Design and Functional Validation of a Mechanism for Dual-Spinning CubeSats

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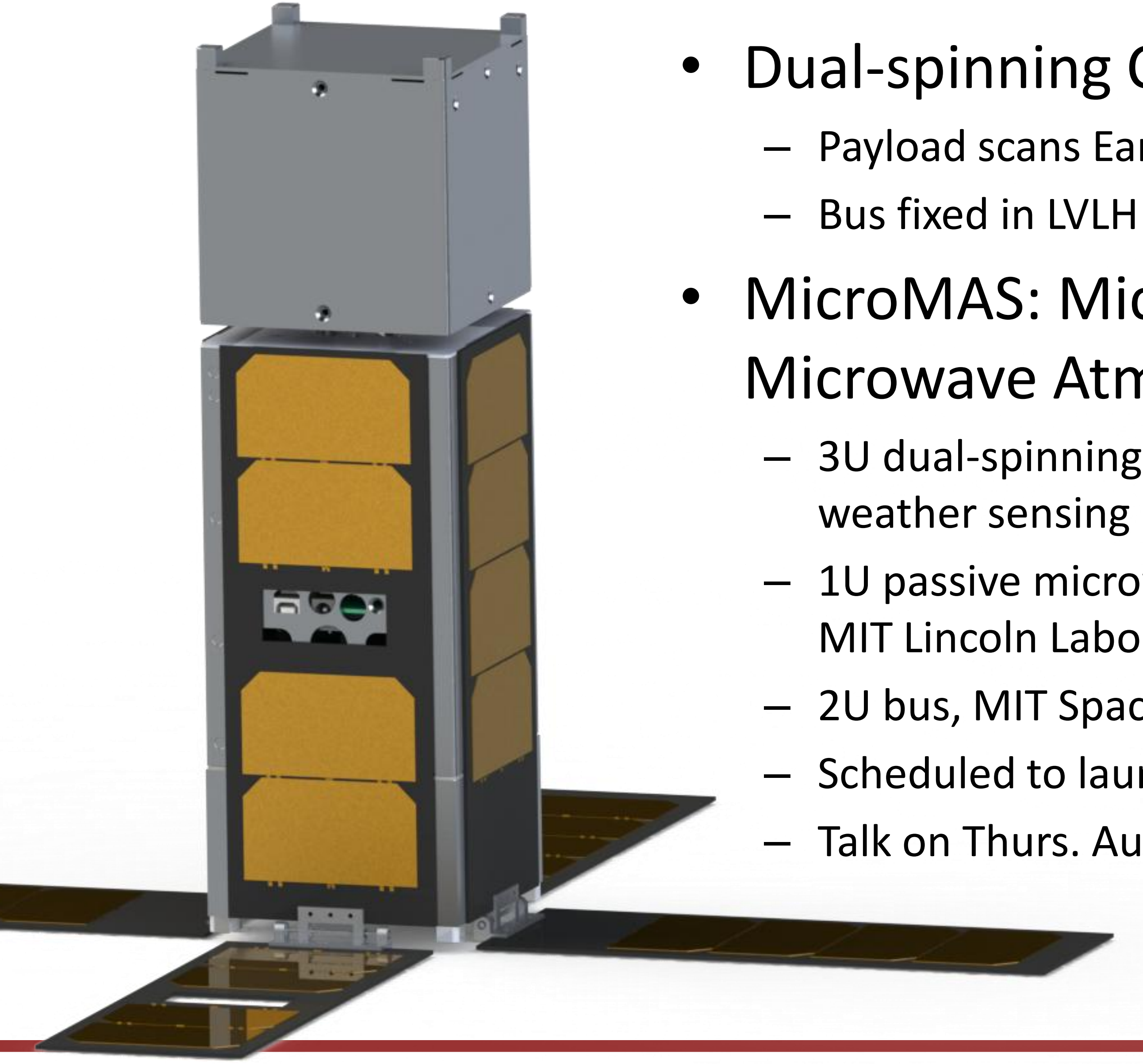
Outline

- Overview / Motivation
- Scanner assembly design
- Structural validation
  - Physical models
  - Structural testing of rotor/shaft interface
  - Notes on tolerance rings
- Thermal validation
  - Test plan
  - Results from thermal testing

