MXL Tech Memo

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MICHIGAN EXPLORATION LABORATORY

Revision history:

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1 Introduction

MCubed-1 was originally launched and deployed in October of 2011. The mission experienced a significant setback when it effectively docked with the Montana State CubeSat. It is believed that this attraction was due to the particularly strong permanent magnets housed in both MCubed and the Montana State Sat. A graduate investigation proved this hypothesis as plausible. To mitigate this risk on MCubed-2, we are considering two magnetic control options: passive (through a permanent magnet and hysteresis rods), and active (through use of an in house magnetorquer). This memo documents the research and design progression for both, and also includes [trade studies on similar missions, an order of magnitude disturbance torque calculation, and a description of planned manufacturing and testing].

As of March 2013, the flight build for M-Cubed-2 current baselen for M-Cubed-2 is: a neodymium ring magnet with a strength of 0.168 A-m^2 and a coil of 30 AWG wire, 193 turns, and a maximum magnetic moment of 0.36 A-m^2 @8.2V and 100% duty cycle. This comesfrom an enclosed area of 6.5 cm x 6.5 cm (more accurately, 45.87 cm^2)

Be warned, this was a working document for reference and so some passages don't follow particularly clearly.

2 Order of Magnitude Torque Disturbances

The worst case torque generated by environmental disturbances is used to size the permanent magnet/-magnetorquer. M-Cubed must overcome the worst case torque in order to control the satellite in any given situation. Although it is unlikely that M-Cubed-2 will be exposed to the worst case torque in space (all disturbances acting in the same direction), we still sum the torques from the [residual dipole, gravity gradient, atmospheric drag, and solar radiation pressure].

Magnetic Disturbance Torque

Magnetic dipoles stem from two sources. First, they can occur transiently from the on-board electronics–especially high-current modules such as radios. Also, the structure of the spacecraft may contain a residual dipole that can also be a source of unwanted disturbance angular moments. As a rule of thumb, residual dipole moment on spacecraft is around 0.01 A-m^2.

$$\vec{B_{Earth}} = \frac{\mu_0 M}{4\pi r^3}\sqrt{1+sin(\lambda)^2} \tag{1}$$

Where $\frac{\mu_0 M}{4\pi}$ is the magnetic dipole moment from the Earth, R is the distance to center of the Earth, λ is the magnetic latitude.

$$T_{res} = \vec{M_{res}} \cdot \vec{B_{Earth}} = 0.01Am^2 \cdot 4\times10^{-5}T = 4\times10^{-7}Nm \tag{2}$$

Where $\vec{M_{res}}$ is the residual dipole of the spacecraft.

Gravity Gradient

$$T_g = (I_{max} - I_{min})3n_{max}^2 = (0.0005kg\cdot m^2)3(0.00108\frac{rad}{s})^2 = 1.75\times10^{-9}Nm \tag{3}$$

Where I is the principle moment of inertia in that axis, and n is the angular rate of orbit.

Atmospheric Drag Force

$$F_d = \frac{1}{2}\rho v^2 C_d A(\vec{N}\cdot\vec{D}) \tag{4}$$

Where ρ is the atmospheric density at the orbit altitude, $\vec{N}$ is the normal vector of the body face, C_d is the coefficient of drag, A is the cross sectional area, and v is the velocity relative to atmosphere.

Atmospheric Drag Torque

$$\tau = P\times F_d = \frac{1}{2}(4.89\times10^{-13}\frac{kg}{m^3})(7550\frac{m}{s})^2 2.5(0.01m^2)0.02m = 6.97\times10^{-9}Nm \tag{5}$$

The torque then, is generated by multiplying with P the lever arm, which is the distance between center of aerodynamic pressure and geometric center (<2cm by CubeSat requirements).

Solar Radiation Pressure

$$T_S = \frac{\phi}{c^2}A(1+Q)(N \cdot S)d = \frac{1367\frac{W}{m^2}}{3 \times 10^8}\frac{m}{s}0.01m^2(1+0.8)0.2m = 1.64 \times 10^{-9}Nm \tag{6}$$

ϕ, universal solar constant c, speed of light Q, panel reflectance S, sun vector (gives angle of incidence)

Torque Type	N · m
Residual Dipole Torque	4.00×10^{-7}
Aerodynamic Torque	6.97×10^{-9}
Gravity Gradient	1.75×10^{-9}
Solar Pressure	1.64×10^{-9}
RMS Sum	4.1×10^{-7}

This results are corroborated with the conclusions from AAU Sat and the CalPoly PolySat.

3 Passive Magnetic Control

Passive Magnetic Stabilization is a popular technique to stabilize CubeSats and has been demonstrated in orbit. QuakeSat, Delfi-C3, and GeneSat are some of several CubeSats currently in orbit utilizing permanent magnets for stabilization. In a low inclination orbit, the magnets will tend to point towards the magnetic north like a compass needle, whereas in a higher inclination orbit such as polar orbit, a magnetically stabilized satellite would perform two cycles per orbit, where it would line up north-to-south over the equator, and tumble over the Earths magnetic poles to line up with the Earths magnetic dipole.

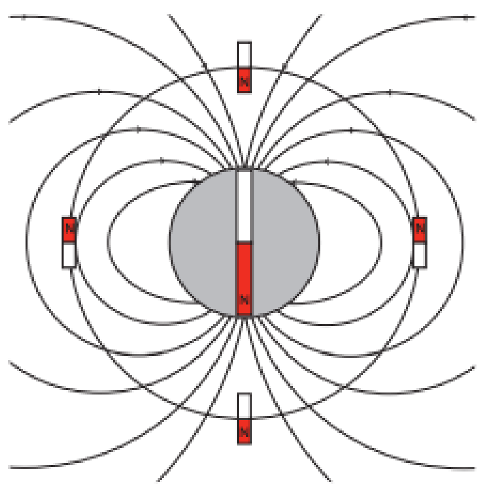


Figure 1: A permanent magnet aligns with Earth's magnetic field

- No power consumption
- No data handling and no computational requirement
- Limited nadir pointing capability at high latitudes
- The permanent magnet induces an undesired oscillatory motion of the satellite due to the principle of conservation of mechanical energy.
- Rotation around the magnet axis in magnetic stabilization is uncontrolled. Spin about the magnet axis, if present, introduces gyroscopic stiffness about the magnet axis.

