Impact of 3-D Attitude Variations of a UAV Magnetometry System on Magnetic Data Quality

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ABSTRACT

Optically pumped vapour magnetometers have an orientation dependency in measuring the scalar component of the ambient magnetic field which leads to challenges for integration with mobile platforms. Quantifying the 3-D attitude variations (yaw, pitch and roll) of an optically pumped vapour magnetometer, while in-flight and suspended underneath a rotary unmanned aerial vehicle (UAV), aids in the successful development of reliable, high-resolution unmanned aerial vehicle magnetometry surveys. This study investigates the in-flight 3-D attitude characteristics of a GEM Systems Inc. GSMP-35U potassium vapour magnetometer suspended 3m underneath a Dà-Jiāng Innovations (DJI) S900 multi-rotor UAV. A series of UAV-borne attitude surveys quantified the 3-D attitude variations that a simulated magnetometer payload experienced while freely (or semi-rigidly) suspended underneath the UAV in fair weather. Analysis of the compiled yaw, pitch and roll data resulted in the design of a specialized semi-rigid magnetometer mount, implemented to limit magnetometer rotation about the yaw axis. A subsequent UAV-borne magnetic survey applying this specialized mount resulted in more than 99% of gathered GSMP-35U magnetic data being within industry standards. Overall, this study validates that maintaining magnetometer attitude variations within quantified limits (± 5 degrees yaw, ± 10 degrees pitch and roll) during flight can yield reliable, continuous, and high-resolution UAV-borne magnetic measurements.

Key words: Magnetics, Potential Field, UAV, Airborne Geophysics

1.0 INTRODUCTION

Magnetometry is a principal form of field-based site investigation used in numerous geophysical applications such as mineral exploration, unexploded ordnance detection, and infrastructure detection. Traditional platforms for collecting magnetic data include high coverage, but low resolution manned airborne surveys (Hood and Ward 1969; Luyendyk 1997), and high resolution, but low coverage terrestrial surveys (Everett 2013; Hinze et al. 2013). For manned airborne surveys, magnetic data is characteristically collected at or greater than an elevation of 100m above the ground; while for terrestrial surveys, magnetic data collection is limited to the Earth's surface. As such, an observational gap persists, extending from the ground surface up to an elevation of approximately 100m. This is typically where neither traditional magnetic surveying platform can safely nor physically operate. Unmanned Airborne Vehicles (UAVs) equipped with magnetometers have the potential to fill this observation gap.

Advancements in platform technology allow UAVs, also known as unmanned aerial systems (UASs) or drones, to successfully operate between the ground and 100m elevation, as shown in the studies of Samson et al. 2010, Stoll 2013, Cunningham et al. 2015, Parvar 2016, Wood et al. 2016, Walter et al. 2017, and Parvar et al. 2018. In doing so, this platform can exploit a higher rate of coverage than terrestrial magnetic surveys, ie. speeds greater than 5 km/h (Cunningham 2016), at a higher resolution than manned airborne surveys, ie. closer than 100m from the target (Malehmir et al. 2017). This new spatial and temporal scale provides a more desirable balance between the existing two end-members of coverage and resolution in magnetic surveys, especially for smaller to medium scale projects on the order of 1-10's km^2 (Cunningham 2016; Parvar 2016; Malehmir et al. 2017; Parvar et al. 2018). Reliable integration of a high-resolution, industry standard magnetic sensor with compatible UAV platform technologies is a very promising endeavour. Previous studies have used UAV magnetometry systems with mixed success (Samson et al. 2010; Cunningham et al. 2015; Cunningham 2016; Parvar 2016; Wood et al. 2016; Malehmir et al. 2017; Walter et al. 2017; Parvar et al. 2018). The main obstacle in UAV magnetometry is separating the magnetometer from the UAV platform to minimize the UAV's magnetic field influencing the observations. The technical realization of separating the sensor from the airframe leads to additional challenges which are related to the magnetometer attitude during flight (Walter et al. 2017). Herein, we focus on quantifying the impact of yaw, pitch and roll of a suspended magnetometer on the magnetic data quality towards achieving industry standard magnetic measurements based on 4th difference values (Coyle et al., 2014).

Single-rotor and multi-rotor UAVs are specifically attractive due to their ability to perform spatially unrestricted take-off, landing and hovering manoeuvres (Cunningham 2016), making piloting them in remote areas or tight spaces more practical (Malehmir et al. 2017). In addition, rotary UAVs can readily accommodate unconventional payload schemes, such as suspending a magnetic sensor away from airframe components. Their flight flexibility and 3-D surveying capability are additional advantages towards the acquisition of magnetic gradient observations. Unwanted magnetic field contributions from the UAV platform can be reduced by suspending the magnetic sensor payload below the rotary UAV platform (Caron et al. 2014; Cunningham 2016; Parvar 2016). This technique is employed to avoid using complex compensation algorithms; a practice commonly used in manned airborne surveys (Hood and Ward 1969; Hinze et al. 2013; Camara et al. 2016) to filter out the unwanted magnetic signals emanating from the platform's airframe (Forrester 2011). In addition, suspending the magnetometer below the UAV platform at a predetermined offset distance aids in achieving airborne magnetic data quality standards (Parvar et al. 2018). Studies such as Wells 2008, Cunningham 2016, and Parvar 2016 have investigated the magnetic signals produced by various UAVs and their on-board components and provided guidelines for sensor placement. Studies such as Cunningham 2016, Parvar 2016, Malehmir et al. 2017, and Parvar et al. 2018 have all concluded that minimal platform magnetic signal interference occurs when a magnetic sensor is suspended greater than 3m below a DJI S900 UAV platform.

Presently, three types of mobile magnetic sensors (magnetometers) have been integrated with rotary UAV platforms for geophysical surveys. These studies include: fluxgate magnetometers (Stoll 2013), proton precession magnetometers (Malehmir et al. 2017) and optically pumped vapour magnetometers (Cunningham 2016; Parvar 2016; Walter et al. 2017; Parvar et al. 2018). Of these three magnetometer types, optically pumped magnetometers are more favourable for integration with rotary UAV platforms, based on their high sensitivity (0.0003 nT/Hz), high sampling frequency (up to 20 Hz) and light weight (~2 kg) (Smith 1997; GEM Systems Inc. 2013, 2014a). Yet, the reliable integration of these high-performance, optically pumped vapour magnetometers with rotary UAV platforms is challenging due to the specific physical processes employed to measure the magnetic field. Herein, we investigate the performance of optically pumped vapour magnetometers suspended under a UAV.

Optically pumped magnetometers have an orientation dependency of measuring the magnetic field based on the Zeeman Effect (Smith 1997; Billings and Wright 2009; GEM Systems Inc. 2013, 2014a). The optimal angle in 3-D space that maximizes the Zeeman Effect is a 45° angle (Smith 1997; Billings and Wright 2009; GEM Systems Inc. 2013, 2014a, 2014b), measured between the optically pumped magnetometer's sensor axis and the external total magnetic field vector ($\vec{B}$-field). In the same plane as the optimal 45° angle, and extending out symmetrically, is an approximate ± 30° operational window where the Zeeman Effect remains sufficiently strong. As such, keeping the magnetometer sensor axis within this ± 30° angle allows the magnetometer to gather reliable magnetic field measurements (the operational window between the sensor axis and magnetic field vector ($\vec{B}$-field) is shown with green shading in Figure 1). However, variance of the sensor axis outside of the ± 30° operational window (also called magnetometer dead zones, shown with red shading in Figure 2) reduces the strength of the Zeeman Effect, subsequently reducing the accuracy and reliability of recorded magnetic measurements. Therefore, when using an optically pumped magnetometer, the sensor axis must remain oriented within the ± 30° operational window in 3-D space to collect industry standard data. If the sensor axis moves outside of the 3-D operational window, the data quality is either compromised or the magnetometer may lose lock to the external magnetic field resulting in no valid observations.

