Improving the Performance of a Geophone through Capacitive Position Sensing and Feedback

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Good morning, welcome to my talk on "Improving...."

I'm Aaron Barzilai, I did this work in collaboration with Tom, Steve, Tom at JPL, and my advisor at Stanford, Tom.

Abstract

- The seismological community would like an affordable, broadband seismometer.
- A geophone is an affordable seismometer used for high frequency measurements.
- **Modifying a geophone to sense proof mass position capacitively enables its use in low frequency applications.**
- A capacitive geophone requires feedback to maintain its high frequency capability.

I'd like to begin with a quick summary of my talk.

First, we'll take a look at the instrumentation needs of the seismological community and their current options.

Next, we'll ADDRESS the question of "What is a geophone?" The answer is "It's a commercially available seismometer..."

Then, we'll discuss the real substance of this work, how to transform a geophone into a sensor appropriate for measuring low frequency signals. We'll do this by changing it into a capacitive sensor.

Now, this benefit trades off the geophone's performance at high frequencies. At the end we'll take a look at how applying feedback will maintain the high frequency performance.

Low Frequency Seismology

- The Earth acts as a low pass filter.
- Only the low frequency components of a seismic signal will travel great distances.
  - Information about the deep structure of the Earth can be obtained from studying low frequency signals.
  - Low frequency signals are used for studying global seismicity.

As I said, this work focuses on improving the geophone's performance at low frequencies. There's really only one fact you need to know about low frequency seismology:
"The Earth acts as a low pass filter."

As a result, if you want to measure waves that have traveled great distances, must study low frequency signals.

There are a number of applications of studying waves that have traveled great distances. One of the most important is understanding the deep structure of the Earth. Much of what we know about the mantle and the core has been gathered from analysis of the seismic waves that have passed through those portions of the Earth.

Also, studies of global seismicity rely on detecting waves from afar. Local and regional networks can rely on high frequency measurements, but distant earthquakes need low frequency measurements.

Thus far we've established that there are many reasons to measure low frequency signals. Now let's look at some common, currently available seismometers.

Commercial Seismometers

Type	Streckeisen	Guralp	Geophone
Bandwidth	8.33mHz-50Hz	33mHz-50Hz	4.5Hz-400 Hz
Resolution	0.01 ng/√Hz	1 ng/√Hz	1 ng/√Hz
Price	$20,000	$10,000	$50

- A $500, 33mHz-50Hz seismometer with a resolution of 1 ng/√Hz would add another price-performance point to the currently available instrumentation options.

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The Streckeisen brand of seismometers are generally concerned to be the state of the art seismometers, emphasizing the word “art”. These instruments are more like a Stradivarius than an HP. They have a wide bandwidth(120 sec to 50 Hz), and incredible resolution, but they cost a bundle and also have lead times as large as 6 months, as they’re made by one family owned business in Switzerland.

Guralp is another company in the UK that produces broadband seismometers, they compete at the top-of-the line and also have their “affordable” version, which still has great performance and still sells for about $10,000.

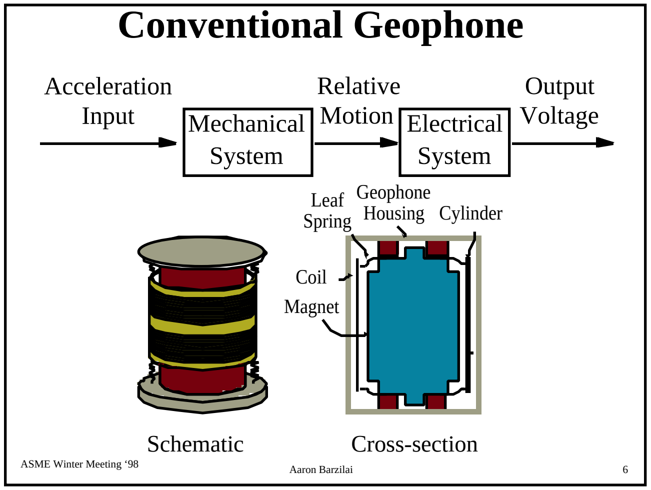
Meanwhile, people studying higher frequency signals typically use a geophone. You can see that commercially available geophones don’t measure low frequency signals, but they do have good resolution and a great price.

Putting this together, it seems that an affordable, broadband seismometer with good but not Streckeisen like performance would meet a need that is not being served by the current instrumentation options.

