Modular Operations, Resource & Power Hub (MORPH)

Space Power Workshop
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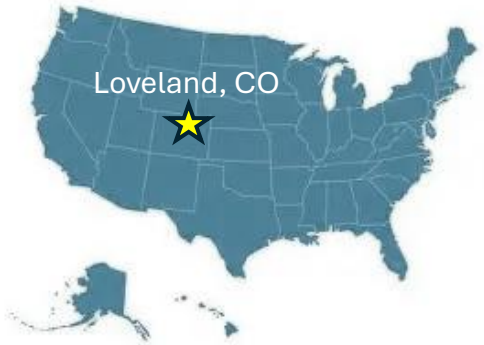
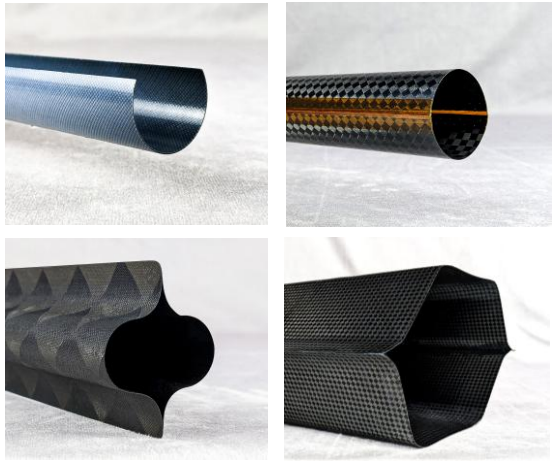
AS9100 Certified
DCAA Approved
CMMC Compliant

Opterus Overview – Advanced Space Structures & Systems

- **US-Owned & Operated Aerospace Contractor**
  - Loveland, CO
- **Vertically Integrated**
  - 26,500 sq ft engineering & production facility
  - System & component design
  - Composites manufacturing
  - Flight systems build & test
- **Certified Business Systems**
  - AS9100 certified
  - CMMC L2 compliant
  - DCAA/DCMA approved



Opterus Overview – Advanced Space Structures & Systems

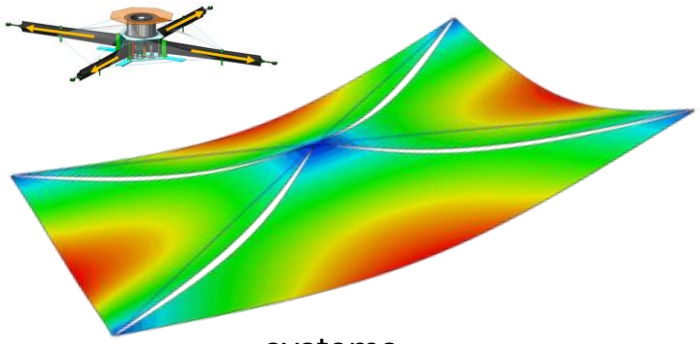


rollable booms & masts

composite hinges

Products & Services

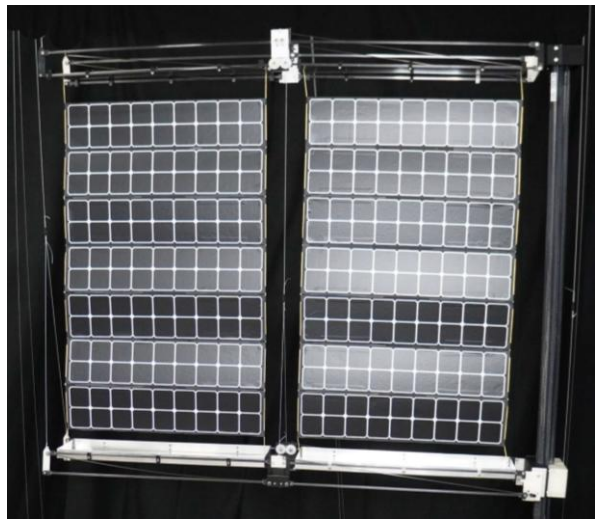
1. Rollable Booms & Composite Hinges
2. RF Antenna Systems
3. Solar Array Systems
4. Precision Deployable/ISAM Structures



systems

deployers

antennas



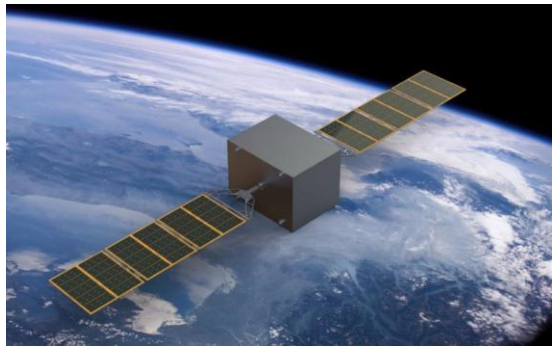
solar arrays

Opterus Overview – Advanced Space Structures & Systems

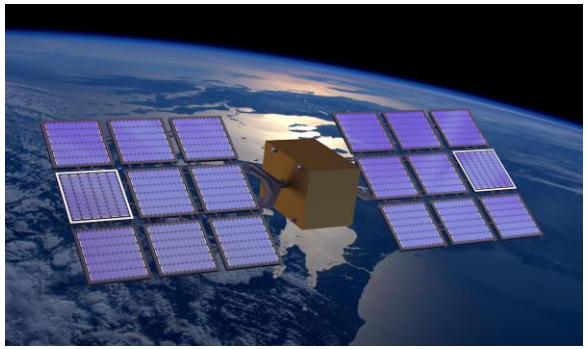
Solar Arrays

- Opterus specializes in non-traditional solar array structures that offer a performance advantage (e.g., W/kg, kW/m^3) over traditional sandwich panel arrays.
- Opterus partners with cell and SPM manufacturers to integrate their products with Opterus structures to deliver complete wing solutions to our customers.
- Opterus also supplies composite components (booms, hinges) to our customers interested in integrating their own solar array wings.

