Scalable Tethered Power Systems for Planetary Grids

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California Institute of Technology

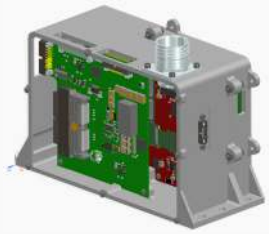
Motivation

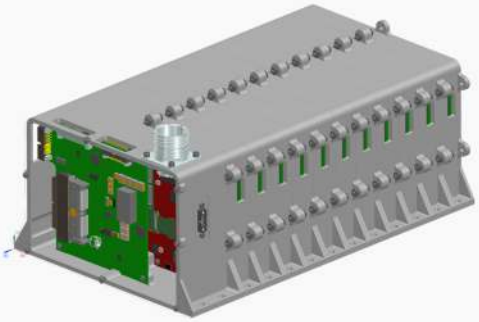
Deploying a Moon Base will require scalable power systems, connecting nuclear and solar power generation to human and robotic assets

Moon Base
Credit: NASA

Multiple Sources Demand Scalable Systems – MVDC Enables Scaling

- Even for short distances and small generation sources, medium voltage DC (MVDC) and AC (MVAC) reduce power distribution mass
- By architecting modular power systems, distribution voltages can be scaled as needed to reduce electronics and cable mass
- As shown below, MVDC is the preferred approach across most applications



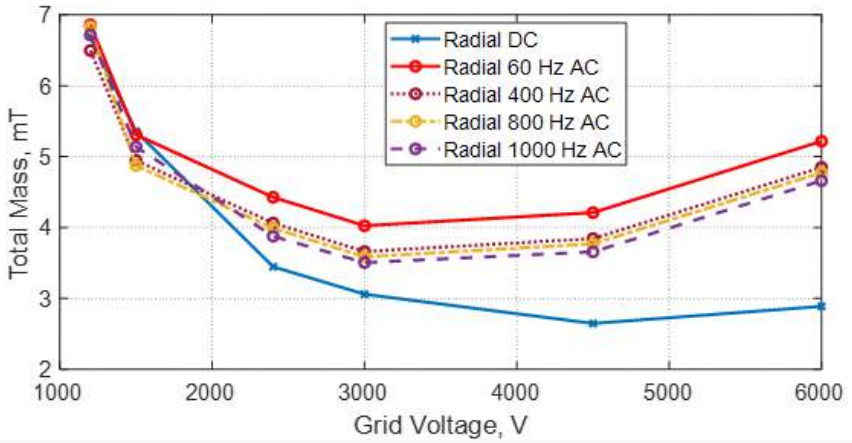


Specification	Radioisotope Thermal Generator	Radioisotope Stirling Generator	Pressurized Rover	Local Vertical Solar Array	Remote Vertical Solar Array	Nuclear Fission Surface Power
Power Generated	150 W	300 W	6 kW	10 kW	10 kW	100 kW
Output Voltage	28 V_{DC}	28 V_{DC}	120 V_{DC}	120 V_{DC}	120 V_{DC}	3000 V_{AC}
Distance to Base	100 m	100 m	100 m	100 m	1000 m	1000 m
LVDC Mass	8.7 kg	14.7 kg	N/A	N/A	N/A	N/A
MVDC Mass	**2.2 kg**	**2.6 kg**	**10.6 kg**	**20 kg**	**105.2 kg**	1147 kg
MVAC Mass	2.8 kg	3.7 kg	37.8 kg	67.9 kg	160.2 kg	**1312 kg**
Recommended Option	**MVDC**	**MVDC**	**MVDC**	**MVDC**	**MVDC**	**MVAC**

AC and DC Power Transmission Systems

Both AC and DC systems have application for Lunar systems. Where DC systems enable low-mass implementations for CLPS and large-scale solar, AC systems simplify integration of nuclear reactors.

