Simulation of Torsion Pendulum Discharging Measurements

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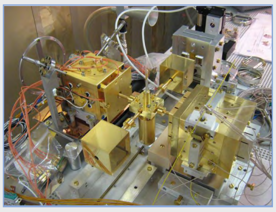
Introduction

As part of preparation for LISA Pathfinder, discharging measurements have been made with the four-mass torsion pendulum experiment at the University of Trento. The discharging properties of the system are dependent on a number of interrelated factors. These include the photoelectric and reflective properties of the inertial sensor surfaces as well as the distribution of the illuminating UV light. In addition, the geometry of the system and the presence of varying electric fields play important roles. In order to better understand the discharging system as a whole, simulations have been produced which incorporate all these factors and where possible use experimentally measured parameters to describe them. The simulation has been used to help understand some unexpected discharging results from the pendulum experiment and can be used in future to optimise the design of the LISA system.

The simulation consists of two distinct parts. First, a ray-tracer written in Geant4, models the propagation of the UV light within the inertial sensor which determines the percentage of light absorbed by the various surfaces. The second part is written in MATLAB and uses the calculated absorption ratios to model the flow of the emitted photoelectrons, within region-specific electric fields. This allows discharge rates and the instantaneous test mass potential to be estimated under a variety of operating conditions.



Photograph of the four-mass pendulum experiment. The test mass of interest and surrounding housing can be seen on the left with two ISUKs entering from above. Photograph courtesy of UTN.

UV Ray Trace

The UV ray trace is written in the Geant4 framework. While originally created to model the propagation of particles through matter, Geant4 also contains reflection physics models and highly versatile methods for describing complex geometries. Once the system geometry has been described within Geant4 the ray trace follows a common procedure:

1) A ray is generated within the ISUK tip with a random polarisation and a direction randomly sampled from the experimentally measured ISUK light distribution.

2) The ray propagates in a straight line through the geometry until it is incident with a surface.

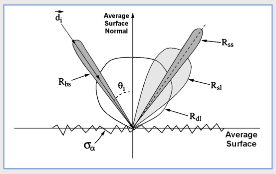
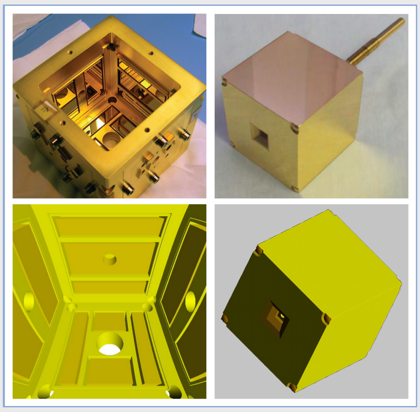


Diagram of the possible ways an incident ray, d_i, can be reflected in Geant4. The four possibilities are in a specular spike (R_{ss}), a backscatter spike (R_{bs}), a diffuse lobe (R_{dl}) or a specular lobe (R_{sl}). The shape of the specular lobe is determined by the value of σ_α, which describes the standard deviation in the micro-facet angular distribution.



Top Left: The electrode housing used at the four-mass pendulum, with the lower z face removed. The inner dimensions are 54.0, 51.8 and 53.0 mm in x, y and z respectively. Top Right: The 46 mm3 test mass (TM3) used at the four-mass pendulum. Bottom Left: The simulated four-mass electrode housing. Bottom Right: The simulated test mass. Photographs courtesy of UTN.

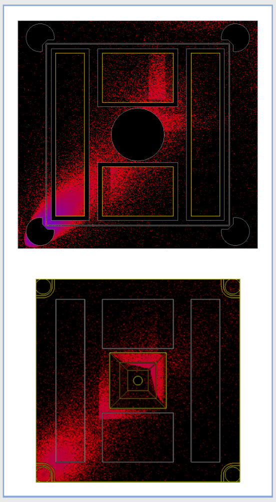
3) Using the Fresnel equations, it is then either absorbed or reflected, depending on reflection properties of the surface, the angle of incidence and the ray's polarisation. The complex refractive index at 254 nm of the gold surfaces within the sensor has been measured and agrees with the literature values.

4) If the ray is reflected it is given a new direction, dependent on the reflection properties of the surface. The smooth surfaces within the sensor (r.m.s<10 nm) are known to reflect specularly while the unknown reflective properties of the rougher surfaces can be varied.

5) A ray will continue to propagate and reflect until it is eventually absorbed. This is repeated for a user-specified number of rays, typically greater than 10^6.

6) The inertial sensor is split into regions and the percentage of light absorbed by each is recorded and outputted to an ASCII file at the end of a run.

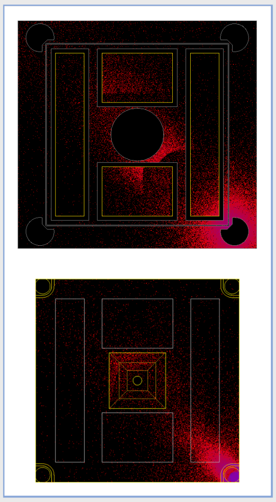
Several runs have been carried out where the unknown reflection properties of the rougher gold surfaces have been varied. The ray trace allows several general observations to be made that are true whichever properties the unknown reflection distributions take. For example, a large percentage of light is effectively 'wasted', particularly when illuminating the housing where 63−73% of the light is absorbed within gaps and particularly the nearest caging hole. A further general observation is that upon illuminating the test mass a significant amount of light falls on the x and y faces in addition to the nominal z face. Although the distribution of the light varies, reassuringly the total absorbed by either the test mass or housing remains roughly the same, irrespective of the unknown reflection distributions. When the housing is illuminated just 19−26% is absorbed by housing surfaces 'useful' to discharging, while 8−11% is absorbed by the test mass. Meanwhile, when the test mass is illuminated 65−69% is absorbed by the test mass and 15−17% is absorbed by housing surfaces 'useful' to discharging.



