Single-beam Vector Magnetometry

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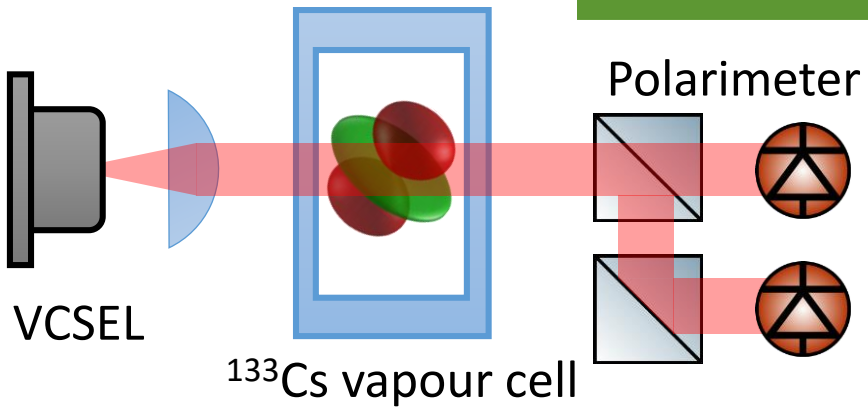
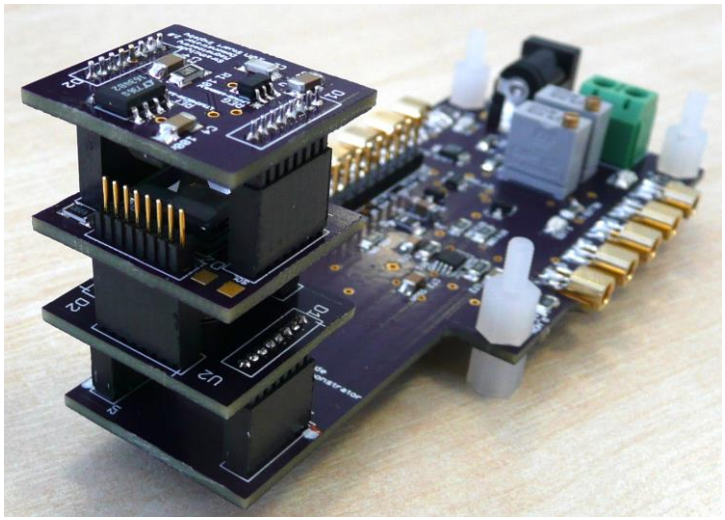
Motivation

- Low-SWAP
  - FPGA demodulation
- Unshielded
  - No extra coils
  - Single-beam
  - Double-resonance
    - >50 μT
  - Noise-robust
    - Polarimeter
- Dead-zones?
- Heading systematics?
  - $\Phi_{DEMOD} \rightarrow f_0$