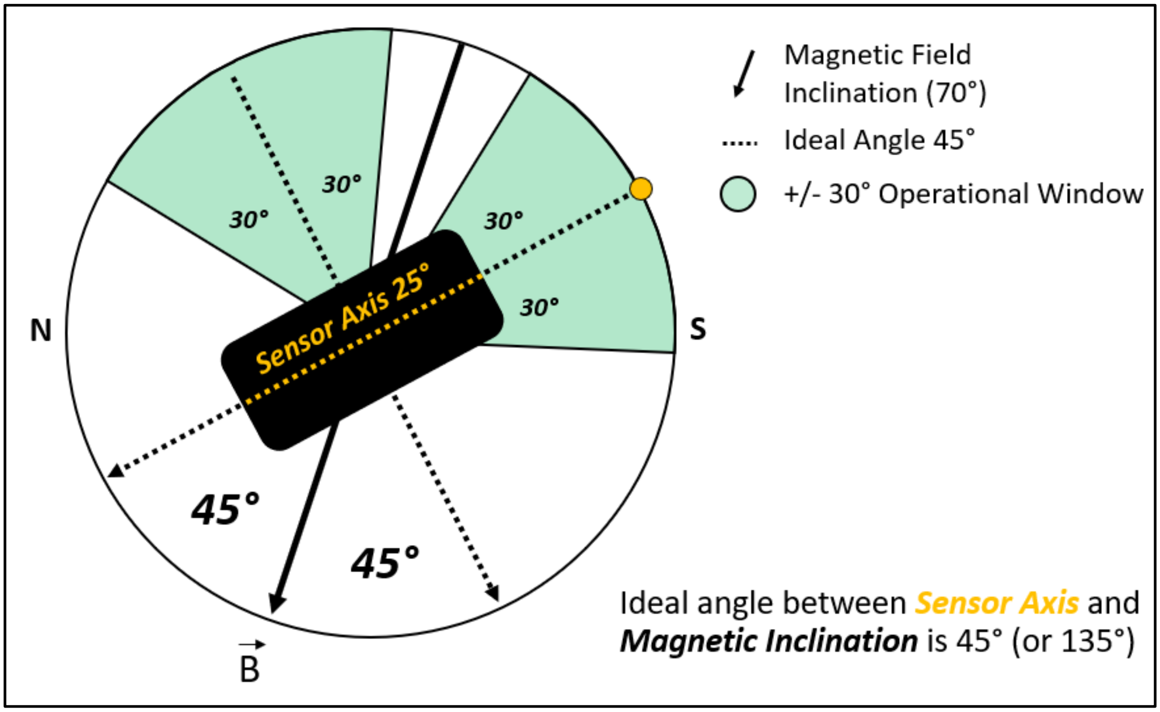

Figure 1 2-D North-South cross-sectional diagram demonstrating the ideal in-line angle of 45° (dashed black arrows) between the sensor axis of the GSMP-35U magnetometer (inclination of 25° - yellow dashed line) and the Earth's magnetic field at Kingston, Ontario, Canada (inclination of 70° - solid black arrow).

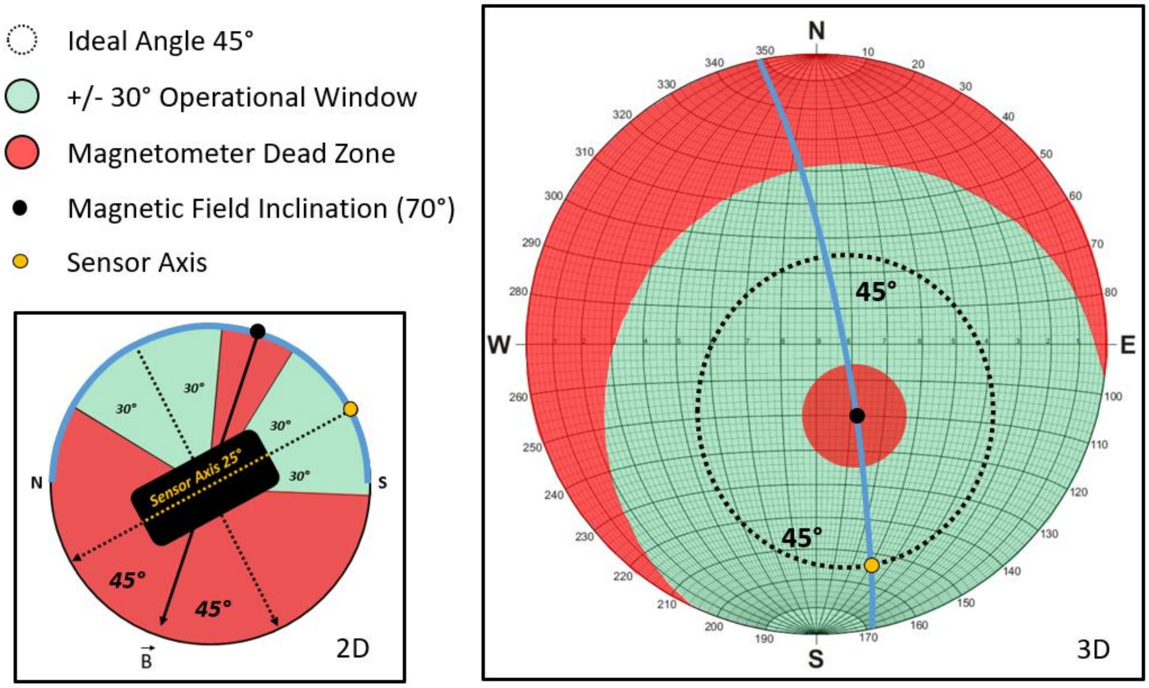

Figure 2 Illustrated diagram demonstrating the ideal angle of 45° between the sensor axis of an optically pumped magnetometer (yellow dot) and the magnetic inclination of the Earth's field at Kingston, Ontario, Canada (inclination 70°, declination 12°W - black dot) in both 2-D cross-section and 3-D stereonet view.

For relatively stationary magnetic applications using optically pumped magnetometers, maintaining the sensor axis attitude within the ± 30° operational window can be achieved by optimally orienting the magnetometer prior to the survey and limiting magnetometer axis rotations throughout the survey (Smith 1997, Billings and Wright 2009; GEM Systems Inc. 2013, 2014a, 2014b). However, when mounting an optically pumped magnetometer underneath a mobile UAV platform, there is an inherent, non-trivial design challenge of keeping the sensor axis correctly oriented with respect to the primary magnetic field vector. A suspended magnetometer will experience periodic, sinusoidal rotations about all three orthogonal axes (Cunningham 2016; Parvar 2016; Malehmir et al. 2017) as a rotary UAV navigates during flight. The extent of these periodic axis rotations given parameterized inputs such as flight speed, wind speed and suspended length, have yet to be well documented. As such, quantifying these rotations and predicting the attitude interactions between a rotary UAV platform and a suspended optically pumped vapour magnetometer, given an initial set of flight and surveying parameters, is highly relevant.

Two experiments were conducted towards quantifying the impact of sensor yaw, pitch, and roll variations on magnetic data quality: i) an attitude survey and ii) an aeromagnetic survey. The main objective of this study was to quantify the impact of sensor attitude variations on magnetic data quality given the initial design constraint of having the magnetometer suspended 3m below the DJI S900 UAV. The UAV-borne magnetic data collected by the potassium vapour magnetometer was compared with the airborne magnetic data standard, a fourth difference of ± 0.05 nT (Coyle et al., 2014).

First, the 3-D attitude variations of a simulated optically pumped vapour magnetometer freely suspended 3m underneath an Observer-6 multi-rotor UAV were quantified, given an initial and consistent set of flight and payload parameters. The gathered attitude variations during nine flights were plotted on both 2-D and 3-D diagrams to determine how they relate to the theoretical ± 30° operational window of an optically pumped magnetometer.

Secondly, a magnetic survey was conducted using a GSMP-35U UAV magnetometer system provided by GEM Systems Inc. The sensor was suspended 3m below a DJI S900 multi-rotor UAV. The attitude variations of the magnetometer were controlled by a semi-rigid mounting system, which restricted the yaw variations, while leaving the pitch and roll variations free. It is worth noting that fixing the pitch and/or roll axes of the suspended magnetometer could result in decreased flight stability of the UAV. The calculated fourth difference of the gathered magnetic data was analysed to determine which navigational manoeuvres caused a decrease in magnetic data quality.

2.0 MATERIALS AND METHODS

2.1 Attitude variation survey

The UAV platform employed for the attitude surveys was an Observer-6 (OB-6) multi-rotor UAV manufactured by Kildir Technologies, as shown in Figure 3. The OB-6 UAV platform equipped with a Pixhawk flight controller is compatible with the open source Mission Planner ^{TM} software, which allows for detailed flight missions to be planned at a ground station prior to taking off. The OB-6 has a maximum payload of 2 kg and a corresponding flight endurance of approximately 5-7 minutes using two 4500 mAh batteries.

The simulated magnetometer payload used to measure attitude variations in flight was comprised of the functioning internal navigation components of an OB-6 UAV. This payload system was assembled from spare OB-6 parts including: a GPS antenna, inertial measurement unit, power distribution board, microcontroller board, radio transmitter and receiver and a 4S 4500 mAh LiPo battery power supply. The internal navigation components of the OB-6 were retrofitted and positioned securely inside of a compact payload container. The payload container was suspended 3m underneath the OB-6 UAV via an unrestricted and freely rotating cable. This setup mimicked the suspension of the optically pumped magnetometer via its electrical cable with no rotational restrictions about any axis (Figure 3). The rotational and positional data of the payload container (simulated optically pumped magnetometer) was recorded at 1 Hz with the internal navigation system and recovered via the telemetry logs.