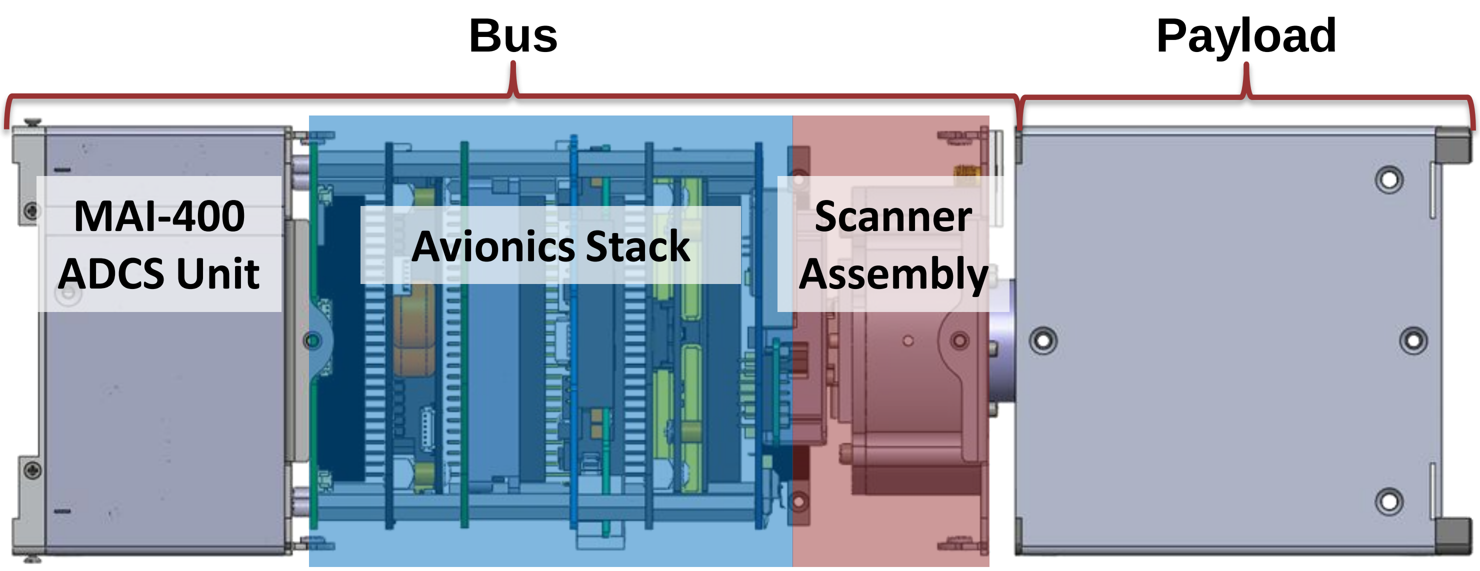
Motivation



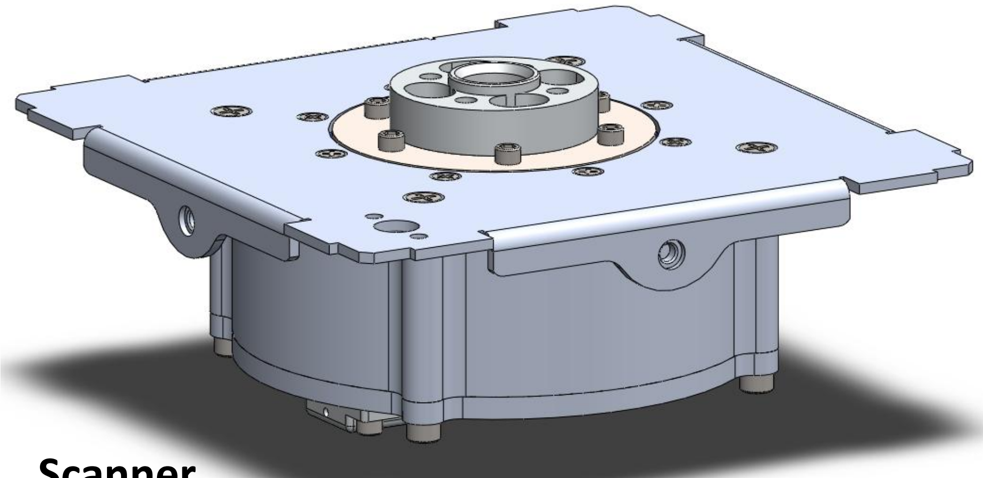
- Dual-spinning CubeSats
  - Payload scans Earth cross-track for coverage
  - Bus fixed in LVLH frame for pointing
- MicroMAS: Micro-sized Microwave Atmospheric Satellite
  - 3U dual-spinning CubeSat for remote weather sensing
  - 1U passive microwave radiometer payload, MIT Lincoln Laboratory
  - 2U bus, MIT Space Systems Laboratory
  - Scheduled to launch in winter 2013-14
  - Talk on Thurs. Aug 15th @ 10:30am

Design Requirements

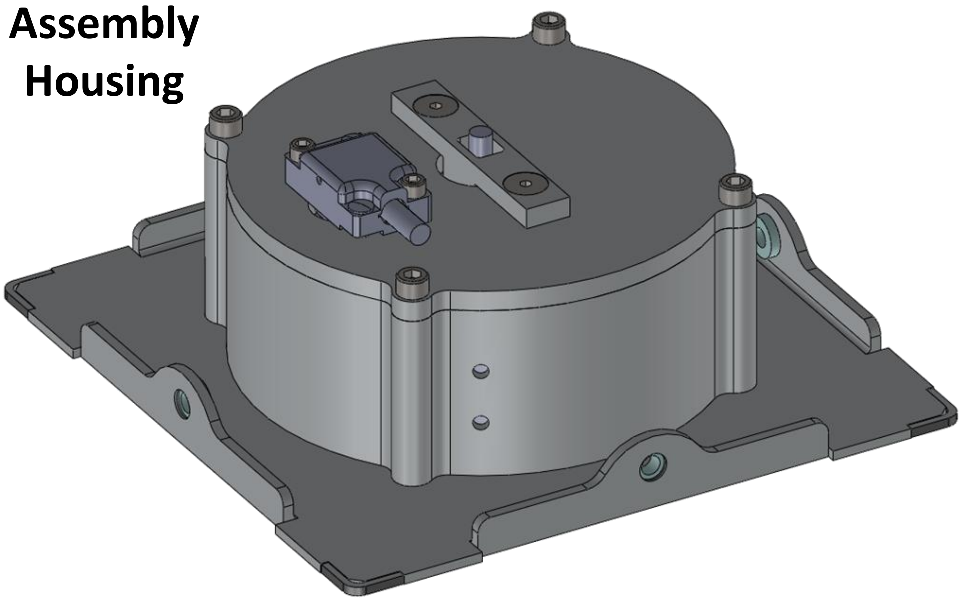
- Scanner assembly must:
  - Fit in 10cm x 10cm x 3.5 cm volume
  - Rotate 1U payload at ~1 Hz (60 rpm)
  - Have angular position knowledge of < 6 arcmin (0.1 deg)
  - Have 8+ electrical feed lines for power/data transfer between bus and payload
  - Operate continuously in space environment



COTS Hardware



Scanner Assembly Housing



Bearing

- NHBB RI-3026 thin section bearing with vacuum-rated cage and lubricant

Encoder

- MicroE M1500V vacuum-rated sensor
- Glass rotary grating disc with 7200 counts per revolution (0.01 degrees per count)