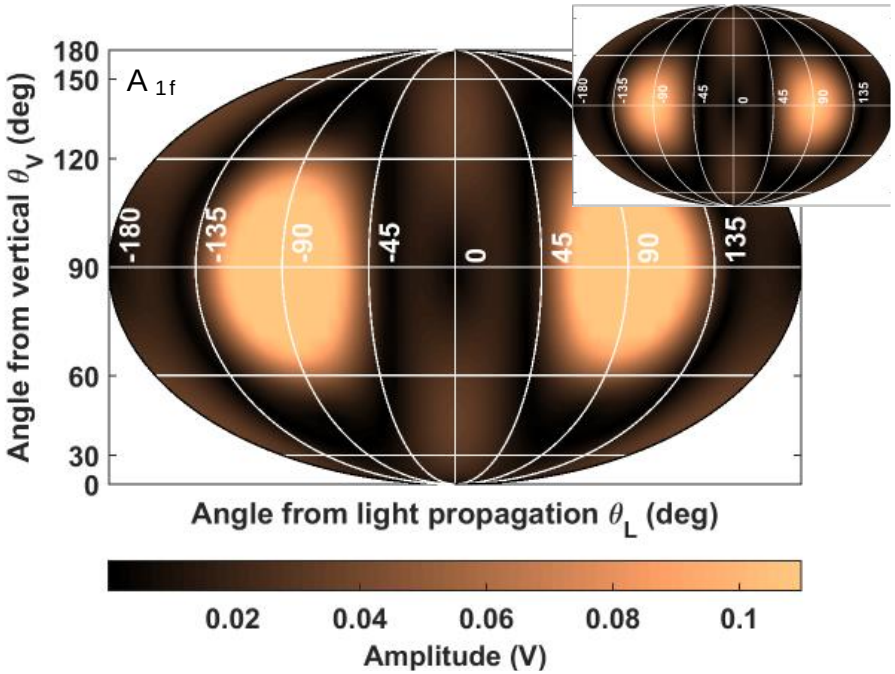


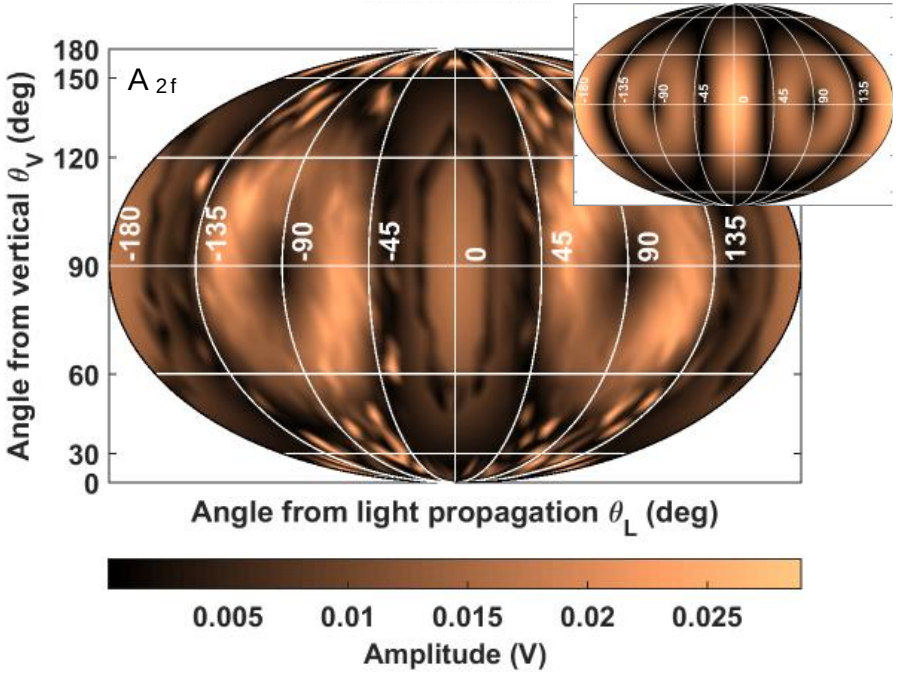
UK National Quantum Technology Hub Sensors and Metrology

Dead-zones

$$A_{1f}^2 = \bar{m}^2 S^2 \left((\cos\psi_V \cos\psi_L)^2 + (\cos 2\psi_V \sin\psi_L)^2 \right)$$

$$A_{2f}^2 = \bar{m}^2 S^4 \left(\tfrac{1}{2} \sin 2\psi_V \sin\psi_L \right)^2 + (\sin\psi_V \cos\psi_L)^2$$





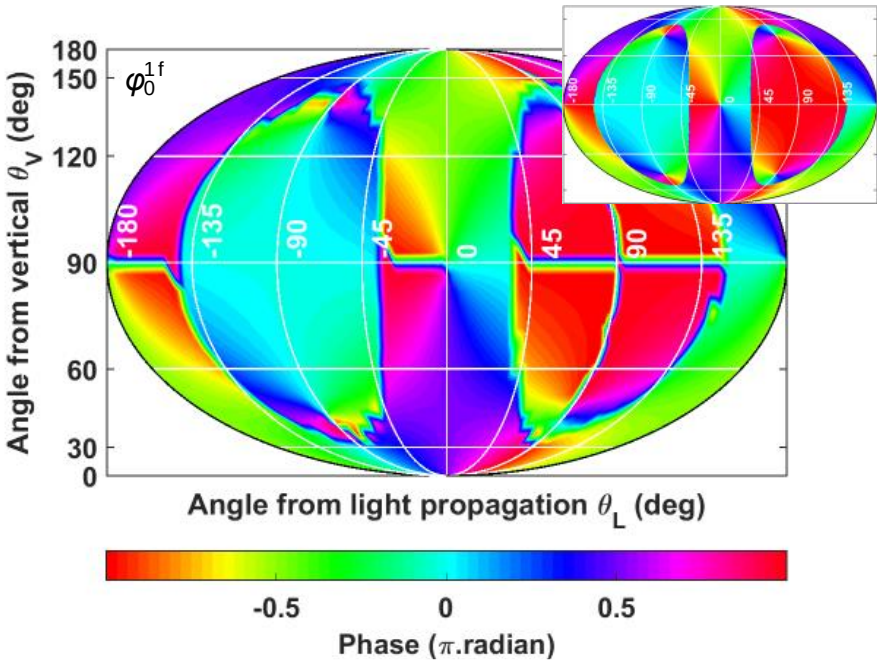
- S = 0 if B_{RF} parallel to B_0 (z-axis in this case)
- m ∝ projection of m_{EQ} onto m_{PUMP}

