# Micromachined Earth-Sensor based on direct measurement of the Gravity Gradient Torque

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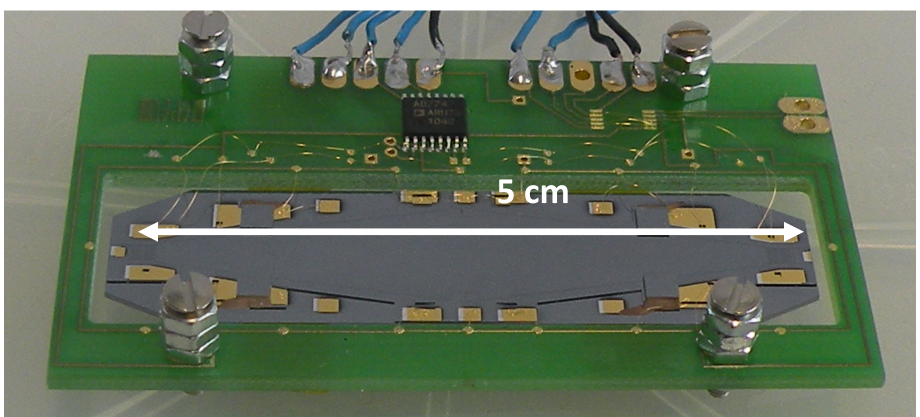
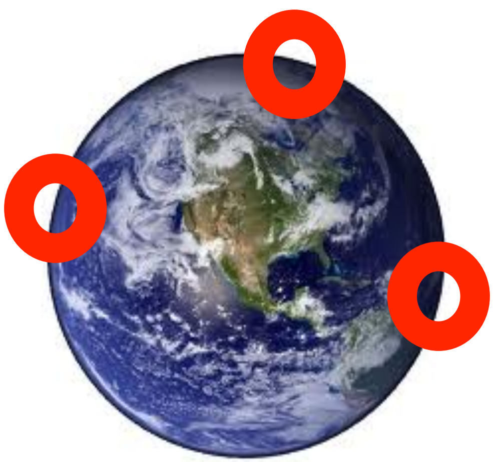



# Introduction – Limitations of current Earth Sensors

Current Earth Sensors and sensors based on astronomical references have a limited Field of View

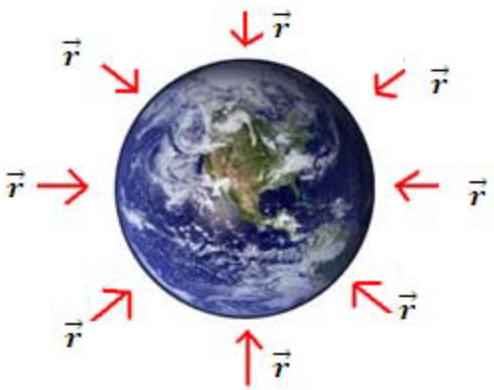
- Multiple units required all over satellite for complete coverage
- Limits ability to reacquire attitude on a tumbling satellite
- Prone to saturation due to presence of sun / moon in field of view

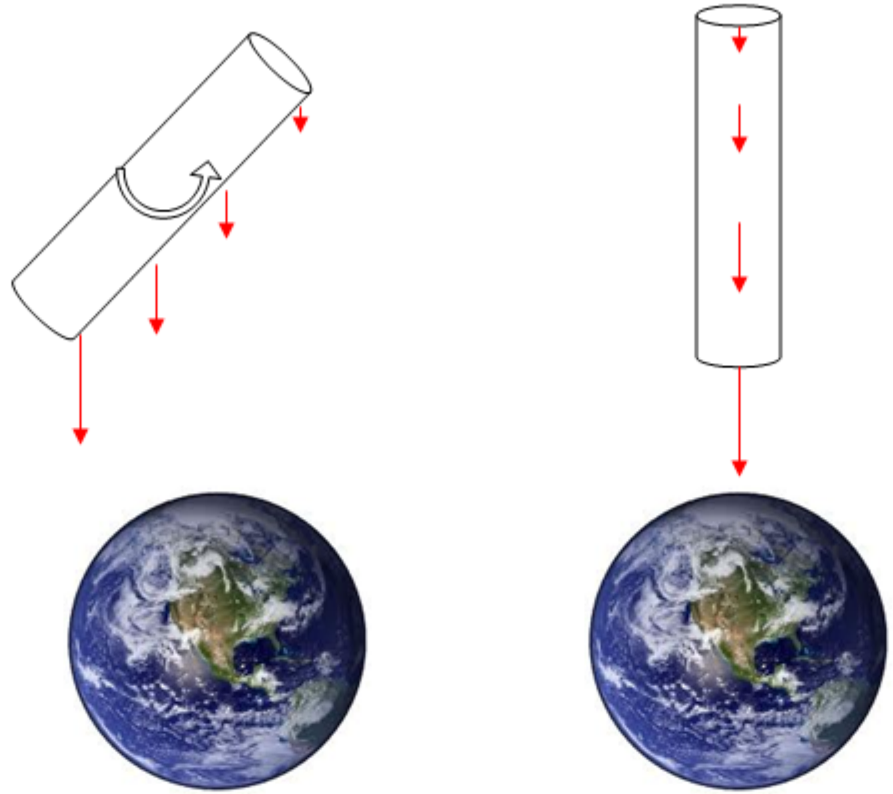
To overcome limitations of existing sensors, a new sensing scheme needed

