OSCAR-QUBE: Student made diamond based quantum magnetic field sensor for space applications

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Abstract

Project OSCAR-QUBE (Optical Sensors Based on CARbon materials - QUantum BElgium) is a project from Hasselt University and research institute IMO-IMOMEC that brings together the fields of quantum physics and space exploration. To reach this goal, an interdisciplinary team of physics, electronics engineering and software engineering students created a quantum magnetometer based on nitrogen-vacancy (NV) centers in diamond in the framework of the Orbit-Your-Thesis! programme from ESA Education. In a single year, our team experienced the full lifecycle of a real space experiment from concept and design, to development and testing, to the launch and commissioning onboard the ISS. The resulting sensor is fully functional, with a resolution of < 300 nT/ sqrt(Hz), and has been gathering data in Low Earth Orbit for over six months at this point. From this data, maps of Earth's magnetic field have been generated and show resemblance to onboard reference data. Currently, both the NV and reference sensor measure a different magnetic field than the one predicted by the International Geomagnetic Reference Field. The reason for this discrepancy is still under investigation. Besides the technological goal of developing a quantum sensor for space magnetometry with a high sensitivity and a wide dynamic range, and the scientific goal of characterizing the magnetic field of the Earth, OSCAR-QUBE also drives student growth. Several of our team members are now (aspiring) ESA Young Graduate Trainees or PhD students in quantum research, and all of us took part in the team competition of the International Astronautical Congress in October 2021, where we won the Hans Von Muldau award. Being an interdisciplinary team, we brought many different skills and viewpoints together, inspiring innovative ideas. However, this could only be done because of our efforts to keep up a good communication and team spirit. We believe that if motivated people work hard to improve the technology, we can change the way magnetometry is done in space.

Keywords

Quantum Magnetometer, Interdisciplinarity, International Space Station

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1. Introduction

Quantum sensing is a quickly expanding branch of quantum science, in which basic research concepts rapidly evolve towards practical applications, drawing attention in terms of high sensitivity and precision. Currently quantum technology and its utilization in the space environment is still in its infancy, but it has the potential to become the next standard with possible applications for space magnetometry, and for terrestrial applications such as geology and mining, navigation, and biomedical technologies (MRI, NMR, etc.). The project OSCAR-QUBE (Optical Sensors based on CARbon materials - QUantum BElgium) is tackling this topic by giving undergraduate students of different disciplines (physics, electrical and software engineering) the chance to work hands-on in the field of quantum and space technology, and providing them with experience in R&D early on in their career.

The aim of project OSCAR-QUBE is the development of a diamond based quantum magnetometer, using opto-magnetic defects, called nitrogen-vacancy (NV) centers, found inside the crystalline lattice of the diamond material. The NV centers can be exploited as magnetic field probes with a theoretical sensitivity down to 10 fT/sqrt(Hz), a fast response time of < 200 ns and a very wide dynamic range (from fT to 0.1T) [1]. Diamond is a very robust and radiation hard material, which makes the sensor perfectly suited for the harsh space conditions. Due to the tetrahedral structure of the its lattice, there are four different crystallographic axes along which the NV centers can be located, enabling vector magnetometry.

The working principle [2] of the sensor is entirely quantum mechanical and relies on the optical excitation of the NV centers (see fig. 1a) using green laser light, and the subsequent relaxation (fig. 1b). The method of relaxation can be either dark or fluorescent (emitting red light, fig. 1c) and depends on the spin of the NV center, which can be addressed by a resonant microwave field, creating a dip in the red light spectrum at the resonance frequency (fig. 1d). External magnetic fields affect this spectrum, splitting the dips. The distance between the dips is proportional to the applied field (fig. 1e). This method of determining the ambient magnetic field is called the Optical Detection of Magnetic Resonance (ODMR) [1]. In fact, two of these dips will occur in the signal for each one of the four crystallographic axes, generating in total eight dips. Each pair of dips gives the magnetic field component in one direction and the 3D vector field can be determined by making the vector sum of all these components.

