Capacitance Position Sensor for LISA Noise Measurement

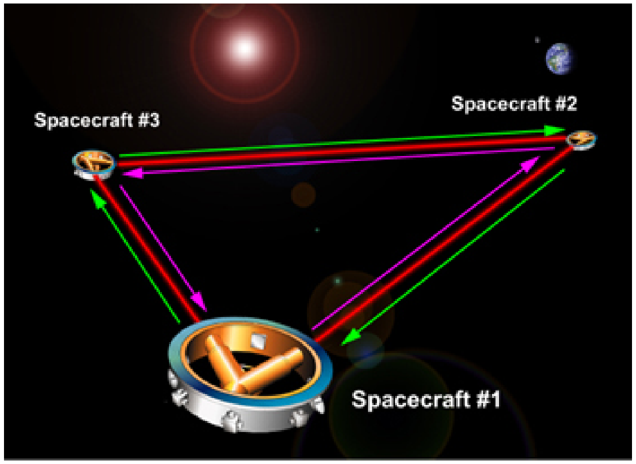
Hal Finkel

August 18, 2004

University of Washington REU Program

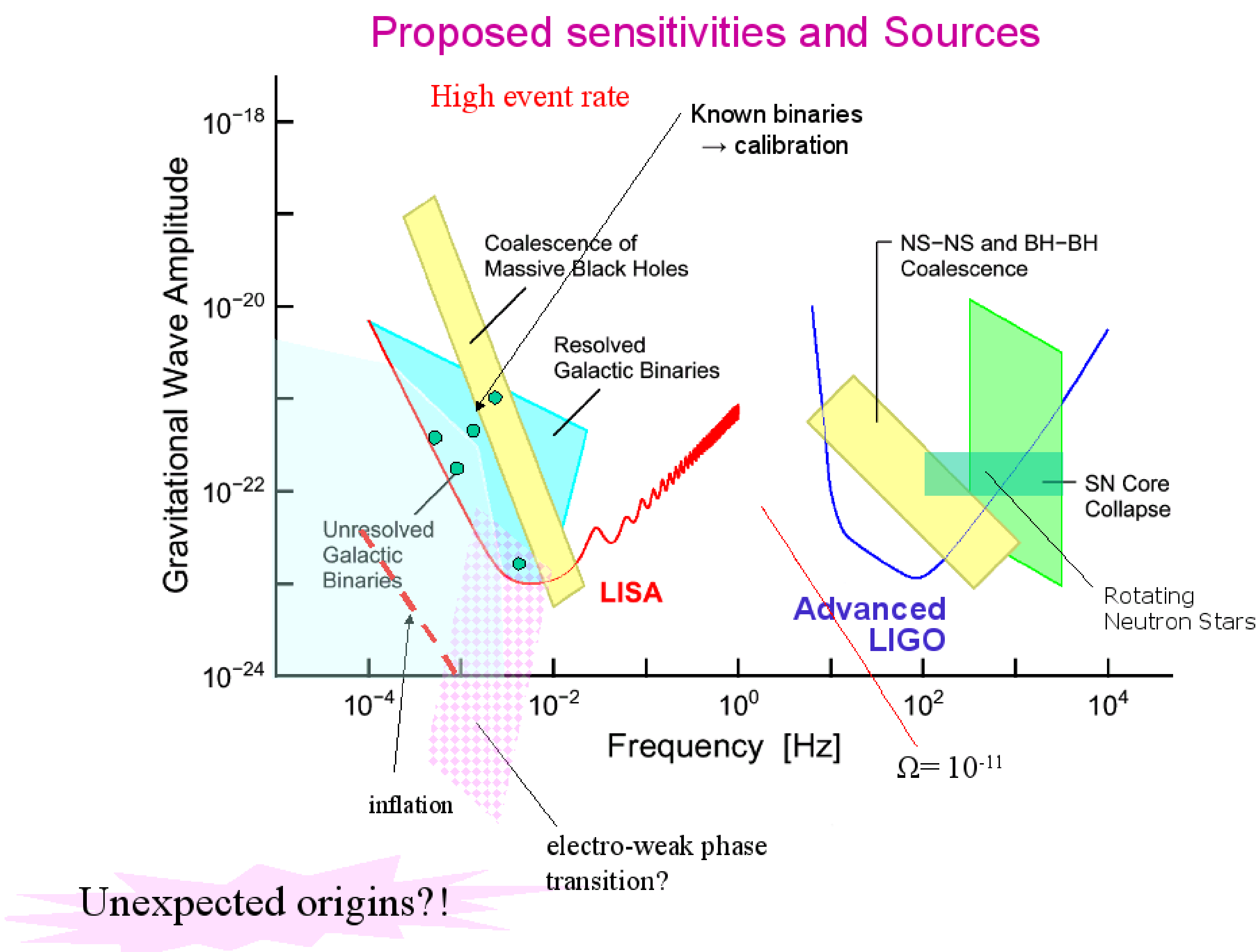
LISA Overview