MOdular Small Sat Arrays (MOSSA)

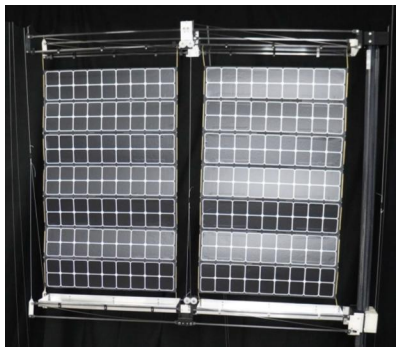


100W-500W



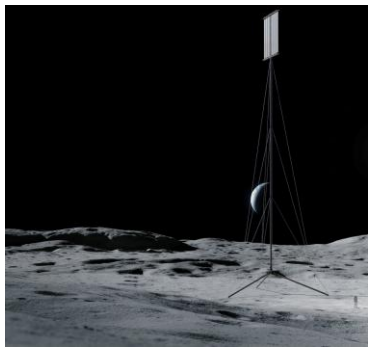
500W-2.5kW

Blanket Arrays



1kW to 10kW+

Vertical Solar Arrays



10kW+

NASA Ignition – Architectural Shift

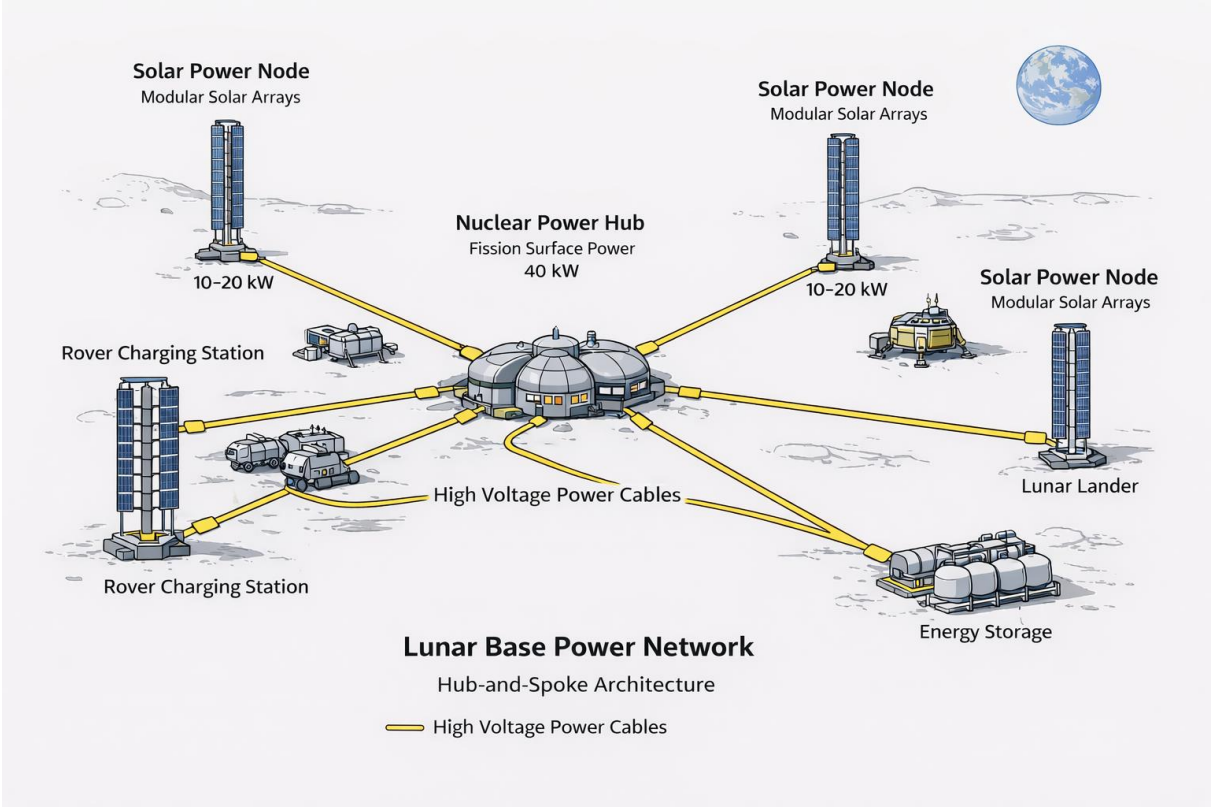
Building the Permanent Base at Lunar South Pole

- Surface systems prioritized
- High-frequency CLPS & human landing cadence
- Phased infrastructure build out
  - Phase 1 (2027+) – Scout
  - Phase 2 (2029+) – Basic Infrastructure
  - Phase 3 (2033+) – Scale Up
- Modular, repeatable deployments
- Commercial + reusable systems

