Phaeton Mast Dynamics: On-Orbit Characterization of Deployable Masts

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Abstract—The PMD instrument is a set of three custom-designed triaxial accelerometer systems designed specifically to detect and characterize the modal dynamics of deployable masts in orbit. The instrument was designed and built as a payload for the NuSTAR spacecraft, but it is now sponsored by the Air Force Research Laboratory's DSX project. It can detect acceleration levels from 1µg to 0.12g over a frequency range of 0.1Hz to 30Hz, the results of which can support future modeling and designing of deployable mast structures for space.

This paper details the hardware architecture and design, calibration test and results, and current status of the PMD instrument.[1][2]

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1. INTRODUCTION

The Phaeton Mast Dynamics (PMD) team at the Jet Propulsion Laboratory (JPL) designed a small payload to characterize the on-orbit structural behavior of the Nuclear Spectroscopic Telescope Array (NuSTAR) spacecraft. NuSTAR is a high-energy X-ray telescope with a grazing optics bench separated from a detector bench by a 10-m deployable mast. In Spring 2010 after initial qualification for space flight, JPL management decided to remove the PMD payload from the scope of the NuSTAR mission and instead added it to the Air Force Research Laboratory's Demonstration and Science Experiments (DSX) mission. PMD is scheduled to launch with DSX in Fall 2012.

The PMD instrument consists of three triaxial accelerometer units, each composed of three single-axis accelerometers in a mounting block with collocated electronics for signal conditioning. One unit also includes a power conditioning board to supply each of the sensors and their associated electronics. As a NuSTAR payload, the PMD instrument was distributed at three locations on the NuSTAR optics bench at one end of the telescope's mast, which would allow for full reconstruction of the rigid-body motions of the optics bench. Figure 1 depicts the PMD instrument as it would be situated on NuSTAR.

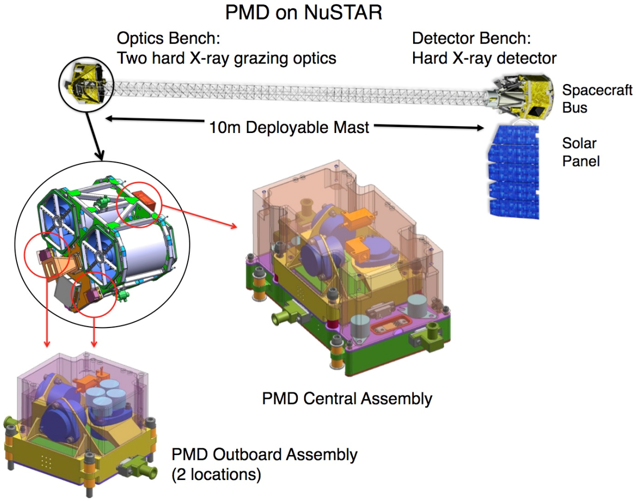

Figure 1 – PMD configured as a NuSTAR payload

PMD data would combine with NuSTAR laser metrology data to measure the relative displacement between the optics bench and the detector bench for characterization of the deployable mast's dynamic behavior in orbit.

The low levels of accelerations expected for deployable masts in orbit combined with the high dynamic range of motions of interest require a sensitive electronics design to minimize noise and interference. The PMD instrument detects accelerations from 1µg to 0.12g in the frequency range of 0.1Hz to 30Hz, and it outputs a scaled analog voltage to the host mission's corresponding analog-to-digital converter (ADC).

2. BACKGROUND

The PMD team was formulated to develop an instrument for one of the two inaugural projects in JPL's Phaeton

[1] 978-1-4244-7351-9/11/$26.00 ©2011 IEEE.
[2] IEEEAC paper #1305, Version 1, Updated December 21, 2010

program—a program designed to give select new hires with less than three years experience an opportunity to go through an entire flight project lifecycle from concept to delivery. The Phaeton program negotiated with the NuSTAR project to allow the PMD team to deliver a small payload to detect and characterize the motions and resonant frequencies of the spacecraft's 10-m deployable mast. The two Level 1 requirements for PMD became:

(1) The PMD Project shall measure on-orbit data for the purpose of studying the dynamic characteristics of the mast of the NuSTAR observatory.

(2) Any single failure of the PMD project shall be contained to within the PMD system and not affect the NuSTAR satellite or mission success.

Minimum mission success for PMD would be on-orbit measurement of one degree of freedom for motion of the NuSTAR mast's first bending mode. Additionally, PMD would have to guarantee that any single PMD failure mode would not propagate to or negatively affect the NuSTAR system (i.e. PMD was required to be a separate single-fault containment zone).

Given these initial conditions, the PMD instrument was designed and tailored specifically to comply with NuSTAR requirements and constraints. After design, build, assembly, and full qualification for flight per NuSTAR environmental requirements, and just two months prior to delivery of PMD to NuSTAR integration and test (I&T), NuSTAR de-scoped the payload from the mission. JPL management then negotiated with the Air Force Research Laboratory's Demonstration and Science Experiments (DSX) project to host the PMD payload for similar characterization of its several deployable masts, so PMD underwent a comprehensive requalification program to guarantee compliance with new and more stringent environmental requirements. Delivery to DSX occurred in November 2010, and launch is scheduled for Fall 2012.

