NASA's Photovoltaic Energy Research Plans and Programs

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Photovoltaic Needs and Goals

- General Needs for PV development programs:
  - Increased cell efficiency, reduced cost, reduced weight, improved radiation tolerance
- NASA specific needs
  - Higher power systems: Solar Electric Propulsion (Gateway, Mars Cargo), ISS, Human Landing System
  - Power for Lunar and Mars Surface Missions (rovers, landers, power stations, site specific needs) including dust mitigation
  - Unique environments with high radiation and/or intensity/temperature extremes
- Overall Goals of the GRC PV Group
  - Serve as an Independent verification/validation of PV technologies for other government agencies and industry
  - Provide expertise to flight missions
  - Build on interactions and collaborations with other government agencies

State-of-the-Art Space Photovoltaics

- Major US cell suppliers are SolAero Technologies and Spectrolab
  - Nominally >30% in-space conversion efficiency
  - Gallium arsenide-based multijunction (3+ junction) solar cell technology
  - Fully space-qualified to AIAA Standards
  - Designed for End-of-Life (EOL) performance (within the space radiation environment)
  - VERY EXPENSIVE (compared to terrestrial solar cells)
- More "traditionally terrestrial" photovoltaic technologies are being seeing greater use

Terrestrial PV Technology for Space

- Application of low-cost solar array blanket manufacturing methods and terrestrial solar cell technology for space missions
  - Automated manufacturing and modularity
  - Use of silicon PV for short duration missions
  - Focus is on ”lower cost” cell technology
  - NASA has conducted in-space flight experiments of terrestrial PV to evaluate long-term survivability under NASA mission requirements
- Use of lower cost epitaxial grow techniques for gallium arsenide-based higher efficiency solar cells
  - Hydride Vapor Phase Epitaxy (HVPE) growth techniques being developed at National Renewable Energy Laboratory (NREL)
- Increased interest in perovskite solar cell technology
  - Potential for high efficiency terrestrial technology at lower fabrication costs
  - Recent test results indicate potential for in-space radiation hardness

GRC PV Team

Civil Servant

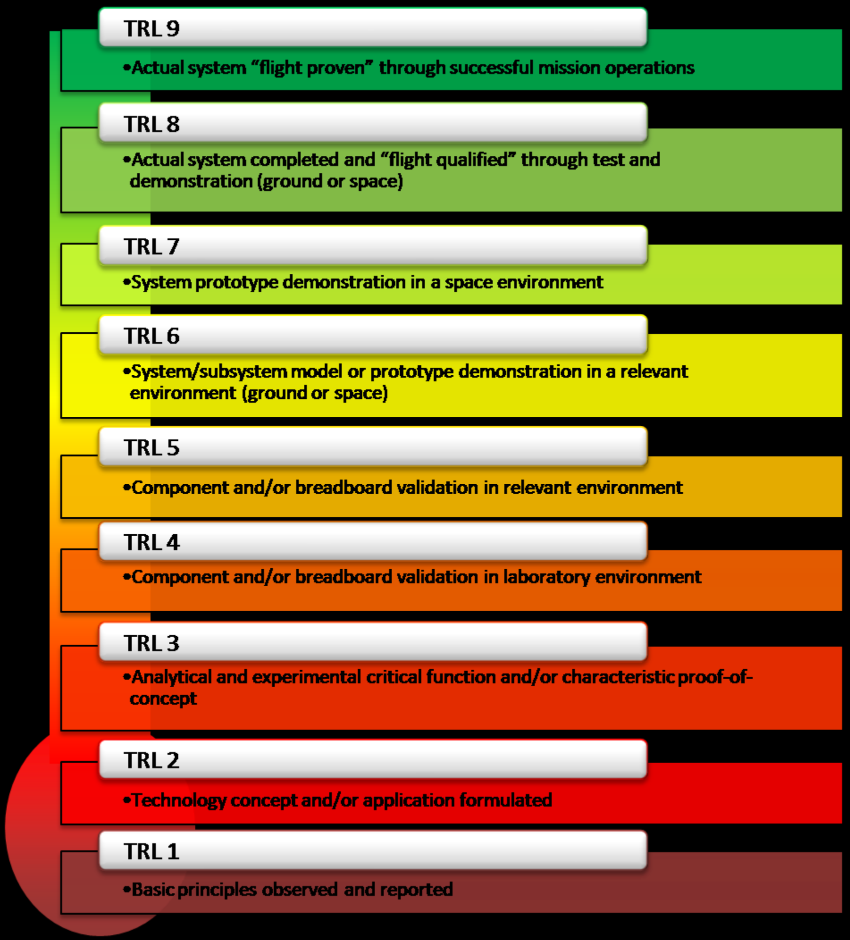
- Jeremiah McNatt: PV Technology Lead
- Meghan Bush: Solar Cell Measurement / Calibration
- Geoff Landis: PV Cell Technologies for Unique Missions
- Lyndsey McMillon-Brown: Perovskite and Thin Film PV, Optical Coatings
- AnnaMaria Pal: PV Cell Tech, Lunar Surface Solar Arrays
- Jeremiah Sims: Solar Cell Measurement

Contractor

- Kaitlyn VanSant: Post Doc – Perovskite Technologies
- Boris Vayner: PV Cell/Array Arcing & Charging

Project Scope

- Efforts span the NASA Technology Readiness Level (TRL) Scale
- Low TRL
  - NIAC - NASA Institute for Advanced Concepts
  - NSTGRO – NASA Space Technology Graduate Student Research Opportunity
  - Early Career Initiative / Center Innovation Fund
- Mid TRL
  - SBIR – Small Business Innovative Research
  - Environmental Testing
- High TRL
  - Flight Demonstrations
  - Mission Support



Graduate Student Program

- Lower Cost / High Efficiency Cell Development
  - 2 NASA Space Technology Graduate Research Opportunities (NSTGRO) at University of Illinois Urbana-Champagne with efforts focused on III-V materials on Si with improved radiation resistance
    - Ryan Hool – Graduated in August 2022
    - Brian Li – Started as NSTGRO fellow in Fall 2019
- Microcell CPV for Extreme Space Environments
  - NSTGRO at Penn State developing a space-optimized system with a geometric concentration ratio of 30x that is ultra-compact (<600 μm thick) and capable of >350 W/kg at >33% power conversion efficiency under AM0
    - Christian Ruud – Graduated August 2022
- Laser Power Converters for Lunar Exploration
  - NSTGRO at Rochester Institute of Technology growing and comparing lattice matched and metamorphic grade laser power converters.
    - Katelynn Fleming – Started as NSTGRO fellow in Fall 2022

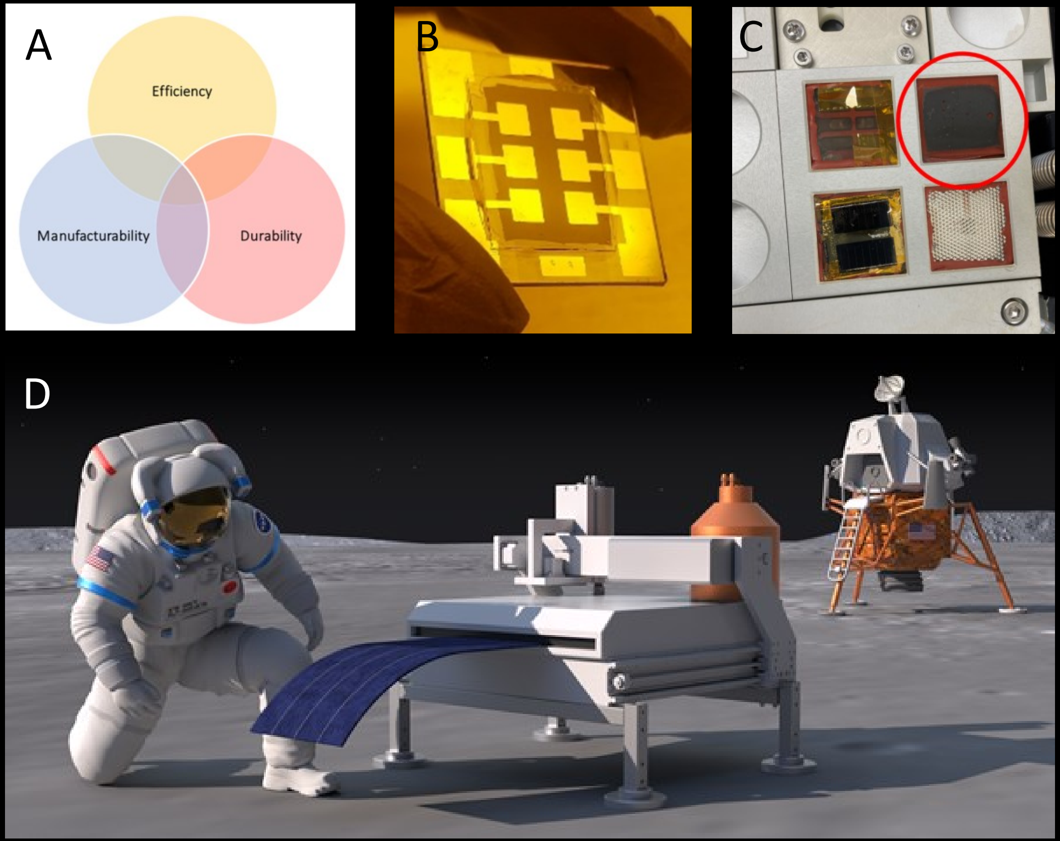
- Call for New Proposals will be Released annually on https://nspires.nasaprs.com/
  - Looking for strong candidates (MS/PhD) developing space-related technologies (PV, batteries, fuel cells, PMAD)

Perovskite Solar Cells for Very Large Arrays: Space power at terrestrial costs

Goal: Enable large area (>100kW), flexible thin film perovskite solar arrays on flexible substrates for lunar surface habitats.

Strategy: Develop high efficiency, manufacturable, and durable space qualified perovskite solar arrays.

Agency Need: Lunar surface power is unlike most other space power: the need is for very large areas, significantly reduced cost. These goals are more readily met by perovskite thin films than by SOA.



