Magnetorquer Calibration and Requirement Verification Procedure.

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Contents

Table 1: Version History

Revision	Date (dd-mm-yyyy)	Revised By	Description
1.0	20-10-2020	PK, RC,	First Release of Document
1.1	01-03-2021	PK	Replace ManitobaSat-1 with IRIS, as well as, add version history.
1.2	21-07-2021	PK, RC, GC	Updated the data analysis section with physical measurements (weight and length) of the six magnetorquers manufactured (3 flight models, 3 backup models).
1.3	05-08-2021	PK	Requirements updated according to current state of Valispace. Verification status matrix updated to reflect current progress.

Table 2: Applicable Documents

Abbreviation	Document Name
AD-1	IRIS ADCS Hardware Overview.doc
AD-2	LOTAD and MOLTRES Test Procedure.doc
AD-3	HBridgeDataSheet.pdf

Table 3: Table of Tables

Table 4: Table of Figures

1 Introduction

This document outlines the procedure for the characterisation of magnetorquers for Nano-satellite and CubeSat application. Magnetorquers are commonly used in Nano-satellites and CubeSats in LEO, as the magnetic field in this region is strong enough to provide a sufficient torque. Magnetorquers are solenoids that contain a core with a relatively high permittivity to increase the magnetic moment. Magnetorquers need to be calibrated as imperfections in the wire winding, core material, coating, and other factors that can lead magnetorquers' response to differ from the ideal response. Another reason to characterise the magnetorquers on Nano-satellites and CubeSats comes from the small size of the satellite that limits the distance and thus separates the Magnetorquers and Magnetometers. This can possibly cause two problems: The magnetorquers and magnetometers will never be able to be used together due to the magnetic field interference between the two; and the core of the magnetorquer bends the magnetic field lines even when turned off due to the high permeability. This needs to be tested to see if the bending of the magnetic field lines through the magnetorquers is a significant amount enough to interfere with the readings of Earth magnetic field through the magnetometers.

1.1 Background Knowledge

Magnetorquers produce a magnetic moment and de-magnetising factor given by equation 1 and 2, respectively. The magnetic moment of the magnetorquers directly relates to the torque produced with equation 3. The more accurately this value is known, the more accurate the satellite pointing accuracy is. As the pointing accuracy is a requirement on most missions, including IRIS, the magnetic moment generated needs to be known to a certain accuracy. Measuring the active field produced by the magnetorquers at different known distances will allow the magnetic moment to be calculated from equation 4.

$$N_d = \frac{4[\ln ln\left(\frac{l_c}{r_c}\right) - 1]}{\left(\frac{l_c}{r_c}\right)^2 - 4ln\frac{l_c}{r_c}} \quad 1$$

$$D = \frac{r_c V}{2W_w}[1 + \frac{\mu_r - 1}{1 + \left(\mu_r - 1\right)N_d}] \quad 2$$

$$\tau_{mag} = D \times B \quad 3$$

$$B_{mag}(r) = \frac{\mu_o}{4\pi}\left(\frac{3r(D \cdot r)}{|r|^5} - \frac{D}{|r|^3}\right) \quad 4$$

In the above equations: N_d represents the de-magnetisation factor; l_c represents the length of the core; r_c represents the radius of the core; D represents the magnetic moment; V represents the applied voltage; W_w represents the resistivity of the wire; μ_r represents the relative permittivity of the core; τ_{mag} represents the torque caused by the magnetorquers; B represents the external magnetic field; $B_{mag}(r)$ represents the dipole generated magnetic field; r represents the distance from the magnetic moment to the location the magnetic field is measured.

The known physical parameters of the York University designed magnetorquers are shown in Table 4.