Courtesy NASA

Implications for Power Systems

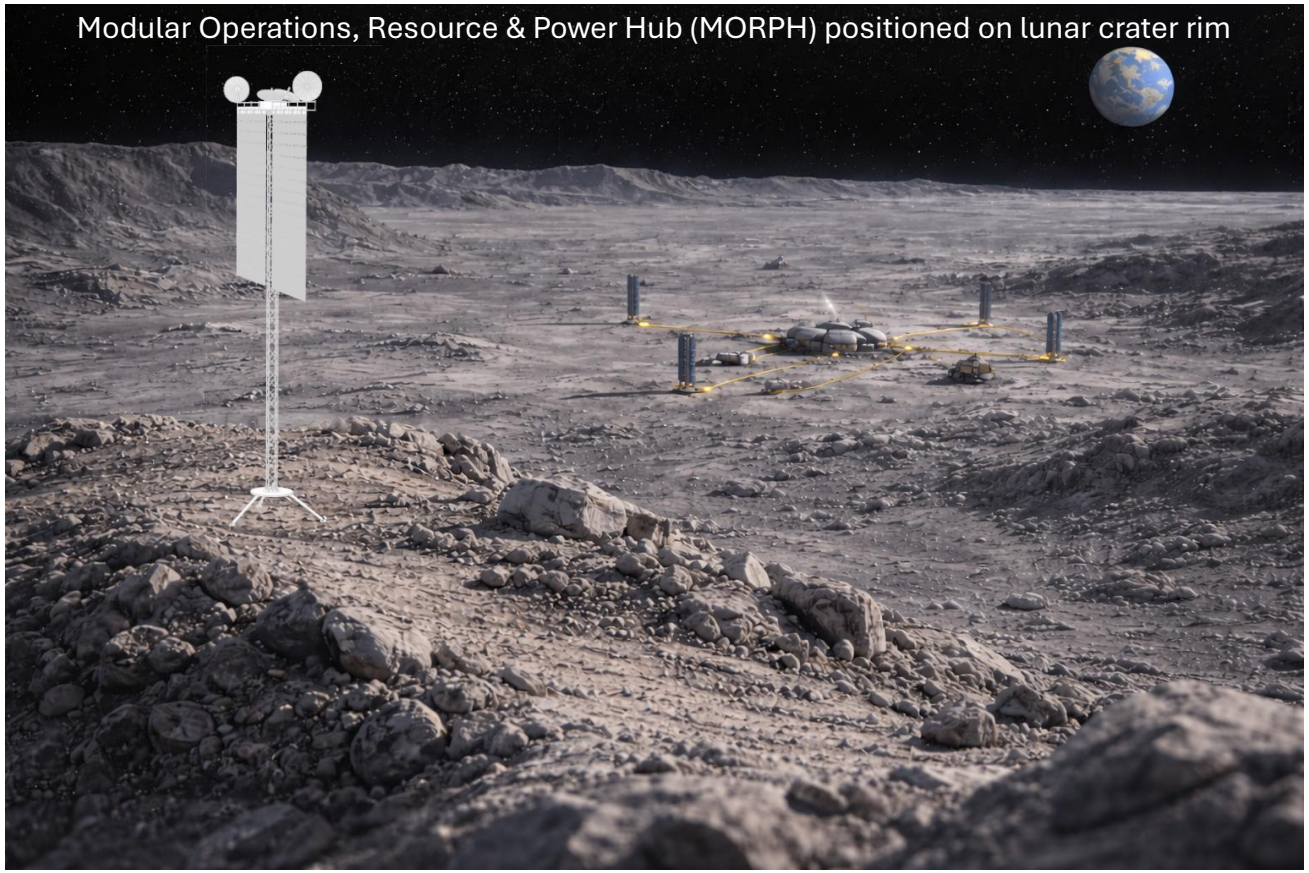
- Incremental build-out
  - Mission by mission
- Fault tolerant grid with distributed generation nodes
  - Primary Hub – Nuclear
  - Secondary Hub – Vertical Solar Array Towers (VSAT)
- VSAT's may be placed "off grid"
  - Kilometers away from base camp
  - Self-sufficient
- VSAT's will have integrated payloads:
  - Communications (cell towers)
  - PNT
  - Situational Awareness
  - Power beaming



Courtesy ChatGPT

MORPH: a VSAT + “cell tower” concept

NASA asked for modular 50 kW VSAT concepts with multi-use structure



Main Design Objectives:

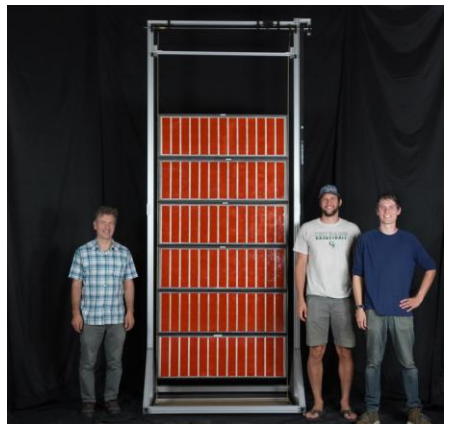
- 35 to 50 meter tower
- 50 kW+ solar power (“industrial scale”)
- 500 kg of additional payload capacity
  - Comms, PNT, SSA, power beaming

Opterus Approach:

- Hybrid deployable and robotically assembled structures
- Focus on logistics, maintenance and scalability
- Lower cost, readily-available panel technology

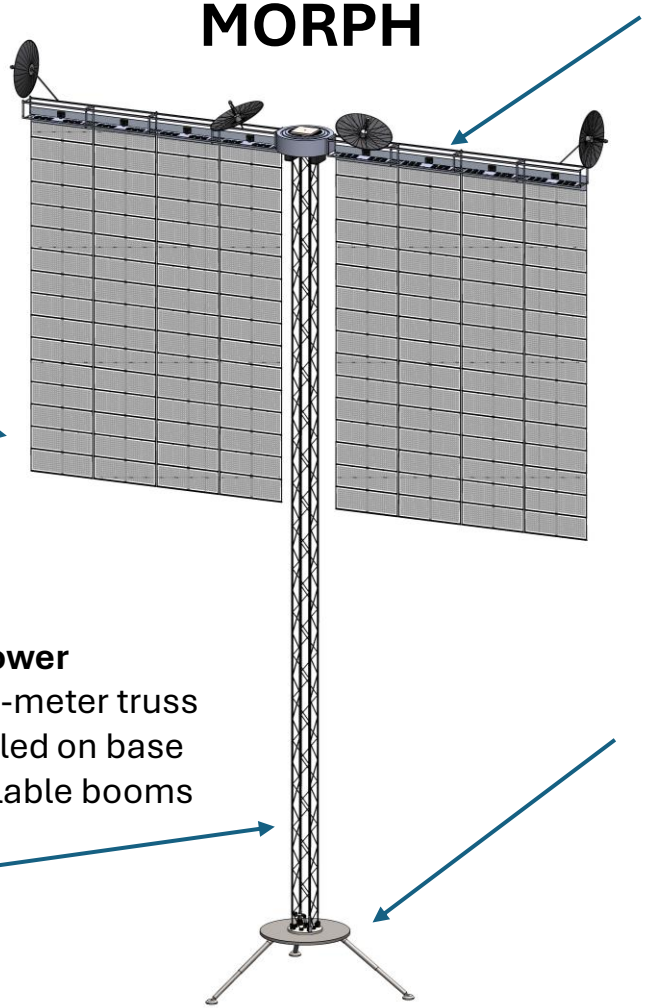
MORPH: a VSAT + “cell tower” concept

VSAT blanket demo



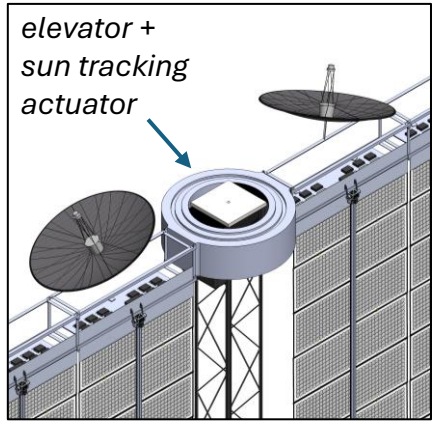
8x 15-meter Solar Blankets

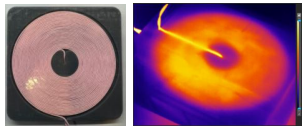
- ~7.5 kW each (Si)
- Deployable/ retractable
- Z-fold or rollable



