A High-Sensitivity, Low-Drift MEMS Relative Gravimeter for Multi-Pixel Imaging Applications

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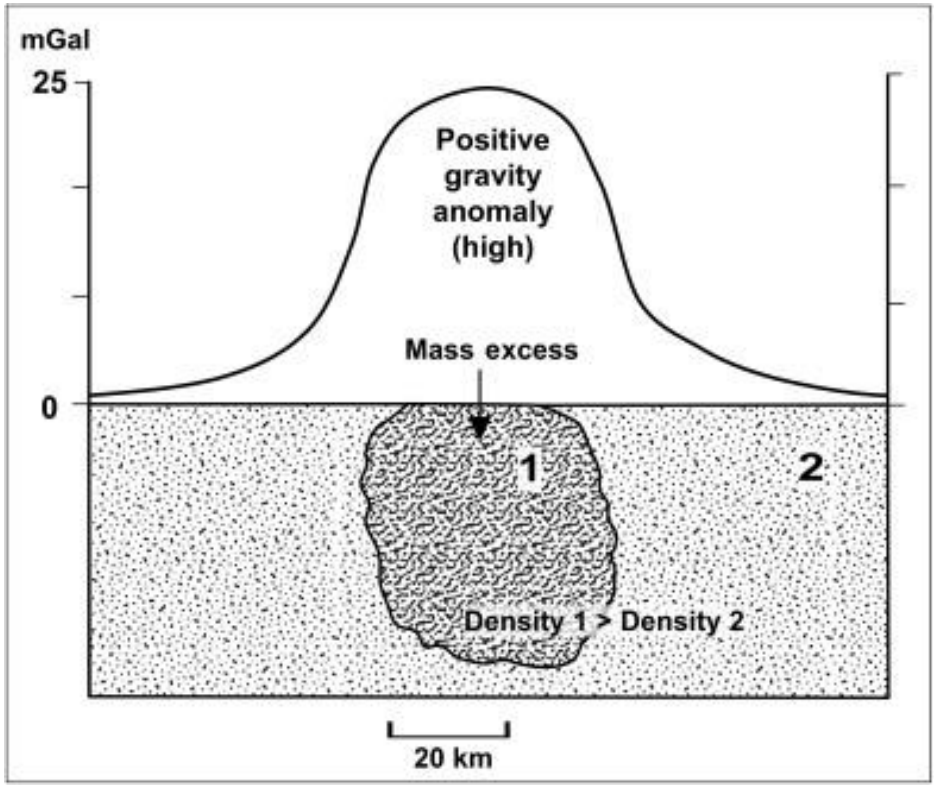
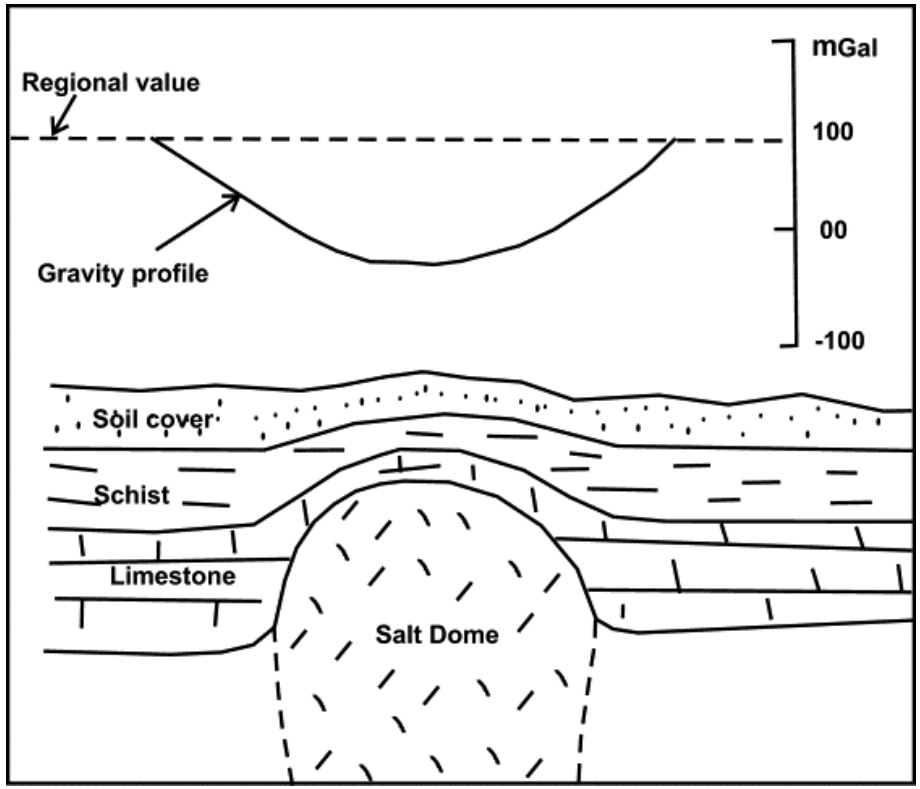
Gravimetry





- Subsurface density anomalies produce tiny changes in the local *g*

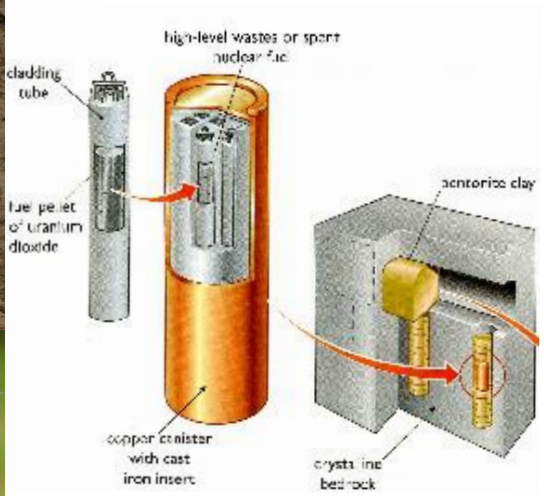
1 Gal =1 cm/s^2= 0.01 m/s^2

https://www.sciencedirect.com/topics/earth-and-planetary-sciences/gravimeters

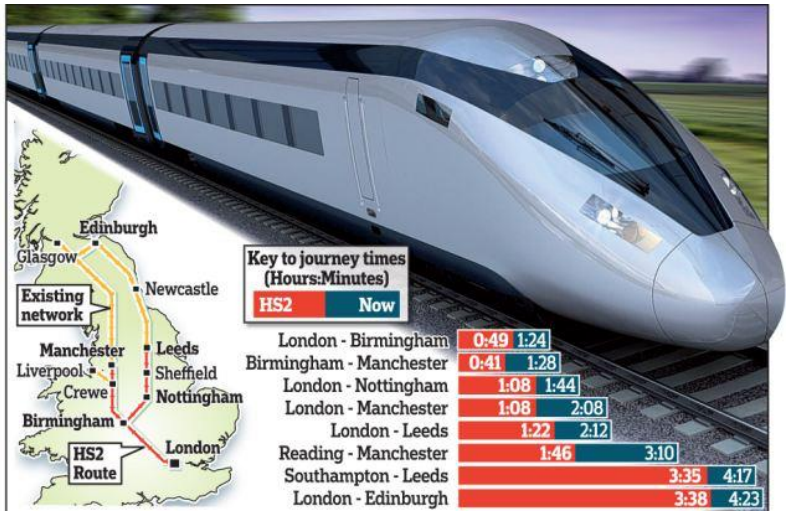
Gravity ‘Imaging’ Applications

Oil & gas prospecting

Environmental monitoring



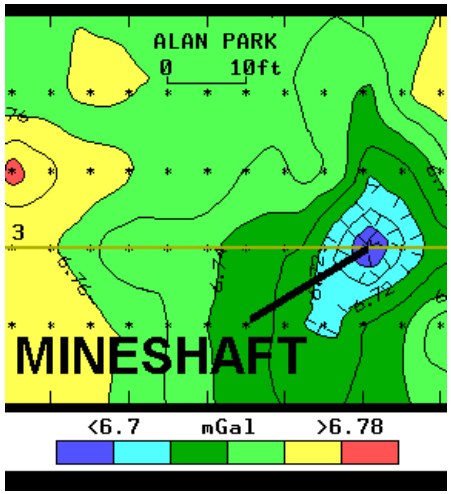
HS2



Security & Defence

Volcano monitoring

Sink hole detection



Commercial Gravimeters

Commercial gravimeters have:

- High instrumentation cost
- Large form-factor

This leads to:

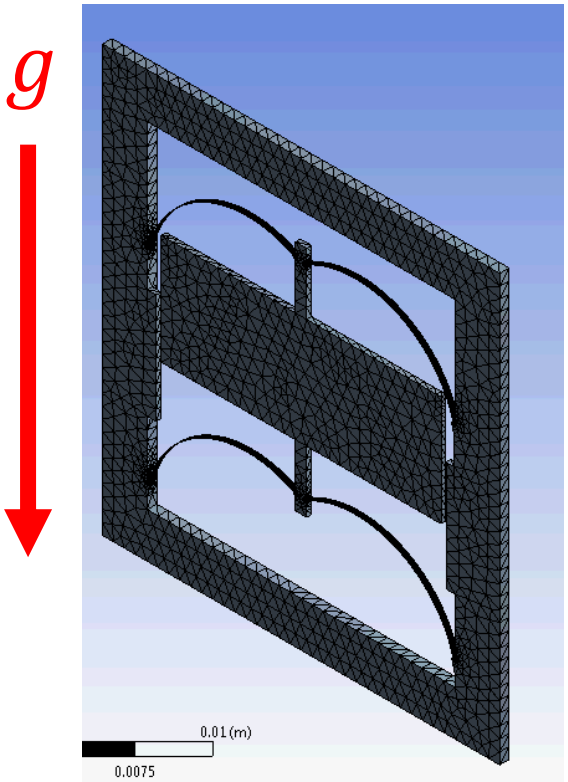
- Limited deployment capabilities
- Point-measurements
- Financially risky