A) Design considerations schematic. B) Fabricated perovskite solar cell. C) $MAPbI_3$ thin film integrated on MISSE-13. D) Artist rendering of in-space manufacture of perovskite solar cell

External Collaborators:
Joseph M. Luther (NREL) – Perovskite Ink Development
Sai Ghosh (UC-Merced) – Electrospray Perovskite Cells

NASA Point of Contact: Lyndsey McMillon-Brown (lyndsey.mcmillon-brown@nasa.gov)

Laser Power Beaming

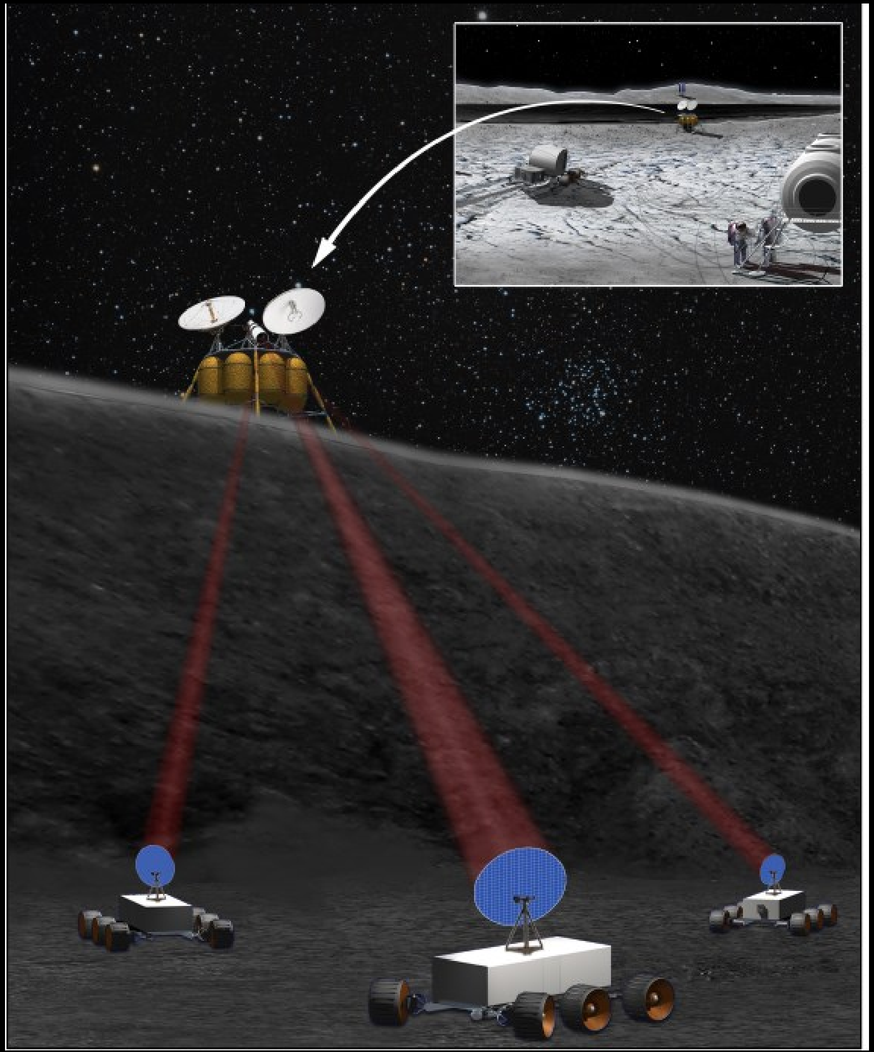
- Use of laser to beam power to photovoltaic cell allows application of lightweight photovoltaic power to regions with no sunlight

- Particular application being developed is power for multiple rovers operating in permanently shadowed craters near the lunar poles

NASA Glenn activities:

- GRC is technical lead for Space Technology Research Grant project with University of California Santa Barbara to develop and test laser power beaming as part of the Lunar Surface Technology Research (LuSTR) program

- Impact
  - Technology could enable future rovers in permanently shadowed craters on the moon



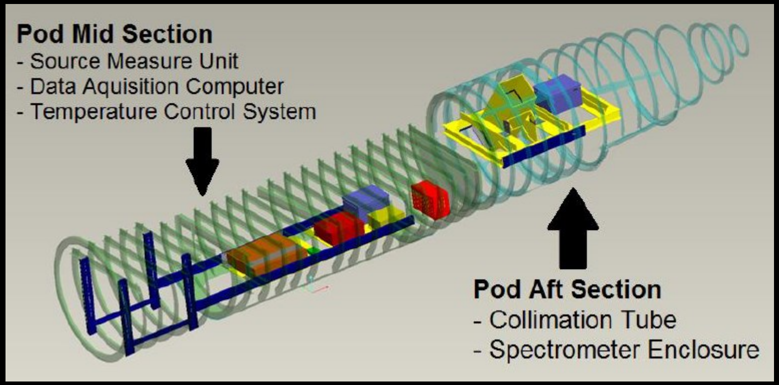
Laser power beaming for lunar polar power

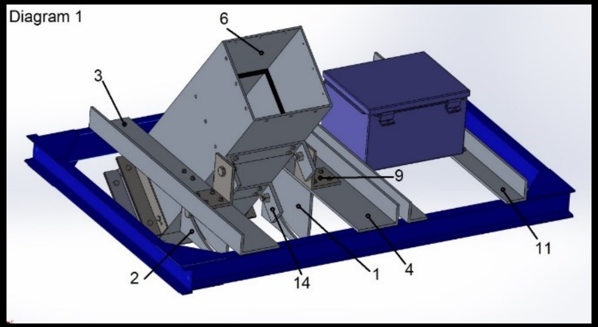
SBIR Programs

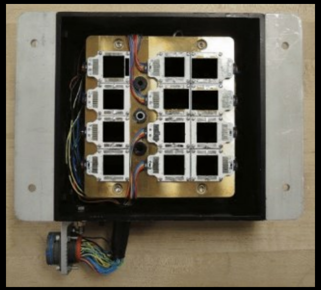
- GRC has supported the development of low/middle technology readiness level (TRL) photovoltaic devices, blankets, arrays, and testing equipment for many years through the Small Business Innovative Research (SBIR) program
- Work closely with Langley Research Center and the Jet Propulsion Lab to develop solicitations and manage SBIR programs
- Subtopics change every year but the need for in-space power is always there
- IGNITE Special Low Cost PV topic: https://sbir.nasa.gov/solicit-detail/80089
    - Proposals due on Sept 1, 2022
    - Can address any area of cost reduction, from substrate, to cell growth, to processing, to qual/testing at the blanket/array level.

Ground Testing – High Altitude Measurement

- ER-2: High altitude (70k ft) experiment platform utilized for solar cell standard development
- Planned for a Fall Campaign. 2020 season was cancelled due to Covid-19. 2021 has been cancelled due to aircraft delays, looking for future aircraft availability
- 2nd flight pod built (not yet flown) to increase cell area per flight
- Collaborating with Blacksky Aerospace and Angstrom Designs on high altitude balloon testing

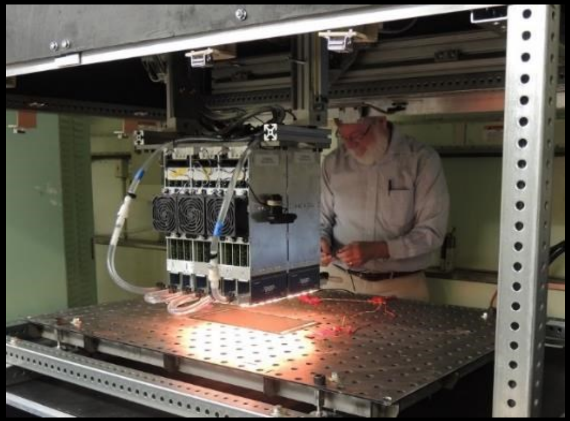


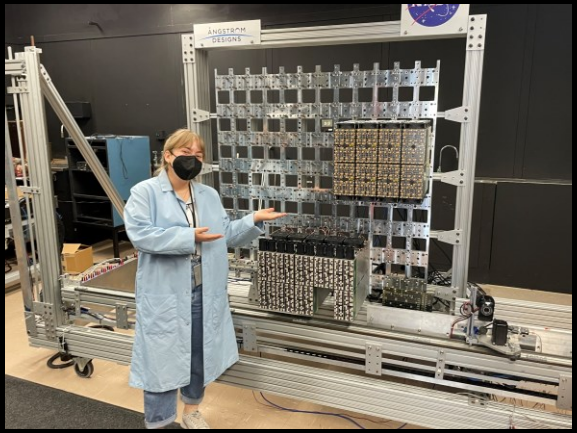




Ground Testing – Solar Simulators

- Solar Simulators
  - 3 zone – Spectrolab X25 based system
    - Option for variable temperature chamber with quartz window
  - 6 zone – Angstrom Designs LED based
    - Approximately 10” x 10” illumination area
  - 5 zone – Angstrom Designs LED based large area pulsed solar simulator
    - Approximately 33” x 12” illumination area capability
    - 17 total modules (reconfigurable to match string length)





Advancement of Qualification Protocols for IMM-α

- NASA Space Technology Mission Directorate – Announcement of Collaboration Opportunity awarded to Maxar Technologies along with GRC and MSFC to test 5-junction solar cells through qualification protocols similar to AIAA S-111/112 to raise the TRL
  - Solar cell electrical performance testing capabilities at GRC
  - Space environment testing facilities at MSFC
  - Maxar is providing the SolAero IMM-α coupons

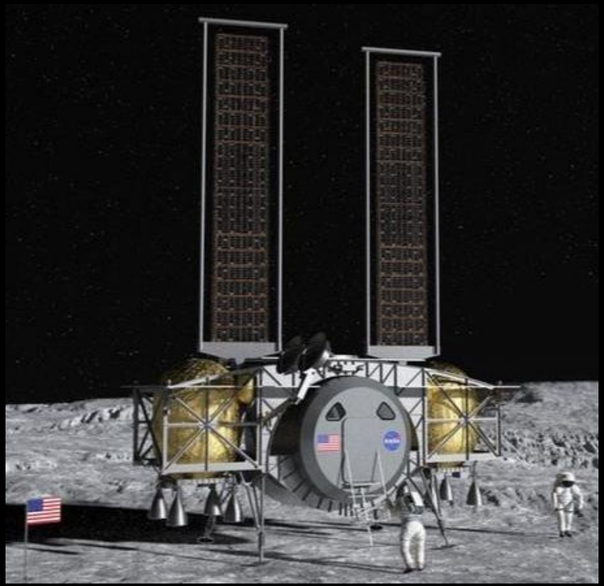
- Impact
  - Enable future commercial and NASA missions with higher power at a lower mass
  - For small satellites more power can enable additional payload capabilities
  - Smaller area footprint (W/m2) and higher specific power (W/kg). Driving metrics for solar arrays in space and on lunar surface

