A Gravitational Wave Spin-Off: MEMS Gravimetry

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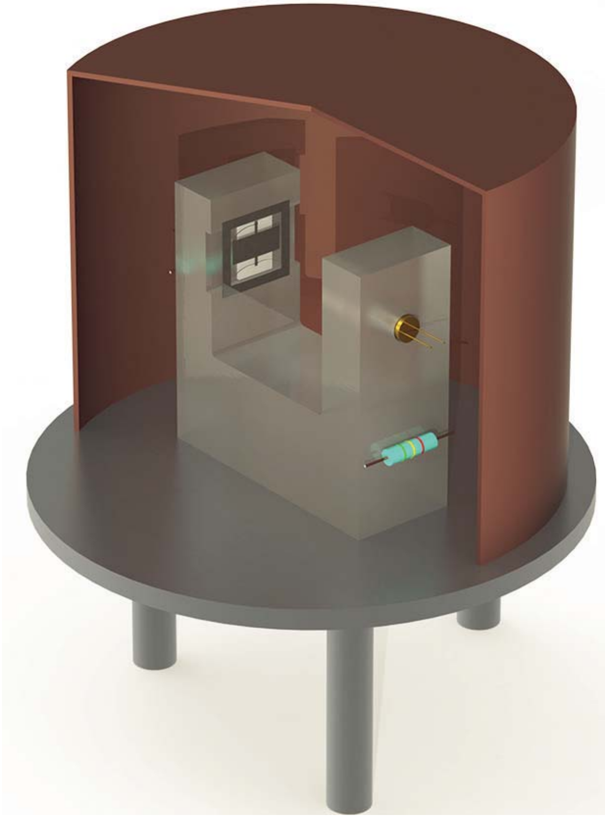
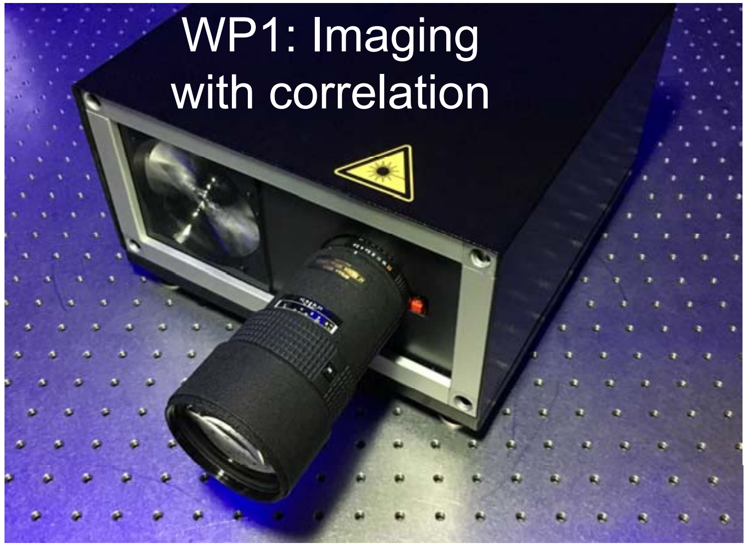
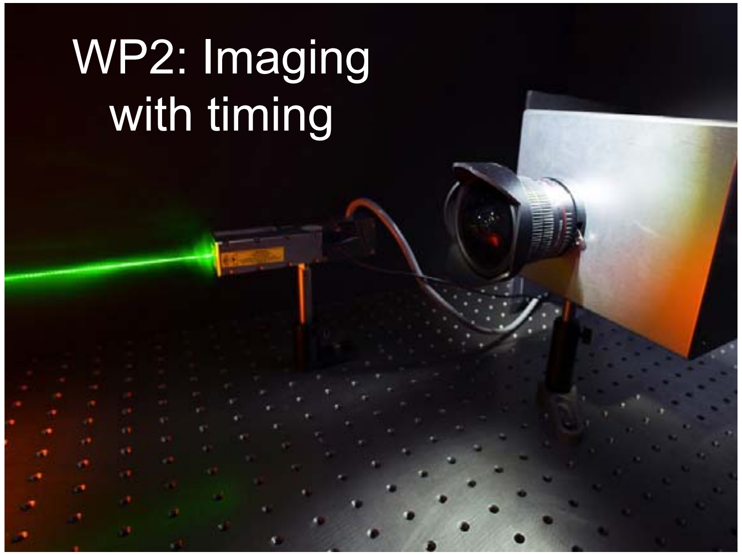
Overview

- The QuantIC Hub
- Gravity imaging applications
- Wee-g: the Glasgow MEMS gravimeter
  - device design
  - optical readout
  - noise performance and long term stability
- Field prototype
  - electronics board
- MEMS: on ground, underwater, in the air and in space
- Future directions

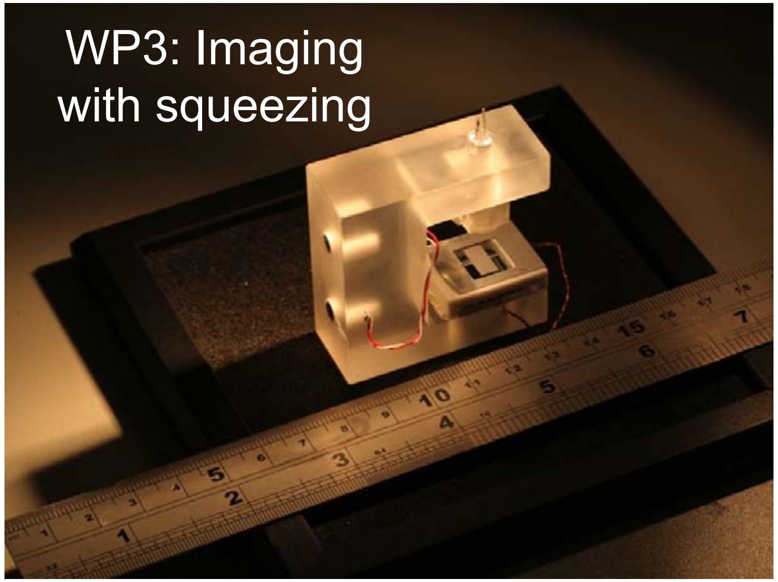


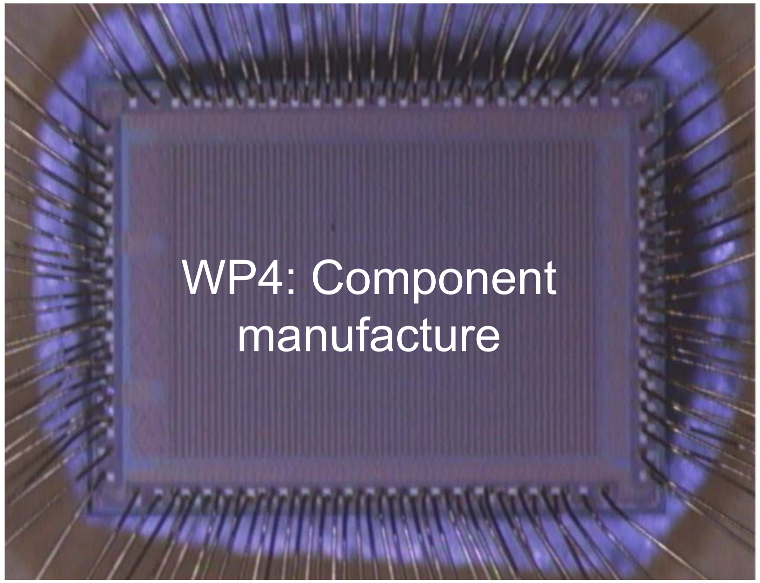
QUANTIC





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

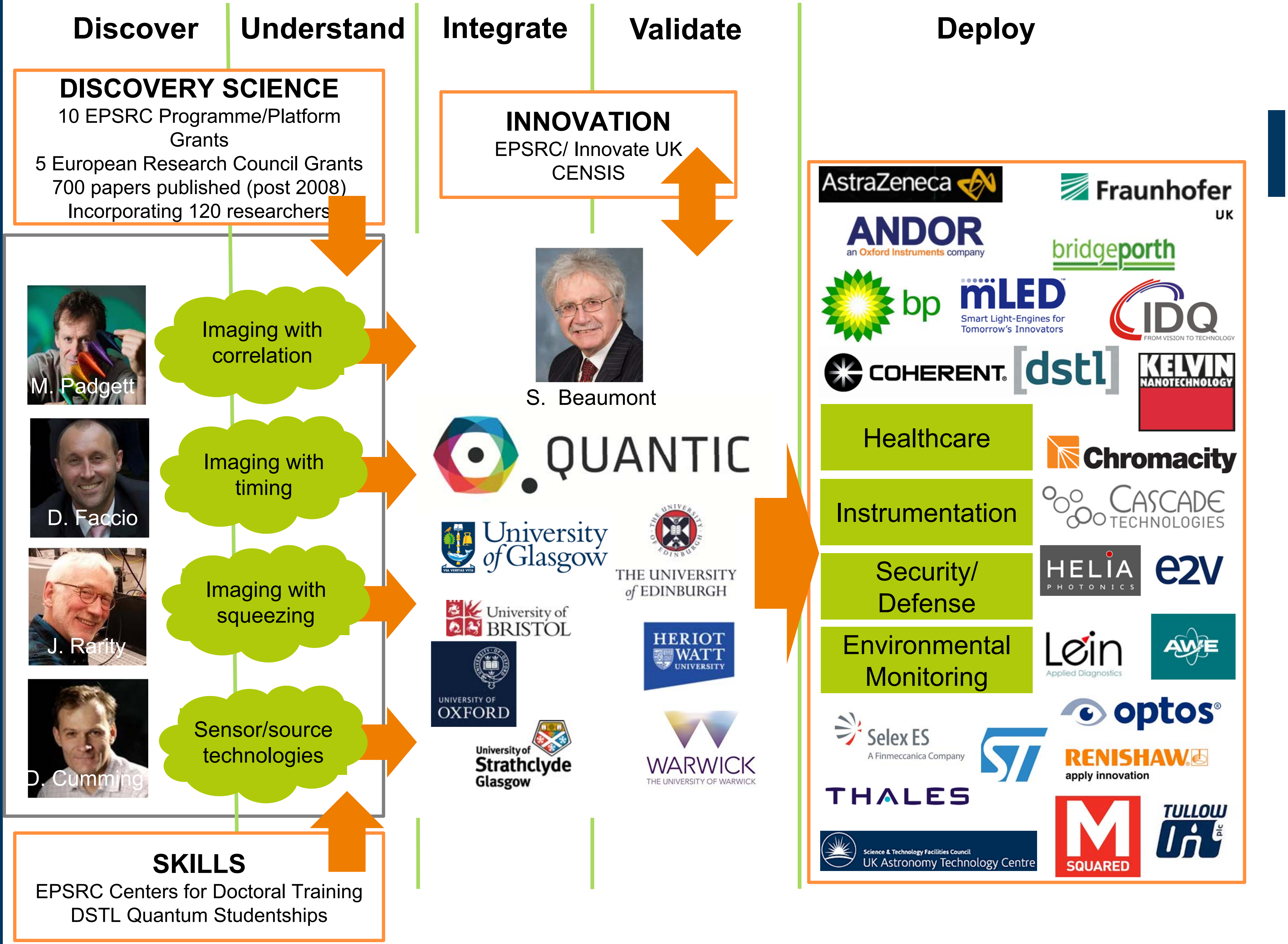




UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

EPSRC
Pioneering research and skills

Scottish Funding Council
Promoting further and higher education



Discover
Understand
Integrate
Validate
Deploy
DISCOVERY SCIENCE
10 EPSRC Programme/Platform Grants
5 European Research Council Grants
700 papers published (post 2008)
Incorporating 120 researchers
M. Padgett
Imaging with correlation
D. Faccio
Imaging with timing
J. Rarity
Imaging with squeezing
D. Cumming
Sensor/source technologies
SKILLS
EPSRC Centers for Doctoral Training
DSTL Quantum Studentships
INNOVATION
EPSRC/ Innovate UK
CENSIS
S. Beaumont
QUANTIC
University of Glasgow
THE UNIVERSITY of EDINBURGH
University of BRISTOL
HERIOT WATT UNIVERSITY
UNIVERSITY OF OXFORD
University of Strathclyde Glasgow
WARWICK
THE UNIVERSITY OF WARWICK
AstraZeneca
Fraunhofer UK
ANDOR
an Oxford Instruments company
bridgeporth
bp
mLED
Smart Light-Engines for Tomorrow's Innovators
IDQ
FROM VISION TO TECHNOLOGY
COHERENT
[dstl]
KELVIN NANOTECHNOLOGY
Healthcare
Instrumentation
Security/ Defense
Environmental Monitoring
Chromacity
CASCADE TECHNOLOGIES
HELIA PHOTONICS
e2v
Lein
Applied Diagnostics
AWE
optos
Selex ES
A Finmeccanica Company
RENISHAW
apply innovation
THALES
Science & Technology Facilities Council
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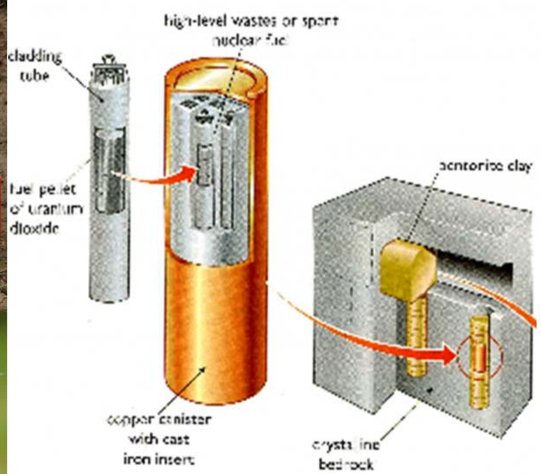
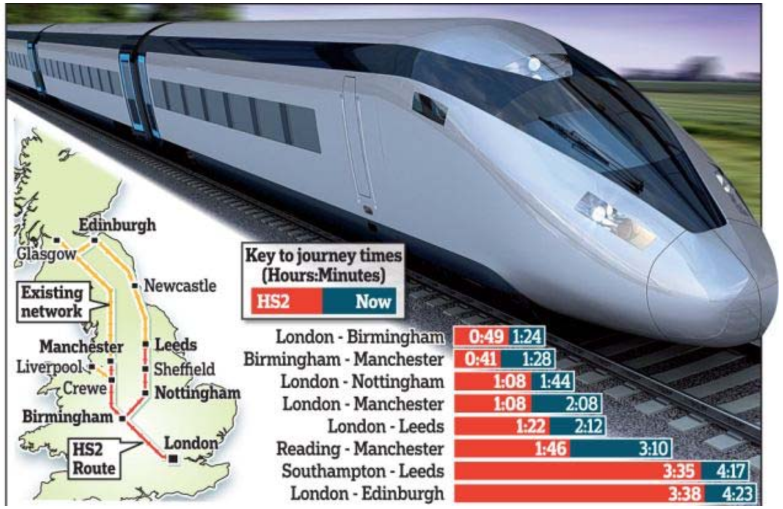
Gravity Imaging Applications

