SSC20-WKVII-04

On-Orbit Polymer Degradation Results from MakerSat-1: First Satellite Designed to be Additively Manufactured in Space

Ben Campbell, Connor Nogales, Braden Grim, Mitch Kamstra, Dr. Joshua Griffin, and Dr. Stephen Parke
Northwest Nazarene University
623 S. University Blvd., Nampa, Idaho
sparke@nnu.edu, benjamincampbell@nnu.edu

ABSTRACT

MakerSat-1, a 1U cubesat, is a proof-of-concept mission from Northwest Nazarene University (NNU) and Made In Space (MIS). It demonstrates microgravity additive manufacturing of a cubesat aboard the International Space Station (ISS). It is the first satellite specifically designed to be 3D printed and easily snap-assembled in microgravity. Its structural frame was 3D printed on the ISS AMF printer in August 2017. In late 2019, MakerSat-1 was loaded in a SEOPS Hypergiant Slingshot deployer and then launched to the ISS aboard SpaceX CRS-19 Dragon on Dec. 5, 2019. On Jan. 31, 2020, this deployer was mounted on the hatchdoor of the Cygnus NG-12 spacecraft, unberthed from ISS, and raised to a 300 mile high orbit. MakerSat-1 and other cubesats were deployed from Slingshot into orbit on Feb. 1, 2020. In the four months following deployment, MakerSat-1 has been carrying out research on the durability of 3D printed polymer samples in the orbital space environment. The results of this science data are reported here.

MOTIVATION AND OVERVIEW

To date, small satellites have been manufactured on earth and deployed into orbit aboard high-g, high-vibration rocket launches. This has placed severe limits on reducing their mass, materials, cost, complexity, and development time. If cubesats and other spacecraft could be made in the microgravity of Earth orbit, they could use a myriad of more fragile novel materials, structural designs, and simpler assembly methods that might not withstand a typical launch or even their own weight on Earth.

Most of today's cubesats utilize a rigid aluminum frame with a stack of electronic boards mounted inside. This Earth-assembled structure must be able to withstand the high g-forces and vibrations that are present in the launch vehicle that will be used. However, once the cubesat is deployed into orbit in the microgravity environment, its required structural integrity is dramatically reduced. When designing a cubesat structure for assembly and use only in microgravity, a simpler and more advantageous approach can be taken.

To prove this concept, our undergraduate student team developed a mission concept (Fig. 1) for the on-orbit 3D printing, assembly, and deployment of a 1U cubesat aboard the ISS:

1.A ground-built cubesat kit of six pre-cabled PC boards, arranged in a flat-sat, unassembled configuration, are shipped to the ISS on a cargo resupply mission.

2.An ISS crew member uses the Additive Manufacturing Facility (AMF) from Made In Space to 3D-print the polymer frame components of the cubesat.

3.The crew member then performs a simple ten-minute snap-together assembly of the PC board kit and its 3D-printed polymer frame.

4. The cubesat battery is charged via USB and a self-test program is run to guarantee full functionality.

5.The cubesat is loaded into one of the ISS standardized deployer systems and then deployed into orbit.

Figure 1: MakerSat-1 mission concept

A variety of cubesats and smallsats could be manufactured aboard the ISS in this manner by stashing a number of standardized, reconfigurable computer boards, science/sensor boards, solar boards, power/battery boards, and communication radio boards aboard the ISS, and then assembling them on-demand with 3D-printed structures, programming via ground-uploaded code, and immediately placing them into service. The ISS crew or an onboard robot could perform simple and quick snap-together assembly, battery charge, code load, and self-test prior to the satellite's deployment from one of the ISS standardized deployers.

In addition to this opportunity aboard the ISS, robotic additive manufacturing and assembly *outside* the ISS may also be performed in orbit, in deep space, or on a planetary surface using technology currently under development, such as "Archinaut."[5]

NNU CUBESAT HISTORY

Over the course of the past six years, NNU undergraduate engineering students and faculty (with much help from corporate partners) have designed, built, and orbited Idaho's first three cubesats: MakerSat-0 (Nov 2017), RFTSat (August 2019), and MakerSat-1 (Feb 2020). The MakerSats are a pair of proof-of-concept missions designed to demonstrate the advantages of on-orbit manufacturing, assembly, and deployment of cubesats from the International Space Station (ISS) in collaboration with Made In Space.

MakerSat-0 (reported at 2018 SmallSat), deployed on November 18, 2017, hosts two onboard experiments: an ionizing radiation particle counter built by Caldwell ID High School (CHS) students, and a 3D printed polymer degradation experiment built by NNU students. Four different 3D printed polymer samples: ABS (acrylonitrile butadiene styrene),PEI/PC/Ultem (polyetherimide/polycarbonate), Nylon12, and PLA (polylactic acid) are being exposed to the conditions of long term spaceflight, and are experiencing ongoing erosion and mass loss due to monoatomic oxygen radicals, outgassing, extreme temperatures, ultraviolet (UV) radiation, solar and cosmic ionizing radiation. This polymer degradation (mass loss) was continuously measured for two weeks in orbit using a vibrational cantilever mass measurement system. The primary aim of this satellite was to study the durability of these different 3D printable polymers in space, to help researchers determine which of these polymers could be best suited for use in long-term space applications.

