MEMS-based Earth Sensor Using the Gravity Gradient

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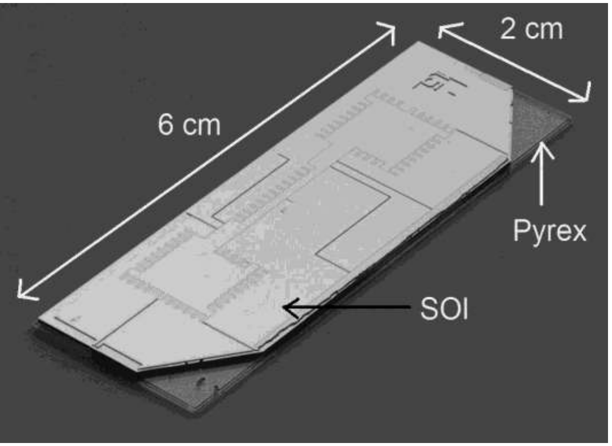
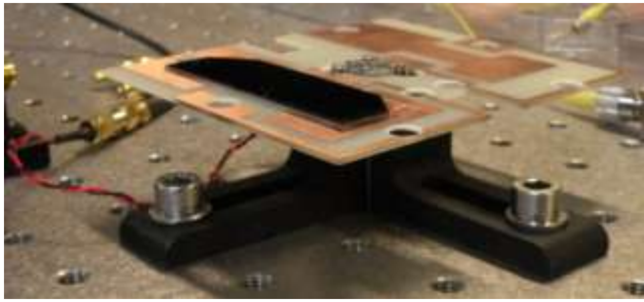




Outline

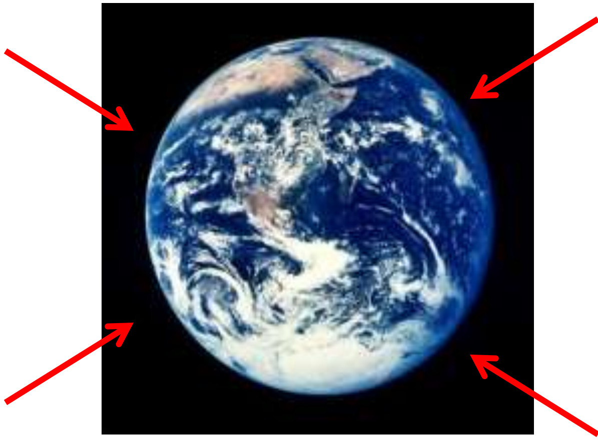
1. Concept for the MEMS based Earth Sensor
2. First generation chips
3. Effect of Satellite spin
4. Second Generation MEMS ES
5. Error Sources and Noise Estimation for 2nd gen MEMS ES
6. 2nd Generation Earth Sensor design

Goals & Motivation

- Standard Earth Sensor requires optical access
  - Important constraints on mounting and thermal management
  - Need one ES per side that might point to Earth
  - Typical specs: 10 kg, 10 W, 250 k€, 0.2 accuracy

GOODRICH

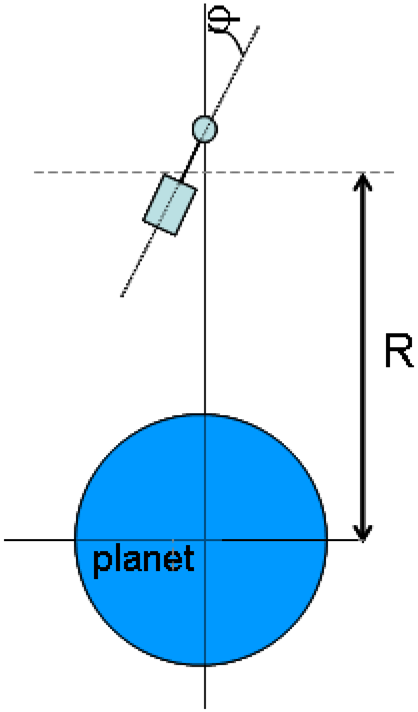
- In order to significantly reduce mass and cost, and increase flexibility, need a <u>new sensing concept</u>
  - ➢ **Directly measure the gravity gradient vector.**
  - No need for optical access
    - One single ES works for entire 4Π
    - Flexible positioning
  - Power goal: <1 W
  - Mass goal: 250 g thanks to MEMS technology
  - Accuracy goal: 2



GG vector points to center of the Earth

Goals & Motivation: measure the gravity gradient TORQUE (GGT)