Oil & gas prospecting

Environmental monitoring



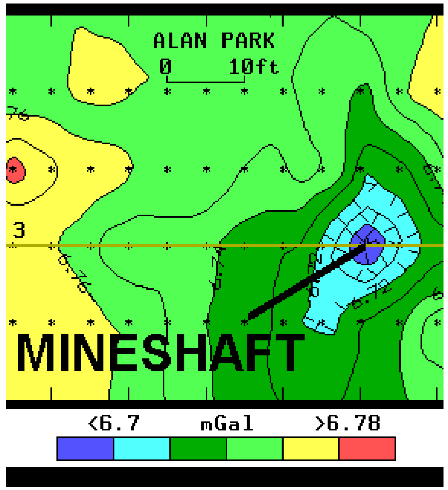
HS2



Security & Defence

Volcano monitoring

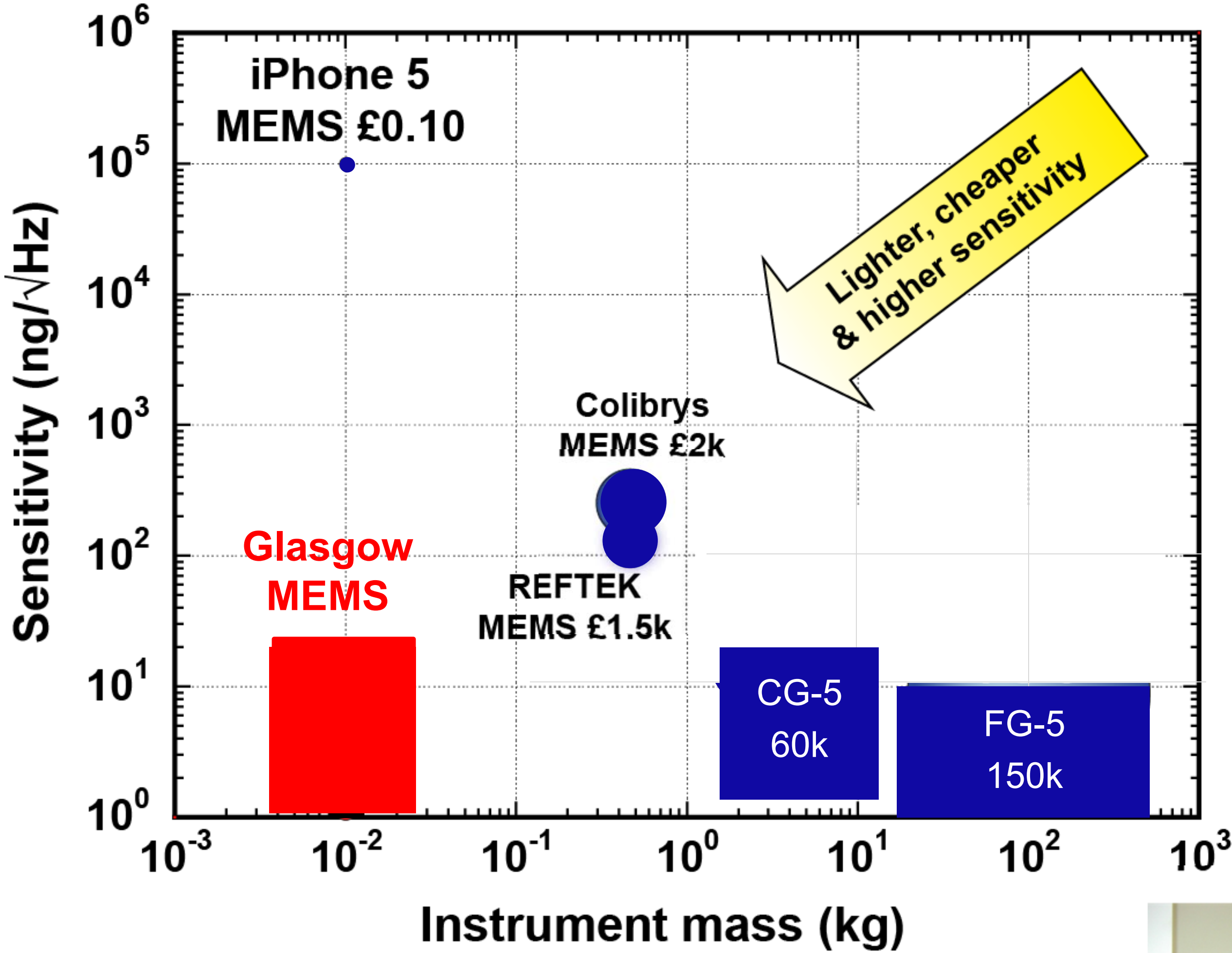
Sink hole detection



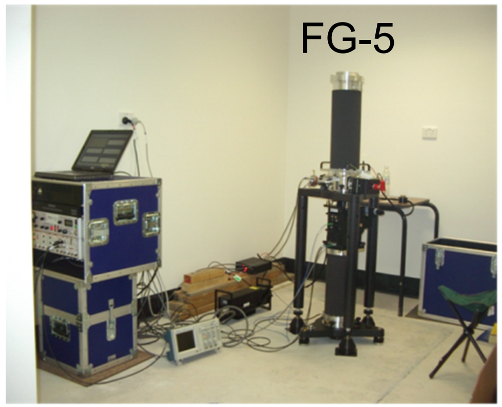
Accelerometers/Gravimeters

IPhone

Colibrysy



CG-5



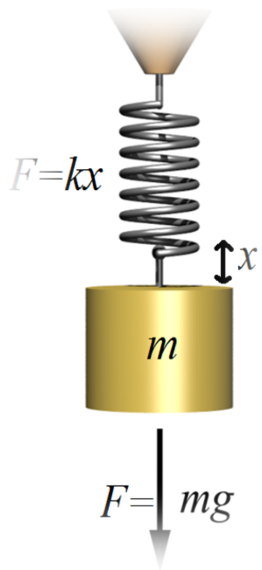
- Explore a new region of sensitivity-mass/cost space

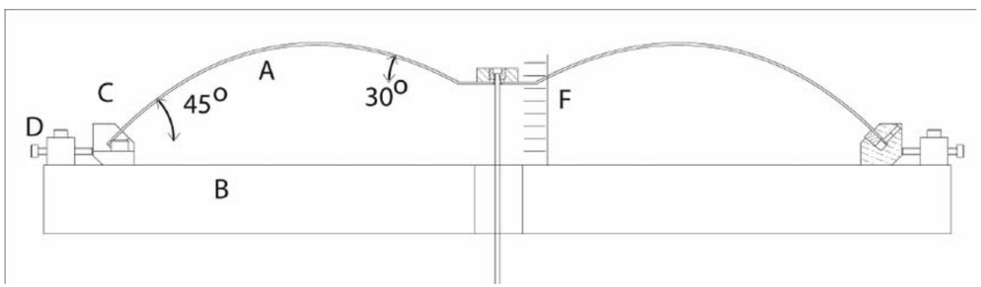
Glasgow MEMS Device

- We wanted a proof mass displacement of a few nanometres for a 300uGal acceleration

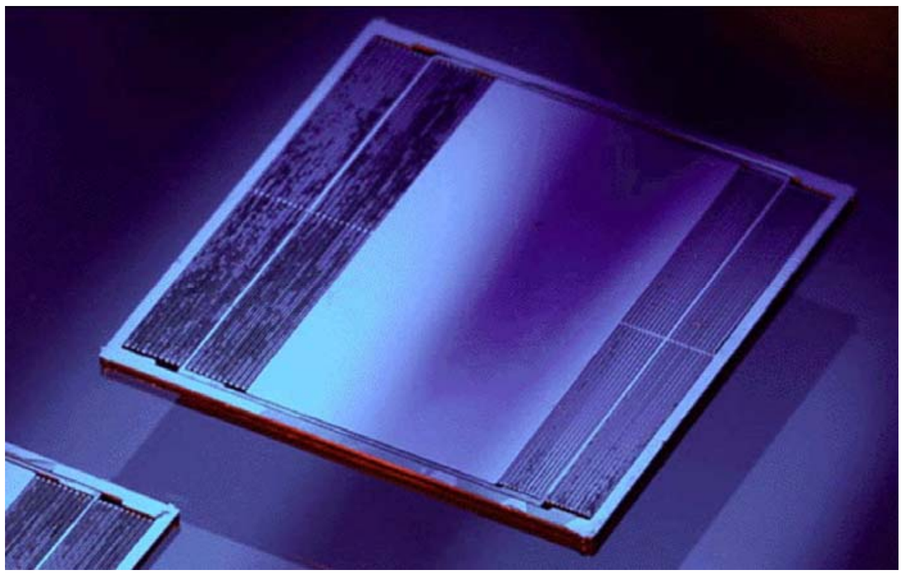
$$\ddot{x} = -\omega_0^2 x$$

- This requires a system with sub 5Hz resonant frequency. Tricky with traditional MEMS flexures requiring long flexures and serpentine geometry
- Geometric anti-springs offer a more compact geometry



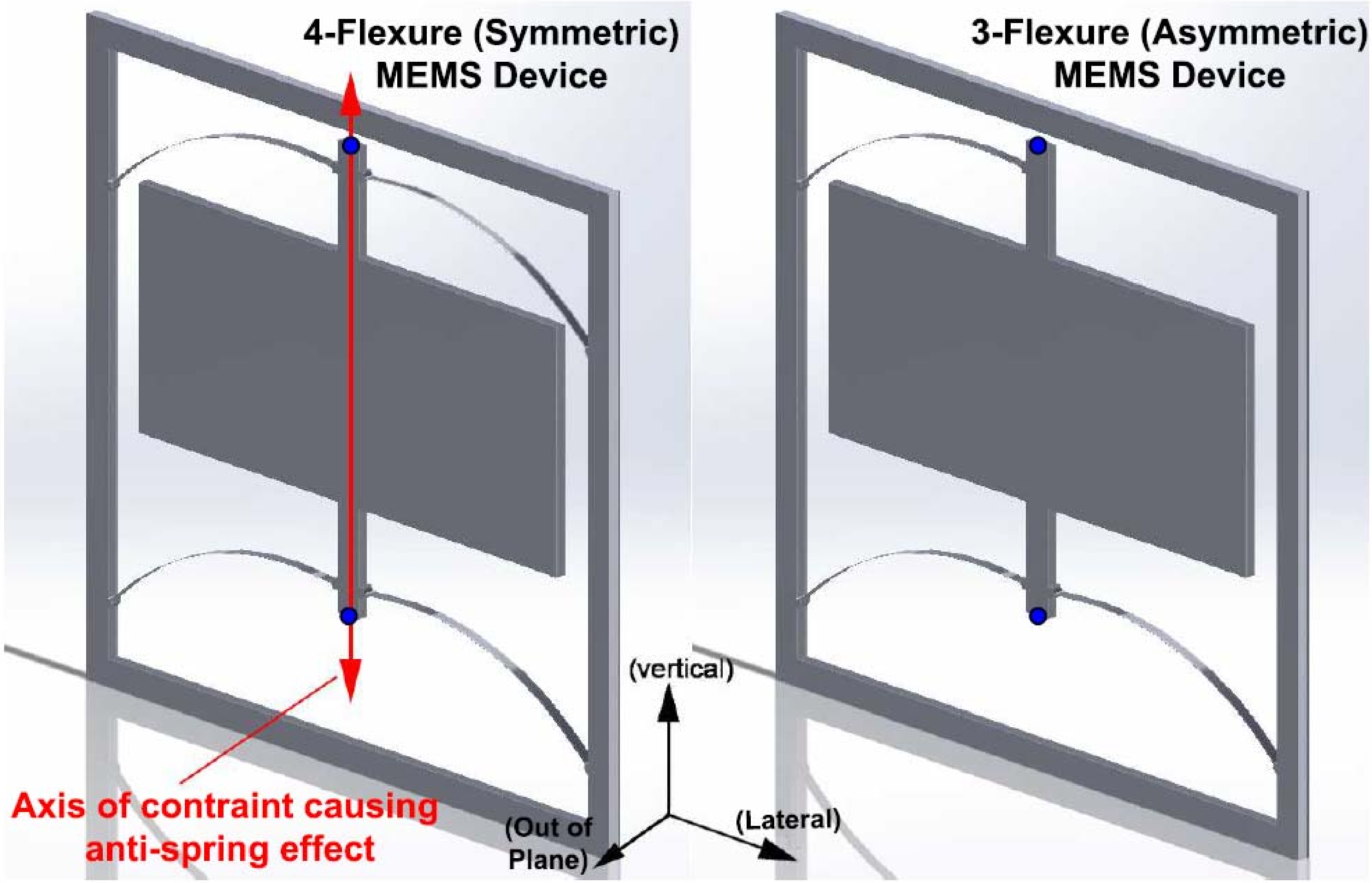


Geometric antisprings used in gravitational wave detectors (LIGO P-040002-00-D)



Imperial College (10Hz)

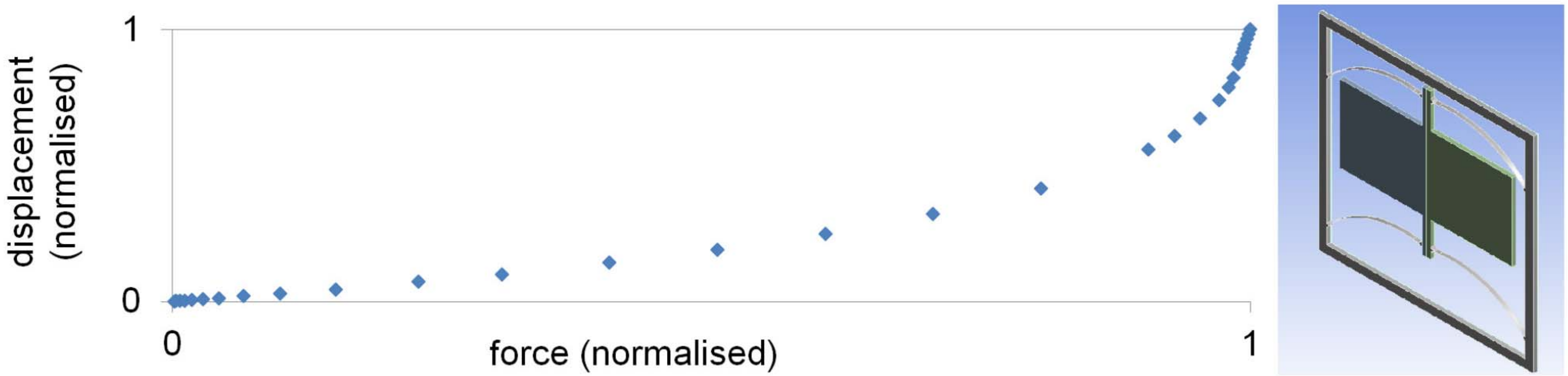
Geometric Antispring: I

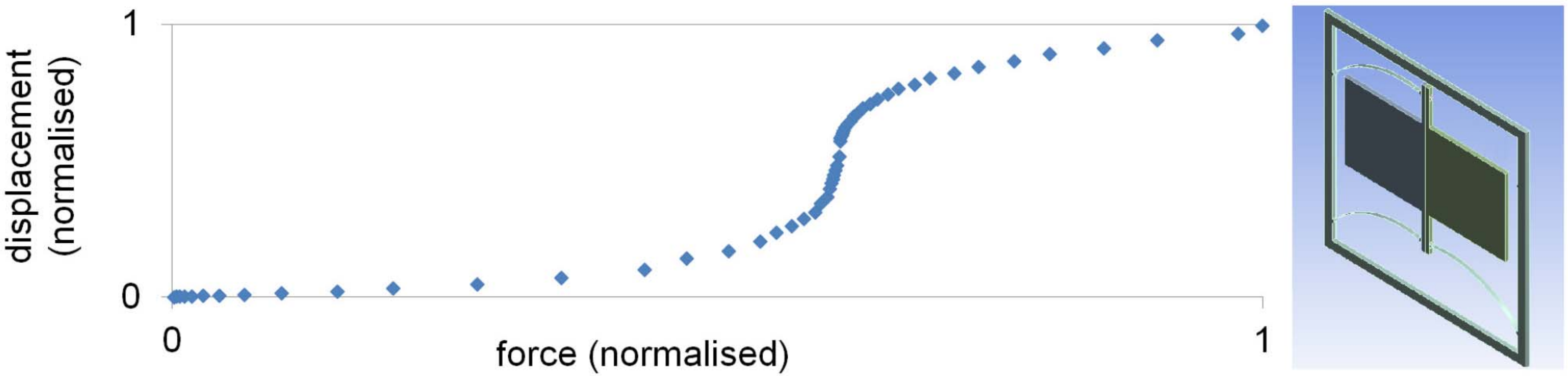


4-flexure: unstable device, frequency tends to zero as displacement increases

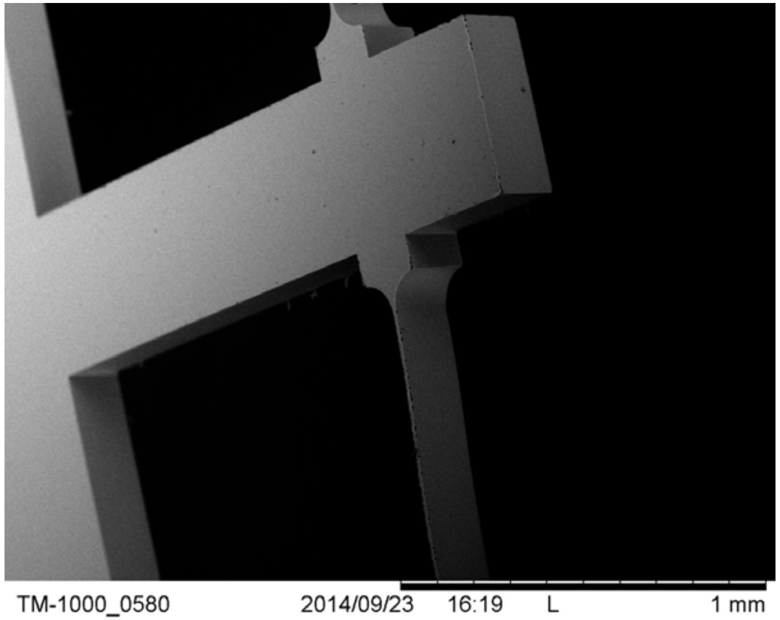
3-flexure: stable device, frequency has a minimum