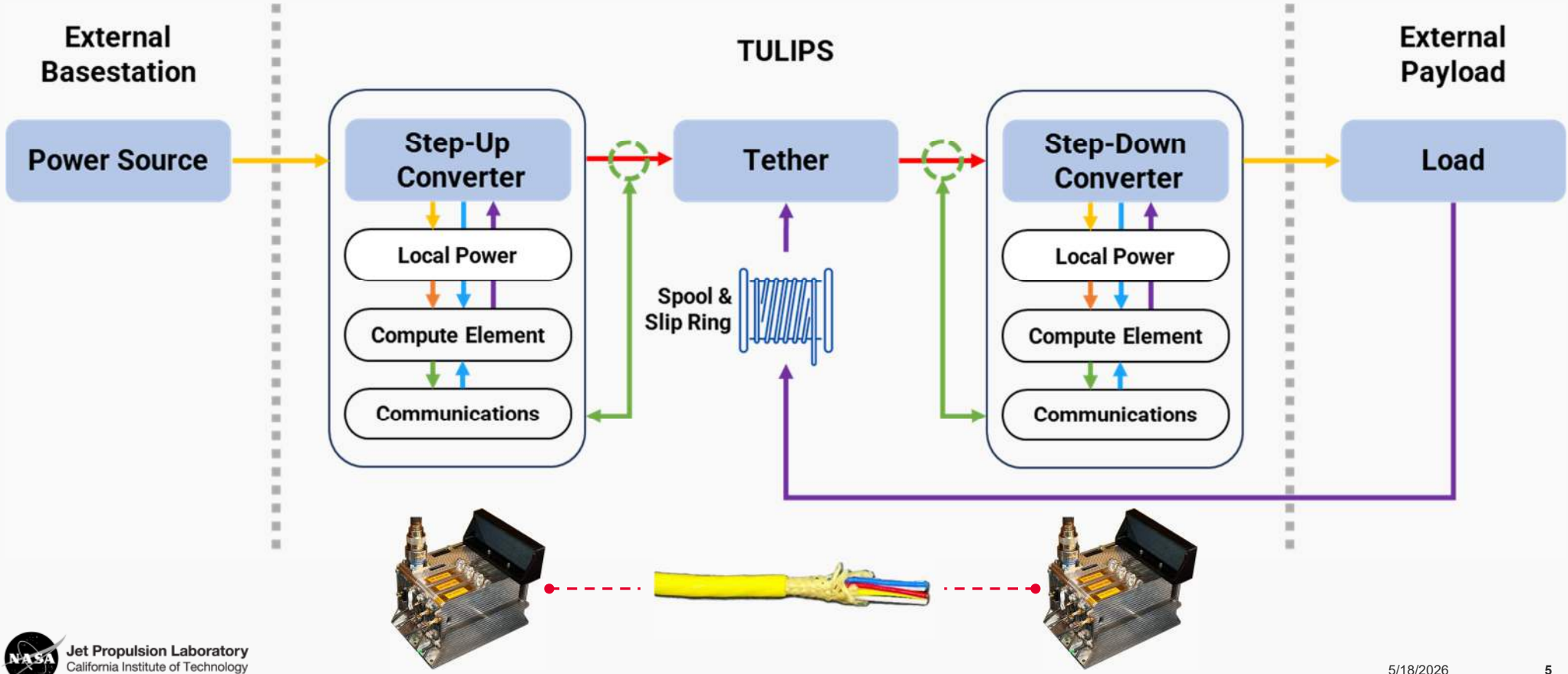
	Description	Pros	Cons
Multilevel DC-DC systems	IPOS/ISOP LLC converters leverage **combinations of stacked DC/DC** modules to drive a DC grid, operating at high frequency to reduce mass	**Lowest mass. Mass scales modularly**. Low mass cost for redundancy. **High efficiency.**	High component count, **complex design.** Requires electronic circuit breakers.
Traditional AC Systems	Single-level converter provides the **simplest means of reaching high voltage**, using AC transformers to raise and lower voltage	**Simpler design**. **High efficiency.** Simple circuit breakers.	Low frequency transformers results in significant **mass and volume**. **Transformer has high mass cost for scaling and redundancy.**



Comparative Study of AC and DC System Mass based on Grid Voltage. DC grids are shown to be equivalent in mass up to 1.5 kV and lower in mass by 15% at 3 kV.