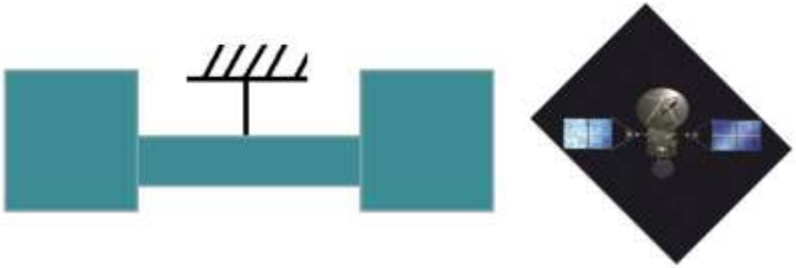
- Measure the torque due to gravity gradient (i.e., measure the gradient more directly).
- An elongated body (such as a suspended pendulum) in the gravitational field of a much larger body tends to align itself towards the center of the larger body.
- This technique is used to stabilize small satellites, but has never been used as a sensing scheme.



μ=4 10^{14} m^3s^{-2}

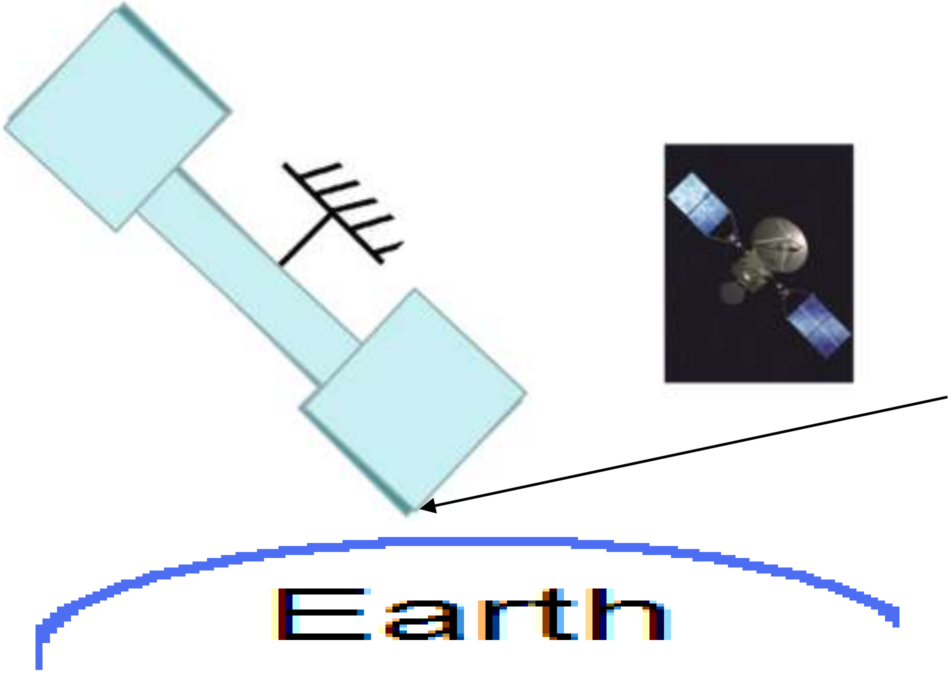
$$\text{Torque} = \frac{3\mu}{2R^3_{orbit}} \left| I_z \right| \sin(2\varphi)$$

Chip Concept Overview



When the proof mass is orthogonal to the Earth Vector the GGT is 0

$$\text{Torque} = \frac{3\mu}{2R^3_{orbit}} \left| I_z \right| \sin(2\varphi)$$



When satellite attitude changes, the proof mass is displaced due to GGT, and the resulting displacement is measured to calculate the angle

Microgravity vs 1g tradeoff

For more sensitivity in microgravity:

- Since torque is of the order of 10^{-14} Nm, bigger proof mass with more inertia
- Very compliant spring for more displacement, higher SNR
- Softer spring means lower readout rate

In 1g

- Size of mass and compliance of spring is limited by the need to have chips that survive and are testable
- Size is limited by the need to obtain enough chips from a single wafer (At least four chips per wafer for a complete ES unit)

- the sensor mass has to be constrained from moving, AS PART OF the fabrication process, and not as a final packaging step
  - Under maximum allowed displacement of 30 μm, max stress less than 25% of yield strength of Silicon
  - The sensor is thus expect to survive large shocks.

