Jet Propulsion Laboratory
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2023 Space Power Workshop

Powering Mars Sample Retrieval

The Power Subsystem Architecture of the Sample Retrieval Lander

April 26th, 2023

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The decision to implement Mars Sample Return will not be finalized until NASA's completion of the National Environmental Policy Act (NEPA) process. This document is being made available for information purposes only.

Artist's Concept

Agenda

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- MSR Campaign/SRL Mission Overview
- Power Architecture Drivers
- Architecture Description
  - Bus Regulation
  - Power Generation
  - Energy Storage
  - Power Distribution
  - Command and Telemetry

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Planned Mars Sample Return (MSR) Campaign Overview

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Source: JPL MSR/SRL Project Documentation

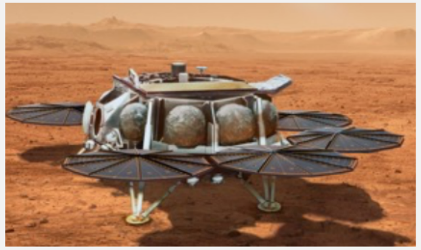
Mars Sample Return Program

1

Sample Caching Rover (Mars 2020) Operations
- *Sample acquisition / caching*
- *Sample (subset) delivery*

Initiates the Campaign

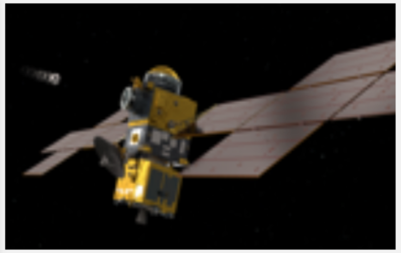
2



Sample Retrieval Lander
- *Orbiting Sample (OS) container*
- *Mars Ascent Vehicle*
- *Recovery Helicopters*

New Flight Element

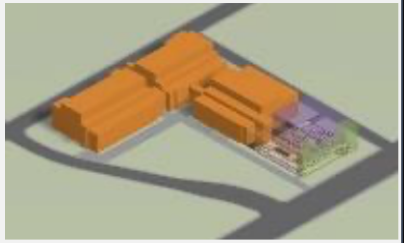
3



Earth Return Orbiter
- *Capture/Containment System*
- *Earth Return Vehicle*

New Flight Element

4



Mars Returned Sample Handling
- *Sample Receiving Facility*
- *Curation*
- *Sample science investigations*