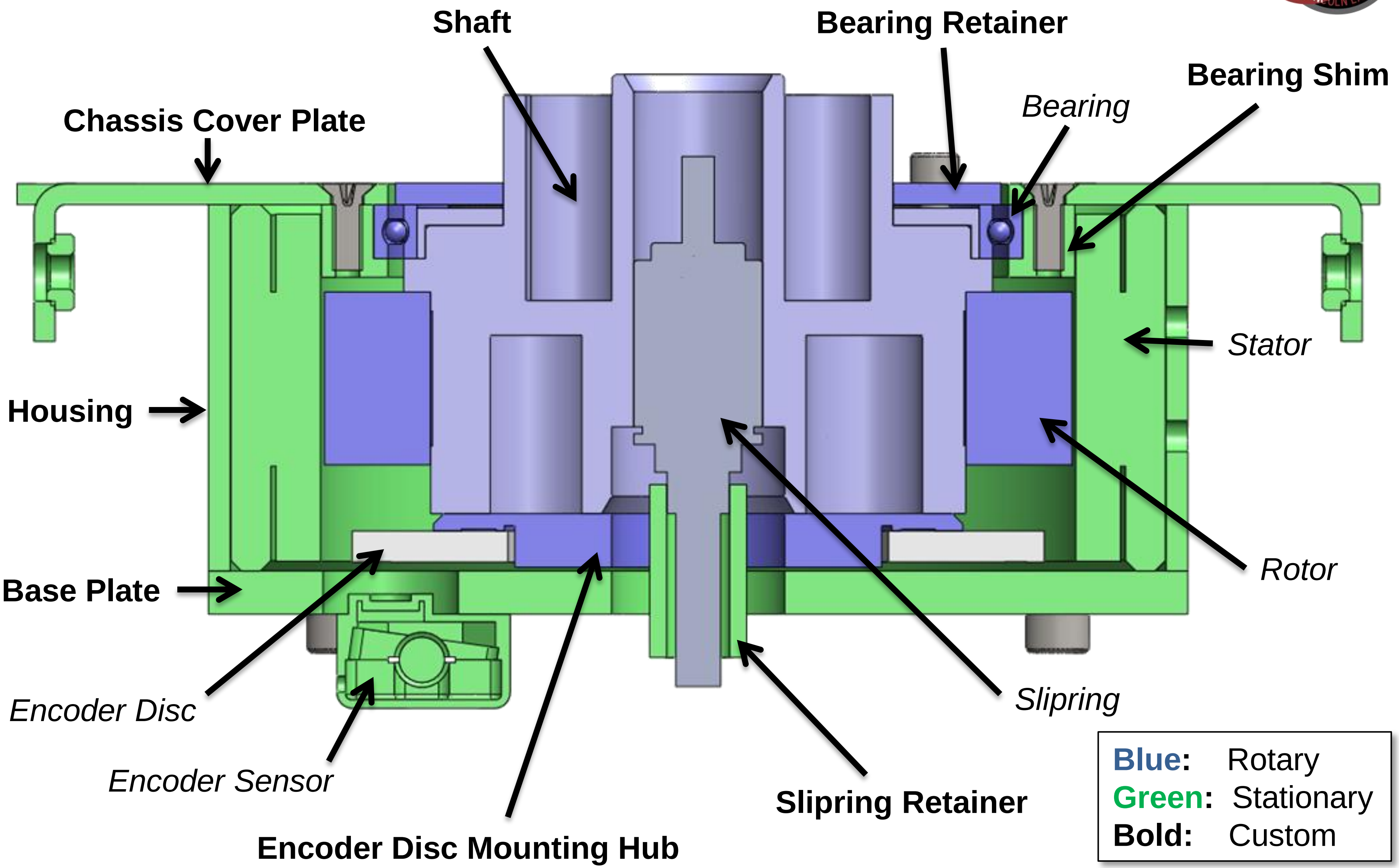
Rotor/Stator

- Aeroflex Z-0250-050-3-104 zero-cogging brushless DC motor

Slipring

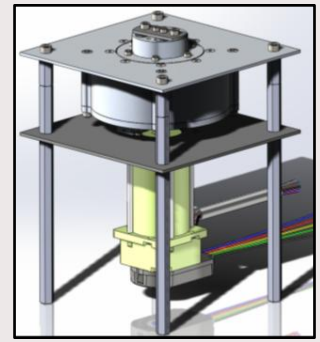
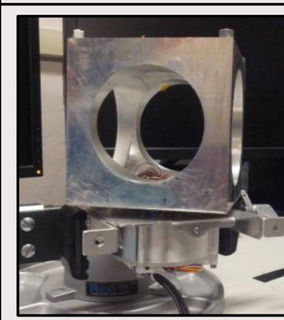
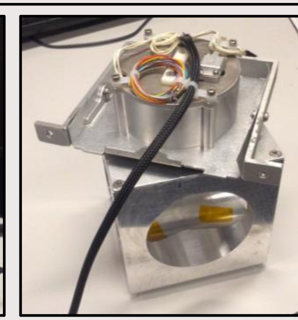
- Aeroflex CAY-1398 with 12 lines for power/data transfer

Design Overview



Structural Validation of Scanner Assembly

Scanner Assembly Prototypes

3D Print Unit	• Check volume • Check fit • Verify assembly procedures	 
Engineering Design Unit	• Verify mass properties • Verify machining procedures • Early functional testing with non-flight components	
Rotor/Shaft Test Units	• Test/prove different mating methods work for interface	
Engineering Test Unit	• Verify custom parts function, cost, schedule • Functional test with flight-like components	 

Rotor/Shaft Interface

- Concern: thermal expansion, loss of contact between rotor (stainless steel) and rotor shaft (aluminum)
- Tested several mating methods

