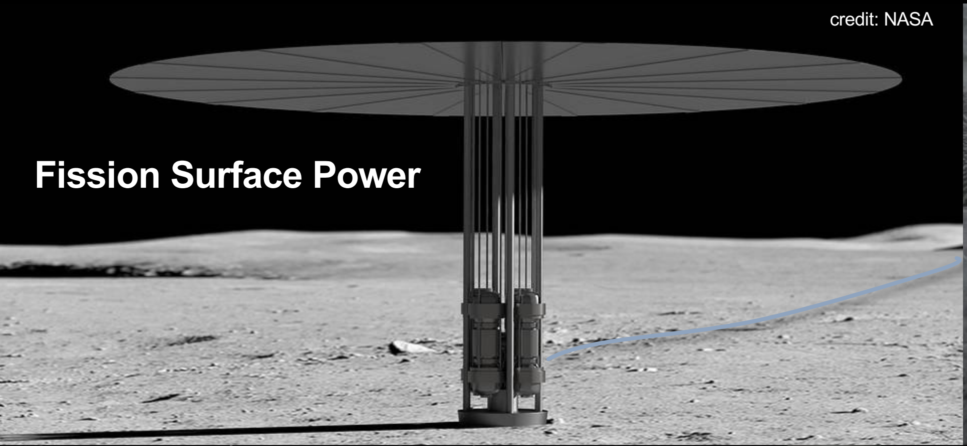
Tethered Power Systems for Lunar Mobility and Power Transmission

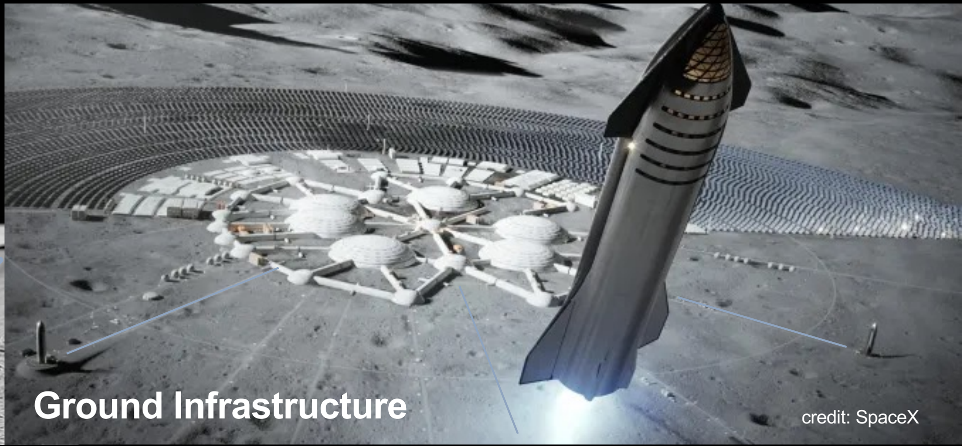
Ansel Barchowsky, Ahmadreza Amirahmadi, Kyle Botteon, Austen Goddu, Gregory Carr, Curtis Jin, Patrick McGarey, Shelly Sposato, and Summer Yang

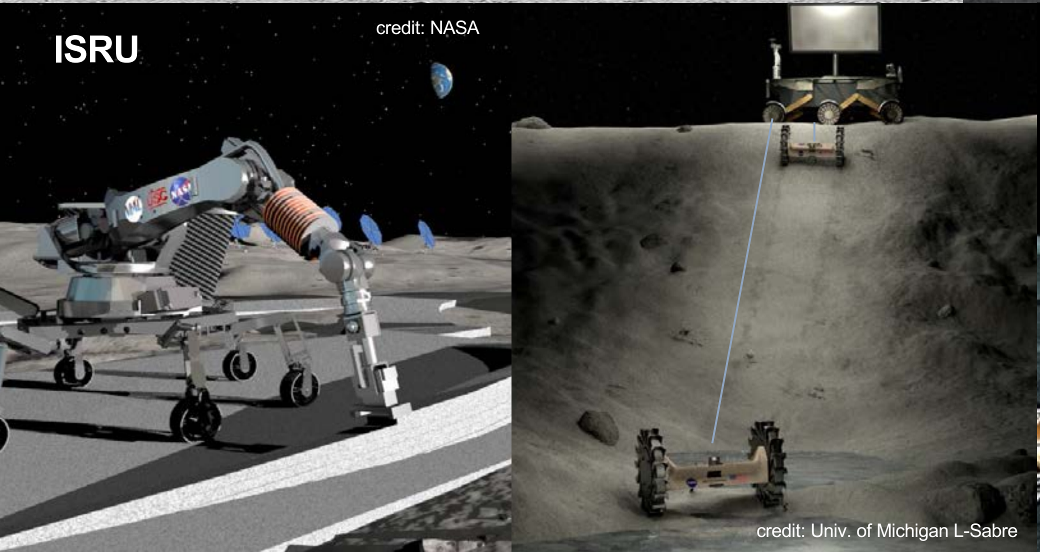
Jet Propulsion Laboratory
California Institute of Technology