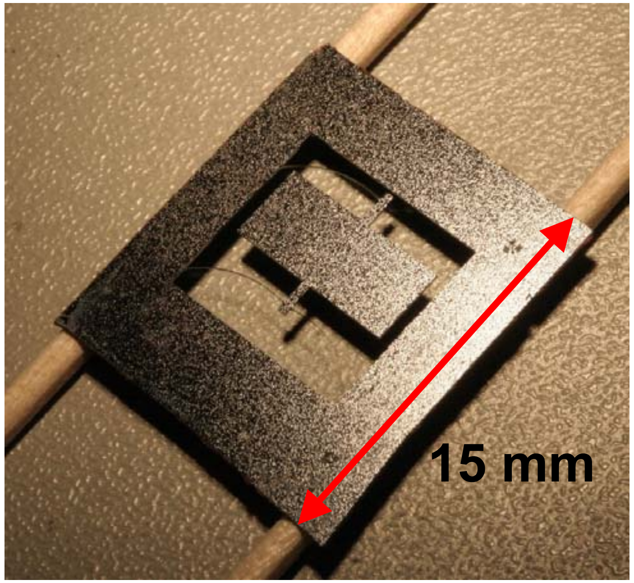
Geometric Antispring: II



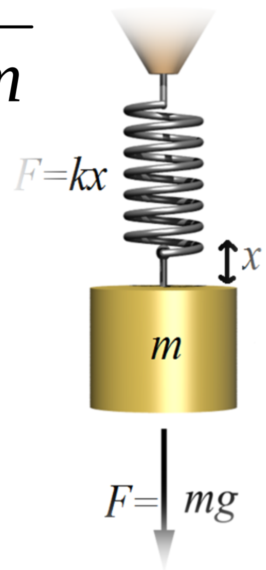


Glasgow MEMS Device

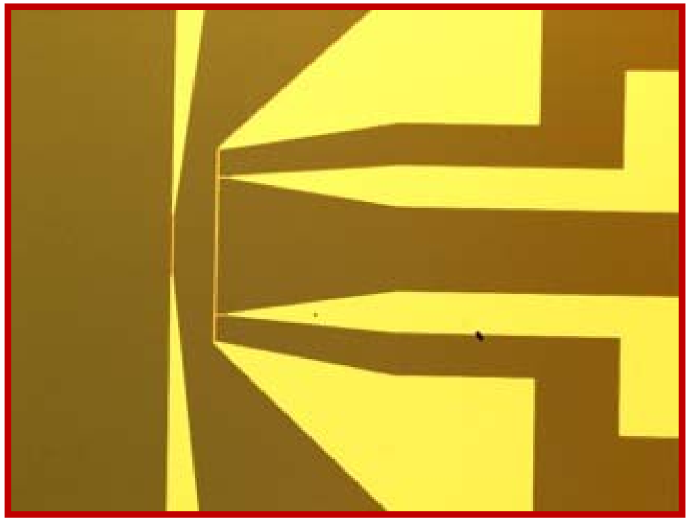




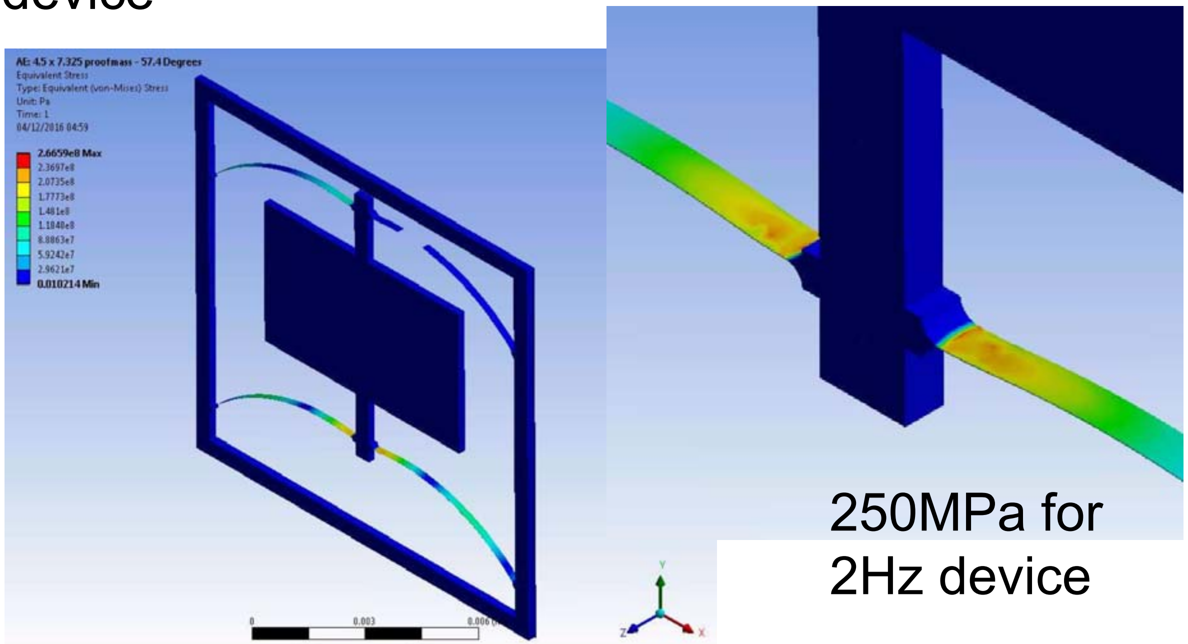
$$g = \frac{kx}{m}$$



MEMS device

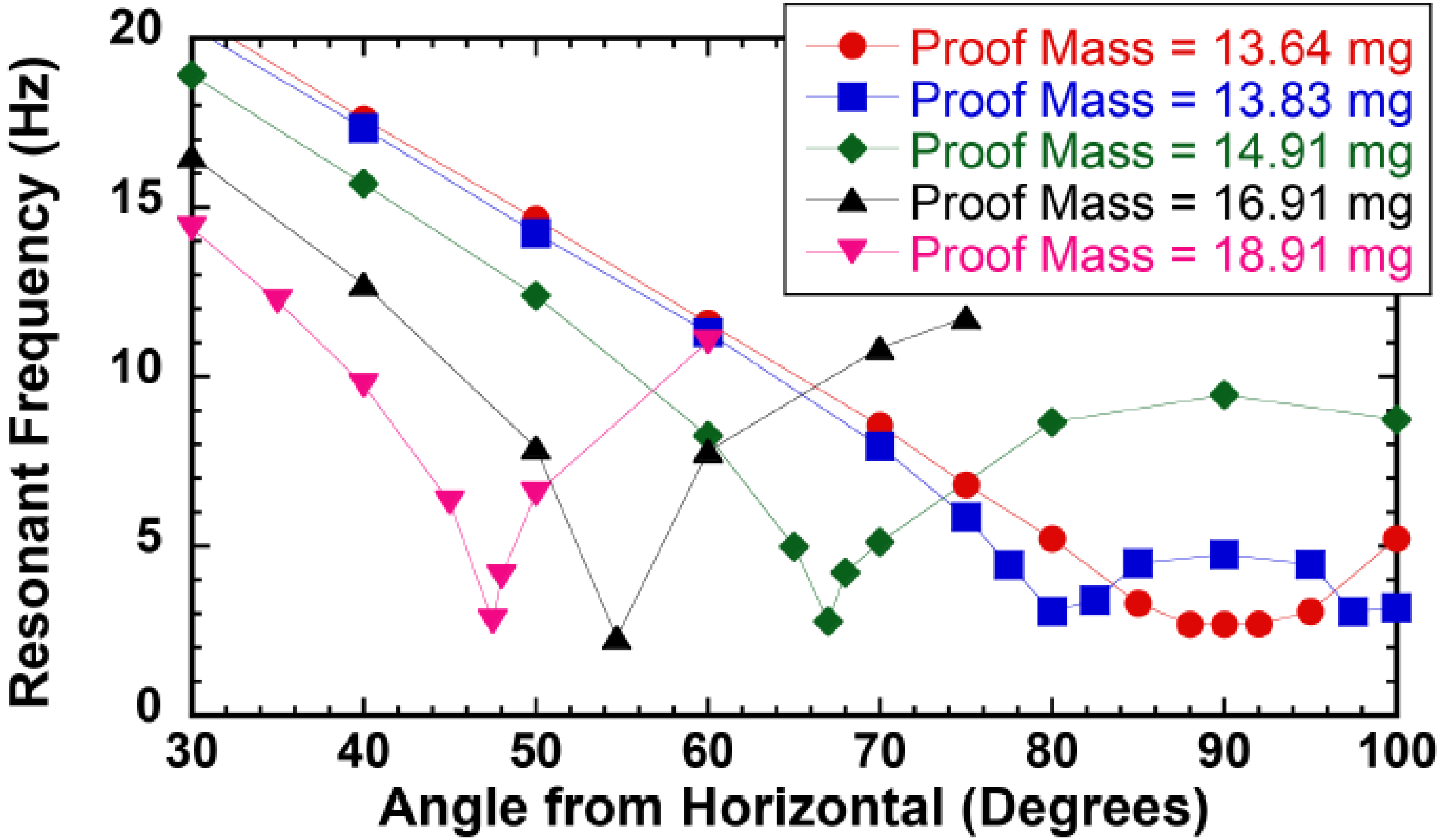


Integrated heater/thermometer

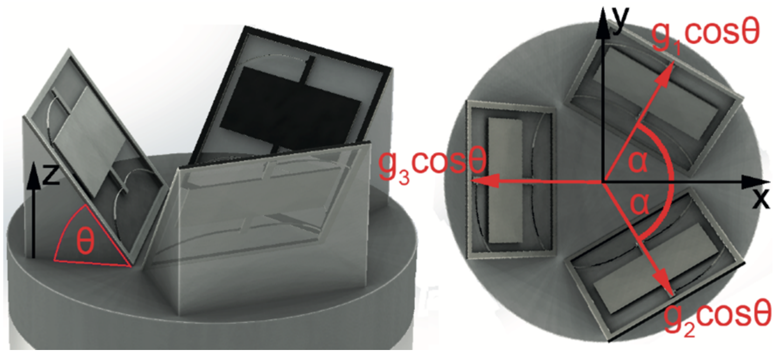


250MPa for 2Hz device

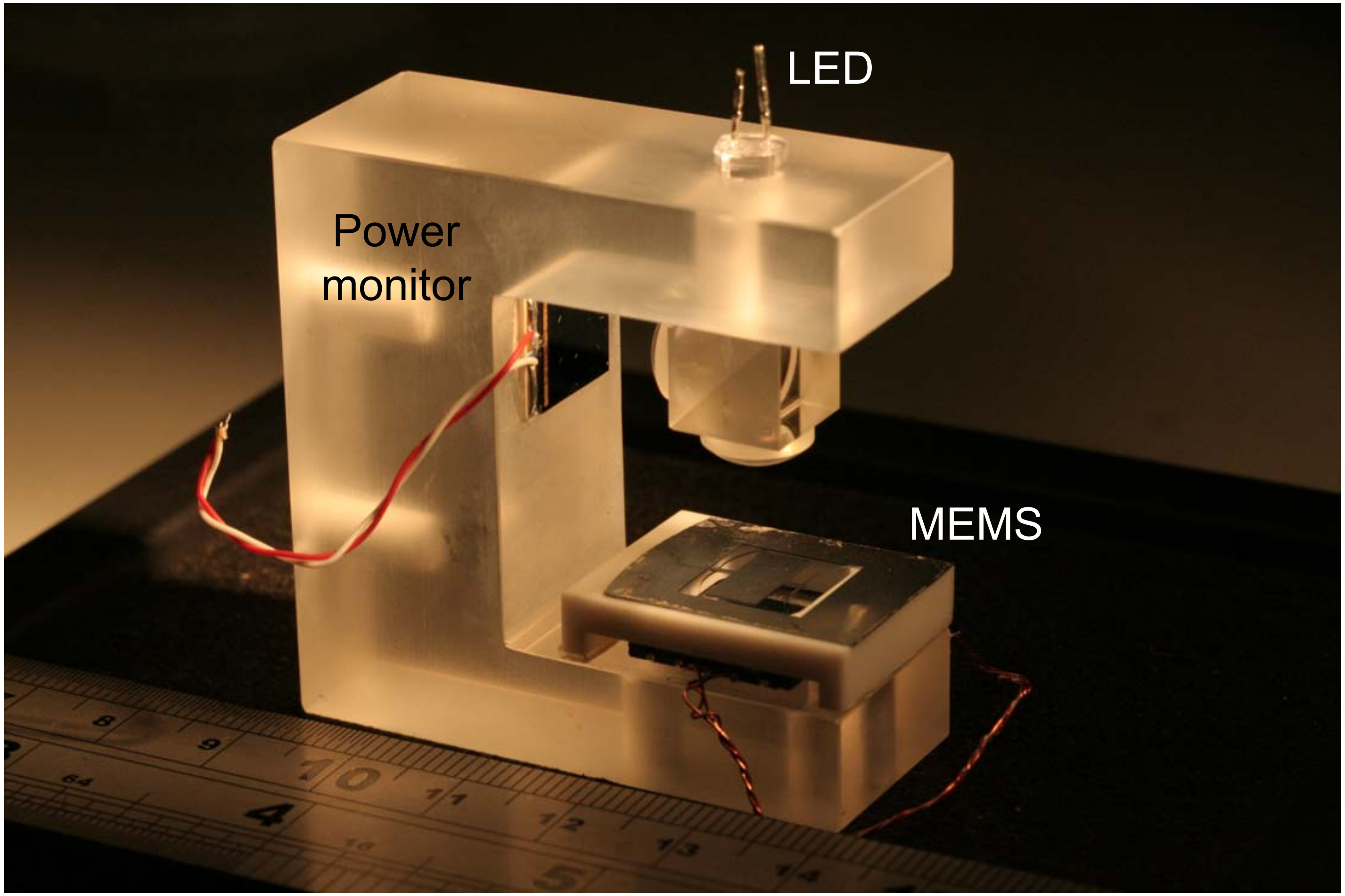
Tri-axial Devices

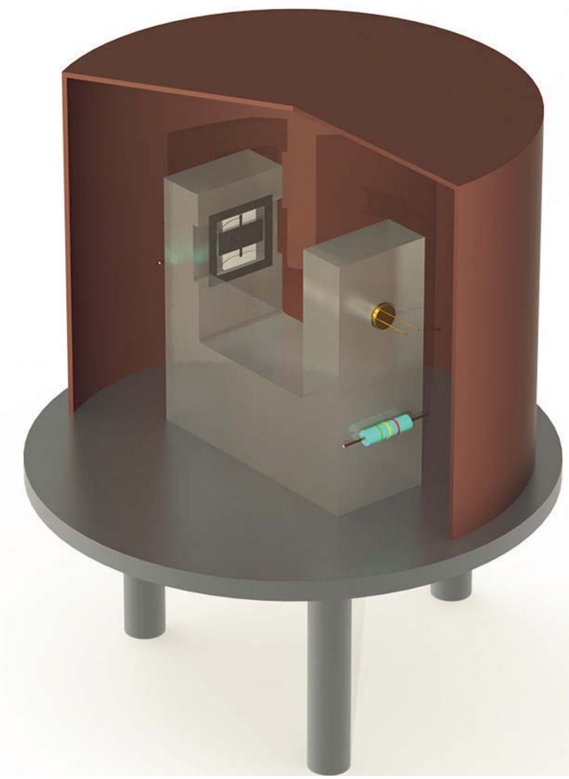


- Can build 1-2Hz resonators which are stable, with minimum frequency at a wide variety of angles => 3 axis devices



Glasgow MEMS Device

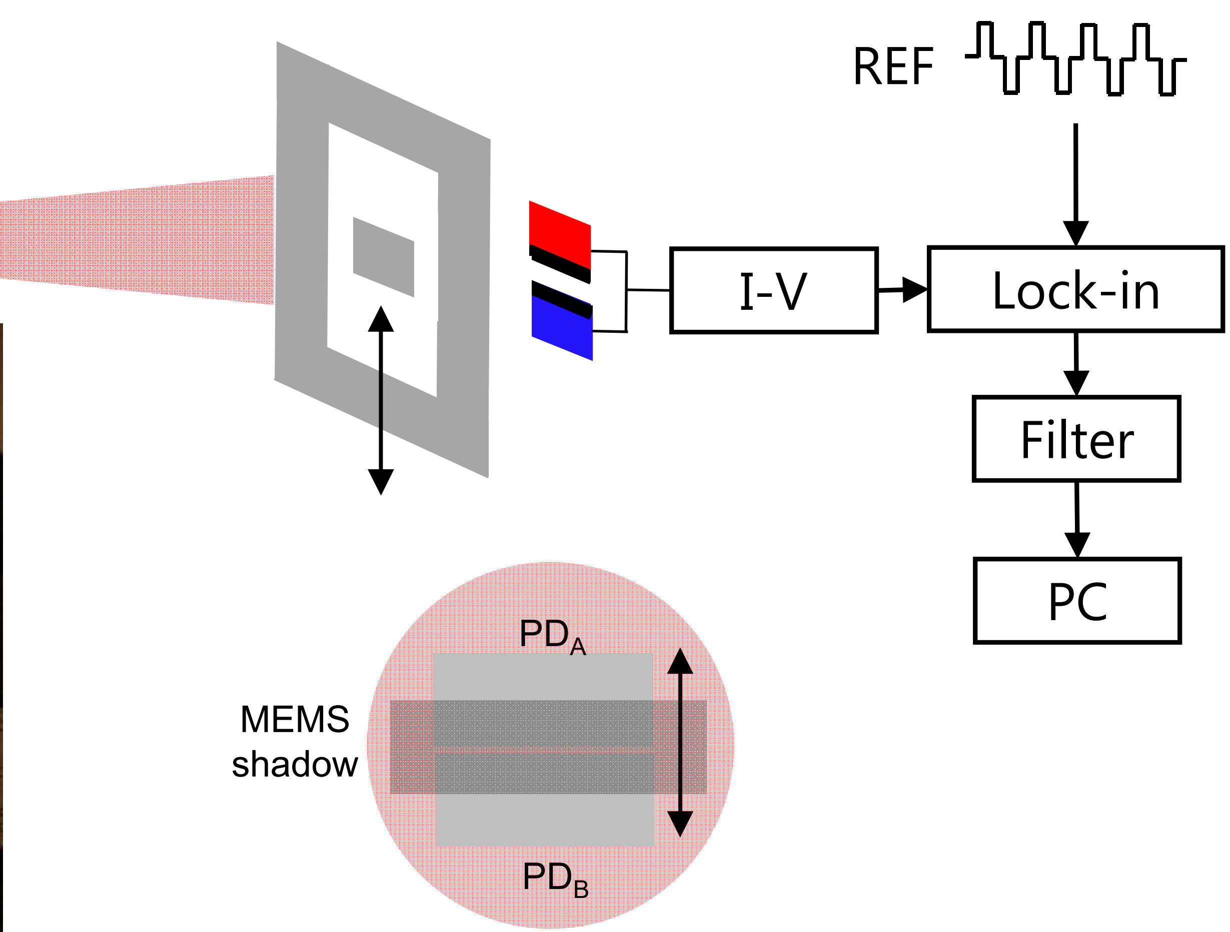


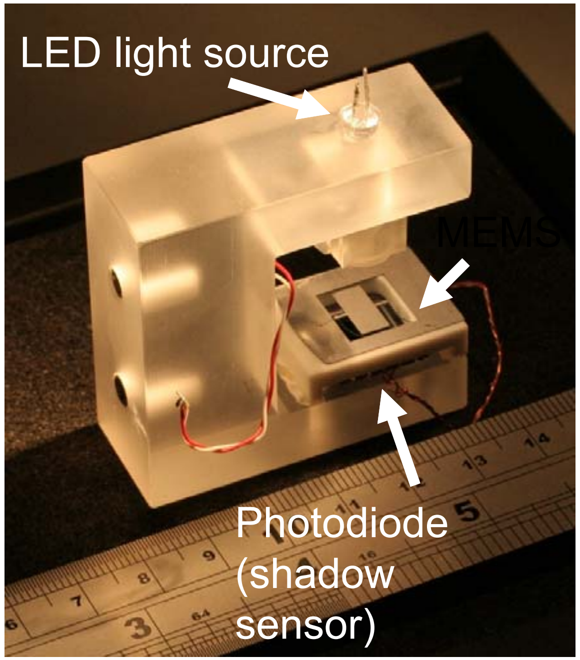


- Prototype built on fused silica structure for high thermal stability
- Thermal control of LED/MEMS/Outer shield required for nanometre precision over several days

