Characterization and compensation of magnetic interference resulting from unmanned aircraft systems

by

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Abstract

Unmanned aircraft systems (UAS) are a viable platform for aeromagnetic surveys but the interference generated during flight can greatly impact data quality. In this thesis, the problem of interference reduction was approached from two directions: mapping to identify sources and manoeuvre compensation.

Problematic interference sources were identified using magnetic intensity mappings of the UAS. For these mappings to be accurate, the UAS must have: (1) the motors engaged, (2) the flight surface servos powered and in a steady-state position, and (3) the electrical systems drawing a constant current. The strongest sources were the servos and the motor system with the largest field attributed to the direct current battery cables between the motor batteries and the electronic speed controller. Reduction methods recommended included the twisting of direct current cables, demagnetisation of steel components, and increasing the distance between the servos and the intended magnetometer installation point.

To improve mapping quality, a magnetic scanner was designed and built to compare the magnetic intensity mappings and profiles of four different types of electric-powered UAS; a single-motor fixed-wing, a single-rotor helicopter, a quad-rotor helicopter and a hexa-rotor helicopter UAS. These UAS were found to have: (1) similar interference signatures under rotation, (2) interference levels dependent on the electrical current drawn by the motor(s), (3) a mixture of interference types composed of both material magnetisation and electrical current.

The removal of interference produced by a 35 kg gasoline-powered UAS was demonstrated using a real-time compensator. The UAS was prepared with interference reduction techniques that reduced the heading error and 4th difference to acceptable levels. Two novel low-altitude calibration methods, named a “stationary” and “box” calibration, were tested in three geographic locations with different magnetic gradients. The best calibration using each method yielded an improvement ratio of 8.595 and 3.989, respectively and a standard deviation of the compensated total magnetic intensity of 0.075 and 0.083 nT, respectively. A best estimated Figure-of-Merit of 3.8 nT was calculated; the lowest value reported for a rotary-wing UAS to date. The stationary calibration was robust and compensated non-native flight data with a cross-correlation index of 1.073.

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Preface

This document is an integrated thesis consisting of three articles published or submitted to peer-reviewed scientific journals on the topic of locating and reducing magnetic interference:

1. Tuck, L., Samson, C., Laliberté, J., Wells, M., and Bélanger, F., 2018, Magnetic interference testing method for an electric fixed-wing unmanned aircraft system (UAS): *Journal of Unmanned Vehicle Systems*, **6(3)**, 177-194 (doi: 10.1139/juvs-2018-0002).

Published [Chapter 3]

2. Tuck, L., Samson, C., Laliberté, J., and Cunningham M., 2019, Magnetic interference mapping of unmanned aircraft systems used for geomagnetic surveying: submitted to *Pure and Applied Geophysics*. Submitted [Chapter 4]

3. Tuck, L., Samson, C., Polowick, C., and Laliberté, J., 2019, Real-time compensation of magnetic data acquired by a single-rotor unmanned aircraft system: submitted to *Geophysical Prospecting*. In press [Chapter 5]

Table and figure numbers have been standardized and updated to be consistent within the thesis, and a list of references has been compiled at the end.

For article 1, L. Tuck planned, collected, processed and analyzed the experimental data and wrote the manuscript. C. Samson assisted in establishing the research objectives and provided extensive comments on the technical results and the manuscript. J. Laliberté assisted in establishing the research objectives and provided valuable comments on the

manuscript. M. Wells, and F. Bélanger provided project support, including the loan of some experimental equipment, and provided valuable comments on the manuscript.

For article 2, L. Tuck planned, collected, processed and analyzed the experimental data and wrote the manuscript. C. Samson assisted in establishing the research objectives and provided extensive comments on the technical results and the manuscript. J. Laliberté assisted in establishing the research objectives and provided valuable comments on the manuscript. M. Cunningham assisted with the design and construction of the scanner as part of a graduate study project, assisted with the diagram of the scanner (Figure 4-2) and provided valuable comments on the manuscript.

For article 3, L. Tuck planned, evaluated the magnetic signature and prepared the UAS for magnetic calibration as well as collected, processed and analyzed the experimental data and wrote the manuscript. C. Samson assisted in establishing the research objectives and provided extensive comments on the technical results and the manuscript. C. Polowick of RME Geomatics provided, piloted and maintained the rented single-rotor UAS, oversaw UAS operations, technical support for the UAS and the review of test plans. J. Laliberté provided valuable comments on the manuscript.

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List of Symbols

Symbol	Description	Units
ΔB_{G_max}	Maximum variation of the ambient magnetic intensity to which the UAS is subject to during the calibration	Tesla (T)
$\Delta B_{x-y\ Hz}$	Frequency band between limits x and y	Hz
$\lambda_{Nyquist}$	Nyquist wavelength	m
μ_0	Magnetic permeability in a vacuum	$N \cdot A^{-2}$
σ_c	Standard deviation of the compensated total magnetic intensity	T
σ_u	Standard deviation of the uncompensated total magnetic intensity	T
Δs	Displacement	m
∇	Gradient	m^{-1}
a_{ij}	Constants in the induced compensation terms	-
B	Magnetic field	T
B_d	Magnetic field of a dipole	T
B_{ed}	Magnetic field resulting from eddy currents	T
B_G	Geomagnetic field	T
B_i	Magnetic field resulting from induced magnetisation	T
b_{ij}	Constants in the eddy current compensation terms	-
B_m	Magnetic field measurement made by the magnetometer	T
B_n	Magnetic noise	T
B_p	Magnetic field resulting from permanent magnetisation	T
cc	Cubic centimeter	cm^3
CE_{line}	The line closure error	T
CE_{map}	The map closure error	T
Dec	Declination	$^\circ$
f_{G_max}	Highest geologically-related signal frequency in the calibration flight that the compensator can successfully remove	Hz
H	External magnetising field	$A \cdot m^{-1}$
I	Current	A
Inc	Inclination	$^\circ$
l	Length	m
M	Magnetisation	$A \cdot m^{-1}$
m	Magnetic moment	$A \cdot m^2$
M_i	Induced magnetisation	$A \cdot m^{-1}$
M_p	Permanent magnetisation	$A \cdot m^{-1}$
M_{px}, M_{py}, M_{pz}	The x,y and z directional components of the permanent magnetisation	$A \cdot m^{-1}$
p_1, p_2, p_3	Permanent magnetisation components in the T, L, and V directions	T
r	Source-measurement distance	m
R	Electrical resistance	Ω
R^2	Coefficient of determination	-
S	Magnetic flux surface	m^2
t	Time	s
T_x	Discrete magnetic measurement of indices x	T
u_1, u_2, u_3	Directional cosines in the between the T, L, and V directions and the direction of B_G	-

u_1', u_2', u_3'	The time derivative of the directional cosines in the between the T, L, and V directions and the direction of B_G	-
v	speed	m/s
w_i	The weight assigned to a certain variable in a weighted index overlay	-
$x_{1/2}$	full width at half maximum measured on the TMI profile	m
Z	An index value of a pixel in a weighted index overlay	-
z_p	The limiting depth of a geological source	m
ΔTMI	Maximum change in total magnetic intensity	T
L	Line spacing	m
$\nabla \times$	The curl operator	-
μ	Magnetic permeability	$N \cdot A^{-2}$
χ	Magnetic susceptibility	-

List of Acronyms

Acronym	Description
AC	Alternating current
AGL	Above ground level
AVG	Average
CB	Carp box calibration
CCI	Cross-correlation index
CS	Carp stationary calibration
DC	Direct current
DRH	Dual-rotor helicopter
ES	Embrun stationary calibration
ESC	Electronic speed controller
FOM	Figure-of-Merit
FOM*	Estimated Figure-of-Merit
FW	Fixed-wing UAS
GNSS	Global navigation satellite system
GPS	Global positioning system
HRH	Hexa-rotor helicopter UAS
IGRF	International geomagnetic reference field
IR	Improvement ratio
L	Longitudinal axis of an aircraft
LiDAR	Light detection and ranging
LiPo	Lithium polymer
NSERC	Natural sciences and engineering research council of Canada
ON	Ontario
ORH	Octo-rotor helicopter
PB	Plevna box calibration
PS	Plevna stationary calibration
PVC	Polyvinyl chloride
QRH	Quad-rotor helicopter UAS
RMI	Residual magnetic intensity
RMS	Root mean square
RMSD	Root-mean-square deviation
RPM	Revolutions per minute
RTK	Real-time kinematic
SRH	Single-rotor helicopter UAS
STD	Standard deviation
T	Transverse axis of an aircraft
TF	Total-field
TMI	Total magnetic intensity
UAS	Unmanned aircraft system
V	Vertical axis of an aircraft
VMI	Vector magnetic intensity

1. Introduction

1.1. UAS magnetic surveying

The work undertaken in this thesis is to address one of the main issues that arises from combining the emerging field of unmanned aircraft systems (UAS) (Gupta *et al.* 2013) with the established field of aeromagnetic surveying (Reford and Sumner 1964; Nabighian *et al.* 2005; Hood 2007); the magnetic interference that arises from the UAS. UAS are expected to provide higher resolution survey data through lower altitude flight (Anderson and Pita 2005), operate at lower costs compared to traditional airborne and ground systems (Kroll 2013), and ultimately be a safer method for collecting magnetic data (Versteeg *et al.* 2007). Yet the issue of interference has slowed UAS acceptance as an alternative method for surveying by the exploration industry. UAS interference is an issue frequently cited in literature (Funaki and Hirasawa 2008; Kaneko *et al.* 2011; Koyama *et al.* 2013; Forrester *et al.* 2014; Funaki *et al.* 2014; Sterligov and Cherkasov 2016; Parvar *et al.* 2018). These levels typically exceed the aeromagnetic specifications of noise generated by manned aircraft (Table 1-1) (Teskey 1991; Coyle *et al.* 2014) and limits the sensitivity of the surveys.

As the number of new discoveries containing economically viable mineral deposits decreases (Whiting and Schodde 2006), exploration activities are increasingly focused on finding small and/or subtle targets that were missed in previously explored regions. For these types of surveys, minimal noise levels are critical (Hood *et al.* 1979). Among recent

peer-reviewed publications that mention UAS aeromagnetic surveys (Table 1-2), few UAS meet the minimum performance specifications and, in many cases, noise measures such as the heading error, noise envelope, and Figure-of-Merit (FOM) are in part or fully ignored (Table 1-1). As beyond visual line of sight (BVLOS) operations are being introduced in Canada for UAS (Fang *et al.* 2018), the prospect of these systems competing with manned aeromagnetic systems for large-scale survey contracts becomes more probable. For UAS to become a feasible alternative for these missions the issue of interference must be overcome.

Table 1-1: The performance specifications of aeromagnetic surveys that are minimally acceptable (Teskey 1991; Coyle *et al.* 2014).

Specification	Values
Sensitivity	0.01 nT
Absolute accuracy	±10 nT
Ambient range	20,000 to 100,000 nT
Sampling interval	0.1 s
Heading error	< 2.0 nT
Figure-of-Merit (FOM) – fixed wing/helicopter	1.5/2.0 nT
Noise envelope	0.10 nT
4 th difference	±0.05 nT

Even though most UAS do not currently comply to aeromagnetic survey standards, UAS are being hailed as a potential replacement for traditional ground survey (Parshin *et al.* 2018). Their ability to fly along straight and tightly-spaced lines at low-altitudes over complex landscapes is said to provide comparable sensitivity to an otherwise difficult and expensive ground survey. Since the magnetic field of a target falls off as the inverse cube of the distance, the stronger signal recorded at lower-altitude does not require the low levels of noise for targets to be detected. Currently, UAS are being used to perform

targeted aeromagnetic surveys on the scale of $<1 \text{ km}^2$ (Versteeg *et al.* 2010; Eck and Imbach 2012; Macharet *et al.* 2016; Parshin *et al.* 2018; Parvar *et al.* 2018), $<10 \text{ km}^2$ (Kaneko *et al.* 2011; Koyama *et al.* 2013; Wood *et al.* 2016; Malehmir *et al.* 2017), and larger (Anderson and Pita 2005; Funaki *et al.* 2014; Wenjie 2014; Pei *et al.* 2017; Cherkasov and Kapshtan 2018).

Table 1-2: Recent peer-reviewed publications on UAS aeromagnetic surveying. AGL: above ground level; FW: fixed-wing; SRH: single-rotor helicopter; DRH: dual-rotor helicopter; QRH: quad-rotor helicopter; HRH: hexa-rotor helicopter; ORH: octo-rotor helicopter.

Peer-reviewed Publication	UAS			Magnetometer		Survey Parameters					Performance specifications		
Authors	Type	Weight (kg)	Power	Type	Installation	Altitude (m AGL)	Speed (km/h)	Line spacing (m)	Flown distance (km)	Area (km ²)	FOM	4 th difference	Other reports of noise
(Anderson and Pita 2005)	FW (pusher)	19	Fuel	Alkali-vapour	Nose	100	70	200 x 1000	620	100	1.7	0.05	
(Partner 2006)	FW (pusher)	19	Fuel	Alkali-vapour	Nose	100	70	300 x 1000	13000	>100	1.32	0.08	
(Funaki and Hirasawa 2008)	FW (pusher)	15	Fuel	Magneto-resistant	Front – Boom	200-500			500	2			
(Kaneko <i>et al.</i> 2011)	SRH	84	Fuel	Alkali-vapour	Towed – 3m	25-50	18	25	139.7	135			<10 nT @3m
(Hashimoto <i>et al.</i> 2014)	SRH	84	Fuel	Alkali-vapour	Nose	100-300	18						
(Eck and Imbach 2012)	SRH	30	Fuel	Fluxgate	Front – Boom	1-2	7.2	1-2	3000	0.2			
(Koyama <i>et al.</i> 2013)	SRH	84	Fuel	Alkali-vapour	Towed – 4.5m	100	36		85	6			
(Funaki <i>et al.</i> 2014)	FW (pusher)	28	Fuel	Fluxgate	Front – Boom	500/780	118	1000	302	162			63 nT increase for 17s?
(Funaki <i>et al.</i> 2014)	FW (puller)	9	Fuel	Fluxgate	wingtip	363	118		105.4				
(Wenjie 2014)	FW (pusher)	640	Fuel	Alkali-vapour	Wingtip boom	120	180	500	3000	140	1.65	0.065	
(Gavazzi <i>et al.</i> 2016)	DRH (single coaxial)			Fluxgate		5		10					
(Macharet <i>et al.</i> 2016)	ORH (4 coaxial)		Electric	Fluxgate	Front – Boom	3-20		2	0.181	0.381			
(Wood <i>et al.</i> 2016)	FW (puller)	55	Fuel	Alkali-vapour	wingtip	150	90	120	13	9		0.05	

(Malehmir <i>et al.</i> 2017)	ORH	10	Electric	Overhauser	Towed – 3m	30	28.8	100	20	2			
(Pei <i>et al.</i> 2017)	SRH	545	Fuel	Alkali-vapour	Side – boom	300-400	90	600 x 3000	511	260			0.625 nT line intersection difference
(Cherkasov and Kapshtan 2018)	QRH	10	Electric	Alkali-vapour	Towed – 20m	30-150	60	30-100		0.8-42			0.35 nT line intersection
(Cunningham <i>et al.</i> 2018)	ORH (4 coaxial)	20	Electric	Alkali-vapour	Boom	80	32			0		0.04	
(Parshin <i>et al.</i> 2018)	HRH	15	Electric	Overhauser	Towed ~ 3m	5	25-36	50-100	20	1			
(Parvar <i>et al.</i> 2018)	HRH (3 coaxial)	8	Electric	Alkali-vapour	Towed – 3m	20/60		30	12	0.36		0.005-0.011	
(Walter <i>et al.</i> 2018)	HRH	15	Electric	Alkali-vapour	Towed – 3m	10	21.6		2.7	0.03		0.05	

1.2. Types of magnetic interference

Before the types of magnetic interference may be discussed, it is important to distinguish them from the noise specifications defined in Table 1-1. Noise can be anything that obscures the recording of the geomagnetic field by the aeromagnetic system. Attempts are made to quantify the noise using measures such as the noise envelope and FOM, for example. In its simplest form, a magnetic field measurement made by a magnetometer ($\vec{B}_m$) is the sum of the geomagnetic field ($\vec{B}_G$) with the noise ($\vec{B}_n$):

$$\vec{B}_m = \vec{B}_G + \vec{B}_n \quad (1.1)$$

Interference is a type of noise that is specifically produced by the UAS platform. For example, the variation in measurement caused by a propeller is interference and contributes to the overall noise of the system whereas the variation that is produced by the swing of a suspended magnetometer is noise, but not interference.

The magnetic interference that is produced by a UAS can be a complex combination of multiple time-varying and interdependent sources. In order to guide the analysis of the interference of the UAS as a whole, the interference generated by individual sources should be understood. The analysis of each component can be guided using magnetic theory and measurement. This section provides a brief explanation of the theory of material magnetisation, magnetostatics, and electrodynamics as it applies to the analysis of magnetic interference produced by a UAS.

The magnetisation ($\vec{M}$) of a material is a collective sum of its domains, each with a magnetic moment ($\vec{m}$). $\vec{M}$ can be divided into two types: permanent ($\vec{M}_p$) and induced ($\vec{M}_i$):

$$\vec{M} = \vec{M}_p + \vec{M}_i \quad (1.2)$$

$\vec{M}_p$ occurs as an ingrained preferential alignment within a material that resists aligning with an external magnetising field ($\vec{H}$). It is therefore regarded as “permanent” and the field it produces can be considered in most situations as static. Alternatively, $\vec{M}_i$ is the result where the domains align with $\vec{H}$:

$$\vec{M}_i = \chi \vec{H} \quad (1.3)$$

where χ is the magnetic susceptibility; a dimensionless measure of how much a material will become magnetised in $\vec{H}$. The magnetic susceptibility is closely related to the magnetic permeability of a material (μ); a measure of the ability of a material to support a magnetic field.

$$\chi = \frac{\mu}{\mu_0} - 1 \quad (1.4)$$

where μ_0 is the magnetic permeability of free space, defined as $4\pi \times 10^{-7} \text{ N}\cdot\text{A}^{-2}$. μ is the proportionality factor between the sum of $\vec{M}$ and $\vec{H}$ and the magnetic field ($\vec{B}$).

$$\vec{B} = \mu(\vec{H} + \vec{M}) \quad (1.5)$$

The magnetic field produced from permanent and induced magnetisation of components, the current in electronic systems, and eddy-currents in conductive materials are defined in magnetostatic and electrodynamic theory. In its most basic form, the magnetic field of a magnetised material can be modelled as a positive and negative magnetic pole; a dipole. The magnetic field of a dipole ($\vec{B}_d$) at a source-measurement distance ($\vec{r}$) is given by (Wiegert and Purpura 2004):

$$\vec{B}_d(\vec{r}) = \frac{\mu_0}{4\pi} \frac{3\hat{r}(\hat{r} \cdot \vec{m}) - \vec{m}}{|\vec{r}|^3} \quad (1.6)$$

For example, a UAS control surface servo has been previously modelled as a dipole (Wells 2008; Forrester *et al.* 2014; Huq *et al.* 2015; Sterligov and Cherkasov 2016).