- Three very large Michelson-Morley interferometers
- Arm length of 5 million km
- Able to decipher 20pm length changes at 0.0001Hz to 0.1Hz
- The three 200kg spacecraft to be launched in 2012 or 2013



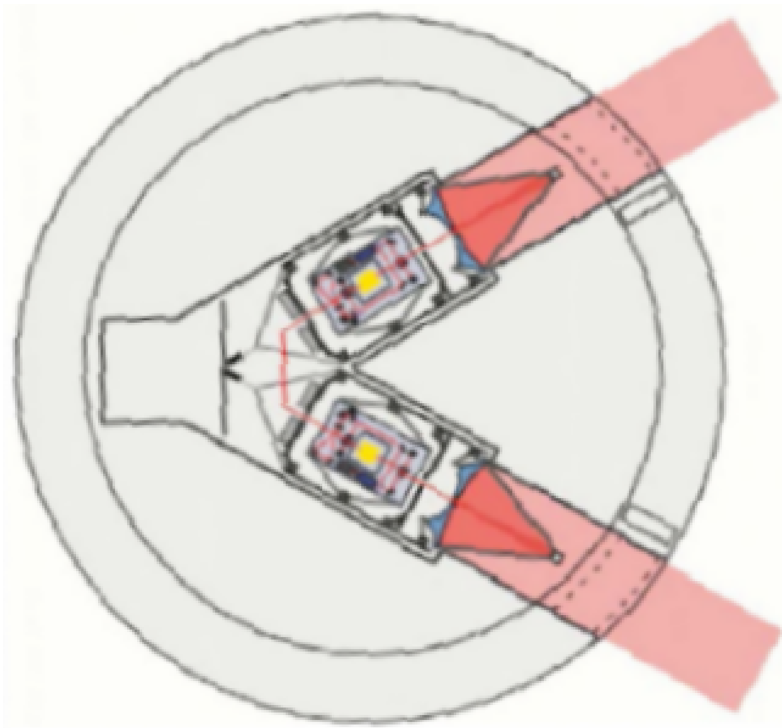
Why LISA?

