ICESat-2 ATLAS
Beam Steering Mechanism (BSM)

SLAMS Presentation

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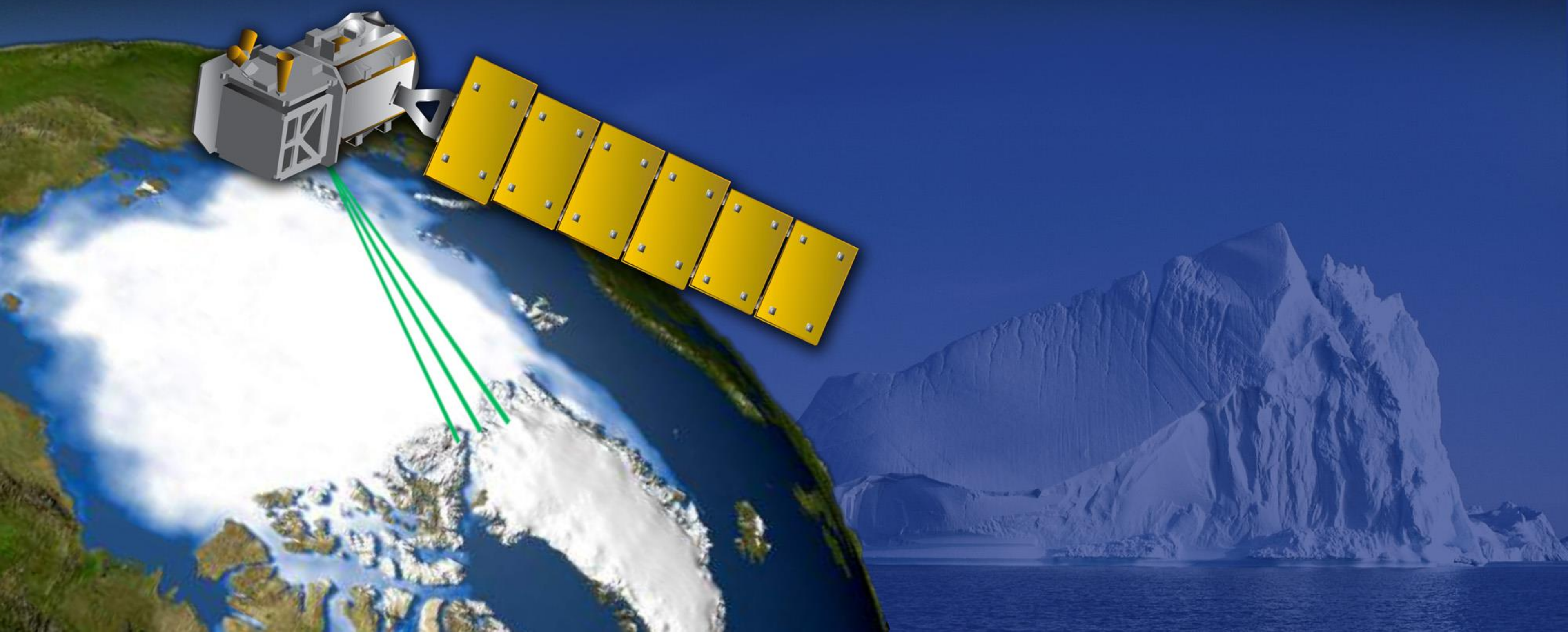
9/1/2015



BSM Overview Agenda

Goddard Space Flight Center

- ATLAS Overview
- BSM Driving Requirements
- BSM Components
- Flexure
- Actuator Torque Margin
- Mirror Mount
- DPSS
- Major Testing & Results
- Conclusion

Advanced Topographic Laser Altimeter System

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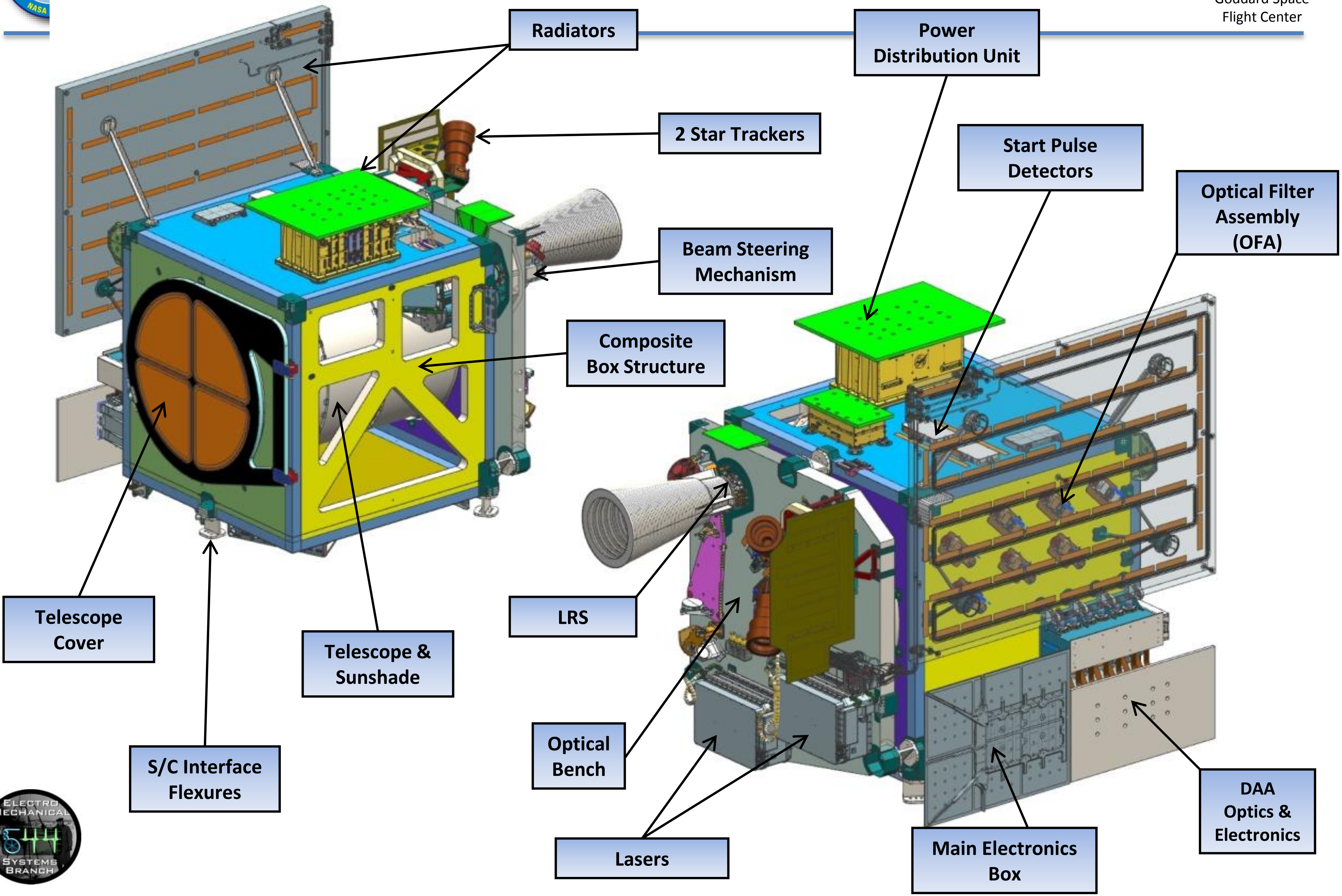

Advanced Topographic Laser Altimeter System (ATLAS) Instrument Overview

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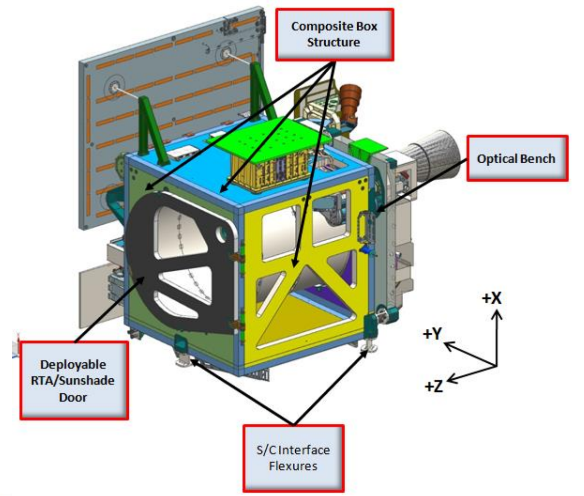
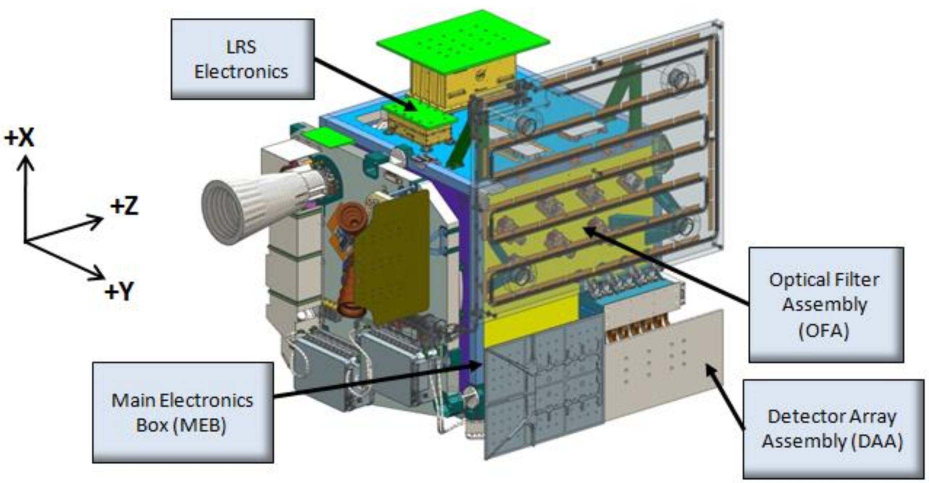
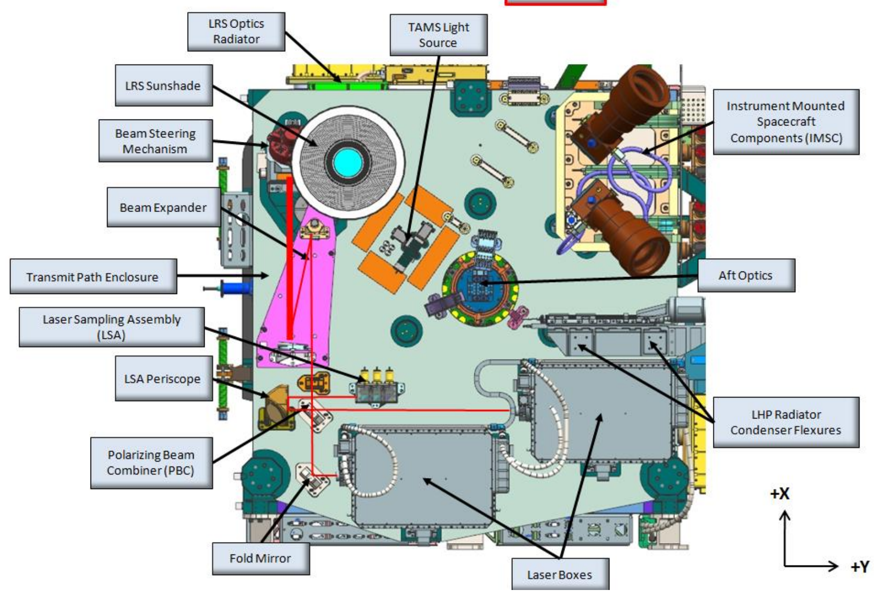
Multi-beam Micropulse Laser Altimeter