- *Electrical Checkout and performance using LED-based pulsed solar simulator*
- *Sine vibe testing*
- *Thermal balance testing*
- *Electrostatic discharge testing*
- *UV radiation exposure*
- *Electron radiation exposure*
- *Proton radiation exposure*
- *Thermal cycling*

High-Energy Accelerator Lab at MSFC (Electron and Proton Radiation Testing)

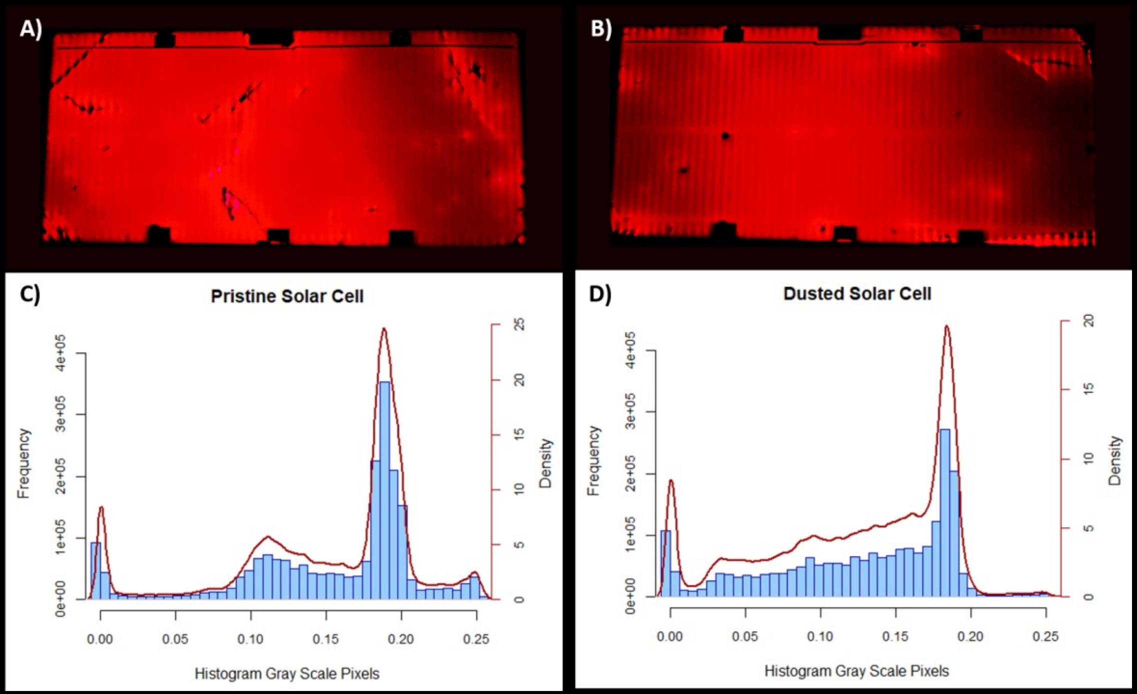
DMFlex - Dust Mitigation on Flexible Solar Arrays

- NASA Space Technology Mission Directorate – Announcement of Collaboration Opportunity awarded to Maxar Technologies along with GRC to explore lunar dust mitigation methods for vertical, flexible solar arrays
- Investigating whether vibratory motion and/or electrostatic dust shielding effectively remove deposited lunar simulant on vertical arrays, verify using **electroluminescence imaging + image processing**
- Tests performed as a function of illumination, charging level, temperature and angle of solar array



Rendition of a lunar lander with vertical solar arrays

Regolith is notable for getting kicked up by surface activity and sticking to surfaces; could reduce solar array output



Flight Test – MISSE 16

Materials ISS Experiment (MISSE)

- MISSE 15, 6-month (planned) exposure to Low Earth Orbit (LEO) conditions launched in Aug 2021
- MISSE 16, 6-month (planned) exposure to Low Earth Orbit (LEO) conditions planned launch July 2022
- Includes lightweight, novel solar cells and modules (including Perovskites, Concentrators)
- Passive exposures similar to past ISS experiments in zenith direction

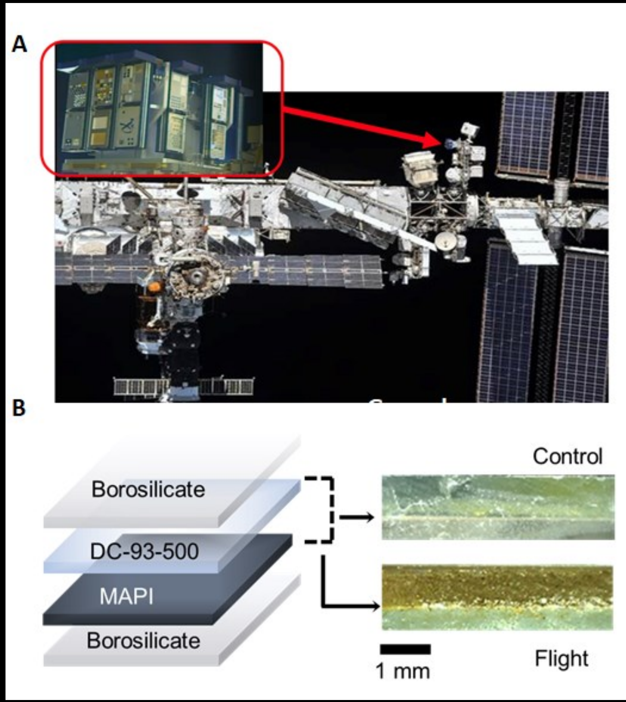
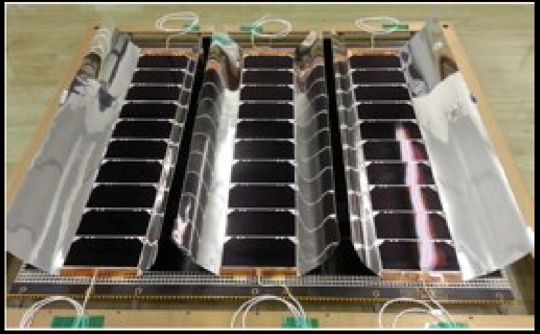


Figure. A) MISSE on the ISS B) Schematic of perovskite active layer flown for 10 months in LEO on MISSE-13. C) Launch of MISSE-16

Solar Cell & Array Development – Outer Planets (LILT)

- Extreme Environments Solar Power (EESP): Develop solar cell and array technologies for use in low intensity, low temperature (LILT) environments (beyond 5 AU) and high radiation environments in this region (Jupiter and its inner moons)
- Project Goal: 35% beginning of life (BOL) cell efficiency, 28% EOL efficiency at the blanket (or equivalent) level, measured at 5 AU and -125 ^{o}C; 8-10 W/kg measured at EOL, Packaging density at least 60 kW/m^3
- Project started in June 2016 with 4 contract Base Phase Awards, 2 later Option Phases led to 1 current award to Johns Hopkins Applied Physics Laboratory (APL)

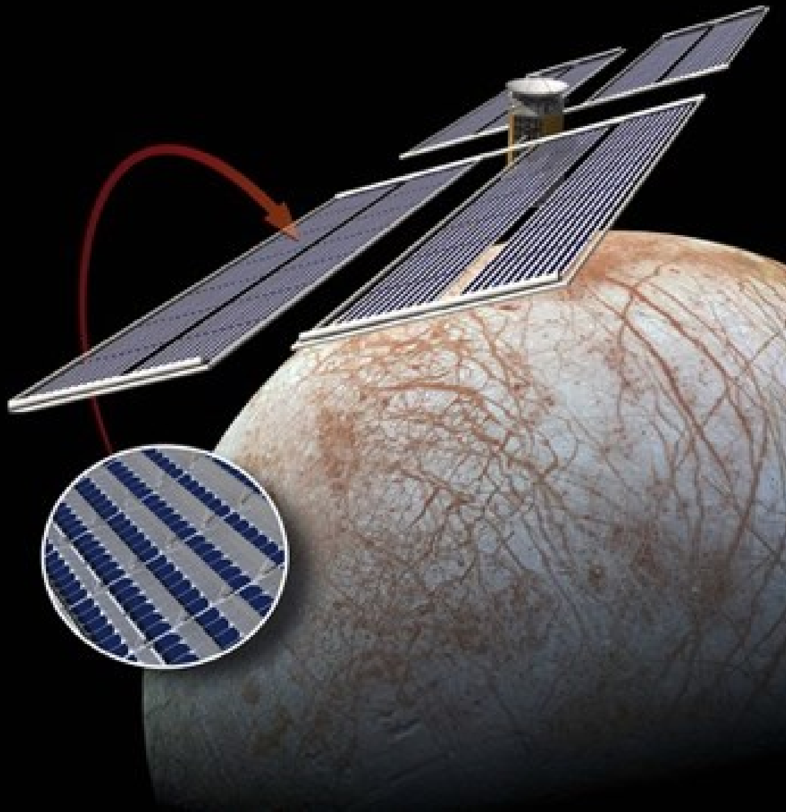
APL: Transformational Array (TA)



Flexible Array Concentrator Technology (DSS, APL)

System Concept

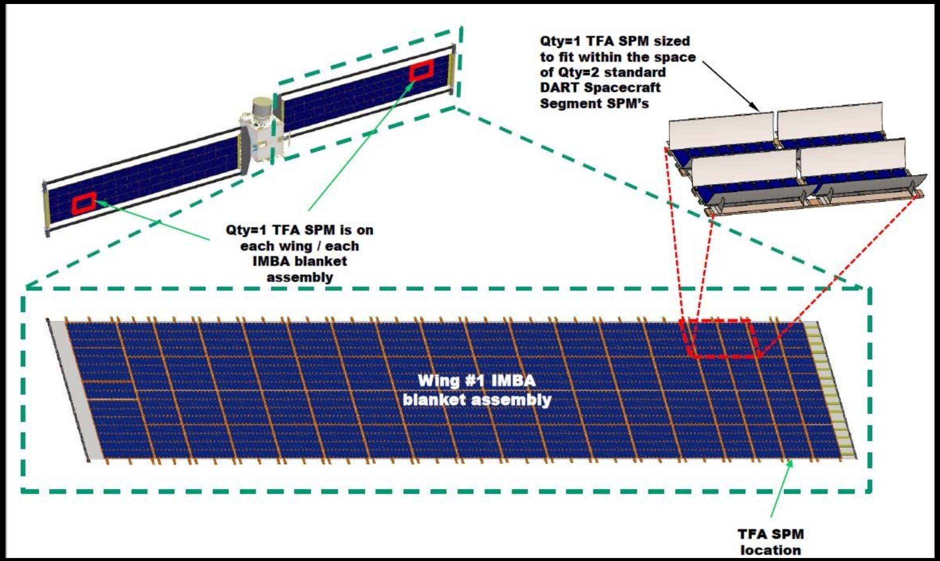
- Uses DSS Roll Out Solar Array (ROSA) for the array structure and blanket.
- Populated the array with high efficiency IMM solar cells which also offer longer life in radiation environments (SolAero IMM4 cell)
- Populated the array with concentrators to reduce array mass, volume, and cost and increase intensity on the cells by 2x.
- Current missions being planned to Jupiter's moon Io and to Neptune's moon Triton are considering including demonstrations of the Transformational Array.