Characteristic frequency of the oscillatory motion:

$$f = \frac{1/2}{\pi} * \sqrt{\frac{|\vec{m}| * |\vec{B_E}|}{I}} \tag{7}$$

3.1 Permanent Magnet

The choice of a suitable permanent magnet is based on an iterative process, where different magnetic materials and sizes are considered. Two different types of magnets have been considered: AlNiCo-5 and rare earth magnets such as neodymium:

Type	ρ[g/cm^3]	H$_c$[A/m]	B$_r$ [T]
AlNiCo-5	7.3	5.09×10^4	1.25
Neodyme Iron bore (NdFeB)	7.5	1.50×10^6	1.3

where B$_r$ is the remanence (measuring the strength of the magnetic field created by the magnet), and H$_c$ is the coercivity (material's resistance to becoming demagnetized). Neodymium magnets have much higher coercivity than AlNiCo magnets. Materials with low coercive forces such as AlNiCo-5 is easily demagnetized if not handled with care. Bringing together poles in repulsion would lead to the loss of magnetization. For optimum performance of AlNiCo-5, the magnetic length should be approximately 5 times the other typical dimensions of the rod. If this geometry is used, the risk of demagnetization is lowered.

AlNiCo and Neodymium magnets are hard and brittle. In general, it is preferable to store magnetized materials under vacuum-sealed film so that the magnets do not collect ferromagnetic dust particles over time. These are the primary figures of merit for selecting a permanent magnet:

- **Environment**: The permanent magnet must be suitable for use in space and the size must be small enough to fit in the CubeSat. On MCubed, we have a vertical high constraint of 25mm as decided by the structures team. This can be allocated between a magnetorquer board and the coils themselves.
- **Magnetic field strength**: The magnetic field strength of the permanent magnet affects both the output torque and the measurements from the magnetometer.
- **High remnance**: The higher the magnetic field strength remnance, the smaller weight and size the magnet can be for a given output torque.
- **High coercitivity**: A high resistance towards demagnetization is preferable as the permanent magnet will be exposed to various magnetic fields originating from the on board magnetorquers.
- **Suitable operating temperature**: Both neodymium and AlNiCo-5 have operating temperatures between -100°C and 80°C, making them suitable for use in space.

- **Low corrosion resistance**: High corrosion resistance is preferable for use in satellites. However, the surface of the magnet can be protected by coatings with high corrosion resistance e.g., stainless steel.

We begin by considering the strength of magnetic dipoles employed by recent CubeSat missions (table).

Mission	Magnetic Dipole ($A\text{-}m^2$)	Material	Dimensions	Notes
MCubed	1.415			
RAX/RAX-2	3			Magnetic moment decreased significantly after launch
AAUSAT3	0.0030	N35 sintered neodymium	1mm x 2mm.	Coercitivity=892e3 A/m, corner placement
E1P	1.856			
Kysat-1	0.59	AlNiCo-5	0.59^3	
AubiSat-1	0.5			
XI-IV	0.046			
MUNIN	0.3			21x2121 cm
UNISAT-4	1			Massive mini-sat
QuakeSat	2.933	AlNiCo 8He	0.6x0.6x10	4 of those magnets
CPoT		Neodymium 35		
CSSWES	0.3		xxx	
CalPoly	0.2			Describes 0.2 as a "good compromise" to perform detumbling in a reasonable ammount of time.
OUTFI-1	0.32	AlNiCo-5	4x4x20 mm	1U, use 2 rods
Hermes	0.005 Amp/m^2 (I know)	1in x 3/16 in		

The Colorado Student Space Weather Experiment (CSSWE) studied the publications of Santoni and Zelli, controls engineers on UNISAT-4 who recommended this general rule of thumb for magnet sizing:

$$m \leq 10\frac{T_{RMS}}{B_{min} \cdot sin(\beta_{max})} = 10\frac{4.1 \times 10^{-7}}{2.0 \times 10^{-5} \cdot sin(20deg)} = 0.5847A - m^2 \tag{8}$$

where T_{RMS} is the root means squared sum of independent environmental torques, B_{min} is the minimum field strength at 600 km (2.0 $\times 10^{-5}$ Tesla), and β_{max} is the desired point accuracy. The 10 comes in from increasing the bar strength by an order of magnitude to account for demagnetization during integration and launch. Note that decreasing the strength of the bar magnet would also decrease the required hysteresis material within the volume-limited CubeSat.

3.1.1 Magnet Acquisition

M-Cubed and RAX magnets were manufactured and purchased by Storch Magnetics. For the sake of heritage, MCubed-2 originally baselined the same supplier. Storch Magnetics provides small magnets in a variety of dimensions (diameter, length) and can custom size them to order. The AlNiCo-5 are magnetized to full saturation–magnetic field (rather than magnetic moment) is measured on the end surface of the magnet (in Gauss).

Magnetic field is related to the magnetic moment by:

$$B_{axis} = \frac{\mu_0}{4\pi}\frac{2 * m * r}{(r^2 - l^2)^2} \tag{9}$$

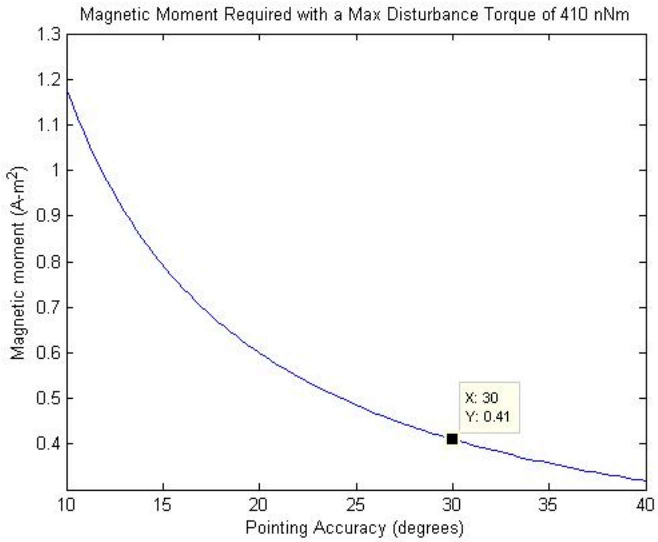


Figure 2: Magnetic Moment Required with a Max Disturbance Torque of 410 nNm

Material	Diameter	Length	Magnetic Field Reading (Gauss) at Distance from Surface (inch)	Mag Moment (A-m^2)
AlNiCo-5	0.187	0.75	111@ 0.5	0.086
AlNiCo-5	0.25	1	111@ 0.75	0.46
AlNiCo-5	0.312	1	111@ 0.875	1.05
AlNiCo-5	0.375	1	111@ 1	1.89
AlNiCo-5	0.437	1	111@ 1.12	2.96