- Redundant Single laser beam
- Split into 6 beams by DOE
- 10 m ground footprints
- On-board boresight alignment system
- Laser Reference System gives absolute laser pointing knowledge
- Instrument Mass: 500 kg







Elevation Measurement

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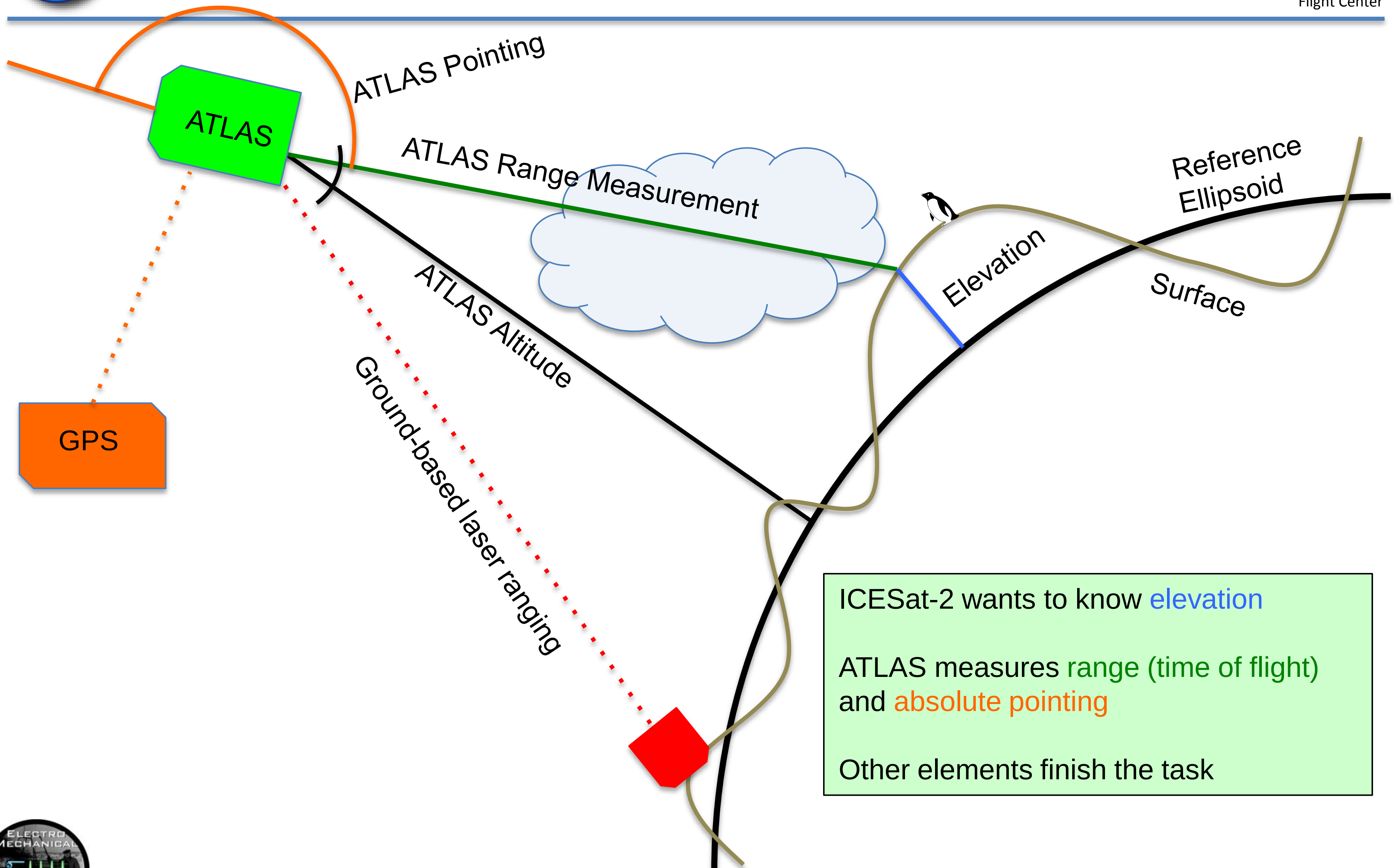

ICESat-2 wants to know elevation

ATLAS measures range (time of flight) and absolute pointing

Other elements finish the task

Transmit/Receive Alignment

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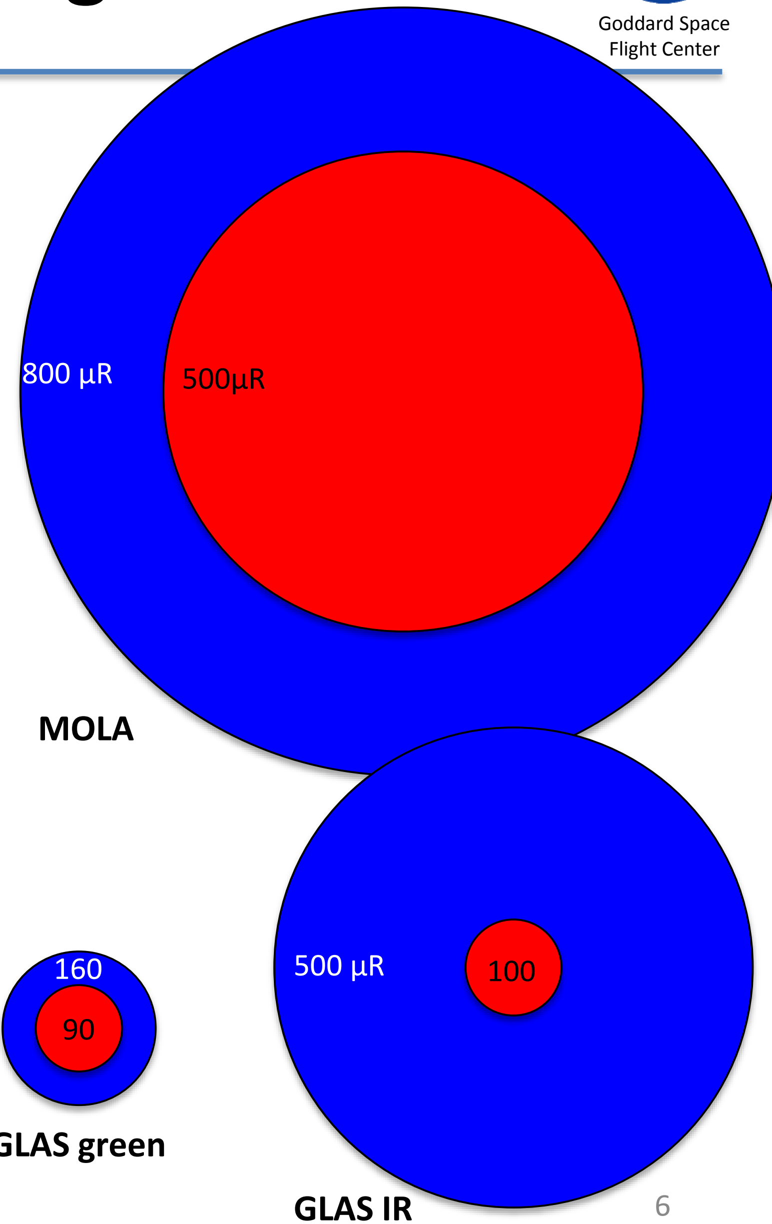
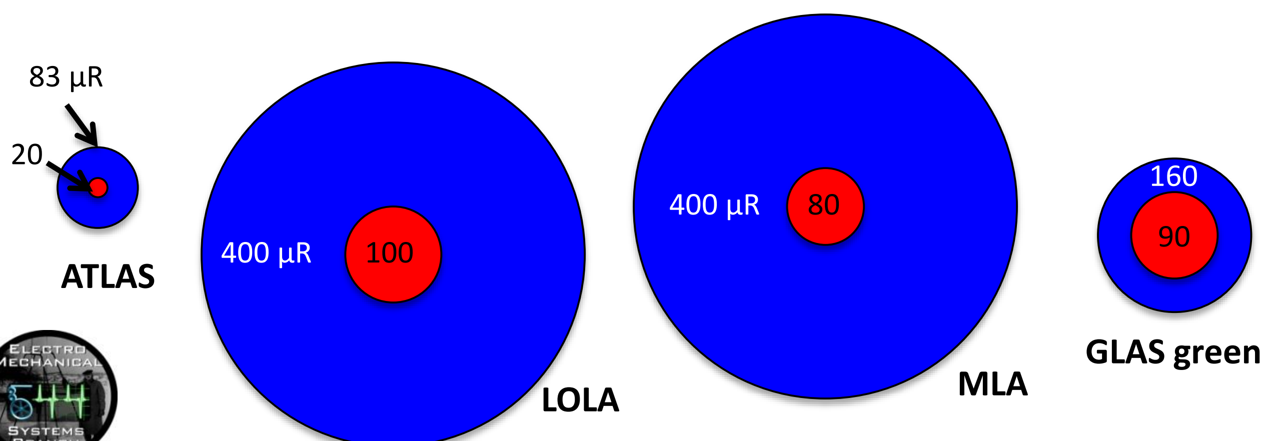
- Necessary to maintain alignment between the transmitter and receiver
- MOLA, GLAS IR channel, MLA, and LOLA depended on structural stability
- GLAS green channel had ground-commandable steering mirror in receiver
- ATLAS has the smallest transmitted beam, smallest receiver FOV, and smallest alignment margin of GSFC space-borne laser altimeters
- With such small margin, only an active alignment system can guarantee the required signal capture





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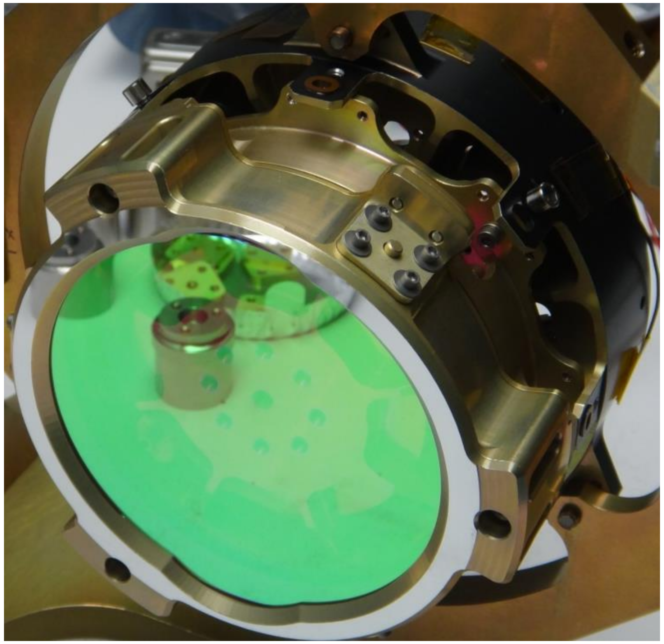

