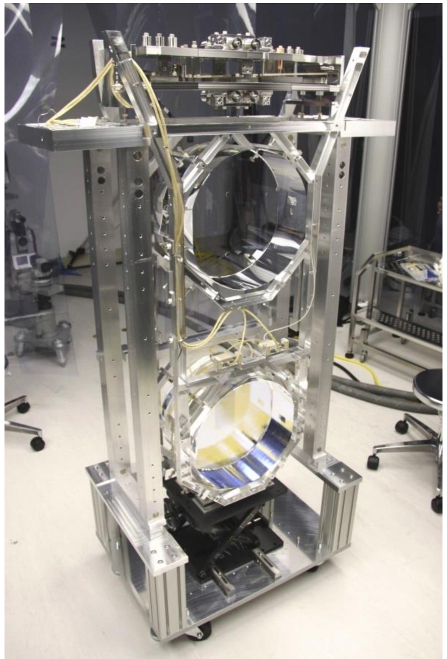
A Low Cost MEMS Gravimeter

Abhinav Prasad
Institute for Gravitational Research
SUPA, University of Glasgow
Abhinav.Prasad@glasgow.ac.uk
Giles.Hammond@glasgow.ac.uk

A. Prasad, R. P. Middlemiss, S. Bramsiepe, A. Noack, M. Aftalion, M. Sinclair, G. A. Marocco, J. Hough, S. Hild, S. Rowan, D. J. Paul & G. D. Hammond,

Fundamental Research-Quantum Technologies

University of Glasgow



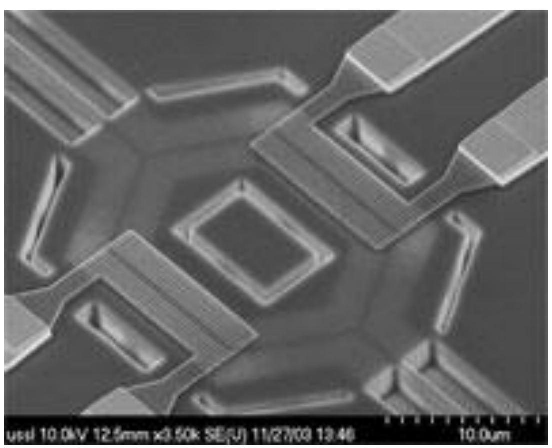
Institute for Gravitational Research
(https://www.physics.gla.ac.uk/igr/)

THE ROYAL SOCIETY

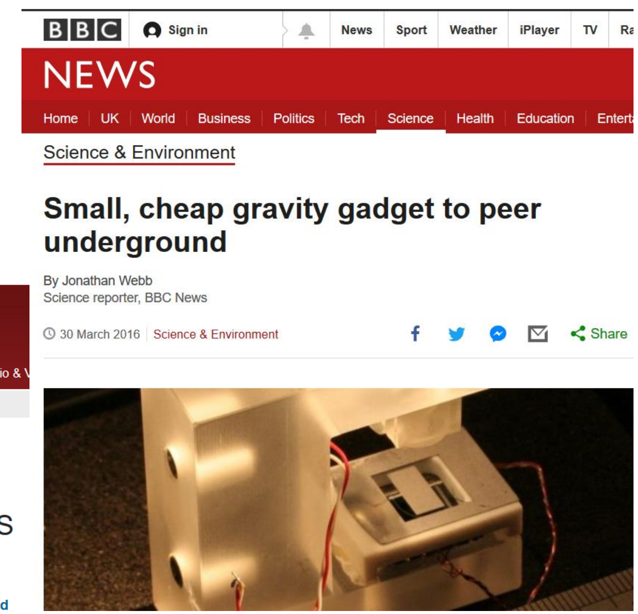
Paul Instrument Fund

Fundamental research

Applied research



James Watt Nanofabrication Centre
(http://www.jwnc.gla.ac.uk/about.html)


BBC NEWS

Home | UK | World | Business | Politics | Tech | Science | Health | Education

Science & Environment

Small, cheap gravity gadget to peer underground

By Jonathan Webb
Science reporter, BBC News

30 March 2016 | Science & Environment


nature International weekly journal of science

Home | News & Comment | Research | Careers & Jobs | Current Issue | Archive | Audio & V

Archive > Volume 531 > Issue 7596 > Letters > Article

NATURE | LETTER

日本語要約

Measurement of the Earth tides with a MEMS gravimeter

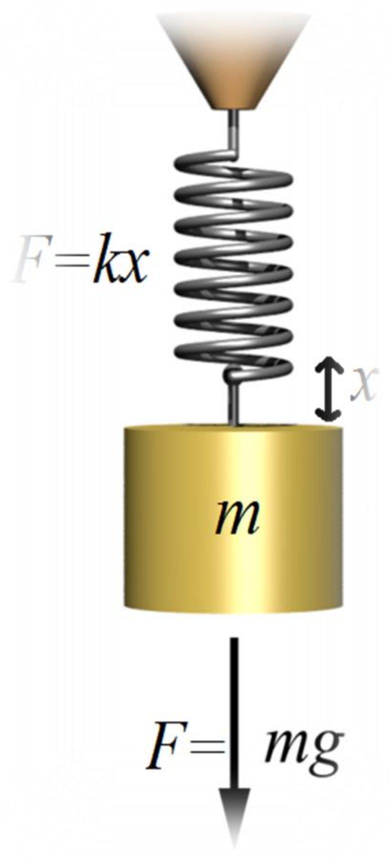
R. P. Middlemiss, A. Samarelli, D. J. Paul, J. Hough, S. Rowan & G. D. Hammond

UK Quantum Technology Hub in Enhanced Quantum Imaging (https://quantic.ac.uk)

QUANTIC

Gravimeters

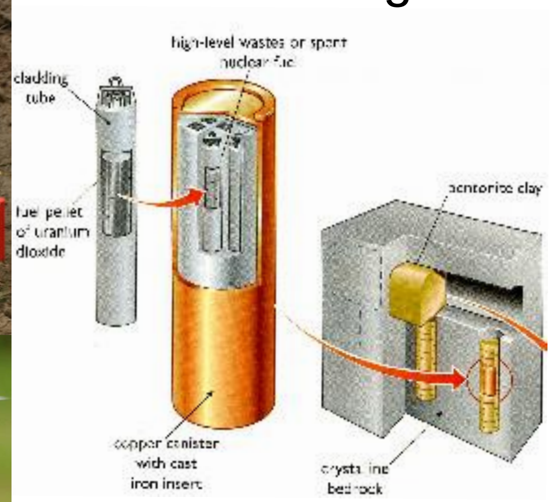
- A gravimeter is a device which measures changes in the local gravitational acceleration (1*g* = 9.81 m/s^2)
- Variation in local density causes changes at the level up to 30 billionths of *g*



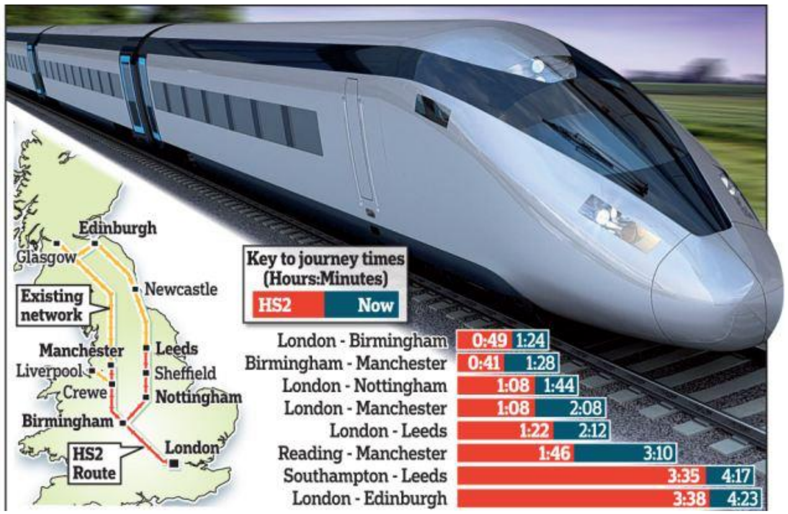
Gravity Imaging Applications

Oil & gas prospecting

Environmental monitoring



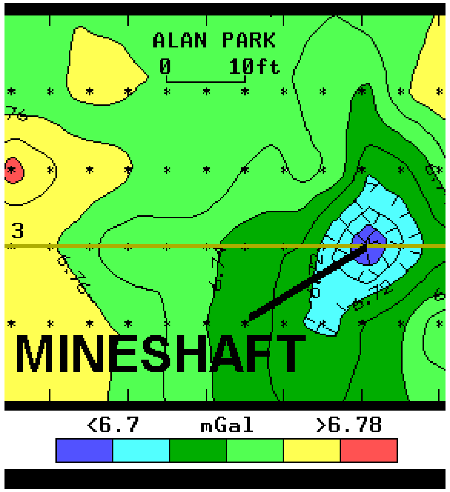
HS2



Security & Defence

Volcano monitoring

Sink hole detection



Commercial Gravimeters

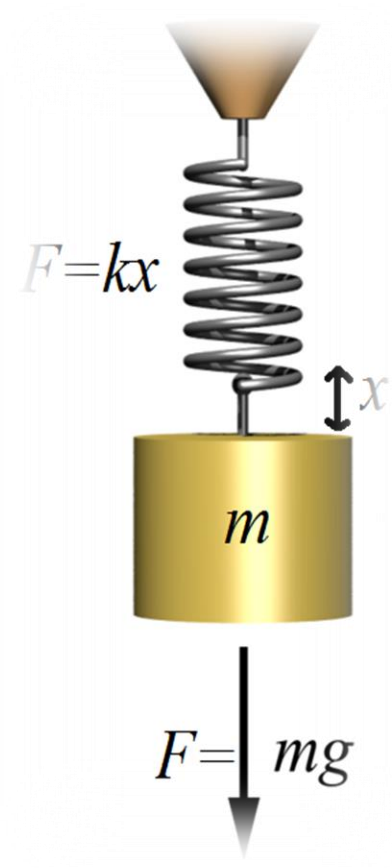
iPhone

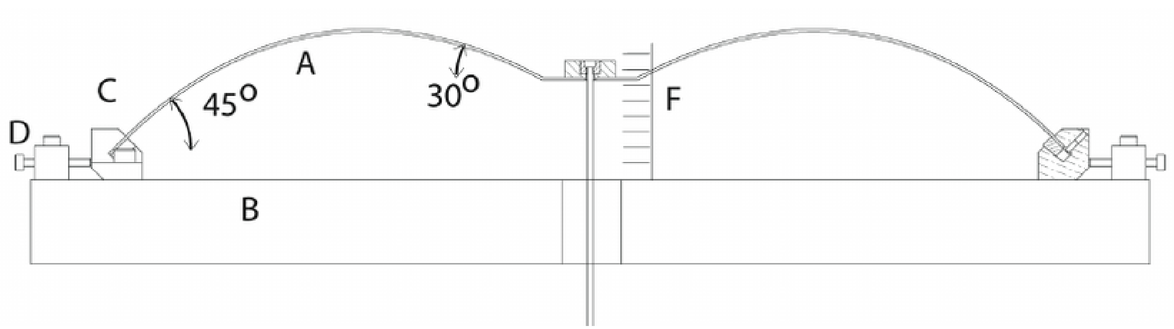
CG-6

- Cheap but 10000 times too insensitive
- Very good sensitivity but £70,000 (nano-g and sub nano-g sensitivity)

Gravimeters

- A gravimeter is a device which measures changes in the local gravitational acceleration (1*g* = 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
- A geometric anti-spring offers a very compact geometry which can be etched in silicon, providing a soft spring



