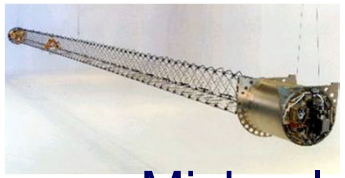
Phaeton Mast Dynamics:

On-Orbit Characterization of Deployable Masts



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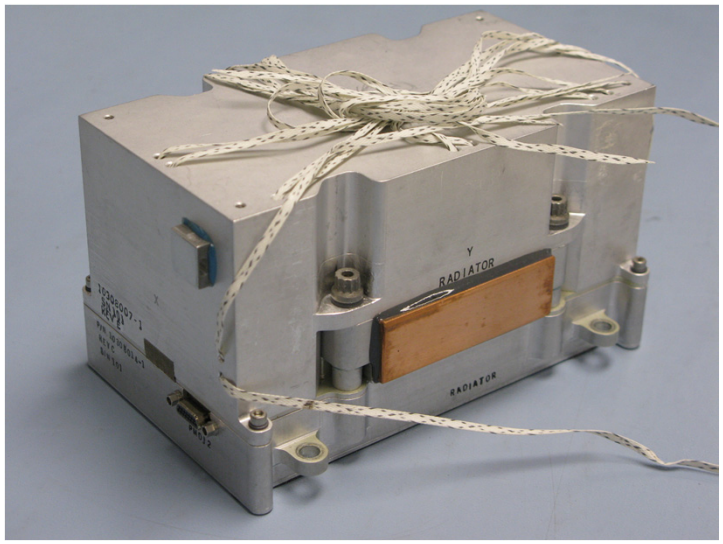


Background

The PMD instrument was designed and built for the Nuclear Spectroscopic Telescope Array (NuSTAR) spacecraft. After instrument completion, NuSTAR de-scoped PMD for NuSTAR-internal reasons. PMD is now hosted by the Air Force Research Laboratory's (AFRL) Demonstration and Science Experiments (DSX) mission.

This presentation discusses the PMD instrument architecture and design, including design constraints, design solutions, and instrument results. Since the design and build phases were completed with PMD as a NuSTAR payload, the presentation discusses NuSTAR's constraints and initial accommodations.

The instrument results presented here are independent of the host mission, but the effects of a host mission's data handling design on PMD capabilities is discussed in 2011 IEEEAC Paper 1305.

Objective

Purpose

– Characterize the on-orbit structural behavior of the NuSTAR spacecraft's 10-m deployable mast

Minimum Mission Success

– Measurement of one degree of freedom for motion of the mast's first bending mode

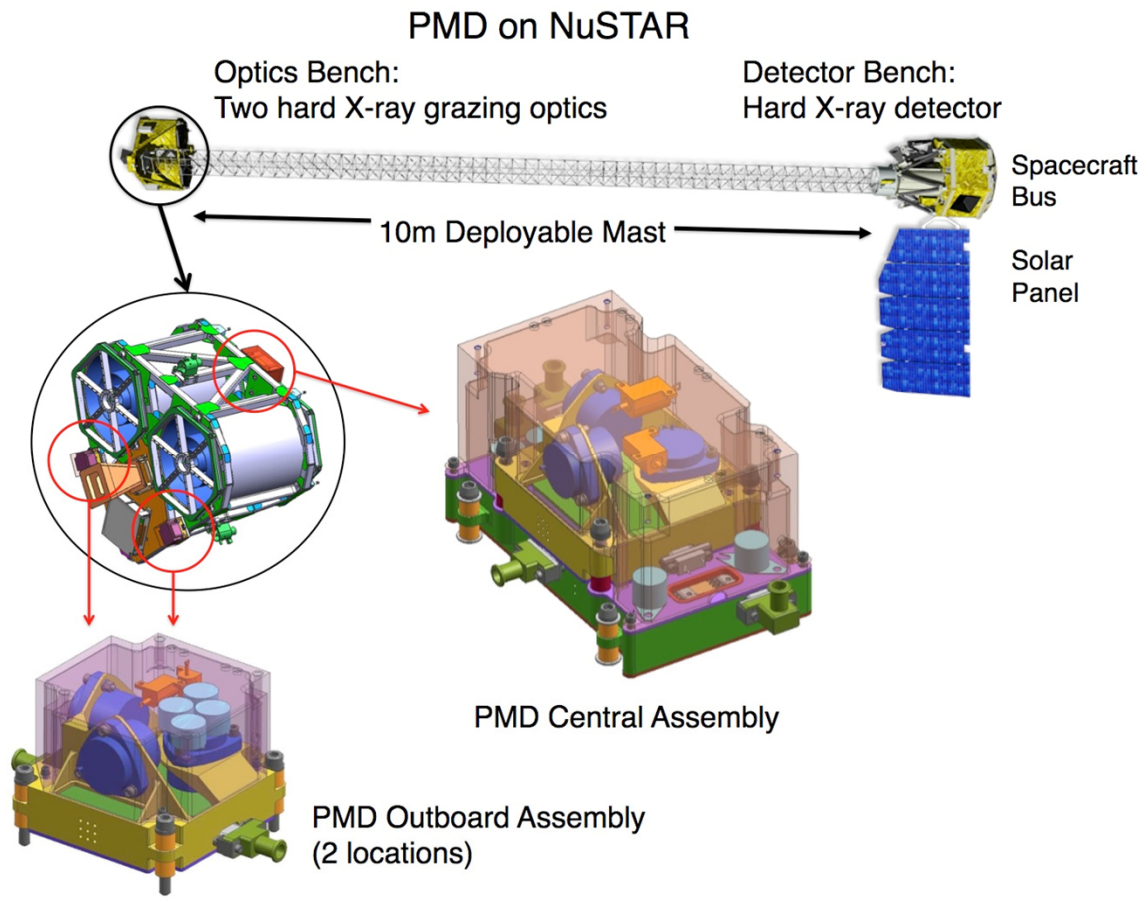
Dynamic Range of Interest

– 1-5 Hz motions with 1-10 micron displacement (100's of µg)