3. PMD SYSTEM ARCHITECTURE

3.1. PMD on NuSTAR Structure

Due to the limited budget provided by the Phaeton program, and due to PMD's proximity to sensitive optical hardware on NuSTAR, PMD concept brainstorming limited sensor selection to accelerometer arrays and inertial measurement units (IMUs). The PMD team desired to string an accelerometer array along the length of NuSTAR's 10-m deployable mast, but the mast design was already too mature to accommodate such additions. The NuSTAR project initially allowed only one instrument footprint on its optical bench.

Figure 2 – Honeywell QA2000 Accelerometer [1]

The PMD team ultimately selected Honeywell's QA2000 accelerometer (shown in Figure 2) as the sensor of choice due to its high resolution, its sufficient tolerance to the shock and vibration of NuSTAR's launch environment, its flight heritage, and its size relative to commercially available IMUs. Since the QA2000 unit is a single-axis accelerometer, at least six of these sensors would be required to reconstruct full lateral and rotational degrees of freedom. NuSTAR then agreed to provide three footprints on the optical bench, each of which would house three triaxially mounted accelerometers and their associated signal conditioning electronics. The three PMD boxes would be situated as far away from each other as possible (while minimizing the effects on the NuSTAR design) allowing for direct measurement of x, y, and z directions, indirect measurement of yaw, pitch, and roll rotations (via relative differences in lateral motions about the rotational axes), and functional redundancy by the addition of a third unit.

3.2. PMD with NuSTAR Electronics

To minimize the impact of the PMD instrument on NuSTAR electronics, NuSTAR wanted PMD data to come into their Optical Bench Electronics Box (OBEB) as analog signals such that they could be multiplexed directly into the OBEB's analog-to-digital converter (ADC), which had a single analog input pin capable of converting signals in the range of ±3V. This constraint simplified the PMD electronics design to require only analog signal conditioning circuitry and power conditioning circuitry, but it also restricted the design to deliver only single-ended analog signal outputs rather than differential as would have been preferred for noise reduction. PMD data would therefore be more susceptible to noise pickup and power loss on cabling, though it ultimately allowed PMD to be modular and compatible with a variety of single-ended ADCs.

3.3. PMD Signal Conditioning Electronics

QA2000 accelerometers output acceleration-proportional current, so the fundamental building block for the PMD electronic design was a transimpedance amplifier. This circuit was responsible for converting sensor output current as low as 1.3nA to voltage levels spanning the range of NuSTAR's ADC.

PMD's frequency range of scientific interest was 1Hz to 5Hz, its required frequency range was 0.1Hz to 30Hz, and

NuSTAR offered a maximum data rate of 57.6 kbit/s, so a sampling frequency of 200Hz per channel was selected to cover all data channels with sufficient design margin. Since NuSTAR electronics accommodated only multiplexing, it was necessary for PMD electronics to include its own anti-aliasing filter. This filter attenuates all high frequency signals that could appear as low frequency data to levels at or below the intrinsic noise of the system.

3.4. PMD Power Conditioning Electronics

In addition to providing analog-to-digital conversion of PMD data, NuSTAR provided PMD with +28V primary power via their operational heater power bus, and they provided an independent +28V survival heater connection to be used as needed. The PMD power system design included DC isolation between primary and secondary power, inrush current limiting to protect other systems on the primary bus, EMI filtering to limit conducted emissions, conversion to ±15V secondary power, and voltage regulation to provide clean, stable power to the signal conditioning circuitry.

Since there were three PMD boxes to house triaxially-mounted accelerometers and their respective signal conditioning circuitry, the electronic designs for each sensor board were exactly identical and consisted of all the respective secondary electronics required for signal conditioning and power regulation beyond the ±15V supplies. Conversely, there would be only one +28V primary supply from NuSTAR, so only one power board was required to perform the power conditioning functions. The PMD system would use internal cables to deliver ±15V power from the power board to each of the three sensor boards. The power board and one sensor board were collocated and housed into a single unit named the PMD Central Assembly (PCA), shown in Figure 3. The other two sensor boards were assembled into two smaller, yet identical, outboard units, shown in Figure 4.

The +28V survival heater connection provided by NuSTAR was fed into a fully redundant, passively controlled heater system. The thermal hardware for each subassembly was bonded mechanically to the respective chassis and connected electrically to the respective sensor board. The power board merely passed the connections through to each of the cables connecting the sensor boards with ±15V lines and survival heater power lines. Figure 5 shows the internal components of the PCA.

Thus the final architecture for the PMD system was set and ready for design. Figure 6 is a block diagram summarizing the PMD system.

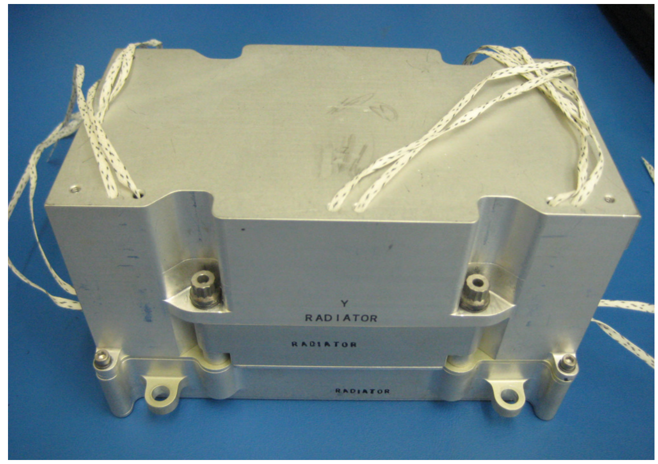

Figure 3 – PMD Central Assembly (PCA)