	Epoxy	Tolerance Ring	Press-Fit
Advantages	• Flight heritage (ACIS instrument, bond held with ΔT of -200 °F)	• Robust to thermal expansion/contraction • Known torque and radial load capacities	• No additional parts needed • Simple to design
Disadvantages	• High CTE • Estimated elastic modulus • Requires careful application, curing	• No prior experience • No flight heritage • Tests needed to get groove fit right	• Loss of fit with thermal variation • Requires additional equipment
Tests Performed	Torque testing	Torque testing	Thermal testing

Rotor/Shaft Mating Tests

- **Purpose:** Test strength of rotor/shaft interface
- Use peak torque provided by motor (4 in-lb) on epoxy and tolerance ring

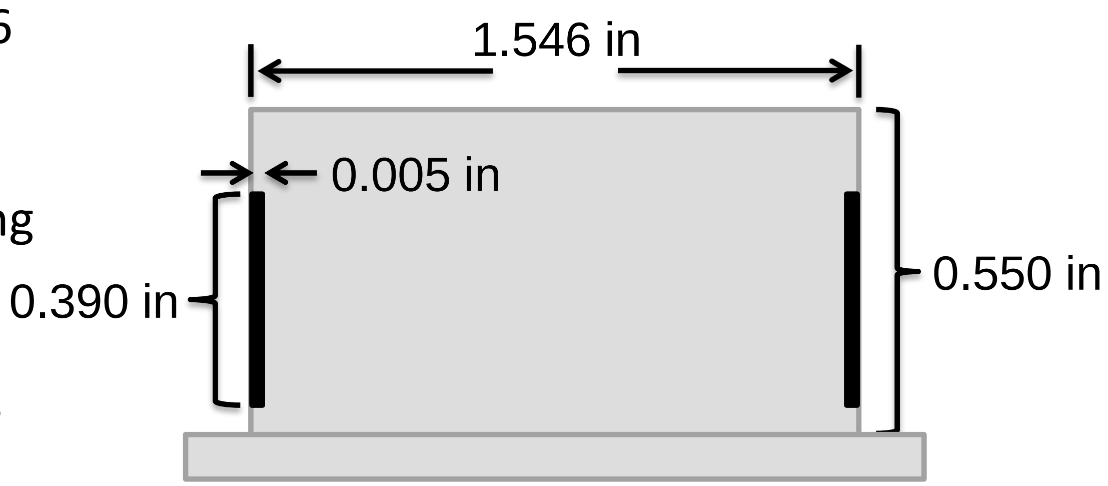
- **Setup:** Used identical flight-like shaft + rotor ring sets

Shaft

- Aluminum alloy 6061-T6
- Cut grooves for epoxy
- Found deeper groove needed for tolerance ring

Ring

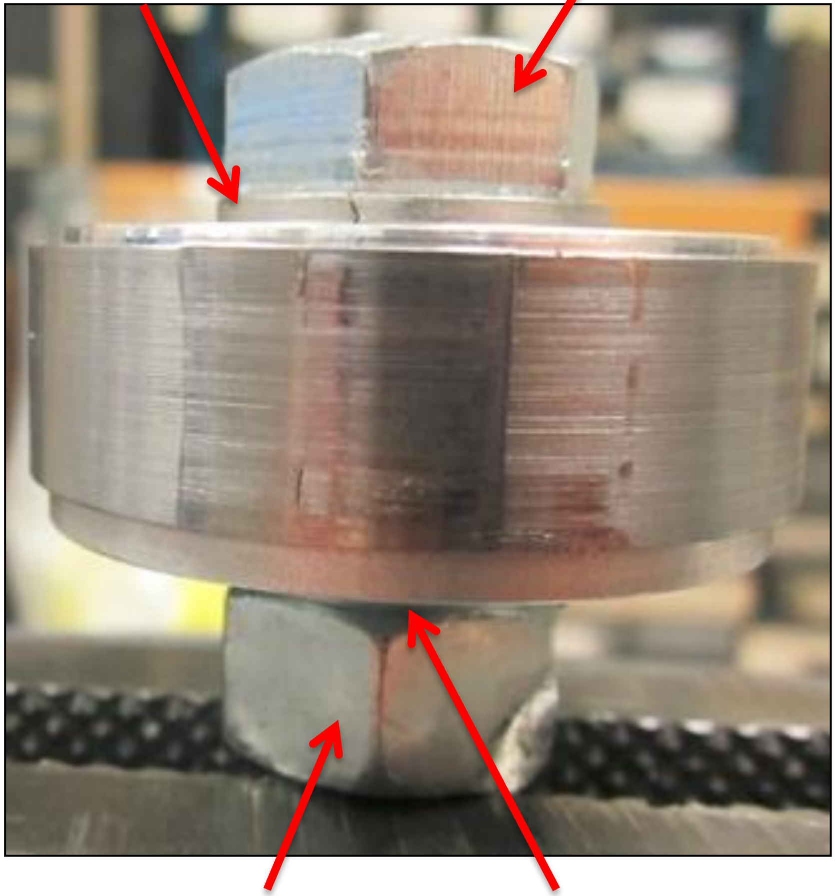
- A513 mild steel
- Smooth internal surface



Shaft + rotor ring test rig

Torque Testing Setup

- 1/2”-13 bolt secured through bore in center of test shaft
- Flat washers placed between shaft-nut and shaft-bolt
- Fastener installation torqued to 120 in-lb
- Ring held by vise while torque applied to the bolt



Tolerance Ring Attempts

- First attempt, tolerance ring forced out of the groove
  - Initial 0.005" groove depth too shallow
- Machined new shaft with groove depth of 0.022”
  - Designed to fully retain the 0.020” un-corrugated portion and ¼ of the corrugated portion
- Trimmed length of ring to maintain gap of 0.060” between edges
  - Gap of 0.040” - 0.080” recommended by product engineers