Here, μ_0 is the permeability constant (4 π $\times 10^{-7}$ T/mA), r is the distance from the center of the dipole in meters, m is the magnetic moment, and l is the length of the magnet. The magnet is sized iteratively with Storch, since they build a magnet to order via size and fully saturate it. In order to find the magnetic moment of the magnet, they measure the magnetic field in the far field (¿2 times the length). Storch provided 5 experimental samples and we solved for their magnetic dipoles via:

$$m = \frac{B_a xis 4\pi (r^2 - l^2)^2}{\mu_0 r} \tag{10}$$

Update: The main concern with using neodymium magnets is that they are not as stable at high temperatures. There are different heat rated neodymium materials and we needed to ensure that our selected magnet met the maximum bakeout temperatures of 100 degrees celsius. In addition to the material, geometry actually plays a role in the stability. Al-Ni-Co-5 magnets meet the stability requirements, but we used the calculators on K J magnetics to determine if a neodymium magnet was stable or not. Because neodymium magnets are smaller for the same dipole, a neodymium magnet was ultimately chosen M-Cubed–R422. The magnetic moment of 0.163 A-m^2 was achieved by stacking two R422 magnets on top of each other. This was done because (1) such a dimensioned ring magnet was not sold by K J Magnetics with the desired strength, (2) stability was still guaranteed at higher temperatures, and effectively lengthening the magnet only makes it stabler.

3.1.2 Magnet Selection

Before the final magnet is selected, the following parameters had to be confirmed and agreed upon:

- The residual dipole of the spacecraft is 0.001 $A - m^2$. Conflicting sources have called for 0.01 and 0.001.
- The pointing accuracy (used in the Colorado sizing equation) should be 30 degrees.
- The magnet will likely be demagnized (by X amount) during transportation, storage, integration, vibe and launch. The RAX-2 magnets lost 67 percent of their magnetization by the time they reached orbit. Demagnetization not likely caused by cutting set screw channel as long at it is cut in the South pole.
- Based on the above items and the median dipole strength of the 1U CubeSat magnet trade study (=0.50 $A - m^2$), we should select a magnetic dipole of 0.4 $A - m^2$.
- This leads to the expected Gauss, length and diameter of the bar magnet.
- The maximum height of the magnet should be less than or equal to 1 inch.

3.2 Hysteresis Material

Magnetic hysteresis is a physical property of ferromagnetic material. The material becomes magnetized when an external magnetic field is applied forcing the magnetic domains on the atomic level to polarize. Depending on the magnetic remanence of the material, it will retain a magnetic dipole of some strength when the external magnetic field is removed. Typically, hysteresis rods are mounted in pairs orthogonal to the bar magnet to maximize dampening per rod.

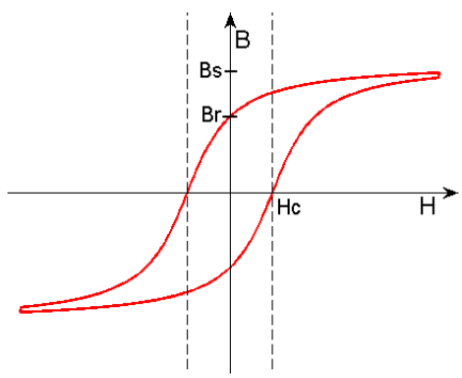


Figure 3: Generalized hysteresis curve

The magnetic coercivity of the material is the intensity of the external magnetic field applied against the polarity of the material required to diminish the magnetization to zero after it has been driven to saturation. The lag (or Hysteresis) in tracking the externally applied magnetic field caused by the coercivity and remanence of the ferromagnetic material results in energy lost as heat in the material. The phenomenon can be thought of as the magnetic dipoles having friction when their orientation changes.

Magnetic hysteresis material, when chosen with low enough coercivity that the Earths magnetic field is sufficient to magnetize and demagnetize it, is an effective angular rate damping method for light weight satellites. It is also a completely passive and simple solution; it is only required to include a calculated amount of hysteresis material on board the satellite to achieve damping.

Quantifying the amount of hysteresis material to include in a satellite design is challenging. The amount of damping caused by hysteresis material is not a fixed or calculated amount, it is a result of the behavior of the hysteresis material interacting with the Earths magnetic field.
The magnetic moment of the hysteresis material is found from:

$$k = tan(\frac{\pi M_r}{2M_s H_c}) \tag{11}$$

$$M = \frac{2M_s}{\pi} tan^{-1}[k(H + / - H_c)] \tag{12}$$

$$m = MnV \tag{13}$$

Where M_r is the remanent magnetization or remnance, M_s is the spontaneous magnetization corresponding to the saturated state where $M = M_s$, H_c is the coercivity, H is the magnetic field strength along the axis of the rod, k is the dimensionless forming factor, V is the volume of each rod, n is the number of rods along each principal axis, and m is the dipole moment induced on the rod.

$$\vec{m}_{hysteresis} = \frac{\vec{B}_{hysteresismaterial} \vec{V}_{hysteresis}}{\mu_0} \tag{14}$$

where $\vec{V}_{hysteresis}$ is the volume of the hysteresis material along the three axes.
We begin by observing the heritage of hysteresis rods on CubeSats. There are two primary materials used: HyMu80 and Permenorm.

Quantity	Hy-Mu-80	Permenorm
ρ[g/cm^3]	8.747	8.25
H_c[A/m]	1.59	5
B_s[T]	0.73	1.55
B_r[T]	0.35	0.755
$B_s \cdot H_c$[J/m^3	1.16	7.75

Mission	Material	Dimensions	Notes
MCubed	HiMu80	0.063cm thick	1g in each axis
RAX/RAX-2	HiMu80	7 x 0.25 x 0.063 cm	0.11 cm^3, 0.96 g
Quakesat	Permalloy 49NM	0.6x1.25x31cm	Two pieces
Hermes	Ni80/Fe15.5/Mo4.5	1in x 3/16 in	Coercitivty=1.59 A/m, Saturation=0.73T, Remanence=0.35T
KySat	HuMu80	0.8cm^3 per axis	2 axes, 8 rods
MUNIN	Permallloy 79NM	0.93 cm^3	
UNISAT-4	Permalloy 79NM	15cmx 0.1cm diameter	mass=1.35g
Delfi-C3	Permenorm 5000H2		1 per axis
CSSWE	HuMu80	1mm x 9.5	
Turksat 3USat	HyMu80	0.48cm^3	6 rods total
OUFTI-1	Permenorm 5000 H2	1mm diameter, 2.5$\times$10^{-7} m^3	4 bars

After reviewing the governing equations and lessons learned from a variety of spacecraft, the following general guidlines regarding hysteresis material can be deduced:

- The oscillation frequency about the magnetic field lines increases the stronger the magnets are.

