Sensitive and accurate quantum magnetometry for GNSS-denied positioning, critical national infrastructure and magnetic anomaly detection

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ABSTRACT

Optically pumped magnetometers (OPMs) exploiting alkali metal vapours for accurate, precise magnetometry have benefited from improvements in components and techniques in recent years. Microfabrication of alkali cells and chip-scale lasers allow mass-production of compact sensors, and feedback an spin-preparation techniques, such as light-narrowing, allow enhanced performance, comparable with cryogenic SQUID magnetometers. I will introduce two OPM modalities developed at Strathclyde for geomagnetic operation- the digital alkali-spin maser and geophysical free-precession magnetometer. I will discuss the potential impacts of using these sensors for geophysical applications, including Global Navigation Satellite System (GNSS)-denied positioning, monitoring of space weather and magnetic anomaly detection. I will present developments in microfabrication and digital signal processing which will enable their widespread adoption.

Keywords: magnetometry, geomagnetism, space weather, magnetic anomaly, quantum sensing

1. INTRODUCTION

Exploiting alkali ground-state Zeeman resonances in non-zero fields [1-2], geomagnetic optically pumped magnetometers (OPMs) can achieve simultaneous high precision and accuracy, offering a new sensing modality for measurement of the Earth's magnetic field. Geomagnetic field measurements over extended measurement times require the combination of sensitivity and calibration, which is commonly achieved in practice using classical fluxgate magnetometers, which can achieve picotesla (pT) sensitivity with kilohertz (kHz) bandwidth, with low-cadence (> 1 s) baseline correction provided at this level by proton-precession (Overhauser) magnetometers. We report the use of optically pumped alkali magnetometers, based on miniaturised sub-components, which can deliver femtotesla (fT) sensitivity, with reference to the fixed scale of finite-field Zeeman resonance frequencies. With this approach we propose to develop single compact devices with performance equivalent to the combination of both classical devices.

Field demonstration of these OPM systems is essential, and we introduce the miniaturised components and subsystems which make this possible. These also open the potential for mass production of OPMs based on these techniques. Field-deployed systems of this type can be used for sensitive, accurate measurements of temporal fluctuations induced by solar activity on the geomagnetic field (space weather). Space weather measurements, in addition to their intrinsic value in geosciences and Earth observation, have a critical role in the maintenance and resilience of critical national infrastructure (CNI), such as power distribution and communication networks. For example, relatively small voltage discrepancies resulting from space weather ground-induced currents (GICs) can significantly compromise the integrity of railway signalling [3]. The development of portable, scalable OPMs also offers enhanced performance in the measurement of spatial variation in the geomagnetic field, induced by the permanent fixed field of crustal magnetic anomalies. The use of low-systematic error accurate OPM sensors will increase the resolution of magnetic anomaly mapping, and the reduction of systematic artefacts in the measured magnetic field opens the potential for positioning by magnetic map matching [4] to add a complementary navigation tool to classical and non-classical dead-reckoning systems. These systems are an important fall-back in the presence of GNSS denial or jamming, and are increasingly sought where resilient positioning and navigation is required.

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2. PORTABLE OPTICALLY PUMPED MAGNETOMETERS

Figure 1: Portable optical magnetometer sensor head developed at the University of Strathclyde. This sensor head contains the microfabricated caesium vapour cell, VCSEL light source and analogue detector electronics. It weighs < 200 g and has a volume of 100 cubic centimetres.

Figure 1 shows a portable OPM sensor head developed at the University of Strathclyde. Full details of its construction are given in [5]. Of critical importance are the chip-scale vertical-cavity surface emitting laser (VCSEL) and microfabricated caesium vapour cell. By resonantly driving a thermal atomic vapour of caesium-133 on both the optical D1 transition (using the single-mode 895 nm VCSEL light), and their ground-state magnetic resonance (~3.5 Hz/nT, using a small oscillating magnetic field), a dynamic tension is established between optical and magnetic interactions, resulting in strong magneto-optical back-action, which can be detected by polarimetry of transmitted VCSEL light. Digital feedback may be used to maximise signal-to-noise in this system and achieve parts-per-billion (fT) resolution of geomagnetic fields [5]. Design, fabrication and characterisation of the microfabricated caesium vapour cell is described in [6-7], including optimisation of these cells for magnetometer applications.