- Use Earths gravity field as a reference

# Introduction - The Earth's Gravity Gradient

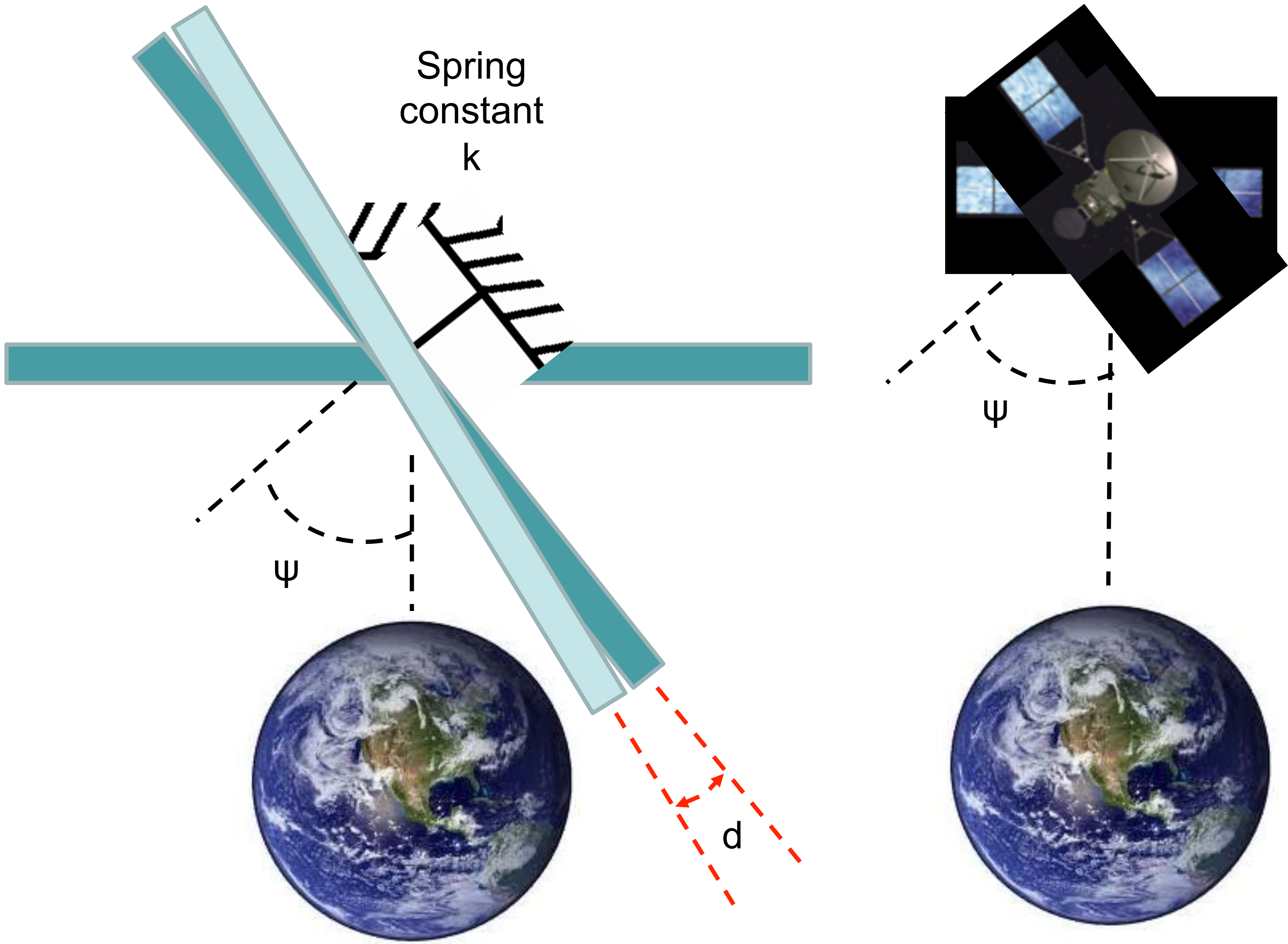
$$\vec{F} = \frac{GM}{R^2}\ \vec{r}\ [m/s^2]$$



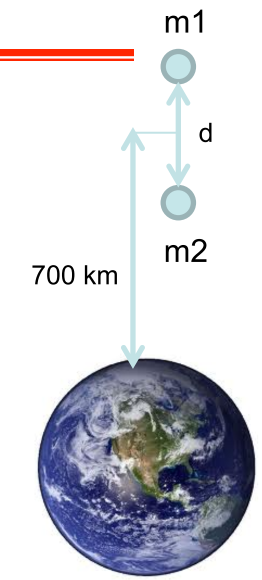


- Used to passively stabilize the attitude of satellites designed with an elongated shape [GEOSAT]
- Goal – Use this phenomenon to develop an Earth Sensor with a mass of 1 kg and volume of 1 $dm^3$ for LEO
- Measure pitch and roll angles with an accuracy of +/- 2 degrees @ update rate 1 Hz

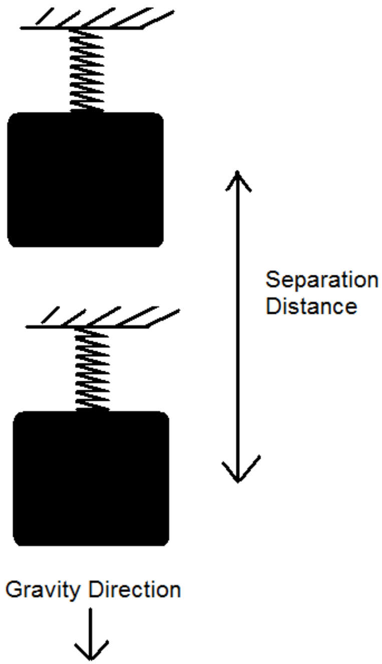
# Introduction – Inertial Sensor to measure Gravity Gradient Torque



