Smaller Satellites, Bigger Return

A Versatile Magnetorquer Design for Microsatellite Constellation Missions

2020 Frank J. Redd Student Competition

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Motivation

- Satellite constellation missions becoming very popular
- Microsatellite technology accelerating to extend payload capabilities
- Magnetic attitude control is an effective and inexpensive approach for small satellite constellations in Low Earth Orbit (LEO)
- The magnetorquer developed for constellation missions:
  - Has a single design for each satellite platform
  - Improves assembly and test efficiency
  - Reduces non-recurring engineering efforts

Magnetorquers

- Magnetorquers generate a magnetic dipole that interacts with Earth's magnetic field to torque the spacecraft
  - Coarse attitude control
  - Reaction wheel momentum management
  - Detumbling from high angular body rates

$$\boldsymbol{\tau_m} = \boldsymbol{m_m^{\times}} \boldsymbol{B} \qquad \boldsymbol{m_m} = I\boldsymbol{A}N$$

$\boldsymbol{\tau_m}$: Magnetic Torque

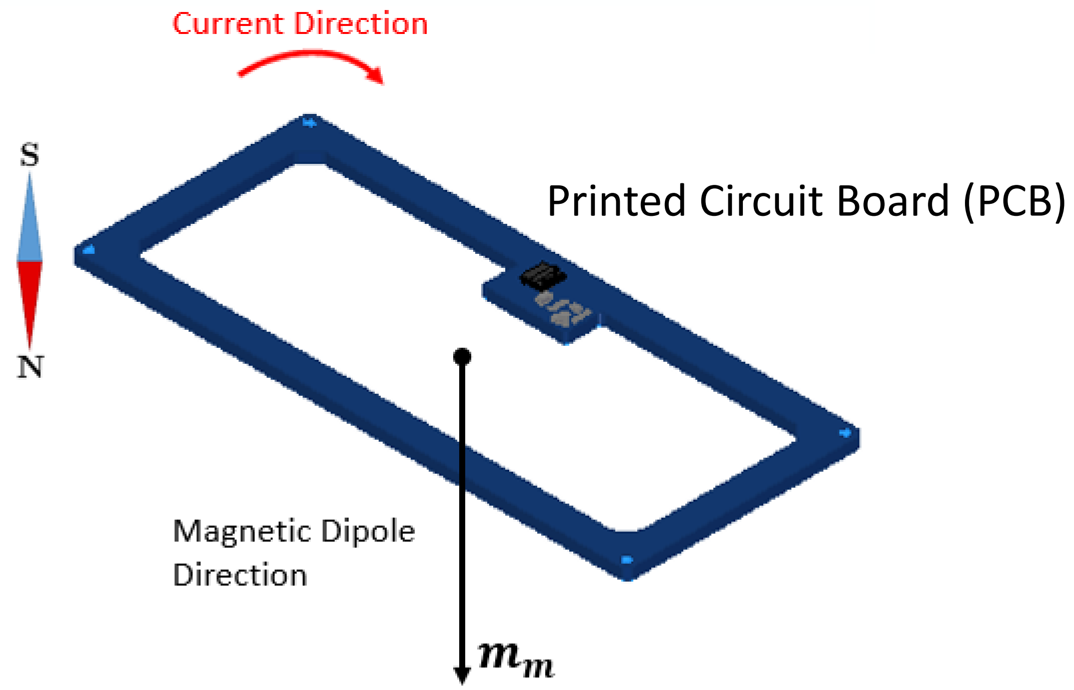
$\boldsymbol{m_m}$: Magnetic Dipole

$\boldsymbol{B}$: Earth's Magnetic Field

I: Current

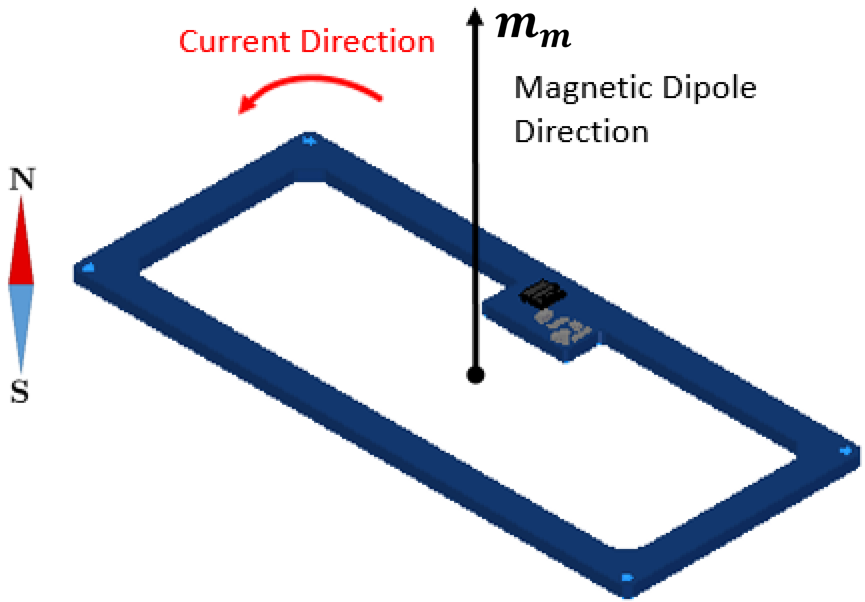
$\boldsymbol{A}$: Area Vector

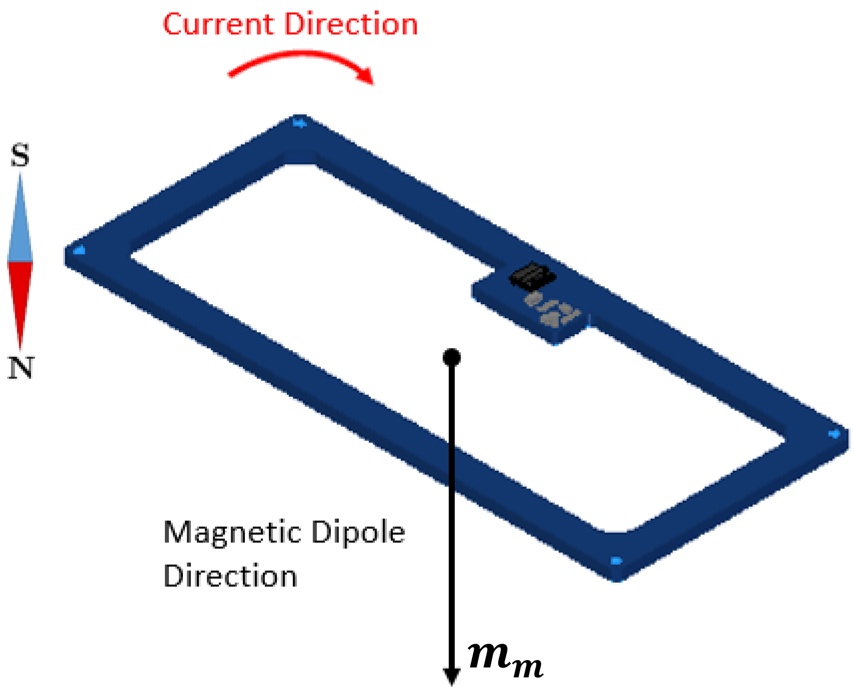
N: Number of coil windings



Magnetorquers

- An H-bridge circuit controls the current direction, which changes the magnetic dipole direction





Magnetic Dipole Requirement

- For a rigid spacecraft with reaction wheels, the motion expressed in the body frame is governed by Euler's equation:

$$\boldsymbol{I_b}\dot{\boldsymbol{\omega}}_{\boldsymbol{b}} + \boldsymbol{\omega_b}^{\times}(\boldsymbol{I_b}\boldsymbol{\omega_b} + \boldsymbol{h_w}) = \boldsymbol{\tau_c} + \boldsymbol{\tau_d}$$

- Over time, the wheels accumulate and store angular momentum while compensating for disturbance torques acting on the spacecraft:

$$\Delta\boldsymbol{h_w} = \int_{\boldsymbol{t_o}}^{\boldsymbol{t_f}} \boldsymbol{\tau_d}\, dt$$

$\boldsymbol{I_b}$: Inertia Matrix, $\boldsymbol{\omega_b}$: Angular Velocity, $\boldsymbol{h_w}$: Wheel Momentum, $\boldsymbol{\tau_c}$: Control Torque, $\boldsymbol{\tau_d}$: Disturbance Torque