A magnetic field produced from electronic current can be described by the Biot-Savart law (Griffiths 1999):

$$\vec{B}_{el}(\vec{r}) = \frac{\mu_0}{4\pi} \int_C \frac{Id\vec{l} \times \hat{r}}{|\vec{r}|^2} \quad (1.7)$$

where $d\vec{l}$ is a vector along the path C whose magnitude is the length of the differential element of the wire in the direction of the current (I). An example of this is the direct current (DC) drawn through cables of an electric motor system which will produce interference (Tuck *et al.* 2018).

Eddy currents on the surface of conductive materials will also produce interference (Leliak 1961, Fitzgerald and Perrin 2015). The induction of an eddy current ($\vec{I}_{ed}$) is described by Lenz's Law (Griffiths 1999) and is produced from a time-varying $\vec{H}$.

$$\vec{I}_{ed} = -\frac{\mu}{R} \frac{d}{dt} \int_S \vec{H} dS \quad (1.8)$$

where R is the electrical resistance of the material and S is the magnetic flux surface. This current will then produce a magnetic field (equation 1.7). As an example, this interference is produced from currents induced in the conductive skin of an aircraft during flight (Fitzgerald and Perrin 2015).

The equations 1.6, 1.7, and 1.8 can be used to guide the analysis of the interference of individual components and, in turn, the UAS as a whole. To assist with this analysis, some assumptions can be made:

1. The law of superposition can be applied and sources can be analyzed individually. This implies that the interplay between sources is insignificant and can be ignored.
2. The far-field approximation can be used to model a magnetised source as a dipole. A simple and accurate method used to characterize a single point dipole source was outlined by Zaffanella *et al.* (1997). The far-field approximation holds for distances greater than three times the source's largest dimension (Olsen and Lyon 1996; Wiegert and Purpura 2004).

3. The permanent magnetisation of a material does not change over time. A number of processes can change the permanent magnetisation of a material. This topic is beyond the scope of the thesis, and the reader is referred to Telford *et al.* (1990).

1.3. Previous types of UAS interference testing

Instead of dividing interference based on their types of sources, Teskey (1991) divided the interference into two types based on their wavelength in the data; naming them “static” and “dynamic”. Static interference is a non-oscillatory field that results from permanent and induced magnetisation of ferrous components, eddy-currents, and DC loops in the electrical system. Alternatively, dynamic interference is produced by oscillatory field variations which result from aircraft manoeuvres and alternating electrical interference. Teskey (1991) further divided these two types as continuous and discontinuous interference and expanded on how these interferences are tested for and their relation to the noise specifications (Table 1-1). These specifications include the heading error, used as a measure of static interference and the noise envelope, used as a measure of the high-frequency interference. The FOM specification is calculated from a calibration test and is a measure of interference at frequencies both lower than and including that measured by the noise envelope. Under normal turbulence conditions there is a direct empirical relationship between the noise envelope and FOM (Hood 1986):

$$Noise\ envelope = \frac{FOM}{15} \quad (1.9)$$

Several investigations involving UAS magnetic interference have been published (Versteeg *et al.* 2007, 2010; Forrester 2011; Kaneko *et al.* 2011; Sterligov and Cherkasov 2016; Cherkasov and Kapshtan 2018; Parvar *et al.* 2018) but only a few provide in-depth analysis and fewer address reduction methods based on their analysis.

Versteeg *et al.* (2007) were the first to report on interference testing of a UAS, specifically a 25 kg gas-powered single-rotor helicopter (SRH). They found that mounting an alkali-vapour magnetometer directly underneath the airframe resulted in a quadrupole-like effect with 800 nT peak-to-peak variation over a 360° rotation. They then repeated the experiment with a 0.5 m and 1.2 m long boom mounted in front of the helicopter which resulted in 80 and 40 nT variations, respectively. Their second test was to slowly pull the helicopter with the motor running at 1500 revolutions per minute (RPM) over a magnetometer 0.77 m below the airframe and measured a peak variation of 38 nT. Lastly, they measured a 15 nT variation associated with the motor running mounted directly beneath the airframe and 4 nT with the magnetometer 0.8 m in front of the helicopter.

Versteeg *et al.* (2010) followed up their original study with a second that used a revised testing method to evaluate the interference. They approached the UAS with a magnetometer in the four cardinal directions and repeated the approach path without the UAS present. This test was performed on two SRH; a 25 kg and a 250 kg UAS. In both cases, the permanent magnetisation was more prevalent than induced magnetisation.

Forrester (2011) investigated a 95 kg gas-powered fixed-wing (FW) UAS using a hand-held uniaxial fluxgate magnetometer and identified three major interference sources

in order of severity: the servo(s) (50-100 nT at 0.55 m), the engine and engine assembly (60 nT at 0.55 m), and the avionics package (30 nT at 0.38 m). He then proceeded to investigate each source individually and produced a method for reducing the magnetic signature of servos by pairing them. Parts of his work were later published in Forrester *et al.* (2014) and Huq *et al.* (2015).

Kaneko *et al.* (2011) magnetically mapped a 50 kg gas-powered SRH. The magnetic signature of this UAS presented as a quadrupole similar to that reported for the gas-powered helicopter studied by Versteeg *et al.* (2007). Kaneko *et al.* (2011) found that the magnetometer needed to be installed more than 3 m away to maintain a noise level less than 10 nT. This finding guided Kaneko *et al.* (2011) to tow the magnetometer at a distance from the UAS rather than installing it on a boom.

Sterligov and Cherkasov (2016) mapped a 10 kg electric-powered flying-wing UAS by placing it under a planar surface as a measurement guide and identified the major sources of magnetic noise as the electric motor (<800 nT), servos (<600 nT), and ferromagnetic elements (<300 nT). They noted that the best option for the magnetometer placement was the wingtips, where interference varied the least between -4 to +4 nT but also discovered that the motor “can provide magnetic noise with amplitudes more than 10 nT” measured at the wingtips. They concluded, however, that with the wingtip installation of the magnetometer, the UAS would be too unstable to fly.

Parvar (2016) used a surface to map multiple planes beneath a 3 kg quad-rotor helicopter (QRH) and a 10 kg hexa-rotor helicopter (HRH) UAS and produced three-dimensional interference maps of that space. By subtracting the maps with the motor on

and off he was able to isolate effects from the motor and reported interference as high as 350 nT at 0.4 m and a 4th difference of 0.21-0.27 nT. This experiment was repeated by Parvar et al. (2018) on a QRH with a similar result of 350 nT at 0.4 m below but an improved 4th difference between 0.005-0.011 nT.

Most recently, Cherkasov *et al.* (2018) has discussed the “magnetic noise” of their quadrotor UAS. They report the noise as 5, 1, and 0.1 nT at 1, 2, and 3 m, respectively, below the UAS but provide little additional information on how, and under what conditions, these measurements were attained.

Although there are several studies on magnetic interference testing, they vary with respect to the methods used for measuring and quantifying the interference, and, in some cases, do not properly constrain the dynamic elements on the UAS for accurate testing. In some cases, the interference is measured at certain frequencies, but ignores others. For example, the noise generated from the pendulum swing of towed magnetometers may not be identified by high-frequency measures like the 4th difference. Instead, noise may exist at lower frequencies undetected by this measure. In some cases, studies provide insufficient information to decipher how the interference was calculated and leave the reader without a method to follow for comparison or reproducing results.

1.4. Previous UAS compensation studies

There are fewer studies on the magnetic compensation of UAS than on magnetic interference. A compensation is the removal of types of continuous interference. Traditionally, this refers to the removal of variations in the magnetic field that arise from

pitch, roll, and yaw manoeuvres of the aircraft (Leliak 1961) but can also include other types of interference such as fields that arise from varying electrical current (Noriega and Marszalkowski 2017). For the interference to be compensated, it requires a “calibration” test to tune the compensation algorithm. The compensation method is further described in Section 2.3.2.

Some of the first published works about UAS aeromagnetic survey (Anderson and Pita 2005; Partner 2006) included a noise measure calculated from a calibration test, the FOM. The military-grade FW UAS used in both studies achieved FOMs of 1.7 nT and 1.3 nT, respectively, where the latter FOM was below the aeromagnetic specification for FW aircraft (Table 1-1). No published study has reported an FOM that has satisfied this specification since. Unfortunately, no further information on the calibration or the conditions of how it was performed was provided.

A UAS calibration was flown by Versteeg *et al.* (2010) by executing a “cloverleaf” around a test field with a 250 kg SRH UAS. The study did not include a calculated FOM or other quality metrics but used the calibration terms to compare the contributions of different types of interference. They found that the largest amount of interference came from permanent magnetisation of the UAS (10-15 nT), then induced magnetisation (5-7 nT), and finally eddy currents (1-2 nT).

Zhang *et al.* (2011) simulated the compensation of a large FW UAS. Using two opposite flown lines, they asserted that the eddy-current effects in the compensation algorithm could be neglected in cases where the UAS is manufactured with insulative synthetic materials.

Naprstek and Lee (2017) have mentioned ongoing research on compensation of interference from both manoeuvres and electrical current in both FW and rotary-wing UAS. As well, private companies such as GEM Systems (2019) advertise compensated FW UAS systems with improvement ratios between 10-20. The consensus is that UAS compensation is achievable and a worthwhile practice.

1.5. Statement of the problem

As discussed in Section 1.1, recent UAS studies have mostly focused on semi-quantitative-demonstrations and case histories featuring targeted small-scale aeromagnetic surveys. Studies that attempt to address the quality of UAS data are rare and, in most cases, incomplete. Those few studies that investigate the interference of the UAS reported difficulty attaining acceptable limits and many operators reverted to towing the magnetometer (Kaneko *et al.* 2011; Cherkasov and Kapshtan 2018; Parshin *et al.* 2018; Parvar *et al.* 2018) or choosing a new UAS of different design (Sterligov and Cherkasov 2016). This suggests that the problem of interference is still a largely unresolved problem. As UAS technology will develop further, attention will focus on quality improvement. In turn, as a primary constituent of survey noise that directly affects the quality, interference is therefore a problem that must be addressed.

Section 1.3 describes a handful of studies that approach this problem by either identifying problematic components or assessing the interference of the UAS as a whole. The first approach risks oversimplification and can neglect the effect that each component has on others. The second approach does not identify sources for which

interference reduction practices can be used. In both cases, the UAS must be properly constrained to identify static and dynamic effects. Each study provided valuable insights into the interference of a specific UAS under certain conditions, but critical questions remain, and, in some cases, important factors were overlooked or ignored.

The problem of UAS compensation, as described in section 1.4, has been avoided in literature since the first publications over a decade ago (Anderson and Pita 2005; Partner 2006). Details regarding how compensation was achieved were not included and the calibration altitude may have been much higher than achievable today due to regulation. Regardless, the method for calibration of UAS at low-altitudes have not been published to date and remain a problem to be addressed.

In summary, the overarching problem of interference generated by a UAS can be broken down as three specific research questions:

1. What method should be used for identifying and characterizing the interference generated by the UAS as a whole and by discrete sources onboard?
2. Can common sources of interference be identified among a number of different UAS and, based solely on the criterion of minimizing magnetic interference, which type is best suited for magnetic surveying?
3. Can the interference produced by UAS manoeuvres be compensated?

1.6. Research objectives

The research presented in this integrated thesis is organized into three studies (corresponding to Chapters 3, 4, and 5), with each marking a contribution to the objective of characterizing and compensating the magnetic interference produced by a UAS. The objectives of each study are outlined here:

- 1. To define a method to measure the interference of a UAS:** The first study in this thesis aims to address problem (1) above by mapping the interference of a 21 kg electric-powered FW UAS that was designed and built for magnetic surveying. It defines a method for mapping the UAS on the ground with the motor turned on. The mapping is used to inform installation locations for magnetometer(s) on the UAS and suggests methods for interference reduction and modification.
- 2. To compare the interference generated by different types of electric UAS capable of flying high-resolution magnetic surveys:** The second study in this thesis aims to further address problem (1) by improving the mapping method. At the same time, it addresses problem (2) by measuring changes in magnetic intensity due to both spatial variations and motor current draw for four different types of electric-powered UAS. Both maps and profiles are used to identify and compare the sources of interference, and to discuss possible paths for reduction. As well, the type of UAS with the lowest level of interference is to be identified.
- 3. To develop a method for UAS calibration at low-altitude:** The third study in this thesis addresses problem (3) while integrating elements from the first two studies in order to prepare a gas-powered SRH UAS for calibration testing. The UAS is then used to develop new calibration methods that can be performed by a UAS at low-

altitudes. These methods are tested in three environments with different magnetic gradients; each representative of a different type of geology. The results are used to propose a general method for UAS calibration so that recorded data can be compensated for interference that arises from manoeuvres.

1.7. Originality of research

As discussed in Section 1.3, studies involving UAS interference testing represents a small body of knowledge; interference mapping represents an even smaller body, with published studies by Kaneko *et al.* (2011), Parvar (2016), and Sterligov and Cherkasov (2016). The first two studies of this thesis (Chapter 3 and 4) expand on this small body of work by adding two novel approaches for mapping the magnetic interference of a UAS. To date, both mapping methods provide the most detailed information on the interference generated by a UAS capable of carrying a survey-grade magnetometer in close-to-flight conditions (with the motors engaged and all electrical systems powered). The two mapping methods integrate different positioning technologies, neither have been used before for this type of study: real-time kinematic (RTK) satellite positioning and high-accuracy stepper motors. In the latter case, the stepper motors were used as part of a new concept for interference mapping, using a magnetic scanner built for this purpose. The scanner was used to compare the magnetic interference of four different types of UAS. The method was also extended to investigate an aspect ignored in previous investigations: the impact of varying motor current draw on the magnetic signature.

Studies on the magnetic compensation of UAS are even more rare than interference testing and there is no peer-reviewed published work detailing low-altitude calibration procedures specifically for UAS. The third study in this thesis proposes two solutions that can be reproduced for future academic research or industry efforts.

2. Methodology

2.1. Overview

The three body chapters, Chapters 3, 4, and 5, in this thesis each represent a standalone manuscript that are either submitted to a peer-reviewed journal or published (see Preface). As such, they are written to fully describe the methodological approach used in each case. Chapter 3 describes the methodology for measuring the magnetic interference produced by a UAS on the ground. A test stand was mobilized in a grid like pattern around the UAS with the onboard systems engaged. The magnetic measurements were made around the UAS using a survey-grade magnetometer and a RTK global navigation satellite system (GNSS) for high-accuracy positioning. The collection scheme described in Section 3.4 incorporates aspects of traditional aeromagnetic survey design (Reid 1980) but added many novel elements to accommodate the ground based approach, the smaller survey area, the dynamic sources on board the UAS and safety for both the operator and equipment. Some traditional aeromagnetic processing techniques (Luyendyk 1997), such as the temporal field correction, were used on the data to assist in isolating the anomalous field of the UAS. Quality checks that reference the aeromagnetic standards (Teskey 1991; Coyle *et al.* 2014) are used in the processing for reference and, in some cases, to add validity to the method used. The method described in Chapter 4 improves upon the methodology presented in Chapter 3 by measuring the interference produced by a UAS using a computer-controlled stepper motor to improve the spatial accuracy and uniformity of sample spacing. This method increased the safety for both the

operator and equipment while improving the measurement repeatability. The mappings were performed over top of, instead of next to, the UAS allowing for improved identification of artifacts within the UAS body. The method also added orthogonal mappings to aid in distinguishing different types of sources. Chapter 5 describes the measurement of both low- and high-frequency interference generated by the UAS on the ground and in the air. The low-frequency interference was assessed in Section 5.5.1 using a method that was based on the magnetometer absolute reference test (Coyle *et al.* 2014; Ontario Geological Survey 2015) whereas the high-frequency interference was assessed by calculating the 4th difference. This chapter also demonstrates the removal of interference using a real-time compensator. This proprietary technology uses an established methodology for calibrating the compensation algorithm (Leliak 1961). Some parameters and elements of the traditional methods were used to propose two novel methods for UAS calibration at low-altitudes.

As each manuscript uses elements of one or more aeromagnetic methodologies, a concise summary of related topics of survey design, testing and processing techniques are discussed.

2.2. Aeromagnetic survey design

In its simplest form, an aeromagnetic survey is flown in a grid-like pattern composed of a series of parallel traverse lines and perpendicular control lines that tie the traverse lines together (Figure 2-1).

Figure 2-1: An example of an aeromagnetic survey flight lines; north-south direction traverse lines (purple) and east-west direction control lines (blue).

The traverse line spacing and altitude each depend on multiple factors and are selected with the end purpose of resolving a target source. The traverse line spacing is chosen as a trade-off between survey efficiency and resolution. Greater traverse line spacing reduces the distance to be flown, which will reduce cost but will introduce greater aliasing to the gridded data. Aliasing of data occurs when wavelengths less than

twice the line spacing (L) are present. The limiting case is called the Nyquist wavelength ($\lambda_{Nyquist}$).

$$\lambda_{Nyquist} = 2L \quad (2.1)$$

Any anomaly with a wavelength less than $\lambda_{Nyquist}$ will not be identified and will distort the sampling of wavelengths greater than $\lambda_{Nyquist}$.

The flight altitude of a survey is chosen as a trade-off between the sensitivity of a survey and safety. Low-altitude flights are beneficial since the signal strength of a magnetic body attenuates at a rate of a cube of the distance (equation 1.6). Conversely, low-altitude flights can increase the risk of terrain impact. In most cases, a smoothened terrain with added clearance named a “draped surface”, is used as a compromise.