System Architecture

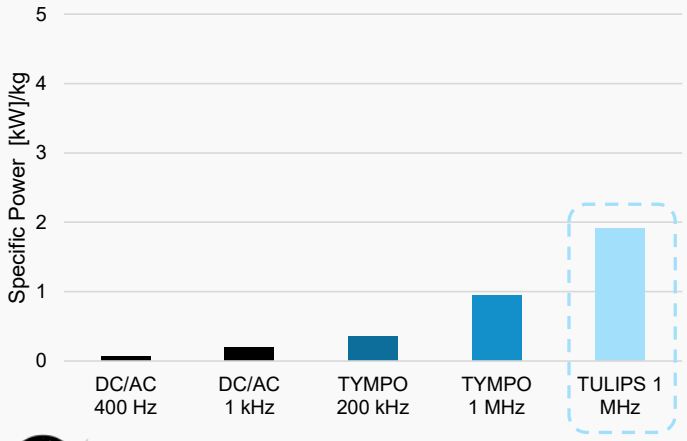
TULIPS is a complete tethered power and communications system, using medium voltage DC to efficiently transmit power on ultralight cables

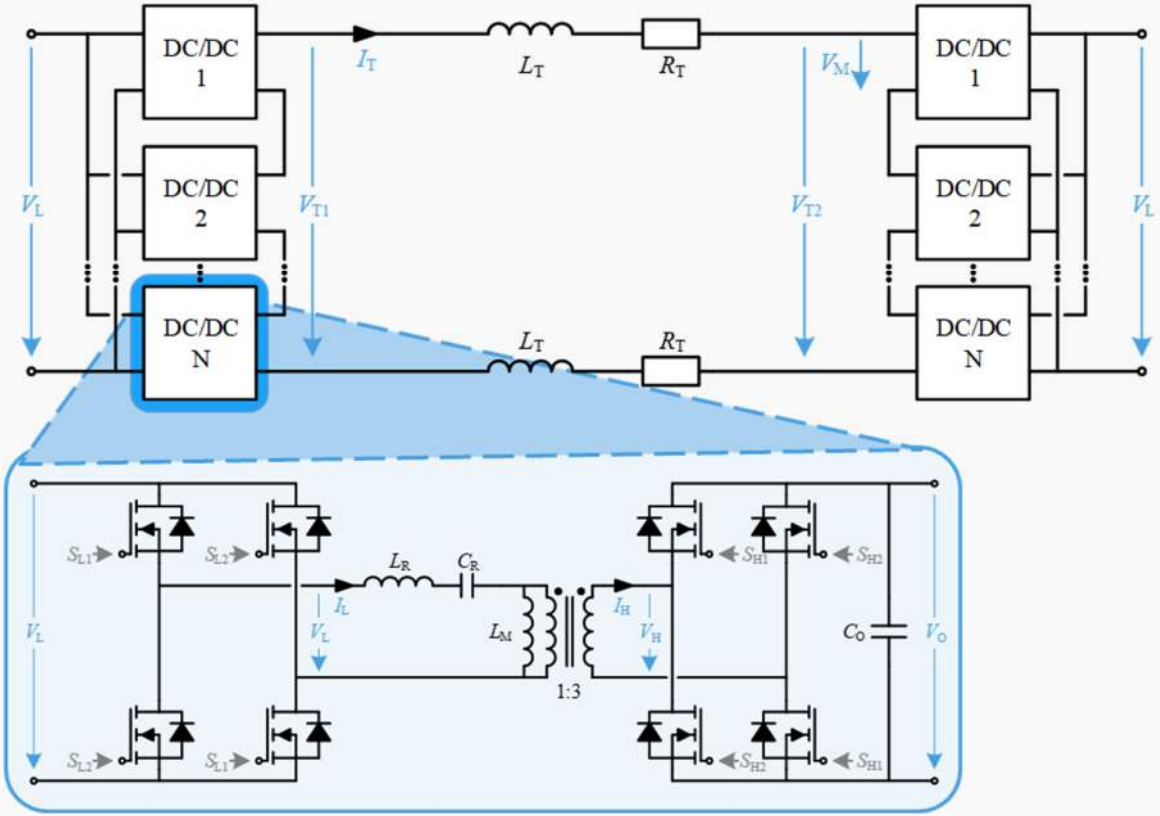


DC Power Transmission

- Stacked LLC power converters enable MVDC power transmission at high efficiency (99%) and high specific power (2 kW/kg)
- By connecting modules in IPOS and ISOP configurations, the systems scales as needed
- MVDC tether transmission voltage is divided between the converters, reducing voltage stress