Table 5: Summery of Final Magnetometer Parameters

Parameter (Variable)	**Value**	**Units**
Maximum Power (P)	0.2	W
Voltage (V)	5	V
Total Resistance (R)	125	Ω
Length of Wire (l_w)	91.91	m
Radius of Wire (r_w)	0.0625	mm
Density of Wire (ρ_w)	8.96	g/cm^3
Resistivity of Wire (W_w)	1.36	$\frac{\Omega}{m}$
Number of Turns (N)	5119	
Number of Wraps (N_{wr})	13	
Radius of Core (r_c)	2.8575	mm
Length of Core (l_c)	5	cm
Density of Core (ρ_c)	8.74	g/cm^3
Relative Permittivity of the Core (μ_r)	100,000	
Demagnetising Factor (N_d)	0.0253	
Magnetic Moment (D)	0.213	A/m^2
Total Mass (m_{total})	21.6	g

Parameter (Variable)	Value	Units
Total Wound Radius (r_{total})	4.5	mm
Inductance (L)	1690	H
Time Constant (τ)	13.51	s^{-1}

1.2 Required Materials

- Magnetorquer/s
- LOTAD PCB
- PCB Mount
- Calibrated Venire Caliper
- Multimeter
- Power Source/ MCU
- Scale

1.3 Verification Mapping

All relevant requirements are listed in Table 5 with the verification map being shown in Figure 1. In the verification map, there are two types of verification: Primary and Secondary. Primary verification is the main method in which the requirement will be verified. Secondary verification is a secondary check or initial sanity check to be further verified by the primary verification. The results for each of the requirements and their status of verification is shown in Verification Matrix and Results.

Table 6: Relevant Magnetorquer Requirements

Identifier	Description	Parent Requirement	Verification Activity	In Valispace?
R-ADC-H-0017	ADCS hardware shall be capable to power on at temperatures from -10 to 45 C.	R-ADC-0056	V-ADC-0460	Yes
R-ADC-H-0110	ADCS board shall use three Torque rods as the satellite actuators.	R-ADC-0083	V-ADC-4080 (doesn't seem related)	Yes
R-ADC-H-0112	In ADCS hardware, Torque rods shall have a ground connection tied to the H-bridges.	R-ADC-0071	V-ADC-0550	Yes
R-ADC-H-0113	Torque Rods shall have a maximum geometric deviation of 1 degree from the normal orientation.	R-ADC-0045	V-ADC-0330	Yes
R-ADC-H-0114	The torque rods shall provide at least 0.1500 A.m^2 magnetic moment.	R-ADC-0560	V-ADC-0047	Yes
R-ADC-H-0115	The torque rods shall use a maximum power of ~~0.2 W~~ 0.67 W at peak operation conditions.	R-ADC-0570	~~V-ADC-4082~~ **V-ADC-4081**	Modified: 0.67 W peak usage
R-ADC-H-0116	Each torque rod shall be less than 60 grams.	R-ADC-0580	V-ADC-4083	Yes
R-ADC-H-0117	ADCS hardware shall make sure that no parts of the torque rods are detachable.	R-ADC-0028	V-ADC-4084	Yes
R-ADC-H-0118	H-bridges shall connect to ADCS ground bus.	R-ADC-0071	V-ADC-4085	Yes
R-ADC-H-0183	ADCS hardware shall ~~have one micro controller to~~ collect data from Torque rods.	R-ADC-0072	V-ADC-0563	Modified: detail removed