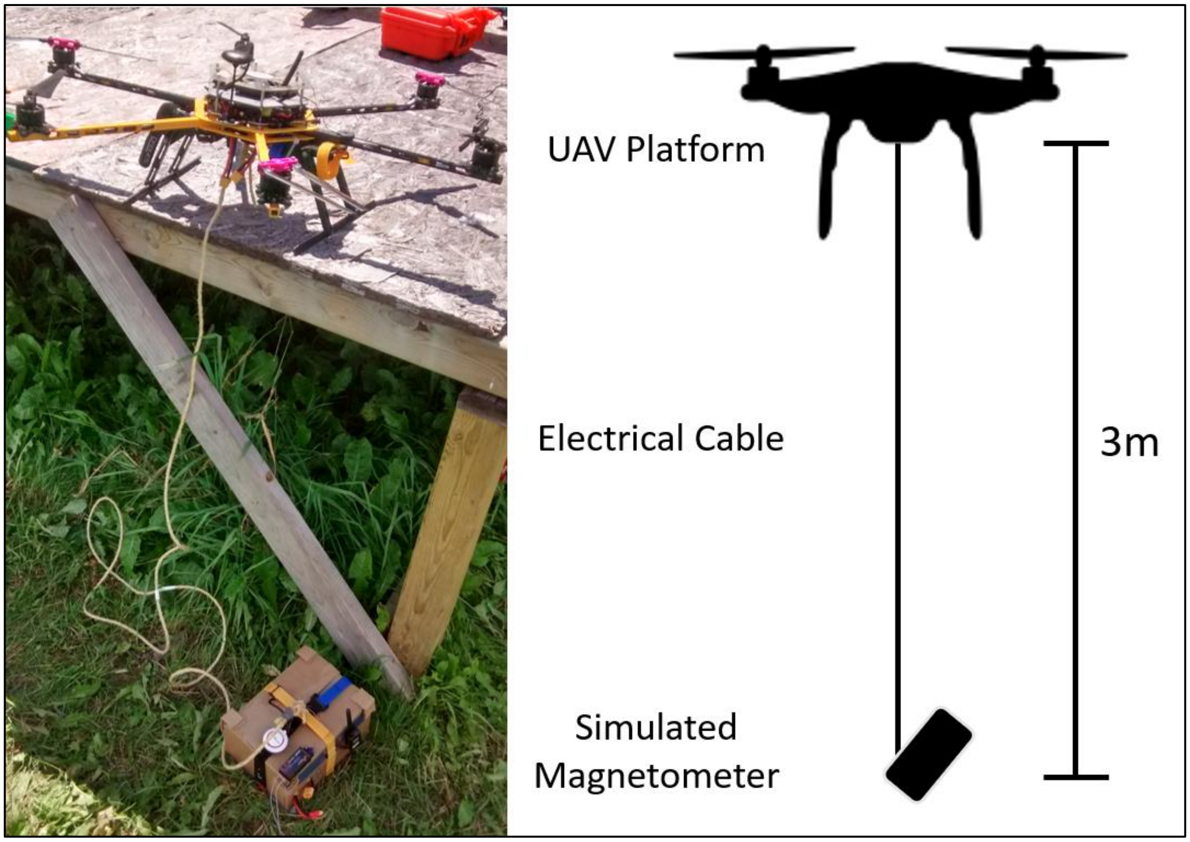

Figure 3 Photograph (left) and diagram (right) of the OB-6 UAV platform, electrical cable and freely suspended, simulated magnetometer payload used throughout the attitude surveys

2.2 UAV-borne magnetic survey

The platform used for the UAV-borne magnetic surveys was a DJI S900 heavy lift multi-rotor UAV, as shown in Figure 4. The UAV platform was equipped with an A2 flight controller, compatible with the DJI Ground Station 4.1 software. This allowed the magnetic surveys to be planned at a ground station prior to take-off. In addition to the platform and main payload, a data acquisition system was used to collect and store magnetic and positional measurements. The developed data acquisition system included an on-board computer (Raspberry Pi 2), an additional global positioning system (GPS) receiver (ublox EVK-7), laser altimeter (Lightware SF-11) and an external 5V battery pack.

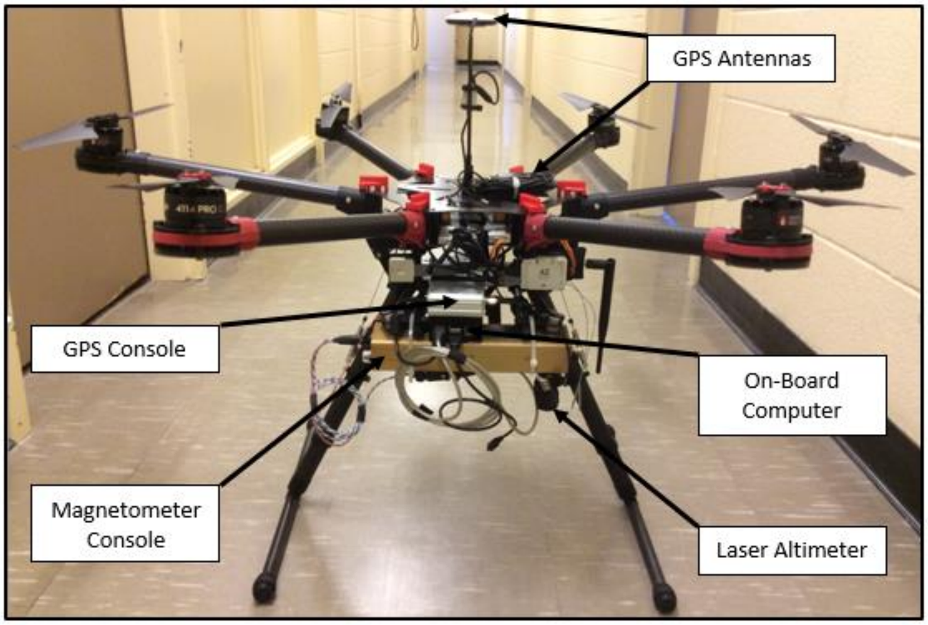

Figure 4 Photograph of the DJI S900 UAV platform and data acquisition system used throughout the February 2017 UAV-borne aeromagnetic survey

The primary payload of the DJI S900 UAV was a GEM Systems GSMP-35U potassium vapour magnetometer. The magnetometer was composed of two main parts: (i) the magnetometer electrical console and (ii) the magnetometer sensor head. The magnetometer electrical console was used to store the magnetic measurements and was secured directly to the frame of the multi-rotor UAV. The magnetometer sensor head was used to measure the magnetic field. The sensor head was semi-rigidly mounted to the UAV and suspended 3m below the airframe. The components of the semi-rigid mount, which contained the electrical cable of the magnetometer sensor head, are presented in Figure 5. Overall, the combined magnetometer payload, specialized semi-rigid mount, and data acquisition system weighed a total of 2.2 kg. Magnetic data collection with the potassium vapour magnetometer took place at 10 Hz, resulting in approximately two observations per meter along the flight trajectory (nominal surveying speed was ~6 m/s).

Figure 5 The semi-rigid mounting system, which includes: a set of lightweight, stiff plastic tubes (clear) and semi-rigid electrical conduit (black) encasing the sensor cable. Both components are fixed in the yaw. However, the black electrical conduit is flexible in the pitch and roll axes, allowing the mount to collapse upon landing.

3.0 SURVEYS & RESULTS

3.1 Attitude survey

The attitude variation study was conducted over a two-day period in August 2016, Southwest of Thunder Bay, Ontario, Canada. The test site was the McCluskey Corners UAV flying field. Conditions on the first day of surveying, August 24th, were fair (sunny and calm, with negligible wind). Conditions on the second day, August 25th, were sunny but with a noticeable and consistent wind from the west. According to historical weather data gathered at the Thunder Bay International Airport (Government of Canada 2017) 12 km away from the flying site, the wind speed averaged less than 1 m/s from the south on August 24th, 2016 and ~5 m/s from the west on August 25th, 2016. The historical weather data affirms the empirical observations from the field notes and gives a reasonable estimate for the wind speeds each day.

The pre-programmed flights were conducted at a speed of approximately 6 m/s with two 150m long traverse lines, trending roughly Northwest separated by a 50m diameter turn on each end, as shown in Figure 6. This programmed flight speed was chosen to correspond with the known maximum flight speed of the DJI S900 when towing the suspended 2.2 kg GSMP-35U magnetometer system. Flights were conducted in both a clockwise and counter clockwise direction around this circuit with a constant heading command applied to the multi-rotor UAV platform. The flight elevation for all attitude surveys was set to 10m above the ground, ensuring a reasonable offset over the relatively flat grassy terrain.

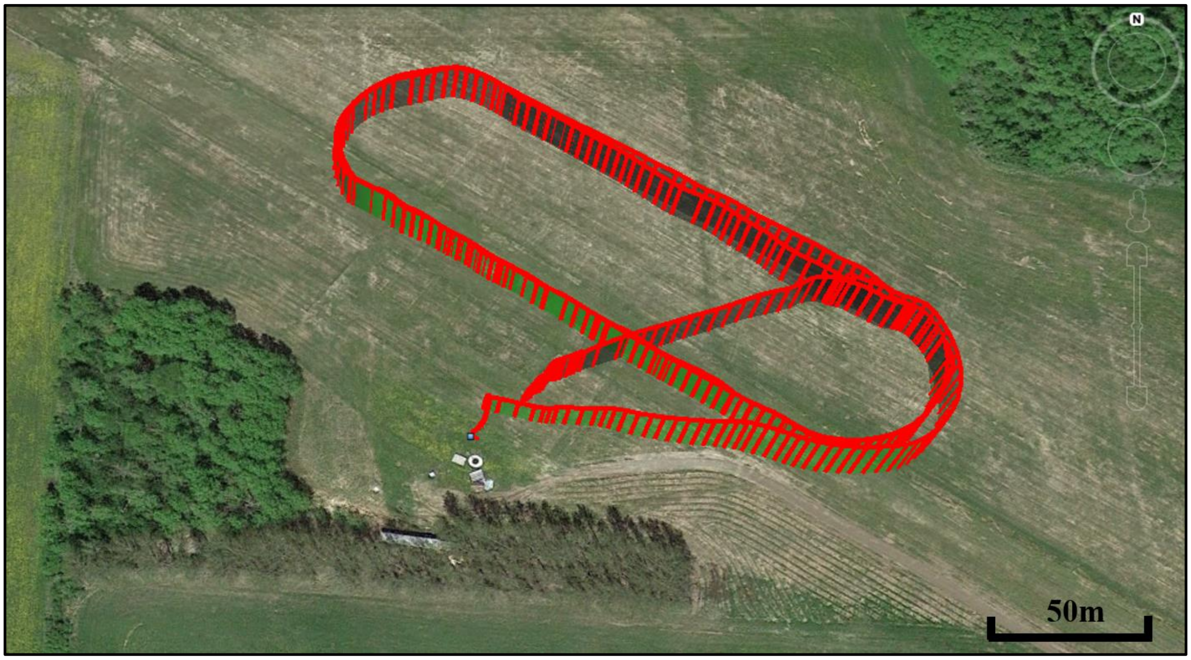

Figure 6 Google Earth image created from the UAV telemetry log depicting the flight path used throughout the Thunder Bay, Ontario, survey.