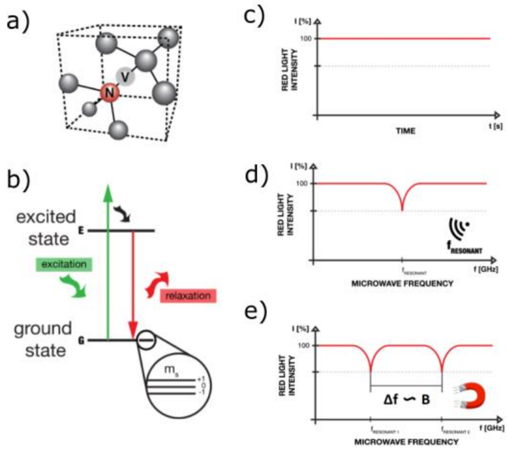

Figure 1. Principle of ODMR. (a) NV center in diamond lattice. (b) Simplified energy level scheme (with spin dependency) and transitions. (c) Radiative relaxation gives a stable red light signal. (d) Applying a resonant microwave field increases the probability of relaxation via a dark state. (e) Applying an external magnetic field changes the energetic spectrum of the NV center, giving rise to two resonances at a distance proportional to the magnetic field strength.

The OSCAR-QUBE was selected in the framework of the ‘Orbit Your Thesis!’ (OYT) program organized by European Space Agency (ESA) in April 2020 [3], with the aim to develop an experiment capable of mapping the Earth’s magnetic field within a single year. The benefit of the OYT program is the close connection with the space sector and expert guidance throughout the review process. This way our team got to experience the full lifecycle of a space project, acquiring knowledge of design standards, requirements, and test campaigns, generating a successful result and launch of our device to the International Space Station (ISS).

In the following sections, the paper will describe the project journey, experiment principle and findings, and also the team formation and team dynamics with focus on interdisciplinarity and diversity. It will underline the importance of communication and planning of a student project, and it will highlight the educational return of an R&D space project.

2. Experimental part

2.1. Selection

The journey of the OSCAR-QUBE team begins with the team and idea formation phase, initiated end 2019 (when ESA Education opened the call for submissions for the 2nd OYT program). This was a suitable candidate platform for the experiment as the ISS provides global coverage and allows us to focus on the development of the device without taking into account power generation, orbital control, space debris, etc.

To enter the OYT program our team leader wrote a letter of intent, after which we all wrote a project proposal. We focused on the scientific concepts, and on the fit between the program and our experiment. We were shortlisted for the Selection Workshop on the 25th of February. At this workshop, we gave a presentation about our project, after which we got contacted by ESA , asking us to clarify some aspects of the QUBE. In mid-April, we were selected [3].

2.2. *System design*

First, we defined the four main parts of our experiment: laser, microwave generator, optical detector, and the control and power system to operate the other components. One team member was responsible for each subsystem and we set up a testbench where we slowly replaced commercial components with our own subsystems, allowing us to optimize each single subsystem without needing to touch the others.

The first review we had was the Preliminary Design Review (PDR). We had to provide the experts with our complete design and a detailed description of hardware and software. The ESA experts gave us feedback in the form of RIDs, which varied from functional concerns to grammatical errors. After corrected all the RIDS, the PDR data package was accepted [4].

2.3. *Integration and manufacture*

After optimization of the subsystems on the testbench, we went for integration. The general mechanical design of the structure was constrained by the OYT program and had to be a cube with size 10 x 10 x 10 cm^3. The electronics team then designed the individual boards. The main challenge was the compatibility of the different designs, which was checked in several meetings

After creating our design, we had to pass the Critical Design Review (CDR). The goal of the CDR is to freeze the design and to make sure there are no last minute changes implemented, compromising the experiment or the safety of the astronauts. Therefore, we had to provide again every detail of our design. By this time we already had a functional cube, so we were confident in our design. After correcting our RIDs, we received ESA's blessing to continue and start building the flight model [5], of which figure 2 shows a schematic.

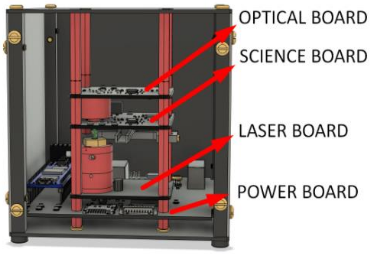

Figure 2: Schematic drawing of the QUBE. Standoffs are used to separate the four boards.

Software was created to store and transmit the measured data in packets (NV and reference data). If the QUBE is not connected to the ground, the packets are stored on an SD card, otherwise it transmits all data via Ethernet. This data is entered in a self-made User Home Base (UHB), developed to monitor the status and data of the sensor. Space Applications Services (SAS) has its own open-source mission control software package called Yamcs that is designed to receive telemetry and send telecommands while storing the incoming packets and formatting the raw values. The downside of Yamcs was that it only offered a basic web interface so we chose Javascript and Python to develop a GUI to interact with the sensor and display the real-time data.

