Improved Low Frequency Performance of a Geophone

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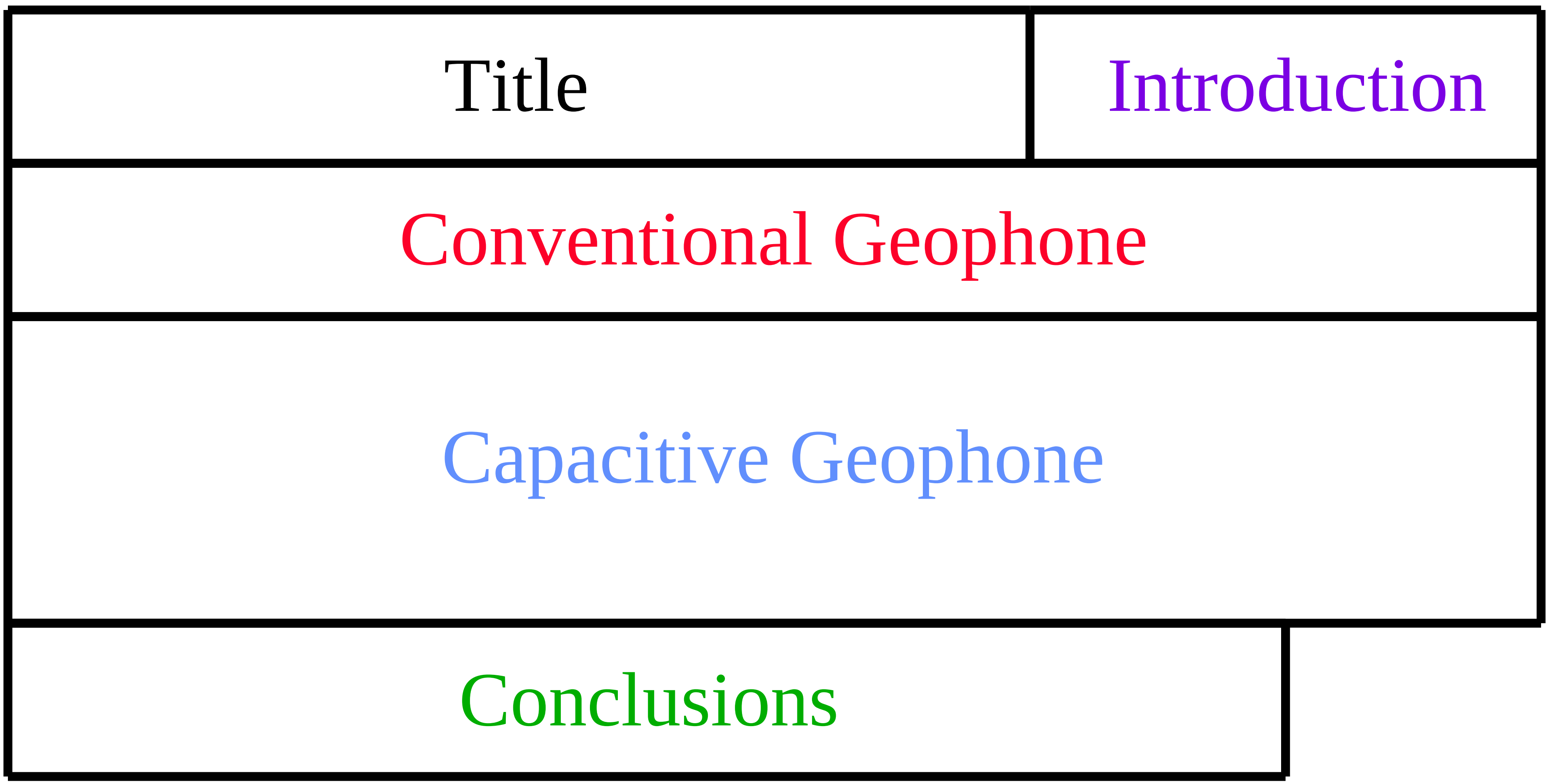
Poster Map

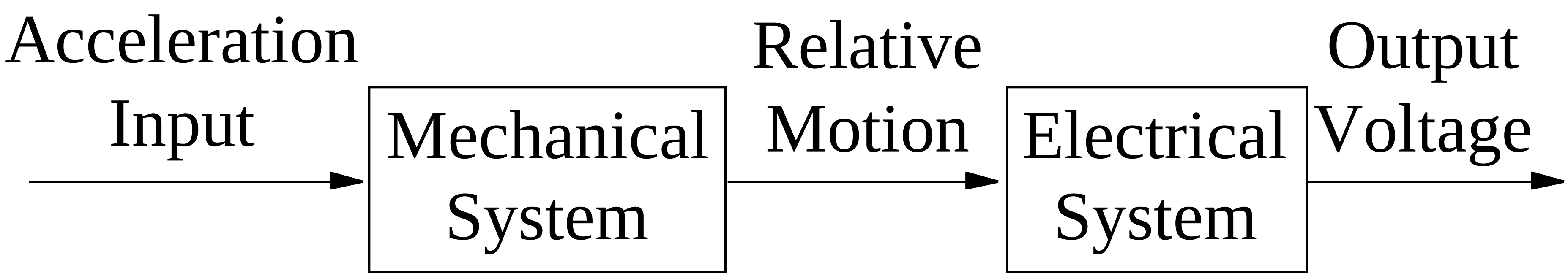

Title
Introduction
Conventional Geophone
Capacitive Geophone
Conclusions

Objective

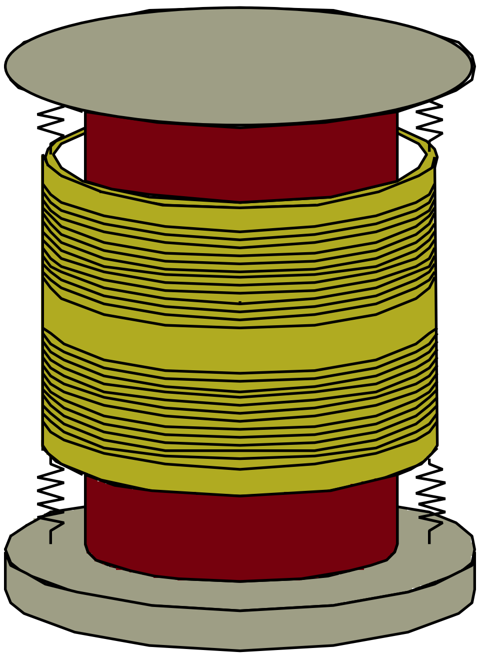
- Develop an Affordable, Robust Broadband Seismometer with Resolution Comparable to the Earth's Seismic Noise