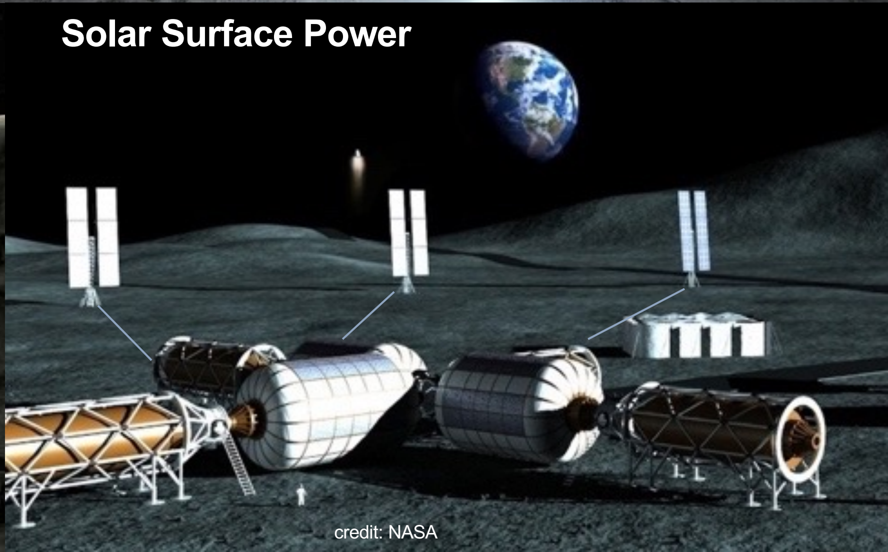
© 2022 California Institute of Technology. Government sponsorship acknowledged.

Motivation (Part I): Long Term Sustainability on the Lunar Surface

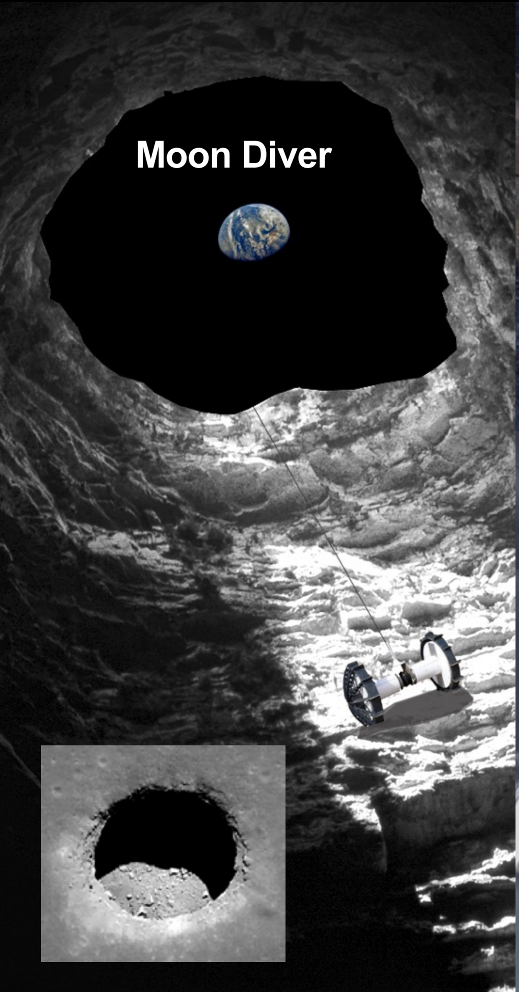


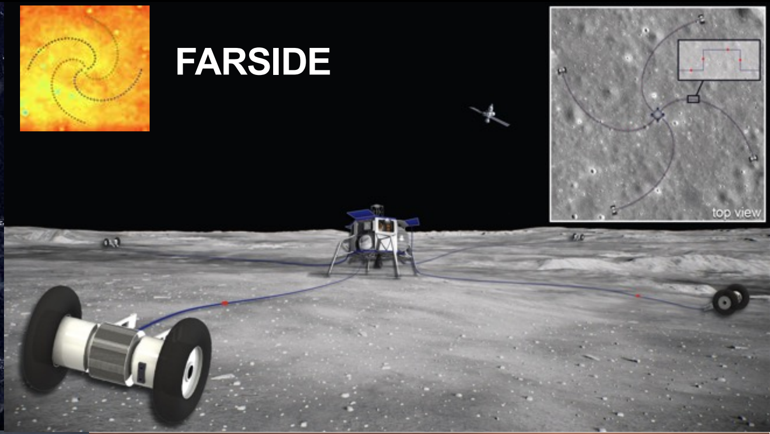






Motivation (Part II): Extreme Terrain Planetary Exploration





Power Delivery

200 W – 10 kW

To support everything from small rovers like large HEO, we need to deliver scalable power in small form factors, pushing the design towards a high voltage, modular architecture.

Communications

1 Gb/s fiber, 8 Mb/s power line

For autonomous control and big data capabilities, we need high bandwidth and low error rates. We need a dual comms platform, with power line carrier for extreme terrain and fiber optics for everything else.