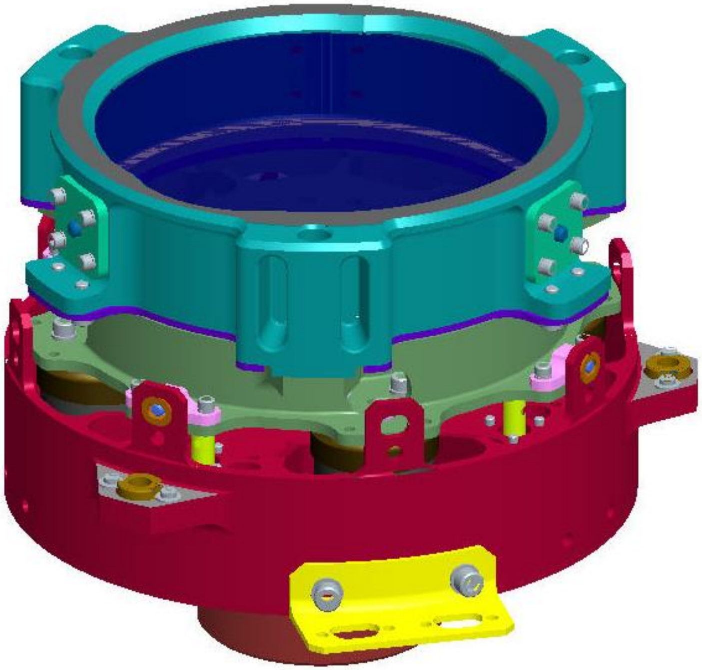

Beam Steering Mechanism (BSM) Overview

Driving Requirements (1 of 2)

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- Mechanical
  - Provide two axis steering of the transmitted laser beam
  - Mass: 5 Kg top level, everything mounted to the bench
  - Envelope: Volumes defined in ICD; Acceptable sunshade clearance in current CAD model
  - Range of Motion: ± 5000 μRad = ± 0.3 degrees mechanical motion each axis
  - Fundamental Frequency: Between 10 Hz and 15 Hz (power and bandwidth considerations)
  - Structural Modes: Desired to be greater than 400 Hz (bandwidth, performance, and mass considerations) Settled for greater than 200 Hz for the flexure
  - Interface: Defined in ICD
- Electrical
  - Power 4.875 Watts per axis available (carried in MEB)
  - Voltage ± 9.75 volts minimum available (after driver, sense, and harness drops)
  - Current 0.375 amps per axis available
  - Interface - as defined in the EICD
- Thermal
  - Operational -5 to +40 C (interface)
  - Survival -20 to 55 C (interface)
  - Heat into bench 2 Watts maximum
  - No active thermal control
  - 3 Temperature Sensors; 1 read by HKT, 2 read by MCE (1 per actuator axis)

Driving Requirements (2 of 2)

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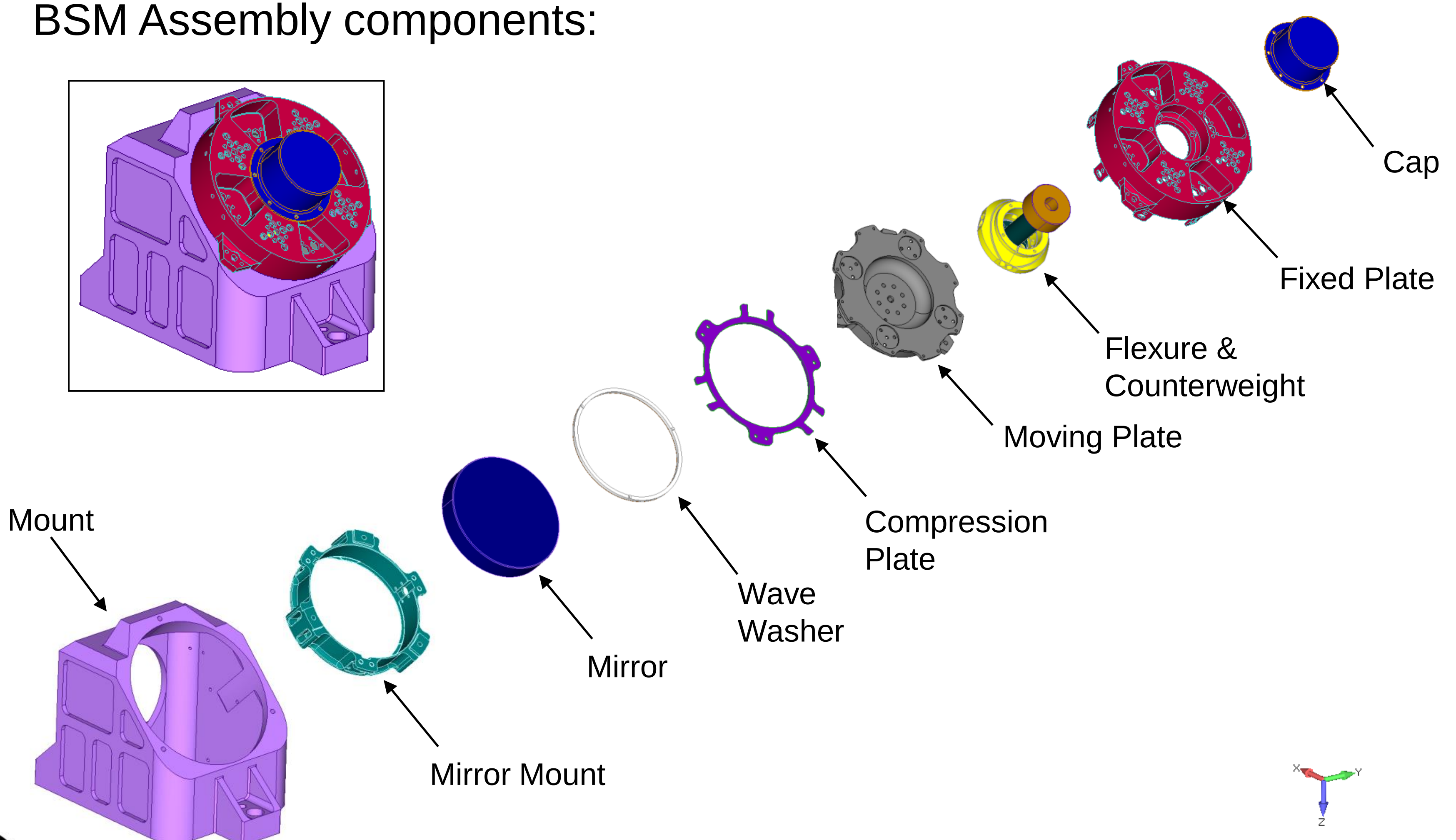
- Operational
  - Pointing Stability (mirror): 1.5 µRad RMS for science and cal
  - Motion Profiles: Calibration mode profile is a triangle wave motion 10 to 20 seconds
  - Pointing Knowledge: ±0.75 µRad mechanical bias, ±2.5 µRad mechanical noise
    - Range ± 9.25 volts over ± 5000 µRad
    - Sensor Bandwidth 10 Khz minimum
  - Max Mirror Velocity: 10.2 mRad/sec {170 µrad / (1/60) sec}
  - Max Mirror Acceleration: 25 rad/sec^2 for calibration mode
- Life: 3 years on orbit
- Redundancy: None required, Class C mission; Risk mitigation includes redundancy in actuator windings
- Optical
  - Clear aperture: 100 mm (66 mm at 45 degrees plus)
  - Mirror Diameter: 105 mm (101.6 mm for EM)
  - Coating: 99.5% reflectance at 532 nm
  - Surface Flatness (Installed): λ/8 over temperature
  - Scratch/Dig: 20-10

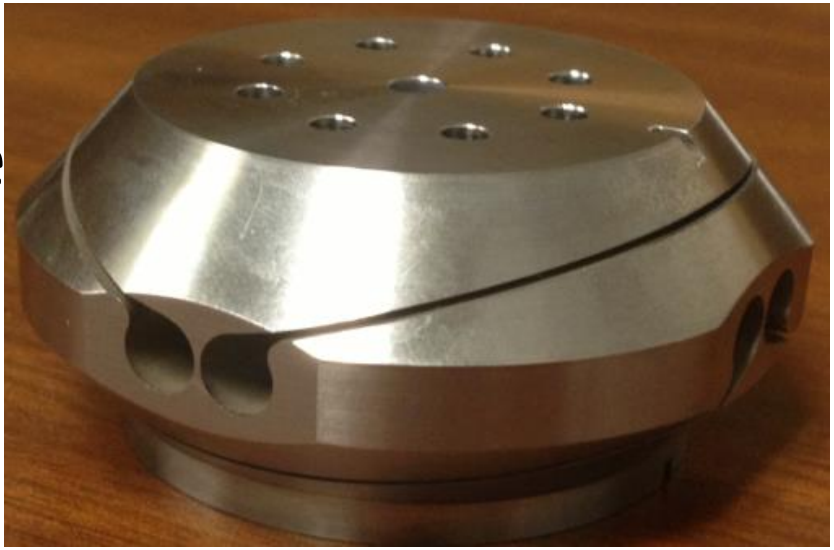
BSM Views 1

BSM Assembly components:



Flexure Unit

- Titanium 2-axis flexure unit
- Very significant flexure analysis focus throughout the program
- Analyses of 0.015 in and 0.020 in flexure thicknesses
- Analyses indicate positive margins and infinite life



BSM Views 2

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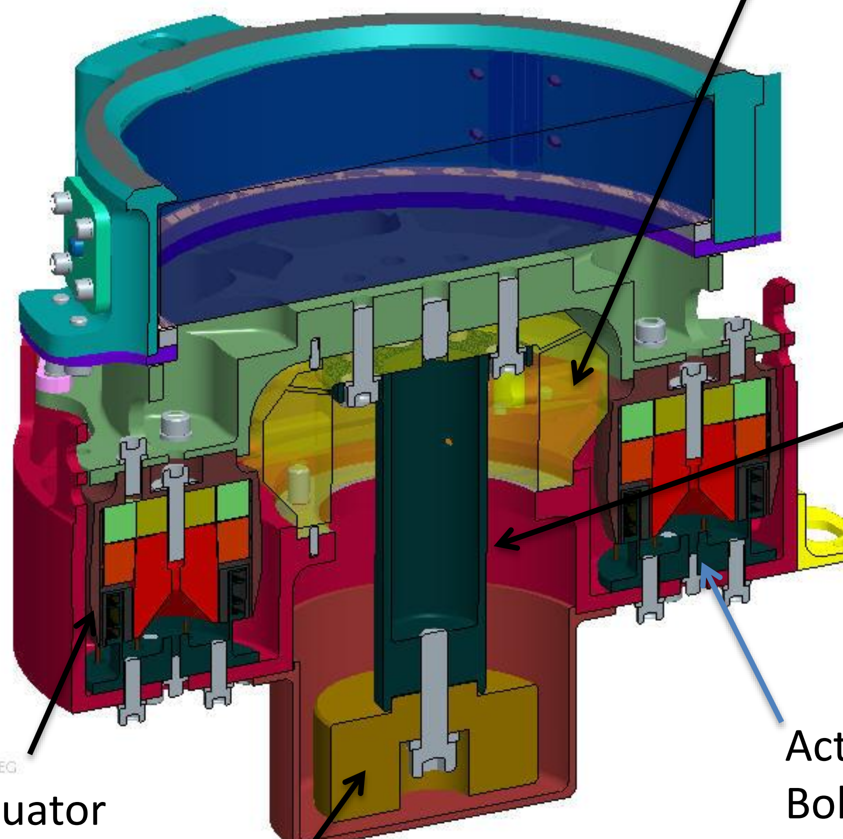