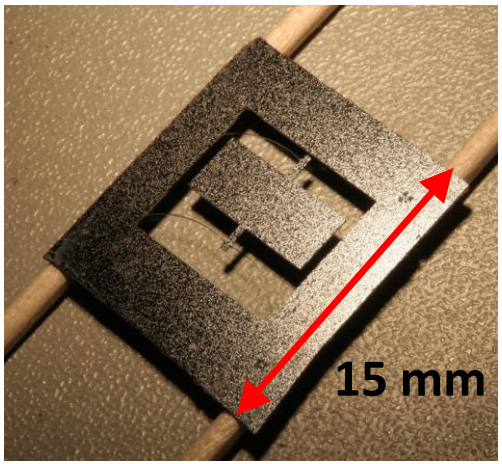
FG5-X Absolute Gravimeter by Microg LaCoste

CG-6 Autograv Gravity Meter by Scintrex

- Very good sensitivity (<1µGal) but > £80,000 price tag

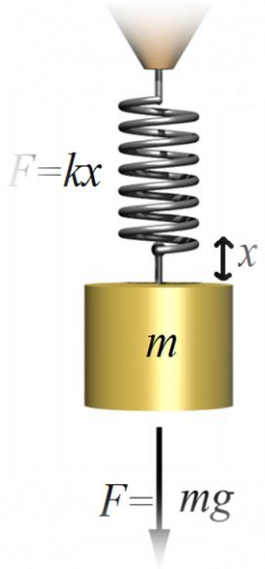
Wee-g Gravimeter Principle





$$\delta g = \left(\frac{k}{m}\right)\delta z$$

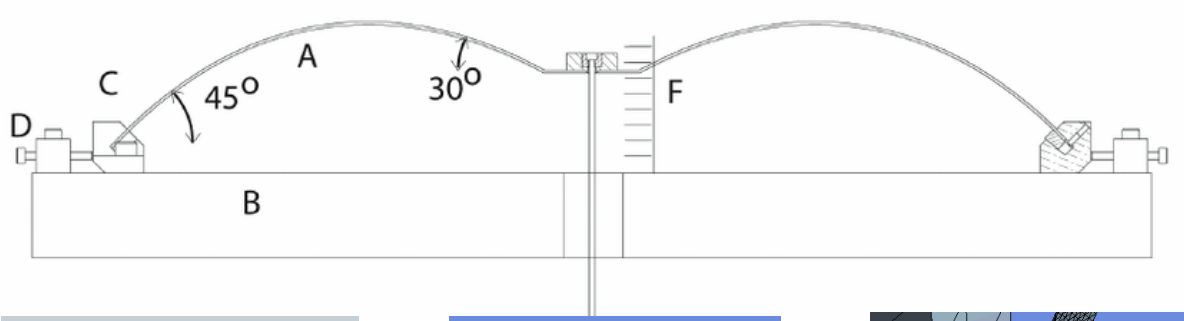
$$= \omega_0^2 \delta z$$



- A gravimeter is a device which measures changes in the local gravitational acceleration ($1g$ = 9.81 m/s^2)
- Variation in local density causes changes at the level up to 30 billionths of g
- This requires a soft spring and a large mass, a very good displacement sensor, or both

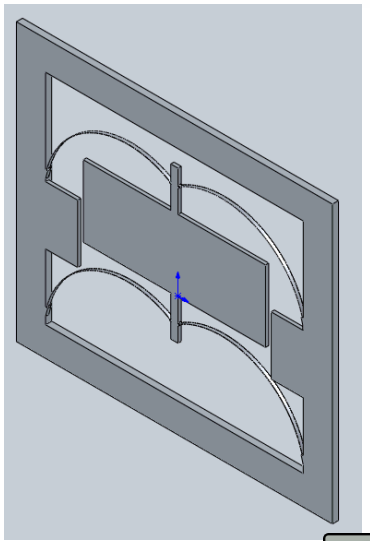
Geometric Antispring

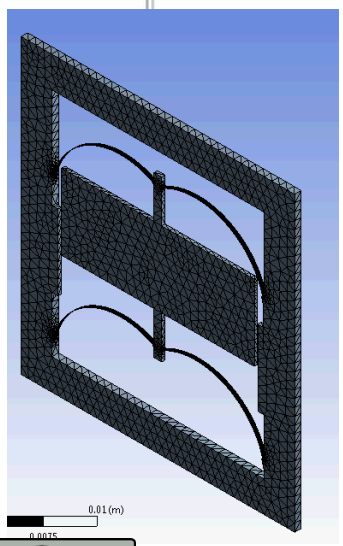
- A geometric antispring offers a very compact geometry which can be etched in silicon, providing a soft spring
- Geometric antisprings used in gravitational wave detectors (VIRGO) for seismic isolation; springs that get softer as you load them

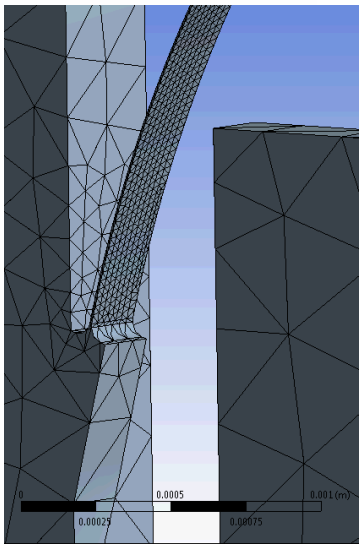


Geometric antisprings used in gravitational wave detectors (https://doi.org/10.1016/j.nima.2004.10.042)

