Quantum Magnetometers as Sensors in Small Satellite Missions

Mark P. J-L. Chang
Capgemini UK
40 Holborn Viaduct, London EC1N 2PB
UNITED KINGDOM

mark.a.chang@capgemini.com

Simon Jordan
Cambridge Consultants Ltd
29 Science Park, Milton Road, Cambridge CB4 0DW
UNITED KINGDOM

simon.jordan@cambridgeconsultants.com

Tony Holt
In-Space Missions
8 Oriel Court, Omega Park, Alton, Hampshire GU34 2YT
UNITED KINGDOM

tony@in-space.co.uk

ABSTRACT

Space is a dynamic and rapidly evolving domain, essential to the Alliance's deterrence and defence. This was recognised in 2019 as the fifth operational domain supporting operations in communications, navigation, and intelligence. NATO's principle to foster cooperation with space-related industry and the commercial sector opens up the opportunity to rapidly develop quantum technology-based capabilities for the space domain, to the benefit of the Alliance. The quantum technology potential that we explore here are quantum magnetometers as attitude sensors for small satellite missions (satellites <500 kg).

In recent years the small satellite market has boomed, with constellations being put into operation because, compared to larger satellite systems, they provide cheaper, more frequent, and up-to-date data. Magnetometers are the primary attitude sensors, especially for the smallest satellites, as they represent a lightweight solution to the attitude determination problem. Implementation has been a challenge, due to a combination of errors inherent to the sensors and errors caused by satellite or local environment disturbances. Thus, magnetometer-based attitude control is a low precision capability compared to larger, more massive alternative systems.

These factors have presented obstacles for conventional magnetometers, but they also present an opportunity window for quantum device versions. We describe the state-of-knowledge of satellite attitude sensors using magnetometers and examine the advantages and complexities quantum systems bring to this function, which have been investigated through simulation in the literature and through a bench model built by Cambridge Consultants. Furthermore, we describe practical routes to rapid testing with small satellites that In-space Missions can provide ranging from hosted payloads to a primary mission function.

1.0 INTRODUCTION

Small satellites are becoming increasingly important in the field of defence. Overall, more than 6,000 small satellites, ranging from a few kilogrammes up to 500 kg have been launched since 2000 for civil, exploratory, and military reasons. These spacecraft offer several advantages over terrestrial capabilities e.g., improved situational awareness, enhanced communication capabilities, and increased resilience, usually provided from low Earth orbit, that is up to 2000 km altitude. Being cost effective and compact systems, they allow for quick deployment into surveillance, reconnaissance, and monitoring missions. Their small size permits greater flexibility in mission planning and reduces the risk of detection. The integration of small satellites into NATO defence systems would enhance military capabilities, contributing significantly to freedom of action, information, and ultimately operational advantage.

All satellite mission operations require the capability to orient the spacecraft in a specific direction. To perform these manoeuvres, knowledge of the spacecraft orientation in space – its attitude – is required. Attitude determination provides the necessary input to satellite attitude control, which exerts a control torque through actuators to drive the system to the right position. To date, large satellites in Earth orbit make use of star trackers, Sun sensors, Earth sensors and magnetometers to carry out attitude determination. Star trackers, Sun and Earth sensors are comprised of photodetectors and imagers that operate in the visible and infrared. Magnetometers are described in the next section. Of this suite of attitude sensors, magnetometers have the potential to be the smallest, lightest and most power efficient, which is a “north star” ambition in the manufacture and operation of small satellites.

2.0 MAGNETOMETERS

What are these sensors? Magnetometers are instruments used to measure the strength and direction of a magnetic field. In the context of satellites, magnetometers are specifically designed to measure the Earth’s magnetic field. Magnetometer payloads can in principle enable satellites to accurately detect their position and maintain stability. However, conventional magnetometers are limited and do not provide the necessary three-axis attitude information from a single three-axis sensor. Moreover, signals are distorted by magnetized objects and current loops in the neighbourhood of the sensor.

The optical sensors mentioned in Section 1.0 supplement and correct magnetometer outputs. In small satellites, these additions are too bulky and power consuming to be useful; in micro- (10-100 kg) and nanosatellites (1-10 kg) such as CubeSats, the available size, weight and power (SWaP) budget only permits attitude determination by magnetometers. For such small satellites to be useful for defence, precise attitude determination is a mandatory requirement. Attitude determination is complicated by the typically large magnetic moment of satellites with small inertia, causing magnetic bias noise from the interaction of the Earth’s magnetic field with the magnetic field of the small satellite.