The orthogonal sensor axis variations actively monitored for each of the nine UAV-borne attitude missions were the yaw, pitch and roll axes as shown in Figure 7. The names of these axes described throughout the study are taken from general aviation terms commonly used throughout UAV and airborne studies (Camara et al. 2016; Cunningham 2016; Luyendyk 1997; Hood and Ward 1969), where yaw refers to rotations about the vertical axis in 360° (also known as heading). Pitch refers to rotations about the lateral horizontal axis (between +180° and -180°). Roll refers to rotations about the longitudinal horizontal axis (between +180° and -180°).

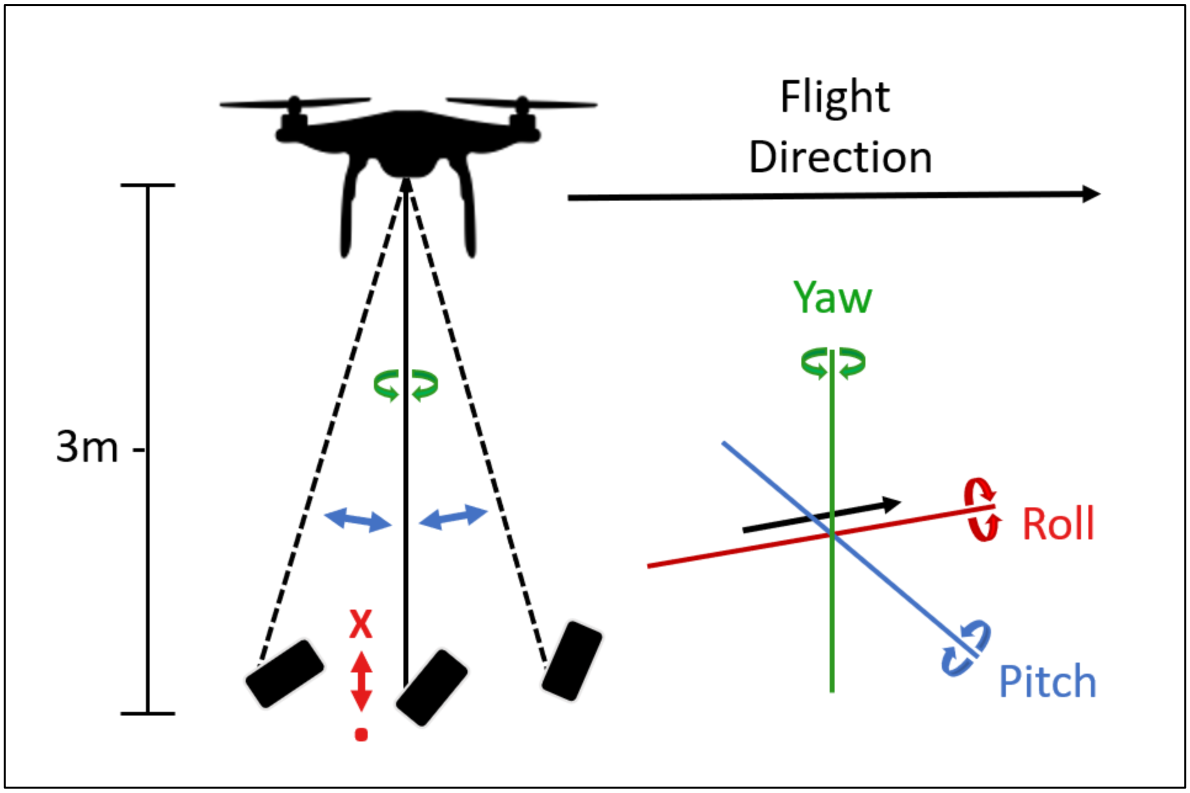

Figure 7 The in-flight 3-D orientation axes (yaw, pitch and roll) of a simulated optically pumped vapour magnetometer payload while freely suspended 3m underneath a UAV.

Prior to each flight, the simulated magnetometer payload was levelled to orient the pitch and roll attitude of the inertial measurement unit about 0° pitch and 0° roll. This process is analogous to optimally orienting a potassium vapour magnetometer with the Earth's magnetic field vector at the surveying site prior to take-off (Smith 1997; Billings and Wright 2009; GEM Systems Inc. 2013, 2014a, 2014b). This procedure minimizes the chances that the magnetometer rotates outside of the operational window of ± 30°.

3.2 Attitude survey results

The gathered yaw, pitch and roll attitude variations of the simulated magnetometer are presented in 2-D and 3-D plots. The pitch and roll axes are compared, representing the horizontal swinging of the magnetometer in flight, both back and forth and side to side. Likewise, the yaw axis attitude is plotted against the pitch axis attitude, together representing the lateral rotations about the vertical vector (yaw) and the vertical rotation about the horizontal, lateral axis (pitch). Overall, there were approximately 3200 data points collected from nine flights during this survey. The data was gathered from both the corners and the main 150m long traverse lines trending approximately Northwest and Southeast.

3.2.1 Payload Pitch and Roll Variations

The compiled pitch and roll attitude variations of the payload from all nine flights are presented in Figure 8a. The variations demonstrate that 95% of the data are within approximately ± 10° from the mean. The largest pitch axis variation was approximately ± 22°, while the largest roll axis variation was approximately ± 25°. These larger attitude variations were recorded as the UAV navigated the corners. The mean for this data (yellow data point) is centred around the origin (0, 0) and represents when the magnetometer is suspended directly below the UAV (in-line with the gravity vector). The border of the diagram represents the limits of the potassium vapour magnetometer operational window at ± 30° variation from the mean (optimal orientation).

The quantified pitch and roll attitude variations (light blue envelope) are plotted on the 3-D operational window diagram in Figure 8b. From this diagram, the attitude variations in pitch and roll remain inside the operational window of the potassium vapour magnetometer (green envelope), if the magnetometer is optimally oriented to the ideal 45° angle (dashed line/yellow dot) prior to the survey.

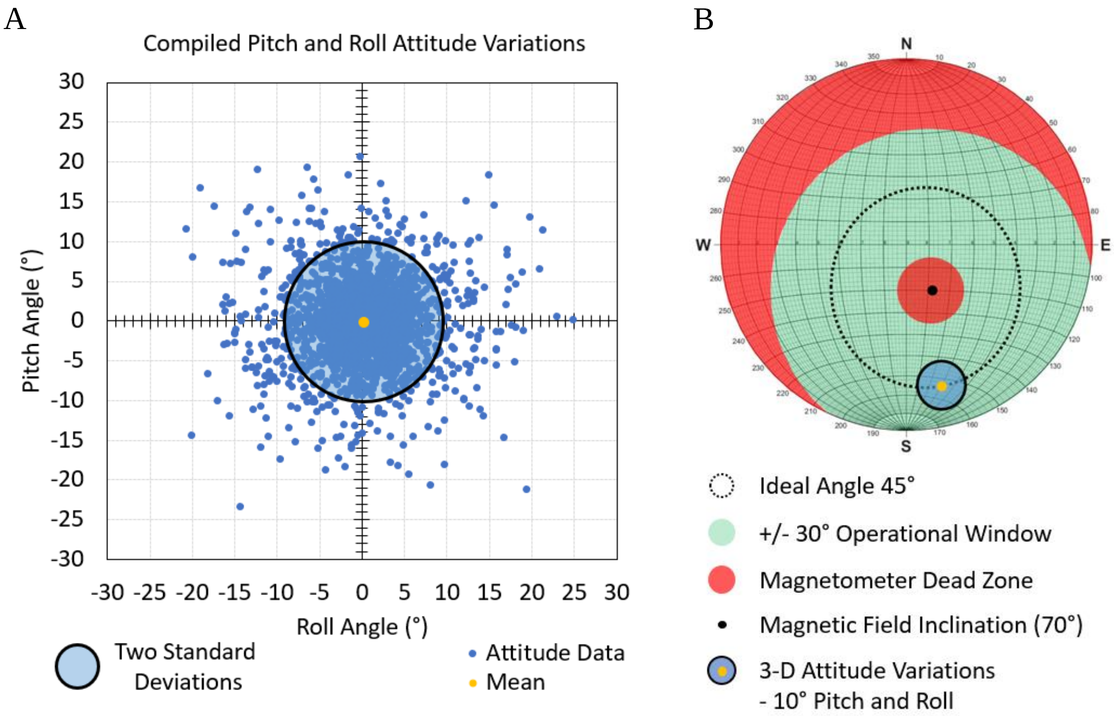

Figure 8 (a) Compiled pitch and roll attitude variations of the freely suspended payload (~3200 blue data points). Approximately 95% of the data points fall within ± 10° from the mean (yellow data point). **(b)** 3-D diagram showing the pitch and roll attitude variations (± 10°) of the simulated magnetometer during flight. Note: these unrestricted attitude variations do not exceed the ± 30° envelope of the operational window (green), when the magnetometer is optimally oriented about the optimal 45° angle (yellow dot) prior to flight.

