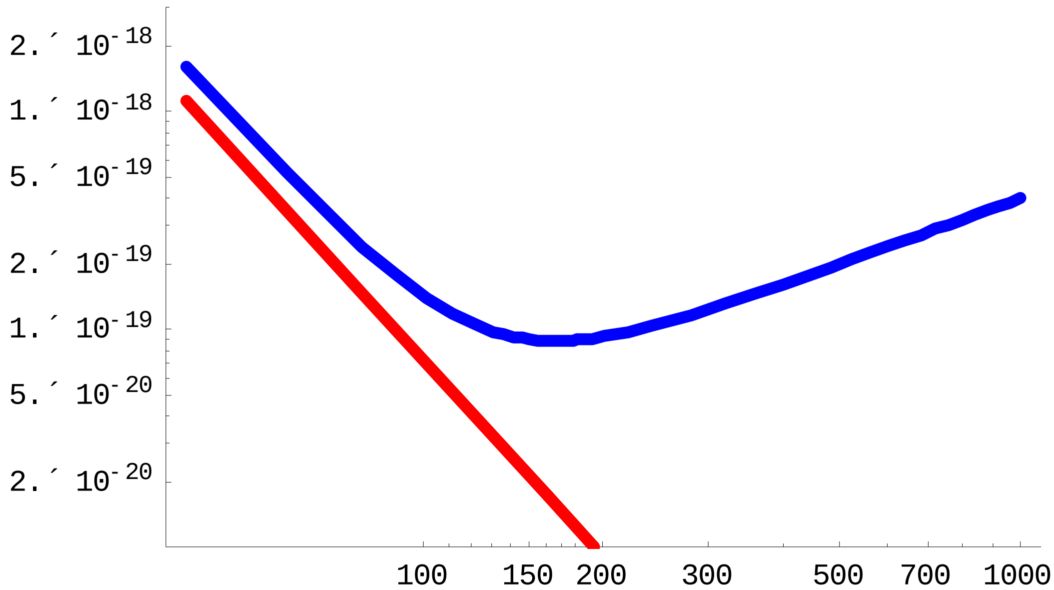

Figure 3. – Position noise during S5 at LHO circa March 2007 (blue) compared to calculated noise from charge transferred from a viton earthquake stop to a relatively dirty optic (red).

Initial LIGO with clean optics

Same parameters as Scenario 1, but with

Correlation time – 8000 hours (2.9 10^7 seconds), minimum value from Mitrofanov, G070204, using a very clean optic

$x(f) = 5.1\ 10^{-14}/\ f^3$ m/√Hz, about a factor of 8 below the LLO Feb 2006 noise. This is still plausible given the uncertainty of charge transfer from viton to glass.

This graph compares the charge noise to the S5 Initial LIGO noise circa March 2007. The charge noise is about a factor of 2 below the total noise.

