SAND2011-0180C

MEMS Seismometer

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Advanced MEMS S&T

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,
for the United States Department of Energy's National Nuclear Security Administration
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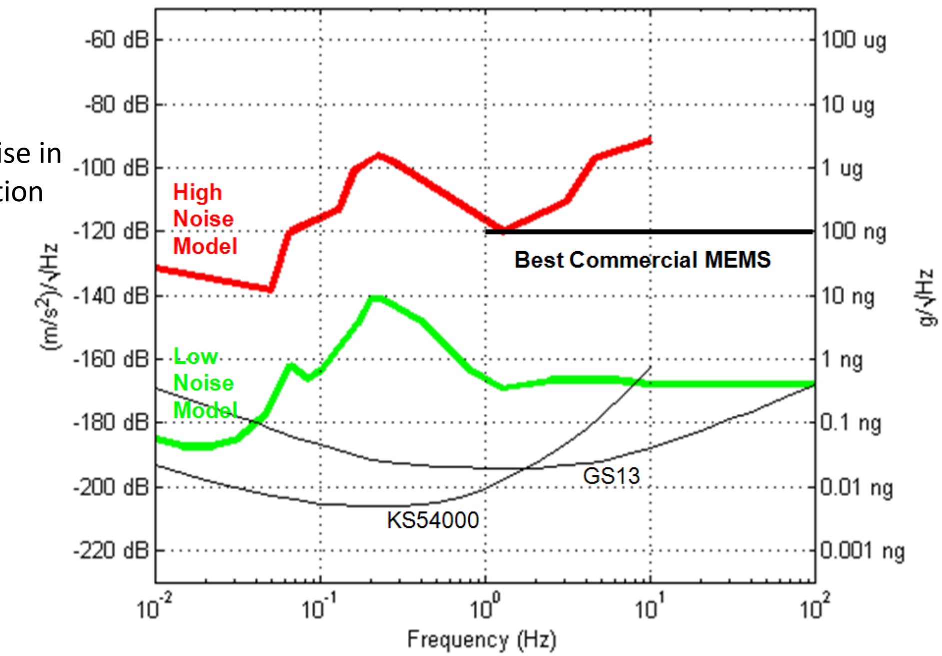
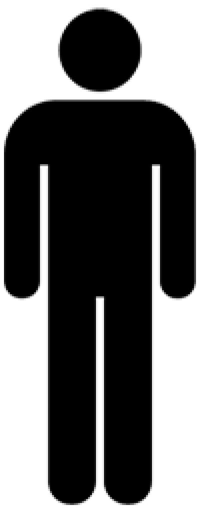
Overview

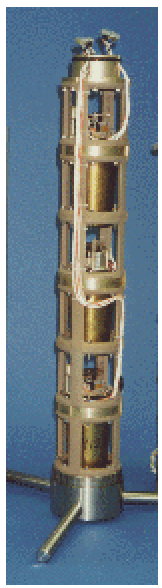
- Seismic instrumentation
- MEMS/microsystems advantages
- Project timeline
  - Prototype 1 (spring/proof-mass)
  - Prototype 2 (+ miniaturized optics and locking mechanism)
  - Prototype 3 (+ force balance feedback)
- Future work

Seismic Instrumentation

Sensor noise in acceleration







Geotech KS54000

3 Channel Borehole Seismometer

Guralp CMG3-TB

3 Channel Borehole Seismometer

Geotech GS13

Single Channel Seismometer

Kinematrics STS-2

3 Channel Seismometer

Geotech S13J

Single Channel Seismometer

Colibrys MEMS

3 channel accelerometer and 24 bit digitizer

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Seismic Instrumentation

- Trends in instrumentation have led to decreases in size and power at the cost of increased noise, lower sensitivity and smaller bandwidth.
- There is a large market for strong-motion sensors (seismic surveys for exploration, earthquake monitoring) - however, the market pull for high sensitivity and small seismometers is - small.