2.3. Aeromagnetic testing

Generally, four tests are performed before a survey to reduce noise and improve repeatability of aeromagnetic data: (1) magnetometer absolute reference test; (2) compensation test; (3) lag (parallax) test; and (4) radar altimeter calibration (Coyle *et al.* 2014). Only the methodology for the first two are relevant to this thesis.

2.3.1. Magnetometer absolute reference test

This test is used to measure static noise and correct measurements to their true geomagnetic values. This allows measurements to be consistent for a multi-aircraft

survey and enables synthesis of multiple surveys. The test is performed in a calibration range at the start and end of a survey. Test ranges in Canada are located at Bourget, Ontario, Meanook, Alberta, and Baker Lake, Nunavut (Coyle *et al.* 2014). The test is performed by flying through a reference position at an altitude of 152 or 304 m (500 or 1000 ft) in the same direction as the traverse and control lines, creating a “cloverleaf” pattern. After diurnal corrections are applied, the predetermined difference between the reference position and the local observatory can be applied to correct a measurement to the true geomagnetic value. Any difference between a measurement at the reference position and the true geomagnetic value is the sum of the absolute reference error and the heading error. The absolute reference error, which results from the permanent interference (B_p), would appear as an offset from the true geomagnetic value regardless of the direction flown by the aircraft. Whereas the heading error, which results from the induced interference (B_i), is dependent on the direction flown. For example, the magnetic measurement obtained over a reference position would be corrected as:

$$B_G = B_m - B_p - B_i \cdot \hat{w} \quad (2.2)$$

where $\hat{w}$ is a unit vector of ± 1 depending on direction flown. Acceptable heading error limits are included in Table 1-1.

2.3.2. *Manoeuvre compensation test*

This test is used to measure a type of dynamic noise associated with the manoeuvres of the aircraft. Tolles and Lawson (1950) were the first to propose a 16-coefficient equation for modelling the magnetic interference associated with the change in attitude of

an aircraft. A solution to the aircraft interference model was later attempted using sinusoidal manoeuvres by Leliak (1961). The model assumes that the total interference of an aircraft is composed of three components: permanent magnetization ($\vec{B}_p$), induced magnetization ($\vec{B}_i$), and eddy-currents ($\vec{B}_{ed}$). These variables are added to the geomagnetic field ($\vec{B}_G$) to yield the field measured by the sensor ($\vec{B}_m$):

$$\vec{B}_m = \vec{B}_G + \vec{B}_p + \vec{B}_i + \vec{B}_{ed} \quad (2.3)$$

The model requires the projection of each type of interference along the transverse, longitudinal and vertical axes of the aircraft (T, L, and V, respectively) onto the direction of $\vec{B}_G$ (Figure 2-2). X, Y, and Z are the respective angles between T, L, and V and $\vec{B}_G$; traditionally calculated from the measurements made by a 3-axis fluxgate magnetometer onboard the aircraft.

The sources of permanent magnetisation are attached to the aircraft and do not vary with manoeuvres. Therefore the projection of the three permanent magnetisation components in the T, L, and V directions (p_1 , p_2 , and p_3) can be written as (Bickel 1979):

$$\vec{B}_p = \sum_{i=1}^3 p_i u_i \quad (2.4)$$

where u_1 , u_2 and u_3 are the directional cosines defined as $u_1 = \cos X$, $u_2 = \cos Y$, $u_3 = \cos Z$.

The magnetisation of induced sources will produce a field that is proportional to $\vec{B}_G u_1$, $\vec{B}_G u_2$, and $\vec{B}_G u_3$. Since the direction of the induced field is not fixed to the aircraft, this type of interference can be written as a double sum:

$$\vec{B}_i = \sum_{i=1}^3 \sum_{j=1}^3 a_{ij} u_i u_j \quad (2.5)$$

where a_{ij} are constants. Due to symmetry of the coefficients and the removal of constant coefficients by using a high-pass filtering operation, the nine coefficients are reduced to five.

Eddy currents will produce a field that is proportional to the time derivative of $\vec{B}_G u_1$, $\vec{B}_G u_2$, and $\vec{B}_G u_3$. Since the direction of the eddy current field is not fixed to the aircraft, this type of interference is written as a double sum:

$$\vec{B}_{ed} = \sum_{i=1}^3 \sum_{j=1}^3 b_{ij} u_i u'_j \quad (2.6)$$

where b_{ij} are constants and u'_j is the derivative of u_j with respect to time. Using a mathematical equality, one term can be eliminated and the nine coefficients can be reduced to eight.

These coefficients are calculated using a calibration test discussed in depth in Chapter 5. The test is carried out in a low gradient area, typically at altitudes approximately 3000 m where 3 pitch ($\pm 5^\circ$), 3 roll ($\pm 10^\circ$), and 3 yaw ($\pm 5^\circ$) manoeuvres are executed along the 4 survey line directions. A compensation FOM for the aircraft is calculated from a sum of the peak-to-peak amplitudes that result from each manoeuvre. Acceptable FOM limits are included in Table 1-1.

Figure 2-2: The magnetic interference model of an aircraft. The types of magnetic interference of the UAS (B_p , B_i , and B_{ed}) summed with the geomagnetic field (B_G) to make the measured magnetic field (B_m) illustrated with respect to the traverse (T), longitudinal (L), and vertical (V) coordinate system of the aircraft.

2.4. Aeromagnetic data processing techniques

In regard to aeromagnetic surveying, the processing of survey data involves the removal of effects that are not due to the distribution of magnetic minerals in the subsurface, so that the resulting data can be interpreted in terms of geology. Processing methods are described in detail by Luyendyk (1997). The standard procedure for processing aeromagnetic data comprises of the following steps summarized in Table 2-1. Pertinent processing steps to this thesis are discussed in more detail below.

Table 2-1: Processing steps, in order.

#	Processing step
1	Data extraction
2	Manoeuvre compensation
3	Manual editing
4	4 th difference
5	Split into survey lines with XY locations
6	Temporal field correction
7	Geomagnetic reference field removal
8	Levelling
9	Micro-levelling
10	Gridding and contouring

2.4.1. 4th difference

The 4th difference is a high-pass filter that is used as a standard quality assurance measure to detect high-frequency interference and is defined as:

$$4^{th} \text{ difference} = - \frac{(T_{-2} - 4T_{-1} + 6T_0 - 4T_{+1} + T_{+2})}{16} \quad (2.7)$$

At a sample rate of 10 Hz, the 4th difference is to be less than 0.05 nT (Table 1-1).

2.4.2. Temporal field correction

This is a correction for the variation of the geomagnetic field in time. Typical variations of the geomagnetic field over the period of a day is on the order of tens of nT and are normally strongest in the auroral zone (55°N-70°N), and weakest in the equatorial zone (10°S-10°N). This is a result of a combination of effects resulting from short-period changes such as micro-pulsations to multi-year field variations from secular migrations. The temporal field correction of magnetic data is performed by direct subtraction of base station magnetometer readings from the UAS magnetometer readings on a reading-by-reading basis.

3. Magnetic interference testing method for an electric fixed-wing unmanned aircraft system (UAS)

3.1. Abstract

One of the barriers preventing unmanned aircraft systems (UAS) from having a larger presence in the geophysical magnetic surveying industry is the magnetic interference generated by the UAS and its impact on the quality of the recorded data. Detailed characterization of interference effects is therefore needed before remedial solutions can be proposed. A method for characterizing magnetic interference is demonstrated for a 21 kg, 3.7 m wingspan, 6 kW electric fixed-wing UAS purposely built for magnetic surveying. It involves mapping the spatial variations of the total magnetic intensity resulting from the interference sources on the UAS. Dynamic tests showed that the motor should be engaged and the aircraft control surfaces levelled prior to mapping. Experimental results reveal that the two strongest sources of magnetic interference are the cables connecting the motor to the batteries, and the servos. Combining three factors to assess the level of magnetic interference – the total magnetic intensity, 4th difference, and vertical magnetic gradient – an index overlay shows that the magnetic sensor(s) should be located at least 50 cm away from the wingtips or tail to ensure an interference level of <2 nT, a 4th difference of <0.05 nT, and a gradient of <10 nT/m.

3.2. Introduction

Aeromagnetic surveying is among many of the industries that can benefit from UAS technologies (Kroll 2013). Currently, most aeromagnetic surveys are flown using manned aircraft at low-altitude (~150 m) for mapping both natural (e.g. Jelinek 1981) and man-made (e.g. Nelson and McDonald 2006) magnetisable bodies with contrasting susceptibilities with their host environment. Potential benefits of unmanned aircraft systems (UAS) over conventional platforms include higher spatial resolution, lower operational costs, a smaller environmental footprint, and less human risk.

Aeromagnetic surveys using UAS are increasingly used to identify various rock types and structures in the subsurface to vector towards ore deposits (Cunningham 2016; Malehmir *et al.* 2017; Parvar *et al.* 2018) or locate ferrous objects such as unexploded ordnance (Perry *et al.* 2002; Trammell III *et al.* 2005). Several studies discuss the feasibility of using either fixed-wing (Funaki and Hirasawa 2008; Wells 2008; Cunningham 2016; Wood *et al.* 2016) or rotary-wing (Perry *et al.* 2002; Trammell III *et al.* 2005; Versteeg *et al.* 2010; Koyama *et al.* 2013; Hashimoto *et al.* 2014; Cunningham 2016; Parvar 2016; Malehmir *et al.* 2017) UAS for aeromagnetic surveys. In general, fixed-wing UAS have better aerodynamic properties and therefore longer survey times and cover greater distances per flight. Rotary UAS have the advantage of not requiring a runway and can fly closer to the ground and more slowly. Several of these studies cite magnetic interference as a problematic issue and suggest that a better understanding of the interference between the UAS platform and the magnetic sensor it carries is needed for the aeromagnetic UAS industry to continue to progress (Sterligov and Cherkasov 2016).

Traditionally, two methods are used to reduce the level of noise affecting magnetic data acquired using manned aircraft: (1) to locate the magnetic sensor away from aircraft components that generate interference fields; and (2) to apply a magnetic compensation in real-time or in post-processing (Coyle *et al.* 2014; Fitzgerald and Perrin 2015; Dou *et al.* 2016a,b). In practice, the transfer of these methods to an UAS is problematic.

Mounting the magnetometer on a boom as an extension of the airframe structure (Eck and Imbach 2012; Funaki *et al.* 2014; Cunningham 2016) often results in a compromise between UAS interference and boom length; where a longer boom reduces interference but increases flight instability and vibration-induced noise. For example, Kaneko *et al.* 2011 found that the magnetometer needed to be placed more than 3 m away from the body of their SRH UAS to meet a noise level requirement of <10 nT when the engine was turned off. For rotary-wing UAS, other groups (Kaneko *et al.* 2011; Koyama *et al.* 2013; Malehmir *et al.* 2017; Parvar *et al.* 2018) have elected to suspend the magnetometer on a cable below the main airframe to ensure that the magnetometer is kept away from the rotors. This design, however, introduces other issues such as directional and positional error of the magnetometer (Coyle *et al.* 2014; Walter *et al.* 2016) and potential damage from impact to the magnetometer (Kaneko *et al.* 2011).

Aircraft compensation is a technique that relates attitude to the permanent and induced magnetisation of the aircraft, and to eddy-currents generated by varying magnetic fields. It relies on flight maneuvers executed by the aircraft at high altitude over an area with a minimally varying magnetic field (Leach 1979). For many UAS, this is not an option because they cannot fly at the required high altitude due to both regulatory restrictions and design limitations. Finally, magnetic interference is a more complex problem for

UAS than for manned aircraft. Due to the smaller size of UAS, the magnetic sensors are in closer proximity to multiple sources of interference such as motors, electric-powered devices, and conductive materials. New methods are therefore required to identify sources of interference and assess their level of severity to inform UAS design and post-processing compensation strategies. It is of additional benefit that these methods be as simple as possible so they can be employed when building or acquiring a commercial off-the-shelf UAS.

Two methods of magnetic mapping have previously been proposed for fixed-wing UAS. In the earliest study, Forrester (2011) investigated a large 95 kg gas-powered fixed-wing UAS. A hand-held uniaxial fluxgate magnetometer was used to identify interference sources in the vicinity of the unpowered UAS. Sources were then isolated and subjected to various individual tests to characterize their magnetic signature. More recently, Sterligov and Cherkasov (2016) mapped a 10 kg electric-powered flying-wing UAS by collecting measurements in a 10 cm grid using a smooth non-magnetic surface. From these results, a magnetometer location was chosen for further “dynamic experiments” where the interference from the powering and actuation of the motor and servos were studied. The studies of Forrester (2011) and Sterligov and Cherkasov (2016) successfully located sources of interference but neglected to address the complex interplay between active and passive components. Additionally, the approach of Forrester (2011) may prove too time consuming in practice, while the approach of Sterligov and Cherkasov (2016) may be difficult to implement for larger and non-planar UAS. Interestingly, in both cases, the UAS investigated were deemed unacceptable in their current state for magnetic

surveying based on the intensity or gradient of the magnetic interference measured at the proposed sensor location.

This paper proposes a new method for mapping magnetic interference from a fixed-wing UAS to identify problematic sources of noise and inform magnetometer location. The method uses the magnetometer system intended for surveying operations and does not require any additional equipment beyond a tripod.

3.3. Fixed-wing UAS

The proposed method is employed to characterize “Corvus”, a 21 kg electric-powered fixed-wing UAS built specifically for magnetic surveying (Table 3-1; Figure 3-1). The UAS is a modular high-wing monoplane with a pusher propeller and a boom mounted high T-tail constructed using prefabricated composite panels, off-the-shelf filament wound composite tubes, and custom-manufactured wings and tail surfaces. Although careful steps were taken to design the UAS with low-susceptible components, steel was occasionally used, for example the wheel axles and tail fastening fixtures. The UAS is fully electric, powered by a 6 kW brushless motor (Turnigy C80-85-170) and a 45 cm diameter 2-bladed plastic propeller that is mounted on the rear panel of the fuselage in a “pusher” configuration. The brushless motor contains 14 permanent magnets that rotate around 12 wire wound cores. The motor is powered by 3-phase, variable frequency alternating current provided by a Castle Creations Phoenix Edge electronic speed controller (ESC) designed for a maximum of 160 A. Four 6S (22.2 V @ 10 Ah) lithium polymer (LiPo) batteries, located in the nose of the UAS, are used to power the motor.

Five Hitec HSR-5990TG high-torque titanium gear servos are installed on the UAS; one for each aileron, for the rudder, for the elevator, and in the nose as part of the independent flight termination system. A Pixhawk autopilot, Spectrum receiver and a pair of 4S (14.8 V @ 2 Ah) LiPo batteries are mounted in the centre of the fuselage compartment.

Table 3-1: Specifications of the UAS.

Type of UAS	Fixed-wing UAS
Propulsion System	Turnigy C80-85-170, 6 kW brushless DC motor (12 poles)
PayLoad	5 kg
Cruise Speed	100 km/h
Weight	21 kg
Dimensions	3.66 m wingspan/2.76 m length
Servos	5 Hitec HSR-5990TG high-torque titanium gear
Batteries	4 6S LiPo, (2 in series) in parallel configuration
Electronic Speed Controller	Castle Creations Phoenix Edge HV 160 A

Figure 3-1: Component layout of the UAS. Servos are not drawn to scale.

3.4. Outline of proposed method

The proposed testing method is for mapping the magnetic interference from a fixed-wing UAS to identify problematic sources of noise and inform magnetometer location. This method rests on two assumptions. The first assumption is that the interference will reach acceptable levels away from the UAS given enough distance from the magnetic sources. Acceptable inference levels are defined by three metrics: pre-compensation total magnetic intensity (TMI), the 4th difference of the TMI, and the vertical magnetic gradient. Teskey (1991) and Coyle et al. (2014) suggest a maximum noise envelope of 0.1 nT after compensation for commercial aeromagnetic surveys. Since compensation on manned aircraft can provide an improvement ratio of 20 or more (Goldak and Heath 2002; Noriega 2015), a pre-compensation TMI threshold of 2 nT is chosen. The 4th difference is an airborne magnetic survey quality metric calculated as:

$$4^{th} \text{ difference} = - \frac{(T_{-2} - 4T_{-1} + 6T_0 - 4T_{+1} + T_{+2})}{16} \quad (3.1)$$

where T_x is the x^{th} TMI measurement in time centered around the value T_0 . Teskey (1991) and Coyle et al. (2014) suggest an acceptable 4th difference limit of ± 0.05 nT. The vertical magnetic gradient is also of importance as magnetometer movement relative to the sources of interference might occur due to vibrations and flexing of the wings in this direction. The vertical gradient limit can be expressed as the maximum noise envelope threshold divided by the largest expected displacement relative to the magnetic source. For the UAS investigated, a wingtip vertical displacement of 12 cm has been observed relative to the fuselage during flight. Using this value as the largest possible

displacement relative to a magnetic source, a vertical gradient limit of 1 nT/m is suggested.

The second assumption is that, for survey operations, the magnetometer will ultimately be mounted on a boom attached to the UAS with consideration to minimize aerodynamic drag and boom length. To best satisfy these considerations, the area of interest is then restricted to a thin three-dimensional space oriented along the wing-level of the UAS that can be investigated as a two-dimensional horizontal plane. Should a different plane be of interest, such as the interference in the plane under the wing, the plane of interest could be adjusted accordingly by reducing the height where measurements are made.

Based on the assumptions above, the proposed method employs the following procedure for measuring magnetic interference:

1. The survey should be conducted in a magnetically quiet area where cultural interference is less than 0.1 nT and the ambient vertical magnetic gradient is less than 1 nT/m.
2. Diurnal variations are recorded using a magnetometer deployed on a base station near the survey area. Diurnal variations should not exceed more than a 3.0 nT (peak-to-peak) deviation from a long chord equivalent to a period of 1 min and should be subject to the same cultural interference and vertical gradient conditions as in step 1.
3. A background survey measures the TMI without the UAS present, where the magnetometer is at the same height that will be used when the UAS is present in step 4 and in the same horizontal plane as the wings. A station spacing of 0.5-1.0 m is

- sufficient where the magnetometer is held stationary and level while recording a minimum of 10 samples (e.g. the recording time is 1 s at a sampling frequency of 10 Hz).
4. The UAS survey strategy is similar to step 3, with the UAS positioned on a non-magnetic stand in the centre of the survey area to distance it from the ground. A 0.5 m station spacing is used around the perimeter of the survey area and is reduced closer to the UAS to capture smaller spatial variations.
 5. The TMI data is post-processed to produce magnetic maps and a weighted index overlay.
 - 5.1. The TMI background (step 3) and UAS data (step 4) are corrected for diurnal (step 2) variations;
 - 5.2. Outliers are rejected based on magnetometer movement and attitude. The 4th difference is calculated;
 - 5.3. The remaining data is gridded using a minimum curvature algorithm and the TMI background is removed from the TMI with the UAS present;
 - 5.4. A vertical gradient map is calculated;
 - 5.5. A weighted index overlay is generated using the TMI, 4th difference and vertical gradient.