Transmission

1 – 10 km

Many HEO and robotics missions require distances of at least 1 km, so we're starting there and extending to 10 km to support future missions. That means we need a high power, low mass tether than can be tightly spooled.

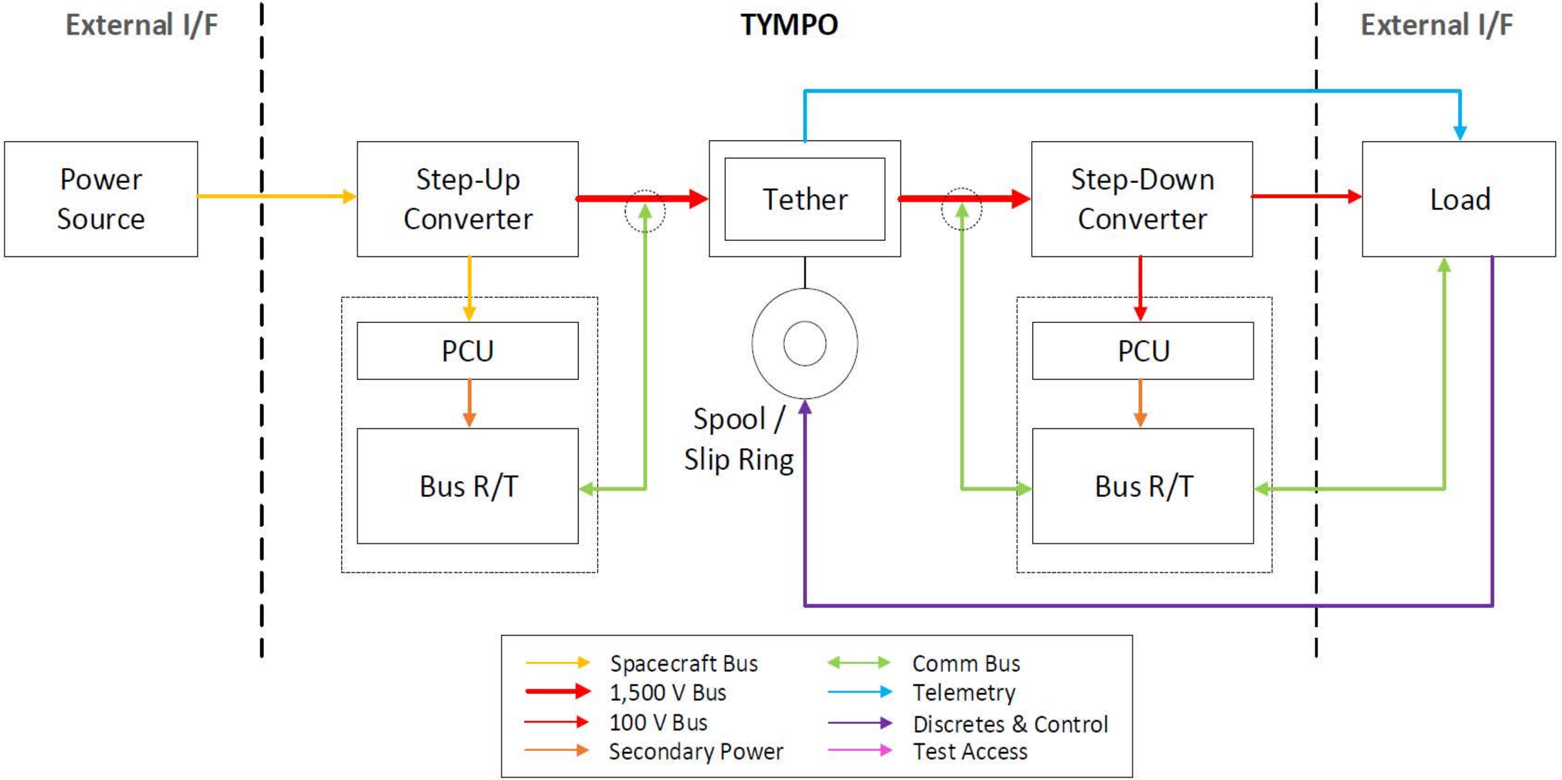
Near-term TYMPO capabilities

Long-term TYMPO capabilities

Follow on efforts

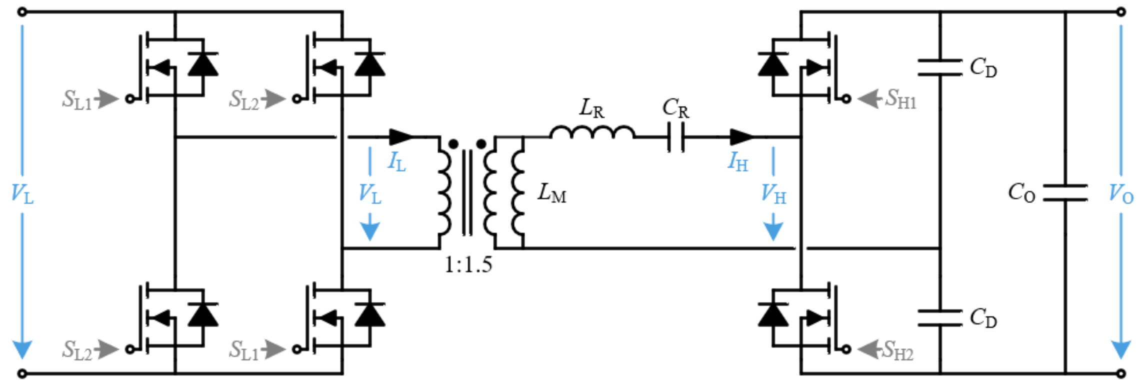
	Mission	Potential Launch	Power (W)	Comm (Mb/s)	Length (m)	Tensile Load (N)	Duration (days)	Tether Management	Temp Min (C)	Temp Max (C)
Moon	Moon Diver	2020s	54	0.18	300	200	14	Active	-30	130
	ISRU Proc. Demo	2020s	1,000	TBD	5,000	TBD	1,000	TBD	-173	130
	ISRU Proc. Pilot	2020s	2,000	TBD	5,000	TBD	1,000	TBD	-173	130
	ISRU Proc. Full	2020s	150,000	TBD	5,000	TBD	1,000	TBD	-173	130
	FARSIDE	2030s	72	1,000	12,000	-	1,825	Active	-173	130
	PSR Rover	2020s	TBD	TBD	1,000	TBD	14	Active	-250	130
