Characterizing a Low Earth Orbit Dust Detector

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Background Information

Low Earth Orbit (LEO) contains a large amount of man-made debris. NASA has developed a model of objects greater than 10 cm diameter (Fig. 1), but are unable to track small dust particles. The ARMADILLO CubeSat (Fig. 2) will detect dust particles in LEO and further develop NASA's model of the debris field around Earth.

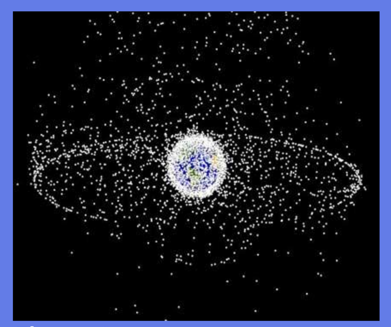


Figure 1. NASA model of space debris

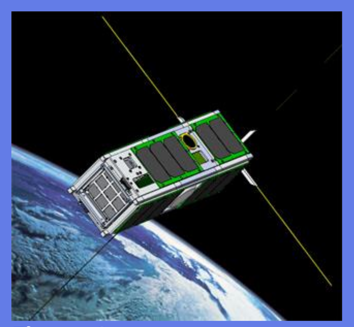


Figure 2. ARMADILLO CubeSat

Piezoelectric Dust Detector (PDD)

The PDD, mounted on the forward velocity vector of the ARMADILLO, utilizes the piezoelectric properties of Lead Zirconate Titanate (PZT) to detect micron size particle impacts. Stress applied to the PZT crystal structure produces an electrical field that can be converted into signal data. The PDD is comprised of a circuit board stack, a 3x3 PZT Main Detector Unit (MDU), a single PZT Secondary Detector Unit (SDU), and a detection Grid (Figs. 3-6).

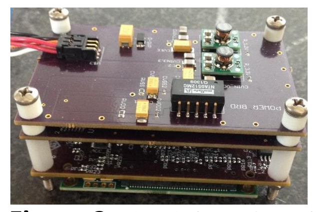


Figure 3. Circuit board stack

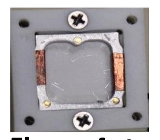


Figure 4. Secondary Detector Unit. The SDU will face deep space, in the event of a cosmological particle impact.

Figure 4. Main Detector Unit

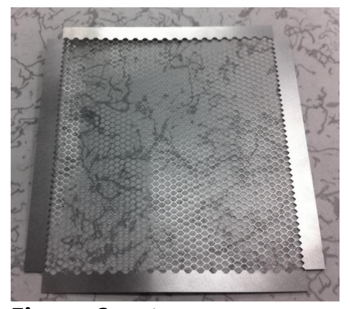


Figure 6. Velocity Detection Grid

Data Analysis

Raw data is given as a set of 2048 data points, which are multiplied by an Analog to Digital Converter (ADC) quantization value, then plotted as a Time vs. Amplitude graph (Fig. 8).