3.5. Magnetic mapping of the UAS

3.5.1. *Experimental set-up and background survey*

The survey was performed outdoors, on the magnetically quiet grounds of the Ottawa Geomagnetic Observatory (45.403° N, 284.448° E). In the survey area, the local geomagnetic field had an intensity of $54,418 \pm 9$ nT, a declination of -13° , and an inclination of 70° . The diurnal-corrected background TMI of the survey area is shown in Figure 3-2 (right).

Measurements were made using the geophysical instruments intended for the UAS during survey operations (magnetic sensor, autopilot, real-time kinematic (RTK) GPS mounted on an aluminum test stand (Figure 3-2, left). The test stand height was adjusted so that the magnetic sensor was 120 cm above ground, where the wings of the UAS would be. Negligible interference was observed by powering test stand instruments on and off, and when the test stand was placed in close proximity to the base station. A maximum change in total magnetic intensity (Δ TMI) of 0.8 nT was observed when the attitude of the test stand changed by $\pm 10^\circ$.

TMI measurements were collected using a battery powered GEM Systems potassium-vapour magnetometer sampling at 10 Hz. A Pixhawk autopilot system sampling at 5 Hz recorded attitude information used to reject misaligned or unlevel measurements. An Emlid Reach RTK GPS was installed on the test stand for horizontal positioning at a precision of ± 2 cm at 10 Hz. The GPS reference station was located near the magnetic base station, 10 m east of the survey area. The reference station position was computed

using NRC1 CACS-GSD GPS station number 943020. An Overhauser magnetometer sampling at 0.25 Hz was deployed as the magnetic base station to record the data needed for the diurnal corrections. All the data presented in this paper will have been diurnally-corrected.

Figure 3-2: (Left) The test stand used for mapping mounted with a) RTK GPS, b) potassium total-field magnetometer, and c) autopilot. (Right) Map of the diurnally-corrected background TMI. Crosses indicate the path of the test stand around the UAS during magnetic mapping with the motor engaged at 50% throttle (Figure 3-10). Magnetometer measurements could not be made close to the running motor due to loss of lock, so the spatial sampling coverage is less dense on the starboard side of the UAS between the wing and the tail.

3.5.2. Investigation of the impact of active components on the UAS

Five tests were performed to gauge the magnetic interference originating from active components on the UAS before the magnetic signature was mapped. Variables and conditions investigated included:

1. Actuation and orientation of the control surfaces controlled by the servos;

2. Orientation of the propeller controlled by the electric motor;
3. Actuation of the electric motor;
4. Powering the autopilot on and off;
5. Powering the receiver module on and off and communication with the transmitter.

In the first test, the servos were actuated to move the individual control surfaces (port aileron, starboard aileron, elevator and rudder) to their maximum negative and positive deflection angles in successive two second intervals. This test was repeated three times at the nine locations around the UAS (Figure 3-3) for each individual servo; results were repeatable (Figure 3-4). The actuation of the emergency servo located in the nose of the UAS was not evaluated as it is not used during survey. The locations with the largest variation in TMI (ΔTMI) for each actuated control surface are shown in Figure 3-5. Typically, the ΔTMI diminished with distance from the actuating servo. For example, a ΔTMI as large as 13 nT was measured at the tail during elevator actuation but was less than 1 nT at the wingtips. The lowest ΔTMI for all four servos was measured at the wingtips. In all cases, the ΔTMI was less than 2 nT outside of 1 m from the actuating servo. The interference caused by the servos is attributed to the permanent magnets in the servo's motor.

In the second test, the propeller, mounted on the motor shaft, was slowly rotated by hand (at 1 RPM) and then engaged using the flight controller at 50% throttle (approximately 2850 RPM) while the TMI was recorded at the nine locations around the UAS shown in Figure 3-3. The ΔTMI for both rotation speeds for locations A and B is presented as an example in Figure 3-6. Results show that the propeller rotation can introduce a $\Delta\text{TMI} > 100$ nT close to the motor (location I). When the propeller rotates

quickly, the Δ TMI has a lower amplitude than when it rotates slowly. At high rotation speed, the oscillatory response produced by the rotation of the motor is averaged over the 0.1 s sample period of the magnetometer averaging the positive and negative response and producing a less severe distortion. Conversely, a stationary propeller parked at different angles would result in a different field throughout the airframe resulting in a map less representative of the interference of the UAS and reducing the reproducibility of measurements. Testing of the motor and propeller separately found this interference field to originate from the motor, likely from the permanent magnets that rotate with the axle, and not from the plastic propeller itself.

The third test was to record the Δ TMI at the same locations (Figure 3-3) with the motor engaged at approximately 25, 50, 75 and 100% throttle. Throttle percentages were estimated by dividing the controller dial in four equal increments. Data recorded by the ESC showed that the percentage of throttle is linearly related to the rotation speed of the motor, whereas the current draw increases exponentially. The TMI for each throttle percentage was measured for 3 s and the test was repeated three times. No data was collected at locations H and I since the magnetometer could not “lock” on to the magnetic field, presumably because the field variation near the electric motor were beyond its AC slew rate specification. An example of the results is shown in Figure 3-7. The Δ TMI recorded with the motor engaged was repeatable whereas the Δ TMI recorded when the motor was powered off and stationary varied according to final orientation of the propeller.

The Δ TMI and the standard deviation of the 4th difference measurements are presented with respect to throttle percentage for each measurement location in Figure 3-8. In general, both values increase with increased throttle percentage. Only the wingtip locations have a Δ TMI below the 2 nT threshold and a standard deviation of the 4th difference below 0.05 nT for most throttle positions. Results for position B closest to the nose where batteries are situated are discrepant; at this position, there is a strong negative Δ TMI anomaly and a large standard deviation of the 4th difference.

The results presented in Figure 3-8 (top left) were used to pinpoint the source of interference from the motor system by plotting the Δ TMI with respect to distance from each motor component. The motor system is composed of the motor connected to the ESC by 3 AC cables which in turn connects to the 4 batteries via a pair of direct current (DC) cables. The best fit of Δ TMI measurements with distance corresponded to the DC battery cables which run from the batteries in the nose to the ESC (Figure 3-1), with a coefficient of determination $R^2 > 0.9$. The distance from the centre of the motor showed little correlation with Δ TMI, with a $R^2 < 0.4$. This suggests that the bulk of the magnetic interference is due to the high DC current flowing to the ESC in the battery cables and not by the motor or the ESC themselves. The amount of DC current flowing from the batteries to the ESC and the orientation of the DC cables are assumed responsible for the high Δ TMI when the motor was engaged.

In the fourth and fifth tests, powering the autopilot and receiver module on and off and communicating with the radio transmitter produced no notable effects on the Δ TMI or 4th difference.

The dynamic tests revealed that for several active components the ΔTMI is >2 nT and the standard deviation of the 4th difference is greater than 0.05 nT, the acceptable limits specified in Section 3. Therefore, before mapping of the UAS, the experimental set-up was modified to take into account the following considerations:

1. The motor must be either removed or be engaged at a sufficient rotation speed to average the varying field associated with propeller orientation; if practically possible, a high rotation speed is best as it is closer to survey configuration;
2. The servos should be powered and the control surfaces oriented without deflection.

<i>Position</i>	
A	20 cm from starboard wingtip
B	30 cm from nosetip
C	30 cm from tailtip
D	20 cm from port side wingtip
E	70 cm from port side wingtip
F	70 cm from nosetip
G	70 cm from tailtip
H	50 cm from centreline & 25 cm from leading edge of portside wing
I	50 cm from centreline & 25 cm from hind edge of portside wing

Figure 3-3: Diagram showing the 9 locations used for investigation of the impact of active components.

Figure 3-4: Δ TMI for each control surface actuation. Each action is marked by a number: (1) zero to maximum negative deflection (control surface pointing down or port side); (2) maximum negative to zero deflection (3) zero to maximum positive deflection (control surface pointing up or starboard side); (4) maximum positive to zero deflection. The test was repeated three times.

Figure 3-5: Maximum ΔTMI for each control surface actuation at the 9 different locations around the UAS shown in Figure 3-3.

Figure 3-6: ΔTMI at positions A and B for 1 RPM and 2850 RPM rotation speeds over a duration of 60 s.

Figure 3-7: ΔTMI at position F with the motor cycled between off and 50% throttle. Burgundy-coloured boxes indicate when the motor was powered for 3 s. When the power is shut off (right edge of the burgundy box) the motor decelerates over 4 s and comes to a complete stop after another 3 s. The test was repeated 3 times.

Figure 3-8: ΔTMI (left, top) and standard deviation of the 4th difference (left, bottom) measured at 7 different locations around the UAS with respect to throttle percentage. ΔTMI (right, top) and standard (right, bottom) deviation of the 4th difference at 50% throttle.

3.5.3. Static mapping of the UAS

For static mapping, the UAS was oriented pointing in the magnetic north direction, mounted on two 90 cm tall, 18" diameter PVC pipes, and tethered to the ground with plastic pegs and rope. The UAS controls were calibrated for flight surfaces oriented without deflection. Measurements were recorded in a 10 m x 10 m survey area at 0.5 m station spacing (step 4 of the testing method).

Two separate mapping surveys of the UAS were performed, one survey with the motor removed (Figure 3-9) and another with the motor engaged at 50% throttle (Figure 3-10). Figure 3-2 (right) shows the sampling path for the survey with the motor engaged at 50% throttle; a similar path was used for the survey with the motor removed. The low and high TMI values shown on the maps highlight areas of notable interference that

correspond well with installed elements on the aircraft. The servos and landing gear produce a magnetic high while the fuselage without the motor produces a low. Installing and engaging the motor changed the intensity throughout the fuselage from a negative to a positive anomaly. This might be due to the high DC current flowing to the ESC and induced magnetisation of ferrous components within the fuselage. In both maps the port side of the UAS airframe yields a higher TMI. This could be caused by the asymmetric installation of the servos on the tail or components in the fuselage (Figure 3-1), a disparity in the magnetisation in the servos or asymmetric sampling. Subtracting the UAS magnetic anomaly map with the motor removed (Figure 3-9) from the map with the motor engaged at 50% throttle (Figure 3-10) isolates the contributions due to the running motor system (Figure 3-11). The largest change between the two maps occurs throughout the fuselage but a reduction in TMI around the servos is also observed.

Although installed in different orientations, the servos appear as positive TMI anomalies adding intensity in the direction of the geomagnetic field. The wing servos create strong anomalies in Figure 3-9 and Figure 3-10 while the tail servo anomalies are less pronounced. From the maps, the 2 nT TMI contour associated with each wing servo is at a distance of approximately 1-1.5 m from the servo or 50-70 cm beyond the wingtip. This finding is in agreement with the results of the first dynamic test where the only location that consistently features interference less than 2 nT is position E, located 70 cm from the port side wingtip.

The absolute value of the 4th difference for the survey with the motor engaged at 50% throttle is shown in Figure 3-12 highlighting similar areas of high interference as shown in Figure 3-10.

The vertical gradient calculated from the magnetic anomaly map with the motor engaged at 50% throttle (Figure 3-10) is shown in Figure 3-13. Vertical gradients of <1 nT/m were difficult to distinguish from the background, so the vertical gradient limit was relaxed to 10 nT/m. Vertical gradients under this new limit are found less than a metre away from the UAS airframe with the most practical locations being about 50 cm outside the wingtips and tail.

Figure 3-9: UAS magnetic anomaly map with the motor removed. Contours of ± 1 (thin), ± 2 (red), ± 10 and ± 100 nT (bold) overlay the grid.

Figure 3-10: UAS magnetic anomaly map with the motor engaged at 50% throttle.
Contours of ± 1 (thin), ± 2 (red), ± 10 and ± 100 nT (bold) overlay the grid.

Figure 3-11: ΔTMI map calculated by subtracting the map presented in Figure 3-9 from the map presented in Figure 3-10. Contours of ± 1 (thin), ± 2 (red), ± 10 and ± 100 nT (bold) overlay the grid.

Figure 3-12: Map of the absolute value of the 4th difference of the data presented in Figure 3-10. Contours of multiples of 0.05 nT overlay the grid.

Figure 3-13: The vertical gradient of the UAS with the motor engaged at 50% throttle.

3.6. Discussion

Table 3-2 summarizes the magnetic interference levels measured at the nine locations around the UAS shown in Figure 3-3. Generally, the motor system was the larger source of interference, more specifically the cables connecting the ESC to the batteries under high current load, followed by the servos. The orientation of the propeller and control surfaces have a significant impact on the interference field around the UAS and should be constrained for proper mapping. As the vertical gradient consistently exceeds 1 nT/m, either structural modification or source interference reduction is required of the UAS.

Table 3-2: Magnetic interference levels at the 9 different locations around the UAS shown in Figure 3-3 when the motor is engaged at 50% throttle. The star indicates a variable which is independent of the percentage of throttle. Measurements greater than 2 nT (TMI limit), 0.05 nT (4th difference limit) or 1 nT/m (vertical gradient limit) are in highlighted in red.

Location		Individual Components			Interpolated maps		
ID	Location Description	Servo Actuation* (nT)	Motor ΔTMI (nT)	Motor 4 th Difference (nT)	TMI (nT)	4 th Difference (nT)	Vertical Gradient (nT/m)
A	Starboard wingtip	2.0	0.6	0.03	18.8	0.03	-18
B	Nosetip	0.2	-52.1	0.51	34.6	0.12	207
C	Tailtip	13	3.0	0.12	10.5	0.01	-15
D	Port side wingtip	3.8	0.4	0.04	17.8	0.03	-20
E	Port side wingtip	0.8	0.2	0.02	1.0	0.01	-8
F	Nosetip	0.3	6.8	0.12	16.2	0.03	62
G	Tailtip	2.5	3.0	0.05	0.4	0.01	-14
H	Front port side wing	0.8	N/A	N/A	52.4	0.13	-37
I	Rear port side wing	13	N/A	N/A	53.6	0.18	-27

A visual way to assess the most suitable magnetometer location for installation on the UAS is to use a weighted index overlay. A weighted index overlay combines several spatial variables using:

$$Z = \frac{\sum_{i=1}^n w_i x_i}{\sum_{i=1}^n w_i} \quad (3.2)$$

where w_i is the weight assigned to a certain variable and x_i is the corresponding pixel value of that mapped variable. Figure 3-14 presents an equal-weighted index overlay for the UAS with the motor engaged at 50% throttle combining the three variables used to assess interference levels: TMI, 4th difference and vertical gradient. The maps shown in Figure 3-10, Figure 3-11 and Figure 3-13 were each classified to a binary spatial representation based on 10 cm pixels using the proposed specifications, and were

summed to produce the index overlay in Figure 3-14. The index overlay shows the most suitable locations for the fixed-wing UAS under consideration (indicated in green), where all 3 specifications are met, with the closest locations being more than 50 cm away from the wingtips or tail.

Figure 3-14: Equally-weighted index overlay combining the TMI, 4th difference and vertical gradient for the motor engaged at 50% throttle (a vertical gradient limit of 10 nT/m was used instead of 1 nT/m). Colours indicate unsatisfactory (red) to satisfactory (green) areas for magnetometer location.

3.7. Recommendations and concluding remarks

Based on the experimental results presented in this paper, the following modifications are suggested for this UAS and similar aircraft:

1. **The DC battery cables should be minimized in length, secured and immobile, and the hot-return wires should be equidistant to the intended sensor mounting point.** Measurements from the ESC reported that 50% throttle corresponded to 14.7 A during the mapping of the UAS; whereas the UAS was designed for currents in excess of 80 A. This current will also vary with load which is a function of variables that change during the course of a typical survey line, including airspeed, drag and climb rate. Biot-Savart law can be used to predict the magnetic field generated by two conducting wires. Using this law, a 20 cm hot-return pair spaced 1 cm apart radially from the magnetometer and a current of 1 A would meet the 2 nT TMI threshold at a distance of 0.56 m; at the same distance, the vertical gradient would be 10 nT/m. Having the cables equidistant to the sensor, or using a high-current co-axial cable, should result in a cancelation of the field. The Biot-Savart law also suggests that the length of the cables between the batteries and the ESC should be kept as short as possible. Additionally, the wires and batteries should be secure and immobile where movement between flights might affect repeatability or vibration could create additional interference.
2. **Steel components should be demagnetised.** Components such as the landing gear axles, tail fastening fixtures or other steel elements located in the motor or servos can become permanently magnetised.
3. **The wings should be stiffened to reduce displacement and vibrations during flight.** Displacement between magnetic sources and the magnetometer results in varying interference. The largest displacement relative to the centre of the UAS

occurs at the wingtips and should be stiffened should the magnetometer or servos be mounted in them.

4. Servos should be moved away from the chosen magnetometer location.

Interference could be reduced at the wingtips by moving the aileron servos into the fuselage and introduce push-pull rods for their respective control surfaces. Having the two aileron servos paired using a genetic algorithm magnetic signature optimization strategy (Forrester *et al.* 2014) could further reduce interference where their respective fields are destructive.

- 5. A compensation algorithm could be employed.** Several sources of noise have a consistent and repeatable interference signature (e.g. deflection of the control surfaces, motor current, etc.) which are measured by the autopilot and ESC and could be corrected for with post-processing. Traditionally, compensation algorithms for manned aircraft address 3 types of interference that are related to aircraft attitude, permanent and induced magnetic fields, and eddy-currents (e.g. (Teskey 1991)). These same interferences will be generated by UAS airframes and studies regarding UAS compensation methods have been proposed (Zhang *et al.* 2011).