Optical Readout

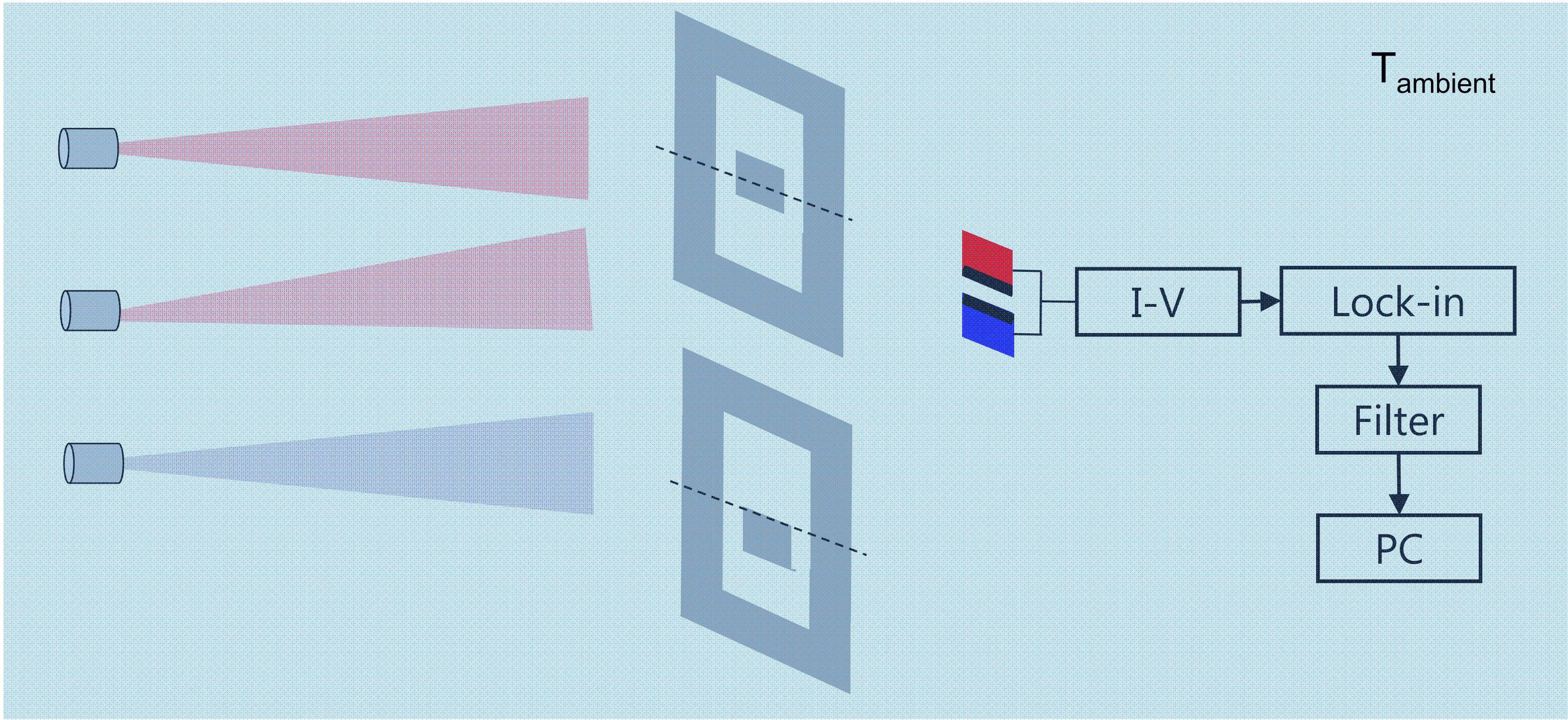
- Developed a shadow sensor that can provide stability of ±4nm over several days
- Split photodiode provides zero output at shadow centre, and immunity to relative intensity noise





Challenges to nm Level Readout

- Temperature variations
  - beam wobble, colour change (peak/FWHM), intensity change, Young's modulus change of silicon, thermal expansion of silicon, temperature dependent electronics/gain
- Aging
  - colour change, intensity change, anelasticity, creep



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

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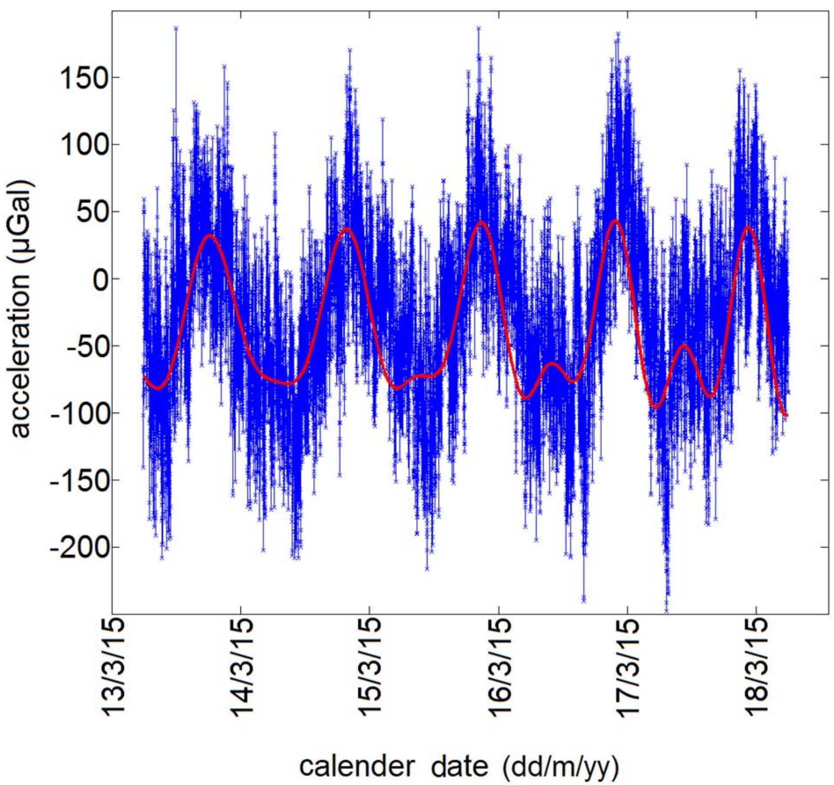
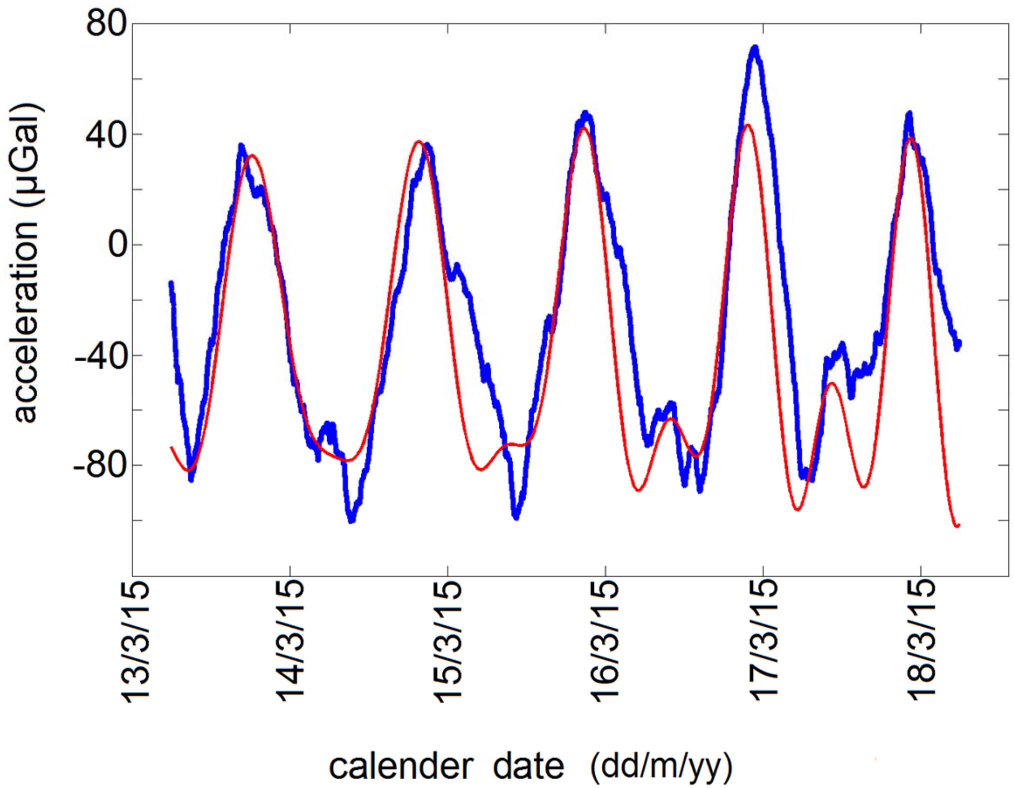
Earth Tides

- There is a daily/twice-daily change in the local acceleration of gravity due to the Earth-Moon tidal potential (300μGal ≈ 300ng maximum variation)
  - changing shape of solid earth (Earth tides)
  - ocean loading due to water tides (not in phase and 5%-8% in Glasgow)
- This is a good signal to test long term stability. Measured during 2015-2016





University of Glasgow

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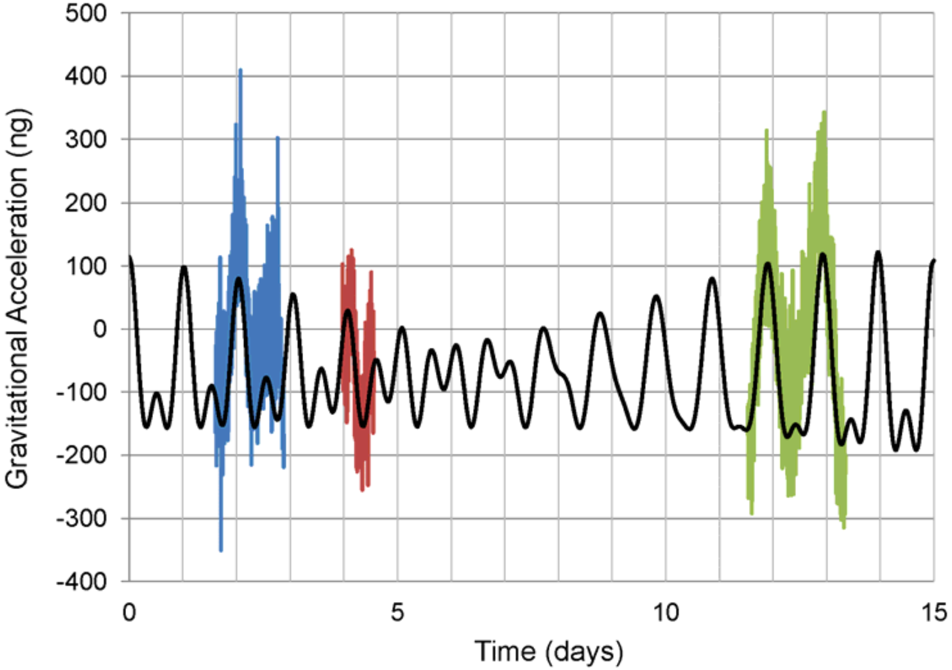
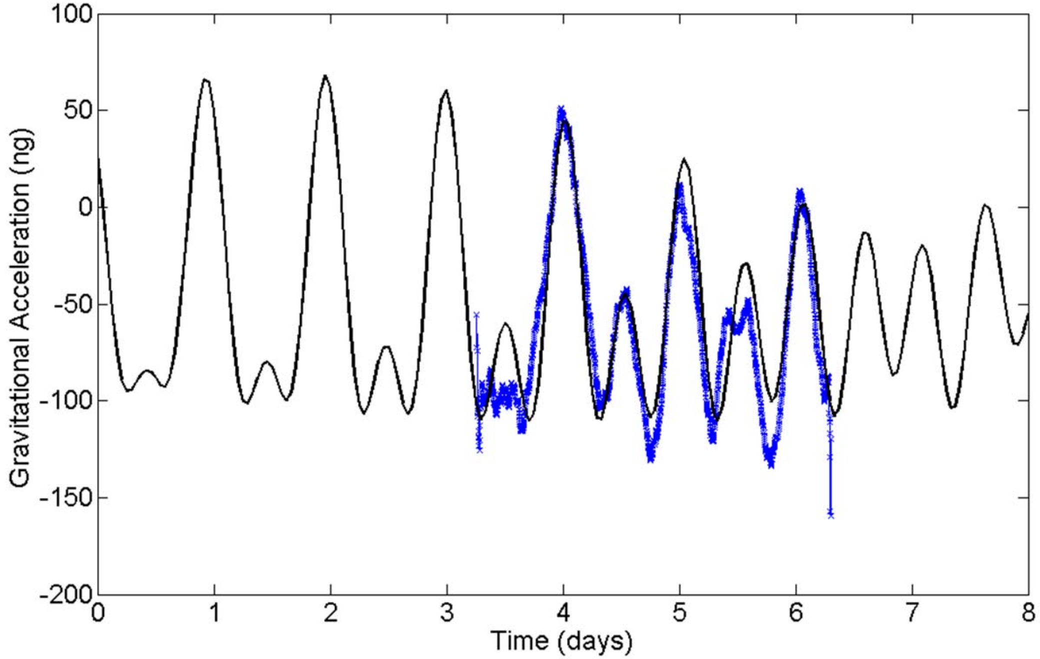
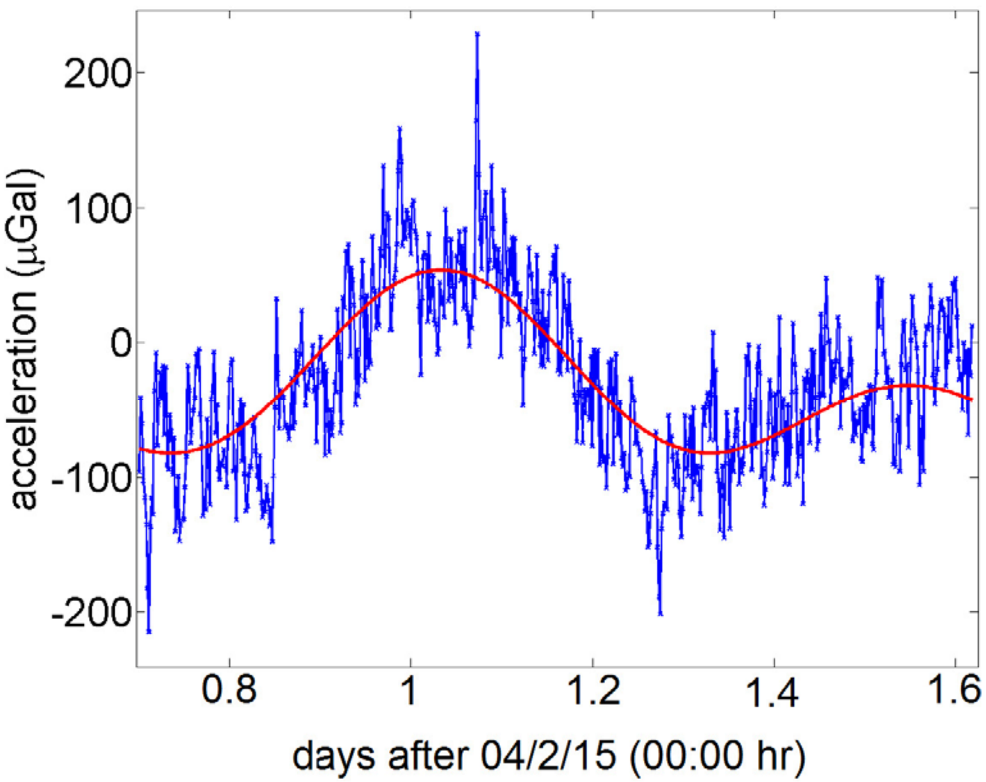


