Measurement of Angular Stray DC Potentials for Test Masses in LISA Pathfinder

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Abstract

Launched in December of 2015 and still in space currently, LISA Pathfinder is an essential mission to test the technologies necessary for a space based gravitational wave detector. The functionality of a space based gravitational wave detector depends on our ability to keep force noise low. A source of force noise comes from stray electrostatic potentials that exist on the test masses and their electrode housings. Here I present a scheme for measuring stray electrostatic potentials for both test masses in two angular degrees of freedom, and the results of those mea-

surements. Combining these angular measurements with measurements in the translational degrees of freedom will allow scientists to better compensate for these stray potentials and thus decrease force noise.

1 Introduction: General Relativity, Gravitational Waves, and Gravitational Wave Detectors

In 1916, Albert Einstein published his theory of General Relativity. The theory states that massive objects warp the geometry of spacetime. In addition, when massive objects accelerate in a way that is not spherically or cylindrically symmetric, these objects emit gravitational radiation. In the early 1960s, Joseph Weber proposed a method for detecting gravitational waves using heavy metallic bars. A gravitational wave emitted by a nearby astrophysical source would cause distant metallic bars to undergo a resonant excitation of their acoustic modes. If this excitation could be measured with enough precision, then perhaps gravitational waves could be detected. Weber claimed to have made a detection with his bar method, drawing several other scientists into the field, but no one was able to confirm his "detection." An additional method for detecting gravitational waves using laser interferometry was proposed by Gertsenshtein and Pustovoit. Laser interferometers take advantage of the way that gravitational waves distort spacetime as they travel: the passing gravitational waves will lengthen one arm of an interferometer while contracting the perpendicular arm. Thus, a passing gravitational wave will create a specific interference pattern according to the properties of that wave. Several ground based interferometers exist today, most notably the Laser Interferometer Gravitational Wave Observatory, LIGO, with 4 km arm detectors in Livingston, Louisiana and Hanford, Washington. It has now detected two separate gravitational wave events; both were black hole mergers in the frequency range of 35-250 Hz. Other ground based detectors include GEO600 in Sarstedt, Germany; VIRGO in Pisa, Italy; and KAGRA, which is currently under construction in Gifu, Japan. Due to seismic noise (see Figure 1) ground based detectors are fundamentally unable to detect gravitational waves below 10 Hz.