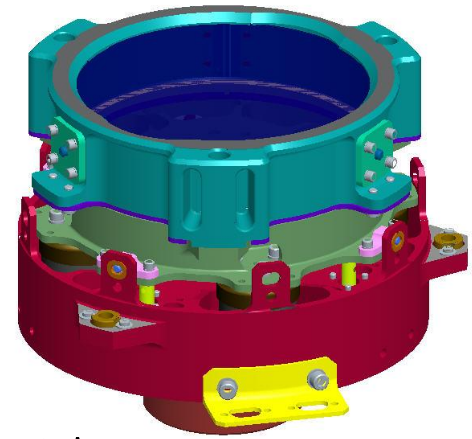

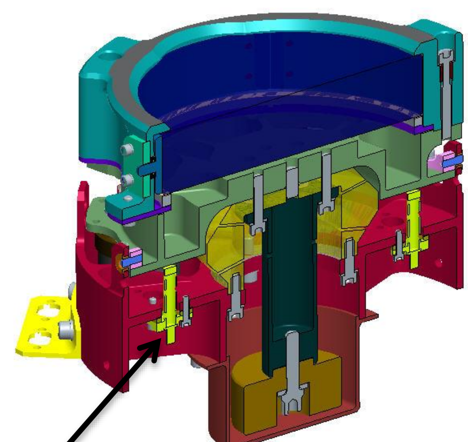

BSM Views 3

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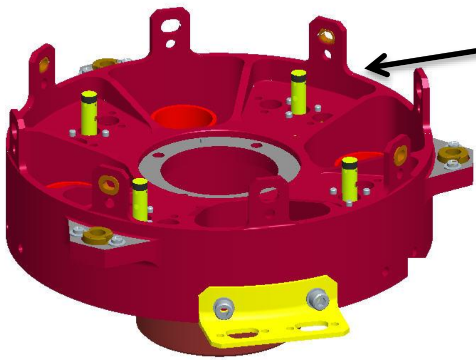
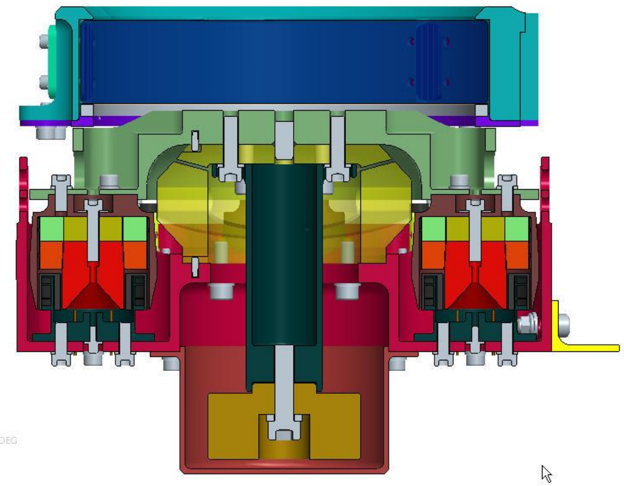
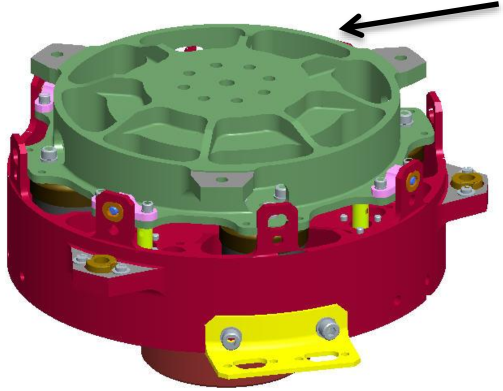
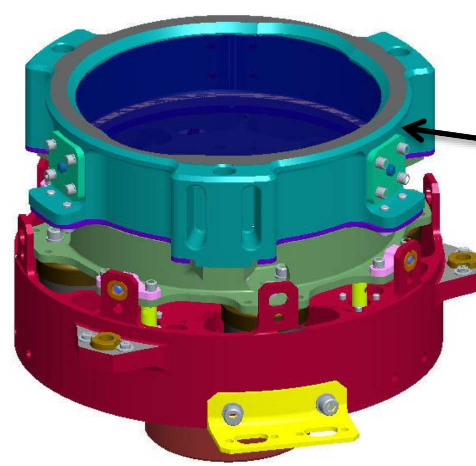


Fixed Plate





Moving Plate



Mirror Mount

Flexure Torque versus Angle

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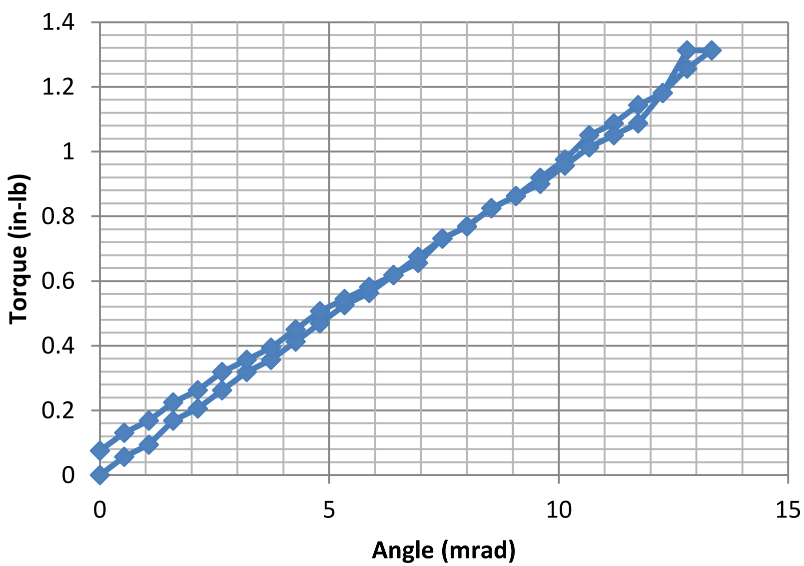
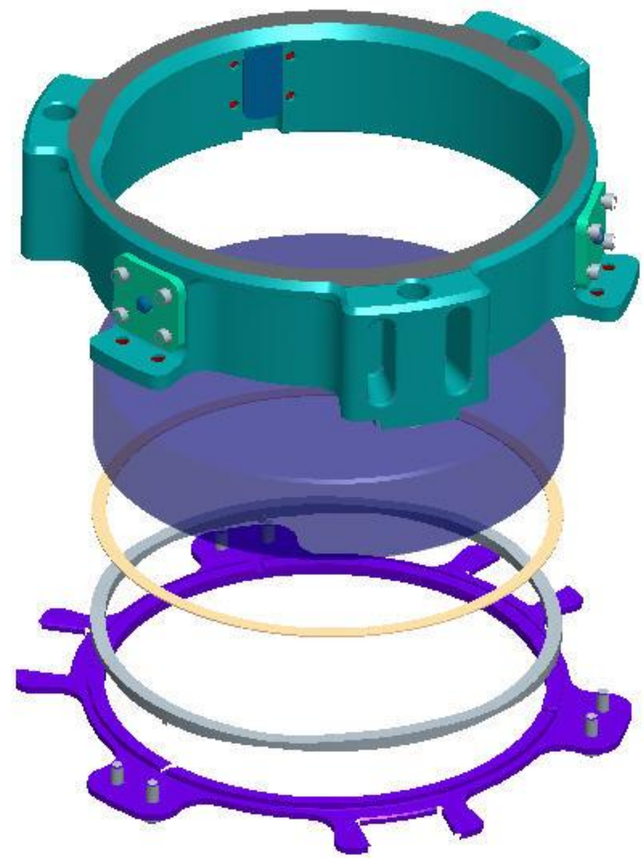
Test Date: 1/25/13
Flexure Thickness: 15 mils
Test Mode: +Y
Average: Ks = 99.77 in-lb/rad
Ks = 11.25 N-m/rad



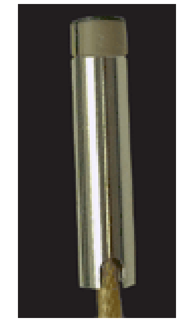
Mirror Mount

- Mount designed as a modular unit
- Diamond turned surfaces at three locations contact the mirror front surface
- Titanium wave spring provides axial preload of 10.8 N (48 lbs)
- Design has been modified to eliminate radial preload and incorporate small radial clearance
- Testing indicated figure is being met at ambient temperature

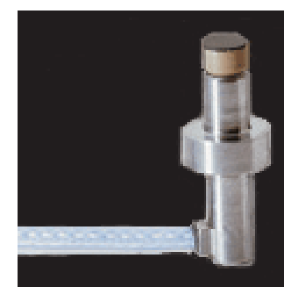


Differential Position Sensor System (DPSS)

- Blue Line Inductive Sensors
- Four sensors; two differential per axis
- Relative pointing knowledge of 0.75 μrad accuracy over a calibration cycle is required
- BSM targets incorporated as a diamond turned surface on the flexure rotation axes
- Industrial and Space Qualified versions
- Supply Voltage ± 15 volts
- Bandwidth 32 KHz
- JWST has completed space flight qualification program of these sensors
- Blue Line was under contract for flight delivery at the end of June 2013 and non-screened flight version (EM) delivery in latter April 2013



Industrial



SFQ Space Qualified

Major Testing

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- Closed Loop Testing
  - Frequency and Time Responses
    - Closed Loop Frequency Response
    - Step Response
    - Sweep Response
    - Pointing Stability (DPSS & 3-axis Zygo)
    - Gain & Phase Margins will be determined without an open frequency response
- Disturbance Rejection Test
- Exported Disturbance Test
- Sensor (DPSS) Verification, Scaling & Linearity
  - This is a BSM level test
  - Sensor versus 3-axis Zygo
  - Sensor versus autocollimator
- Thermal Balance Test
- Vibration Testing
- Mirror Only & Mirror with Mount Figure Testing
  - Ambient B5 figure measurement Zygo
  - Over Temp B33 chamber & figure measurement Zygo
- Life Testing
  - 10 M cycles each axis $\pm$ 120 urad near end of travel
  - 10 Hz operation for 24 days