Icy Moons	EELS Enceladus	2040s	500	1,000	5,000	100	3,650	Hybrid	-240	-128
Venus	Venus Aerobot	2030s	-	1,000	50	50	365	Hybrid	-50	125
Earth	EELS Earth	2020s	2,000	1,000	250	1,000	-	Active / Offboard	-23	23

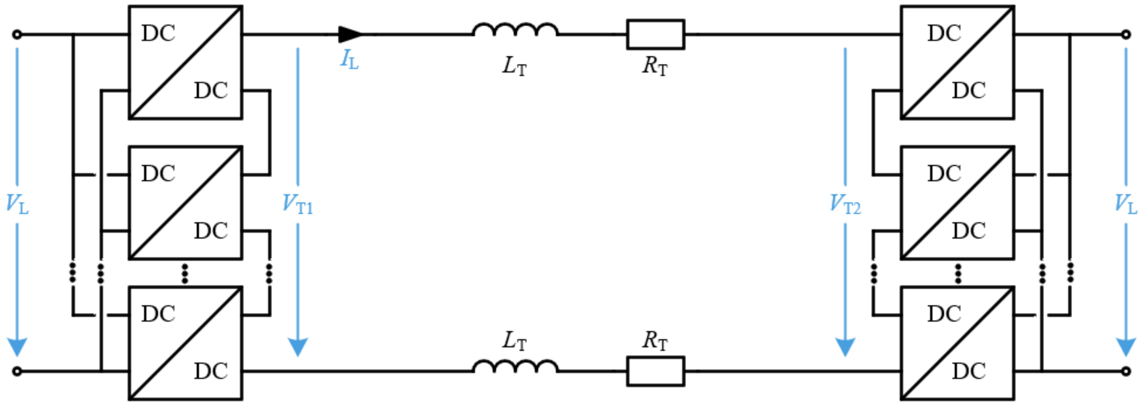
TYMPO: Enabling Long-Distance Planetary Missions



© 2022 California Institute of Technology. Government sponsorship acknowledged.

Conversion Design – Multilevel Converter Architecture





DCX and LLC converters have been demonstrated to be extremely efficient (99%+). A full bridge primary with a 1:1.5 transformer and a voltage doubler secondary gives us a 1:3 conversion ratio.

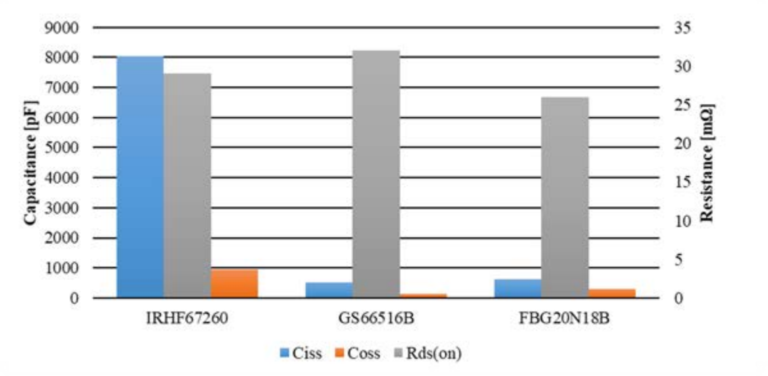
By combining modules in Input Parallel, Output Series we can build step-up converters. Input Series, Output Parallel for step-down. With 5 in series, we achieve 1.5 kV with 300 V on each switch.

© 2022 California Institute of Technology. Government sponsorship acknowledged.