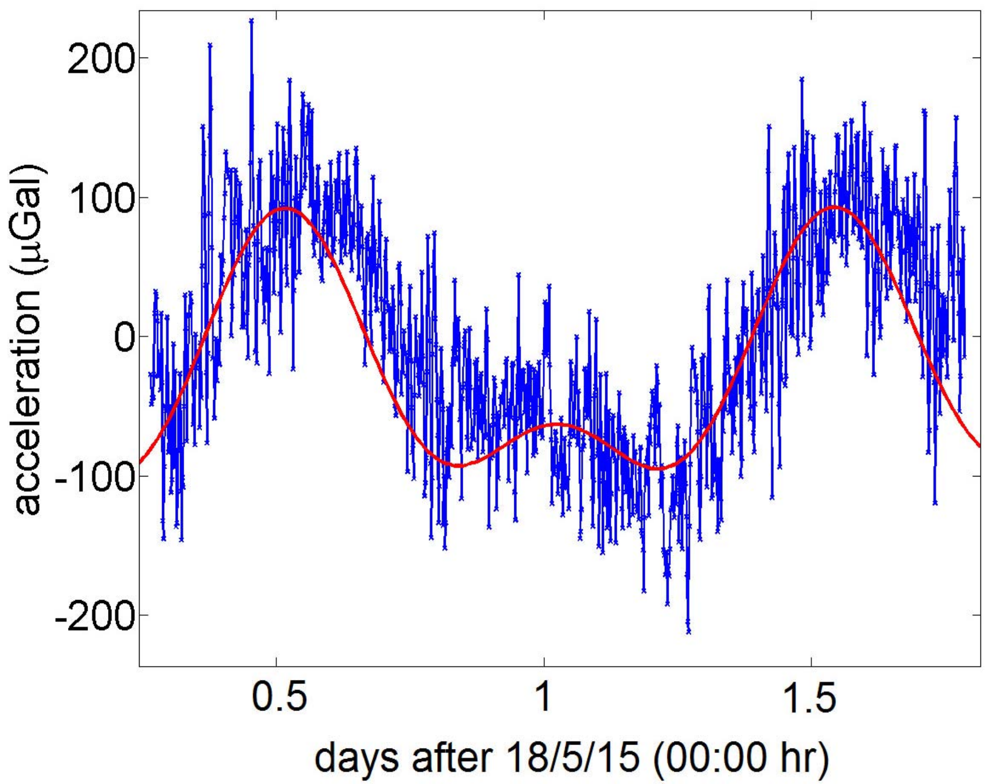


IGR

JWNC The James Watt Nanofabrication Centre

Earth Tides

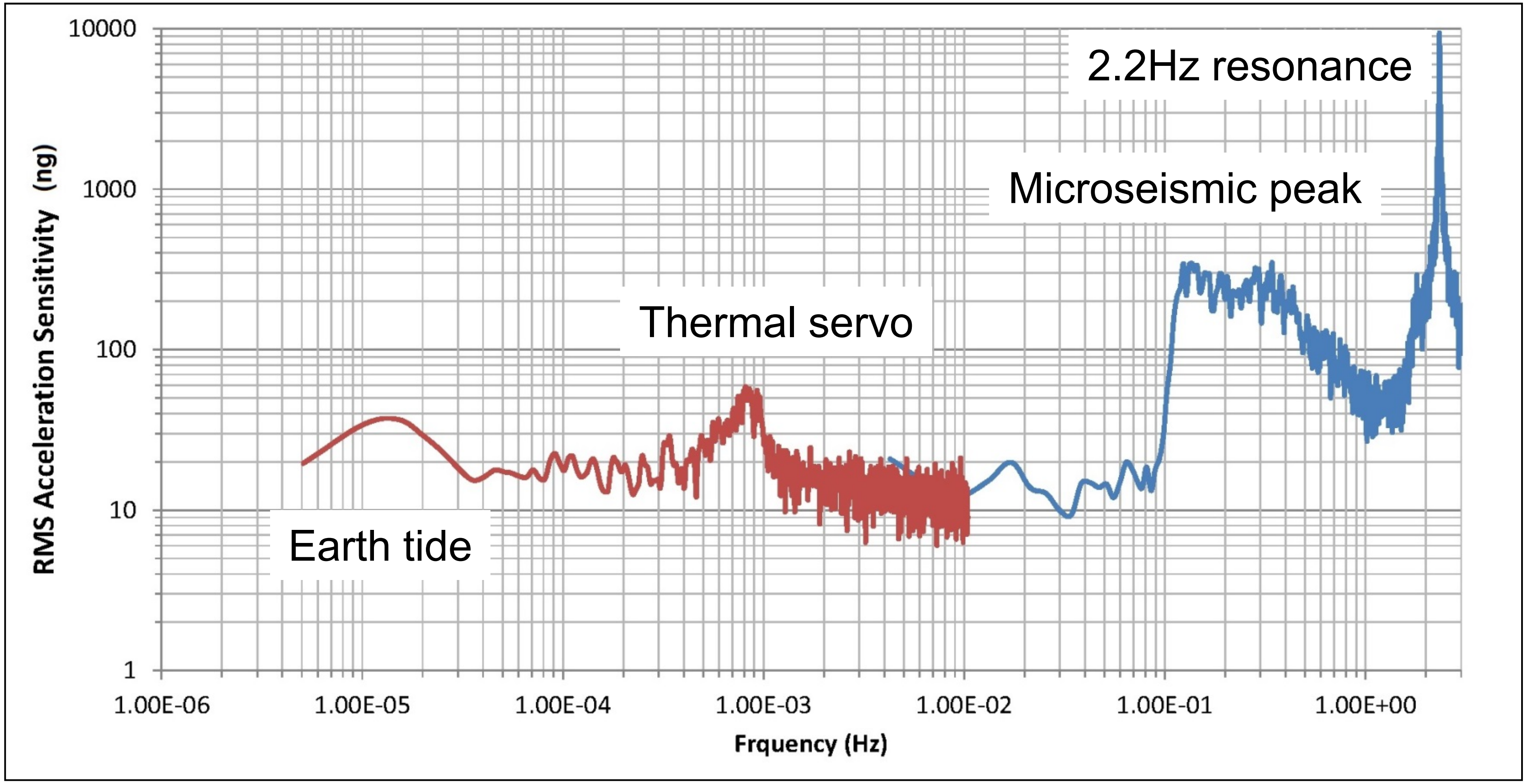




- Two data sets separated by approximately 4 months

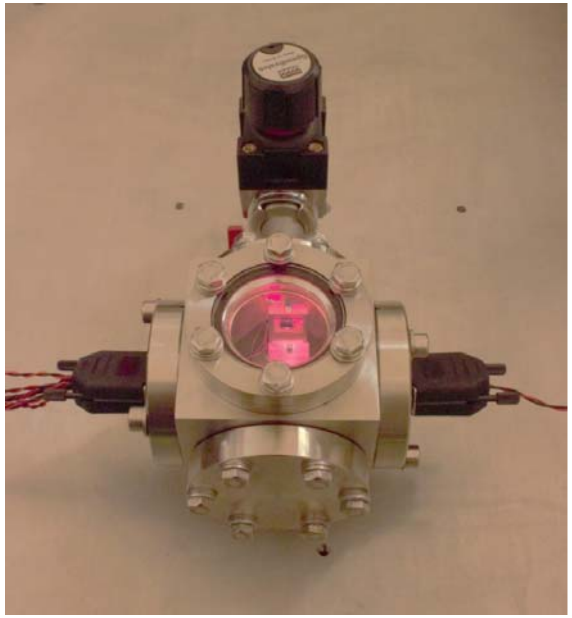
Seismic Noise

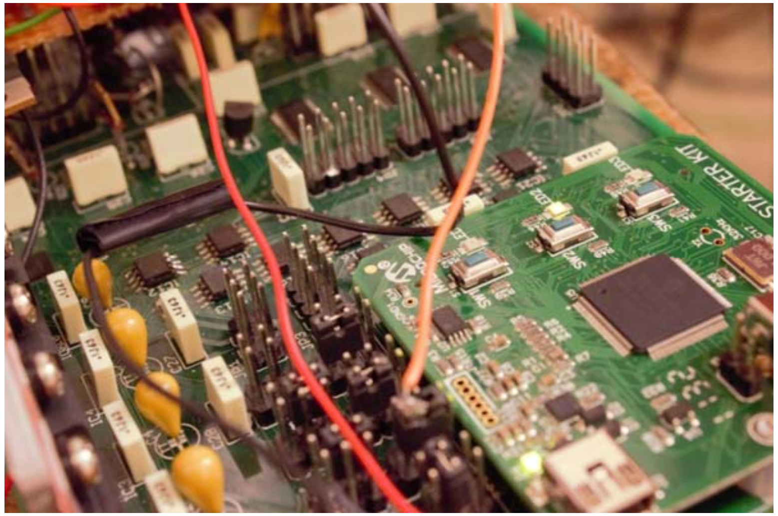
- The device can be operated over a wide range of frequencies (5 orders of magnitude): seismometer-accelerometer-gravimeter



- Seismic nose excites resonant mode to about x10-x100 earth tide signal

Field Prototype





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

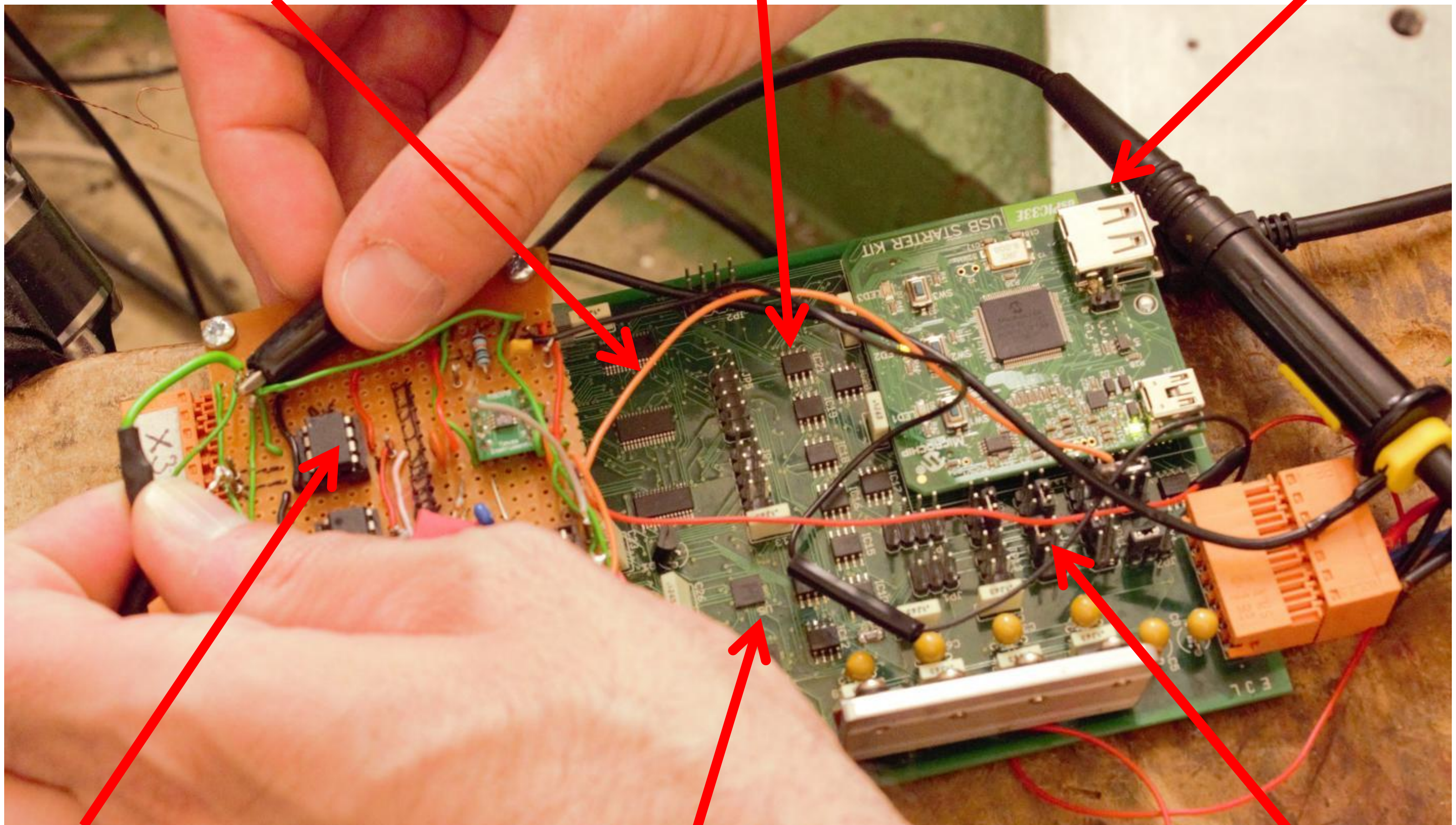
2016: shoebox sized field demonstrator, battery power

Electronics Board

3x 24 bit ADC's

16 bit DACs for LED drive/heater control

dsPIC processor



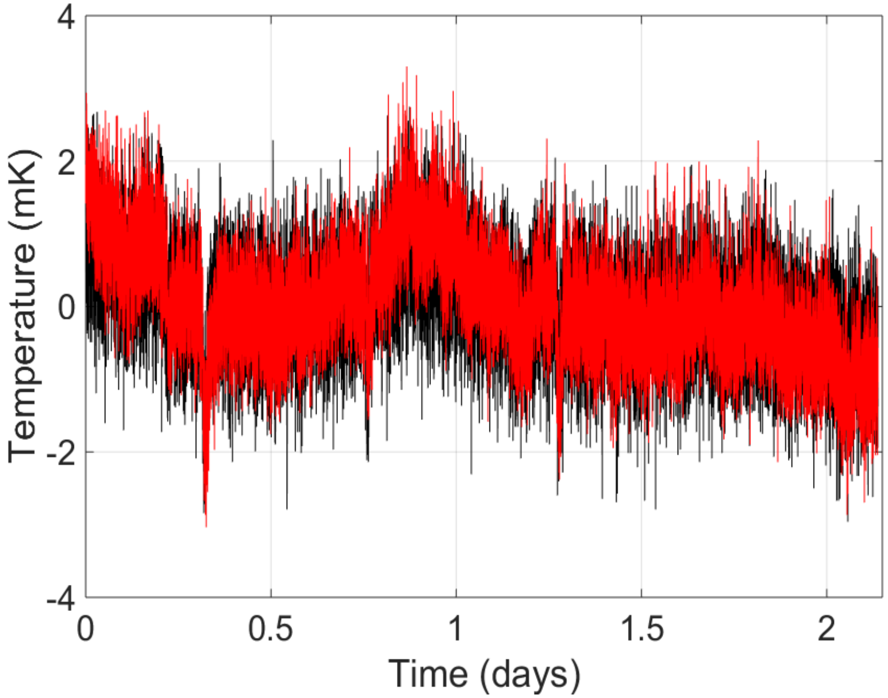
Signal conditioning and I-V converters, tilt sensor readout

3x 24 bit temperature sensors (PT100)

Voltage regulators and references

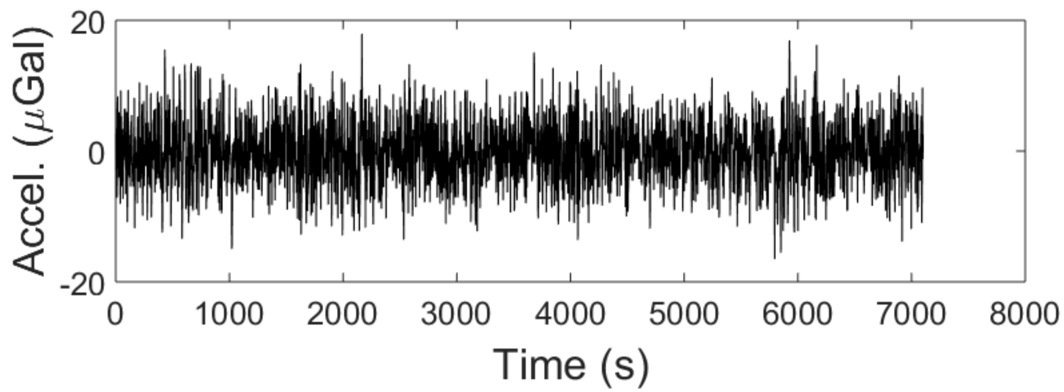
- Data logger module to run autonomously in field