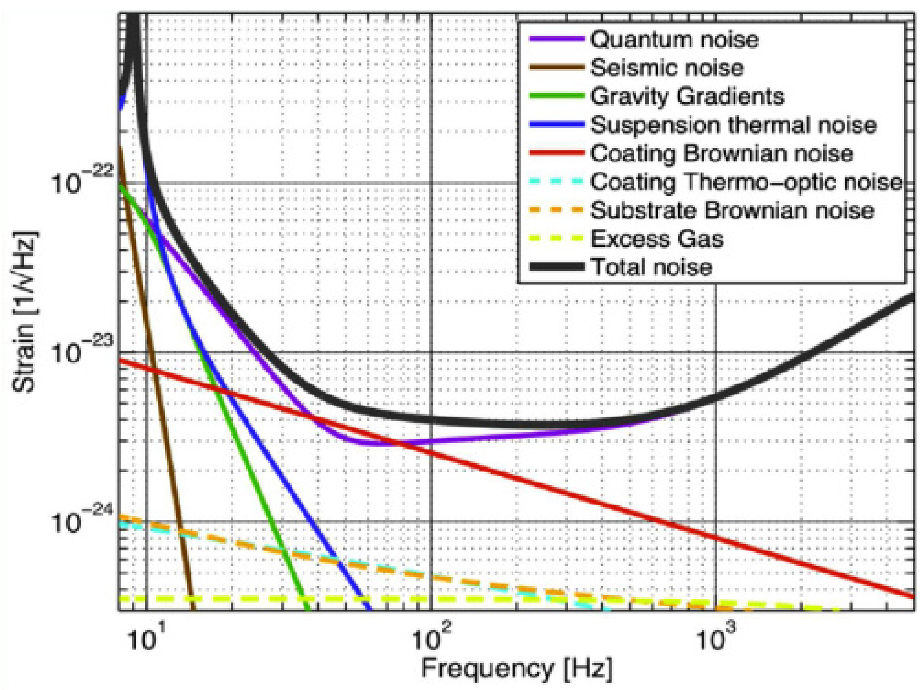

Figure 1: Noise limits for GW Detectors

A clear way to avoid seismic noise altogether and detect gravitational waves at lower frequencies is to move the laser interferometer into space. The Laser Interferometer Space Antenna, LISA, aims to do just this. LISA will be a constellation of three spacecrafts, forming a triangle with an arm length of 5 Mkm. Each spacecraft will hold free floating test masses. These test masses are shielded from outside forces and their positions are read out with an interferometer. LISA will be sensitive to a frequency range from 0.03 mHz and 0.1 Hz. A space mission of this magnitude is expensive, and the technologies must be proven reliable before sending a three arm constellation into space.

2 LISA Pathfinder

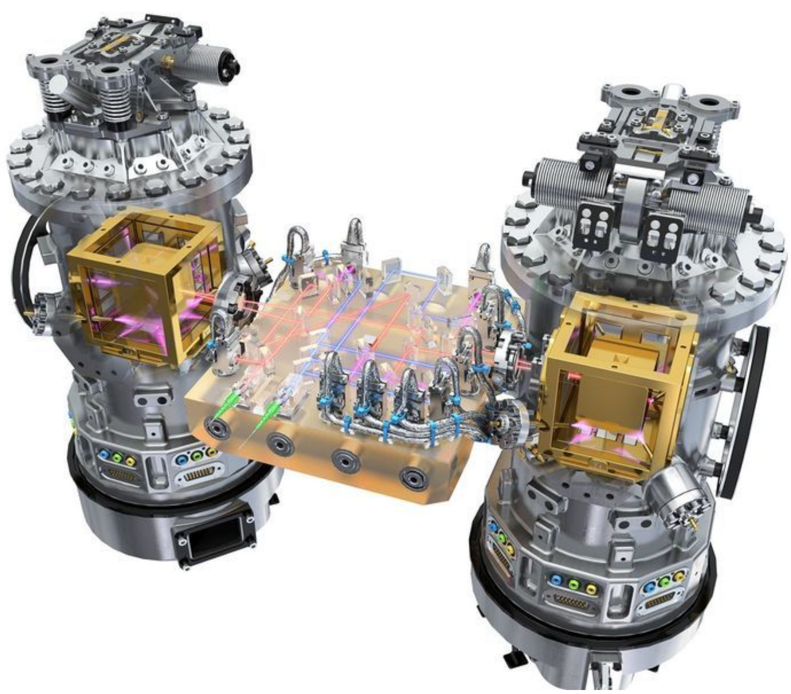

Figure 2: LISA Technology Package

In order to test the technologies necessary for a space based gravitational wave observatory such as LISA, the European Space Agency launched LISA Pathfinder on December 3, 2015. LISA Pathfinder's mission is to demonstrate free fall of test masses at a level similar to that necessary for a LISA mission. LISA Pathfinder spent its first 50 days traveling to the L1 sun-earth system lagrange point, where it subsequently separated from its propulsion module. On the 74th day, two test masses were released in free fall and science began on the 89th day. LISA Pathfinder takes one arm of a LISA-like mission and shrinks it from 5 Mkm to 40 cm. With this arm length, LISA Pathfinder is incapable of detecting gravitational waves; however, it is capable of testing and demonstrating the capability of current technology for detecting gravitational waves. A LISA like mission will require a single test mass acceleration amplitude spectral density of $3\frac{fm}{s^2\sqrt{Hz}}$ at 0.1 mHz. LISA Pathfinder's requirements are slightly relaxed with a differential (relative between the two test masses along an axis intersecting both of their centers) acceleration amplitude spectral density of $30\frac{fm}{s^2\sqrt{(Hz)}}$ at 1 mHz.

