Interaction of the ESD with electrical charges of the test masses in Advanced LIGO

L.G. Prokhorov, J. Kissel

Moscow State University, LIGO Hanford Observatory

LVC-2016, March 14-18, 2016, Pasadena, USA

Introduction

Charging or redistribution of electrical charge on the LIGO mirrors could change the force applied by the electrostatic drive (ESD). It results in changing of the actuation coefficient of the ESD and additional fluctuating force acting on the test masses. In this document we discuss the forces acting on the test mass from the ESD and the results of the charge measurements of the Advanced LIGO test masses.

Force acting on the test mass

Total electrostatic force acting on the test mass (TM) from the ESD includes several components.

$$F = A(V_b - V_s)^2 + B(V_b - V_s) + C\left(\frac{V_b + V_s}{2} - V_{ref}\right)^2 + D\left(\frac{V_b + V_s}{2} - V_{ref}\right) + E \qquad (1)$$

where V_b is the electric potential of the bias electrode, V_s — of the signal electrode, V_{ref} — potential of the cage and other surroundings.

If we use $V_{ref} = 0$, this equation can be written in a more common way :

$$F = \alpha(V_b - V_s)^2 + \beta(V_b + V_s) + \beta_2(V_b - V_s) + \gamma(V_b + V_s)^2 + \delta \qquad (2)$$

α characterizes the dipole attraction of the TM to ESD. It depends mostly on the distance between them.

β characterizes the charge amount and distribution along the whole test mass

β_2 characterizes the charge amount and distribution on the test mass near the ESD electrodes. β and β_2 depend on the amount of charge and it's distribution on the test mass so they may vary significantly.

γ characterizes the dipole interaction between the uncharged dielectric TM and nonuniform electric field from the ESD to the grounded surroundings. γ changes with movement of grounded surroundings (cage) relative to the test mass.

Figure 1 illustrates how the electric field changes if we use $V_b + V_s = 0$, where we can ignore β and γ, versus $V_b + V_s \neq 0$. In the latter case we have a significant electric field going through the test mass to the grounded surroundings, so we have to use all the terms of the equation.