3. SPACE WEATHER MEASUREMENT WITH FREE-INDUCTION OPM

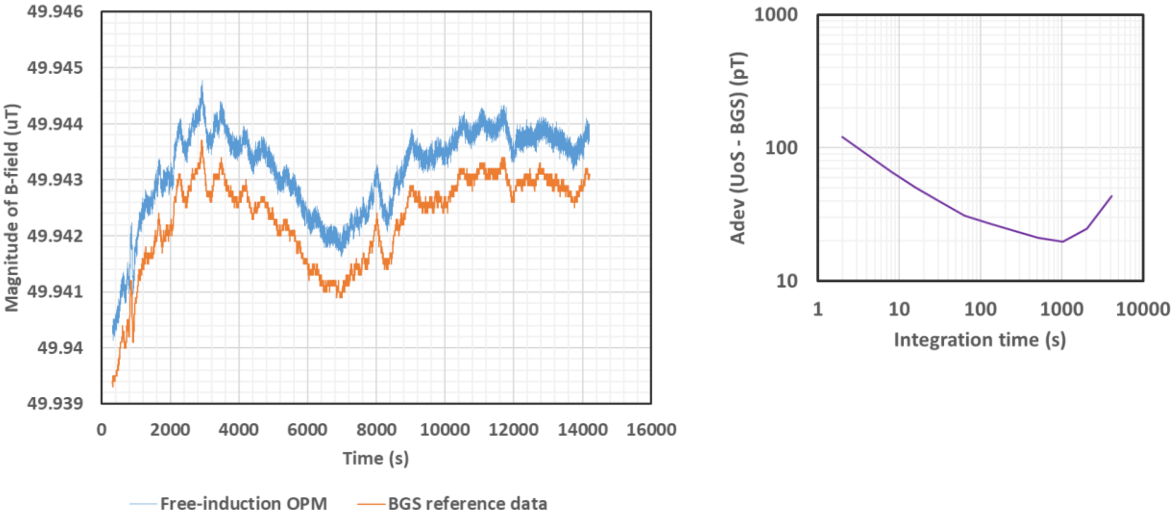

Figure 2: Free-induction optical magnetometer data measured at the British Geological Survey (BGS) Eskdalemuir Observatory on February 13th 2024. (Left) Geomagnetic field magnitude measured by Strathclyde free-induction OPM (blue) and BGS reference magnetometers (orange), as a function of time from measurement start. (Right) Overlapping Allan Deviation of difference between Strathclyde OPM and BGS reference magnetometer.

The intrinsic calibration of geophysical OPM sensing can be seen most clearly in extended-duration measurement of space weather induced fluctuations in the geomagnetic field magnitude, as shown in Figure 2. In this case a free-induction OPM based on a microfabricated caesium cell, with enhanced spin preparation, and off-resonant probe light, was used. A full description is found in [8]. The separation in both time and frequency between optical pumping and probing allows minimisation of light-shift systematic effects [9] and operation in the high-sensitivity light-narrowed regime [10], at the expense of an additional laser system and optics, which may, nevertheless, be assembled in a portable and scalable form factor. Comparison of the data obtained during measurements at the British Geological Survey (BGS) Eskdalemuir magnetic observatory with the observatory's reference instrument suite reveals excellent agreement over extended measurement times (1000's of seconds). The residual 20 pT discrepancy is at a level consistent with the spatial variation of geomagnetic fluctuations on these timescales.

4. GEOMAGNETIC ANOMALY MEASUREMENT

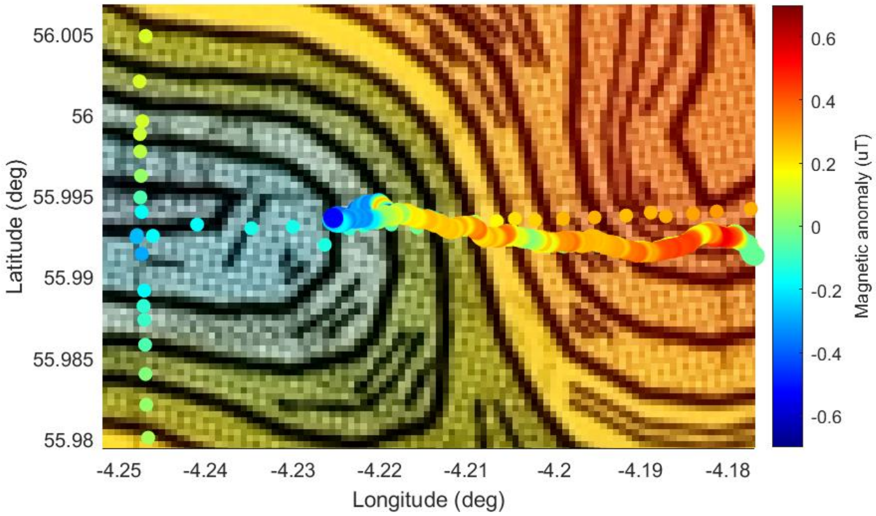

Figure 3:Measurement of geomagnetic anomalies using the University of Strathclyde portable optical magnetometer, carried in a rucksack on March 21st 2023 (large circles). Comparison is shown with BGS Aeromag aerial survey data (small circles) and interpolated anomaly map (background image).

The resonant single-laser OPM described in [5] is sufficiently compact and ruggedized to be operated successfully over extended periods from a modest lithium-ion power pack, and is sufficiently lightweight to be carried on foot over rough and remote ground. Figure 3 shows the results of such a test, carried out in the Campsie Fells (Scotland), over a distance of several kilometres. Magnetic anomaly map datasets in the United Kingdom are made publicly available by the British Geological Survey, based on a wide range of data sources. Data for the Campsie Fells region was surveyed by air using a fluxgate magnetometer, and this survey data is shown in Figure 3 as small sparse coloured dots, alongside the OPM data (large closely packed dots), and general agreement can be seen. The potential for enhanced surveying is under further development with the integration of this OPM with an unmanned aerial vehicle. Potential for GNSS-denied positioning is also there, with the further development of accurate surveying and interpolative algorithms for positional inference.

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