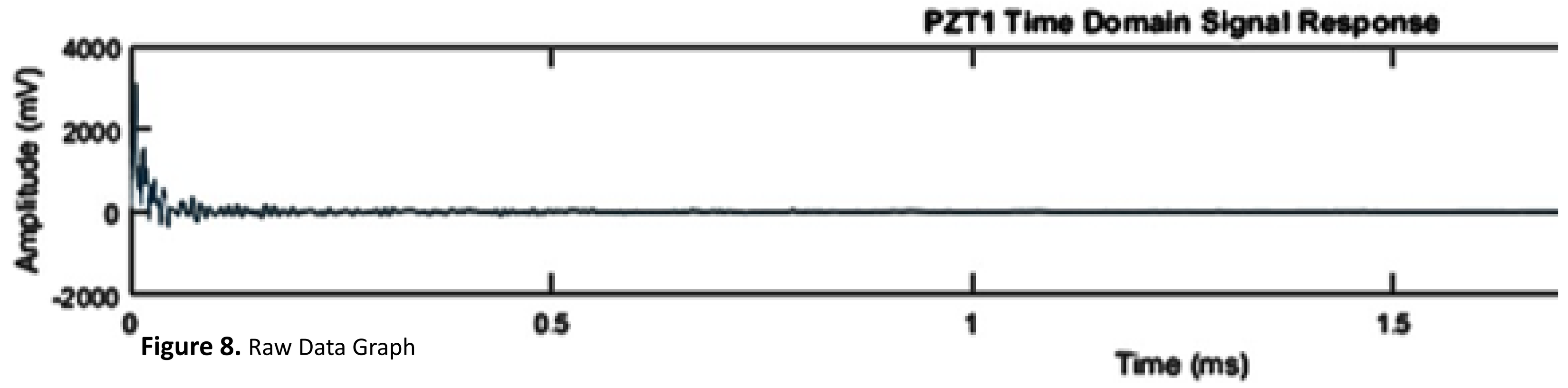


Figure 8. Raw Data Graph

The MATLAB program then runs a Fast Fourier Transformation (FFT) algorithm on the data, producing a Frequency vs. Amplitude graph (Fig. 9).

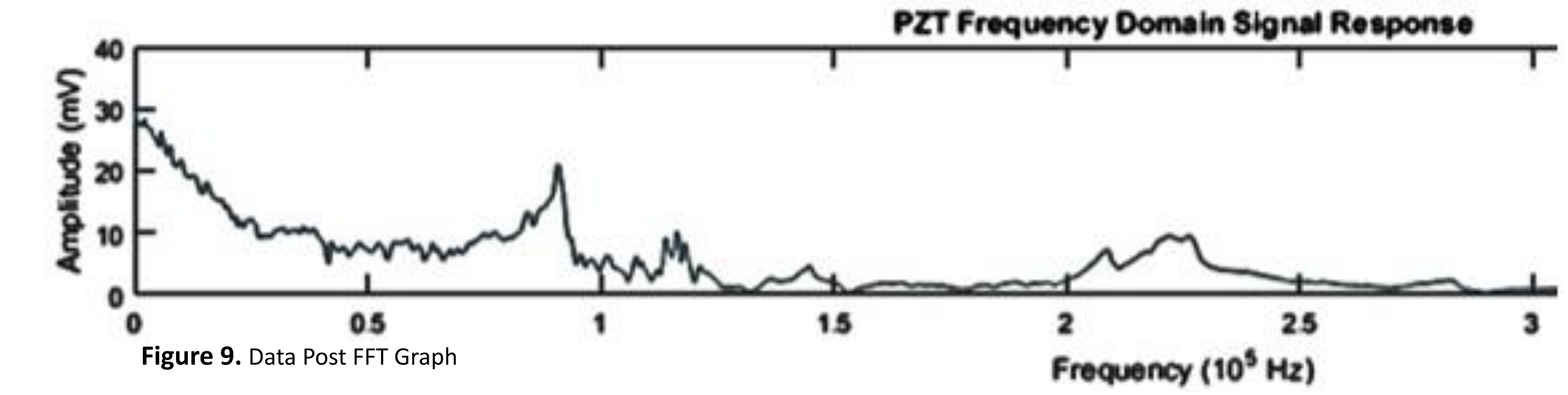


Figure 9. Data Post FFT Graph

After the FFT is performed, a Butterworth Filter of 80-110 kHz is applied to the data to produce Figure 10. The PZT plates have a primary harmonic resonance frequency of 98 kHz, as given by the plate manufacturer, so the maximum recorded amplitude is extracted from that area.