The RadioFrequencyTag RFTSat 3U cubesat mission was a collaboration between NNU and Georgia Tech's RF Lab. Its mission was to develop and demonstrate the first space-based 5.8GHz RF tag backscattering communications system, to allow a widely-distributed network of wireless RF tag "sensor stamps" to harvest RF energy transmitted through space from a centralized RF reader, store that energy, power an MCU and various sensors on the tag, and transmit this sensor data back to the centralized reader by modulating it on the backscattered RF signal. These passive sensor tags can potentially be used at distances up to 100m from the reader on large space structures or in flying sensor swarms. Use of energy harvesting sensor tags allows the tag mass/size to be small by eliminating the need for a solar array, charger, and battery. The tag communicates data back to the reader by modulating it onto the EM wave that is backscattered from its antenna. The amplitude and/or phase of the scattered EM wave can be modulated by varying the impedance that is connected to the tag's antenna, a process called load modulation. The main advantage of a backscatter RF tag system is that energy consumption and complexity are minimized on the passive RF tag. All of the complexity and power consumption are kept on the reader. In the RFTSat mission, a miniature Georgia Tech designed RF reader was housed in the NNU designed 3U satellite. Successful system operation in space was verified over RFTSat's three month long mission.

MakerSat-1, deployed on February 1, 2020, is the successor to MakerSat-0, and is the first cubesat to utilize a fully 3D printed frame. Its science payload replicates MakerSat-0, with the NNU polymer degradation experiment and the CHS radiation experiment. Lessons learned from the MakerSat-0 mission were incorporated into improved MakerSat-1 solar/power system, communications, and flight code designs. It has been fully functional and provided considerable radiation and polymer science data for the past four months prior to this writing.

MAKERSAT-1 STRUCTURAL DESIGN

The MakerSat-1 flat-sat pre-assembly configuration (Fig.2) is folded together like origami, as shown in Fig.3.

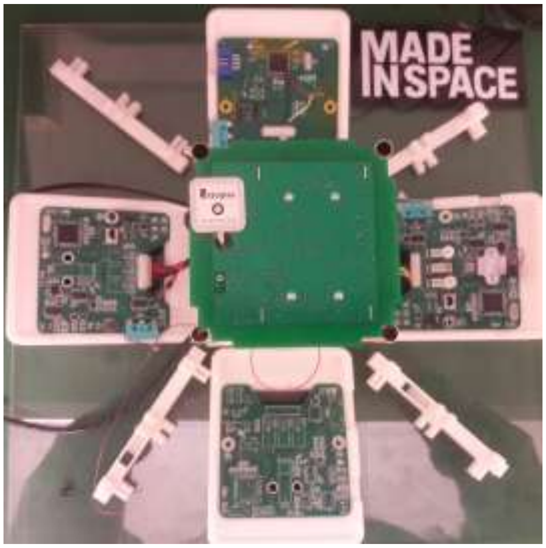

Figure 2: MakerSat-1 PC board "flower-petal" configuration ready for shipment to ISS and easy snap-together assembly.

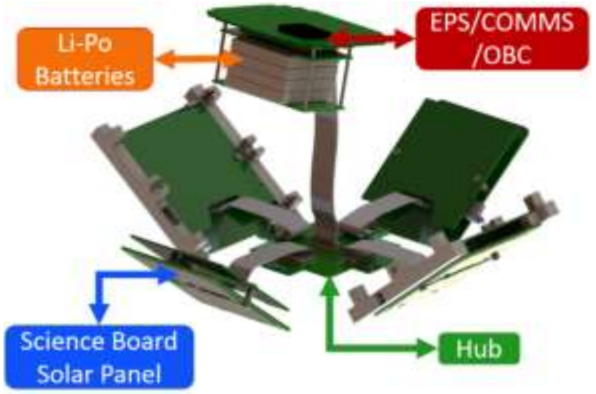

Figure 3: MakerSat-1 showing the EPS/COMMS/OBC/Batteries assembly, four science board/solar panel assemblies, and the Hub assembly, folded together like origami.

A training video was created for the astronaut crew on how to perform the simple ten-minute snap-together assembly, using no screws, tools or adhesive. Here is the link: www.youtube.com/watch?v=shLPETczsF4. The assembly is quick, easy, and safe without the dangers of any free-floating small parts such as screws, nuts, or washers. It uses as little of the ISS crew's valuable time as possible, and could be robotically automated.

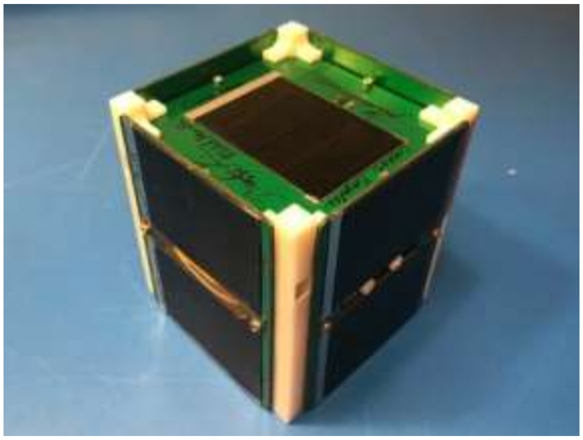

Figure 4: Assembled MakerSat-1

The MakerSat-1 polymer structural frame (four white rails shown in Fig. 4) was designed to be 3D printed aboard the ISS using the Additive Manufacturing Facility (AMF) from Made In Space. Figure 5 shows these frame components being additively manufactured by the AMF printer on the ISS in August 2017. Figure 6 shows these components displayed by the crew in the ISS's Cupola window.

LAUNCH & DEPLOYMENT

MakerSat-1 was ground-assembled, vibe tested, and loaded in the Slingshot deployer from SEOPS Hypergiant (Figure 7).

Figure 5: MakerSat-1 frame being 3D printed by the AMF printer from Made In Space aboard the ISS.