- Enhance the Ability of Seismometer Arrays to Detect Low Frequency Signals

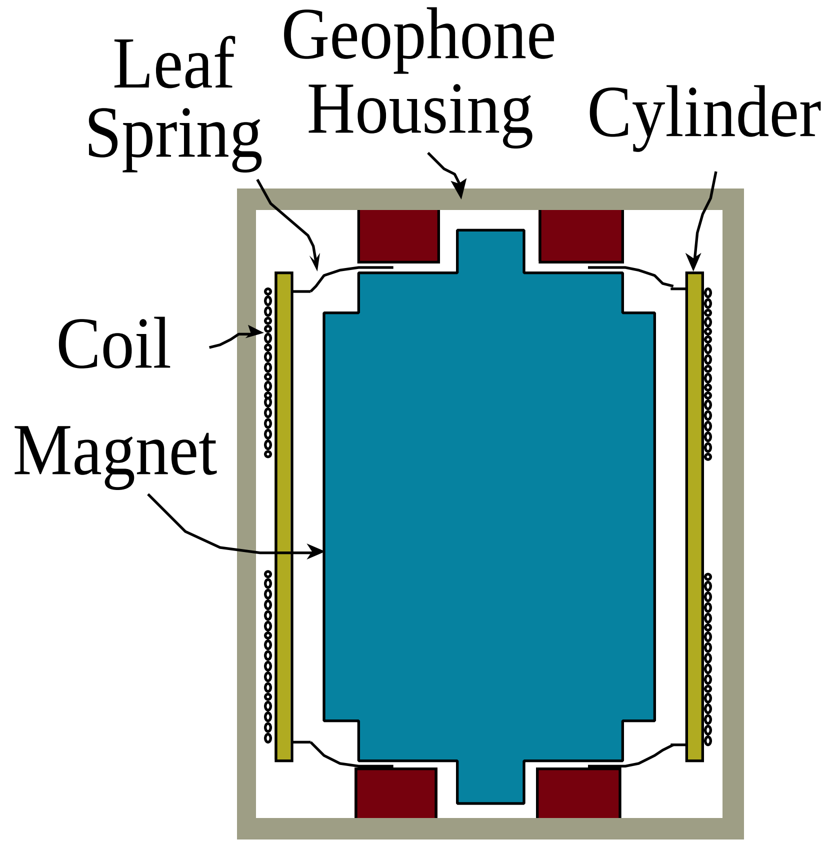
Seismometer Information Flow



A Conventional Geophone: OYO Geospace 4.5 Hz GS-11D

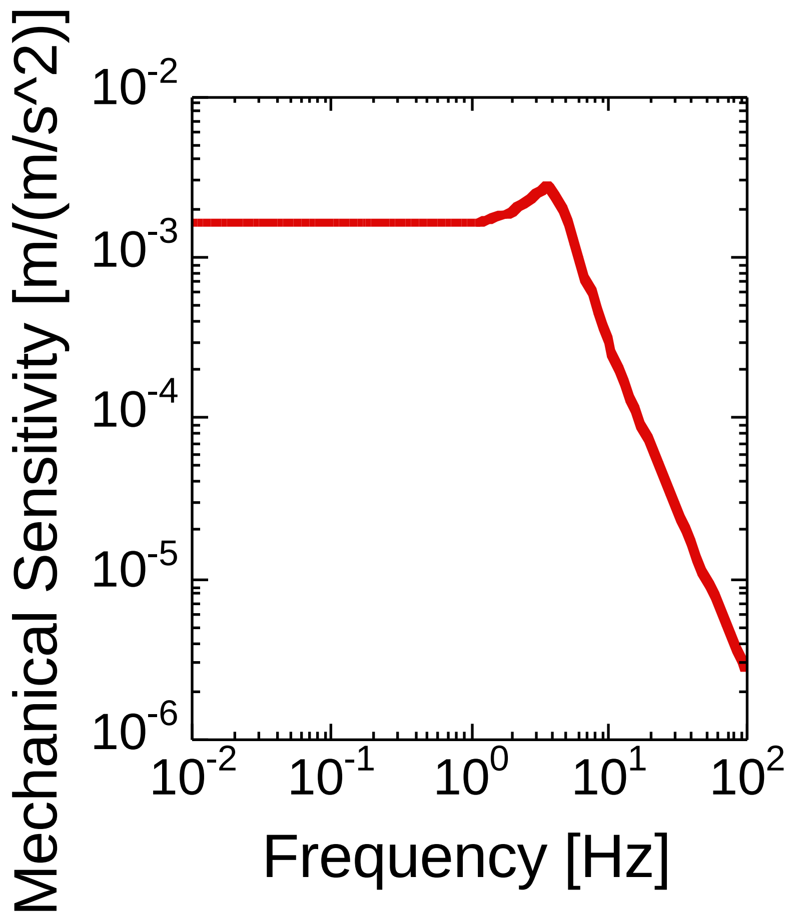


Schematic



Cross-section

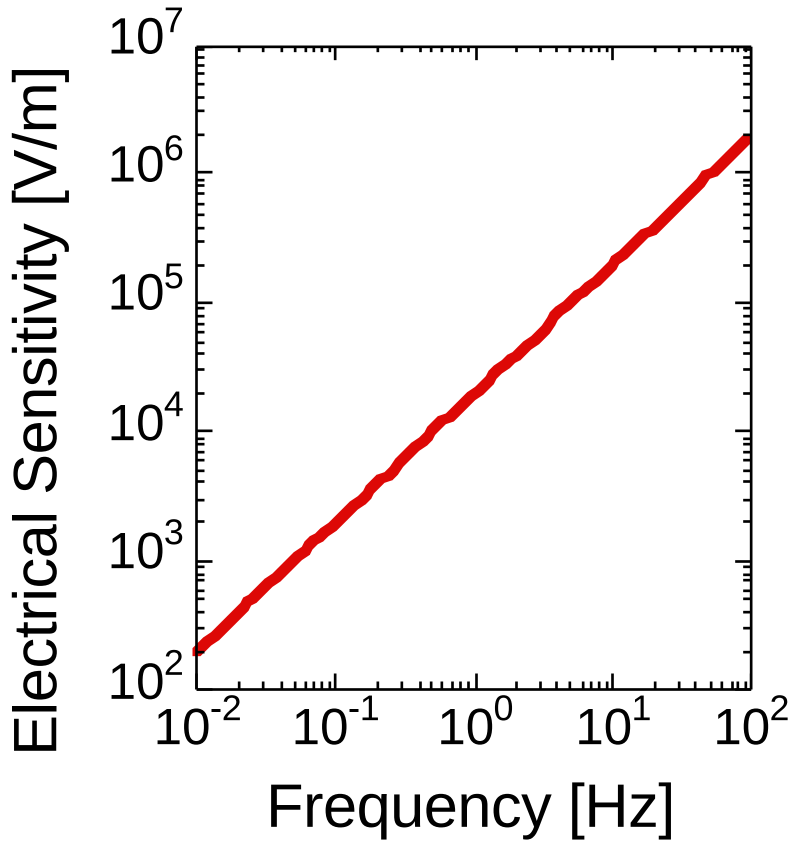
Mechanical Sensitivity



- Acceleration Causes Relative Motion Between the Coil and the Housing

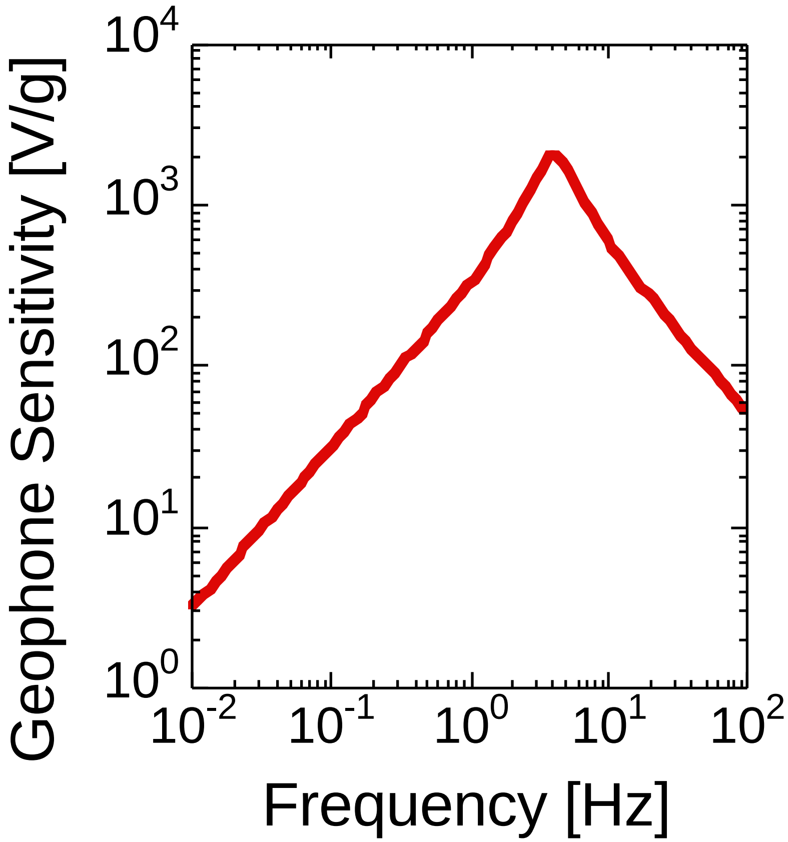
- Constant Sensitivity Below the Resonant Frequency

Electrical Sensitivity



- **Inductively** Measure Motion of the Coil Relative to the Magnetic Field
- Output Voltage Proportional to the Proof Mass **Velocity**