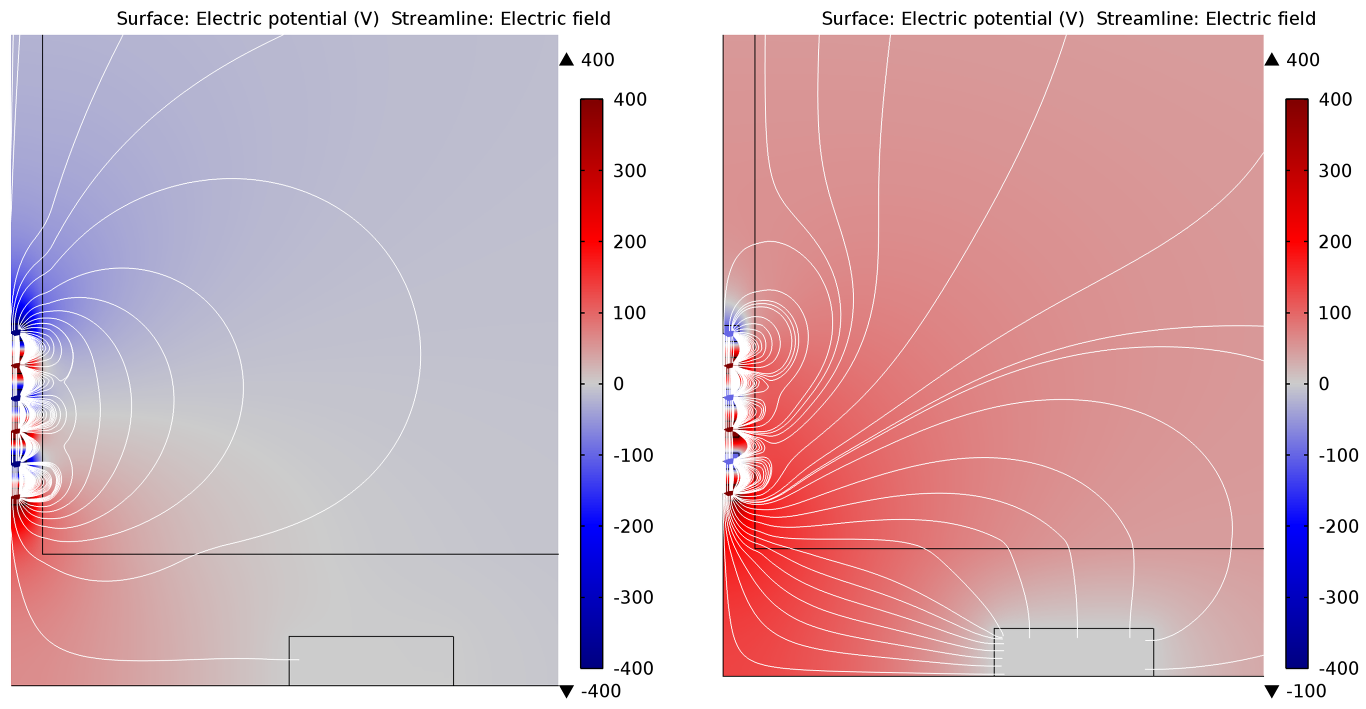

Figure 1: The voltage (color) and electrical field (lines) distribution if ESD voltage is: *(a)* $V_s = -V_b = -400V$; *(b)* $V_s = -100V$, $V_b = +400V$. ESD electrodes are on the left and the grounded ring heater is at the bottom

Force components associated with the electric charges can be written using β_s – charge coupling to signal voltage and β_b – charge coupling to the bias voltage. We can find $\beta_s = \beta - \beta_2$, $\beta_b = \beta + \beta_2$. So equation (2) can be written as follow:

$$F = \alpha(V_b - V_s)^2 + \beta_b V_b + \beta_s V_s + \gamma(V_b + V_s)^2 + \delta, \qquad (3)$$

Linear term of the force applied to test mass using signal voltage $V_s = V_{s1} sin(\omega t)$ is:

$$F_\omega = [2V_b(\gamma - \alpha) + \beta_s] V_{s1} sin(\omega t) \qquad (4)$$

We see that the force acting on the TM depends on α, β and γ. Although α is a constant with good precision and we had a lot of discussions and care about charges on the test masses, the effect of γ needs a careful consideration as well as charge review involving β and β_2.

Effective bias voltage as an estimation of the test mass charge

Electrical charge of the LIGO test masses is measured by applying a set of bias voltages while electrode voltage is sine: $V_s = V_o \cdot sin(\omega t)$. At different bias voltage the linear term of the test mass response is different, proportional to the linear force term (4). We use the linear fit of response dependence on the bias voltage to find the bias voltage with zero response. This voltage is named the effective charge bias voltage V_{EFF}.

$$F_\omega = [2V_{EFF}(\gamma - \alpha) + \beta_s] V_{s1} sin(\omega t) = 0, \text{ so}$$

$$V_{EFF} = \frac{\beta_s}{2(\alpha - \gamma)} = \frac{\beta_s}{2\alpha} \cdot \frac{1}{1 - \gamma/\alpha} \qquad (5)$$

We see that V_{EFF} characterize the charges coupled to signal voltage. It does not include β_b and we measure the combination of β and β_2. It might be good due to it include both nearby charges and charges located far from the ESD. But there is some part of charge near the bias electrode which is ignored.