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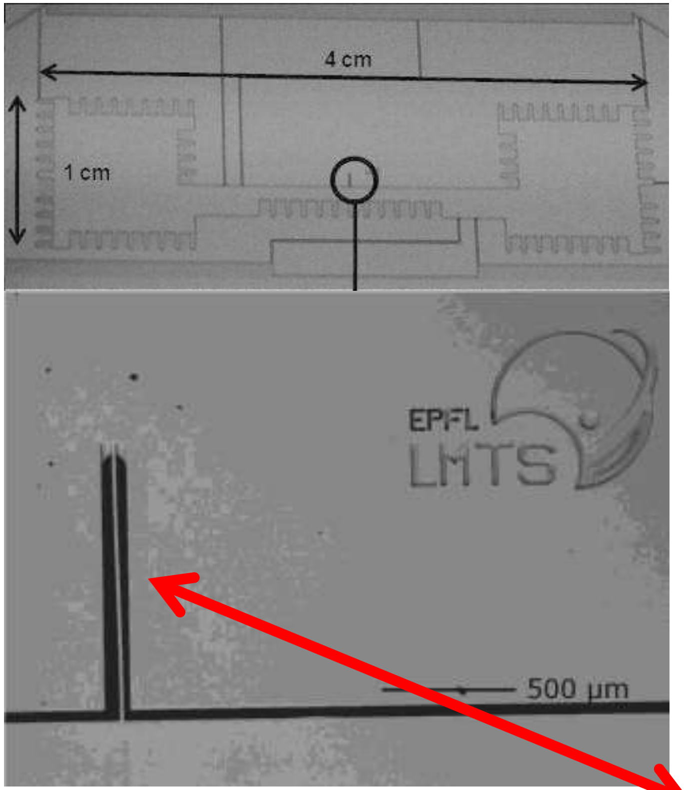
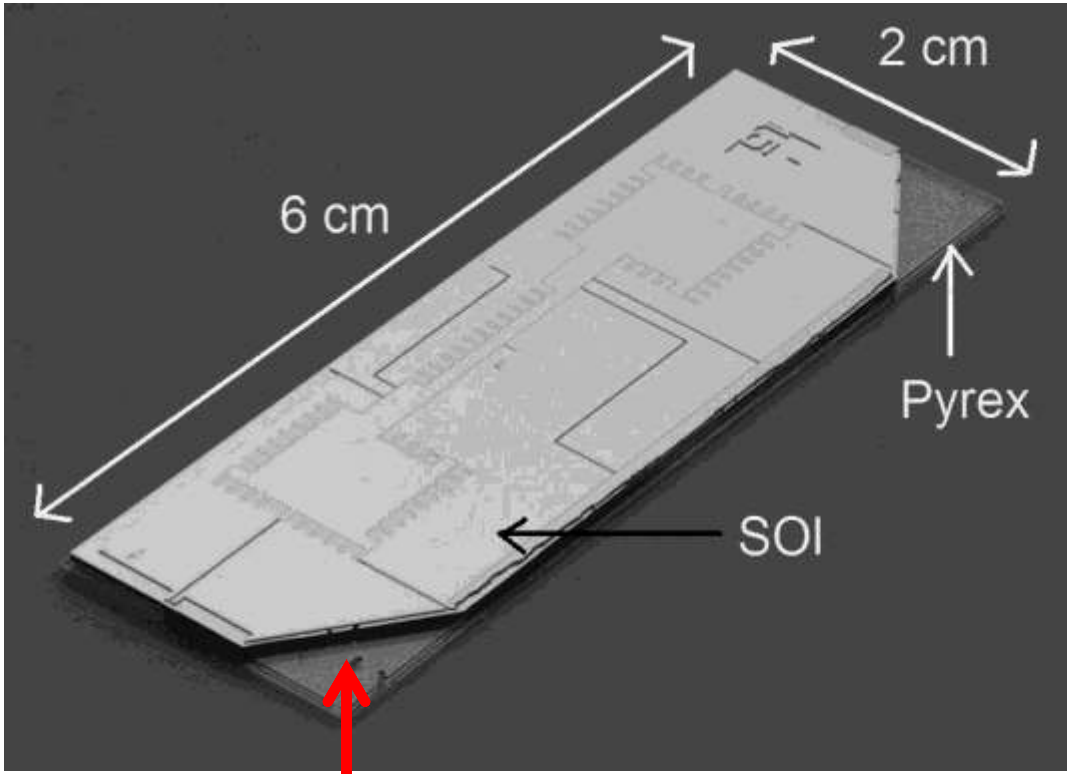
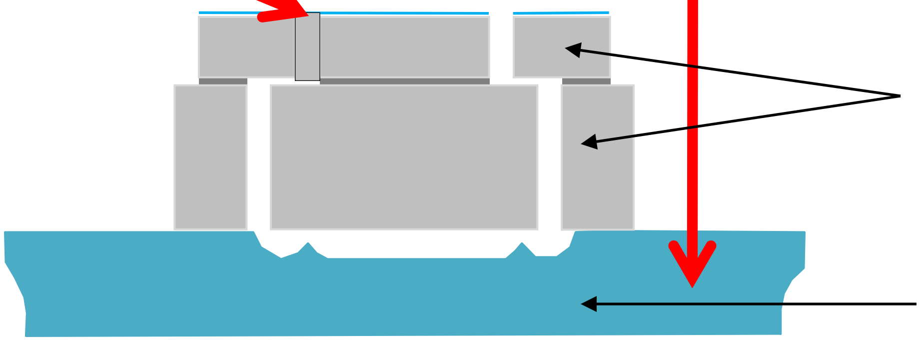
1st Generation Overview

