‘It’s Only a Paper Moon…’

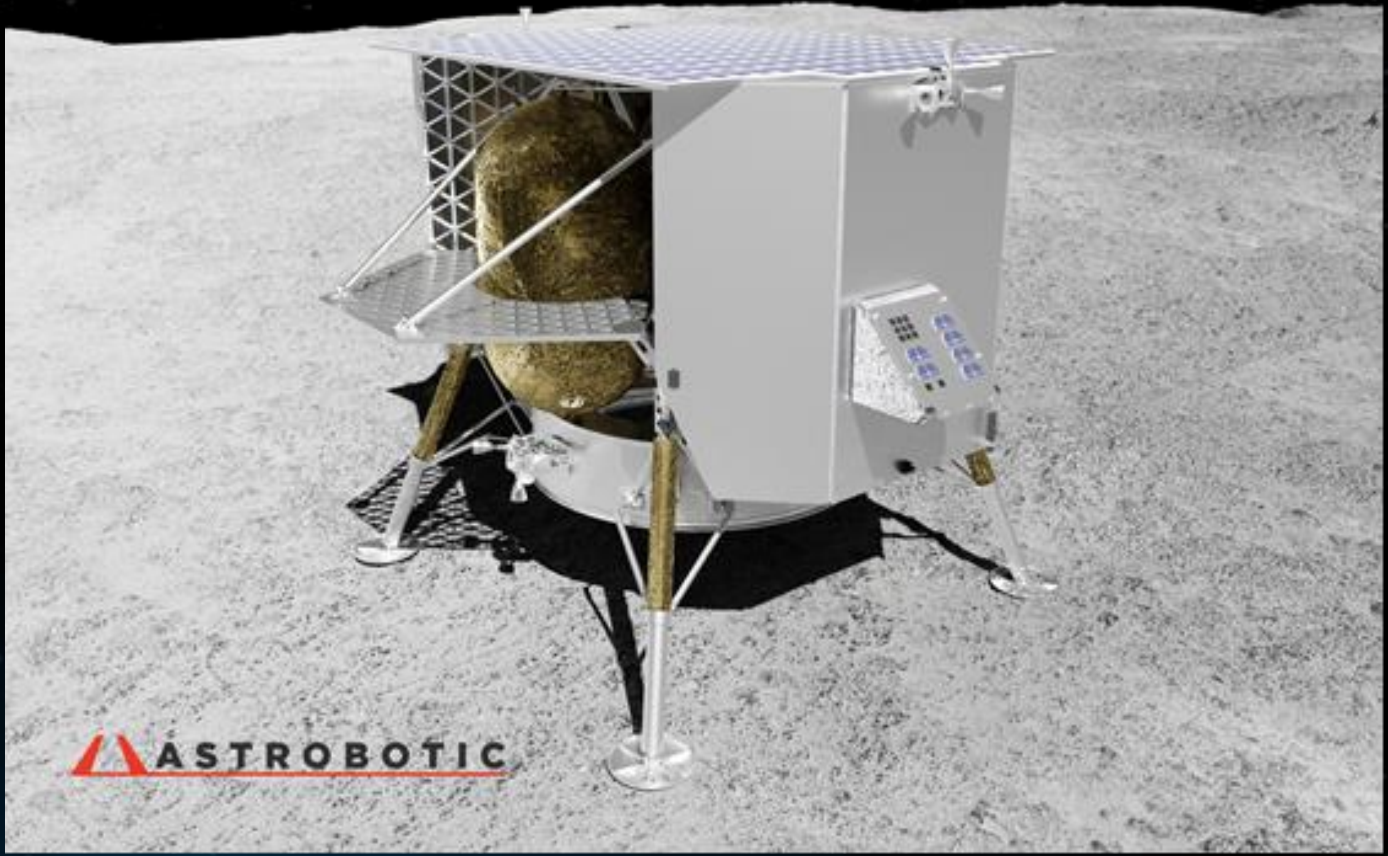
Or: meet me in Cleveland, so we can put something on the lunar surface

National Aeronautics and
Space Administration

Dr. Timothy Peshek, Research Electrical Engineer
NASA Glenn Research Center
Friday, March 12th, 2021

Photovoltaic Investigation on the Lunar Surface (PILS)

- Make this a reality…



Outline

- ‘It’s only a paper moon…’ – PILS, documentation, and how I’m a changed researcher.
- ‘Sailing over a cardboard sea…’ – the plasma environment in space, space isn’t a great *void*
- ‘But it wouldn’t be a make believe…’ – The need for low cost space PV
- ‘If you believed in me…’ – making thin film perovskites work.

It’s only a paper moon

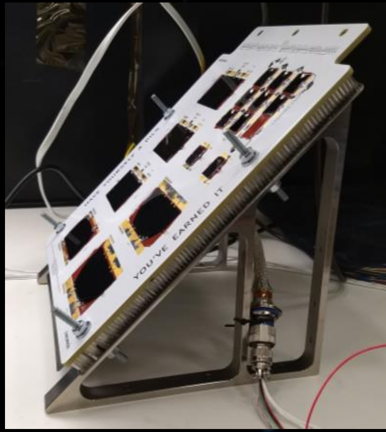
Background:

- PILS proposed to Lunar Development Exploration Program (LDEP) call
- LDEP sought mature payloads for first group of commercial lunar landers
- Selected by LDEP as one of 12 NASA payloads
- Then selected by Astrobotic (AB), target landing late 2021

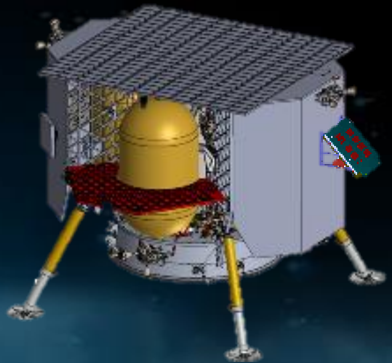
Classified as a “do no harm” payload (no impact on lander success or failure)

Summary:

- Lunar surface demonstration and validation of select *solar cells* and a *solar array equipped with NASA-developed plasma charging measurement circuitry*
- Solar cells include state-of-the-art, next-gen, and thin-film
- Heritage on “Materials on the International Space Station Experiment” (MISSE) solar cell flight test platform
- Dimensions: 30 x 30 x 4cm (without mounting brackets)
- Budget: $1.58M FY19-22
- Delivery: November 2020

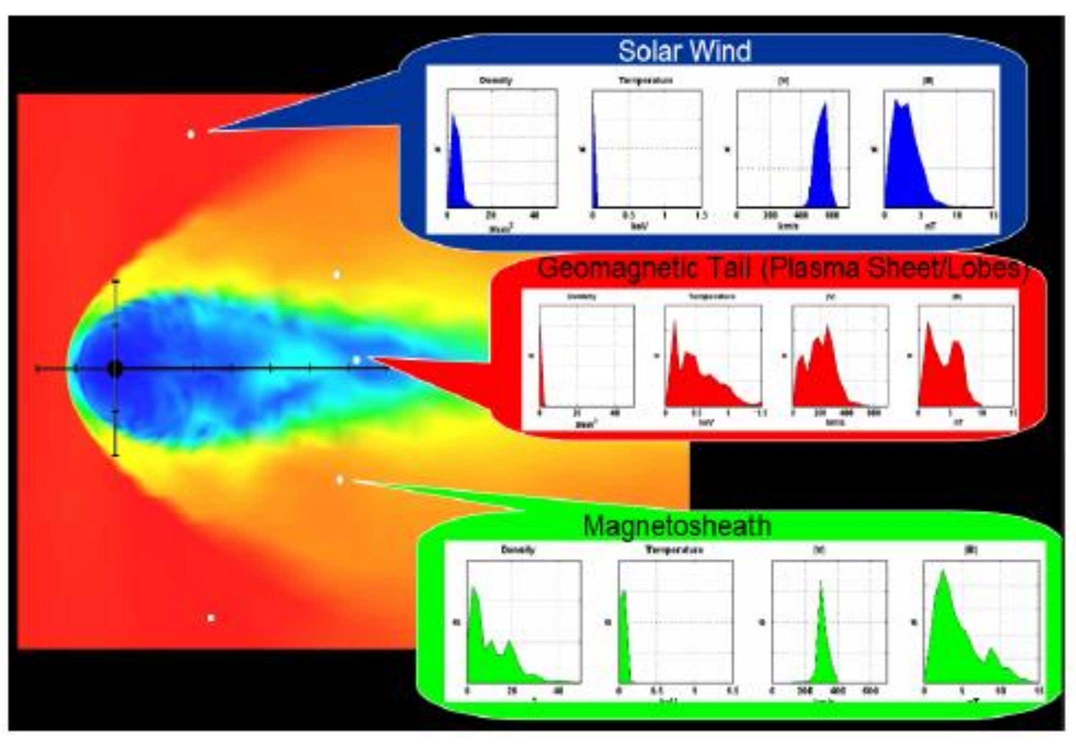


PILS before
MLI Installation



PILS Objectives

1. Determine charge buildup on solar arrays and arcing hazards in the lunar environment
   - Characterize charging phenomena on lunar surface
   - Mitigate risk for future high voltage solar arrays on the moon
2. Enhance existing models for future power generation systems
   - Refined & higher fidelity simulations on ground
   - Allow more accurate simulated plasma interactions
   - Measure plasma properties for ground-based simulation, arc threshold, and damage rate
3. Shape design rules for large solar arrays on the lunar surface
4. Increase TRL of cells and arc detection capability



Plasma environments the moon passes through. This illustrates a highly variable environment that also does not include secondary electron emission from the lunar surface regolith

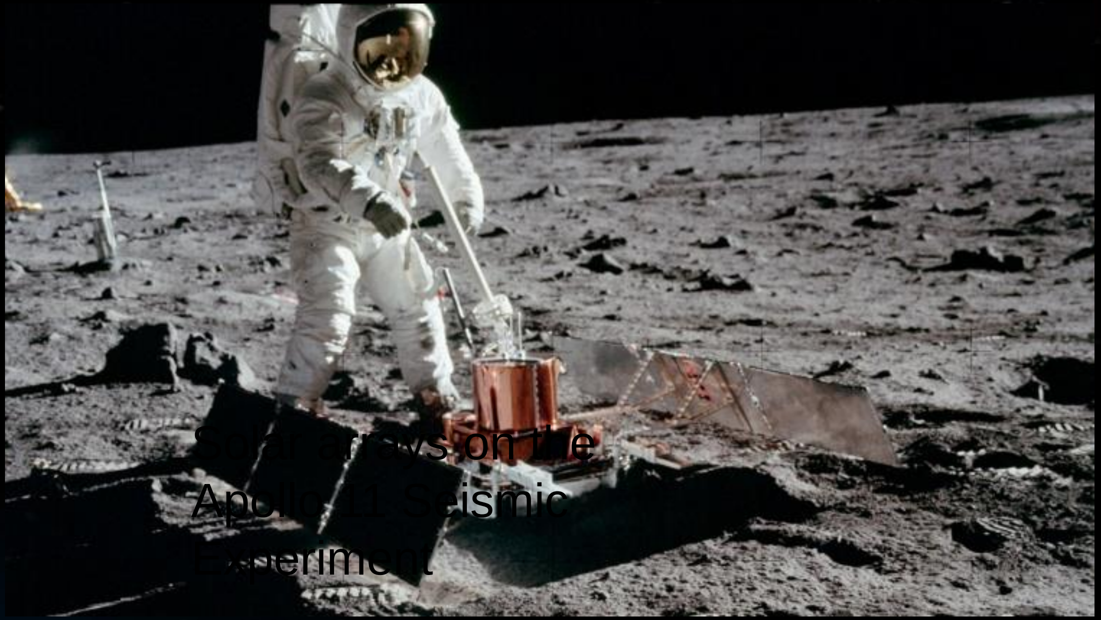
Proposal Process (1 of 2)

PIs (McNatt/Peshek) responded to a Request for Payloads (RFP) for the Development of NASA Provided Lunar Payloads (NPLP) requesting:

- *Description of the payload capability and development approach*
- *Milestone date for delivery of detailed payload data package including:*
    - *Expected payload flight mass*
    - *Launch, acoustic, and shock load limits*
    - *Thermal conditioning requirements*
    - *Communication interfaces (e.g. wired/wireless, interface ports), volume, bandwidth)*
    - *Power requirements (e.g. nominal, peak, power conditioning, pin configuration)*
    - *Mechanical interfaces (e.g. thermal isolation, bolt-hole pattern)*
    - *Optical sensitivities (e.g. dust, chemicals, line-of-sight needs)*
- *Milestone date for hardware delivery to commercial lander provider*
- *Flight hardware development cost and schedule*
    - *Describe resource-supported milestones including critical design (pre-fabrication) review*
    - *Describe the cost to support integration with the commercial Lunar lander*
    - *Describe the cost to support mission operations and data analysis*
- *Describe the specific risks to cost and fabrication/testing schedule?*
- *Include a science statement relating the payload’s science capabilities to SMD, HEOMD, and/or STMD objectives including reference to SKGs or decadal science questions*

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
- Payload was awarded in March 2019, due in November 2020 (Rapid!)
- Selected by Astrobotic for CLPS-1 in June 2019
- Headed to the moon in Q4 2021



Solar arrays on the Apollo 11 Seismic Experiment

PILS Design Concept

- Heritage on “Materials on the International Space Station Experiment” (MISSE) solar cell flight test platform
- Dimensions: 30 x 30 x 4cm (without mounting brackets)
  - Designed to be mounted flat (without brackets) and scaled in size if testing less cell technologies (adaptable for multiple lander platforms and footprints)
  - Capped mass at 4.5 kg for AB design
- Requires approximately 2W for solar cell and plasma charging experiment. Additional power may be needed for heaters during cruise.
- Team designed PILS platform to accommodate interfaces with the AB lander in terms of power, communication, mounting, environmental concerns
- Solar cells include state-of-the-art (qualified and regularly used), next-gen (in-qualification and have had little in-space use), and thinned silicon (a low cost terrestrial technology)

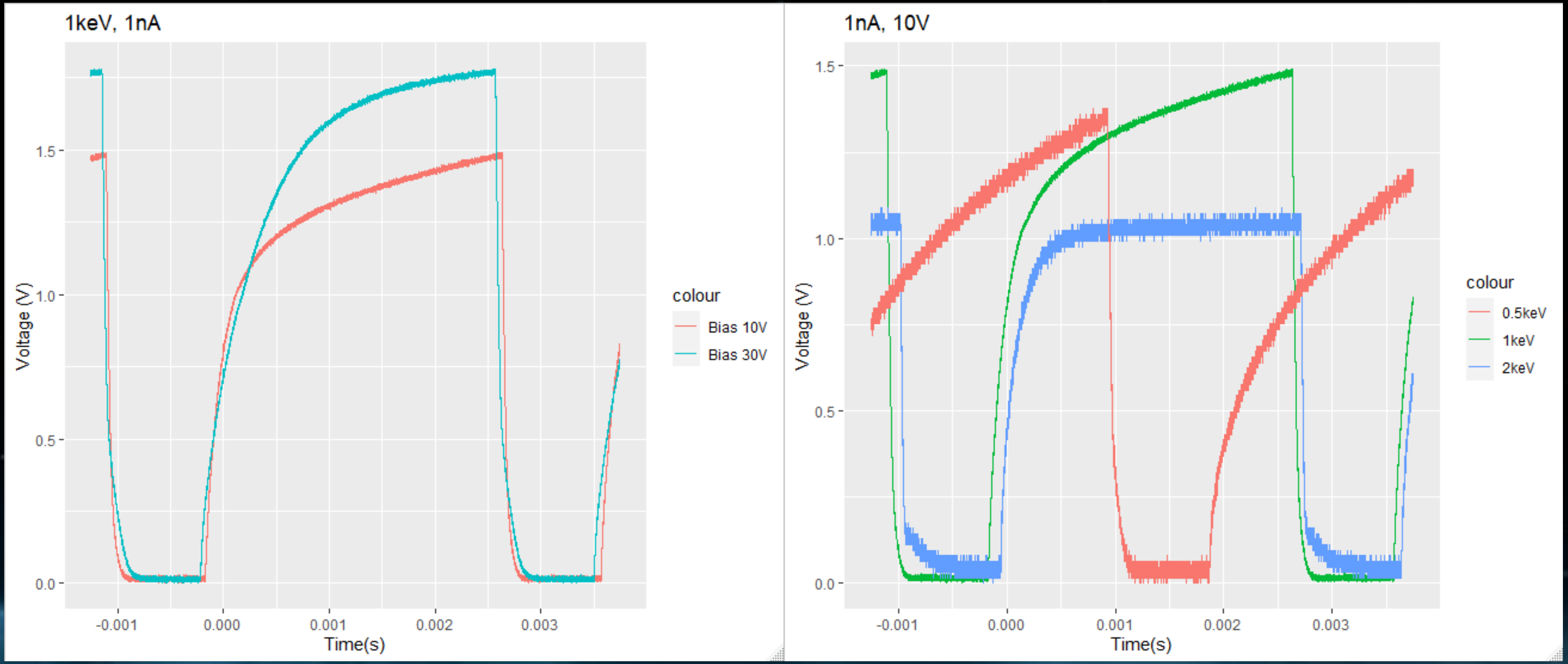
Robotic Refueling Mission (RRM) Solar Cell Experiment on International Space Station designed from MISSE Heritage hardware and experience

Construction of Charging `Sensor’

- Built per document: PILS-PRO-110-10
- Document written to mimic test design. Design needs:
    - triple junction solar cell materials, silver gridlines and interconnects
    - coverglass with ITO, no AR coating
    - Electrical contact to ITO
- Needed to source uncoated coverglass, ITO deposition at CWRU.
- Electrical contact to ITO with Indium solder (alloy content dependent on thermal model)
- Contact lead copper or Ni-clad copper only (No Ag or Au)
- Test article was constructed and subjected to testing in accordance with ISO 11221: 2011
- Test data fulfills requirement: PILS-REQ 3.2.1-3

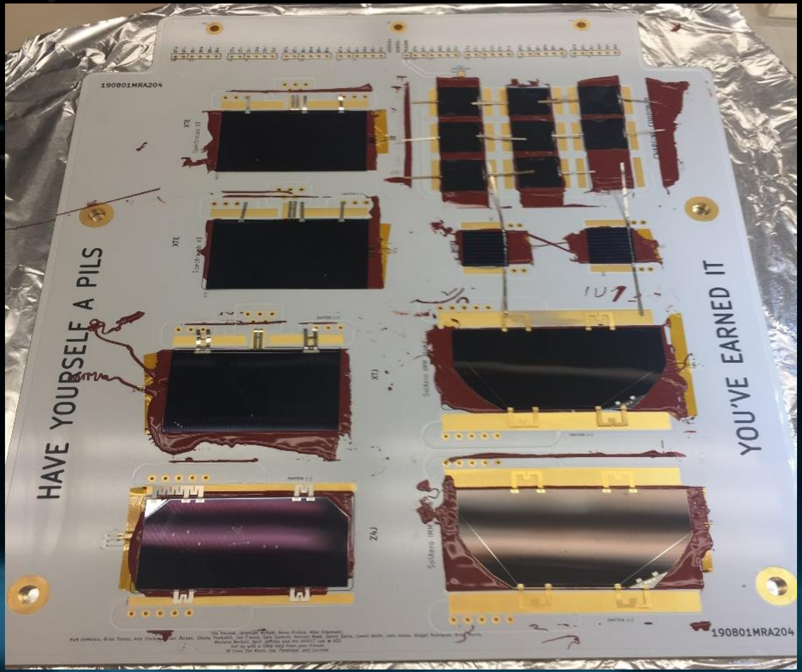
Charging circuit test data

- In accordance with ISO 11221
- Placed in VF21, irradiated with electron gun 0.5-3 keV, 1 nA/cm^2 irradiance
- See proper function for 4 cell test article, bias on array determines efficacy of current collection. Data are in agreement with faraday cup.