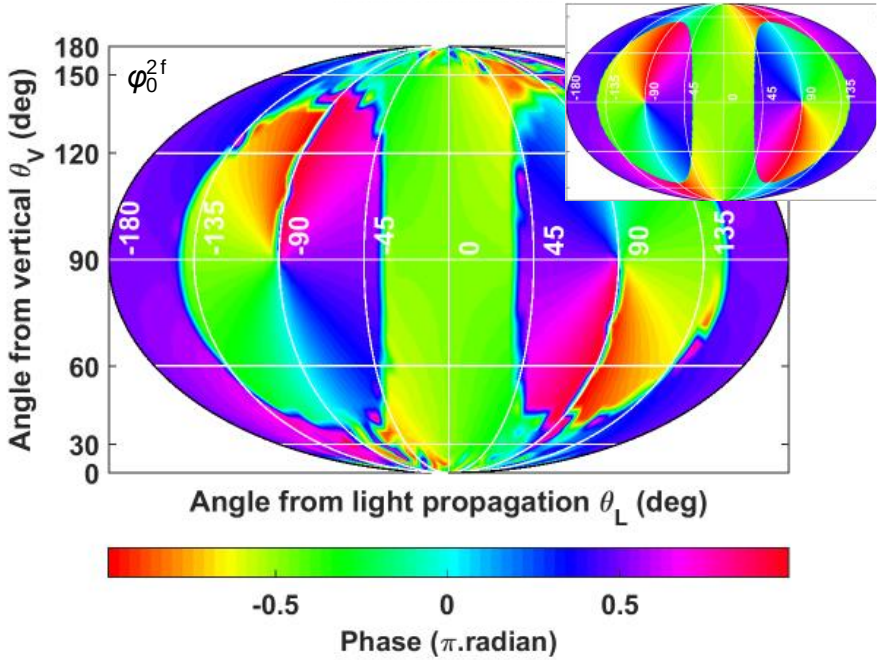
Phase Relations

- π-polarised light
- B_{RF} z-axis
- 1st and 2nd harmonics
  - Unique, invertible mapping to θ_L, θ_V