- LISA and LIGO have different sensitivity ranges



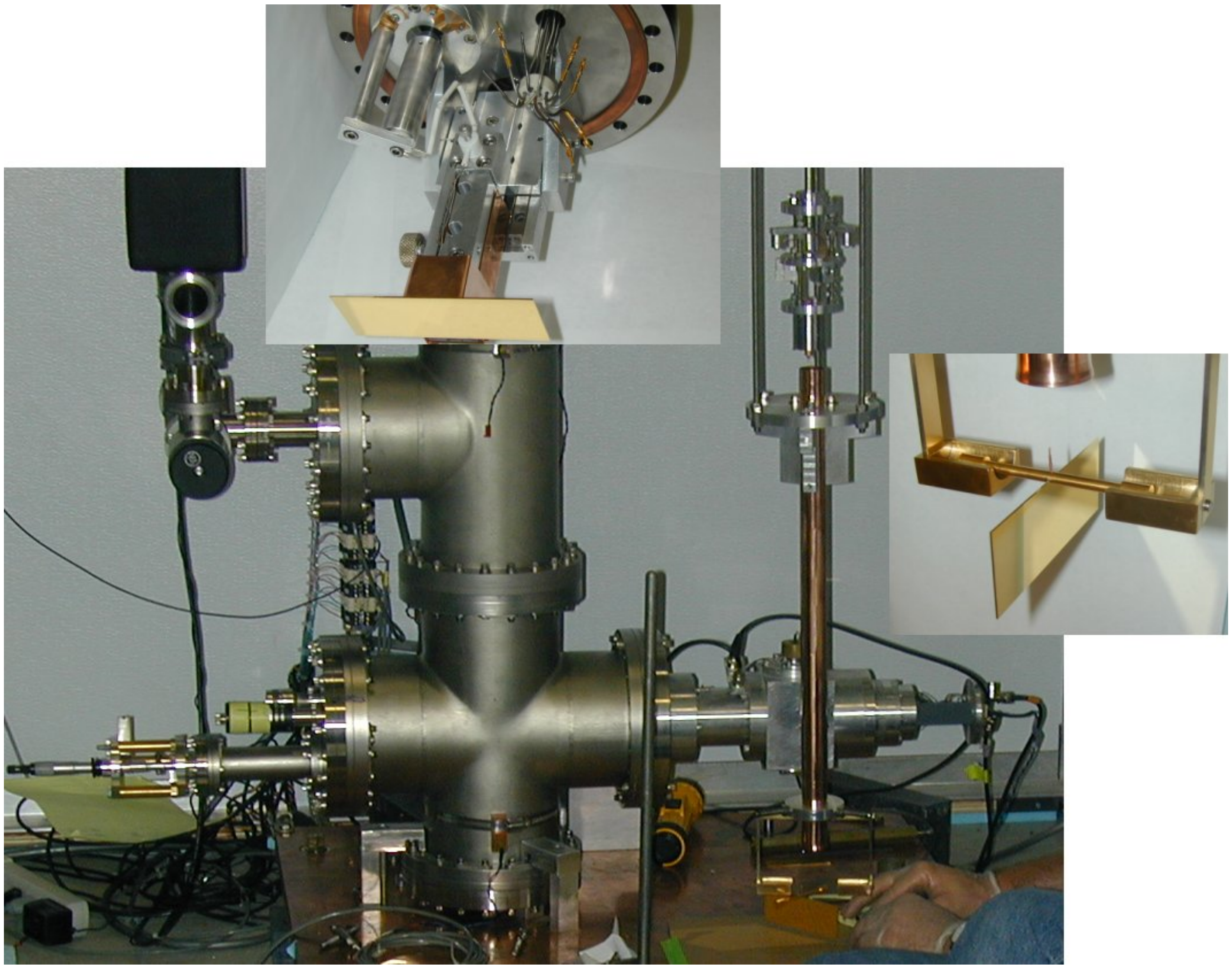
Our Task

- Identify forces which will act between the proof masses and the spacecraft



How We Do It

- Measure the forces between a torsion pendulum and a movable plate



Position Sensor Needed

Unfortunately, the current setup lacks a way to measure the translational (X,Y) position of the pendulum. This is needed to enable isolation of the components of the rotational position data correlated with translational oscillations.

Position Sensor Requirements:

- Resolution on the order of one micron (sub-micron preferable)
- Do not introduce new significant forces acting on the pendulum (keep the pendulum grounded)
- Be easy to implement within the existing setup

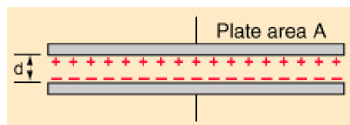
How Do You Do That?

It can be done by measuring:

How Do You Do That?

It can be done by measuring: Capacitance!

Using the pendulum or something attached to it as one plate of a parallel plate capacitor:

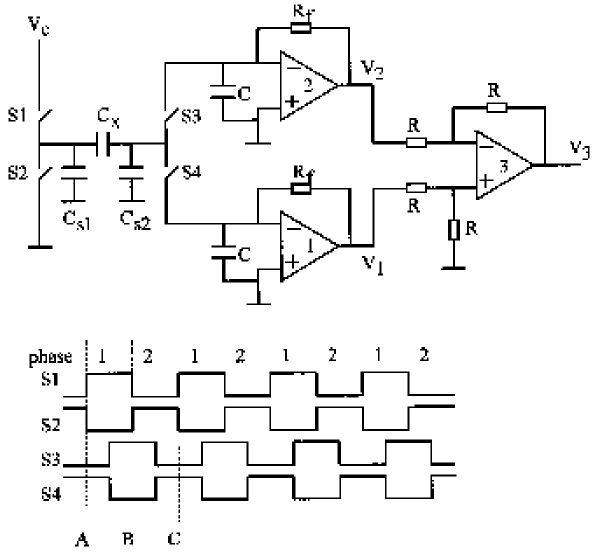


$$C = \frac{\varepsilon A}{d} = \frac{k\varepsilon_0 A}{d}$$

Two types of circuits were tried:

1. "Active" design using direct measurement
2. "Passive" design using differential measurement

Direct Measurement



The circuit charges and discharges the capacitor C_x once per clock cycle. Each clock cycle can be divided into two phases of equal duration:

1. C_x is charged to V_c
2. C_x is discharged

Charge transfered during each phase is:

$$Q = V_c C_x$$

Thus, the current is:

$$I = fQ = fV_c C_x$$

This gives:

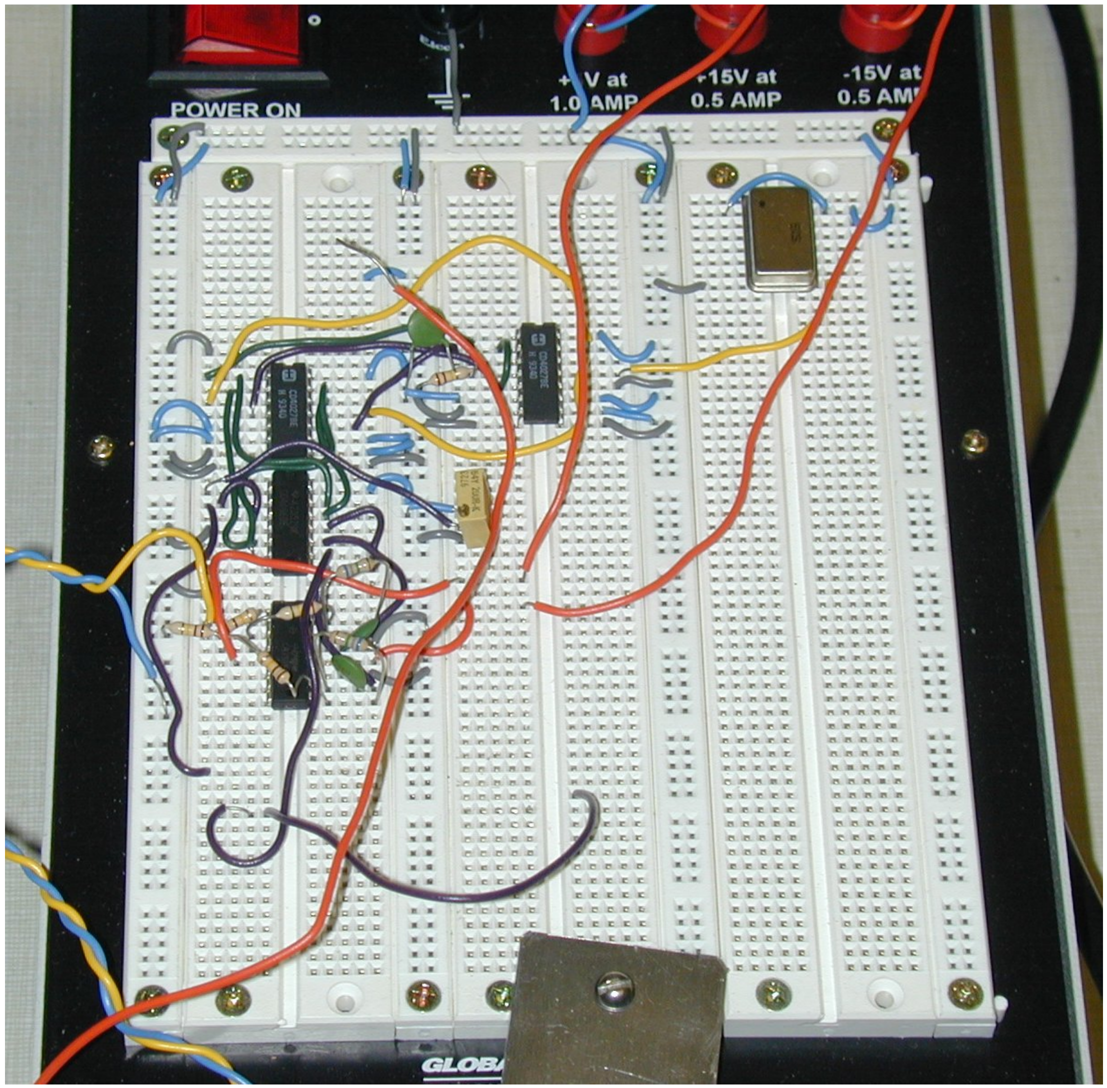
$$V_1 = -fV_c C_x R_f$$

$$V_2 = fV_c C_x R_f$$

$$V_3 = -2fV_c C_x R_f$$

Note: the negative signs come because the op-amps labeled 1 and 2 form inverting amplifiers

Here is a working implementation (excluding C_x connections):



Direct Measurement Advantages

This technique has several advantages:

Direct Measurement Advantages

This technique has several advantages:

- Minimal change to existing setup