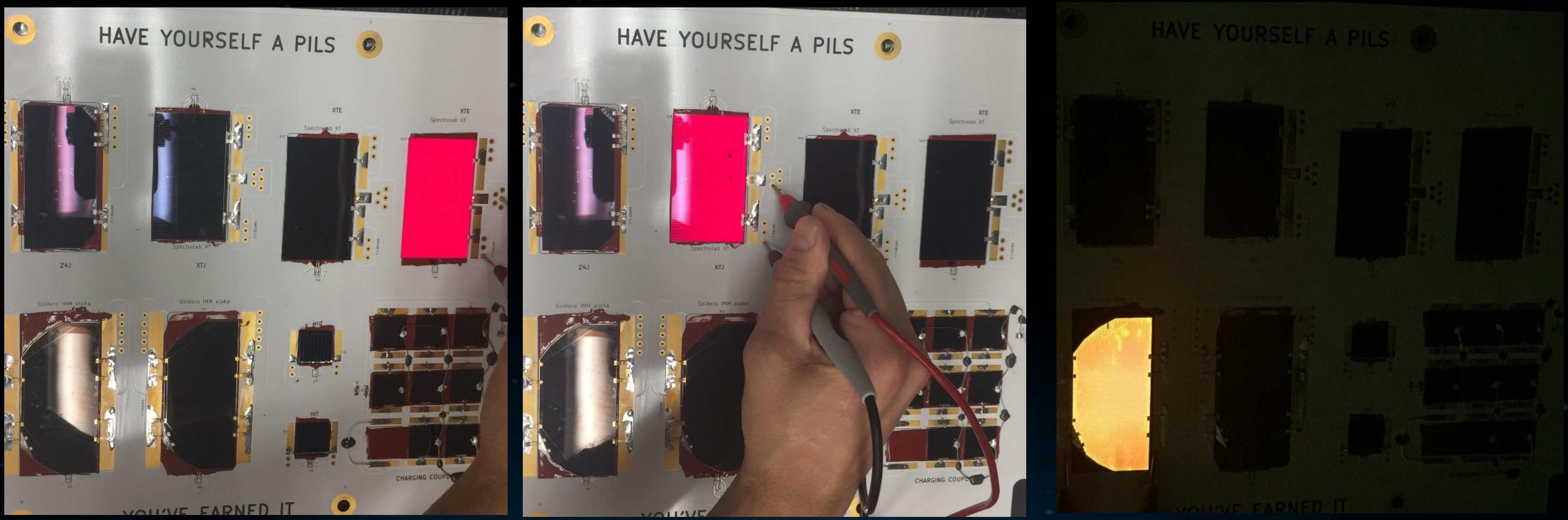
Frontsheet Assembly

- Frontsheet designed and procured from Advanced Circuits (AS9100)
- Built per document PILS-PRO-110-03, including laminating all solar cells, soldering all solar cells, and resistors to charging array to define voltages.
- After procedure complete, solar cell functional checkout performed per PILS-PRO-110-08



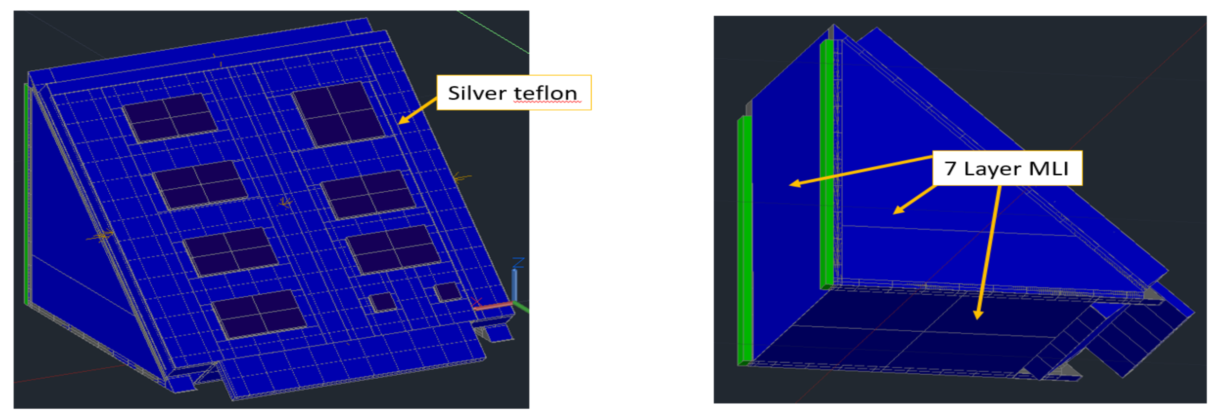
Solar Cell Checkout

- Performed according to PILS-PRO-110-08
- Due to COVID-19 mandatory telework, unable to get maintenance on X25 solar simulator for AM0 spectrum.
- Alternative characterization performed including electroluminescence imaging

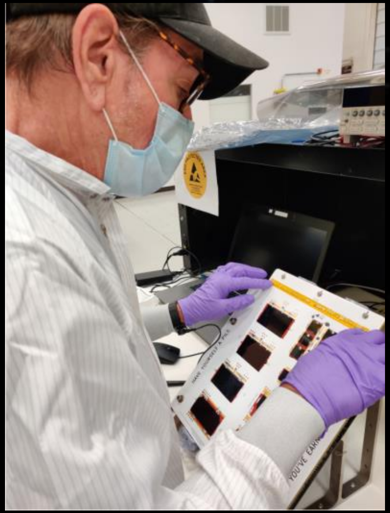


Thermal Analysis

- Thermal Analysis Report: PILS-RPT-133
- Analyses conclusion:
  - All critical components (internal PCBs) will be within survival temperature limits (-55C to 150C) throughout the mission, considering proto-flight margins from SMC-S-016. [Meets SRD 3.2.3-2 requirement]
  - All critical component (internal PCBs) will be operational within temperature limits of -40C to 85 C considering proto-flight margins from SMC-S-016. [Meets SRD 3.2.3-3 requirement]
  - All components are found to be within operational limits throughout transit. Require 5.9 Watts of heat at most upon landing on the lunar surface. (Sized with 25% margins from SMC-S-016)
  - Known risks: silver teflon tape
    - This tape on the Front sheet is predicted to be 1 C past its survival limit at lunar noon. However, this poses minimal risk to the mission objectives as described in deviation # PILS-D-004.

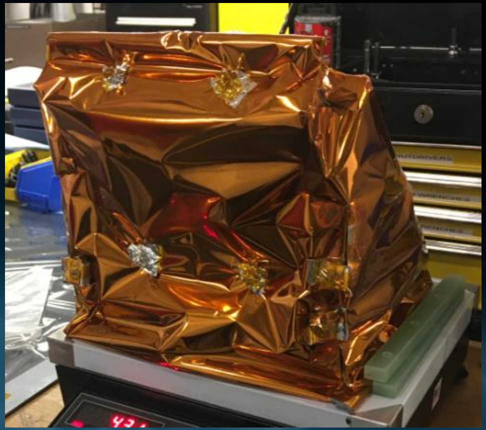


Thermal Design: Passive & Active



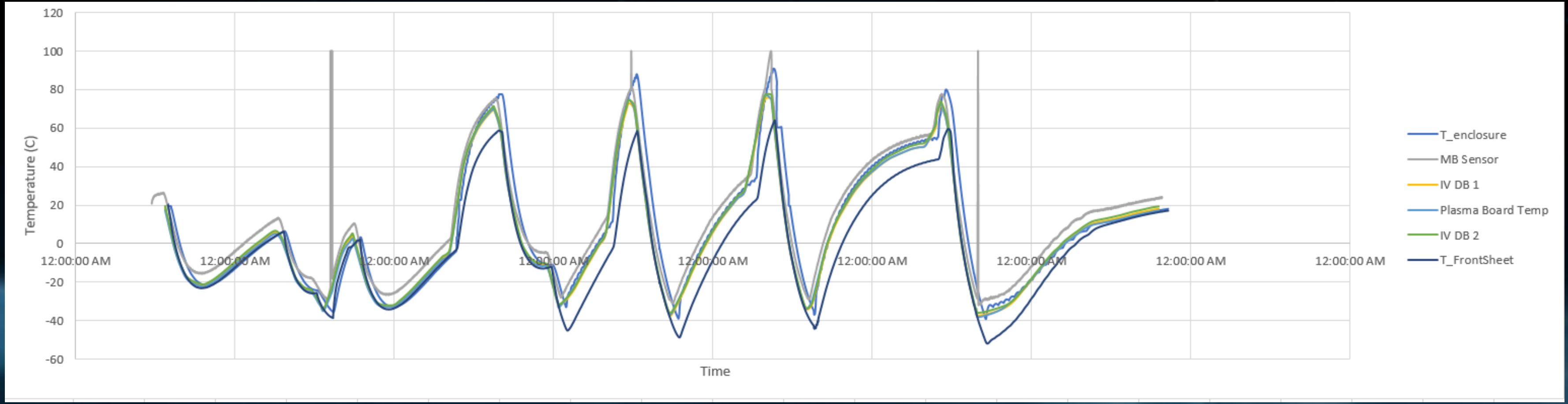
Mark Springowski (MLI technician)

- Passive: Multi-layer Insulation (MLI)
  - MLI Optical Properties Test: PILS-PRO-110-06
    - Designed MLI provides ε* = 0.0008
    - Designed MLI provides absorptivity (α)= 0.386
- Active: Heaters
  - Onboard heaters designed to deliver 12 Watts of heat.
- Analyses Comparison:
  - MLI properties: ε* = 0.08, (α)= 0.44.
  - The as-built MLI has a lower ε* and α- ensuring better performance than the one in the analyses
  - Heaters: Require 5.9 Watts of heat at most. Onboard heaters in flight unit are more than capable to handle the mission environments.

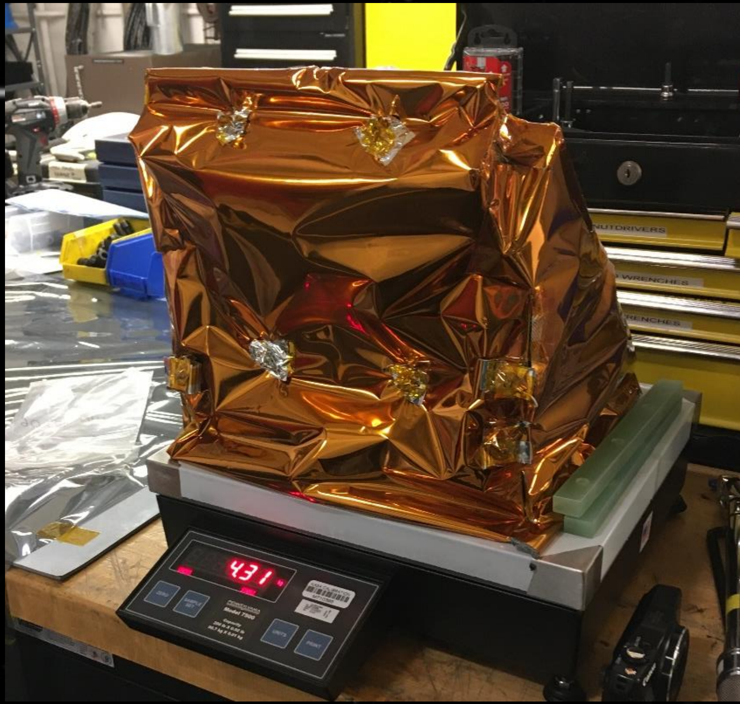


Thermal Vacuum (TVAC) Testing

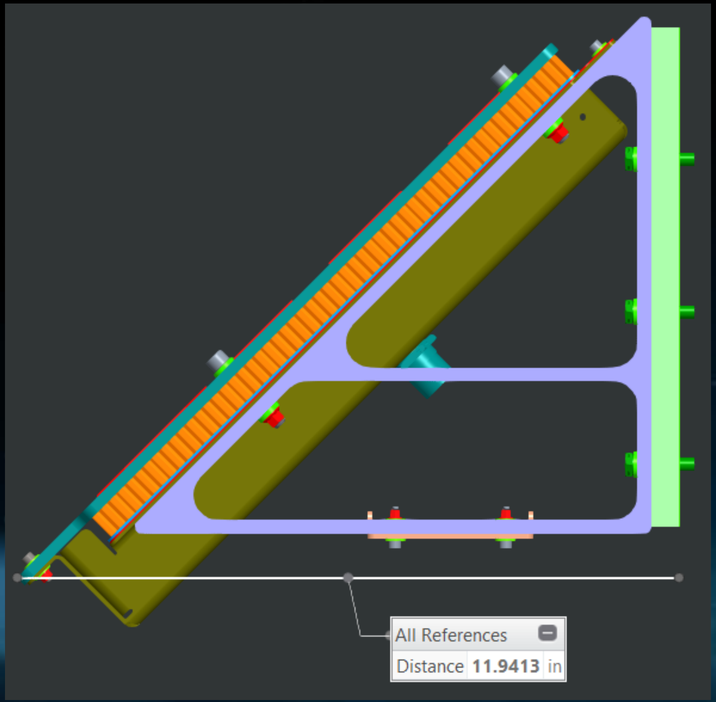
- TVAC Testing Deviation: PILS-D-005
  - Not following SMC-S-016
  - Includes: 4 TVAC cycles, 1 cold start
- As run TVAC Testing: PILS-PLN-127-R1-SN#1
- TVAC Test Report: PILS-RPT-144
- Observed 4 restarts in the PILS unit:
  - First one before thermal cycling began, while looking for the “cold set point” per PILS-PLN-127
  - Second and third one during 2nd and 3rd thermal hot soak respectively. Demonstrated hot start
  - Fourth one demonstrated cold start
- Passed functional checkouts at the end of testing
- Applicable SRD requirements have been met:
  - 3.2.3-1: TVAC test plan was based on analyses and ICD.
  - 3.2.3-2: PILS unit does maintain storage temperatures within -55 C to 150 C.
  - 3.2.3-3: PILS unit does maintain operational temperatures for internal electronics (-40 C to 85C).
  - 3.2.3-8: PILS unit monitors temperature and turns off the unit when exceeding 85 C.

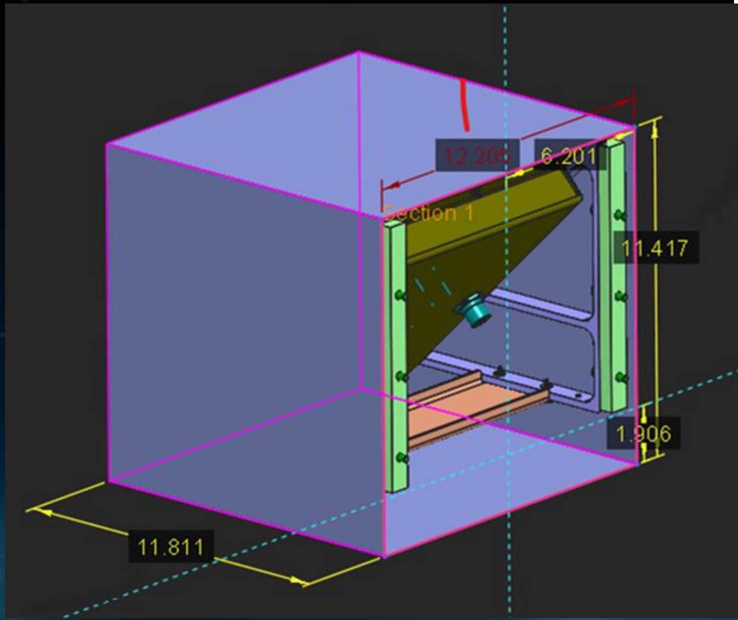


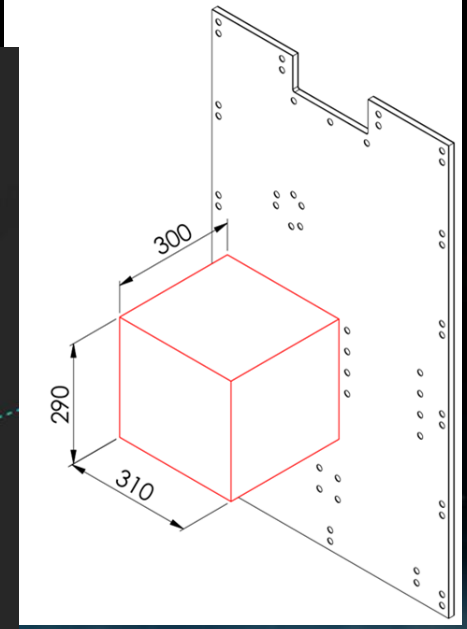
Mass Properties (it fits!)