A New Broadband Seismometer: The Capacitive Geophone

- The existing mechanical system of a geophone provides the basis of the seismometer.
- **Capacitively** measuring coil **displacement** yields excellent low frequency sensitivity and resolution.
- A capacitive geophone can be made for under $200.

We propose to meet this target with a new, capacitive geophone. We’ll use the existing geophone as the basis of of our sensor, and then modify it to measure proof mass displacements capacitively. As we’ll see, this will change the geophone from a high frequency sensor to one that is appropriate for low frequency sensing. Since these are relatively simple changes that will be made, they won’t drastically increase the cost above that of a conventional geophone. The higher end seismometers cost more because they must be large to obtain their excellent resolution. Since we’re targeting a relatively middle-of-the-road performance, we can avoid the costs associated with the specifications of the Streckeisens.



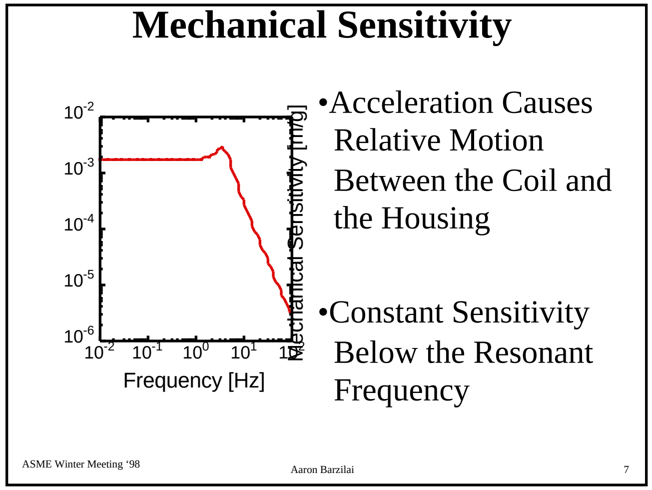
So, let's take a look at how a geophone works and why it is currently used in high frequency applications. I have a sketch of the inside of a geophone and a cross-section. Remember, a geophone is cylindrically symmetrical.

Like all seismometers and accelerometers, a geophone first converts the acceleration it sees into relative motion of its proof mass. In the case of the a geophone, this motion is of a cylinder relative to the geophone's housing. It is couple by leaf springs.

This motion is then detected inductively, by the interaction of a coil of wire on the cylinder with a magnetic field that is stationary inside the geophone.

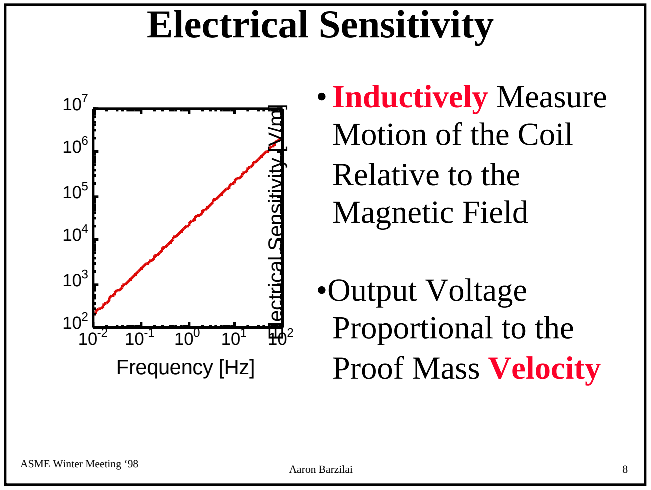
So, the whole sensor shakes, causing relative motion. Then, this relative motion is measured.

Let's take a look in more detail.

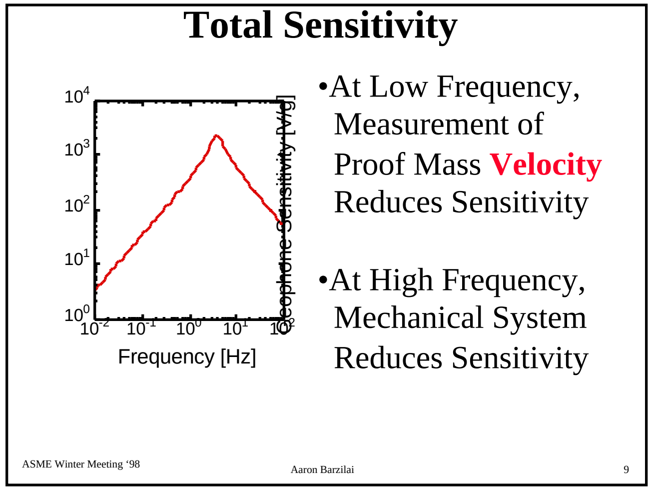


The mechanical system, which converts the input acceleration into relative motion, behaves like a typical second order system. Below the resonant frequency, the sensitivity is constant. Above the resonance, the sensitivity falls off at 40 dB/decade.