2.1 Magnetometers as Satellite Attitude Sensors

One of two key challenges for small satellites is to compensate for the magnetic bias noise. The other key challenge is to obtain full three-axis attitude determination using a magnetometer only, as our ambition is to deploy the fewest, smallest, least power demanding attitude sensors feasible.

The bias noise is usually compensated for by filtering the signal through a mathematical operation called a Kalman Filter 0. The full attitude determination can be done by comparing magnetic field readings to an accurate model of the Earth’s magnetic field such as the International Geomagnetic Reference Field (IGRF) model. Solutions like the DADMOD algorithm [2] produce 2º attitude accuracy and 0.01º/s angular rate accuracy.

A minor hurdle is that these methods are computationally expensive, requiring sophisticated models for vector estimation. Some of the highest accuracy algorithms also demand specific attitude control to be effective which makes it hard to implement on the Field Programmable Gate Array (FPGA) of a satellite's On-Board Computer (OBC). Small satellites, especially CubeSats, commonly use FPGA based OBCs as modern hardware/firmware/software flexibility allows on-ground and in-orbit low risk reconfiguration. Fortunately, there are attitude determination strategies that can be implemented on CubeSat class architectures [1] which meet the constraints of FPGAs for implementation in nanosatellites. Of course, transient effects of magnetic disturbances onboard the satellite must also be accounted for during the lifetime of its mission. This can be met through careful, regular on-orbit calibration, or the use of additional magnetometers in different parts of the satellite to give near real time measurements.

A further key challenge to some "heritage" magnetometers are drifts to scale factors and voltage offsets with both time and temperature, requiring periodic recalibration – not a convenient nor desirable activity for small satellite operations. Those magnetometers that are robust to the calibration problem happen to be massive, voluminous with high power requirements which exclude their use in small satellites. Heritage magnetometers relevant to satellites are,

- Fluxgate magnetometers [3][4][5][6][7]
- Vector helium magnetometer [8]
- Scalar helium magnetometer [9]

To solve the drift and SWaP problem, we can turn to solution candidates in the next generation of magnetometers, ones which employ quantum physics.

3.0 QUANTUM MAGNETOMETERS

John Preskill's "Quantum Supremacy" concept has arrived already for sensors – they are making measurements that were not possible before. In this section we will describe the three classes of this technology's cutting edge first, followed by our steps to lower costs and cultivate the exquisite skills required for practical development. Finally, we describe a dependable route to accessing space to demonstrate quantum magnetometer innovation in orbit, a vital step to obtaining space heritage and space qualification.

3.1 Atomic Vapour Cell (AVC) Magnetometers

Atomic magnetometers consist of a vapour of alkali atoms (usually K, Rb, or Cs) enclosed in a glass cell, generally heated to about 400 K. When a laser beam passes through the vapour cell, the spins of the atoms' unpaired electrons align in the same direction. In the presence of a magnetic field, the electrons precess. This leads to a polarisation or amplitude change in the transmitted light. The optical feature change can be detected and used to infer the magnetic field.

The sensitivities achieved can be very high, on the order of 160 $\mathrm{aT/Hz^{1/2}}$ [10], with spatial resolution down to mm. Some systems show a high dynamic range and can operate in the Earth's magnetic field, while others have a low dynamic range and require magnetic shielding or closed-loop operation [11]. Operation bandwidths typically range from DC to ~1 kHz. The atom–light interaction is sensitive to the orientation of the magnetic field, allowing vector magnetometry. The most sensitive commercially available magnetometer is based on atomic magnetometry; these can achieve a sensitivity of 300 fT at 1 Hz [12]. If financial cost is not a constraint, chip-scale atomic magnetometers show great potential. The significant reduction in SWaP [13] makes them competitive candidates for future nanosatellite projects, with rice grain sized vapour cells.

It is interesting to note that e.g., Korth et al. [14], have proposed miniaturized atomic scalar magnetometers based on the ^{87}Rb isotope for space applications. This magnetometer's vapour cell would be fabricated using silicon-on-sapphire (SOS) complementary metal oxide-semiconductor (CMOS) techniques, resulting in a volume of only 1 mm^3. With control circuitry, the design indicates a magnetometer system of under 0.5 kg, requiring less than 1 W of power, and a lab-measured sensitivity of 15 pT/Hz$^{1/2}$ at 1 Hz. The result is comparable with high-sensitivity heritage technologies, at a much-reduced SWaP.