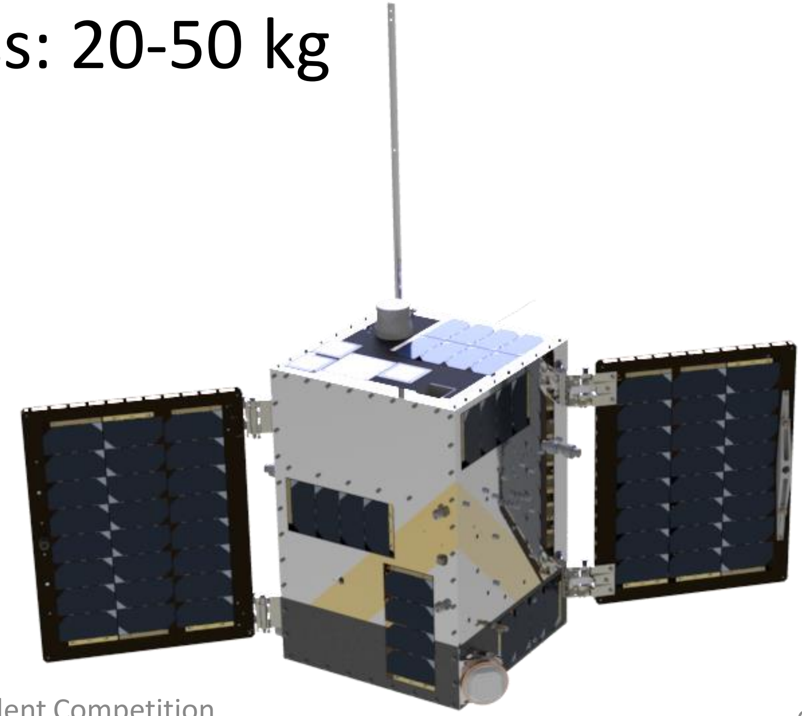
SFL Satellite Platforms

SPARTAN Platform

- 6U XL nanosatellite
- Mass: 6-12 kg

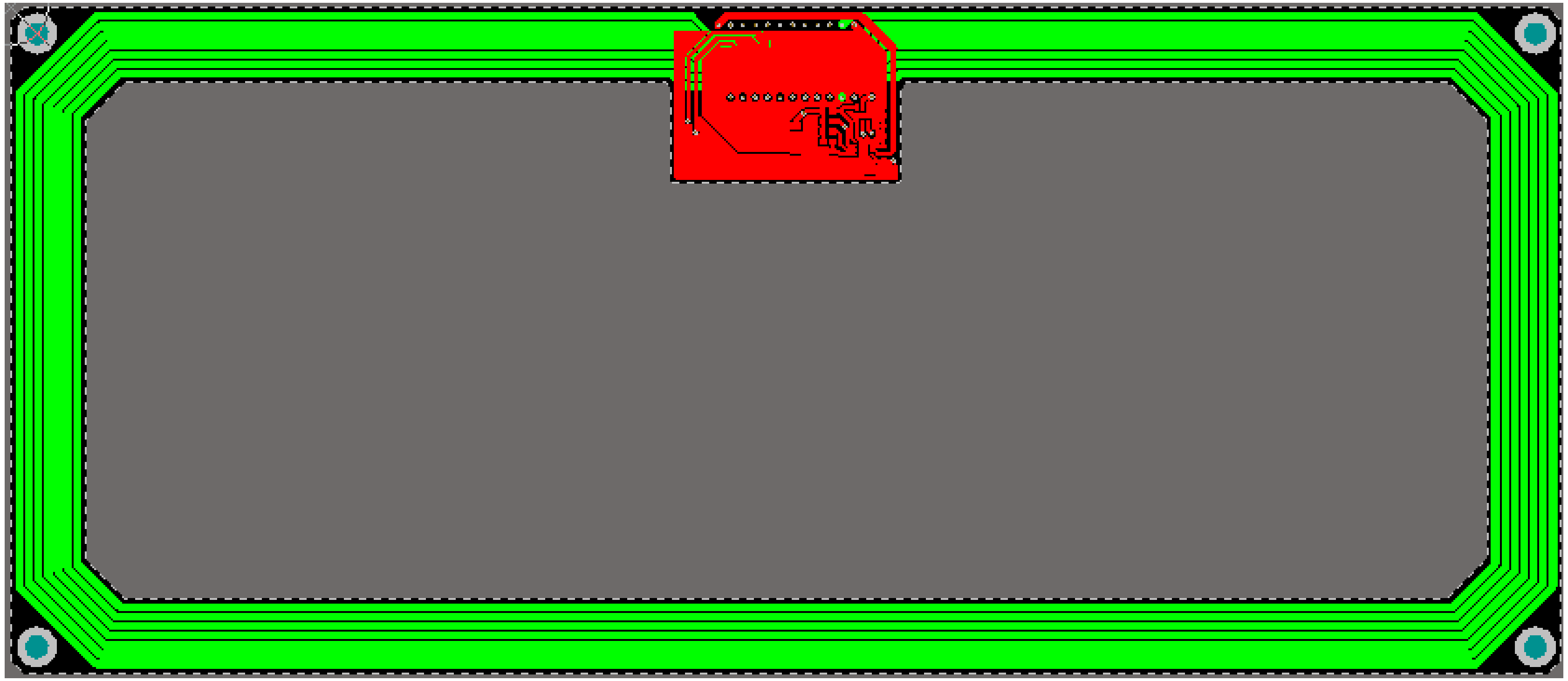
DEFIANT Platform

- 36cm x 36cm x 45cm microsatellite
- Mass: 20-50 kg



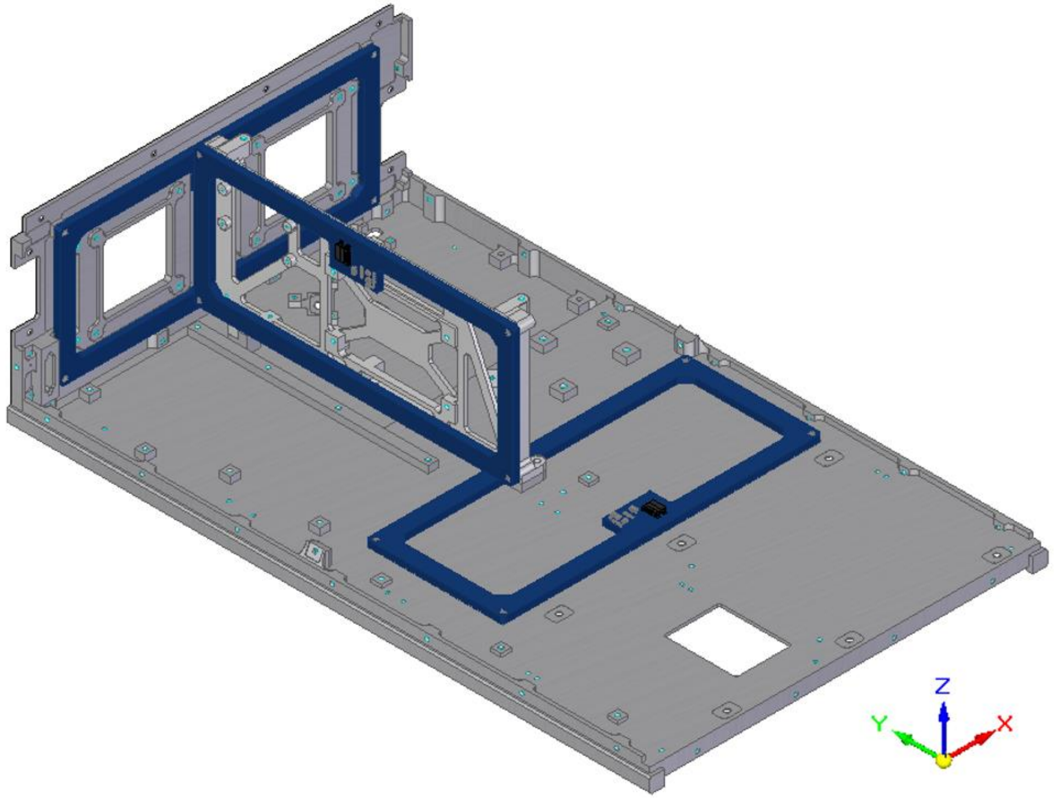
SPARTAN Magnetorquer Design

- Printed Circuit Board (PCB) with embedded coils
  - Multiple layers of coil loops connected through vias