Conversion Design – GaN Benefits to Power Conversion

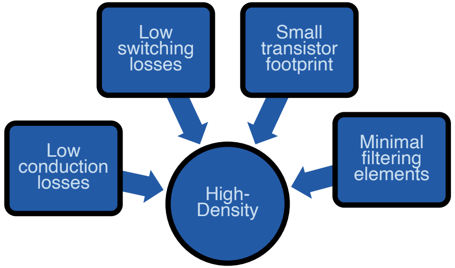
GaN Performance vs. Flight Silicon:

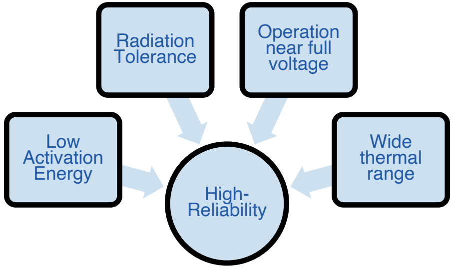
- Commercial applications have rapidly embraced GaN due to figure of merit improvements over Si MOSFETs
- For deep space applications, these improvements are even more dramatic compared to qualified Si MOSFETs
- Some relevant advantages over Si MOSFETs are:
  - Comparable RDS,ON, including temperature variance
  - Reduced C_{ISS} by a factor of 10 to 20
  - Reduced C_{OSS} by a factor of 3 to 10
  - Reduced package size by a factor of 3 to 15



Converter Improvements from GaN:

- The reduced activation energy of GaN devices allows for optimization of converters for improved:
  - Efficiency through reduction in switching losses
  - Power density through reduction in filtering needs
  - Specific power through reduction in filtering needs
- The reduced activation energy of GaN devices allows for optimization of converters for improved:
  - Efficiency through reduction in switching losses
  - Power density through reduction in filtering needs
  - Specific power through reduction in filtering needs

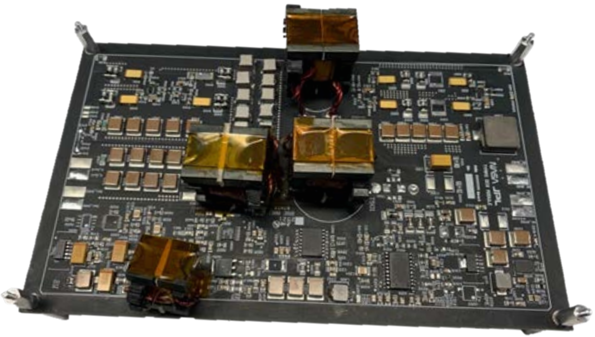




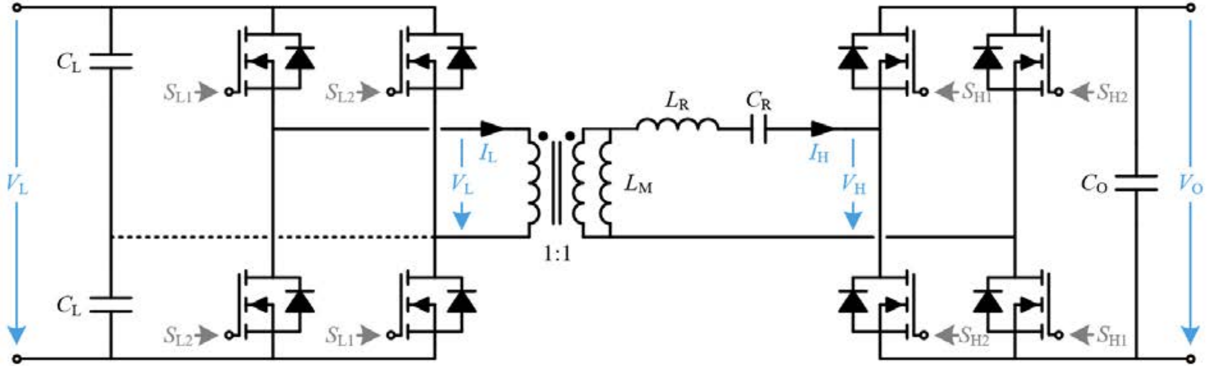
© 2022 California Institute of Technology. Government sponsorship acknowledged.

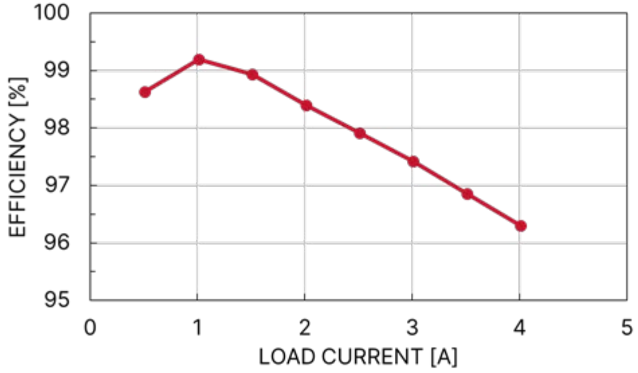
Conversion Design – Demonstration DCX Converter

To demo the module structure, we built a breadboard of our DCX module, which can be configured as a full bridge or half-bridge doubler. Achieving 99 % peak efficiency, this demo helps us design the full-scale power stage.