- Mass: 4.31 kg
- Volume from ICD: not to exceed 290 mm × 310 mm × 300 mm (L x W x H).
- Volume according to Creo
  - 10.9949 in x 12 in x 11.9413 in
  - = 280 mm x 305 mm x **303 mm**



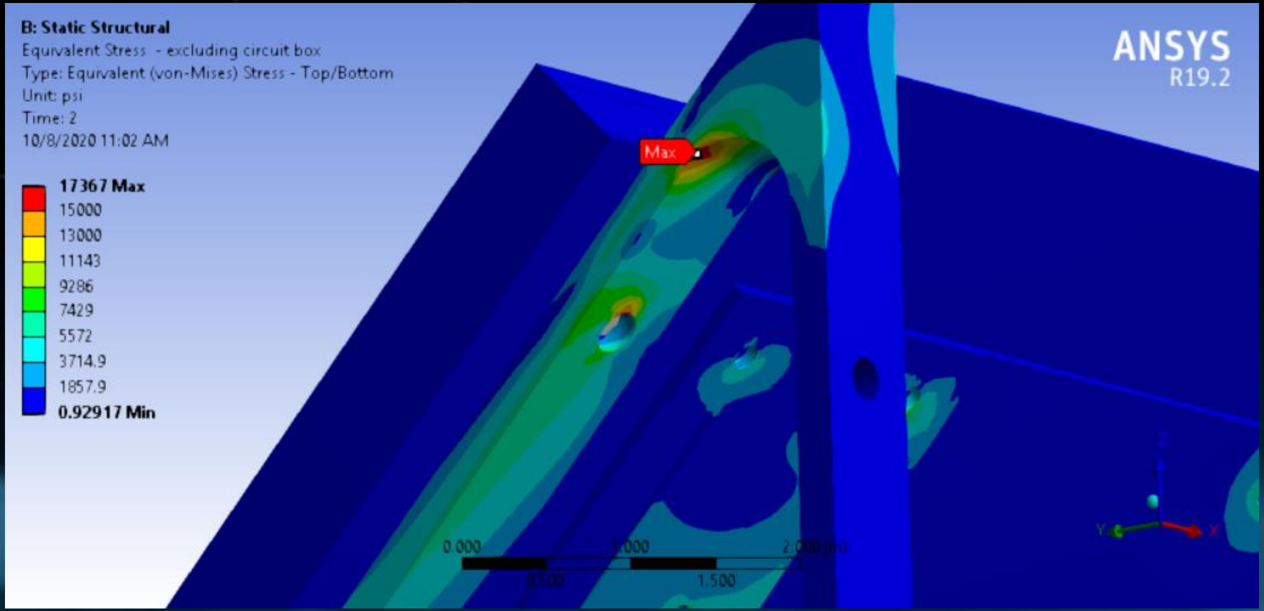




Structural Analysis (FEA)

- Modal and structural analysis performed with static structural and 3σ random vibration loads included.
- Bolt calculations performed with EFAST for external safety critical bolts, and all margins are positive.
- Venting analysis – large enough gaps in PCB cover.
- Acoustic and Shock testing waived.

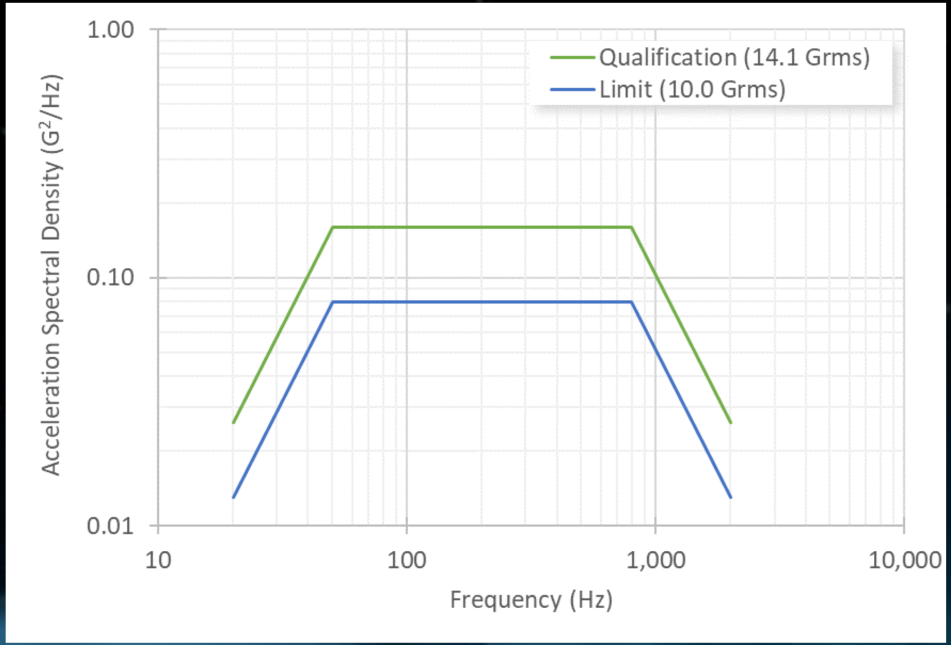
Load case	**Acceleration x (g's)**	**Acceleration y (g's)**	**Acceleration z (g's)**
1	0	0	-1
2	78.7	+91.7	+118.1
3	78.7	+91.7	-114.3
4	78.7	-91.7	+118.1
5	78.7	-91.7	-114.3

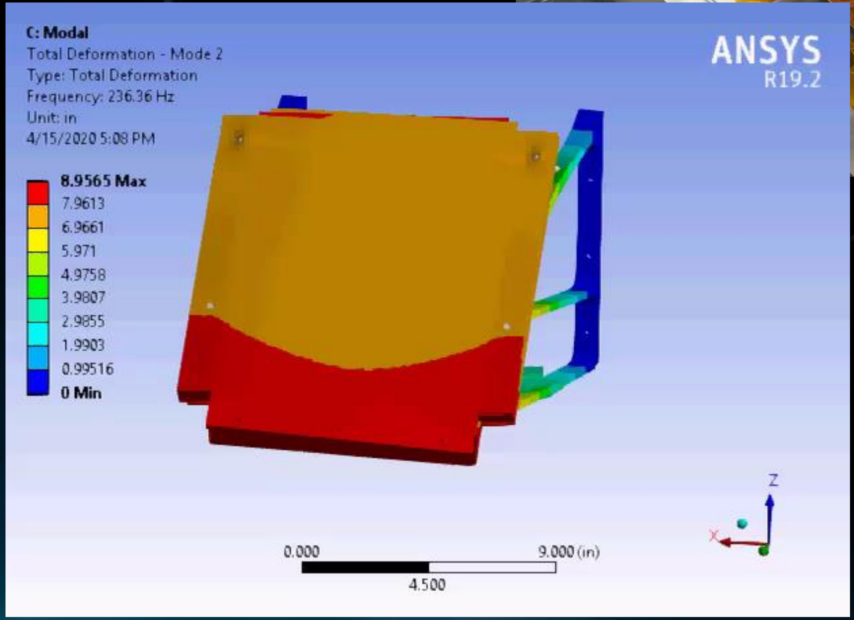


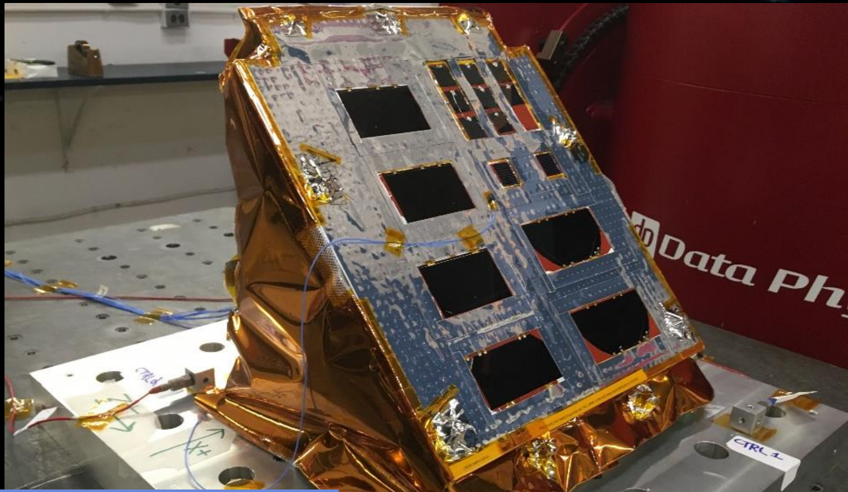
- Max equivalent stress occurs in load case 2:
- (+78.7, +91.7 G, +118.1 G).
- 17,367 psi on the right angled bracket.
- Yield stress for 6061-T6 aluminum is 36,000 psi.

Vibration Testing

- All 3 axes tested with low level random, qualification levels, and low level random again.
- Functional checkout after each axis test verified that PILS generated IV curves.



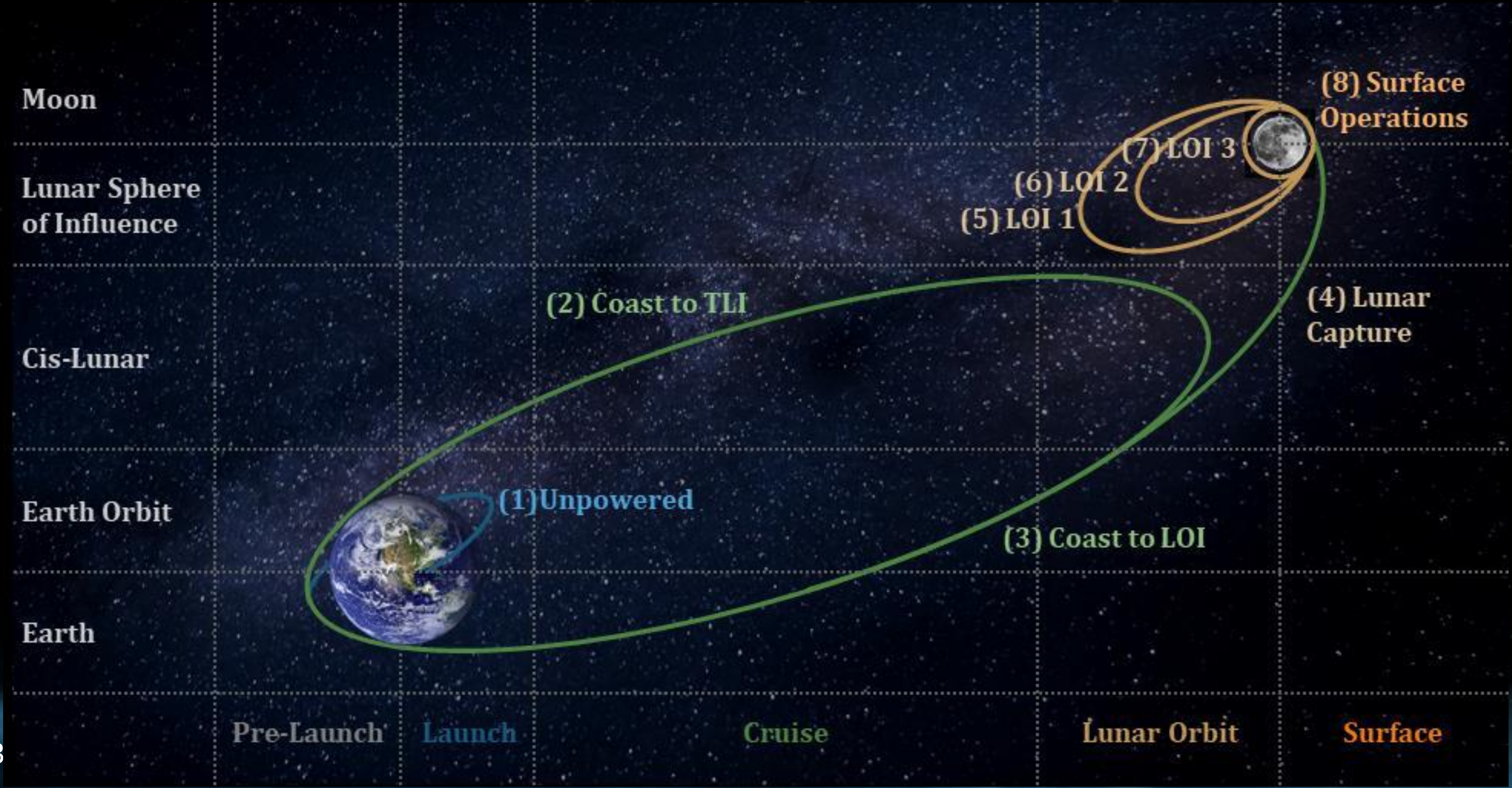

C: Modal
Total Deformation - Mode 2
Type: Total Deformation
Frequency: 236.36 Hz
Unit: in
4/15/2020 5:08 PM



System Requirements Verification Summary

- PILS SRD lists 55 total requirements.
- Only one of five waivers affects requirements – TVAC Test Plan Deviation from SAR. The deviation involved limiting the number of thermal cycles performed per the SAR. There was no impact to Astrobotic thermal interface requirements.
- Completed and signed Verification Requirement Data Sheets (VRDS) can be found in Z:\PILS\VerificationSheets. A detailed status of each verification is listed.
- Pending any issues with Astrobotic waivers, there are no issues with PILS verification to prevent the payload from completing its mission.

Payload Operations



Payload Operations

Launch

- Launching on the Vulcan Centaur from SCL-41 at Cape Canaveral
- During Launch, there will be no payload operations
- AB recommends that PILS team staff their PMCC
- PILS team will provide a list of off-nominal events that occur during pre-launch and launch within 30 days of Launch
- Following separation, start-up activities will last approximately 4 hours before payloads are provided power

Rendering of ULA Vulcan Centaur
https://www.ulalaunch.com/about/news/2019/08/19/astrobotic-selects-united-launch-alliance-vulcan-centaur-rocket-to-launch-its-first-mission-to-the-moon

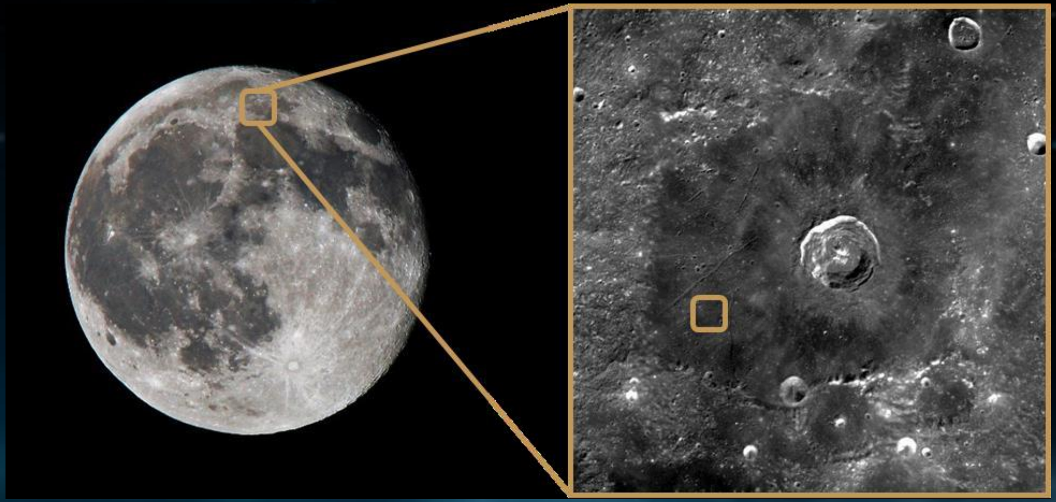
Payload Operations

Surface Operations

- Less than 6 hours after touchdown, the AB spacecraft will begin Morning Surface Operations lasting for ~120 hours
    - PILS team will monitor lander conditions and request operational power after flight unit minimum temperature is reached
    - PILS has requested data transmission at a frequency of 7 hours of data and 1 hour off through Morning Surface Operations
- The lander is expected to go into low power (“siesta”) operations for a span of ~24 hours around lunar noon
    - PILS has requested to operate during this time to best observe direct incident sunlight
- Afternoon Surface Operations will return lander to nominal power conditions extending for ~72 hours

End of Mission

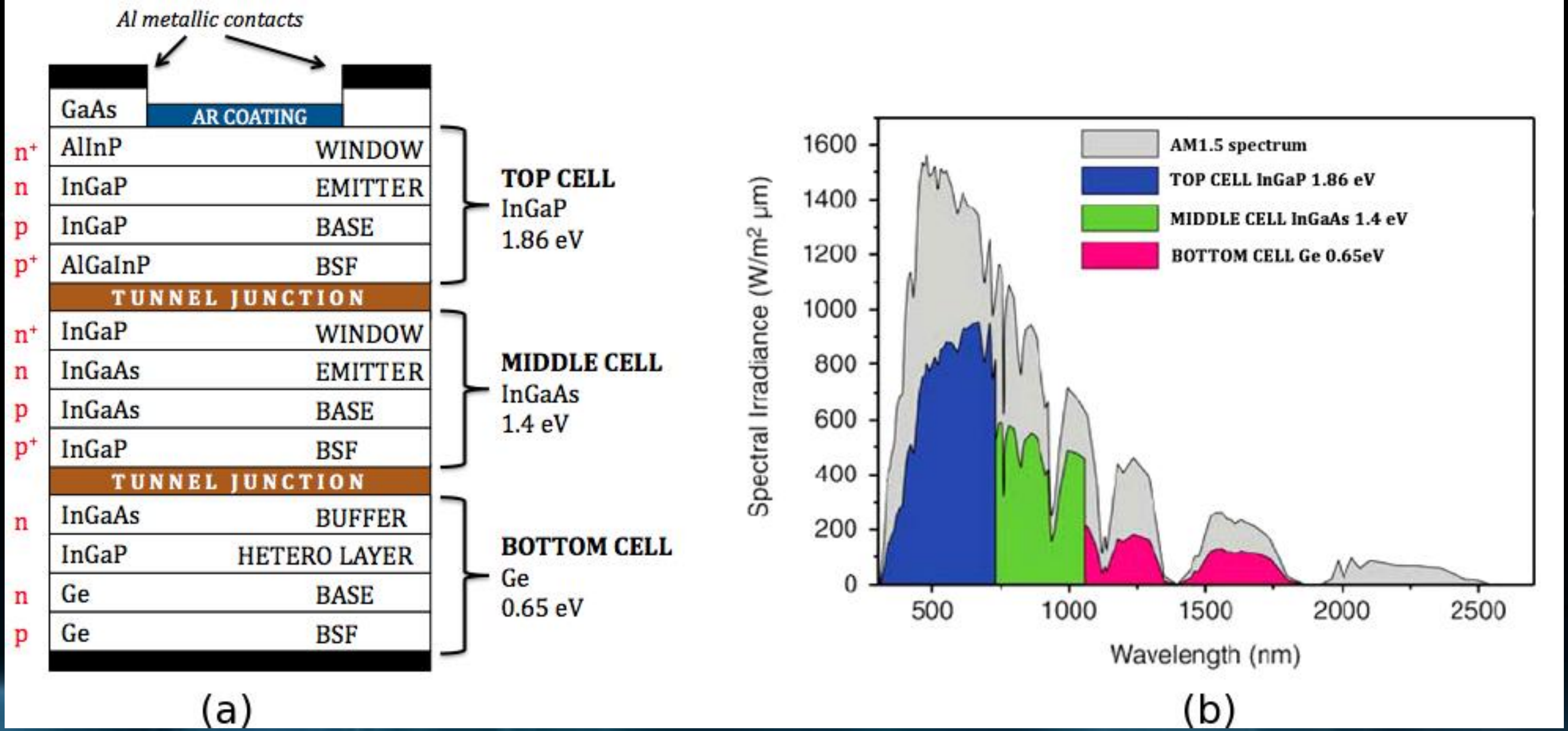
- End of Mission is defined by final lander shutdown occurring before lunar night
- An End of Mission Deliverables Package will be due to AB within 30 days
    - Includes off-nominal events



Target Landing Site – Lacus Mortis plateau

Why the complement of Solar cells?