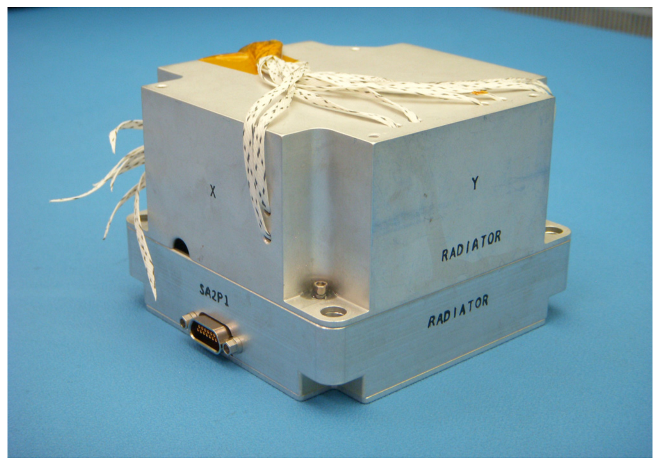

Figure 4 – PMD Outboard Assembly

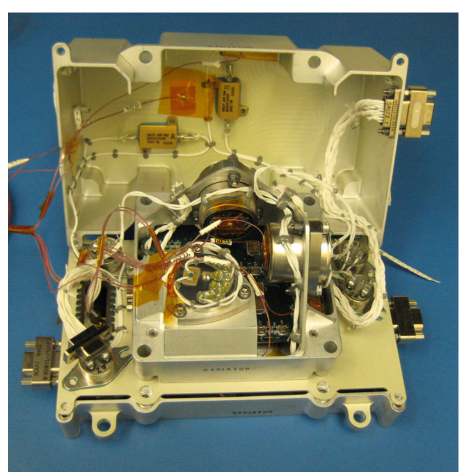

Figure 5 – PCA Internal Hardware

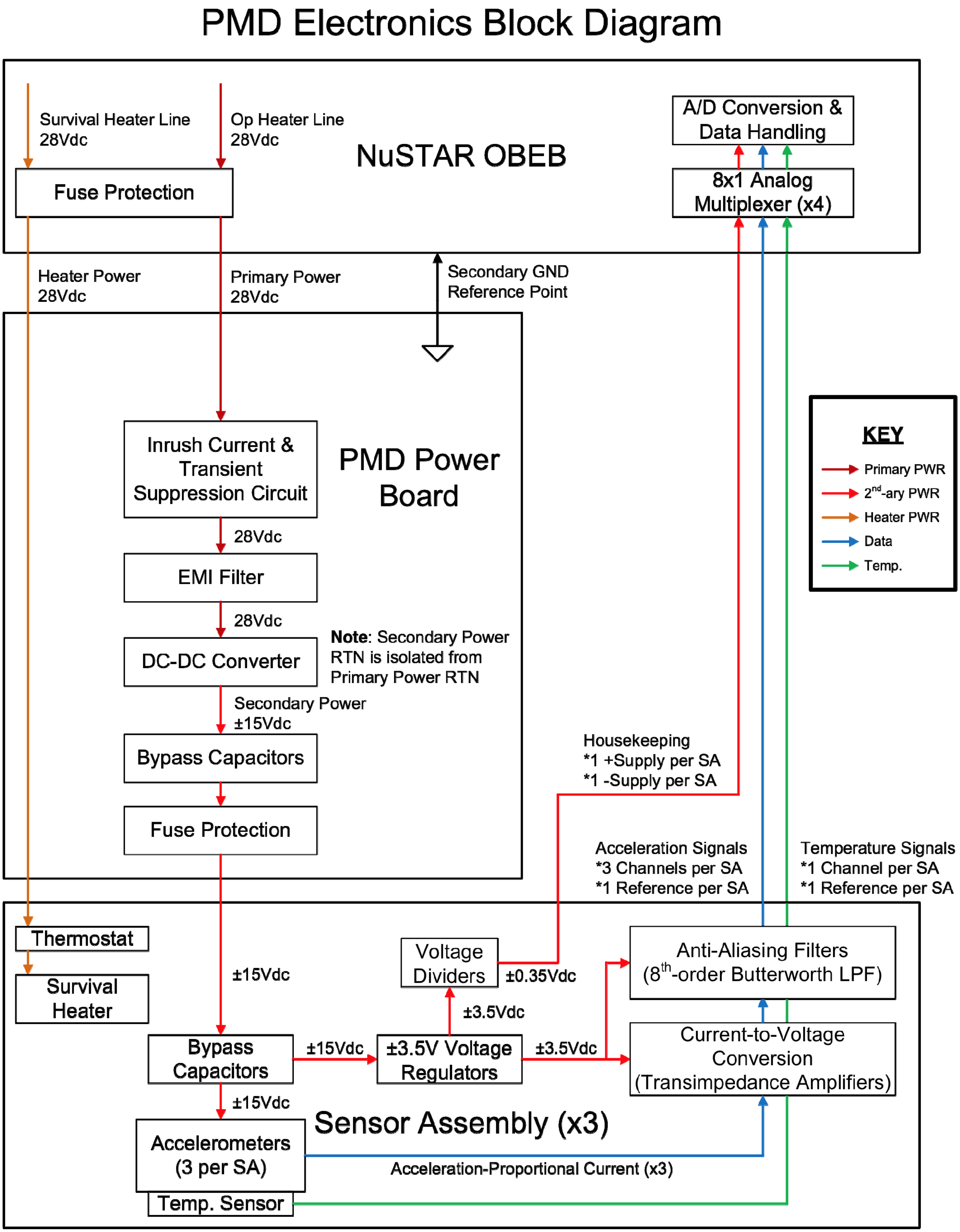

Figure 6 – PMD Electronics Block Diagram

4. PMD ELECTRONICS DESIGN

4.1. Signal Conditioning

Although the basic building blocks of the PMD signal chain were relatively straightforward, particular care was needed in part selection and application in order to optimize science return and guarantee that NuSTAR was protected from all potential PMD failure modes. To convert the QA2000's acceleration-proportional current output to a voltage suitable for NuSTAR's ADC, the transimpedance amplifier configuration shown in Figure 7 was used.