Total Sensitivity

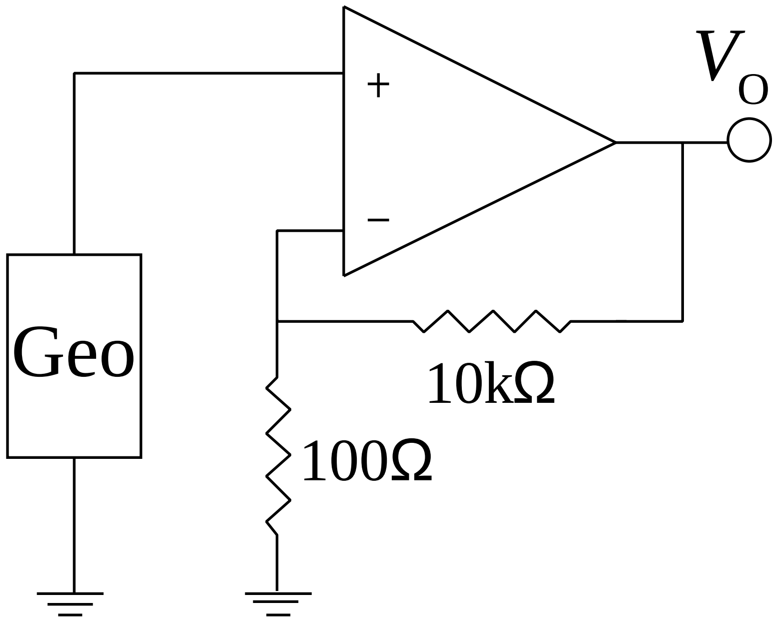


- At Low Frequency, Measurement of Proof Mass **Velocity** Reduces Sensitivity

- At High Frequency, Mechanical System Reduces Sensitivity

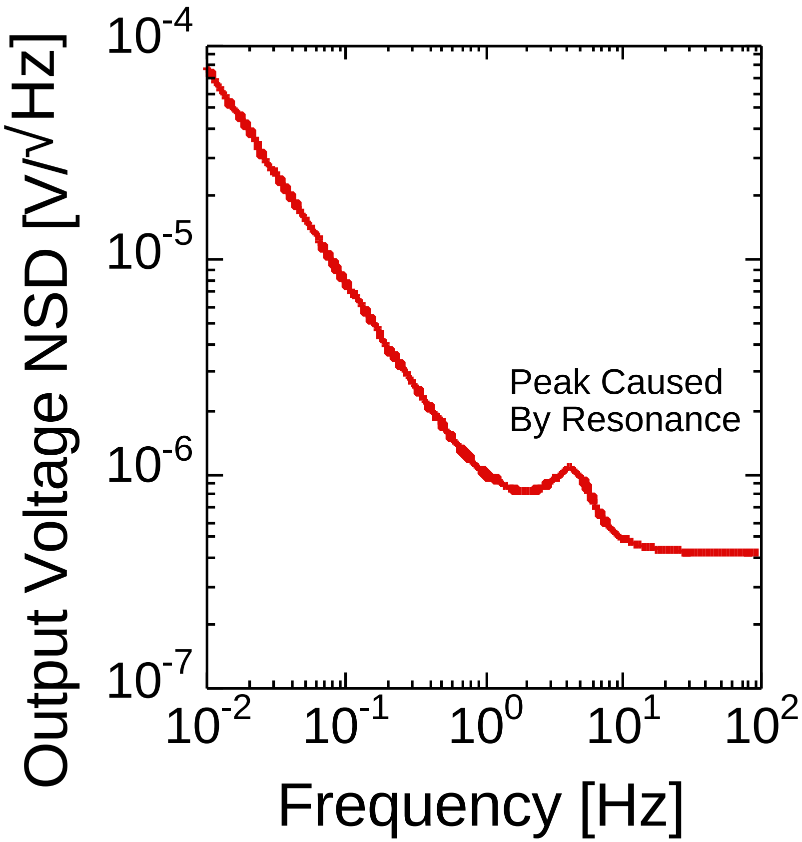
Circuitry Noise

Typical Circuit



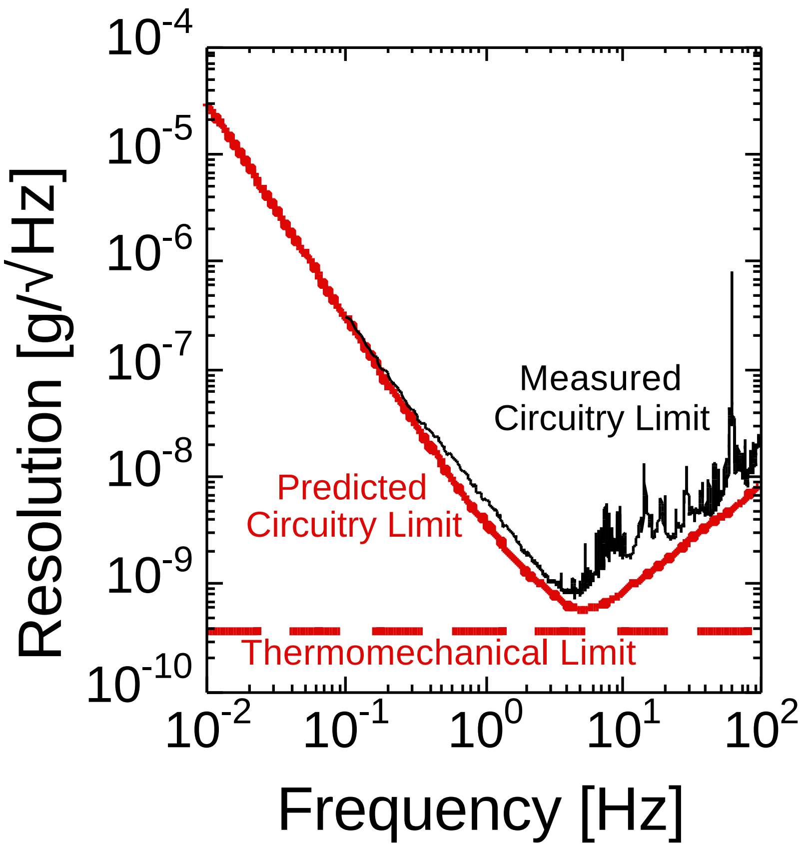
100x Ampifier

Output Voltage Noise Spectral Density



Conventional Geophone Resolution

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



- **Poorer Resolution at Low Frequency** caused by Reduced Sensitivity