Typically, higher order modes appear above 400 Hz and therefore don't affect the response over the frequencies of interest.



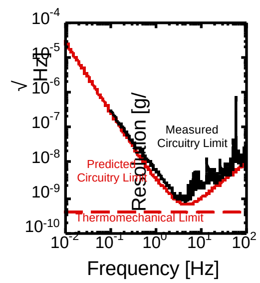
Since the measurement of relative motion is inductive, the output voltage is proportional to proof mass VELOCITY. Therefore, the electrical sensitivity is large at high frequencies and attenuated at low frequencies.



As a result, at low frequencies the cylinder is undergoing large motions, but the electrical system does not measure them well. At higher frequencies, the electrical sensitivity is great but the mechanical system reduces the sensitivity.

Conventional Geophone Resolution

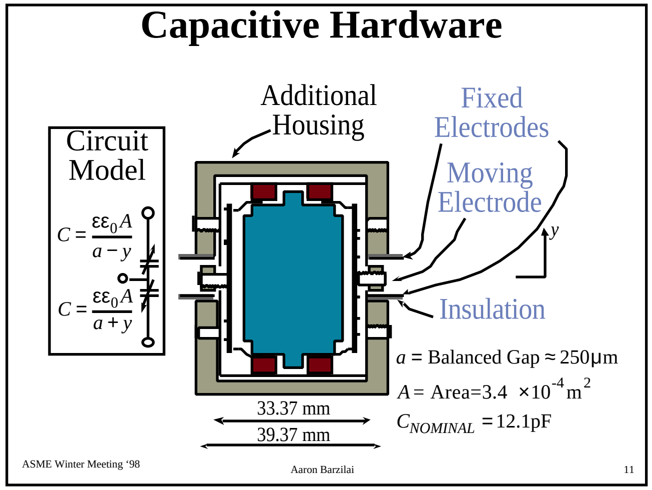
$$\text{Resolution}\left[\frac{g}{\sqrt{Hz}}\right] = \frac{\text{Noise}\left[\frac{V}{\sqrt{Hz}}\right]}{\text{Sensitivity}\left[\frac{V}{g}\right]}$$



- **Poor resolution at low frequency** is caused by reduced sensitivity.

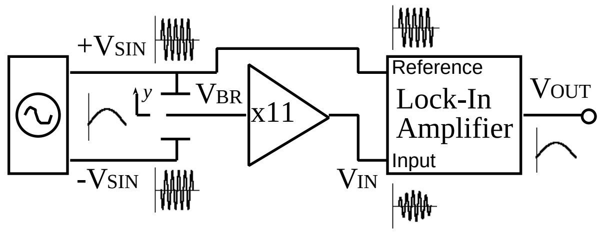
As you probably know, the resolution is given by the noise over the sensitivity. In a geophone, the reduced sensitivity at low frequencies worsens the resolution. This is combined with 1/f noise in the electronics to produce a very steep slope below the resonance. The resolution drops off more slowly at high frequency because it is only affected by the decreasing sensitivity at high frequency. Thus, you can measure signals further from the resonance at the high end. This has led to geophone use for high frequency measurements, but the poor resolution at low frequency prevents its use as a broadband seismometer.

As I said earlier, though, the problems at low frequency arise because of the inductive velocity measurement. By switching to a capacitive, displacement measurement of the relative motion, we can have constant sensitivity at low frequency, which will improve the geophone's low frequency resolution.