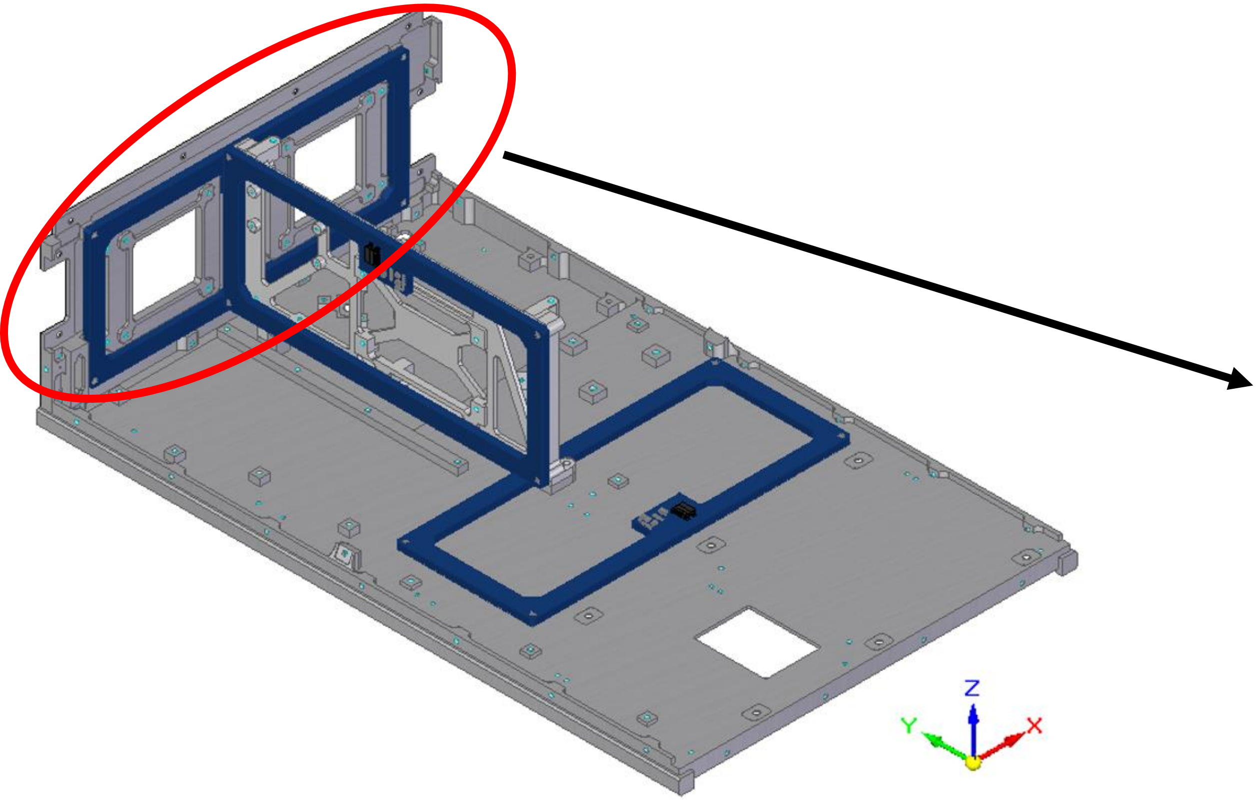


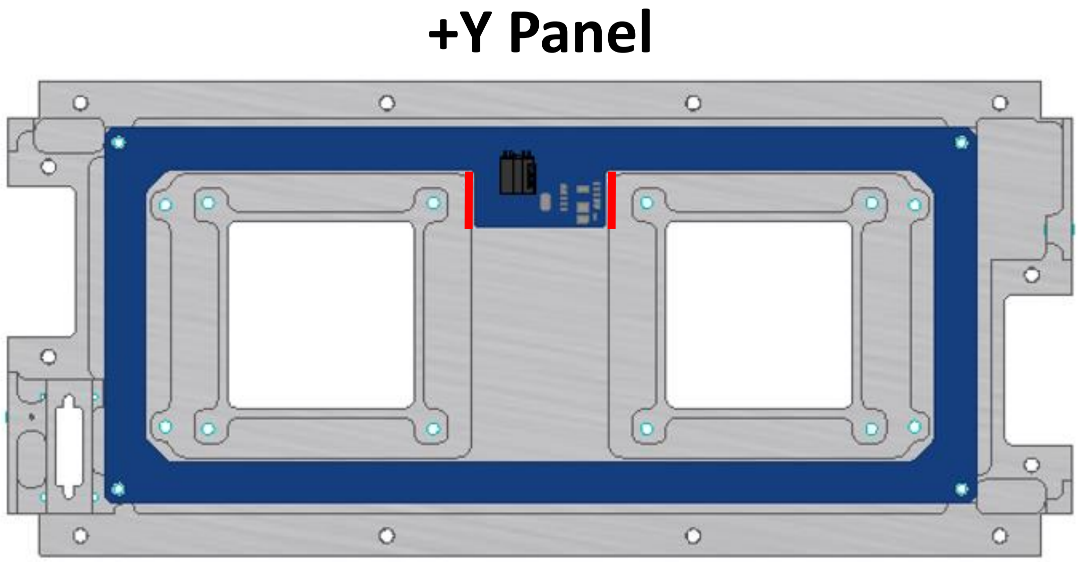
SPARTAN Magnetorquer Design

- Design Challenge: Mechanical Fit

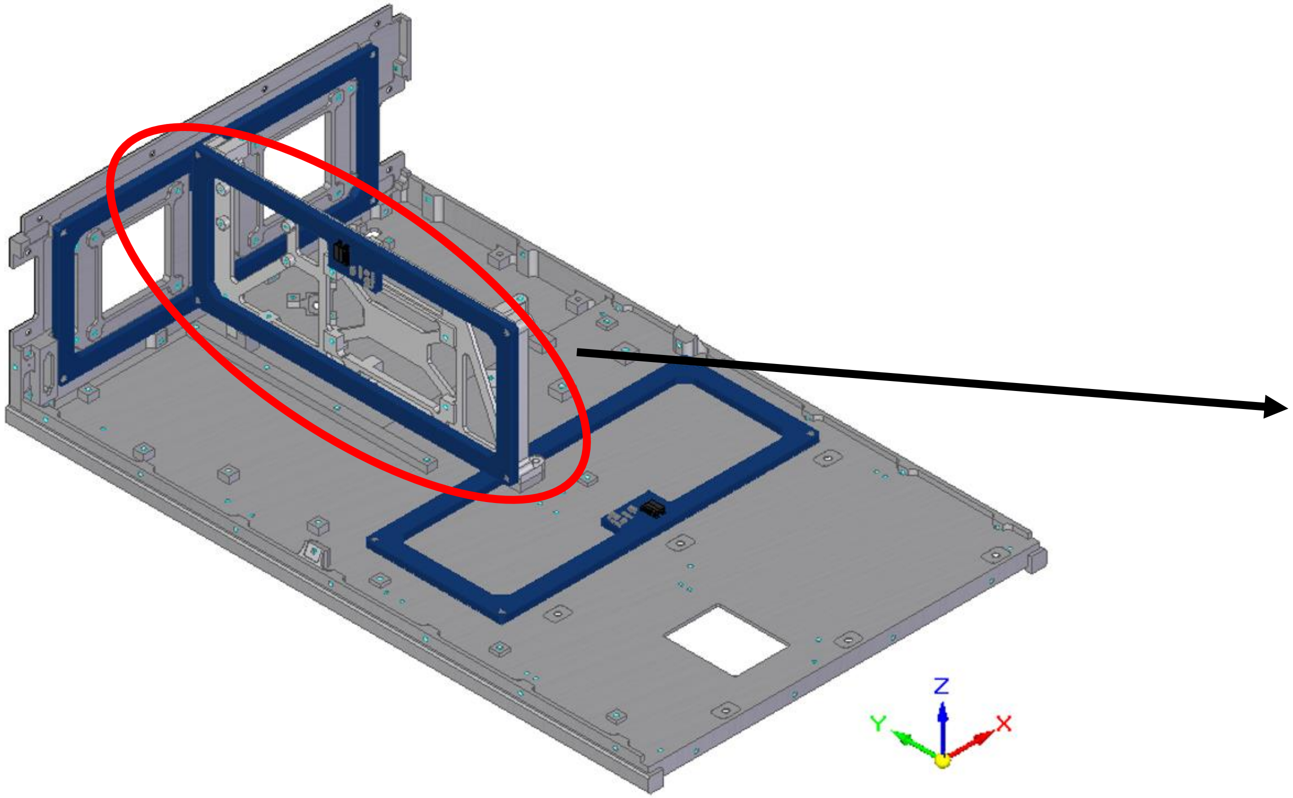


SPARTAN Magnetorquer Design

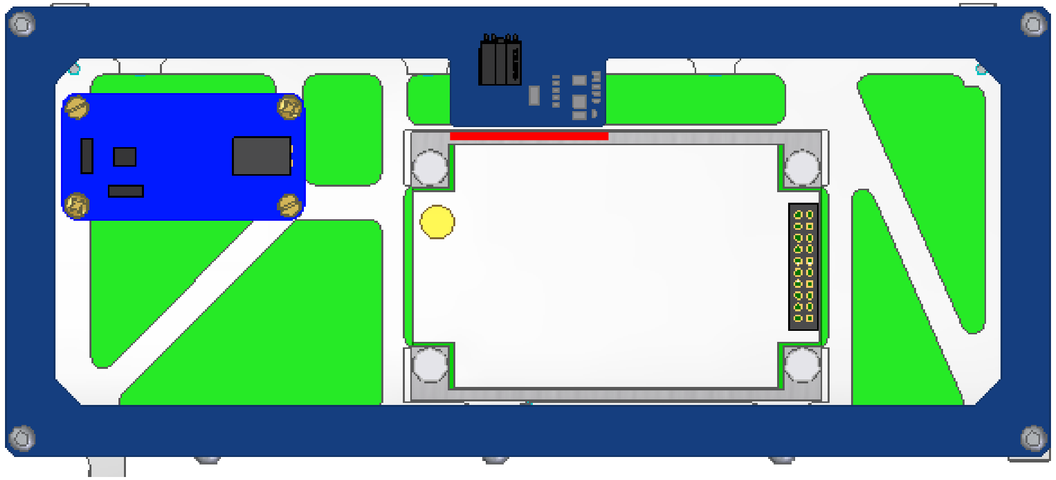




SPARTAN Magnetorquer Design

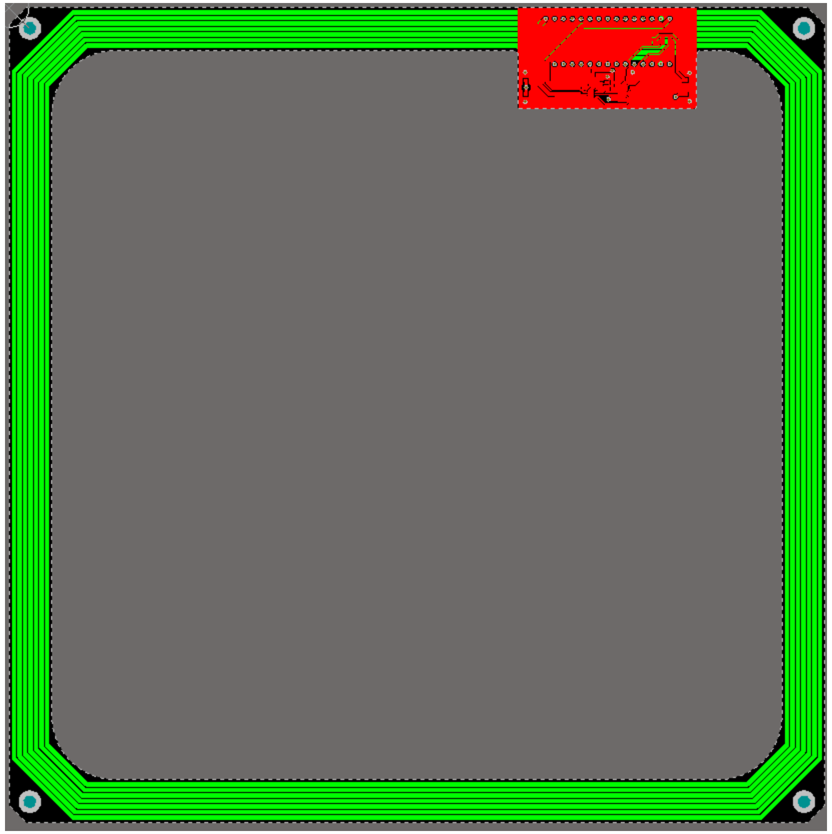


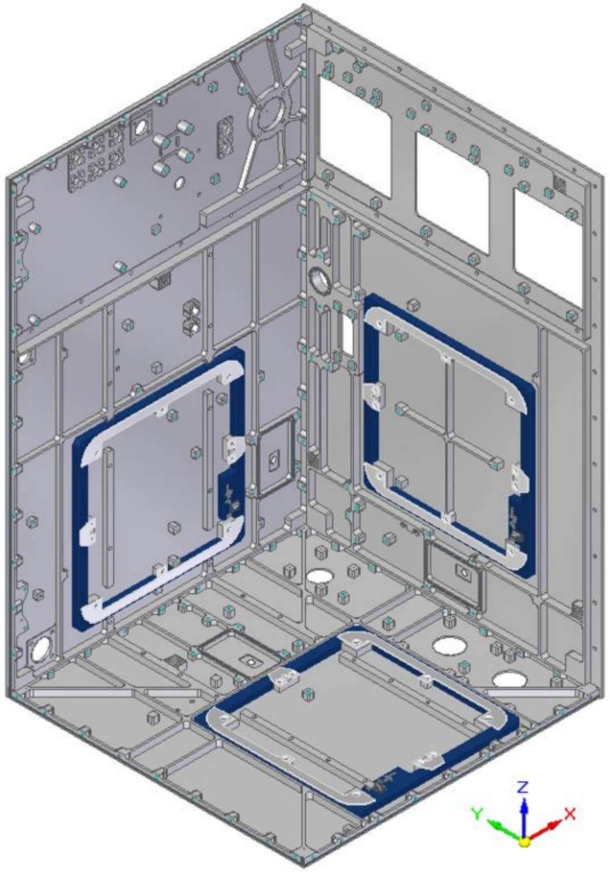
Avionics Bracket



DEFIANT Magnetorquer Design

- Design adapted to the DEFIANT platform
  - Same electrical components & connector
  - Same number of coil loops per layer