3.2 SERF Magnetometers

AVC magnetometers can obtain improved absolute sensitivity by operating with a dense gas at elevated temperatures. With this, collisions between the alkali atoms no longer scramble the electronic polarization, improving the sensor's signal-to-noise ratio. These "Spin Exchange Relaxation-Free" or SERF devices sacrifice dynamic range for sensitivity; SERFs fail in the presence of micro-Tesla fields that standard AVCs can work with. SERFs require magnetic shielding (which is typically heavy) or active magnetic cancellation (which requires additional control circuitry). They have increased power requirements because of the elevated temperatures involved. This appears to discount them as attitude sensors for small satellites. Nevertheless, SERFs are promising candidates for nuclear magnetic resonance sensing [15] — a technique to detect biochemical or chemical signatures, which might be suitable to detect e.g., hostile anti-satellite weapon (ASW) deployment such as chemical sprays or environmental in-orbit contamination.

3.3 Atomic Defect (AD) Magnetometers

Another channel to sense magnetic fields are the defects that lie within crystalline materials. These crystal defects (substitutions, vacancies, and combinations) lead to so-called "colour centres": magnetically sensitive artificial atoms embedded within the crystal, addressable by microwave and visible wave electromagnetic fields. Silicon vacancies in silicon carbide [16][17] have been used to detect magnetic fields in proof-of concept experiments (~100 nT/Hz$^{1/2}$). Current best-in-class are nitrogen-vacancy (NV) diamond sensors. A negatively charged NV$^-$ defect has a triplet ground state ($^3A_2$), a triplet excited state (^3E), and two intermediate singlet states (^1A and ^1E). The energy separation between the sub-levels in the triplet ground state varies with the magnetic field aligned to the NV quantization axis. Green light illumination causes the defect to photoluminesce at 637 nm; the intensity of the emitted light is higher when the $m_s = 0$ ground state sub-level is populated and exhibits a dip when the population is transferred to the $m_s = \pm 1$ sub-levels. The Zeeman splitting of the ground state, and thus the magnetic field the defect is exposed to, can be measured.

NV-magnetometers naturally have a very high spatial resolution (single-defect magnetometers have been demonstrated by e.g., [18]). The NV$^-$ defects have four possible orientations within the carbon crystal lattice, enabling vector magnetometry techniques to be deployed. Sensitivities as good as 0.9 pT/Hz$^{1/2}$ have been demonstrated in laboratory conditions [19] and operation frequencies vary from DC up to a few gigahertz [20][21][22], albeit with sensitivity variations. This is a very new technology and has limited integration into deployable options at the present time.

3.4 Realising a COTS Based Quantum Magnetometer as a Bench Model

The quantum magnetometer solutions mentioned have all been developed with significant financial budgets. We have developed a quantum AVC magnetometer using commercial-off-the-shelf components which takes benefit from

- new techniques which allow us to manipulate and control atom spin states
- new components in the form of commercially available, modern vertical emission laser diodes (VCSELs).

with the aim to demonstrate a reduced cost magnetometer system for economic small satellite buses. The materials cost of the laboratory system shown in the figure is in the order of USD 10,000.

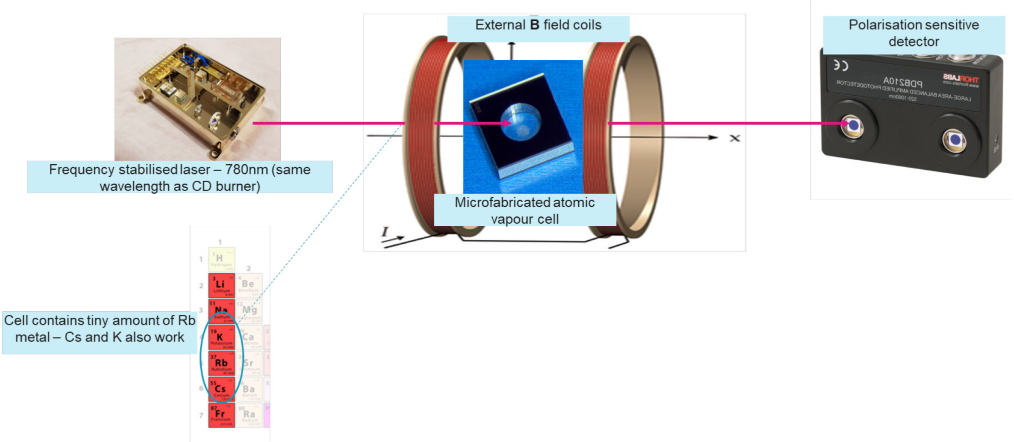

Figure 1: Cambridge Consultants' COTS benchtop quantum magnetometer.