The method presented was developed for a fixed-wing UAS and so further work would be required to extend it to single-rotor and multi-rotor UAS. For instance, an important finding of this study is the necessity of having the UAS flight ready and the motor engaged during the mapping of the UAS. Mapping around the propeller of the fixed-wing UAS required a fair birth so as not to risk contact between it and the test stand. Such risks would be greater with single- and multi-rotor UAS because these UAS have larger, or multiple, areas of concern, which leaves few areas of interest to map.

Alternatively, choosing a plane beneath the UAS could have adverse effects on the GPS while choosing a plane over the UAS would not be possible with the proposed test stand. Additionally, the proposed method assumes that fixed-wing UAS have two comparatively separate systems; the propulsion and flight control systems. Rotary UAS combine these systems. The blades of a single-rotor will change angle depending on the angle of the swashplate whereas each motor of a multi-rotor UAS will change speed independently to vary attitude and heading. The proposed method does not address how to approach these multi-variable systems so that the interference they generate can be mapped repeatably.

Other future work could include extending the proposed method which has been designed for a 2D planar canvas to 3D. This would require the mapping of multiple planes by adjusting either the magnetometer or the aircraft height. A similar method was employed by Parvar (2016), who investigated the static field around a multi-rotor with the motors engaged and without the use of GPS. As high-accuracy GPS signal may be difficult to get with a UAS overhead, the use of indoor positioning systems could be explored.

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4. Magnetic interference mapping of unmanned aircraft systems used for geomagnetic surveying

4.1. Abstract

A magnetic field scanner was built for mapping the interference that is produced by an unmanned aircraft system (UAS) to be used as an informative tool for interference reduction. The scanner was used to map and compare four types of electric-powered UAS capable of carrying an alkali-vapour magnetometer for geomagnetic surveying; (1) a single-motor fixed-wing, (2) a single-rotor helicopter, (3) a quad-rotor helicopter, and (4) a hexa-rotor helicopter. The scanner's repeatability was measured by calculating the average root-mean-square deviation of the background total magnetic intensity over time and found to be 4.2 nT. Each mapping was performed above the UAS with the motor engaged and with the UAS facing in two orthogonal directions. By comparing the UAS maps, common sources of interference were located such as servo(s) and the direct current cables between the motor battery and the ESC. Magnetic intensity profiles were measured at various motor current draws for each UAS and a change in intensity was observed for currents as low as 1 A. The profiles were used to distinguish between interference from material magnetisation and electrical current to the propulsion motor(s). This information can guide the choice of compensation methods.

4.2. Introduction

Unmanned aircraft systems (UAS) are being hailed as a replacement for traditional ground surveys (Parshin *et al.* 2018) and are being used to perform geomagnetic surveys on the scale of $<1 \text{ km}^2$ (Versteeg *et al.* 2010; Eck and Imbach 2012; Macharet *et al.* 2016; Parshin *et al.* 2018; Parvar *et al.* 2018), $<10 \text{ km}^2$ (Kaneko *et al.* 2011; Koyama *et al.* 2013; Wood *et al.* 2016; Malehmir *et al.* 2017), and larger (Anderson and Pita 2005; Funaki *et al.* 2014; Wenjie 2014; Pei *et al.* 2017; Cherkasov and Kapshtan 2018). Their ability to fly along tightly-spaced lines at low-altitudes produces higher-resolution maps than those produced by typical manned aeromagnetic surveys. One of the main obstacles that impede the further acceptance of UAS in surveying is the magnetic interference generated by the UAS itself on the data recorded (Cherkasov and Kapshtan 2018).

Magnetic interference from the UAS can be introduced from multiple types of magnetised sources. Firstly, a combination of permanent and induced magnetisation can occur in ferromagnetic materials where the strength of the latter magnetisation is a function of the background field. This type of source includes electric or fuel propulsion motor(s), and control servo(s) (Wells 2008; Forrester *et al.* 2014; Cherkasov and Kapshtan 2018). Secondly, a field is produced from electronic systems; particularly those that conduct large electrical current (Teskey 1991). Examples of this type of component are electric motor(s), electronic speed controller(s) (ESC), and batteries (Tuck *et al.* 2018). Thirdly, induced currents in conductive materials can also produce interference (Leliak 1961; Fitzgerald and Perrin 2015). Each source can have different dependencies and therefore there is a need to locate and identify the sources of interference so their impact can be successfully mitigated.

The issue of magnetic interference has been addressed in a variety of ways; both in hardware and in software. In hardware, a straightforward approach is to increase the magnetometer-UAS separation. One method has been to tow the magnetometer below the UAS at a distance where the interference becomes negligible; often reported as >3 m (Koyama *et al.* 2013; Malehmir *et al.* 2017; Cherkasov and Kapshtan 2018; Parvar *et al.* 2018; Walter *et al.* 2018). This can introduce new issues such as heading and location error (Walter *et al.* 2016), reduced flight stability, increased drag, and increased risk of impact damage to the magnetometer upon landing (Kaneko *et al.* 2011). Additionally, these methods have not been demonstrated for fixed-wing UAS. Another option is to mount the magnetometer on a boom as an extension of the airframe's structure (Eck and Imbach 2012; Funaki *et al.* 2014; Cunningham *et al.* 2018). This often results in a compromise between UAS interference and boom length; where a longer boom reduces interference but increases flight instability. Additional reduction methods such as compensation using coils or rings (Leliak 1961), shielding using permalloy (Leliak 1961; Telford *et al.* 1990), demagnetisation using a degaussing coil (Versteeg *et al.* 2007; Camara and Guimarães 2016), optimal source positioning strategies (Forrester *et al.* 2014; Huq *et al.* 2015) or component replacement (Versteeg *et al.* 2007) can be used. Furthermore, attitude compensation can be applied in real-time or post-processing (Noriega 2011; Naprstek and Lee 2017).

Regardless of the methods used to mitigate interference, it is desirable to identify the location of magnetic sources and to assess the severity of the interference effects through detailed magnetic interference mapping. This activity will help to locate areas of low interference and inform magnetometer placement. The results of several magnetic

interference investigations have been published (Versteeg *et al.* 2007, 2010; Forrester 2011; Kaneko *et al.* 2011; Sterligov and Cherkasov 2016; Cherkasov and Kapshtan 2018; Parvar *et al.* 2018) but only a few include a detailed methodology for mapping the UAS. Forrester (2011) mapped a 95 kg gas-powered fixed-wing UAS using a hand-held uniaxial fluxgate magnetometer and identified three interference contributors in order of severity: the servo(s) (50-100 nT at 0.55 m), the engine and engine assembly (60 nT at 0.55 m), and the avionics package (30 nT at 0.38 m). The method described by Forrester (2011) included rigorous testing of each component individually. Sterligov and Cherkasov (2016) mapped a 10 kg electric-powered flying-wing UAS using a planar surface as a measurement guide over top of the UAS and identified the major sources of magnetic noise as the electric motor (<800 nT), servos (<600 nT) and ferromagnetic elements (<300 nT). Parvar (2016) introduced three-dimensional mapping and isolated effects from the motor by calculating the difference in magnetic intensity when the UAS was powered on and off. He mapped a 10 kg electric powered hexa-rotor UAS and reported a 350 nT interference peak at 0.4 m. The experiment was repeated by Parvar et al. (2018) on a quad-rotor with a similar result. In both studies, the magnetometer was deployed 3 m below the UAS to mitigate interference. Finally, Tuck et al. (2018) mapped a 25 kg electric-powered fixed-wing UAS with the motor powered on and off using a non-magnetic test stand equipped with high-precision satellite positioning. They measured intensities as high as 53.6 nT at a distance of 0.25 m behind the port side wing and as low as 0.4 nT at a distance of 0.7 m from the tail tip. Additionally, they found that interference from the motor system arose from the batteries or direct current cables whereas the effect of the permanent magnets in the motor were cancelled at sufficiently

high rotational velocity. Although the UAS in each study mentioned above vary in size and type, they each demonstrate high levels of interference that are not always symmetrically distributed across the UAS. In order for UAS to meet survey noise limits (e.g. <10 nT (Kaneko *et al.* 2011), <1 nT (Parvar 2016), <2 nT (Sterligov and Cherkasov 2016), <2 nT (Tuck *et al.* 2018)), interference sources must be identified and mitigated.

Many different types of UAS are of interest for magnetic surveys and each have a different magnetic signature that can evolve as modifications are made to the UAS. A robust and practical method is needed to:

- map all types of UAS;
- identify sources of interference with sufficient positional accuracy to distinguish problematic areas;
- allow the UAS motor(s) to be engaged during mapping while keeping both the operator and the hardware safe;
- enable multi-directional mapping to discriminate between induced and permanent effects;
- identify interference that results from electrical currents.

This paper presents a method for magnetic interference mapping of a UAS that meets the above requirements. The method is demonstrated on four different types of electric UAS capable of carrying a high-resolution alkali-vapour magnetometer: a single-motor fixed-wing (FW), a single-rotor helicopter (SRH), a quad-rotor helicopter (QRH) and a hexa-rotor helicopter (HRH) UAS (Figure 4-1, Table 4-1). The mapping was performed with the motor(s) engaged at a single current. As a complement to each mapping,

interference profiles were collected at different motor current draws in order to determine the impact of amperage on the magnetic interference.

Figure 4-1: Photographs of the UAS investigated in this study: a) single-motor fixed-wing, b) single-rotor helicopter c) quad-rotor helicopter, and d) hexa-rotor helicopter.

Table 4-1: UAS specifications.

	Fixed-wing (FW)	Single-rotor helicopter (SRH)	Quad-rotor helicopter (QRH)	Hexa-rotor helicopter (HRH)
UAS make and model	33% Scale Piper Pawnee	T-Rex 600E Pro	DYS D800 X4	DJI S800 Evo
Electric propulsion system	1x Hacker Q80 -6L V2 7000 W 180 kV, brushless outrunner motor	1x E-flite Heli 700, 700 W 500 kV, brushless outrunner motor	4x E-flite 5008, 610 W 330 kV, brushless outrunner motor	6x 4114 Pro, 500 W, 400 kV, brushless outrunner motor
Batteries	12S-22Ah (motor), 4S-2.2Ah (autopilot), 3x 2S-5Ah (avionics)	12S-10Ah (motor), 2S-1Ah (avionics)	6S-16Ah	6S-15Ah
Electronic speed controller	Castle Phoenix Edge HV 160 A	Castle Phoenix 120 A	4x ESC 40 A	6x ESC 40 A
Maximum payload (kg)	5	4	6.5	4.3
Dimensions (cm)	330 wingspan/240 length	21 x 116	80 x 80	80 x 80
Servos	7 servos - 4 wing, 3 tail (1 rudder, 2 elevator)	4 servos (3 swashplate, 1 tail)	0	1 gimble servo

4.3. Instrumentation: Magnetic Scanner

A scanner was designed and built to accurately map the magnetic interference of a UAS indoors while allowing the operator to remain at a safe distance while the UAS was in operation (Figure 4-2). The scanner was also used in a previous study to map an unmanned ground vehicle for magnetic surveying (Hay *et al.* 2018). The scanner, constructed of low-susceptibility materials, moved a carriage transporting two magnetometer systems along an aluminium track above the UAS. The carriage was instrumented with a potassium-vapour total field (TF) magnetometer system (GSMP-35U, GEM Systems) powered by a 4 Ah lithium polymer (LiPo) battery and a triaxial fluxgate magnetometer (Mag649, Bartington Instruments) which recorded to a microcomputer (Raspberry Pi 3) powered with a 1.8 Ah LiPo battery. Both magnetometers were suspended on a rigid plastic boom 50 cm below the carriage and operated at a sampling rate of 10 Hz. The TF magnetometer was used for mapping; the fluxgate magnetometer was used to record the field direction.

The magnetic scanner was set up in a 6 m x 8 m laboratory and the length of the track was oriented along the magnetic north measured from the middle of the track. For each line, the carriage was towed along the track above the UAS using a timing belt and two 12 V stepper motors. The motors were operated by a control board located at one end of the track that delivered a maximum of 750 mA. The cart moved at a constant speed of 2.41 ± 0.01 cm/s across the track translating to a measurement every 0.241 cm or 415 samples per metre.

Figure 4-2: Magnetic scanner a) two stepper motors, b) magnetometer battery, c) magnetometer computer, d) triaxial fluxgate magnetometer, e) TF magnetometer, f) stepper motor control board, g) UAS, and h) fluxgate microcomputer. Cables are removed for simplicity.

4.4. Method

The scanner was used to perform two tests for each UAS; (1) to produce an interference map at a constant motor current which is used to inform the spatial distribution of magnetic intensity and (2) to produce interference profiles at various motor current draws which is used to inform how the magnetic intensity distribution would change with amperage.

Although the method fulfills the requirements listed in Section 1, it has two drawbacks as a result of performing the mapping indoors and on the ground. The first drawback is that spatial variations of the background field are larger indoors than outdoors. These variations will affect the induced magnetisation and will introduce a distortion to the mapping. For the tests, it is assumed that the spatial variations are small compared to the background ($<4\%$ /m) and therefore introduce a small level of distortion to the induced magnetisation component of the UAS interference field. The second drawback is that eddy currents are not representative of survey conditions while the UAS is stationary. In many cases, interference from eddy currents are low as UAS are often fabricated with composites with a low electrical conductivity (Samson *et al.* 2010). Magnetic calibration studies have also demonstrated one case where eddy currents can be considered negligible (Zhang *et al.* 2011).

4.4.1. Background magnetic intensity

In an indoor environment, the background magnetic field can have a strong spatial gradient and be prone to large temporal variations. Each mapping therefore required careful measurement of the background to be used to both isolate the anomalous field associated with the UAS and as a measure of error. The background was measured as a collection of repeat lines without the UAS present for various track lengths to a maximum of 2.9 m (Figure 4-3). Over this maximum length, the magnetic field varied smoothly between an intensity of $52,100 \pm 2500$ nT, a declination of $0.6 \pm 50.6^\circ$, and an inclination of $85.2 \pm 3.1^\circ$.

Figure 4-3: The TMI, inclination and declination profile of 6 background lines collected during the FW north mapping. Repeat background lines appear superimposed at this scale. The location of the line lengths (Table 2) used for each mapping is noted at the base of the plot.

Background lines were collected before, during, and after each mapping, and statistics were calculated by mapping (Table 4-2). Lines were grouped by carriage direction and compared to the first line of each mapping (x_o). Changes in the background field were evaluated using the root-mean-square deviation (RMSD) defined as:

$$RMSD = \sqrt{\frac{\sum_{i=1}^N (x_{m,i} - x_{1,i})^2}{N}} \quad (4.1)$$

where i is the i^{th} of N total measurements along the line and x_m is the m^{th} codirectional line. The RMSD has previously been used as a measure of accuracy for quantifying error between time series (Barnson 1992; Hyndman and Koehler 2006).

Over the 8 mappings carried out, the average (AVG) and standard deviation (STD) of the RMSD for all lines was 4.2 ± 1.1 nT. Graphical inspection of the residuals for each line, that is the data remaining after the first codirectional line was subtracted, revealed

coherent signals attributed to: (1) imprecise start and end line positions, or “parking” errors, (2) pendulum swing of the TF magnetometer due to air turbulence, (3) interference from the stepper motor apparent towards one end of the line, and (4) an irregularity in the middle of the track. The “parking” errors were apparent in the residuals as a low-frequency signal. This was produced by a positional shift of the line within the substantial gradient of the laboratory. For most lines, this error is the main contributor to the RMSD. Magnetometer pendulum effects, stepper motor noise, and the track irregularity were apparent in the residuals as higher frequency signal and were removed with a low-pass filter with a cut-off of 0.25 Hz in Section 4.2.

Table 4-2: Statistics on background lines for each mapping.

Mapping	Line length (m)	Number of background lines	Mapping time (min)	AVG RMSD (nT)	STD CE_{line} (nT)	CE_{map} (nT)
FW-north	2.9	6	138	4.9	4.0	13.9
FW-west	2.9	6	95	7.4	4.4	6.9
SRH-north	2.1	6	88	3.5	1.2	1.8
SRH-east	2.1	6	68	3.1	1.9	1.6
QRH-north	1.6	8	89	4.7	2.1	0.5
QRH-east	1.6	13	101	3.4	1.2	1.5
HRH-north	1.6	6	120	5.0	3.2	0.7
HRH-east	1.6	13	107	3.6	3.2	2.9

Temporal variations in the background lines were monitored during the experiment by calculating the closure error for each return to the north-end parking position (CE_{line}); a quantity comparing the last measurement of the current line to the first measurement of the previous line:

$$CE_{line} = |x_{m,N} - x_{m-1,1}| \quad (4.2)$$

Similarly, a quantity that compares the parking position between the end and start of the mapping was used as a closure error for the whole map:

$$CE_{map} = |x_{M,N} - x_{1,1}| \quad (4.3)$$

where M is the last line. Lines with a CE_{line} value greater than 5 nT were repeated. The $AVG \pm STD$ of CE_{line} was 0.0 ± 2.6 nT for the 8 mappings. CE_{line} values were randomly distributed which was attributed to imprecise “parking”. The $AVG \pm STD$ of CE_{map} was 2.2 ± 5.6 nT for the 8 mappings.

4.4.2. UAS scanning setup

Each UAS was fastened to a box made of non-magnetic materials and the height of the box was adjusted so that the top of the UAS was 30 cm below the magnetometer path. The QRH and HRH propeller blades were reversed to provide downward force when the motors were engaged. The minimum magnetometer-UAS separation was chosen as a trade-off between magnetometer safety and the mapping resolution which is a function of measurement distance from a source. Using the relationship between aliasing and the height to line-spacing ratio calculated for airborne surveys (Reid 1980) and considering the collection time limited by the UAS battery, a line spacings of 30 cm was chosen for the FW because of its larger dimensions, and of 10 cm for the other UAS (Table 4-3).

Table 4-3: UAS mapping parameters.

UAS type	Motor speed (RPM)	Current (A)	Nominal voltage (V)	Line spacing (cm)
FW	1300	10	45.6	30
SRH	1400	1.5	45.6	10
QRH	2100	10	22.8	10
HRH	2200	5	22.8	10

Each mapping was performed with the UAS assembled, the motor(s) engaged, and the electrical systems powered as per Table 4-3. UAS motor currents were measured using an ammeter. Motors were powered with rotational speeds much larger than 100 RPM to average the field dependency on the orientation of the permanent magnets in the brushless outrunner motor (Tuck *et al.* 2018). The motor controller of the multi-rotors (QRH and HRH) were reconfigured so that each motor on the individual UAS had the same rotational speed and similar current draw.