Requirements

– Detect accelerations from 50 µg to 2000 µg in the 0.1–30 Hz range

– PMD experiment to be a separate fault containment zone



System Architecture

Sensor Selection

– Honeywell QA2000 accelerometer chosen for:
  - 1 µg resolution
  - Tolerance to NuSTAR's launch environment
  - Flight heritage
  - Low mass

– Additional attributes include:
  - Single axis measurement
  - ±15 V operation
  - Acceleration-proportional current output

NuSTAR Provisions & Constraints

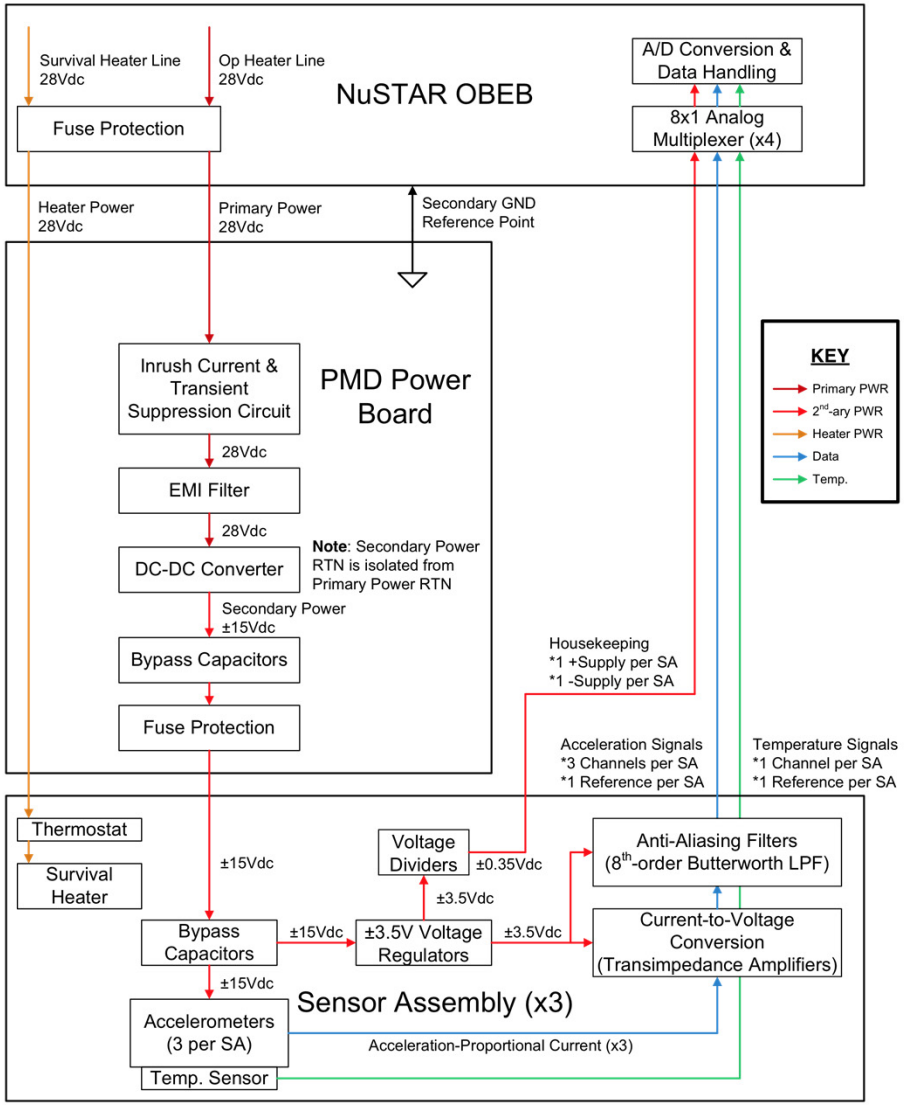
– PMD footprint options only on Optics Bench
  - 3 locations offered
– A/D conversion and data handling performed by NuSTAR
  - Single analog input with ±3 V range
  - 57.6 kbit/s maximum data rate
– +28 V primary supply voltage
  - Independent survival heater power line included

Resulting Architecture Design

– PMD System:
  - 3 units - each with 3 triaxially mounted QA2000's and collocated signal conditioning circuitry
  - Allows for full reconstruction of the rigid-body motions of the optics bench relative to the detector bench
  - 6 degrees of freedom measured: X, Y, Z (directly), yaw, pitch, roll (indirectly)
– Signal Conditioning Electronics:
  - Transimpedance amplifier
  - 8th-order Butterworth low pass anti-aliasing filter accommodating a 200 Hz sampling frequency per channel
– Power Conditioning Electronics:
  - Interpoint DC-DC converter & EMI filter
  - ±15 V secondary voltage for QA2000's
  - ±3.5 V regulated voltage for amplifiers
  - Inrush current limiter
  - Fully redundant, passively controlled heater system

