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LONG-TERM STABILITY ASSESSMENT OF QUANTUM DIAMOND MAGNETOMETERS IN LOW EARTH ORBIT

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ABSTRACT

Space magnetometry is essential for studying Earth's core and crustal processes as well as space weather monitoring. Modern mission requirements pose challenges to current sensors related to size, weight, and power restrictions while demanding highly sensitive systems. As such, recently emerging quantum sensing technologies are being explored for future Earth Observation missions. One of the promising platforms is the Nitrogen-Vacancy center in diamond. This work demonstrates an initial long-term stability assessment of a quantum diamond-based magnetometer tested in low Earth orbit aboard the International Space Station. Successful operation of the sensor for nine months is presented, where both the sensor performance and measurement parameters remained stable. The deviation of the sensor was evaluated and compared to Earth's magnetic field model, showing no degradation over the mission duration. This study points towards the viability of diamond-based sensors as a compact and stable sensing solution for future space applications.

Index Terms— Quantum diamond magnetometer, Long-term stability, Geomagnetic field, Nitrogen-Vacancy (NV) centers, Space magnetometry

1. INTRODUCTION

The study of Earth's magnetic field is essential for comprehending geomagnetic dynamics and challenges in regions like the South Atlantic Anomaly. Advanced measurements are vital for unraveling Earth's formation and geological processes. The magnetic field serves as a shield, influencing space weather by controlling the location of radiation belts and cosmic ray trajectories. Understanding these interactions is key to addressing correlations between solar activity and climate variations. Precision magnetometry plays a critical role in studying Earth's dynamics and its impact on space weather [1].

Measuring magnetic fields in space is challenging due to spacecraft-generated electromagnetic noise, which requires a boom to minimize the magnetic interference [2]. During long-term space missions the sensors are exposed to the harsh environment, such as temperature fluctuations, microgravity, space radiation, and vibrations, which may affect the sensor stability due to degradation or calibration drift. Furthermore, due to the increasing popularity of smaller platforms (i.e. CubeSats) for Earth Observation, sensors are required to have decreased in size, weight, and power (SWaP) parameters while becoming increasingly sensitive. Currently used classical sensors, such as fluxgates, are reaching their sensitivity and SWaP limits [3], driving the demand for novel magnetic field sensing platforms. Alternatively quantum sensors, such as atomic vapor cells, have been used in space enabling high sensitivity. However, they typically have large SWaP, limiting their usability in missions operating on smaller spacecrafts [3], [4].

Recently emerging quantum sensing platform, allowing for high precision measurements and promising high degree of integration [5], is based on an optically active nitrogen-vacancy (NV) defect in diamond crystal. Diamond has a large band gap, is inherently radiation-resistant and thermally stable, and can withstand a wide range of pressures [6]. The NV-based sensors have high theoretical sensitivity (~10fT/√Hz), wide dynamic range (linear up to 0.1T), high bandwidth (DC-MHz), and vector magnetometry capabilities, while usable for simultaneous temperature measurements [7].

Demonstrations of NV-based sensors are still largely found in laboratory environments; however, recent efforts have been focused on miniaturizing the NV sensing technology [8], [9] with demonstrated sensitivities reaching nT/√Hz and below [10], [11]. Despite these integration advancements, the sensors described in previous papers are typically referring solely to a sensor head, without the driving electronics integrated. Therefore, further research is crucial to miniaturize NV sensors since space applications require integrated and portable solutions.

This work aims to evaluate the long-term stability and viability of a recently demonstrated novel type of portable quantum magnetic field sensor tested in the space environment aboard the International Space Station (ISS), within the OSCAR-QUBE [12] student project mission.

2. QUANTUM DIAMOND MAGNETOMETER

2.1. NV quantum magnetometry principle

The operational principle of NV-based magnetometers relies on optically active point defects in the diamond crystal lattice consisting of a substitutional nitrogen atom (N) and adjacent lattice vacancy (V). Negatively charged NV-centers demonstrate spin-dependent fluorescence resulting in Optically Detected Magnetic Resonance (ODMR). Upon excitation with a green (here, 520 nm) laser light, the NV-center emits red (650 nm) photoluminescence (Fig 1.a). Application of microwave frequency (MW), resonant with the NV spin transition in the ground state, results in controllable spin initialization. Spin state $m_S=\pm1$ can relax through the non-radiation metastable state, which allows optical readout of different spin states (bright state $m_S=0$ and dark state $m_S=\pm1$). It makes it possible to observe the external magnetic field based on the Zeeman effect (Fig. 1.c). The exact magnetic field can be recalculated based on detected ODMR [13]. Due to the tetrahedral structure of diamond, NV centers can be located along the four crystalline axes, enabling 3D vector magnetometry (Fig. 1.b). More precise detection can be performed by pulsed measurements, which are currently out of the presented work scope and will be investigated later.