- The greater the amount of hysteresis material, the greater the steady-state error (lag) relative to the magnetic field lines.
- The hysteresis material may suffer from saturation from the permanent magnets included in the satellite, since hysteresis material is not truly anisotropic (directional). A bias in the hysteresis material would make the earths magnetic field sweep smaller areas and reduce heat loss. The performance of a certain amount of hysteresis material would be overestimated under this phenomenon. This motivates including a larger amount of hysteresis material.
- Other components in the spacecraft, such as the structure for example, contribute to damping with hysteresis and Eddie Current effects to a small degree. The hysteresis effects the satellite undergoes would be under-estimated when simulated for a certain amount that is assumed to be solely due to hysteresis material. This motivates a conservative design.
- Satellite material surrounding the hysteresis material could shield the magnetic field, and make it less effective. This factor motivates including more hysteresis material.

3.2.1 Hysteresis Selection and Acquisition

The current M-Cubed 2 baseline is to fly approximately 0.9 g. M-Cubed, RAX, and RAX-2 all flew aproximately 1g of hysteresis strips and M-Cubed-2 will build on that heritage. The hysteresis material is to be obtained from Magnetic Shield Corp, and we still have some material left over that we plan to use. The most current baseline is:

Mission	Material	Dimensions	Notes
MCubed-2	HiMu80	0.063 x 4.566 x 0.383 cm	0.9 g in each axis

4 Active Magnetic Control

A magnetorquer consists of a coil of wire that produces a rotational torque when an electric current is passed through the coil similar to inductors. Unlike inductors that are wound to produce maximum inductance, magnetorquers are wound to provide maximum rotational torque on the coil For CADRE they will provide momentum dumping for the reaction wheels and will work on three axes. For MCubed-2, they solely control orientation by aligning with the Earth's magnetic field.

- Low power consumption and low mass
- Suitable for restricted volumes due to custom design possibility
- No moving elements
- Slow transient response due to low torque production capacity
- Uncertainty in magnetic field model and errors in measurements can lead to unstable control. Even the most accurate models (such as IGRF) are only approaching reality.

In orbit, this presents the problem that only two axes are controllable at any given time. Since the spacecraft experiences two full rotations of the Earths magnetic field per orbit, though, all axes are controllable over time.

Magnetic dipole moments are produced by magnetorquers, which are proportional to the electric current running through them. The magnetic dipole, m, produced is defined by:

$$\vec{m} = N * i * A * \hat{n} \tag{15}$$

Here, N refers to the number of turns, i is the electric current, A is the area of the coil, $\hat{n}$ is the normal vector of the coil. If the magnetorquer vector is not aligned with the Earths magnetic field at its location, a torque is induced on the coil of wire defined by:

$$\vec{\tau} = \vec{m} \times \vec{B} \tag{16}$$

4.1 Literature Review

Mission	**Type**	**Magnetic Moment ($A\text{-}m^2$)**	**Power (mW)**	**Mass (g)**	**Size**	**Notes**
AAUSat	Air Core		122	20	8cmx9cm	X-Sec $A=10mm^2$, C=356mm, R=100 ohms, Vbus=10V
AAUSat-3	Iron Core	0.03	6.8	19	200	XXX
CanX 2	3 Air Cores	0.1	40	100	XXX	5-35°C, built own winder
COMPASS-1	Air Core	0.085	26	19.2	400 turns	XXX
U Toronto GNB	Air Core	0.19	26	104	210 turns	XXX
GNB (2)	XXX	0.19	21	108	235 turns	XXX
Illinois, ION	Air Core	0.149	100	XXX	1500 turns	1.32e-8 m^2 X-sectional area, f Belden heavy armored poly-thermaleze 38 AWG
Illinois, TinySat	PCB Traced	XXX	114mA	XXX	120 loops	R=96.3Ω, 0.0007 in wire
CalPoly PolySat	PCB Traced		300mA		54 turns	0.1503 m^2
Cute 1.7	3 Air Core	0.15	91	5	58.5 x 78.3 mm	2U Cubesat, 1 coil, 13mA drive current
SwissCube	3 Air Core	0.0285	XXX	XXX	XXX	Bdot and LQR
ISIS	Alloy Core	0.2	200	30	7 cm x 1 cm	-35 to 75°C, 1200
CubeTorquer	Iron Core	0.2	209	22	6 cm x 1 cm	Supra50 core, 1200 Euro

4.2 Vacuum Core vs. Solid Core vs. Inscription

Introducing a metal core in the magnetic torquer increases the dipole moment of the solenoid by up to 300 times (gain factor k=100-300). To reach the same dipole moment with an air core magnetic actuator, you need to either increase the enclosed area/number of turns (and thus mass) or increase the current flowing through the windings (and thus power). However, the air core still has a lower specific mass because the added solid core outweighs the extra required windings.

The previous equation for magnetic moment is modified to:

$$\vec{m} = kNi\vec{A} \tag{17}$$

where k depends on the length/diameter shape factor and permeability of the material.

While a ferromagnetic core rod will enhance the efficiency of the magnetic torquer, a main drawback comes from the non-linear hysteresis. Different possibilities exist to take care of the non-linear behavior. The first possibility is simply to stay in the linear range of the ferromagnetic coil. This technique however limits the magnetic moment for a given weight of ferromagnetic core. The second possibility is to use some methods to extend the linear range of the torquer. For fairly big magnetic torquers, a common way to do so is to sense the magnetic field near the torquer in order to generate a feedback signal. Another way is to use a mathematical model of the hysteresis, keeping in mind that the magnetic moment of the coil changes slowly for a given input due to the hysteresis of the core.

Air cores are typically constructed first as a pathfinder before moving into solid core torquerods. A significant motivation for this is the physical winding process and structural mounting. When winding around an iron core, care must be taken to evently distribute each layer of turns and also, most winders (specifically the ones in Moldwin's lab) are not setup to rotate around a metal core. For these reasons, most university satellite missions use air cored magnetorquers. Indeed, we have not found any university materials documenting fabrication of an iron core magnetorquer. Kevin, an MXL visitor, used to make air core (due to their simplicity in manufacturing) and now he has graduated to iron core.

Common materials for a solid core are: iron cobalt and nickel-iron.