System Architecture

PMD Electronics Block Diagram

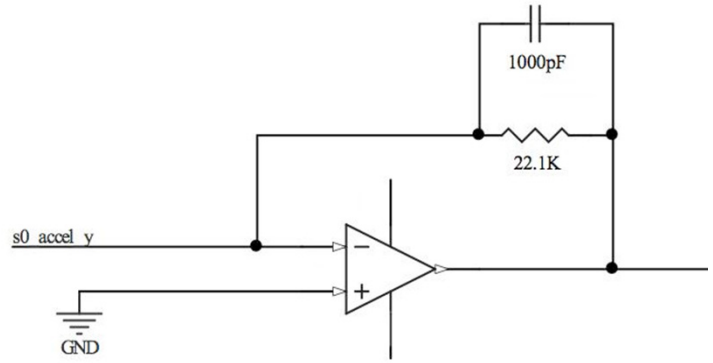


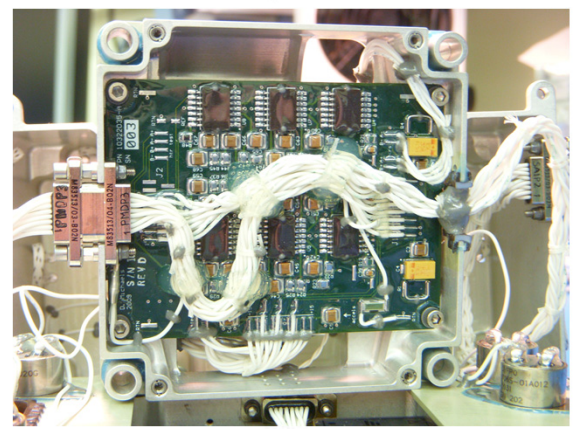
Electronics Design

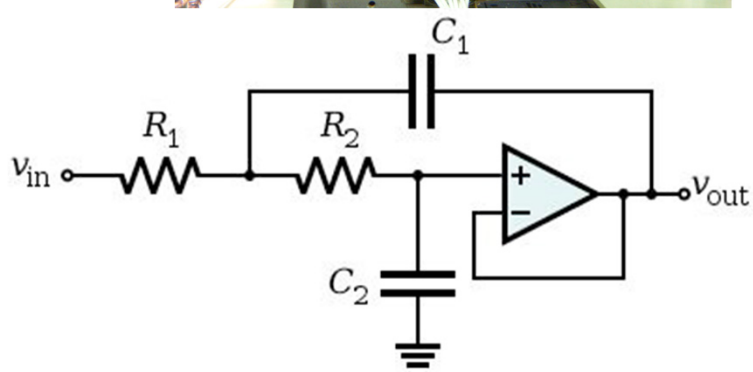
Signal Conditioning Electronics

– Transimpedance amplifier design:
  - Op-amp selected with low input bias current to meet the 65 nA (or 50 μg) minimum detection requirement, the 16 nA (or 13 μg) LSB with NuSTAR's ADC, and the 1.3 nA (or 1 μg) QA2000 resolution limit
  - Input offset voltage no concern to calibrated data
  - 22.1 kΩ load resistor selected for full ±3 V ADC range at 0.1 g input
  - A single 22,100-Ω transimpedance gain stage is sufficient to keep the QA2000 sensors from saturating

– Anti-aliasing filter design:
  - 8th-order Butterworth low pass filter using cascaded versions of the Sallen-Key topology
  - 30-Hz cutoff frequency allows for 84 dB attenuation by the 100-Hz Nyquist frequency
  - Butterworth filter minimizes amplitude distortion
  - Phase distortion is inconsequential to PMD data