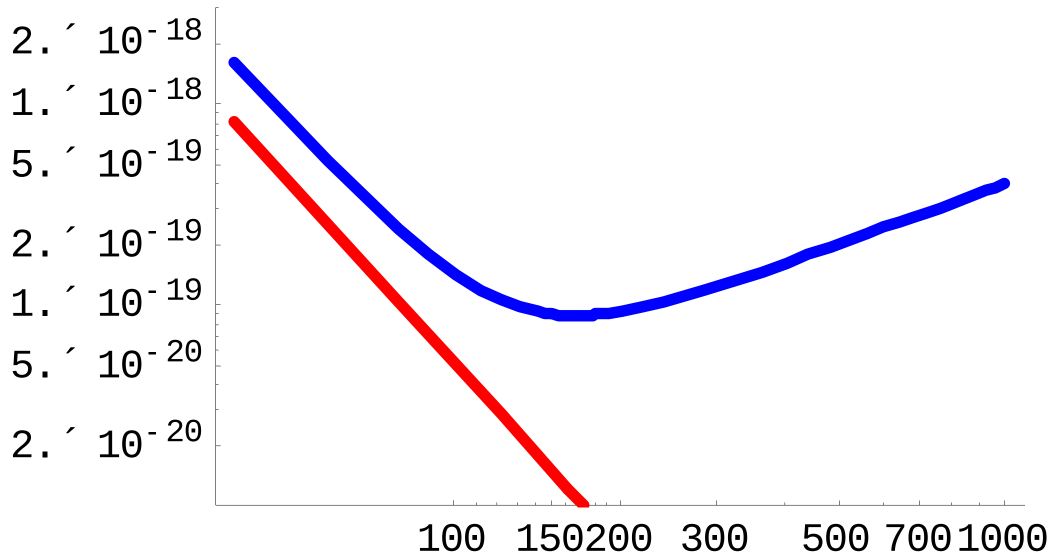

Figure 4. – Position noise during S5 at LHO circa March 2007 (blue) compared to calculated noise from charge transferred from a viton earthquake stop to a relatively clean optic (red).

Enhanced LIGO with clean optics

The difference here is the use of fused silica tipped earthquake stops instead of viton, which will result in less charge transfer on contact with the optic.

Charge – 5 10^6 electrons (or 8 10^{-13} C) from Mitrofanov, G070204.

Other parameters the same as Scenario 2 and give a noise level of

$x(f) = 5.1\ 10^{-18}/f^3$ m/√Hz, or graphically as

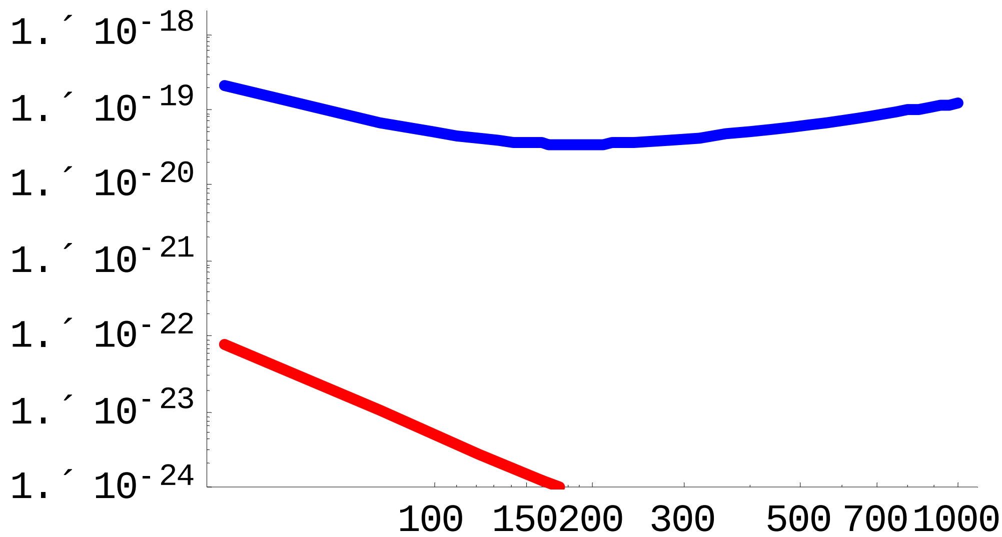

Figure 3. – Expected position noise during S6 compared to calculated noise from charge transferred from a silica-tipped earthquake stop to a relatively clean optic (red).

This is well below (about 3.5 orders of magnitude) the projected Enhanced LIGO noise around 50 Hz in T060156. It remains well below this noise even if the correlation time from Ugolini, G070079, for the dirty optic is used.

Advanced LIGO with clean optics, charged from earthquake stops

This is the same as Scenario 3, except the test mass is now 40 kg. The resulting noise is

$x(f) = 1.4\ 10^{-18}/f^3$ m/rtHz,

which is about 4 orders of magnitude below the expected Advanced LIGO noise at 100 Hz.

Advanced LIGO with clean optics, charged from contact with electro-static drive (ESD) – CHECK CHARGING LEVEL

This is the same as Scenario 4, except the charge buildup comes from contact with the electrostatic drive. This was seen in the GEO 600 interferometer in December of 2006. Contact between the ESD and the test mass in GEO is believed to have happened at solder joints to the ESD, where the gap is only about 1 mm.

Charge – the GEO test mass was charged to 100 V measured by an ESD 3 mm away. This corresponds to a charge density of 3 10^{-7} C/m^2, or 7 10^{-9} C spread evenly over the full 18 cm diameter, from S. Hild's talk at the March 2007 LSC Meeting, G070172.