Mobile Payload Truss (MPT)

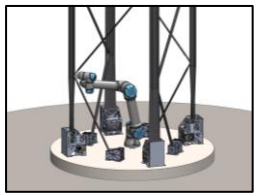
- Provides attachment points
  - Dust-tolerant
  - Misalignment-tolerant
  - Low insertion/ removal force
- Elevator raises & lowers payloads & blankets
- SADA tracks sun
- Z-fold flex harness carries power to base





wireless power transfer

ISAM truss demo for DARPA’s NOM4D project



35-meter Tower

- 1.5 x 1.5-meter truss
- Assembled on base from rollable booms

Self-leveling base

- Tolerates 15° slope
- Aligns to within 0.5° of normal
- Ballast (regolith) or drilled anchors

arctic test of planetary drill with ballast (sandbags)

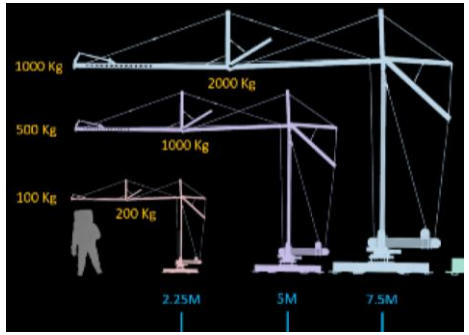
OPTERUS

MORPH: a VSAT + “cell tower” concept

Logistics Considerations

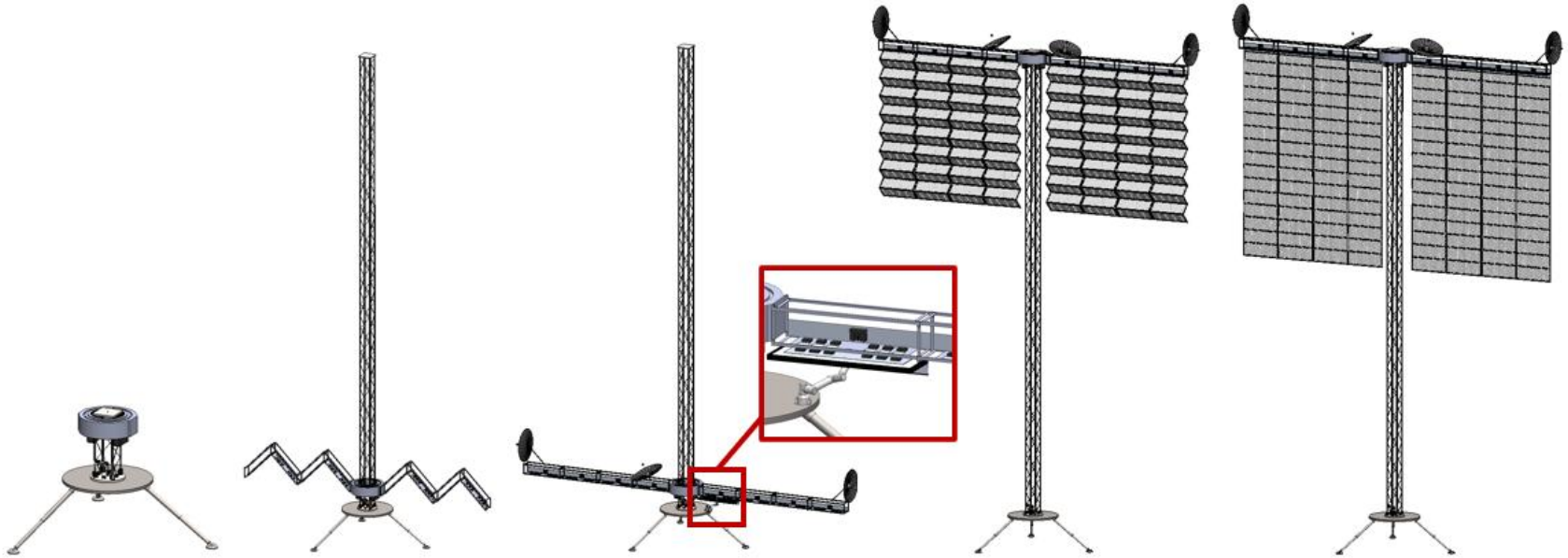
- Modules transportable by Lunar Terrain Vehicle (LTV)

- Assembly by LTV-mounted Lunar Surface Manipulation System (LSMS) and small dexterous robotic arm



MORPH Modular Assembly Process

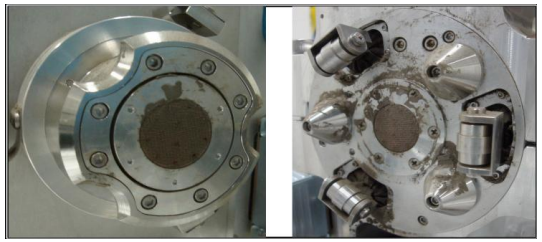
(robotic process with humans in the loop)



1. Base deployed, leveled and stabilized
2. LSMS places tower kit/MPT actuator modules on base
3. Tower assembled by small dexterous arm
4. LSMS attaches MPT deployable truss modules
5. MPT truss deploys
6. LSMS and small dexterous arm collaborate to offload and install solar blanket and payload modules on the MPT
7. Elevator raises MPT with payload and solar blanket modules
8. Solar blanket modules are deployed
9. MPT tracks sun
10. Payloads point independently via their gimbals
11. Solar blankets retracted and MPT lowered for repairs/upgrades

Key Challenges & Questions

- ✓ Robotic assembly stability
  - Structural flexibility and dynamics
- ✓ Robot system accuracy, dexterity, complexity
- ✓ Power cable routing
  - Outfitting large structure cannot be afterthought
- ✓ Dust mitigation
  - Sliding electrical contacts and slip rings must be completely sealed or avoided
- ✓ Thermal environment and management
- ✓ Low mass/volume modules for transport
- ✓ Low cost (ideally nearly expendable)



"Dust tolerant" electromechanical connectors are typically heavy, bulky, complex, require large forces to mate/de-mate and are life limited.