g



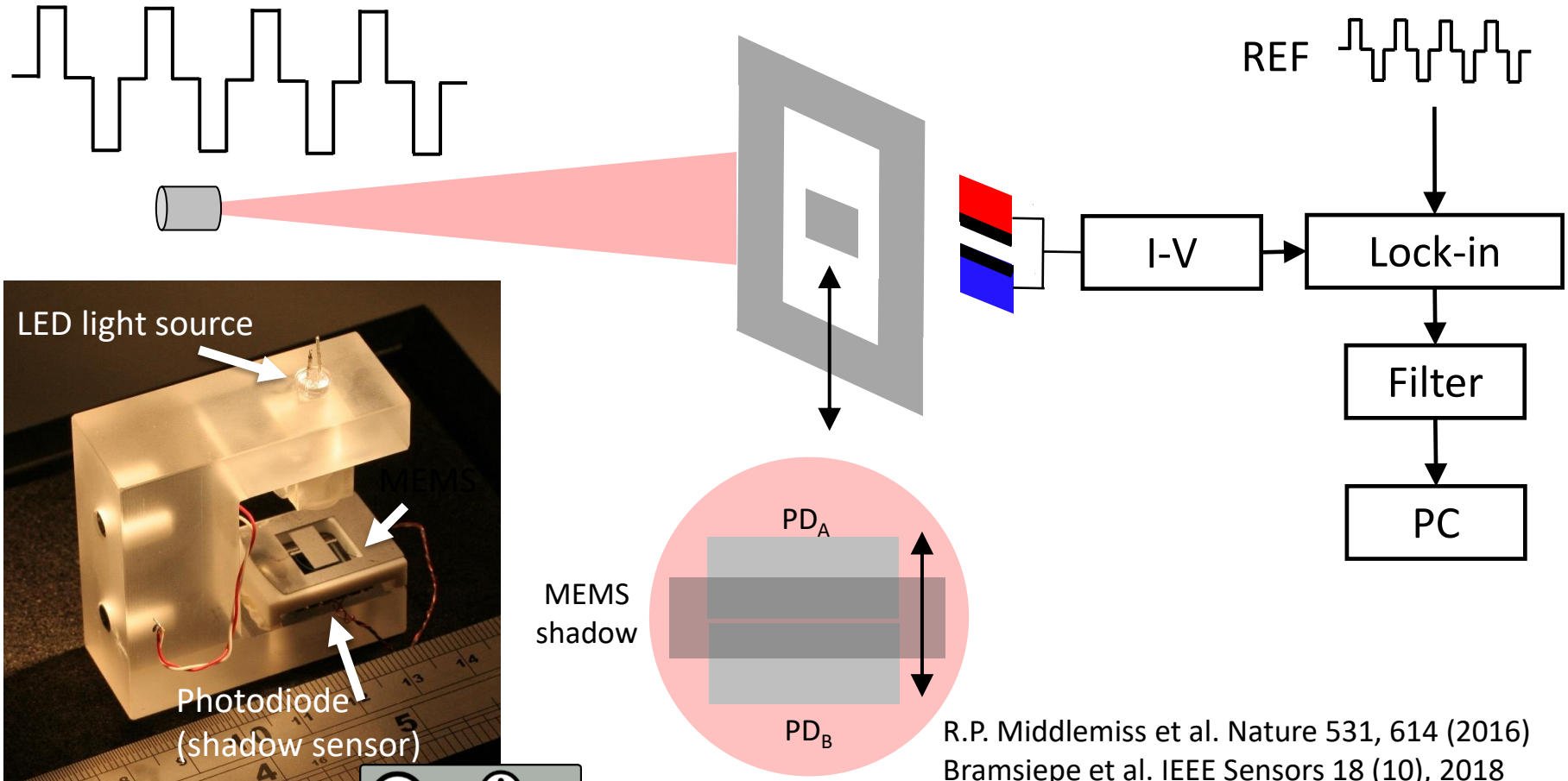




- We can build MEMS devices with 1Hz oscillation frequency and 0.02mg proof mass

Wee-g v1: Optical Shadow Sensor

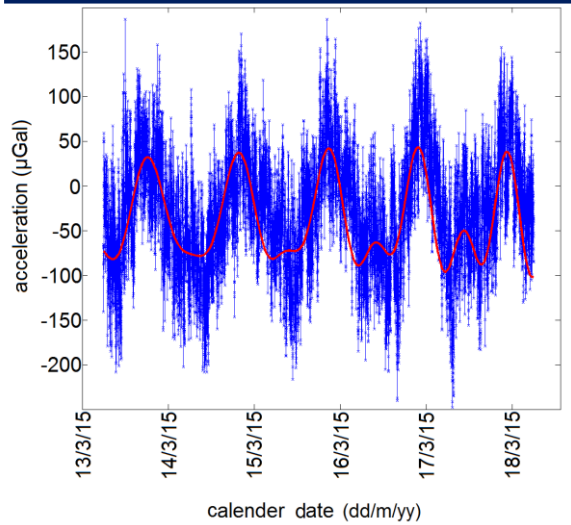
- Developed a shadow sensor that can provide stability of ±4nm over several days
- Split photodiode provides zero output at shadow centre, and immunity to relative intensity noise



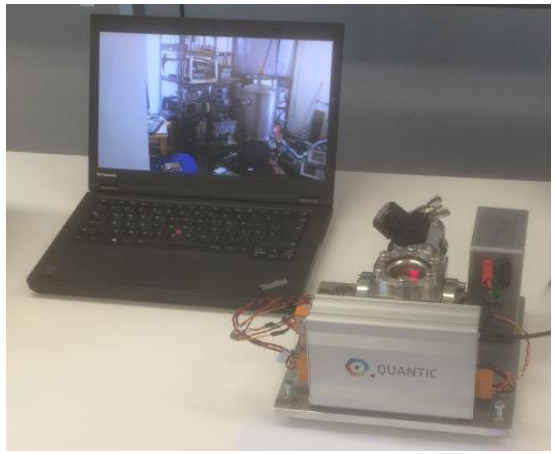
R.P. Middlemiss et al. Nature 531, 614 (2016)
Bramsiepe et al. IEEE Sensors 18 (10), 2018
Toninelli et al. Optics Express 25 (18), 2017

Wee-g v1: A portable MEMS Gravimeter

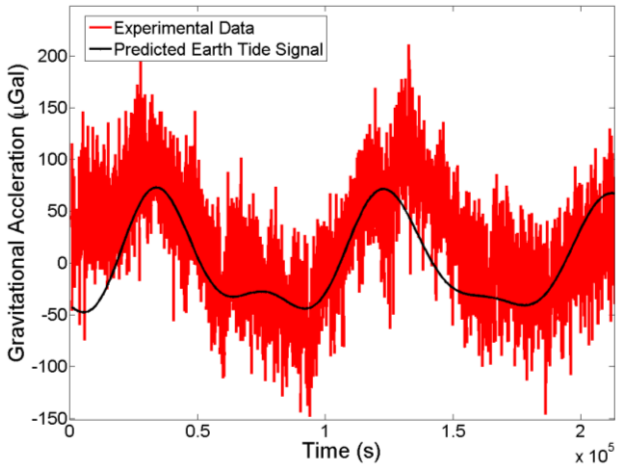
2015: lab-based system with mains power, rack mount electronics