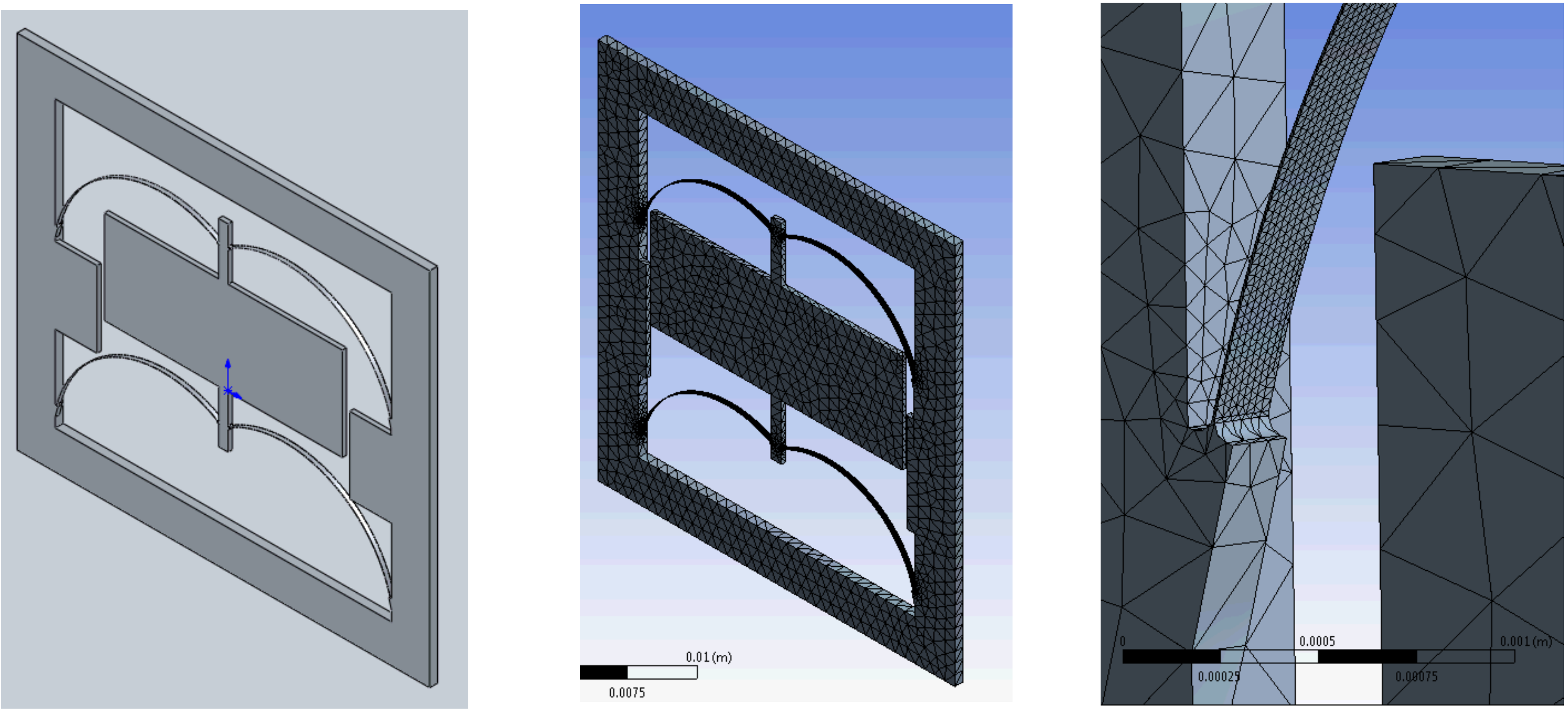


Geometric antisprings used in gravitational wave detectors (https://arxiv.org/abs/gr-qc/0406091)

IGR
JWNC
The James Watt Nanofabrication Centre

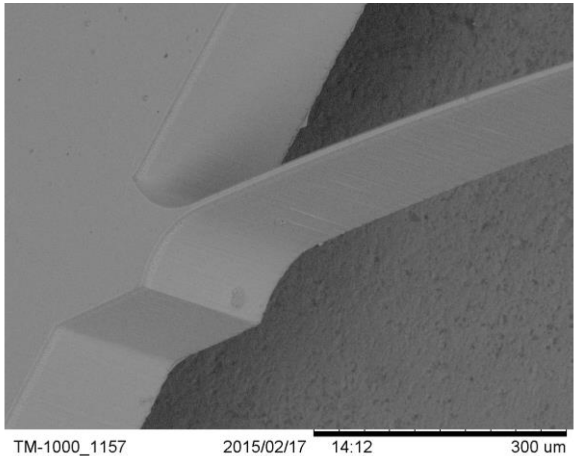
Geometric Antispring

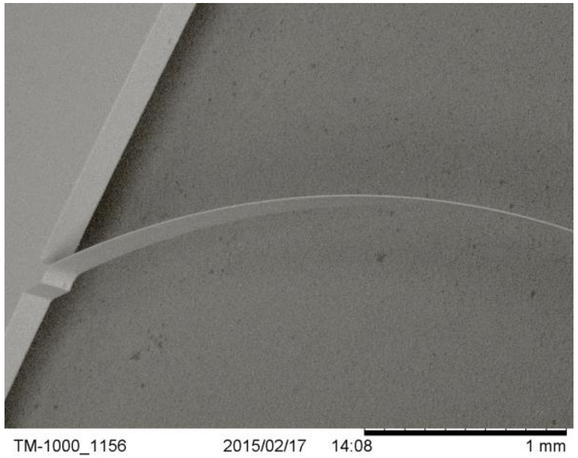
- Geometric antisprings used in gravitational wave detectors (VIRGO) for seismic isolation; springs that get softer as you load them



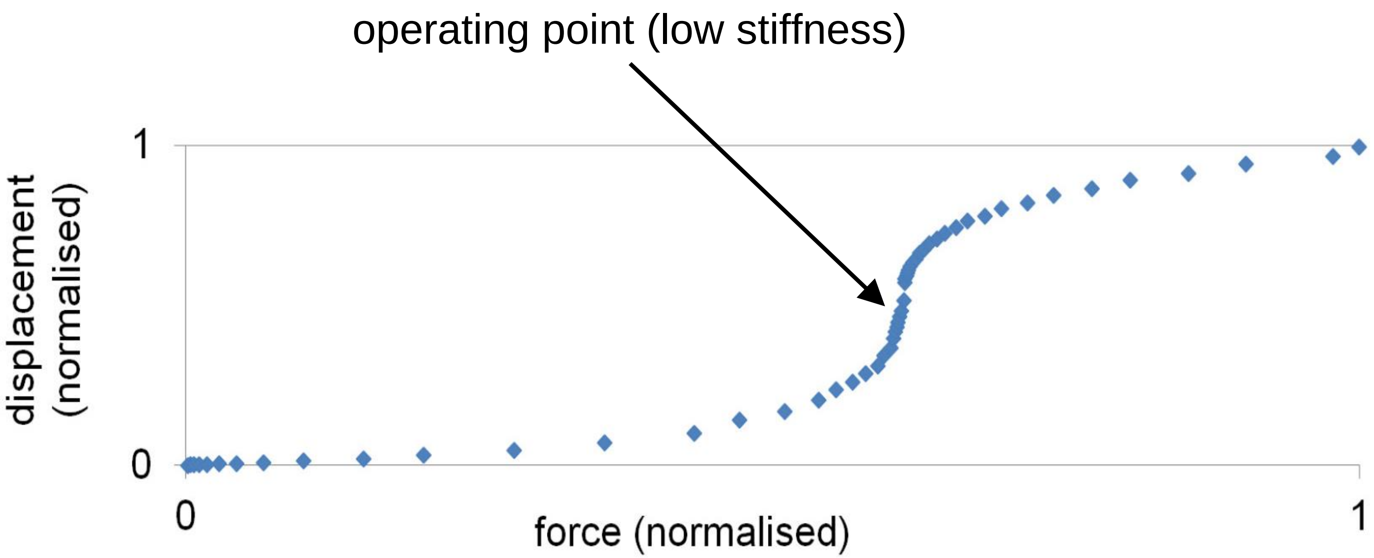
- We can build MEMS devices with 1Hz oscillation frequency and 0.02mg proof mass
- Excellent agreement between modelled proof mass displacement/frequencies and the measured ones

Geometric Antispring



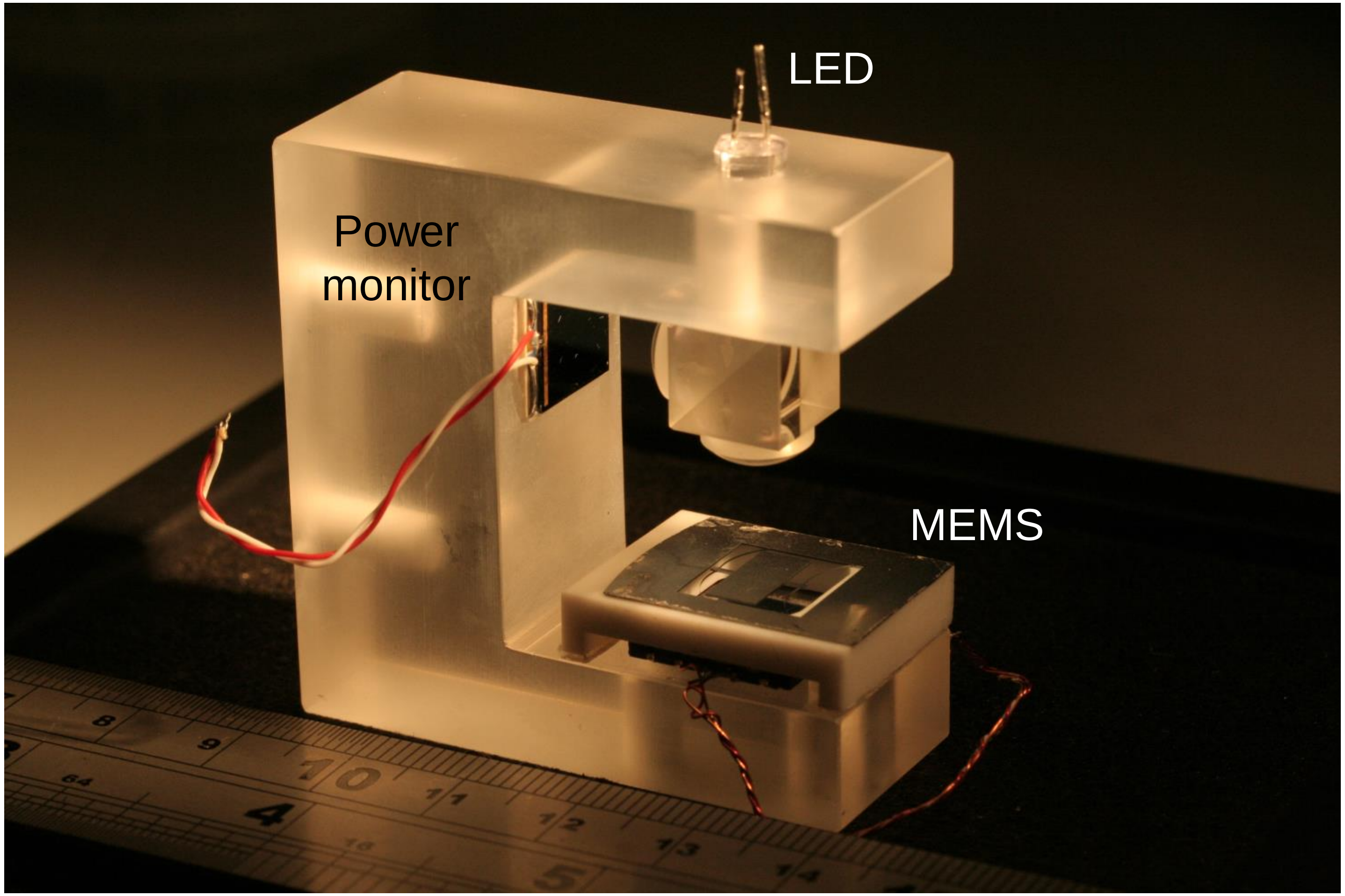


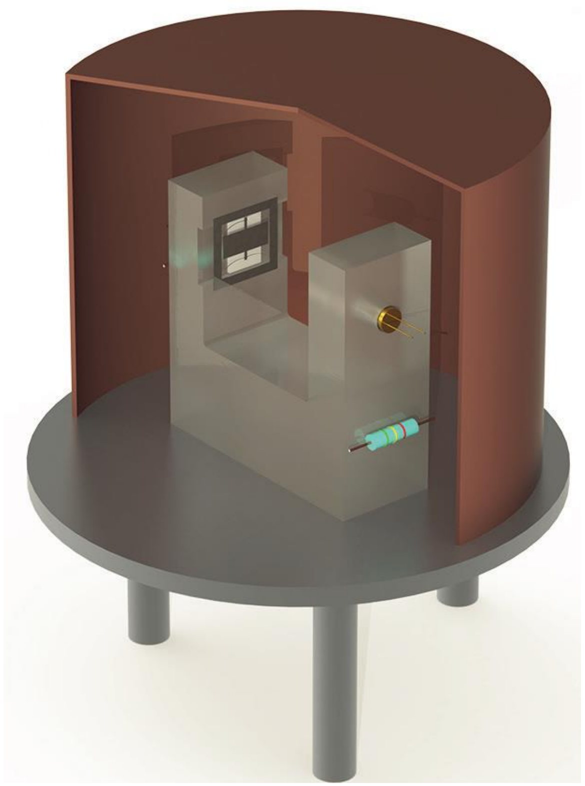
Silicon flexures are Deep-Reactive-Ion-Etched (DRIE); 220μm thick and 9μm wide