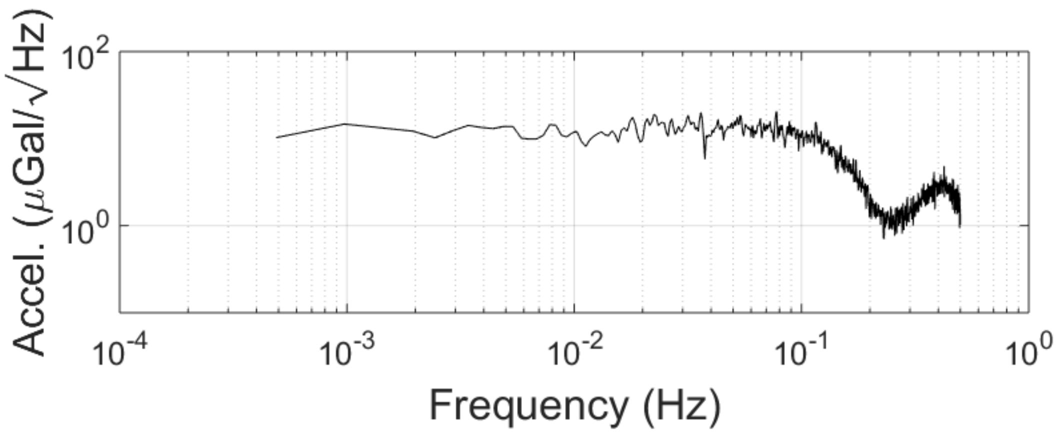
Electronics Board



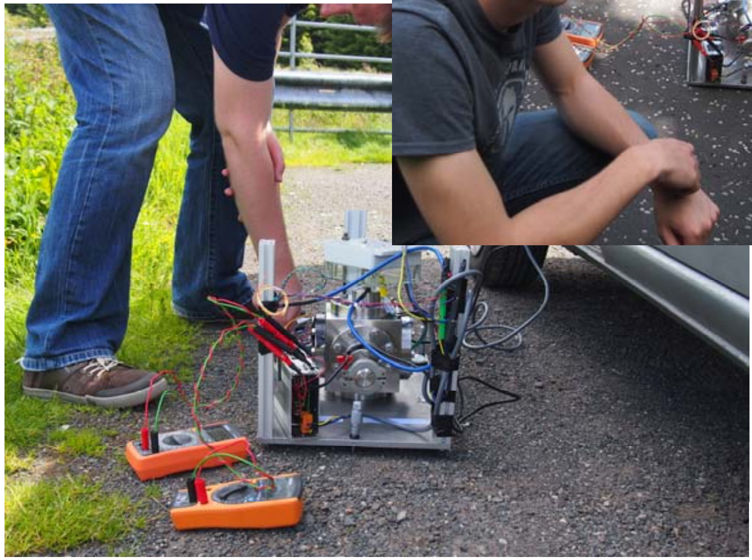
- mK temperature sensing required to minimise coupling via thermal effects

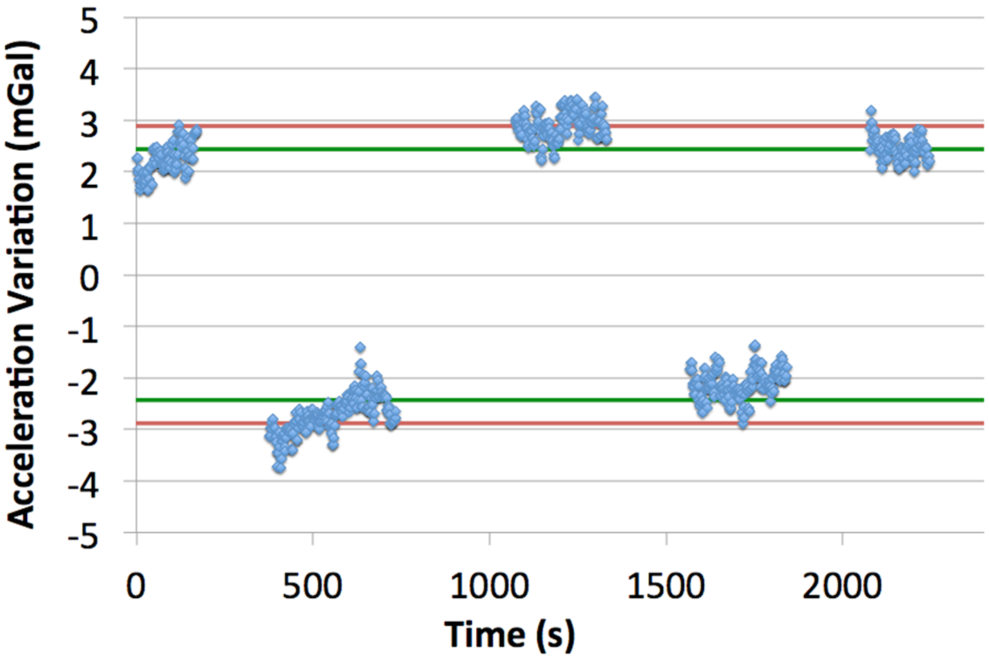
- Digital lockin is robust against thermal drift and is re-configurable. Provides 10μGal/√Hz noise performance (can be improved using PGA on input)



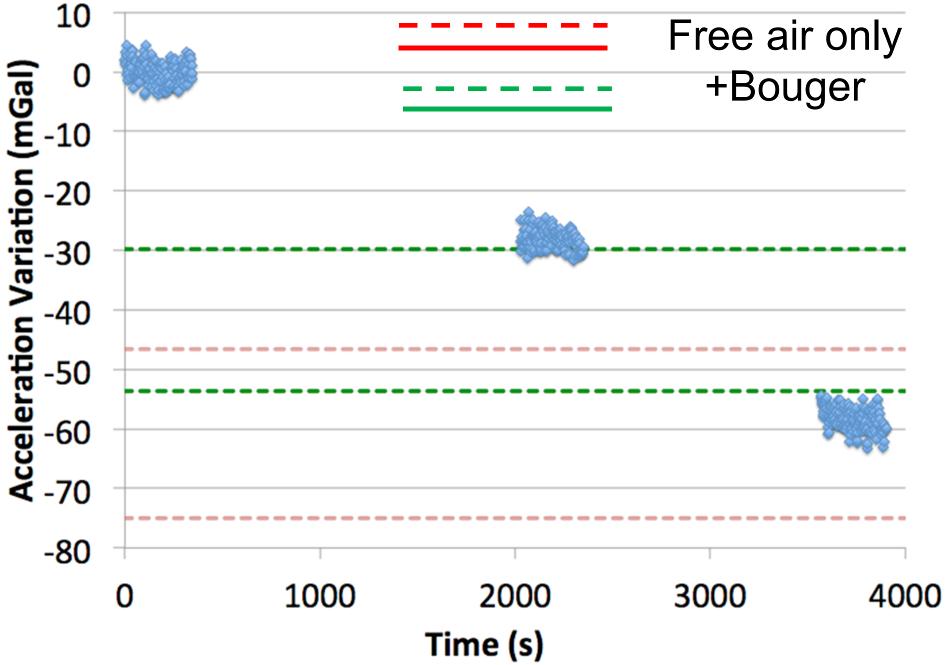


Field Tests (2017)





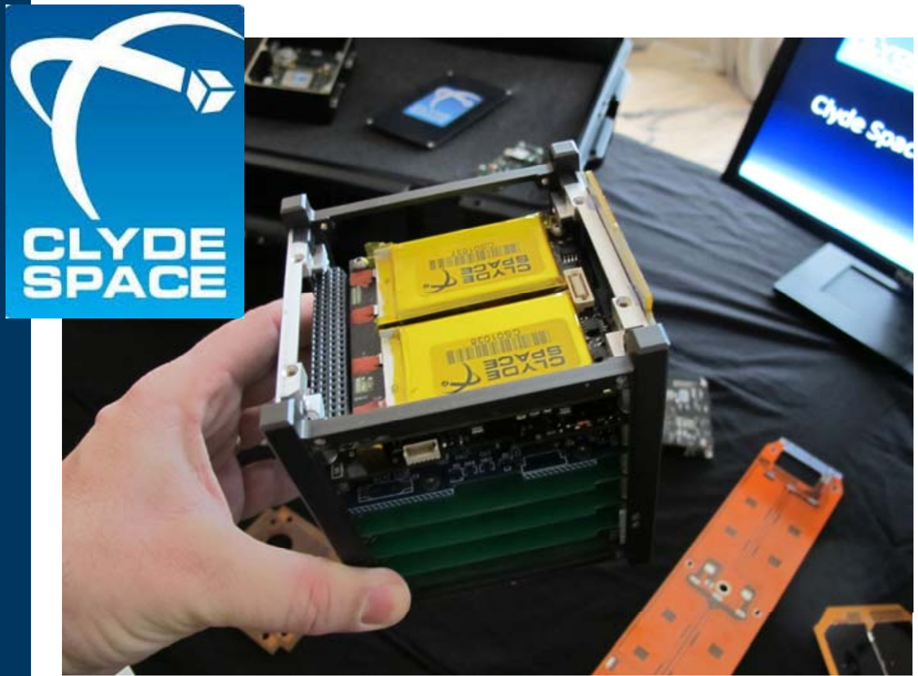
20m lift test



270m altitude change (Campsie Hills)

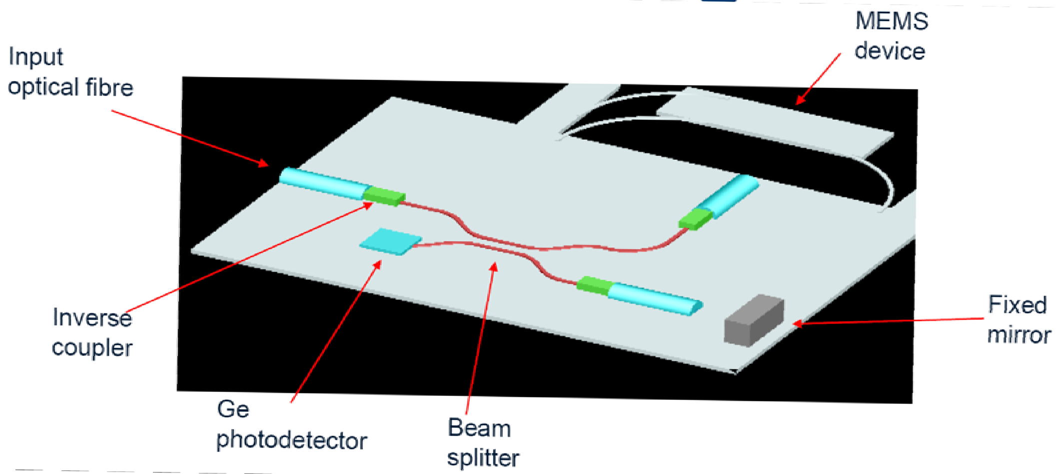
Ongoing Projects

University of Glasgow



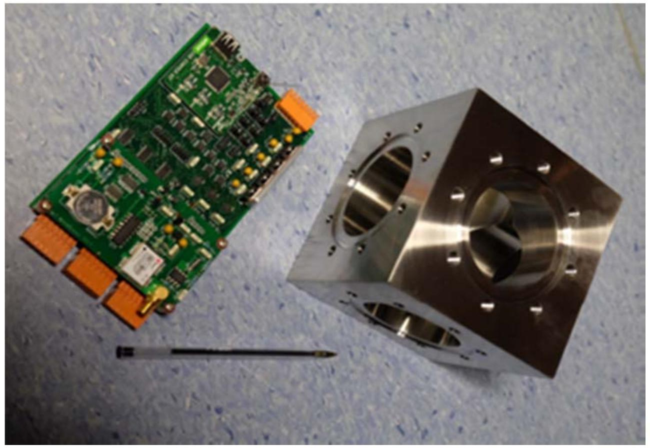
Attitude control (EngD/CENSIS)

Schlumberger



Miniature interferometric sensing

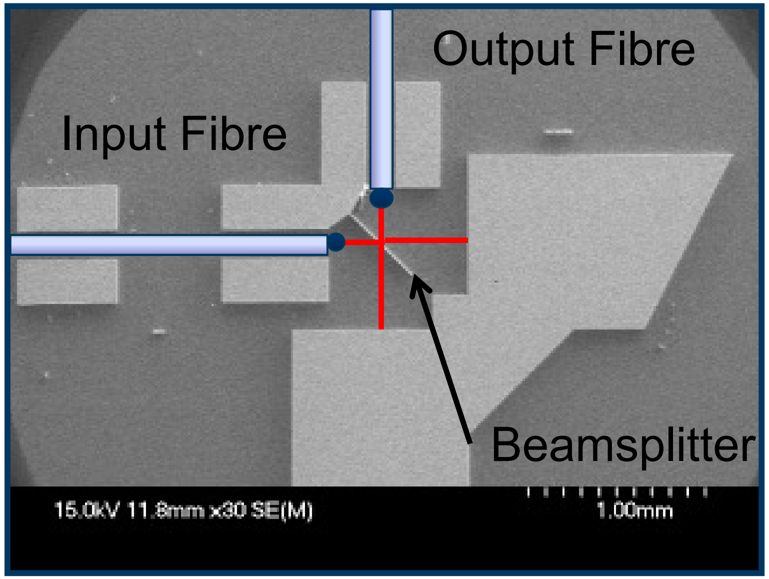
Underwater sensing



Field prototype (CDT) bridgeporth

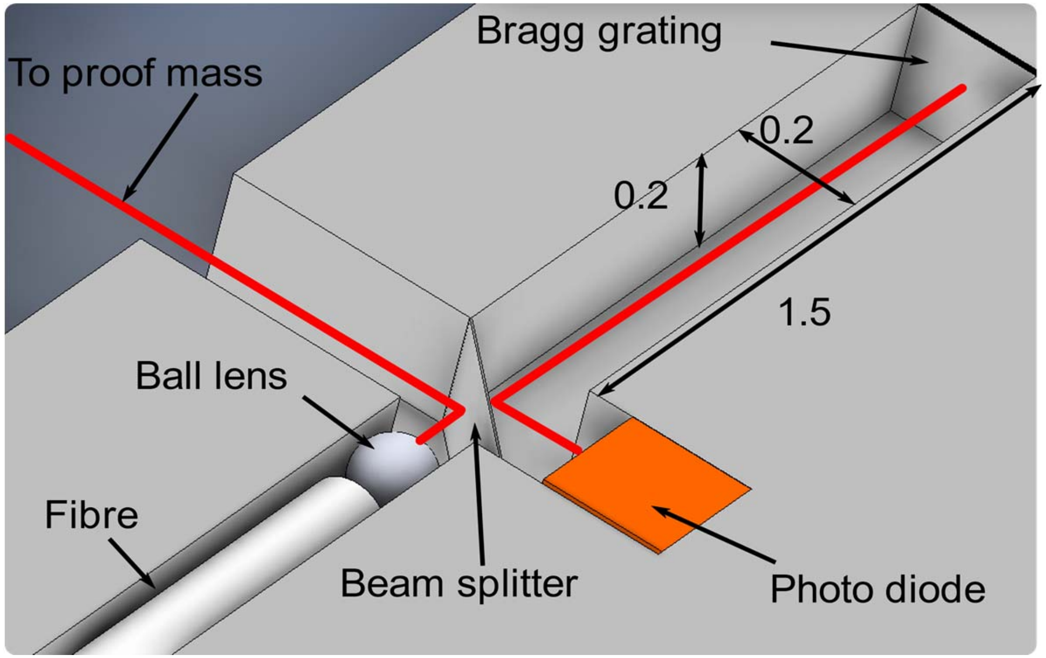
Chip-Scale Interferometer

- Interferometric readout promises high sensitivity (10^{-12} to 10^{-15} m sensitivity)
- Build chip size interferometer
- Develop simple readout