Distribution of absorbed UV light upon illuminating the four-mass sensor. Purple represents high absorption, red low absorption and black zero absorption. The test mass sides and electrodes were given purely specular properties, the test mass corner regions had a σ_{tm} = 15° and the housing had a σ_{eh} = 25°.

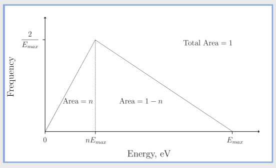
Housing Illumination.
Top Left: Absorption taking place on the housing lower z face. Bottom Left: Absorption taking place on the test mass lower z face.

Test Mass Illumination.
Top Right: Absorption taking place on the housing lower z face. Bottom Right: Absorption taking place on the test mass lower z face.



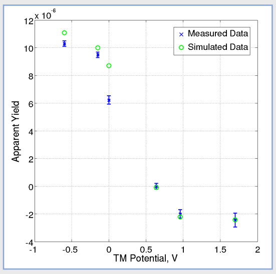
Photoelectron Flow Model

A simple photoelectron flow model has been developed in MATLAB. By making several assumptions and approximations it uses the output of the ray trace to estimate the performance of the entire system, given the photoelectric properties of the individual surfaces. The photoelectron flow model's core concept is to split the inertial sensor up into adjacent pairs of regions on the test mass and electrode housing. The net flow of photoelectrons between these parallel surfaces can then be estimated, while taking into account the potential difference between the surfaces as well as the energy distribution of the emitted photoelectrons.

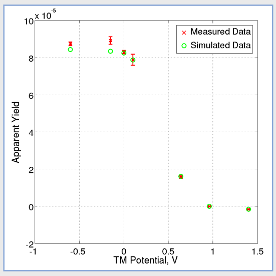


The triangular distribution used to model the energy of the emitted photoelectrons. The distribution is described by two parameters E_{max}, which is related to a surface's work function, and n, the peak position.

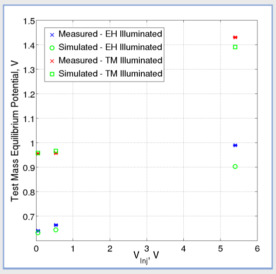
Each gold surface is described by its quantum yield, work function and a parameter n which describes the emitted photoelectrons energy distribution.



The simulated and measured apparent yields at different test mass potentials, for both illuminations. At a particular test mass potential the apparent yield is the net number of electrons exchanged with the test mass per UV photon entering the inertial sensor. Left: Illuminating electrode housing. Right: Illuminating test mass.



Comparing measured and simulated results suggest uniform properties for test mass and housing but that there is a large asymmetry between the two. Simulation has found that the housing quantum yield is 9.8 × 10^{-6} e/photon (work function 4.5 eV) while the test mass is over an order of magnitude higher at 1.3 × 10^{-4} e/photon (work function 3.8 eV). The parameter n was found to be 0.2 in both cases. It is predominately this large asymmetry in yields which prevents bipolar discharge with the four-mass system. Quantum yield measurements on separate gold samples have observed large variations like these which are thought to be due to surface contamination from exposure to air.



The simulated and measured equilibrium potential reached with 100 kHz AC injection voltages of 0.054, 0.54 and 5.4 V. While qualitatively the simulated results are good there is some quantitative disagreement, particularly at 5.4 V.

While the simulated results are generally very good there are some discrepancies. This is not surprising given the simplicity of the model and can likely be explained by a combination of two weaknesses. Firstly, although the UV ray trace can approximately predict the total amount of light absorbed by either the test mass or housing, the exact distribution in absorbed UV light is still uncertain. To predict this with confidence one requires measurements of the reflection profiles of the rough surfaces. As the distribution in absorbed light determines which electric fields emitted photoelectrons are influenced by, this affects the discharging behaviour. It should be noted that the distributions currently predicted with σ_{tm} = 15 and σ_{eh} = 25 do not seem far off the true properties given the subsequent good agreement with the measured discharge properties. Possible evidence for this theory is the fact that the predictions of the model fit less well with a large applied injection bias. This may suggest the amount of UV absorbed within the injection regions is slightly out.

The second weakness in the simulation, and possibly the more likely cause of the discrepancies, is that it assumes that the photoelectrons only travel between adjacent surfaces. This is a good approximation when potential differences are large, greater than the photoelectron energies in eV, as the resulting electric fields dominate the photoelectron trajectories. However, when the potential differences are small, less than the energy of the photoelectrons in eV, the likely cosine distribution in the direction of emitted photoelectrons would allow some of them to cross into different regions. In the case of photoelectrons emitted from the housing, when the potential differences are small some would miss the test mass altogether. In addition, some photoelectrons emitted within the gaps could reach the test mass. Possible evidence for this theory is the discrepancy between measurement and simulation when the TM potential is near zero and the housing is illuminated.

Conclusions

The ability of the photoelectron flow model to reproduce the behaviour observed at the four-mass experiment is encouraging and also builds further confidence in the UV ray trace. So far the simulation has performed very well in fitting results obtained while applying dc voltages to sensor electrodes. Further work is on-going to test the model against measurements made with ac biases, while using the same set of parameters.