Commercial MEMS Accelerometers

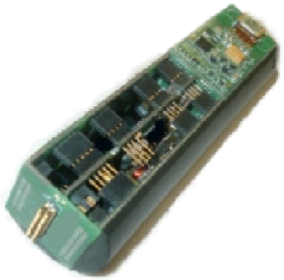
There are many manufacturers of MEMS Accelerometers.

Most are targeted towards consumer, automotive, and industrial applications.

Only a few approach the noise levels necessary for strong-motion seismic applications

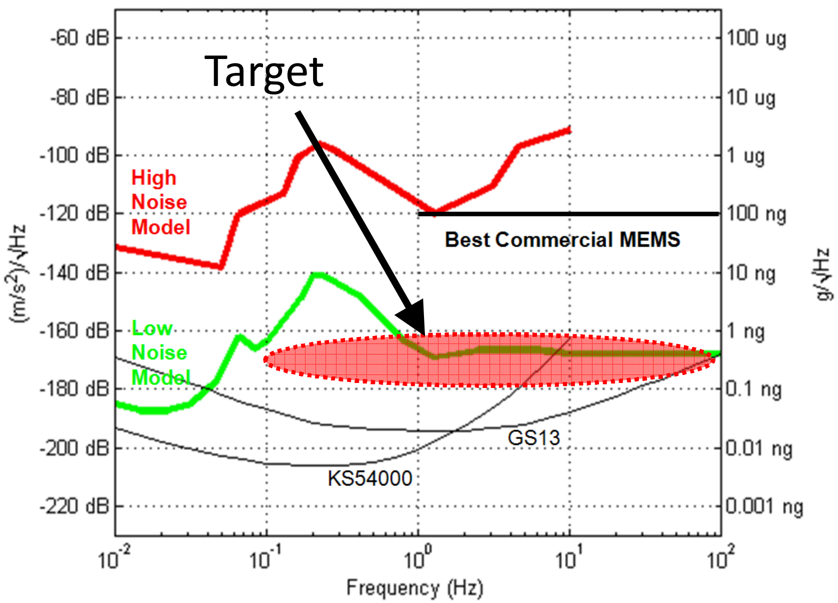
Manufacturers
Analog Devices
Bosch-Sensortec
Colibrys*
Endevco*
Freescale
GeoSIG*
Kinemetrics*
Kionix
MEMSIC
PCB*
Reftek*
Silicon Designs
STMicroelectronics
Summit Instruments
Sercel*
Wilcoxon*

*Noise Floor < 1 ug/√Hz



Sensor Requirements

What are the desired capabilities?



	Strong Motion Seismology	Weak Motion Seismology
Noise	< 1 ug/√Hz	**< 1 ng/√Hz**
Bandwidth	> 1-2 Hz	SP: 0.1 Hz to 10's Hz LP: < 0.01 Hz to 1's Hz BB: 0.01 Hz to 10's Hz
Peak Acceleration	1-2 g's	< 0.25 g
Dynamic Range	~100 dB	>120 dB