The laser is tuned to D-line of alkali metal. This excites the atom into a magnetically sensitive state. The magnetic field makes it oscillate (Larmor precession); we detect this optically. The Larmor frequency is proportional to the total magnetic field with extreme precision, giving us a mechanism to measure tiny (0.1 pT) magnetic fields. This bench demo operates on a few Watts, and is a few kilos. Building on this success we developed a service that ideates, explores, designs, builds and operates physical and digital space missions, to help global customers keen to get their technology on orbit quickly. The figure below shows the inception-to-space qualification flow that our clients can take advantage of.

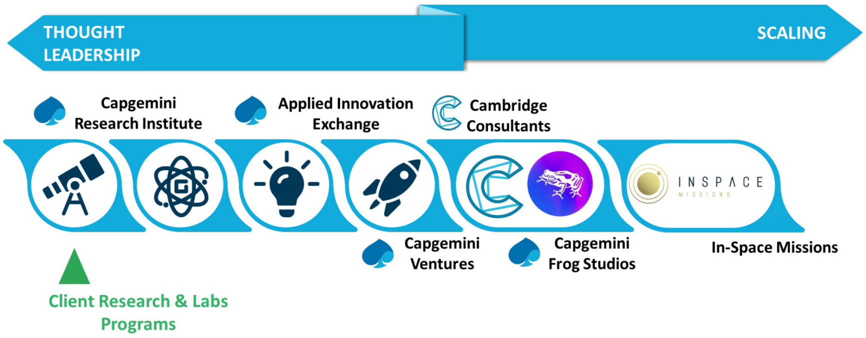

Figure 2: The span of our collaborative services.

With Capgemini and Cambridge Consultants supporting the innovation journey at the left-hand side and In-Space supporting rapid in-orbit prototype testing and spaceflight qualification, we provide a flexible and competitive route to realising new technologies. Meanwhile, our partnership with In-Space provides two offers “Space as a Service” and “Client ownership” class missions, to bring quantum magnetometers for satellite attitude and orbit control to production maturity at pace.

- InSpace Rideshare satellite platform service, allows for long-life, low-cost, payload flight opportunities for early service and technology demonstration in low Earth orbit.
- InSpace Dedicated is a 100kg+ small satellite platform offering flexible payload accommodation up to 60kg for a client to own. The mission can be augmented with an on-orbit solution to support low latency applications.

4.0 REFERENCES

[1] Hajiyev C.; In-orbit magnetometer bias and scale factor calibration, Int. J. Metrol. Qual. Eng., 7 1 (2016) 104, DOI: https://doi.org/10.1051/ijmqe/2016003

[2] Natanson, G.A.; McLaughlin, S.F.; Nicklas, R.C. A Method of Determining Attitude from Magnetometer Data Only; NASA Goddard Space Flight Center, Flight Mechanics/Estimation Theory Symposium: Silver Spring, MD, USA, 1990; pp. 359–380.

[3] Candidi, M.; Orfei, R.; Palutan, F.; Vannaroni, G. FFT Analysis of a Space Magnetometer Noise. IEEE Trans. Geosci. Electron. 1974, 12, 23–28.

[4] Lu, C.C.; Huang, J.; Chiu, P.K.; Chiu, S.L.; Jeng, J.T. High-sensitivity low-noise miniature fluxgate magnetometers using a flipchip conceptual design. Sensors 2014, 14, 13815–13829.

[5] Can, H.; Topal, U. Design of Ring Core Fluxgate Magnetometer as Attitude Control Sensor for Low and High Orbit Satellites. J. Supercond. Nov. Magn. 2015, 28, 1093–1096.

[6] Miles, D.M.; Mann, I.R.; Ciurzynski, M.; Barona, D.; Narod, B.B.; Bennest, J.R.; Pakhotin, I.P.; Kale, A.; Bruner, B.; Nokes, C.D.A.; et al. A miniature, low-power scientific fluxgate magnetometer: A stepping-stone to cube-satellite constellation missions. J. Geophys. Res. Space Phys. 2016, 121, 11839–11860.