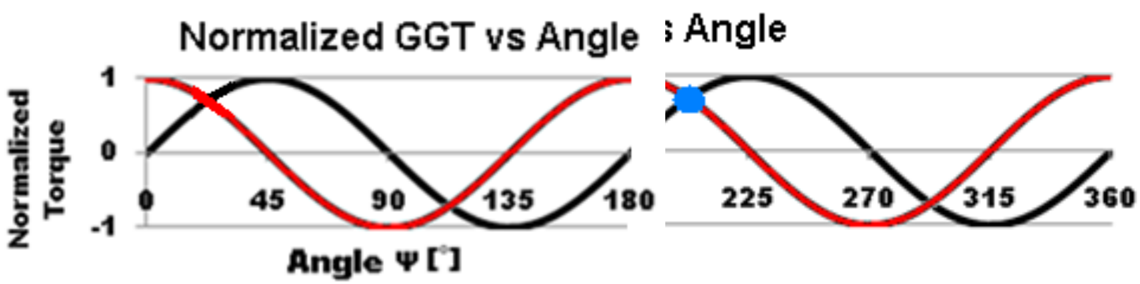
# Introduction – Measuring the Gravity Gradient

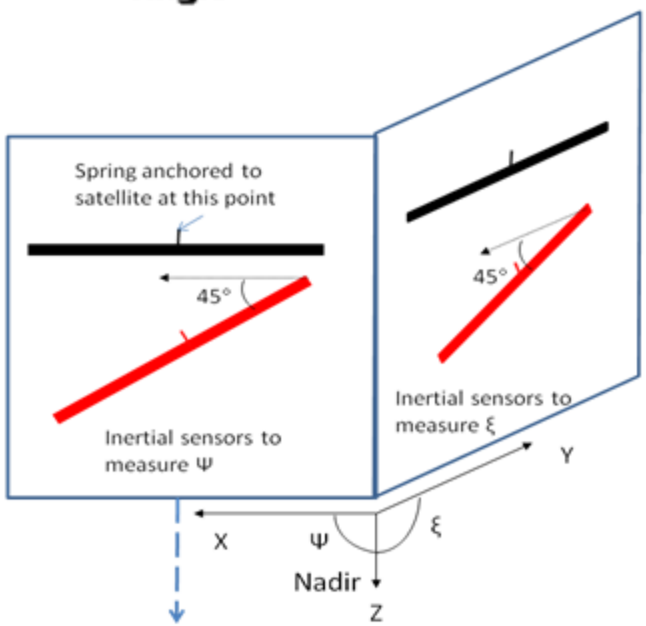


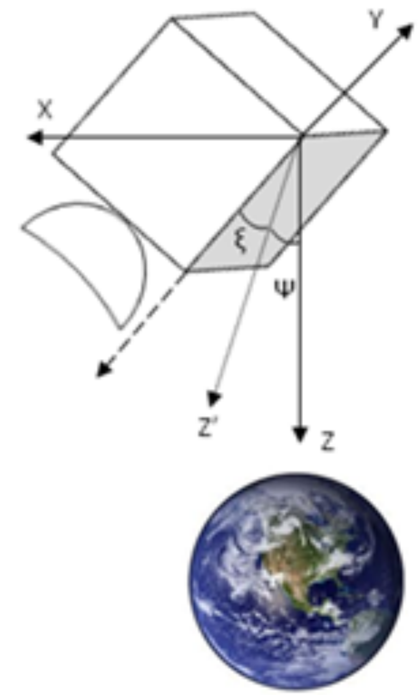

- Two 0.1 g masses separated by 5 cm in an orbit of 700 km will have a difference in the magnitude of gravity of **1 x $10^{-12}$ $g_o$**
- Missions for gradiometry, such as GOCE have custom accelerometers weighing tens of kilograms that can measure this difference
  – The satellite attitude is known and very stable
  – Complex and bulky readout scheme
- Centripetal forces on a tumbling satellite can reach 1 x $10^{-4}$ $g_o$
  – Satellite can be tumbling when attitude has to be acquired
- For a more compact solution, measuring the Gravity Gradient Torque from a single inertial sensor is more feasible



# Introduction - Periodicity of GGT




- Total of four MEMS sensors needed per instrument
- Hybrid sensing approach needed to resolve whether ES measures an angle from 0-180° or 180-360°

# Goals

For the attitude determination instrument with MEMS ES

- Single unit with 4pi steradian coverage
- +/- 2° accuracy
- Volume < 1 $dm^3$
- Mass < 1 kg
- Power < 5 W
- Update rate > 1 Hz

# Challenges

To achieve sufficient Signal to Noise Ratio to measure pitch and roll with the required accuracy in LEO:

- “Big” proof mass desired (0.1 g)
- Soft spring needed

Challenges

- Develop a reliable fabrication process and packaging so that sensor can be fabricated and tested in 1g
- Test setup to reproduce the expected displacement in microgravity in 1g
- Sensitive yet robust displacement measurement scheme capable of measuring sub-nm displacements