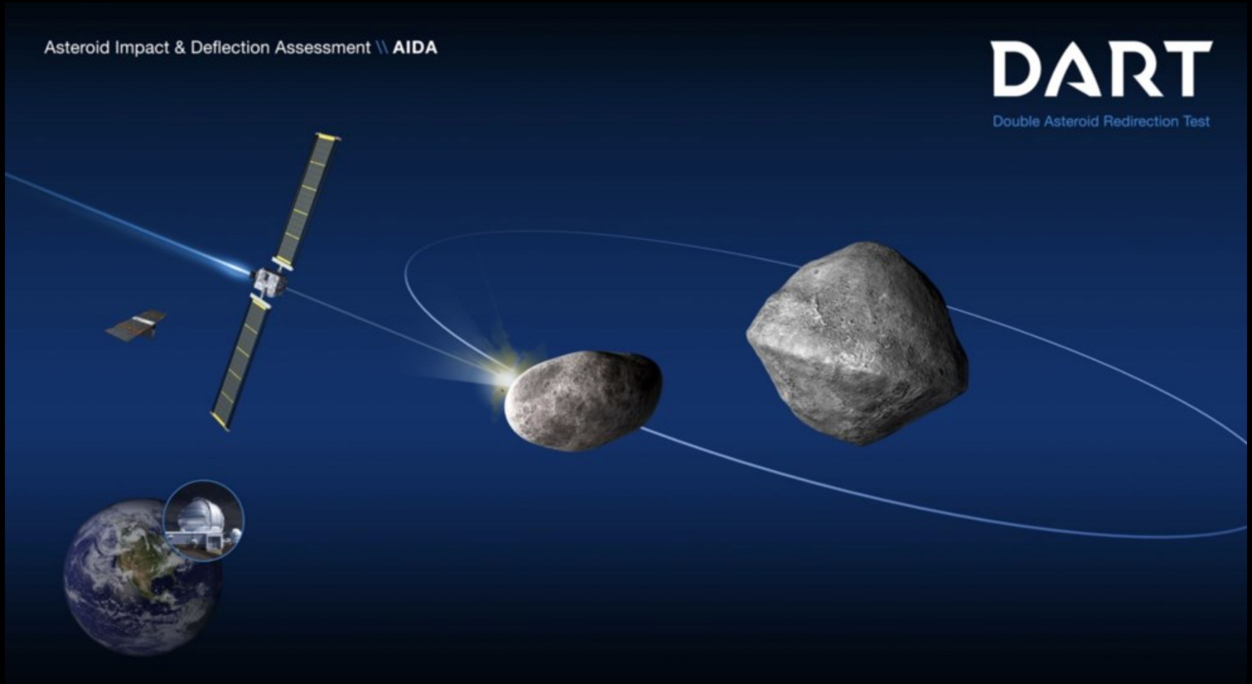


Flight Test – EESP on DART

Double Asteroid Redirection Test (DART) Mission: Launched November 24th, 2021

- Opportunity existed for test of the APL Transformational Array cell and concentrator technology in similar flight configuration for near Earth mission
- The TA array technology will be placed on the portion of the array that provides power to the spacecraft
- The current from the TA strings and service strings will be measured using existing circuitry in the power system
- Data will be collected over the year long cruise to Didymos (Impacted on September 26, 2022)

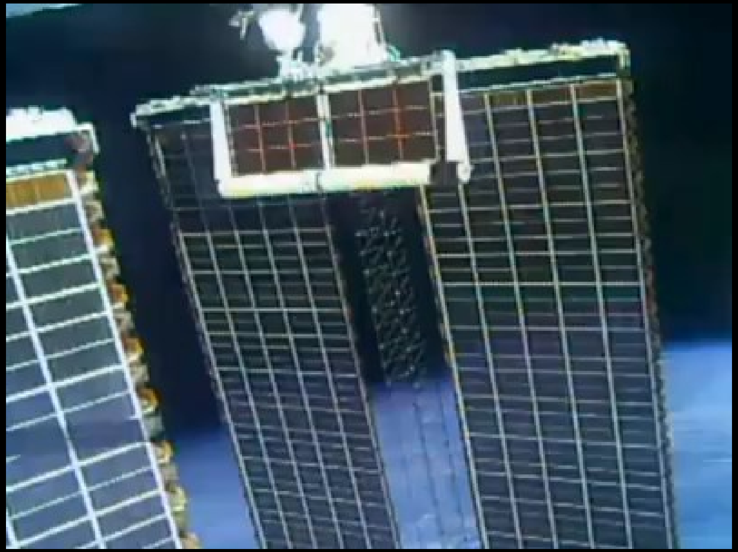




Schematic of the DART mission shows the impact on the moonlet of asteroid (65803) Didymos

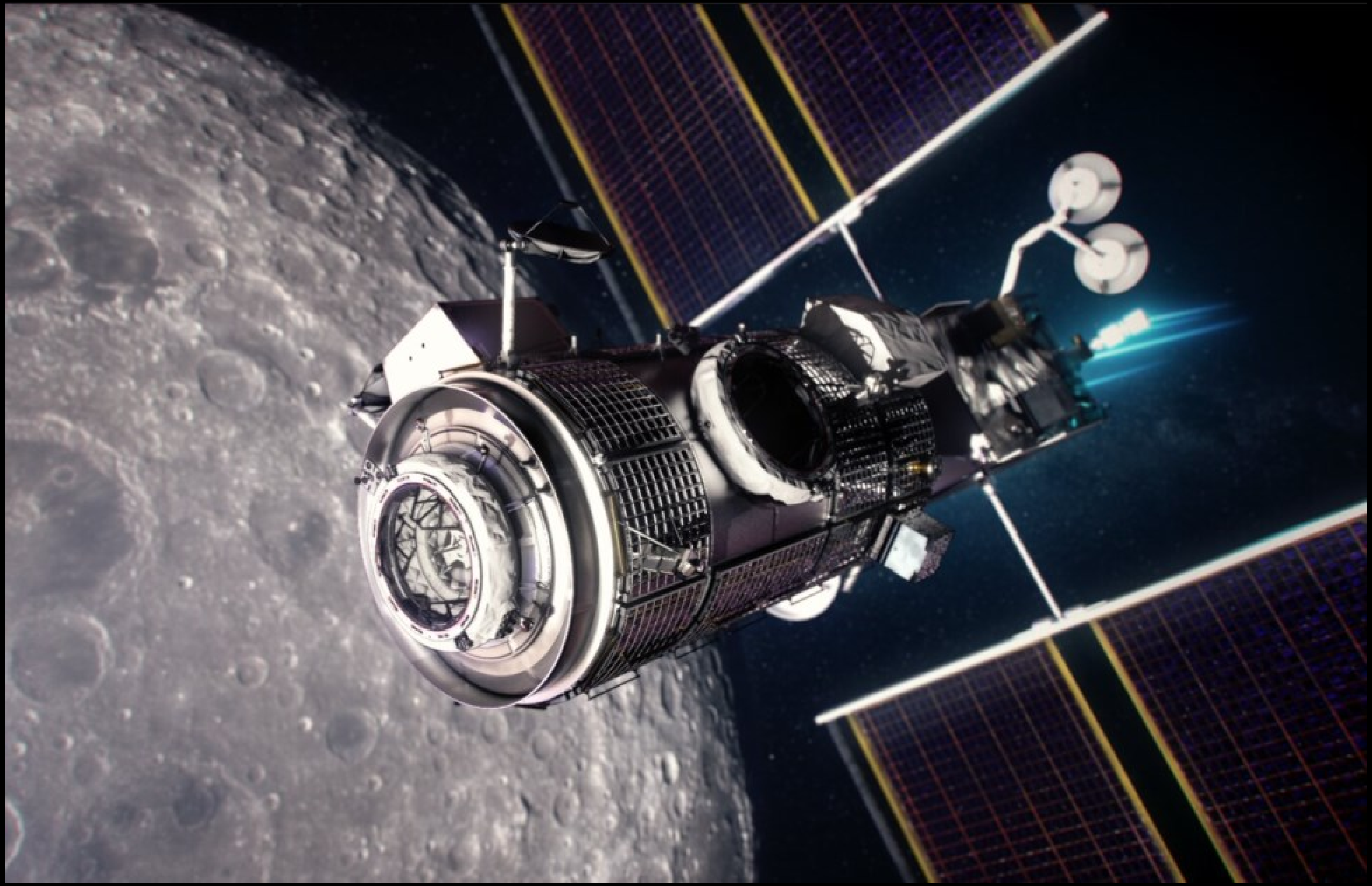
ROSA Power Augmentation to ISS

- 6 ROSA are being added to ISS to increase power production
- 2 ROSA have been installed (June 2021)
- Each new solar array is ~20 kilowatts (total ~120 kilowatts)
  - New arrays do partially shadow current arrays
- Remaining uncovered solar arrays and partially uncovered original arrays will continue to generate ~95 kilowatts of power
- New total for ISS ~215 kilowatts (215,000 watts) from ~160 kW previously