Between each line, the UAS was moved perpendicular to the track length in equal increments described in Table 4-3 for full coverage. Data was recorded with the front of the UAS oriented northwards and then eastwards to capture the dependence of the interference on the orientation of the background field. One exception was the FW which could not be oriented eastwards because the space in the lab could not accommodate its large wingspan.

4.5. Results

4.5.1. Interference mapping

The interference maps for the FW, SRH, QRH, and HRH, under the conditions described in Table 4-3, are presented in two orthogonal orientations in Figures 4-4, 4-5, 4-6, and 4-7, respectively. These figures show the magnetic intensity associated with the UAS after the subtraction of the background field.

The interference map of the FW, when powered with a 10 A current, exhibits two large dipolar anomalies in both the north (top) and west (bottom) orientations which remain fixed to the airframe under rotation (Figure 4-4). The anomalies are centered in the fore and aft of the UAS. The position of the fore dipole corresponds with the motor system in the nose of the UAS in the north ($north_{min} = -127.4$ nT) and in the west ($west_{max/min} = +110.9/-106.3$ nT). Its position overlies the motor battery, ESC, motor, and associated cables. The other dipole is located around the tail ($north_{max/min} = +167.2/-121.1$ nT and $west_{max/min} = +161.2/-153.2$ nT) and coincides with the location of 3 servos and the steel supports located in the tail. The negative lobe of the tail dipole connects to a negative lobe associated with each wing, possibly associated with the flaperon and aileron servos (located at 120 cm and 75 cm from each wingtip, respectively) or the steel linkages that connect the servos to the moveable flight surfaces.

The SRH blades were removed for safety and the maximum power that could be delivered to the motor was 1.5 A. The interference of the SRH presents a negative monopolar anomaly in both mapping orientations. Due to its symmetrical signature, no

conclusion could be drawn regarding intensity changes resulting from airframe rotation (Figure 4-5). The interference minimum ($north_{min}=-574.2$ nT, $west_{min}=-566.8$ nT) coincides with the centre mast, motor and servo batteries, motor, ESC, servos, and motor controller/receiver and associated cables. Since the large negative monopole was generated under low current conditions, it suggests that the source was unrelated to the motor's electrical system. Instead, the anomaly could be from the four servos located around the centre mast or the magnetisation of ferromagnetic components also located in the centre mast.

The interference map of the QRH, when powered with 10 A current, exhibits a positive monopolar anomaly ($north_{max}=+66.1$ nT, $west_{max}=+75.0$ nT) which remains fixed to the airframe under rotation (Figure 4-6). The interference anomaly peaks at the centre of the body but displays some amplification along the conductive aluminum arms possibly due to eddy currents. The anomaly does not follow one arm, forming a triangular shape. This lower interference could be a result of different wire twisting or an issue with this motor. In general, the field is not associated with the motors but appears to be from a single source located at the centre of the UAS where the battery, ferromagnetic fasteners in the battery carrier, and the motor controller/receiver are located.

The interference map of the HRH exhibits a dipolar anomaly when powered with a 5 A current (Figure 4-7). In the mapping plane, the dipole is predominantly a negative ($north_{max/min}=+103.4/-464.4$ nT, $west_{max/min}=+21.4/-470.2$ nT) and remains fixed to the airframe under rotation. The centre of the dipole corresponds with the centre of the UAS where the battery, battery cables, ESC, and gimble servo are located. It does not coincide with the 6 motors or 6 ESCs that are located at the end of each plastic arm.

Figure 4-4: Interference map of the FW facing magnetic north (top) and west (bottom). Border units are in metres. Edge effects are present on both maps.

Figure 4-5: Interference map of the SRH facing magnetic north (left) and east (right).
Border units are in metres.

Figure 4-6: Interference map of the QRH facing magnetic north (left) and east (right).
Border units are in metres.

Figure 4-7: Interference map of the HRH facing magnetic north (left) and east (right).
Border units are in metres.

4.5.2. Interference profiles

The interference profiles were measured for each north-facing UAS at different motor current draws (Figure 4-8). Each UAS was positioned so that the magnetometer path ran directly through the centre of the UAS. The throttle was adjusted between profiles using a remote transmitter and the UAS was not moved.

The motor current draw could not exceed 1.5 A for the SRH with the blades removed and therefore the interference relationship with amperage could not be investigated above this value. The FW, QRH, and HRH profiles change with increasing current; changes are visible for currents as low as 1 A. For these three UAS, the greatest changes coincide with the position of the battery and cables going to the ESC(s).

An interference profile without current-induced interference (0 A) can be calculated for each UAS (Figure 4-8) by linear extrapolation and represents the permanent and induced magnetisation (herein magnetisation interference). This magnetisation interference was subtracted from each higher current profile leaving the current-induced

interference for each amperage (Figure 4-9 (top) for the HRH). The minimum intensities (for FW) and the maximum intensities (for QRH and HRH) of the current-induced interference are plotted with respect to current (Figure 4-9, bottom). Each curve has a linear relationship to current ($R^2 = 0.998, 0.991, \text{ and } 0.999$, respectively) with slopes of -7.5, 2.8 and 10.4 nT/A, respectively. Since the interference remains fixed with the airframe under rotation (Section 4.1), the magnetisation interference appears to be largely permanent.

The separation of the interference profile provides new information that compliments the mapping shown in Section 4.1. For example, the apparent dipole observed in the mapping of the HRH was in fact two monopoles from separate sources that are centred at different locations. The location of the magnetisation interference centre relates well to the location of the gimbal servo whereas the centre of the current-induced interference coincides with the cables from the battery. Another example was the magnetisation interference in the QRH profile that, unlike the other three, cannot be attributed to a servo. Further investigation found a group of ferromagnetic fasteners located in the battery-carrying cage that may have become magnetised.

Figure 4-8: The interference profiles for each UAS oriented in the north direction at different motor current draws. Profiles have been filtered using a 0.25 Hz low-pass filter. A profile was calculated for 0 A (dashed profile). The location of the UAS system components are marked on the top border of each profile set. Components are denoted as a: avionics controller/receiver, m: motor, s: servo, t: tail, c: SRH centre mast, b_m: motor battery, b_s: servo battery, b_a: the autopilot battery, e: ESC. Brackets indicate components are located laterally with respect to the profile axis.

Figure 4-9: (Top) The current-induced interference profiles for the HRH. Circles indicate current-related peak values. (Bottom) A plot of the peak/trough values of the current-induced interference for the FW, QRH and HRH with respect to current.

4.6. Discussion and concluding remarks

Four different types of UAS capable of carrying an alkali-vapour magnetometer were magnetically mapped using a scanner. The scanner was built with the purpose of minimizing positional inaccuracies utilizing stepper motors designed for printing applications since these inaccuracies can cause large errors in the measured magnetic field in a high gradient environment such as an indoor laboratory. The repeatability of the measurements was estimated by calculating the RMSD of the background lines over time (AVG $\pm$ STD of 48 lines over 8 mappings: 4.2 $\pm$ 1.1 nT) and found to be small with respect

to the large anomalies associated with the UAS. In general, the largest contribution to the RMSD values was a result of lines with a high “parking” error and a high magnetic gradient. This was the most prevalent on the edges of the FW mappings. The RMSD could be reduced by mapping in an area of lower gradient or by programming exact line lengths into the stepper motor controller to reduce parking error. In the case where the parking error is small, shielding the stepper motors and reducing the pendulum swing would reduce the RMSD.

For each mapping, the magnetic interference is measured at levels significantly beyond typical survey noise limits (Section 1) and therefore interference reduction and the selection of the sensor location are critical. For each system, the interference is expressed as a monopolar or dipolar anomaly within the measurement plane. These anomalies are centred around suspected sources such as the servo(s), the main batteries, and direct current cables between the motor battery and the ESC. Sources that are expected to produce alternating fields at frequencies substantially higher than the magnetometer sample rate, such as the electrical motors used for thrust, contribute little to the interference; although this result may be dependent on the magnetometer bandwidth.

The majority of interference from each UAS remains fixed to the airframe under rotation indicating that the sources are predominantly due to permanent magnetisation or related to electrical current. Both Sterligov and Cherkasov (2016) and Versteeg et al. (2010) demonstrated that the predominant type of magnetisation of their UAS was permanent. Since interference resulting from permanent magnetisation is measured at a single location as a bias, it can be subtracted or removed using classical compensation

methods (Leliak 1961). It should be noted that Leliak (1961)'s method does not distinguish fields due to permanent magnetisation from those produced by electrical currents; the latter is shown to affect the interference signature of the UAS for currents as low as 1 A. Therefore, the current-induced interference must be removed before Leliak (1961)'s compensation method can be applied. The most effective way to remove current-induced interference is to locate the magnetometer outside the zone of influence of the interference sources. Alternatively, it can be removed by modelling the relationship between interference and amperage. The FW, QRH and HRH interference profiles demonstrate a linear dependence on motor current and the relationship can be used for this purpose. Current-induced interference compensation has previously been demonstrated by Noriega and Marszalkowski (2017).

Without using any reduction strategies, the QRH produces the smallest levels of magnetic interference and do not require servos. Based on these merits, it would be the best choice for geomagnetic surveying. A subtraction of the calculated magnetisation and current-induced interference from each QRH interference profile leaves a residual peak <5 nT. This would represent a 93% reduction in interference of the peak measurement of the 25 A interference profile.

4.7. Acknowledgements

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5. Real-time compensation of magnetic data acquired by a single-rotor unmanned aircraft system

5.1. Abstract

Two methods for low-altitude calibration of a single-rotor unmanned aircraft system (UAS) using a real-time compensator are tested: (1) a stationary calibration where the UAS executes manoeuvres while hovering in order to minimize ambient field changes due to the local geology; and (2) an adapted box calibration flown in four orthogonal directions. Both methods use two compensator-specific limits derived from established methods for manned airborne calibration: the lowest frequency used by the compensator for the calibration algorithm and the maximum variation of the ambient magnetic intensity experienced by the UAS during calibration. Prior to flying, the UAS was magnetically characterized using the heading error and 4th difference. Magnetic interference was mitigated by extending the magnetometer-UAS separation distance to 1.7 m, shielding, and demagnetisation. The stationary calibration yielded an improvement ratio of 8.595 and a standard deviation of the compensated total magnetic intensity of 0.075 nT (estimated Figure-of-Merit of 3.8 nT). The box calibration also yielded an improvement ratio of 3.989 and a standard deviation of the compensated total magnetic intensity of 0.083 nT (estimated Figure-of-Merit of 4.2 nT). The stationary and box calibration solutions were robust with low cross-correlation indexes (1.090 and 1.048, respectively) when applied to a non-native data-set.

5.2. Introduction

Unmanned aircraft systems (UAS) are increasingly used for small-scale ($<10 \text{ km}^2$) high-resolution magnetic surveys in part because they offer reduced mobilization time and operating costs compared to traditional manned airborne surveys (Funaki and Hirasawa 2008; Eck and Imbach 2012; Koyama *et al.* 2013; Hashimoto *et al.* 2014; Macharet *et al.* 2016; Wood *et al.* 2016; Malehmir *et al.* 2017; Cunningham *et al.* 2018; Parshin *et al.* 2018; Parvar *et al.* 2018) and offer faster data collection at lower cost per kilometer than ground surveys (Parshin *et al.* 2018). The interference generated by the UAS on the recorded magnetic data is a major impediment for further penetration into the commercial market. There have been reports of levels of interference beyond those accepted in the manned airborne industry (e.g. Coyle *et al.* 2014) up to 3 m away from a UAS (Koyama *et al.* 2013; Parvar 2016).

In most cases, magnetic interference caused by a UAS originates from sources within the aircraft. First, permanent and induced magnetisation of materials can generate strong fields. These materials are often located in the propulsion motor(s), control servo(s), and other iron alloy components (Wells 2008; Forrester *et al.* 2014). Secondly, magnetic interference results from electronic systems where fields increase in strength with increased current. Thirdly, fields arise from eddy currents circulating in conductive materials subjected to an external time-varying magnetic field. Although many UAS are fabricated with non-magnetic and less conductive composites (Samson *et al.* 2010), it is difficult to remove interference sources completely.

A simple method to mitigate magnetic interference effects is to increase the distance between the magnetometer and the sources of interference by suspending it on a long

cable beneath the UAS (Kaneko *et al.* 2011; Koyama *et al.* 2013; Malehmir *et al.* 2017; Parvar *et al.* 2018). This can prove problematic as this design can introduce directional and positional errors and increase the risk of impact to the magnetometer (Kaneko *et al.* 2011). Instead, where the magnetometer is rigidly fixed to the airframe or mounted on a boom (Versteeg *et al.* 2010; Cunningham *et al.* 2016, 2018), methods for locating, modelling and reducing interference have been developed (Forrester 2011; Tuck *et al.* 2018).

For manned aircraft, the issue of minimizing interference on aeromagnetic data has been addressed thoroughly by developing compensation strategies both in software and in hardware (Hardwick 1984; Noriega 2011, 2013, Dou *et al.* 2016a,b). In both cases, compensation requires a calibration flight to establish the relationship between flight manoeuvres and the corresponding changes in the magnetic signal (Leliak 1961; Zhang *et al.* 2011; Jianjun *et al.* 2014). These calibration flights are executed in box patterns covering large areas ($\sim 10 \text{ km}^2$) and at high altitudes ($\sim 3000 \text{ m}$ above ground level (AGL)) in magnetically “quiet” zones close to the intended survey area (Coyle *et al.* 2014). The same approach is not directly applicable to UAS where these criteria cannot be met due to technical and regulatory limitations that restrict the altitude and require operation within line-of-sight.

Conventionally, the quality of a calibration is measured using a Figure-of-Merit (FOM). Typical contracts require this FOM, for $\pm 5^\circ$ pitch, $\pm 10^\circ$ roll, $\pm 5^\circ$ yaw manoeuvres, to be less than 1.5 nT for fixed-wing manned aircraft and less than 2.0 nT for helicopters (Teskey 1991; Coyle *et al.* 2014). To date, few UAS have achieved this

standard; the closest found in literature was for a fixed-wing UAS reported with an FOM of 1.7 nT (Anderson and Pita 2005).

This contribution proposes two new calibration methods that are practical for UAS to execute at low altitude. The effectiveness of the calibration methods are evaluated in three sites with different magnetic gradients resulting from the local geology.

5.3. Instrumentation

This system requires a magnetometer and compensator to be installed on a single-rotor UAS. A light boom was constructed to mount the magnetometer in front of the helicopter (Figure 5-1). The position of the batteries was adjusted to evenly distribute the payload around the rotor hub.

5.3.1. Unmanned helicopter

The RenegadeTM from RME Geomatics is a single-rotor UAS with a maximum take-off mass of 35 kg (Figure 5-1, Table 5-1) mostly used to fly high-resolution LiDAR surveys (McAnuff *et al.* 2019). This UAS was selected for this study for three reasons: (1) it can lift the compensator and the magnetometer (mass = 3 kg) and fly for a minimum duration of 30 mins; (2) it can take off and land without a runway; and (3) it had previously flown with a magnetometer mounted on a boom.

The nominal speed of the main propeller of the UAS is 1450 RPM above 30% throttle, above which the thrust is further increased by changing the collective angle of attack of the blades without increasing the motor's RPM. The main propeller is 2.2 m in diameter, composed of two 1 m blades in addition to the main rotor hub. The blade angles are controlled by three brushless stainless-steel servos and a swashplate. There are two additional servos, one located in the tail that controls the tail rotor blade angle and another that controls the engine throttle. A magneto is located at the front of the engine with an ignition coil and spark plug located on either side of the engine. Three lithium polymer (LiPo) batteries are positioned together midway along the tailboom and power the servos, the avionics and the payload, respectively. Two Novatel Global Navigation Satellite System (GNSS) antennas are located at the front of the engine and towards the tail of the UAS. Two strobe lights are located at the bottom edges of the fuselage that triple pulse every second. Control and telemetry radio antennas are located at the aft and front of the fuselage, respectively.

Figure 5-1: Side view of the Renegade™ UAS. Components: a) tail servo, b) rear GNSS antenna, c) three LiPo batteries, d) magnetometer sensor electronics, e) three swashplate control servos, f) main rotor hub, h) engine, i) strobe light, j) front GNSS antenna, k) AARC52 compensator, l) fluxgate magnetometer, m) total-field magnetometer head.

Table 5-1: Specifications of the Renegade™ UAS

UAS type	Single-rotor helicopter	Unit
Blade length	1	m
Payload mass	11	kg
Endurance	60	min
Engine	80 cc gas and oil, two-cylinder, air cooled	
Maximum take-off mass	35	kg
Payload battery	8000 (6S)	mAh
Servo Battery	6800 (2S)	mAh
Electronics Battery	4400 (3S)	mAh
Autopilot	Micropilot	

5.3.2. Magnetometers

Two total-field (TF) and one vector (fluxgate) magnetometers were used in this study. Initial ground testing was performed with a GEM Systems potassium-vapour GSMP-35U TF magnetometer. This magnetometer is designed specifically for high-resolution magnetic UAS applications and has a sensitivity of $0.3 \text{ pT}/\sqrt{\text{Hz}}$ RMS at 1 Hz, an absolute accuracy of 0.05 nT, and a maximum sampling rate of 20 Hz. A Geometrics G-822A cesium-vapour TF magnetometer was used for flight tests as part of the compensator system because it has a higher sampling rate than the GSMP-35U. The G-822A magnetometer has a sensitivity of $1 \text{ pT}/\sqrt{\text{Hz}}$ RMS at 1 Hz, an absolute accuracy of 3 nT, and a maximum sampling rate of 1280 Hz. The compensator also used a Billingsley TFM100-G2 3-axis fluxgate magnetometer for attitude reference.

A 1.7 m long boom (measured from the main rotor hub) was fabricated from parallel carbon fibre tubes to increase the separation between the magnetometer and the UAS and minimize vibration (Figure 5-1). Nylon fasteners were used to bind the structure and a friction fit tube was used to house the magnetometer head.

5.3.3. Compensator

The AARC52 is an instrument designed to provide real-time magnetic compensation processing based on previous AARC500 series compensators built for manned aeromagnetic surveying (Noriega 2011) but specifically redesigned for a UAS. The compensator's mass is 2 kg (excluding cables, mounting hardware and magnetometers) with a nominal current draw for both the compensator and the magnetometers of 3.5 A. Data from the Geometrics G-822A and Billingsley TFM100-G2 magnetometers were sampled by the compensator at 640 Hz and recorded at 10 Hz with a 0-1.6 Hz bandwidth.