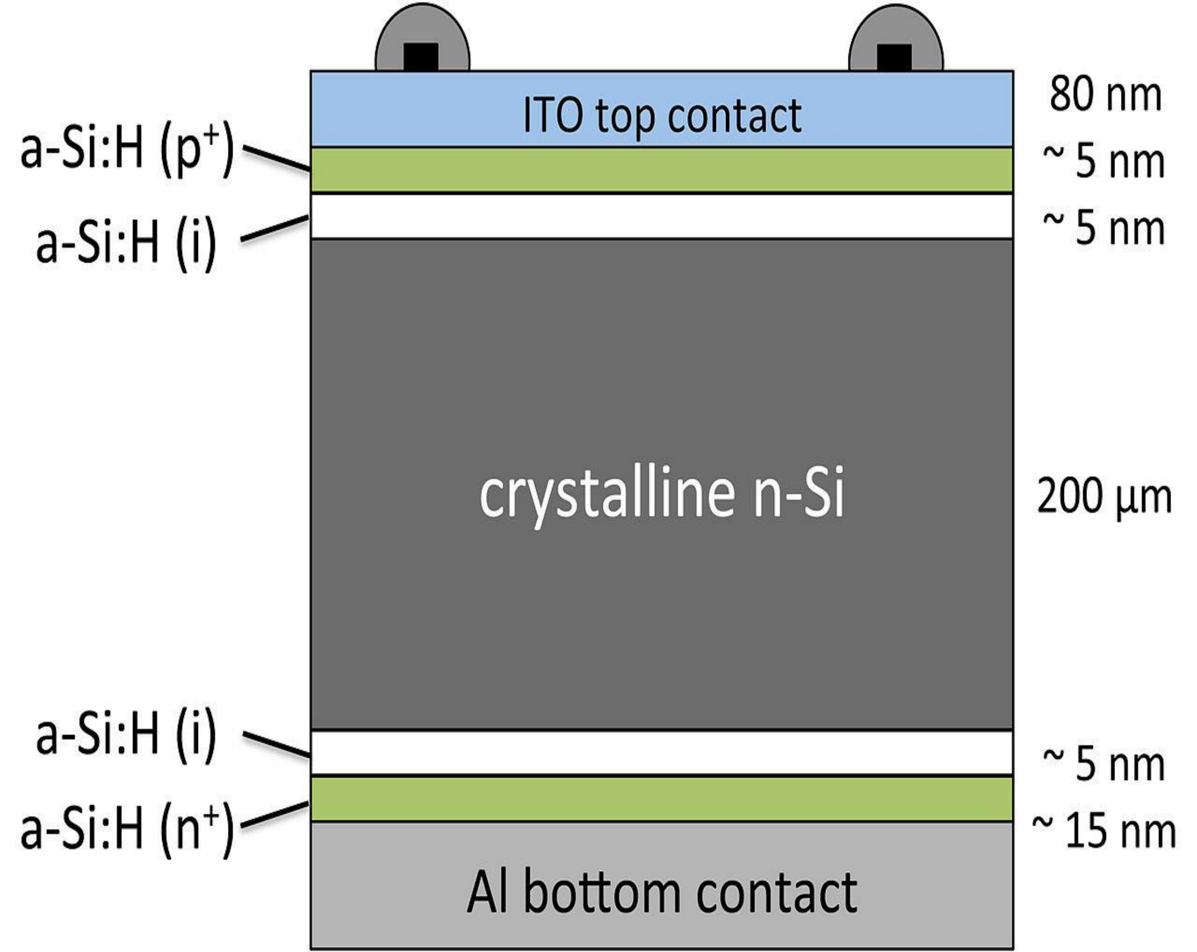
- Little lunar surface data exists for solar cells, and none public on multijunctions.
- These cells are multiple thin films, monolithically deposited to take advantage of different bands of light
- SOA cells are essentially a benchmark, (1 each) but the new cells, notably more layers (4 and 5J) are novel (2 each onboard), and silicon
- How are they sensitive to thermal conditions? How well do they perform with possible surface albedo?



(a) (b)

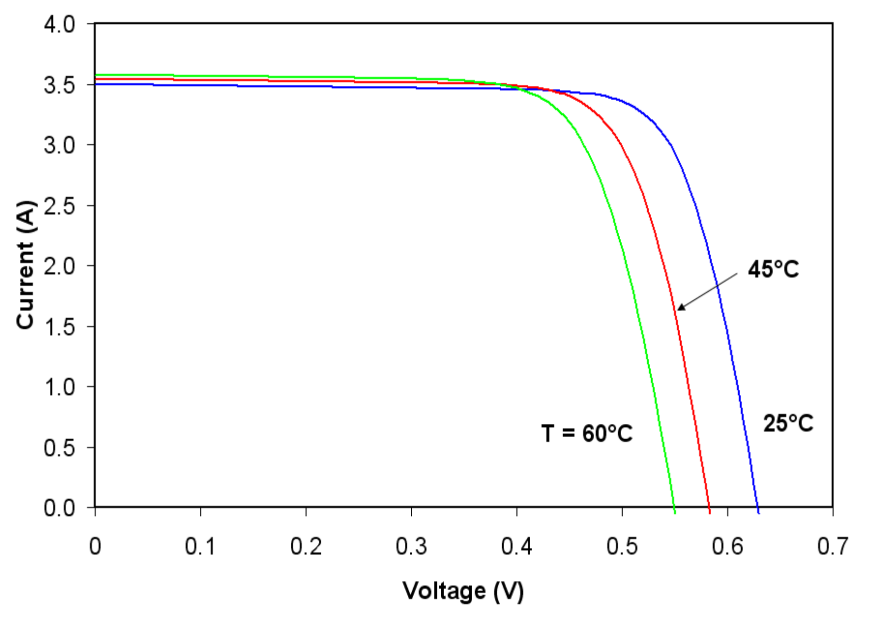
Silicon cells and possible ISRU connection

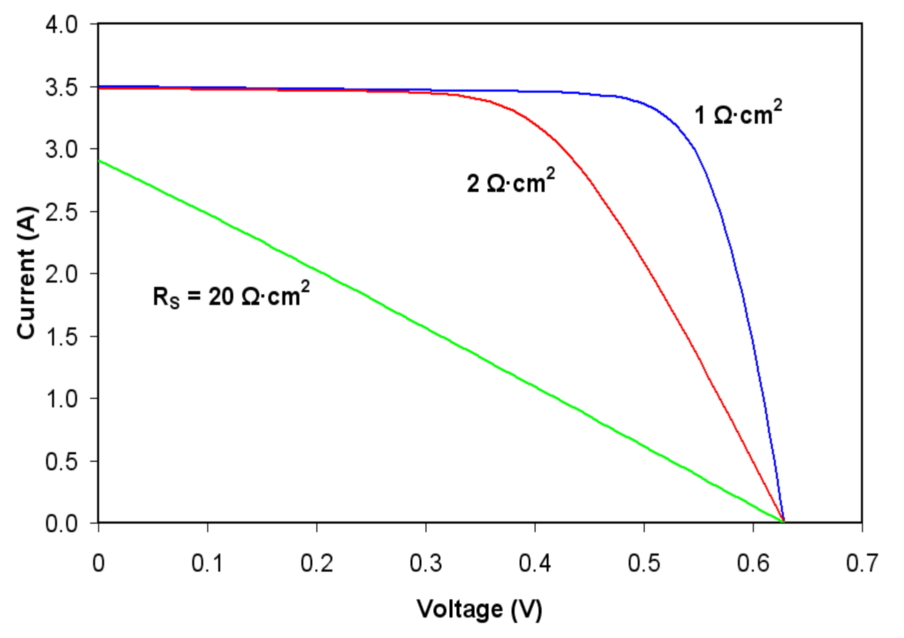
- Bifacial HIT cells have great promise for high energy harvest relative to cost
  - Very low cost compared to space SOA (~1000/1)
  - Reduced tracking needs at lunar polar
- Lunar regolith comprised primarily of silicates.
  - ISRU methods desire reduction of silicates for oxygen
  - The silicon byproduct could be refined to manufacture this type of cell on lunar surface
- We'll demonstrate first HIT cells on lunar surface, data to provide feedback for design improvements.



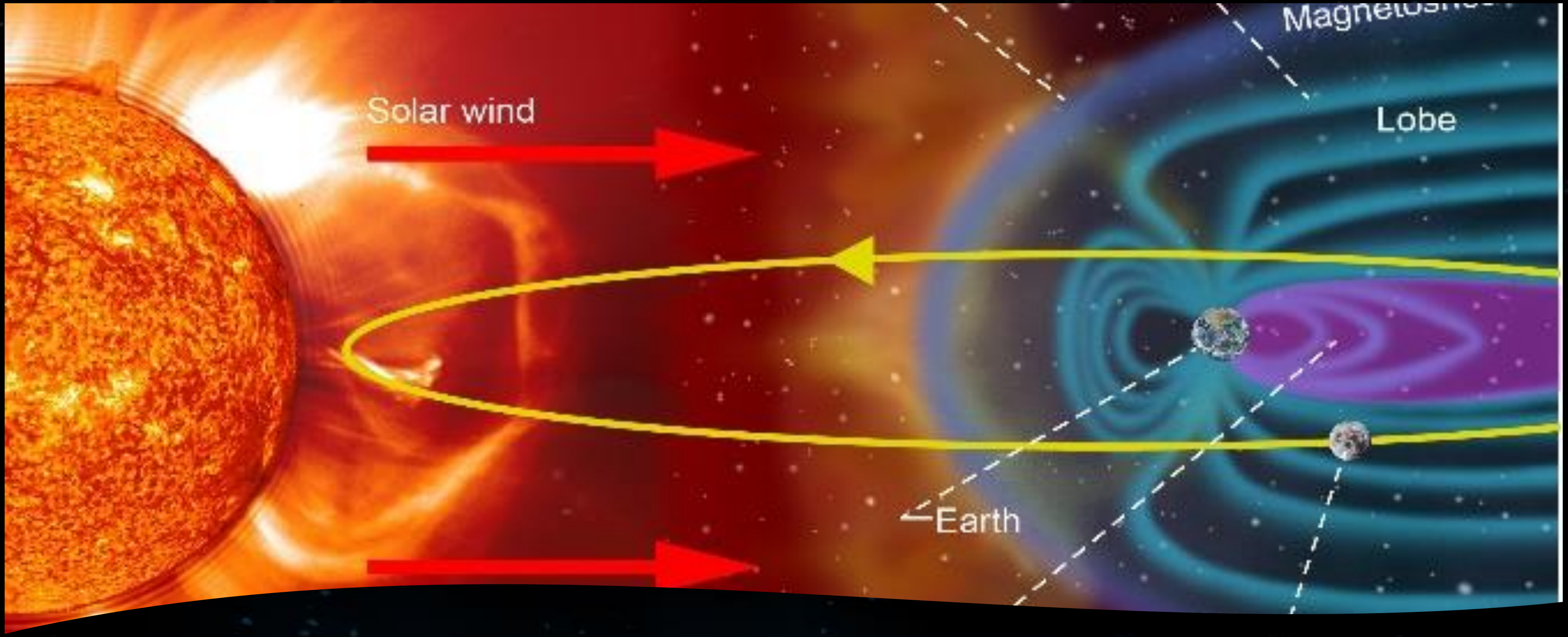
Performance of cells

- Current vs voltage characteristics are collected on the cells as time series datastreams.
- These data are high fidelity for the underlying characteristics of the cell.
- In essence, no load voltage is sensitive to structure and temperature, no resistance condition is sensitive to light intensity, in between is sensitive to resistance losses.
- But we have sophisticated ways to analyze data.





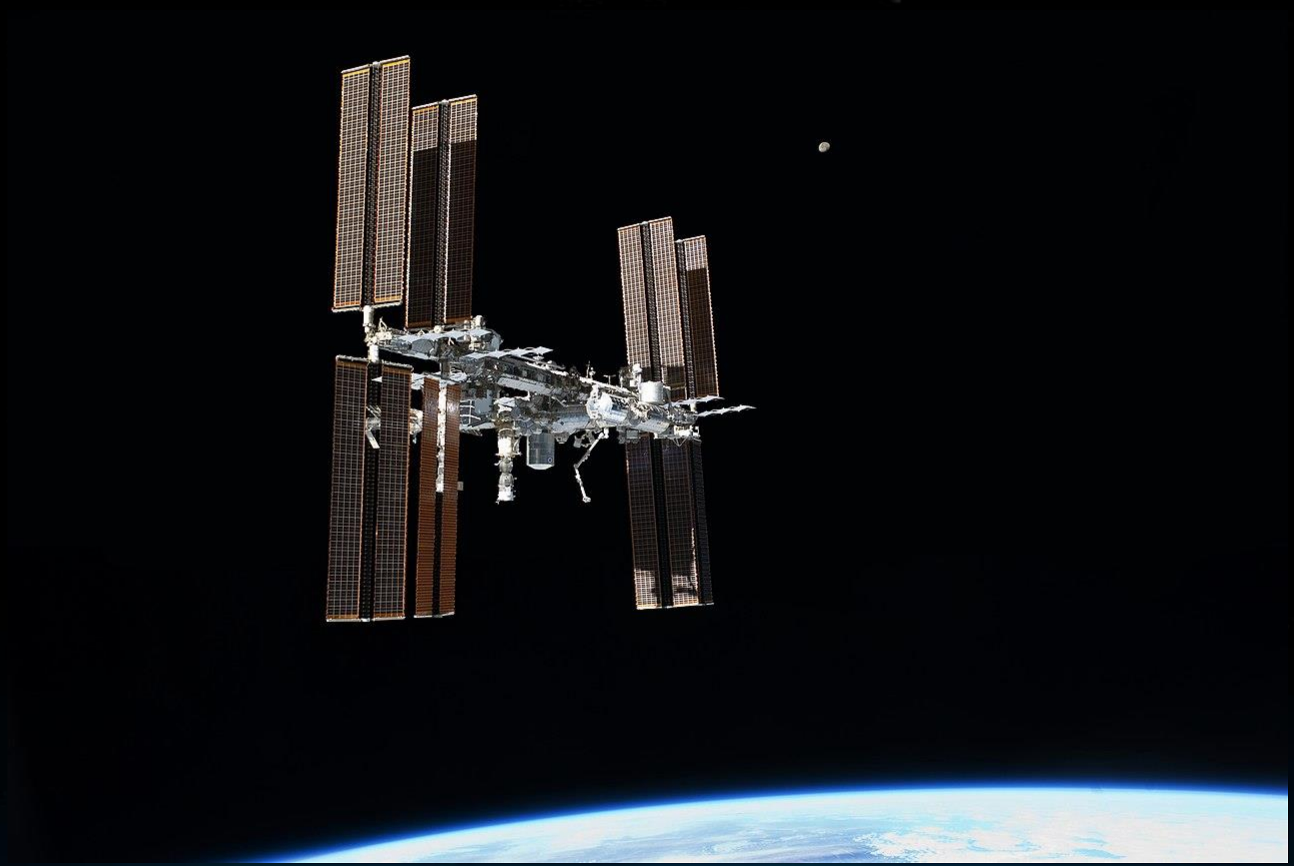
Sailing over a Cardboard Sea:



- The plasma environment around the moon is challenging to understand. The UV component of sunlight combines with plasma to charge the lunar dust.
- The charging of solar arrays limits bus voltage – primary arcs can lead to arcs generated by the arrays
- We want high voltage because of efficiency, mass and utility concerns.
- We will get data from at least half of lunar cycle and possibly through a day-night terminator

Plasma interaction science

- To better understand spacecraft charging let’s consider the ISS



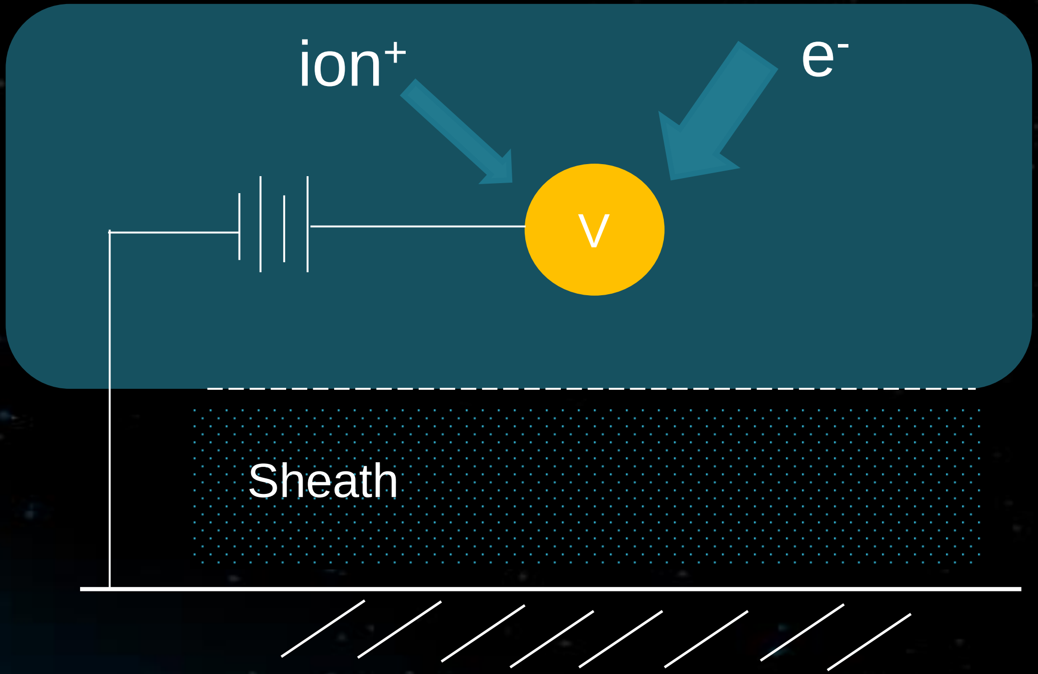
By NASA - STS-135 Shuttle Mission Imagery direct link, Public Domain, https://commons.wikimedia.org/w/index.php?curid=15942935

Floating Potential

☐ The potential of a body in the space plasma is determined by a balance of the various charging currents: ram ion current, electron thermal currents, secondary ion and electron currents, photoemission currents, etc.