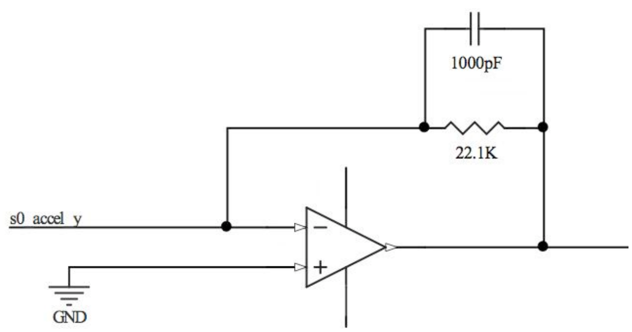

Figure 7 – Transimpedance Amplifier Configuration

PMD was required to detect accelerations from 50μg to 2000μg (with a goal of 0.1g), which corresponds to 65nA to 130μA with the QA2000's scale factor. The 22.1kΩ load resistor was selected to ensure the maximum acceleration utilized the full range of the ±3V input on the ADC with some design margin (~5%). A single 22,100Ω transimpedance gain stage was sufficient to keep the QA2000 sensor from saturating and operating outside of its linear region. The operational amplifier (opamp) was selected such that the input bias currents were negligible compared to both the 65nA detection requirement and the 0.366mV (or 16nA or 12.8μg) least significant bit (LSB) level of NuSTAR's 14-bit ADC (i.e. the highest resolution possible as limited by NuSTAR). The input offset of the device was on the same order of magnitude as the LSB, but it was determined to be of no concern to the data. The final unit would be calibrated, and the overall offset for each individual accelerometer channel would be characterized against a known input. Moreover, the end data analysis would be looking at deviations from the nominal environment—relative data rather than absolute—during significant spacecraft motion events. A failure mode analysis revealed that accelerations greater than 4g could damage the opamp's input pin while powered on. While this shock scenario was deemed extremely unlikely for both flight and test, a 4.22kΩ resistor was added in series with the QA2000 output signal to guarantee absolute protection from this failure mode. This additional resistance was not significant enough to bring the accelerometer into saturation.

The required frequency range for PMD data as a NuSTAR payload was 0.1Hz to 30Hz with the expected range of interest from 1Hz to 5Hz. The principle investigator (PI) for PMD wished to over-sample the PMD data as much as practical given NuSTAR's data rate limit of 57.6 kbit/s. NuSTAR agreed to sample each of the accelerometer channels at 200Hz resulting in a Nyquist frequency of 100Hz. To guarantee all aliased signals remained below the LSB at 30Hz and lower, it was necessary to develop an anti-aliasing filter with at least 84dB attenuation at 330Hz (aliased at 30Hz). An 8^{th}-order analog Butterworth low pass filter was selected to minimize amplitude distortion, and it was designed using cascaded versions of the Sallen–Key topology shown in Figure 8.

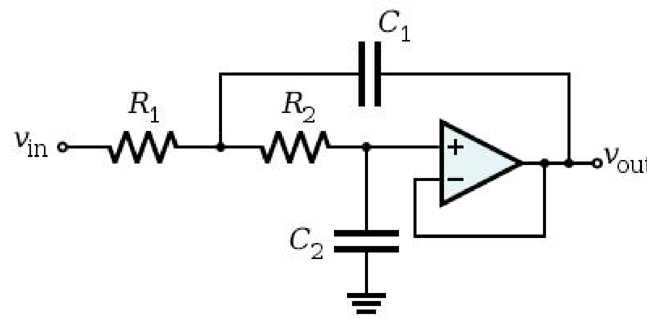

Figure 8 – Butterworth Low Pass Filter [2]

The cutoff frequency of the filter was designed to be exactly 30Hz, and it allowed for attenuation of 84dB by 100Hz, ensuring clean signals in the frequencies of interest as output by the PMD instrument. Other high frequency pickup downstream of the instrument would require digital signal processing filtration during data analysis. The significant phase distortion resulting from an 8^{th}-order Butterworth low pass filter was inconsequential to PMD data as it had little effect at the most significant frequencies and could be mathematically backed out during data analysis.

To complete the PMD signal chain, NuSTAR supplied analog multiplexers to feed into the ADC. To guarantee that no PMD over-voltage or over-current failure mode could propagate into NuSTAR, they included series 3kΩ resistors on each data line, which would unequivocally prevent damage to the multiplexer input pins and other associated circuitry. This resistance was small compared to the high input impedance of the device, and it did not contribute to loading effects that could alter PMD data.

Figure 9 shows a picture of the PMD sensor board situated within an outboard mounting structure.