- We can build MEMS devices with 1Hz oscillation frequency and 0.02mg proof mass
- Excellent agreement between modelled proof mass displacement/frequencies and the measured ones

Glasgow MEMS Device

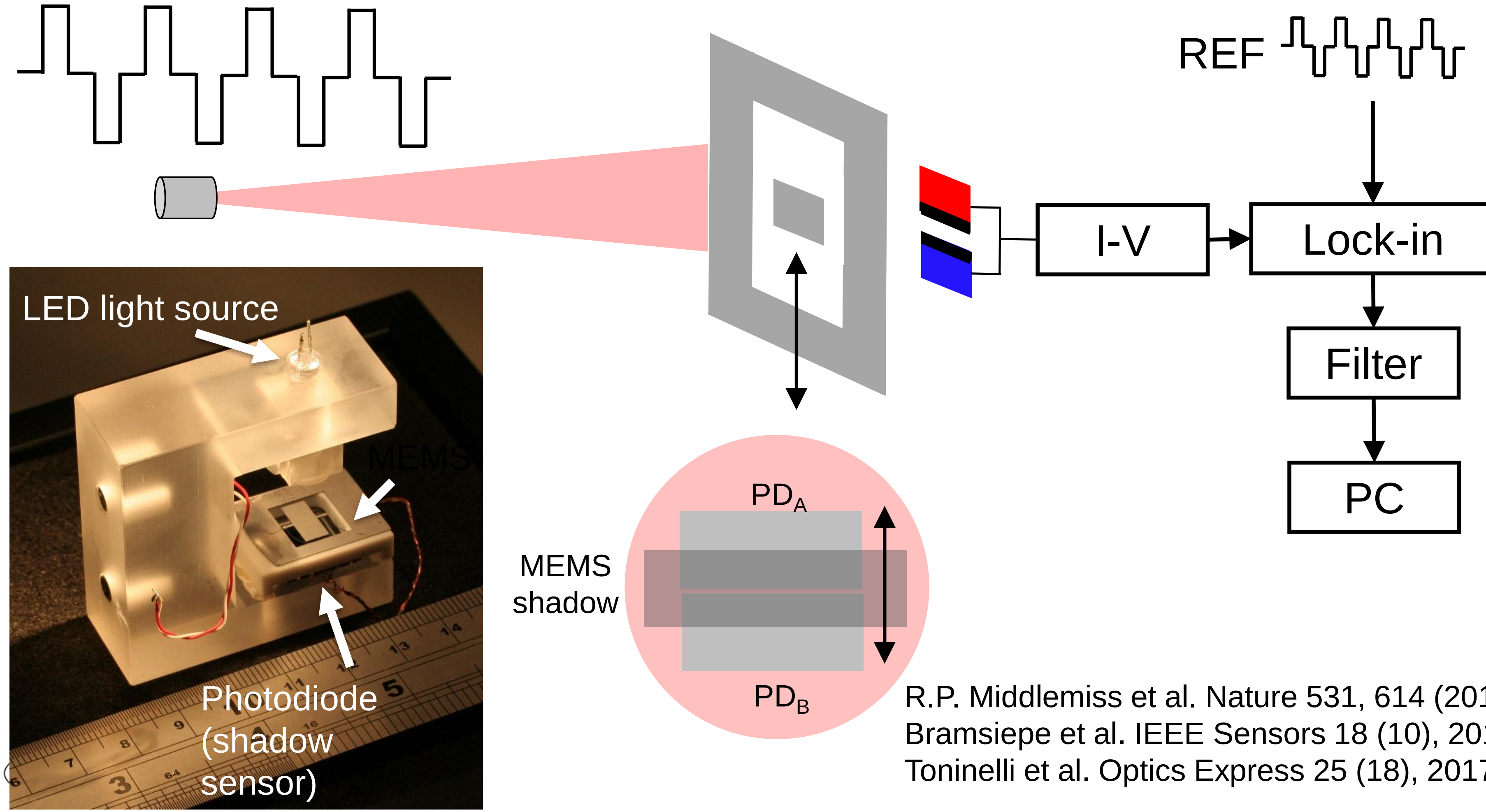




- Prototype built on fused silica structure for high thermal stability
- Thermal control of LED/MEMS/Outer shield required for nanometre precision over several days

Optical Readout

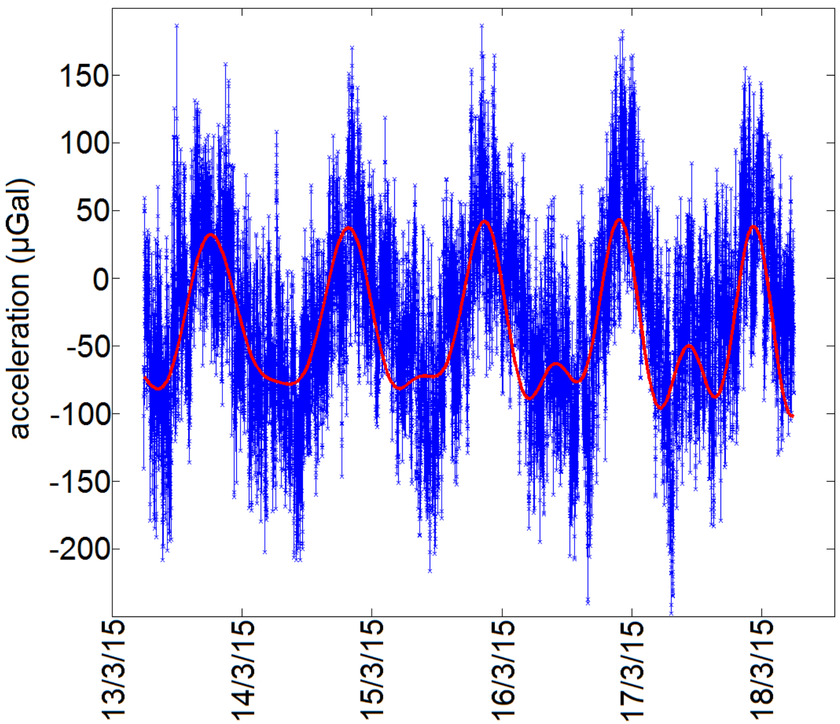
- Developed a shadow sensor that can provide stability of ±4nm over several days
- Split photodiode provides zero output at shadow centre, and immunity to relative intensity noise



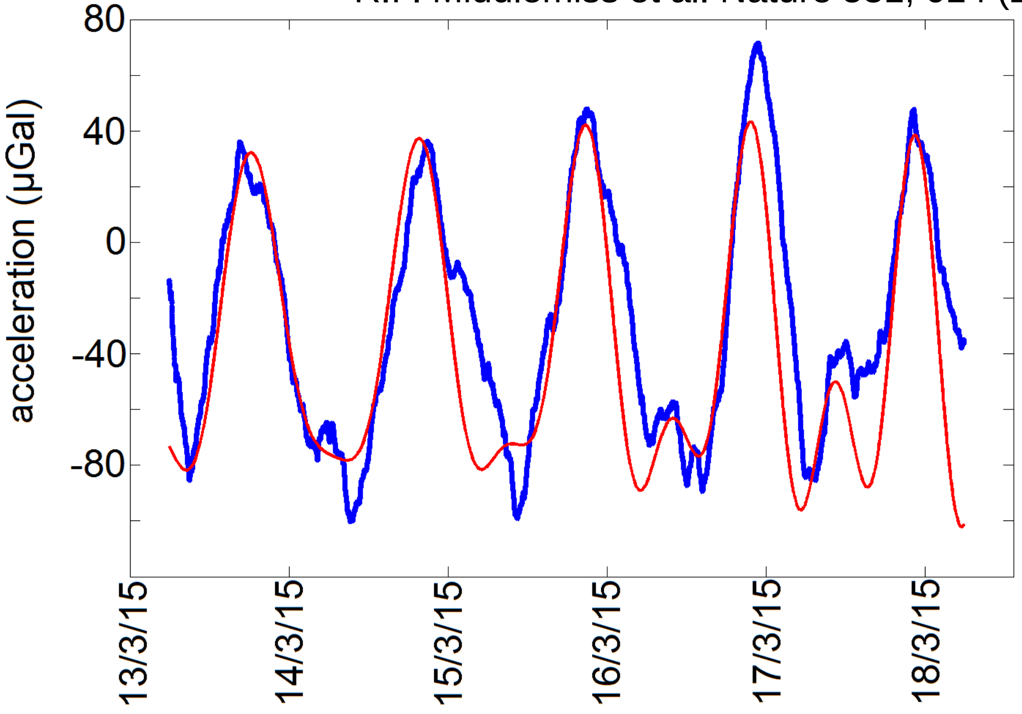
R.P. Middlemiss et al. Nature 531, 614 (2016)
Bramsiepe et al. IEEE Sensors 18 (10), 2018
Toninelli et al. Optics Express 25 (18), 2017

Earth Tides

- There is a daily/twice-daily change in the local acceleration of gravity due to the Earth-Moon tidal gravitational potential (250µGal ≈ 250ng maximum variation)
  - due to changing shape of solid earth (Earth tides; 30cm-40cm change in radius)
- This is a good signal to test long term stability. Measured during 2015-2016
- We demonstrated a sensitivity of 40ng/√Hz



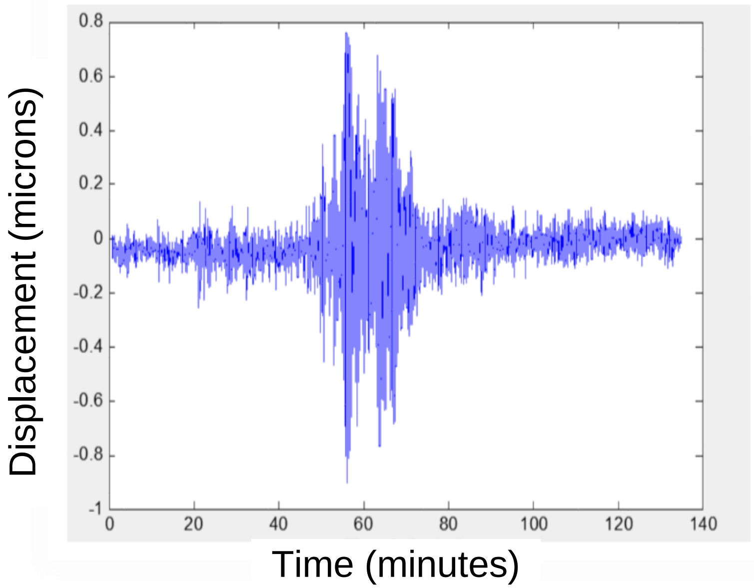
R.P. Middlemiss et al. Nature 531, 614 (2016)



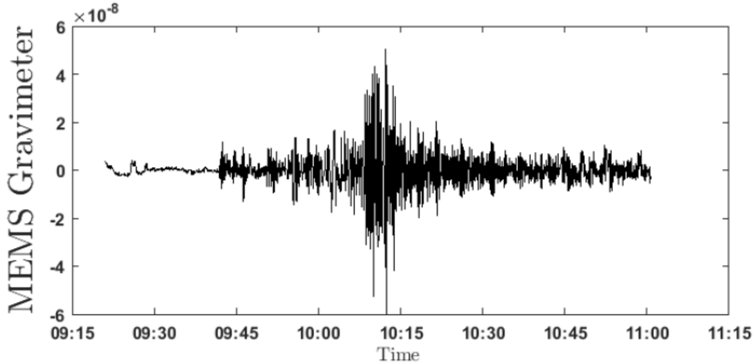
1 µGal =1 cm/s² = 0.01 m/s²

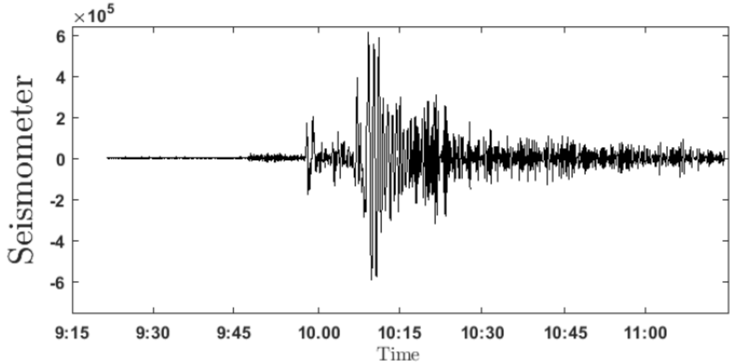
Seismic Noise

- The device can be operated over a wide range of frequencies (5 orders of magnitude): seismometer-accelerometer-gravimeter