Chamber Setup

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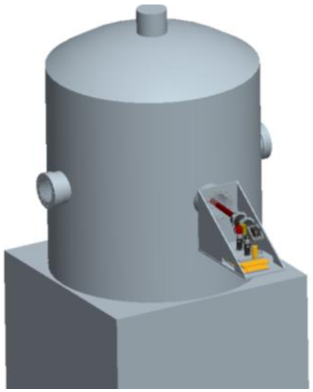
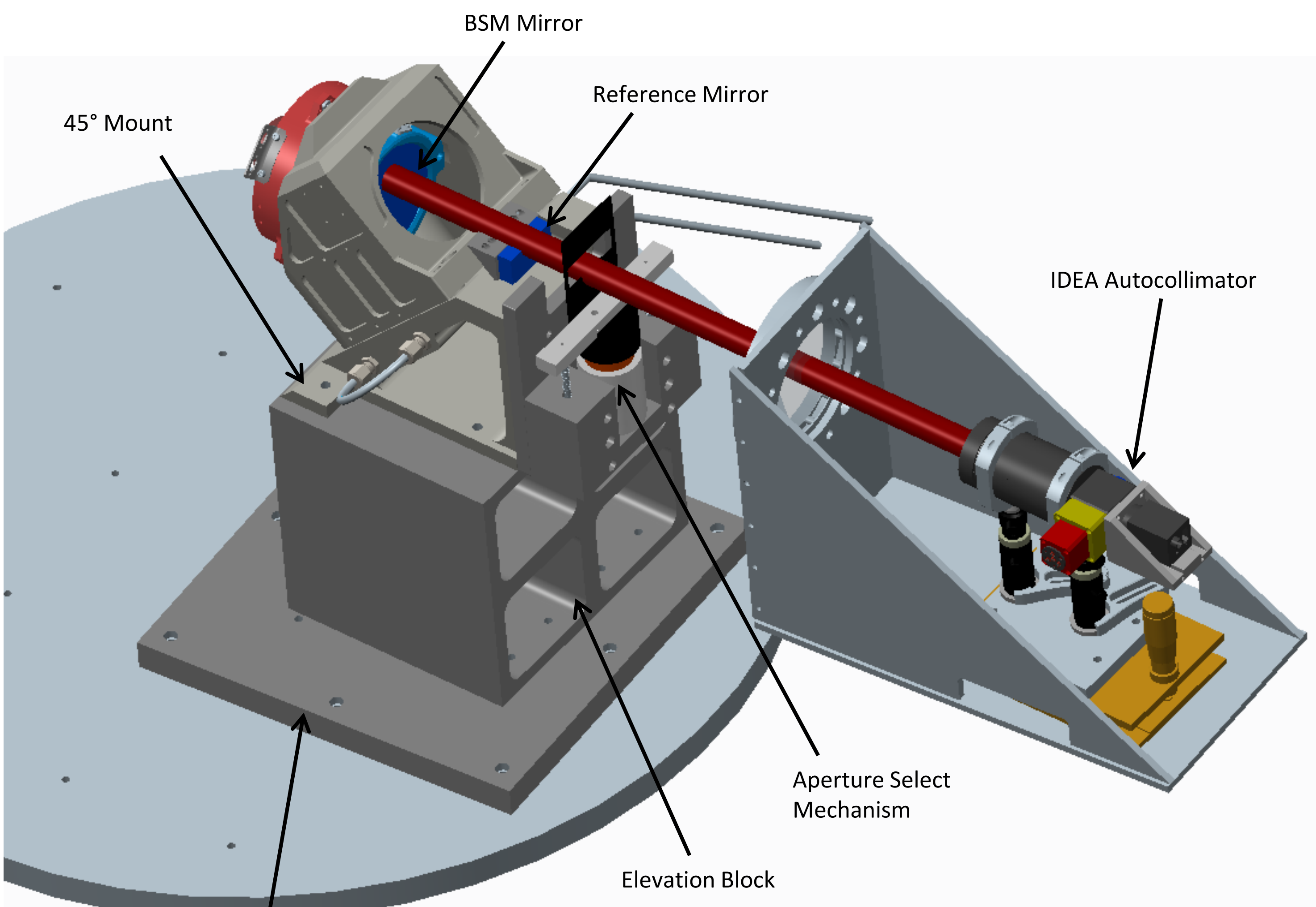
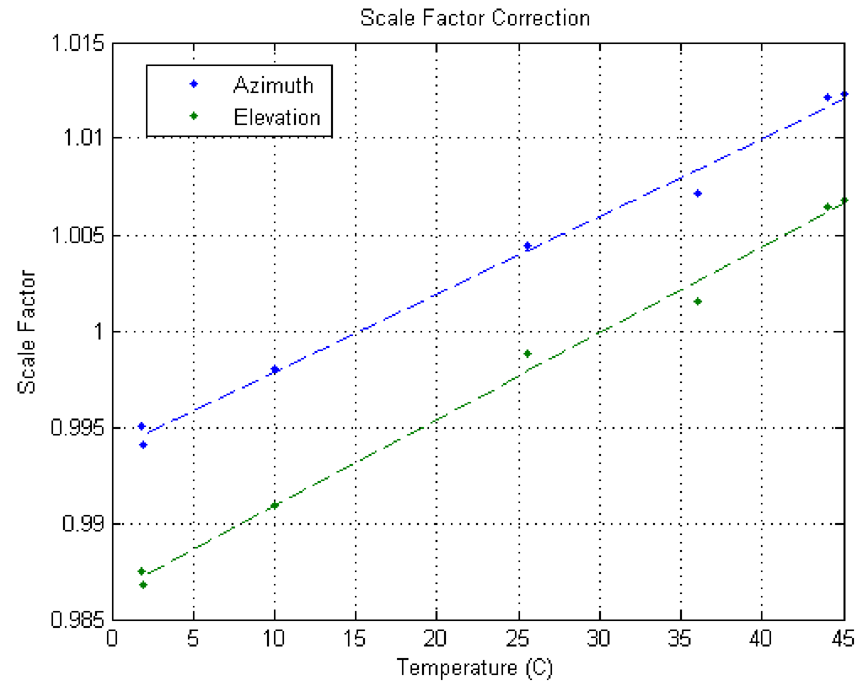




Requirement ID = BSM309, BSM310
IDEA Scale Factor

- Same fit function used on theodolite data was applied to IDEA point data
- Slope for each channel was extracted from fit data and plotted against temperature
- Fitting a line to slope vs temperature gives the adjustment coefficient for scale factor



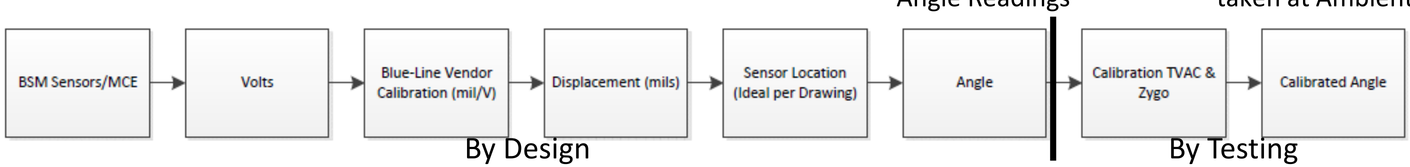
Scale Factor taken from TVAC

BSM Sensor Readings

$$Optical\ angle = k(T_{BSM}) * k_{Ambient} * Sensors_{BSM}$$

IDEA Optical Angle Readings

Scale Factor taken at Ambient



Conclusion

- Very significant flexure analysis and testing aided in the production of 1 of the BSM's most critical components
- Structural & thermal requirements have been met
- Figure testing led to an improved mount design that meets requirements
- Thermal Vacuum testing with the IDEA provided us with a relationship between the BSM sensors and an objective reference
- Through the BSM team's efforts, we were not only able to meet tight requirements, we far exceeded our initial expectations

Back-Up Slides

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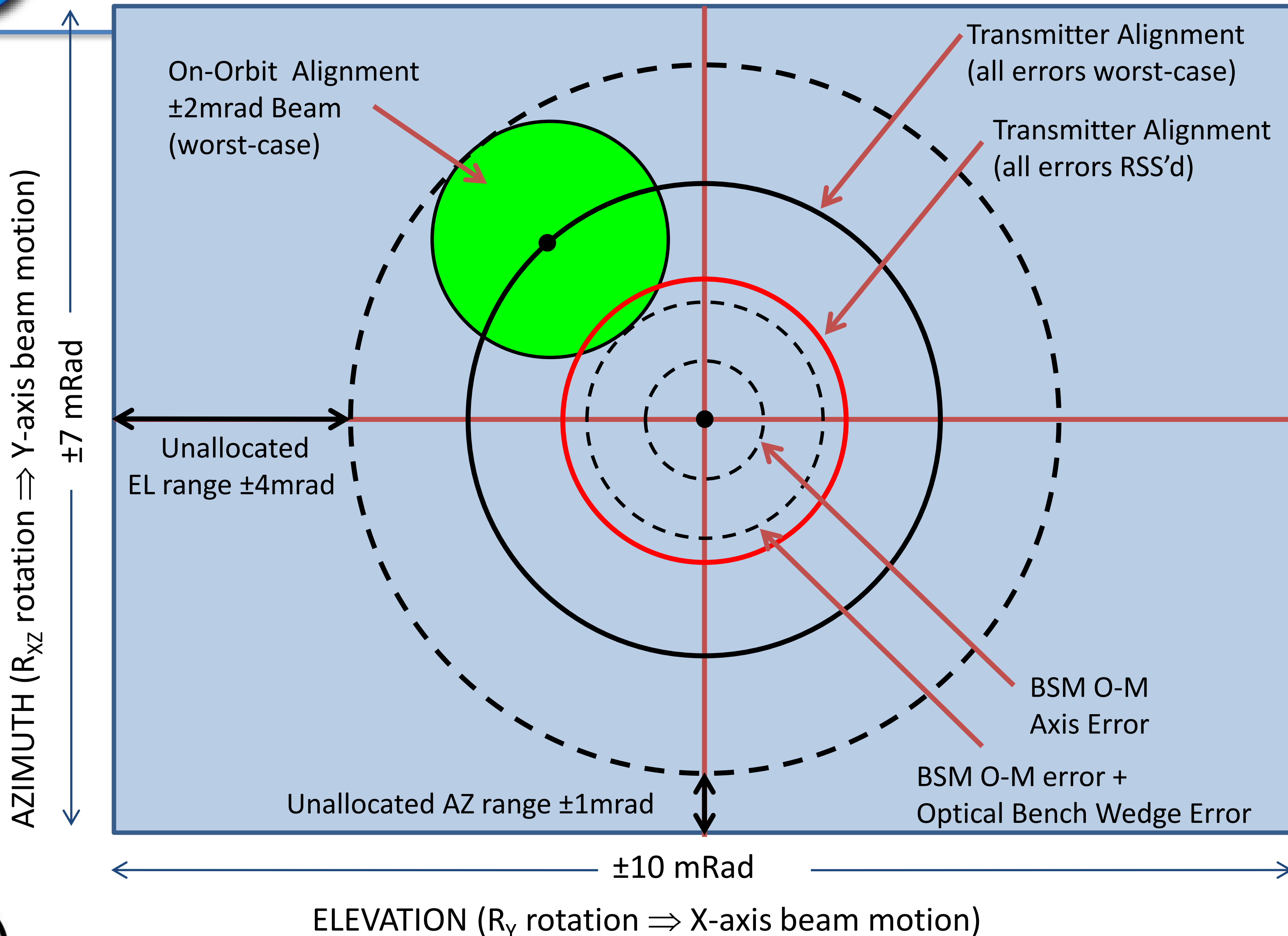
BSM Optical Adjustment Range