  - ➢ Floating Potential (FP) is defined as the potential where the net current to a body is zero.

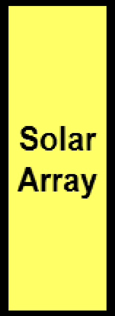
☐ Measurement of the FP is accomplishing by placing a conducting surface (or probe) under high impedance isolation (>> 1 G-ohm) at a distance beyond the body sheath and determining the voltage (V) at which the total current $I_{total} = 0$



Spacecraft body
FP = -V

Ionospheric Currents to High Voltage Solar Arrays drive ISS Charging

Spacecraft View

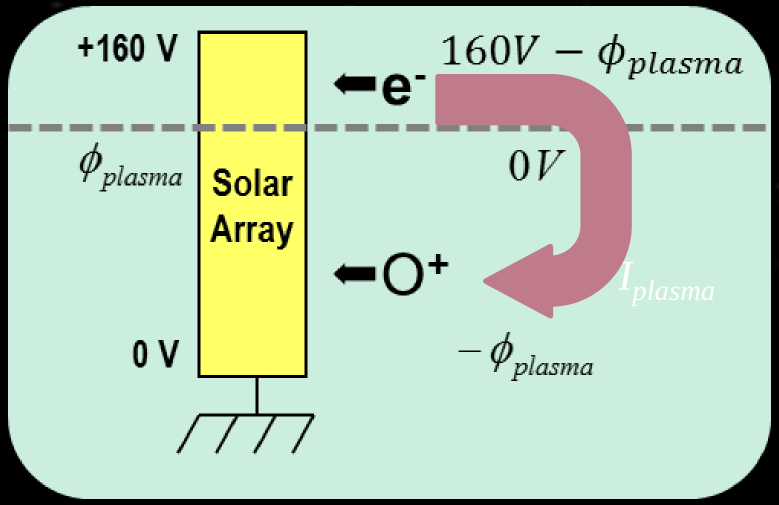


Idealized representation of a 160-V solar array connected to spacecraft chassis ground.

$$n_{O^+} \approx n_e \approx 10^{10} - 10^{13}\ m^{-3}$$
$$T_e = 0.1 - 0.2\ eV$$

ISS ionospheric plasma constituents mainly oxygen ions (O^+) and electrons (e)

Plasma View

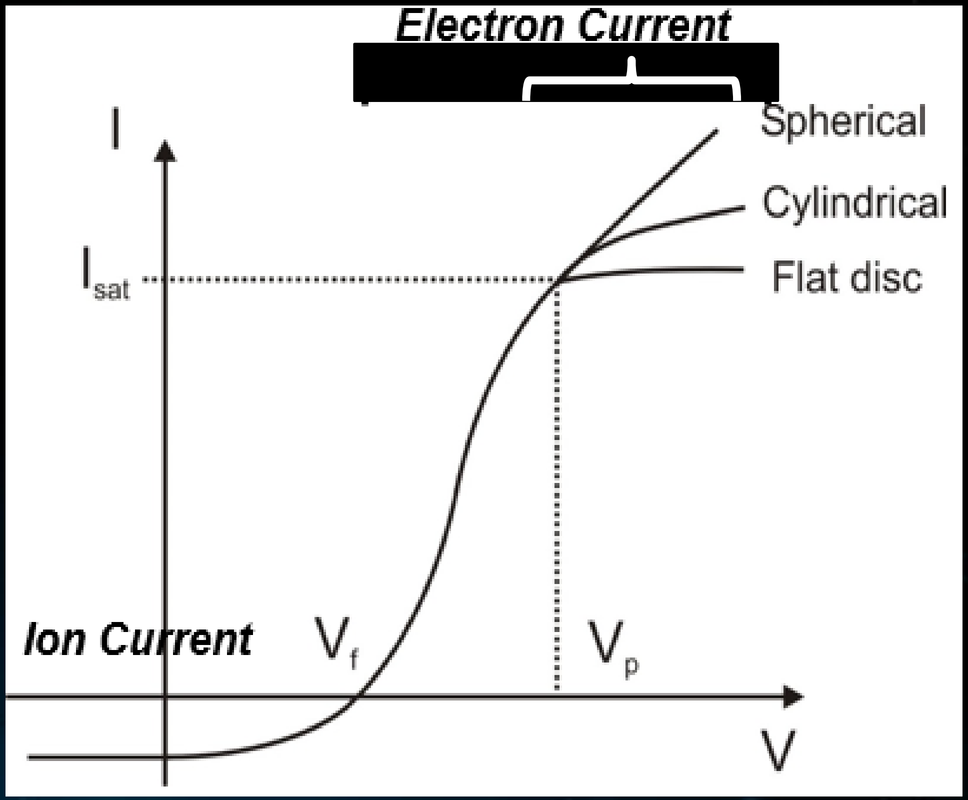


Solar array driven current through the ionosphere. The voltage scale on the left is with respect to spacecraft chassis ground; the voltage scale on the right is with respect to the local ionospheric plasma ground. This figure omits the magnetically induced potential.

Current Collection

This is an illustration of an I-V sweep showing how ions and electrons collect differently and how the shape of the surface can affect the electron current.

Notice, spheres are the best collecting shapes while flat plates are the least efficient.



Current collection from the space plasma

In order to solve for the current provided by the plasma, one first needs to solve for the flux

$$\underset{\overset{\nearrow}{\textbf{flux}}}{\Gamma_e\left(\vec{r},t\right)} = \underset{\overset{\nearrow}{\textbf{Number density}}}{n_e}\underset{\overset{\nwarrow}{\textbf{Mean velocity}}}{\vec{u}} = \int \vec{v}\underbrace{f\left(\vec{r},\vec{v},t\right)}_{\textbf{Distribution function}}d^3v$$

The resulting flux is $\Gamma_e = \frac{1}{4}n\bar{v}$ ***where*** $\bar{v} = \left(\frac{8k_BT_e}{\pi m_e}\right)^{\frac{1}{2}}$ ***is the average thermal electron speed***

So, the thermal electron flux is

$$\Gamma_e = \frac{1}{4}n\left(\frac{8k_BT_e}{\pi m_e}\right)^{\frac{1}{2}} = n\left(\frac{k_BT_e}{2\pi m_e}\right)^{\frac{1}{2}} \longrightarrow \overbrace{J_{th} = q\Gamma_e = qn_e\sqrt{\frac{k_bT_e}{2\pi m_e}}}$$

Note: $v_{th} = \left(\frac{k_BT_e}{2\pi m_e}\right)^{\frac{1}{2}}$ ***or*** $v_{th} = \left(\frac{qT_e}{2\pi m_e}\right)^{\frac{1}{2}}$ ***depending on the*** $\boldsymbol{T_e}$ ***units***

In the literature, v_{th} ***often refers to the thermal velocity*** $v_{th} = \left(\frac{k_BT_e}{m_e}\right)^{\frac{1}{2}}$

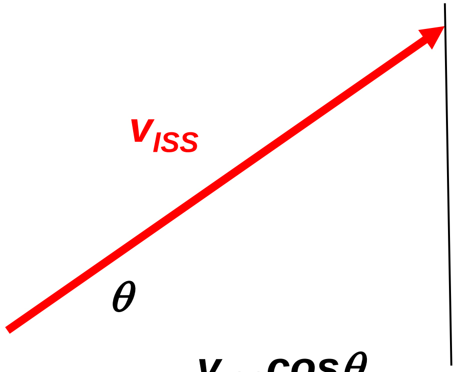
Plasma Current (Ion Ram Energy)

Ion current is dependent on the surface area projection normal to the ram velocity, ram velocity, ion number density, and the FP at the location the current is being calculated. C_1 and C_2 will be explained on the next page.

$$v_{normal} = v_{ISS} \cos\theta$$

$$E_0 = \frac{1}{2} m v^2$$

$$I_{ion} = C_1 n_i q A v_{normal} \left(1 - \frac{\left(q\Delta V_{sheath}\right)}{E_0} \right)^{C_2}$$

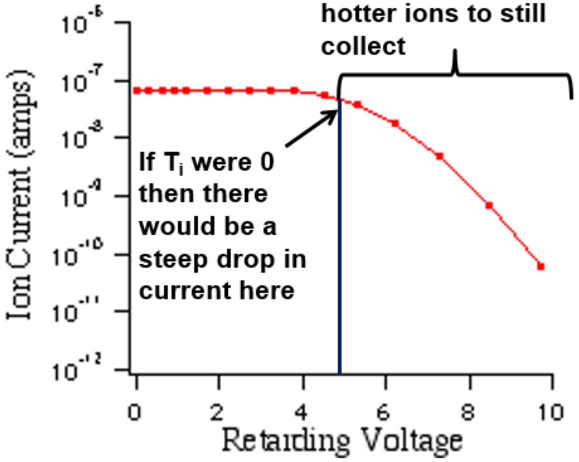


v_{ISS}

Collecting surface

θ

$v_{ISS}\cos\theta$



T_i dependency allows hotter ions to still collect

If T_i were 0 then there would be a steep drop in current here

The point where ions stop collecting is when the value of qV and E are equal. This equation ignores the ion thermal velocity and any drift speed of the ions. In actuality, the hotter ions would still collect at that point.

Electron and Ion Currents

The resulting equation formats for the electron and ion currents are used in the PIM software tool calculations. The C_1 and C_2 coefficients depend on the collecting surface properties. C_2 is the γ in the focusing factor, and C_1 depends on the materials efficiency to collect current.

$$I_{electron} = C_1 n_e q A \left(\frac{k_B T_e}{2\pi m_e} \right)^{\frac{1}{2}} \left(1 + \frac{q \Delta V_{sheath}}{k_B T_e} \right)^{C_2}$$

$$I_{ion} = C_1 n_i q A v_{normal} \left(1 - \frac{q \Delta V_{sheath}}{E_0} \right)^{C_2}$$

What this means is that electrons move much faster than ions, and the currents (especially in transients) may be different until an equilibrium arrives. This equilibrium is related to the Debye sheath thickness, as well as material dependent properties such as exposed conductors.

Sustained Arcs

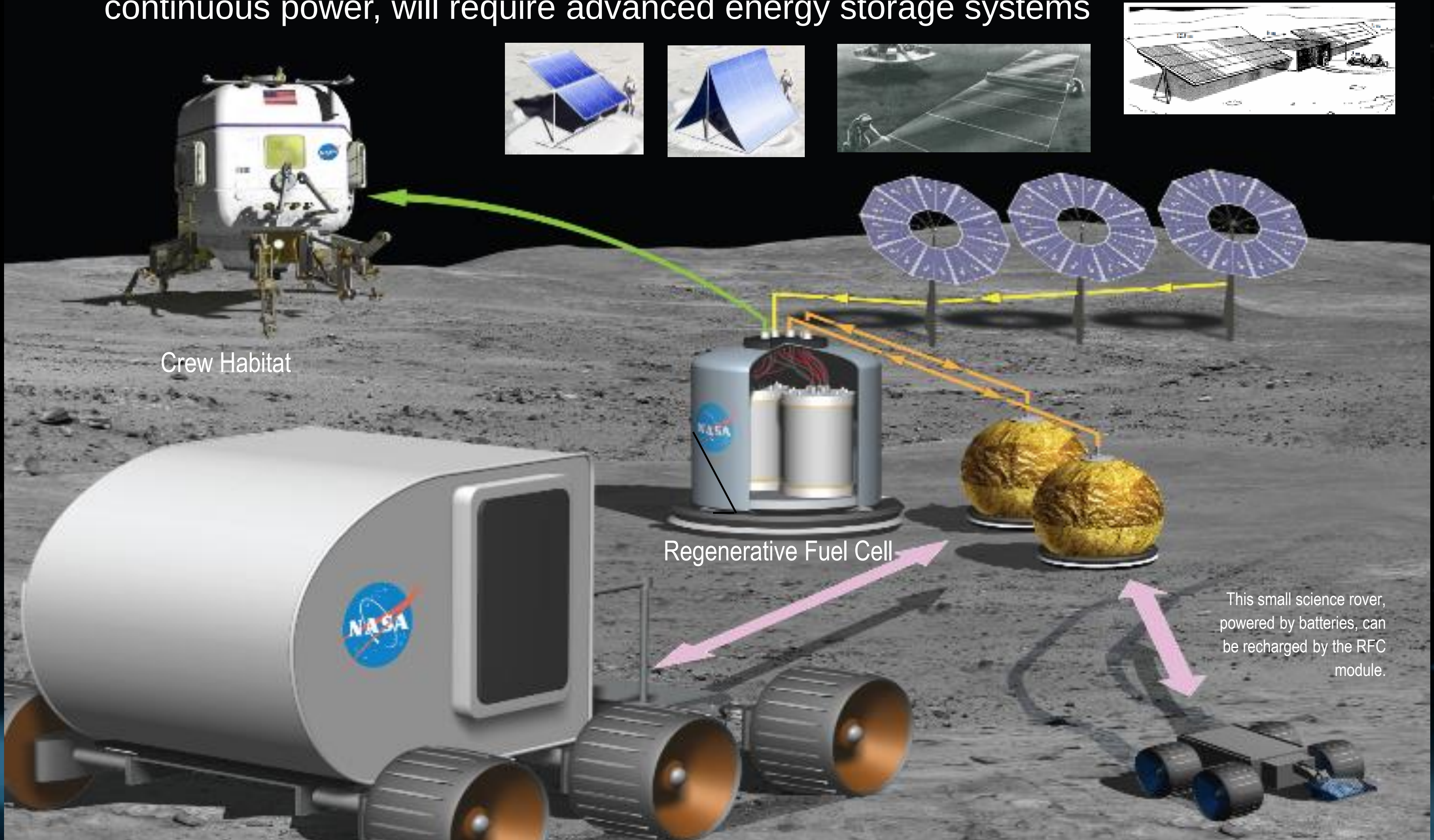
- Long Duration ~1 ms to seconds
- Low Current ~1 – 5 amps
- Two cells coupled electrically
- Requires differential voltage
- (Current limited by array design)
- Pyrolysis of support structure

What is happening???

- A primary (trigger) arc occurs at the right place, and arcs out to space
- Through a process called ‘flashover’ the arc acts in vacuum as an expanding plasma of energetic charged particles
- The flashover pulse interacts with surface charging of neighboring cells and may offer a low resistance path between cells
- The path is then coupled to the cell performance and the current from the cells feeds the arc.
- Sometimes the arc never ceases
- Don’t let this happen to you!

Power for Crewed Surface Missions: Moon

- There has been interest in solar power for lunar applications spanning decades
- 28 Earth-day rotation period of the moon creates challenges to provide continuous power, will require advanced energy storage systems



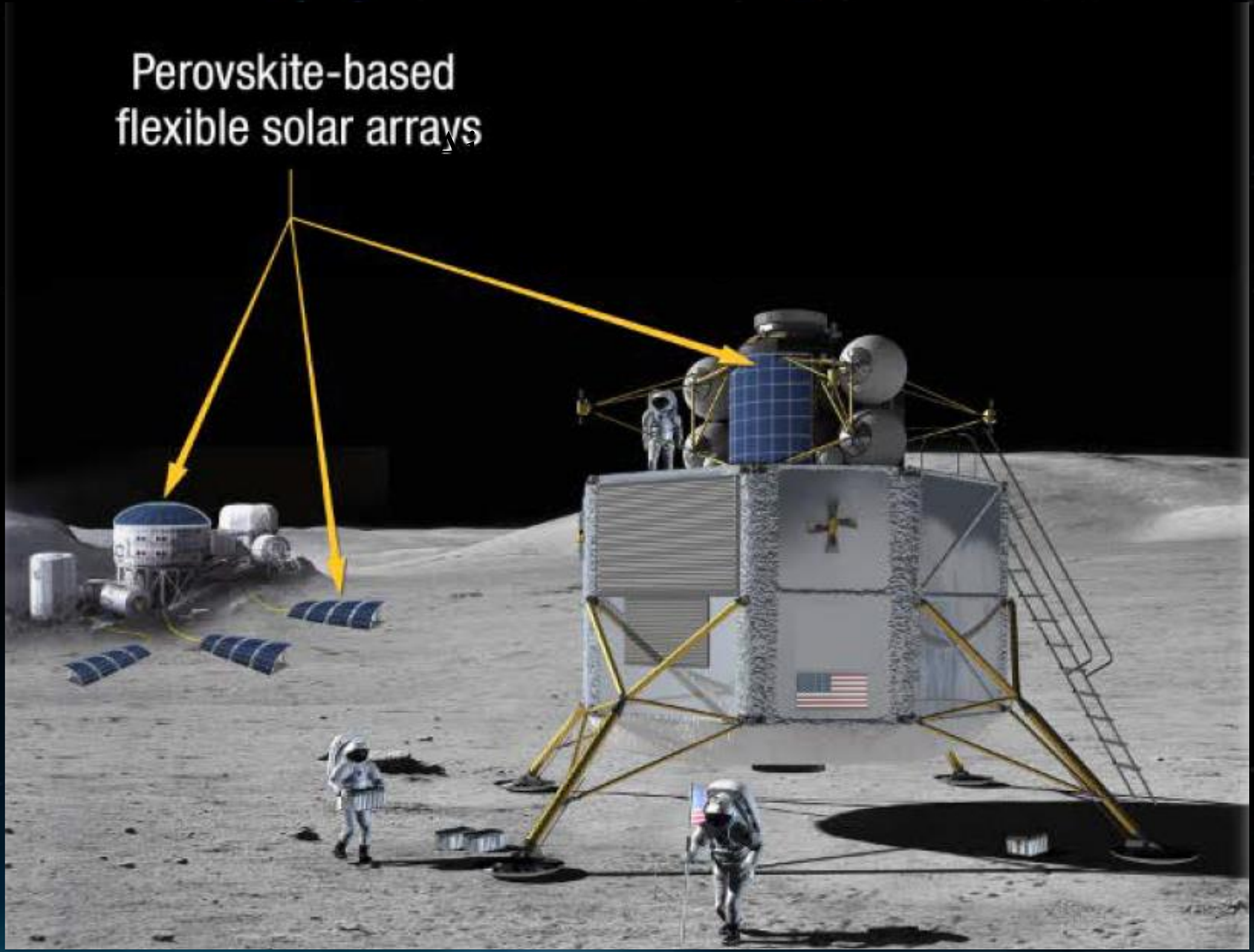
This small science rover, powered by batteries, can be recharged by the RFC module.

If You Believed in Me

- Need a LOT of solar. Can't be too close to human interactions that kick up dust.