- Very minor modifications
  - Physical size
  - Tab location
  - Increased number of layers





Attitude Simulations

B-dot Control: $\boldsymbol{m_m}(t) = -\boldsymbol{K}\dot{\boldsymbol{B}}(t)$

- SPARTAN platform shall be capable of detumbling body rates up to 25°/s
- Sample mission parameters:
  - 525 km Altitude
  - 15:00 LTAN SSO
  - Summer Solstice

$\boldsymbol{m_m}$: Magnetic Dipole

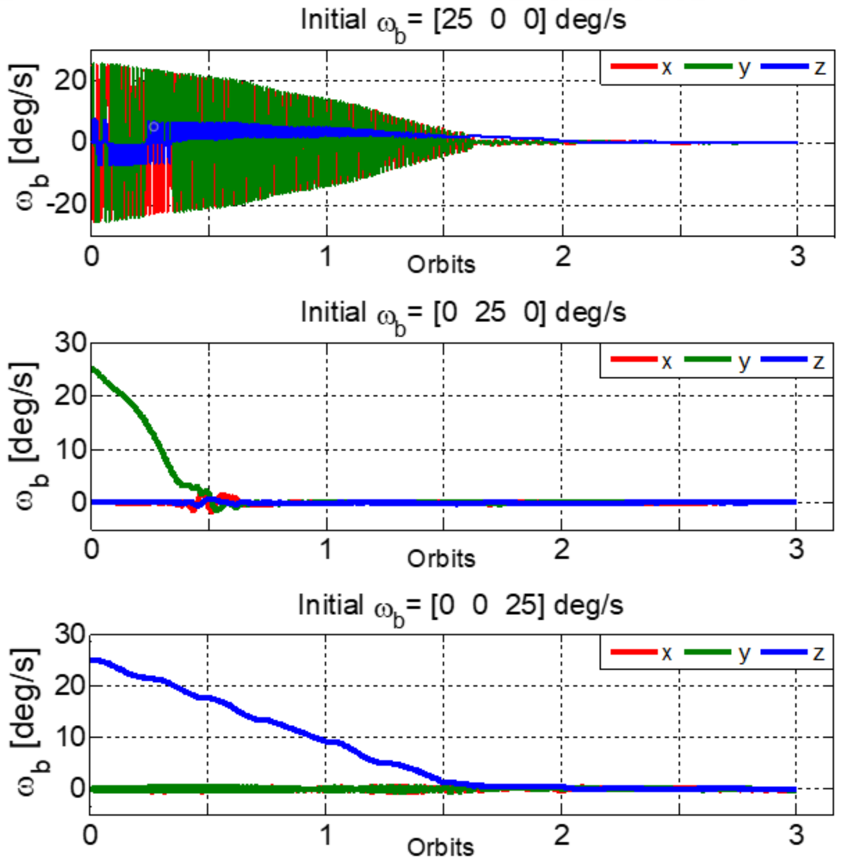
$\boldsymbol{K}$: B-dot Control Gain $\boldsymbol{B}$: Earth's Magnetic Field