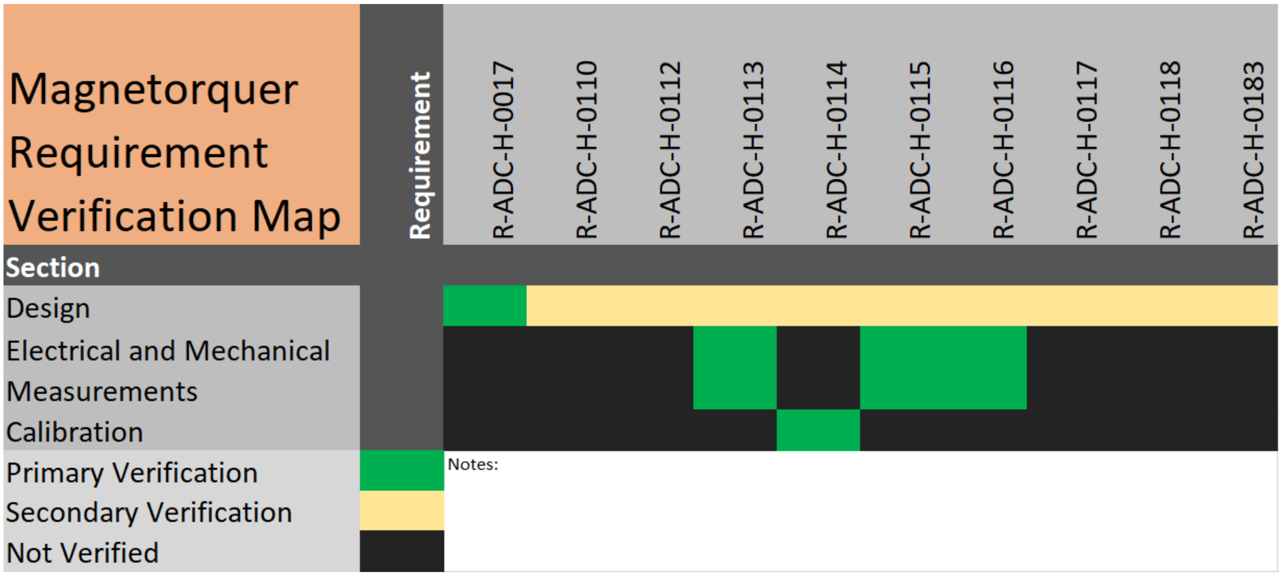

Figure 1: Magnetorquer Requirement Verification Map

2 Measurement Procedure

Three different experimental setups and measurement taking procedures are needed to properly characterise the magnetorquer and verify all relevant requirements. The four different experimental setups are: Design, Electrical and Mechanical Measurements, Passive vs Generated Magnetic Field, and Hard and Soft Iron Perturbations. Each of the experimental setups will have a short introduction, as well as the steps for properly taking measurements for each set up.

2.1 Design

The design experimental set up focuses on verifying the requirements that are met during the design process or through visual inspection. This has the format of stating the requirement, the brief explanation on the requirement and how it was either primary or secondary validated through the design phase.

R-ADC-H-0050:

This requirement specifies that all components will be able to be powered in the temperature range of -10 to 45°C. To verify this, Table 6 is a table of the survival temperature of the different components with the survival range at the bottom. This verifies this requirement for both components. The datasheet of the H-Bridges can be found in AD-3.

Table 7: Magnetorquer Component Thermal Range

Component	**Lower Thermal Bound**	**Upper Thermal Bound**	**Pass, Marginal, or Fail**
Magnetorquers	-80	80	Pass
H-Bridges	-55	150	Marginal
Thermal Range	-50	80	N/A

R-ADC-H-0050:

This requirement specifies that all components will have survival temperatures set by the thermal subsystem. Table 6 above is a table of the survival temperature of the different components with the survival range outlined by the thermal system at the bottom, which verifies this requirement.

R-ADC-H-0110:

This requirement specifies that the ADCS sub system is using magnetorquers as satellite actuators, which is verified through the design in which 3 magnetorquers are used. This can be seen in AD-1 and acts as the secondary verification with primary verification happening at the board level in AD-2.

R-ADC-H-0112:

This requirement specifies that the magnetorquers are attached to H-Bridges which are then attached to the ground. This shows that the current can be reversed in the magnetorquers to allow for positive and negative dipole to be generated. Through the design schematic shown in AD-1, the magnetorquers are shown to be connected to the H-Bridges, which are connected to the star ground, verifying this requirement. This acts as the secondary verification with primary verification happening at the board level in AD-2.

R-ADC-H-0113:

This requirement specifies that the magnetorquers are mounted in respect to the magnetorquer frames with less then 1^o difference. This is validated twice in this test procedure with the design portion being the secondary validation with the primary validation taking place in Electrical and Mechanical Measurements.

The secondary validation is done by looking at the accuracy of measurements with the available equipment at York University to make sure that the mounting accuracy can be measured within tolerances. Figure 2 and Figure 3 show the math for the different components verifying that York University has the required accuracy to verify this requirement.