Drawn to scale

BSM Mechanical Range of Motion

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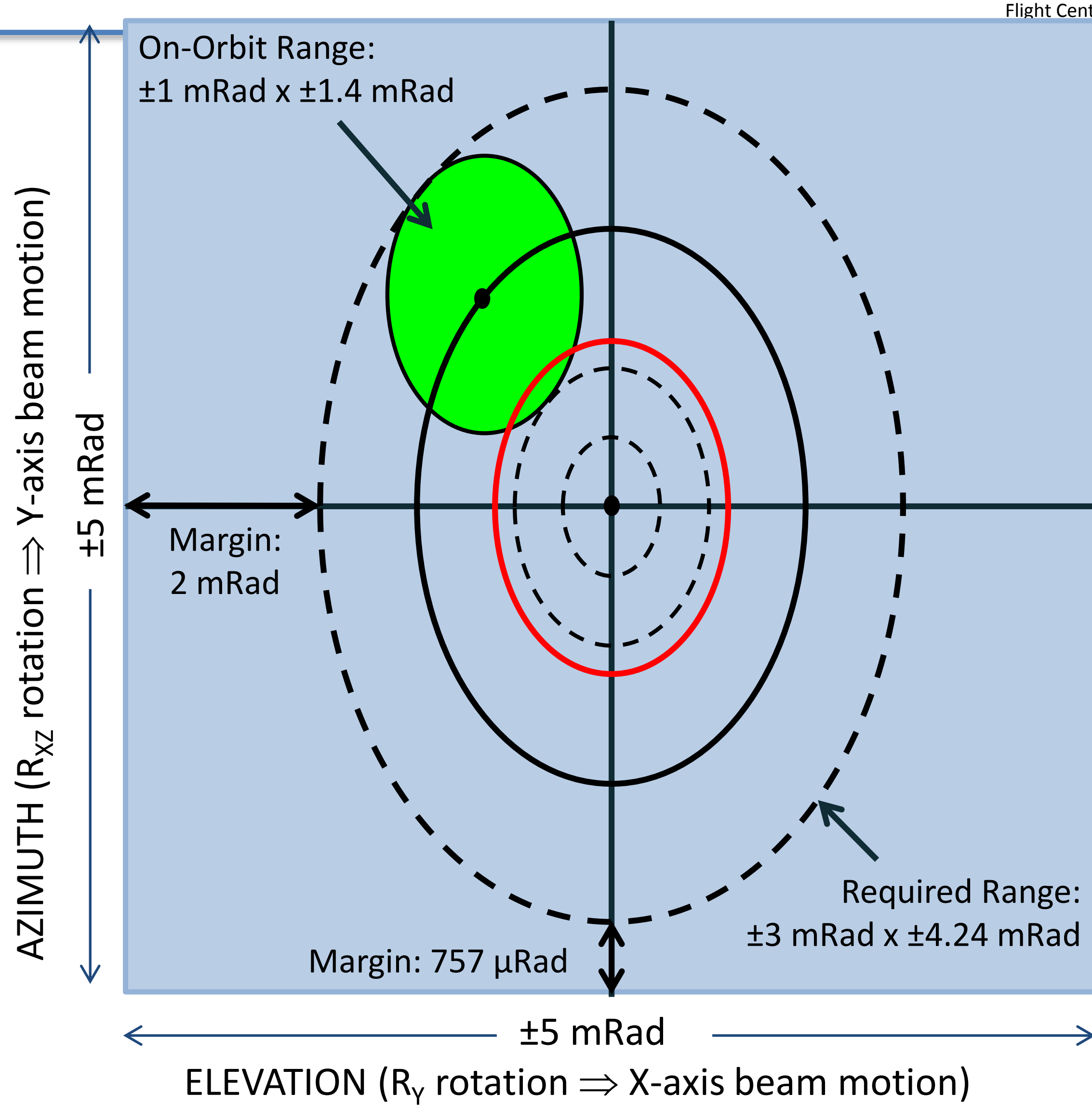
- Mechanical to Optical
  - R_Y: 2x gain
  - R_{XZ}: 1.414x gain
  - Due to 45° AOI of incoming beam (+X)
- Azimuth sensor axis nominally aligned to R_{XZ}
- Elevation sensor axis nominally aligned to R_Y

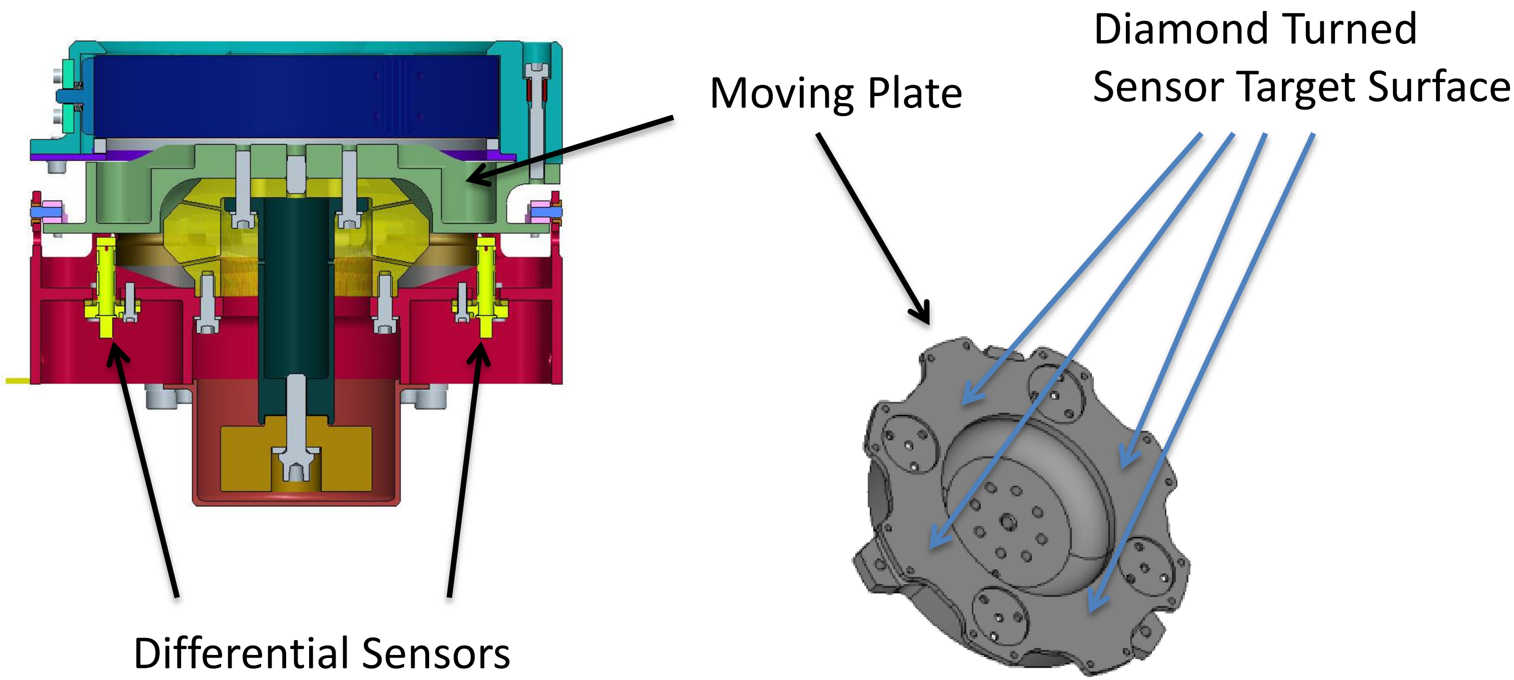


Drawn to scale

DPSS Considerations

- Sensor performance is critical to BSM performance
- EM BSMs to date each has an industrial DPSS, which has better performance than flight
- All EM performance presented is with an industrial DPSS
- Recent vendor testing of the flight-like DPSS indicates that requirements are being met
- Worst-case performance over life is a risk at this time, but will be answered once the worst-case analysis is completed
- Flight-like DPSS with non-screened parts will soon be integrated into a BSM and evaluated

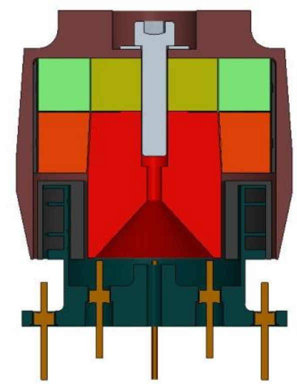
DPSS Geometry



$\pm$ 5000 µrad => $\pm$ 9.25 volts => $\pm$ 9.375 mils

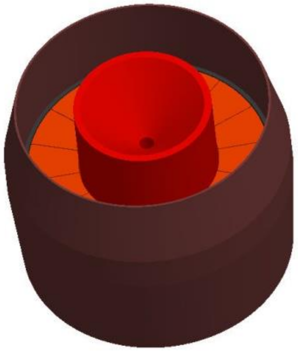
Actuators

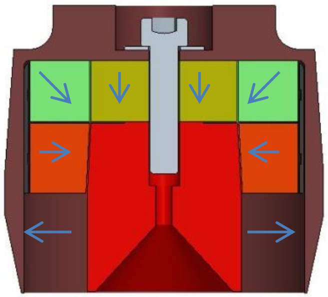
- EMs use commercial BEI Kimco actuators
- Custom actuators to be retrofitted to EM2
  - Optimized for highest efficiency
  - Redundant windings
  - High level of damping
  - Hiperco back iron
  - Neodymium Iron Boron magnets
  - Designed and fabricated in-house by Code 544



Actuator Magnets

- Magnets fabricated by Electron Energy Corp (EEC) are NdFeB 42 high temperature (150 C)
- Segmented magnets require each segment to be aluminum ion vapor deposition (IVD) coated and iridited before magnetization
- Segmented magnets are bonded into an assembly by EEC holding tolerances without OD or ID grinding





Actuator Specifications

Kf = 8.04 N/A

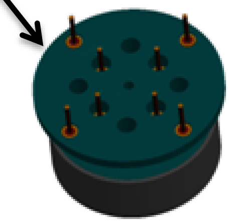
Ka = 1.93 N/sqrt (watt)

R = 17.3 ohms

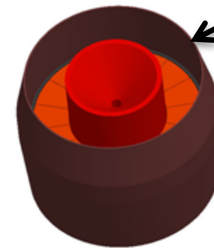
Cd = 38 N/m/s

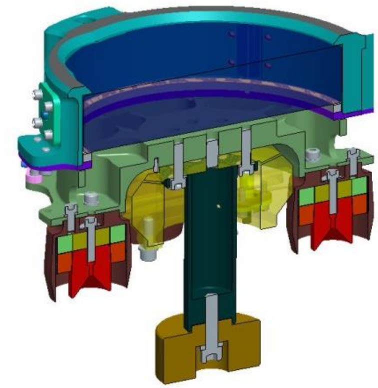
Magnet Wire Gage:	34.5 AWG
Magnet Wire Type:	HML
Turns/Layer Primary:	16
Number of Layers:	14
No. of Turns Primary:	224
Turns/Layer Redundant:	8
No. of Turns Redundant:	112

Bobbin



Field





Bobbin

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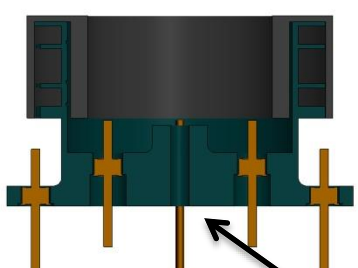

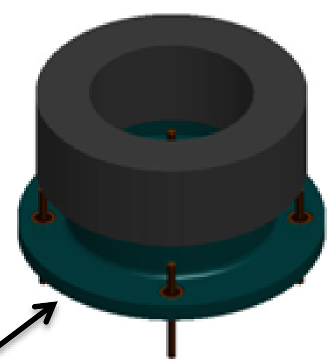

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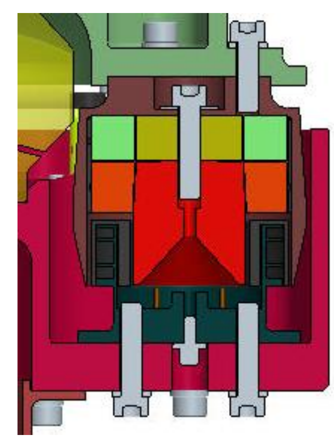