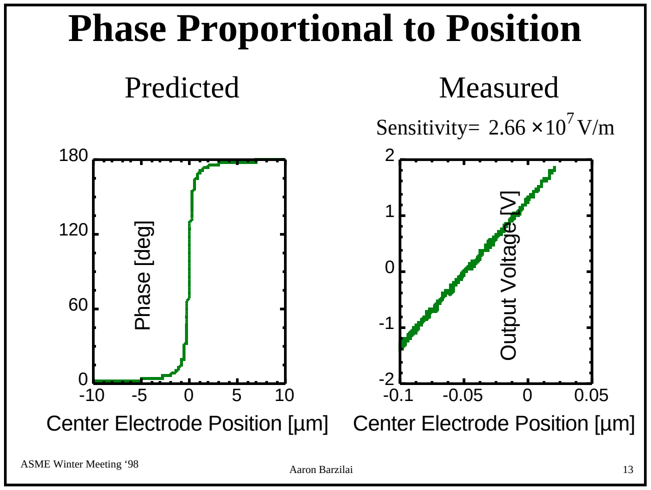
To make a capacitive measurement, we'd like to form a differential pair of capacitors as shown on the left. To do so, we have added a bit of hardware on the outside of a commercial geophone. We place a cylinder on the top and bottom of the housing, and attach two rings which will form the fixed electrodes in our circuit. Then, we attach another ring directly to the proof mass, the cylinder inside the geophone. This ring is clamped by tightening some screws. Now, as the cylinder moves, the gaps will vary. In general, we want the gaps balanced for maximum sensitivity, and typically the gaps are about 250 μm, leading to capacitances of order 10 pF. The stray capacitance is of order 0.1pF.

Capacitive Electrical System



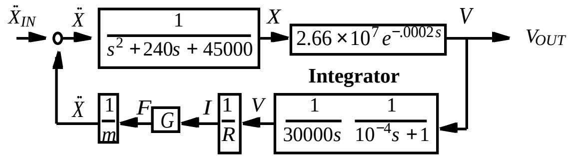
- V_{BR} is a sine wave at the drive frequency with amplitude and phase modulated by *y*.
- A Lock-In Amplifier demodulates V_{BR} and outputs the amplitude and phase of the signal.

To measure the motion, we apply sine waves approximately 180 degrees out of phase from each other to the fixed electrodes. The motion of the proof mass causes a modulated version of the driving sine wave to appear on the center electrode. This signal and the driving sine wave is fed into a Lock-In amplifier, which outputs the amplitude and phase of the signal at the center electrode.



It turns out the phase is the signal we're most interested in. You can see the relationship is non-linear, with the highest sensitivity occurring when the gaps are balanced. Our experiments have shown that in practice we obtain very high sensitivity of about 25 MV/m of 25 V/µm, and that in the center the relationship is approximately linear.

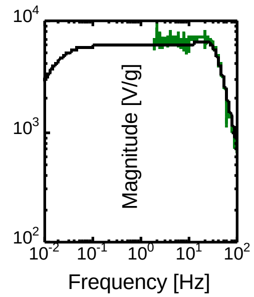
Operate with Integral Feedback



- Integral feedback applies forces at frequencies below the range of interest to keep the coil centered and the gaps balanced.

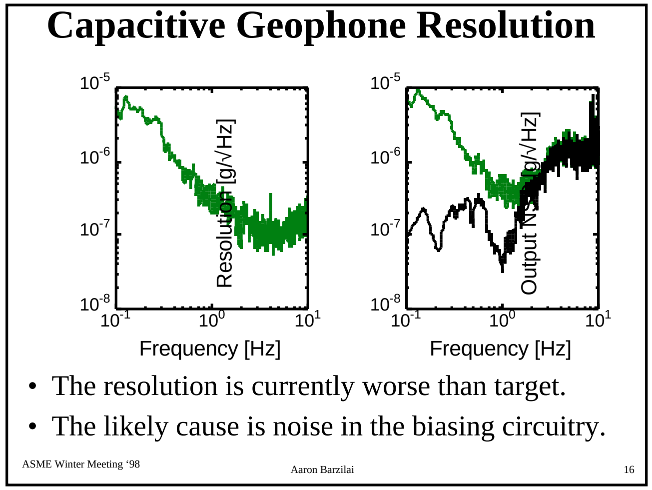
To stay in the operating range with maximum sensitivity, we need to keep the capacitive gaps balanced. This is achieved by operating with integral feedback, which will apply forces at very low frequency. Signals in the frequency range of interested are virtually unaffected by feedback. The feedback force is applied by running current through the coil. Therefore, we are using the sensing element of a conventional geophone as the actuator in the capacitive geophone.