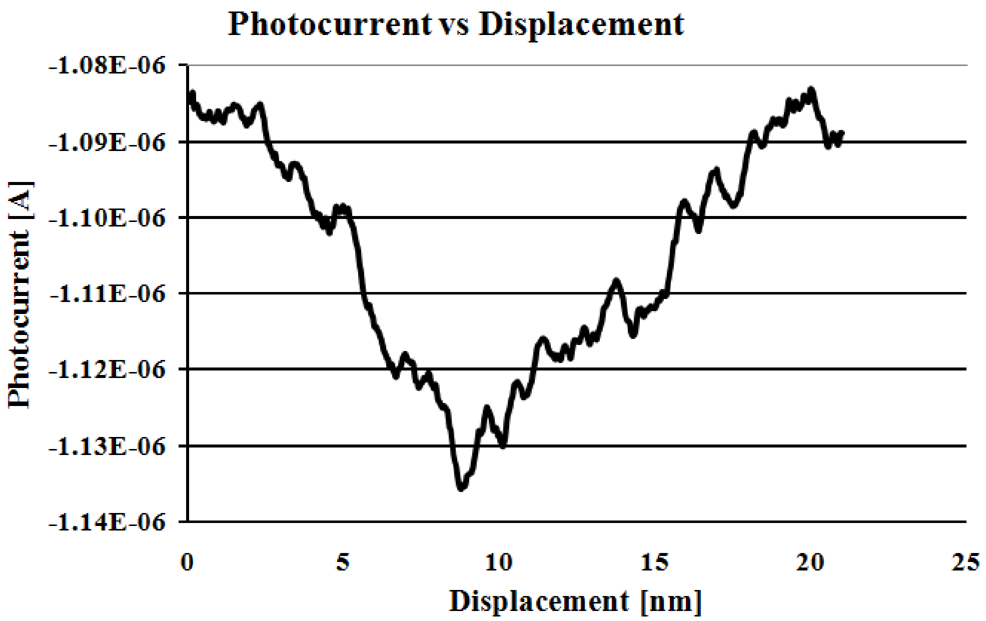


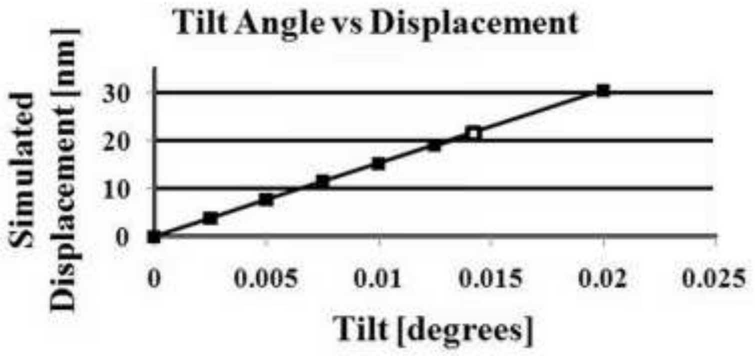


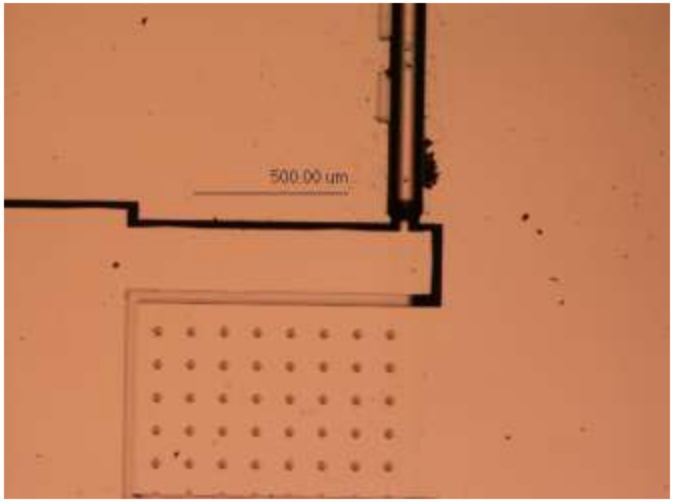
Silicon proof mass is suspended by a single spring. The device is fabricated in cleanroom. Proof mass is protected from excessive movement by Si and Pyrex hard stops.