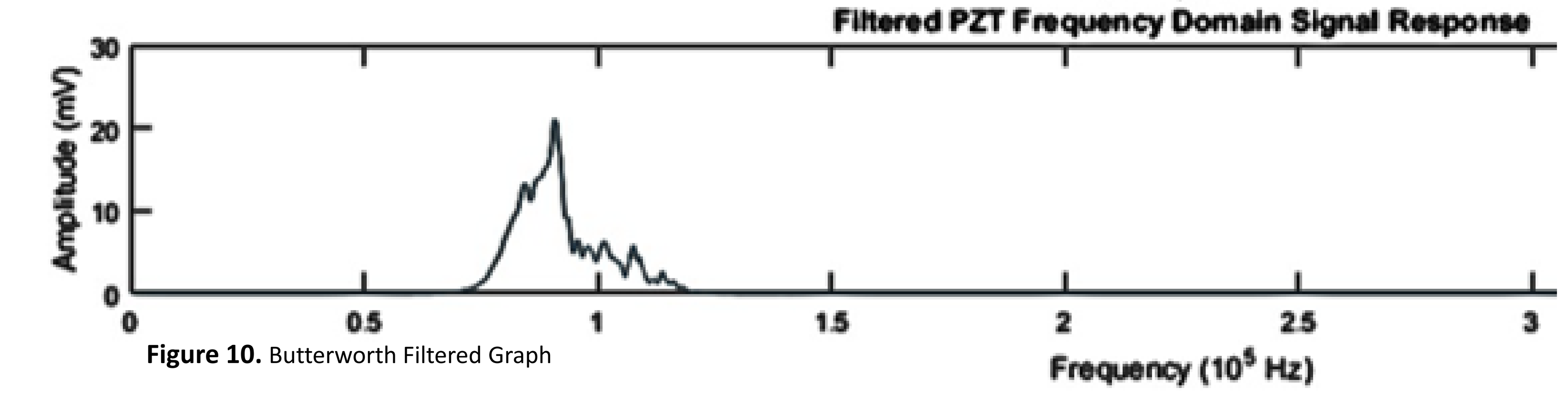


Figure 10. Butterworth Filtered Graph

For a single impact, this analysis process is simultaneously repeated 9 times over, once for each PZT. The maximum recorded amplitude usually indicates the PZT that was impacted, but graphs still requires a visual inspection to ensure proper analysis. Frame impacts or noise may cause false triggers to the system, so the data must be double checked for actual impact data, as there will be no way to physically inspect the PDD once it is in space.

Pellet Firing Tests

Initial shots were fired with aluminum pellets against a paper target. To preserve durability of MDU sensor, smaller and lighter Teflon pellets were fired, they being the smallest particle size able to be detected by the dual laser fan. See Table 2 for values. Figure 11 resulted from a day of firing, which, despite having numerous broken plates, continues to emit signals almost indistinguishable from unbroken plates.

Material	Diameter	Mass	Gas	Pressure	Velocity	Energy
Aluminum	1.53 mm	11.7 mg	Nitrogen	200 PSI	133 m/s	0.104 J
Teflon	1.48 mm	5.18 mg	Nitrogen	200 PSI	156 m/s	0.063 J

Table 2. Pellet Firing Test Values

Comparative Space Dust Impact Energies				
Diameter→ Velocity↓	10 microns	50 microns	100 microns	1000 microns
2 km/s	4.2E-6 J	5.2E-4 J	4.2E-3 J	4.2 J
5 km/s	2.6E-5 J	3.3E-3 J	0.0262 J	26.2 J
10 km/s	1.0E-4 J	0.0131 J	0.105 J	104.7 J

Table 3. Comparative Space Impact Energies

Comparative calculations show that laboratory impacts are similar to space impacts (Table 3).