Distance to ground plane – 3 mm, spacing of electrostatic drive from test mass.

$x(f) = 1.8\ 10^{-10}/f^3$ m/rtHz,

which is about 4 orders of magnitude above the expected Advanced LIGO noise at 100 Hz.

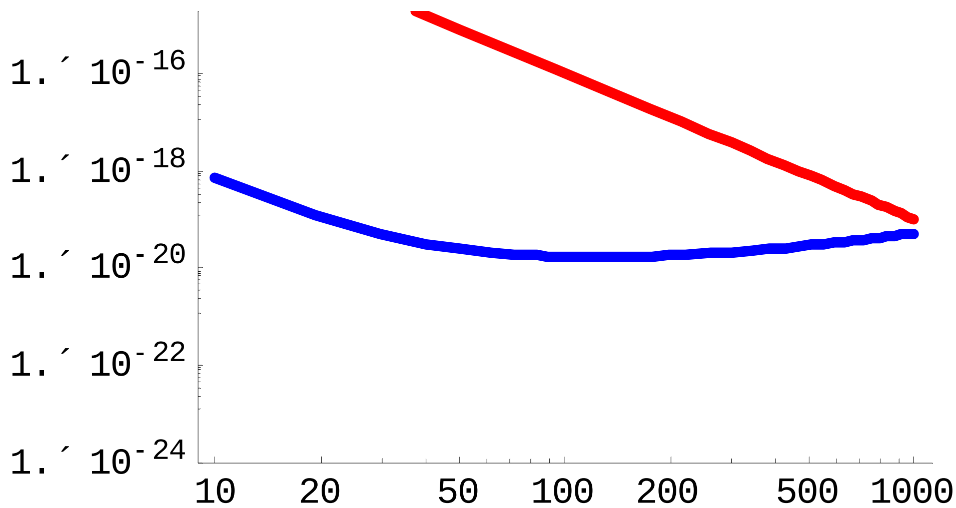

Figure 4. – Expected position noise during Advanced LIGO (blue) compared to calculated noise from charge transferred from the electro-static drive to a relatively clean optic (red).

Advanced LIGO with charging from cosmic rays

This is a case where charge from cosmic rays interacting with the vacuum chambers causes an electron shower which charges up a mirror.

Charge – maximum of 1700 electrons (or 3 10^{-16} C) spread evenly over optic. From V Braginsky *et al*, Physics Letters A **350** (2006) 1. Assume it is only a 5 mm radius patch near the earthquake stops that interact with the ground plane.

Distance to ground plane – 4 mm, estimate of distance to metal shaft of earthquake stop from optic when hanging normally, from R. Weiss's LLO ILOG entry, May 10, 2006.

Correlation time – 170 days (1.5 10^7 seconds) from Ugolini, G070079. This is for a relatively "dirty" optic.

Mass – 40 kg

Using the noise model in T960137, these parameters predict a noise level of 16 orders of magnitude below the Advanced LIGO noise curve.

Advanced LIGO with parameters from LHO event of June 2006

This case uses estimated parameters from measurements at Hanford in June of 2006. The charging is likely from viton touching the optics, so may not a plausible mechanism for Advanced LIGO.

Charge – 10^{-10} C. This comes from an observed misalignment of about 15 microrads. Assuming equal charge on the optic and the stop, and a distance of 4 mm between them, the needed torque, and thus charge can be estimated.

Distance to ground plane – 4 mm, estimate of distance to metal shaft of earthquake stop from optic when hanging normally, from R. Weiss's LLO ILOG entry, May 10, 2006.

Correlation time – 1000 s. This is an estimate from the observed exponential return to alignment that Cheryl Vorvik observed at LHO. See C. Vorvick's LHO ILOG entry, June 9, 2006.