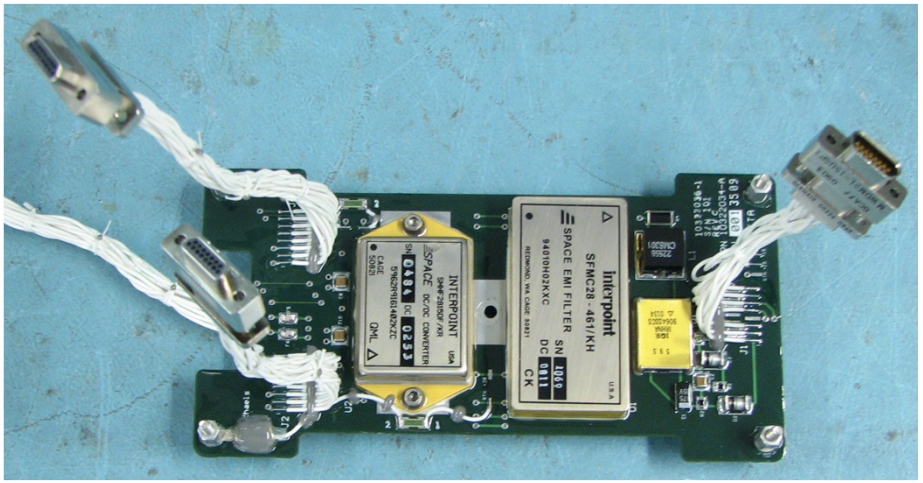


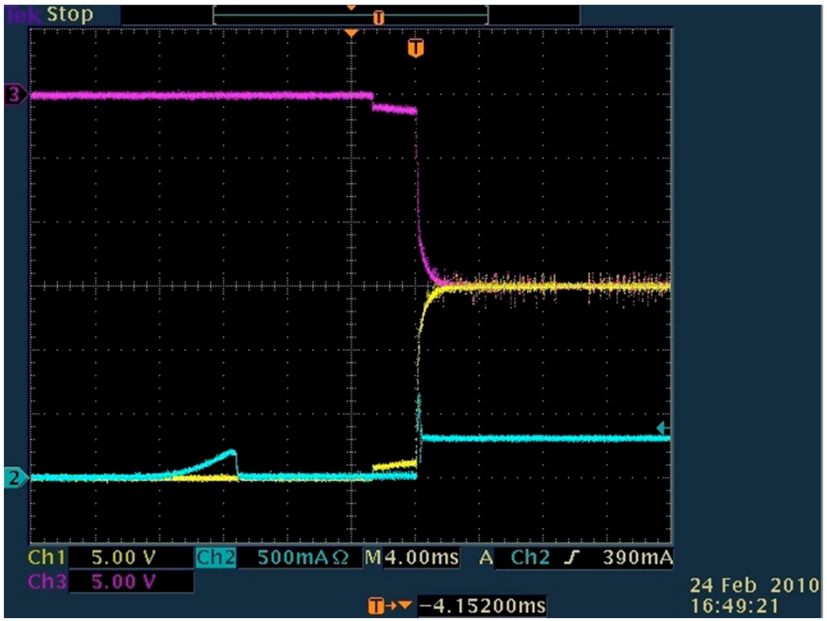


Electronics Design

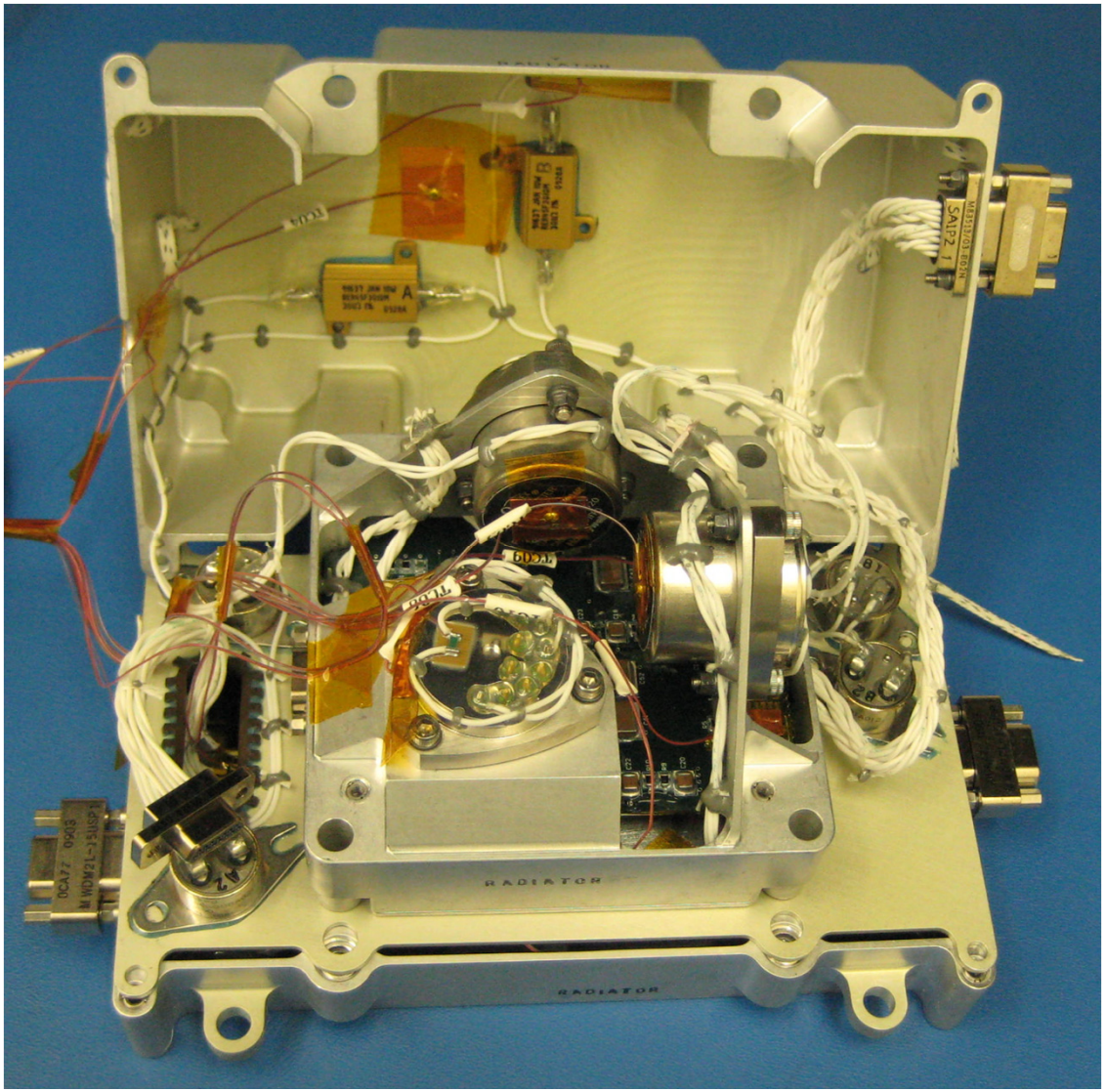
Power Conditioning Electronics

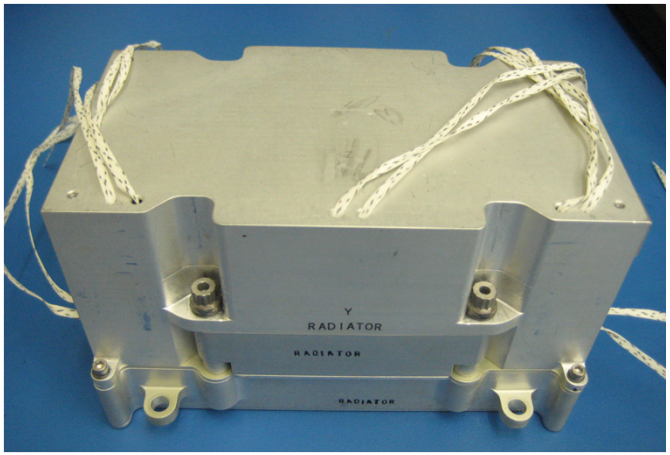
- Interpoint DC-DC converter & EMI filter selected to provide ±15 V secondary supply voltage to PMD electronics
  - Supplies QA2000's
  - Provides DC isolation between PMD electronics and NuSTAR's heater power bus
- Linear voltage regulators provide ±3.5 V to signal conditioning electronics from ±15 V secondary supply
  - Allows headroom for full use of NuSTAR's ±3 V ADC input range
  - Limits PMD data from encroaching the ADC's ±5 V absolute maximum input voltage rating
- Soft-start circuit keeps inrush current limited to under 2 A