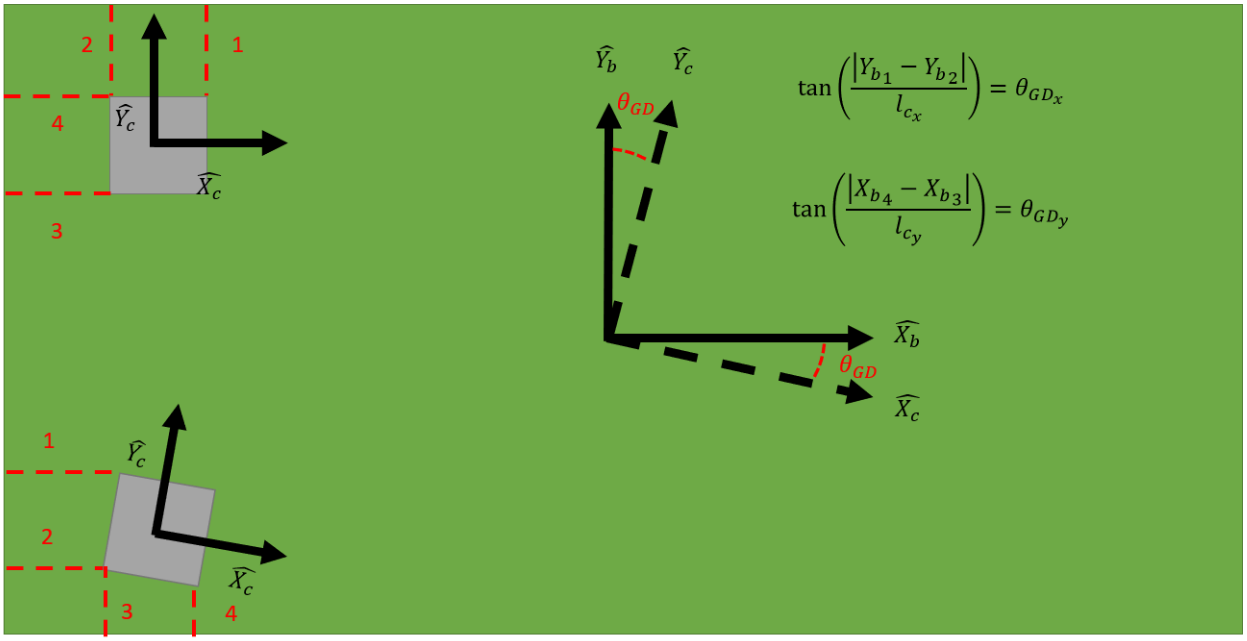

Figure 2: Geometric Model for Component Mounting and the Required Measurements

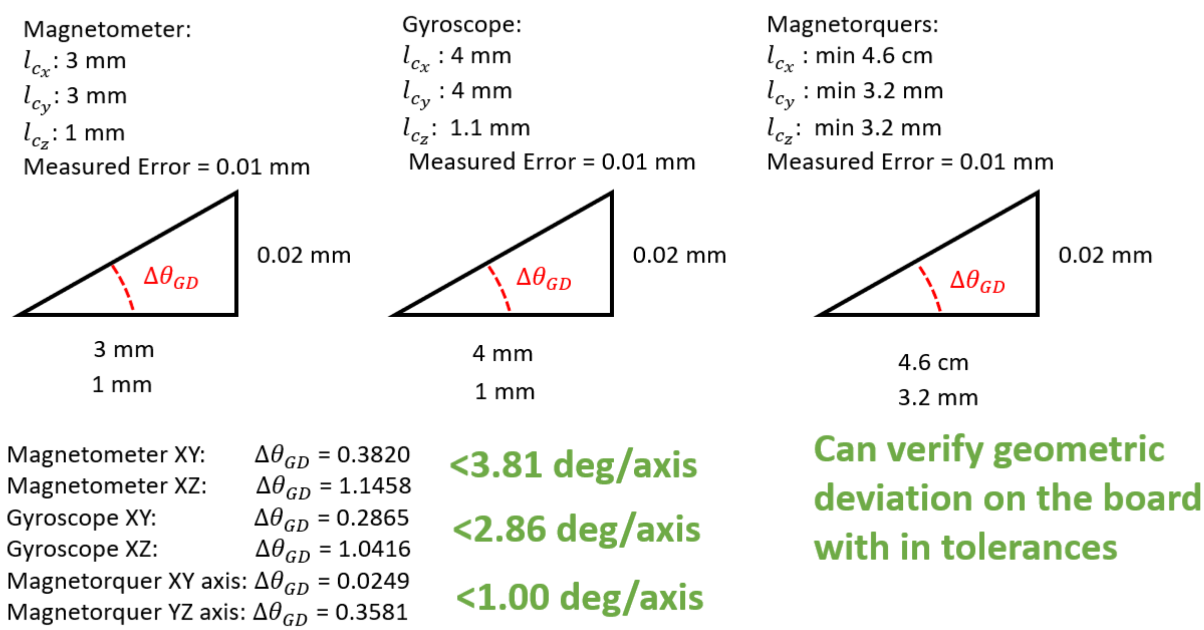

Figure 3: Sensitivity Analysis for Mounting Accuracy to Verify the Geometric Derivation of the Different ADCS Components

R-ADC-H-0114:

This requirement specifies that the magnetorquers provide the minimum magnetic moment required to control the satellite. This is validated twice in this test procedure, with the design portion being the secondary validation and the primary validation taking place in Generated Magnetic Field in section 2.3.

From Table 4 above we can see the magnetorquers are designed with a magnetic moment above the 0.1500 A/m^2 threshold value, verifying this requirement. For the calculation of this value please see AD-1.

R-ADC-H-0115:

This requirement specifies that the magnetorquer has a maximum power draw of 0.2 W, per magnetorquer. This was a constraint set during the design of the magnetorquers, which will allow it to be validated twice in this test procedure. The design portion is the secondary validation method, with the primary validation taking place in Electrical and Mechanical Measurements in section 2.2.

From Table 4 above, we can see the magnetorquers are designed with a power draw of 0.2 W, verifying this requirement. For the calculation of this value please see AD-1.

R-ADC-H-0116:

This requirement specifies that the magnetorquer has a maximum mass of 60 g per magnetorquer. This was a constraint set during the design of the magnetorquers, which will allow it to be validated twice in this test procedure. The design portion is the secondary validation method, with the primary validation taking place in Electrical and Mechanical Measurements in section 2.2.

From Table 4 above, we can see the magnetorquers are designed with a mass of 21.6 g, verifying this requirement. For the calculation of this value, please see AD-1.

R-ADC-H-0117:

This requirement make sure the magnetorquers do not have detachable parts that might come off in orbit. This requirement is validated at a magnetorquer level and again at the board level, with the primary validation being at the magnetorquer level and secondary at the board level.