2.1 Geometry of LISA Pathfinder

LISA's two test masses are separated by a distance of 376 mm and this axis is taken to be the x-axis. Each degree of freedom is displayed in Figure 1. Each cubic test mass has a length of 46 mm and a mass of 1.928 kg. They are made of a high purity gold aluminum alloy and each is contained in an electrode housing system. The distance between each side of the test mass and its housing varies between 2.9 mm and 4 mm, depending on which side of the mass is in question (See Figure 4). These electrode housings shield the test masses from cosmic rays, readout the positions of the test masses, and actuate forces on the test masses.

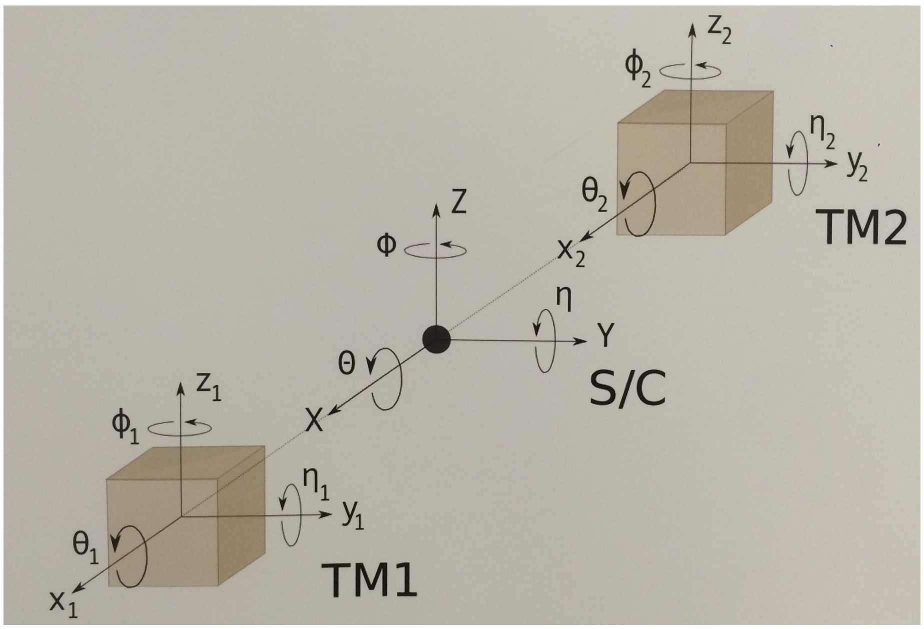

Figure 3: Visualization of the degrees of freedom for LISA Pathfinder test masses

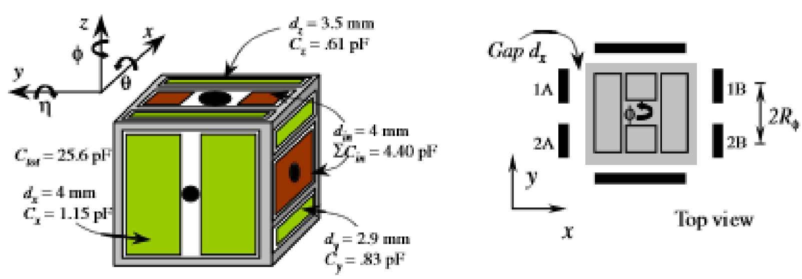

Figure 4: Single Test Mass with Electrode Housing

3 Electrostatic force noise due to stray electrostatic fields

In principle, the test masses and their electrode housings are equipotentials. However, different crystallographic grains and contaminant atomic layers can cause spatially varying potentials, "patch fields", along the test masses and their housings. When combined with test mass charging or dielectric noise, force gradients are created that contribute to acceleration noise. Scientists at the University of Trento have developed and implemented methods of measuring and compensating these stray potentials in the x-direction. This summer I did the same for the angular degrees of freedom, eta and phi.