Specification	Parameter
Module Power	100 W
Input Voltage	28 V
Output Voltage	28 V
Primary FET	GS61008T
Secondary FET	GS61008T
Resonant Capacitor	0.125 µF
Resonant Inductor	5 µH
Resonant Frequency	150 kHz

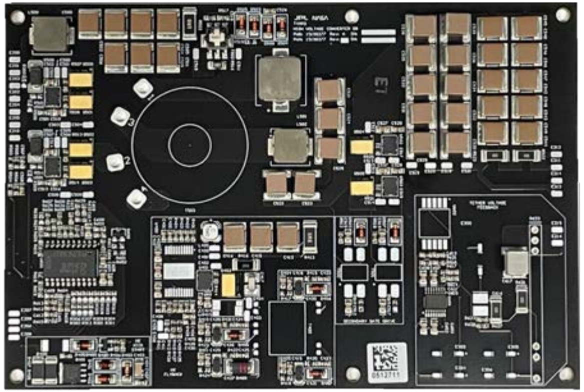




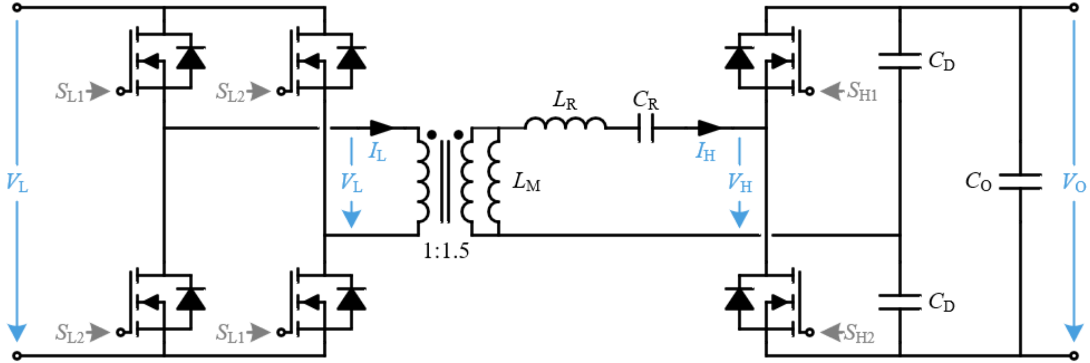
© 2022 California Institute of Technology. Government sponsorship acknowledged.

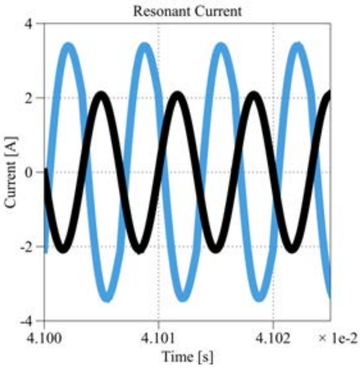
Power Conversion – Transmission Scale Converter

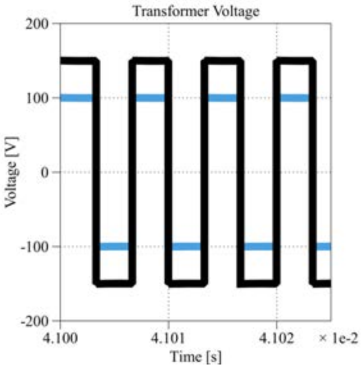
The full power converter is a scaled version of the demo hardware. The 650V GaN FETs have been shown to survive SEGR and SEB to 75 % of rated voltage, making our applied 300 V low-stress for the converter in flight.



Specification	Parameter
Module Power	200 W
Input Voltage	100 V
Output Voltage	300 V
Primary FET	GS66506T
Secondary FET	GS66506T
Resonant Capacitor	0.3 µF
Resonant Inductor	4.4 µH
MV Resonant Capacitor	1 µF
Resonant Frequency	150 kHz