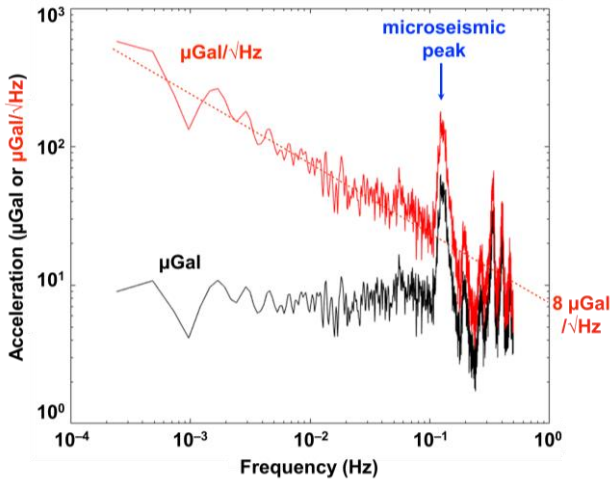


2016-18: shoebox sized field demonstrator, battery power



10 kg, 3.2W, 15 hrs battery
±2mK temp. control,
dsPIC μcontroller & SD card

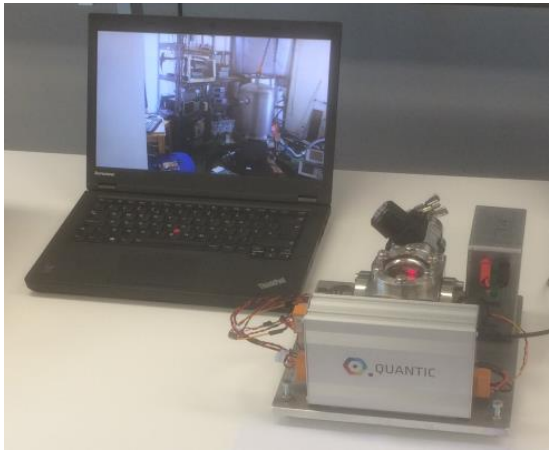


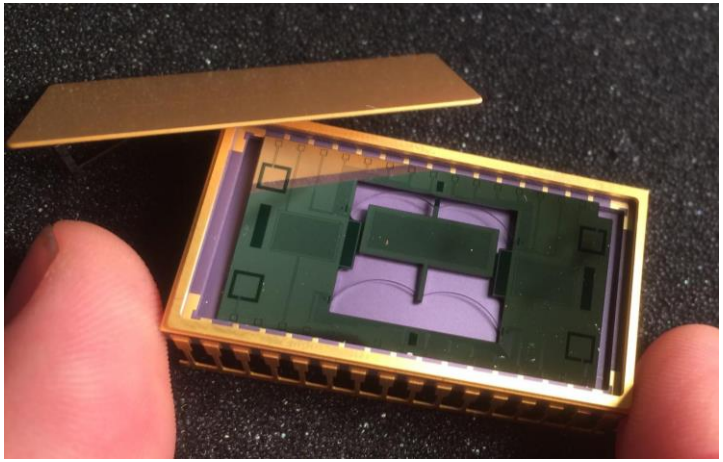


Wee-g v2: Capacitive Sensing

2015: lab-based system with mains power, rack mount electronics

2016/18: shoebox sized field demonstrator, battery power

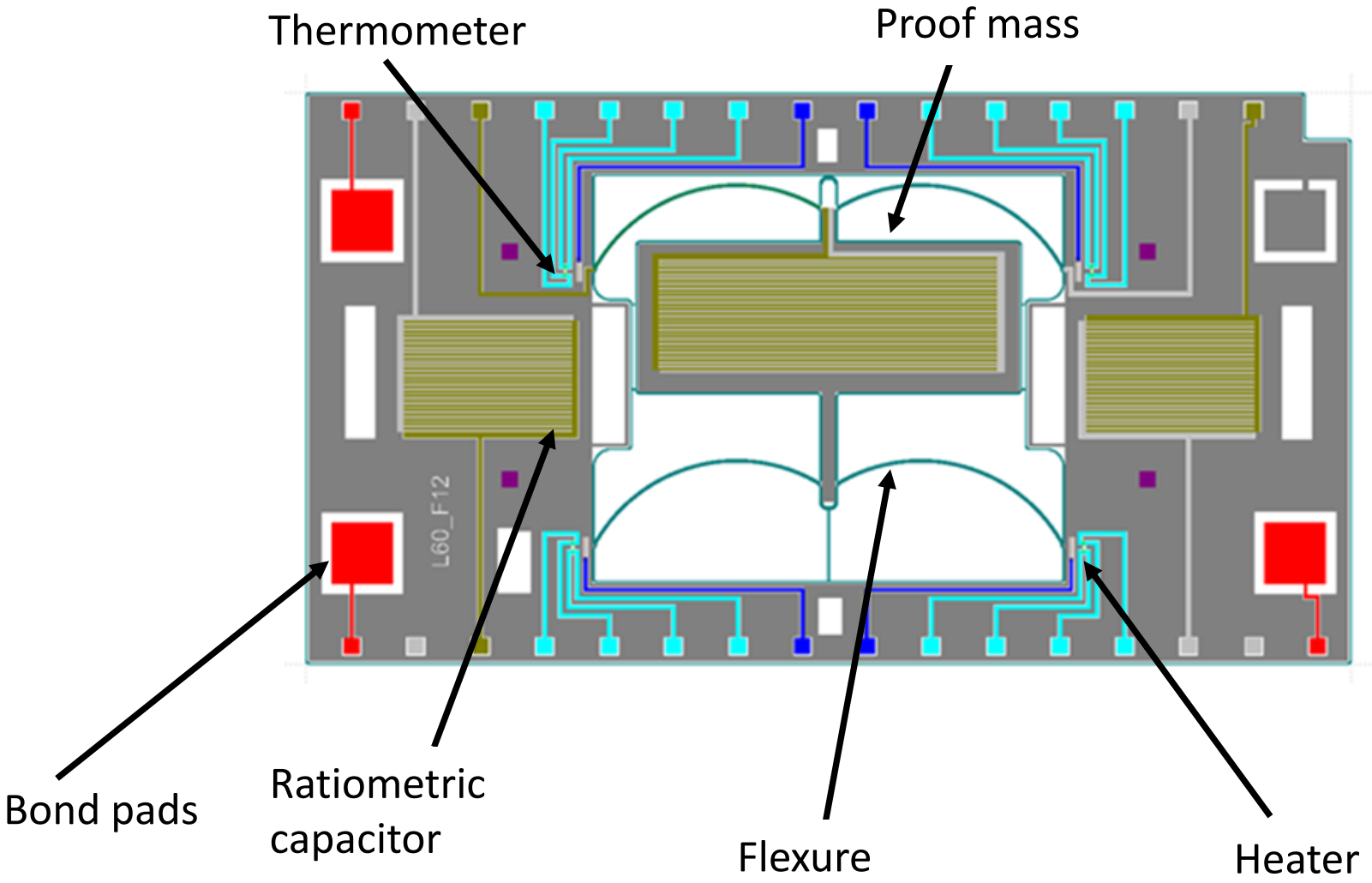




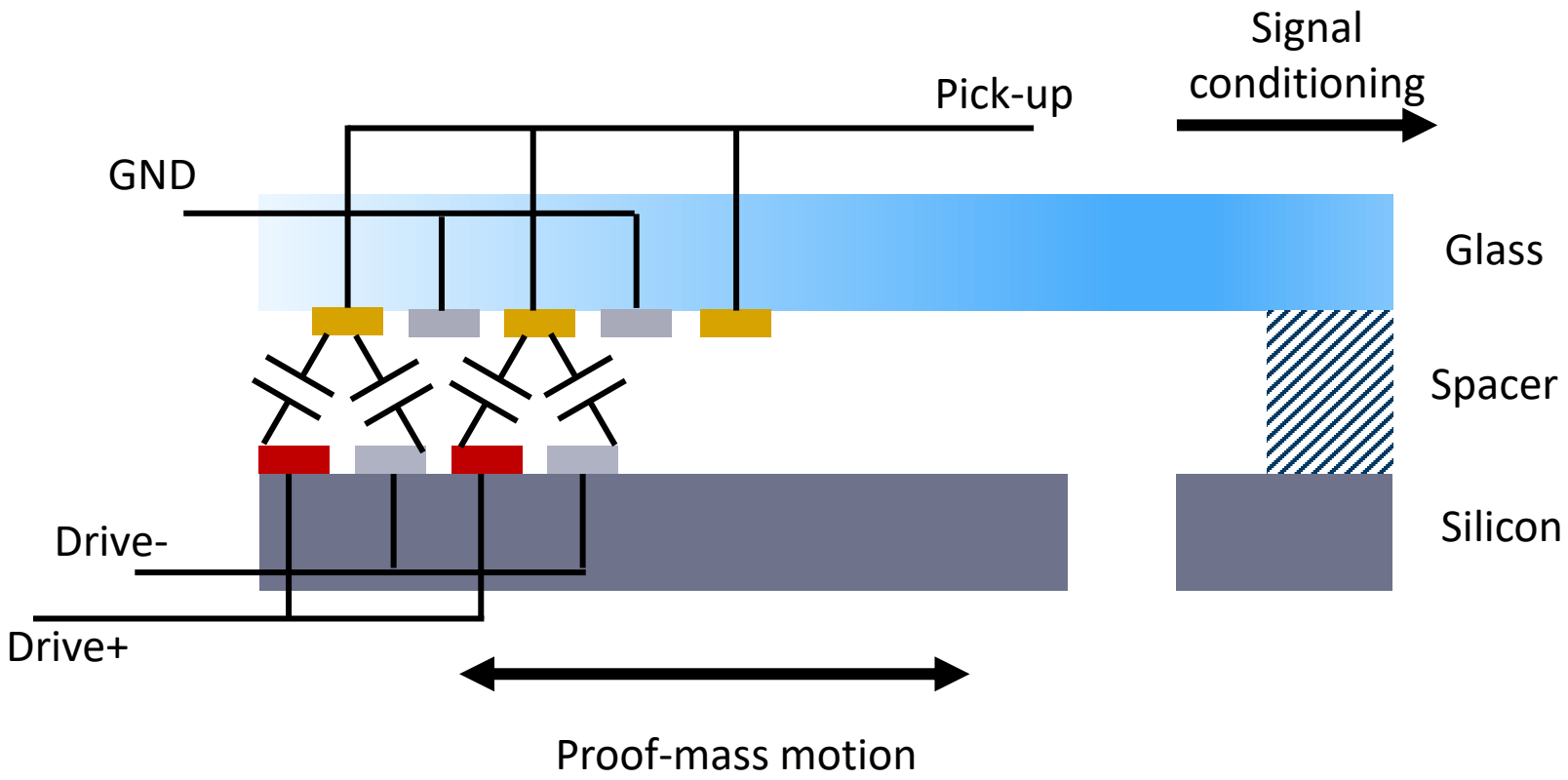
2018/20: packaged device with FPGA readout