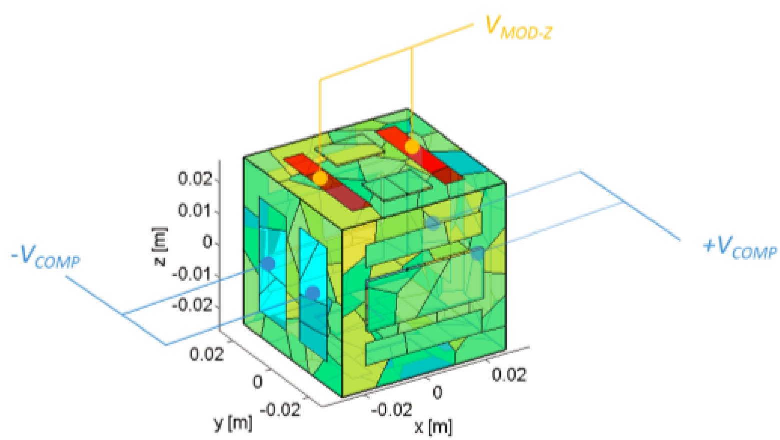

Figure 5: Cartoonized picture of possible stray electrostatic potentials

3.1 Modulation Experiments

Here I will discuss the method for measuring stray potentials. I will specifically explain this in the context of a Z Modulation experiment done on 2016/06/06 for TM1 in the phi degree of freedom. An analogous measurement was done with TM2 in phi and both test masses in eta. However, for eta, Y modulation experiments are used.

In order to measure these stray potentials for the phi degree of freedom, a sinusoidal signal $V_\Delta \sin(\omega_0 t)$ is applied to the four z sensing electrodes. This causes the potential of the test mass to oscillate with an amplitude of $\frac{4C_z}{C_t} V_\Delta = \alpha V_\Delta$.

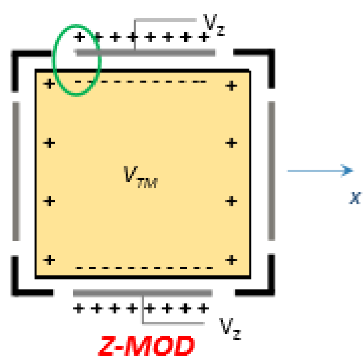

Figure 6: Z Modulation on TM

The input of an oscillating voltage from the z electrodes causes opposing charges to line up on the z faces of the test mass. These charges on the z face cause an imbalance of charge on the test mass, resulting in a leftover charge of the same sign as the input voltage on the x and y faces (see Figure 6).

This leftover charge on the x and y faces mimics a real charge in these directions. For a test mass close to its central position, the torque due to this modulation in the phi direction is given by:

$$N_\phi = -\alpha V_\Delta \sin(\omega_0 t)\Delta_\phi \frac{\partial C_x}{\partial \phi} \tag{1}$$

where

$$\Delta_\phi = \delta V_{1A} + \delta V_{2B} - \delta V_{2A} - \delta V_{1B} \tag{2}$$

Where N_ϕ is the total torque on the test mass, $V_\Delta sin(\omega t)$ is the commanded modulating voltage, $\frac{\partial C_x}{\partial \phi}$ is the partial derivative of the x direction capacitance with respect to phi, and Δ_ϕ is a measurement of the stray electrostatic potentials coming from each electrode sensor (See Figure 4).

In order to find Δ_ϕ, we must first construct N_ϕ. N_ϕ is constructed by multiplying the moment of inertia about the z axis, I_{zz}, by the total relative angular acceleration in phi of the two test masses: $\Delta\Gamma_\phi$.

$$N_\phi = I_{zz}\Delta\Gamma_\phi \tag{3}$$

with

$$\Delta\Gamma_\phi = (\frac{N_{ext2}}{I_{zz2}} - \frac{N_{ext1}}{I_{zz1}}) - (\kappa_2^2\phi_2 - \kappa_1^2\phi_1) + (\frac{N_{com2}}{I_{zz2}} - \frac{N_{com1}}{I_{zz1}}) \tag{4}$$

The first and third terms represent accelerations due to external and commanded torques, while the middle term represents an acceleration due to a springlike stiffness coming from the interaction of test masses with their electrode housings.

In order to calculate $\Delta\Gamma_\phi$, I modified a previously used model in LTPDA that was used to calculate the differential acceleration in x, Δg.