The quality of a calibration is assessed using various metrics (Noriega 2011, 2013; Coyle *et al.* 2014). The following metrics are calculated automatically by the AARC52:

σ_u – the standard deviation (STD) of the uncompensated total magnetic intensity (TMI)

σ_c – the STD of the compensated TMI

IR – the improvement ratio, defined as:

$$IR = \frac{\sigma_u}{\sigma_c} \quad (5.1)$$

norm – the vector norm is a measure of ill-conditioning that represents a numerical issue in the calculation of the solution. Typically, this parameter is less than 100 for a full 4-heading calibration.

bias – difference between the mean of σ_u and σ_c .

CCI – the cross-correlation index is a measure of calibration solution robustness. It reflects the performance of a calibration solution applied to the uncompensated data of a different calibration attempt. It is calculated as the ratio of the STD of the data after the calibration is applied to a non-native uncompensated dataset ($\sigma_{A(B)}$) to the STD of the calibration applied to its own native uncompensated dataset ($\sigma_{A(A)}$):

$$CCI = \frac{\sigma_{A(B)}}{\sigma_{A(A)}} \quad (5.2)$$

A robust solution will yield a CCI close to unity.

Another commonly used metric is the 4th difference which estimates the level of high-frequency noise in airborne magnetic data:

$$4^{th} \text{ difference} = -\frac{(T_{-2} - 4T_{-1} + 6T_0 - 4T_{+1} + T_{+2})}{16} \quad (5.3)$$

where T_x is the x^{th} TMI measurement in time centered around the value T_0 . The industry accepted level for the 4th difference is less than 0.1 nT peak-to-peak when applied to 10 Hz data. Assuming a gaussian distribution centered around a mean of 0 nT, the STD of the 4th difference limit is then 0.017 nT.

5.4. Proposed UAS calibration methods

The proposed UAS calibration methods use two compensator-specific limits that are estimated from the typical box calibration method used for manned aircraft (Noriega 2011). The first limit, f_{G_max} , is the lowest frequency used by the compensator for the calibration algorithm. For example, if the compensator used a band-pass filter to isolate the signal variation that results from manoeuvres, f_{G_max} would be the low-frequency cut-off of the band-pass filter. This would consequently remove lower frequency signal contributions that could arise from flying through the magnetic gradient caused by the spatially varying geology. The second limit restricts the maximum variation of the ambient magnetic intensity to which the UAS is subject to during the calibration (ΔB_{G_max}). These limits are in addition to the 4th difference limit (STD: 0.017 nT) mentioned in Section 5.3.3.

During calibration, the signal recorded by the magnetometer measures variations caused by manoeuvres of the UAS (ΔB_M) and variations from flying through the geomagnetic field (ΔB_G). The latter variations are approximated as:

$$\Delta B_G \approx \Delta \vec{s} \cdot \vec{\nabla} B_G + \frac{1}{2} (\Delta \vec{s} \cdot \vec{\nabla})^2 B_G \quad (5.4)$$

where $\Delta \vec{s}$ is the displacement from its original position and $\vec{\nabla} B_G$ is the spatial gradient of the geomagnetic field. To minimize $\Delta \vec{s}$, manoeuvres can be executed while hovering. Alternatively, $\vec{\nabla} B_G$ can be minimized by executing the calibration where the magnetic field is constant. In practice, neither variables are equal to zero. If ΔB_G can be separated

from ΔB_M , by filtering for example (Leach 1979; Jia *et al.* 2004), some contribution from ΔB_G over time is acceptable; this will depend on f_{G_max} and ΔB_{G_max} .

For a successful calibration, the ΔB_G is treated as interference by the compensator and must be removed. Therefore, it is a requirement that the bulk of the spectral content of ΔB_G be less than f_{G_max} . Any spectral content above this limit will affect the quality of calibration. The minimum spatial wavelength of ΔB_G at a given altitude can be estimated using a breadth-to-depth relationship (Smellie 1967):

$$z_p \approx 1.4 x_{1/2} \quad (5.5)$$

where z_p is the limiting distance between the magnetometer and a magnetic source and $x_{1/2}$ is the full width at half maximum measured on the TMI profile. For the minimum $x_{1/2}$, the topography is the closest magnetic source and therefore z_p is the flight altitude. By fitting a sinusoid to the TMI profile, f_{G_max} is estimated by substituting equation (5.5) into the wave equation:

$$f_{G_max} = 0.7 \frac{v}{z_p} \quad (5.6)$$

Substituting values for manned aircraft calibrations (v : 50 m/s, z_p : 3000 m AGL) gives an f_{G_max} of 0.01 Hz. This is an order of magnitude below the frequency range of 0.20-0.25 Hz of typical calibration manoeuvres (Coyle *et al.* 2014). Using f_{G_max} as a constant regardless of altitude, a calibration flown at 120 m would then be limited to a velocity of 1.7 m/s. A calibration flown at a higher altitude would allow for a higher velocity to be flown.

The second limit, ΔB_{G_max} , must be less than 200 nT and ideally less than 100 nT (RMS Instruments, AARC52 Adaptive Aeromagnetic Real-Time Compensator User's Guide: revision 2). This limit is calculated from hundreds of calibrations with the AARC500 series compensators used for manned aircraft calibrations.

Based on the above discussion, the following values are assigned to the two limits to maintain an acceptable ΔB_G in the design of the proposed UAS calibration methods:

$f_{G_max} < 0.01$ Hz – This is achieved by limiting the velocity of the calibration flight.

Using this, four frequency bands can be defined for analysis: a low-frequency band (<0.01 Hz) where frequencies, assumed from flying through the geological gradient, are removed by the compensator during calibration ($\Delta B_{<0.01Hz}$), a separation band (0.01-0.1 Hz) ($\Delta B_{0.01-0.1Hz}$) with minimal signal, a band conventionally used for manoeuvres (0.1-1 Hz) ($\Delta B_{0.1-1Hz}$), and the high-frequency band (>1 Hz) ($\Delta B_{>1Hz}$).

$\Delta B_{G_max} < 100$ nT – This is achieved by limiting the length of the size of the calibration flight area.

Two separate calibration methods are proposed:

A stationary calibration is flown where the UAS executes manoeuvres while hovering in order to minimize ambient field changes due to the local geology. It allows the permanent and induced components of the compensation algorithm to be determined but neglects some of the eddy currents fields that arise from flying through the local geological gradient.

A *box calibration* is flown at survey speed in four orthogonal directions. Box lengths are calculated by limiting the expected TMI variation over the box to be less than $\Delta B_{G_{max}}$ or by using the distance covered in 60 s (the time it would normally take to execute all the manoeuvres), whichever length is smaller. This method should better compensate for fields generated by eddy currents but risks including varying fields related to the geology.

5.5. Results

The study included two activities, performed on 4 different dates. First, the magnetic interference of the UAS was characterized to determine the length of the boom and whether modifications were needed to reduce the interference of the UAS. The second activity was to demonstrate the two calibration methodologies at low altitude in three sites with different magnetic gradients produced from the local geology. The regional geomagnetic field for each location was calculated using the IGRF-12 (2015) International Geomagnetic Reference Field (Thébault *et al.* 2015) and gradient statistics for each location were calculated using 40 m grid cell, 150 m AGL, 200 m traverse line spaced, airborne residual magnetic intensity (RMI) data obtained from the Geophysical Atlas of Ontario (Ontario Geological Survey 2017) (Table 5-2). Spatial gradient components calculated from the IGRF for each location were negligible (<0.0004 nT/m) compared to those calculated from the RMI grids and were therefore not considered.

Table 5-2: Characteristics of the geomagnetic field at the 3 test locations on the dates of study, calculated using IGRF-12 (2015). TMI: total magnetic intensity; Inc: inclination; Dec: declination.

Location	Date	IGRF-12 - B_G					RMI - $ \nabla B_G $ (nT/m)			
		Latitude (°)	Longitude (°)	TMI (nT)	Inc (°)	Dec (°)	min	max	AVG	STD
Carp, ON	10/20/17	45.3490	-75.0558	53959	70.209	-13.626	-	-	-	-
Embrun, ON	03/29/18	45.2933	-75.2666	53918	70.168	-13.468	0.001	0.043	0.010	0.006
Carp, ON	04/13/18	45.3490	-75.0558	53909	70.169	-13.600	0.189	0.481	0.345	0.059
Plevna, ON	07/19/18	44.9124	-76.9373	53956	70.156	-12.377	1.145	1.962	1.496	0.218

5.5.1. Magnetic interference mitigation

5.5.1.1. Pre-installation ground testing

Two ground tests were performed prior to the installation of the compensator onboard the UAS in order to measure the interference caused by the intermittent and continuous sources of noise on the UAS. In the first test, the UAS was readied for flight, positioned facing northward, and the potassium-vapour TF magnetometer was installed on the boom at 1.5 m from the main rotor hub. The peak-to-peak magnetic response was recorded as components were individually engaged (Table 5-3). The response of the propellers was measured by rotating them slowly by hand while attached to the main rotor hub (~1 RPM). Separate testing of the main rotor hub and blades found that the blades were responsible for the response of 37.2 and 10.8 nT.

The second test was to assess the heading error and the high-frequency interference (evaluated using the 4th difference) generated by the UAS under conditions similar to

those during flight. The potassium-vapour TF magnetometer and boom was detached from the UAS frame and mounted on a moveable sled built from materials with low-magnetic susceptibility. The TMI was measured for 10 s at different distances (measured from the centre of the main rotor hub), in front of the UAS with the engine running at 100% throttle. This was repeated with the UAS oriented along the geographic cardinal directions while maintaining a single location. Background measurements were collected at the same locations with the UAS removed. All measurements were corrected for diurnal variations and averaged over the collection period. Figure 5-2 shows the heading error associated with the UAS (top) and the STD of the 4th difference (bottom).

The results of the second test showed (Table 5-4) showed that the heading error and the STD of the 4th difference interference to be highest in the north direction (-82.4 nT and 0.062 nT, respectively). The directional dependency in the results suggest that induced magnetism is the primary type of interference. The strongest negative intensities were in the north direction with weaker negative intensities to the west, consistent with the north-northwesterly orientation of the geomagnetic vector in the Ottawa area.

The heading error can be compensated. Airborne standards specify that the maximum heading error should be 2.0 nT after compensation (Teskey 1991; Coyle *et al.* 2014). Noriega (2011) found 83% of aircraft with a boom mounted magnetometer using an AARC500 series compensator had improvement ratios (IRs) between 4-12. Assuming the average (AVG) IR of 8, a precompensated heading error of 16 nT would be acceptable. The UAS heading error was well above this limit.

High-frequency interference is not accounted for by the compensation model. The largest STD of the 4th difference was measured in the north direction to be 0.062 nT and above the limit of 0.017 nT.

Table 5-3: Peak-to-peak magnetic response of individual components recorded at a distance of 1.5 m using the GSMP-35U magnetometer. The background measured without the UAS present was 0.1nT.

Interference source	Response (nT)
Throttle servo	2.0
Tail servo	1.3
Pitch servo	1.7
Roll servos (pair)	1.3
All swashplate servos	2.1
Strobe light system	0.2
Move the swashplate manually	<0.1
Propeller 1	37.2
Propeller 2	10.8

Based on the results of the pre-installation ground tests, the following modifications were made to the UAS:

- Both propellers and the main rotor hub were demagnetised using a degaussing coil.
- The boom was extended to 1.7 m, the maximum length achievable in practice due to flight instability concerns arising after the pre-installation ground tests.
- Strobe lights were disabled for all further testing and flying.
- The fuel servo and three swashplate servos were wrapped in 0.1 mm thick, 80% nickel, magnetic shielding.
- A 10x10 cm magnetic shield was installed over the magneto.

High amperage wires (>1 A) were not twisted because of damage concerns although doing so is recommended in the future. The AARC52 system records the 10 Hz data with a bandwidth of 0-1.6 Hz whereas there is no bandwidth specified by the manufacturer for the recording GSMP-35U.

Figure 5-2: (Top) Residual magnetic intensity measured at various distances from the UAS in four cardinal directions. (Bottom) The STD of the 4th difference calculated for each TMI measurement time series. Distances have ± 10 cm error.

5.5.1.2. Post-installation testing

After modifications described in Section 5.5.1.1 were made, the compensator, the fluxgate magnetometer, the cesium-vapour TF magnetometer, and a short-range wireless

router were installed on the UAS. Two post-installation tests were performed to evaluate the impact of the modifications on interference reduction.

The first test was a repeat of the propeller test after demagnetisation at a magnetometer-main rotor hub distance of 1.7 m. The peak response was reduced to -3 nT after three passes over the demagnetiser. It is assumed that magnetisation of a steel filament located near the leading edge of the blade is responsible for this response.

In the second test, the heading error and the STD of the 4th difference was re-evaluated while the UAS hovered at an altitude of 20 m AGL (Table 5-4). The TMI was recorded for 10 s facing each of the cardinal directions and the average was removed. The data shows a significant reduction in the interference from the UAS. The largest heading error occurred in the north direction (-6.9 nT) and was below the 16 nT pre-compensated limit. The STD of the 4th difference was highest in the west direction (0.003 nT) and below the 0.017 nT limit.

Post-installation testing confirmed that the interference due to the UAS and its subsystems had been mitigated to a level acceptable for calibration flights to proceed.

Table 5-4: The heading error and STD of the 4th difference in the four cardinal directions measured near Carp, ON. The pre-modification testing was performed on the ground; the post-modification testing was performed as a flight.

Direction	Heading error (nT)		STD of 4 th Difference (nT)	
	Pre-modification ground test	Post-modification flight	Pre-modification ground test	Post-modification flight
North(N)	-82.4	-6.9	0.062	0.002
East(E)	18.6	1.3	0.020	0.001
South(S)	52.8	6.8	0.029	0.002
West(W)	-43.5	-1.2	0.016	0.003
N-S diff	-135.2	-13.7	-	-
E-W diff	62.1	2.5	-	-

5.5.2. Testing of proposed UAS calibration methods

Stationary calibrations were performed over a 3-month period (Table 5-2). Stationary calibrations were performed in three locations (Embrun, Plevna, and Carp, Ontario, Canada); box calibrations were performed in the latter two locations. The three locations were chosen based on their spatial magnetic gradient (Table 5-2). Embrun is a low-gradient ($AVG|\vec{\nabla}B_G|$: 0.010 nT/m) location situated on a deep north-south striking basement structure with a relatively high magnetic susceptibility overlain by sediment with a relatively low magnetic susceptibility. It shares a magnetic basement with Bourget, ON, reputed for its low-magnetic gradient and used historically for calibrations of manned airborne magnetic systems (Teskey 1991; Ontario Geological Survey 2015). Plevna is a mid-gradient ($AVG|\vec{\nabla}B_G|$: 0.345 nT/m) location with folded magnetic metasediments (Caron *et al.* 2014) and is an area of considerable mining activity. Carp is a high-gradient ($AVG|\vec{\nabla}B_G|$: 1.496 nT/m) location with a mix of clastic metasedimentary and felsic plutonic rocks; with some areas overlain by limestone. Additionally, the

locations were chosen because they were absent of visible cultural sources of noise and operationally compliant. Demagnetisation was performed before each mobilization. After the calibrations were performed in Embrun, a 2.4 GHz long-range communication link was added to the compensator to allow for real-time control and monitoring of the calibration during flight. The addition of the long-range link had no affect on the 4th difference of the TMI.

5.5.2.1. Stationary calibrations

Stationary calibrations involved executing a total of 3 pitch ($\pm 5^\circ$), 3 roll ($\pm 10^\circ$), and 3 yaw ($\pm 5^\circ$) manoeuvres (~ 4 -5 s per manoeuvre) sequentially in four orthogonal directions. A limitation of the Renegade UAS is that such manoeuvres could only be executed using manual controls. In order to maintain proper control, lower calibration altitudes (20, 60 and 100 m AGL) than the maximum permitted by Canadian flight regulations (Canadian Aviation Regulations (2019), SOR/2019-11) for this UAS (120 m AGL) were used.

Two calibrations were flown in Embrun (ES or individually: ES1, ES2), two in Plevna (PS or individually: PS1, PS2) and three in Carp (CS or individually: CS1, CS2, CS3), and solution statistics are summarized in Table 5-5. Variables IR and σ_c were used to evaluate the calibration quality; example profiles of the uncompensated TF TMI and fluxgate vector magnetic intensity (VMI) measurements from each location are provided in Figure 5-3 and the high-pass filtered uncompensated and compensated TMI as output from the compensator (Figure 5-4, left). The lower σ_c will directly reflect the output signal quality, whereas the IR will reflect the improvement to the data by the compensator. One case where these variables seemingly contradict is where the output

signal is of good quality but of low improvement, for instance if the input manoeuvre amplitudes were small.

Figure 5-3: The uncompensated TF TMI (right axis) and fluxgate VMI (left axis) measurements for stationary calibrations ES2 (top), PS1 (middle), and CS2 (bottom).

Table 5-5: Calibration solution statistics.

Calibration Type	Location	Calibration #	σ_u (nT)	σ_c (nT)	IR	Norm	Bias (nT)	STD of 4 th Difference (nT)
Stationary	Embrun	ES1	0.664	0.082	8.079	14.484	-6.064	0.004
		ES2	0.644	0.075	8.590	16.041	-9.414	0.005
		ES1+ES2	0.652	0.080	8.129	13.420	-	-
	Plevna	PS1	0.639	0.199	3.206	34.176	-8.742	0.003
		PS2	0.661	0.283	2.338	62.254	-21.120	0.004
		PS1+PS2	0.650	0.253	2.566	40.953	-	-
	Carp	CS1	0.851	0.592	1.438	47.309	5.707	0.003
		CS2	0.968	0.621	1.558	51.415	-1.421	0.003
		CS3	0.995	0.649	1.533	62.984	5.723	0.003
		CS1+CS2+CS3	0.878	0.601	1.462	46.393	-	-
Box	Plevna	PB1	0.309	0.091	3.389	34.117	-21.861	0.003
		PB2	0.330	0.083	3.979	31.573	-19.484	0.003
		PB1+PB2	0.320	0.088	3.623	31.018	-	-
	Carp	CB1	0.542	0.337	1.606	120.854	49.975	0.004
		CB2	0.567	0.344	1.649	150.043	51.641	0.004
		CB3	0.557	0.343	1.621	103.136	21.197	0.004
		CB4	0.598	0.339	1.766	106.072	30.451	0.004
		CB1+CB2+CB3+CB4	0.563	0.346	1.625	124.942	-	-

Figure 5-4: The uncompensated (black) and compensated (red) TF TMI measurements for box calibration for ES2 (left) and PB2 (right) demonstrating the reduction in manoeuvre noise.