2.2. OSCAR-QUBE sensor

The OSCAR-QUBE sensor is a quantum diamond-based magnetometer developed by a team of interdisciplinary students as part of the 'Orbit Your Thesis!' programme organized by ESA Academy. The team was selected for the programme in April 2020. After the design, development, and testing phase, the device was installed aboard the ISS inside the ICECubes Facility in the Columbus module in September 2021. The device was decommissioned in August 2022. The main components of the sensing system are the laser, diamond, microwave subsystem, optical readout system, and NdFeB permanent magnet to apply a bias magnetic field for vector magnetometry. The specifications of the sensor are presented in Table 1.

Table 1: OSCAR-QUBE sensor specifications.

Parameters	Value	Comments
Size	1U	10x10x10 cm3
Weight	420 g	
Power consumption	5 W	Peak power consumption
DC Sensitivity	< 300 nT/√Hz	
Measurement rate	< 40Hz < 1.3kHz	Vector mode Scalar mode
Dynamic range	1.86 mT	
NV concentration	2 ppm	CVD diamond

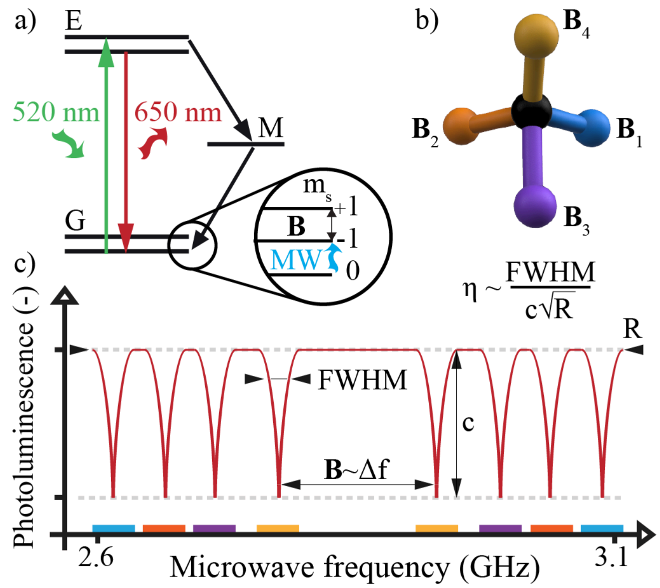

Fig. 1: a) Energy diagram of negative NV center with spin-sublevels m_S in the ground state G, excited state E, and metastable state M. b) Representation of four NV center orientations in a tetrahedral crystal lattice of a diamond, necessary for vector magnetometry. c) ODMR spectrum with parameters influencing the sensitivity, namely linewidth FWHM, contrast c, and photon count R. The positions of ODMR lines are determined by initial crystal and external parameters (magnetic field and temperature).

3. LONG-TERM STABILITY EVALUATION

Diamond-based quantum magnetometers utilize fundamental properties of NV centers and positions of their energy levels to detect magnetic fields. As such, measurements are stable against degradation due to the inherent robustness of diamond material. However, the long-term stability and reliability of such detectors may be affected by temperature fluctuations, aging of the internal components and electronics, magnetic interference noise, and drifts due to the harsh space environmental conditions, including cosmic radiation.

To assess the degradation of the OSCAR-QUBE sensor, measurements over a span of ten months were acquired. The parameters of ODMR, namely spectrum consistency and signal-to-noise ratio, baseline, contrast, and FWHM, serve as indicators for the long-term stability of the entire system. It allows for the evaluation of the observed magnetic field deviation over the mission duration.

The majority of measurements were performed under 29 mW laser excitation, with microwave power +26 dBm in range of 2.6-3.1 GHz. However, during the operation phase, these parameters were adjusted to test different operational modes, which impact the collected data and are crucial during data processing. Due to the lower sensitivity, there was no detectable influence of platform induced magnetic interference on the data.