Direct Measurement Advantages

This technique has several advantages:

- Minimal change to existing setup
- Keeps pendulum at a virtual ground

Direct Measurement Advantages

This technique has several advantages:

- Minimal change to existing setup
- Keeps pendulum at a virtual ground
- Works for V_c at fractions of a millivolt

Direct Measurement Advantages

This technique has several advantages:

- Minimal change to existing setup
- Keeps pendulum at a virtual ground
- Works for V_c at fractions of a millivolt
- Inexpensive

Direct Measurement Problems

What was wrong with it?

Direct Measurement Problems

What was wrong with it?

- For low values of V_c non-ideal op-amp behavior and other factors introduce large offsets

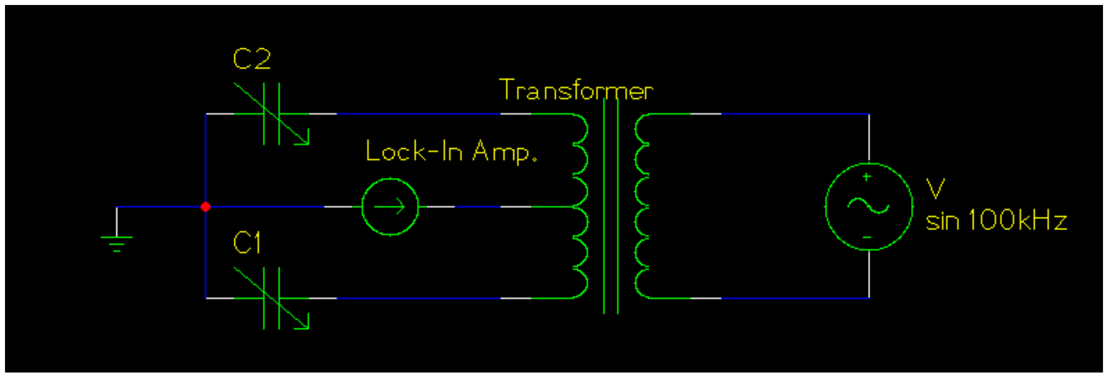
Direct Measurement Problems

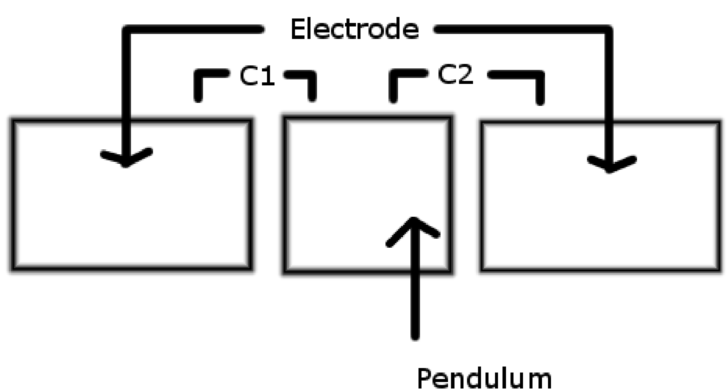
What was wrong with it?