Reaction Wheel Momentum Management

- Reaction wheel speeds shall remain below saturation limit (DEFIANT platform)
- Sample mission parameters:
  - 550 km Altitude
  - 15:00 LTAN SSO
  - Winter Solstice
  - Svalbard Ground Station Access

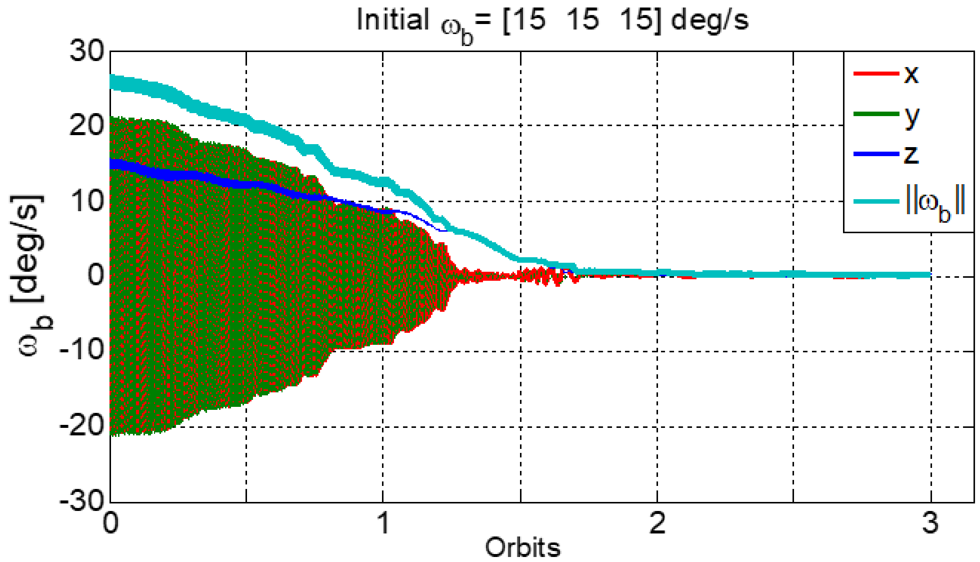
B-dot Control Results

Body Rate Damping with B-dot Control after an Initial Tip-off Rate of 25°/s per Axis



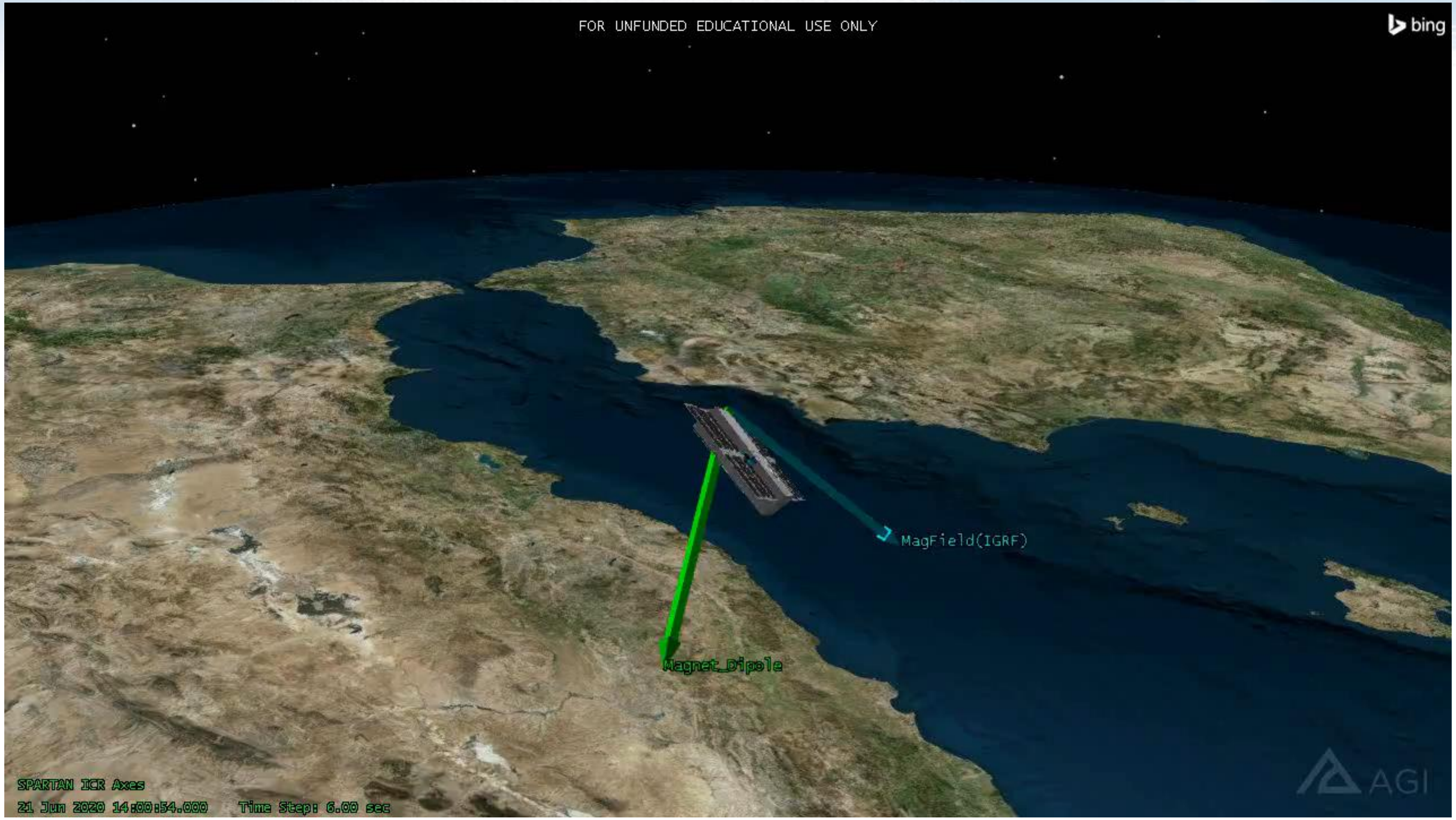
$I_{zz} > I_{xx} > I_{yy}$

Body Rate Damping with B-dot Control after Initial Tip-off Rates of 15°/s in each Axis



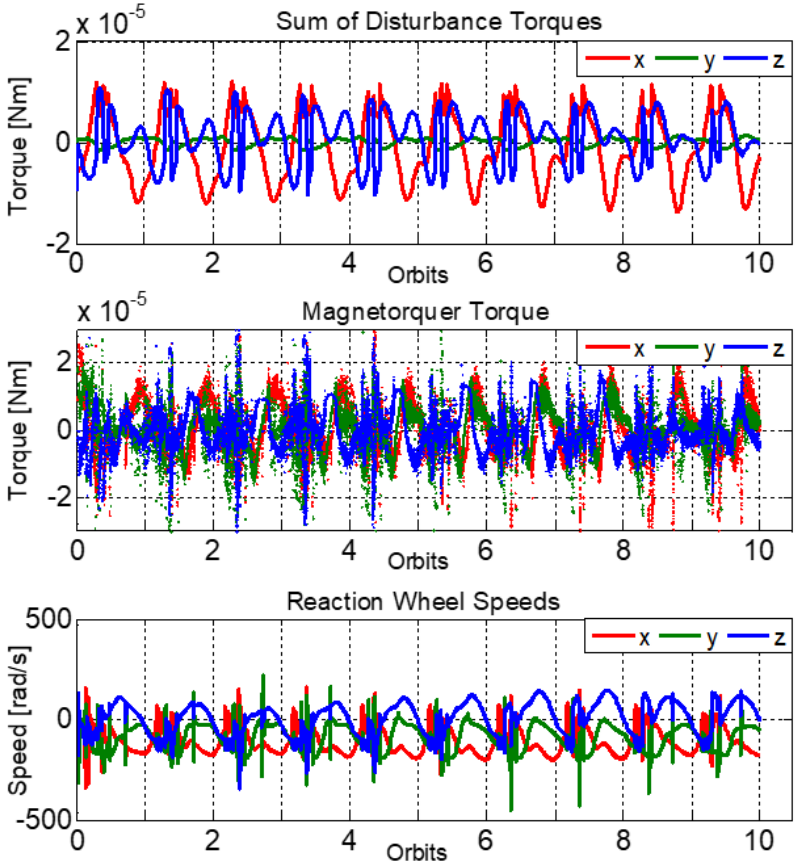
- All simulations show magnetorquers reduce body rates to near zero within two orbits