Key Challenge:

Electrical power integration of panel, payload, structural modules

Desired Attributes:

Dust-tolerant, low force, low profile (mass, volume), low cost

Hypothetical Solution:

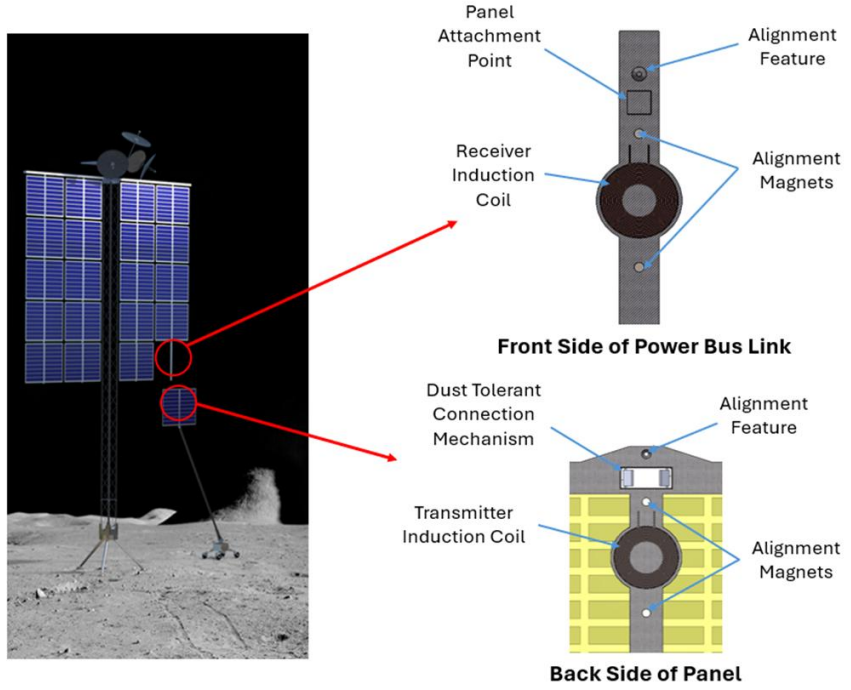
Wireless Power Transfer (WPT) at module interfaces

Key Questions:

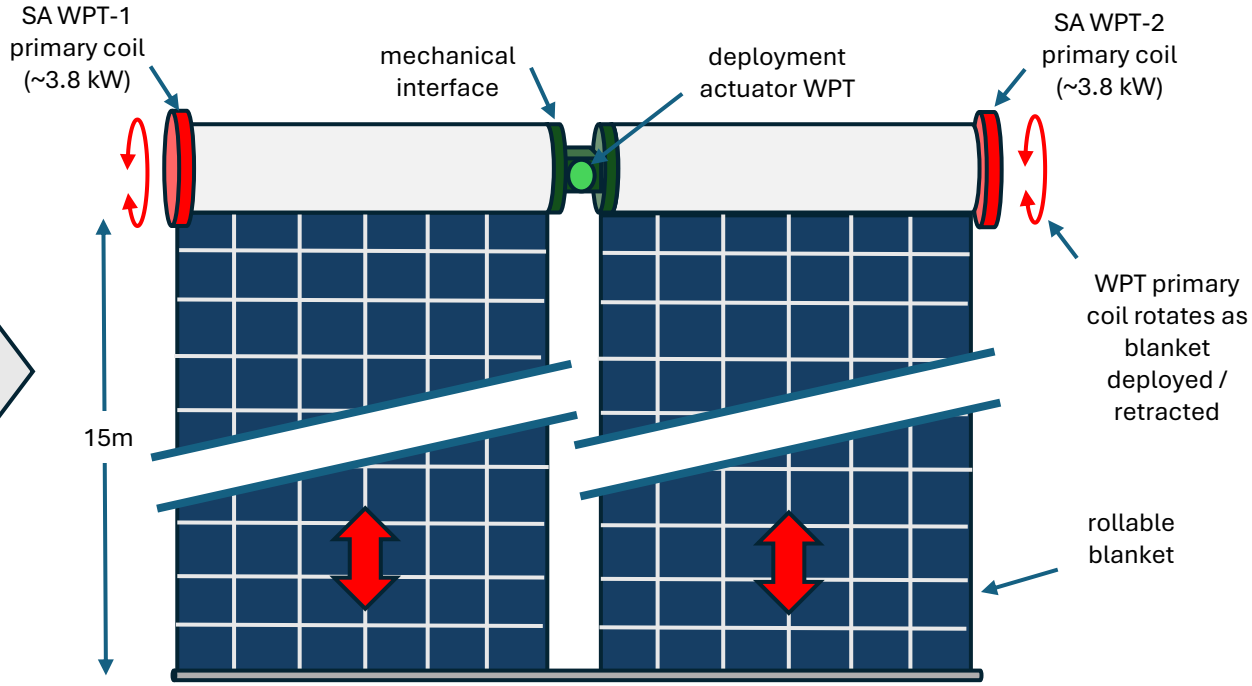
- How small can the WPT elements be?
- How efficient can the WPT elements be?
- How sensitive is WPT to misalignment and other variables?

Modular Solar Panel Design

- **Initial modular concept:** mosaic of 3m x 3m panels (~1.5 kW each); robot places 40 panels; abandoned for several reasons (e.g., too many modules, inefficient operations, difficult to retract array)



- **Final modular concept:** array of 8x 3m x 15m blankets (~7.5 kW each); integrated actuator deploys and retracts blanket; inductive coupling doubles as "slip ring" as blanket deploys/retracts



Low profile wireless power transfer (WPT) couplings were incorporated into the solar panel module to: (1) reduce installation loads, (2) avoid fouling dust-sensitive electrical contacts and (3) minimize complexity of robotic system

Wireless Power Transfer (WPT) Design

- **Silicon cells** assumed for cost and availability. 386 cells per string combined with temperature range defines the input voltage range of wireless power system (125V to 350V).
- **Battery**: a series string of 84 lithium-ion cells has a maximum charge voltage of 350C and minimum discharge voltage of 210V. This defines the output voltage range of our wireless power system (210V to 350V).
- Considering the industry-standard voltage ratings of ceramic capacitors and power MOSFETs, combined with the NASA-recommended voltage deratings, a maximum system voltage of approximately **350V leaves a broad selection** of cost-effective candidate components.