Test Result - Interferogram







- Interferogram shows the mass moves freely (20 nm)
- Optical readout works, resolution ~1 nm
- The testing scheme for a device intended for micro-gravity works in 1G

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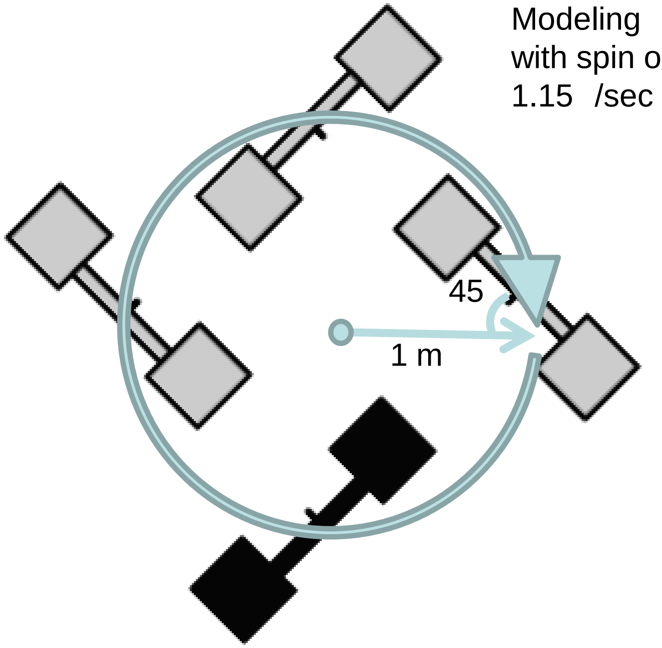
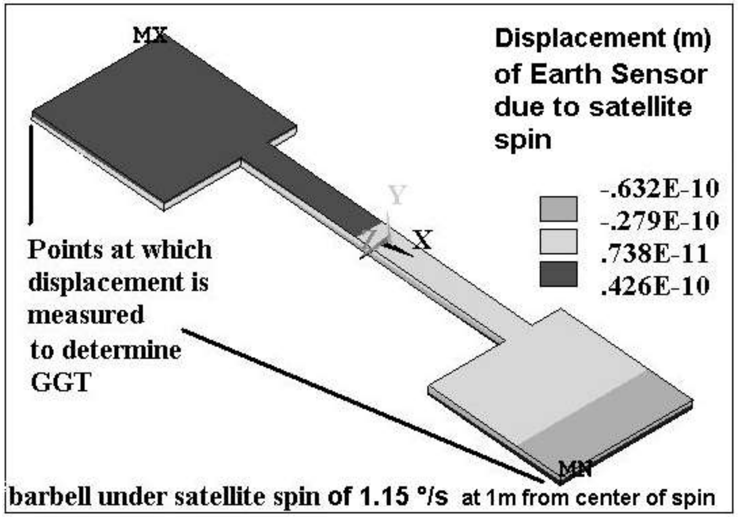
Satellite Spin

- The effect of satellite spin depends on orientation of the sensor with respect to the axis of rotation of the satellite
- No effect when sensor proof mass is symmetrical to axis of spin
- When centroid of mass coincides with centroid of spring, modeling shows that the sensor output is not disturbed when the satellite is spinning



Modeling
with spin of
1.15 /sec



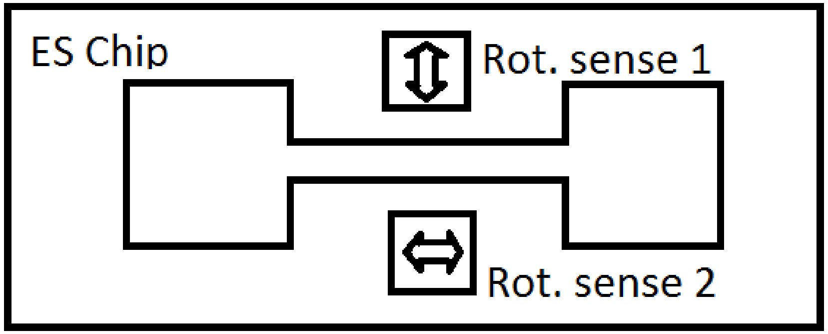
Displacement (m) of Earth Sensor due to satellite spin

Points at which displacement is measured to determine GGT

barbell under satellite spin of 1.15 °/s at 1m from center of spin

Satellite Spin – Effect of Micro-fabrication Tolerances

- Due to tolerances in the microfabrication process the centroid of proof mass and spring diverge
- Tolerances arising from photolithography are eliminated by defining the proof mass and springs in a single step
- Tolerances arising from fabrication steps such as DRIE are compensated for in two stages
  - additional microfabrication steps to better balance the ES proof mass and spring. The perturbation introduced can be reduced by order of magnitude from ~1 nm to ~0.1 nm
  - By incorporating rotation sensors on the same chip to determine if the ES chip is rotating, the error due to rotation can be subtracted from the ES output
- Locating the sensor close to CG of satellite reduces this error