3.2.2 Payload Yaw Variations

The combined yaw and pitch attitude variations are depicted in Figure 9. The yaw axis data indicates that the magnetometer is freely rotating 360° around the vertical axis during flight. Given this unrestricted yaw attitude variation, the magnetometer will rotate outside of the ± 30° operational window during flight, as shown in Figure 10. An envelope (light blue rectangle) depicts the calculated two standard deviations of the data. The calculated mean (yellow data point) is centred about 189.81° yaw and 0.21° pitch.

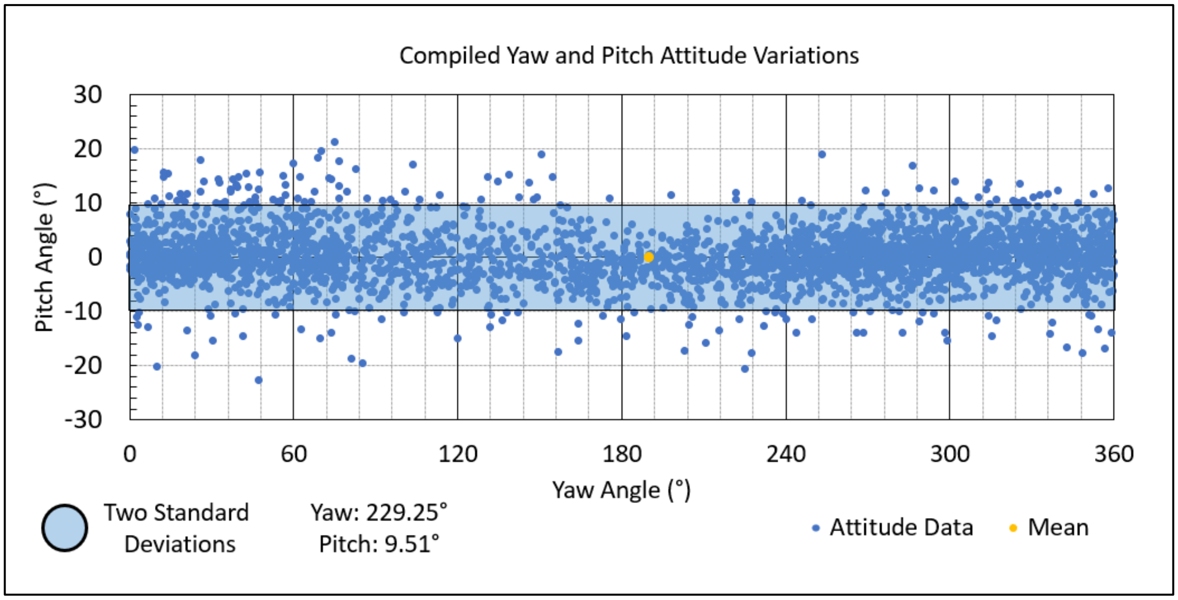

Figure 9 The compiled yaw and pitch axis data points (~3200 blue) from two days of surveying, representing an unrestricted rotation about the yaw axis of the simulated magnetometer

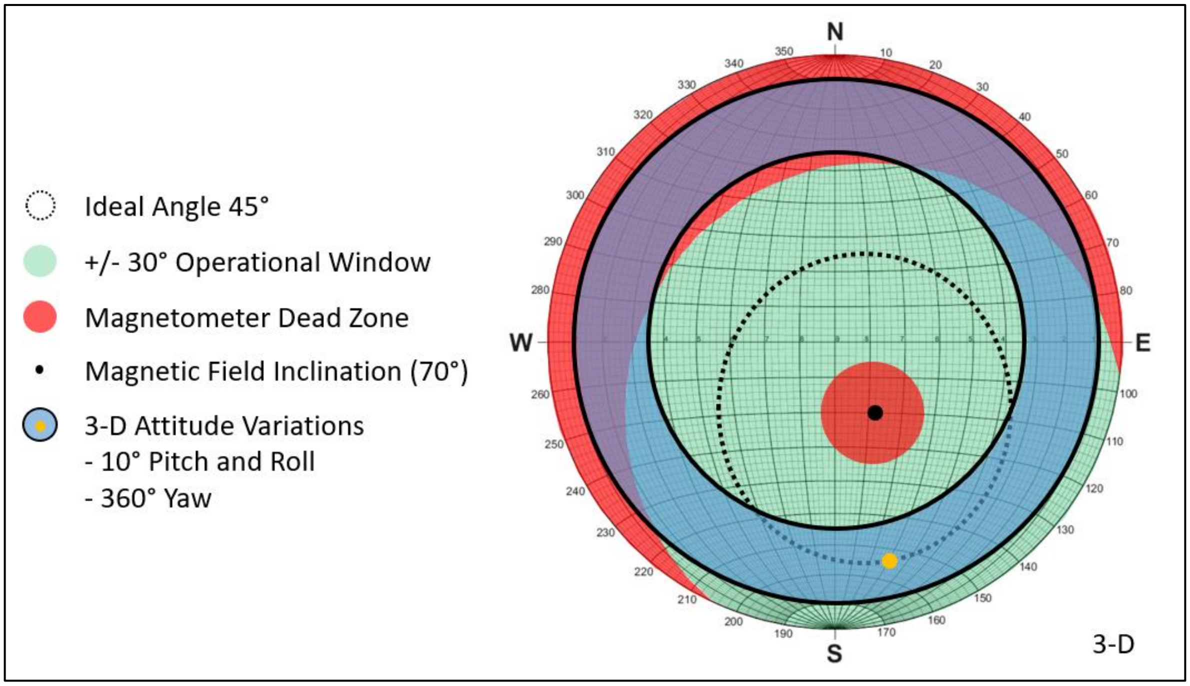

Figure 10 3-D diagram demonstrating the unrestricted variations in pitch, roll and yaw of the simulated magnetometer sensor axis during flight. Note: the 360° unrestricted attitude variations about the yaw axis results in orientations outside the ± 30° operational window (purple), even when the magnetometer is optimally oriented (yellow dot) prior to the survey.

3.2.3 UAV Yaw Variations

For UAV-borne aeromagnetic surveys conducted in Canada (Earth's magnetic field inclination of 70° or more) and other regions of high (>65° and <-65°) and low (between +25° and -25°) magnetic field inclinations, it is not desirable to have 360° of magnetometer yaw rotation throughout a UAV-borne magnetic survey. Consequently, this yaw rotation must be limited to remain within the ±30° operational window of the magnetometer in 3-D space. To stabilize the magnetometer in flight, the magnetometer yaw axis was fixed to the yaw axis of the UAV. This stabilization technique was developed by observing the relatively stable yaw axis of the UAV throughout flight when a constant heading command was applied to the platform. An aerodynamic approach to stabilizing the yaw axis of the magnetometer was not implemented due to the low flight speed of the DJI S900 multi-rotor UAV (~6 m/s), the additional payload weight, and the subsequent reduced flight times. Rigidly fixing the magnetometer and UAV yaw axes together, while applying a constant heading command to the multi-rotor UAV will result in the magnetometer pointing in one constant heading throughout the entire survey (with a slight ± yaw axis variation). However, if a constant heading command is not applied to the platform then there will be two dominant yaw headings 180° apart from each other, with the same small ± variation. As such, the ± variation of the OB-6 UAV yaw axis was recorded throughout flight and quantified.

The combined UAV yaw and payload pitch attitude variations from four flights on August 25th, 2016, totalling 1300 data points, are depicted in Figure 11a. The variations experienced in the UAV yaw axis show that two standard deviations (95% of the data) are equal to approximately ± 2.84° from the mean, when a constant heading command (307°) is applied. This is a significant reduction from the unrestricted yaw variations experienced by the freely suspended magnetometer (Figure 10).

The theoretically restricted magnetometer yaw attitude variations are plotted on the 3-D operational extent diagram in Figure 11b, with the previously established pitch and roll variations of ± 10° (light blue envelope). This demonstrates that attitude combinations about all three axes remain inside the operational window of a potassium vapour magnetometer (green envelope), provided that the magnetometer has been optimally oriented to the ideal 45° angle (dashed line/yellow dot) prior to the survey and that the magnetometer yaw axis has been rigidly fixed to the UAV. The UAV yaw attitude variations were observed to be more stable in flight than the yaw attitude variations of the freely suspended payload. Consequently, the payload yaw axis was rigidly coupled with the UAV airframe to limit the yaw attitude variations during flight. This aided in stabilizing the magnetometer payload and restricted all attitude variations to within the operational window of the magnetometer.