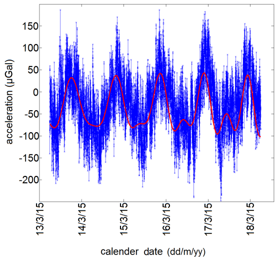
Chile 7.6 mag. earthquake measured on 25th Dec, 2016

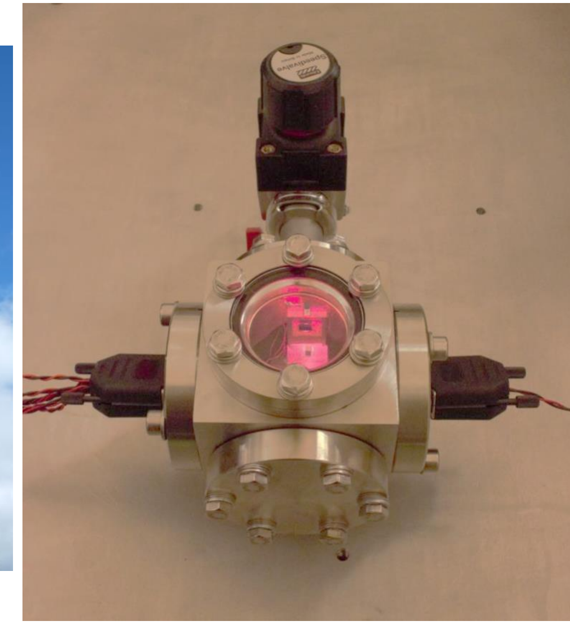


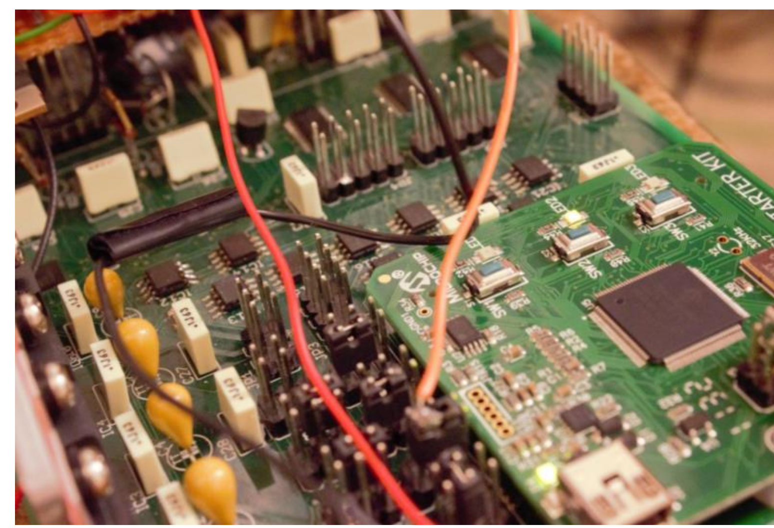


Alaska 7.9 magnitude earthquake measured on 23rd Jan, 2018

Field Prototype







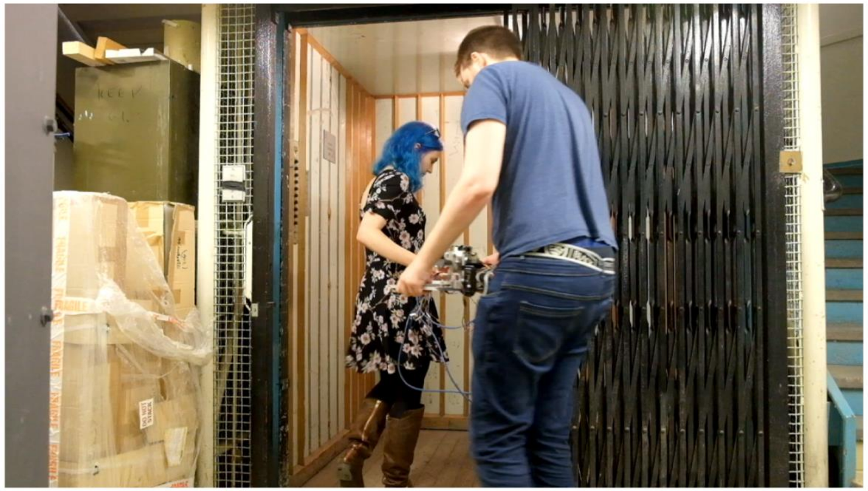
2015: lab based system with mains power, rack mount electronics

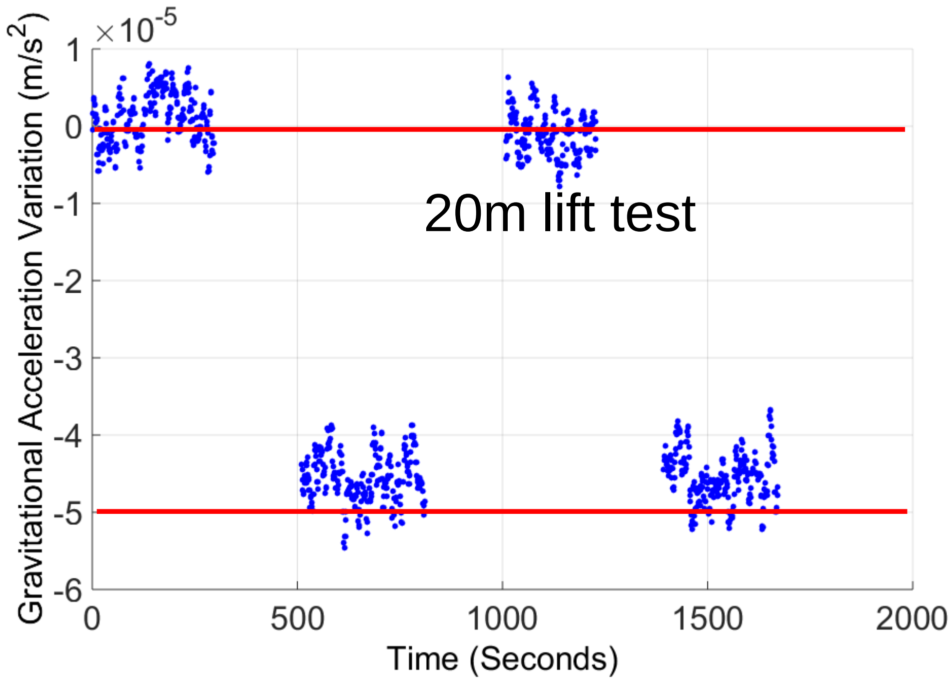
Bramsiepe et al. IEEE Sensors 18 (10), 2018

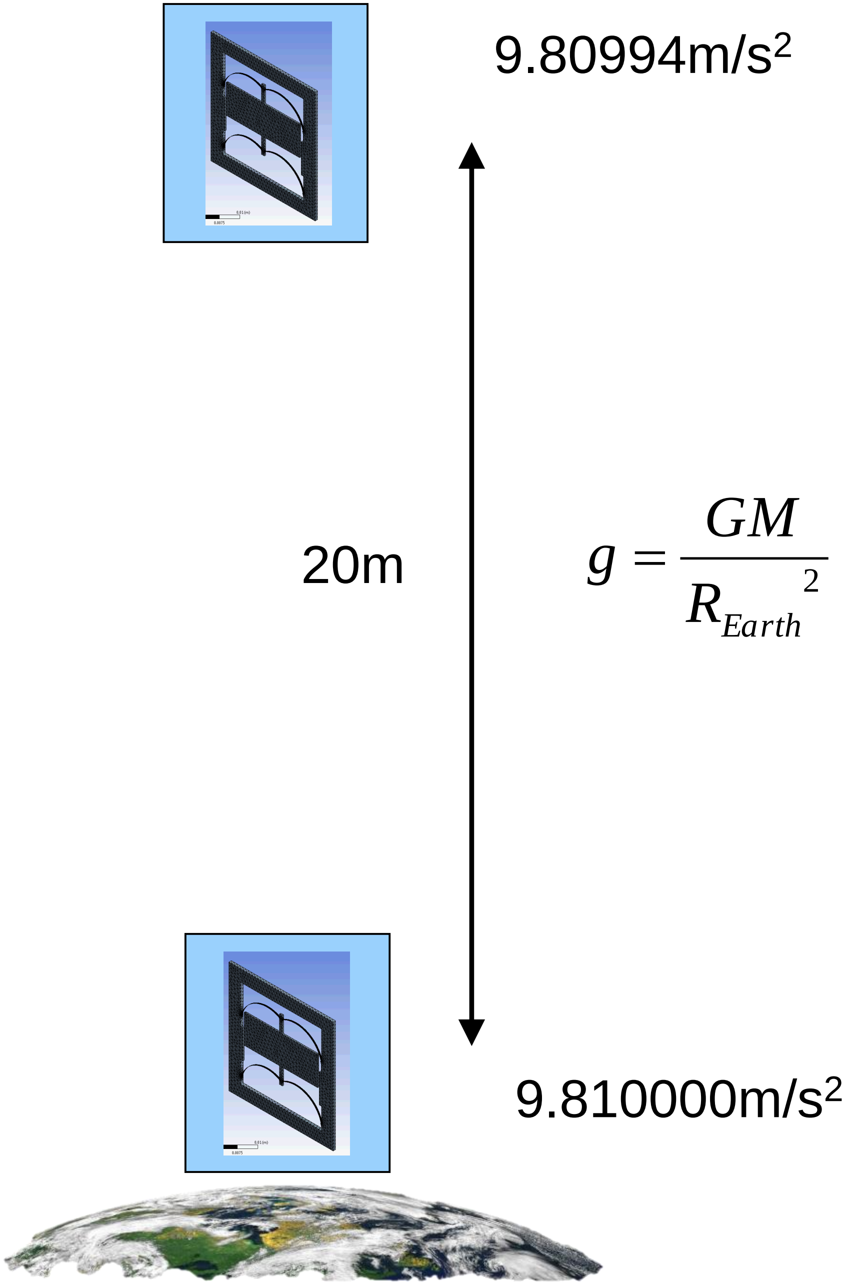
2016: shoebox sized field demonstrator, battery power