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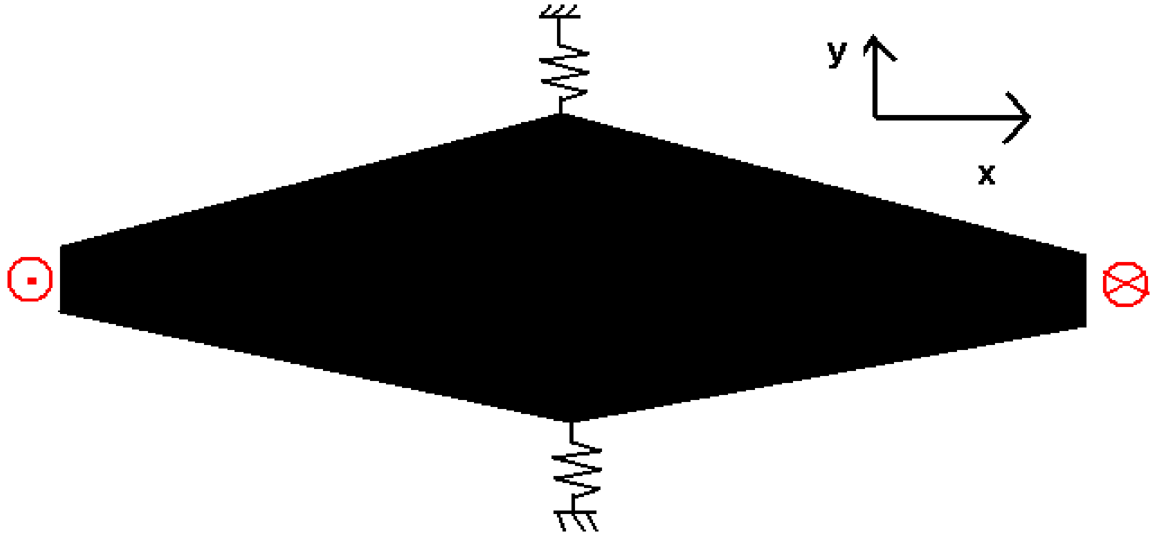
2^{nd} Generation Earth Sensor

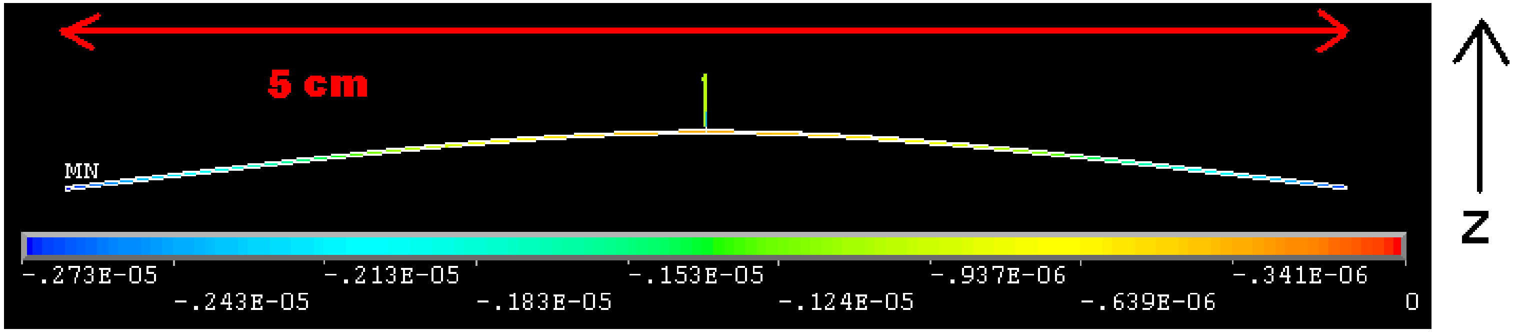
The displacement due to GGT is out of plane and measured by sensing a change in capacitance.

Two spring design allows for easier testability

Electronic readout eliminates need for thermally stabilised and radiation shielded laser.