Graphs of $\Delta\Gamma_\phi$ and $V_\Delta \sin(\omega_0 t)$ for a Z Modulation experiment are shown in figures 7 and 8 respectively

Following the construction of $\Delta\Gamma_\phi$, both $\Delta\Gamma_\phi$ and $V_\Delta \sin(\omega_0 t)$ are demodulated and Δ_ϕ can be computed using a modified equation (1) :

$$\Delta_\phi = \frac{N_{\phi,Demod}}{M} \tag{5}$$

where

$$M = -\alpha V_\Delta \frac{\partial C_x}{\partial \phi} \tag{6}$$

and $N_{\phi,Demod}$ is simply N_ϕ constructed with the demodulated $\Delta\Gamma_\phi$.

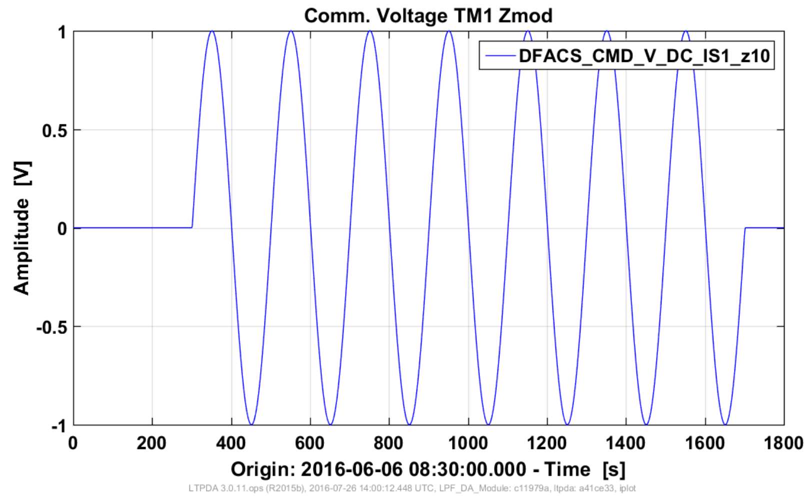

Figure 7: Commanded Voltage @ 5mHz, $V_\Delta \sin(\omega_0 t)$, for TM1 Z Modulation 2016/06/06

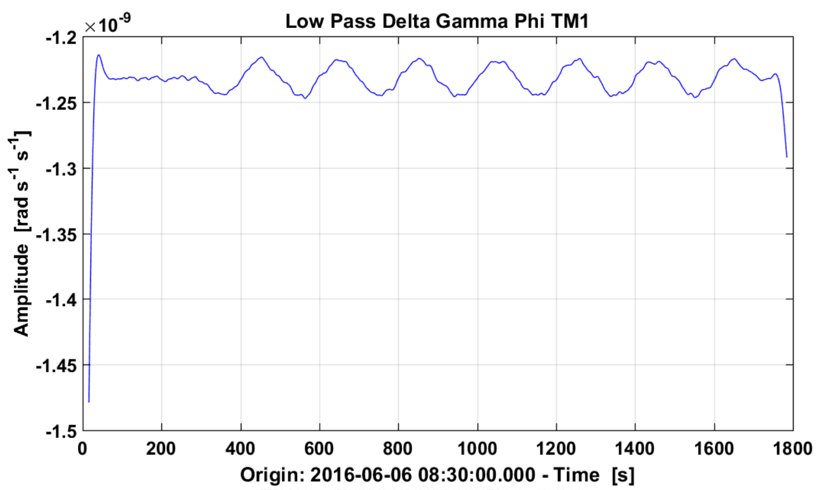

Figure 8: $\Delta\Gamma_\phi$ for TM1 Z Modulation 2016/06/06

For TM1 on 2016/06/06, I obtained five Δ_ϕ values (Figure 9), averaging to 35.118833 mV with an error of 0.319717 mV