2017 Field Tests: In a Lift

R. P. Middlemiss et al, Sensors **2017**, 17, 2571.

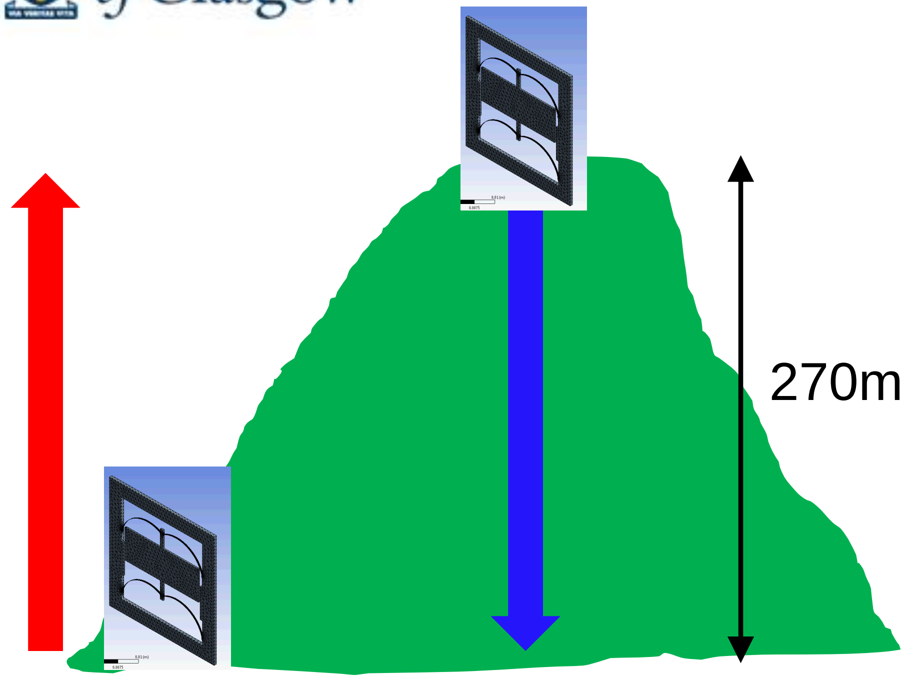






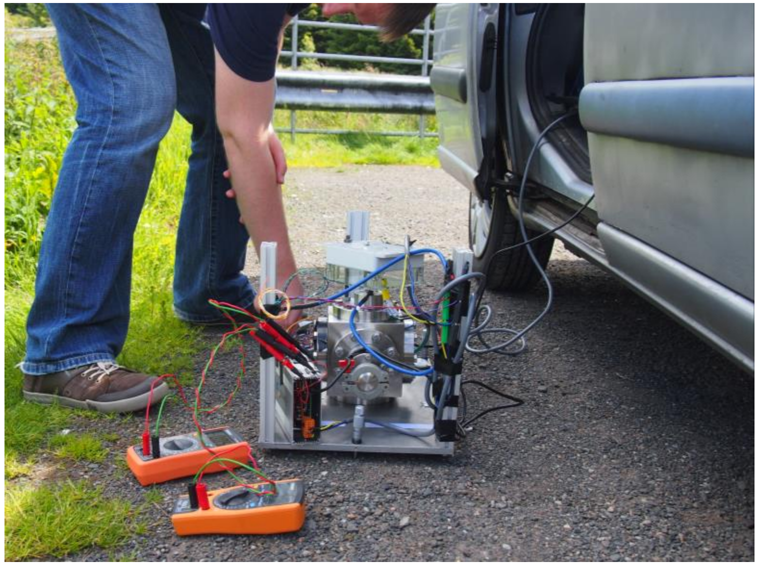
$$g = \frac{GM}{R_{Earth}^{\ \ 2}}$$

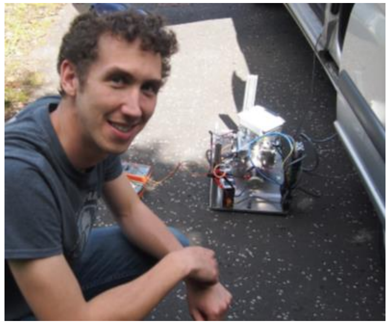
2017 Field Tests: Up a Hill

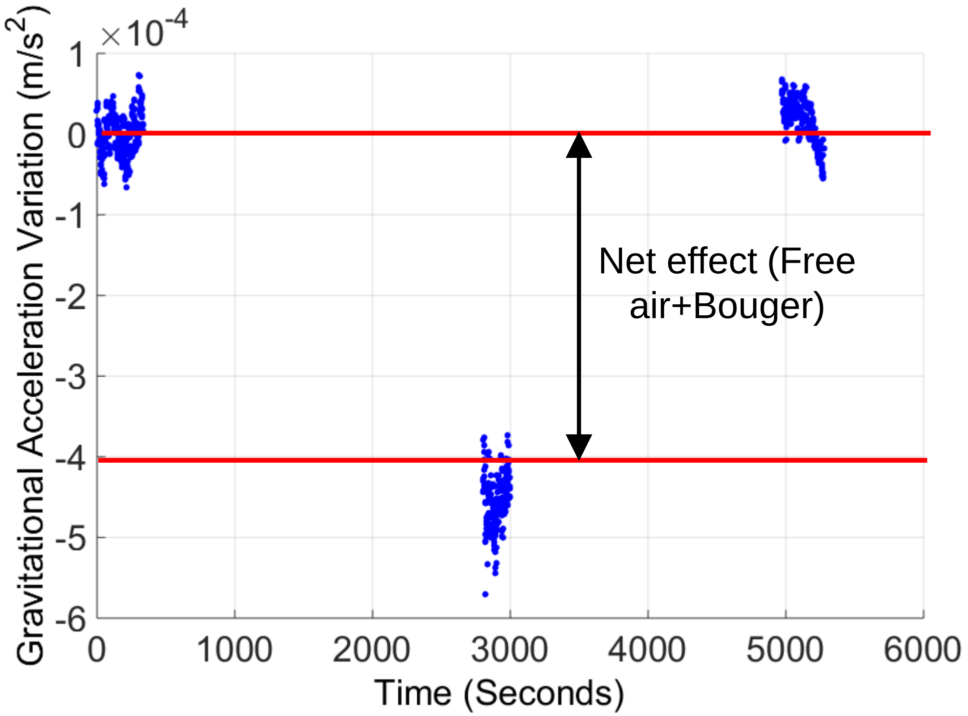


g reduces as moving away from earth (free air effect)

g increases as sitting on local rock (Bouger effect)



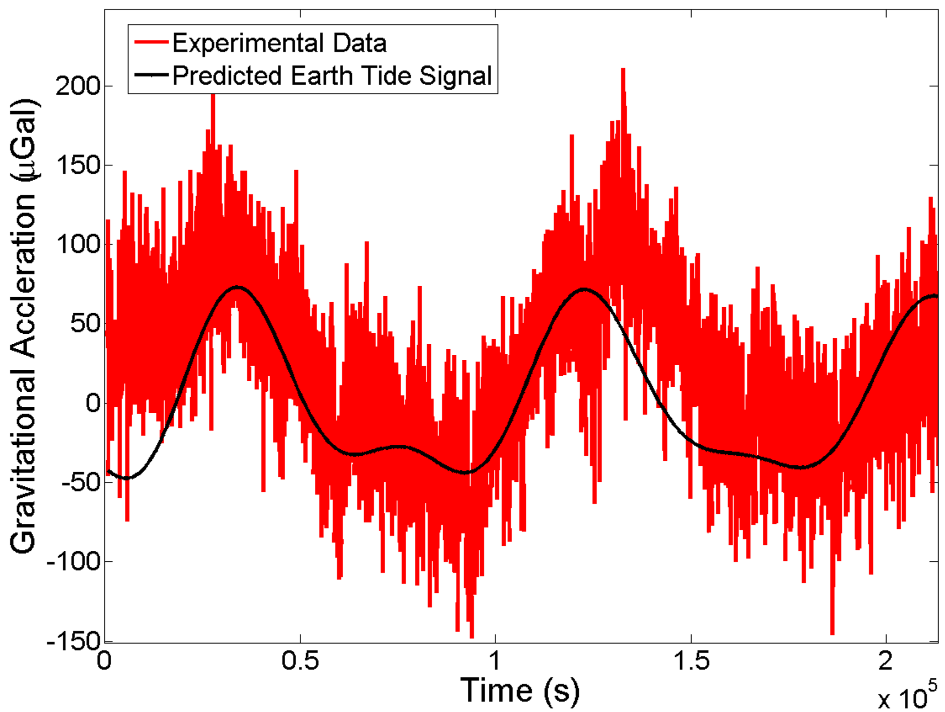


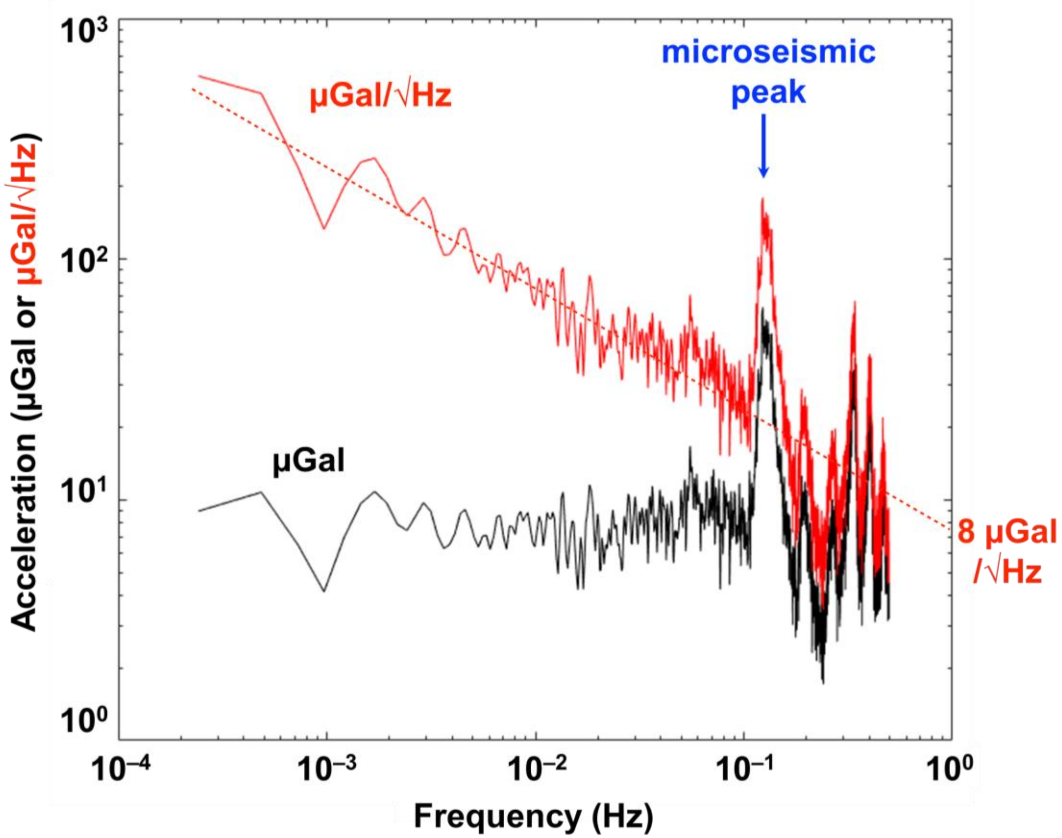


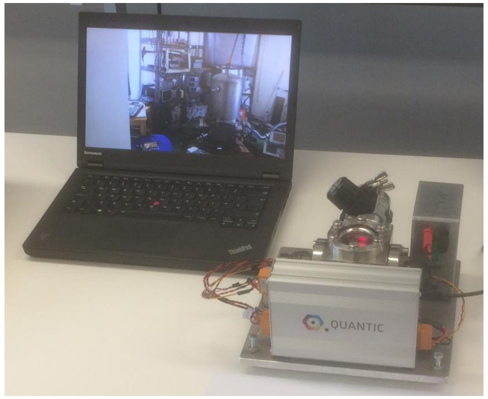
270m altitude change (Campsie Hills)

R. P. Middlemiss et al, Sensors **2017**, 17, 2571.

Tidal Measurements on Portable System



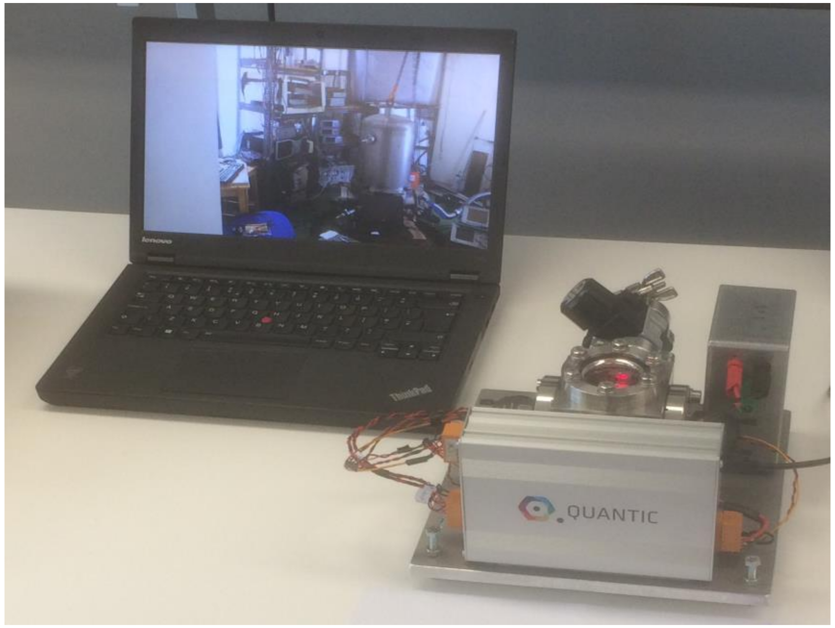




10 kg, 3.2 W, 15 hours battery
± 2 mK temperature control,
dsPIC μcontroller & SD card

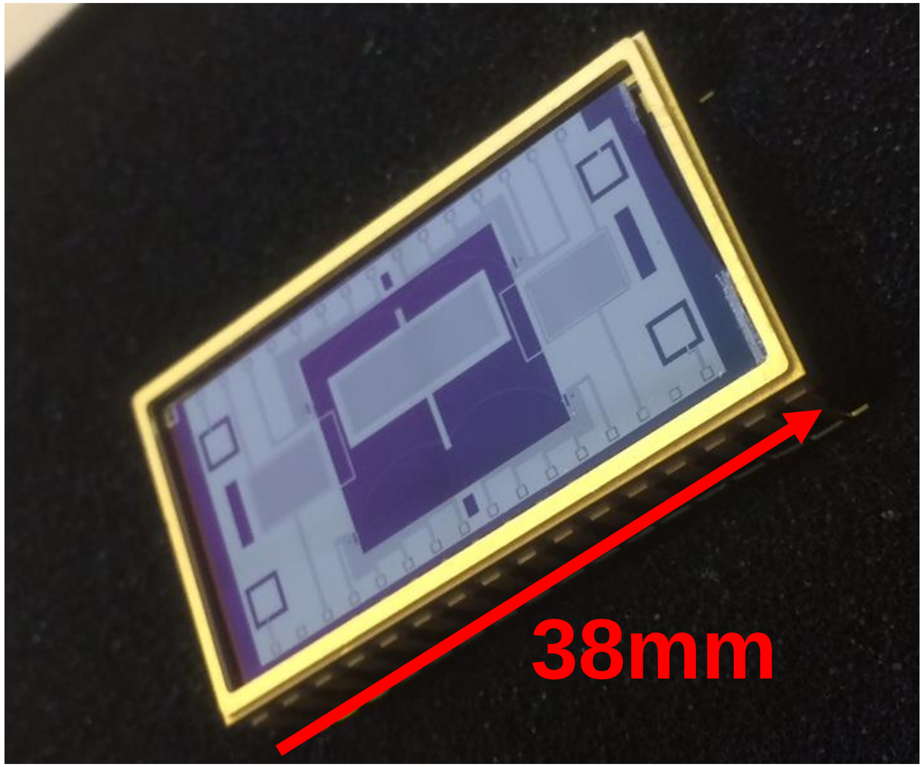
Miniaturising the Gravimeter

Now: Shoebox sized field demonstrator



10 kg, 3.2 W, 15 hours battery
± 2 mK temperature control,
dsPIC µcontroller & SD card