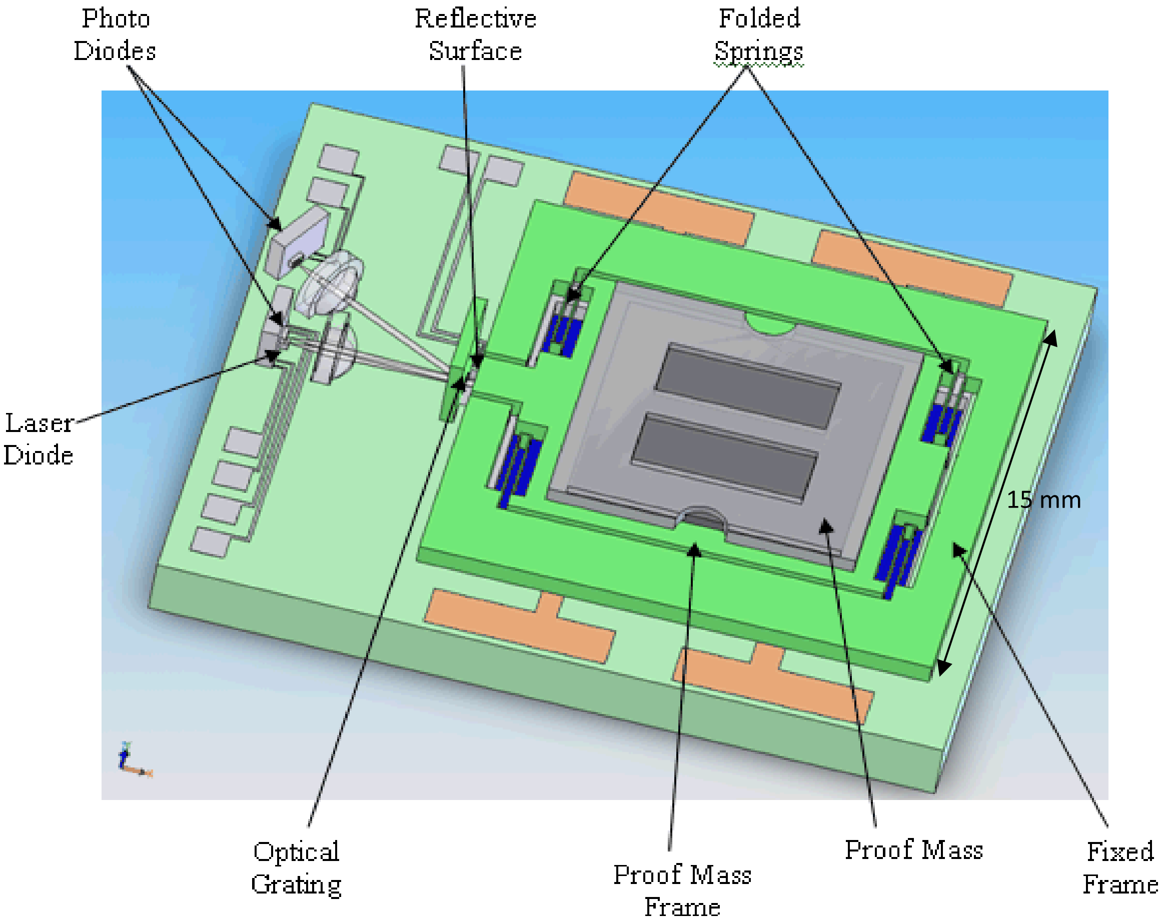
Sensor capability needs

- Self Noise Below Low Noise Model
- Dynamic Range > 120dB
- Frequency Range at least 0.2 -40 Hz
- Power Consumption < 100 mW
- Installation Flexibility
- Low Weight
- Small Size < 1 inch^3
- Robustness
- Stable Response

Microsystems Advantages

- Micromachined silicon provides near-ideal (mechanical Q ~ 10,000), smallest dimension springs.
- Increased proof-mass with tungsten insert (~1 gram).
- Optical interferometric displacement detection ~ 10^{-14} m (10 femtometers)/√Hz (proton cross-section ~ 1 fm).
- Batch fabrication of spring/proof-mass frame.

Sensor Design

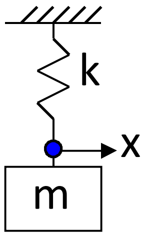


- 1 gram tungsten proof mass supported on folded silicon springs.
- Interferometric motion detection (Michelson interferometer or grating/reflector)
- Feedback control of the proof mass (magnetic).
- Theoretical self-noise of ~0.2 ng/√Hz and dynamic range greater than 120 dB using feedback control. Two primary sources of noise:
  - Mechanical
  - Electronic

Sensitivity/Noise Limits

Two physical limits

Thermomechanical noise
(harmonic oscillator)



$$a_n = \sqrt{\frac{4 k_B T \omega_o}{Q \cdot m}}$$

k_B=1.38x10^{-23} J/K T=300K

ω_o=314.16 rad/s (50Hz) → ω_o=√(k/m)