# Goal and Constraints continued

- Expected GGT on MEMS in low Earth orbit is on order of $10^{-14}$ N.m

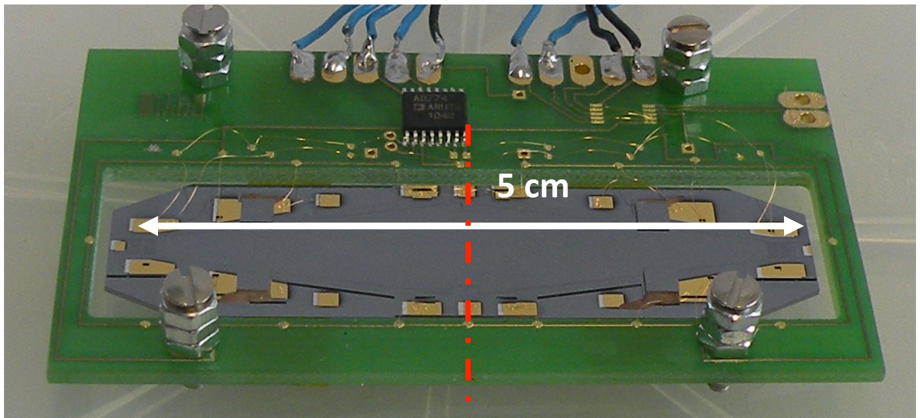
To achieve sufficient SNR (Fundamental limitation due to thermo-mechanical noise) to measure this torque:

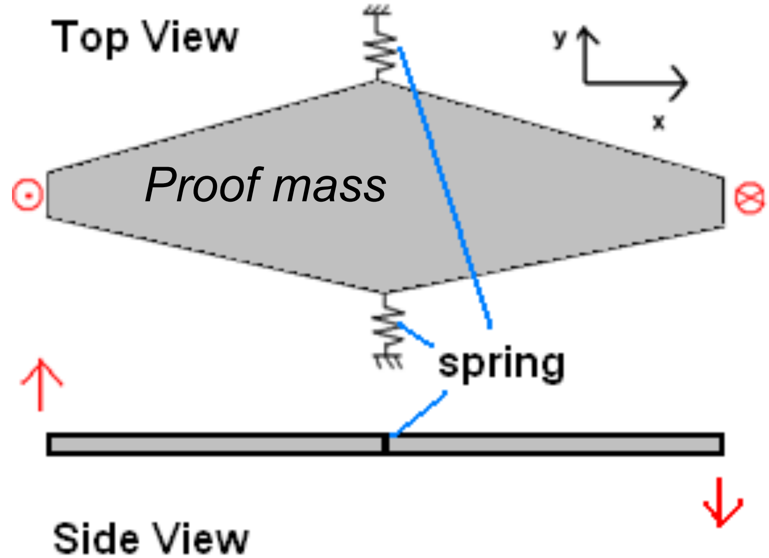
- MEMS mechanical sensing element resonant frequency of the order of 1 Hz, kept to a minimum above the required readout rate (therefore very compliant spring)
- Quality factor in vacuum on the order of hundreds or more

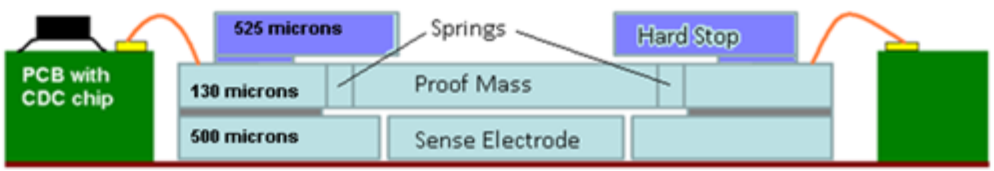
Challenges

- Develop a reliable fabrication process and packaging so that sensor can be fabricated and tested in 1g
- Test setup to reproduce the expected displacement in microgravity in 1g
- Sensitive yet robust displacement measurement scheme capable of measuring sub-nm displacements