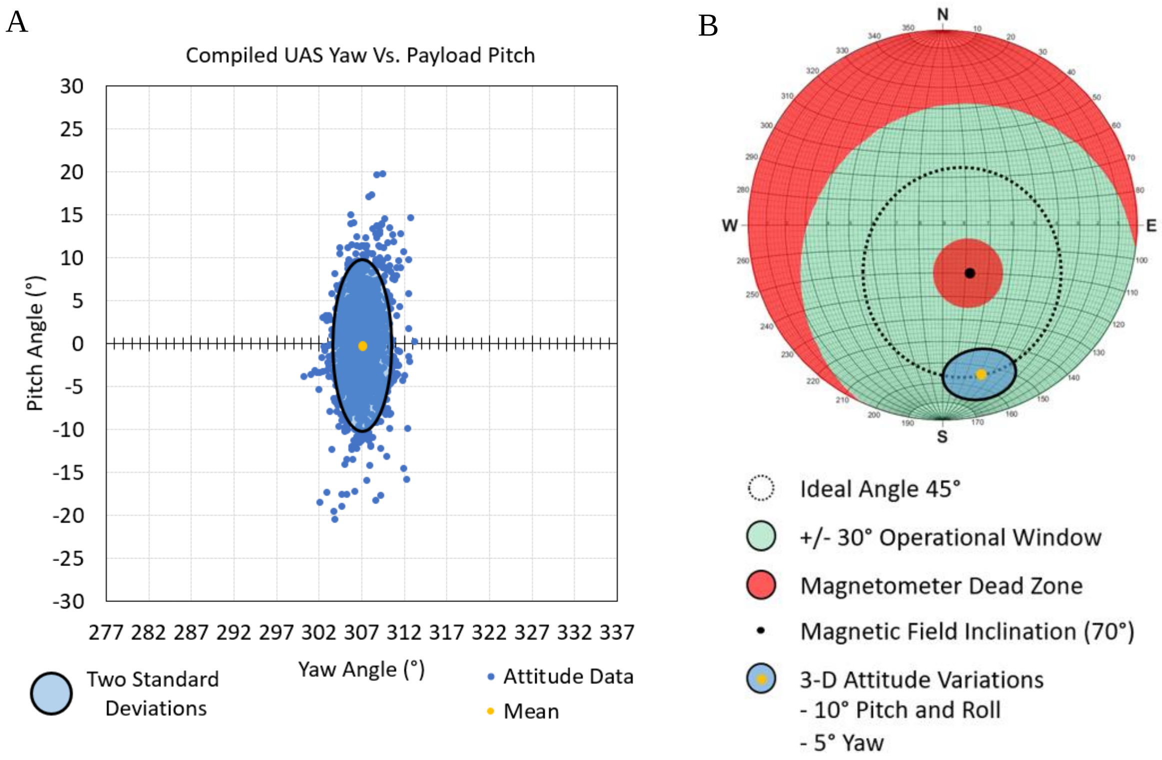

Figure 11 (a) Compiled data points (~1300 blue), representing the yaw axis rotation variations of the OB-6 UAV plotted against the pitch axis variations of the simulated magnetometer. The yaw scale has been adjusted to represent the ± 30° operational window. **(b)** 3-D diagram demonstrating the unrestricted variations in pitch and roll of the simulated magnetometer during flight, combined with restricted variations in the yaw rotation axis (if magnetometer yaw attitude variations are fixed to the UAV yaw). Note: these ± 10° (pitch and roll) and ± 5° (yaw) sensor axis variations do not exceed the ± 30° envelope of the operational window, if the magnetometer is optimally oriented about the mean prior to the survey (yellow dot).

3.3 UAV-borne magnetic survey

The magnetic data collection campaign was conducted on February 28th, 2017 Northeast of Kingston, Ontario, Canada. The test site is an isolated vegetation-covered lake within the Queen’s University Biological Station, underlain by marble of the Grenville Province. Conditions on February 28th, 2017 were sunny, cool and relatively calm, with low winds. According to historical weather data gathered at the Kingston/Norman Rogers Airport (Government of Canada 2017), 40 km away from the flying site, the wind speed averaged approximately 3 m/s from the Southeast and the temperature was on average 5°C.

Pre-programmed flights were conducted at a surveying speed of ~6 m/s along ~300m long lines. This was the fastest flight speed possible with the UAV’s A2 flight controller during autonomous flight, given the total payload weight of 2.2 kg (~75% maximum payload). The automated flight speed restriction occurs due to the relative workload of the electric motors and the pitch angle of the airframe needed to balance platform lift and forward motion. Eight traverse lines trending 025/205 were flown parallel to one another, separated by 10m. A flight elevation of approximately 10m above the ground/semi-frozen vegetated lake was used. This flight elevation was chosen to maximize the sensitivity of the magnetometer while also flying at a safe height above obstructions. Overall, an average flight lasted between 10-12 minutes using a 10000 mAh battery and ~15 minutes using a 16000 mAh battery.

Prior to each flight, the magnetometer payload was optimally oriented at a 45° angle with respect to the ambient magnetic field vector. A constant heading command applied to the UAV flight path, coupled with the semi-rigid magnetometer mount would have limited the yaw attitude of the magnetometer to one constant heading throughout the entire survey; the main advantage to using a multi-rotor UAV platform. However, the DJI Ground Station 4.1 software that is compatible with the A2 flight controller, does not accommodate such constant heading commands. Instead, at the end of each flight line the UAV conducted a 180° turn, subsequently resulting in an unavoidable 180° turn of the semi-rigidly mounted potassium vapour magnetometer. As such, to keep the magnetometer ideally aligned with the Earth’s magnetic field in both adjacent survey lines (a heading change of 180°), the magnetometer yaw was optimally oriented facing an approximate East-West direction.

At the Queen’s University Biological Station, the Earth’s magnetic field vector has an approximate inclination of 70° dipping towards the North and an approximate declination of 12° West (International Geomagnetic Reference Field 2017). The angle created between the sensor axis of the potassium vapour magnetometer and the Earth’s magnetic field is symmetrical about the axis of declination, resulting in the magnetometer sensor axis being oriented in an approximately East (78°) and West (258°) azimuth. Given the

Earth’s magnetic field inclination (~70°), declination (~12° W), and the approximate East and West azimuth of the magnetometer sensor axis, the ideal sensor inclination (pitch) angle was calculated to be ~ 49° from the horizontal plane. This relationship resulted in the optimal ‘q’ angle of 45° between the magnetometer sensor axis and the Earth’s magnetic field vector in 3-D space using Equation 1 (GEM Systems Inc. 2014a). In this equation, ‘a’ is the sensor azimuth (the angle in the horizontal plane between the magnetometer sensor axis and the direction of magnetic north), ‘b’ is the magnetometer sensor inclination (the angle in the vertical plane between the horizontal and the magnetometer sensor axis), and ‘g’ is the Earth’s magnetic field inclination.

$$q = \arccos\,(\cos a\ \times \cos b\ \times \cos g + \sin b\ \times \sin g) \qquad (1)$$

3.4 UAV-borne magnetic survey results

A UAV-borne magnetic survey carried out with a semi-rigid magnetometer mount resulted in the reliable collection of industry standard UAV-borne magnetic data. The semi-rigid mount was incorporated in the UAV-borne magnetic survey to reduce yaw attitude variations to approximately ± 5° (estimated to be twice the observed UAV yaw variation), subsequently keeping the magnetometer within the operational window down traverse lines. Stabilization is achieved by rigidly fixing the yaw axis of the magnetometer, to the yaw axis of the UAV via the semi-rigid mount. However, the pitch and roll axes remain unrestricted for two reasons: (1) based on the attitude survey, the pitch and roll attitude variations were not found to deviate outside the magnetometer operational window (i.e. the force of gravity was sufficient to stabilize the magnetometer in pitch and roll given these flight speeds), and (2) the UAV pitch and roll axes need to be unrestricted to allow the UAV to manoeuvre efficiently without reducing flight stability. Hence, this design is a semi-rigid mount, depicted in-flight in Figure 12, with one axis restricted (yaw) and two axes free (pitch and roll).

Figure 12 DJI S900 multi-rotor UAV platform carrying the data acquisition system and semi-rigidly mounted potassium vapour magnetometer during the February 28th, 2017 survey at the Queen's University Biological Station north of Kingston, Ontario, Canada.

There are some instances within the UAV-borne magnetic survey where the attitude of the magnetometer exceeded the ± 30° operational window. These instances resulted in the magnetometer losing lock, further causing the omission of magnetic data collection. The occurrences are depicted in Figure 13a and typically transpired as the UAV rounded the tight corners at the end of the traverse lines, causing the magnetometer to rotate 180° about the yaw axis and out of lock. However, once the UAV begins to travel down the next surveying line, the magnetometer attitude stabilizes and regains lock. Data points that are locked onto the magnetic field are plotted in green, while data points indicating the loss of magnetic lock are plotted in red. Further analysis found that over 99% of the 6552 locked magnetic data points fell within the industry standard for airborne magnetic measurements (a fourth difference of ± 0.05 nT) (Coyle et al. 2014). The fourth difference calculation dataset is depicted in Figure 13b, where 29 of the 6552 magnetic data points fall outside the industry standard envelope (shown in red). The regions where the magnetic data was not of industry standard quality dominantly occur when the UAV exited the corners at the end of traverse lines. Overall, the reliable collection of industry standard UAV-borne magnetic data was proven by employing a semi-rigid UAV magnetometer mount to limit magnetometer attitude variations throughout flight.