Solar Array Development – Lunar Orbit

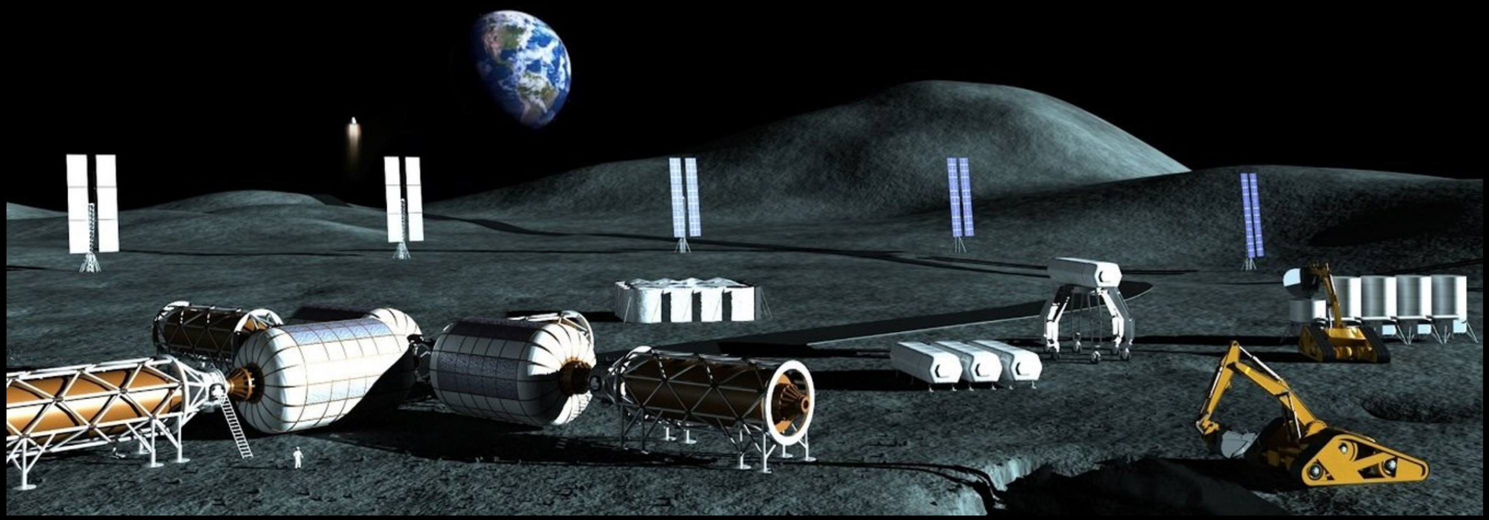
- PV Systems will be used to power many near-term lunar missions
- Gateway Power and Propulsion Element (PPE) will be powered by 2 ROSA solar arrays (50 kW class)
- Human Landing System (HLS) includes elements of photovoltaics



Vertical Solar Array Structures (VSAT)

VSAT Program Overview

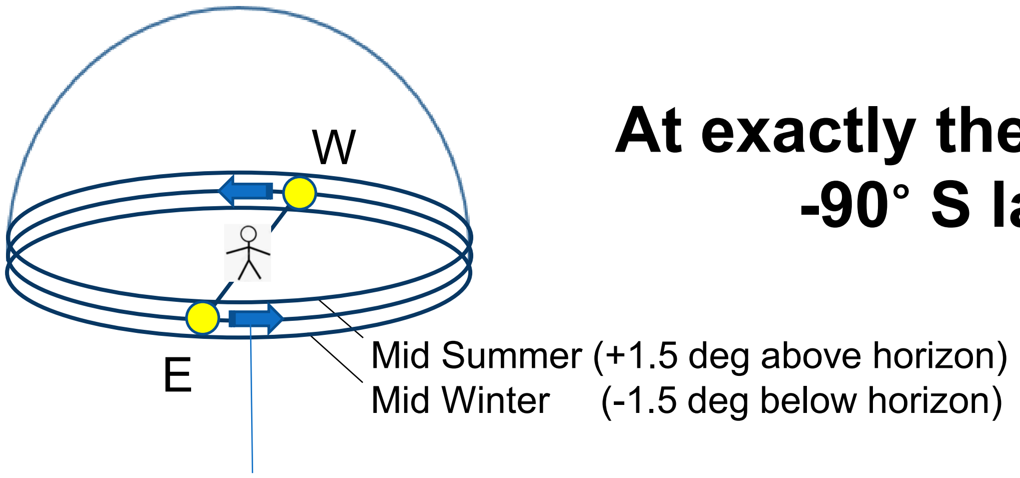
- Vertical Solar Array Technology (VSAT) for Lunar Surface
  - NASA STMD Game Changing Development program
  - Led by NASA Langley and NASA Glenn (Richard Pappa/LaRC and AnnaMaria Pal/GRC)
- Autonomous deployment, 10kW class systems
- 10 meter minimum height at bottom of the array
- Stable on steep terrain (adaptable to deploy vertically on slanted terrain up to 15 degrees)
- Resistant to abrasive lunar dust
- Minimized both mass and packaged volume for ease in delivery to the lunar surface



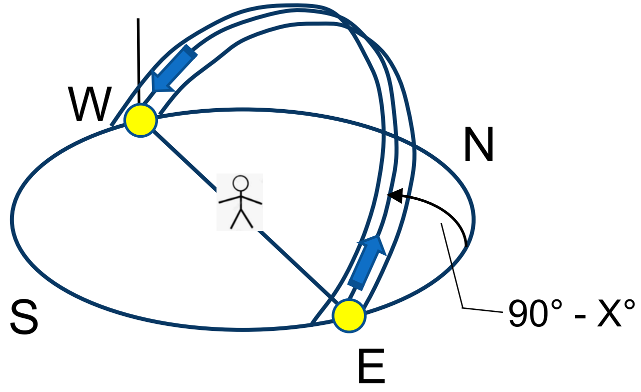
Motivation

- Lunar polar locations are of high interest for many NASA missions due to potential for ice and materials in permanently shadowed craters

- Moon's rotation is slow, approximately 1 rotation every 29.5 Earth days
- Moon's equatorial plane is tilted by only 1.5°
- Locations exist that can have long durations of illumination with minimum shadowing (down to <100 hours) at high elevations



At exactly the South Pole, -90° S latitude



In general, at -X° S latitude, Sun paths tilt up by 90° - X°

For example, at -88° S latitude, Sun paths tilt up by 2°

Motivation

Sun Paths at an Elevated Site Near the South Pole (Movie)

At Mid-Summer

At Mid-Winter

video shows 1 full lunar day

Provided by James Fincannon, GRC

Initial (Base) Phase

Base period contracts, valued at up to $700,000 each, awarded as 12 - month fixed price contracts to:

- Astrobotic Technology, Pittsburgh, PA
- Northrop Grumman (ATK), Goleta, CA
- Honeybee Robotics, Brooklyn, NY
- Lockheed Martin, Littleton, CO
- Maxar Technologies, Palo Alto, CA

Contracts started in Spring 2021 to further system design, perform initial testing and modeling and prepare plans for Option Phase which includes scaled hardware testing

Plan was to down select up to two companies and provide additional funding, up to $7.5 million each, to build prototypes and perform environmental testing

Option Phase

Option Phase Award was announced on August 23, 2022. https://www.nasa.gov/press-release/three-companies-to-help-nasa-advance-solar-array-technology-for-moon

3 Companies selected to go forward to build hardware for environmental testing

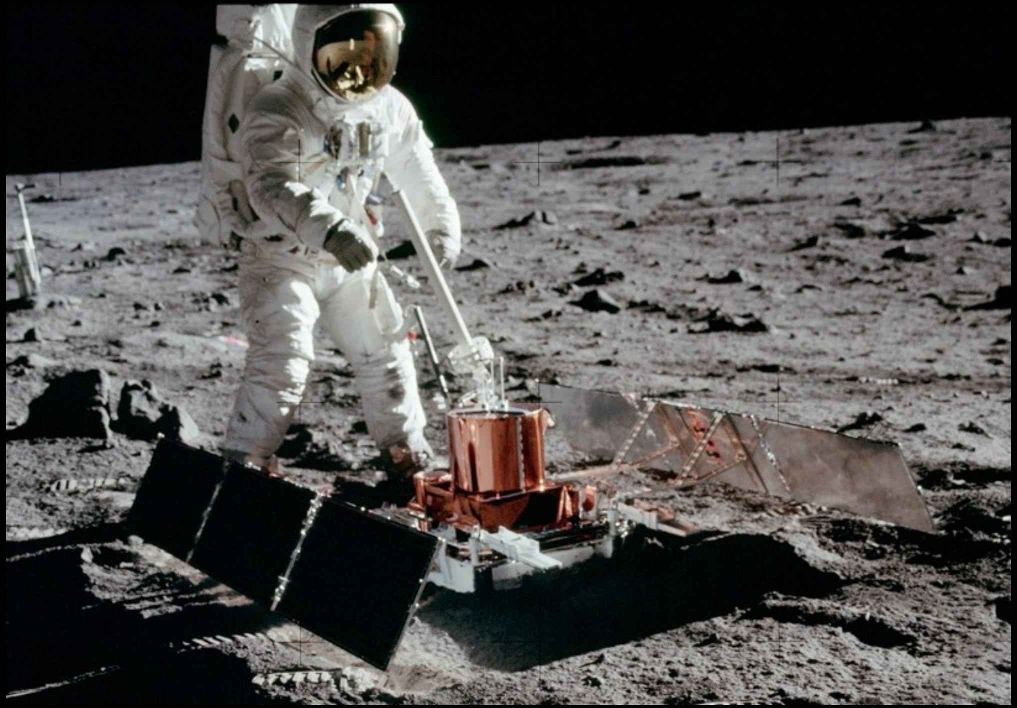
- Astrobotic Technology of Pittsburgh, Pennsylvania: $6.2 million
- Honeybee Robotics of Brooklyn, New York: $7 million
- Lockheed Martin of Littleton, Colorado: $6.2 million