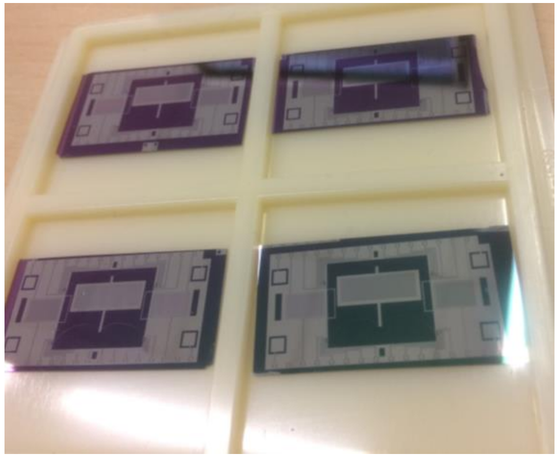
Next: Standard MEMS vacuum package



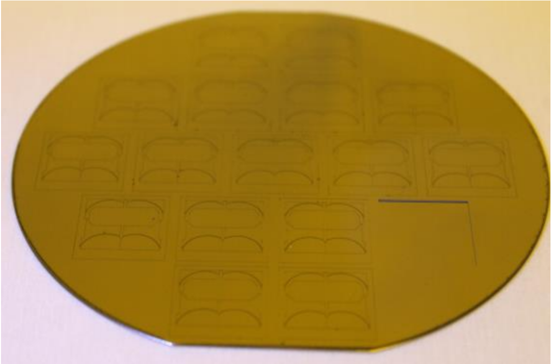
Aim: < 1 kg, < 3.2 W
24 hours battery

Capacitive Displacement Sensing: Fab & Packaging

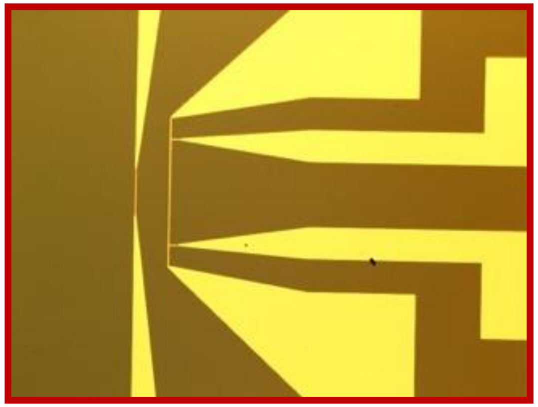
- Capacitive sensing brings down the size of the platform, helps in more efficient
- Capacitive read-out is 10 times more sensitive than the optical read-out
- To be used with the optical sensor and interferometeric read-out for stabilizing the proof mass (force-feedback)
- We are working with KNT to mass produce the sensors



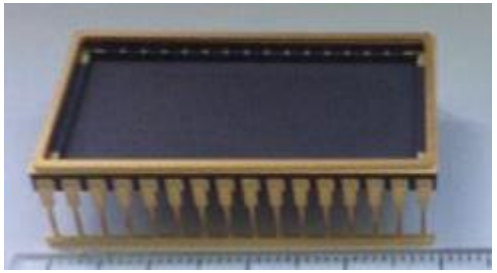
An image of the capacitive electrodes that will be used to measure the displacement of the MEMS



Wafer scale fabrication to improve yield



On-chip temperature control

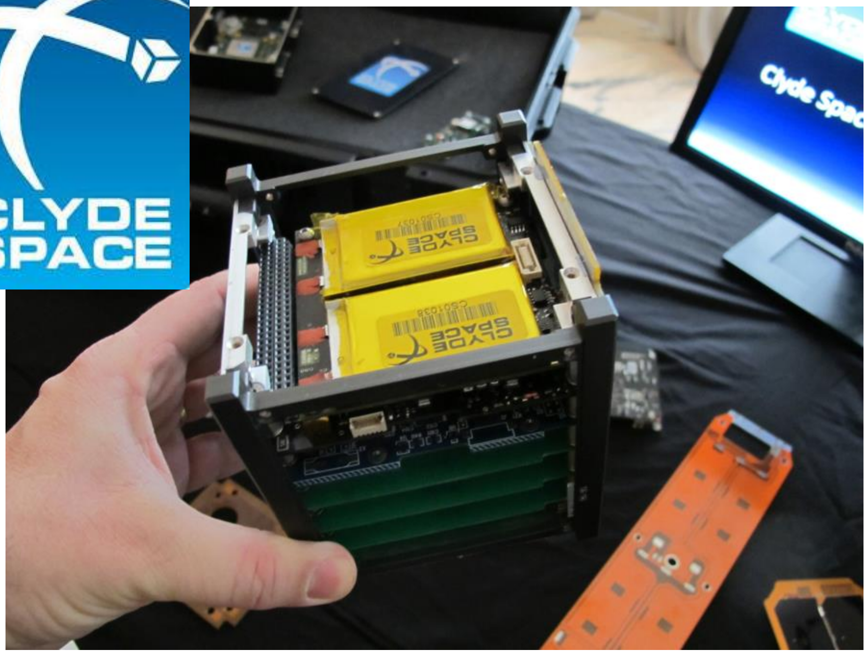


MEMS Package

Ongoing Industrial Projects

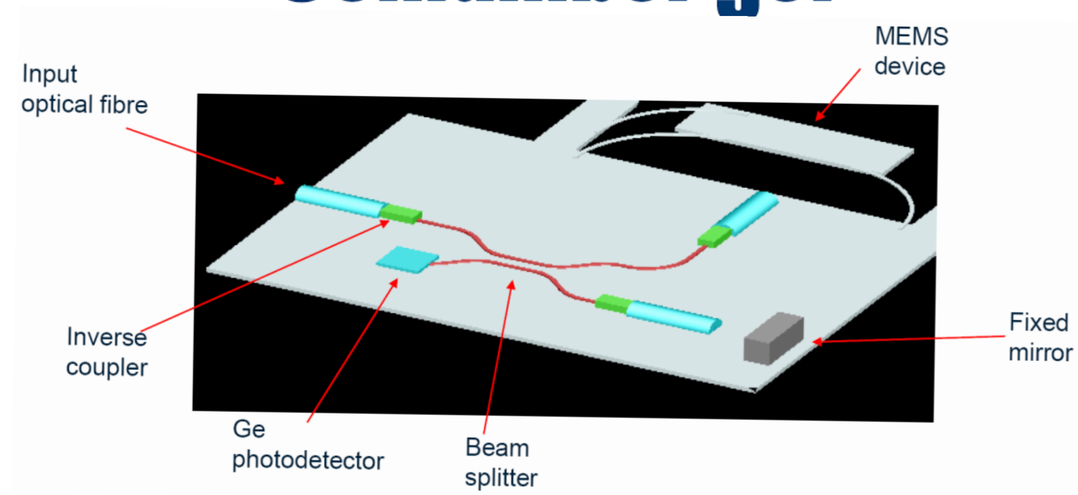
University of Glasgow

CLYDE SPACE



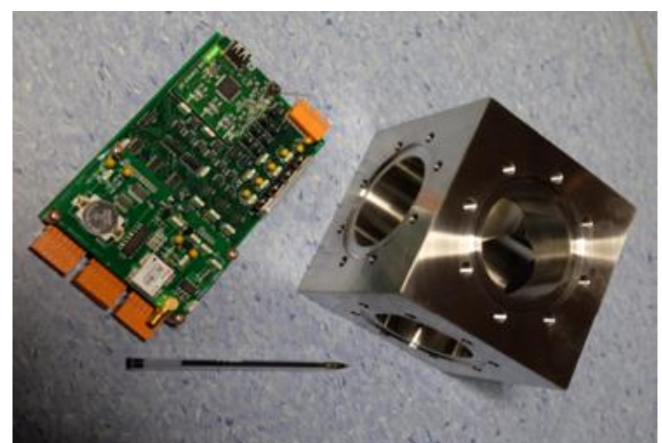
Attitude control (EngD/CENSIS)

Schlumberger



Miniature interferometric sensing

Underwater sensing



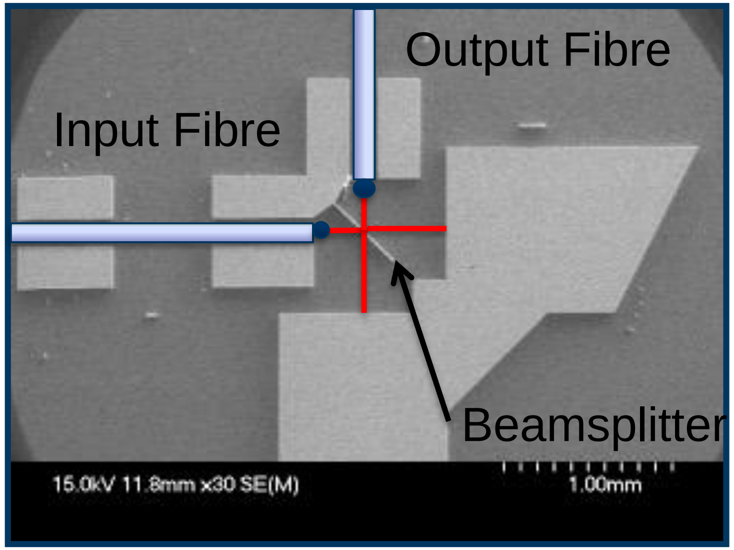
Field prototype

bridgeporth

Schlumberger

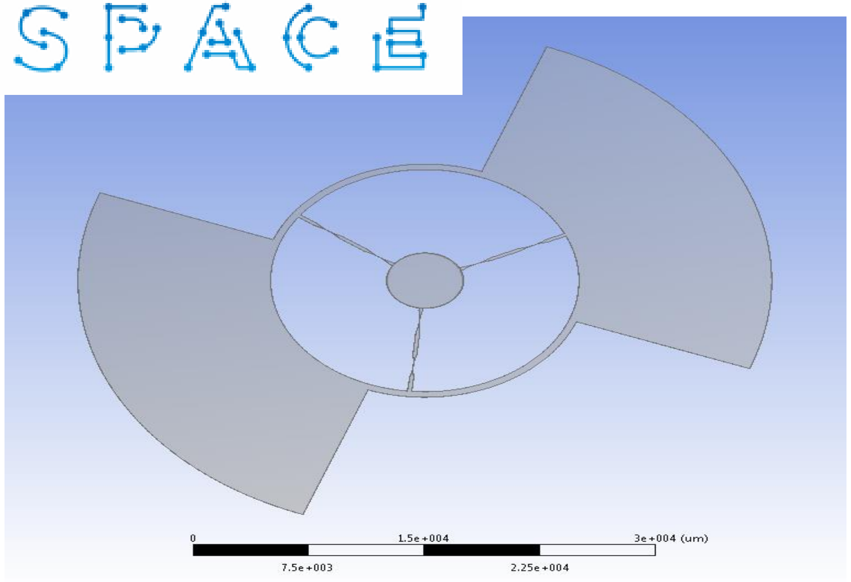
[dstl]