Image from:
USA Tolerance Rings

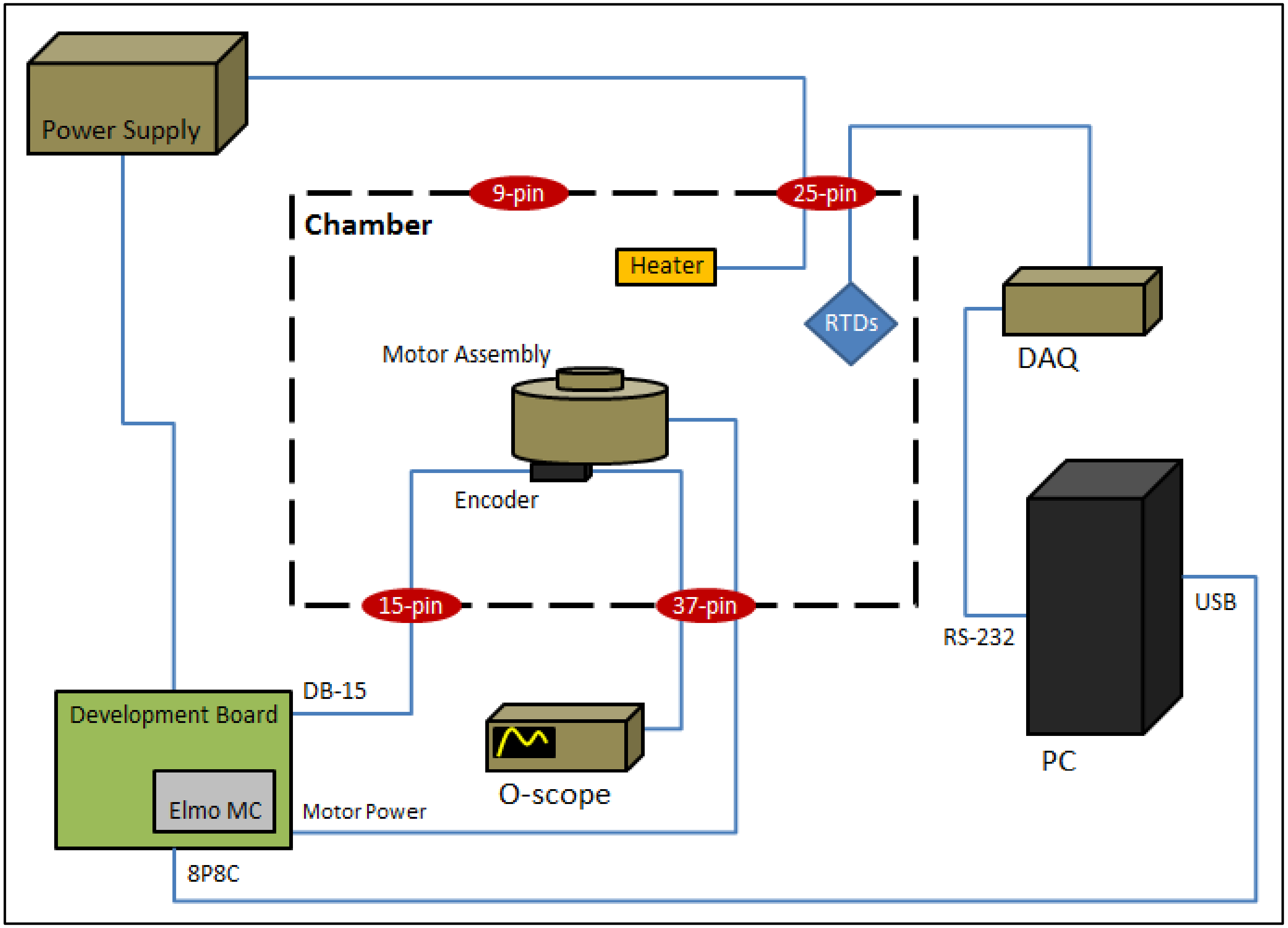
Torque Testing Results

- First, test to peak torque provided by motor during nominal operations (4 in-lb)
  - If successful, then test to point of failure
- Results:
  - Both epoxy and tolerance rings survived up to **65 in-lb** torque
  - Point of failure was not reached for either epoxy or tolerance ring
    - At 65 in-lb, lock washers used in test apparatus dug into aluminum shaft
    - Test was halted and not continued to higher torques
- Note:
  - Tolerance ring: tested to less than max torque capacity of rings *(65 in-lb test << 675 in-lb predicted capacity)*
  - Epoxy: tested to *much less* than epoxy shear strength at ~25°C *(tested 44 psi << rated 3800 psi)*

Thermal Validation of Scanner Assembly

Thermal Testing

- **Purpose**: Characterize encoder + motor assembly performance over operational/survival temperatures in vacuum



- Analog output from encoder → Oscilloscope
- Digital output from encoder to motor controller → PC
- Temperature data w/ 9 x 100-Ω RTDs → Agilent DAQ