- Resolution worse than Fundamental Limit

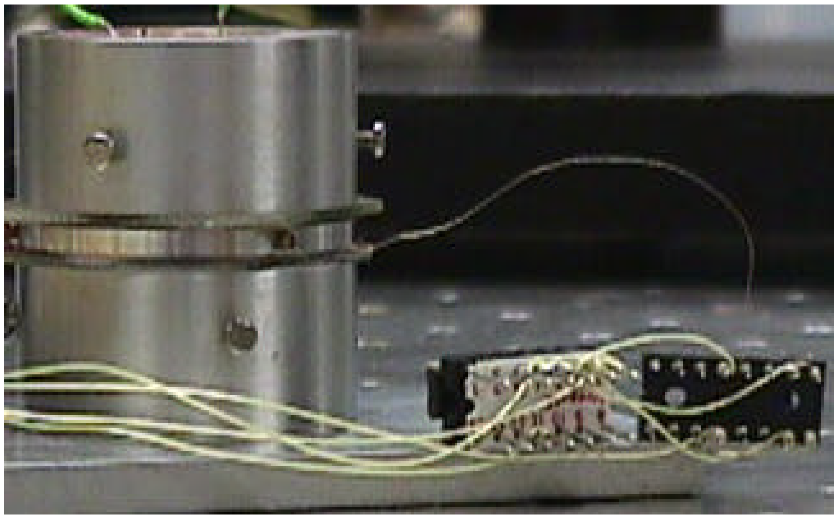
Reference: Barzilai et al., "Technique for Measurement of the Noise of a Sensor in the Presence of Large Background Signals," Rev. Sci. Instrum., Accepted for Publication

An Improved Seismometer: A Capacitive Geophone

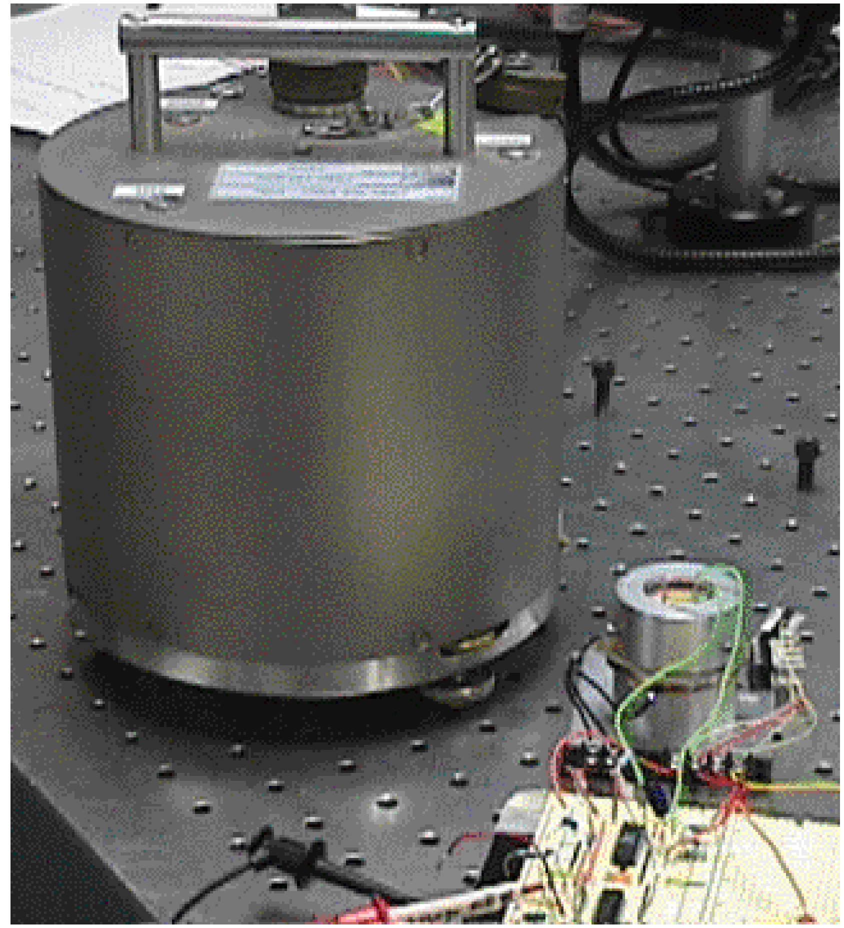
- Use a Commercial, Off The Shelf Geophone as the Mechanical System

- Improve Low Frequency Sensitivity by **Capacitively** Measuring Proof Mass **Displacement** with only Simple, External Modifications