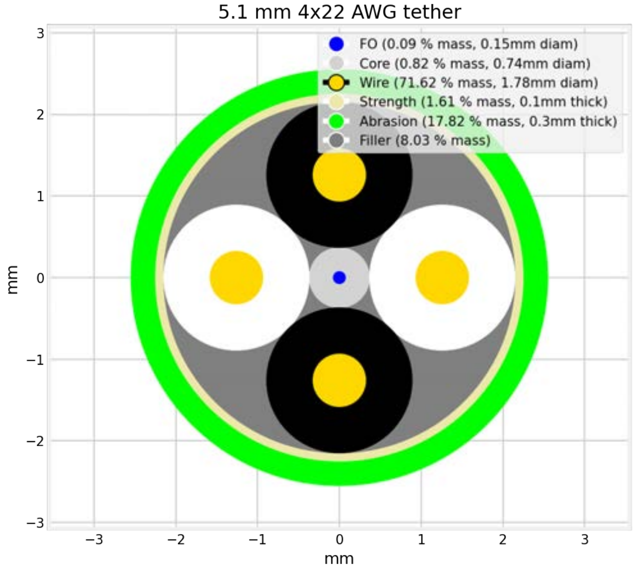


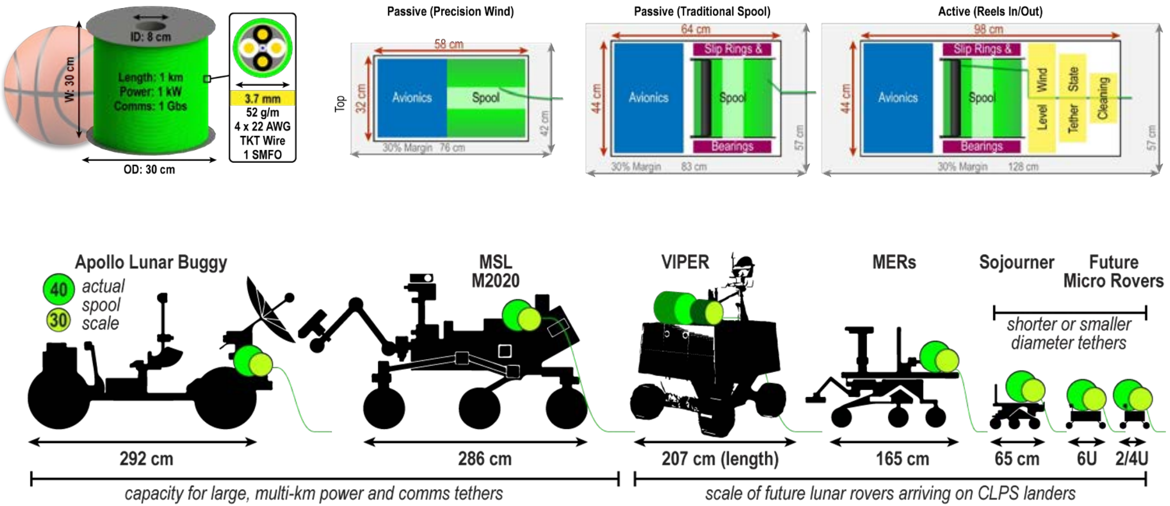


© 2022 California Institute of Technology. Government sponsorship acknowledged.

Tether – Design Methodology

Fitting the tethers onto rovers is a challenge. Minimizing the tether volume allows for smaller rovers to hold the tethers, but trades off against voltage withstand capabilities. We have designed a four-conductor tether, comprised of a core supporting structure with embedded fiber optics, four 22 AWG conductors with high voltage insulation with semiconductive coating to avoid flashover in vacuum, a strength layer to support heavy loads, and an abrasion layer for the harsh Lunar regolith.



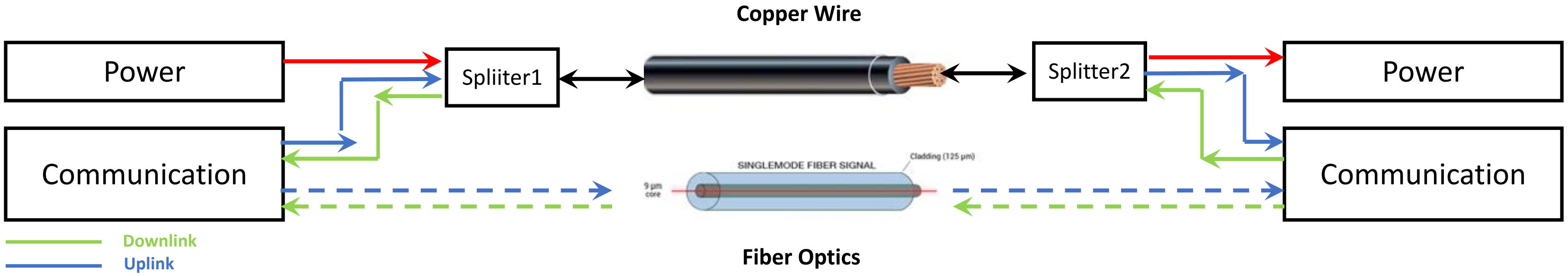


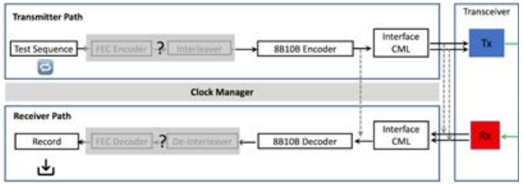
© 2022 California Institute of Technology. Government sponsorship acknowledged.

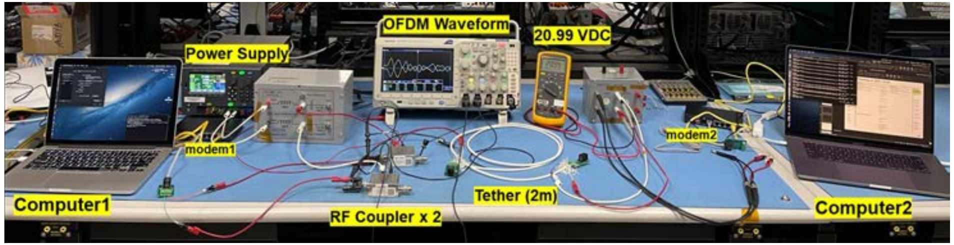
Communications

For missions that demand high speed TYMPO provides 1 Gb/s fiber communications. We use fiber for all missions who don't encounter too extreme of terrain.