  - Delay on DC-DC converter's inhibit pin separates primary and secondary inrush peaks
  - 10 ms timing separation between peaks maintains operability from -35 C to +60 C and with input voltage from +22 V to +34 V

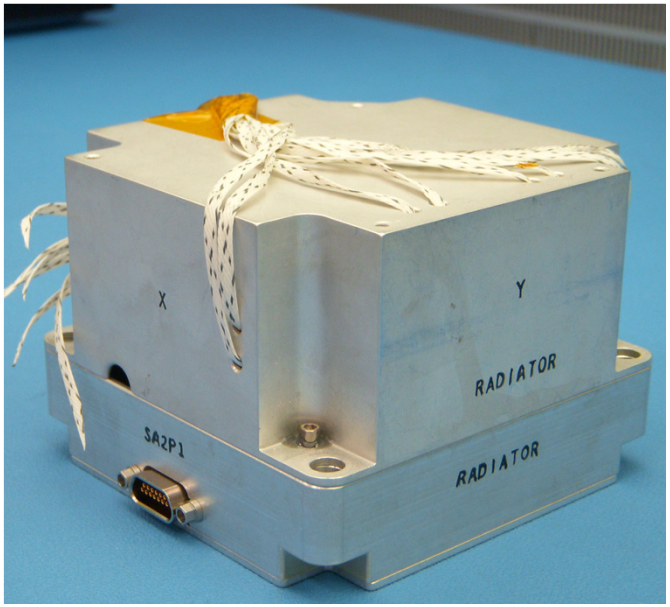




PMD Units


RADIATOR
RADIATOR
SA1P2


Y
RADIATOR
RADIATOR
RADIATOR

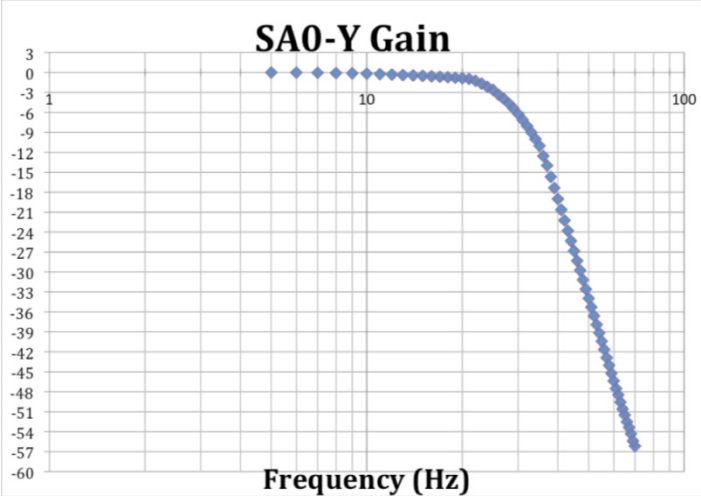

X
Y
RADIATOR
RADIATOR
SA2P1

Performance Verification

PMD Performance Goals

– 0.1-30 Hz required frequency range
  - Measure 1st-order bending mode (1-5 Hz)
  - Measure 1st three modal frequencies (1-20 Hz)

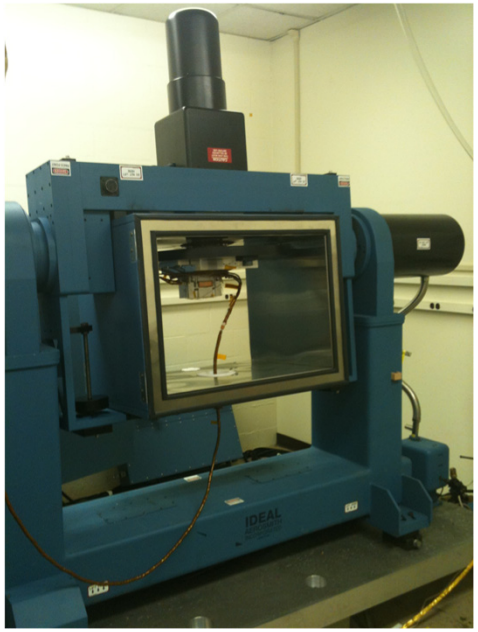
– 50-2000 µg required amplitude range
  - Goal of 1 µg resolution
  - Goal of 0.1 g at ±3 V ADC limits