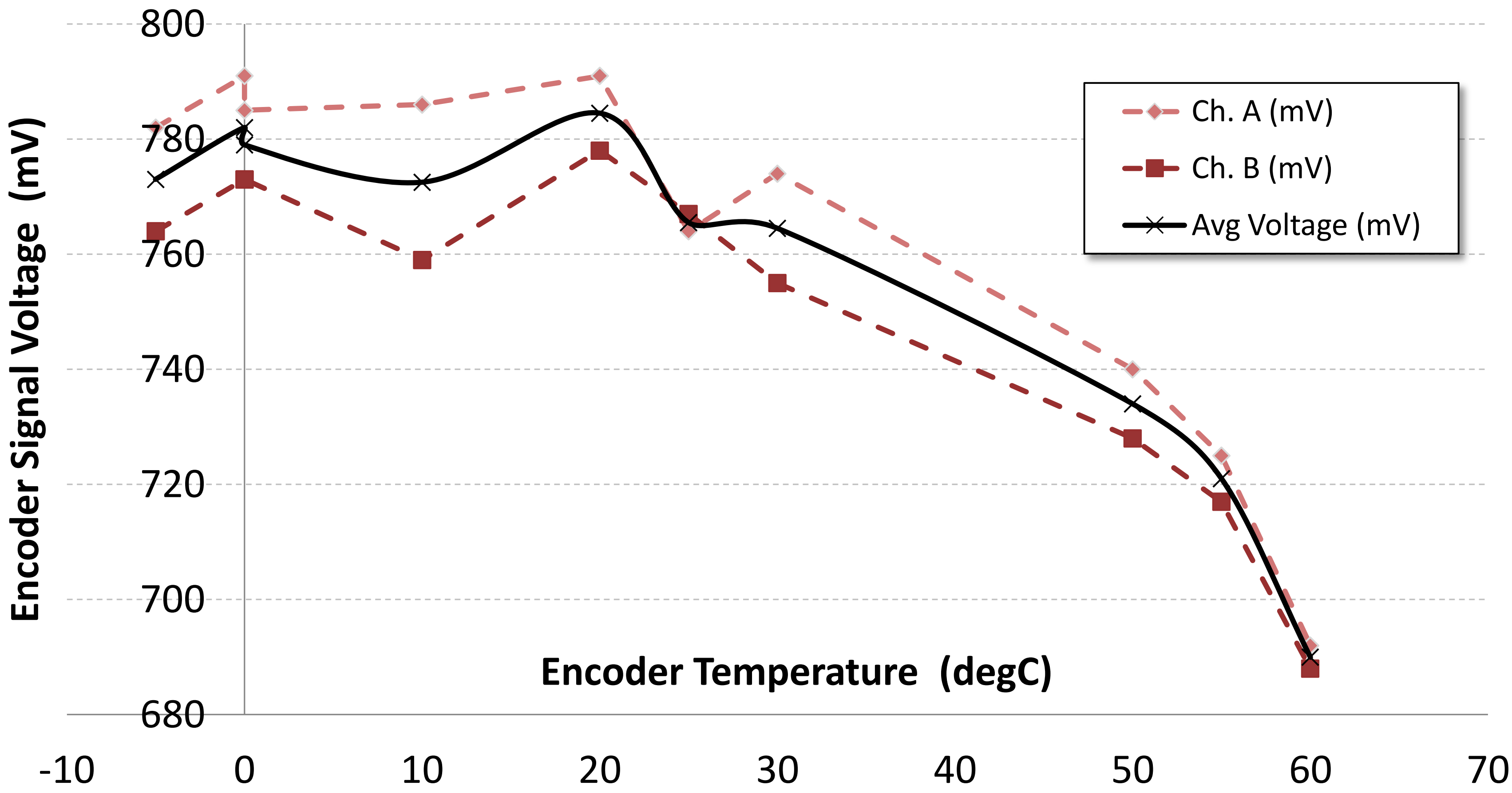
Thermal Test Plan

Encoder specified operational temperature range = [0,70] °C
Predicted on-orbit temperature range = [-5,25] °C

Scenario	Chamber State		Test Procedure
TS **Test Setup**	Room Pressure & Temperature		• Prep chamber, test rigs, articles, + sensors • Check function + calibrate test articles + sensors • Collect benchmark data
T-0 **Functional Checks**	Ambient Vacuum (25 °C)		• Pump-down chamber to ~1e-05 torr • Functional checks on test articles + sensors • Command motor to 60 rpm • Collect data until thermally stable
T-1 **Cold Test**	Cold Vacuum (< 0 °C)		• Continue running motor at 60 rpm • Continue collecting data • Supply LN2 to bring encoder temperature to 0°C • Monitor encoder, slowly lower T to -10 °C
T-2 **Thermal Cycling**	Cold Vacuum (0 °C)	Hot Vacuum (70 °C)	• Command motor to 60 rpm, collect data • Complete 1+ full thermal cycles by switching between LN2 cooling and resistor heating