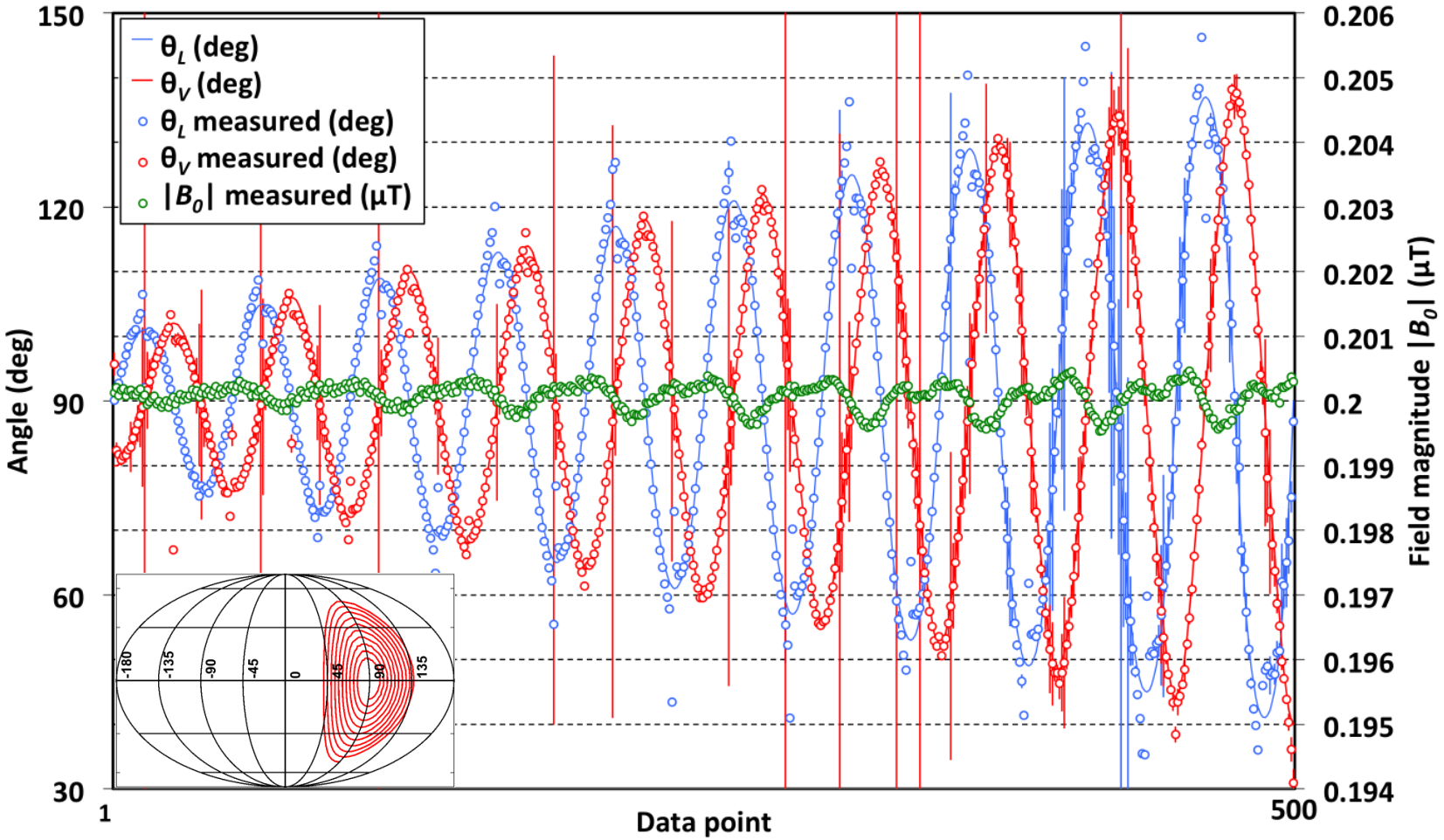
$$\tan\varphi_0^{1f} = \frac{-\bar{m}S\cos\chi_V\cos\chi_L}{\bar{m}S\cos 2\chi_V\sin\chi_L} \qquad \tan\varphi_0^{2f} = \frac{2\bar{m}\sin\chi_V\cos\chi_L}{-\bar{m}\sin 2\chi_V\sin\chi_L}$$

$$\tan^2\chi_V = 1 - \frac{\tan\varphi_0^{2f}}{\tan\varphi_0^{1f}} \qquad \tan\chi_L = \frac{-\cos\chi_V}{\cos 2\chi_V\tan\varphi_0^{1f}}$$