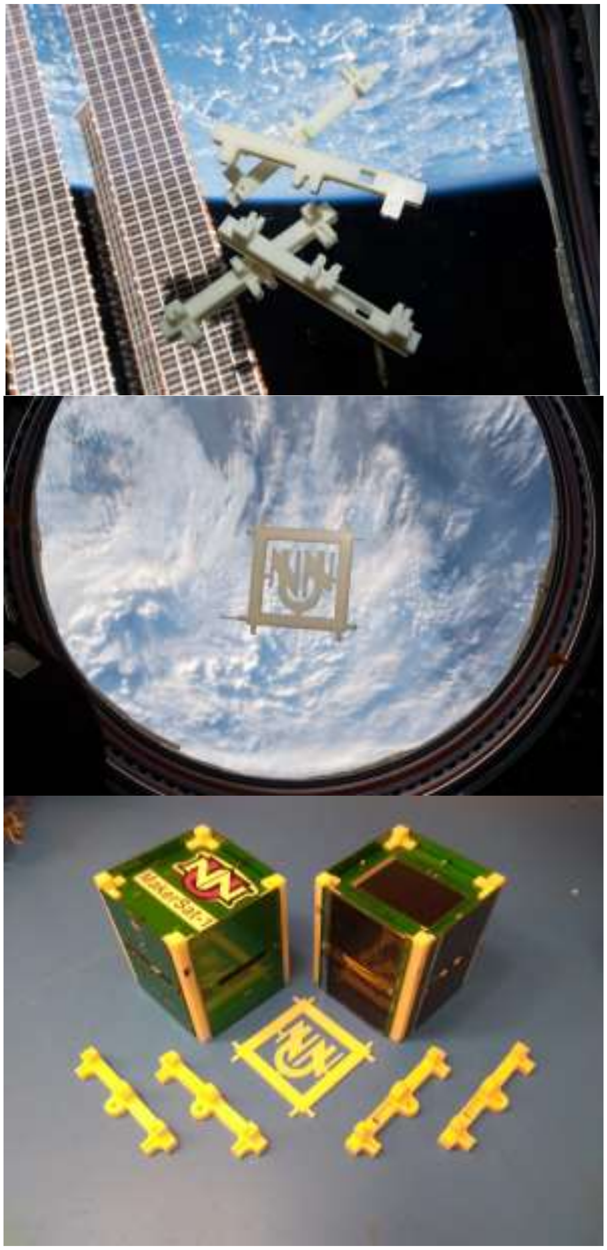

Figure 6: MakerSat-1 3D printed frame components aboard ISS

This deployer was launched to the ISS inside the Dragon cargo capsule of SpaceX CRS-19 on Dec. 5, 2019 (Figure 8). Following two months of stowage aboard ISS, the Slingshot deployer was mounted onto the hatchdoor of the Cygnus NG-12 cargo ship by NASA crew (Figure 9). Cygnus unberthed from ISS on January 31, 2020 (Figure 10), and then raised to a 300 mile high orbit, where MakerSat-1 and other cubesats were deployed into orbit on Feb. 1, 2020. It has been fully functional since.

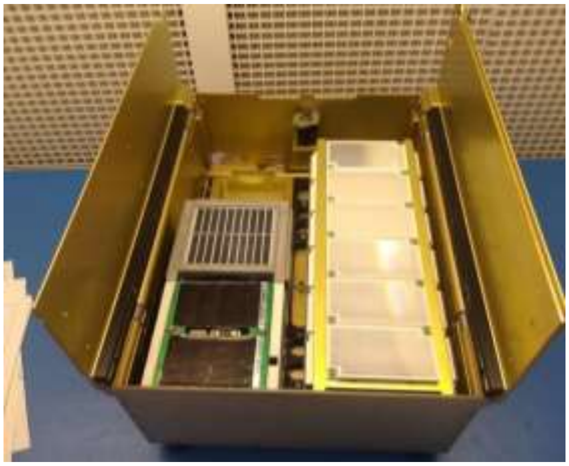

Figure 7: MakerSat-1 (lower left) loaded in Slingshot deployer

Figure 8: SpaceX CRS-19 launch to ISS (December 5, 2019)

Figure 9: US astronauts Christina Koch (left) and Jessica Meir (right) mounting Slingshot deployer (MakerSat-1 is center right), to Cygnus hatch prior to unberthing from ISS (January 31, 2020)

Figure 10: Cygnus NG-12 departing ISS (January 31, 2020)

MAKERSAT-1 ARCHITECTURE

MakerSat-1 is a multi-project satellite that provides four science teams the opportunity to fly their experiments in space together, supported by the generic core satellite.

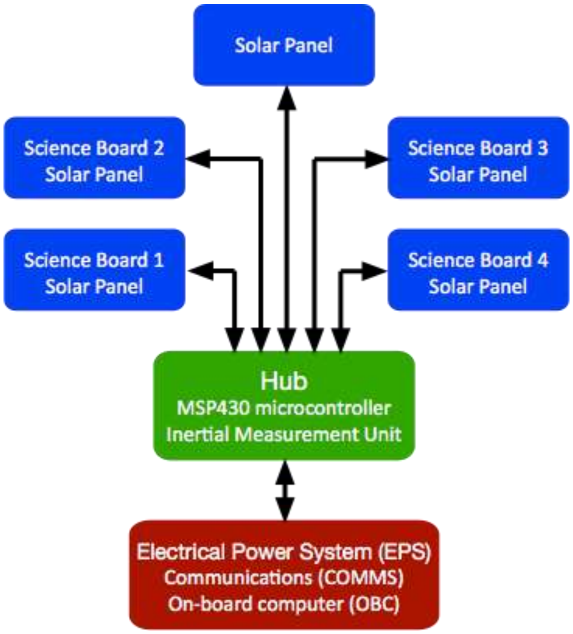

Figure 11: The MakerSat-1 system block diagram showing a central Hub, satellite Bus (EPS/ COMMS/OBC/Batteries), and four science board/ solar panel assemblies.