Encoder Performance

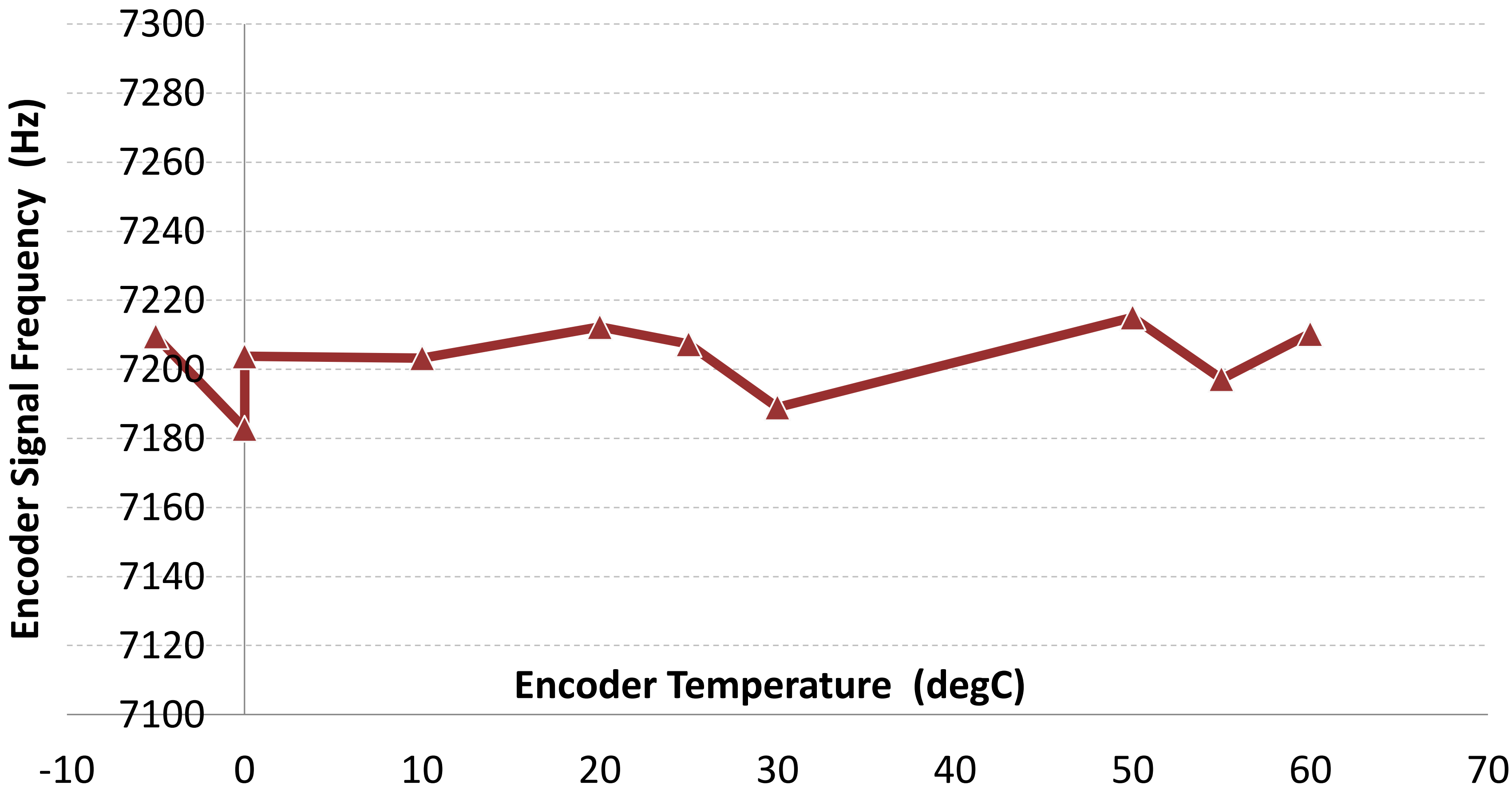
Nominal = 800 mV, minimum acceptable = 400 mV



Encoder V still in nominal range (> 400 mV) despite drop at higher temps

Scanner Performance

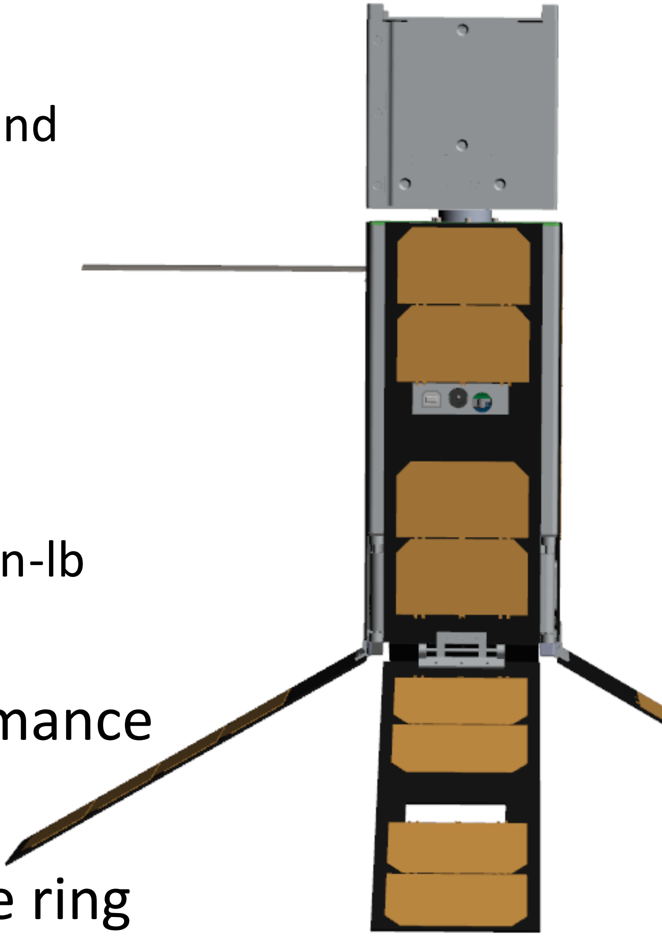
Nominal signal frequency = 7200 Hz



Encoder signal frequency stable over temp → stable scanner performance

MicroMAS Scanner Summary

- Validated scanner assembly: design achieves requirements
- Successful iterative design process
  - Prototypes and physical models for structural and thermal testing
- Successful tests on two rotor/shaft mating methods
  - (1) Epoxy + grooves
  - (2) Tolerance rings
  - Both methods passed torque tests of up to 65 in-lb
  - Selected Epoxy + grooves
- Successful test of encoder/scanner performance with temperature at vacuum pressure
- Future work: Thermal test epoxy/tolerance ring