B-dot Control Simulation

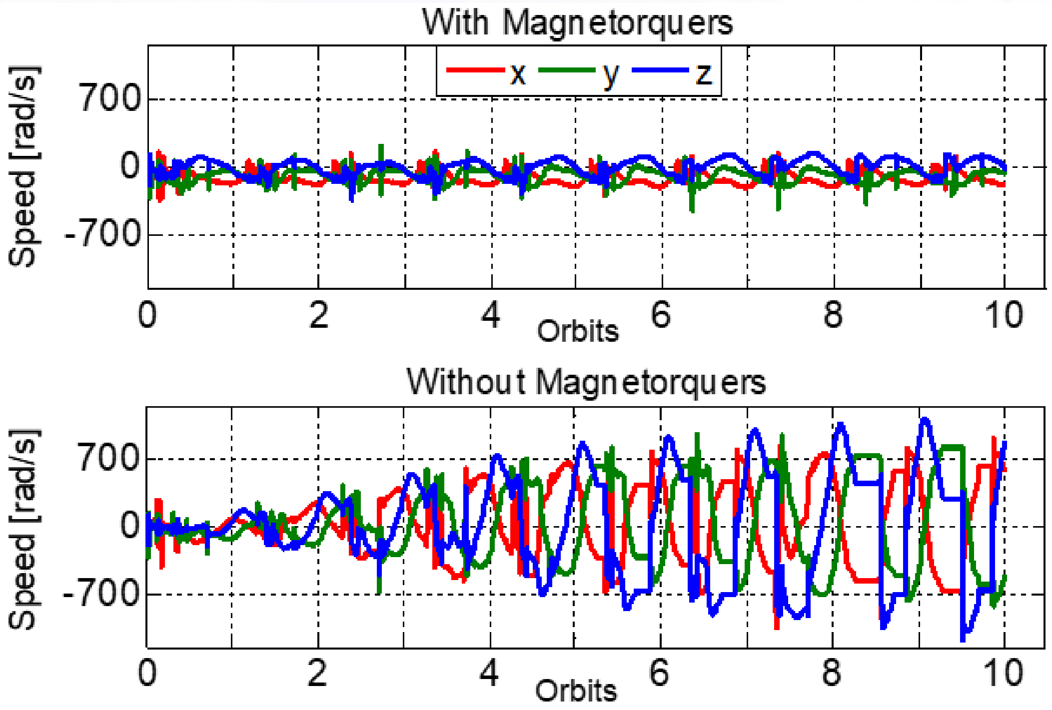


Momentum Management Results

Momentum Management Simulation Results



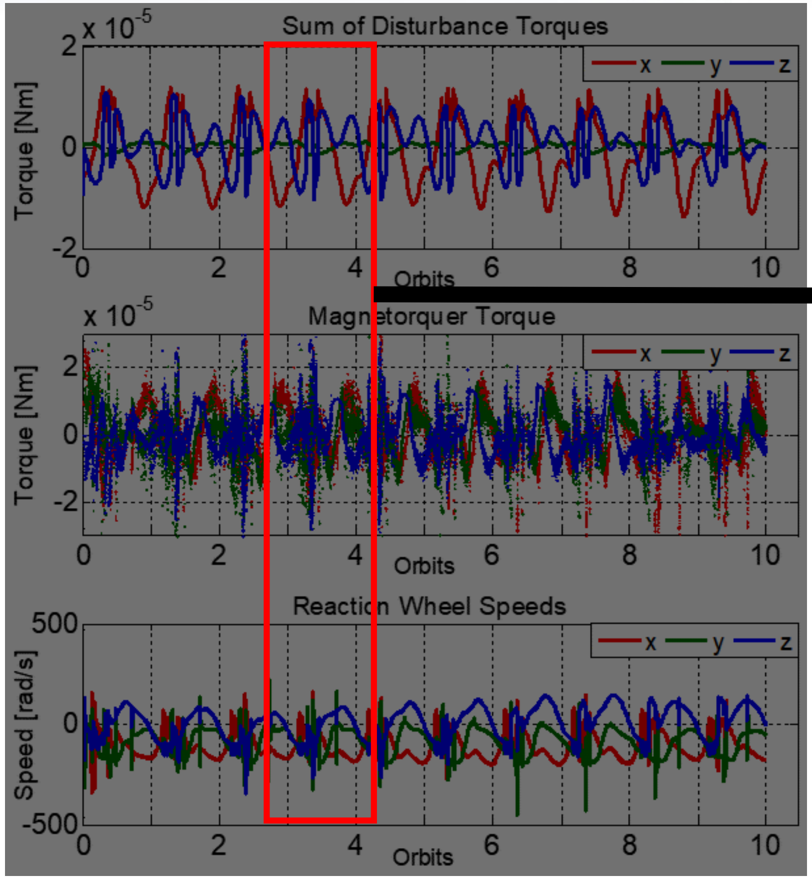
Reaction Wheel Speeds with and without Magnetorquers Activated



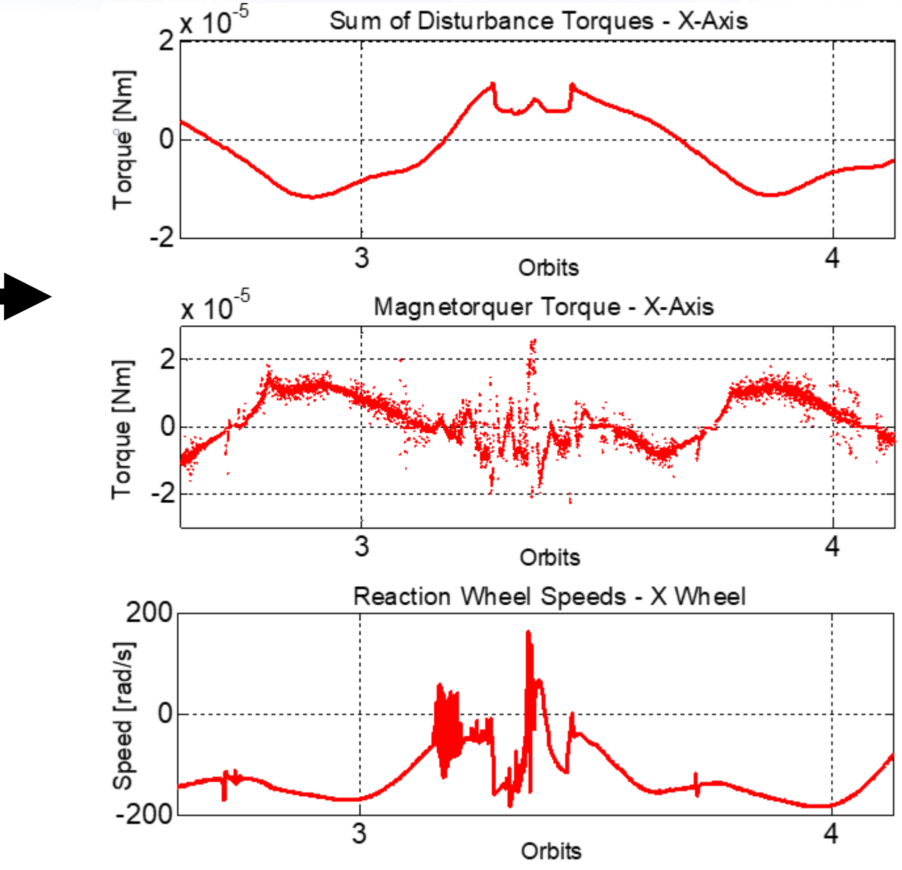
- Simulation with magnetorquers keep reaction wheels below the saturation speed limit of 700 rad/s