All satellite power, control, computing, and radio communication tasks are made equally available to each of the four science payload boards by the core MakerSat system. Each science board passes its data through the Hub to the communication system (COMMS) for downlink. Fig. 11 shows the MakerSat-1 block diagram. The electrical power system (EPS), COMMS, and the on-board computer (OBC) are on the same assembly with the battery pack.

The science boards and the Hub are mounted to the back of solar array boards (which face the outside of the satellite). The solar array boards contain cutouts (32mm x 9mm) that allow sensors and polymer samples to be exposed directly to space. The EPS/COMMS/OBC, solar panels, and science data are all routed through the Hub. This configuration eases cubesat assembly by providing a common board for all flexible cable connections to converge. The Hub provides each science board round-robin access to the EPS, COMMS, and OBC satellite bus, utilizing an ultra-low power MSP430FR6989 microcontroller with 128kB of FLASH memory for flight code and 130kB of non-volatile, ferroelectric random access memory (FRAM) for computations. The FLASH and FRAM technologies provide increased resistance to single event errors caused by ionizing radiation.

The solar arrays are constructed using flexible triple-junction GaAs solar cells from ALTA. Each cell covers one-half of a 1U face and MakerSat-1 uses two cells connected in series on each solar array board to provide 4.5 VDC at 300 mA (1.35W). Each of the five solar array boards is connected in parallel. The EPS uses peak power tracking (PPT) to regulate the current extracted from the solar cell array so such that the array remains at its peak power point. The EPS charges four lithium-polymer batteries, configured as two series pairs of batteries in parallel. Together, they provide 4.4Ah at 8V.

Passive attitude control for MakerSat-1 is provided by a permanent magnet aligned in the z-axis of the satellite that will slowly align the satellite to the earth's magnetic field. The satellite's rotation is dampened by three orthogonal μ-metal strips.

MakerSat-1 uses an NSL EyeStar radio, which communicates with the GlobalStar satellite constellation to provide a 24/7 data downlink with nearly global coverage to 14 ground gateways. The data received by the ground-gateways is made available to each participating science team via an internet portal.

The science boards on MakerSat-1 consist two polymer mass loss experiment boards from NNU, and one PIN diode radiation particle counter experiment board designed and built by Caldwell ID High School's electronics class.

VOLTAGE AND TEMPERATURE DATA

MakerSat-1 began sending voltage, temperature, radiation, and science data packets just 30 minutes after it was deployed into orbit, transmitting them every 84 minutes. It remained in this initial mode for the months of Feb and March, then entered a longterm mission mode where it hibernated for a month (April), then awoke for a couple of May days of data before it hibernated for another month (May) and awoke again in early June. Its battery pack is charged to 9V by two 4.5V solar panels connected in series on each of its faces. It shows very stable operation over the mission lifetime (Fig. 12). The X and Z solar panels behave normally between 0V in eclipse and 4.5V in sunlight. But, the Y solar panel output only goes up to 3.5V in sunlight.