Q=1000 m=1 gram (10^{-3} kg)

$$\approx 2.3 \times 10^{-9} m/s^2 \sqrt{Hz}$$

(~0.2ng/√Hz)

Displacement detection
(optical-electronic noise)

$$\approx 10^{-14} m/\sqrt{Hz}$$

(measured in earlier projects)

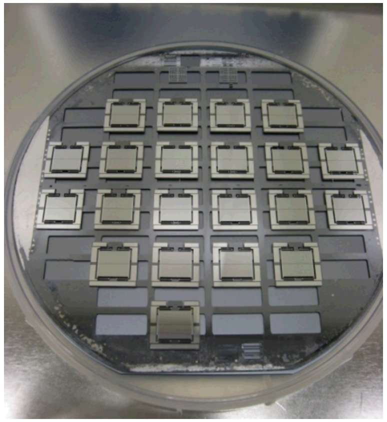
→ k=98.7 N/m

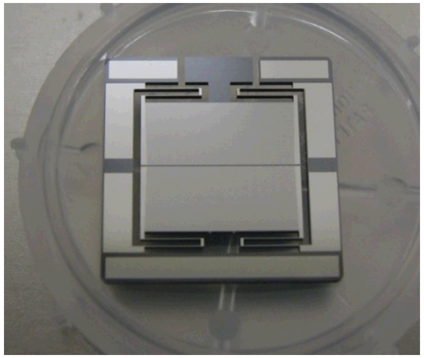
k.x = m.a

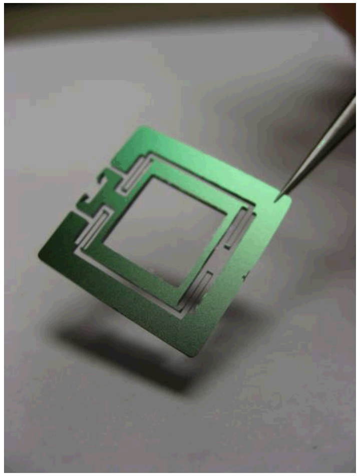
$$\approx 9.8 \times 10^{-11} m/s^2 \sqrt{Hz}$$

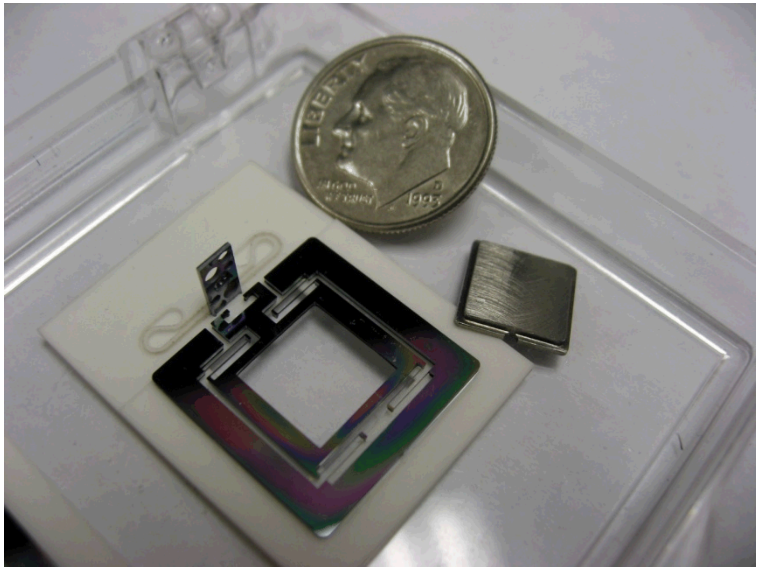
(~0.01ng/√Hz)