Momentum Management Results

Momentum Management Simulation Results



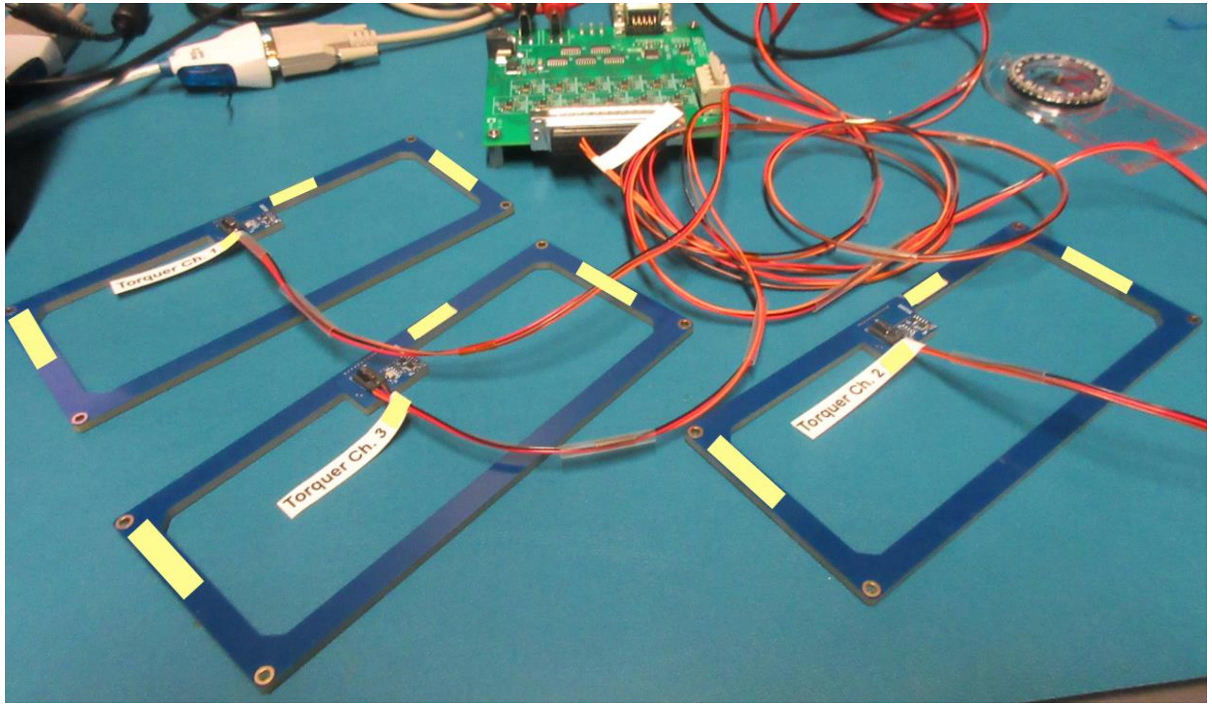
Momentum Management Simulation Results – X-Axis Comparison



Acceptance Testing

1. **Functional Test**
2. Thermal Shock
3. Thermal Cycling
4. Magnetic Field Measurement

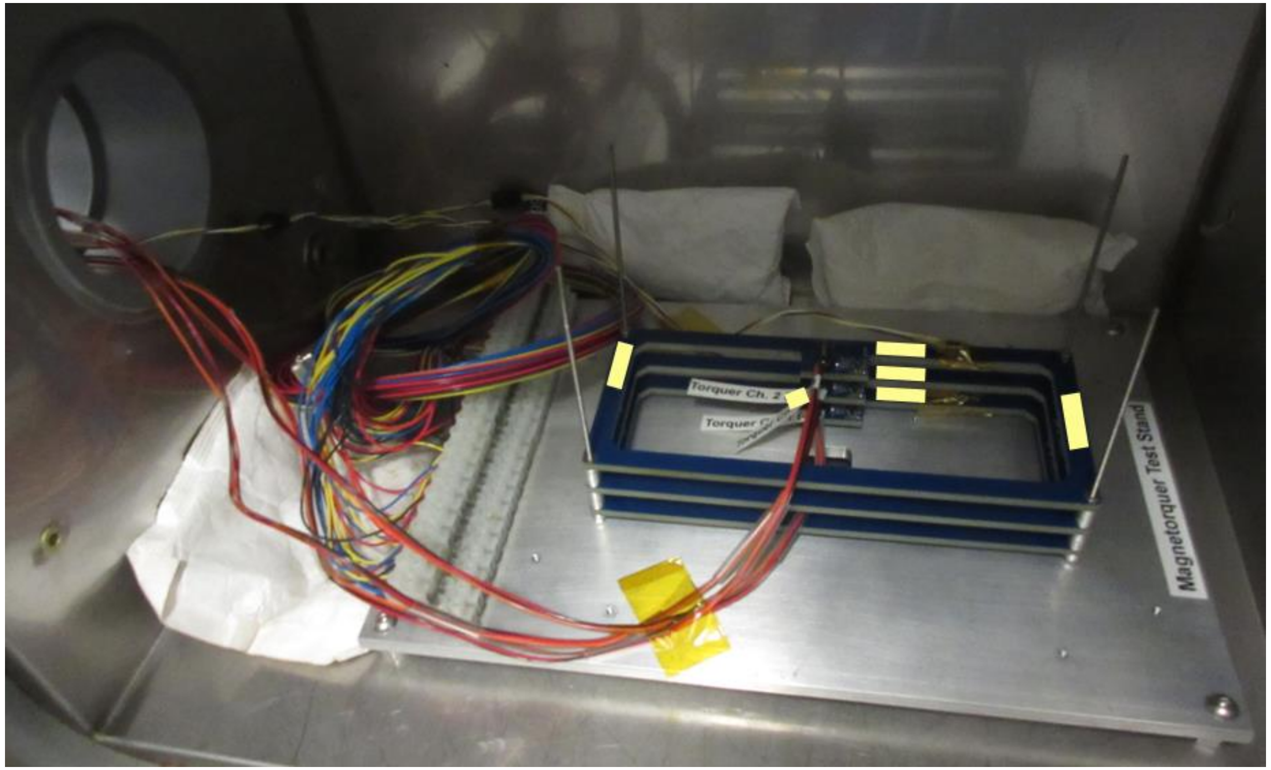
- Confirm current draw in each state is as expected



Acceptance Testing

1. Functional Test
2. **Thermal Shock**
3. Thermal Cycling
4. Magnetic Field Measurement

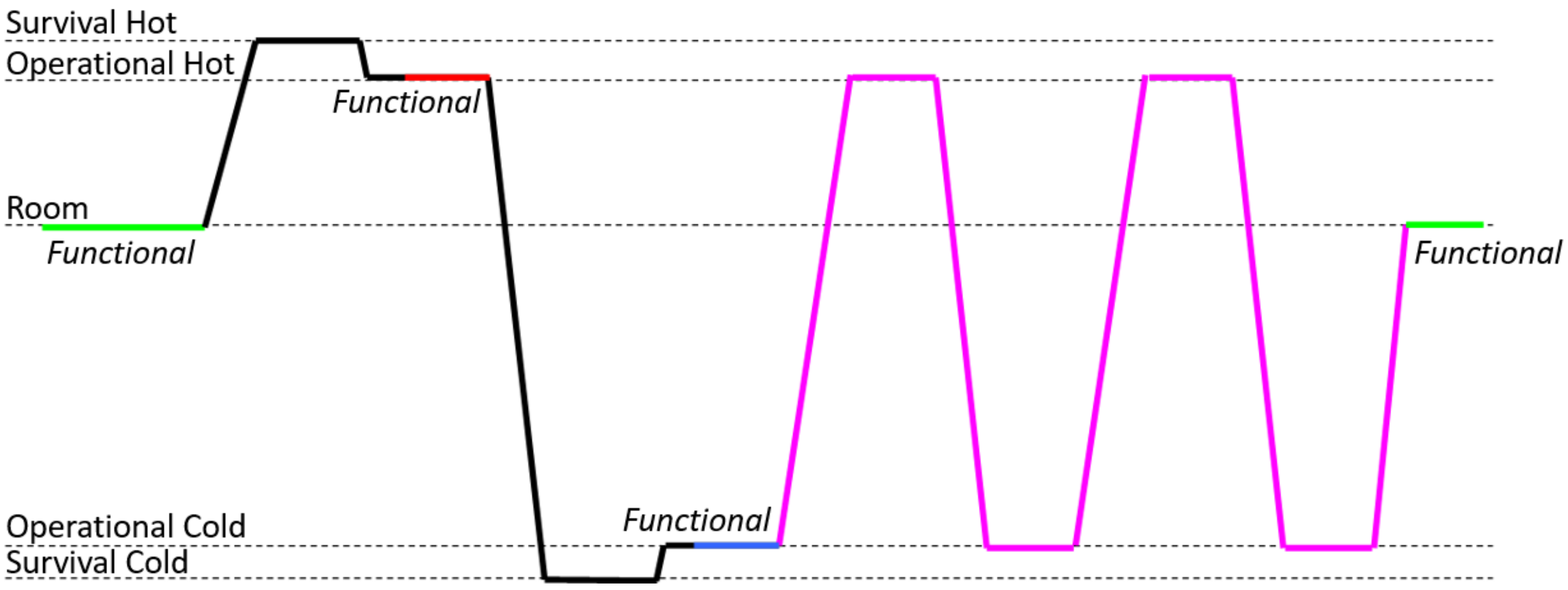
- Validate workmanship on the solder joints