PMD Performance Verification

– Confirmed frequency response of electronics
  - Done before QA2000 integration

– Instrument Calibration
  - Only practical method of performance testing
  - PMD mounted on rate table with isolation from building and full 360-degree rotation about zenith direction and azimuth axis
  - Known acceleration inputs achieved by aligning specific radial axes with gravity

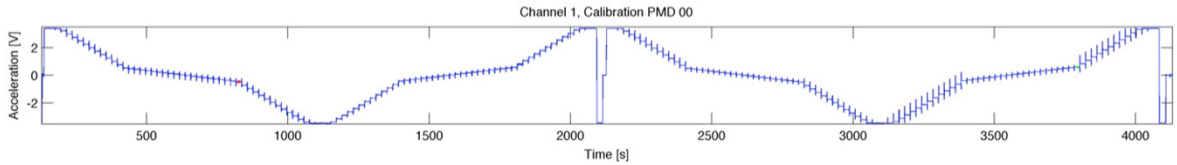


Calibration Details

Purpose

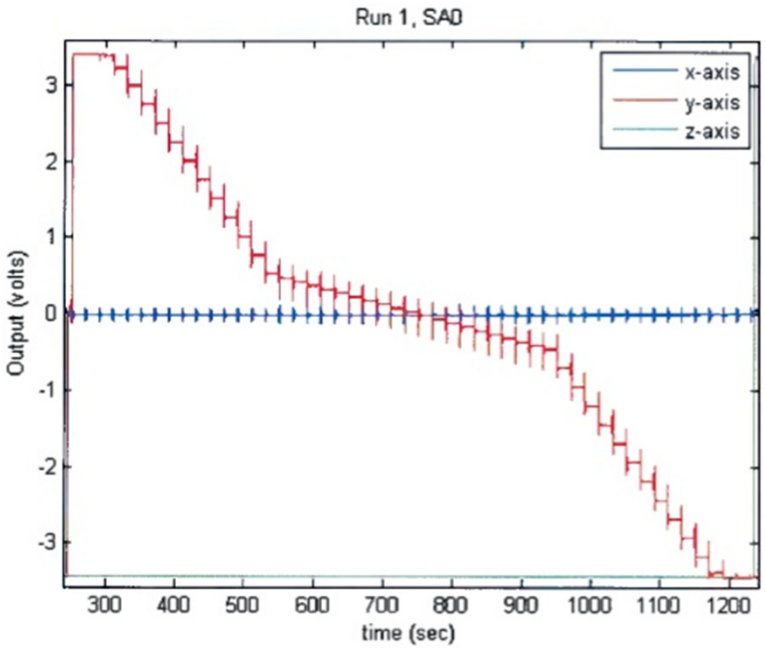
– Completely characterize instrument to allow for full reconstruction of actual motions experienced during flight
  - Determine precise scale factors
  - Determine inherent biases
  - Determine axis misalignments

– Confirm instrument resolution



Method

– Capture data over a series of pre-determined, automated rate table moves
  - 2 planes per axis to determine misalignment (i.e. x-y and x-z planes for x-axis misalignment)
  - 2 directions per plane to determine bias (i.e. +x and –x for x-axis alignment)
  - 12 total runs needed to characterize all accels
  - ±8 degree table tilt needed to exercise full ±3.5 V (or ±0.12 g) range of instrument
  - 20 s hold times at each table position to allow ringing oscillations to dampen out



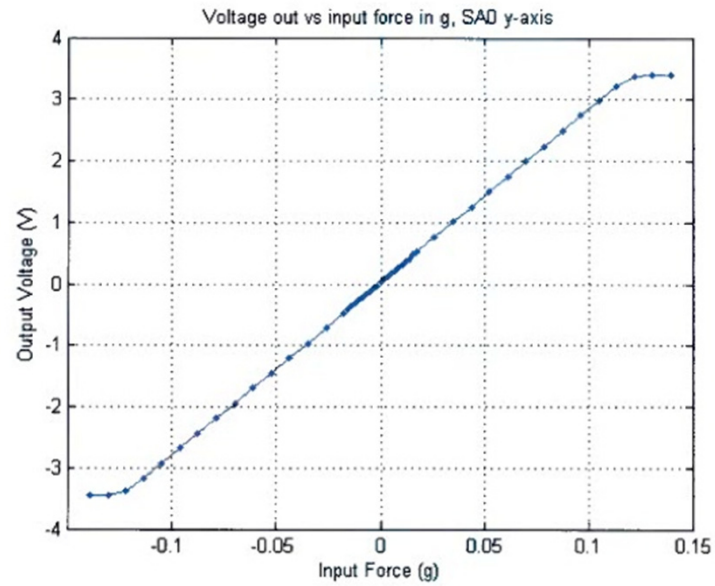
Calibration Details

Data Processing

- Initially first-order approximations
- Voltage v. Acceleration curves
  - Slope = scale factor
  - Bias = (offset_up + offset_down) / 2
  - Misalignment = (offset_up – offset_down) / 2
  - ±0.12 g range confirmed

Calibration Results

- Scale Factor
  - Determined 4 times per accelerometer (two runs per plane, two planes per axis)
  - Consistent results within 0.001 V/g
- Bias
  - Determined 2 times per accelerometer (once per plane, two runs per plane)
  - Consistent results within 10 µg
- Axis Misalignment
  - Results tabulated in paper