Through the schematic design of the LOTAD and MOLTRES boards, it can be seen that all components are soldered to the board with all wires either being soldered or fixed with a harness. This verifies the requirement from a design standpoint.

R-ADC-H-0118:

This requirement makes sure that the H-Bridges are connected to the ground bus. Looking at the schematic of LOTAD, found in AD-1, it can be seen that the H-Bridges are connected to the ground bus, verifying this requirement. This acts as the secondary verification with primary verification happening at a board level in AD-2.

R-ADC-H-0183:

This requirement makes sure that there is a Micro Control Unit (MCU) to control and collect data from the magnetorquers. This is verified in the LOTAD schematic through the use of a ATMega328 MCU, which can be found in AD-1. This acts as the secondary verification with the primary verification happening at a board level in AD-2.

2.2 Electrical and Mechanical Measurements

The Electrical and Mechanical Measurements experiment focuses on verifying mechanical and electrical requirements through measurement. This will also be done to confirm design values that acted as secondary validation in Design section.

Required Equipment

- Magnetorquer/s
- LOTAD PCB
- PCB Mount
- Calibrated Venire Caliper
- Multimeter
- Power Source/ MCU
- Scale

Procedure

R-ADC-H-0113:

1. Mount LOTAD PCB down to a surface, it only needs to be mounted enough so it does not wiggle during measurement.
2. Locate the location of the two attached magnetorquers on LOTAD, the X and Y axis magnetorquers.
3. Referencing Figure 2 and Figure 3, prepare to take 4 different measurement for each magnetorquer will be taken, with 2 corresponding to each axis.
4. Starting with the first magnetorquer, take measurement 1 to 4 then repeat the same measurements with the second magnetorquer.
5. Record the results in a table similar to Table 7. There should be one table per magnetorquer.
6. When complete, look at the different axis combinations of the magnetorquer (X-Z, Y-Z) and repeat steps 3 to 5. This is done to get the Z axis geometric offset.