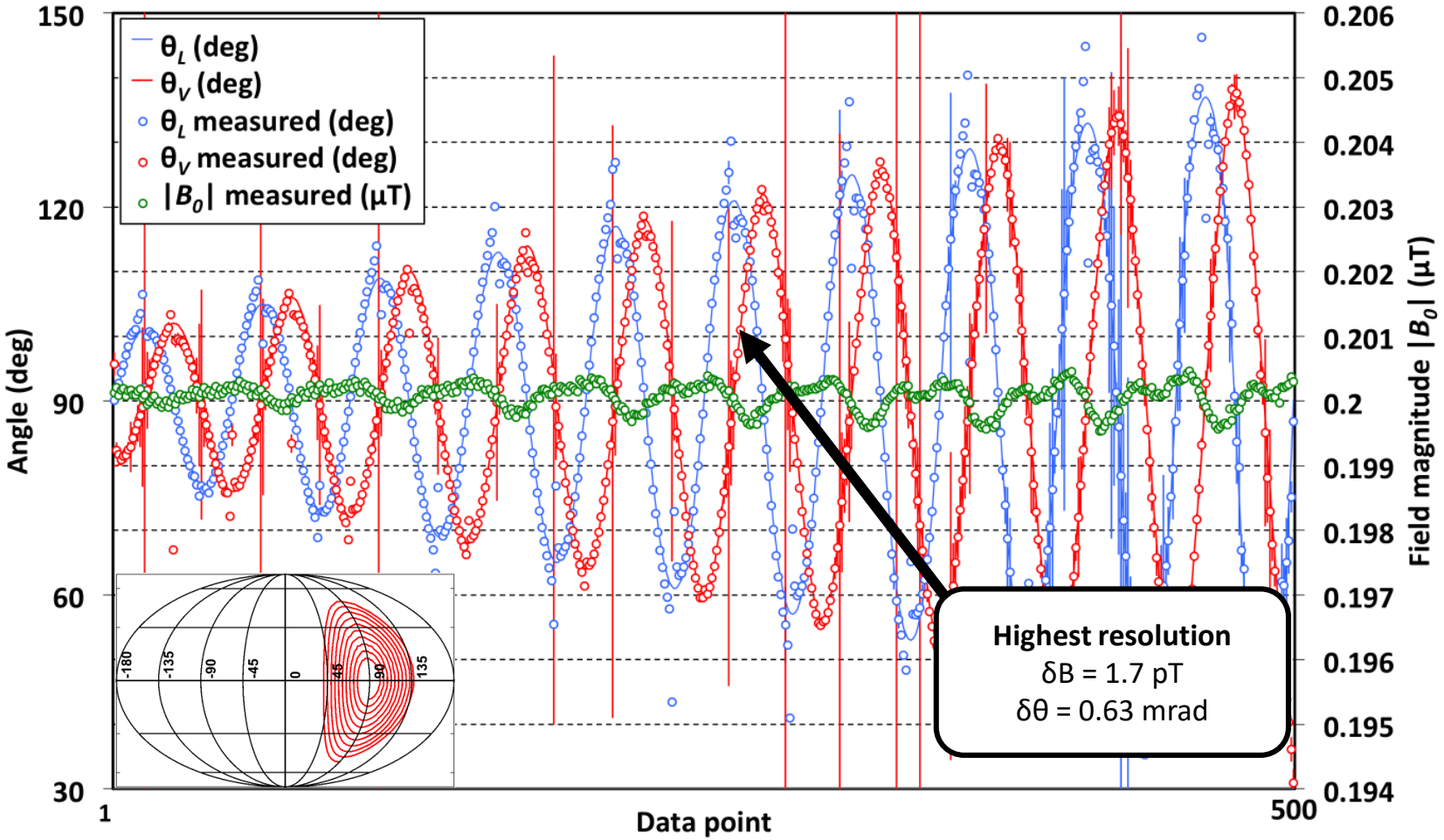




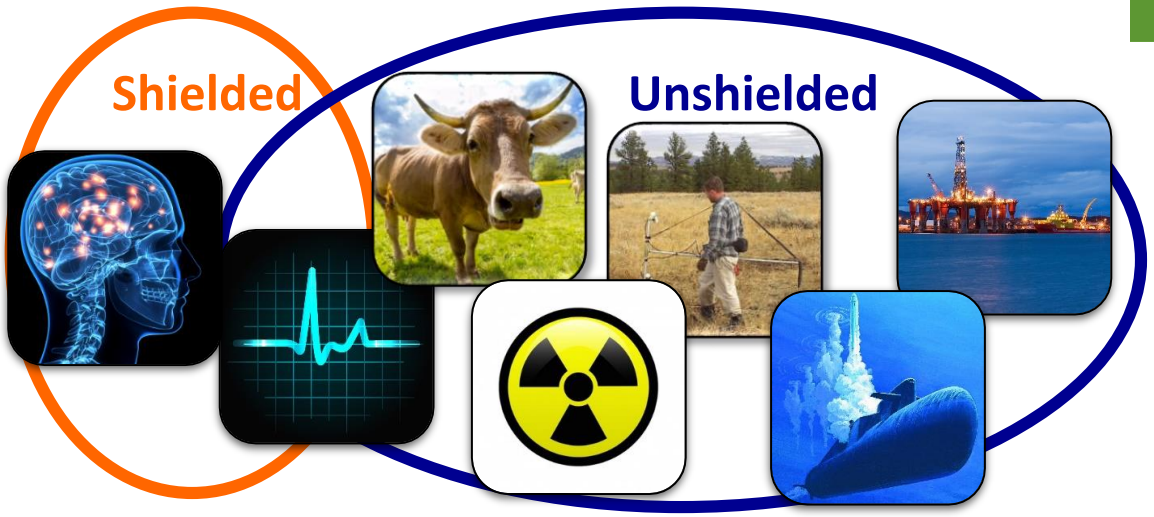
Vector Magnetometry



Vector Magnetometry



Applications



- Focus on unshielded applications

Healthcare
- Veterinary MCG
- Clinical triage by MCG

Security
- UXO detection
- Maritime defence
- Nuclear threat reduction
- GPS-denied navigation