For missions that can't rely on fiber optics or need a backup, TYMPO provides 10 Mb/s power line carrier communications. This platforms the same 1.5 kV tether lines as the power path, reducing tether mass.

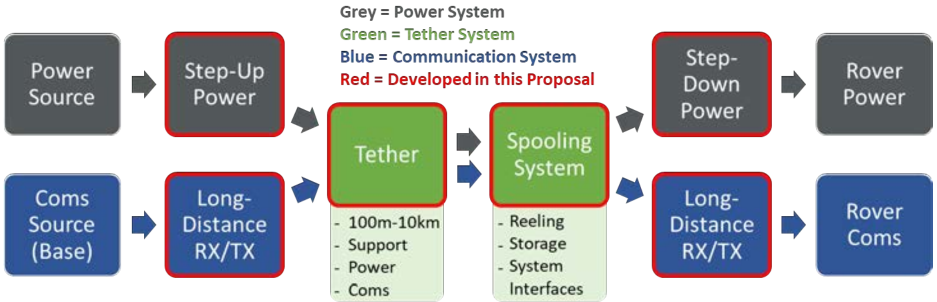




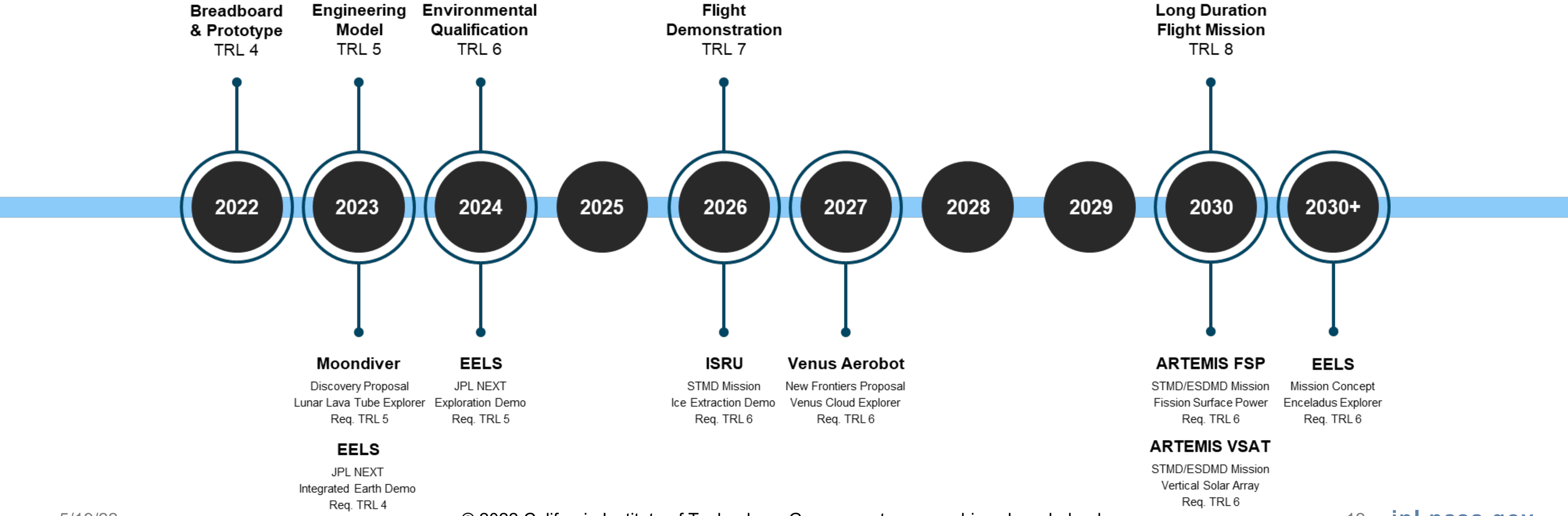


max QAM	BW	# of Carriers	Subcarrier BW	Tx Power	V_p
256 (8 bits)	17.664 MHz	4096	4.3125 KHz	14.5 dBm (28 mW)	2.37 V

© 2022 California Institute of Technology. Government sponsorship acknowledged.



Key Performance Parameter	State-of-the-Art (SOA)	Threshold Value	Goal Value
Step-Up Converter Efficiency	90 %	92.5 %	97 %
Step-Down Converter Efficiency	N/A	92.5 %	97 %
Converter Power Density	0.3 W/cm³	1 W/cm³	2 W/cm³
Converter Specific Power	250 W/kg	500 W/kg	1 kW/kg
End-to-End Efficiency	N/A	80 %	90 %
Tether Communications	N/A	1 Gb/s fiber, 4 Mb/s copper	1 Gb/s fiber, 10 Mb/s copper



© 2022 California Institute of Technology. Government sponsorship acknowledged.

Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov

© 2022 California Institute of Technology. Government sponsorship acknowledged.