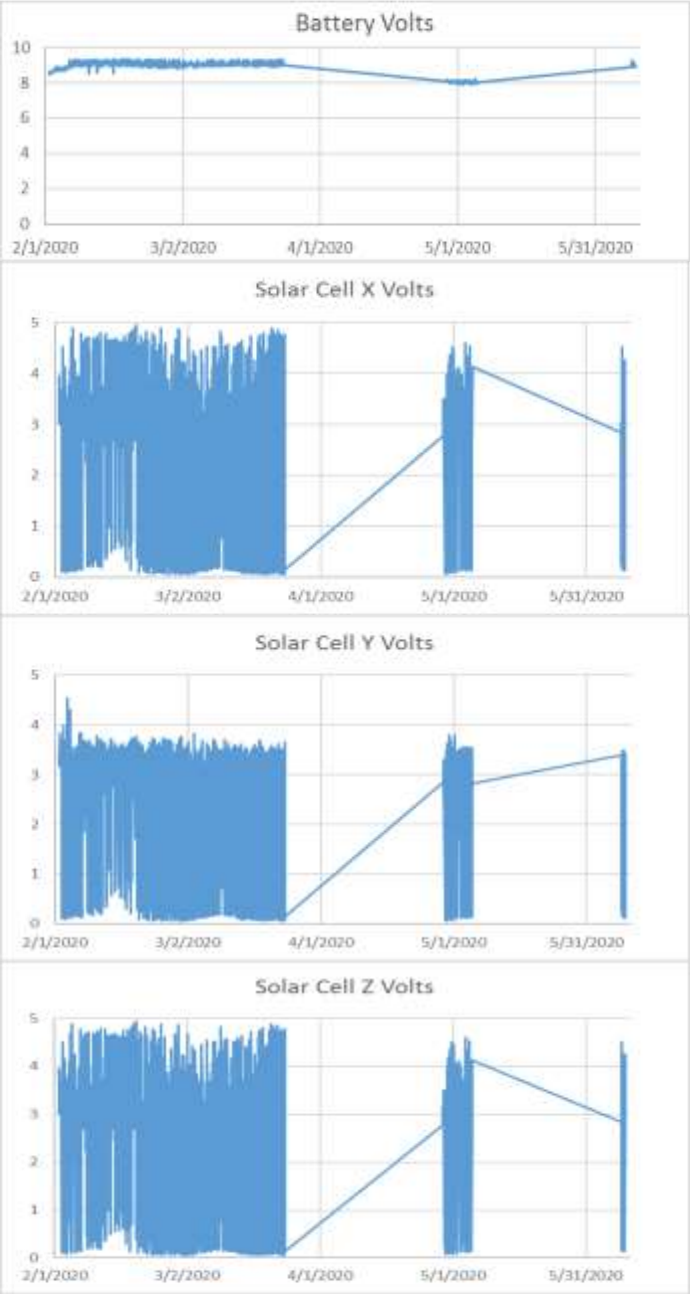

Fig 12. MakerSat-1 Voltages over Time

Fig. 13 shows temperature measurements from each of the cubesat faces. The X+ temp sensor & solar panel was disconnected. The X-, Y+, and Z+ surface temps all varied from -40C in eclipse to +10C in sunlight, while the Y- and Z- surface temps heated all the way to +50C.

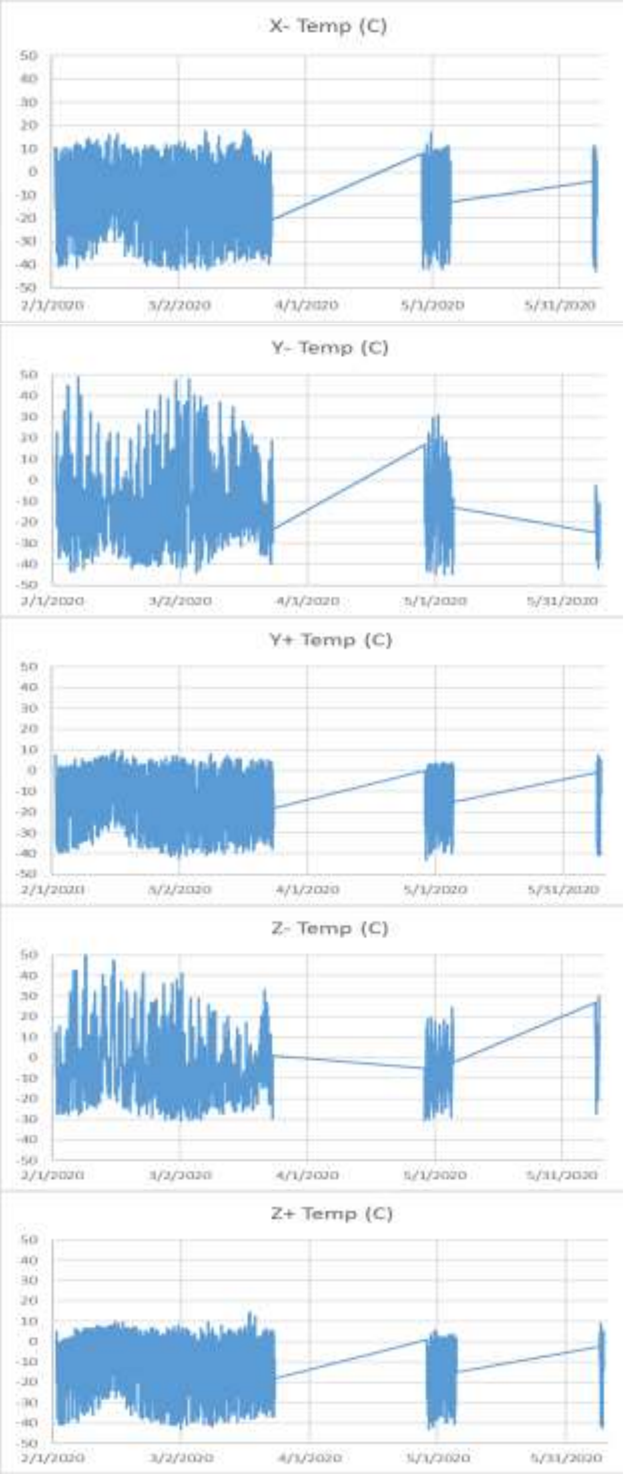

Fig. 13. MakerSat-1 Temperatures over Time

IONIZING RADIATION DATA

MakerSat-1 contained both internal and external PIN diode radiation particle detectors coupled with counter circuits to measure the ionizing radiation particle flux. This data is shown in Fig. 14. Most of the time this flux was nearly zero, but was considerably higher when passing through the polar auroras or the SAMA.