On-chip interferometer
Test of a miniaturised beam splitter

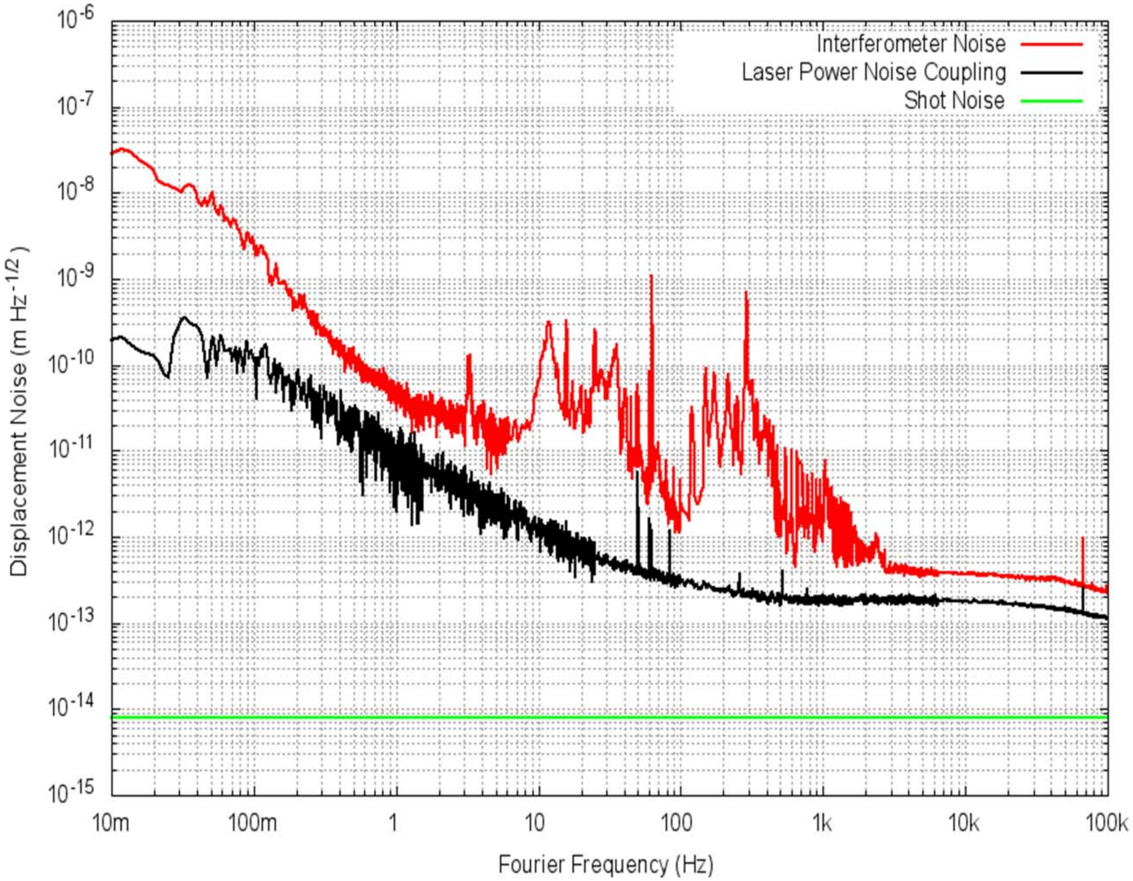
Credit: Antonio Samarelli

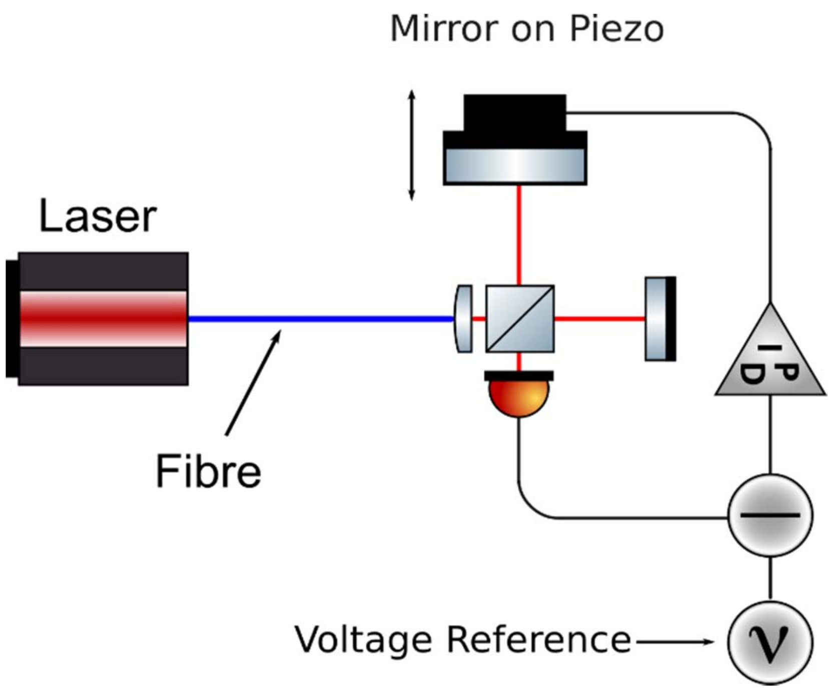


Model of a chip size Interferometer
Distances given in mm

Table-top experiment

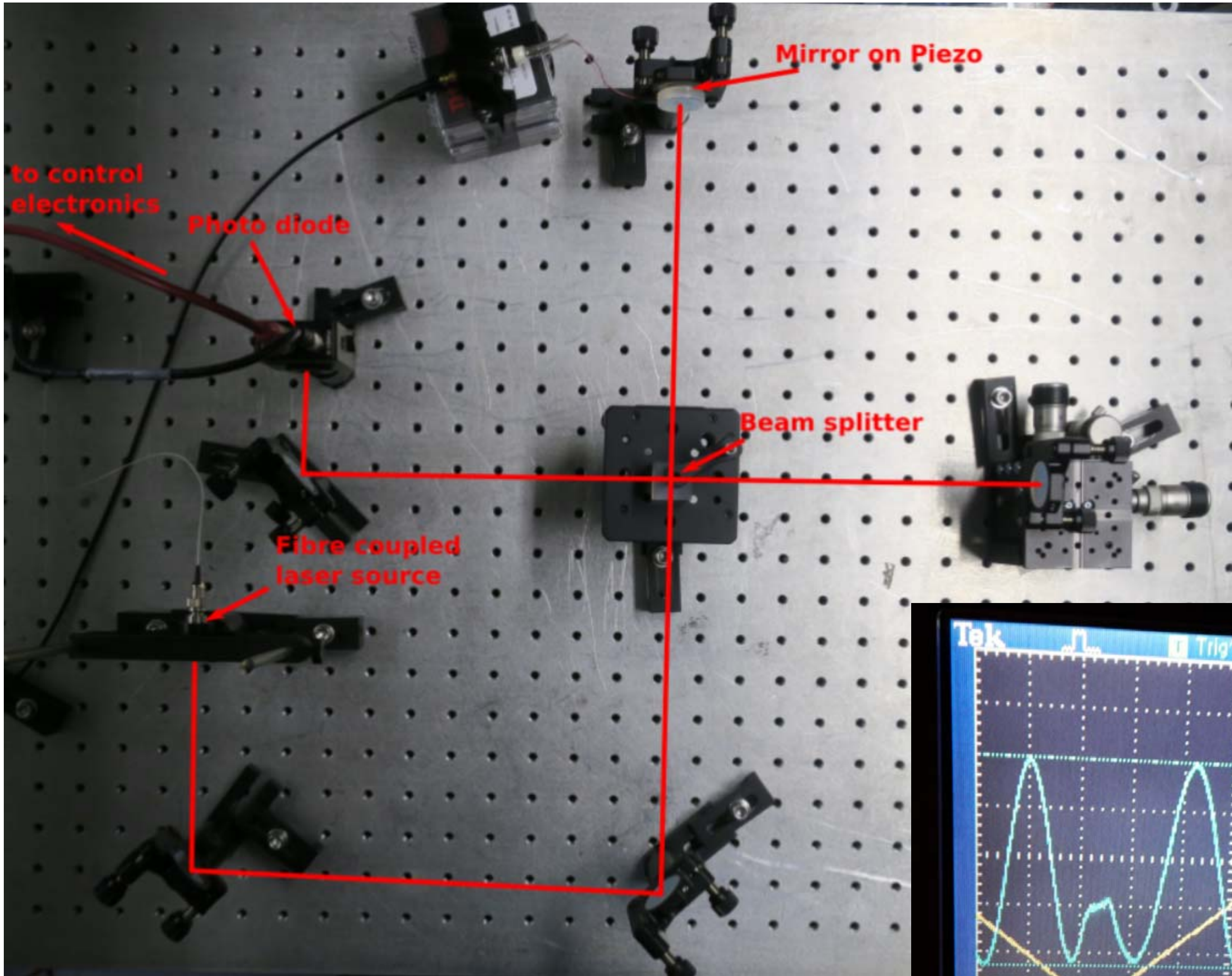
- Testing readout schemes
- Interferometer locked to most sensitive working point

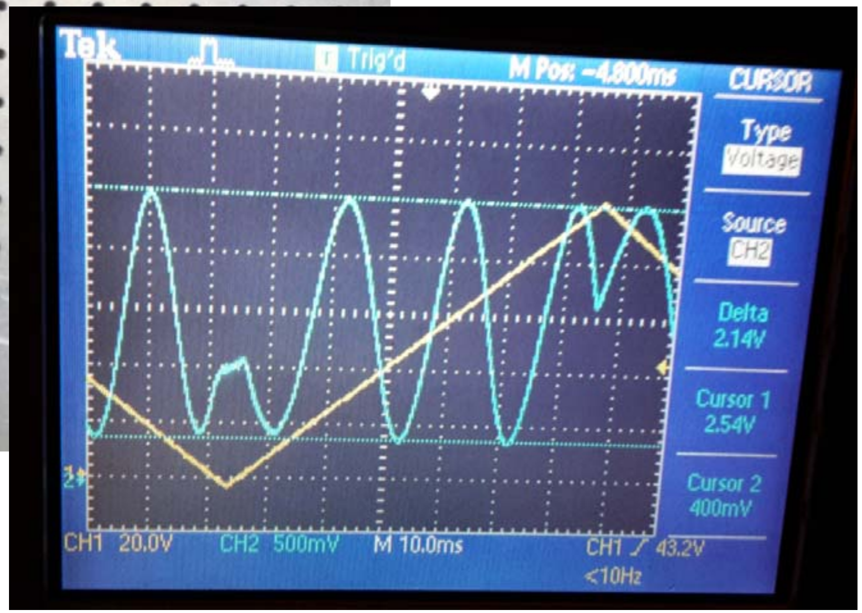




- Sub nm sensitivity at frequencies above 1 Hz
- Seismic, acoustic and power noise dominates
- Further analysis of noise at low frequencies underway

Table-top experiment





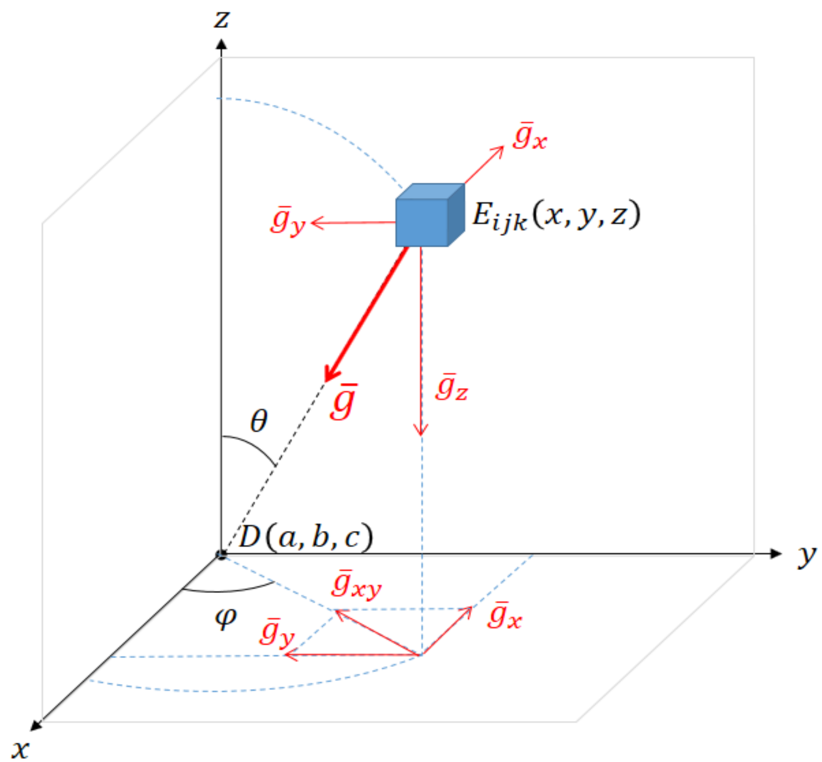
Underwater Gravimetry

- Measurement of gravitational acceleration (g) in a marine environment

- Can be used to detect and navigate submarines

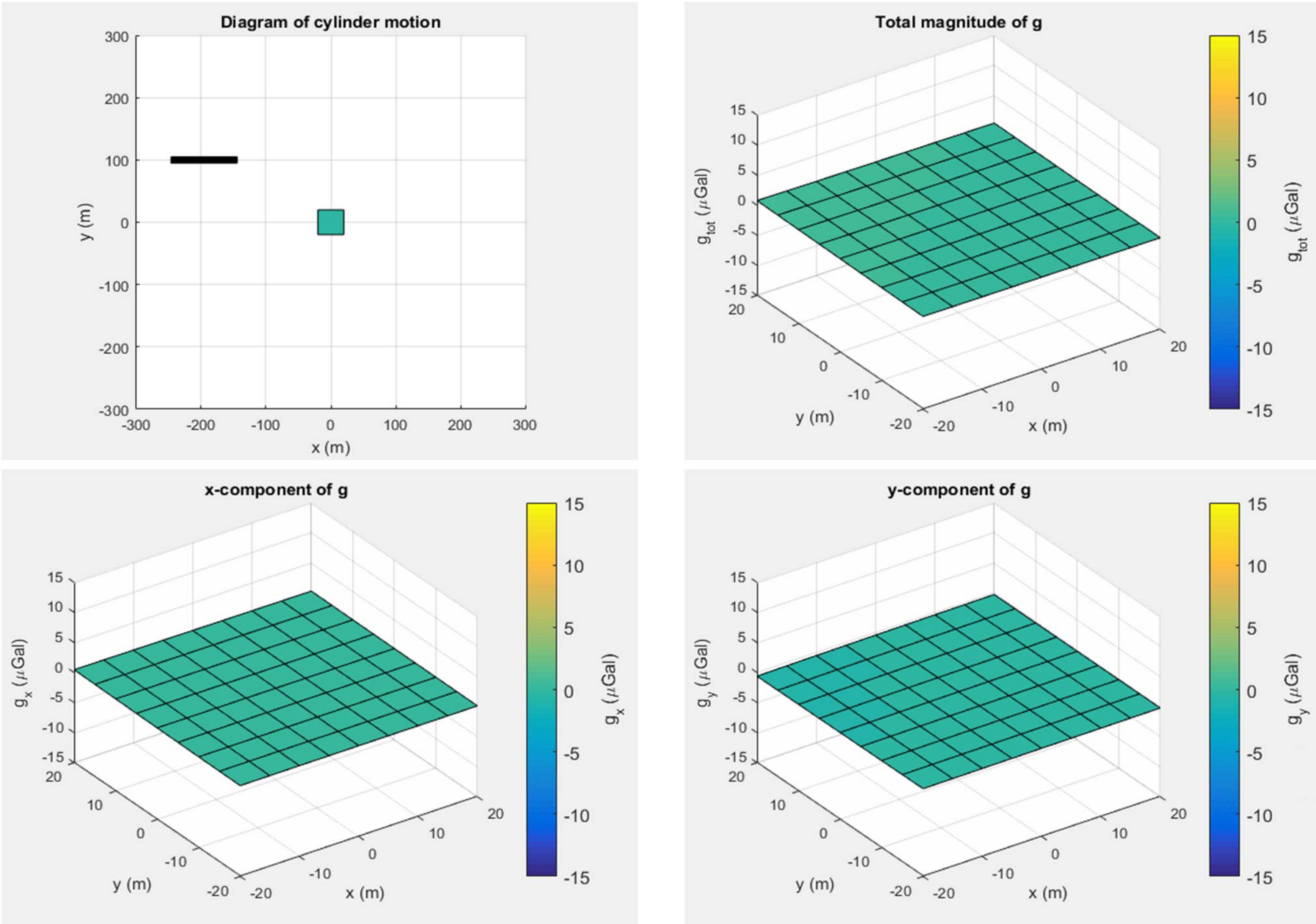
- Benefits of gravimetry:
  – Passive detection of submarines and terrain
  – Gravitational signal cannot be masked

- Drawbacks of gravimetry
  – Gravitational signals are very weak - Limited range



Results from model

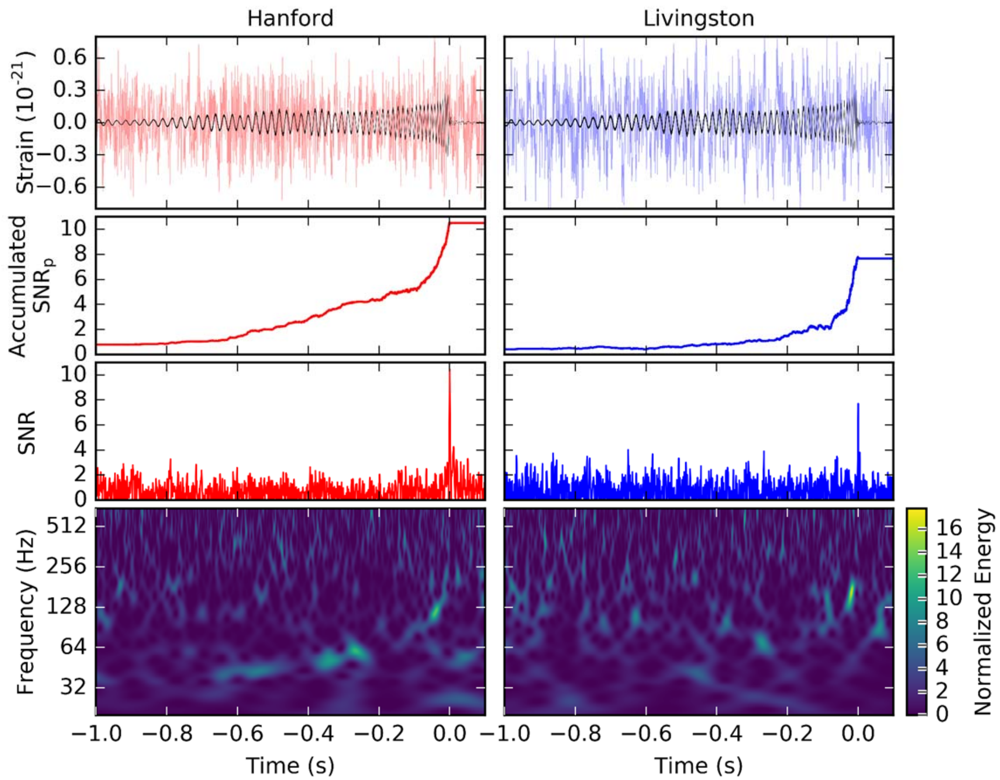
- 80 m away from a gravity meter (neutral density object)