Wee-g v2: The Device

- Capacitive sensing allows vacuum packaging and has an improved sensitivity

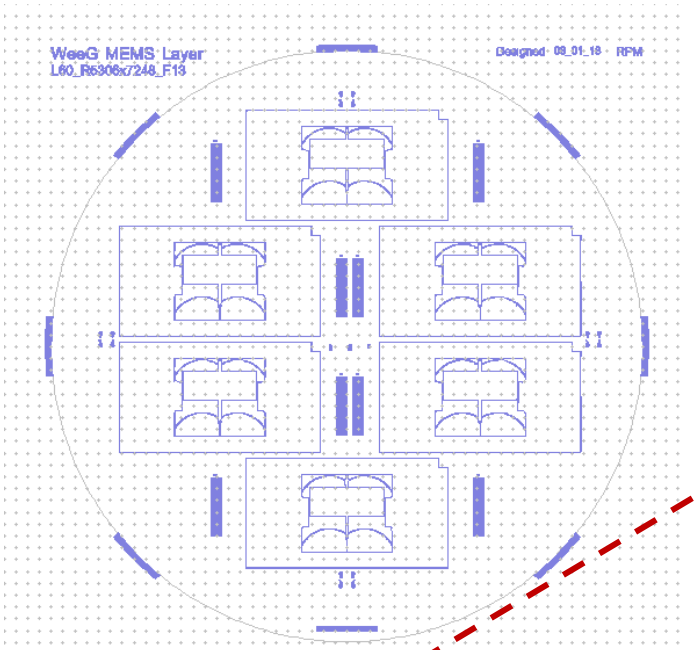


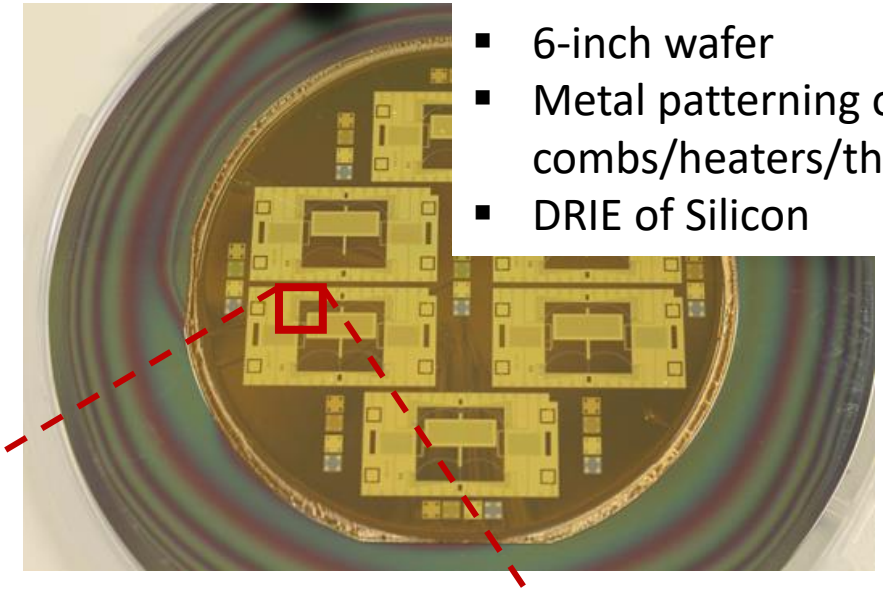
Capacitive Displacement Sensing



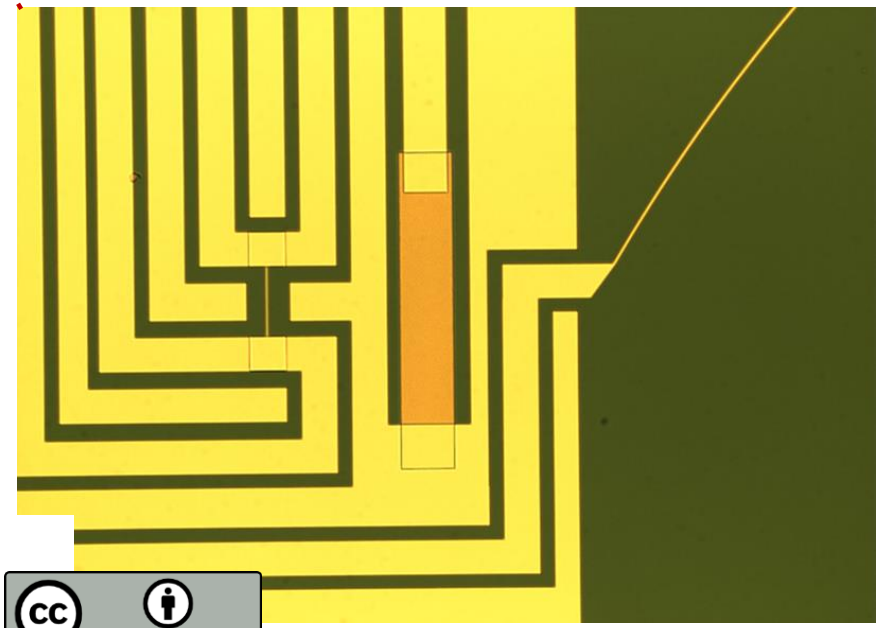
- Interdigitated combs are patterned on the moving proof-mass (Si) and the fixed signal pick-up frame (Glass)
- Proof-mass displacement affects the capacitive coupling between the combs which is read and converted to useful units
- Readout of sub-aF capacitance change possible (or, 10s of pm proof-mass displacement for a 6-7 Hz device)

Fabrication

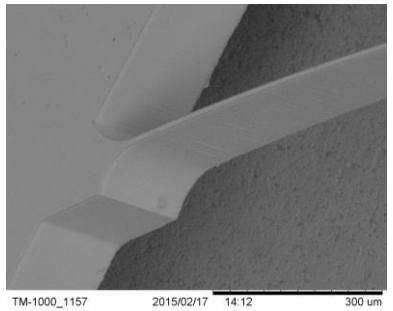


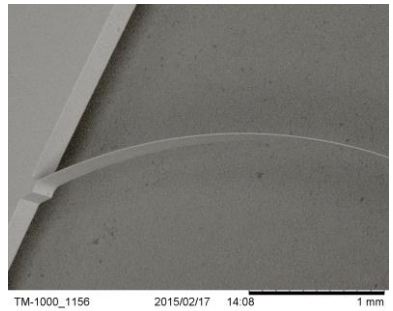


- 6-inch wafer
- Metal patterning of combs/heaters/thermometers
- DRIE of Silicon



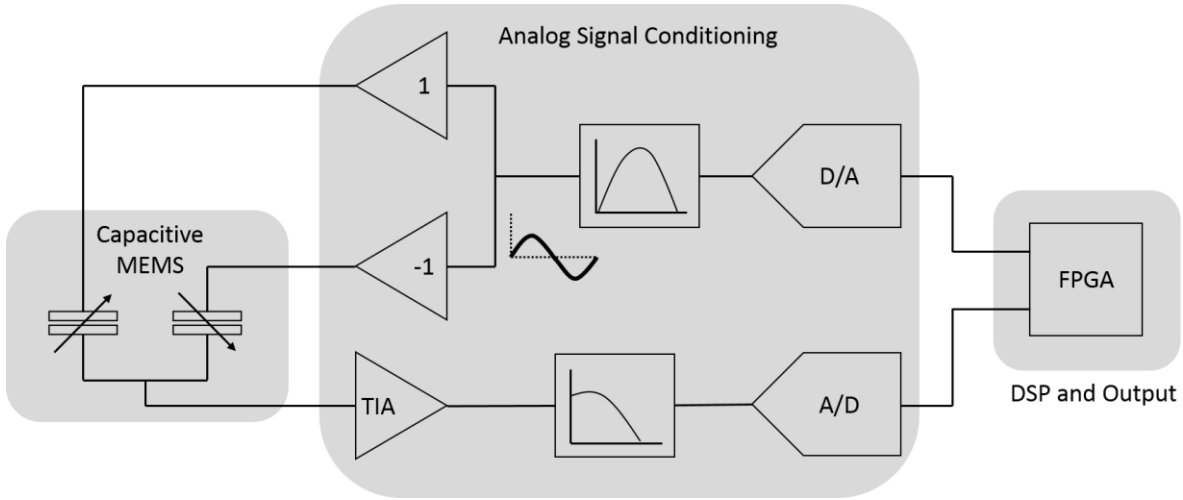
SEM of flexures



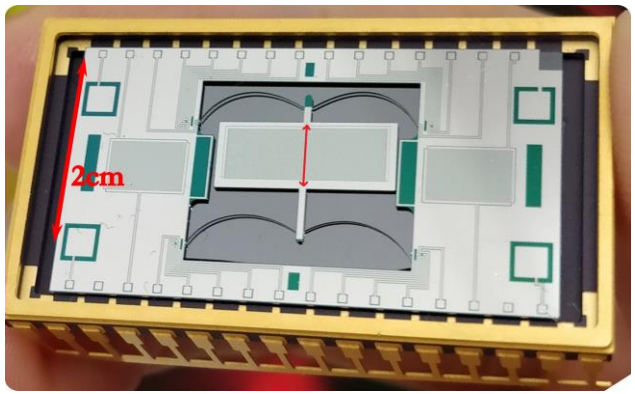


KELVIN NANOTECHNOLOGY

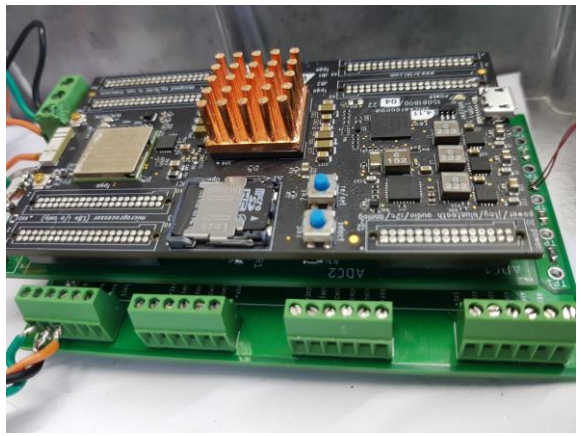
FPGA Electronics



Read-out circuit with sub-aF capacitive detection (~10s of pm in displacement)