Mass – 40 kg

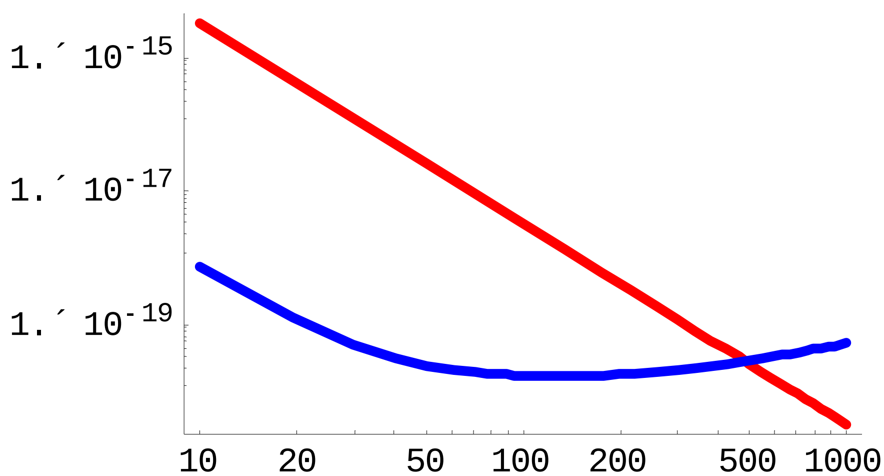

Figure 5. – Expected position noise during Advanced LIGO (blue) compared to calculated noise from charge seen at LHO in June of 2006 on a clean optic (red).

Advanced LIGO with charging from triboelectrification

Triboelectrification is charging due to frictional contact. This could happen to Advanced LIGO optics during pump down, if dust or some other contaminant is dragged across the optic.

Charge – 10^{-10} C. This comes from a charge density of about 10^{-6} C/m^2, which is the scale of triboelectrification according to Coehn's Rule.

Distance to ground plane – 4 mm, estimate of distance to metal shaft of earthquake stop from optic when hanging normally, from R. Weiss's LLO ILOG entry, May 10, 2006. Only charge within 5 mm of the earthquake stop is considered in calculating noise, as farther away the interaction is minimal.

Correlation time –170 days (1.5 10^6 seconds) from Ugolini, G070079.

Mass – 40 kg

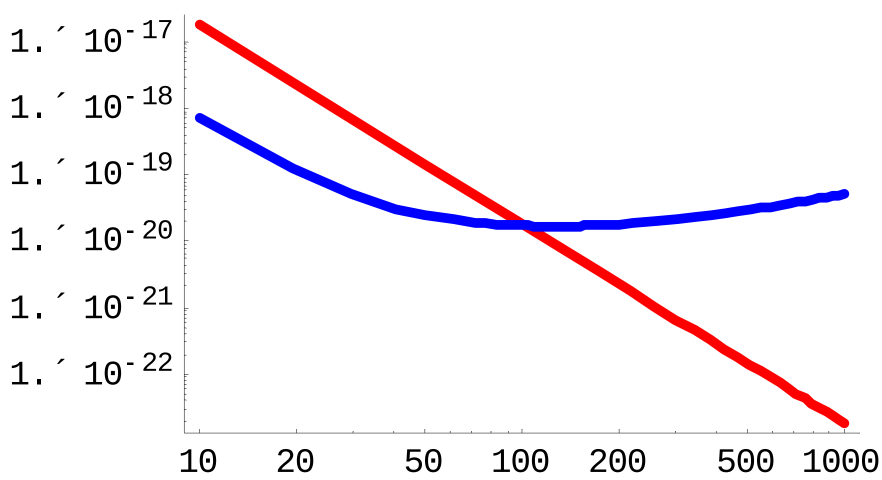

Figure 6. – Expected position noise during Advanced LIGO (blue) compared to calculated noise from charging of a clean optic by triboelectrification (red).

Advanced LIGO with charging from removal of First Contact

First Contact is a commercial polymer that is spread on optics to remove dirt and keep them clean during handling and transport. There are plans to cover the Advanced LIGO optics with First Contact during shipping from coating vendors, handling, and installation at the sites. It is known that conventional First Contact leaves high levels of charge (> 2 10^8 e^-/cm^2). It was hoped that the inclusion of carbon nanotubes in the First Contact would reduce the charging, but preliminary results from Trinity University do not support this. Further tests are planned at Trinity and at Moscow State University.

Charge – 10^{-8} C, from Dennis Ugolini's email report to LSC Charging Working Group, July 24, 2008.

Distance to ground plane – 4 mm, estimate of distance to metal shaft of earthquake stop from optic when hanging normally, from R. Weiss's LLO ILOG entry, May 10, 2006. Only charge within 5 mm of the earthquake stop is considered in calculating noise, as farther away the interaction is minimal.