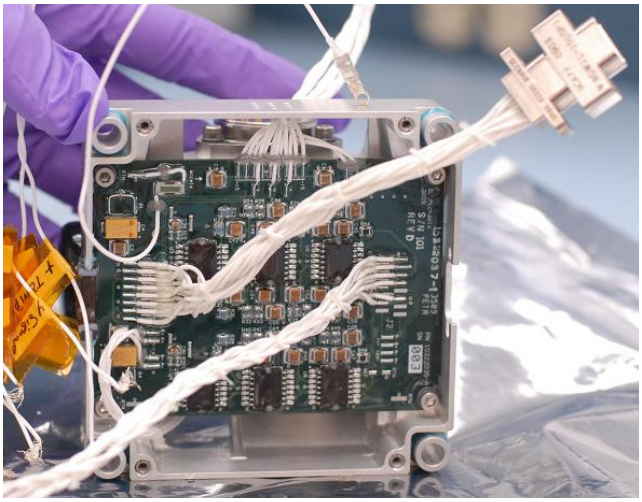

Figure 9 – PMD Sensor Board

4.2. Power Conditioning

NuSTAR supplied a single +28V primary power line to PMD via their operational heater bus. The only imposed steady state requirement on PMD was that it consumed no more than 5W averaged per orbit. The QA2000 sensors utilized 0.5W each, the DC-DC converter operated with 87% efficiency, and additional power consumption in the signal conditioning circuitry was inevitable, so it would not have been possible to meet this requirement without operating the instrument at a duty cycle less than 100%. Since power cycling scenarios were thus necessary for mission operations, intensive power-reduction designs were not explored.

The QA2000 accelerometers operated from ±15V supplies, so PMD used an Interpoint switching DC-DC converter to convert +28V primary power to ±15V secondary power. The switching converter's internal transformer allowed for DC isolation of the PMD circuitry from NuSTAR's heater power bus, and a matching Interpoint electromagnetic interference (EMI) filter was included to minimize conducted emissions onto NuSTAR's bus. While the ±15V secondary lines could feed directly into the sensors, the signal conditioning circuitry required lower levels. Before 3kΩ series resistors were added to PMD data lines on NuSTAR to bulletproof the ADC from over-voltage failure modes, the PMD design guaranteed that nominal data levels could not encroach the ADC's absolute maximum input voltage of ±5V by using linear voltage regulators to provide ±3.5V supplies to the secondary electronics. By supplying opamps with ±3.5V, there was sufficient headroom to utilize the full ±3V input range on the ADC, and nominal PMD data output could never damage the ADC regardless of any accelerations seen during test or flight, and regardless of any analog multiplexer selected by NuSTAR. To provide basic telemetry on the status of PMD's secondary supply levels, a simple voltage divider fed ±0.35V to NuSTAR's ADC for 1Hz data collection (full ±3.5V signals would not have registered meaningfully with the ±3V ADC input range).

NuSTAR required PMD to limit inrush current to 2A. More specifically, they supplied PMD with +28V primary voltage via a 2.0A fuse to ensure their full protection from any shorts or faults on PMD primary-side circuitry. A soft-start circuit was added to the supply line upstream of the switching DC-DC converter, but the circuit was not initially compatible with the nominal functioning of the Interpoint device. To control the startup timing, a simple RC time constant circuit was added to the DC-DC converter's inhibit pin, which allowed all the primary-side circuitry to fully charge before turning on the converter's output and charging up the secondary-side circuitry. The two inrush peaks were small enough in amplitude to allow the soft-start circuit to function properly, and the designed 10ms timing separation between peaks was sufficient to maintain full operability over a -35C to +60C temperature range and a +22V to +34V input voltage range.

Figure 10 shows a picture of the PMD power board before integration into its chassis, and Figure 11 is a screenshot of the PMD turn-on characteristics with inrush current in blue, +15V in yellow, and -15V in purple.