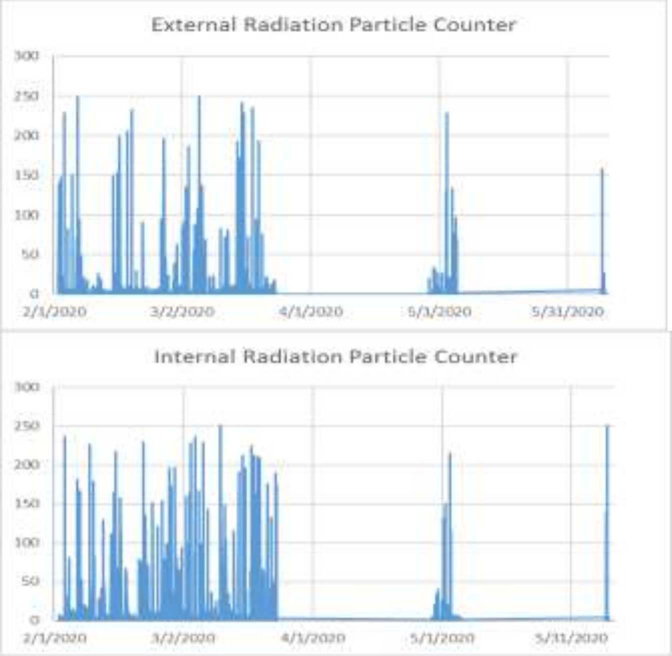

Fig 14. Radiation Particle Counts over Time

3D POLYMER DEGRADATION EXPERIMENT

Erosion and structural degradation of polymers in space happens via monoatomic oxygen radicals, ultraviolet solar radiation, ionizing solar & cosmic radiation, outgassing in vacuum, extreme hot and cold temperatures, and even micrometeorite erosion. The MakerSat-1 polymer experiment measures the in-space mass losses of 3D printed polymers: ABS, PLA, and PEI/PC/Ultem. To quantify the different mass loss rates, an experiment was designed to continuously measure the mass of each polymer sample over time in orbit. It uses piezoelectric cantilever beams, each with a different tiny cylindrical polymer sample mass mounted to the end of its beam. One cantilever beam is left unloaded as a control and used to isolate the polymer mass loss from the effects of space on the sensor itself. These polymer mass samples are directly exposed to the space environment through a small window slot in the satellite exterior. The PCB on which these cantilevers are mounted is excited by a small vibration motor over a 20-120Hz frequency sweep. The natural resonant frequency of each cantilever is measured. This resonant frequency is known to be inversely proportional to the square root of the total mass on the end of the beam (see Eq. 1), allowing precise indirect measurement of mass losses, even in microgravity.

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{3EI}{L^3 m}} \quad \text{[Eq. 1]}$$

where f_{res} is the resonant frequency of the cantilever beam, E is Young's modulus (stiffness) of the cantilever beam, I is the moment of inertia of the cantilever beam, L is the length of the cantilever beam, and m is the total mass on the end of the cantilever beam (the sum of a brass button and the polymer sample).

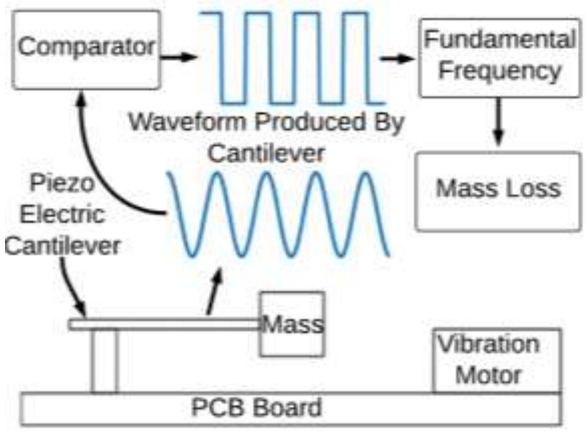

Fig 15. Polymer degradation experiment block diagram

Fig. 15 is a diagram of the polymer experiment. The piezoelectric cantilevers provide an output voltage proportional to the deflection of the cantilever beam. The cantilevers and the vibration motor were mounted in close proximity on a rigid PCB. The vibration motor frequency was swept from 20 to 120Hz, exciting the cantilevers below and above their resonant frequencies. The raw sine wave data as well as the frequency response data was taken, downlinked, and then analyzed onboard the cubesat in real time to extract the value of each cantilever's resonant frequency. This resonant frequency was then post-processed, using ground-based parsing software, to normalize out temperature and other environmental effects using the unloaded control cantilever resonant frequency. It was critical that this experiment was done differentially, using the unloaded control cantilever with a brass dummy mass that does not degrade over time in orbit. Thus, systematic common mode errors were eliminated. Fig. 16 shows the layout of one of the two MakerSat-1 polymer experiment boards.

Each of the two polymer experiment boards have an unloaded cantilever (center) with only a brass button on the end to serve as the experiment control.

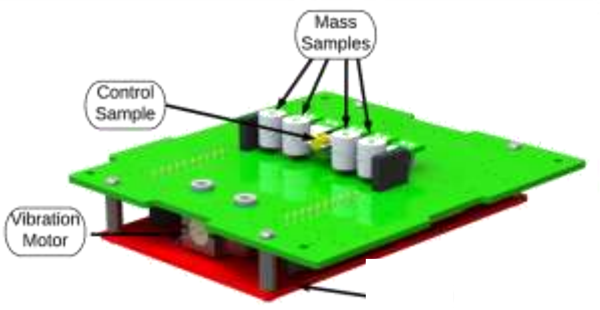

Figure 16: Polymer mass samples mounted on the ends of piezo cantilevers, excited by vibration motor frequency sweep

Examples of the cantilever vibration amplitude vs. time and amplitude vs. frequency responses are shown in Figures 17 and 18. There are typical of the raw data that is transmitted from MakerSat-1 and stored in the database every 84 minutes. Onboard, real-time analysis of this data finds the resonant frequencies and amplitudes of each cantilever and downlinks that information with a timestamp to the database.

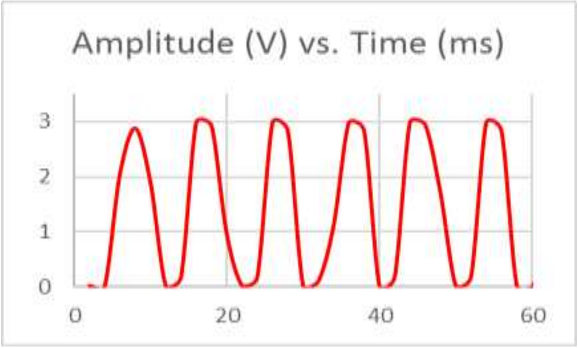

Figure 17: Cantilever amplitude vs. time (T=11ms, f=90Hz for the control cant). Typical of raw data transmitted from orbit.