Actuator Torque Margin

BSM Parameters

θmax = 5.1 mrad

ωmax = 10.2 mrad/sec

αmax = 25 rad/sec^2

I = 0.00302 kg-m^2

Ks = 11.6 N-m/rad

Ct = 0.262 N-m/rad/sec

Torque Required

Tflexure = Ks * θmax = 0.059 N-m

Tdamp = Ct * ωmax = 0.003 N-m

Taccel = Ks * αmax = 0.076 N-m

Ttotal = 0.138 N-m

Force Required

Actuator Mount Circle: D = 95.3 mm

Single Actuator Force: F = Ttotal/D

F = 1.45 N

Current, Voltage, and Power

iload = F / Kf = 1.45 / 8.04 = **180 mA**

V = iR = 0.180 * 34.6 = 6.24 volts (axis)

P = i^{2}R = 0.180^2 * 34.6 = 1.12 watts (axis)

Torque Margin

Available Voltage

Vsupply – Vsense – Vsw – Vsupplyslew – Vdriver – Vharness

= ±14.25 – 0.01 – 0.6 – 0.675 – 3 – 0.2 = **±9.75V**

Available Current

I avail = Vavail / R axis = 9.75 volts / 34.6 ohms = **282 mA**

Load Current

iload = F / Kf = 1.45 / 8.04 = **180 mA**

Factor of Safety

FS = **1.5**

Torque Margin

TM = [i avail / (FS x I load)] - 1 = [282 mA / (1.5 x 180 mA)] - 1

=> Tm = **0.044**

Torque Margin is Positive

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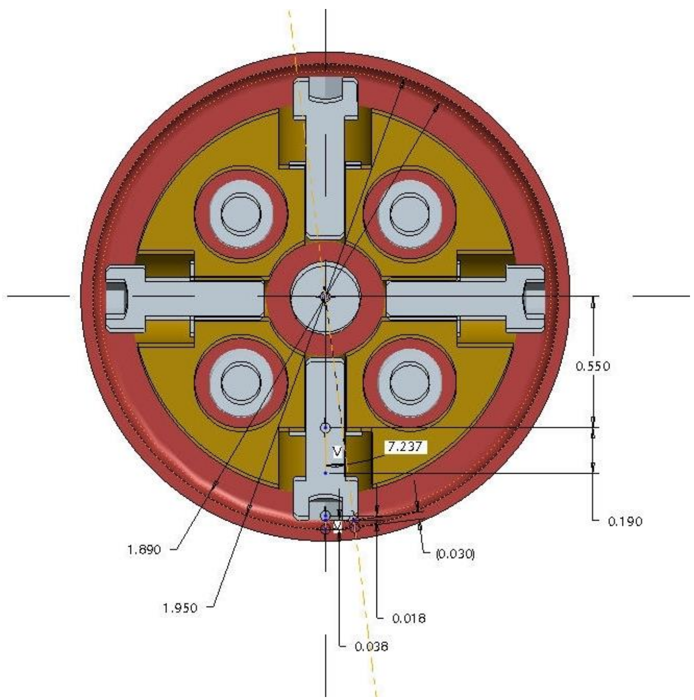
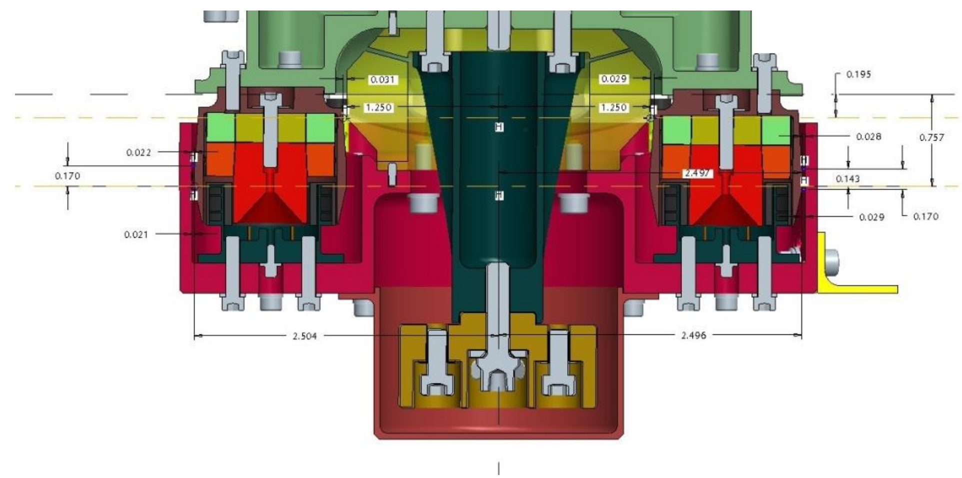
Worst Case Clearances

- Fixed and moving portions of the actuator are aligned during assembly using a close-fit pin





Launch Lock Not Needed

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- A conservative analysis assuming worst-case rotational loads results in a benign impact of the hardstops
- Precision balancing of the moving mass results in benign impact of the hardstops
- High actuator damping ensures energy does not build up
- Balancing set to better than 16 μradians for a 180 degree change in gravity

Balancing of the Moving Mass 1

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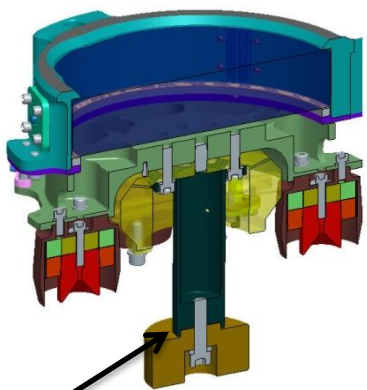
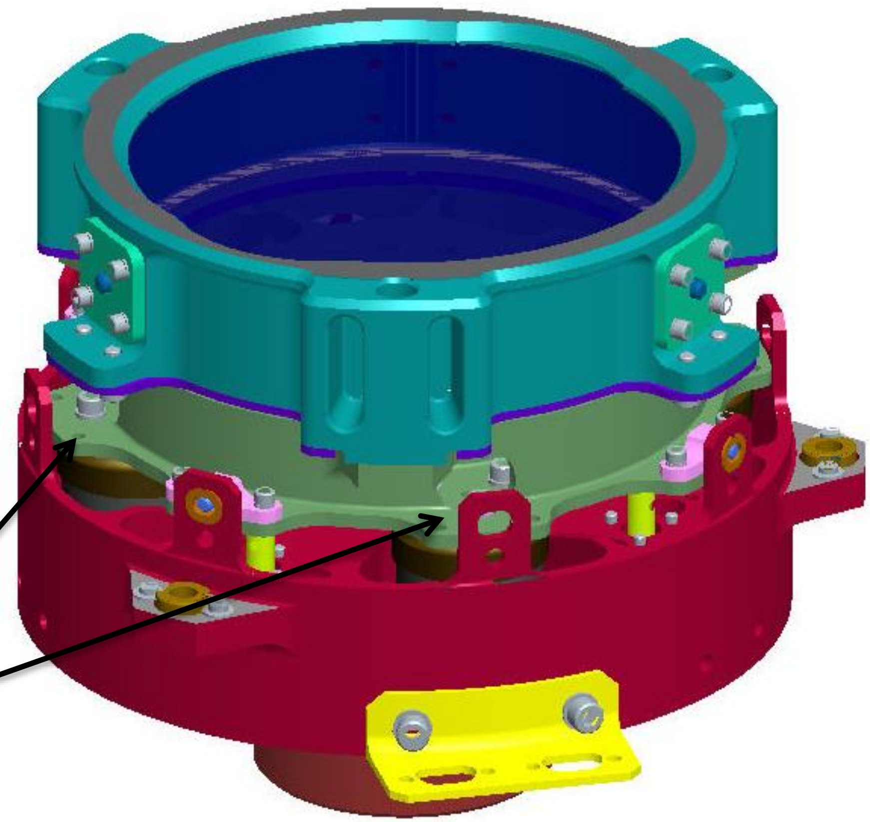
- The internal sensors are used for balancing
- A GSE balancing fixture can orient the BSM in 6 positions: plus/minus x, y, and z
- Balance to better than 16 μradians
- The counterweight is shimmed and weights are ultimately fabricated and attached at four locations in between the four hardstop locations

Balancing of the Moving Mass 2



Shim to Balance



Balance Weight Locations

Tungsten blocks to be used for balancing

Random Error Performance

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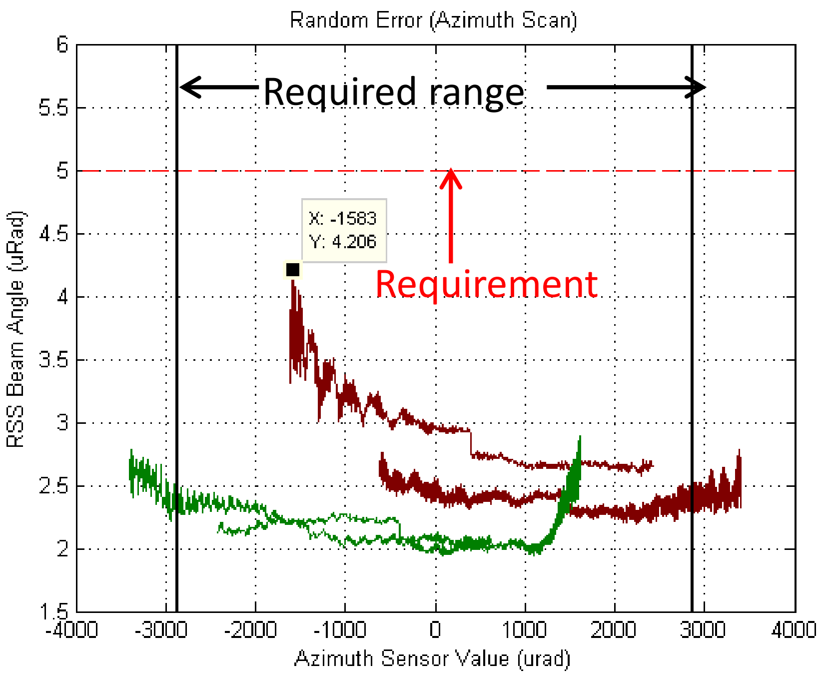
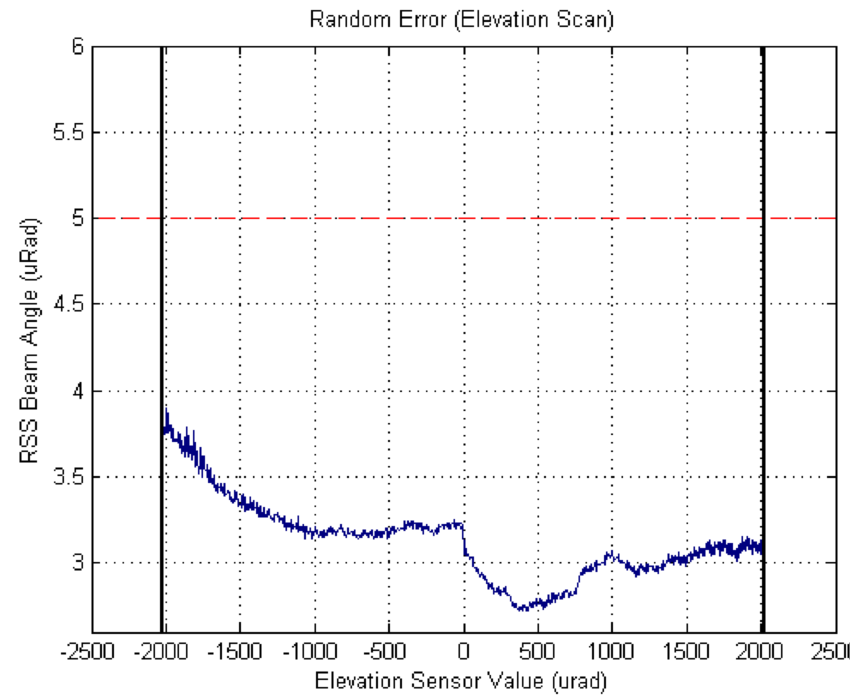
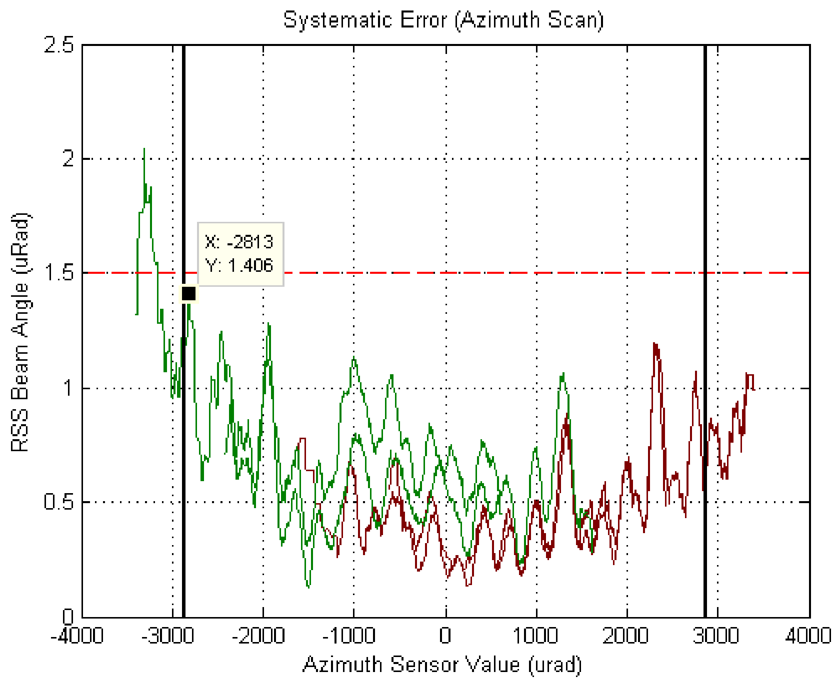