Fabricated Components

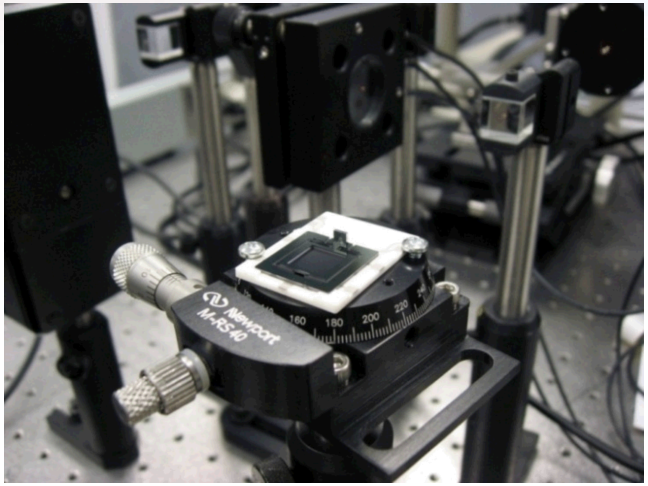




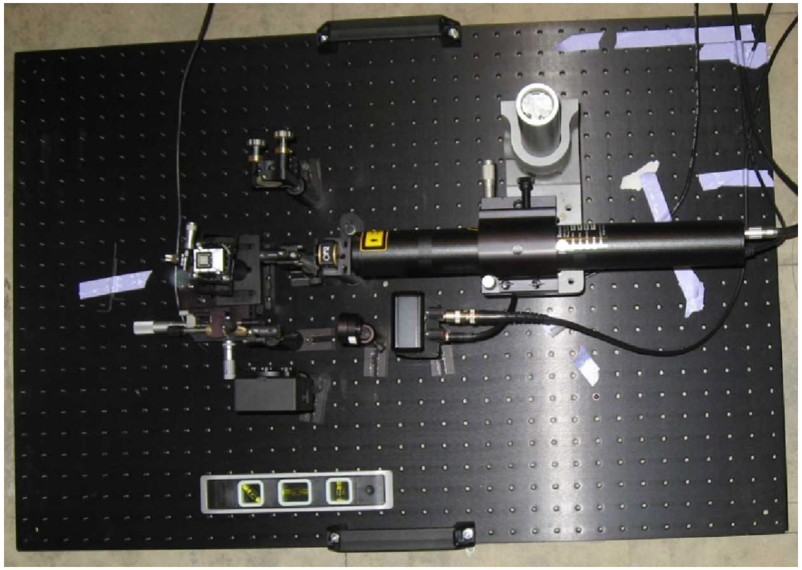


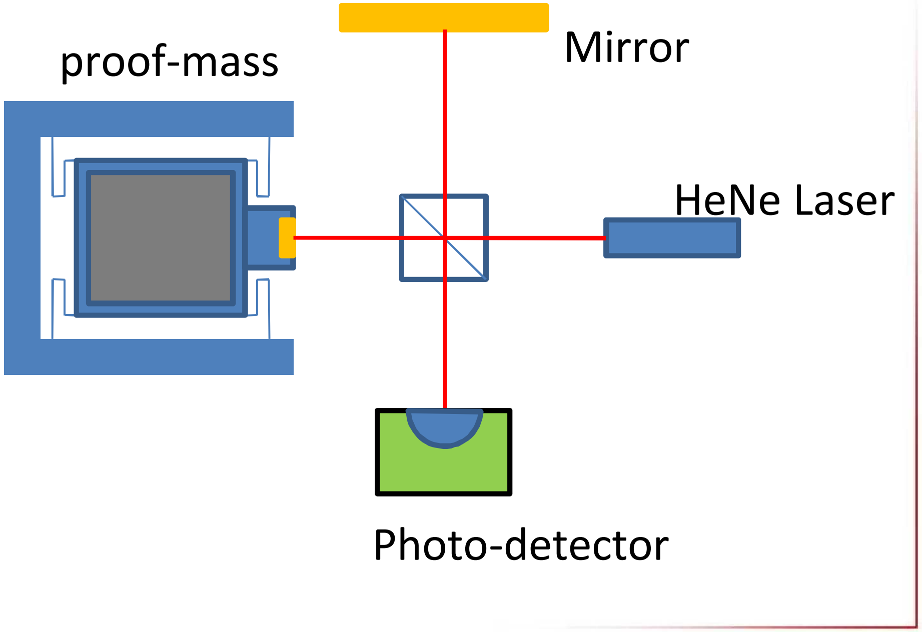


Prototype 1



- Testing functionality of spring/proof-mass frame
- Standard optics breadboard
- Michelson interferometer setup