Acceptance Testing

1. Functional Test
2. Thermal Shock
3. **Thermal Cycling**
4. Magnetic Field Measurement

- Confirm function across operating temperature envelope

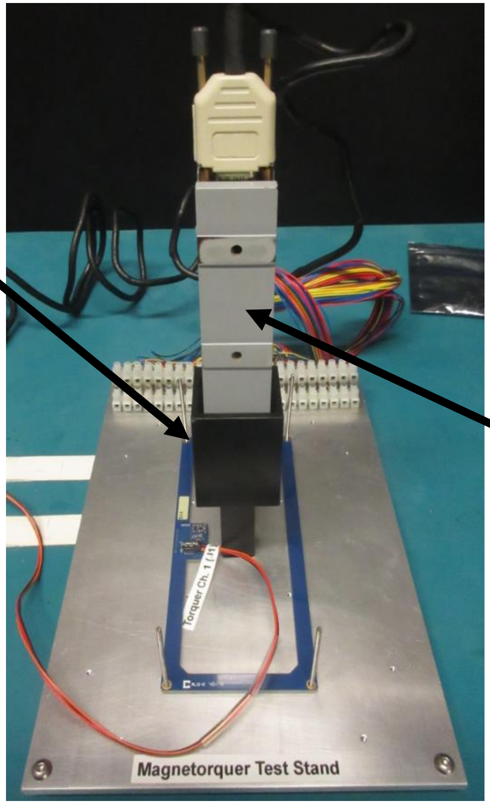


Acceptance Testing

1. Functional Test
2. Thermal Shock
3. Thermal Cycling
4. **Magnetic Field Measurement**

- Confirm magnetic dipole strength is as expected

Non-Ferromagnetic Support Bracket



Calibrated Lab Magnetometer

Conclusion

- Magnetorquer designed for constellation missions
  - Manufacturing is repeatable and reliable
  - No need for separate control electronics
  - Dual current direction allows for greater attitude control coverage
  - Can be easily adapted to other satellite platforms
- Simulations show magnetic dipole strength is sufficient
  - B-dot Control
  - Reaction Wheel Momentum Management
- Environmental acceptance testing completed for each flight unit

Thank you

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Appendix

Disturbance Torque Equations

Torque $[N \cdot m]$	Equation	Parameters
Solar Radiation Pressure $\boldsymbol{\tau}_s$	$\boldsymbol{\tau}_s = \boldsymbol{r}_s^{\times}\boldsymbol{F}_s$ $\boldsymbol{F}_s = p_s C_p A_p(-\hat{\boldsymbol{s}})$	$\boldsymbol{r}_s$: Center of Mass to Center of Solar Pressure Distance $[m]$ $\boldsymbol{F}_s$: Solar Radiation Force $[N]$ p_s: Solar Radiation Pressure $[N/m^2]$ C_p: Solar Radiation Pressure Coefficent A_p: Projected Frontal Area $[m^2]$ $\boldsymbol{s}$: Sun Vector $[m]$
Aerodynamic $\boldsymbol{\tau}_a$	$\boldsymbol{\tau}_a = \boldsymbol{r}_a^{\times}\boldsymbol{F}_a$ $\boldsymbol{F}_a = \frac{1}{2}\rho_o C_D A_p V_{rel}^2(-\widehat{\boldsymbol{V}}_{rel})$	$\boldsymbol{r}_a$: Center of Mass to Center of Aerodynamic Pressure Distance $[m]$ $\boldsymbol{F}_a$: Aerodynamic Force $[N]$ ρ_o: Atmospheric Density $[kg/m^3]$ C_D: Drag Coefficent A_p: Projected Frontal Area $[m^2]$ $\boldsymbol{V}_{rel}$: Spacecraft Relative Velocity $[m/s]$
Gravity-Gradient $\boldsymbol{\tau}_g$	$\boldsymbol{\tau}_g = 3\frac{\mu_E}{a^3}\boldsymbol{r}_b^{\times}\boldsymbol{I}_b\boldsymbol{r}_b$ $\tau_{g,max} = \frac{3}{2}\frac{\mu_E}{a^3}\left\|I_{kk,max} - I_{kk,min}\right\|$	μ_E: Earth Gravitational Parameter $[m^3/s^2]$ a: Orbit Semimajor Axis $[m]$ $\boldsymbol{r}_b$: Spacecraft Orbital Position (Radius) $[m]$ $\boldsymbol{I}_b$: Spacecraft Moment of Inertia $[kg \cdot m^2]$
Magnetic $\boldsymbol{\tau}_B$	$\boldsymbol{\tau}_B = \boldsymbol{m}_r^{\times}\boldsymbol{B}$ $B = \lambda\frac{M}{a^3}$	$\boldsymbol{m}_r$: Spacecraft Residual Dipole $[A \cdot m^2]$ $\boldsymbol{B}$: Magnetic Field of Earth $[T]$ λ: Magnetic Latitude Coefficient M: Earth Magnetic Dipole Strength $[T \cdot m^3]$ a: Orbit Semimajor Axis $[m]$

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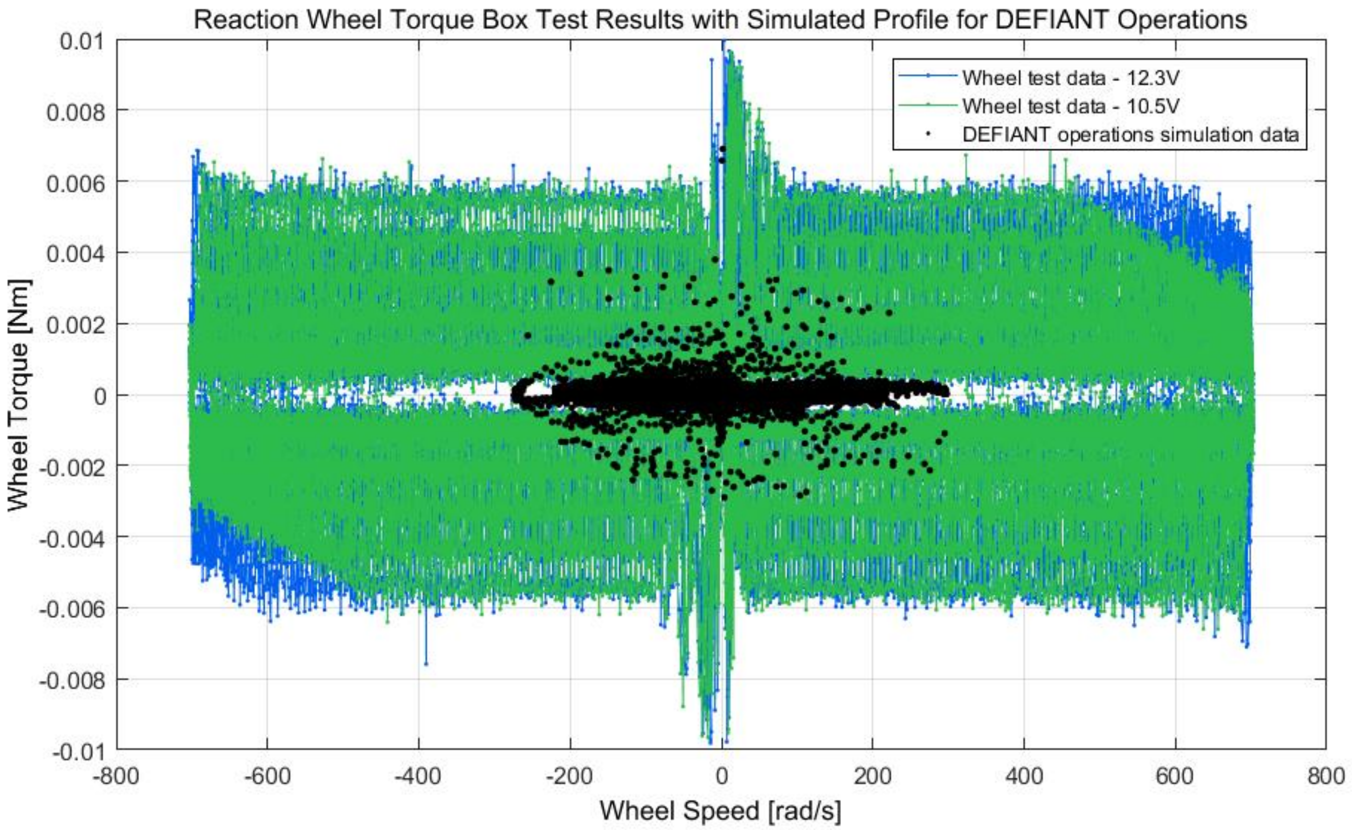
Magnetorquer States

Input State		Output State	Magnetic Dipole Direction
Line 1	Line 2		
Low	Low	Brake	-
High	Low	Forward	North
Low	High	Reverse	South
High	High	Idle	-

Reaction Wheel Torque Box



References

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