The equation for linear term of the force acting on the charged test mass from ESD could be written using the effective charge bias voltage V_{EFF}:

$$F_\omega = -2\alpha\left(1 - \frac{\gamma}{\alpha}\right)(V_b - V_{EFF})\, V_{s1} sin(\omega t) \qquad (6)$$

The measurements of relationship between γ and α was described in [1, 2] using the simplified formula for force acting on the test mass. However, using the equation (2) gives us the similar result. We can find the relation between γ and α using the $V_s = V_{so} + V_{s1} sin(\omega t)$ with different V_{so}:

$$\frac{\gamma}{\alpha} = \frac{\left.\frac{F_\omega}{V_{s1} sin(\omega t)}\right|_{V_b = V_o,\, V_{so} = V_o} - \left.\frac{F_{\omega 2}}{V_{s1} sin(\omega t)}\right|_{V_b = -V_o,\, V_{so} = -V_o}}{\left.\frac{F_\omega}{V_{s1} sin(\omega t)}\right|_{V_b = V_o,\, V_{so} = -V_o} - \left.\frac{F_{\omega 2}}{V_{s1} sin(\omega t)}\right|_{V_b = -V_o,\, V_{so} = V_o}}$$

ESD Linearization

Previous studies of ESD linearization [3, 4] use simplified model of force acting on the test mass. Using (2), one could calculate the linearization equation:

$$V_s = (V_b - V_{EFF})\xi \pm \sqrt{(V_b - V_{EFF})^2 \xi^2 - V_b^2 + \frac{F - F_o}{\alpha + \gamma}}, \text{ where } \xi = \frac{\alpha - \gamma}{\gamma + \alpha},\ F_o = \beta_b V_b - \delta$$

This equation is consistent with the one from [4] if we use $\gamma \ll \alpha$.

Results of the charge measurements

Charge measurements discussed below have been done by Stuart Aston, Betsy Weaver, Corey Grey, Jeff Kissel and Leonid Prokhorov.

Experimental results on LIGO, both in Hanford and in Livingston show the continuous slow charging of the test masses with the charging rate of about 10 V per month. This charging correlates with the voltage applied to the ESD. Changing the sign of the bias voltage changes the sign of charging.

ESD of the end test mass in X-arm (ETMX) was mostly turned off during the observational run O1 due to it is not used when the detector is in low noise state. It was resulted in slowing of the charging of ETMX.