2.4. *Testing*

The operation of the QUBE and associated software was tested during the development of the sensor. First, we characterized the NV axes of the diamond sample, using an in-house created 3D Helmholtz Coil. To make sure that the QUBE would survive the launch and space environment, we did several environmental tests: vibrational testing, thermal/ vacuum testing and EMI/ EMC testing. Interface tests were used at SAS to ensure correct functioning of the QUBE. All tests were passed [5].

2.5. *Shipping and launch*

After testing, the QUBE was put in a vibration minimizing package and shipped to ESA. Then we prepared ourselves for the launch, which happened on the 29th of August [6]. We set up a launch event at our university, where we invited the rectorate, our endorsing professor, our sponsors, and previous OSCAR iterations.

This event was also featured in newspaper articles and on Belgian television [7], helping us share our journey with the public.

2.6. Commissioning and operations

After the launch, we were invited to the ICE Cubes Mission Control Center in Zaventem, Belgium to see how Thomas Pesquet unpacked and installed the QUBE in the ISS [8] (location in fig. 3), after which the first data came in.

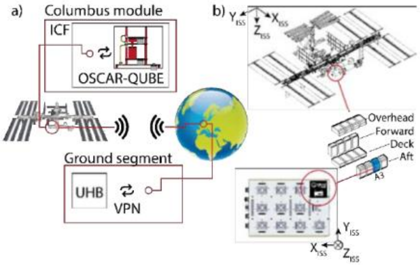

Figure 3: a) Global system overview. b) Reference frames of the QUBE's respective location onboard the ISS.

Once the data is stored on the server, we use Python to process it because of its versatility and the large amount of installable packages. Once a day, the data processing is triggered automatically. First, the packets are sorted by their timestamps to make sure they are in chronological order. Secondly, the positions of the individual peaks are determined by fitting the data with a Lorentzian curve [9] to extract the center frequency of the dip. In the third step, the GPS data and location of the ISS at each measurement point is added. Lastly, the data is made accessible in an understandable way, using an Elasticsearch database together with Kibana [10]. This allows us to make graphs and export specific sections of data for calculations.

To extract information from the ODMR data, equation 1 [11] is solved for the components of magnetic field B along the NV axes (X, Y, Z) and the frequency difference Δf between the corresponding minima in the spectrum. Here, ɣ is the NV gyromagnetic ratio, equal to 28.024 GHz/T. The B and NV axes components are evaluated in the same reference frame. Equation 1 has physical meaning when the components are transformed to the body fixed ISS frame LVLH [12] (local vertical local horizontal). Because the ISS rotates, an attitude correction has to be done by using its Roll, Pitch and Yaw. Another frame used to evaluate the data is the NED [13] (North East Down) frame which is heading invariant. With the data expressed in these coordinates, the magnetic field map of the earth can be created as a function of latitude, longitude and altitude.

$$2\gamma \begin{bmatrix} X_{NV1} & Y_{NV1} & Z_{NV1} \\ X_{NV2} & Y_{NV2} & Z_{NV2} \\ X_{NV3} & Y_{NV3} & Z_{NV3} \\ X_{NV4} & Y_{NV4} & Z_{NV4} \end{bmatrix} \cdot \begin{bmatrix} B_x \\ B_y \\ B_z \end{bmatrix} = \begin{bmatrix} \Delta f_1 \\ \Delta f_2 \\ \Delta f_3 \\ \Delta f_4 \end{bmatrix} \tag{1}$$

2.7. Outreach and team

Team OSCAR wants to inspire as much students as possible to choose a technical, scientific or engineering direction. To do so, we pay a lot of attention to outreach on social media such as Facebook, Instagram and Linked-in. On Facebook, we have 555 followers and our posts have reached at most 2 325 people. We've been featured in Czech [14] and Belgian newspapers and tv on multiple occasions. We also reach out to students directly, in lectures, presentations and in informal ways such as an art competition [7].

To quantify our experience, we held an online survey within the team. The results of this survey will be discussed in the following section.

3. Results and discussion

The OSCAR mission has three important parts: technology, science and student growth. The technological goal was to develop a quantum magnetic field sensor for space magnetometry with a high sensitivity and a wide dynamic range. We did this by creating a diamond-based quantum magnetometer (see fig. 4) that fits inside a cube with a side of 10 cm, weighing only 420 g, with a power consumption of 5 W. The measured resolution of this device is < 300 nT/ sqrt(Hz) and the bandwidth is 1.3 kHz [2].

Figure 4: left) Finished QUBE without side panels. right) the QUBE onboard the ISS during installation by Thomas Pesquet.