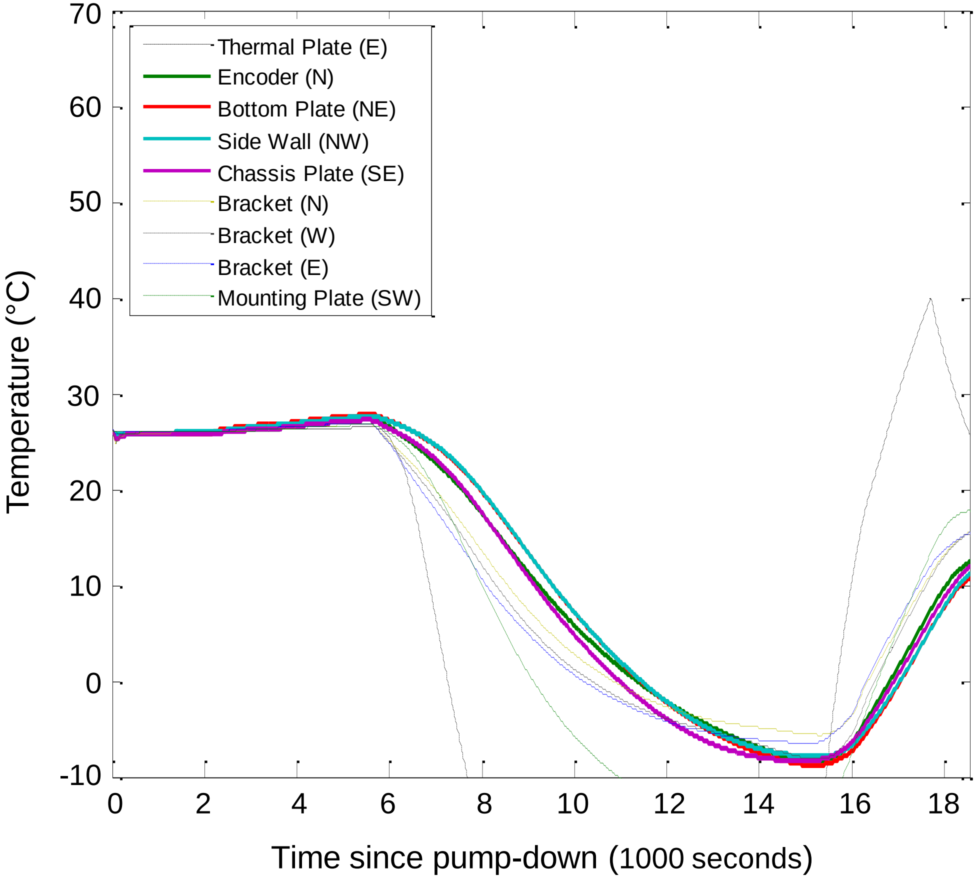


Backup Slides

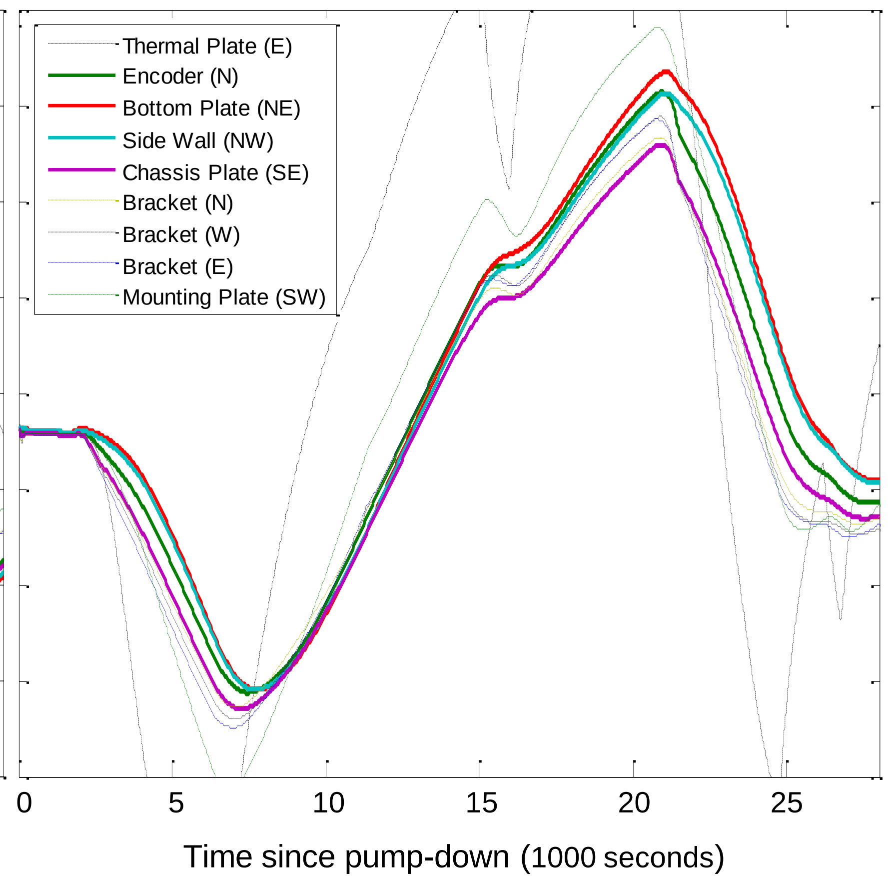
Temperature Data

Motor commanded to continuously spin at 60 rpm during entirety of both tests

Test 1: Cold Test
Test articles cooled to -8.5 °C, then returned to ambient



Test 2: Thermal Cycling
Test articles cooled to 0 °C, then heated to 65 °C



Motor and encoder operated nominally throughout all tested temperature ranges

Encoder Signal at -5 °C

Signal is filtered and averaged by oscilloscope, as will be similarly done by on-board avionics
Nominal signal amplitude: $\geq$ 400 mV *Nominal signal frequency: 7.200 kHz*

Active computation of signal frequency

Active computation of signal amplitude (voltage)

Encoder signal amplitude and frequency are both well within nominal range

Encoder Signal at +60 °C

Signal is filtered and averaged by oscilloscope, as will be similarly done by on-board avionics

Nominal signal amplitude: $\geq$ 400 mV *Nominal signal frequency: 7.200 kHz*

Active computation of signal frequency

Active computation of signal amplitude (voltage)

Though the encoder signal amplitude decreased at higher temperature, the signal amplitude and frequency are both still within nominal range