Figure of Merit	Air Core	Solid Core
Strength	Only active while current passes through, k=1	Retains non transient magnetic moment. k=100=300
Mass	No core but more wires::less mass	Add heavy ferromagnetic solid core
Power	Higher current required for a given area/number of turns	Lower power dissipation across the wire, but potentially extra control actuation due to hysteresis
Hysteresis	Minimal transient hysteresis	Requires extensive ground testing and characterization of the hysteresis of the soft core
Mounting	Larger area footprint, but easy to design custom mount	Requires fabrication of a housing that does not interfere with the dipole
Heritage	Has been used on most CubeSats flown to date that are actively controlled	Commercially available, Most graduate to iron core fabrication after successful implementation of vacuum core

A minority of CubeSats currently being designed are baselining a magnetorquer with wire inscribed into layered PCB. Many challenges must be overcome before successfully flying. First, the team must quantify the dielectric effect from the pcb (compared to air/ferrite core). Second, sizing becomes a challenge. With each line unable to overlap, the effective area gets larger with every turn. This limits the number of turns. Finally, cost is the major driver as multilayer inscribed pcb can be very expensive. To our knowledge, no tests have been conducted on these experimental torquers.

The following was extracted from the MXL design document from W2012. No other resource has referenced this phenomenon: An air core magnetorquer expands and contracts with the thermal environment in orbit. As it changes shape, the torque it provides also changes based on the radius of the coils. This requires sensors on the torquers to give the temperature to the computer to calculate the size of coils and change the current needed for the required torque. Iron core magnetorquers do not change in shape as drastically and so they require fewer sensors and less control by the computer.

4.3 Sizing Attempt 1

By reviewing the governing equations for torque generated by the torque coils, we can deduce the following general design rules:

- The area enclosed by the magnetorquer should be as large as possible in order to reduce the required current and number of windings.
- The magnetorquer should consist of a large number of windings, which also reduce the required current. However, increasing the number of windings adds more weight to the satellite and also takes up more space.
- The current is preferred to be as small as possible to minimize the power consumption. However, reducing the current means that the number of windings must be increased.

The coil design is based on four equations, one for mass, one for power dissipation, one for coil resistance and one for the producible magnetic moment. The mass of one coil can be determined by:

$$M_c = nCa_w\rho \tag{18}$$

Where n is the number of turns, C is the circumference, a_w is the wire cross sectional area, ρ is the wire material density. The power dissipation in a coil can be determined by:

$$P = U_{coil}I = I^2R \tag{19}$$

Where U_{coil} is the voltage supplied to the coil, I is the current in the coil, R is the resistance of the coil. The coil resistance is given by:

$$R = \frac{nC\sigma(T)}{a_w}, \sigma(T) = \sigma_0(1 + \alpha_0 T) \tag{20}$$

Where n is the number of turns, C is the circumference, $\sigma(T)$ is the wire resistivity with temperature coefficient α_0, and a_w is the wire cross sectional area.

From these equations, along with the magnetic moment equation, we can derive a relation between mass, power and magnetic moment.

$$M_c = (\frac{mC}{A})^2\frac{\rho\sigma}{P} \tag{21}$$

4.3.1 Explanation of Sizing Code

The magnetorquer sizing code is designed to take in three inputs/ranges and output the design space of all possible coil designs that satisfy the input constraints. Currently, the code takes as input the desired magnetic torque, the footprint area range, and the mass range. However, these variables could very well have been turn number and cross sectional area, or other parameters so long as they are independent. Area and mass were chosen for simplicity of visualization.

Given an area, mass and torque, Matlab determines the equivalent magnetic moment. The problem then becomes determining the other parameters. Resistance (and subsequently Power) depend on wire length, as does number of turns.

However, we can solve for the power dissipated in solely the coil from the previous equation:

$$P = \frac{\rho_w \sigma_T m^2}{M_c} (\frac{C}{A})^2 \tag{22}$$

Now that we know power, we obtain the coil resistance from:

$$P_{coil} = \frac{V_{bus}^2}{(R_{coil} + R_{hbridge} + R_{filter})^2} R_{coil} \tag{23}$$

by solving iteratively (there is a closed form quadratic solution). This gives two possible values of R_{coil}, a high an a low, which may be imaginary if the mass and area are not sufficient for the torque.

Knowing coil resistance, we find the cross sectional area for this element:

$$a_w = \sqrt{\frac{M_c \sigma(T)}{R_{coil} \rho_{cu}}} \tag{24}$$

Now finding the number of turns is trivial:

$$N = \frac{M_c}{C a_w \rho_c u} \tag{25}$$

This completes the design trade space. Filtering out power consumption, or number of turns can be done to converge on the optimal solution.