Photos

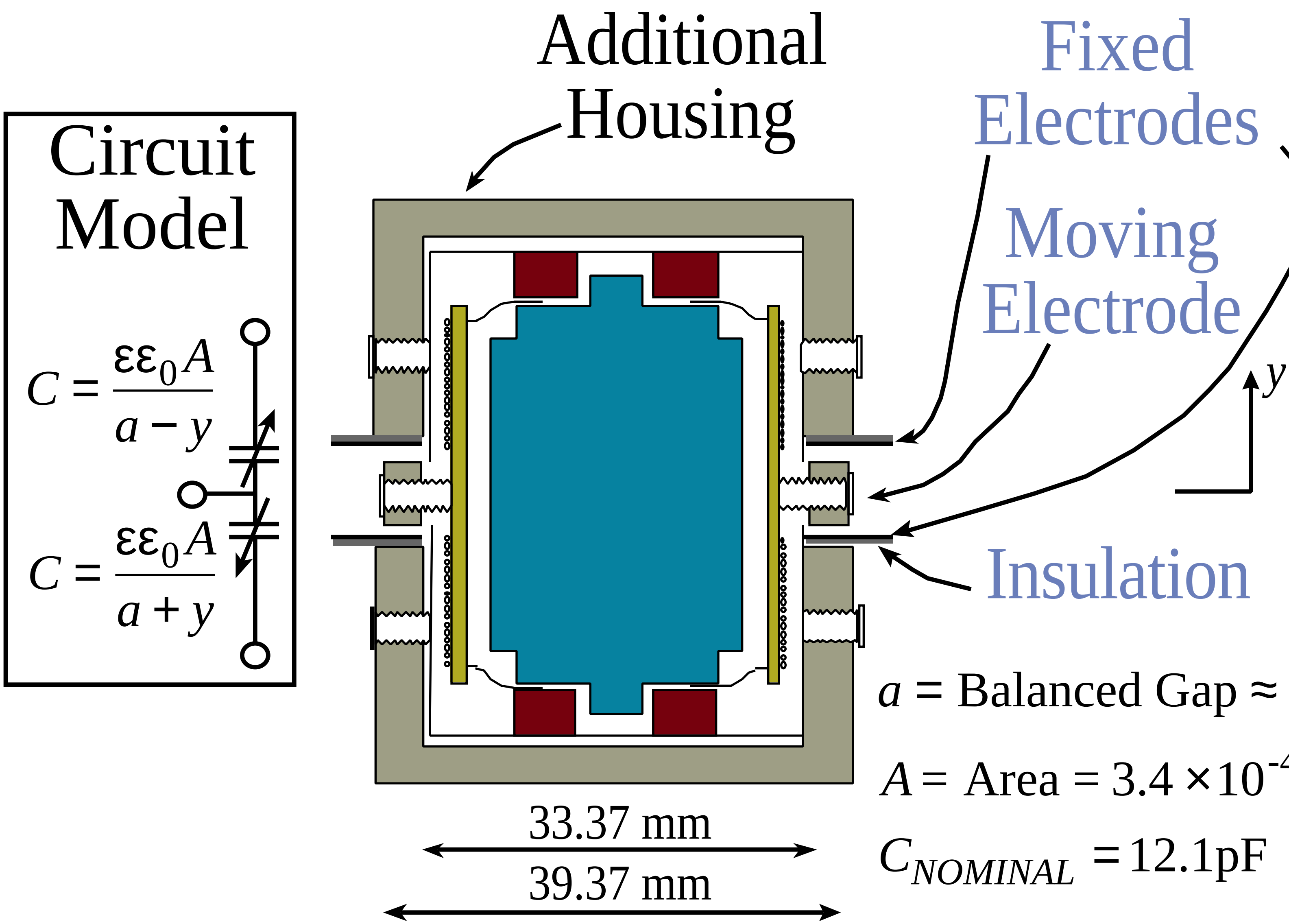


Capacitive Geophone



Guralp CMG-40T and Capacitive Geophone

Capacitive Hardware

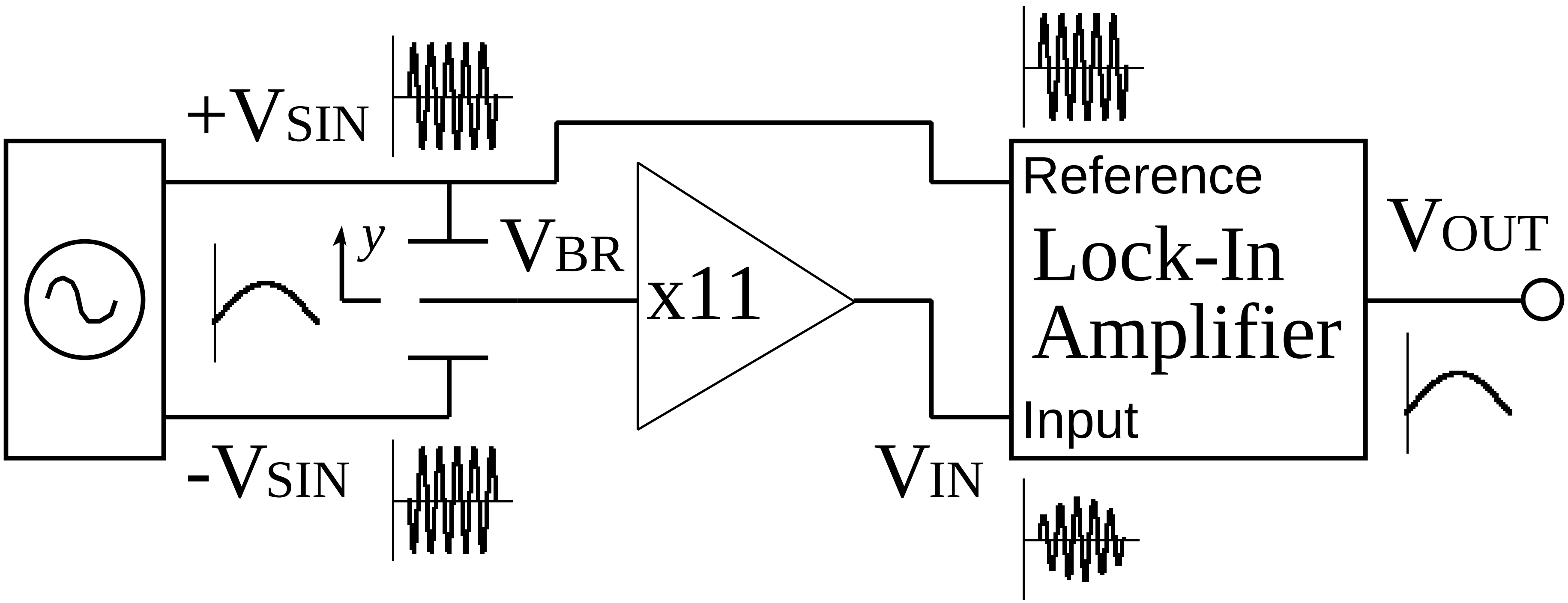


a = Balanced Gap ≈ 250μm

A = Area = $3.4 \times 10^{-4}\,\text{m}^2$

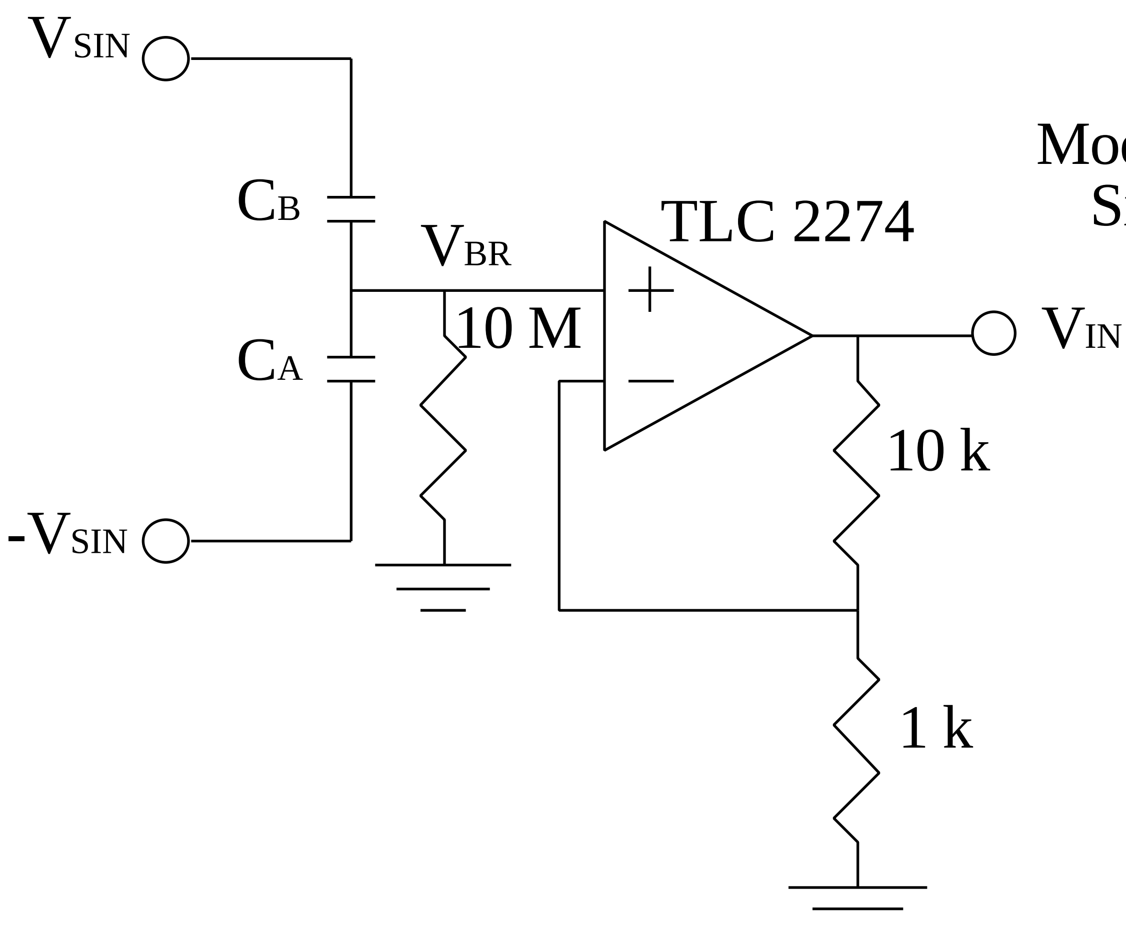
$C_{NOMINAL} = 12.1\text{pF}$

Electrical System Overview



V_{BR} is a Sine Wave at the Same Frequency as V_{SIN} with Amplitude Modulated by *y*. The Lock-In Amplifier Demodulates the Signal to Produce an Output that is Proportional to the **Displacement** of the Proof Mass.

Preamplifier Circuit



Modulated Signal

$$f_{SIN} = 100\text{kHz}$$

$$V_{SIN} = 3.8\text{V}_{pk}$$

$$f_c = \frac{1}{2\pi RC} \approx 600\text{Hz}$$

Preamplifier Circuit Sensitivity

Exact Solution: Voltage Amplitude is a Linear Function of Displacement