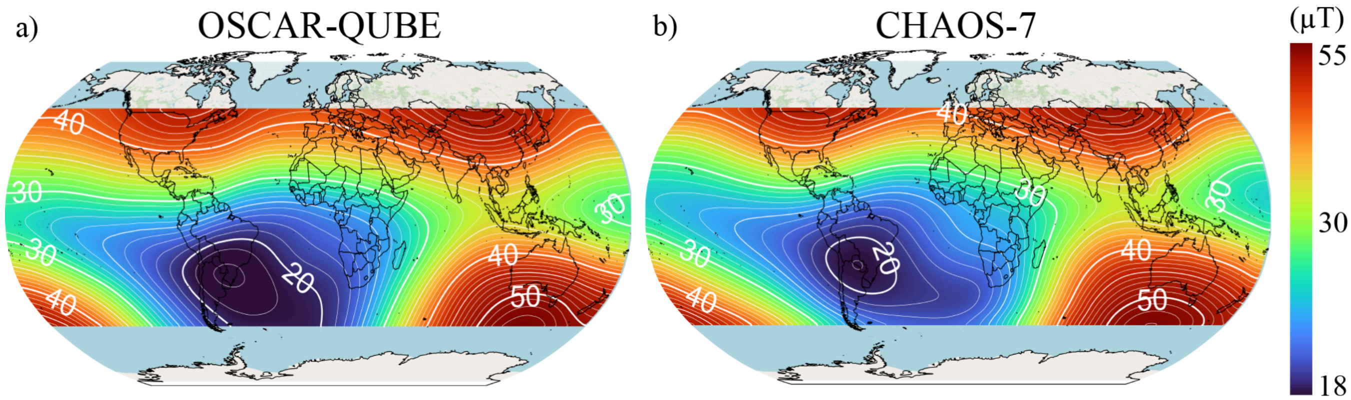

Fig. 2: Map of Earth's total magnetic field strength. a) Map resulting from two months of data acquired during the OSCAR-QUBE mission using a diamond quantum magnetic field sensor onboard the ISS. b) Map generated using the CHAOS-7 model, corresponding to the ISS mission.

4. MISSION RESULTS AND DATA ANALYSIS

Fig. 2.a shows Earth's total magnetic field strength measured in low Earth orbit (LEO) aboard the ISS using the diamond sensor described in previous sections. The range of the observed magnetic field intensity was between 18 and 55 µT. For comparison, the magnetic field derived from the CHAOS-7 model [14] is shown in Fig. 2.b. The correlation between observed and calculated magnetic fields demonstrates the functionality of the quantum sensor in the course of the mission. The data displayed in Figure 2.a was accumulated over the two-months measurement period. The South Atlantic anomaly, or point of lowest field strength, is clearly visible in the performed measurements. The CHAOS-7 model, largely based on Swarm data, includes both core field and external field contributions, where core field has the main contribution to the LEO magnetic field. As the measurements are gathered inside the ISS, the sensor is susceptible to spacecraft-generated magnetic noise. This noise may have affected the accuracy of the sensor which could explain the visible deviations between both maps. The average deviation for the total magnetic field between the maps was calculated to be 0.85 µT.

To investigate the degradation of the sensor, ODMR spectra for different time points spread over the mission duration are shown (see Fig. 3). The photosignal has been normalized in order to effectively compare the data. Fig. 3.a provides a visual demonstration of the ODMR stability over the mission duration. The deviation of measurement contrast was found to be 0.02%, while the FWHM deviation was about 0.1 MHz (see Fig. 3.b and Fig. 3.c respectively). The strongest change in linewidth was detected near the end of the mission and can be explained by different settings of the MW sweep, causing increased noise on the peaks.