Projects will start soon with thermal vacuum testing planned for early 2024

Photovoltaic Investigation on the Lunar Surface (PILS) – PV Testbed for Lunar Landers

Background

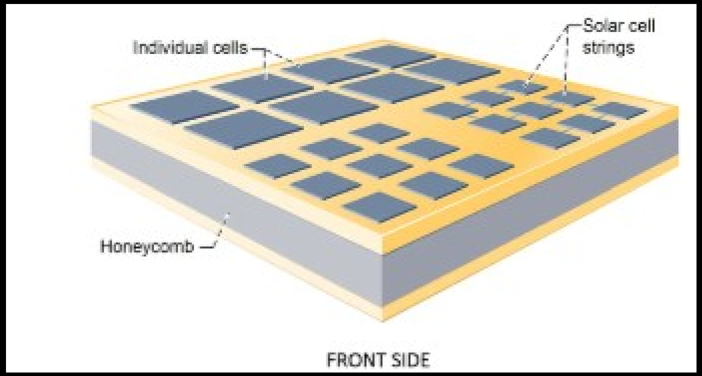
- Photovoltaics and solar arrays have provided reliable power to spacecraft for over 50 years and will enable long duration missions on the lunar surface
- Solar cells have been used on the lunar surface in the past but the technology has matured significantly
- There is still a lot unknown about the energized environment of the lunar surface and how it would impact high voltage solar arrays
- The Commercial Lunar Payload Services (CLPS) program supports Artemis with commercial deliveries to perform science experiments, test technologies and demonstrate capabilities to help NASA explore the Moon and prepare for human missions
- Many of the CLPS providers plan to use photovoltaics to power their spacecraft

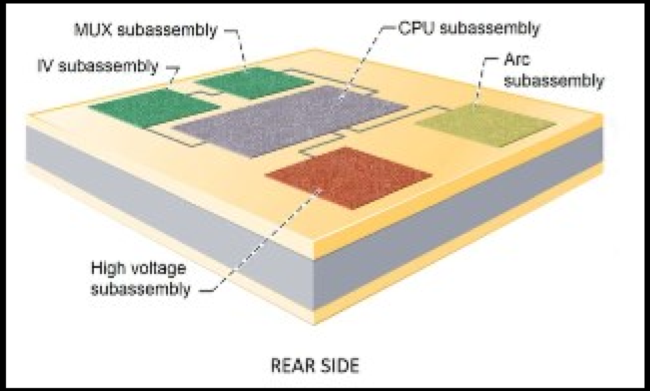


Solar arrays on the Apollo 11 Seismic Experiment

Background

- PILS team responded to a CLPS program call in late 2019 to provide readily available (requiring minimal tech development) payload packages for integration onto future landers
- The team proposed a photovoltaic test-bed to measure electrical performance of state of the art and next generation solar cells, and to measure the charge build up on a small solar cell array
- The concept was based off a heritage Materials on the International Space Station Experiment (MISSE) solar cell flight test platform





- Selected by Astrobotic, which will launch its Peregrine lander on a United Launch Alliance Vulcan Centaur rocket, along with 10 other NASA payloads
- Landing at Lacus Mortis for a lunar day long mission (approx. 10 Earth days)

Prior ISS Solar Cell Experiment

Lacus Mortis circled in Red

Mission Objectives

Technical Objectives

- Successfully deliver flight hardware to Astrobotic for integration onto the Peregrine Lander
- Do not exceed mass, power, size restraints
- Do no hard to the lander or other payloads
- Increase the TRL of solar cells and measure charge accumulation on an array of solar cells

Science Objectives

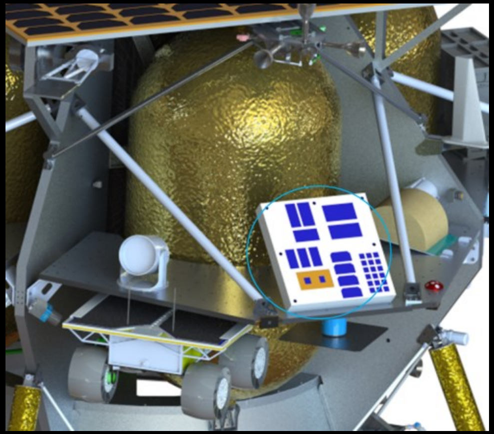
- Science objective 1: Determine performance and health checking of SOA and Next gen solar cells and terrestrial silicon cells over a lunar day. Perform I-V and temperature measurements for each cell regularly throughout mission
  - The cells are not under load (*"powered"* or *"powering anything"*) when not scanning an I-V curve
- Science objective 2: Measure the localized charging environment on a small solar array by collection of charge deposited on solar cell cover glass
  - Charging environment influenced by local neutral plasma.
- Bonus: get data in transit to the moon

Design Concept and Requirements

- Dimensions: 30 x 30 x 4cm (without mounting brackets)
  - Designed to be mounted in multiple configurations (through bracketry) based on landing site and lander design
  - Capped mass at 4.5 kg
- Requires approximately 2W for solar cell and charging experiment. Designed to use additional power for heaters during cruise phase
- Team designed PILS platform to accommodate interfaces with the Peregrine lander in terms of power, communication, mounting, environmental concerns

Early rendering of Peregrine

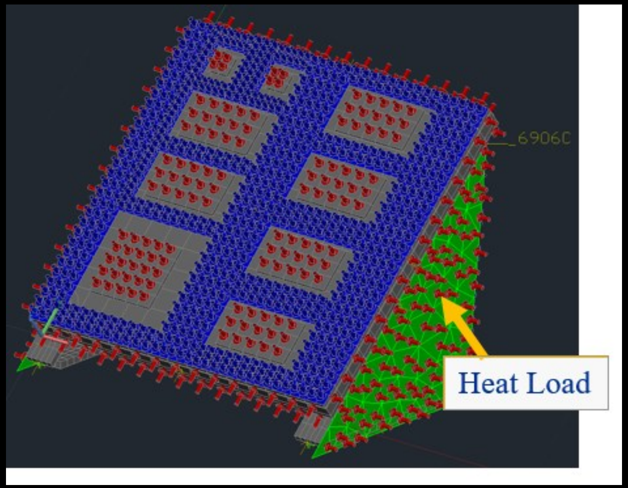
PILS Mock Up Based on Initial Concept



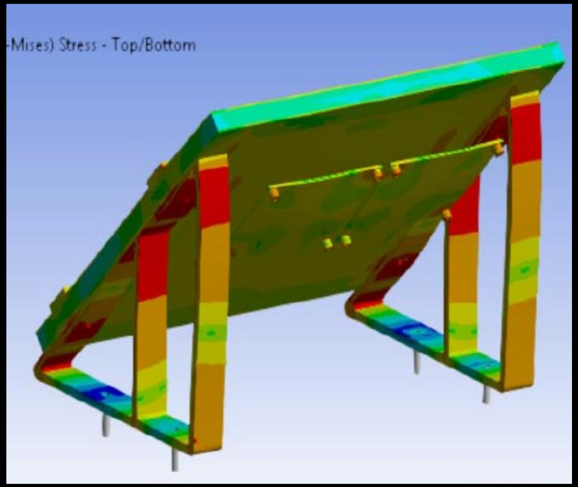
Rendering of PILS mounted on an early Peregrine design

Design Considerations – Lessons Learned

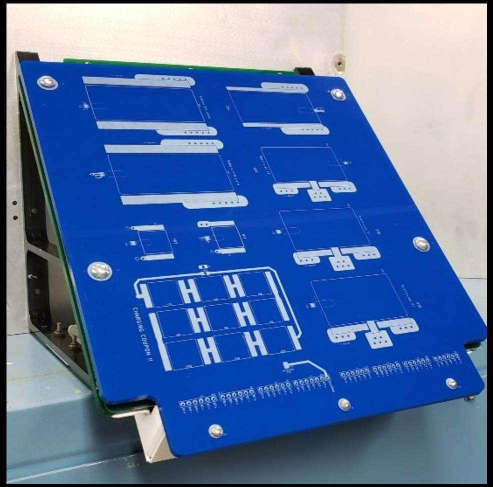
- Initial concept used solar cell high altitude flight calibration holders but they added significant mass. Found a solution to use a single circuit board type top surface to mount the solar cells
- During early design the launch loads were not well known which presented a challenge to design the platform to be lightweight but still robust. Multiple iterations were considered and modeled to get to the final design.
- The thermal environment turned out to be our largest environmental driver. Challenge to keep the electronics warm during transit to the moon and to keep them cool while on the surface during the lunar day. Found solutions with multilayer insulation and thermal tape.
- Built scaled mock-ups of the platform to better understand interfaces and clearances



PILS Thermal Analysis Model



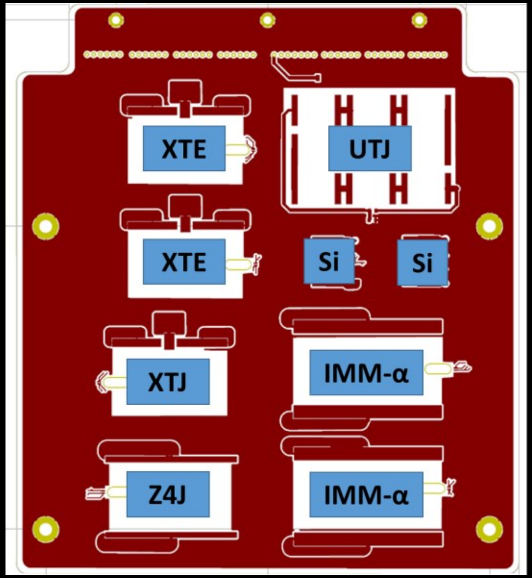
PILS Structural Analysis Model

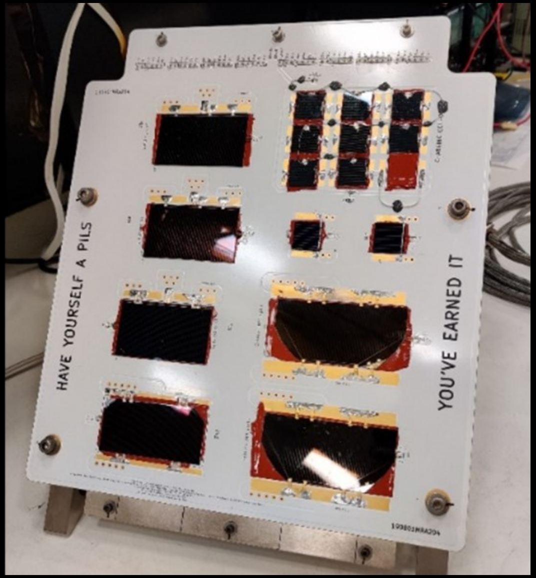


PILS Platform High Fidelity Mock Up

Solar Cell Manifest

- (1) 4x8 cm SolAero Z4J, triple junction III-V
- (1) 4x8 cm SpectroLab XTJ prime, triple junction III-V
- (2) 4x8 cm SpectroLab XTE-SF triple junction III-V
- (2) 4x9 cm SolAero IMM alpha 5 junction III-V
- (2) 2x2 cm ASU Silicon Heterojunction Intrinsic Thin Film (HIT)
- (8) 2x2 cm Spectrolab UTJ triple junction III-V with ITO coated connected coverglass for Surface Charge Experiment