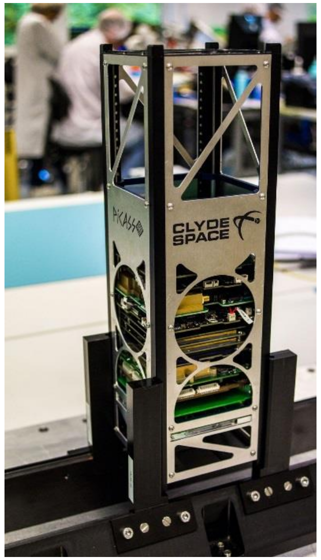
Interferometry/Gradiometry

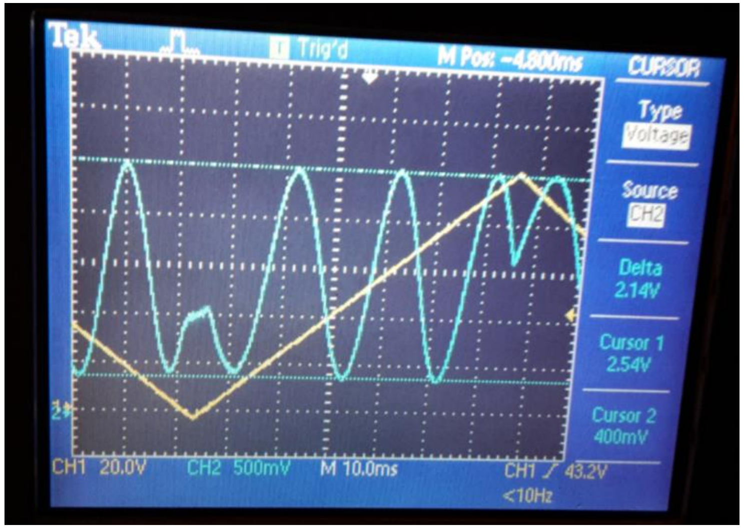


- Achieving 10 pm sensitivity at frequencies above 1 Hz
- Schlumberger in-vacuum interferometer
- DSTL: silicon guided interferometer

CLYDE SPACE





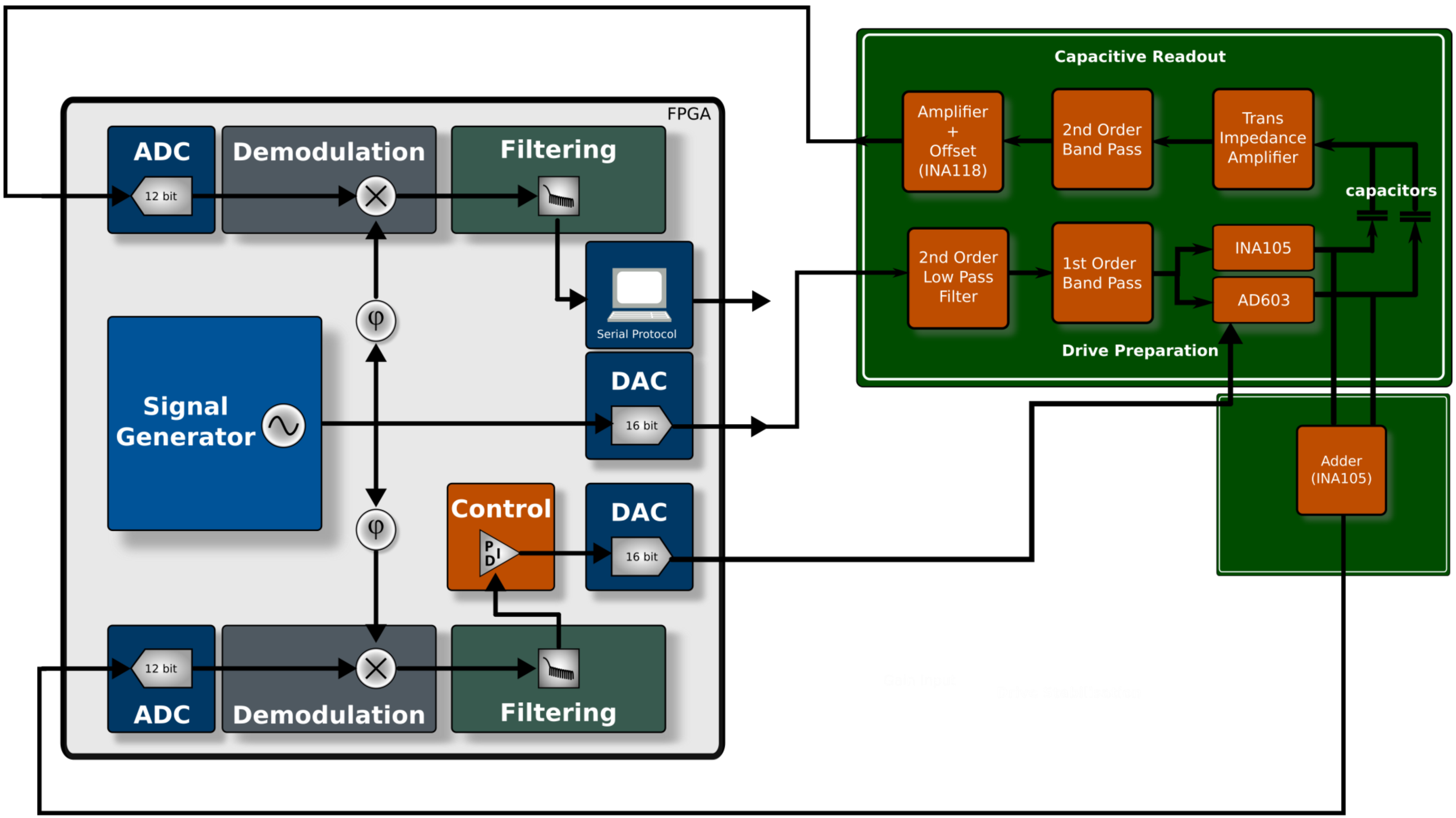


- Developing gradiometers with sensitivity aimed at 10 Eotvos/√Hz
- Capacitive readout and electrostatic closed loop control

IGR

JWNC The James Watt Nanofabrication Centre

Lock-In Readout on FPGA

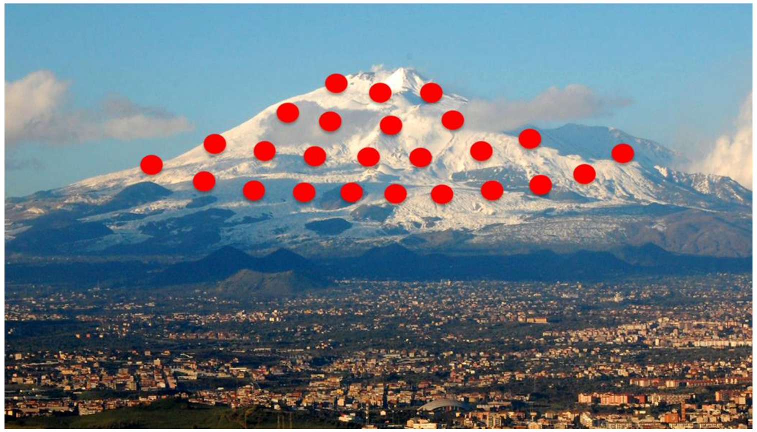


Measured long term sensitivity: $< 0.5 \frac{aF}{\sqrt{Hz}}$ 3~5 $\frac{ng}{\sqrt{Hz}}$

Andreas Noack 05/18

Conclusions and Future Work

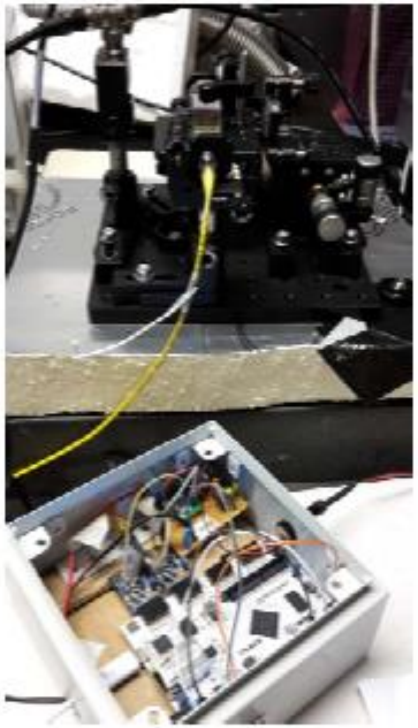
- Field tested portable MEMS gravimeters
- Working with partners (KNT, Optocap) to deliver Vacuum packaged devices
- Engagement with end-users across Oil & gas, environmental monitoring/volcanology, security & defence, space
- Deployment of 80-100 MEMS Gravimeters around Mt. Etna in the coming year for multi-pixel gravity imaging (FET Open EU Grant)
- Working towards developing an on-chip interferometeric MEMS Gravimeter



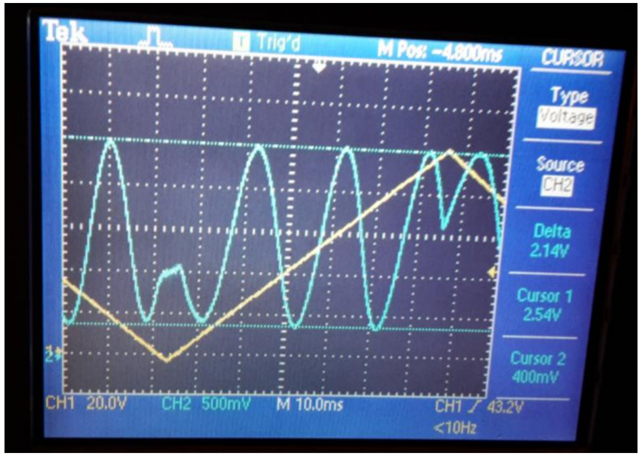
Schlumberger QinetiQ Innovate UK CLYDE SPACE KAIAM IQE KELVIN NANOTECHNOLOGY optocap European Commission

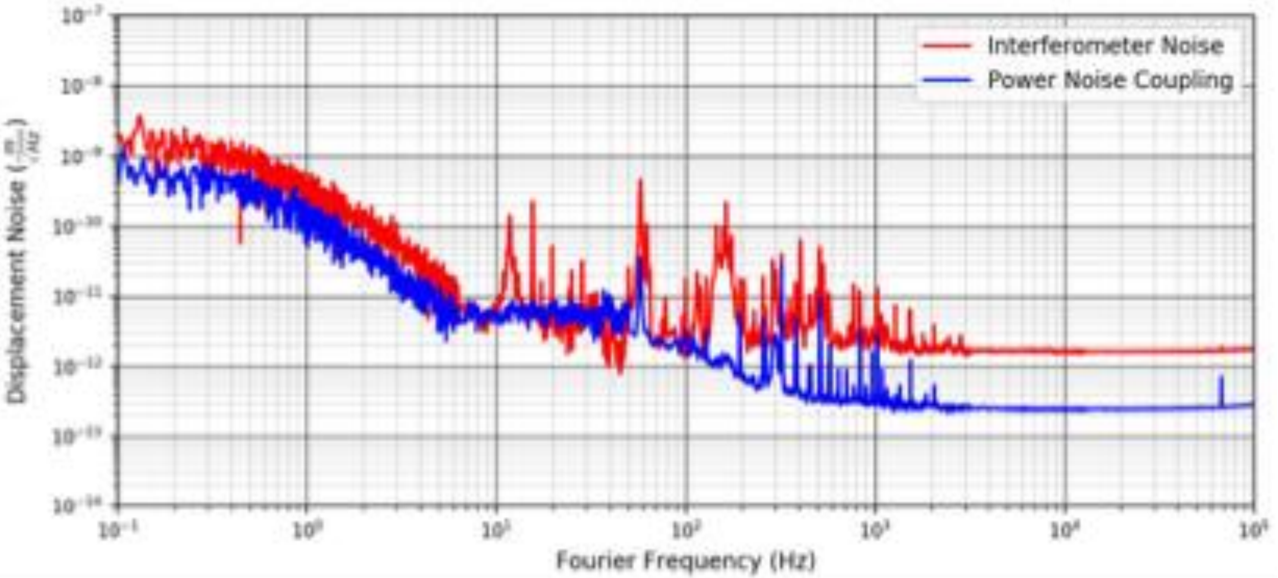
IGR JWNC The James Watt Nanofabrication Centre

Bench Top Interferometer



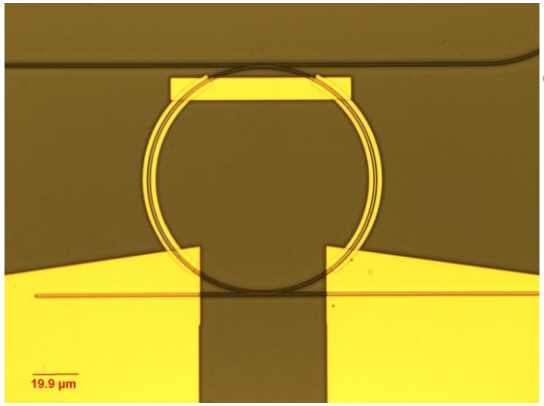
- Bench top interferometer with FPGA digital control loop to lock at mid-fringe
- 2 pm/√Hz measurement is 3 orders of magnitude lower than shadow sensor
- Limited by power noise
- Electronics already available for interferometer