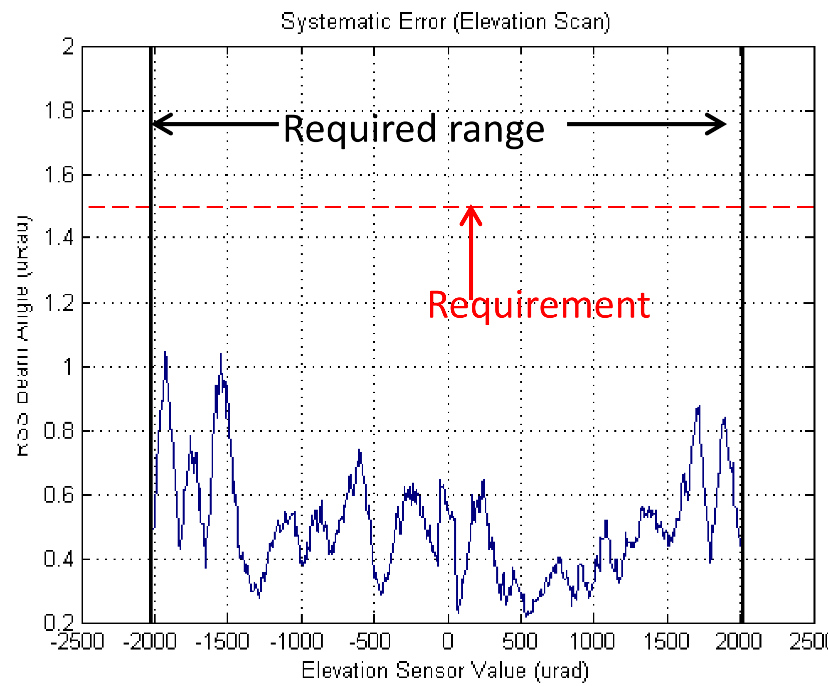


Red curve is with BSM rotated 90 degrees
Green curve is with BSM rotated 90 degrees, shimmed 14 mils
To gauge performance at a certain location look at the max of all curves at that level

Requirement: Random Error < 5 urad
Performance: Random Error < 4.21 urad

Systematic Error Performance



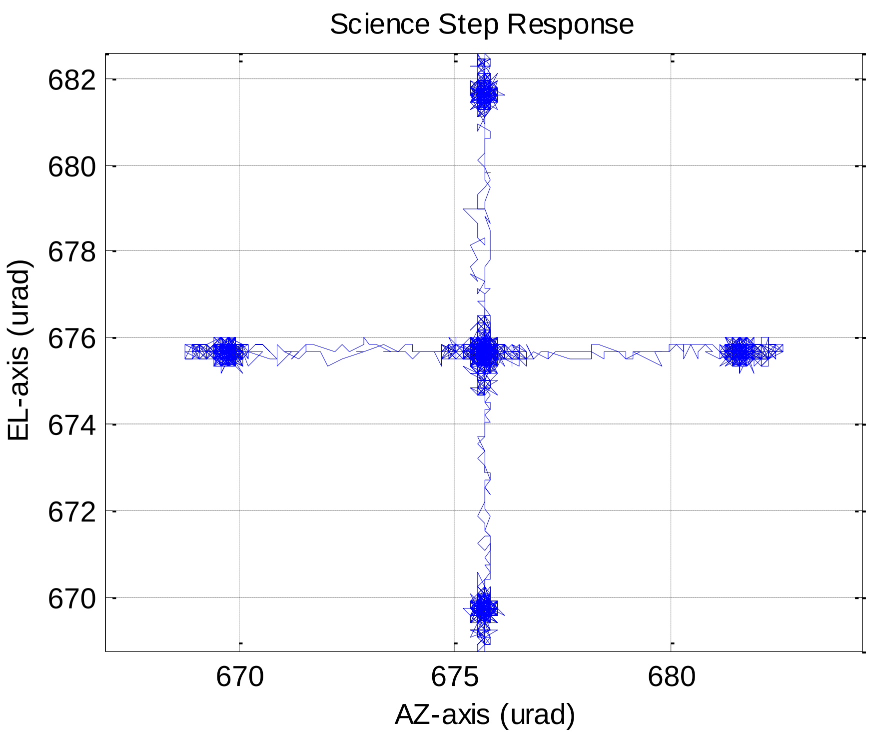


Requirement: Systematic Error < 1.5 urad

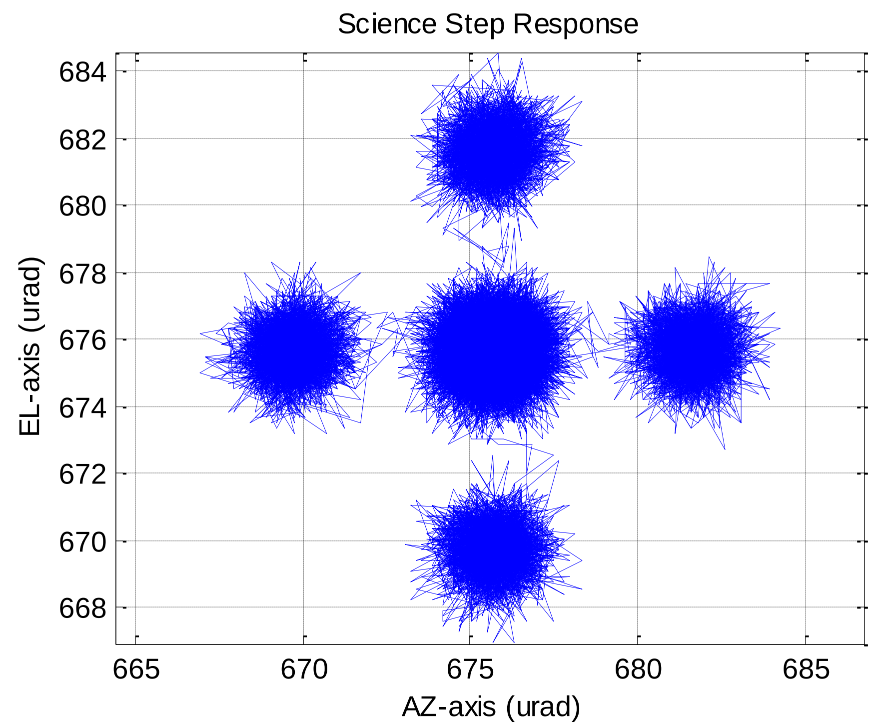
Performance: Systematic Error < 1.41 urad

Science Mode Step Response FIFO Position Data Comparison

Flight BSM + Flight MCE

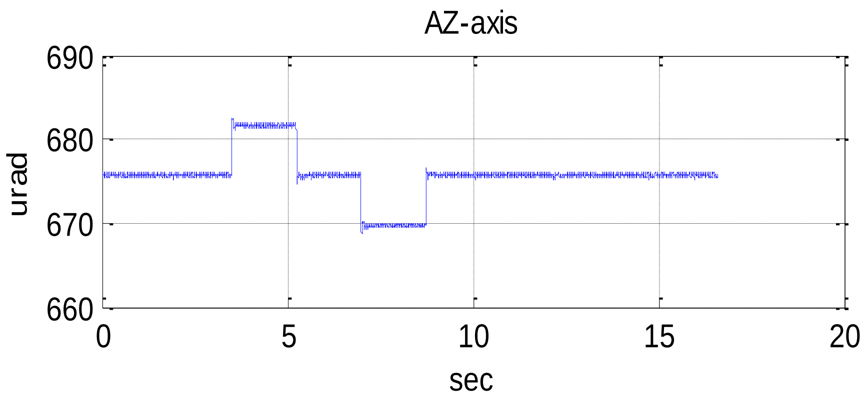


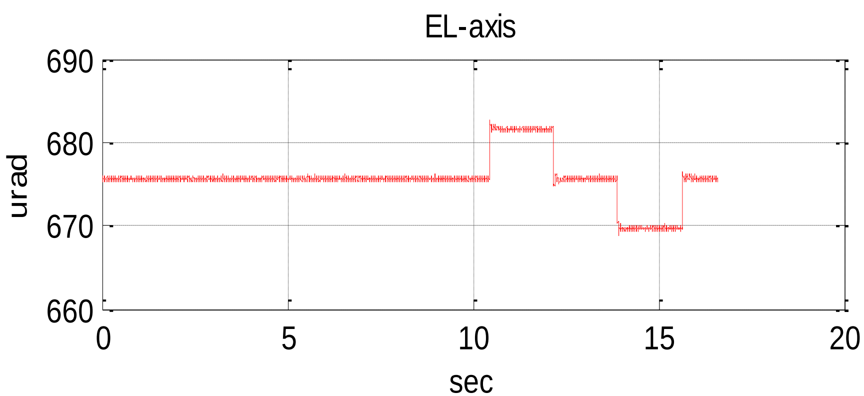
Flight BSM + EM MCE



Science Mode Step Response
FIFO Position Data Comparison

Flight BSM + Flight MCE





Flight BSM + EM MCE