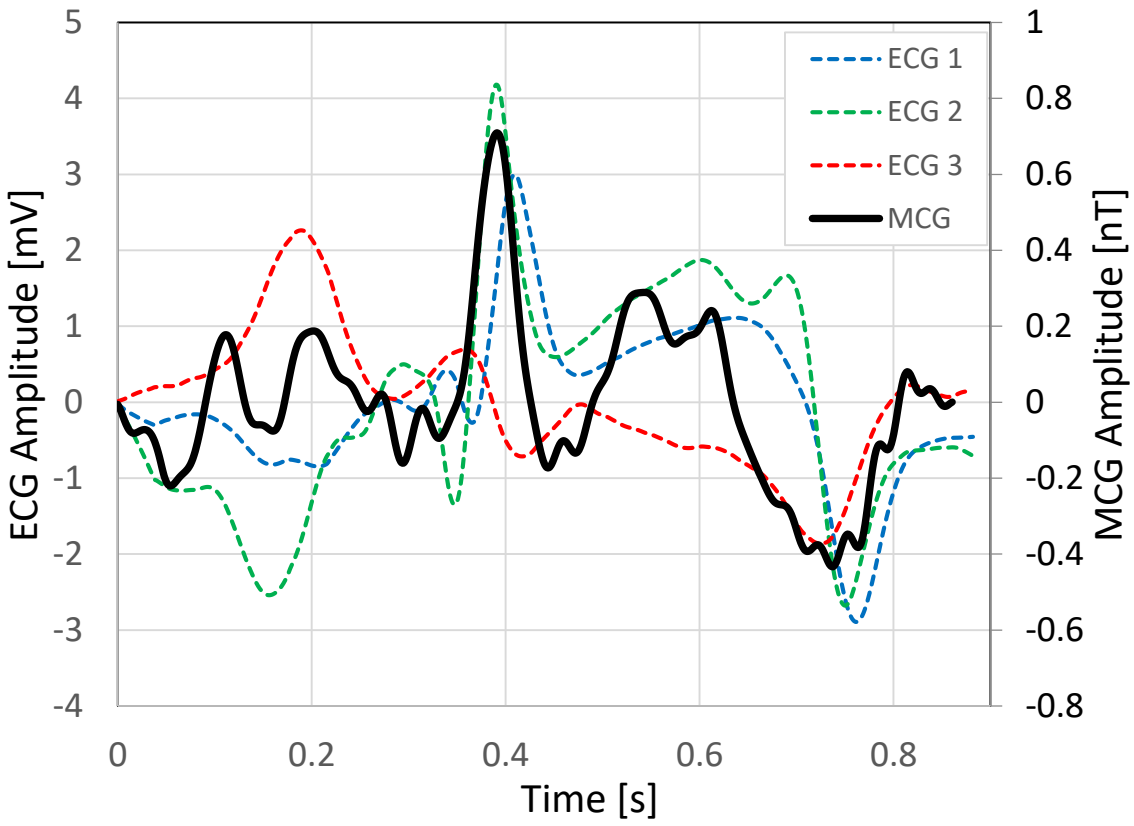
Geophysical
- Portable survey instruments
- Low-drift base station & calibration devices
- Directional drilling

QuBeat: Portable veterinary MCG

- IUK feasibility study
  - Peacock Technologies
  - Ice Robotics
- QuSpin QTFM
  - 1 pT.Hz$^{-1/2}$
- Smart agriculture
  - Mastitis diagnosis
  - Automated herd monitoring

QuBeat Results

- ECG agreement
  - Kruuse Televet 100
  - Einthoven configuration
- New information on signal amplitudes
  - Broad agreement with human MCG
  - 200 pT/mV*
- Further work on sensor locations
  - Diagnostic algorithms



* Perez Alday et al, PLOS One 2016

Conclusions

- Successful proof-of-concept → applications
  - Geophysical base station
  - Inclination/declination sensor
  - MCG diagnostic information

- Bandwidth & sensitivity
  - $X(f_{RF})$, $Y(f_{RF})$ sample time 2 s
    - Need ϕ and δf simultaneously
  - Self-oscillating → f_{LARMOR}

- Broadened cells
- Laser power
- Elliptical polarisation
  - Dead-zones
  - Phase-angle relations