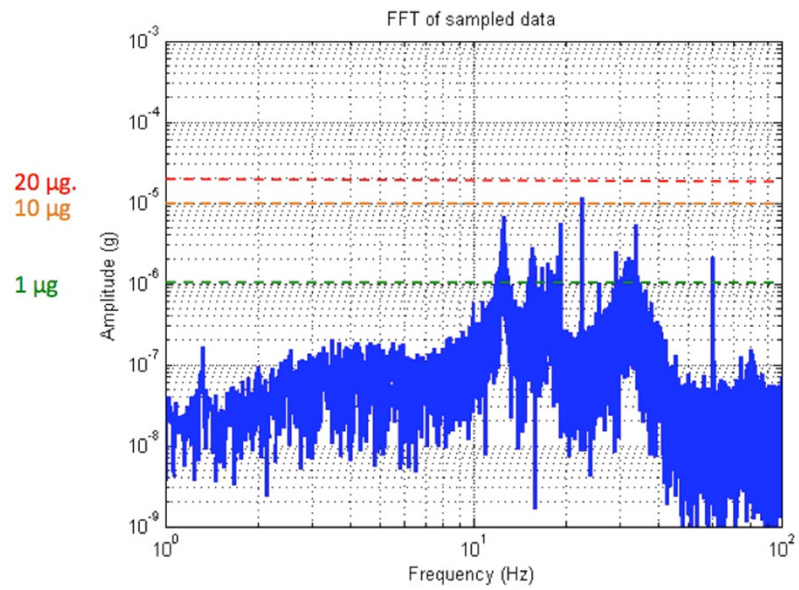


Averaged Values	Axis	Scale Factor (V/g)	Bias (g)
SA0 – Outboard 1	X	28.241	0.00017
	Y	28.296	0.00106
	Z	28.704	0.00127
SA1 – Central	X	28.301	0.00188
	Y	28.494	0.00017
	Z	28.184	0.00184
SA2 – Outboard 2	X	28.330	-0.00110
	Y	28.253	0.00129
	Z	28.344	0.00148
Estimated Error:		0.001	0.00001

Performance & Capabilities

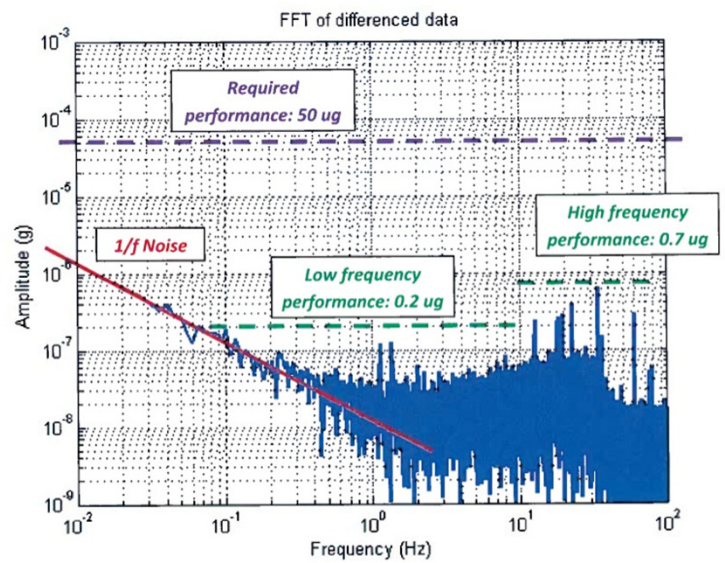
Instrument Resolution

- Data collected for several minutes with rate table powered off
- Single accelerometer data shows detected signal levels under 20 µg
- Subtracting data from two co-linear accelerometers reduces the noise due to real motions of the rate table
  - Detected signal levels under 1 µg over the entire frequency range



PMD Performance Summary

- Sensitivity
  - Measures 3-axis accelerations within 1 µg
- Dynamic Range
  - 0.1-30 Hz
  - 1 µg to 0.12 g acceleration
- Signal Output
  - Scaled analog voltage in ±3.5 V range