A visual inspection of the fluxgate VMI variations associated with the calibration manoeuvres for the three locations show that they were similar in amplitude and period (Figure 5-3). The manoeuvre signal was compared by calculating the STD of the 5th order 0.1 Hz cut-off high-pass butterworth filtered TMI ($\Delta B_{>0.1Hz}$) for each calibration (ES: 0.618-0.960 nT; PS: 0.653-0.720 nT; CS: 0.804-0.996 nT). The similarity of these values supports the interpretation that the manoeuvres were similar and suggests that the approximately 50% higher σ_u values calculated for the CS calibrations include an additional signal contribution at frequencies <0.1 Hz. This contribution is assumed geological.

Calibrations ES1 and ES2 had the highest quality (IR: 8.079-8.590; σ_c : 0.075-0.082 nT) (Table 5-5). The two PS calibrations were poor (IR: 2.338-3.206; σ_c : 0.199-0.283 nT), and calibrations CS1, CS2 and CS3 were very poor (IR: 1.438-1.558 and σ_c : 0.592-0.649 nT). The norm parameter displayed an inverse relationship with the IR whereas no trend can be identified using the bias. For each location, the solutions were combined in post-processing to increase the collection time, but the resulting solution did not improve. Using σ_c to estimate the FOM (Noriega 2011) (hereafter: FOM*), the ES2 calibration had an FOM* of 3.8 nT.

The $\Delta B_{G_{max}}$ correlated inversely to the σ_c (Table 5-6). This was attributed to increased variations in position; specifically variations in altitude (presented as the STD of the altitude difference from the start of the calibration) (Table 5-6). The effects of the variation in position is amplified in areas of higher gradient. To test the $f_{G_{max}}$ limit (0.01 Hz), the STD of $\Delta B_{0.01-0.1Hz}$ was calculated for each heading and averaged per calibration (Table 5-6). The STD of $\Delta B_{0.01-0.1Hz}$ correlated well with σ_c . The increased

signal in $\Delta B_{0.01-0.1\text{Hz}}$ for PS and CS suggests geological frequencies exist above the f_{G_max} limit and a potential for interference with the manoeuvre signal.

The power spectral density (Welch 1967) was computed for each calibration in order to examine f_{G_max} (Figure 5-5, Table 5-6). The spectra display similar peaks between 0.1-0.3 Hz corresponding to increased signal in response to the manoeuvres. The ES and PS calibration spectra look similar whereas the CS spectra display a higher spectral power at the lowest frequencies. Frequencies associated with altitude variations could not be identified using the power spectral density.

ES1 and ES2 were both robust solutions with CCIs of 1.090 and 1.086, respectively. The ES2 solution was applied to both the PS and CS data, but the results did not improve.

Figure 5-5: Power spectral density for stationary and box calibrations. Expected frequency bands for the geology and manoeuvres are shown above the graph.

Figure 5-6: The uncompensated TF TMI (right axis) and fluxgate VMI (left axis) measurements for box calibration for PB2 (top) and CB4 (bottom). Pitch manoeuvres are visible in the fluxgate-y measurements at the start and end of each box length.

Table 5-6: Operational parameters, calculated design limits, measurement, and quality metrics for each calibration.
Calibrations considered good are in bold.

Calibration			Operational parameters			Calculated design limits		Limits calculated from measurements					Quality Metrics			
Calibration type	Location	#	Altitude (m AGL)	v (m/s)	AVG ∇ BG (nT/m)	$\Delta B_{G,max}$ (nT)	$f_{G,max}$ (Hz)	$\Delta B_{G,max}$ (nT)	Power@ (f=0.01Hz) (nT**2/Hz)	Power@ (f=0.1Hz) (nT**2/Hz)	STD $\Delta B_{0.01-0.1}$ (nT)	STD altitude change (m)	σ_c (nT)	IR	CCI	FOM*
stationary	Embrun	ES1	20	0	0.010	0	0	11.0	303.1	6.2	0.4	1.7	0.082	8.079	1.090 (ES2)	4.1
		ES2						10.4	275.6	6.8	0.4	2.1	0.075	8.590	1.086 (ES1)	3.8
	Plevna	PS1	100	0	0.345	0	0	12.9	177.8	5.6	2.0	7.1	0.200	3.226	-	10
		PS2	20					17.4	332.8	9.5	2.4	1.5	0.300	2.289	-	15
	Carp	CS1	60	0	1.496	0	0	32.9	1821.3	9.7	2.6	7.6	0.592	1.438	-	30
		CS2						29.7	734.3	8.4	2.9	6.3	0.621	1.558	-	31
		CS3						30.5	3355.5	5.7	4.1	14.1	0.649	1.533	-	33
box	Plevna	PB1	120	5.1	0.345	84	0.03	120.6	20284.5	1.0	4.1	1.0	0.092	3.319	1.048 (PB2)	4.6
		PB2						121.2	22151.9	1.0	3.8	1.0	0.083	3.989	1.046 (PB1)	4.2
	Carp	PB1	120	5.1	1.496	150	0.03	252.8	259947.8	17.4	25.4	0.4	0.337	1.606	-	17
		PB2						251.6	256109.4	26.1	24.7	0.3	0.344	1.649	-	17
		PB3						250.8	254827.7	19.6	24.8	0.4	0.343	1.621	-	17
		PB4						252.0	232859.7	20.8	25.2	0.5	0.339	1.766	-	17

5.5.2.2. Box calibrations

Calibration boxes were flown autonomously using four waypoints at 120 m AGL and a target speed of 5.1 m/s in Plevna (PB or individually: PB1, PB2) and Carp (CB or individually: CB1, CB2, CB3, CB4) (Table 5-5) (Table 5-6). The calibrations were limited to “natural” manoeuvres resulting from wind and velocity changes, and stationary turns at the corners of the box. The PB box length was confined by time and chosen to be 350 m with an expected ΔB_{G_max} of 84 nT. The CB box length should have been constrained by the ΔB_{G_max} limit of 100 nT leading to a box length of 75 m. There were concerns that this length would not allow sufficient time for reliable calibration parameters to be determined using natural manoeuvres. The ΔB_{G_max} limit was therefore increased to 150 nT thereby increasing the box length to 112 m. Each box was initiated and terminated with the UAS oriented towards the first length. Calibration solution statistics, generated by the compensator, are summarized in Table 5-5 and example profiles of the uncompensated TF TMI and fluxgate VMI measurements from each location are presented in Figure 5-6. The high-pass filtered uncompensated and compensated TMI as output from the compensator (Figure 5-4, right).

The two PB calibrations were of good quality (IR: 3.389-3.979; σ_c : 0.083-0.091 nT), and the four CB calibrations were poor (IR: 1.606-1.766; σ_c : 0.337-0.344 nT) (Table 5-5). The norm parameter for the CB calibrations were above the recommended limit indicating that the compensator had issues calculating the solution. For each location, solutions were added together to increase collection time, but the resulting solution did not show any improvement. The PB2 calibration would have an FOM* of 4.2 nT.

In the TMI measurements, the variations in signal are prominently from flying through the geological gradient rather than a response to manoeuvres or change of heading. The ΔB_{G_max} in PB and CB (Table 5-6). The STD of $\Delta B_{0.01-0.1Hz}$ calculated for PB were above the values calculated for stationary calibrations. Inspection of $\Delta B_{0.01-0.1Hz}$ revealed that signal contributions were related to both pitch manoeuvres at the corners of the calibration boxes in addition to flying through the geological gradient.

The power spectral density for each calibration (Figure 5-5, Table 5-6) does not display a manoeuvre-related peak between 0.1-0.3 Hz corresponding to the absence of controlled manoeuvres contained within that frequency band. Stronger power was observed in the PB and CB spectra at the lowest frequencies compared to the stationary calibrations. This increased signal contribution is assumed to be from flying through the geological gradient. This is corroborated with an elevated value at the $f=0.01$ Hz frequency, yet at $f=0.1$ Hz, the PB value is below the values for the stationary calibrations. The higher power was present in $\Delta B_{0.01-0.1Hz}$ for both PB and CB, but only interfered with manoeuvres for CB. The spectral power of the PB calibrations are similar to those for the ES calibrations at $f=0.05$ Hz indicating a better refined limit for f_{G_max} .

PB1 and PB2 were both robust solutions with a CCI of 1.046-1.048. The ES2 solution was applied to the PB data yielding acceptable results (IR: 2.992-3.555, σ_c : 0.0928-0.1032 nT) and a CCI of 1.133. Similarly, the ES1 solution applied to the PB data yielded a CCI of 1.073-1.083. The PB1 solution applied to the ES1 data was fairly robust with a CCI of 1.288 whereas the PB2 solutions was less robust with a CCI of 1.407.

5.6. Discussion and conclusion

Calibration methods performed at high-altitudes have proven effective for manned aircraft, but a method for low-altitude calibrations where the magnetic gradient can be more aggressive was needed for UAS. For both manned aircraft and UAS, the quality of a calibration relies on the ability of the compensator to distinguish magnetic variations related to the aircraft manoeuvring from other sources of interference; whether that be from sources on the aircraft or from a varying geomagnetic field.

Stationary calibrations in the low-spatial gradient location (Embrun, $\text{AVG}|\vec{\nabla}B_G|$: 0.010 nT/m), yielded an IR of 8.595 and a σ_c of 0.075 nT (FOM*: 3.8). The stationary calibration in the mid- (Plevna, $\text{AVG}|\vec{\nabla}B_G|$: 0.345 nT/m) and high- (Carp, $\text{AVG}|\vec{\nabla}B_G|$: 1.496 nT/m) spatial gradient locations were deemed unsatisfactory. Calibration quality degraded as position deviation increased. This effect was intensified when performed in an increased gradient; whether the higher gradient was due to flying at lower altitudes or to the ambient field of the performed location. This led to magnetic variations with frequencies above $f_{G_{max}}$ that interfered with the manoeuvre band, $\Delta B_{0.1-1Hz}$, and resulted in a poor quality calibration. The choice of the altitude at which to perform stationary calibrations is a compromise between higher altitudes where it is difficult for the pilot to hover and lower altitudes where the magnetic gradient is strongest.

Box calibrations required the UAS to autonomously fly a box pattern using the natural motion of the UAS as manoeuvres. The best calibration solution yielded an IR of 3.989 and a σ_c of 0.083 nT (FOM*: 4.2 nT). Calibrations were of good quality in the mid-level gradient but not the high-gradient locations. The quality degraded with higher

frequency contributions above f_{G_max} and maximum variations above the ΔB_{G_max} limit. The results and the success of the PB calibrations suggest f_{G_max} is likely closer to 0.05 Hz.

The best stationary solution from Embrun compensated the Plevna box flight data with a CCI of 1.073 demonstrating that a robust calibration is possible even if the datasets are from locations 140 km apart (distance between Embrun and Plevna), the UAS was disassembled and reassembled between the flights, and 3 months had passed. This would suggest that an alternative area with a low magnetic gradient and a similar geomagnetic vector could be used for calibration before deployment to the survey site.

On the basis of the results presented in this paper, it is suggested to fly box calibrations starting at the intended survey velocity and to repeat them at decreasing velocities until a good quality solution is achieved. At the limit where the velocity is reduced to zero, a stationary compensation is performed which will yield a solution with a minimum interference from the geology. It is expected that calibrations performed with greater positional and manoeuvre precision, achieved through autonomy at the highest allowable altitude, will further improve the calibration quality. This should be demonstrated in future research.

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6. Conclusion

6.1. Summary

This thesis presented three separate studies that addressed the overarching problem of characterizing and compensating the magnetic interference generated by a UAS during magnetic surveying. The problem was approached from two directions: mapping to identify magnetic sources for individual component interference reduction, and manoeuvre compensation for whole-UAS interference reduction. These two approaches are not mutually exclusive. In fact, the component reduction approach is of large benefit to whole-UAS reduction. Both should be considered as one cumulative method towards achieving the lowest level of interference possible.

It was proposed that problematic components be identified using magnetic intensity maps made from data acquired by the magnetometer survey system intended for installation within the UAS. The first study demonstrated that in order to map the UAS effectively, the UAS must be constrained as follows: (1) motors engaged, (2) servo-controlled flight surfaces engaged and in a steady-state position, and (3) electrical systems drawing a constant current. This setup was used for mapping a 25 kg FW electric UAS but should apply to mapping any UAS. If left unconstrained, the UAS could introduce a change of TMI as large as 5, 3.8, and 0.4 nT measured at the port-side wingtip, respectively. With the application of the constraints listed above, mapping the FW UAS was undertaken and the measurements were processed for both static and high-frequency interference. From the maps, it was concluded that the majority of static

interference was produced by the servos and the motor system with the maximum field attributed to the DC battery cables between the motor batteries and the ESC. Similarly, the high-frequency interference was most prominent around the servos, motor, and DC battery cables. The conclusion was that the interference levels of the UAS would be below the uncompensated limits with a magnetometer installation at 0.5 m beyond the wingtips or tail. With the typical improvement from a compensation, the UAS would be compliant with both the maximum noise envelope and the 4th difference limits (Table 1-1). In addition, other interference reduction methods were recommended including twisting the DC cables, demagnetisation of steel components, and increasing the distance between the servos and the intended magnetometer installation point. These recommendations were later applied in the third study.

The first study suffered from repeatability issues; one factor for this was the position error of the magnetometer and this issue was resolved by building a magnetic scanner with an average root-mean-square deviation of 4.2 nT. Another improvement was made to the methodology of the first study by mapping the UAS in two orthogonal orientations; this provided the ability to discern between permanent and induced magnetisation. Along with the application of constraining factors learned from the first study, the scanner was used to compare the magnetic intensity mappings and profiles of four different types of electric-powered UAS capable of flying with a survey-grade magnetometer; a single-motor FW, an SRH, a QRH and an HRH UAS. While the profiles of the SRH were inconclusive when measured without its blades installed, the other UAS were found to have: (1) similar interference signatures under rotation, (2) interference levels dependent on the electrical current drawn by the motor(s), (3) a mixture of interference types

composed of both material magnetisation and electrical current. The study corroborated that the most prominent interference sources are the servos and the DC battery cables. It was then suggested that these fields could be removed with both manoeuvre and electrical calibrations, respectively.

While the second study mapped the interference, it did not demonstrate the removal of the magnetic interference. The removal of interference related to permanent magnetisation, induced magnetisation, and eddy-currents in a 35 kg gasoline-powered SRH UAS during flight was demonstrated using a real-time compensator. The magnetic signature of the whole-UAS was measured and the problematic components were assumed based on the conclusions of the previous studies. After the boom was lengthened and reduction techniques employed, the heading error and 4th difference were measured to be 12 and 31 times lower, respectively. This brought interference levels below the suggested pre-compensated limits for both the maximum noise envelope and the 4th difference limits (Table 1-1).

After the interference of the UAS was sufficiently reduced, two novel, low-altitude calibration methods, named “stationary” and “box” calibrations, were tested in three geological environments with different magnetic gradients. Each calibration method was designed around two critical compensator-specific limits: f_{G_max} ; the highest geologically-related signal frequency in the calibration flight that the compensator can successfully remove and ΔB_{G_max} ; the maximum variation of the ambient magnetic intensity to which the UAS is subject to during the calibration.

The best stationary calibration yielded an IR of 8.595, σ_c of 0.075 nT, and an FOM*: 3.8 nT. The best box calibration solution yielded an IR of 3.989, a σ_c of 0.083 nT, and an FOM*: 4.2 nT. The best stationary solution was applied to a calibration box that was flown in a location 140 km away from the original calibration area, after the UAS had been disassembled and reassembled, and 3 months had passed between the two flights. The stationary calibration was robust and compensated the flight data nearly as well as the native solution with a CCI of 1.073. This demonstrates that compensated magnetic survey is possible by UAS, but the data quality does not yet meet aeromagnetic standards with an FOM* that is approximately twice the requirement (Table 1-1).

6.2. Future work

Multiple approaches were made to reducing the magnetic interference produced by a UAS. Nevertheless, there remains several avenues of additional work.

Manoeuvre compensation was performed on a gas-powered UAS where current drawn by the onboard systems were both small and constant in comparison to an electric-powered UAS. As demonstrated in the first and second study, the interference that is a result of current must be mitigated and the compensation of current-borne interference from an electric-powered UAS should be demonstrated.

More work is also needed to improve the compensation of the UAS if it is to meet aeromagnetic specifications. The best FOM* achieved was 3.8 nT, whereas the minimum aeromagnetic standard for a helicopter is 2.0 (Table 1-1). To date, there has not been any

published work on a rotary-wing aircraft that meets aeromagnetic specifications. This could be achieved through:

1. Greater vigilance in reducing the magnetic signature of the UAS by characterizing individual interference sources in detail and refining reduction methods. The best case would be to purposely design and build a UAS with low-interference;
2. Autonomous calibrations that control both flight positioning and accurate manoeuvring;
3. The optimization of compensator limits such as the f_{G_max} and ΔB_{G_max} that are specific for low-altitude UAS calibration. UAS-specific parameters could improve low-altitude calibrations since these compensator limits are optimized for high-altitude manned aircraft calibrations.

Lastly, the validity of airborne specifications as applied to low-altitude UAS surveys should be studied and the current performance standards (Table 1-1) may require revisions. As UAS exploit the ability to fly slower and lower than most manned airborne survey aircraft, they measure variations in the geomagnetic field with a greater range over smaller time periods. Therefore, signal and noise bands may shift and possibly converge rendering the current standards invalid. For example, an increased amount of higher-frequency geological-related signal could be apparent at lower altitudes that could increase the 4th difference and would misrepresent the amount of high-frequency interference in the survey data. Similarly, as towed magnetometer systems are gaining acceptance, the noise frequencies generated by these systems may be lower than those measured by the 4th difference. Since FOM tests do not apply to towed systems, new

specifications and testing methods could be needed to properly assess the noise of these systems.

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