4.3.2 Sizing Downselection

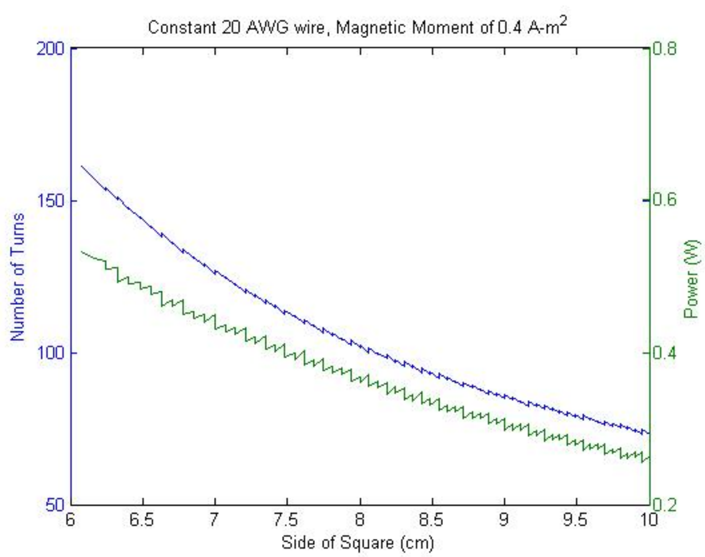


Figure 4: 20 AWG wire with 0.4 A-m^2 mag moment

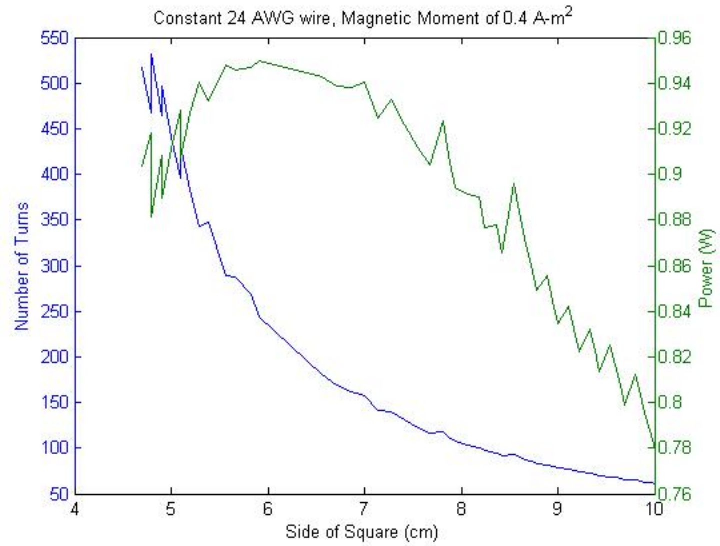


Figure 5: 24 AWG wire with 0.4 A-m^2 mag moment

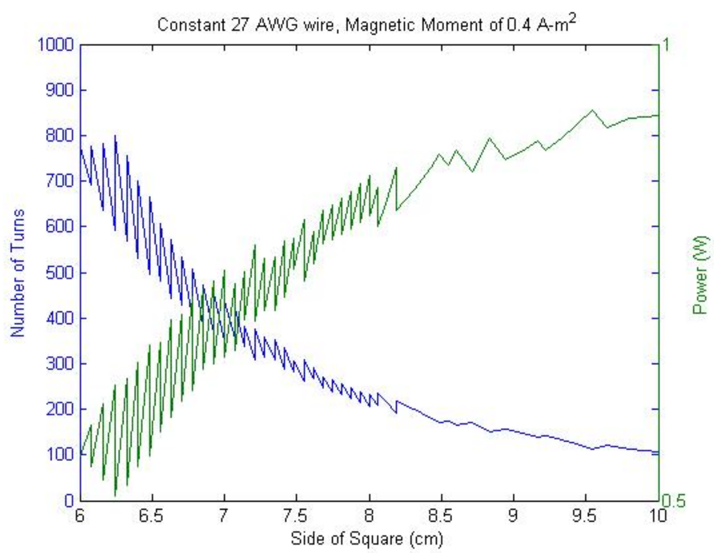


Figure 6: 24 AWG wire with 0.4 A-m^2 mag moment

4.4 Sizing Attempt 2

A second, update procedure we coded up after sizing attempt 1 in order to (1) better understand the design space, and (2) restrict the potential sizes to descrete wire gauges. This resulted in a series of plots that showed trends much more clearly. From these, we were able to select a coil for EDU that did not draw more than 2W of power from EPS and did not mass more than 50g. The currently baselined torquer is shown in the next table. These were generated from $magnet_size_2.m$

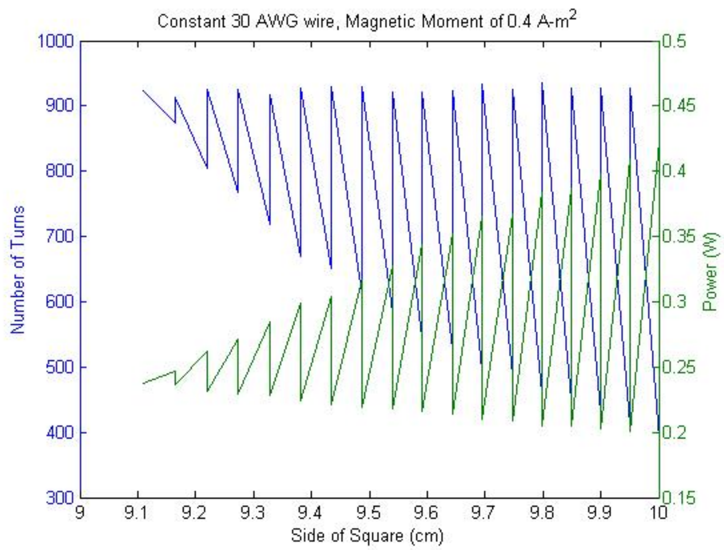


Figure 7: 30 AWG wire with $0.4A - m^2$ mag moment

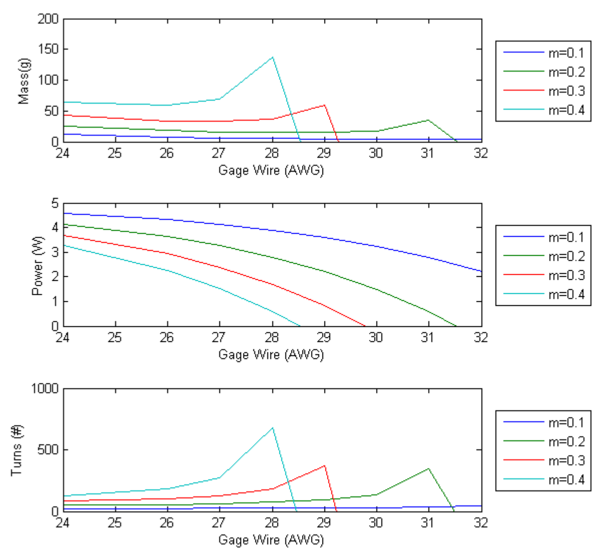


Figure 8: A bus voltage of 5V, no filter resistance

4.5 Construction of Air Core

The construction of our air core magnetorquer is described in greater detail in the MCubed Torquer Fabrication Procedure document. The coil was hand wound and the wire was procured from SPRL who got it from MWS. The wire is technically expired so that SPRL cannot use it for flight, but we checked and it will be fine for our purposes. . Using the winder is mostly only useful for counting the number of turns (via an encoder). As long as someone is dedicated enough to thoroughly and accurately count by hand (me), there's no reason handwinding (with gloves) won't work. David Boprie hand wound many of his flight magnetometers.