- Blue- Low Energy Impact
- Yellow- Impact, No Break
- Orange- Impact, PZT Break
- Red – Impact, PDD Destroyed

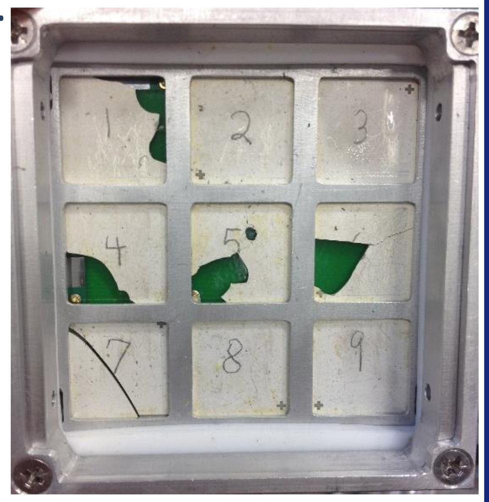


Figure 11. Broken MDU Plates Post Pellet Tests

Dust Firing Tests

Data for lower energy impacts was required, so the PZT plates on the MDU were replaced with new plates. Copper dust was unable to tripper an impact, so 4-7 SS pellets were fired "shotgun" style at the MDU. The size of the pellets was too small for the lasers to detect their velocity (Fig. 12); thus, velocity calculations used a Maxwellian distribution for the impacts registered (Table 4). These tests did not break any PZT plates.

Material	Diameter	Mass	Gas	Pressure	Approximate Velocity	Approximate Kinetic Energy	
Stainless Steel	0.35 mm	0.589 mg	Nitrogen	750-1500 PSI	100-300 m/s	0.003 J	0.03 J

Table 4. Dust Firing Test Values

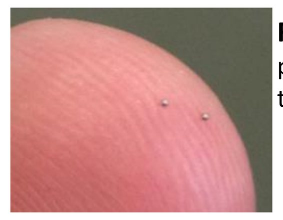
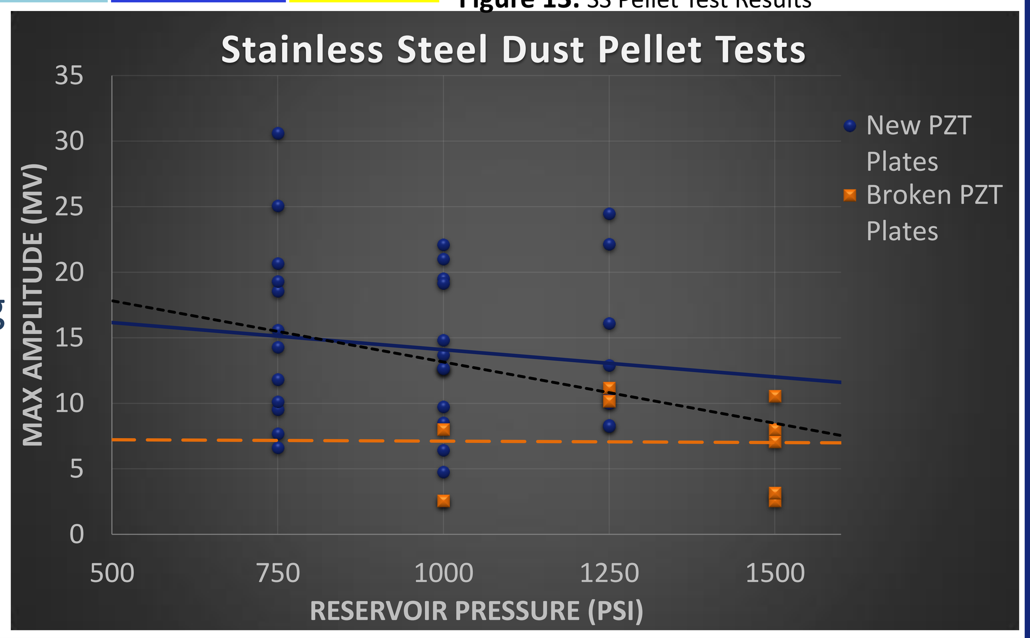


Figure 12. Two SS pellets located on tip of finger.

Maximum amplitudes from SS tests are plotted on Fig. 13. Increasing pressure ought to result in higher velocities and amplitudes, but the black trend line indicates a negative correlation. This is most likely due to the inability to accurately measure small particle velocities. Further testing with more precise velocity tracking methods are required to ensure a complete data set.