Sensitivity with Integral Feedback



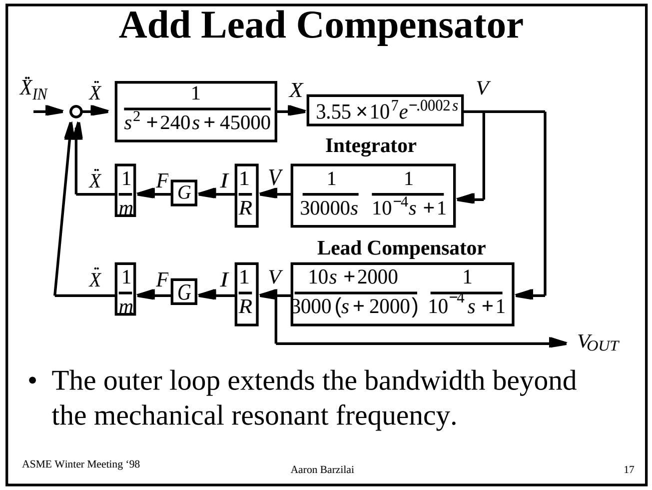
- **Constant Sensitivity At Low Frequency** since Output is Proportional to Proof Mass **Displacement**
- Attenuation at very Low Frequencies caused by Integral Control

In theory, operating with integral feedback will yield constant sensitivity at low frequencies and a 40 dB/decade attenuation above the mechanical resonant frequency. At very low frequencies the control forces attenuate the motion, yielding the low frequency rolloff. This model has been tested by experimentally measuring the sensitivity of an operating capacitive geophone. We had difficulty obtaining data at periods of 10 sec and 50 sec because of the large motions involved in exciting the geophone. We are currently working on methods to obtain valid low frequency sensitivity data.

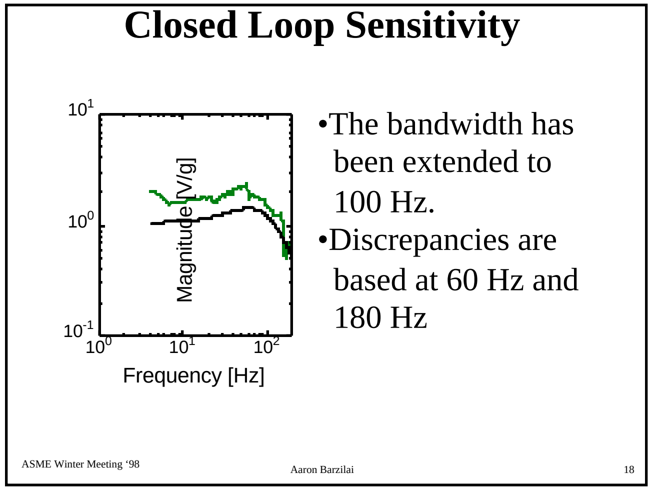


We have also measured the resolution of our capacitive geophone. Currently, it is good but not great, and above the predicted level of 100ng/√Hz. The data was obtained by comparing the capacitive geophone's output(green) to the output of a Guralp CMG-40T(black). At frequencies above 2 Hz, the two sensors measured the same signal. Below 2 Hz, the Guralp is presumably measuring actual signals while the capacitive geophone's output is sensor noise.

We believe the diminished resolution results from noise in the integral feedback circuitry. Currently we are investigating how to reduce this noise and therefore improve the resolution.



Thus far, we have measured the sensitivity and resolution of our capacitive geophone with integral feedback. The story could be done, expect that now the frequency range is limited at the high end by the resonance of the mechanical system. Since conventional geophones are typically used at frequencies well above their resonance, we have added a lead controller to extend the bandwidth.



For our present controller, the model predicts a high frequency rolloff at 100 Hz. Our data seems to match this prediction, but there are some discrepancies. First, we have a constant error in our predicted sensitivity. Secondly, at 60 Hz and 180 Hz there are discrete jumps in the sensitivity. We believe this result is promising, but measurement errors are causing the discrepancies. We will continue to study this until our experimental results match our prediction.

Conclusions

- Modifying a geophone into a capacitive sensor leads to an affordable, broadband seismometer.
- A capacitive geophone has been fabricated based on a 40 Hz geophone.
- Current results are promising, but more testing needs to be performed.
- Future goals include obtaining resolution at the fundamental limits, implementing the modifications on a 4.5 Hz geophone, and measuring phase without a Lock-In amplifier.

In conclusion, I want to emphasize a few major points. First, we have shown how modify a geophone so it can be an affordable, broadband seismometer. We have built and tested such a device. Currently we have not attained our predicted performance, so more work remains. In addition to maximizing the performance we obtain with a capacitive geophone based on a 40 Hz geophone, we are interested in implementing these changes on a 4.5 Hz geophone to obtain better sensitivity and resolution. Additionally we plan on developing a small phase measuring circuit to replace the Lock-In amplifier. These changes should lead to a small, affordable capacitive geophone prototype that could be used in the field.

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