A Gravitational Wave Spin-Off: MEMS Gravimetry

Giles Hammond
Institute for Gravitational Research
University of Glasgow

giles.hammond@glasgow.ac.uk
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
UK Quantum Technology Hub in Enhanced Quantum Imaging (https://quantic.ac.uk)
Gravity Imaging Applications

- Oil & gas prospecting
- Security & Defence
- Environmental monitoring
- Volcano monitoring
- HS2
- Sink hole detection
Accelerometers/Gravimeters

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

### Sensitivity vs. Instrument mass (kg)

- **iPhone 5 MEMS**: £0.10
- **Colibrys MEMS**: £2k
- **REFTEK MEMS**: £1.5k
- **CG-5**: 60k
- **FG-5**: 150k

- Lighter, cheaper & higher sensitivity
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)
4-flexure: unstable device, frequency tends to zero as displacement increases

3-flexure: stable device, frequency has a minimum
Glasgow MEMS Device

MEMS device

Integrated heater/thermometer

\[ g = \frac{kx}{m} \]

250MPa for 2Hz device
• 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.

![Diagram of optical readout system]
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
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
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
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 noise excites resonant mode to about x10-x100 earth tide signal
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
- 3x 24 bit temperature sensors (PT100)
- Voltage regulators and references
- Signal conditioning and I-V converters, tilt sensor readout
- Data logger module to run autonomously in field
- Digital lockin is robust against thermal drift and is re-configurable. Provides 10μGal/√Hz noise performance (can be improved using PGA on input)

- mK temperature sensing required to minimise coupling via thermal effects
Field Tests (2017)

20m lift test

270m altitude change (Campsie Hills)

Free air only + Bouger
Ongoing Projects

Attitude control (EngD/CENSIS)

Underwater sensing

Miniature interferometric sensing

Field prototype (CDT)
• 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
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

- Mirror on Piezo
- Beam splitter
- Fiber-coupled laser source
- Photo diode
- To control electronics

(Insert graph showing waveforms and data)
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
Bridgeporth Project
- Measurement of gravity around Cruachan due to reservoir draining (30-40µGal signal)
• Measurement of gravity around Cruachan due to reservoir draining (30-40µGal signal)
• 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)