Power Stage Specific Power





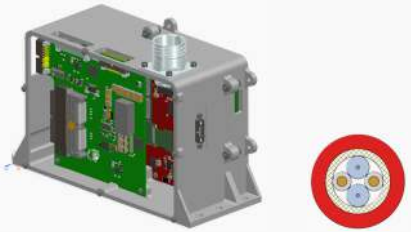
CLPS-Scale Tethered Power

Artist's Concept of Blue Ghost 4 Mission
Credit: Firefly Aerospace

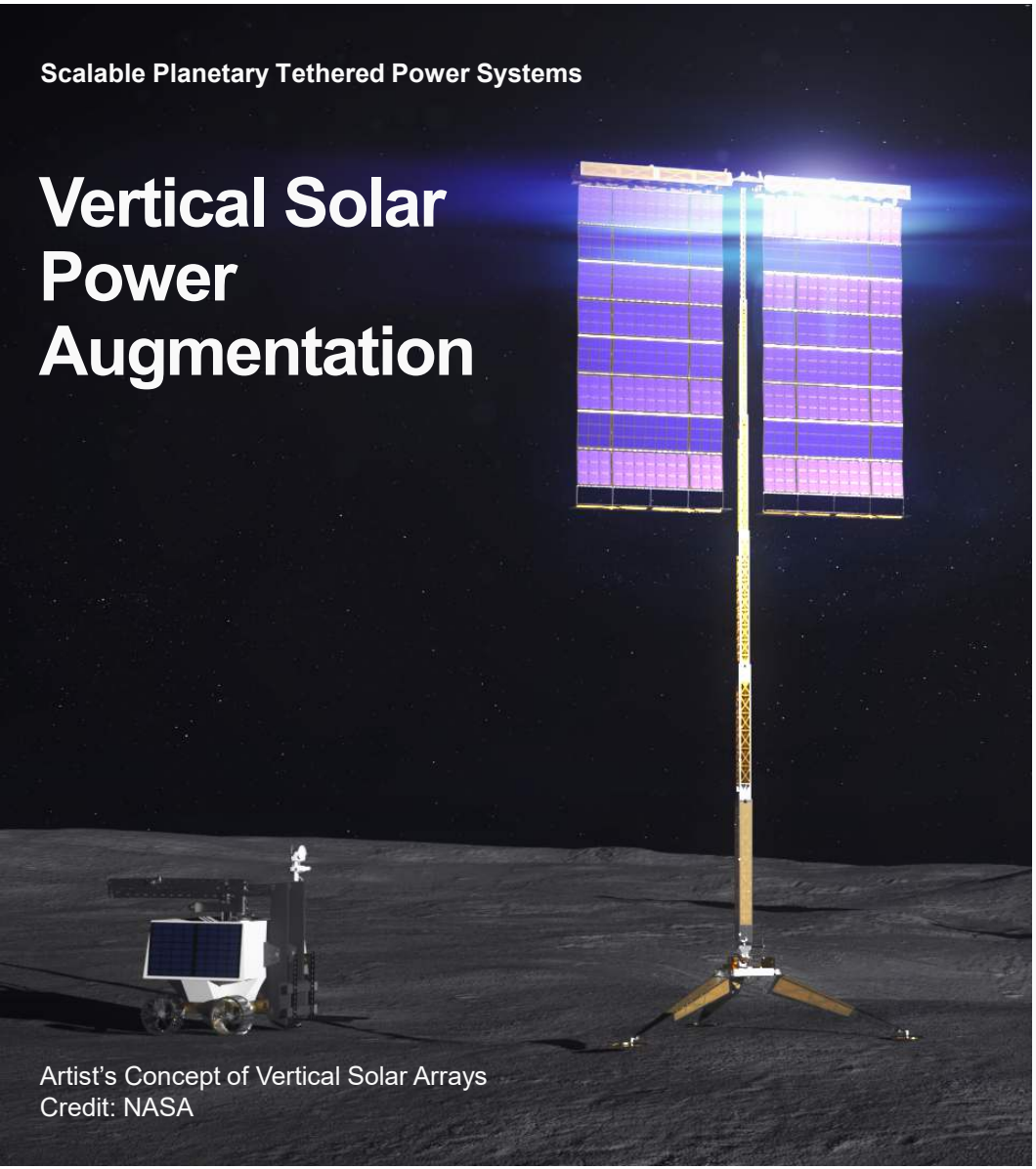
Early tethered systems for the Moon Base will likely rely on CLPS landers or similar small generation sources. Connecting them to rovers will enable construction, resource prospecting, and science.