Underwater Gravimetry

- Next plans are to develop matched filters to search through gravimeter data

- Look for a particular mass model with a given direction/distance from the MEMS array



- This is a very similar problem to gravitational wave analysis, where templates for different masses/spins/orientations are tested for online triggers

- Collaboration with GW/QuantIC expertise in GPU processing

IGR

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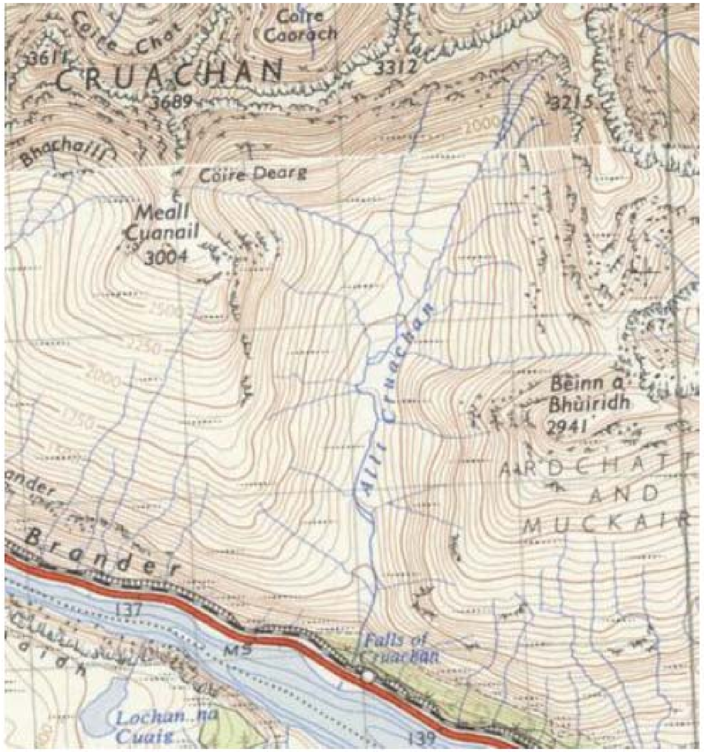
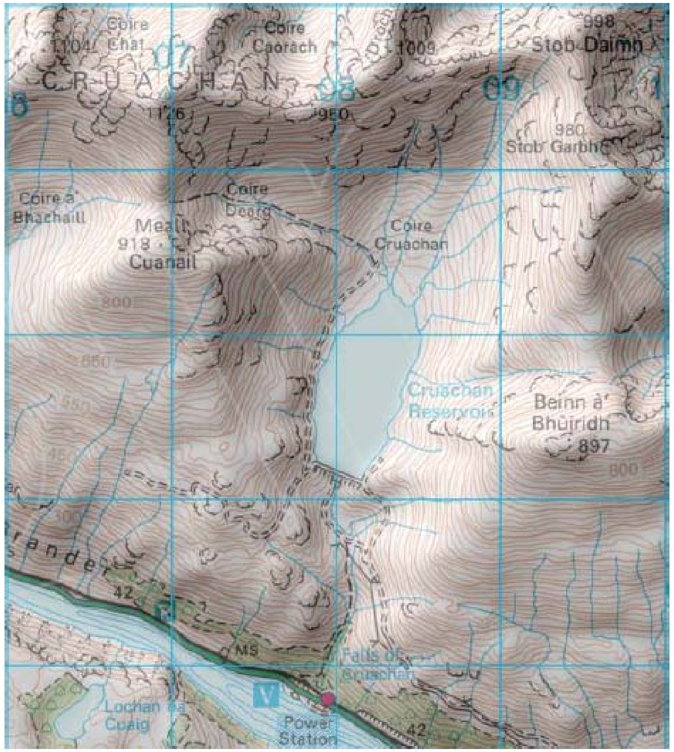
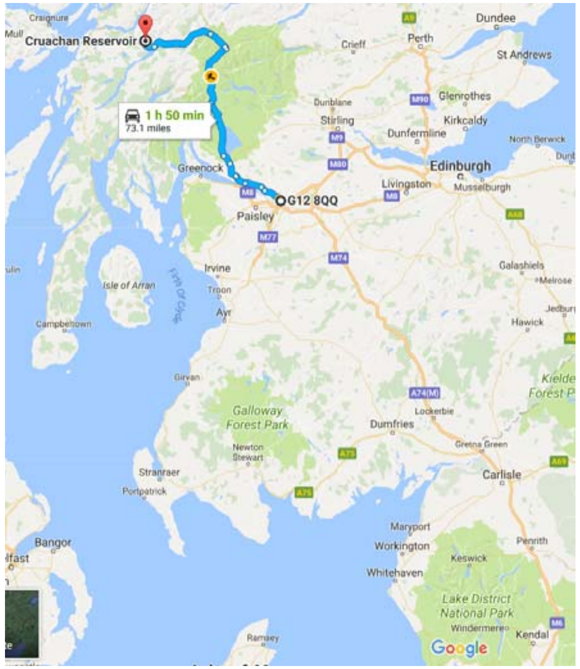
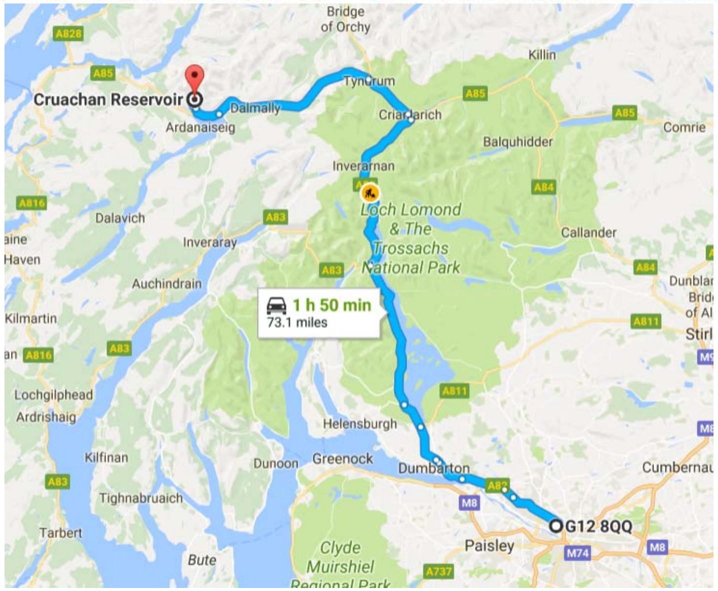
Bridgeporth Project









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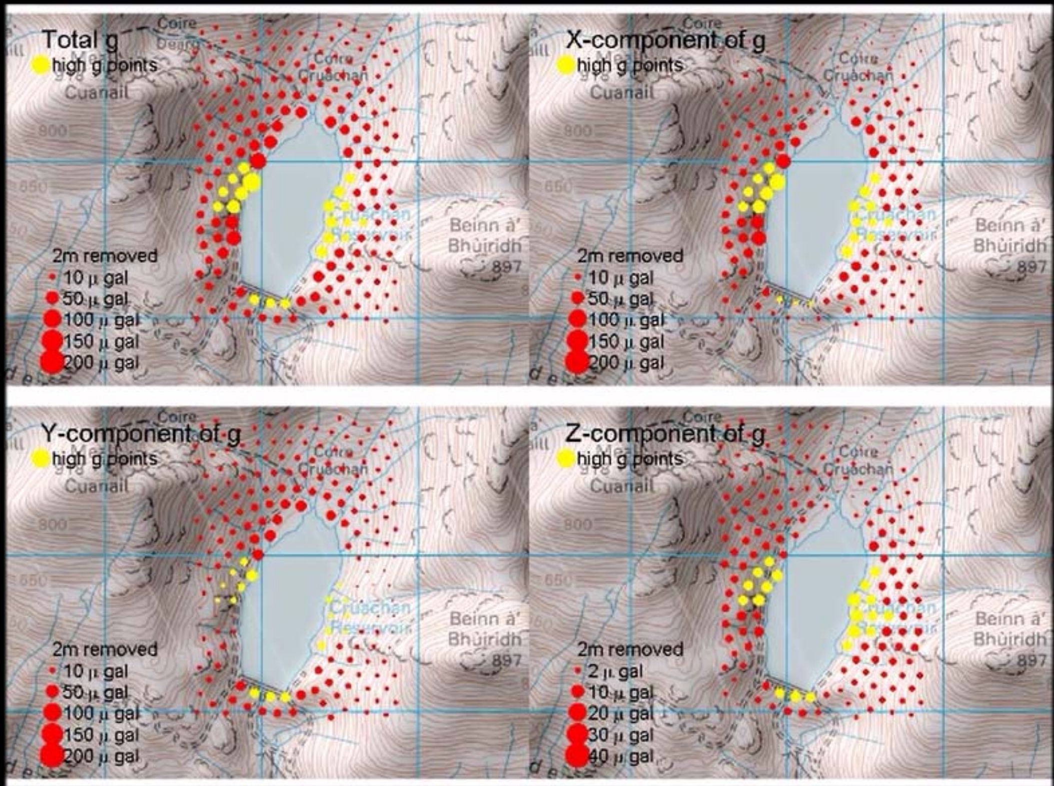

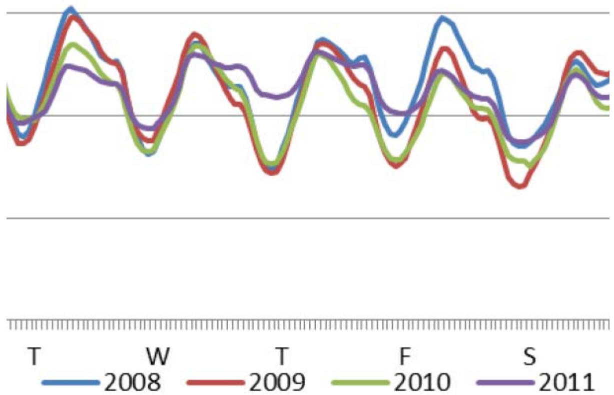

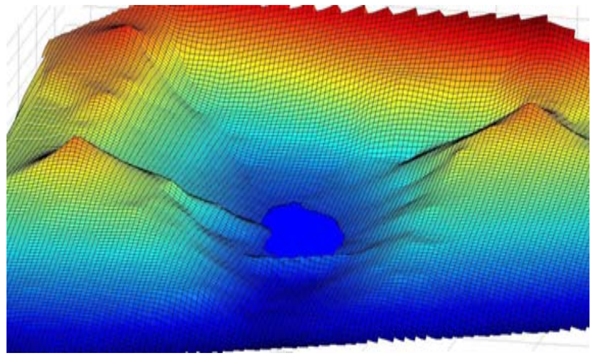

- Measurement of gravity around Cruachan due to reservoir draining (30-40µGal signal)

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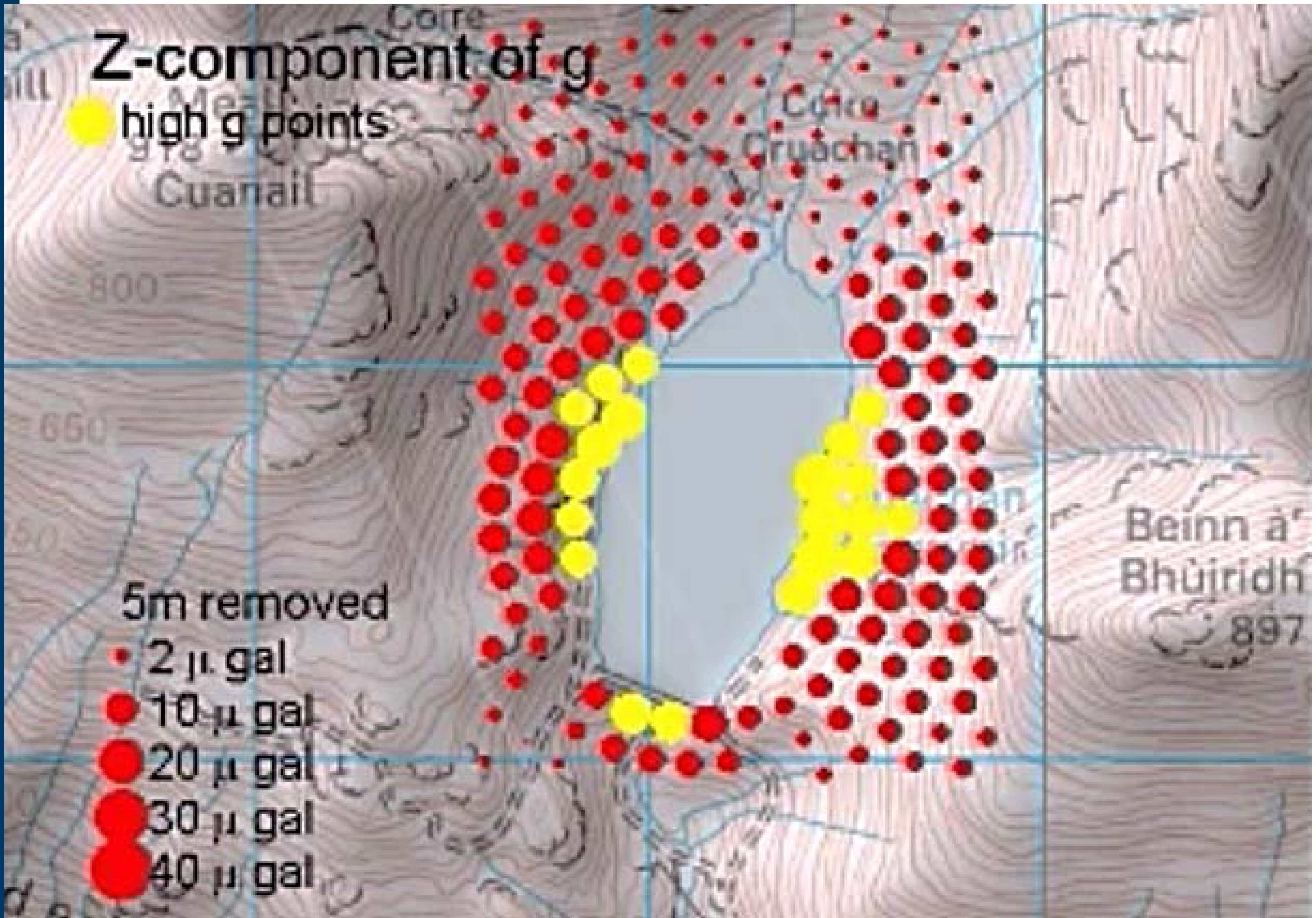

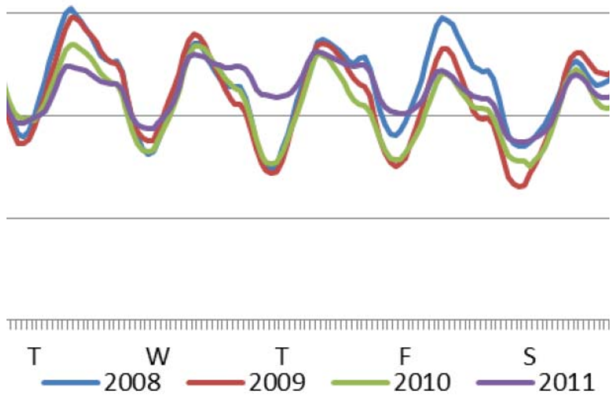

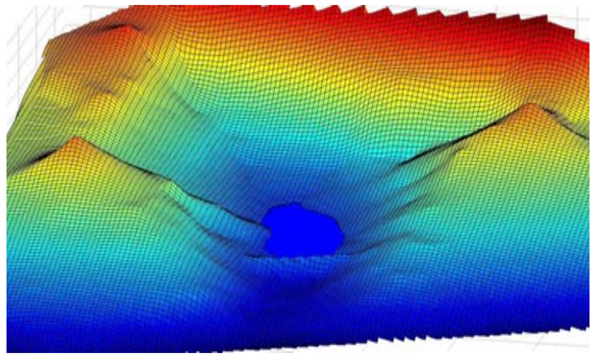

- Measurement of gravity around Cruachan due to reservoir draining (30-40μGal signal)

Future Directions

- Development of 3-axis devices
- Packaged devices with closed loop control (currently working with Kelvin NanoTechnology and OptoCap to fabricate/package)
- Field trials (Richard's talk) around Cruachan reservoir and University campus
- Engagement with end users across oil & gas, environmental monitoring/volcanology, security & defence, space
- Deployment on drones (DSTL)