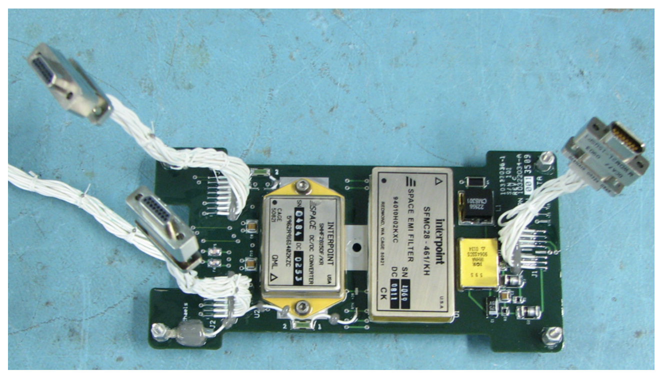

Figure 10 – PMD Power Board

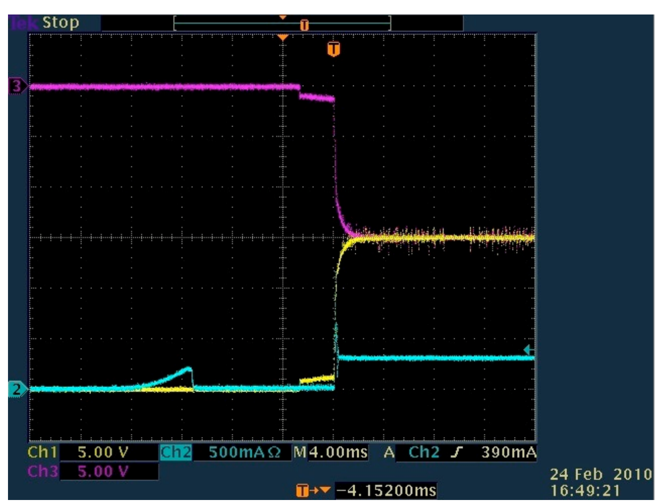

Figure 11 – PMD Startup Characteristics

5. PERFORMANCE AND CALIBRATION

5.1. Performance Requirements

Preliminary modeling of the NuSTAR mast suggested that the first-order bending modes fell in the 1Hz to 5Hz range, and that the first three mast dynamic modal frequencies fell in the 1Hz to 20Hz range. Thus the PMD sensors and electronics were required to measure frequencies from 0.1Hz to 30Hz. Analysis also suggested that amplitudes of motion during NuSTAR slew events could be as small as 50µg. The NuSTAR metrology system was only able to resolve motions of approximately 200µg (and only up to 2Hz), so PMD was required to span the range from 50µg to 2000µg. This ensured capture of the expected motions, and it partially overlapped with NuSTAR's capability for validation of data.

5.2. Design Solutions

The frequency requirements were easily achieved by design: the QA2000 sensor had a bandwidth of greater than 100Hz, and the anti-aliasing filter's cutoff frequency was designed to be 30Hz as previously discussed.

On NuSTAR, the PMD instrument's lower bound to motion amplitudes was limited by the host mission's ADC capabilities and sampling rate. PMD was constrained by a ±3V analog range with 14-bit digitization and 200-Hz sampling. These parameters translated to a 0.366mV or 13µg LSB (or highest resolution), and any aliased signals would be attenuated below this level by the aforementioned 8^{th}-order Butterworth filter. QA2000 output response to the required 50µg minimum motion across the 22.1kΩ load resistor was approximately 1.44mV, giving a factor of nearly 4-LSB margin on the requirement. As a stand-alone instrument, PMD is actually noise-limited by the QA2000 sensor itself, so without constraints from the method of analog-to-digital conversion, PMD should be able to resolve <1µg motions as specified in the QA2000 datasheet.

The PMD instrument's upper bound to motion amplitudes was selected more arbitrarily. Since the design was initially tailored to NuSTAR without much regard to other potential host missions, the upper bound was selected by choosing the highest load resistor value that kept the QA2000 accelerometer operating in its linear region while maintaining a comfortable design margin. Therefore, by design the maximum detectable motion would be the point where the signal conditioning opamps railed—±3.5V for the rail-to-rail opamps selected—corresponding to 0.12g. On NuSTAR, the ±3V ADC limit would constrict the maximum detectible motion to be 0.10g.

5.3. Verification via Test and Calibration

Before the QA2000 sensors were connected to the system, the electronic boards were tested to verify the frequency response of each channel. Known currents were input into each channel at several different amplitudes, and the frequency was swept from 5Hz to 70Hz. A set of response curves all resembling Figure 12 were obtained, confirming the performance of the anti-aliasing filters.

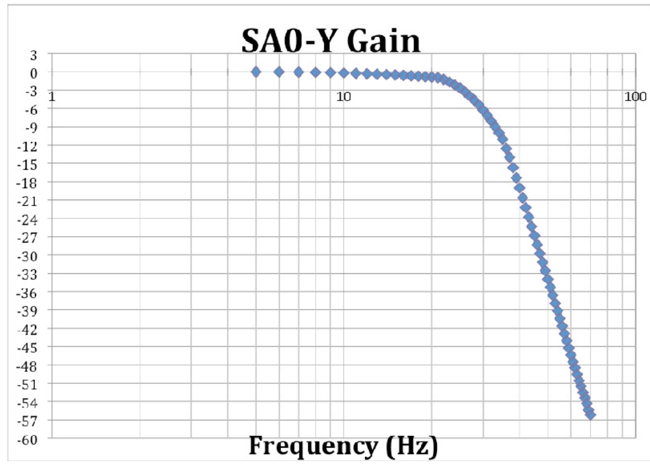

Figure 12 – Frequency Response of Anti-Aliasing Filter

After full PMD assembly, performance tests could only be conducted during calibration. For PMD calibration, the units were mounted on a rate table that was installed directly into the bedrock, physically isolated from the rest of the building, and which provided full 360-degree rotation about both the zenith direction and azimuth axis in a spherical coordinate system. This configuration allowed PMD to be oriented such that any radial axis could align with gravity, allowing for known acceleration inputs by selecting specific components to gravity. Figure 13 shows PMD mounted on the calibration rate table, and Figure 14 shows the table with the outer axis rotated 180 degrees.