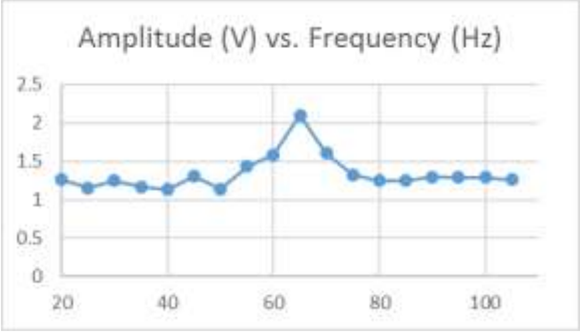

Figure 18: Cantilever amplitude vs. swept excitation frequency showing the resonant peak, typical of raw data transmitted from orbit. Onboard, realtime analysis of this data returned a resonant frequency of 63Hz.

POLYMER DEGRADATION DATA ANALYSIS

The bulk of the data received from MakerSat-1 were these raw time and frequency domain waveforms from the polymer degradation experiment. The extracted values of the various polymer-loaded cantilevers' resonant frequencies were collected with their corresponding orbital timestamps. From this database, we created plots of each cantilever's resonant frequency over time. Some of the noise in this data was smoothed out by using a 4-day moving average. The effect of varying orbital temperatures on the resonant frequencies of the cantilevers was normalized out of our data by extracting a constant from the non-changing control cantilever.

The coefficient and constants E, I, and L of Eq. 1 can be combined into a single variable K, as shown in Eq. 2.

$$f_{res} = \sqrt{\frac{K}{m}} \qquad \text{Eq. 2}$$

To find the mass from the resonant frequency, we use:

$$m = \frac{K}{{f_{res}}^2} \qquad \text{Eq. 3}$$

For the control cantilever, this mass is entirely a non-eroding brass button. For the other cantilevers, this mass is the sum of the non-changing brass button mass and the changing polymer mass. Any change in the resonant frequency of the control cantilever is due to environmental effects on its K value, but not its mass. Using this assumption,

$$K_S = \frac{f_S}{f_E} K_E = \alpha K_E \qquad \text{Eq. 4}$$

Where K_S and f_S are in space and K_E and f_E are on earth. The ratio α varies with temperature in orbit, but applies equally to all of the cantilevers. As a result, the total mass on the polymer-loaded cantilevers is:

$$m = \frac{\alpha K_E}{{f_s}^2} \qquad \text{Eq. 5}$$

The normalized resonant frequency of each polymer cantilever is shown over time in orbit in Figs. 19.

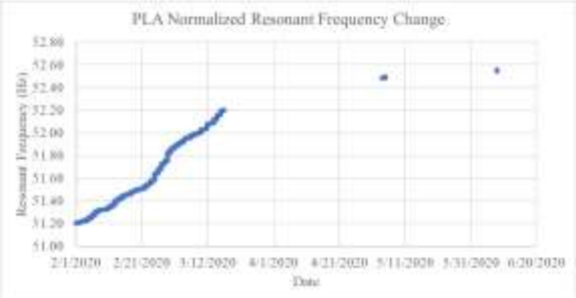

Figure 19a: PLA cantilever resonant frequency over time

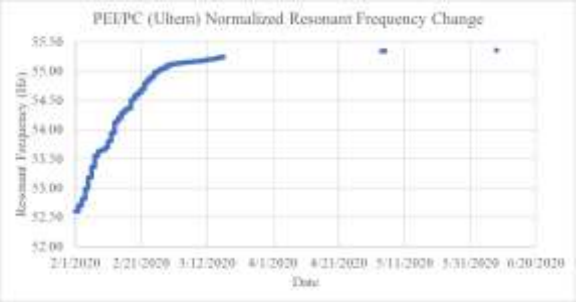

Figure 19b: PEI/PC cantilever resonant frequency over time

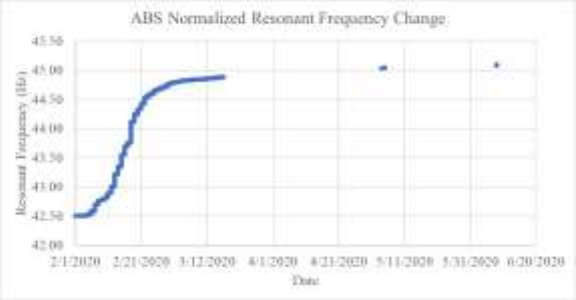

Figure 19c: ABS cantilever resonant frequency over time

This data shows that most of the polymer mass losses occurred during the first three weeks in orbit, followed by a much slower linear mass loss over the following three months in orbit. We believe the large initial mass loss (which was also observed in the MakerSat-0 two week mission data) is due to UV-assisted outgassing, and that the slower mass loss over time is due to monoatomic oxygen erosion. Applying Eq. 5, the polymer samples percent mass degradation/loss was calculated and plotted versus time in orbit, as shown in Figs. 20.