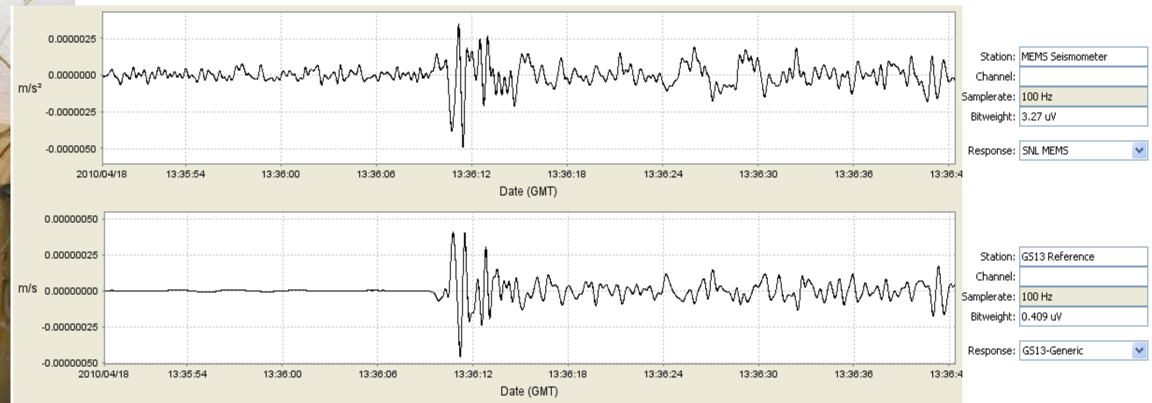


Prototype 1

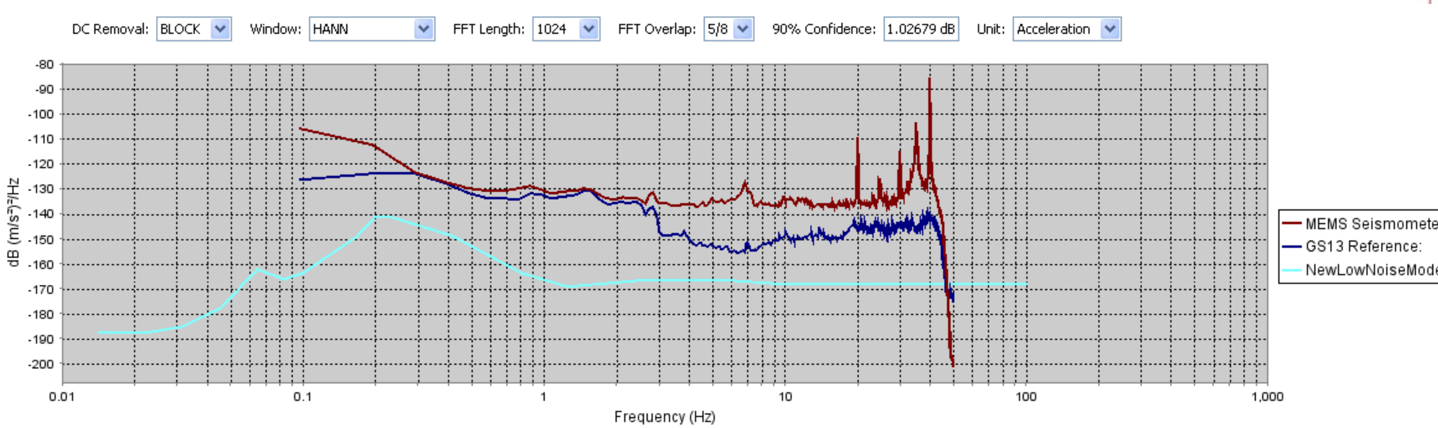
- Conducted lab tests to observe functionality and "quiet" geological test site (USGS ASL) runs to assess sensor noise floor

- Results
  - sensor self noise ~12 ng/√Hz
  - sensitivity 1200 $V/m/s^2$
  - electronic noise ~ 0.1ng/ √Hz

Prototype 1



Time series of the recorded seismic signal. Note that the MEMS Seismometer is shown in acceleration and the reference sensor is shown in velocity.