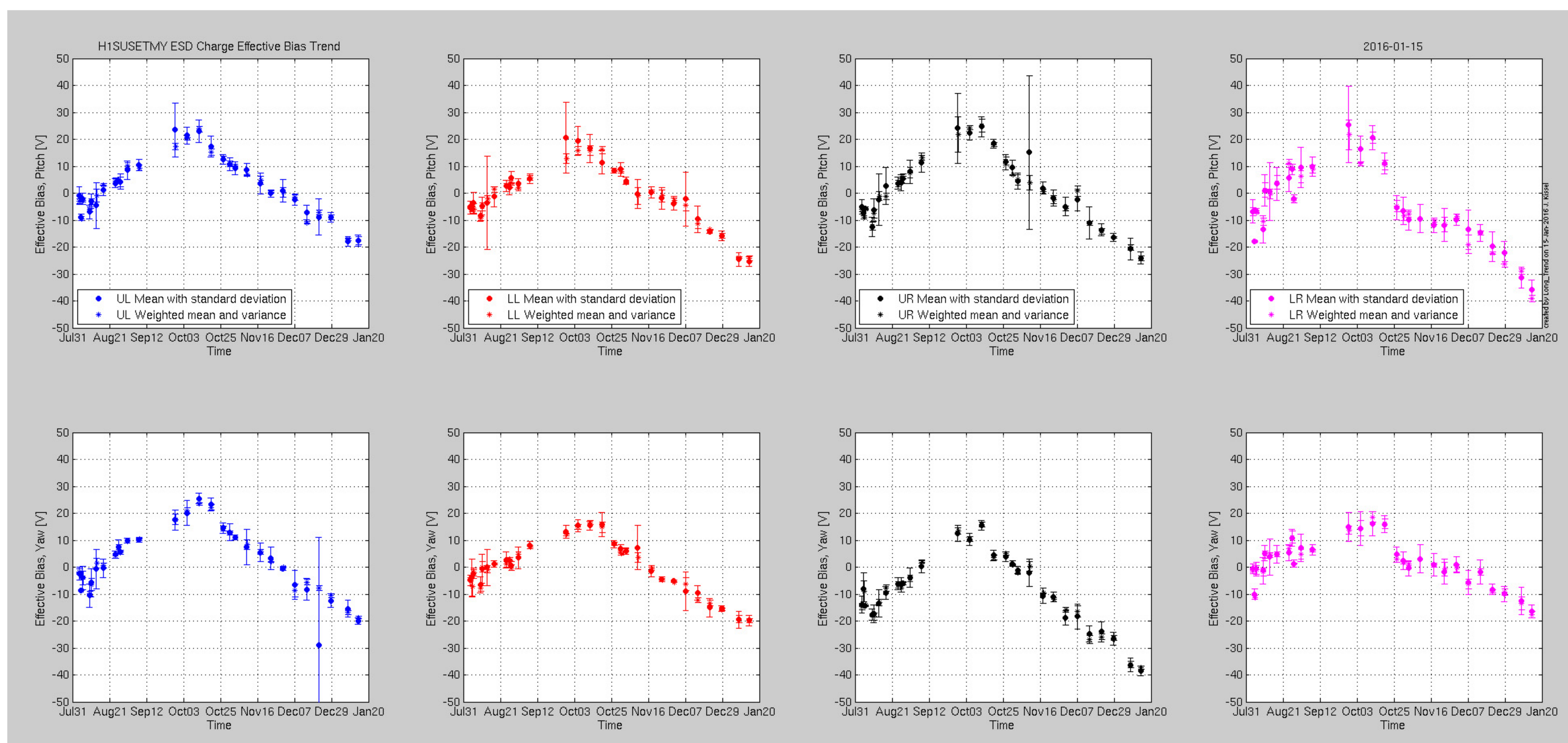

Figure 2: Hanford ETMY effective charge bias voltage. Applied bias voltage: $-380\ V$ (Aug, 10 - Oct, 16), $+380\ V$ (Oct, 16 - Feb)