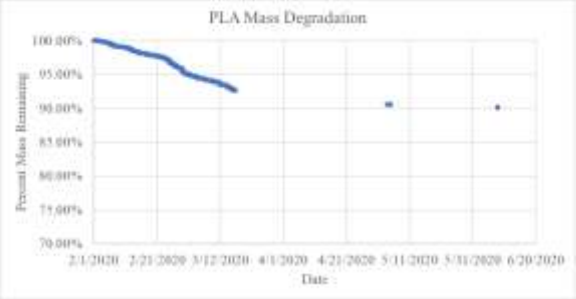

Figure 20a: PLA mass degradation over time

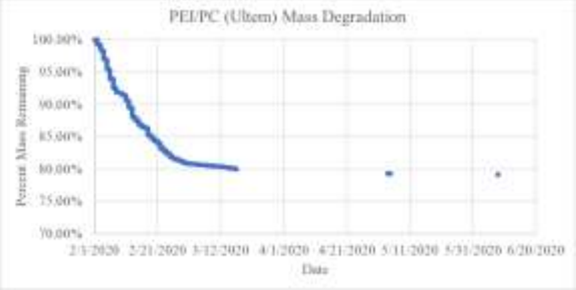

Figure 20b: PEI/PC mass degradation over time

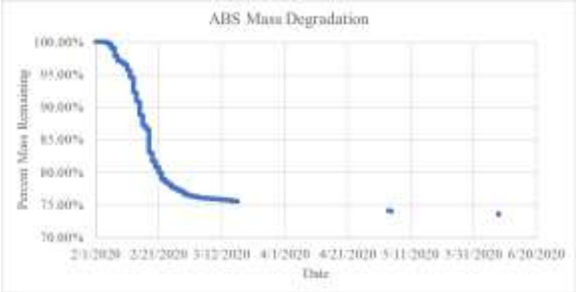

Figure 20c: ABS mass degradation over time

Table I summarizes the MakerSat-1 3D polymer mass losses throughout its time in orbit. The mass loss is reported after two weeks in orbit, in order to compare it with results reported in SmallSat2018 from MakerSat-0.

		Brass (Control)	PLA	PEI/PC (Ultem)	ABS
Preflight Data: Sept 15, 2020	Freq (Hz)	95.40	51.20	52.60	42.50
	Total Mass (g)	337	691	630	583
	Polymer Mass (g)	0	354	293	246
	% Mass Loss	0.00%	0.00%	0.00%	0.00%
Initial Data: Feb 5, 2020	Freq (Hz)	95.40	51.25	53.17	42.53
	Total Mass (g)	337	690	617	582
	Polymer Mass (g)	0	353	280	245
	% Mass Loss	0.00%	0.37%	4.60%	0.33%
2-Week Data: Feb 16, 2020	Freq (Hz)	95.40	51.45	54.33	43.69
	Total Mass (g)	337	684	590	552
	Polymer Mass (g)	0	347	253	215
	% Mass Loss	0.00%	1.90%	13.51%	12.73%
Current Data: June 8, 2020	Freq (Hz)	95.40	52.55	55.35	45.09
	Total Mass (g)	337	656	569	518
	Polymer Mass (g)	0	319	232	181
	% Mass Loss	0.00%	9.92%	20.87%	26.47%

Table I: MakerSat-1 3D Polymer mass loss data summary

This data shows the same results as the MakerSat-0 mission, with PLA being the most resilient, with a 4-month mass loss of 9.9%. PEI/PC (Ultem) showed had a 4-month mass loss of 20.9%, while ABS was the worst, with a loss of 26.5%. In addition, data from MakerSat-0 showed that Nylon 12 had a mass loss of 40.30% in just two weeks.

SUMMARY

The advancements of the space community have continued to progress in recent years, and they show no signs of stopping anytime soon. A growing number of smaller universities and schools (like NNU and CHS) and small companies (like Made In Space) are gaining more access to the arena of space, and the science, engineering, and manufacturing opportunities it holds. By implementing new in-space manufacturing methods such as those in the MakerSat Project, we will further expanding humanity's abilities to produce next-generation spacecraft with which to study our world and those beyond it. We are now at the doorway of an era where designing and building spacecraft in-space and on-demand is a real possibility, instead of being bound to Earth's surface. This concept sparks new degrees of freedom in spacecraft design and in-space manufacturing, which will result in reduced costs, reduced development times, and greater creativity and access for all those wanting to become involved in aerospace.

ACKNOWLEDGEMENTS

This work has been generously funded by the Idaho Space Grant Consortium and Northwest Nazarene University. The authors owe special thanks to Dave Pahlas from Plexus; Matt Napoli from Made In Space; Jeff Dailey from Near Space Launch; Jeff Fitch and Michael Johnson from SEOPS Hypergiant; Dennis Zattiero and his students at Caldwell HS; and the STEM-based educators at Northwest Nazarene University; who with all of their generous guidance, assistance, and support, helped get the MakerSat Project off the ground.

REFERENCES

1. Connor Nogales, Braden Grim, Mitch Kamstra, Benjamin Campbell, Aaron Ewing, Robert Hance, Dr. Joshua Griffin, Dr. Stephen Parke "MakerSat-0: 3D-Printed Polymer Degradation First Data from Orbit" in Proceedings of the AIAA/USU Conference on Small Satellites, 2018.
2. Braden Grim, Mitch Kamstra, Aaron Ewing, Connor Nogales, Dr. Joshua Griffin, Dr. Stephen Parke "MakerSat: A CubeSat Designed for In-Space 3D Print and Assembly," in Proceedings of the AIAA/USU Conference on Small Satellites, 2016.
3. E. Grossman and I. Gouzman, "Space environment effects on polymers in low earth orbit," Nuclear Instruments and Methods in Physics Research, pp. 48-57, 2003.
4. C. McCarthy, B. Banks, K. de Groh, "MISSE 2 PEACE Polymers Experiment Atomic Oxygen Erosion Yield Error Analysis," NASA/TM-2010-216903.