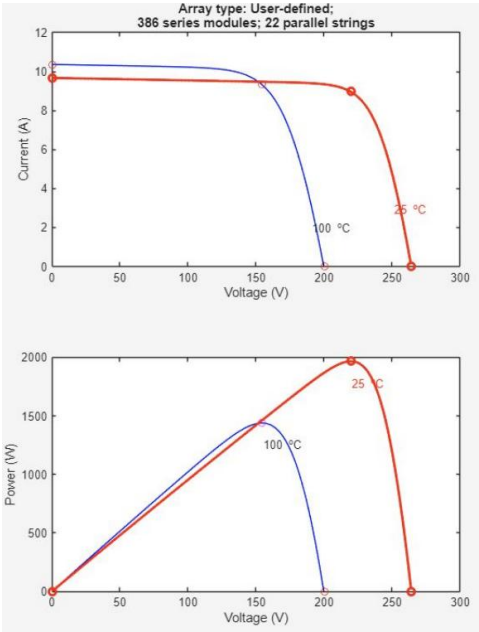
3m x 3m panel	Units	Value
Approx. Power @ 80°C	kW	1.5
Min. Operating Temp	°C	-75
Max. Operating Temp	°C	+125
Cell Type	-	Silicon
String Cells	# cells	386
Approx. WPT Coil Diameter	mm	203
Approx. WPT Coil Thickness	mm	3.2
WPT Coil Separation	mm	3 ± 2
WPT Coil lateral misalignment	mm	< 3

3mx3m Panel String Performance vs Temperature

					STC				
Temp (C)	-75.0	-50.0	-25.0	0.0	25.0	50.0	75.0	100.0	125.0
Voc (V)	348.9	327.7	306.5	285.3	264.0	242.8	221.6	200.3	179.1
Vmp (V)	336.8	305.0	275.0	246.6	219.6	194.0	169.7	146.5	124.4
Isc (A)	8.7	9.0	9.2	9.4	9.7	9.9	10.1	10.4	10.6
Imp (A)	8.0	8.3	8.5	8.7	9.0	9.2	9.4	9.7	9.9
Pmp (W)	2,705.7	2,521.3	2,336.8	2,152.3	1,967.8	1,783.3	1,598.8	1,414.4	1,229.9

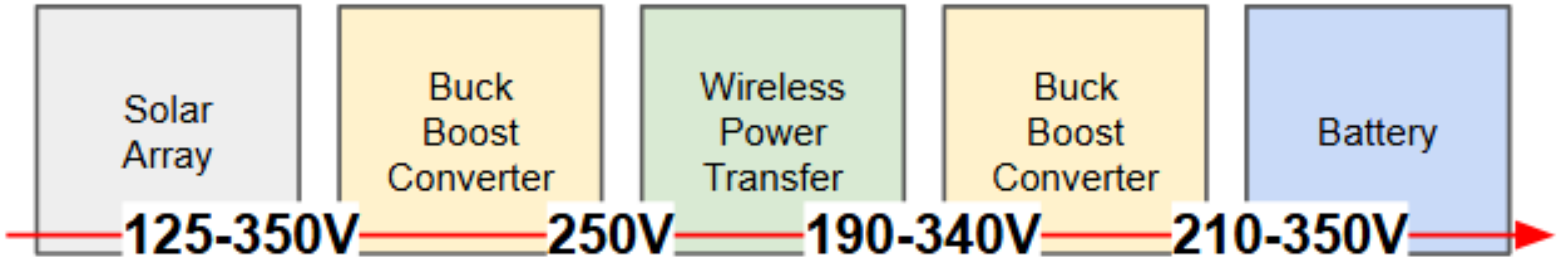
Battery

Series Cells	1.0	84.0
Nominal (V)	3.6	302.4
Charge (V)	4.2	352.8
Discharge (V)	2.5	210.0
Impedance (mohm)	12.8	1,075.2



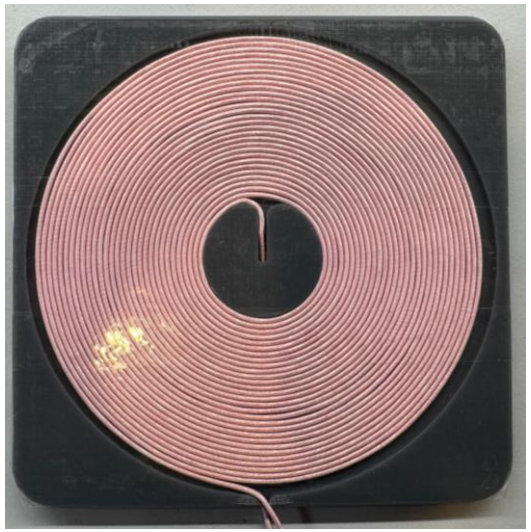
Wireless Power Transfer (WPT) Design

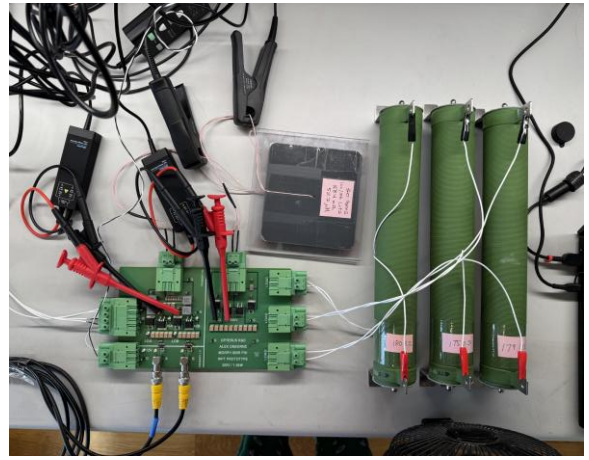
- Designing a wireless power stage with a widely varying voltage gain (while maintaining high efficiency) is exceedingly difficult.
  - MORPH solar panel WPT system must accommodate gains from 2.9V/V (120V solar to 350V battery) to 0.6V/V (350V solar to 210V battery).
- By introducing a buck-boost converter on both sides of the wireless power transfer stage, the design and operation of the overall system is vastly simplified.
  - The solar array is fed into the primary-side buck-boost converter, which outputs a regulated 250V.
  - The wireless power transfer stage then operates open-loop at a fixed-frequency (85kHz, industry-standard) and fixed phase-shift (180deg).
- Because all of the wireless power transfer system “smarts” are on the secondary-side, no wireless communication with the primary-side is required.