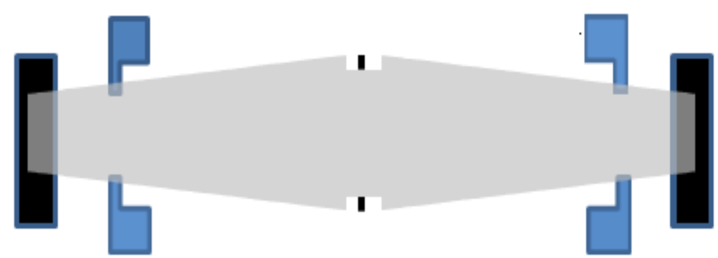
# MEMS Earth Sensor  Design



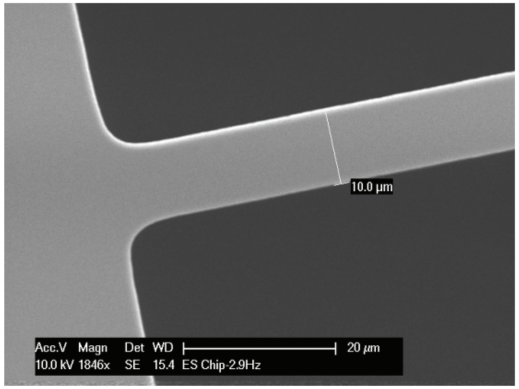



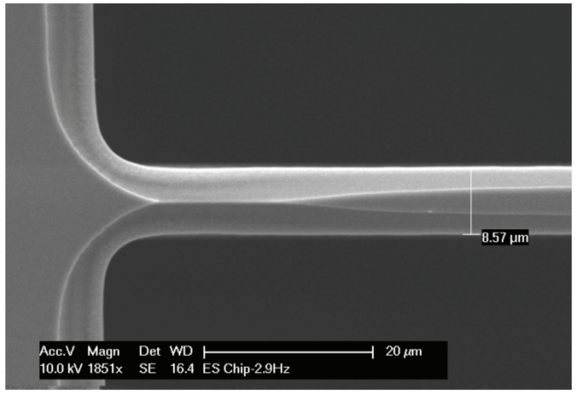

Cross Sectional View

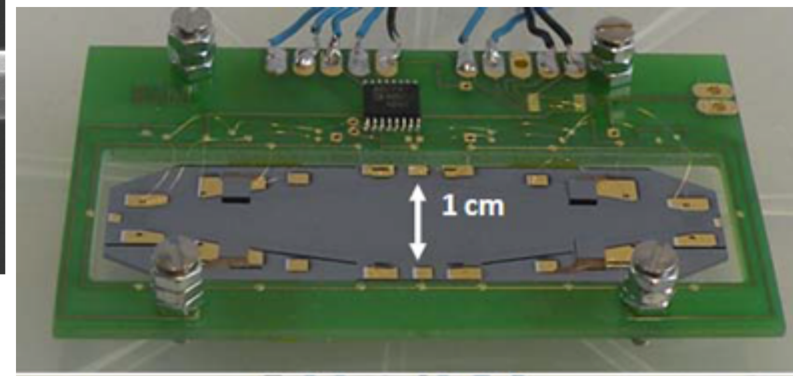



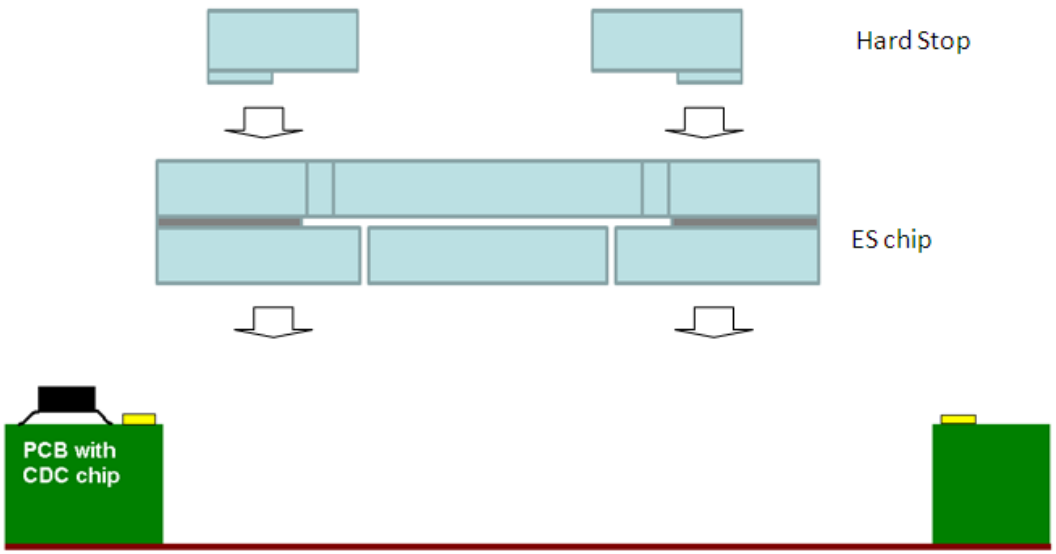
- Two spring teeter toter design with capacitive displacement sensing
- Electrostatic feedback electrodes for closed loop operation