- Generation Types: RTGs, Small Stirling Reactors, CLPS-scale Solar
- Transmission Distance: 100s of meters

PARAMETER	TULIPS CLPS
System Power	0.5 kW
Module Power	0.3 kW
Tether Voltage	0.7 kV
Tether Diameter	2.8 mm
Tether Mass	9.4 g/m
Electronics Mass	1.14 kg



Vertical Solar Power Augmentation

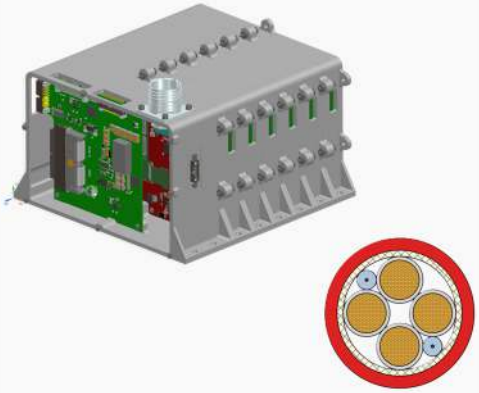


Artist's Concept of Vertical Solar Arrays
Credit: NASA

As the Moon Base expands, vertical solar arrays and small nuclear reactors may be used to augment landed power assets. By spacing them far from the base, permanent power can be provided.

- Generation Types: VSATs, Large Stirling reactors, Small Brayton reactors
- Transmission Distance: 100s of meters

PARAMETER	TULIPS VSAT
System Power	10 kW
Module Power	2 kW
Tether Voltage	1.5 kV
Tether Diameter	6.1 mm
Tether Mass	94.9 g/m
Electronics Mass	4.2 kg



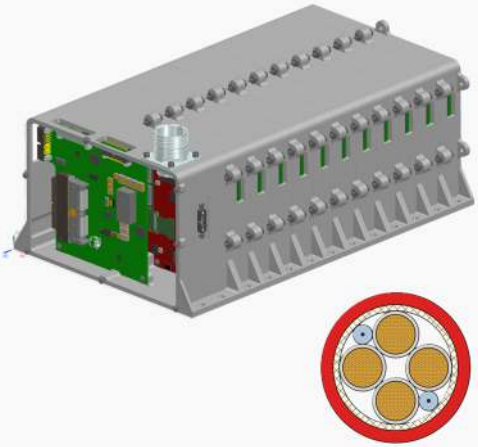
Nuclear Power Augmentation

Artist's Concept of
Fission Surface Power
Credit: NASA

As sustained human presence is achieved, large fission surface power reactors will enable perpetual power for in-situ resource utilization, permanent habitats, and large-scale industry.

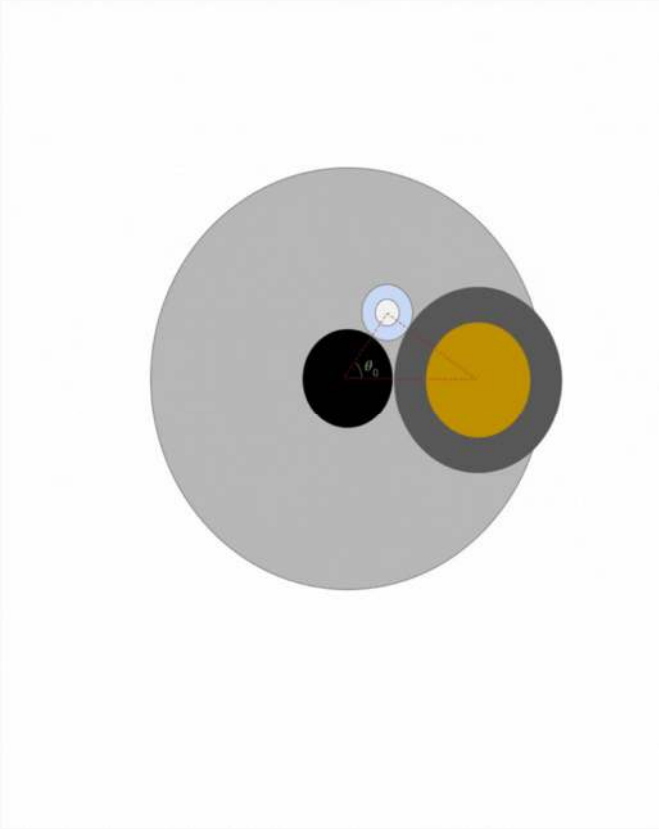
- Generation Types: Large Brayton reactors
- Transmission Distance: 1000s of meters