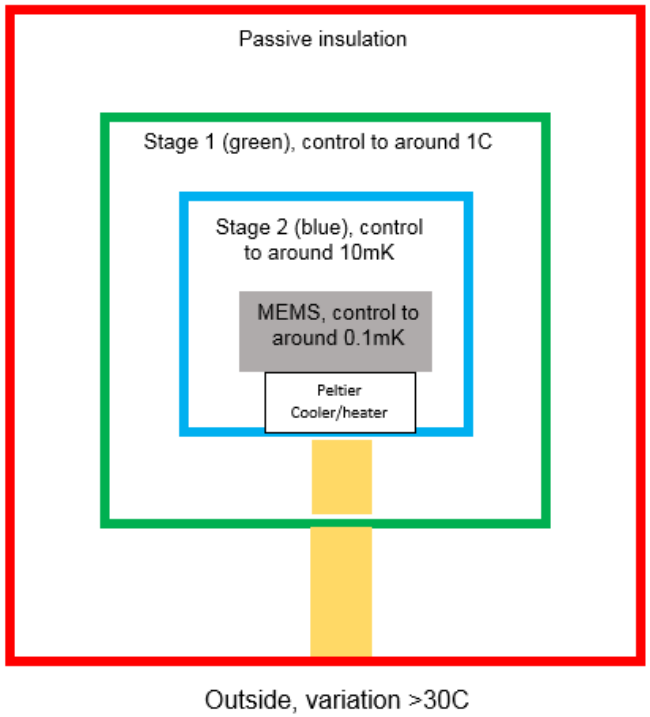
Packaged MEMS



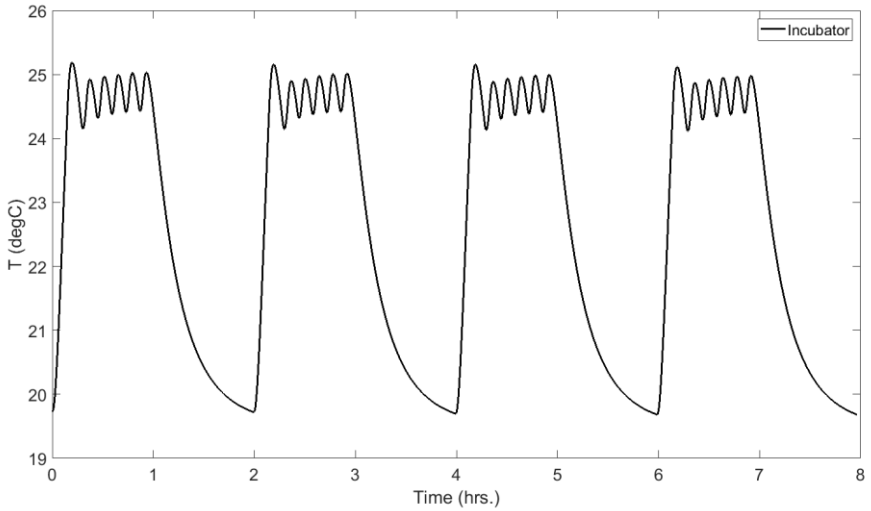
FPGA + Signal Conditioning

Thermal Enclosure

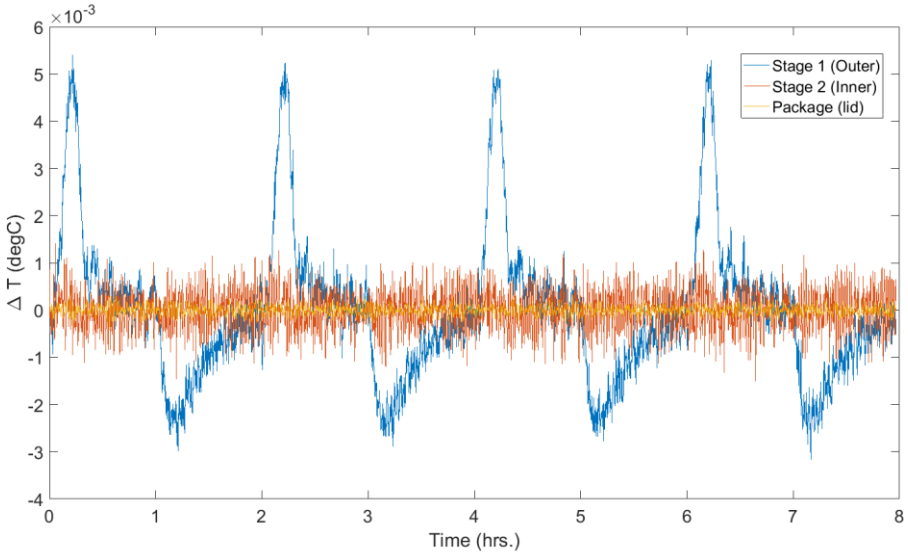
- Device is temperature sensitive (via Young's modulus)
- External active control needs to be implemented
- A thermal enclosure has been developed with ~0.1mK control around the nominal setpoint