Wireless Power Transfer (WPT) Design

- A circular spiral coil design was selected for its flat profile, insensitivity to lateral misalignment, and easy computation of coupling factor without needing to perform finite-element analysis.
- An LCC-S (inductor/capacitor/capacitor-series)[1] compensation scheme was selected for several reasons:
  - Series output capacitance reduces the output voltage dependence on load.
  - LCC input network reduces transistor power dissipation due to zero-volt switching and lower RMS current and provides flexibility to tune voltage gain without altering the resonant frequency.
- A simulation was constructed to verify component selections for voltage and current ratings and also predict the resulting wireless power transfer stage efficiency.
  - Efficiency will vary with load and gap size, with a predicted peak efficiency around 90-95% at 2-3mm of gap.
- A prototype of the WPT (not including Buck-Boost converters) was fabricated and tested.

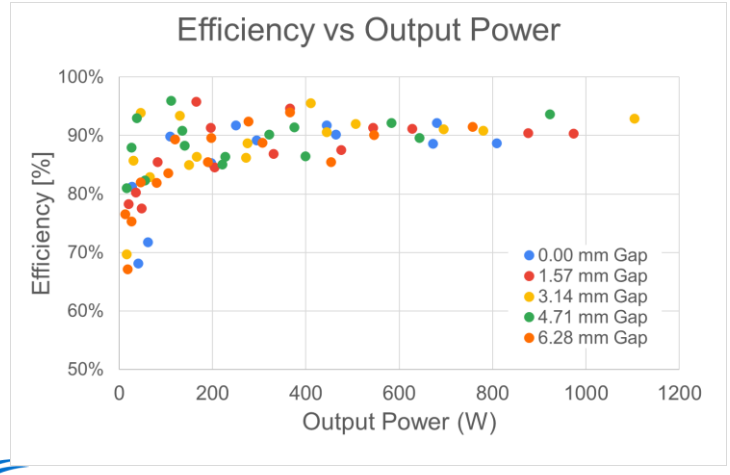


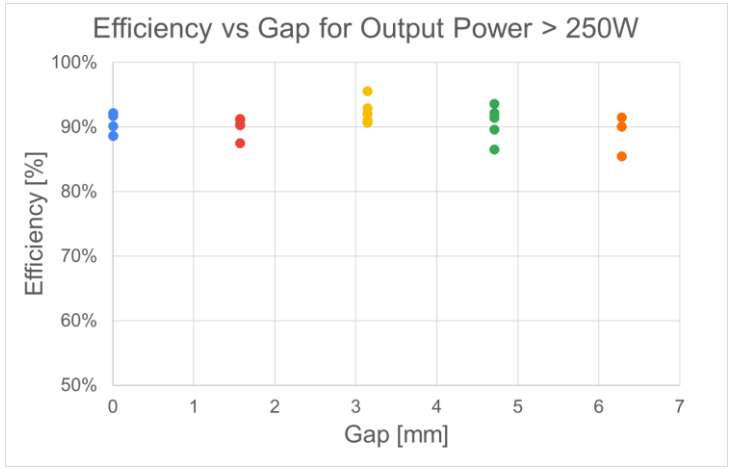


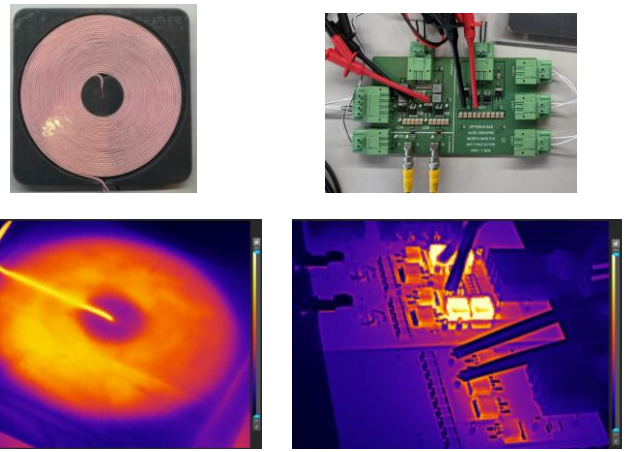
1. W. Wang, et al., "An LCC-S compensated wireless power transfer system using receiver-side switched-controlled capacitor combined semi-active rectifier for constant voltage charging with misalignment tolerance", IET Power Electronics, Vol 16, Issue 7, May 2023.

WPT Prototype Results

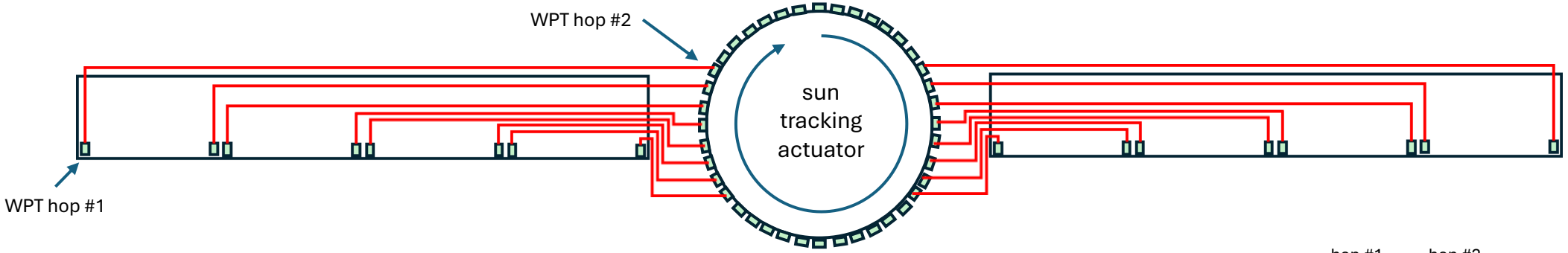
- Scatterplots (below) of the collected data comparing efficiency to output power and gap
  - Above 250W of load, the wireless power stage is over 85% efficient, often over 90%
  - Reduced efficiency at low load was an expected and typical result of all resonant power converters
  - At higher power levels, efficiency is fairly insensitive to gap within the nominal 1mm to 5mm range
- Thermal camera imaging also revealed that no individual components were getting exceedingly hot, with exception of the molded compensating inductors
  - Future revisions should pursue custom inductors with a lower loss magnetic material, which will further increase overall efficiency
  - The coils themselves appear to stay at a very reasonable temperature (<40C)