Figure 13. SS Pellet Test Results



Equipment

A Single-Stage Light Gas Gun (Fig. 7) using compressed Nitrogen was utilized to simulate dust impacts on the MDU. Contains interchangeable barrels, a dual laser fan velocity detection unit, and a vacuum pump to depressurize system to 200 mTorr.

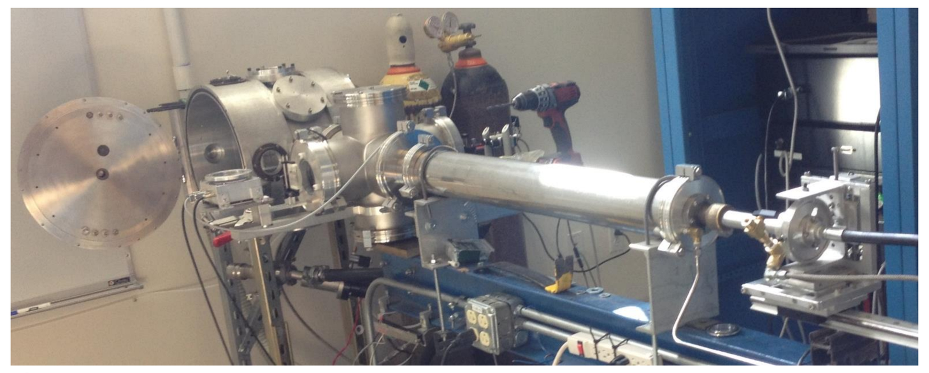


Figure 7. Light Gas Gun Setup

Computer Programs

The PDD is controlled through a Linux command shell run by Oracle VirtualBox. The user can input a set range value, as well as a minimum threshold detection value. The user then enables the PDD to detect impact triggers, after which the system shuts down. Data must be extracted before the system can detect another impact. The data is then analyzed through a MATLAB program

MDU Calibration

The MDU system required 3 calibration tests prior to pellet firing. Values in Table 1.

- Gas Noise- Minimum thresholds were required to distinguish between actual particle impacts and excess gas puffs from LGG causing system triggers.
- Electrical Noise- Inductance from circuit board stack caused system triggers at low threshold values.
- Thermal Noise- Thermal fluctuations might cause change in electrical noise level, but heating tests determined no changes occurred.

Range	Gas Noise 1500 PSI	Gas Noise 1700 PSI	Electrical Noise Level	Probable Trigger Area	No Trigger
+/- 2.5 V	60 mV	65 mV	4 mV	5-9 mV	10 mV
+/- 5.0 V	85 mV	t > 100 mV	3 mV	4-10 mV	11 mV
+/- 10.0 V	N/A	N/A	8 mV	8 mV	9 mV

Table 1. Gas & Electrical Calibration Values

Further Research & Testing

Use of either a high-speed camera, a laser strobe light combined with an open shutter camera photo streak, or a tighter laser optics system will allow for detection of small particle velocities. Testing of the detection Grid will also be performed to determine particle velocities.

The end goal is to create "signature" maps for all 9 PZT's located on the MDU. These maps will be used to compare data with space impacts once the CubeSat is launched into orbit. Space impacts data will then be used to develop NASA's dust debris model to help prevent further damage to orbital equipment.

References

Frank Odom III, Grant Richter, Ben Martinsen, Jimmy Schmoke, Mike Cook, Jorge Carmona Reyes, Truell Hyde. Piezo Dust Detector. Final Project Report, CASPER REU, August 2014

PDD Documentation Manual

Fig. 1- http://space.skyrocket.de/doc_sdat/armadillo.htm

Fig. 2- https://www.nasa.gov/centers/johnson/partnerships/orbital-debris/#.V5pkUzVUWvQ

Logos courtesy of MATLAB, Oracle VirtualBox, Baylor University, CASPER, & NSF

Pictures taken by Matthew Fournier