- For low values of V_c non-ideal op-amp behavior and other factors introduce large offsets
- When connected to the actual setup, its sensitivity was much lower than expected

Differential Measurement

The differential measurement uses an LC bridge circuit:





The circuit works by measuring:

$$I = \frac{\text{Emf}}{Z_L}\left(\frac{Z_{C1}}{Z_{C1} + Z_L} - \frac{Z_{C2}}{Z_{C2} + Z_L}\right)$$

where $Z_L = i\omega L$, $Z_{C1} = \frac{1}{i\omega C_1}$ and $Z_{C2} = \frac{1}{i\omega C_2}$, thus:

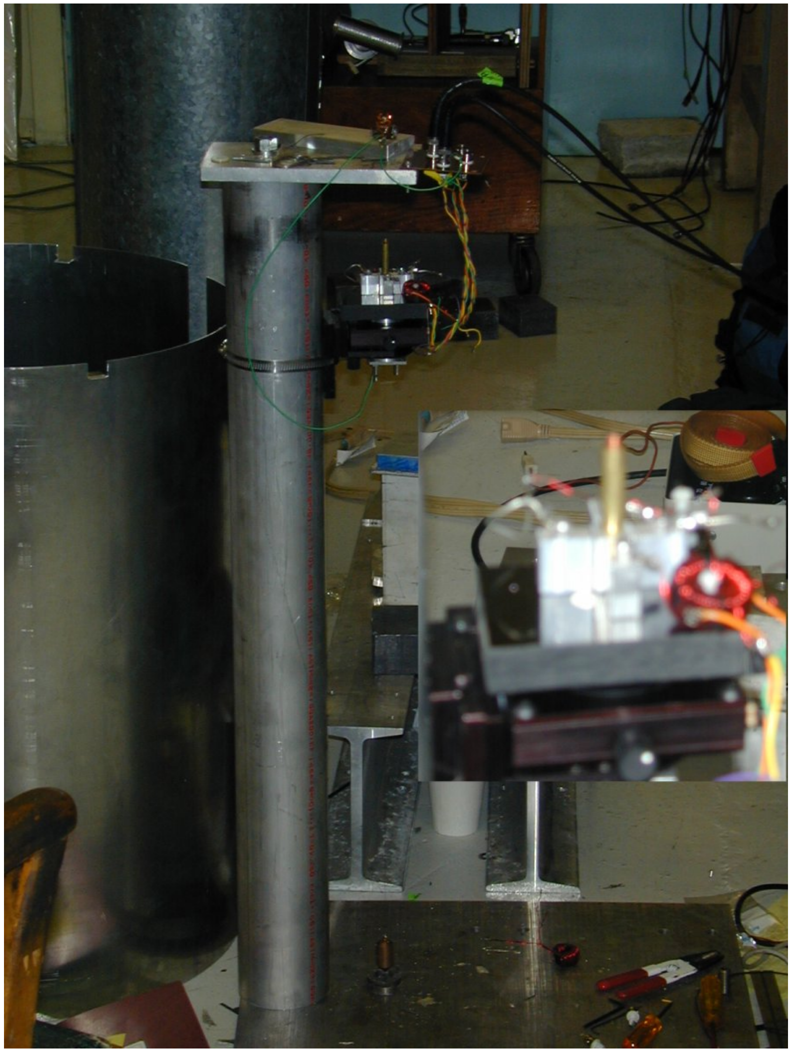
$$I = \frac{i\text{Emf}}{\omega L}\left(\frac{1}{1 - \omega^2 LC_1} - \frac{1}{1 - \omega^2 LC_2}\right)$$

And:

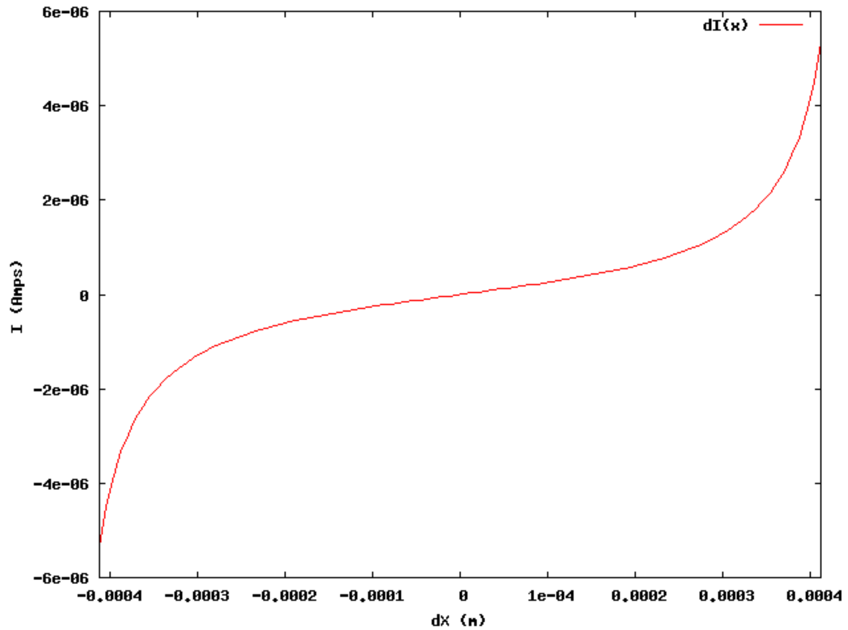
$$C_1 = \frac{\epsilon_0 A}{x + \Delta x}$$