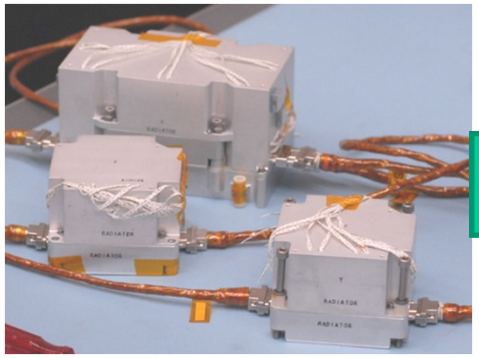
PMD Status & Significance

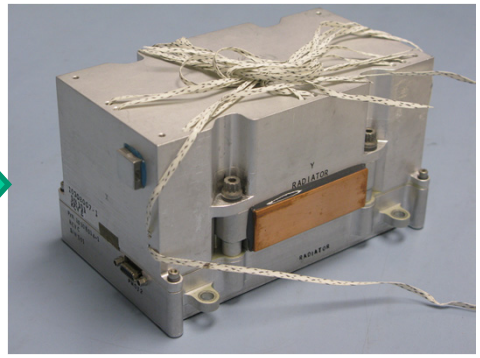
Status of Instrument

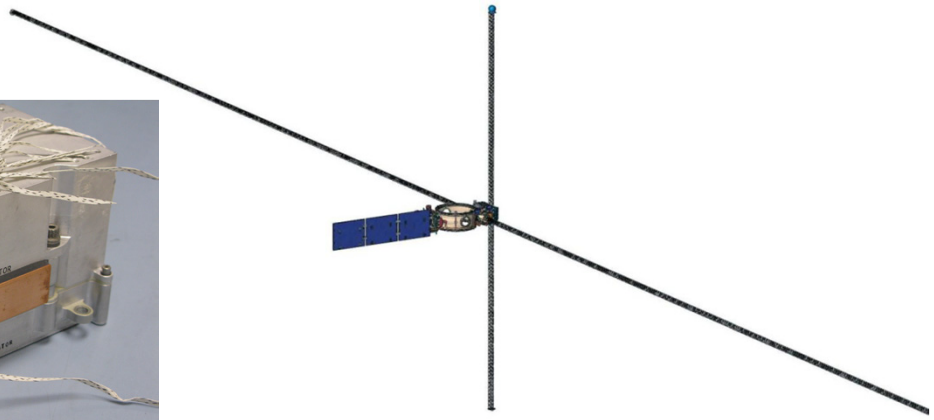
- PMD de-scoped from NuSTAR, April 2010
- PMD Central Assembly (PCA) added to the Air Force Research Laboratory's DSX mission, October 2010
  - Measure 1st & 2nd vibration modes of DSX y-antennas, and correlate with mathematical models
  - Study the effects of aging on composite structures
  - Detect spacecraft motions during antenna deployment
- PMD Outboard Assemblies in long-term JPL storage facility

Significance of Work

- Data return benefits the deployable structures community
  - Provides 0 g characteristics of structures for comparison against 1 g tests
  - Studies ageing effects and overall structural health over an extended period of time in space
  - Detects the structural response to thermally-induced vibrations & spacecraft mechanisms
- Improved sensitivity and dynamic range from commercially available IMU units







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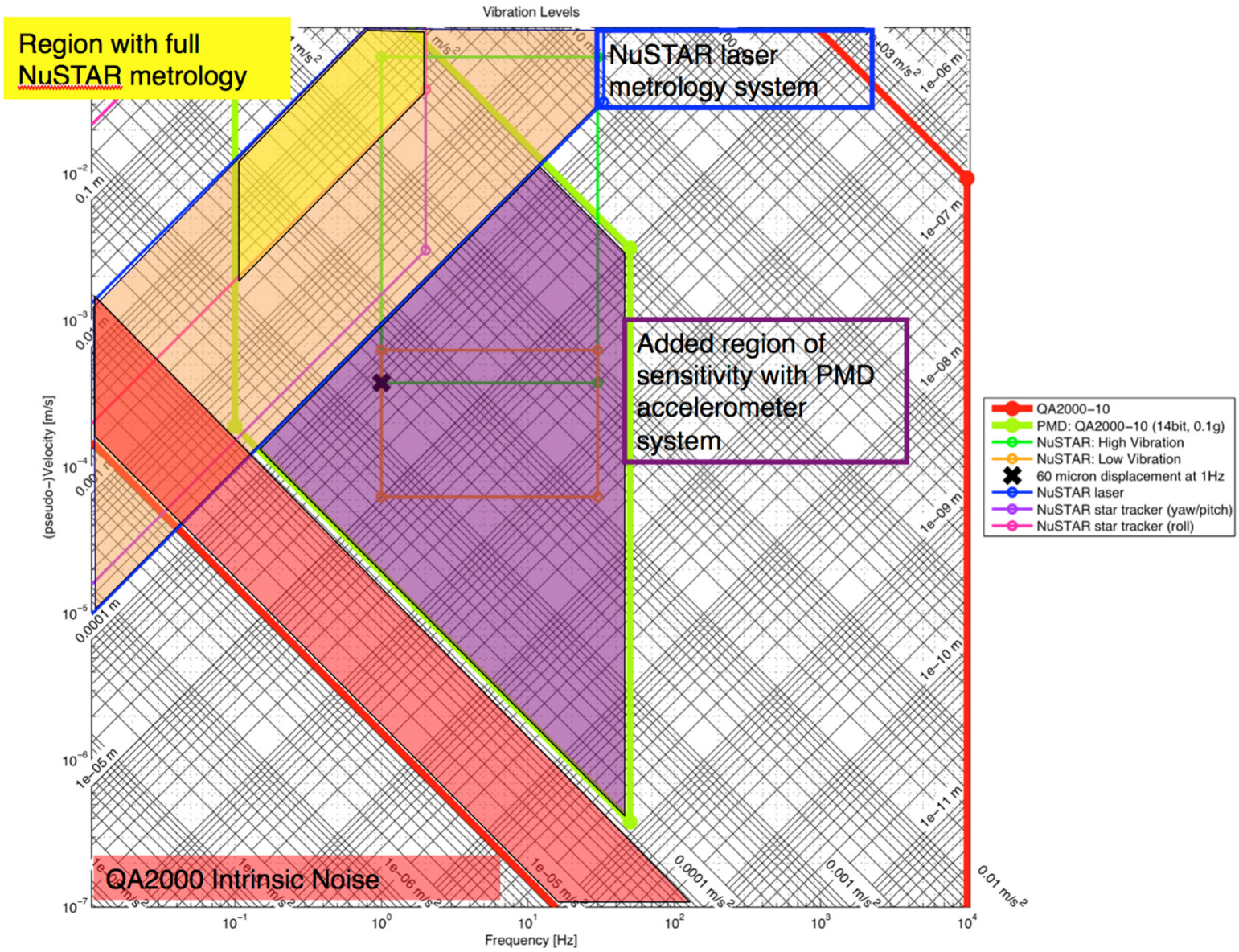
Backup – Vibration Levels