$$V_{IN} = \left(\left[\left(V_{SIN} - \left[-V_{SIN}\right]\right) \frac{\frac{1}{sC_A}}{\frac{1}{sC_A} + \frac{1}{sC_B}} \right] - V_{SIN} \right) \left(1 + \frac{10k\Omega}{1k\Omega} \right)$$

$$V_{IN} = V_{SIN} \left(\frac{sC_B - sC_A}{sC_B + sC_A} \right) (11)$$

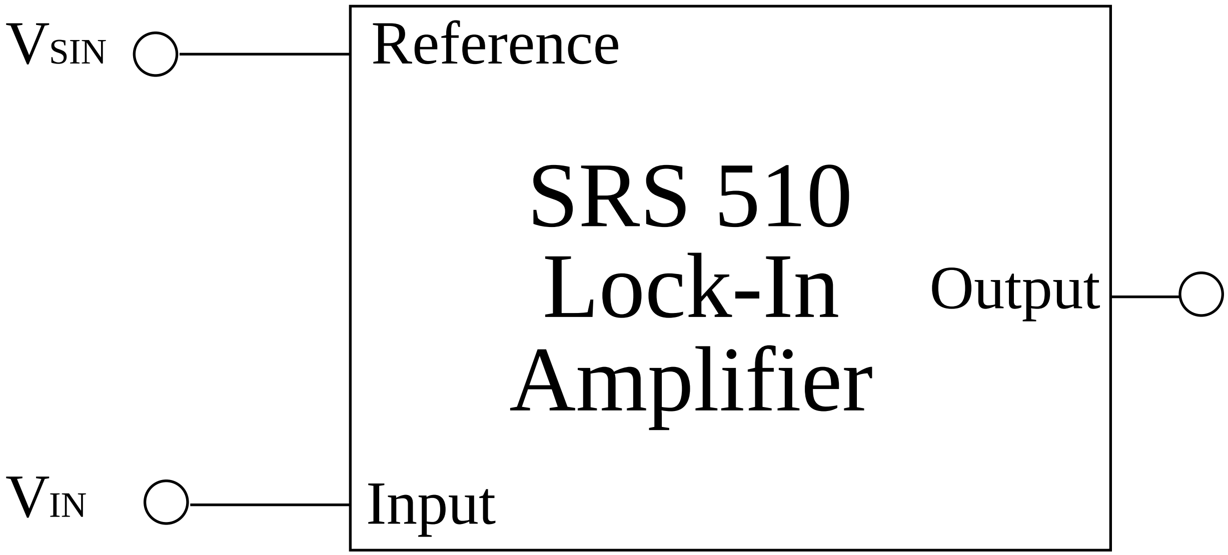
$$V_{IN} = V_{SIN} \left(\frac{\frac{1}{a-y} - \frac{1}{a+y}}{\frac{1}{a-y} + \frac{1}{a+y}} \right) (11)$$

$$V_{IN} = V_{SIN} \frac{y}{a} (11) = 1.7 \times 10^5 \left[\frac{\text{V}}{\text{m}} \right] y[\text{m}]$$

Demodulator

- Demodulator Output is Directly Proportional to the Amplitude of the Input at the Reference Frequency.
- In the Frequency Domain, Low Frequency Amplitude Variations Appear as Signals Near the Reference Frequency. The Demodulator Shifts These Signals Back to Low Frequency.