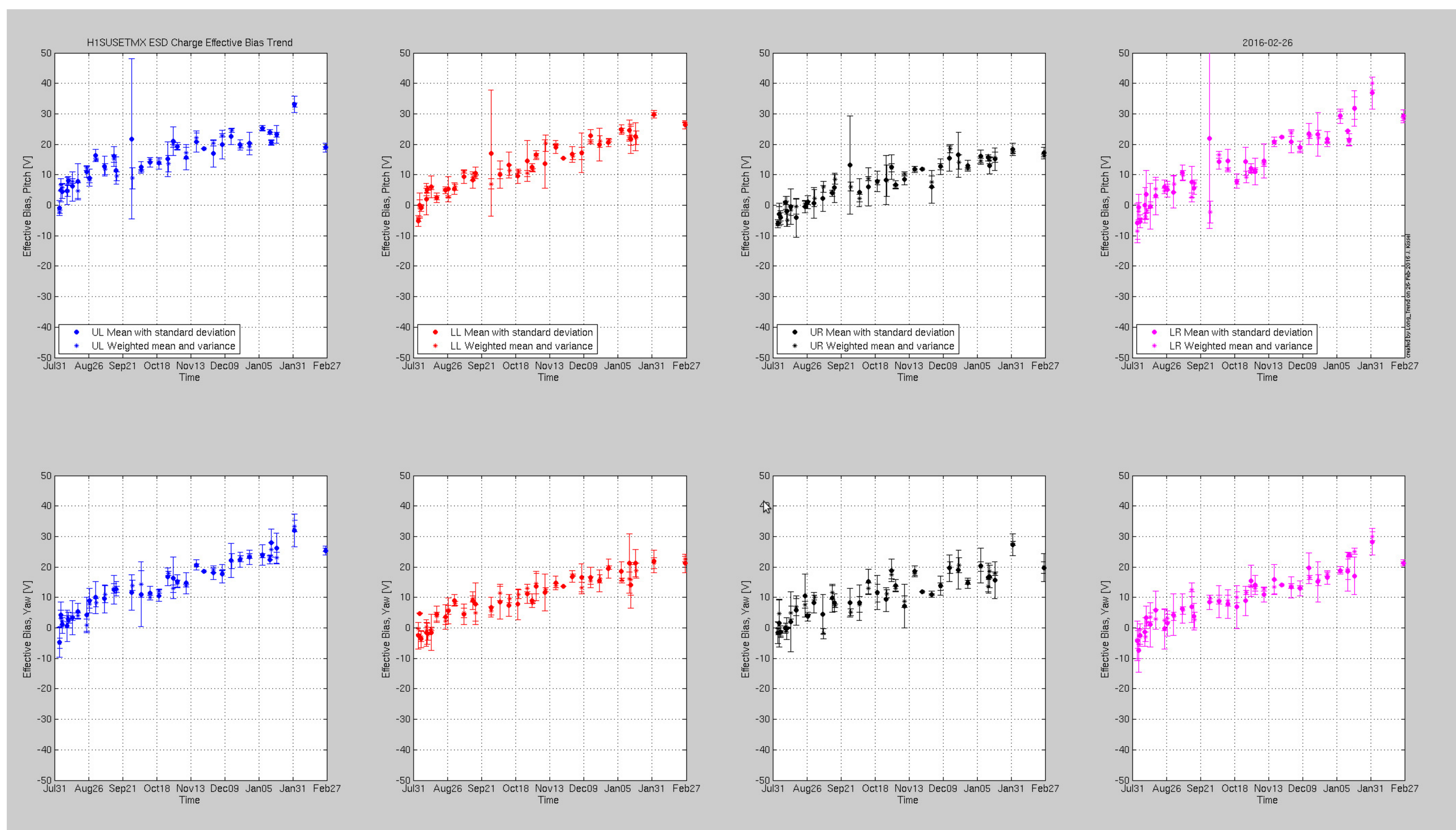

Figure 3: Hanford ETMX effective charge bias voltage. Applied bias voltage: $-380\ V$.

This measured charging of the test masses may be caused by the electrical field of the ESD. Long application of the electric field to the dielectric results in redistribution of charge carriers in it. This slow polarization term create the charge distribution in the test mass. This distribution mirrors the electrode pattern of the ESD. This effect was investigated in [5, 6].

Actuation coefficient changes with the charge accumulated on the test mass according to the equation (6).

Measured relation between γ and α differs for different quadrants of the test mass in range from 0.25 to 0.37. It is probably caused by the difference in geometry of the cage relative to the test mass.

Conclusion

Slow continious charging of Adv.LIGO test masses is observed with rate of about 10 V of effective bias voltage per month. Flipping the bias voltage of the ESD allows one to avoid charge accumulation and to keep the actuation coefficient within necessary limits.

Observed charging of the test masses is the source of additional fluctuating force. The noise level is still unknown. Estimation of this noise is subject for further investigations.

In further investigations one should take into account that the electrical charges on the different sides of the test mass act in different ways, according to the terms 2 and 3 in equation (2).

References

[1] R. Weiss, LIGO document **T1400647**

[2] D. Martynov, PhD Theses

[3] J. Kissel, LIGO document **G1500036**

[4] J. Betzwiesser, LIGO document **T1400490**

[5] L. Prokhorov and V P Mitrofanov 2010 Class. Quantum Grav. **27** 225014

[6] D.Ugolini et al, Instr. and Exp. Tech., **56(2)**, 215 2013.

This work was supported by LSC Fellows program. Authors are grateful to Michael Landry for care and useful discussions. The authors are grateful to NSF and Caltech for support of this research under grant PHY-1305863.