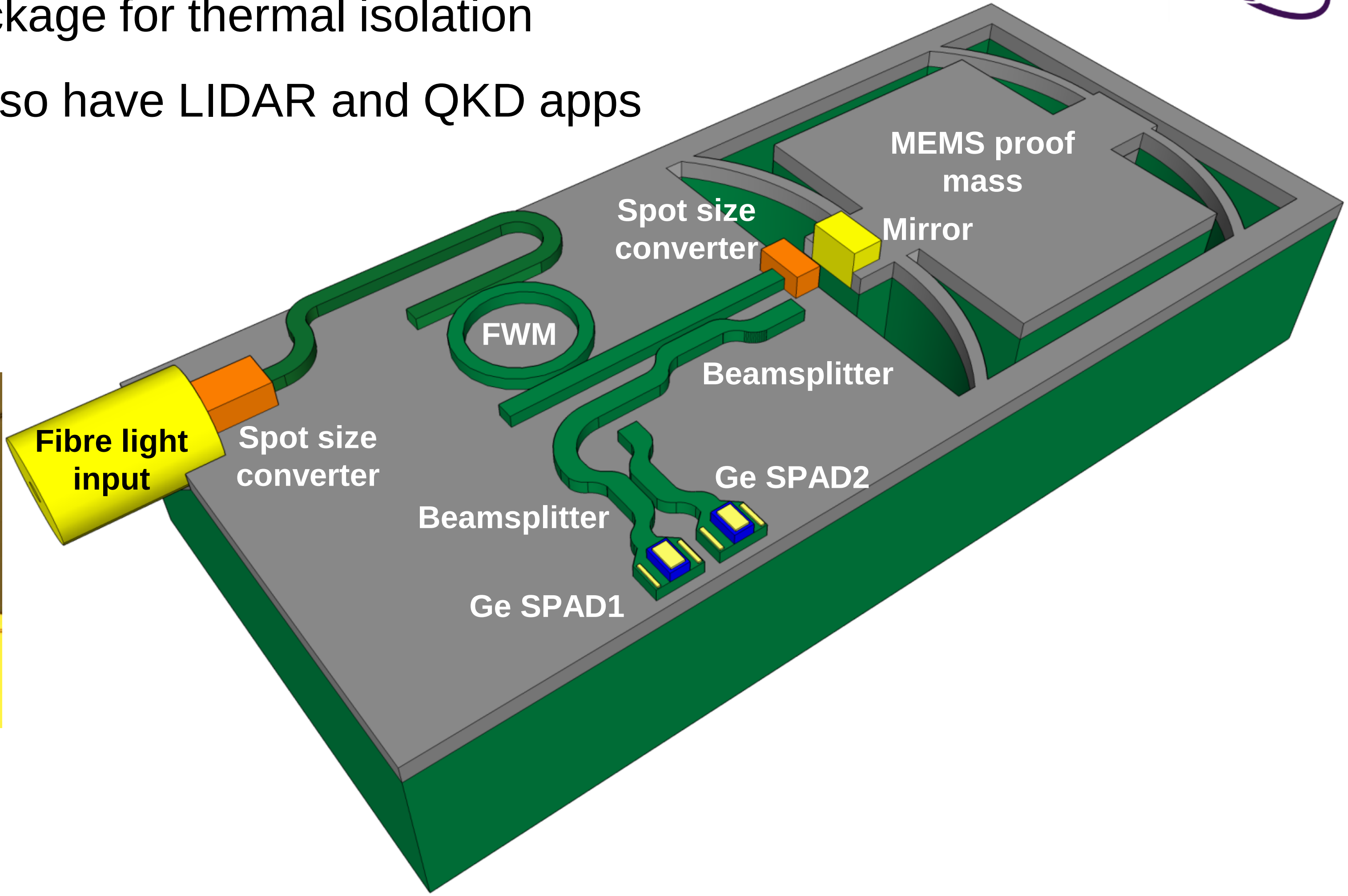




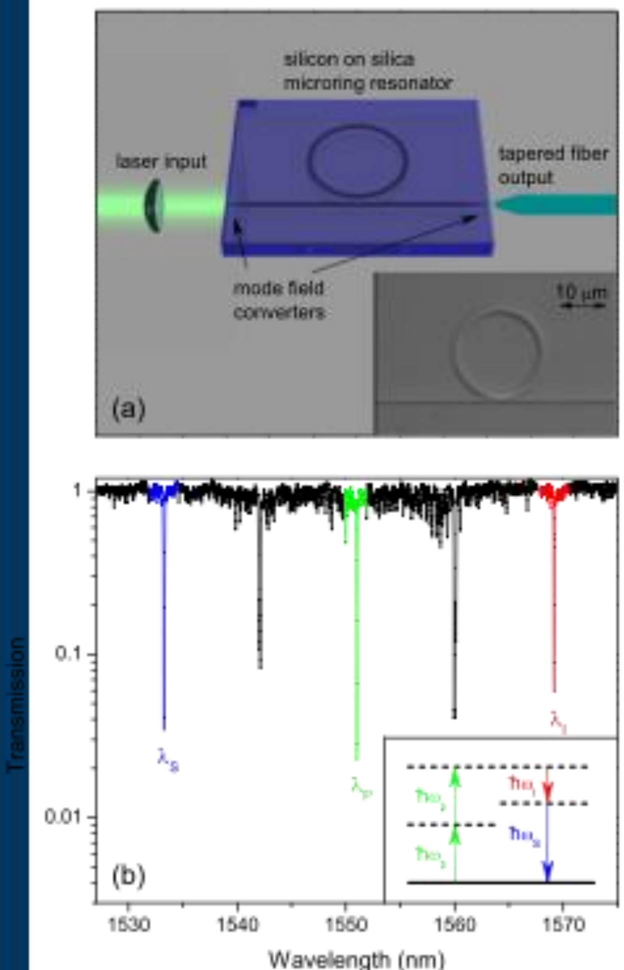
SLAM Gravimeter Project

- Integrated Michelson interferometer with squeezed light on a chip
- Off-chip laser to reduce thermal noise
- MEMS vacuum package for thermal isolation
- Ge-on-Si SPADs also have LIDAR and QKD apps

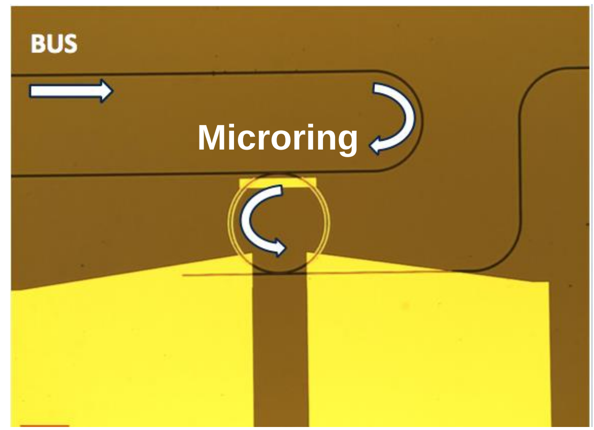


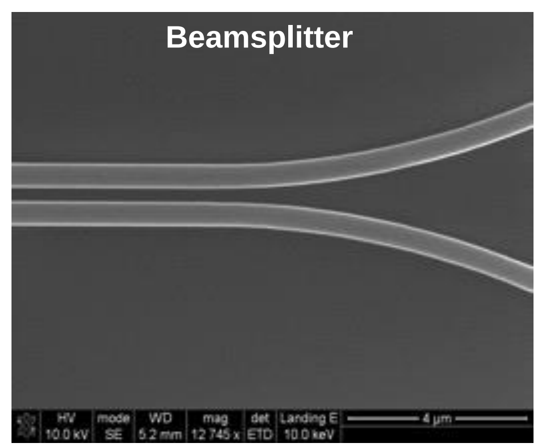


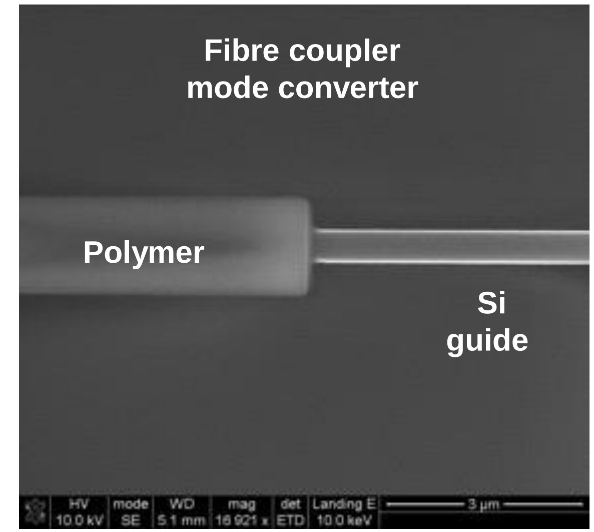
Components of SLAM Gravimeter

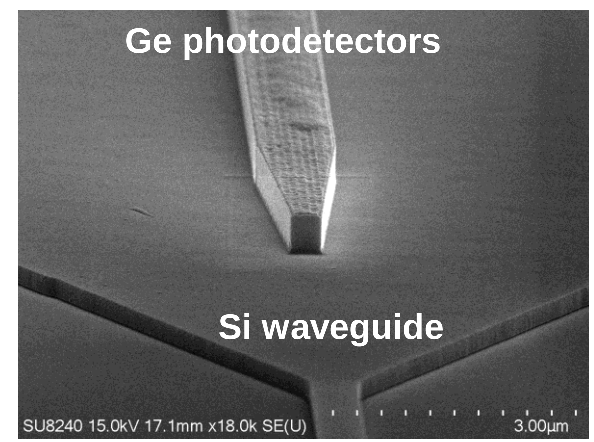


Optica 2, 88 (2015)





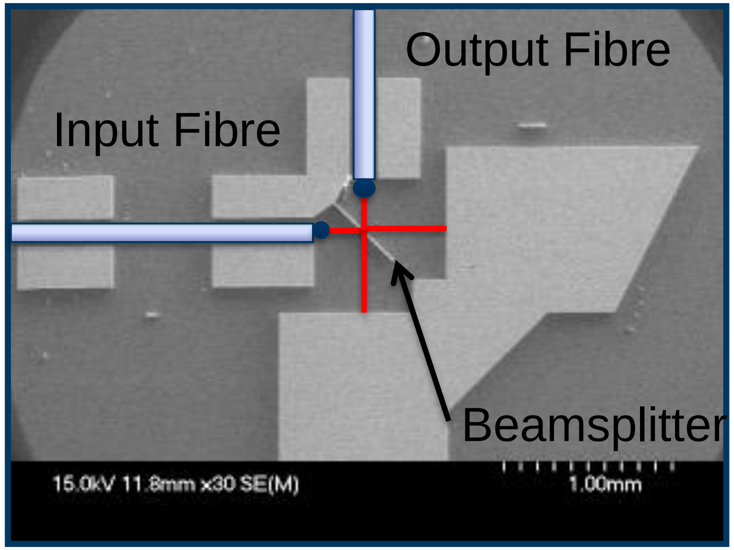




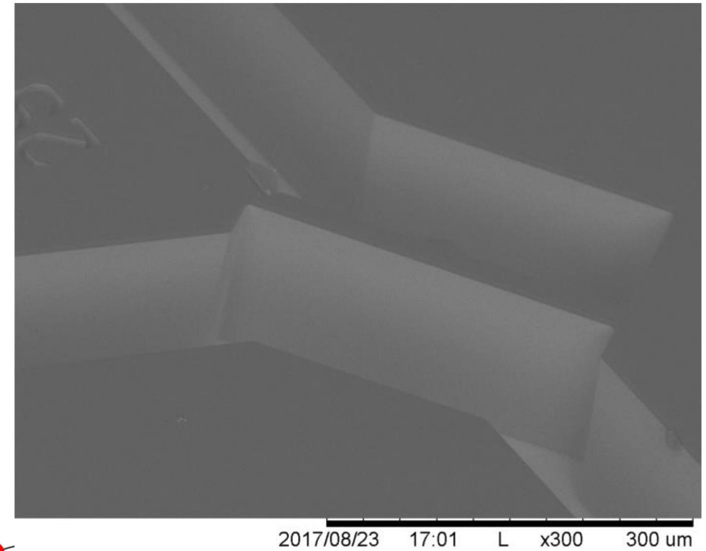
IEEE Trans. Elec. Dev. 60, 3807 (2013)

University of Glasgow

Next Step: Interferometer based MEMS Gravimeter



- Combining the sensitivity of interferometer and small scale of MEMS
- Free-space interferometric displacement read-out
- Single step process to etch out proof mass, mirrors and splitters
- Schlumberger: in-vacuum interferometer
- DSTL: silicon guided interferometer



Schlumberger

[dstl]

Nanofabrication Centre