Demodulator Sensitivity

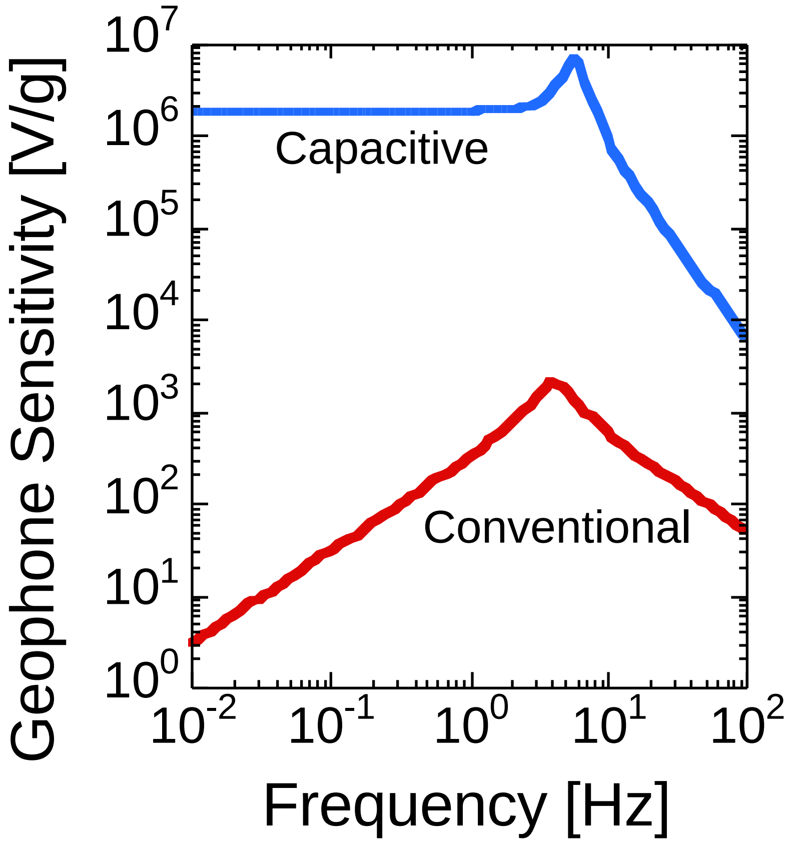


$$V_{OUT} = \frac{10\text{V}}{5\left(10^{-3}\right)\text{V}}\frac{1}{\sqrt{2}}\left|V_{IN}\right|_{pk} = 1414\left|V_{IN}\right|_{pk}$$

Electrical Sensitivity

$$V_{OUT} = (1414)\left(1.7\times10^{5}\left[\frac{\text{V}}{\text{m}}\right]y[\text{m}]\right) = 2.3\left(10^{8}\right)\left[\frac{\text{V}}{\text{m}}\right]y[\text{m}]$$

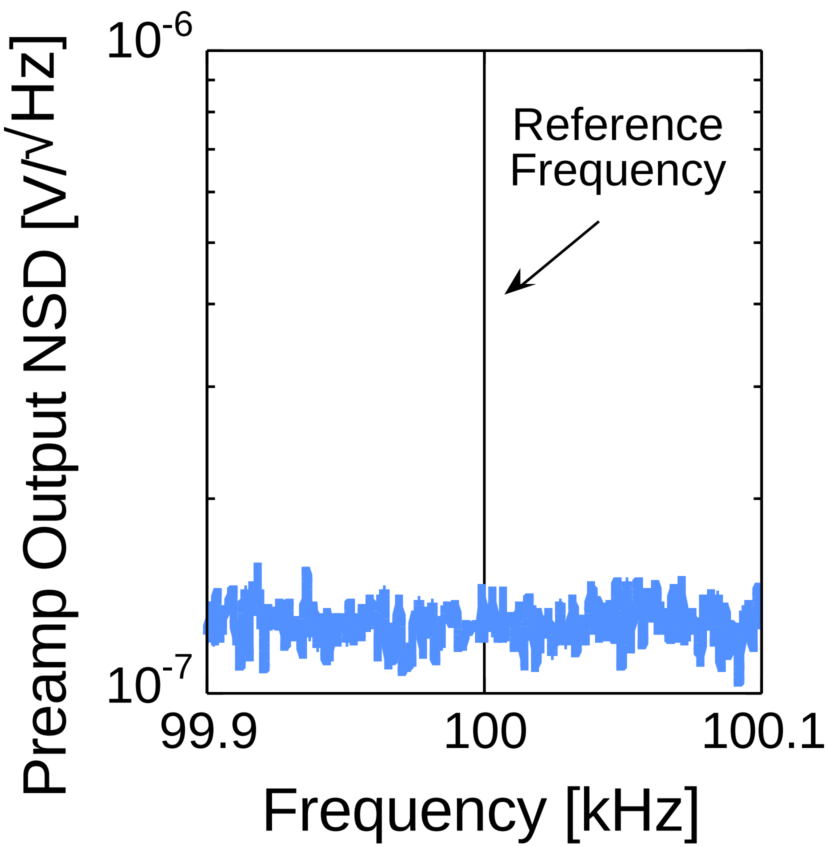
Total Sensitivity



- **Constant Sensitivity At Low Frequency** since Output is Proportional to Proof Mass **Displacement**

Preamplifier Circuitry Noise

Noise Near the Reference Frequency is Mapped to Low Frequencies by Demodulator

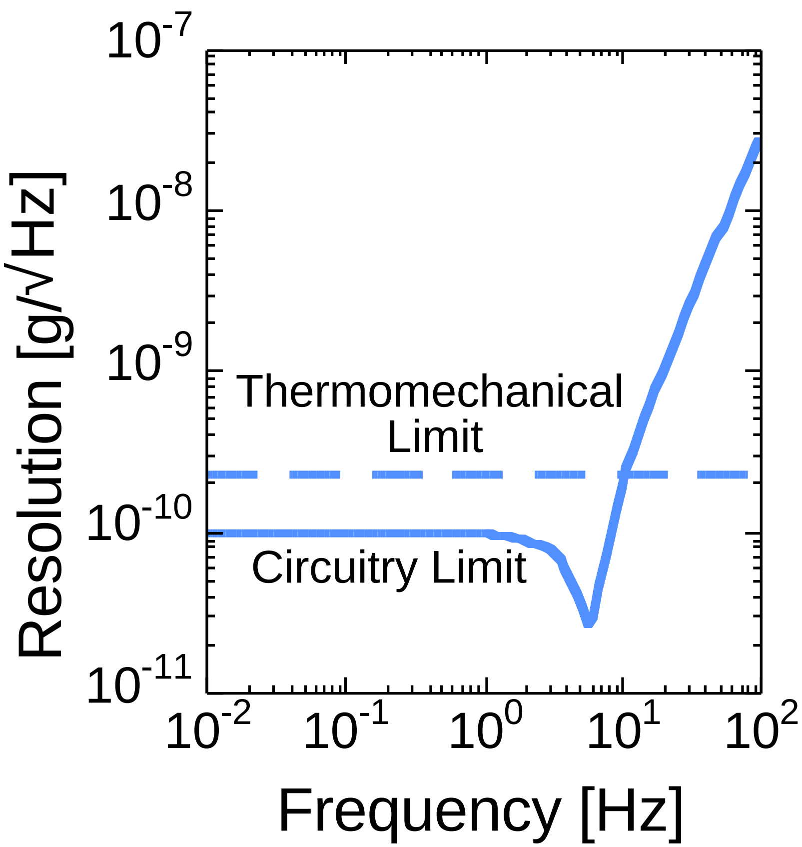


- Noise is Constant Amplitude vs. Frequency

- Lock-In Amplification Produces .18 mV/√Hz Output Voltage NSD at Low Frequencies