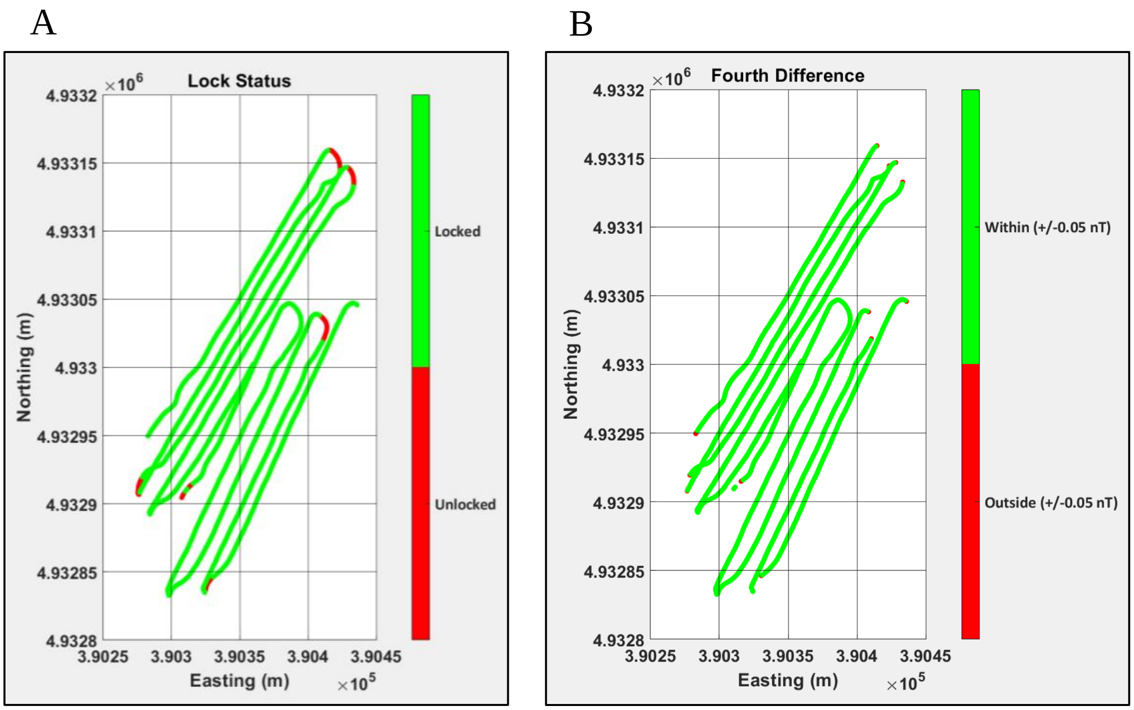

Figure 13 (a) Binary plot of the lock status of the magnetometer throughout flight (green = locked), (red = unlocked). **(b)** Binary plot of the fourth difference data depicting data within the industry standard threshold of ± 0.05 nT (Coyle et al. 2014) (green) and outside the industry standard threshold (red).

Overall, two flights were required to gather the nine survey lines (~300m in length) and one flight was required to collect the ten tie lines (~90m in length). Figure 14a shows the residual magnetic intensity of the locked magnetic data, demonstrating smooth variations and comparable measurements between adjacent survey lines and at cross-overs. Figure 14b shows the flight elevation of the UAV throughout the survey. Noticeably, the tie lines were flown at an elevation ranging between 3m -5m above the main survey lines, independently verified by both GPS elevation measurements and an on-board laser altimeter. In some cases, this is almost an additional 50% of the targeted flight elevation relative to the ground surface. The flight elevation varied between surveys and throughout the day due to a weather front moving through the region. This changed the relative barometric pressure which is what the UAV uses to determine its flight elevation. The gridded residual magnetic field data from the survey, including the tie lines are presented in Figure 15a, demonstrating undulations in the gridded surface due to the varying acquisition height of up to 5m between the tie lines and the main survey lines. In Figure 15b, where the tie lines have been removed and only the survey lines are considered, the gridded data is smooth, demonstrating the magnetic data quality potential of UAV-borne magnetic surveys.

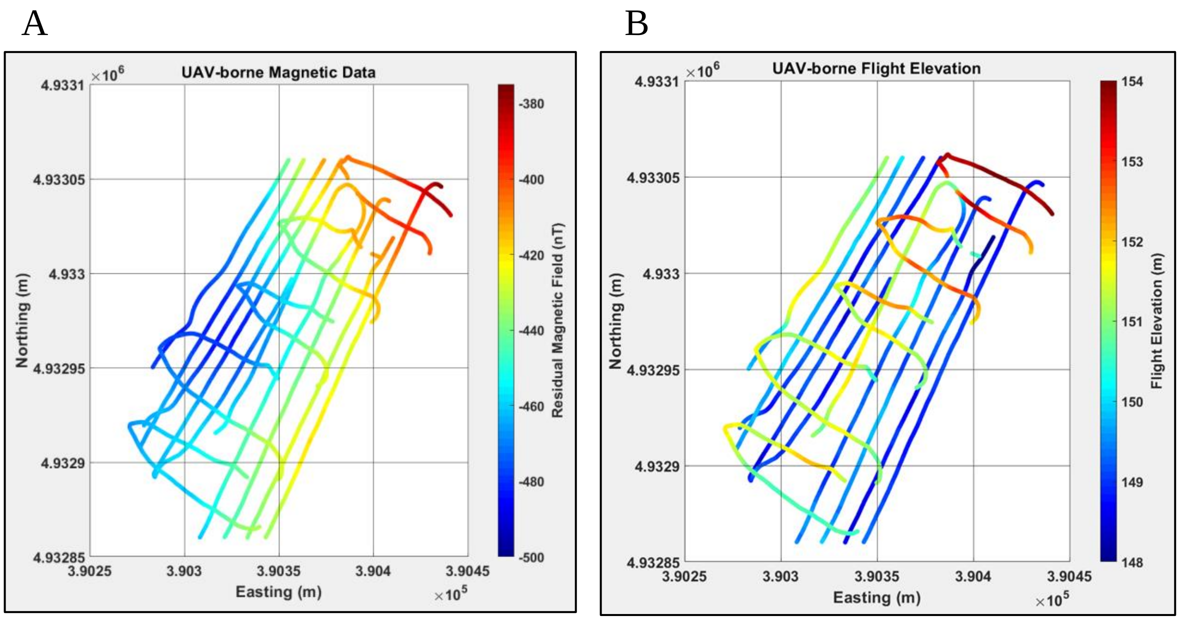

Figure 14 (a) A scattered plot of the residual magnetic field data gathered during flight, including tie lines. **(b)** A scattered plot of the UAV flight elevation throughout the subsequent surveys.

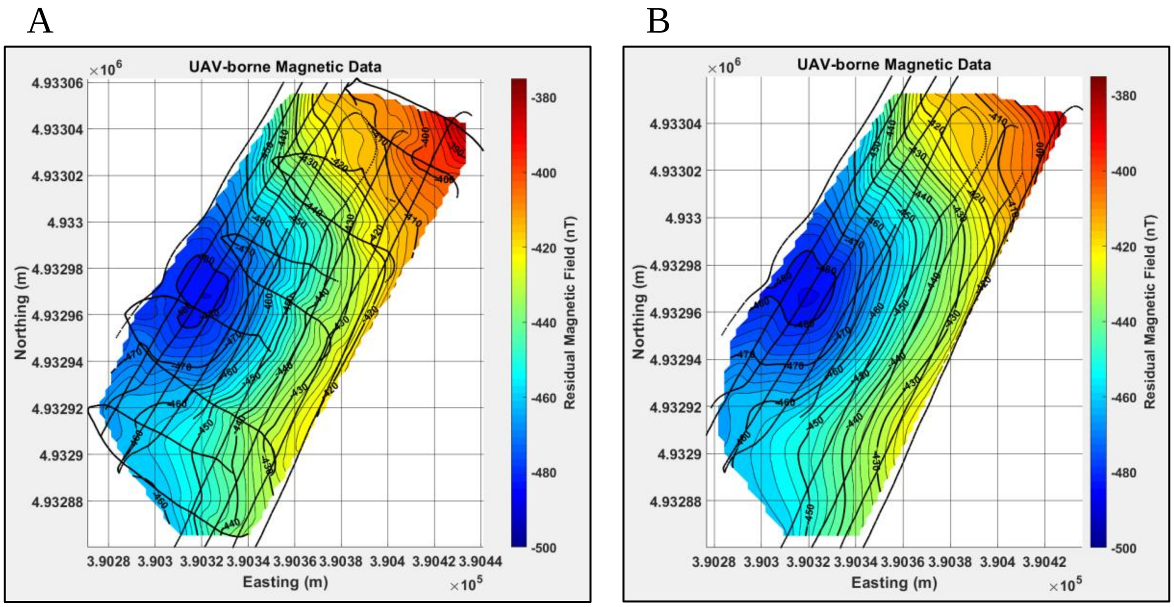

Figure 15 (a) The gridded residual magnetic field data including ~90m long tie lines flown at ~ 3-5m above the main surveying lines. **(b)** The gridded residual magnetic field data without tie lines all within an approximate 2m flight elevation.