Sensitivity: ~1200 V/m/s^2

Self Noise ~12 ng/√Hz.

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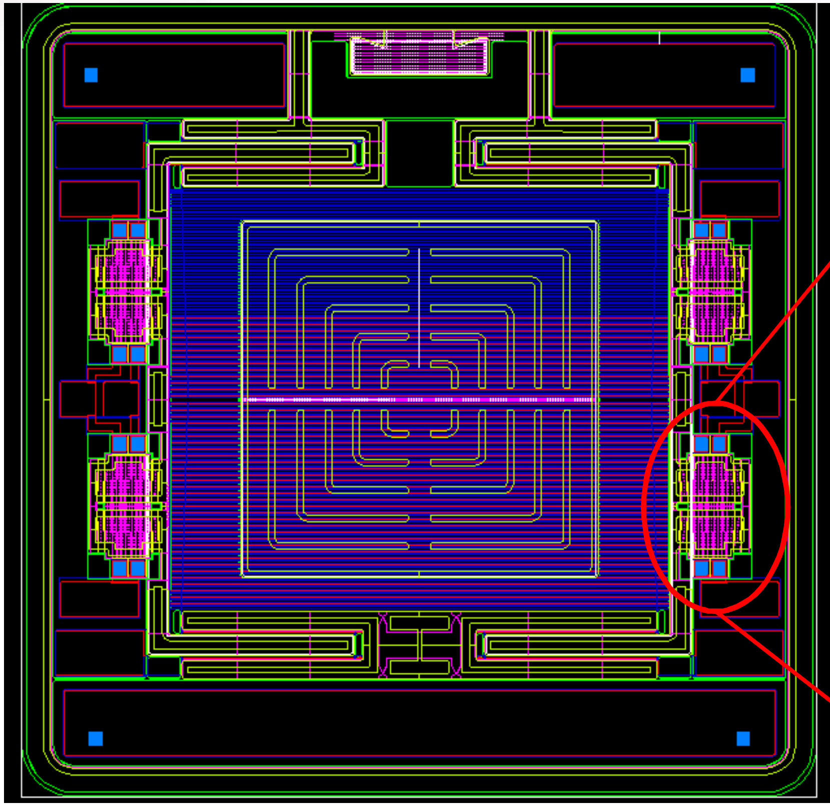
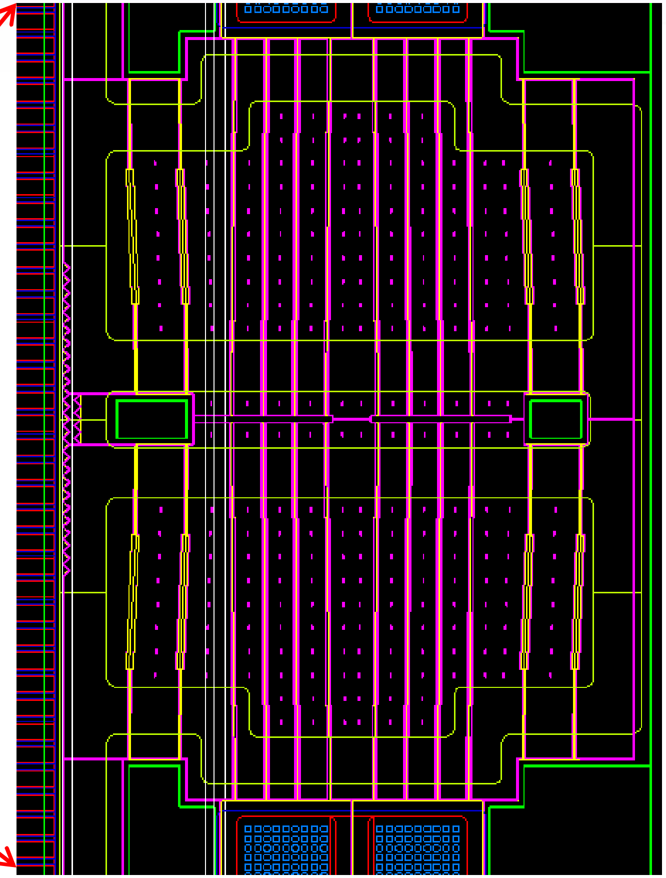
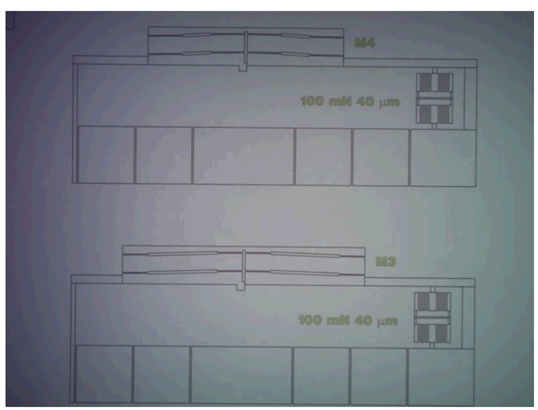
Prototype 2