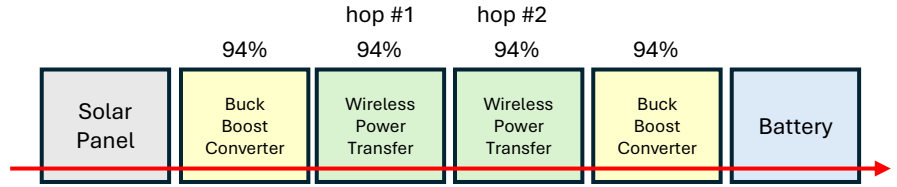




MORPH System Implications



- We assume radiative heat rejection can keep EEE parts within limits
- We assume efficiency can be improved several % with better components
- If one solar array WPT hop, system delivers 49 kW BOL @ 80°C
- If two solar array WPT hops were used:
  - All solar power connections would be wireless to base of tower
  - Overall efficiency from panel output to battery input would be 77% (94% per BB stage, 94% per WPT hop, 600W harness losses) and the system would deliver 46 kW BOL @ 80°C steady state
- Overall MORPH mass would be ~1690 kg not including payload
  - No single module is bigger than what LTR and LSMS can carry

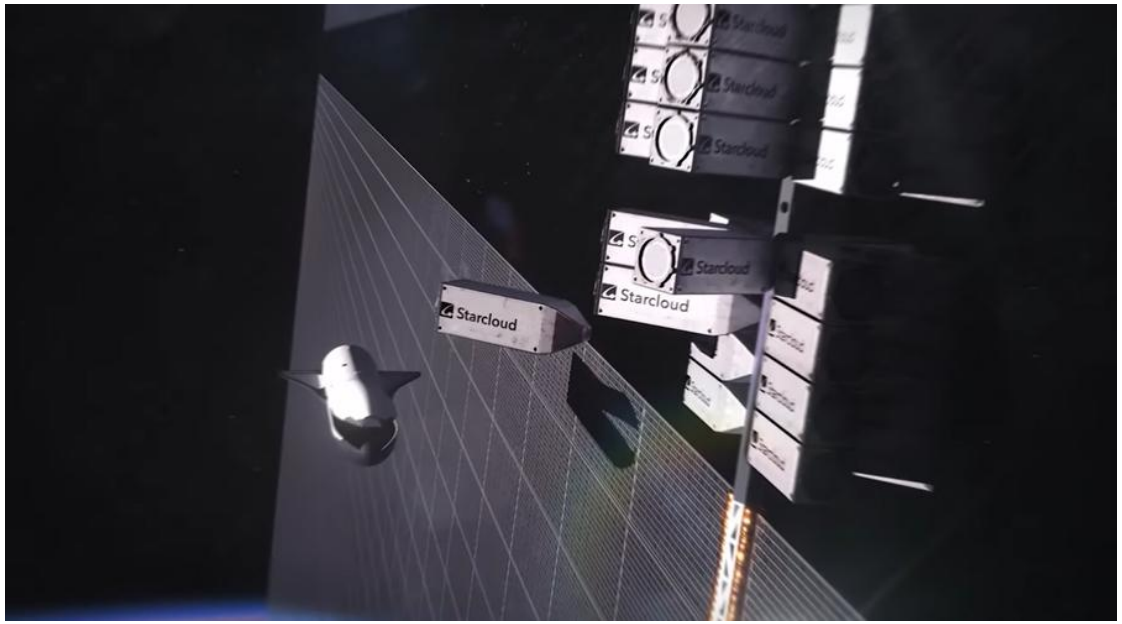


Component	Estimated Mass (kg)	Qty	Total Mass (kg)
Solar panel modules	75	8	600
Arm truss	50	2	100
Elevator cart w/SADA	75	1	75
Elevator winch	25	1	25
Tower flex cable	5	40	200
Payload (arm truss mounted)	500	1	500
Tower truss	80	1	80
Tower truss deployer & robotics	90	4	360
Tower truss base plate	50	1	50
Base platform	200	1	200
Total			**2190**
Total w/o Payload			**1690**

Other Applications of MORPH technology

- Elements of the robotic assembly technology can be used for Mars and On-Orbit applications

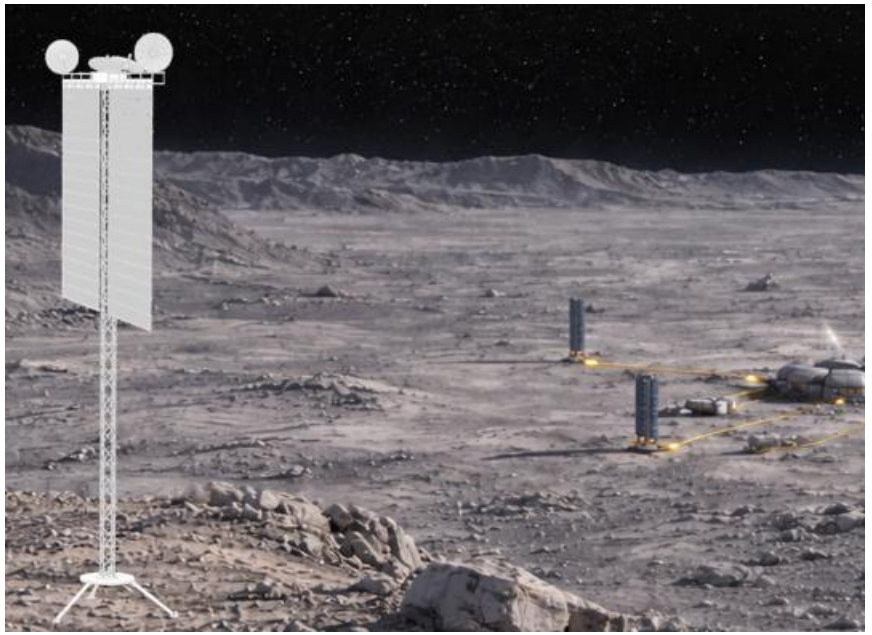
Mars power grid with rollable cleanable solar blankets



Large arrays that need to be serviceable for SBSP and ODC

Conclusions & Thank You!

- MORPH is a viable concept for a modular 50kW-class VSAT and “cell tower” on the Moon
- WPT is efficient and cost effective enough to be considered for robotic dust tolerant and/or flexible structural assembly applications
- Thanks to Alex Osborne, Osborne Electrical Engineering LLC, www.osborneee.com, who designed the WPT architecture!
- Thanks to Jenna Commisso and Katrina Weinmann, MORPH teammates at Opterus!
- Thanks to NASA for sponsoring the MORPH study!



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