Table 8: Magnetorquer Geometric Offset Measurements

	Measurement #	Measurement	Degree Offset	Magnetorquer Average	Requirement Pass or Fail
X axis Magnetorquer	1				
	2				
	3				
	4				
Y axis Magnetorquer	1				
	2				
	3				
	4				

R-ADC-H-0115:

1. Hook up the power source / MCU to the magnetorquers. In both cases, make sure power is not immediately being supplied to the magnetorquer. The maximum power supplied should be 0.2W and it should always be at 5V. **If more than this is used it could damage the magnetorquer.**
2. Connect the multimeter in series between the magnetorquer and power source.
3. Measure the amps flowing through the magnetorquer for the bias current. *Note* Ideally this should be 0 amps
4. Supply 0.01W of power to the magnetorquer.
5. Measure the amps flowing through the magnetorquer and record the results in a table like Table 8 below. *Note* Make sure the amps stop fluctuating and reach steady state or near steady state before recording the measurement
6. Increase the power by 0.01W and repeat step 5 and 6 till the power reaches 0.2W.
7. Stop supplying power to the magnetorquer and after the magnetorquer has powered down disconnect the ammeter and power supply from the magnetorquer.

Table 9: Power vs Current Measurements

Volts Supplied (V)	Power Supplied (W)	Calculated current Draw (A)	Measured Current Draw (A)
5	0.01	0.002	
5	0.02	0.004	
5	0.03	0.006	
…			
5	0.20	0.040	

R-ADC-H-0116:

1. Take the chosen scale and put it on a flat hard surface.
2. Zero the scale.
3. Place one of the magnetorquers on the scale and measure the weight.
4. Take the magnetorquer off and zero the scale again.
5. Reweigh the magnetorquer to confirm the original value.
6. Once the value is confirmed record the value in Table 9 and repeat step 3-5 with all magnetorquers.

Table 10: Magnetorquers Weight Measurements

Magnetorquer	**Measured Weight w/o Mount (g)**	**Measured Weight w/ Mount (g)**	**Requirement Pass or Fail**
FM 1	1: 25.2	27.7	Pass Confirmed: GC, PK
	2: 25.3	27.5	
FM 2	1: 25.2	27.6	Pass Confirmed: GC, PK
	2: 25.2	27.6	
FM 3	1: 25.1	27.5	Pass Confirmed: GC, PK
	2: 25.1	27.5	
BUM 1	1: 24.8	27.5	Pass

	2: 24.8	27.4	Confirmed: GC, PK
BUM 2	1: 25.3	27.9	Pass Confirmed: GC, PK
	2: 25.3	27.9	
BUM 3	1: 25.2	27.6	Pass Confirmed: GC, PK
	2: 25.2	27.5	

Magnetorquer	**Diameter Size (MM)**	**Length (MM)**	**Requirement Pass or Fail**
FM1	1: 11.35	1: 59.9	Pass Confirmed: GC, PK
	2: 11.1	2: 59.87	
	3: 11.19	3: 59.92	
FM2	1: 10.23	1: 60.02	Pass Confirmed: GC, PK
	2: 10.68	2: 60	
	3: 10.83	3: 60.03	
FM3	1: 10.22	1: 60.32	Pass Confirmed: GC, PK
	2: 10.59	2: 60.33	
	3: 10.54	3: 60.34	
BUM1	10.10	60.25	Pass Confirmed: GC, PK
	10.01	60.20	
	10.07	60.22	
BUM2	9.41	60.21	Pass Confirmed: GC, PK
	9.65	60.17	
	9.96	60.16	
BUM3	1: 11.2	1: 62.41	Pass Confirmed: GC, PK

	2: 11.26	2: 63.0	
	3: 11.7	3: 63.08	

2.3 Generated Magnetic Field

The Generated Magnetic Field experimental setup is performed to see the strength of the generated magnetic field at known distances to calculate the effective dipole moment and power draw for the magnetorquers. Calibration between the estimated and true values of the dipole moment generated for different levels of power supplied to the magnetorquers is needed.