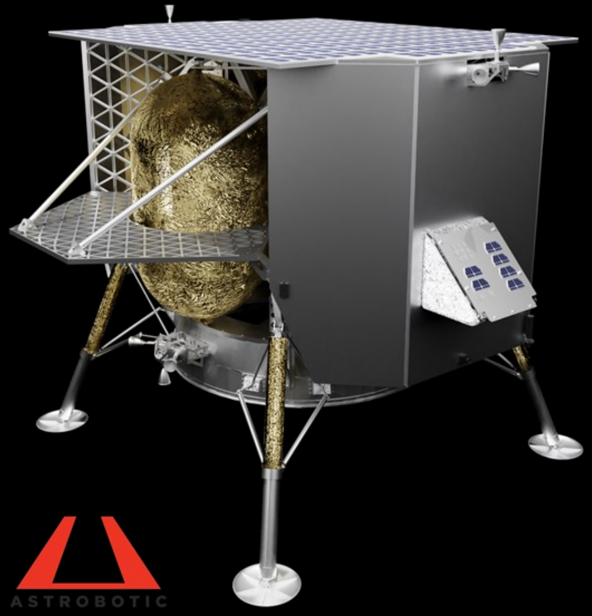


Surface Charge Experiment

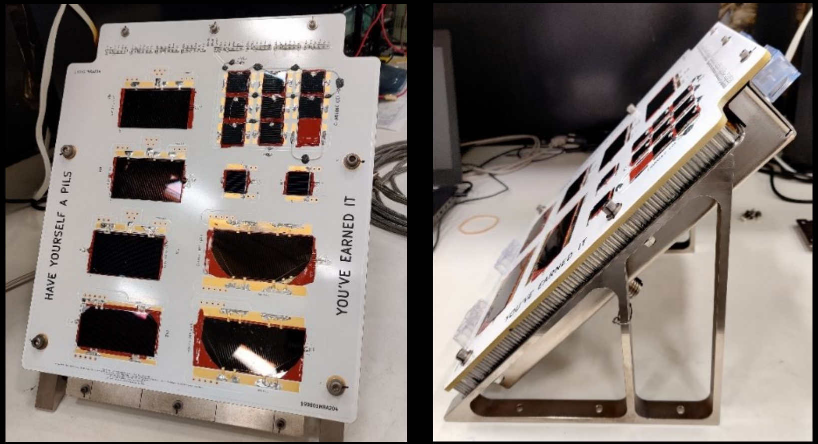
- 2x2cm UTJ solar cells strung in series and shorted through a burden resistor which sets a bias potential from 0V to 18V
- Maximum current is approximately 100mA, not enough for secondary arcing under any voltage.
- Solar cell coverglass coated with <100kOhm/sq ITO to bleed charge, but the charge is isolated by high dielectric constant encapsulant
- Wires are soldered to coverglass to short all surfaces and connect to large series resistor
- Back-end of resistor to be fed to plasma monitoring measurement board

Finalizing Design

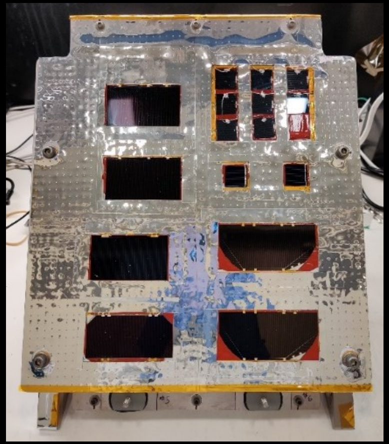
- Astrobotic made a configuration change to the lander, adding walls to two sides
- PILS was now cantilevered off the wall and exposed to additional thermal conditions from the lunar surface
- Software and hardware designs were locked, build and assembly began
- Benchtop testing with Astrobotic payload simulator occurred
- Environmental testing occurred (thermal, vibe, EMI)



Software/Hardware Checkout



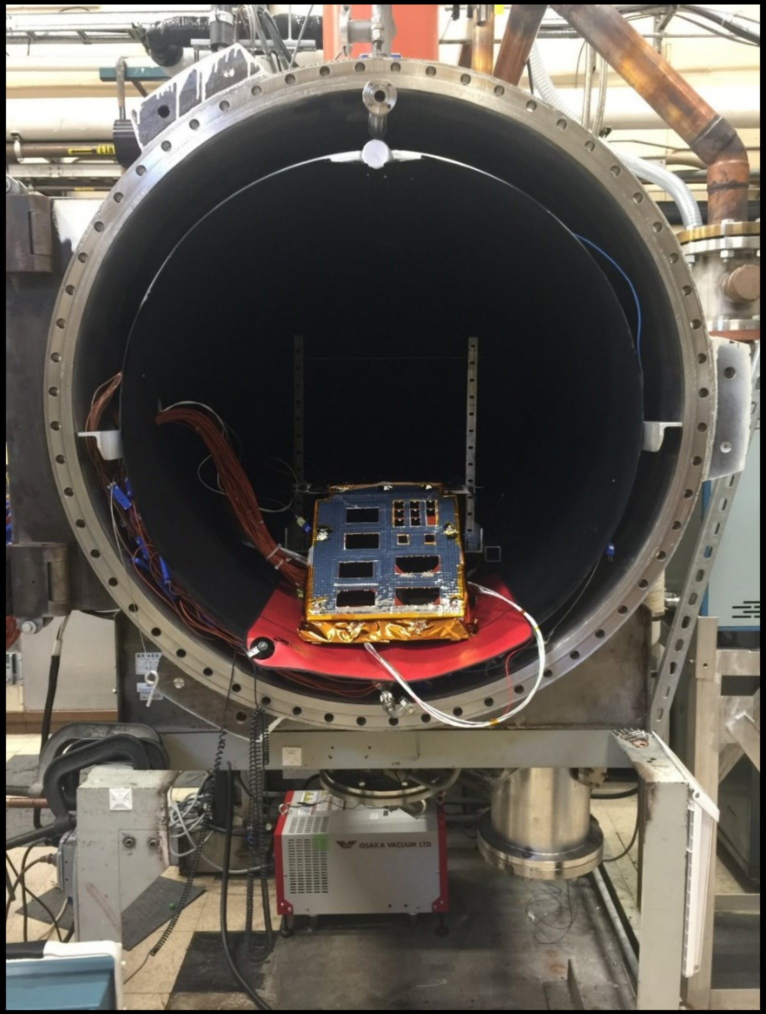
Assembled PILS Flight Unit



Assembled PILS Flight Unit with Thermal Tape Applied to Top Surface

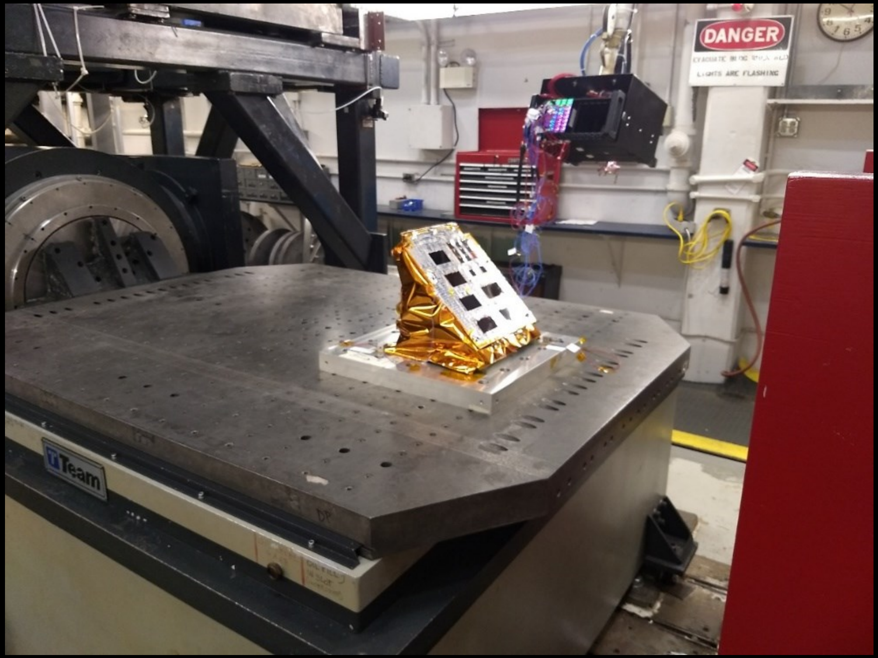
Thermal Testing

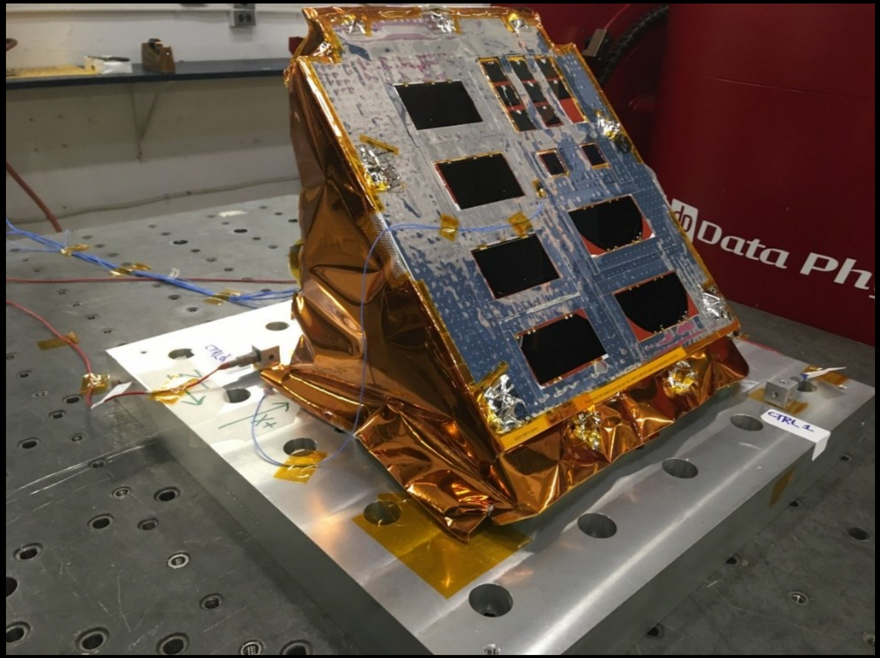
- Testing to ensure survival and operation at expected temperature extremes
  - Range from -40 C to 80 C
- Tested performance in a horizontal vacuum chamber outfitted with a liquid nitrogen cold wall.
- Platform was illuminated by a Spectrolab X25 solar simulator outside the chamber through a quartz window
- Operation was verified through 4 thermal cycles with a cold start performed during the final cycle. The platform operated successfully throughout the tests.