# MEMS Earth Sensor Fabrication

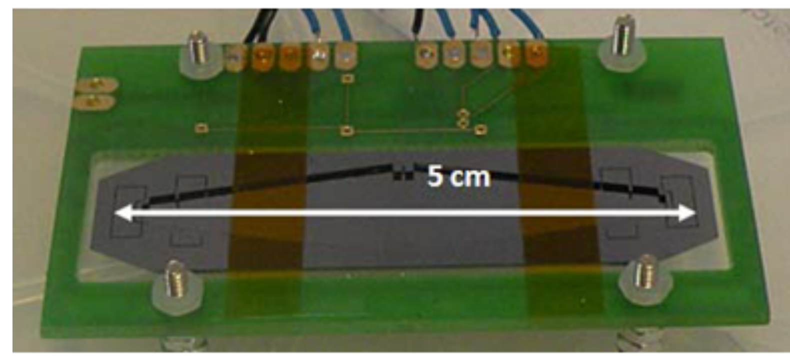


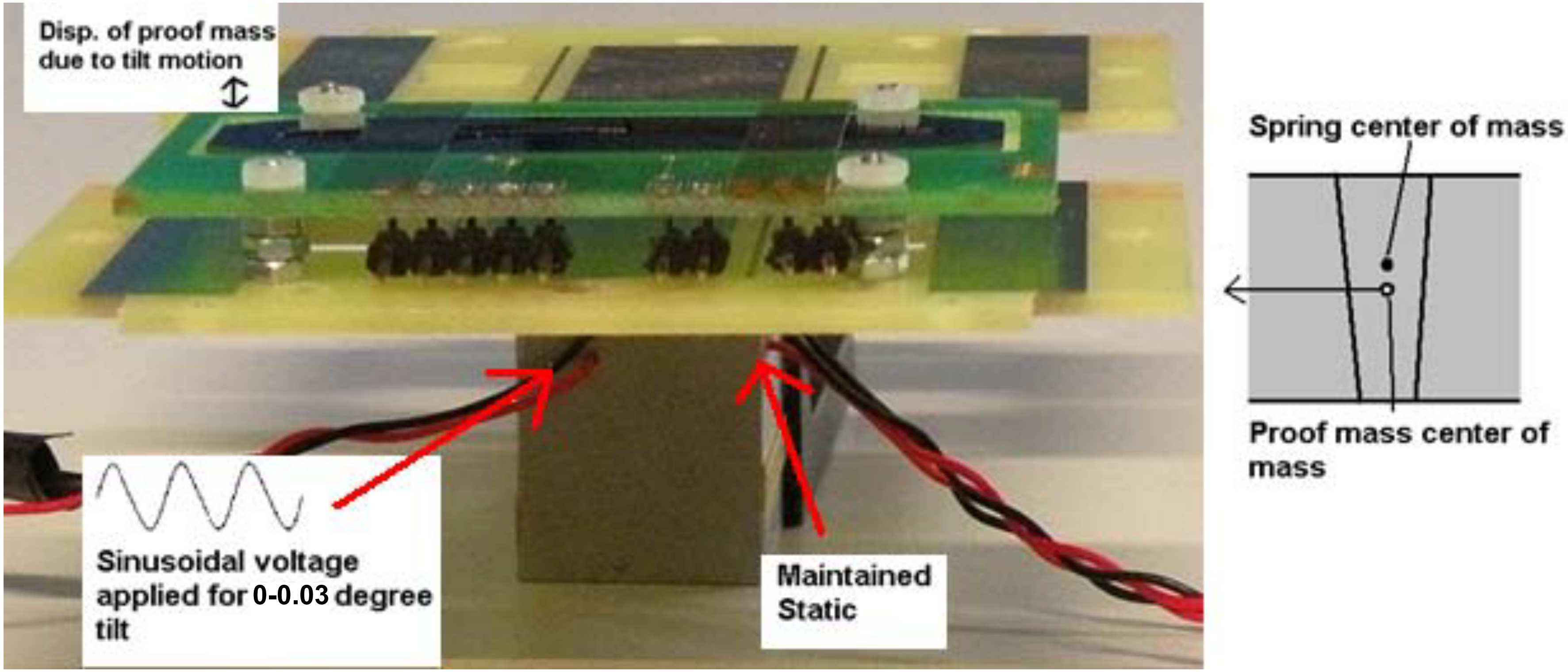




**Kapton tape for mounting ES chip onto PCB with CDC chip**



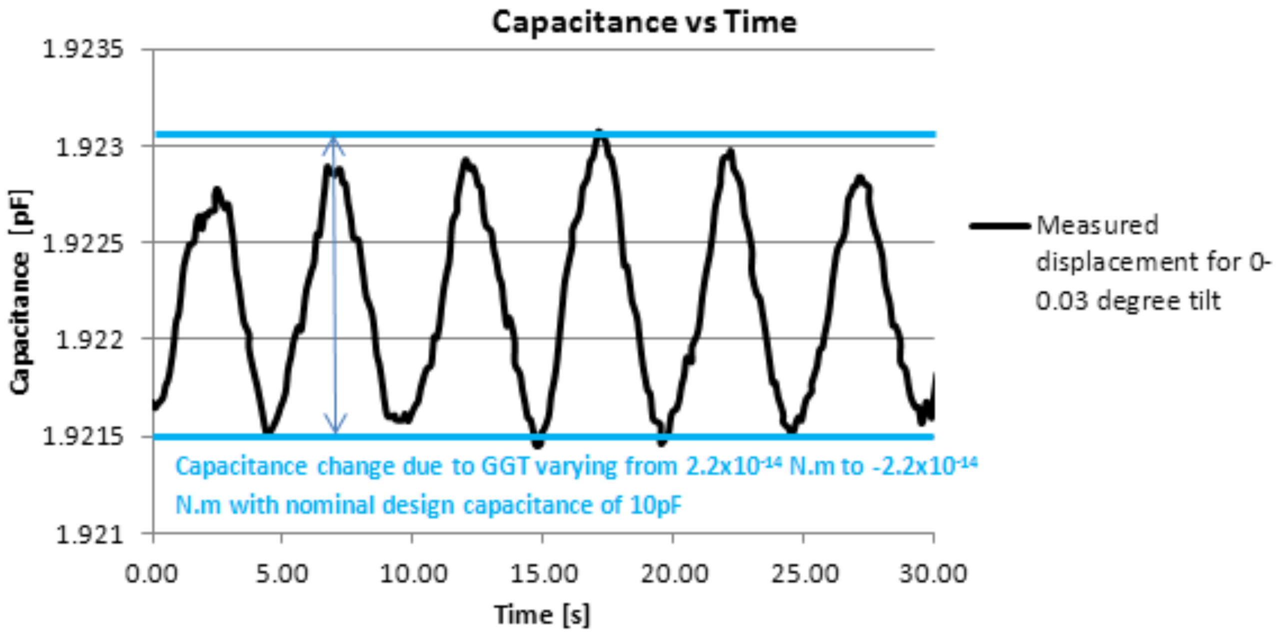

*Shock stops to limit proof mass motion to <10 µm on all axes*

# Testing MEMS Earth sensor in 1g



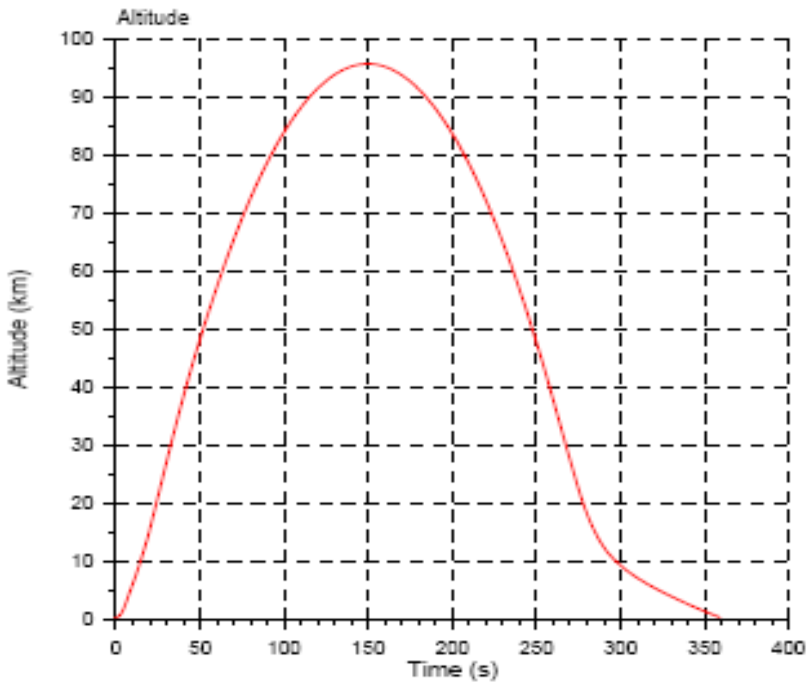

- The sensor is tested by tilting the MEMS ES chip by an angle of 0 to 0.03 degrees using a two-axis piezo stage.
- On a chip with trapezoidal spring cross section, the slight offset between spring and proof mass center of masses, results in a torque of 0 to $10^{-13}$ N.m on the springs due to this motion

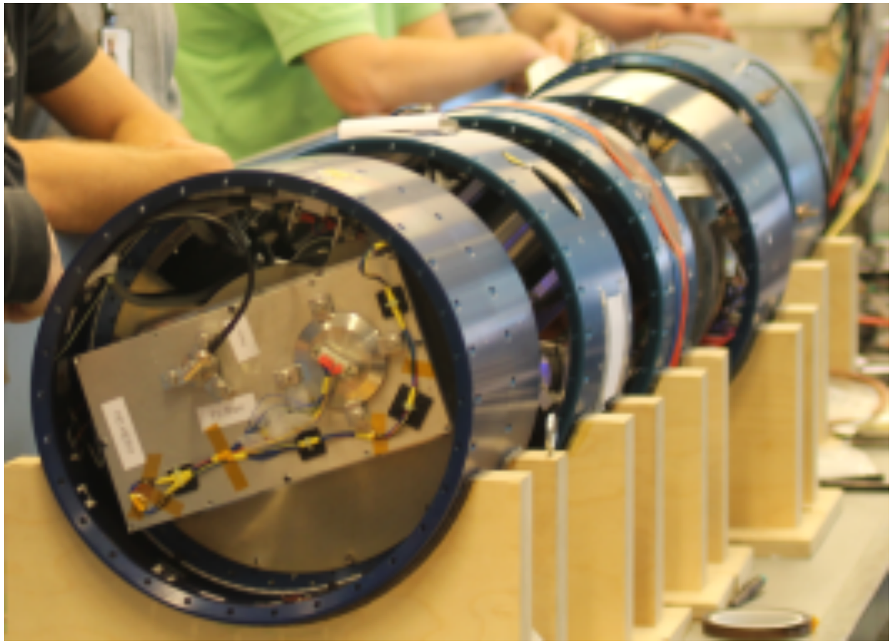
# Measurement of Displacement due to Torque on Springs in 1g




- Black line shows the single ended measured change in capacitance due to tilting by piezo stage
- For comparison, the light blue lines indicate the differential capacitance change due to GGT, as satellite changes pitch/roll from -45° to +45° with respect to the nadir for a 10 pF nominal sense capacitance
- Corresponds to +/-9 degrees of error for ES chip with 2.9 Hz fundamental frequency and 10pF nominal sensing capacitance, in an orbit of height 700km.

# GGES on REXUS 11




# GGES on REXUS 11

- 4 MEMS Earth sensors in a frame based on Swisscube heritage (~1 $dm^3$, mass ~ 0.5 kg)
    - 2 « soft » sensors
    - 2 « stiff » sensors to mitigate launch risk due to vibration

- Passive immobilization of proof mass expected during boost due to acceleration upto 18g

- Approximately 2-3 minutes in microgravity

- Data analysed post flight to determine roll and pitch during ballistic phase

# Conclusions

- Novel method for attitude determination by measuring the Gravity Gradient Torque
- MEMS Inertial Sensor to measure the GGT
  - Largest reported silicon MEMS device
  - Lowest reported resonant frequency for a inertial sensor
  - Reliable fabrication process for MEMS devices with large proof masses
  - Simple and robust displacement detection method to measure sub-nm displacements in microgravity with noise sufficiently low for an accuracy of +/- 9° for a 700 km orbit