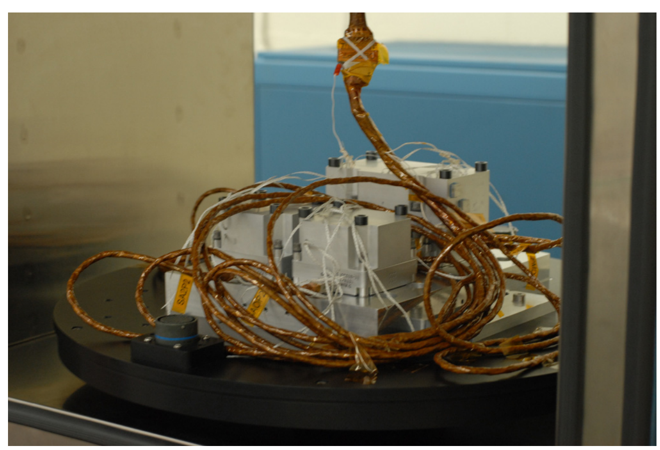

Figure 13 – All 3 PMD assemblies mounted on rate table

Figure 14 – Rate table outer axis rotated 180 degrees

The purpose of calibration was to determine the precise scale factor for each channel (rather than assuming 22,100Ω transimpedance gain), to determine the inherent bias of each channel (resulting from QA2000 biases, opamp input offset voltages, and other cumulative factors), to determine the axis misalignment for each channel (due in part to QA2000 axis misalignment and imperfections in chassis fabrication and system assembly), and to confirm the resolution of the instrument over a wide frequency range. Complete knowledge of the precise scale factor, bias, and axis misalignment values for each accelerometer channel would allow for full reconstruction of the actual motions experienced during flight. To capture data for determining these values, a series of pre-determined (and automated) moves were performed on the rate table. For each accelerometer axis, there were two planes for which axis misalignment needed to be found (i.e. the x-y plane and the x-z plane for x-axis alignment), and each plane required runs taken in both directions (i.e. +x and –x for x-axis alignment) to determine the bias. For each of the twelve runs, the axis under test was tilted from -8 degrees to +8 degrees in steps of 0.5 degrees, decreasing to 0.1-degree steps from -1 degree to +1 degree. The ±8 degree range was selected to exercise the full range of the PMD instrument, which was ±3.5V, or ±0.12g, or approximately ±6-degree tilt, or 96/84-degree component to gravity. The test used 20-second hold times at each position to allow the table's ringing oscillations to dampen out. Dampening generally took 5 to 10 seconds, so the last 10 seconds of each hold could be averaged for determining the value of acceleration. Figure 15 is an example of the resulting raw data. Figure 15(a) is a full 4-run calibration for one axis, and Figure 15(b) is a single run for all 3 axes of one unit. [3]

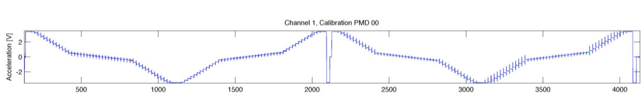

Figure 15(a) – Raw Calibration Data

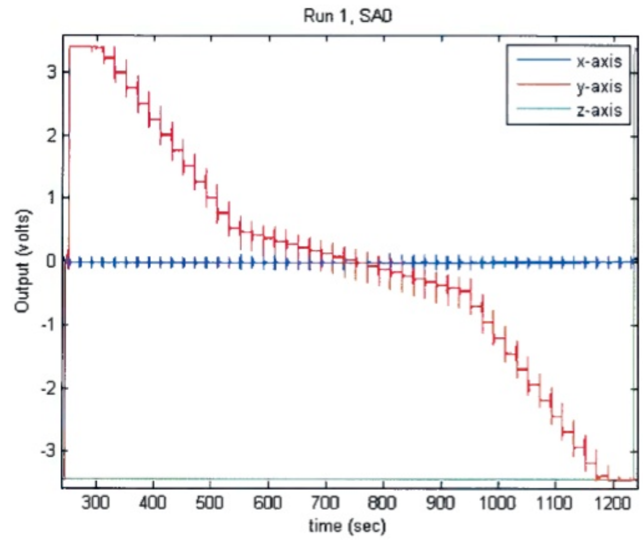

Figure 15(b) – Raw Calibration Data

6. Test Results and Capabilities

6.1. Calibration Test Results

Upon completion of the first calibration, data analysis was performed using first-order and linear approximations. Figure 16 shows that the full range of the instrument is indeed approximately ±0.12g and that it operates linearly to the first order.

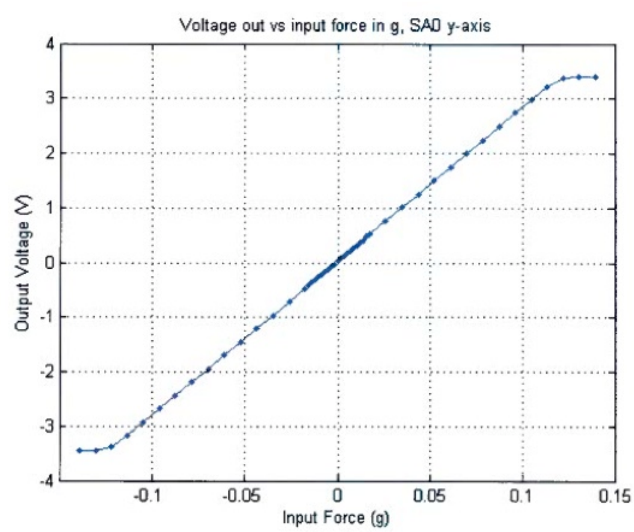

Figure 16 – Processed Data: Voltage v. Accelerations [3]

A linear best fit was performed for each run of each axis, but the railed endpoints were dropped to keep only the linear region. The slope of each line was the scale factor for the accelerometer channel, and the offset was used to determine the bias and axis misalignment values with Equations 1 and 2, respectively [3].

$$\text{Bias} = (\text{offset\_up} + \text{offset\_down}) / 2 \quad (1)$$

$$\text{Misalignment} = (\text{offset\_up} - \text{offset\_down}) / 2 \quad (2)$$

The scale factor was determined four times per accelerometer (two runs per plane, two planes per axis) with consistent results within 0.001V/g. Bias was determined twice per accelerometer (once per plane, two runs per plane) with consistent results within 10µg. Scale factor and bias results are shown in Table 1. Axis misalignment results are shown in Table 2, and additional details can be found in Reference 3.