[7] Zhi, M.; Tang, L.; Cao, X.; Qiao, D. Digital Fluxgate Magnetometer for Detection of Microvibration. J. Sens. 2017, 2017, 6453243.

[8] Frandsen, A.M.A.; Connor, B.V.; Amersfoort, J.V.; Smith, E.J. The ISEE-C Vector Helium Magnetometer. IEEE Trans. Geosci. Electron. 1978, 16, 195–198.

[9] Guttin, C.; Leger, J.; Stoeckel, F. An isotropic earth field scalar magnetometer using optically pumped helium 4. J. Phys. IV Proc. EDP Sci. 1994, 4, C4-655–C4-659.

[10] Alem, O.; Sauer, K.L.; Romalis, M.V. Spin damping in an rf atomic magnetometer. Phys. Rev. A 2013, 87, 013413.

[11] Pyragius, T.; Florez, H.M.; Fernholz, T. Voigt-effect-based three-dimensional vector magnetometer. Phys. Rev. A 2019, 100, 023416.

[12] GEM Systems. GSMP Potassium Magnetometer for High Precision and Accuracy. 2018. Available online: https://www.gemsys.ca/ultra-high-sensitivity-potassium/ (accessed on 14 August 2023).

[13] Kitching, J. Chip-scale atomic devices. Appl. Phys. Rev. 2018, 5, 031302.

[14] Korth, H.; Strohbehn, K.; Tejada, F.; Andreou, A.G.; Kitching, J.; Knappe, S.; Lehtonen, S.J.; London, S.M.; Kafel, M. Miniature atomic scalar magnetometer for space based on the rubidium isotope ^{87}Rb. JGR Space Phys. 2016, 121, 7870–7880.

[15] Ledbetter, M.P.; Savukov, I.M.; Budker, D.; Shah, V.; Knappe, S.; Kitching, J.; Michalak, D.J.; Xu, S.; Pines, A. Zero-field remote detection of NMR with a microfabricated atomic magnetometer. Proc. Natl. Acad. Sci. USA 2008, 105, 2286–2290.

[16] Simin, D.; Soltamov, V.A.; Poshakinskiy, A.V.; Anisimov, A.N.; Babunts, R.A.; Tolmachev, D.O.; Mokhov, E.N.; Trupke, M.; Tarasenko, S.A.; Sperlich, A.; et al. All-Optical dc Nanotesla Magnetometry Using Silicon Vacancy Fine Structure in Isotopically Purified Silicon Carbide. Phys. Rev. X 2016, 6, 031014.

[17] Niethammer, M.; Widmann, M.; Lee, S.Y.; Stenberg, P.; Kordina, O.; Ohshima, T.; Son, N.T.; Janzén, E.; Wrachtrup, J. Vector Magnetometry Using Silicon Vacancies in 4H-SiC Under Ambient Conditions. Phys. Rev. Appl. 2016, 6, 034001.

[18] Sánchez, E.D.C.; Pessoa, A.R.; Amaral, F.; Menezes, L.D.S. Microcontroller-based magnetometer using a single nitrogen-vacancy defect in a nanodiamond. AIP Adv. 2020, 10, 025323. [

[19] Wolf, T.; Neumann, P.; Nakamura, K.; Sumiya, H.; Ohshima, T.; Isoya, J.;Wrachtrup, J. Subpicotesla Diamond Magnetometry. Phys. Rev. X 2015, 5, 041001.

[20] Chatzidrosos, G.; Wickenbrock, A.; Bougas, L.; Leefer, N.; Wu, T.; Jensen, K.; Dumeige, Y.; Budker, D. Miniature Cavity-Enhanced Diamond Magnetometer. Phys. Rev. Appl. 2017, 8, 044019.

[21] Grinolds, M.; Hong, S.; Maletinsky, P.; Luan, L.; Lukin, M.D.; Walsworth, R.L.; Yacoby, A. Nanoscale magnetic imaging of a single electron spin under ambient conditions. Nat. Phys. 2013, 9, 215–219.

[22] Kuwahata, A.; Kitaizumi, T.; Saichi, K.; Sato, T.; Igarashi, R.; Ohshima, T.; Masuyama, Y.; Iwasaki, T.; Hatano, M.; Jelezko, F.; et al. Magnetometer with nitrogen-vacancy center in a bulk diamond for detecting magnetic nanoparticles in biomedical applications. Sci. Rep. 2020, 10, 2483.