To verify the drift and offset of magnetic field measurements over time, the total field strengths were averaged every day and compared over the entire mission duration (see Fig. 4). While the CHAOS-7 model demonstrates a single mean value around 34.4 µT, the measured data during the nine months of operation shows more variation around the mean. The last month of data was omitted since, during this period, the main focus was given to deeper system evaluation, and different operation regimes and parameters were tested. The nature of these variations were further investigated. As shown in Fig. 4, the mean magnetic field values are correlated by the change in laser temperature. These temperature fluctuations influence the ODMR line and should be included in data post-processing analysis. Even though the sensor was located inside a thermally controlled environment, temperature fluctuations can not be excluded completely, and additional temperature monitoring will be performed later for a deeper investigation of the long-term stability of diamond-based

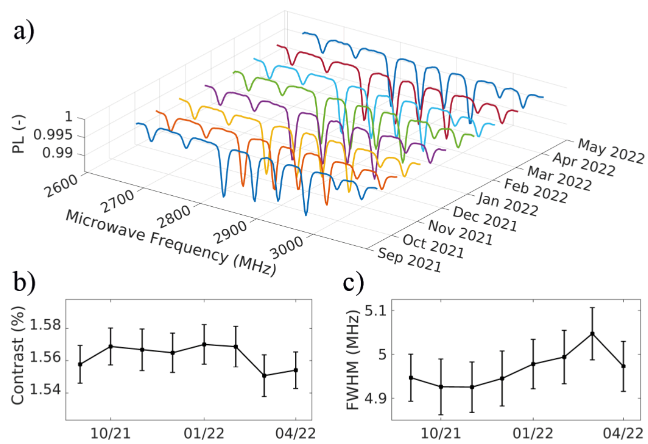

Fig. 3: ODMR measurements and parameters from nine months operation on ISS showing no degradation. (a) ODMR spectra with eight peaks compared (b) Contrast parameter (c) Linewidth parameter. The error bars represent standard deviation.

quantum sensors. Diamond defects can be used not only for magnetometry, but for thermometry as well. It allows the combination of such temperature monitoring and magnetic field observation within the same measurement system. Therefore, such quantum magnetometers can be potentially upgraded with self-correction protocols. Additionally, the influence of different laser and MW powers will be further evaluated. It will allow for the improvement of the data analysis regarding measurement conditions.

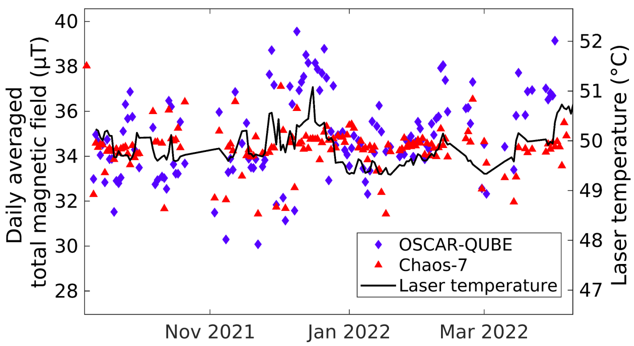

Fig. 4: Daily average of the total Earth magnetic field strength for both OSCAR-QUBE and CHAOS-7 data. The OSCAR-QUBE data shows fluctuations around the mean value and CHAOS-7 magnetic field data. This effect correlates to a change in laser temperature.

5. CONCLUSION

This work assesses the long-term stability of a novel quantum diamond-based magnetometer under real space conditions. The observed map of the Earth's magnetic field is in good agreement with the CHAOS-7 model. Slight deviations can appear due to spacecraft-related electromagnetic noise or thermal fluctuations during particular measurements. The influence of such events and ways of their compensation will be investigated by further data analysis, followed by simulations in the laboratory and in the next space missions. The most important outcome of the presented results is that ODMR spectra and their parameters remained stable over the entire mission. The only minor changes were detected during the last two months and did not disturb performed measurements.

The analysis of the measured magnetic field demonstrates small variations in time that prove the high stability of the developed quantum sensor. However, two mean values for experimental data instead of the one for the model require further investigation. The main reason for the resulting variations is identified to correlate to laser temperature fluctuations, as this influences the ODMR spectrum. This thermal effect will be further explored in future work.

Future research into the stability of NV sensors will focus on in-flight corrections of external electromagnetic noise and temperature fluctuations. Additional improvements in the laser power, bias magnetic field (currently applied by the permanent magnet), and data analysis can increase the sensor stability. Nonetheless, this initial demonstration of the real space application of the quantum diamond-based magnetometer proves its potential to be a highly sensitive scientific tool in longer-duration missions. To deepen the understanding of NV-based quantum systems operating in the space environment, an upcoming iteration of the diamond-based sensor will be tested aboard the inaugural flight of Ariane 6 within the ESA YPSat mission. It will provide the opportunity to further test this novel technology under space conditions.

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