Structural/Vibe Testing

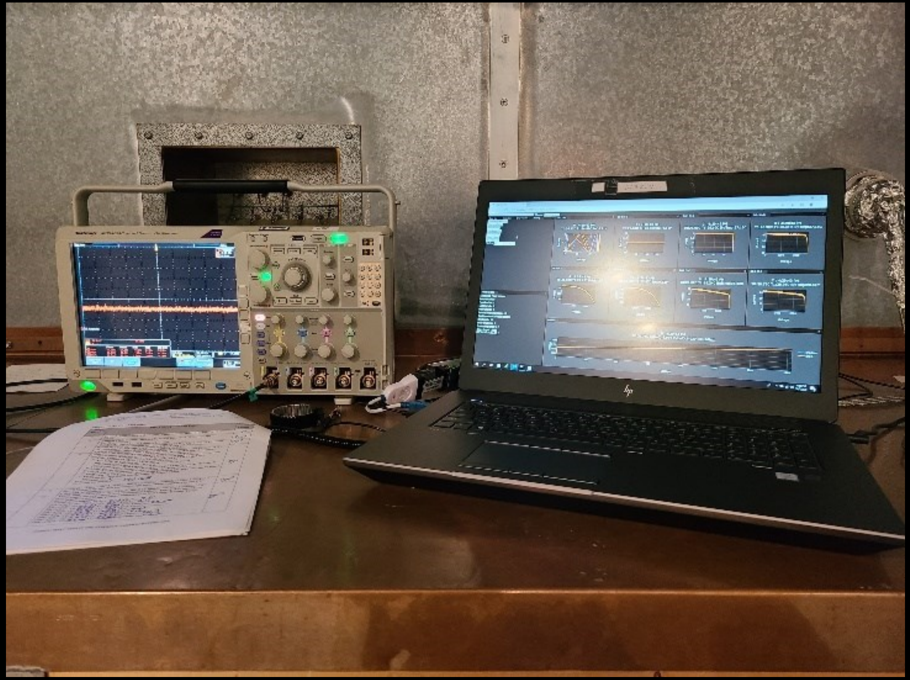
- Modal and structural analyses were performed on the platform to meet the “do no harm” requirement and to ensure that it would survive launch
- The flight hardware was tested in the GRC Structural Dynamics Laboratory under random vibe
- Functional testing was performed pre and post vibe. There was no change in performance and no damage occurred





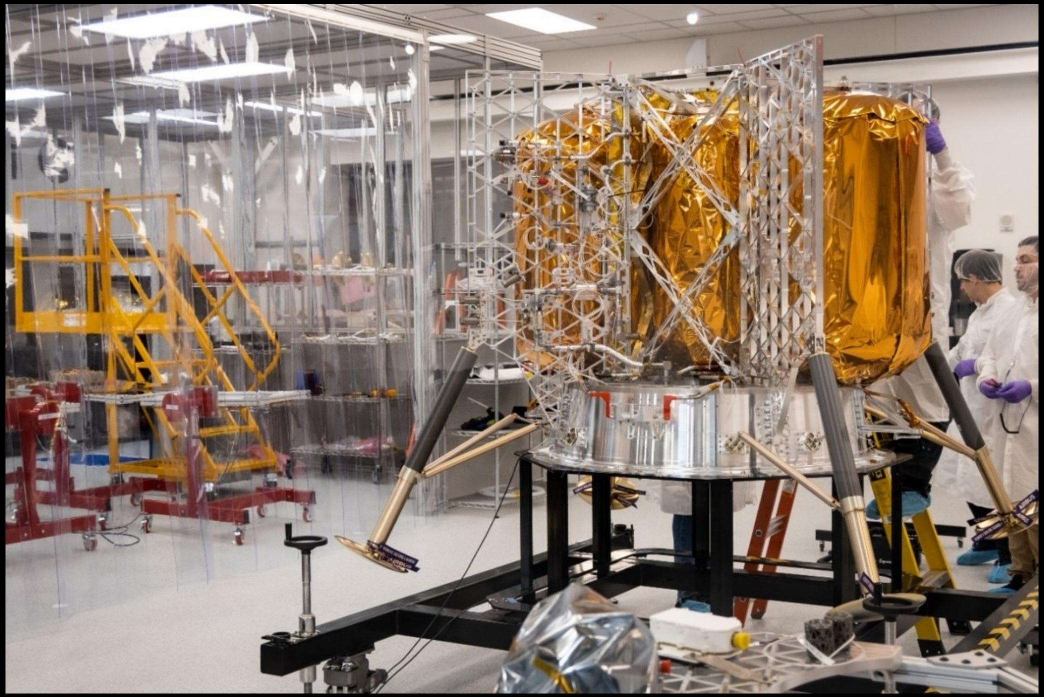
Electromagnetic Interference Testing

- Testing was required to ensure PILS was not susceptible to external electromagnetic signals and that it was not emitting any signals that could interfere with the lander or other payloads
- The hardware was tested following MIL-STD-461G
- Ground software for monitoring performance was ran on a computer in an isolated facility to ensure no loss in communication or data quality
- Hardware passed EMI requirements



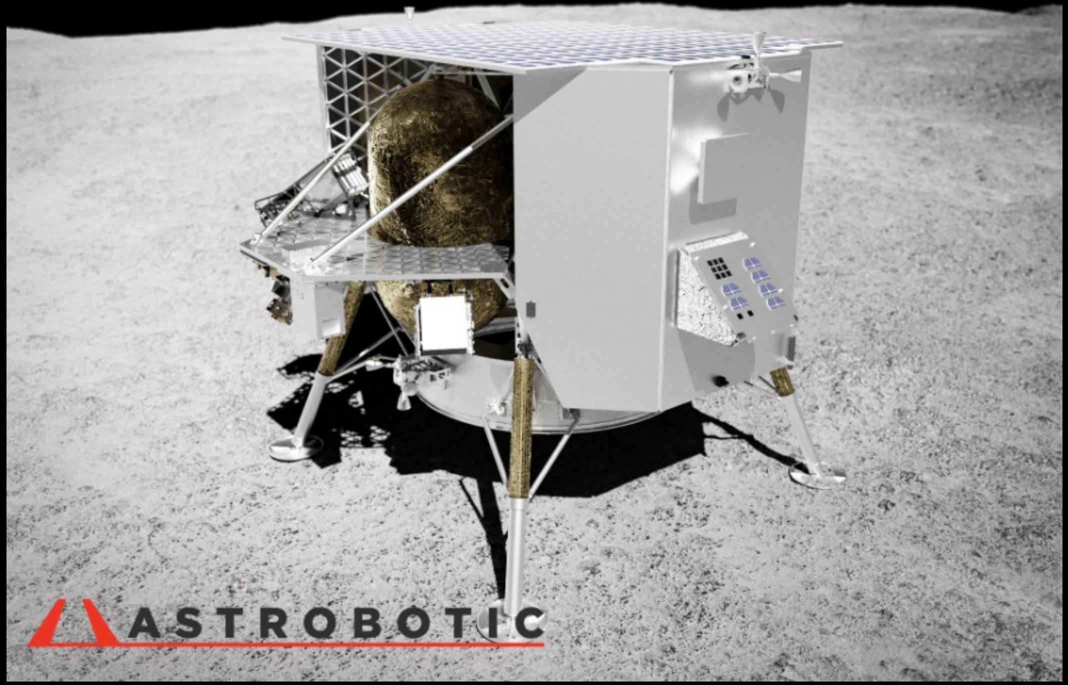
Integration

- PILS was shipped to Astrobotic in December 2021 and physically integrated onto the sidewall panel in January 2022
- Astrobotic continues to build Peregrine and the PILS panel is expected to be integrated onto lander in late August (physical and electrical integration followed by functional testing)
- Peregrine will go through environmental testing where PILS will be functionally tested after major tests



Next Step: To the MOON!

- Peregrine will launch on the United Launch Alliance Vulcan Centaur and head to the moon
- The PILS team will monitor hardware performance and collect data from shortly after launch through the end of the lunar surface phase of the mission
- After the mission is completed, the team will report out on performance of the hardware, the cells (I, V, temperature), and of the charge accumulation on the small array
- The team is interested in a possible PILS-2 (and beyond) at different locations on the lunar surface and with different cell technologies



Summary

- Improving cell technology performance while reducing cost and mass is of interest to NASA and GRC
  - Much of this work is performed through University and SBIR contracts
- Ground testing
  - Facilities at GRC are being upgraded to allow for larger samples with more junctions
  - Working with Flight Provider Firms to investigate small balloon PV cell measurement platforms
- Solar array development
  - Meeting NASA's future needs for solar cells and arrays for unique missions
  - Adaptability and modularity are important aspects being considered
- Flight Programs
  - Testing cells and materials in space to raise the technology readiness level for use in future missions
  - Looking for collaboration opportunities to fly/test different technologies