Table 1 – PMD Scale Factor & Bias Values [3]

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

Table 2 – PMD Axis Misalignment Values [3]

Averaged Values	**Axis**	**X***	**Y***	**Z***
SA0 – Outboard 1	X	1.0000	-0.0049	-0.0001
	Y	0.0052	1.0000	-0.0003
	Z	0.0025	0.0007	1.0000
SA1 – Central	X	1.0000	-0.0006	-0.0012
	Y	-0.0001	1.0000	0.0025
	Z	0.0011	0.0003	1.0000
SA2 – Outboard 2	X	1.0000	-0.0035	0.0007
	Y	0.0052	1.0000	0.0001
	Z	0.0027	0.0012	1.0000
*Orientation of Accelerometer (normalized to 1)				

6.2. PMD Resolution and General Performance

To confirm the resolution of the PMD instrument, the instrument collected data for an extended period of time (several minutes) while the rate table was powered off. Data collected with the rate table powered on, and actively holding the instrument in place, in fact added noise to the system. The spectrum from a single accelerometer channel shows that the detected signal levels were below 10µg for most frequencies and always below 20µg, as seen in Figure 17.

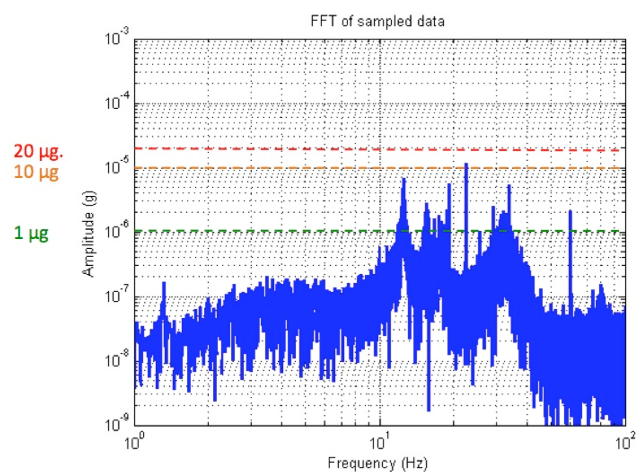

Figure 17 – Single Accelerometer Data Spectrum [3]

By subtracting data from two co-linear accelerometers, the noise due to real motion of the rate table can be reduced to show that PMD can resolve to better than 1µg over the entire frequency range of interest, which agrees perfectly with the value specified for the QA2000 device. This result is shown in Figure 18.

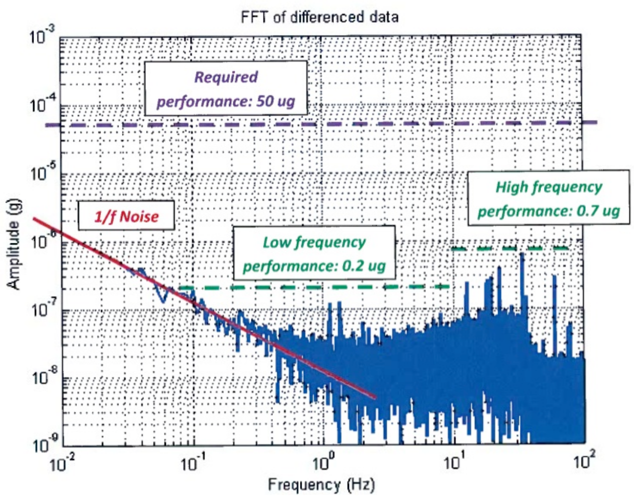

Figure 18 – Full PMD Resolution [3]

7. Summary & Current Status of PMD

The calibration results clearly indicate that the PMD instrument meets and exceeds all the specified performance requirements that were written when it was a NuSTAR payload. The results were obtained using a 24-bit National Instruments data acquisition system sampling at 1kHz, so they provide an accurate statement of the actual capabilities of PMD without limitation from the host mission's ADC and sampling rate. Furthermore, when used as a full system of three triaxial accelerometer units, the relative motion between boxes can be used to infer rotations, giving a total of six degrees of freedom to be measured.

PMD is now a DSX payload, and DSX will fly only the PMD Central Assembly (PCA) to capture the dynamics of similar deployable structures. This single triaxial accelerometer will be used with 14-bit analog-to-digital conversion, a ±10V analog input range, and a 60-Hz sampling rate, which allows for detection of amplitudes of spacecraft motion from 43µg to 0.12g in response to mast motions. Although the wider analog input range and lower sampling rate decrease the resolution of the instrument, the PCA will still be able to detect the first and second vibration modes of DSX masts. This maintains PMD's minimum mission success criterion of measuring one degree of freedom for motion of a deployable mast's first bending mode on orbit. Additionally, the PCA will be powered on during deployment of the masts, a bonus previously not available on NuSTAR.

PMD (or PCA) data return will benefit the deployable structures community by providing 0g characteristics of the structures for comparison against 1g tests, by studying ageing effects and overall structural health over an extended period of time in space, and by detecting the structural response to thermally-induced vibrations and spacecraft mechanisms. This knowledge will provide useful feedback for the design of future deployable structures.

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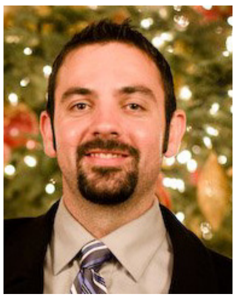

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