# Thank you

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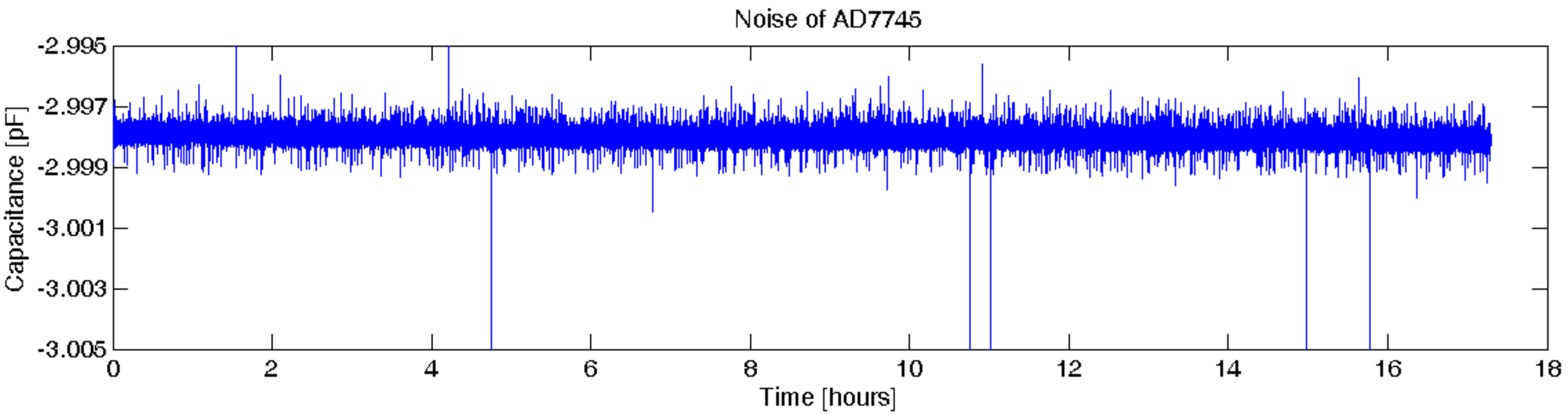
# Noise of measurement electronics (single ended measurement with AD7745)




- Averaged to 1 Hz, the peak-peak noise is 500 aF
- Corresponds to +/-9 degrees of error for ES chip with 2.9 Hz fundamental frequency and 10pF nominal sensing capacitance, in an orbit of height 700km.

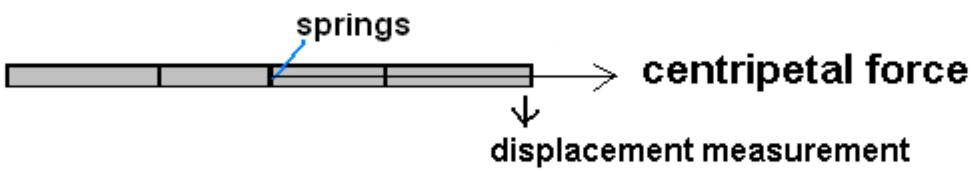
 

# Future Work

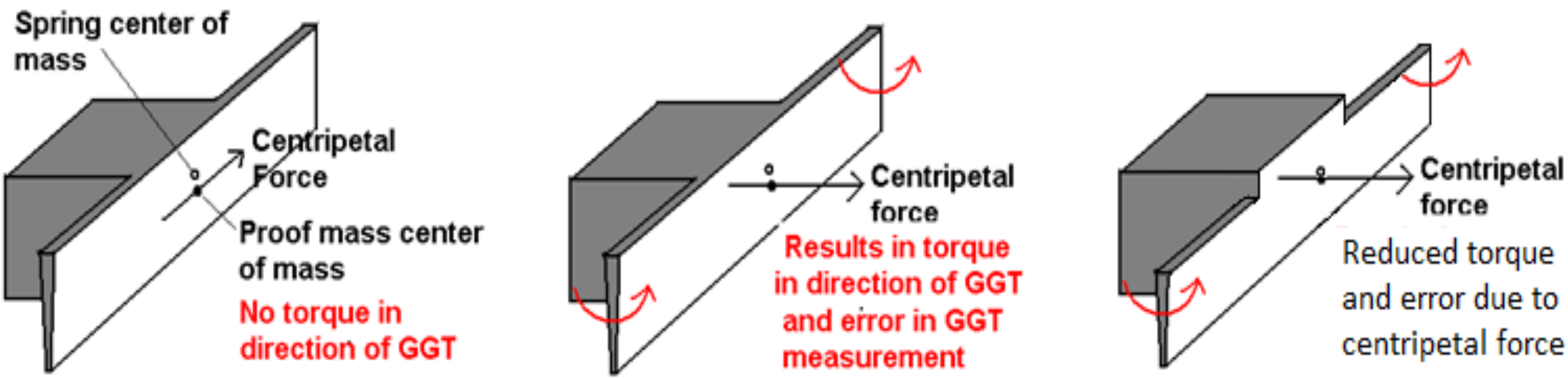
- Design to mitigate differential bow issues arising from SOI wafer
- Improve sensitivity by reducing capacitance sensing gap
- Improve shock and vibration resistance
- The sensor will be tested on the REXUS 11 flight later this year from Esrange

# MEMS Earth Sensor Operation on Tumbling Satellite

## Proof Mass and Springs from single silicon layer




Ideally spring should have a rectangular cross section, the deep reactive silicon etching process (DRIE) used to define the springs results in a trapezoid




No effect of centripetal force on GGT measurement

Worse case effect of centripetal force on GGT measurement

Worse case effect of centripetal force on GGT measurement

Additional process step to compensate for trapezoidal cross section