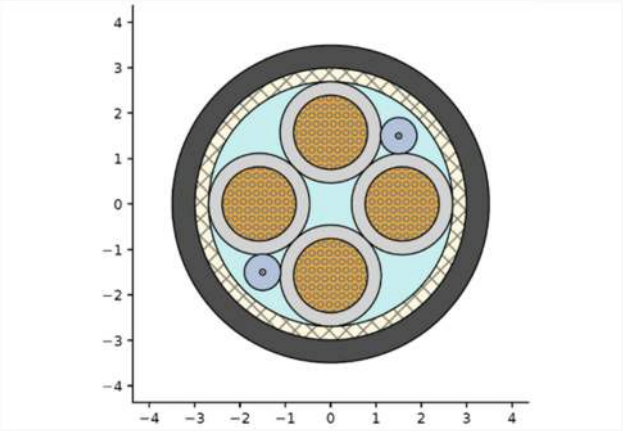
PARAMETER	TULIPS FSP
System Power	50 kW
Module Power	5 kW
Tether Voltage	3 kV
Tether Diameter	10 x 6.11mm
Tether Mass	10 x 94.9 g/m
Electronics Mass	20.6 kg



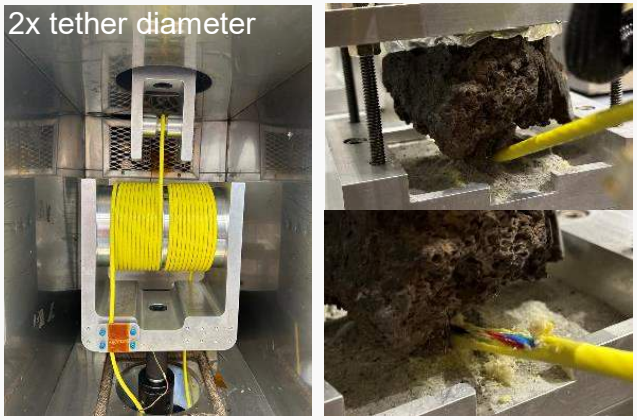
Confidence in Tether Estimates – Design, Fabrication, and Test

TetherCAD (https://github.com/nasa-jpl/TetherCAD) designs Lunar-rated cables using off-the-shelf vendor components, scalable to meet system needs





TetherCAD Cross Section for 1 kW Demonstration Tether



Strain and Abrasion testing of tether in Lunar environment

METRIC	TetherCAD	VENDOR	MEASURED
Outer Diameter	5.99 mm	5.5 mm	6 mm
Tether Mass	67.1 g/m	45.5 g/m	58.2 g/m
Average Strength	8027 N	1193 N	2524 N
Minimum Bend Radius	47.9 mm	109 mm	12 mm

Comparison of key tether parameters between predicted values from TetherCAD, vendor estimates, and measured data

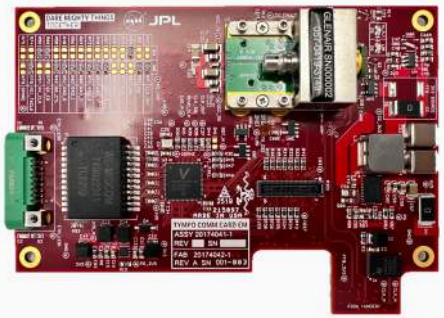
Confidence in Electronics Estimates – Design, Fabrication, and Test

TULIPS has built and demonstrated hardware to provide power, achieve
1 Gb/s fiber communications, and connect to standard Artemis interfaces