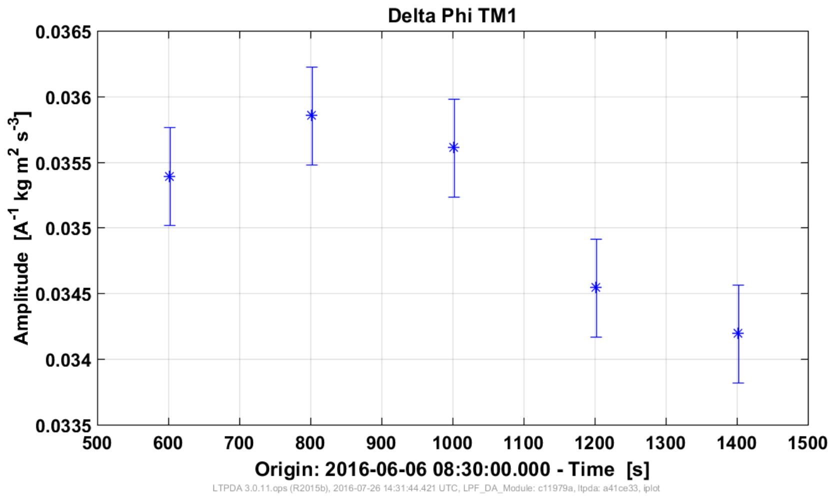

Figure 9: Δ_ϕ for TM1 on 2016/06/06

4 Results

I obtained Δ_ϕ and Δ_η values for several dates, spanning 2016/03/30 to 2016/06/06 for both test masses, as well as an additional measurement for Δ_ϕ for TM1 on 2016/06/24. For the 2016/06/24 measurement, there were three experiments with three different frequencies of commanded voltage, resulting in three separate Δ_ϕ measurements for that date, one for each modulation frequency. For each experiment, I averaged Δ_ϕ and Δ_η, and then plotted these values through time. (See figures 10-13).

All of the values obtained remain within $\pm 150mV$.

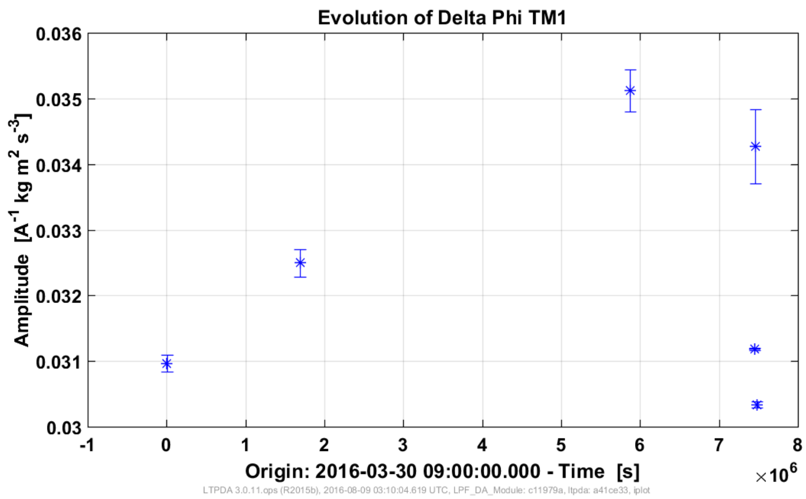

Figure 10: Evolution of Δ_ϕ for TM1. The last three data points contain varying frequency values: for $f = 1mHz$, $\Delta_\phi = 31.181mV$; for $f = 5mHz$, $\Delta_\phi = 34.273mV$; for $f = 0.25mHz$, $\Delta_\phi = 30.337mV$