Required Equipment

- Magnetorquer(s)
- MCU / Power Source
- Calibrated Magnetometer
- Venire Caliper or other way to measure distance.
- Tape or Position Markers.
- Power Generator

Procedure

1) The first step is to prepare your flat desk space and make sure that no metal or electronical items are in the immediate vicinity.
2) Put tape over the area in a cross formation. Make sure the lines of the cross are as perpendicular as possible. This is done so that the distance from the magnetorquers center to each point is known.
3) Once the tape is placed, mark the different points that you would like the measurement to be taken at down the measurement axes. The two different lines in the cross should represent the different axis being looked at.
4) Prepare Table 10 below for each of the different plane configurations, as shown in the background information section both the $\hat{x}$ and $\hat{y}$ axis of the magnetorquer are symmetrical allowing for only one of the $\hat{x} - \hat{z}$ and $\hat{y} - \hat{z}$ planes to be tested.
5) If you are using a power source connect the magnetorquer to the power source. Make sure the power source is off. *NOTE* the magnetorquers can handle a maximum of 0.2w of power at 5V. **Do not go above this or damage to the magnetorquer or other equipment might take place.**
6) If you are using a MCU, connect the magnetorquer to the 5V and GND line and a simple code controlling the voltage should be used.
7) If you are using a zeroing chamber for the magnetometer, the next step is the zero the magnetometer. This is done by putting it in the zeroing chamber then hitting the zero button. *NOTE* the magnetometer might not be perfectly calibrated after the zero. To correct for this,

keep the magnetometer in the zeroing chamber and record the offset. *NOTE* Keep the zeroing chamber as far away from the magnetorquer as possible as the magnetic field can cause interference.

8) Start taking measurements with the magnetometer at the different measurements points which were selected in step 3. This can be done in order or randomly.
9) Once all the measurements are taken, the magnetometer should be zeroed and steps 6 to 9 are repeated for each round of measurements. Repeat as much as the confidence level required. The number of rounds of measurements controls the error in the system, with the more rounds that are taken the less human, random, and measurement error will be in the final results.
10) After all the round of measurements are taken with out the magnetorquer, the magnetorquer is placed in the center of the area and powered with 0.01W. Allow a few seconds for it to charge up.
11) Steps 7 to 10 should be repeated with different levels of power supplied to see the dipole response vs power supplied.
12) After all the measurements for one geometry have been taken, rotate the magnetorquer into a new geometry and repeat the measurements. This is done until all of the unique geometries for the magnetorquer have been rotated through.
13) These steps will need to be repeated for each unique magnetorquer.

Table 11: Magnetorquer Generated Field 0.01W $\hat{x} - \hat{y}$ Calibration

Magnetorquer Generated Field 0.01W $\hat{x} - \hat{y}$ Calibration				
Round #	**Distance from Center**	**Magnetic Field X Axis**	**Magnetic Field Y Axis**	**Magnetic Field Z Axis**
1				
1				
1				
2				
2				
2				

Table 12: Magnetorquer Generated Field 0.01W $\hat{y} - \hat{z}$ Calibration

Magnetorquer Generated Field 0.01W $\hat{y} - \hat{z}$ Calibration				
Round #	**Distance from Center**	**Magnetic Field X Axis**	**Magnetic Field Y Axis**	**Magnetic Field Z Axis**
1				
1				
1				
2				
2				
2				

3 Data Analysis

Using the relationship between the magnetic field and diploe moment, shown in equation 5 below, an overdetermined system is produced. Turning this into spherical coordinates allows us to isolate for the dipole moment as shown in equation 6 and 7, with the conversion for $\hat{r}$ and $\hat{\theta}$ shown in 8 and 9.