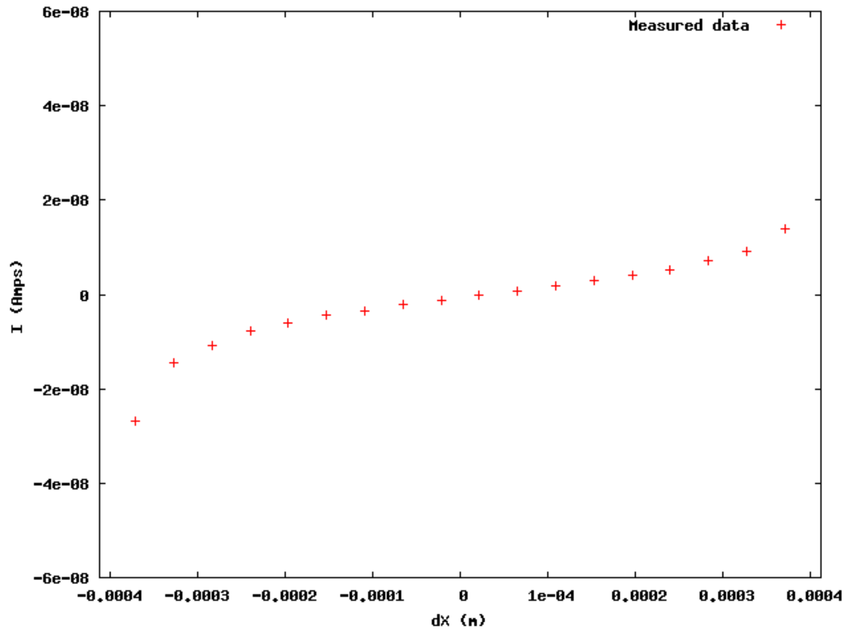
$$C_2 = \frac{\epsilon_0 A}{x - \Delta x}$$

Here is a prototype pendulum setup with a working version of the circuit:



Calculated and Measured Output





Notice that the center region is very close to being linear!

Differential Measurement Advantages

There are several noteworthy advantages:

Differential Measurement Advantages

There are several noteworthy advantages:

- It has very good sensitivity

Differential Measurement Advantages

There are several noteworthy advantages:

- It has very good sensitivity
- It consists of a only a small number of passive components

Differential Measurement Advantages

There are several noteworthy advantages:

- It has very good sensitivity
- It consists of a only a small number of passive components
- The transformer can be put into the vacuum, eliminating most T dependence

Differential Measurement Advantages

There are several noteworthy advantages:

- It has very good sensitivity
- It consists of a only a small number of passive components
- The transformer can be put into the vacuum, eliminating most T dependence
- Output is almost linear with the electrode separation distance

However, this technique also has its detractors:

However, this technique also has its detractors:

- It is expensive (a good lock-in amp. costs thousands of dollars, and one is needed per axis)

However, this technique also has its detractors:

- It is expensive (a good lock-in amp. costs thousands of dollars, and one is needed per axis)
- Resonance peaks can give a non-linear frequency dependence

Conclusions and Future Tasks

- There are multiple ways to measure small capacitance values
- The differential circuit seems to measure the position of the pendulum quite well

A production version should be constructed, but more testing is needed.

Special Thanks To...

- University of Washington Physics Department and CENPA
- The NSF and NASA
- Jens Gundlach
- Stephan Schlamminger
- Charlie Hagedorn