- Basically you want high voltage, like 1000V or more
- Huge arcing risks

- A lot of solar means you need low cost

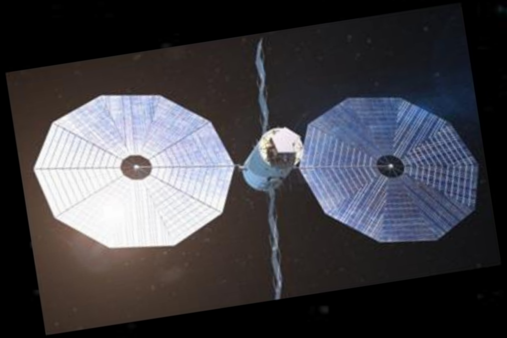


But it Wouldn’t be Make Believe…

- Several mission concepts require very large solar array systems and current technologies are often cost prohibitive.

- Development of dramatically cheaper solar array systems can fulfill the strategic goals for NASA, by developing radical, high payoff technologies and enabling missions.

- Solar arrays have been identified as being critically important for a variety of elements and missions being studied by NASA's Human Spaceflight Architecture Team (HAT).



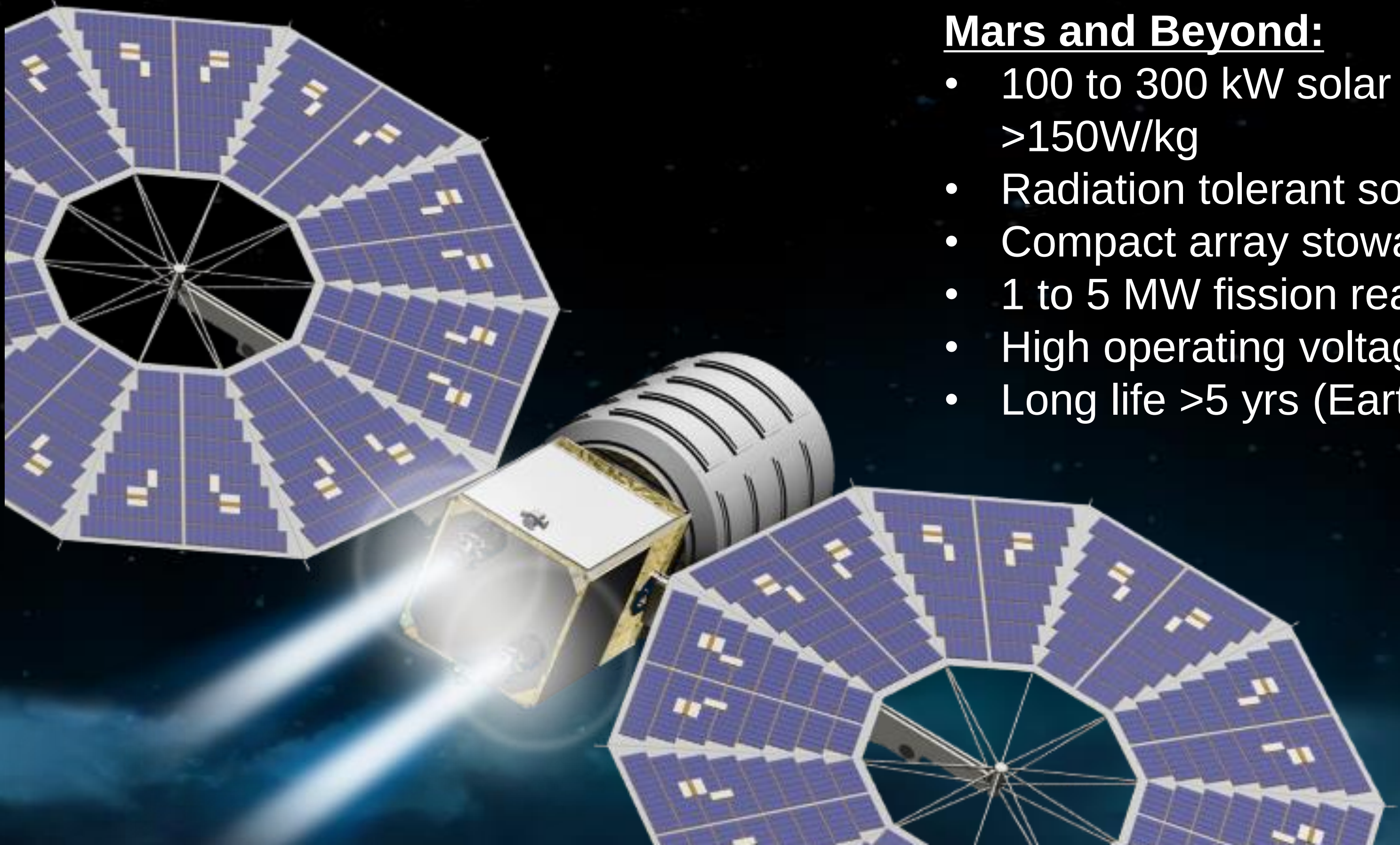
Why Now?

- Future missions demand more and more power which impacts budget
- Advances in robotic assembly lead to automated assembly processes
- Metamorphic and lift-off solar cell advances may allow the potential to reuse expensive substrates
- New cell technologies are gaining in efficiency
- Advanced epi growth processes are developing

Power for In-Space Electric Propulsion

Near Earth Systems:

- 30 to 50 kW solar array wings >100 W/kg
- Compact array stowage >40 kW/m3
- High deployed strength >0.1g and frequency >0.1 Hz
- High operating voltage >160V
- Long life >7 yrs with reuse

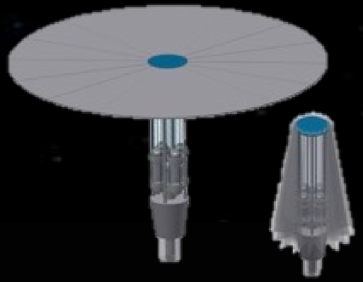


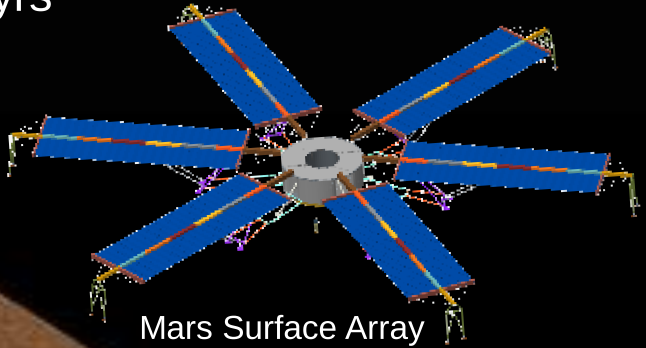
Mars and Beyond:

- 100 to 300 kW solar array wings >150W/kg
- Radiation tolerant solar cells
- Compact array stowage >60 kW/m3
- 1 to 5 MW fission reactors <5 kg/kW
- High operating voltage >300V
- Long life >5 yrs (Earth to Mars)

Powered for Crewed Surface Missions: Mars Surface

Stationary Power:
40 kW continuous power, day & night
High system specific power >5 W/kg
Nuclear fission or PV with energy storage
Human-rated (safety and fault tolerance)
Robotically-deployed (pre-crew arrival)
Survivable for multiple crew campaigns >10 yrs


Kilopower System
(deployed and stowed)


Mars Surface Array
Concept

Mobile Power:
6 to 10 kW rechargeable power, up to 120 kWh
Advanced batteries/fuel cells >300 Wh/kg, >200 cycles
Maximum commonality with other surface assets
Grid-compatible (with stationary power)

Mars Surface Rover Concept


Both: Mars gravity, wind, dust, CO2, temperature, diurnal period

Power for Small Spacecraft

Near Earth Systems:

- Power levels from 100 to 500W
- Body-mounted or deployable solar arrays >200 W/kg
- Advanced batteries >200 Wh/kg, >200 cycles
- Compatible with 2U to 24U CubeSat platforms
- Highly integrated systems with shared structure

Deep Space Systems:

- Power levels from milliwatts up to 60W (nuclear)
- Small RPS using multiple RHUs or single GPHS
- Advanced conversion (TE, Stirling, Alpha/Beta-voltaic) >15% eff

PV Technology Needs of Next Decadal Asteroid Missions

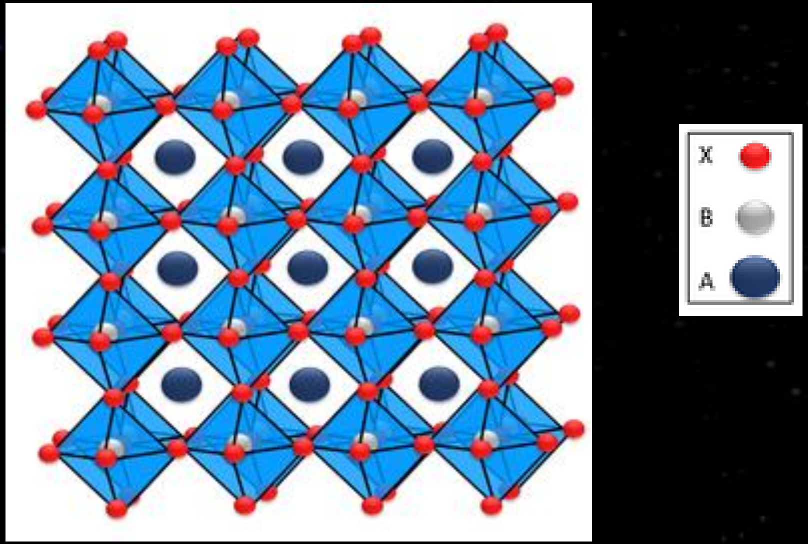
Mission Type	Mission	Needs*	Benefits
Orbiter		High Efficiency Solar Cells (>35%) Medium- High Power (2-30 kW) High Specific Power (> 200 W/kg)	Enhancing
Lander		High Efficiency Solar Cells (> 35%) High Specific Power Solar Arrays (> 200 W/kg) Dust Tolerant Solar Arrays	Enabling/ Enhancing
Sample Return		High Efficiency Solar Cells High Specific Power Solar Arrays (> 200 W/kg)	Enabling/ Enhancing

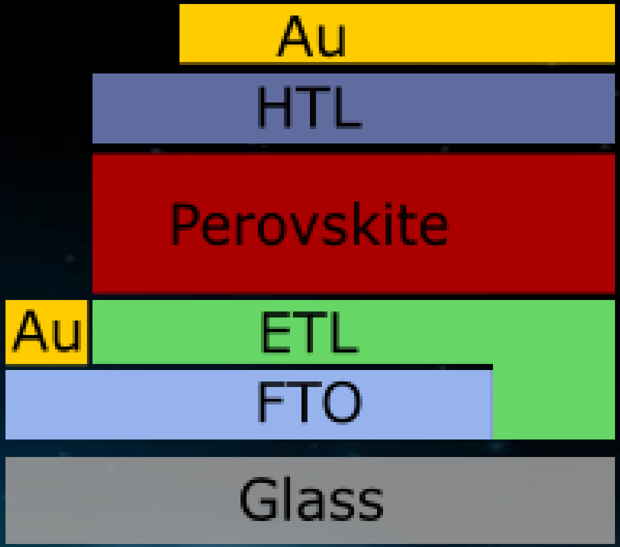
Basics of Perovskites

ABX_3

$(MA/FA)PbI_3$

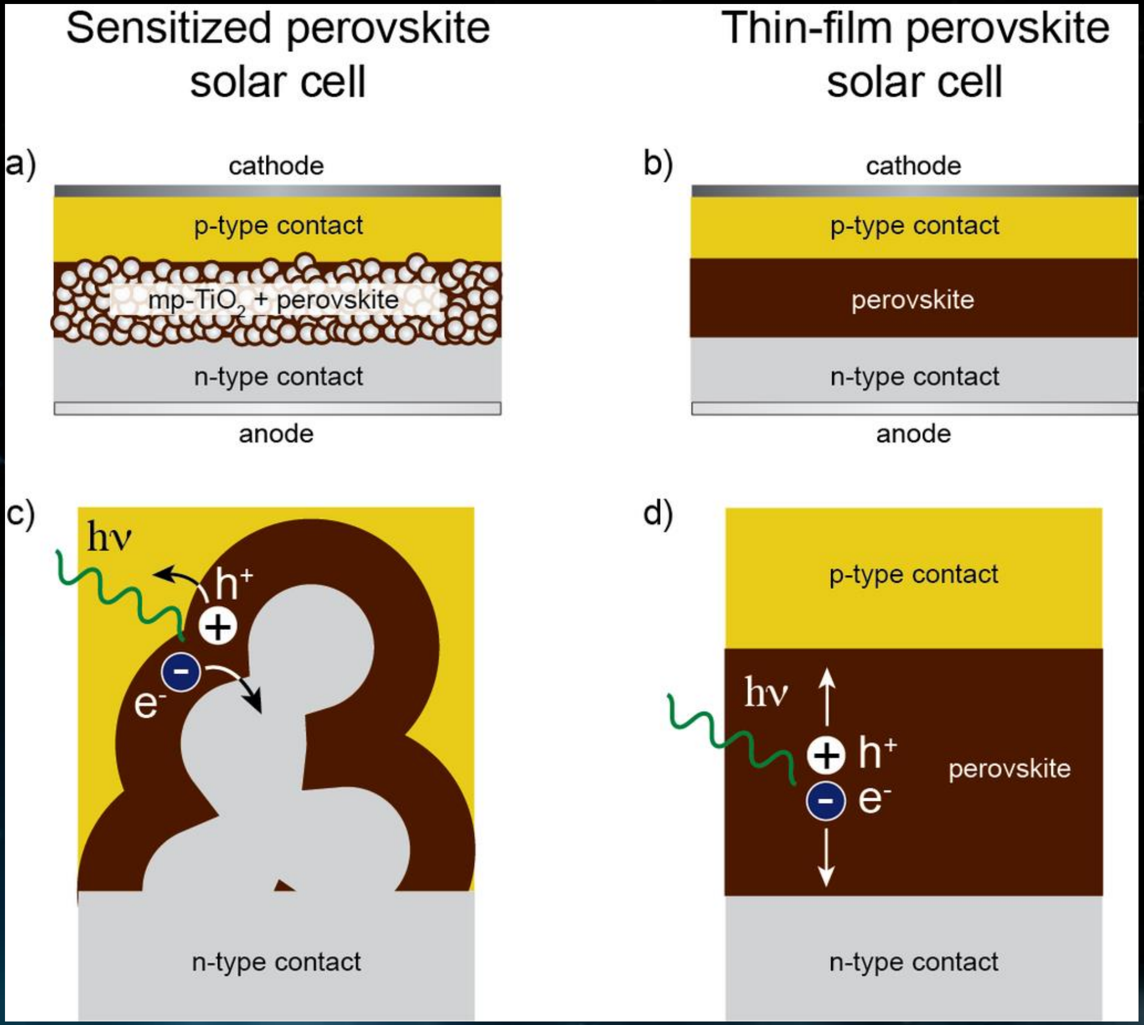
- Thin films (250 nm)
- **Radiation hard**
- Defect tolerant
- **Liquid or vapor phase processable**
- Potentially very flexible
- Multijunction opportunities
- **Lightweight (no encapsulant)**
- Low cost





Why do they work?

- Extremely high absorption – direct band gap
- Extremely long minority carrier lifetimes
  - Spin orbit coupling causes splitting in conduction band minimum
  - Indirect gap lifetimes
  - Direct gap absorptions
- Short distance for carriers
  - 300nm absorber
  - 20nm transport layers



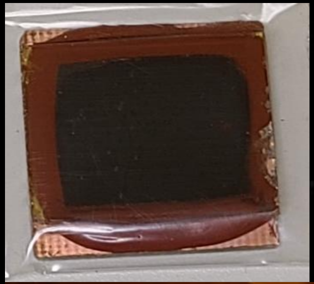
The promise of these materials

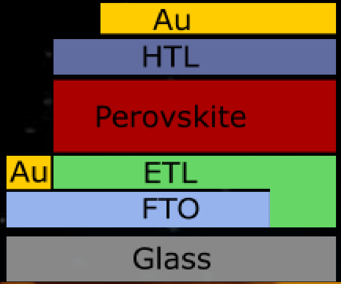
- Low temperature processing (new to thin film PV!)
  - Enables thin polymer substrates
  - But this is a challenge for space!
- EXTREME sensitivity to moisture (ionic salts)
  - But this is a strength for space!

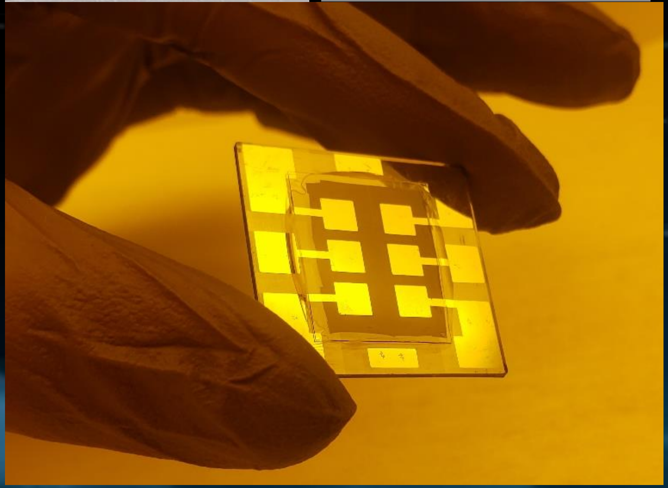
- But…
- Low charging and smoothness means potentially ultra high voltage operations
  - Yet this is difficult to test.
  - Nobody wants to put 1000V over a solar cell on a $100M spacecraft or the ISS!