$$B_{mag}(r) = \frac{\mu_o}{4\pi}\left(\frac{3r(D\cdot r)}{|r|^5} - \frac{D}{|r|^3}\right) \tag{5}$$

$$B_{mag}(r) = \frac{\mu_o D}{4\pi r^3}\left(2 \cos cos\,(\theta)\hat{r} \;+\; \sin sin\,(\theta)\,\hat{\theta}\right) \tag{6}$$

$$D = \frac{4\pi r^3 B_{mag}(r)}{\mu_o\left(2\cos cos\,(\theta)\hat{r} + \sin sin\,(\theta)\,\hat{\theta}\right)} \tag{7}$$

$$\hat{r} = \frac{r}{|r|} \tag{8}$$

$$\hat{\theta} = [\cos cos\,(\theta)\;\; \cos cos\,(\varphi)\quad \cos cos\,(\theta)\;\; \sin sin\,(\varphi)\quad \sin sin\,(\theta)\;\;] \tag{9}$$

Comparing the measured average dipole and uncertainty for each given power input gives the true power verses dipole curve in contrast to the ideal dipole curve shown below. While they should be similar, the calibrated (true) dipole curve will allow the dipole to be generated more accurately helping with the pointing accuracy and detumble.

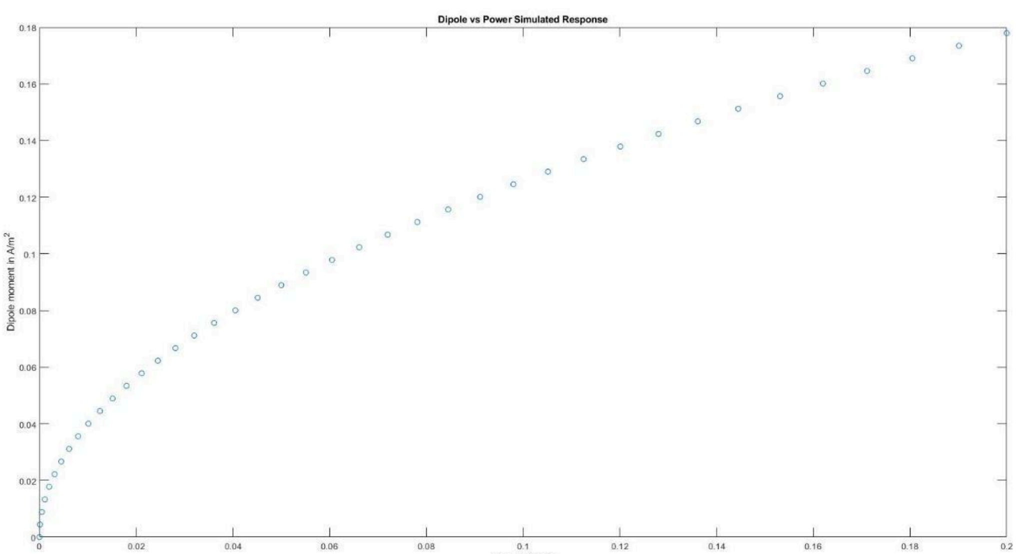

Figure 4: Ideal Power vs Dipole moment Curve

4 Conclusion

After following all of these steps, the verification activities and calibration should be completed for all the Magnetorquer specific requirements. The current status of the completed verification activities and their status are shown below.

4.1 Verification Matrix and Results

Table 13: Verification Status Matrix Legend

Abbreviation / Colour	Meaning
P / Green	Pass
F / Red	Fail
TBP / White	To Be Performed
NCS / Orange	Non Compliance Submitted
NA / Grey	Not Applicable
UoM / Blue	Verification to be completed at University of Manitoba

Table 14: Verification Status Matrix

Identifier	Primary Verification	Secondary Verification
R-ADC-H-0017	P	N/A
R-ADC-H-0110	UoM	P
R-ADC-H-0112	P	P
R-ADC-H-0113	TBP	P
R-ADC-H-0114	TBP	P
R-ADC-H-0115	TBP	P
R-ADC-H-0116	P	P
R-ADC-H-0117	TBP	P
R-ADC-H-0118	UoM	P
R-ADC-H-0183	TBP	P
Total Distribution		
Status	**Primary**	**Secondary**
Pass	3	9
Fail	0	0
To Be Performed	5	0
Non Compliance Submitted	0	0
Verify at UoM	2	0