FEM shows that the 5 cm long mass sags by 2.7 microns in 1g. This sag has to be within 5 microns for testability in 1g



- Reducing sag to achieve testability in 1g is the primary consideration in the shape of the proof mass
- Z displacement limited by stoppers to 5 microns, X and Y displacements to 12 microns to improve shock resistance

Capacitive Displacement Sensing

- Differential capacitance sensed between the two ends of the Earth Sensor proof mass
  - Uses the AD7746/47 CDC
- At 2 degrees from the Earth Vector the displacement to be measured is 0.05 nm
- At 45 degrees 0.6 nm
- Corresponds to a capacitance change of 100 – 2000 aF
- Electrostatic actuation for feedback / damping / electrostatic lockdown

Electrodes for Electrostatic actuation

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Sources of Error

- Noise due to readout Electronics

- Temperature
  - Increased thermal noise (Brownian motion)
- Orbital Altitude
  - Error due to increase in altitude
  - Error due to uncertainity in altitude
- Quality factor (Damping)
  - Effect of change in Q-factor
  - Effect of uncertainity in Q-factor
- Effect of uncertainity of the Earths gravity

Summary of Error Sources

Source of Error	Magnitude	Remarks
Error due to Brownian noise (thermal)	+/- 2.2 , increases by +/- 0.2 for -/+ 50 K	@ 300 K, 700 km altitude, Q 1000
Error due to change in Satellite altitude	+/-2 , increases by +/- 0.1 degrees for every +/- 100 km	@700 km altitude, 300K, Q 1000
Error due to uncertainity in Satellite altitude	0.05 / 1 to Earth vector/ 100 km altitude error	700 km reference altitude
Error due to Satellite spin	Response of ES at a linear velocity of 0.002 m/s, fabrication process designed to balance ES so that error for 0.002 m/s is +/- 1	Determining factors are secondary accelerometer sensitivity (designed for min. 0.002 m/s), balancing of ES at completion of fabrication
Error due to uncertainity in Earth`s gravity of +/- 1 gal	0.05% of expected GGT	Other sources of error will dominate

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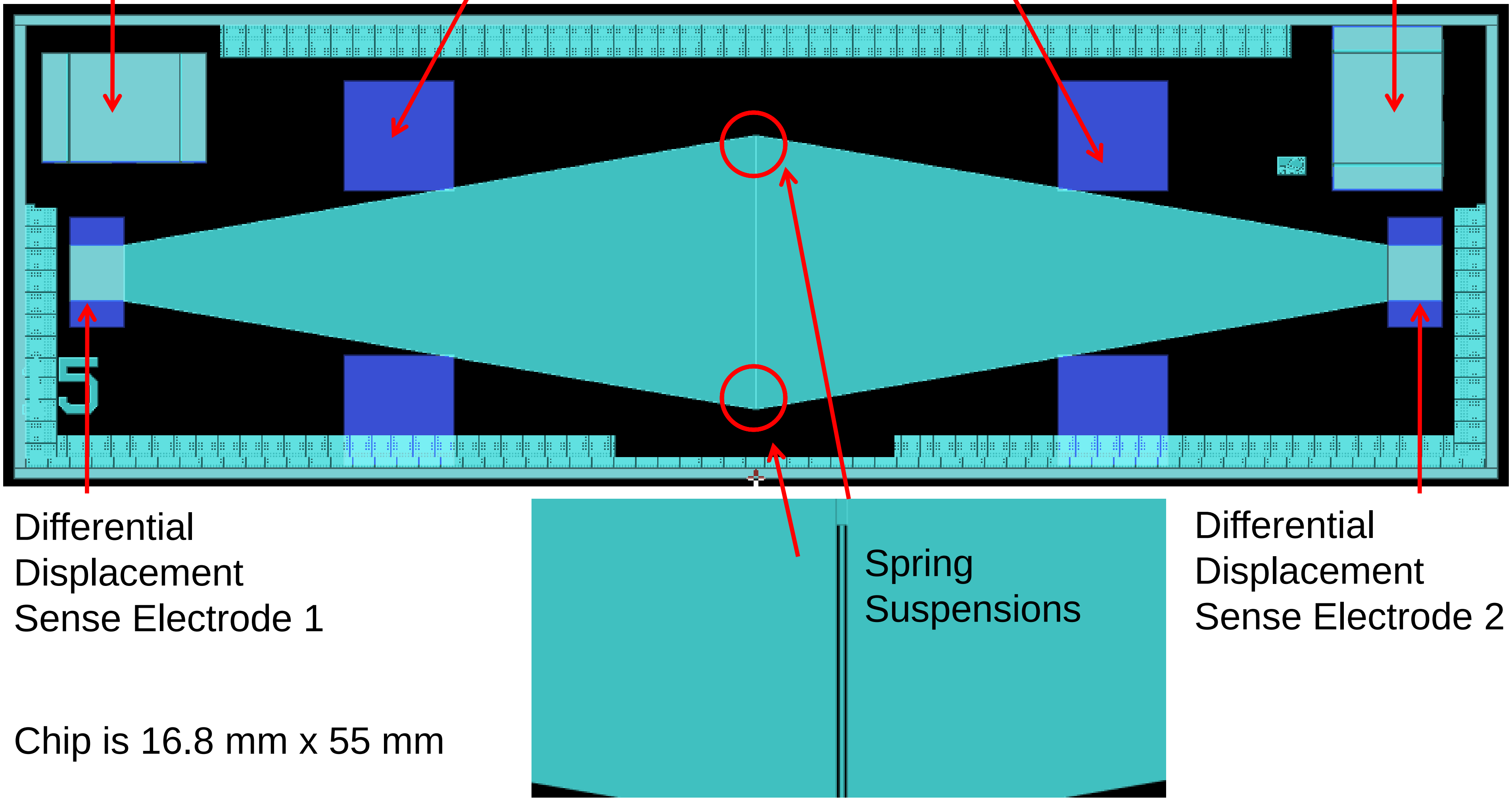
Design of 2nd Gen Earth Sensor