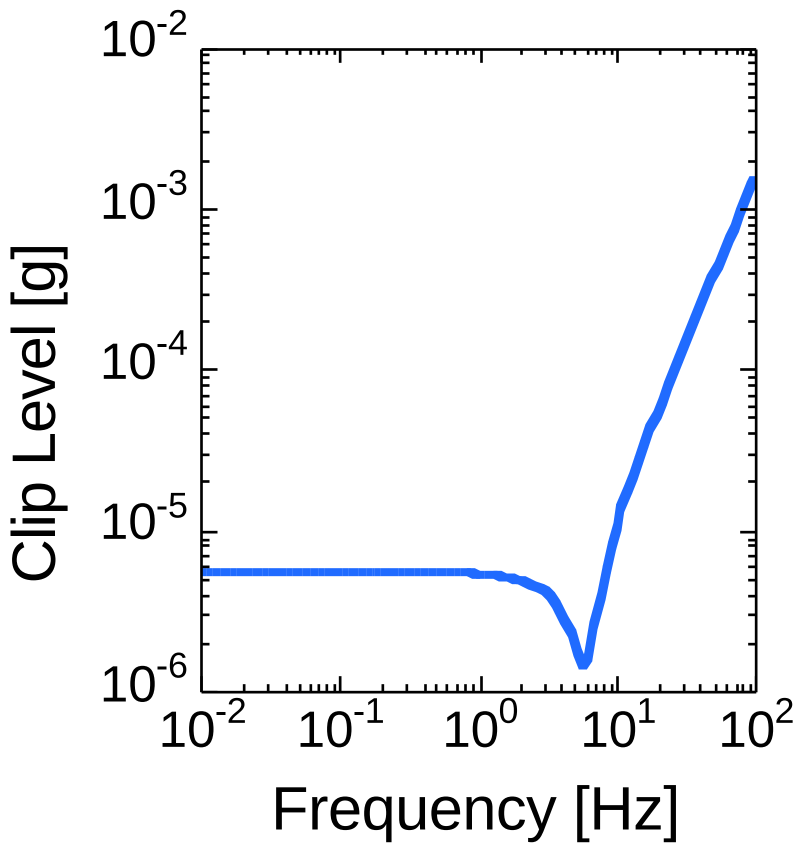
Capacitive Geophone Resolution

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



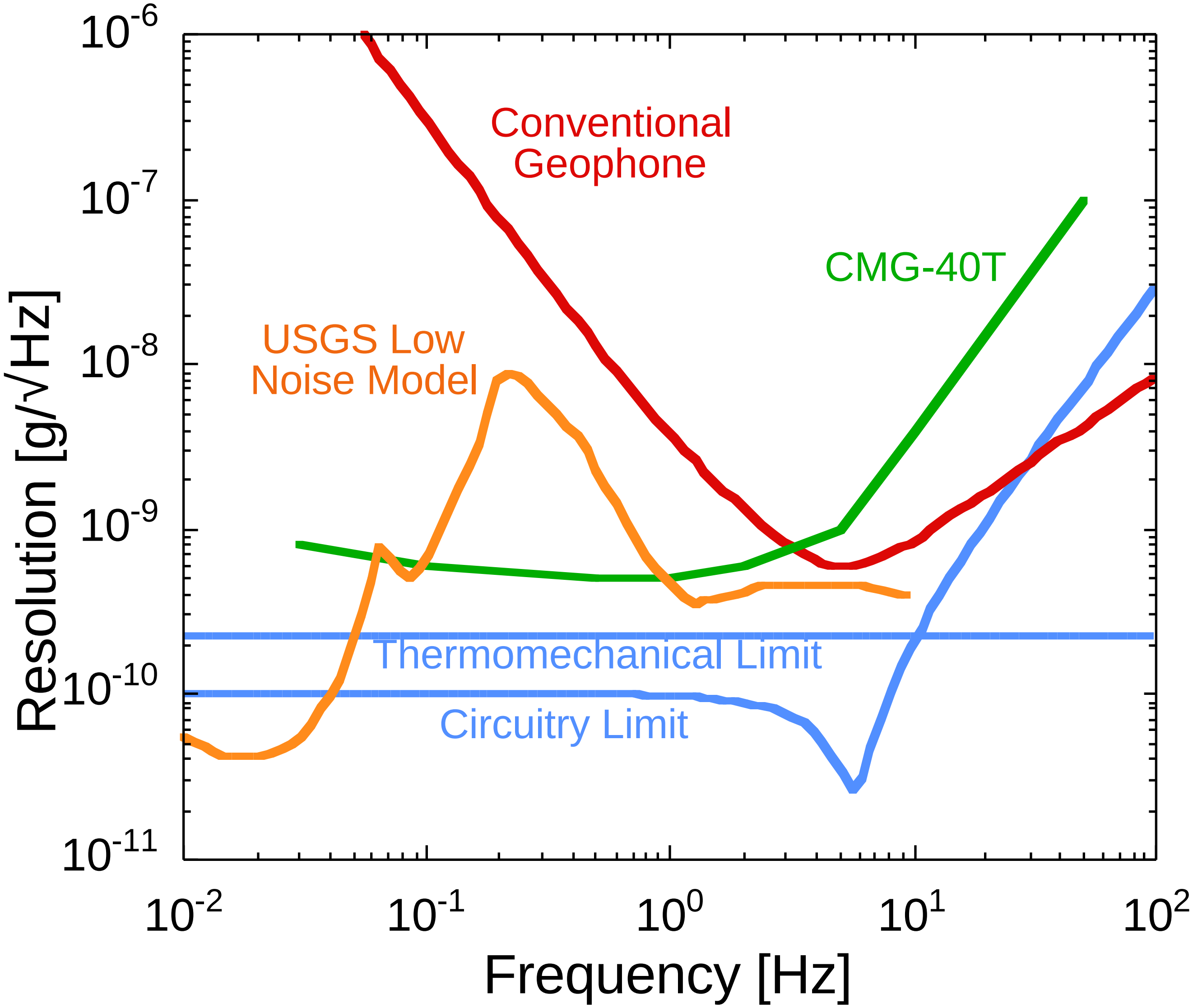
- At Low Frequencies, Resolution is Limited by Thermomechanical Noise, not Circuitry
- **Better Resolution at Low Frequencies** as a Result of Constant Sensitivity

Clip Level



- Demodulator Output Range ±10V
- Corresponds to .040 µm Displacement

Resolution Comparison



USGS LNM:
Seismic Noise
At Quietest
Sites On Earth

Resolution Comparison

- Low Frequency Resolution of a Geophone is Improved by using Capacitive Detection
- Circuitry Noise does not Limit Capacitive Geophone at Low Frequency
- Limits on Resolution of a Capacitive Geophone are Better than the Resolution of a Guralp CMG-40T Broadband Seismometer

Performance Comparison

	Conventional Geophone	Capacitive Geophone	Guralp CMG-40T
Resolution	100 ng/√Hz	.1 ng/√Hz	.5 ng/√Hz
Clip Level	90 mg	5 µg	1 mg
Dynamic Range	120 dB	90 dB	130 dB
Estimated Cost	$50	$500	$10,000

Conclusions

- The Low Frequency Resolution of a Geophone can be Improved by Adding **Capacitive Detection**
- Capacitive Detection Does Not Improve High Frequency Resolution
- Thermomechanical Noise Sets a Resolution Limit ≈ 0.1 n*g*/√Hz on all Geophone Based Seismometers

Future Work

- Experimentally Validate the Predicted Resolution of a Capacitve Geophone
- Reduce Size by Integrating Electronics onto a Single Printed Circuit Board
- Operate as a Closed Loop Sensor to Increase the Dynamic Range and Tune the Frequency Response