Correlation time – 8000 hours (2.9 10^{7} seconds), minimum value from Mitrofanov, G070204, using a very clean optic

Mass – 40 kg

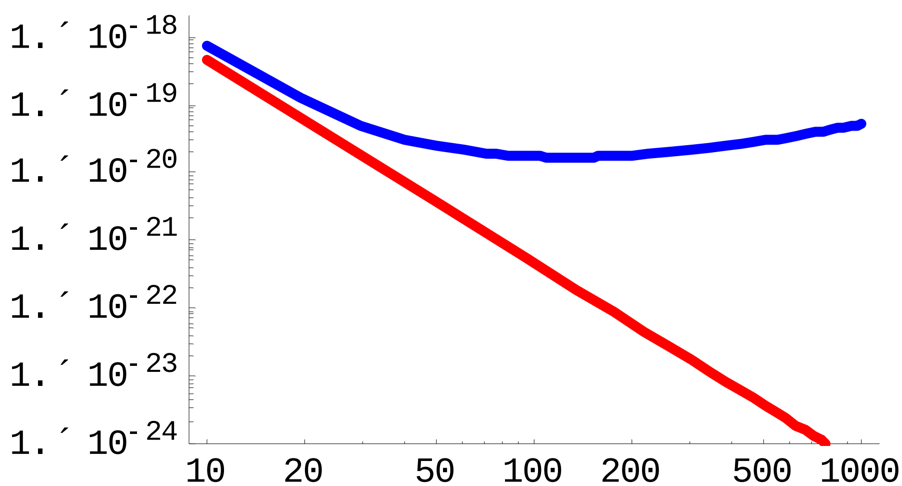

Figure 7. – Expected position noise during Advanced LIGO (blue) compared to calculated lower limit to noise from charging of a clean optic by removal of First Contact with carbon nanotubes (red).

If an ion gun is used after removal of First Contact, reduction of the charge by about a factor of 100 is possible based on the Virgo experience. Assuming this is the case, the charging becomes

Charge – 10^{-10} C, from Dennis Ugolini's email report to LSC Charging Working Group, July 24, 2008, reduced with ion gun

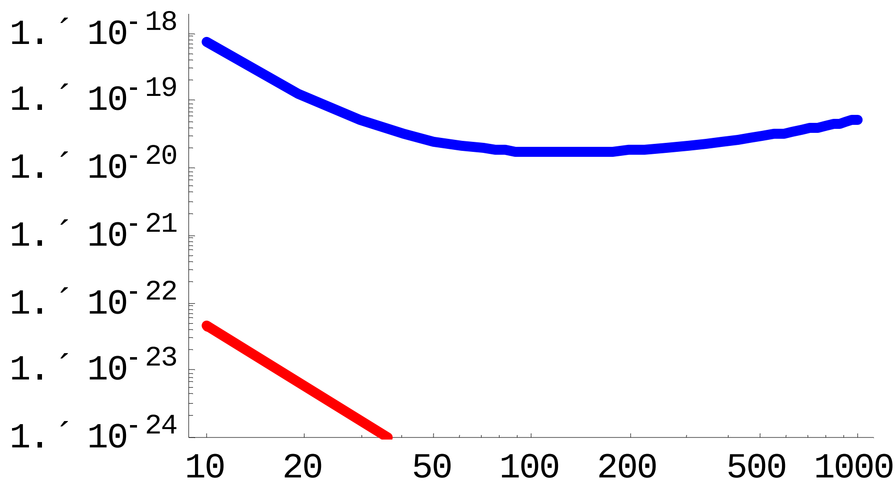

Figure 8. – Expected position noise during Advanced LIGO (blue) compared to calculated lower limit to noise from charging of a clean optic by removal of First Contact with carbon nanotubes and treatment with an ion gun (red).

Future Research Needs

Better understanding of charging noise is necessary to really evaluate its impact on Advanced LIGO. More detailed work on various charging mechanisms is crucial to furthering this understanding. Primary among the understudied charging mechanisms are triboelectrification from dust during pump down, charge transfer during First Contact removal (and what benefit, if any, the inclusion of carbon nanotubes provides), and possible contact with the electro-static drive during uncontrolled optic motion. There is also many orders of magnitude uncertainty in the correlation time which is believed to be related to the exact cleanliness and surface preparation of the silica. Work on measuring charge buildup and decay is ongoing at Trinity University and Moscow State University, with priorities focused on First Contact and dust triboelectrification work.