Testing the performance in an incubator

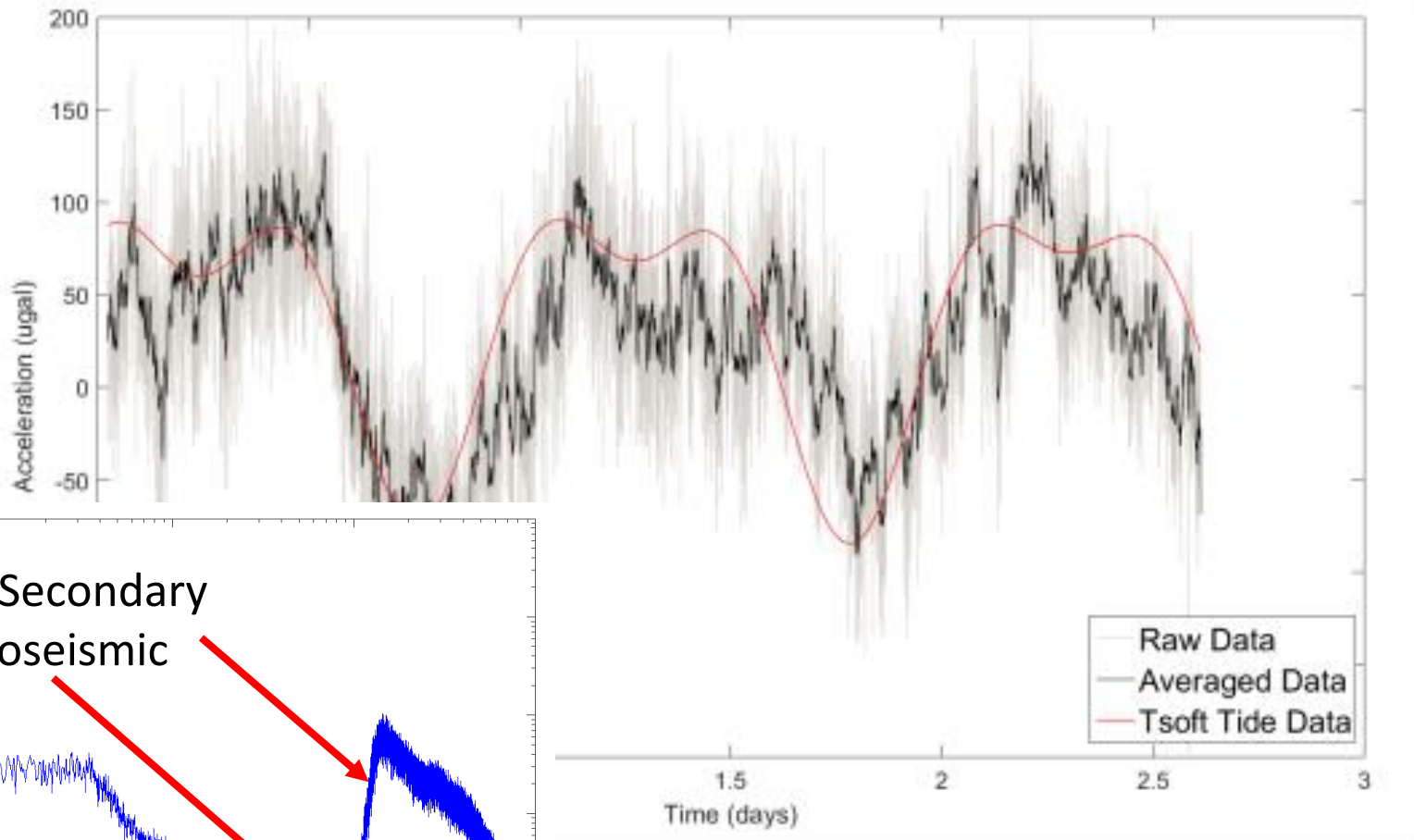


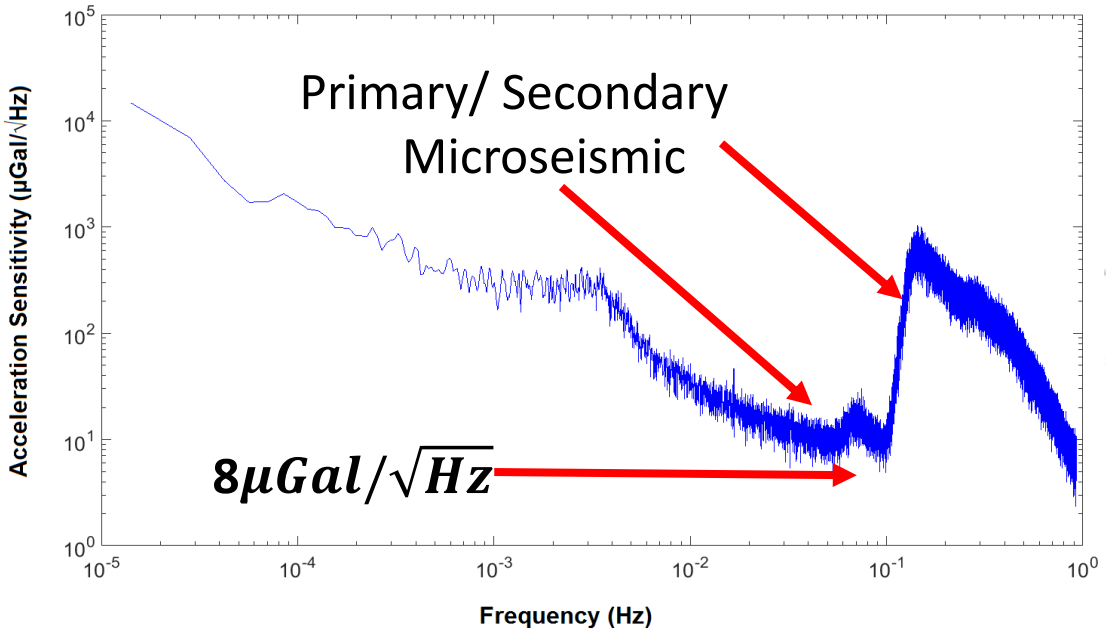
Incubator



Enclosure

Earth Tides Detection





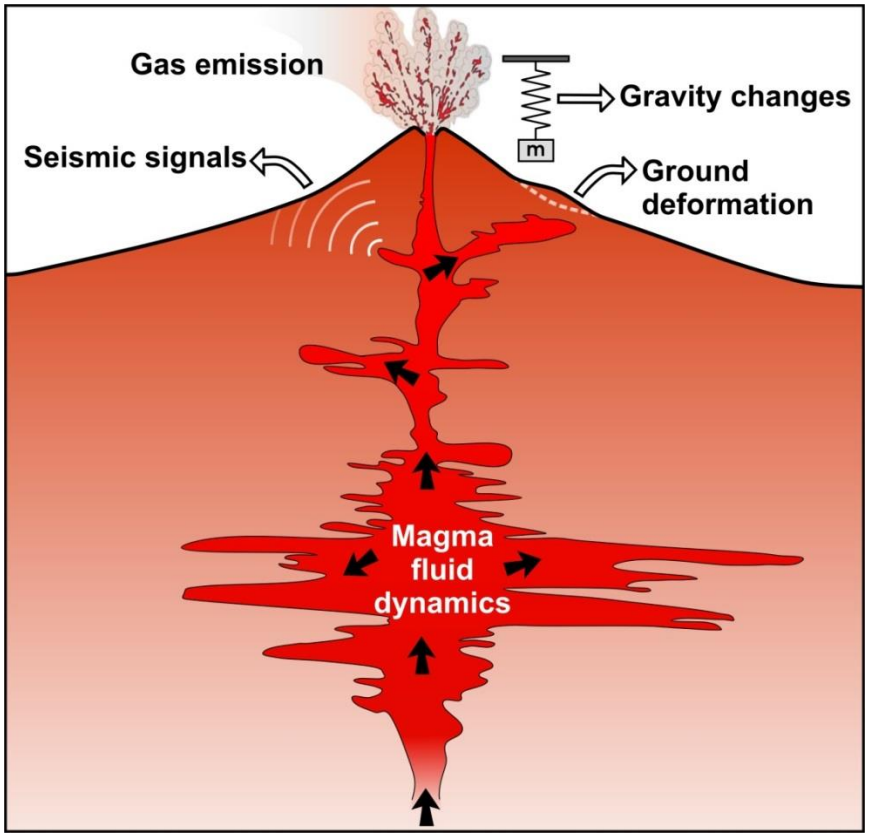
- FPGA readout
- Better sensitivity than using SRS Lock-in

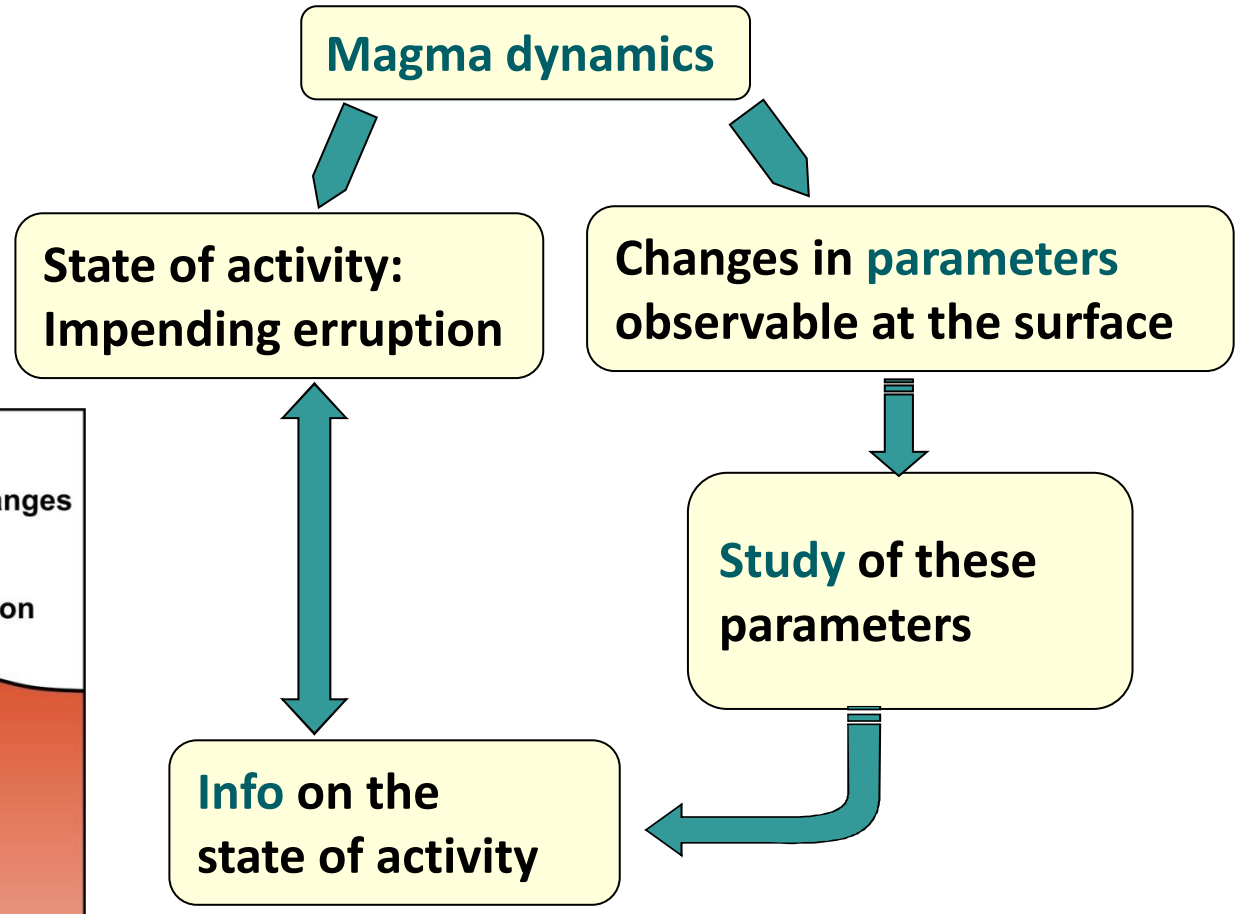
Wee-g on Mt. Etna

- NEWTON-g proposes a paradigm shift in terrain gravimetry, aimed at overcoming the limitations imposed by currently available instrumentation.

- The new "gravity imager" is being developed, including sensors based on MEMS and quantum technologies.

Volcano Gravimetry





- Add multi-pixel gravity imager to existing ground deformation and seismic monitoring

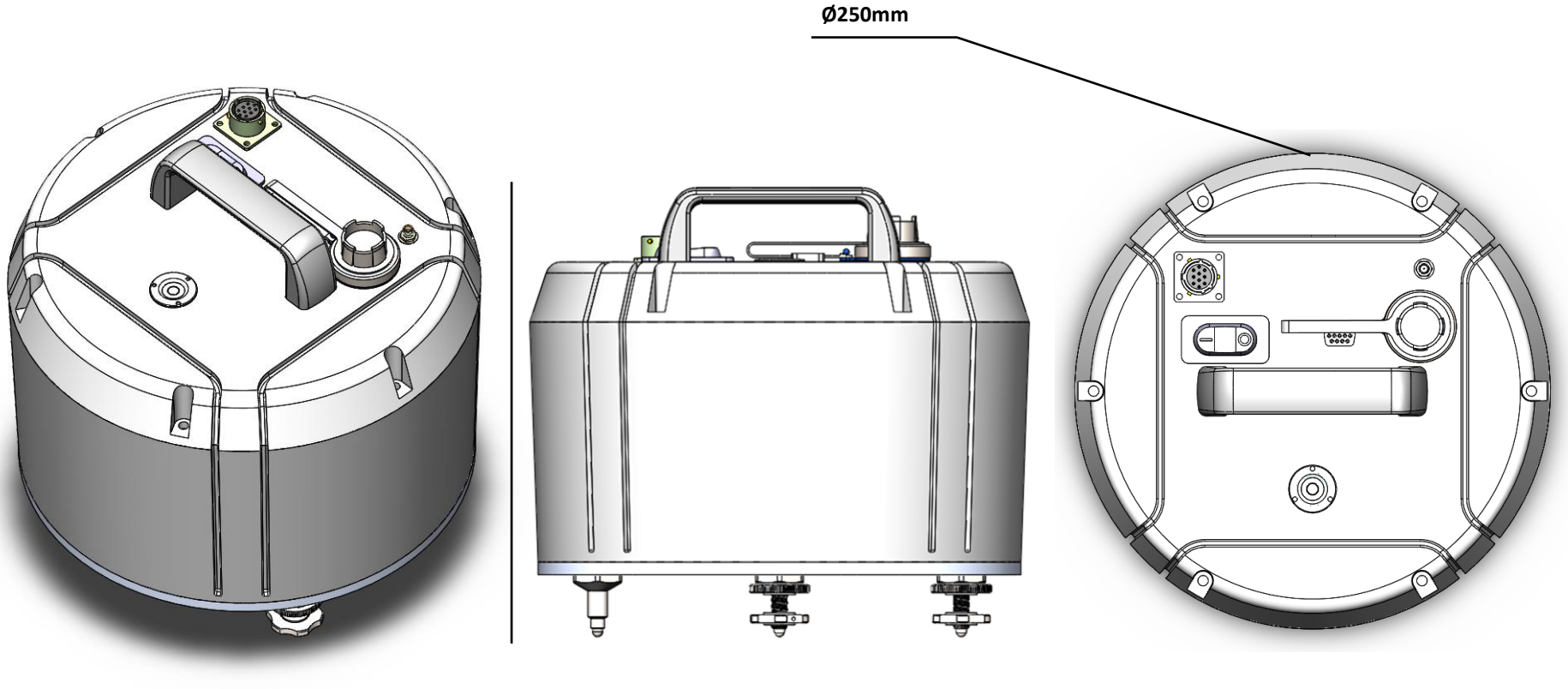
Gravimeter requirements

Multiple Wee-g gravimeters will be deployed on Mt Etna for 'Multi-pixel' imaging

Stringent deployment requirements:

- Constraints on housing
- Power from solar panel +battery
- Adjustment of tilt
- Environmental control
- Self-calibration
- Data communication
- Ingress protection

MEMS Prototype for Field Deployments



Isometric view

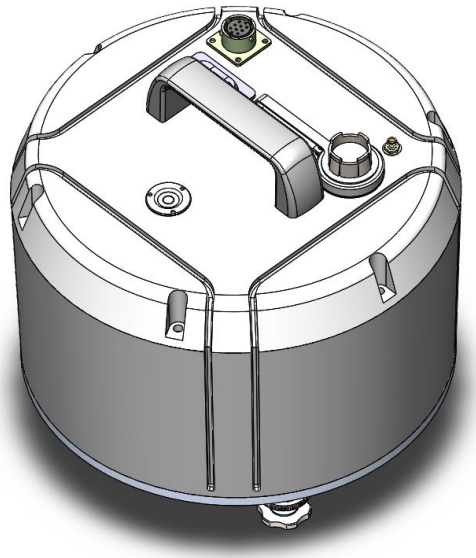
Height 225mm

Elevation view

Top down view

- IP67 enclosure,
- <5kg, 5W
- Embedded sensor and conditioning/control electronics
- Remote tilt adjustment/calibration
- UART data transfer

MEMS Prototype for Field Deployments



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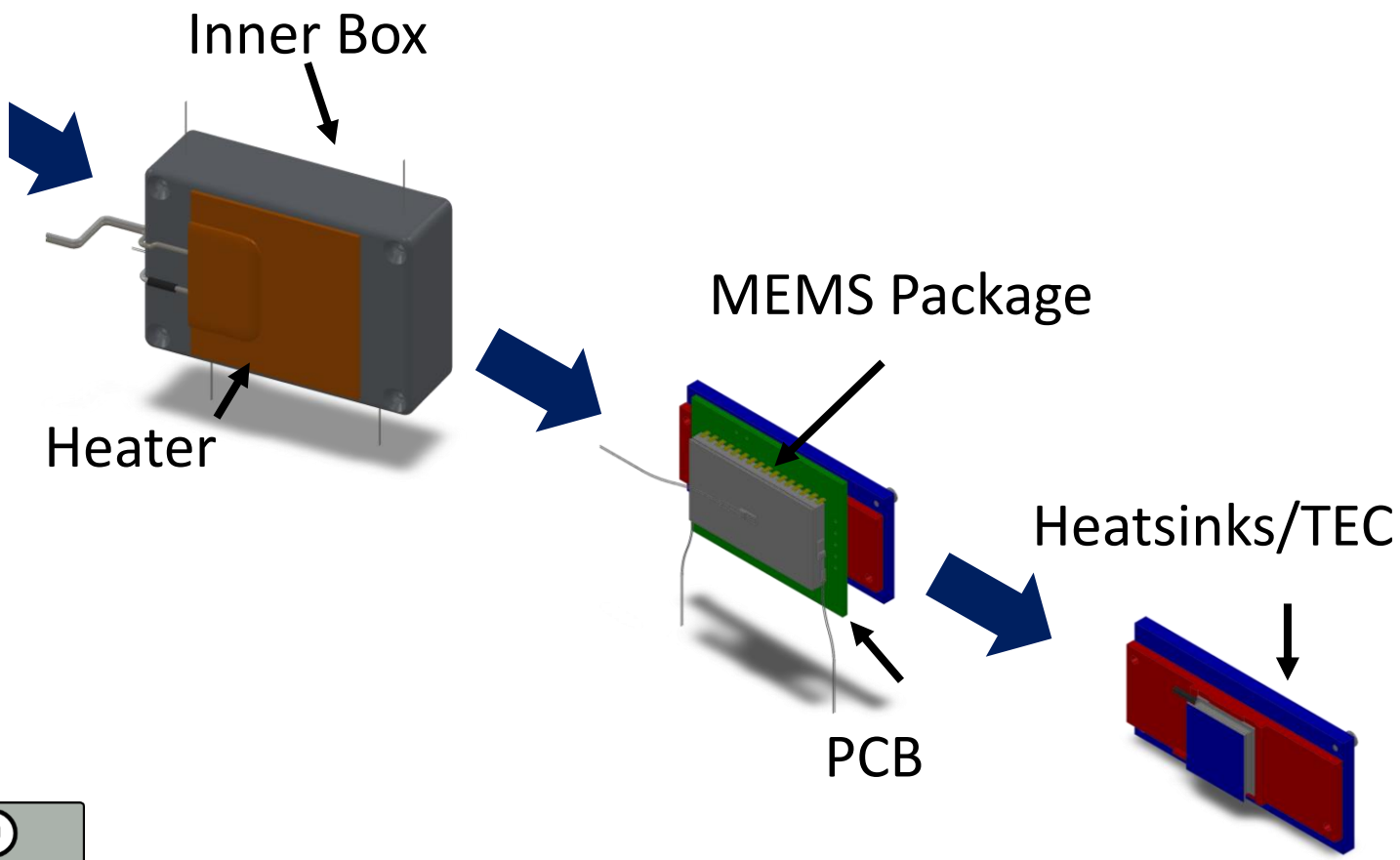
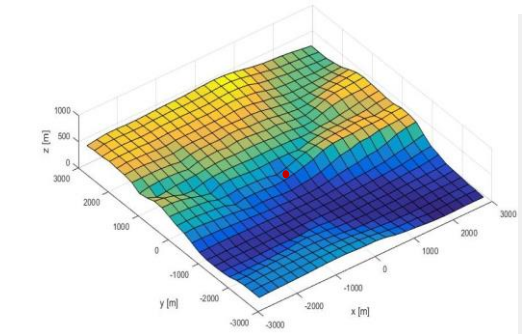


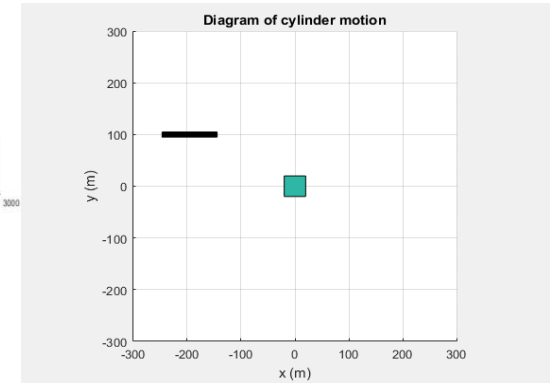
Other applications

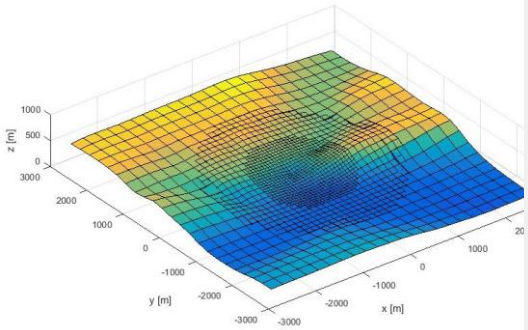
Airborne Gravimetry

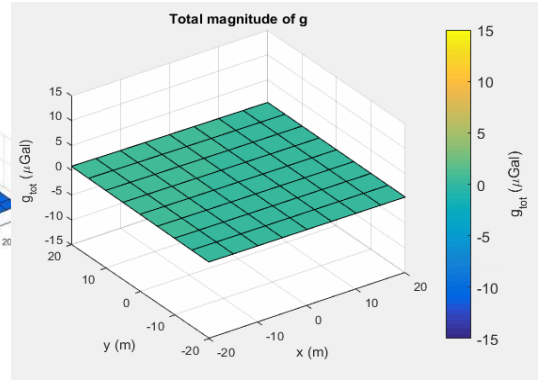
- 100km line gravity surveys with gravimeter/gradiometers on drone platforms
- Recovery of ~1mGal signals

Underwater Sensing









Developing tools for terrain/gravity modelling

University of Glasgow

The Glasgow Team

IGR

JWNC The James Watt Nanofabrication Centre

University of Glasgow

Collaborators

GFZ
Helmholtz-Zentrum
POTSDAM

University of Glasgow

QUANTIC

μQUANS

Koninklijk Nederlands
Meteorologisch Instituut
Ministerie van Infrastructuur en Waterstaat

UNIVERSITÉ
DE GENÈVE

INGV

UK National
Quantum Technology Hub
Sensors and Metrology

Schlumberger

optocap

QinetiQ

Innovate UK

KAIAM

CLYDE
SPACE

KELVIN
NANOTECHNOLOGY

IQE

European
Commission

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