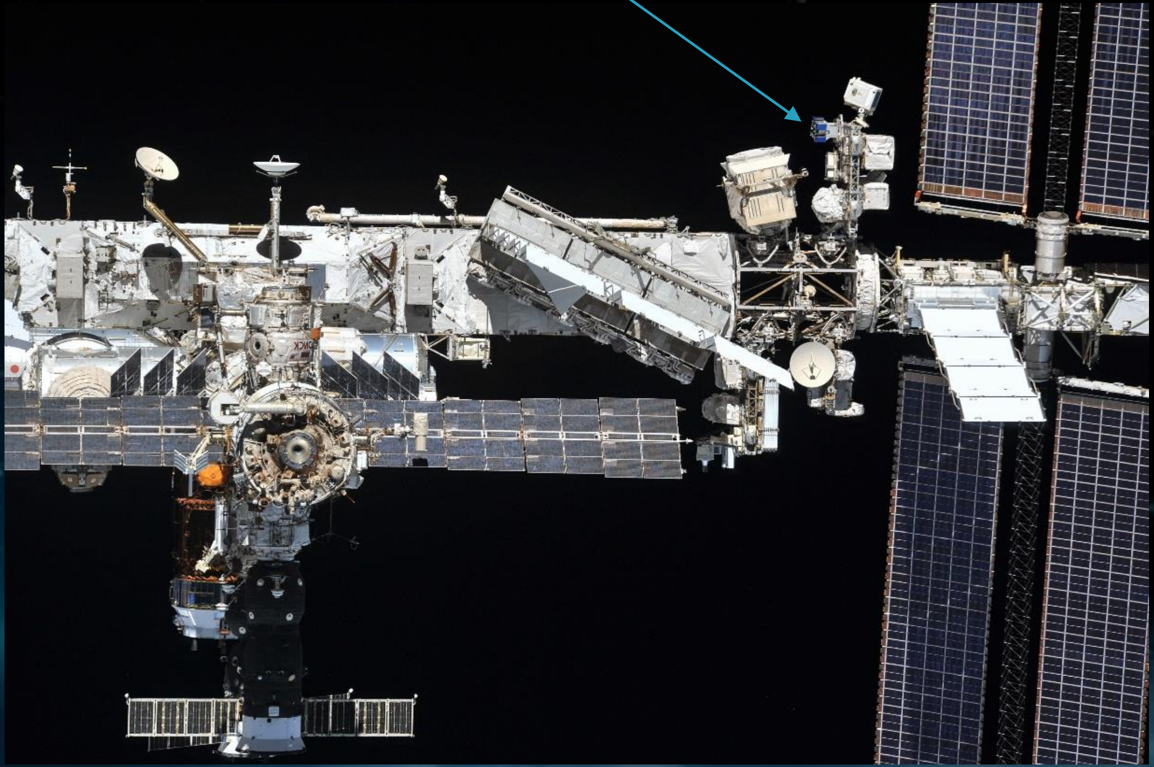
Testing on the ISS

- The MISSE-FF program
- We sent up an encapsulated perovskite for the first time
- Survived 10 months on orbit
  - ~5000 thermal cycles, -80C - +70C
  - atomic oxygen, radiation, plasma









Right there!

Conclusions

- Putting stuff in space is hard. Making it cutting edge materials science is hard also.
- There’s lots of paperwork and junk
- But it’s a blast! Besides most technical career paths have quality management systems to adhere
- So much about the lunar charging environment is unknown
- But there is great promise from some new materials e.g. perovskite solar cells.

Thanks to you and them

- PILS
  - Jeremiah McNatt
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  - Abigail Rodriguez
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  - Kate McGinness
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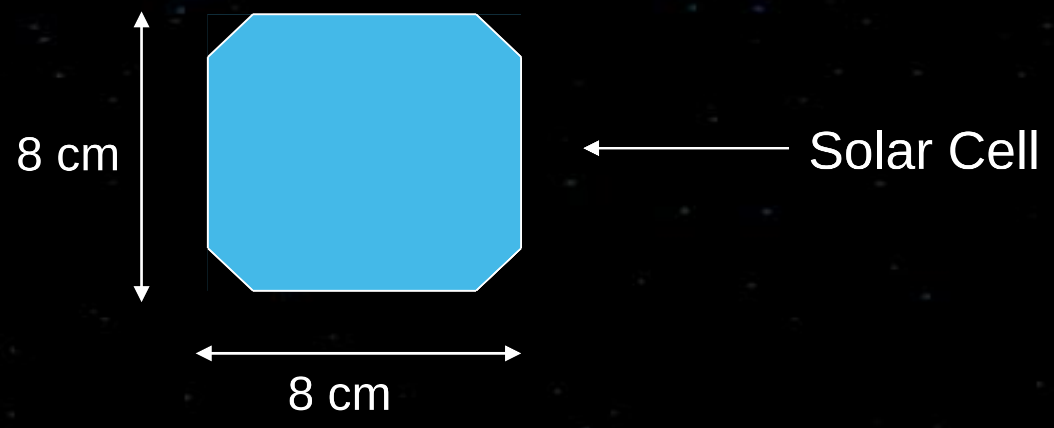
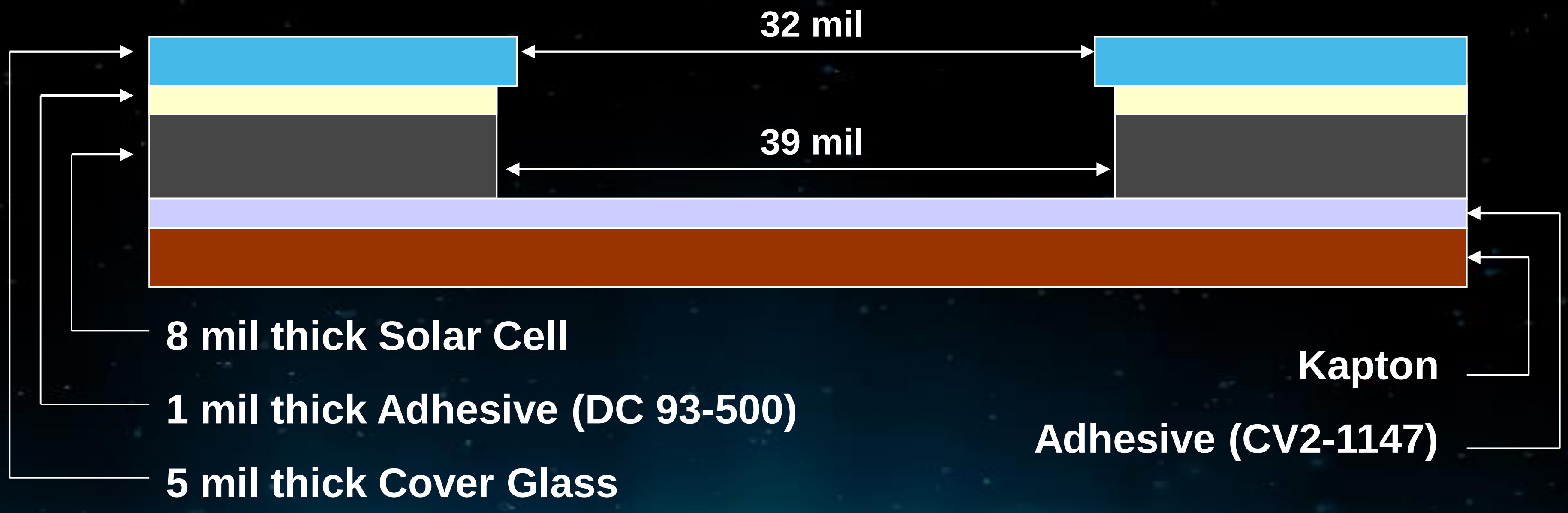
  - Kaitlyn VanSant
  - Kyle Crowley
  - Sayantani Ghosh
  - Joey Luther
  - Maikel van Hest
  - Sam Erickson
  - William Delmas
- Spacecraft charging
  - Boris Vayner
  - Joel Galofaro
  - Dale Ferguson
  - Linda Parker
  - Joe Minow

backup

Typical solar array





8 mil thick Solar Cell

1 mil thick Adhesive (DC 93-500)

5 mil thick Cover Glass

Kapton

Adhesive (CV2-1147)

SBIR

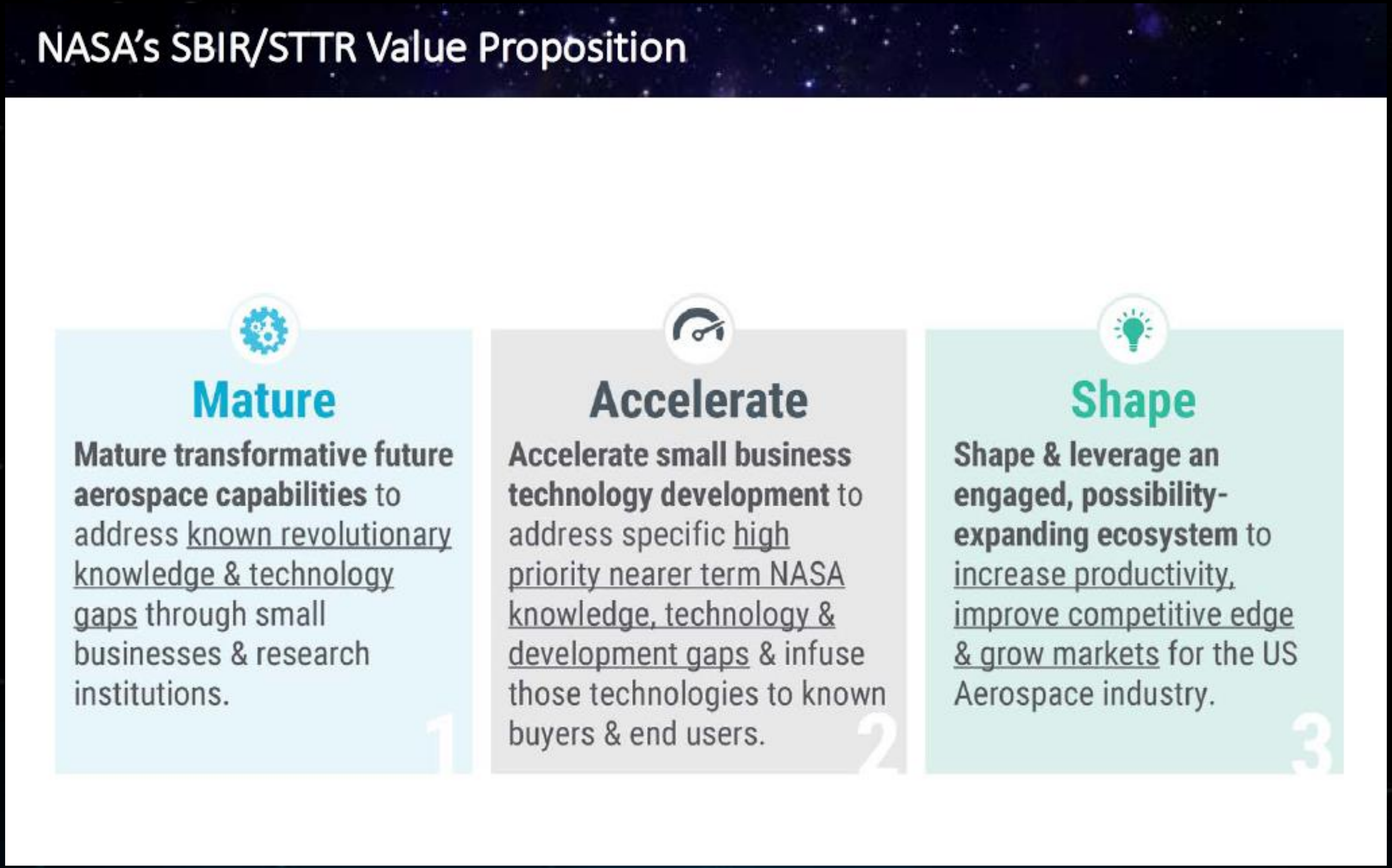
NASA's SBIR/STTR Mission & Vision

MISSION

Create opportunities through SBIR/STTR awards to leverage small business knowledge and technology development for maximum impact and contribution

VISION

Empower small businesses to deliver technological innovation that contributes to NASA's missions, provides societal benefit, and grows the U.S. economy



NASA’s SBIR/STTR Value Proposition

Mature

Mature transformative future aerospace capabilities to address known revolutionary knowledge & technology gaps through small businesses & research institutions.

1

Accelerate

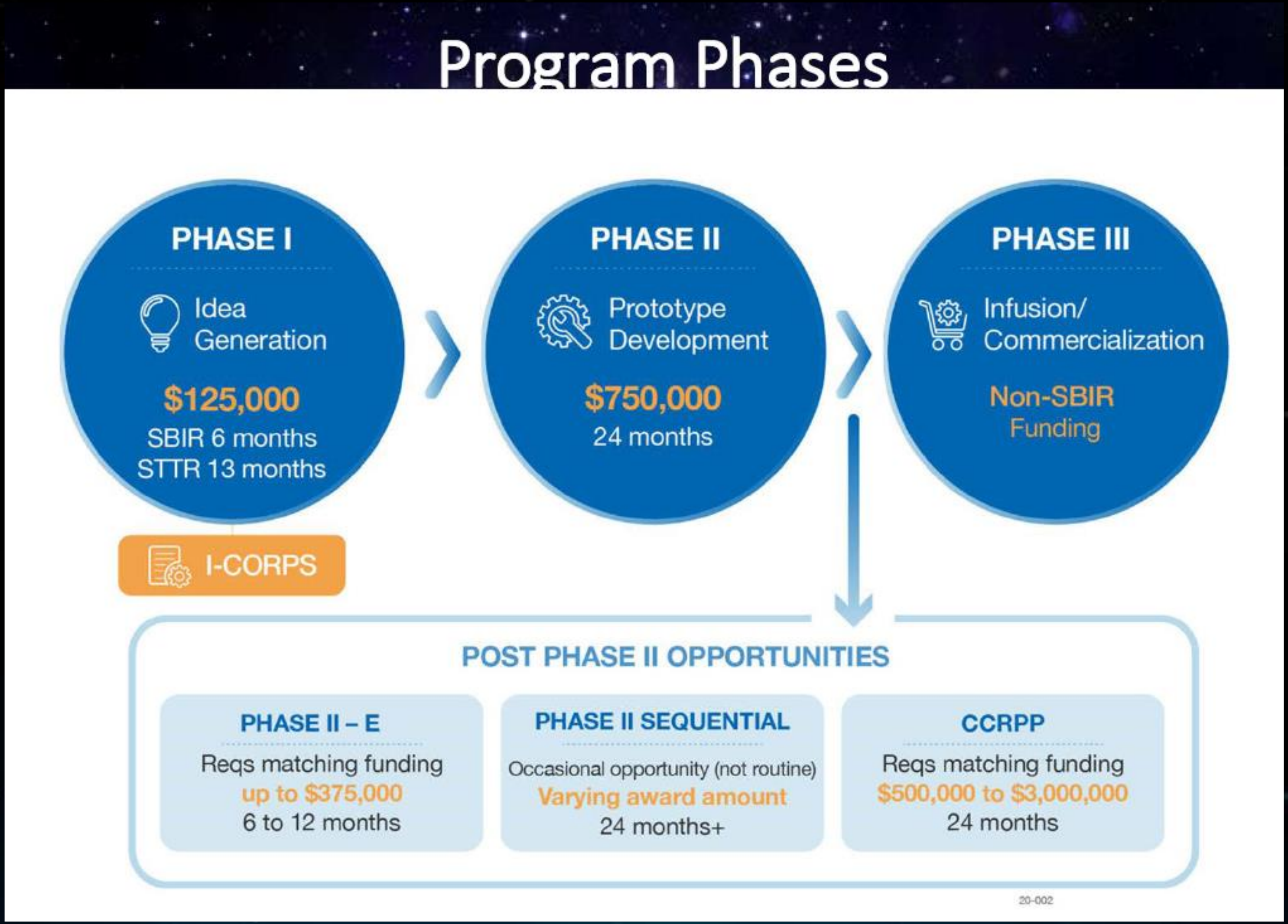
Accelerate small business technology development to address specific high priority nearer term NASA knowledge, technology & development gaps & infuse those technologies to known buyers & end users.

2

Shape

Shape & leverage an engaged, possibility-expanding ecosystem to increase productivity, improve competitive edge & grow markets for the US Aerospace industry.

3



Program Phases

PHASE I

Idea Generation

$125,000

SBIR 6 months
STTR 13 months

I-CORPS

PHASE II

Prototype Development

$750,000

24 months

PHASE III

Infusion/ Commercialization

Non-SBIR Funding

POST PHASE II OPPORTUNITIES

PHASE II – E

Reqs matching funding
up to $375,000
6 to 12 months

PHASE II SEQUENTIAL

Occasional opportunity (not routine)
Varying award amount
24 months+

CCRPP

Reqs matching funding
$500,000 to $3,000,000
24 months

20-002

Photovoltaic Research and Development at GRC

Research and development on a wide variety of solar cell, blanket component, and array concepts to support NASA missions and aerospace technology needs.

Partners range from universities, non-profit organizations and small/large businesses to various NASA Centers and other Government agencies.