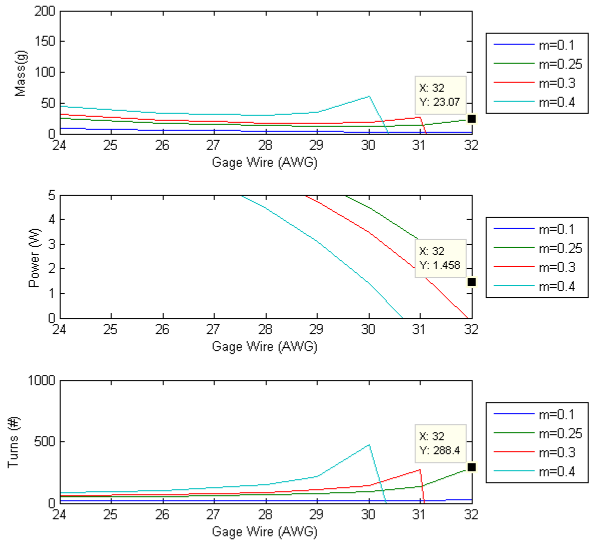


Figure 9: A bus voltage of 8.2V, hbridge resistance of 7 ohms

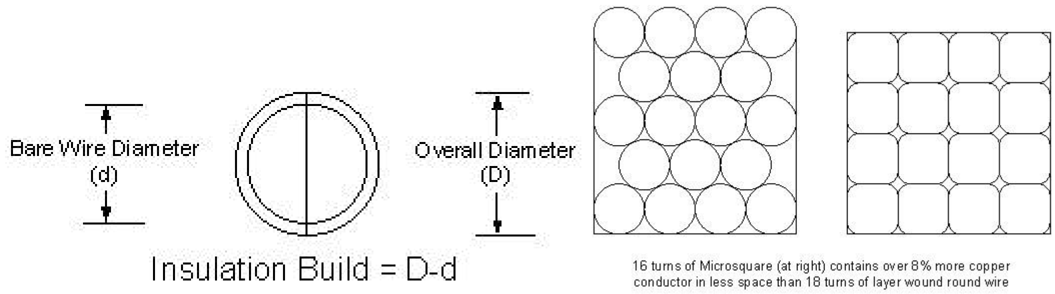
Figure of Merit	Value
Magnetic Moment	0.42 A-m^2 @8.2V @ 100 percent duty
Area Footprint	0.0049 m^2
Side Length	7.5 x 6.5 cm
Mass (just pure copper)	28 g
Cross sectional area	30 AWG
Turn count	220
Coil Resistance	20.0 Ohms
Coil Inductance	7 mH

4.5.1 Magnet Wire Considerations

The insulated copper or aluminum conductor typically used in magnetorquers is known as magnet wire (or alternatively, winding wire) and is also used to wind EM devices like motors and transformers. Aluminum is lighter and less costly per pound than copper. However, the disadvantages include electrochemical decomposition, lower fatigue strength, and the buildup of a hard sapphire oxide coating. In addition, resistivity is higher at 16.782 ohms/cmf compared with 10.371 for copper. The conductivity of electrical conductor grade aluminum wire (Alloy 1350-0) is 61.8 percent of the equivalent cross-sectional area of annealed ETP copper. Therefore aluminum wire must have 1.6 times the cross sectional area for a given copper wire in order to achieve a comparable DC resistance.

The insulation may be a fibrous polyester or fiberglass yarn, a thin film of varnish called enamel, or a combination of both. There are a number of film insulation types ranging from temperature Class 105 to Class 240. Each film type has its own unique set of characteristics to suit specific needs of the user.
For example, many have a nylon (polyamide) topcoat. Nylon is hygroscopic, meaning it absorbs moisture from the surrounding environmnet. With regards to outgassing, the melting temperature of nylon is 258C, but no decomposition products will result from melting. At 160-170C nylon will oxidize and change crystalline structure to where absorbed moisture will be driven off. Thermal degradation of the polymer begins

between 350-400C with ammonia, carbon monoxide and oxides of nitrogen out-gassing.



Square wire is useful where space constraints are concerned. When formed into a coil an equivalent amount of square wire put in a coil can be placed in a tighter coil configuration than the same amount of round wire. However, square wire is less common, more expensive, and not a driver for MCubed-2.

A lubricant is usually applied to film coated magnet wire to ensure compact winding and ease of de-reeling. Lubricants commonly used are very dilute solutions of paraffin wax or mineral oil in a volatile solvent. Isoparaffinic fluids have also been used in certain applications. Without the application of lubricant the winding on the spool may be spongy or become tangled and difficult to de-reel. However, special orders can be manufactured without lube on request.

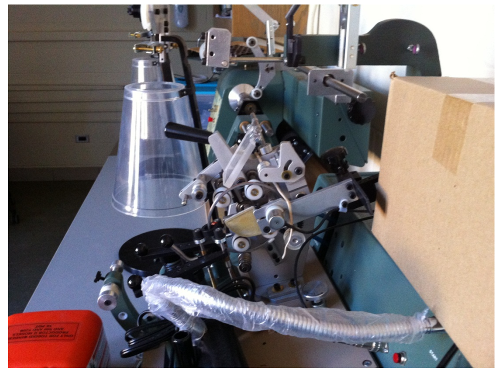
Magnet wire shelf life is not established in commercial specifications. As long as the wire has been carefully stored it may be usable for years to come. The enamel on the magnet wire surface is very stable in ambient environments. Storage in any dry, room temperature environment will ensure the best shelf life. Bare copper and silver items react to oxygen and other trace elements in the air. To slow surface oxidation on bare or plated items they are packaged in anti-tarnish wrappers and plastic bags.

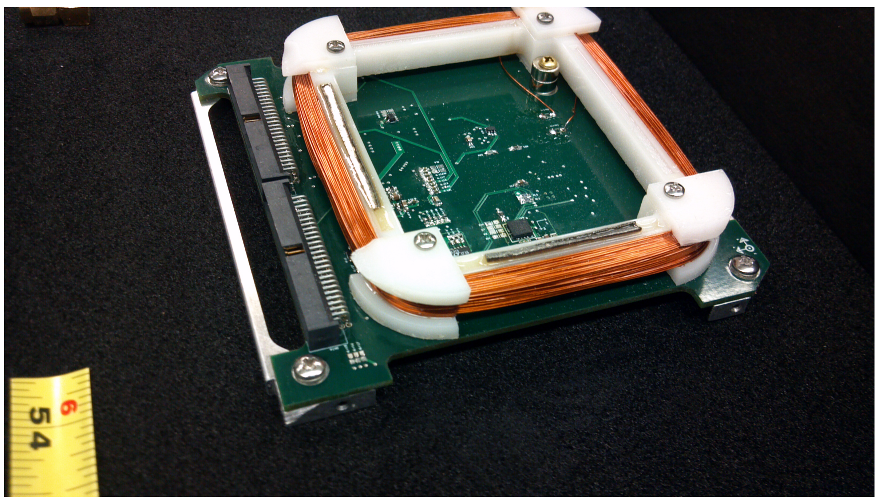
There are two basic techniques for de-reeling round wire. In the first the spool is in a fixed, stationary position where the wire is pulled over one flange and routed through guides and devices to control back tension. A disc fitted with thin plastic filaments at its circumference (wisker disk) can be placed on the spool flange to pre-tension the wire as it passes the spool flange, or a rotating flyer device can be used to guide the wire as it is pulled off the spool. The stationary spool method is unsuitable for flat wire and ribbon because they can permanently twist when de-reeled in this way. In the second technique, the spool rotates on a shaft or other support mechanism and braking force must be carefully applied to provide consistent back tension without stretching the wire.