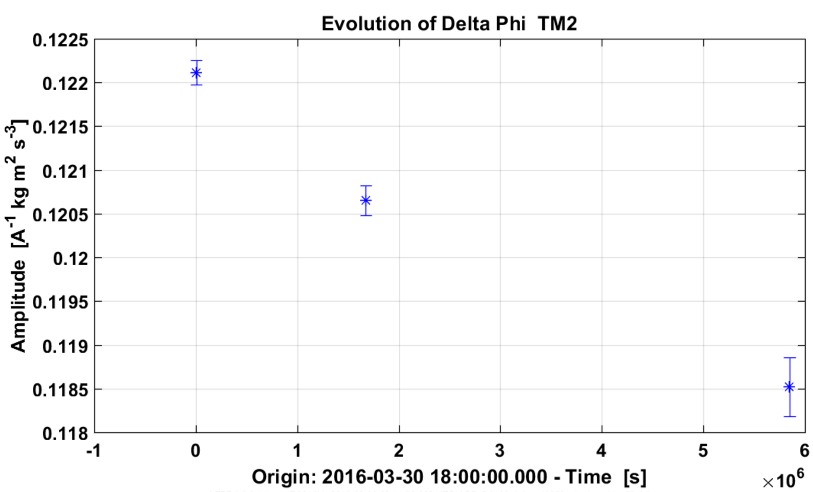

Figure 11: Evolution of Δ_ϕ for TM2

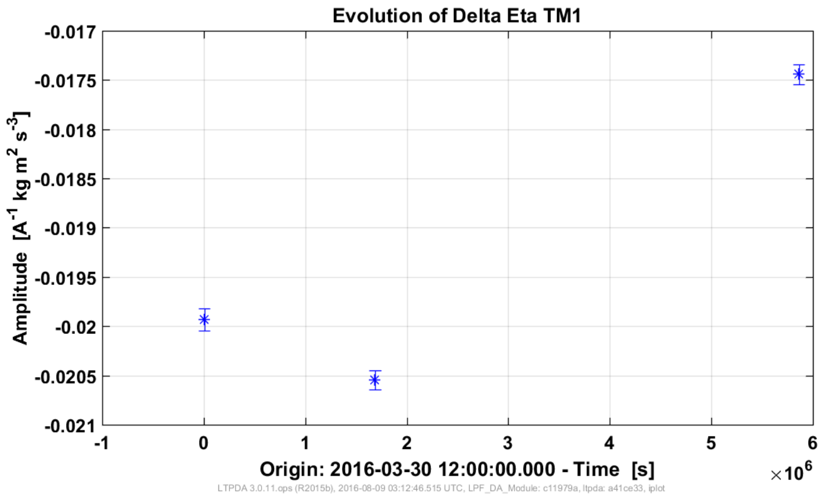

Figure 12: Evolution of Δ_η for TM1

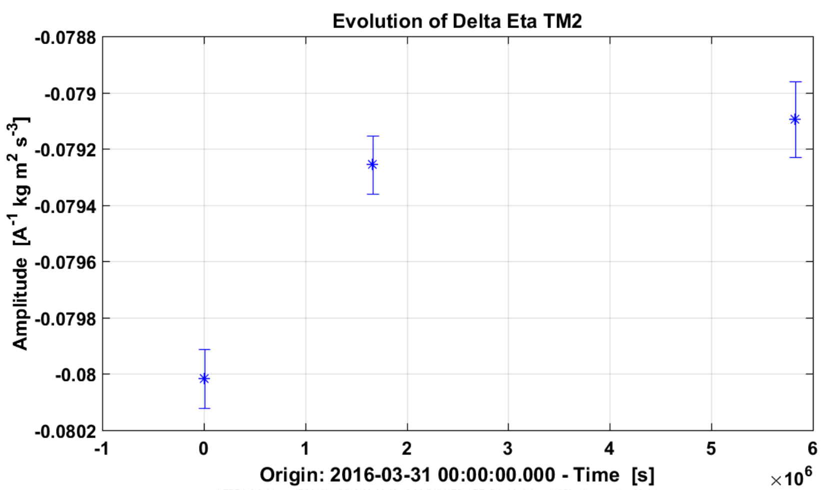

Figure 13: Evolution of Δ_η for TM2

5 Conclusion

The LISA Pathfinder team now has a set of values for Δ_ϕ and Δ_η over a three month period. Combining these values with previous stray potential measurements in translational degrees of freedom, like Δ_x, will allow scientists to better characterize stray potentials coming from individual electrodes. With this characterization, one can apply voltages to these electrodes in order to cancel out the stray potentials and thus get rid of the force noise that comes from them.

6 Acknowledgements

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