4.0 DISCUSSION

The attitude surveys conducted between August 24th and 25th, 2016 indicate that the unrestricted magnetometer pitch and roll variations are within the theoretical ± 30° operational window of a potassium vapour magnetometer. For a flight speed of ~6 m/s, a wind speed not exceeding 5 m/s, and a suspended cable length of 3m, the majority (95%) of the pitch and roll attitude variations are within ± 10° from the mean (gravity vector). As such, the force of gravity was sufficient to stabilize the magnetometer in pitch and roll during flight and there was no justification to limit, restrict or further stabilize these two axes with aerodynamic means. In addition, multi-rotor UAV's navigate primarily by performing a combination of pitch and roll manoeuvres. Keeping these axes free and unrestricted relative to the UAV is vital so that UAV navigational performance and flight stability are not hindered. In converse, coupling these two axes could cause excessive torques on the UAV due to the swinging payload, subsequently decreasing stability, increasing power consumption, and potential for mission failure.

Analysis of the yaw attitude surveys shows that the magnetometer sensor axis variations, when unrestricted, fall outside the theoretical ± 30° operational window. The initial tests in August 2016 demonstrated that the magnetometer yaw variations spanned a full 360° and required restriction. As such, a semi-rigid magnetometer mount was designed to limit the yaw variations of the suspended magnetometer. This was achieved by coupling the magnetometer yaw axis directly to the UAV yaw axis. Thus, by fixing the magnetometer yaw to the UAV's, the stability in the UAV yaw axis is transferred into the magnetometer. Since the UAV stabilizes itself in-flight through manoeuvres in pitch and roll, a fixed yaw axis of the payload does not interfere with flight performance.

The total combined axis variations of the magnetometer from the attitude surveys were inferred to be within the theoretical operational envelope of the magnetometer through incorporating the semi-rigid UAV magnetometer mount. This was empirically proven in the subsequent UAV-borne magnetic survey where reliable industry standard airborne magnetic measurements were consistently achieved along traverse lines. More than 99% of the gathered magnetic data was acquired within the industry standard fourth difference calculation. As such, the reliable collection of magnetic data via a multi-rotor UAV platform and optically pumped vapour magnetometer was demonstrated herein.

To limit the need for real-time magnetic compensation of the gathered UAV-borne aeromagnetic data, the magnetometer was suspended below the UAV platform and outside the measurable influence of the platform's multiple electromagnetic motors. An offset distance of 3m below the DJI S900 multi-rotor UAV was found to be sufficient in attenuating the amplitude of the magnetic field produced by the UAV platform while carrying a 2.2 kg payload. As such, the magnetic field contributions emanating from the UAV platform were not observed in the gathered UAV-borne aeromagnetic data. Subsequently, compensation of the platforms magnetic field was not required. Independent investigations should be conducted to determine the correct offset distance required for other UAV platform and payload combinations using the suspended semi-rigid mounting technique. Furthermore, magnetic compensation should be applied to gathered UAV-borne aeromagnetic data in accordance to industry standards when the magnetometer is known to be within the influence of the magnetic field generated by the platform. The technique of real-time magnetic compensation is required in manned airborne surveys as it is impractical to suspend the magnetometer below the platform airframe resulting in the magnetometer remaining within the non-static magnetic field produced by the aircraft.

A traditional aerodynamic method (tow-bird) was not considered to stabilize the payload mainly due to the DJI S900's relatively low airspeed of ~6 m/s (~22 km/h). At this airspeed, the beneficial aerodynamic effects of a bird system are not sufficient to stabilize the payload in flight. Tow-bird systems employed on UAV's have been shown to be effective at a minimum airspeed of 10 m/s. The second issue when integrating a tow-bird system with a UAV platform is the additional weight added to the payload system (already 2.2 kg). A principle design challenge when working with multi-rotor UAV's is issues arising from increasing payload weight and subsequently reducing flight endurance. Realizing this, the incorporated design focused on the simplest, lightest, and most functional solution, which for this platform and payload setup was a semi-rigidly mounted payload. As larger, more powerful, and faster UAV platforms enter the market in future years, it is conceivable that tow-bird aerodynamic stabilization techniques, will be widely adopted; as is currently conducted with manned airborne surveys. Until this technological advancement takes place, the semi-rigid mount provides a viable stabilization technique for applications of UAV-borne magnetometry that require lightweight payloads and can only navigate at lower air speeds (< 10 m/s).

For regions that have magnetic inclinations between ~65° – 25° (Australia, USA, Central America, Asia) optically pumped vapour magnetometers can be effectively stabilized in flight by orienting the sensor axis vertically (parallel to the gravity vector). By doing this, variations in azimuth throughout flight are not transmitted into the sensor axis orientation of the magnetometer (the largest variation typically being the 180° turn at the end of every flight line). Therefore, if the sensor axis experiences pitch and roll variations less than +/- 30° throughout flight (assuming an external field inclination of 45°), the magnetometer will remain locked. However, for regions which have inclinations below ~25° (parts of South America, Africa, India, Indonesia) and above ~65° (Canada, Russia, United Kingdom, Scandinavia), a vertically oriented sensor stabilization technique cannot be used because the sensor axis will be near (less than 10° away from) the equatorial and polar dead zones, respectively. As such, small variations in pitch and roll (e.g. 10° as was observed in the attitude survey) can cause the sensor axis to point within the polar dead zone, causing a lapse in data quality and/or data collection.

To combat the polar dead zone issue in Canada (as the entire country is above 70° inclination) optically pumped magnetometers are set at an optimized angle to the vertical vector, which is dependent on the inclination and declination of the magnetic field at the surveying site, as well as the azimuth(s) of the magnetometer/surveying lines. Any changes in azimuth (180° rotation at the end of a flight line) throughout the survey will cause a precession of the magnetometer sensor axis around the vertical gravity vector (and potentially out of magnetic lock). To resolve this issue when flying down adjacent survey lines in opposite directions, the magnetometer is oriented in an East-West direction (assuming 0° declination at the surveying site), as the optimal angles created with the magnetic field vector in 3-D space are symmetrical around the axis of declination. By taking these precise steps in polar regions (different actions in equatorial regions) operators can reliably retain magnetic lock when using optically pumped vapour magnetometers.

An additional benefit to using a semi-rigid mount coupled with a multi-rotor UAV is that multi-rotor UAV's can fly an entire survey at one constant heading and transmit this yaw axis stability to the magnetometer; negating the 180° rotations of the magnetometer at the end of flight lines. This would not be the case when using single rotor UAVs, helicopters, or fixed wing aircraft, which are all required to make 180° turns to navigate adjacent surveying lines efficiently. As such, the interaction that the multi-rotor UAV and semi-rigid mount setup provides is essential in polar and equatorial regions but not as relevant for mid latitudes (close to 45° inclination), where yaw variations can also be mitigated through orienting the sensor vertically and a semi-rigid mount could potentially not be required to collect data.

5.0 CONCLUSIONS

In this study, the attitude variations (yaw, pitch and roll) of a simulated optically pumped vapour magnetometer freely suspended 3m underneath a multi-rotor UAV are quantified. The objective was to isolate excessive magnetometer attitude variations leading to the magnetometer losing lock. From the acquired data, it was concluded that the unrestricted attitude variations in pitch and roll are not a significant contributor to magnetic data loss if the magnetometer sensor axis has been optimally oriented with respect to the Earth’s magnetic field. However, given the same surveying conditions, the yaw axis variations, if unrestricted, contribute to magnetic data loss. The first attitude survey highlighted the yaw axis as the limiting factor in deploying a freely suspended, multi-rotor UAV-borne optically pumped vapour magnetometer.

A semi-rigid magnetometer mount was incorporated to fix the magnetometer yaw axis to the UAV yaw axis, while allowing the pitch and roll axes to remain free. The UAV yaw axis is known to be stable throughout flight especially when a constant heading command is applied by the flight controller. In the subsequent UAV-borne magnetic survey, this hypothesis was proven using a developed semi-rigid UAV magnetometer mount and a GSMP-35U potassium vapour magnetometer. Results demonstrated that more than 99% of the acquired magnetic data lies within the industry standard. The benefit of quantifying rotation axis variations of a payload suspended under a UAV is proven herein and has been applied to develop a reliable UAV-borne optically pumped magnetometer system. For any new UAV platform and magnetometry system, such as single-rotor and fixed wing systems, the methodology used herein should be applied to the magnetometer payload to assess attitude variations during flight. This two-step process includes setting the optimal orientation of the magnetometer prior to take-off and then quantifying the attitude variations during flight given expected flight speeds, wind speeds and the magnetometer suspension length. This process of investigation should be undertaken prior to blindly attempting data collection. Otherwise, poor data quality will likely result in wasted surveying time. A further investigation and case study could be conducted to determine the degree to which wind speed, wind direction, UAV airspeed and UAV heading affect attitude variations, magnetometer lock and data quality. The procedures used herein can be applied to other platform and sensor combinations that require stabilization to collect industry standard magnetic data in the observation gap between terrestrial and manned airborne systems.

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