TULIPS 1 kW, 900 V Hardware Stack

A

B



C

D

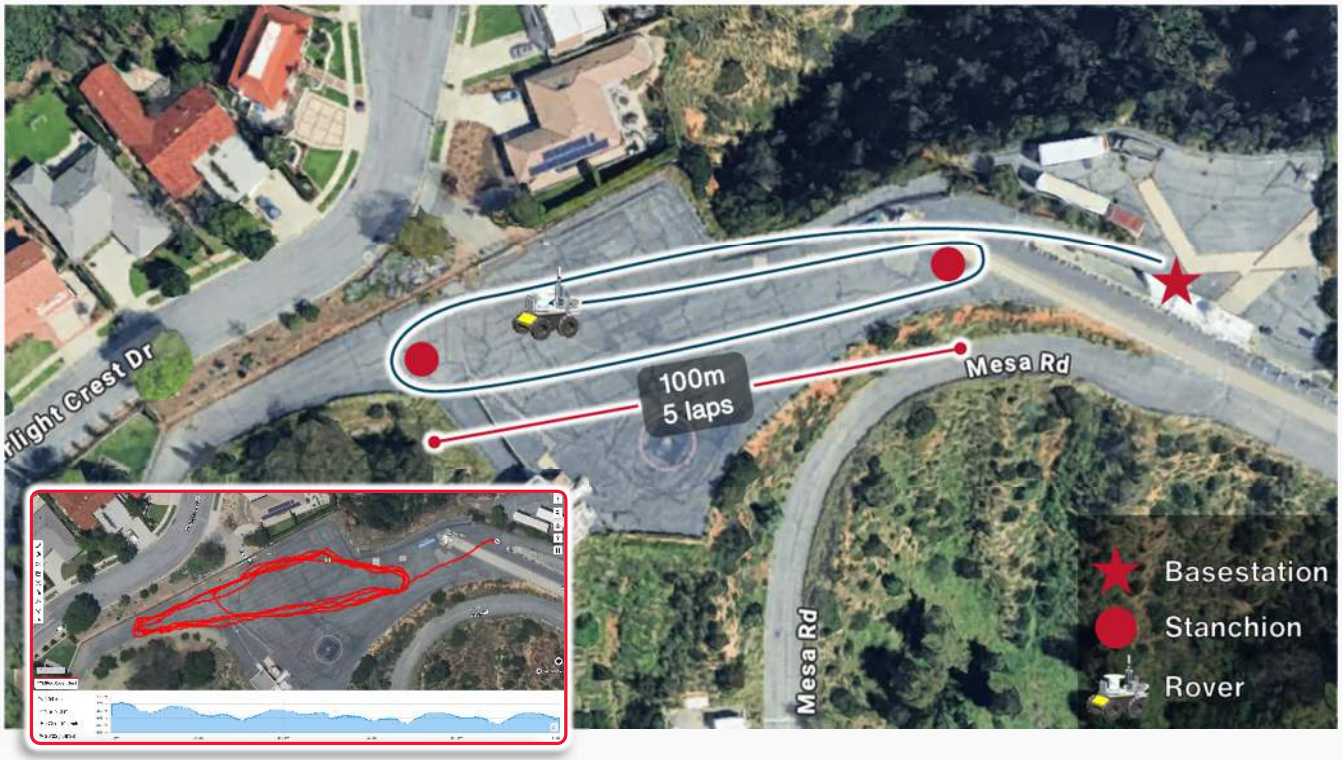
A Honeybee CLPS Rover – Credit: Blue Origin, **B** MoonRanger Rover – Credit: Carnegie Mellon University, **C** Moon Diver – Credit: NASA/JPL-Caltech, **D** Flip Rover – Credit: Astrolab

Confidence in Built Tether Systems – Demonstration

We demonstrated a 1 kW, 1 kV system in a 1 km drive on the JPL Mesa

The rover was **powered** by TULIPS, at 1 kW, 1 kV, enabling continuous driving and exploration

The rover drove **forward for 1 km**, **deploying** the tether
The rover drove **backward for 1 km**, **re-spooling** the tether



Let’s build a Moon Base together!

To work together, reach out to us! We’re here to support NASA and industry in building the future of spaceflight:

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Jet Propulsion Laboratory
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