- Miniaturized optical setup
  - Edge emitting laser diode (v.1)
  - VCSEL (v.2)
  - Thermally controlled micro-stage
  - Micro-assembled piezo for reference arm mirror
- Integrated MEMS locking mechanism in frame to increase robustness/fieldability

Prototype 2 – locking mechanism







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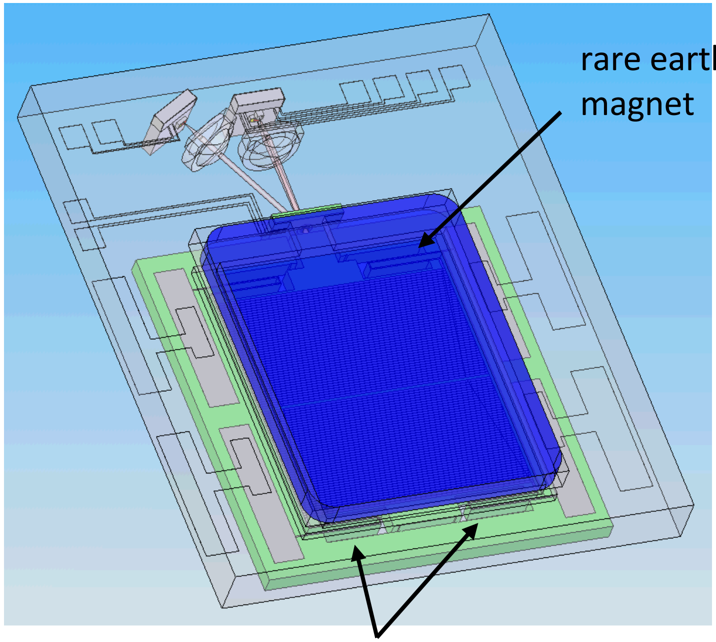
Prototype 3



metal lines on frame for force-balance feedback current

- Rare-earth magnet assembly and current carrying lines for force-balance feedback
  - for increased dynamic range and self-calibration during start-up and periodic checks

Future Work

- Locking mechanism and miniaturized optical test setup getting ready for testing
- Force-balance feedback setup with rare-earth magnets in fabrication
- Lab tests and quiet test site runs planned

- Goal : 1 inch-cube seismometer

Acknowledgements

- Team members:

  Mike Baker, Paul Resnick, Darwin Serkland, Eric Langlois, Rob Jarecki, Randy Shul, Peggy Clews, Darren Hart, John Merchant

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