Modeling will also be important to gaining a complete picture of charging in Advanced LIGO. There are low level modeling efforts to better understand the effect of charge on the electro-static drive (ESD). Included in this is an attempt to estimate the amount of charge transferred to the GEO masses during contact with their ESD, and what a similar accident might mean for Advanced LIGO. The effects of charge on the ESD independent of Gaussian noise, including reduction of actuation, interaction with a gold barrel coating, and dynamic range limitations, are also potentially important and plans are in place to model them. It may be necessary to have a more extensive modeling program in the near future.

There is confidence in the Markov model for Gaussian charge noise based on the reasonable agreement between observed noise in Initial LIGO after optics contacted the viton earthquake stops. It is difficult, however, to get accurate measurements of important parameters (notably the charge level, correlation time, and distance to ground plane) *in situ* in Initial LIGO. Direct measurement of Gaussian noise from charging may be possible in a controlled experiment to confirm and further explore the role of these parameters. It is possible this could be done in an existing prototype such as the Thermal Noise Interferometer at Caltech or LASTI at MIT. However, other priorities (especially at LASTI) and lack of sensitivity at low frequencies (TNI) may make this approach difficult. A dedicated experiment using a low frequency, low noise torsion pendulum may be the best approach to studying Gaussian noise from charge directly. This is being explored at the University of Washington, where extensive experience with torsion pendula exists from LISA and laboratory gravity work, and at the Australian National University.

Mitigation techniques to remove charge will be important if any charging mechanisms do present a limit to Advanced LIGO sensitivity. Ongoing work on UV techniques at Stanford is building off of experience with similar systems gained during work on GP-B and LISA development. However, the UV appears to unacceptably increase absorption in the Advanced LIGO optics, at least for certain wavelength, intensities, and directionality. Research into the effects of changes in wavelength and intensity are in progress, as are indirect illumination methods that may be used in conjunction with a gold barrel coating. There is also a suggestion from Stanford to look at using a very low energy ion gun for mitigation, which would get around problems with UV. This is just a proposal at the moment, and serious laboratory work will be necessary for it to be realized. Any mitigation technique will have to undergoing a prototyping process with possible tests at LASTI or elsewhere before it could be ready for inclusion in Advanced LIGO. It is likely that it will be desirable to at least have a mitigation option available, and significant laboratory research and testing will be necessary to reach that stage.

There is also some concern about non-Gaussian, burst-type, noise from charge buildup. This has been studied primarily as cosmic rays, through a direct cosmic ray detector at Hanford, through charge buildup studies in Moscow, and through modeling of well known cosmic ray fluxes. It does not appear that non-Gaussian noise from cosmic rays will be a significant limitation at Advanced LIGO sensitivity levels, but this is still somewhat understudied at the moment. There may also be other mechanisms leading to non-Gaussian charge noise.

Further work on the theory of noise from charging is also needed, despite the success of the Markov model. Issues that are not addressed by this model include interactions between two charged dielectrics, moving ground planes, noise from charge dipoles (possible with a gold barrel coating on the optics) and the interaction of the electro-static drive (ESD) with charge on test masses. Theoretical work at the University of Texas Brownsville is focused on some of these issues as well as the role of color centers in dielectrics in charge buildup and decay.

Conclusions

The level of possible Gaussian noise from charge buildup on the Advanced LIGO optics can vary from completely insignificant to a possible limiting noise source. This is determined primarily by the amount of charge deposited on the optic by different charging mechanisms; the correlation time plays a secondary role in predicting the noise as it will likely be very large compared to 1/f in the Advanced LIGO band. The distance to the nearest ground plane, typically assumed to be the metal shaft of the earthquake stops, is also an important parameter. Increasing this distance could greatly reduce the expected charging noise. If the tip of the earthquake stop gets charged along with the nearby optic, and these charges can interact in a similar way as in the model, this distance may be much less than assumed here. This has the potential to make charging noise more problematic in Advanced LIGO. Some potentially troublesome charging mechanisms are not as well understood as they need to be for accurate planning.