Rotation Sensor 1

Electrodes for Electrostatic Damping/ Feedback / Lockdown

Rotation Sensor 2



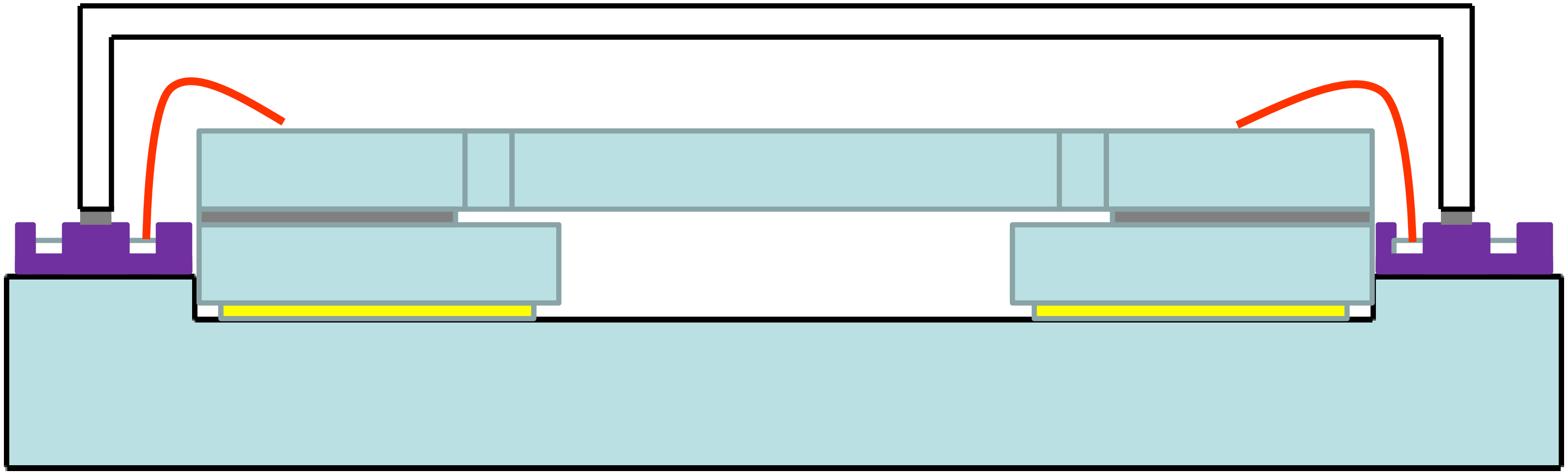
Differential Displacement Sense Electrode 1

Spring Suspensions

Differential Displacement Sense Electrode 2

Chip is 16.8 mm x 55 mm

Packaging



Metal/
Glass
Hermitic
capping

- A 2nd silicon wafer provides interconnects and the base for a hermetic package

Summary

- We have demonstrated the feasibility of a micromachined (MEMS) Earth sensor that does not require optical access and provides 360 x180 coverage
- The device is etched from a single crystal silicon wafer and directly measures the gravity gradient in order to determine the vector to the Earth center.
- The chip does not require special handling, and the limiting the movement of the proof mass to tens of microns allows for robustness.
- The packaged chip measures 7x4 cm^2, the full system volume is expected to be below 1 liter.

References and Contact Details

- "A Micromachined Earth Sensor Based on Measuring the Gravity Gradient Torque", K. Ghose, H. R. Shea, ASME IMECE 2009, November 2009, Orlando
- "Using a MEMS pendulum to measure the gravity gradient in orbit: a new concept for a miniaturized Earth sensor", K. Ghose, H. R. Shea, Eurosensors XXIII, September 2009, Lausanne
- "Fabrication and Testing of a MEMS Based Earth Sensor", K. Ghose, H. R. Shea, Transducers 2009, June 2009, Denver

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