Using the QUBE, the scientific goal of gathering a magnetic field mapping of the world by measuring in Low Earth Orbit was addressed. Figure 5 shows a comparison between NV and reference data measured on the 27th of December. There is a clear resemblance between the two signals for all magnetic field components, which vary on different timescales. This is single orbit data but is representative for multiple orbits.

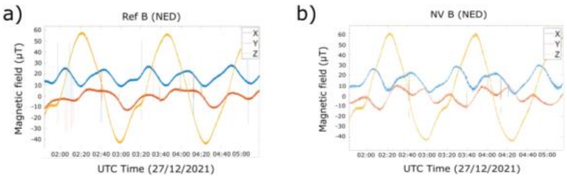

Figure 5: Magnetic field measurements with reference (a) and NV (b) sensor of 90 minutes.

Figure 6 shows the total magnetic field maps of the NV sensor and IGRF simulations created during the orbit in LEO. The NV magnetometer signal is similar to both the reference signal (not shown here) and the IGRF map, indicating that our sensor is capable of determining Earth's magnetic field.

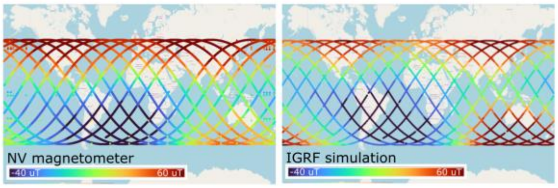

Figure 6: Total magnetic field map of NV sensor for 24h (left) and IGRF simulation (right).

The project opened up new possibilities for the students in terms of personal and professional growth. After finishing their master, two team members became Young Graduate Trainees at ESA (one applied this year) and another one became a PhD student in the Photonics and Quantum Technology group (three applied this year). In October 2021, we presented the experiment in Dubai at the International Astronautical Congress and won the Hans Von Muldau prize for best team project [18].

Many team meetings were held to exploit the advantage of an interdisciplinary team, with the aim of helping members gain insight on different disciplines, both the complex physics and its practical application. The previously mentioned survey checked the validity of this hypothesis and provided some lessons for the future:

- Communication in an interdisciplinary team is not easy (very specific knowledge, misunderstandings, etc.) but important. Done right, the different disciplines bring versatility and many insights.
- Do not provide too much work to individuals with specific skill sets, while others have time to learn this skill as well.
- Let team members get to know each other informally at the start, even more so during COVID restrictions. It makes the threshold to ask for help smaller.
- Do not underestimate the amount of documentation in the space industry. Let experts guide you in this.

The most unexpected thing we learned was different for everyone, but one thing we all have in common is that the reality of where we are today surpassed our initial expectations. Lastly, everyone's favorite moment was asked, which varied from the selection, creating the QUBE, the launch and installation, to the IAC. Other team members expressed how they liked all moments where the team was together and we could talk about topics of shared interest.

4. Conclusion and outlook

In a single year (April 2020 to April 2021), we created a quantum magnetometer based on NV centers in diamond, fit for a real space mission. After passing all required tests, we shipped the device and watched its launch to the ISS. In September 2021 the QUBE was installed and the first data came through to our user home base on ground, proving that our experiment had survived the launch and was fully functional. Now, we have been collecting data for six months and could generate preliminary magnetic field maps that correspond partly to reference measurements. The difference with IGRF predictions is still under investigation.

It has proven to be of utmost importance for us to invest in communication, both formally and informally, especially since we formed our team during the COVID-19 pandemic. The advantage of interdisciplinarity is that we bring different knowledge and perspectives to the table, but on the other hand it's not always easy for us to understand each other. By putting in this effort, we managed to create our sensor, necessary documentation, and content for our followers on social media and other outreach platforms.

Thanks to our sponsors, the QUBE will be brought back from space onboard the SpaceX CRS-25. This allows us to investigate the effect of space conditions on the QUBE and assess more precisely the technological readiness level and possible improvements. Thanks to the OYT programme, we gained visibility in the space industry and received new opportunities. For example, we got selected in the first round of the myEUspace competition from EUSPA, where we presented a spin-off mobile app Aurora Catcher that allows tourists to detect northern lights with quantum magnetometers.

We are also reiterating our sensor to create compatibility another platform in the YPSat project, where a group of ESA Young Graduate Trainees fly their experiment on board the Ariane 6 rocket's maiden flight. The goal is to technically improve the sensor by reducing its size, weight and power consumption, and to push the science by sensitivity improvement and determining the attitude of the launcher.

Acknowledgements

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