Outgassing is definitely a concern for the magnet wire. If the manufacturing process isn't space rated, the coating will melt off during thermal cycling or outgas off in hard vacuum. If the enamel comes off, the wire immediately shorts and the magnetorquer does not function as a magnetorquer. The procedure for finding the best wire (as described by Kevin) is to acquire a bunch of wire from a bunch of companies and tested them ourselves (measure total resistance of wire before winding and after TVac to tell if there is a short).

4.5.2 Magnetic Wire Selection and Acquisition

We obtained many free samples from every major magnet wire supplier (Essux, Zeus, Rea etc), but in the end SPRL had free wire and that is what we ulitmately use. MWS is the supplier.





4.5.3 Coil Fabrication

SPRL applies a varnish ontop of the coil once it's been wound to 1) add a protective layer, 2) keep the wire fixed and in place during shake and bake. They use a varnish called Scotch Cast 280. It consists of two types of resins (A and B). There is a special application procedure involving mixing+baking+curing (technically it's proprietary, but we can probably get a copy).

4.5.4 Winding/Mounting

This section is currently under construction
Be wary of winding the wire directly on the PCB (what Kevin and Tyler had done). The PCB can flex and break, even if the wire tension is at a constant 1 ounce during winding. A better idea would be to make a mold, coat the mold in (turtle) wax, and wind the wire on the wax covered mold. Then heat up the wax (which melts off), loosening the coil and allowing it to be slipped off. All that is necessary to hold the magnetorquer down is a few L-brackets and a couple beads of epoxy (minimal to not affect magnetic strength). Tyler had used a manual lathe to wind the coil with an encoder (counter) and a wire feeder (for constant friction tension).

The second revision of the magnetorquer mount is a single block that is able to be removed from the PCB in the case that the PCB has to be replaced.

5 Electrical Control

Discuss PWM signal control. The current baseline is pulsing the coil (no PWM)

6 Testing

In order to understand how we will integrate magnetic torquers with CADRE, it is necessary to confirm the properties of currently selected torquer. We will do this by testing the torquers characteristics and comparing them with calculations.

Properties for verification:

- Linear range of dipole moments
- Saturation moments
- Residual moments
- Power consumption
- Time constant
- Thermal effects on resistance
- Current range for nominal dipole moment

To ensure that each magnetorquer would perform as expected, each one was subjected to a test in a low-vacuum and a magnetic field test. The low-vacuum test was to ensure the bonding agent did not posess any air bubbles. Each one was put in a bell jar where the pressure was dropped to 50 mbar for 15 minutes. The magnetorquers were also subjected to a magnetic field test to see if they would produce the necessary field. First a known current was passed through the coils and a calibrated magnetomer was used to measure the magnetic field of the coil that resulted along the central axis.

Since metallic objects have significant effects on the magnetic field of the torquer it is important to perform this test in an open field. Metallic objects inside the building distort distribution of the magnetic field lines and cause large experimental errors. Having metallic objects within 1000 mm and keeping magnetometer in axial direction of the torquer will reduce magnetic interference and provide more precise results. Based on tests performed by other groups, it has been noted that misalignment/misplacement of magnetic sensor allows for larger deviation curves. Its important not to place the sensor too far from the torquer because the magnetic field would be weak and disturbances from noise would dominate.

Materials:

1. Magnetometer
2. Driver Board
   (a) Pulse Width Modulated chip/MSP430
   (b) H-Bridge
   (c) Current Sensor
3. 3.3 V or 5 V Power source
4. Computer

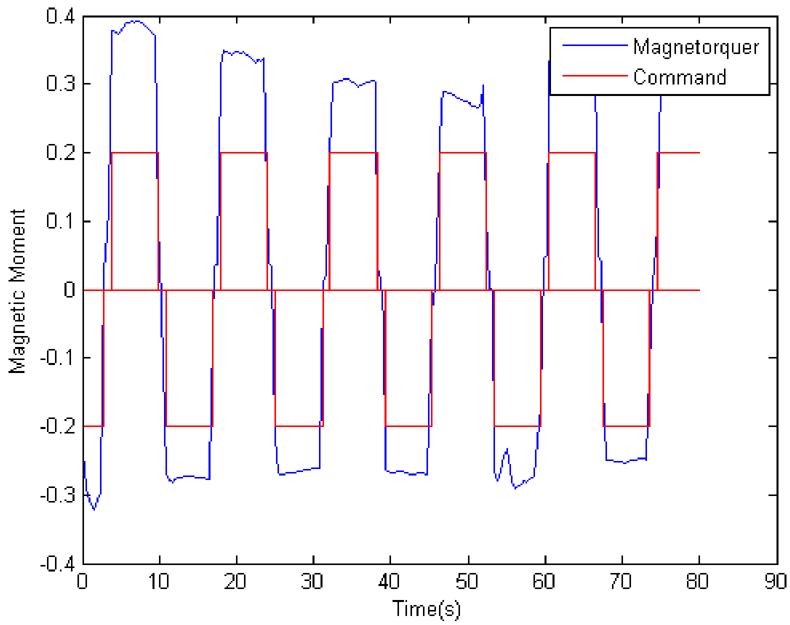


Figure 10: Testing results from JPL rev 1 board performed on 11/25/2012. Note, the command signal is misleading–the amplitude is irrelevant, was just using it for timing.

5. Low-pass filter

Procedure:

1. Place the magnetometer 120 mm (2L) away from the magnetic torquer to maximize measurement efficiency and avoid deviations.
2. Estimate/Approximate Earths magnetic field prior to applying voltage to the torquer by measuring initial field. This is needed in order to subtract it from the achieved in the test measurements.
3. Start at zero Voltage and gradually increase it to 8 V, then decrease it back 0 V and observe second zero voltage. This part will allow the observation of the hysteresis effect.
4. We want to measure the period between the second zero voltage and the power getting turned off. This will help us characterize the residual dipole moment.
5. After the power-off period, decrease the command voltage from 0 to -8 V and then increase it back to 0 V. Observe the effect and record the measurements.
6. Calculate deviation from tested measurements and those provided by the manufacturer.

An initial test was performed on the rev1 torquer used to demo for JPL. A camera was used to caputure readings from the magnetometer and was post processed to record the state at 2 Hz. The magnetic moment was about as expected (noise).

7 Summary and Recommendations

This document has described the theory and heritage for magnetic control of CubeSats. Torquer development will continue to occur in parallel with the permanent magnet/hysteresis materials. [25] [24] [23] [22] [21] [20] [19] [18] [16] [15] [14] [13] [12] [11] [10] [9] [?] [8] [7] [6] [5] [4] [3] [2] [1] [26] [17]

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