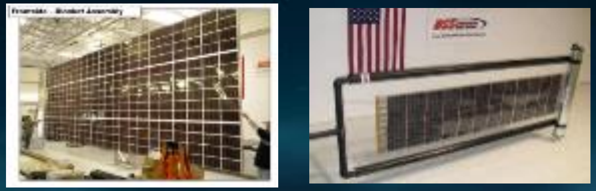
Solar Cell Measurement and Performance Evaluation

High Efficiency III-V, Nanomaterials and Nanostructures Photovoltaic Development

Extreme Environment Operation of Solar Arrays

Solar Cell Air Mass Zero Calibration

Advanced Blanket and Array Technologies



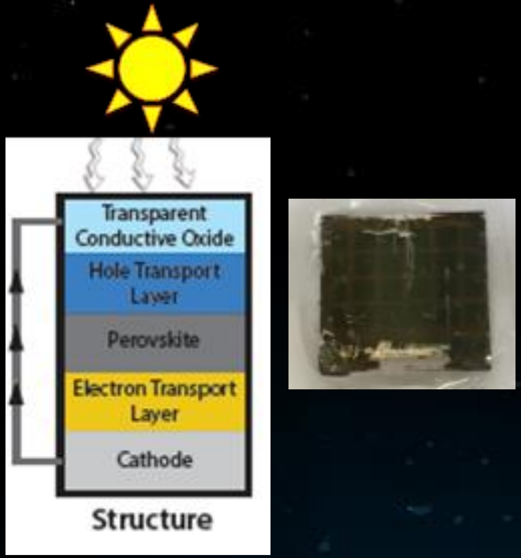
Solar Array Arcing and Charging Effects

PV Supports Broad Range of TRL Activities

TRL 2-4

Examples:

- Advanced Solar Cell Materials and Designs
- Blanket Designs, Materials and Array Concepts



Perovskite solar cell

TRL 5-6

Examples:

- Advanced Technology Performance, Reliability, and Environmental Interactions R&D and Evaluation

Thermal balance & arcing of blanket technology

Accurate cell efficiency measurements

TRL 7-9

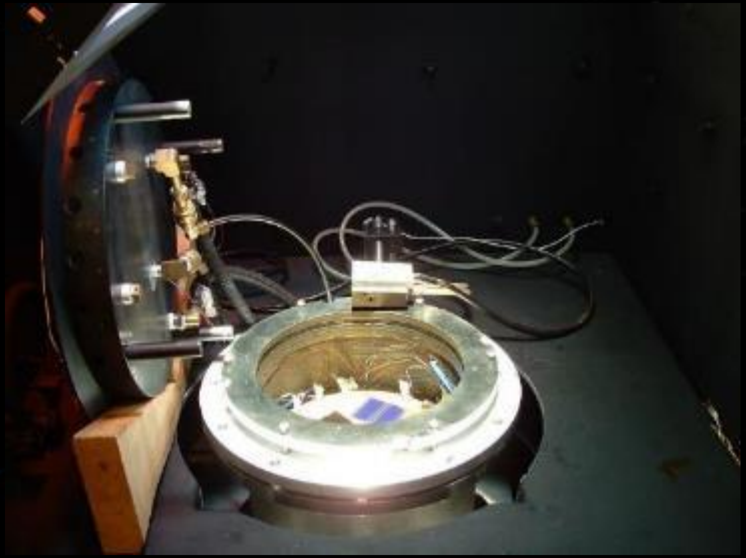
Examples:

- Support NASA Missions Through Technical Expertise
- Evaluate Flight Data for New Technology
- Development of Standards and Guidelines

SCARLET array on Deep Space 1

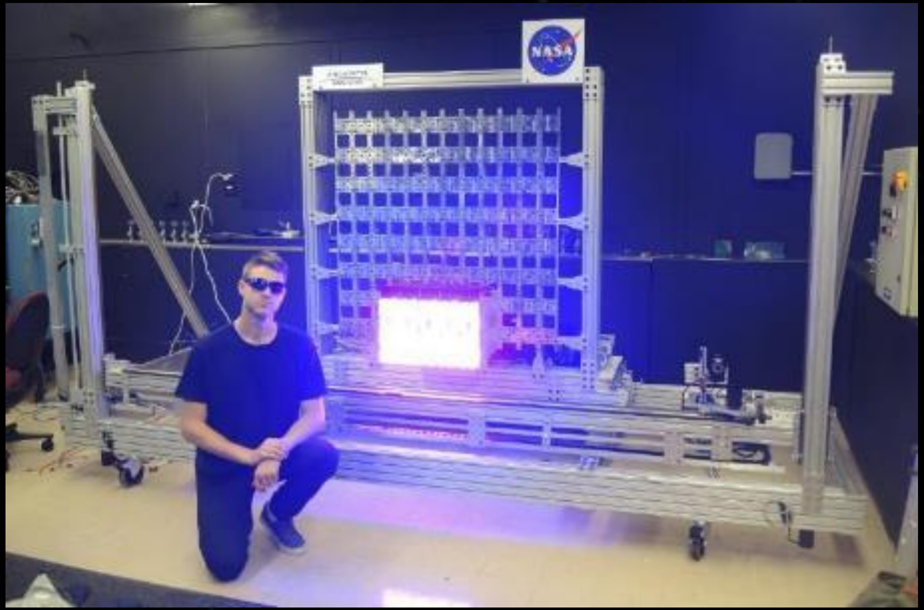
Mars Rover Experiments

X-25 Triple Source Solar Simulator



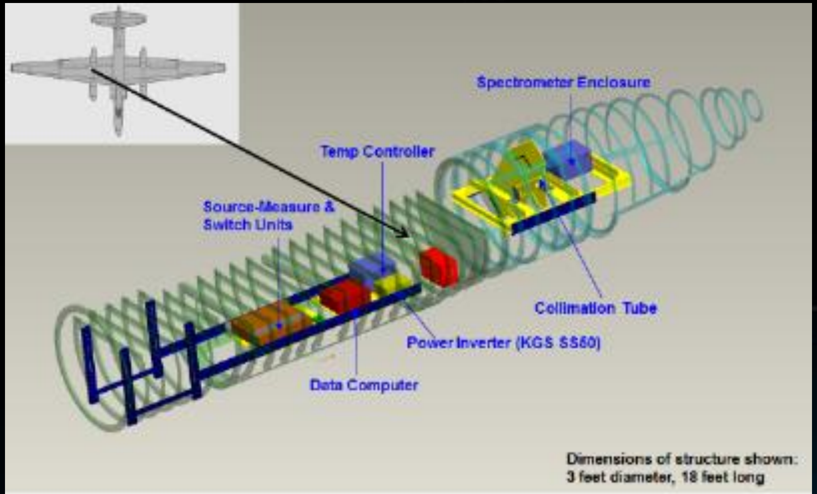
- Unique asset developed at GRC
- LILT and Temperature Coefficients
- Temperature Range: -160°C to 100°C
- Main workhorse for past 10-15 years

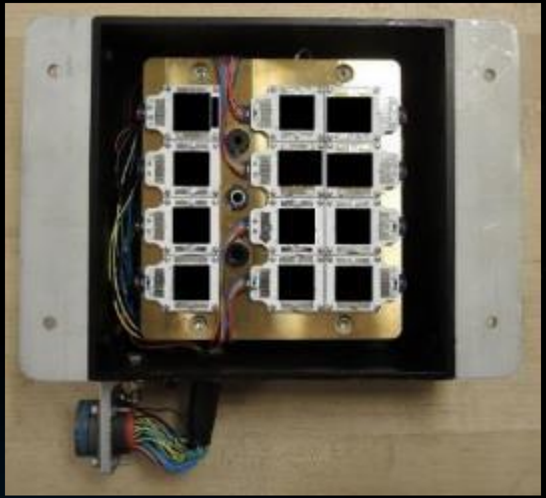
Angstrom Designs Multisource LED Solar Simulators



- Capable of testing emerging technologies up to six junctions
- Keeps GRC ahead of newly emerging technologies
- Developed with assistance from GRC via two Phase II SBIR's
- Successfully commercialized technology

ER-2 High Altitude Calibration Platform





- Generates primary AM0 Standards for GRC
- Supports testing for GRC programs
- Cells flown for PV community including other government and industry

PV Technology Needs of Next Decadal Outer Planet Missions

Mission Type	Mission	Needs*	Benefits
Orbiters/flyby	Jupiter Saturn Europa Titan Enceladus	High Efficiency Solar Cells (>38%@ 1AU) LILT Capability (> 40% at 10 AU) High Power Solar Arrays (>50 kW@ 1AU) High Specific Power Solar Arrays (300 W/kg @ 1AU) Radiation	Enhancing & Enabling

PV Technology Needs of Next Decadal Inner Planet Missions

Mission Type	Mission	Needs*	Benefits
Orbiters	Venus & Mercury	Low- Medium Temperature Operation High Solar Intensities	Enhancing
Aerial	Venus	Medium-High Temperature Operation Venus Solar Spectrum Operation Operation in Corrosive Environments	Enabling/ Enhancing
Landers/Probes	Venus	High Temperature Operation (> 450C) Low Solar Intensity Operational Capability Venus Solar Spectrum Operation Operation in Corrosive Environments	Enabling
Rovers	Venus	High Temperature Operation (> 450C) Low Solar Intensity Operational Capability Venus Solar Spectrum Operation Operation in Corrosive Environments	Enabling

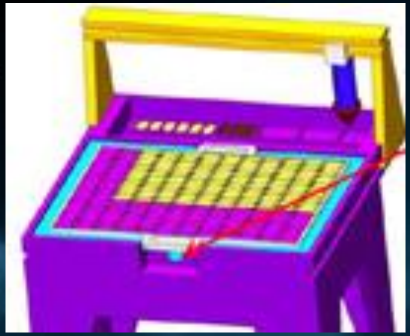
PV Technology Needs of Next Decadal Mars Missions

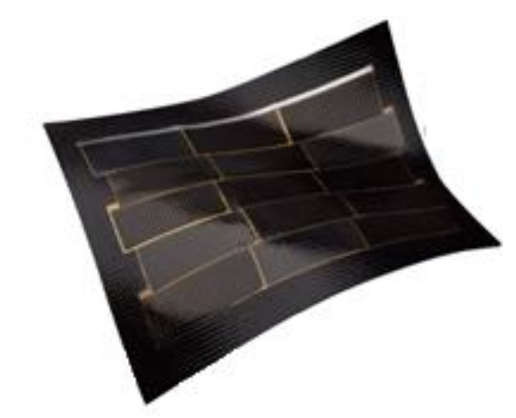
Mission Type	Mission	Needs*	Benefits
Orbiters	Mars Com Orbiter	High Efficiency Solar Cells (>35%) Medium- High Power (2-30 kW) High Specific Power (> 200 W/kg)	Enhancing
Landers	•Robotic Precursor Landers	High Efficiency Solar Cells (> 35%) High Specific Power Solar Arrays (> 200 W/kg) Dust Tolerant Solar Arrays	Enabling/ Enhancing
Rovers	Sample Retriever Rovers	High Efficiency Solar Cells (>35%) High Specific Power Solar Arrays (> 200 W/kg) Dust Tolerant Solar Arrays	
Aerial Vehicles	Helicopter	High Efficiency Solar Cells (> 40%) Light Weight Solar Cells	
Mars Sample Return	MSR	High Efficiency Solar Cells High Specific Power Solar Arrays (> 200 W/kg)	

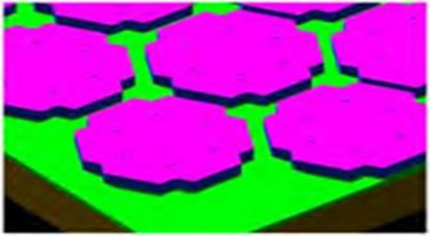
Need

Cell and blanket technologies and manufacturing processes that reduce overall array costs

- Cells: new cell technology comparable to SOA with reduced cost at various production levels
- Blankets: blanket technology compatible with the space environment at costs less than SOA
- Electrical Interconnects and Cell Protection: automated processes for stringing cells and providing protection from the space environment







Internal GRC Low TRL Photovoltaic Research Programs

Dust Abrasion Damage on Martian Solar Arrays

Understand the effects of Martian dust abrasion on solar cell and solar array materials including coverglass, coatings, composite materials, and module substrate materials

Objectives

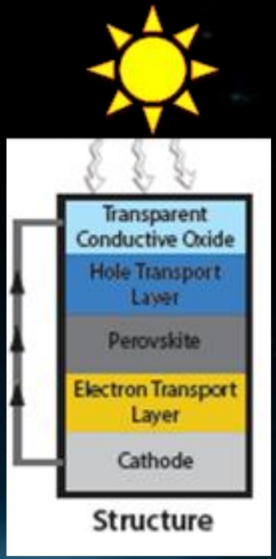
- Test solar cells and array component surface and optical qualities prior to exposure
- Utilize conventional sand blasting system modified with Mars dust simulant media to abrade materials
- Measure surface and optical qualities of the materials

Perovskite-based Photovoltaics

Use existing testing standards to determine the feasibility of space qualifying perovskite solar cells.

Objectives

- Qualify a cohort of functional high efficiency devices according to several relevant performance and lifetime qualification tests
- Research best encapsulants for space applications with low moisture content, barrier layers to preclude moisture ingress
- Perform thermal cycling from -100 to +100 C up to 1000 cycles (material limit is about 95C)
- Perform radiation testing – 1 MeV electrons



Mid-TRL Research Areas

Development of blanket and array materials/structures to improve specific power, reduce stowed volume for high power arrays

Testing solar simulator calibration standards

- ER-2

Measuring cells at Air Mass 0 conditions

- Temperature coefficient measurements
- HIHT/LILT measurements

Testing cells and blankets for durability

- Thermal cycling
- Thermal balance
- Plasma interactions

Semiconductor and Nano-Structured Materials Characterization

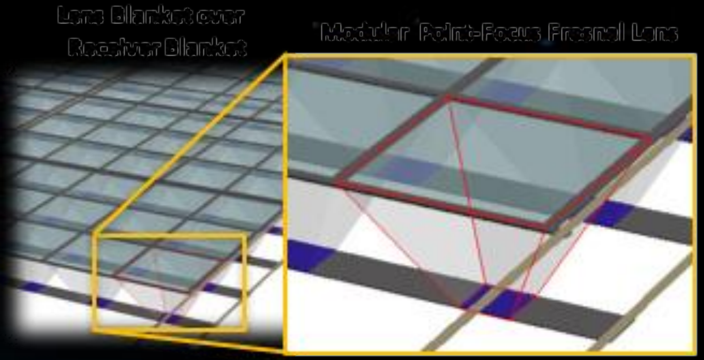
EESP Option 1 Contract Awards

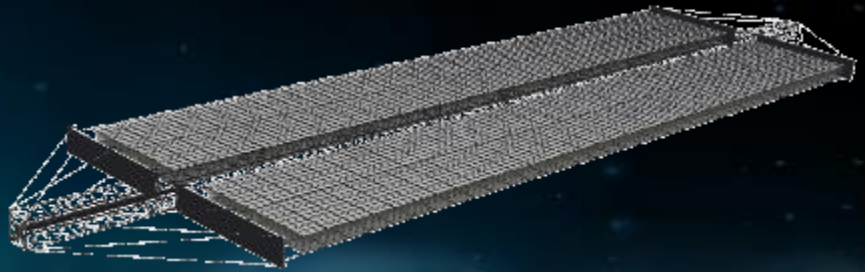
Johns Hopkins Univ. Applied Physics Lab

DSS Roll Out Solar Array (ROSA) equipped with Flexible Array Concentrator Technology (FACT) and Inverted Metamorphic solar cells

Orbital ATK

Point-focus lens concentrator blanket compatible with the Compact Telescoping Array (CTA) platform utilizing state of the art ZTJ solar cells



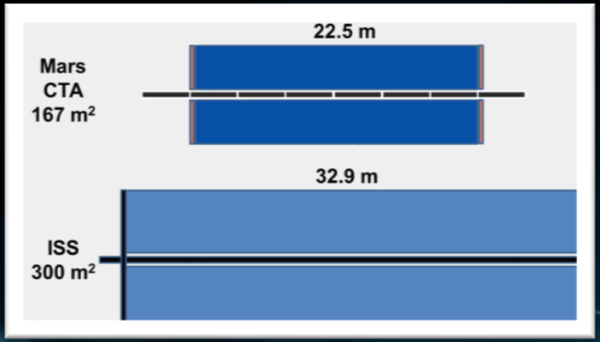


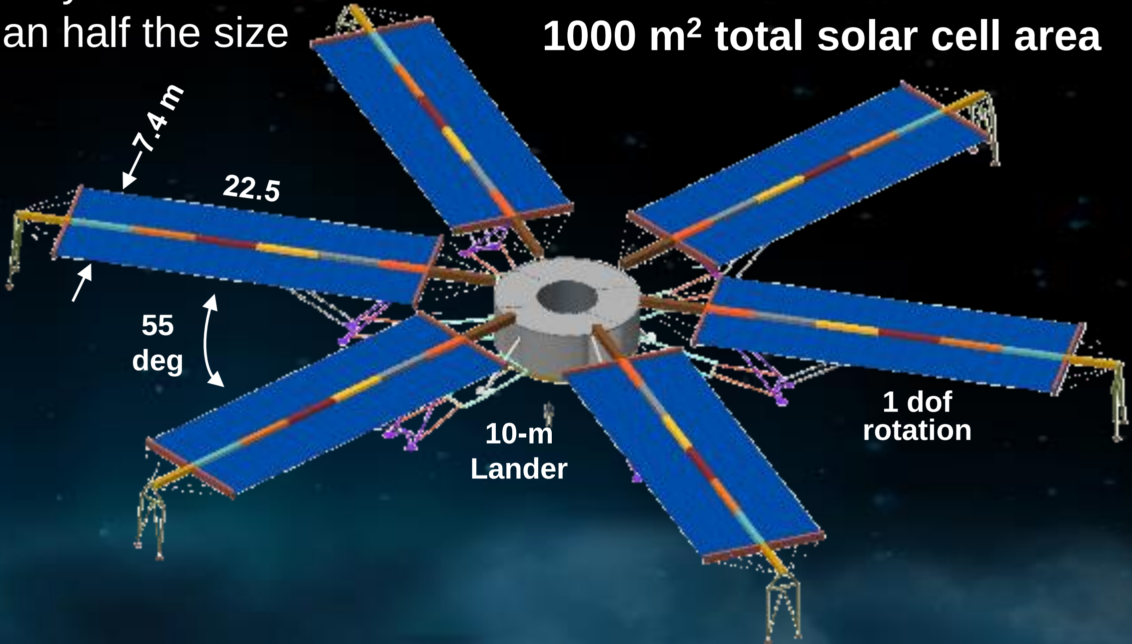
Solar Arrays with Storage (SAWS) Seedling Study

Goal: Develop a credible solar array/energy storage system alternative to nuclear for Mars surface electrical power

- 40 kW class architecture / 10 kW class “modules”
- Can be delivered and deployed on the 1st robotic mission and remain functional for multiple crew missions

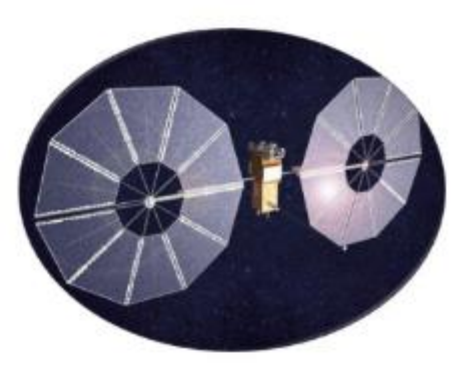
- This represents one configuration that provided the necessary deployed area of solar array
- Each CTA array is 167 m^2, more than half the size of an ISS solar array

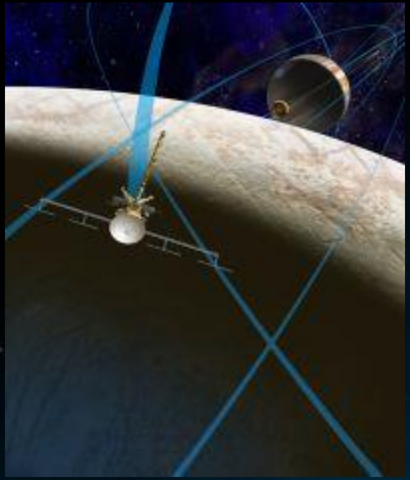



1000 m^2 total solar cell area

High-TRL Research Areas

- Support NASA Missions Through Technical Expertise
- Evaluate Flight Data for New Technology
- Development of Standards and Guidelines
- Power for CubeSat applications





Ultra-Modular High Power Solar Array Architecture

- Compact stowed packaging
- Low mass
- Modular architecture allows ultrahigh power level capability and many configurations
- Very lowcost (low-complexity, reliable deployable structurewith low piece parts / failure modes)

CubeSat Array Testing

Solar simulator size allows testing of CubeSat arrays under 3U at Air Mass Zero

Example:

- X25 - Health check of damage cell to determine power loss and resulting impact to panel operation
    - ✓ 6.3 W to 5.31 W, 15.7% power loss
- LED Simulator – Health check and luminescence of damaged cell to pin-point damaged region
- Optical Microscopy of cell to verify that damage was not limited to cover glass
    - ✓ Observed fracture of device
    - ✓ Observed finger interruptions