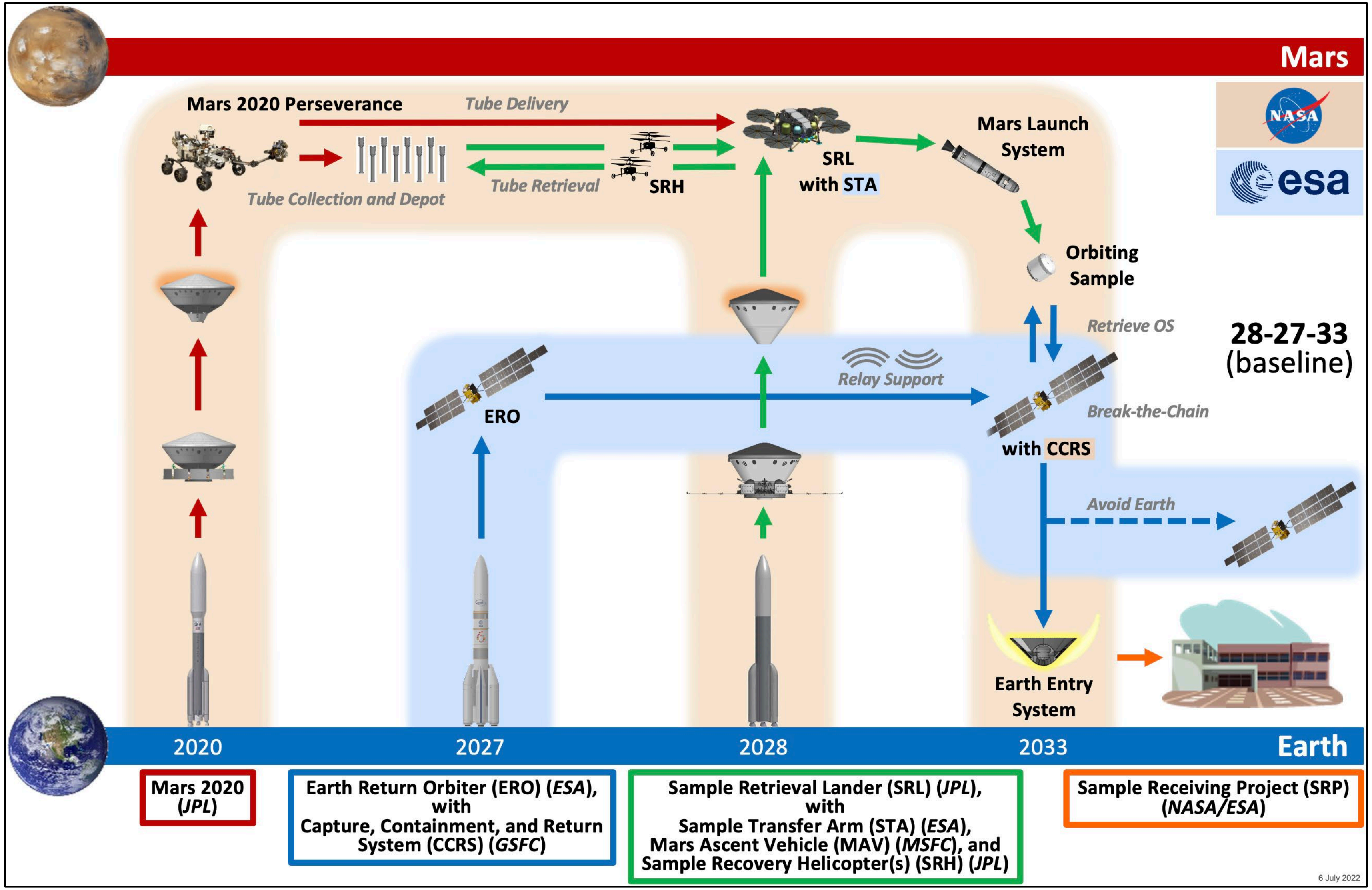
New Ground Element

- The MSR Campaign would span flight elements and one ground element
- The MSR Program would manage development and operations of elements 2 and 3 and interfaces to elements 1 and 4; it would conclude with recovery/containment of samples for transfer to SRF
- The Mars Exploration Program manages Mars 2020 Phase E operations & would be the home of the future SRF Project

Pre-decisional information for planning and discussion purposes only.

Planned MSR Campaign Architecture Overview

Source: JPL MSR/SRL Project Documentation



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Baseline SRL Flight System Configuration

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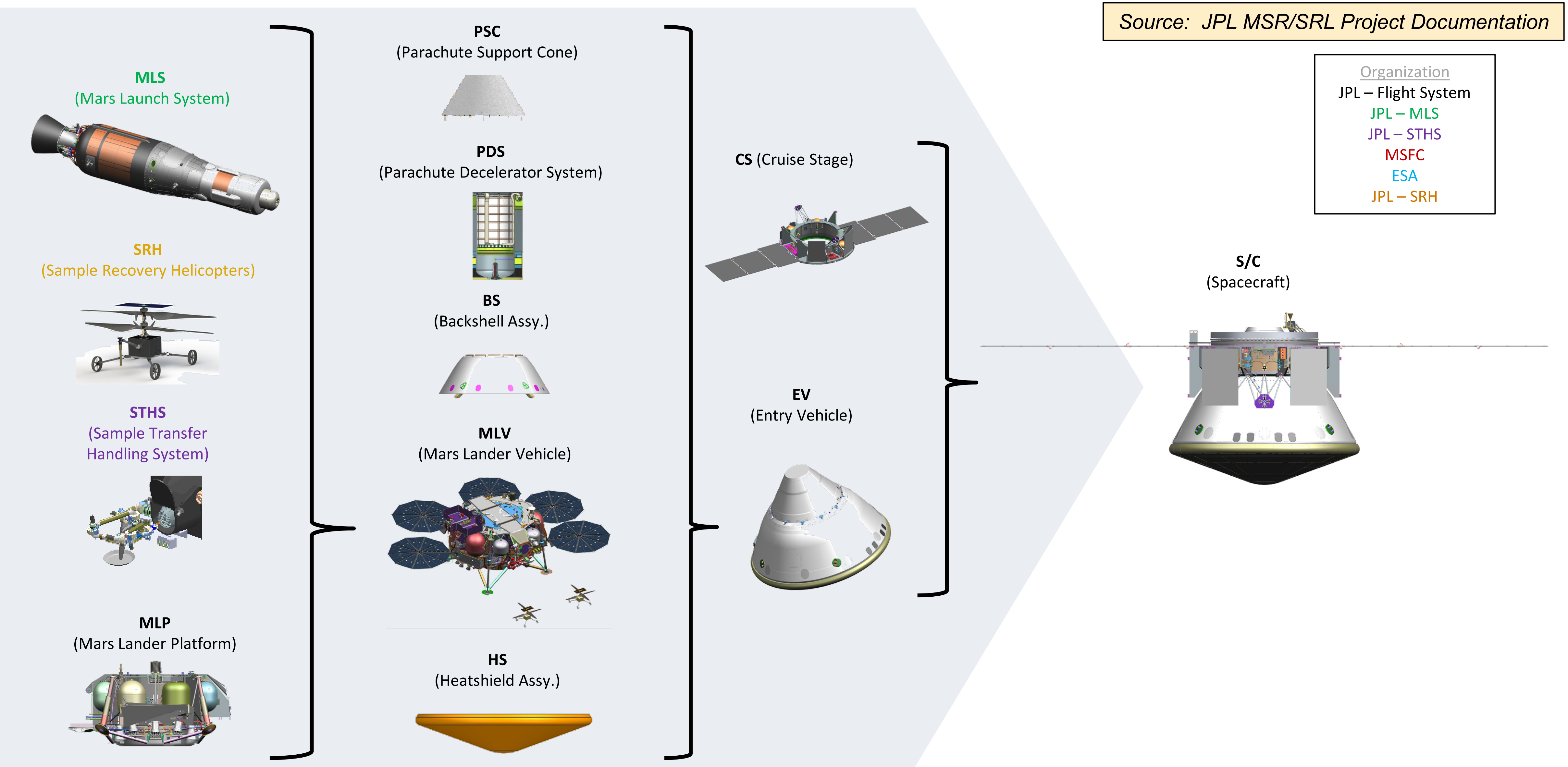
Source: JPL MSR/SRL Project Documentation



Recent Mars Surface Missions (Landed in Last 15 Years)

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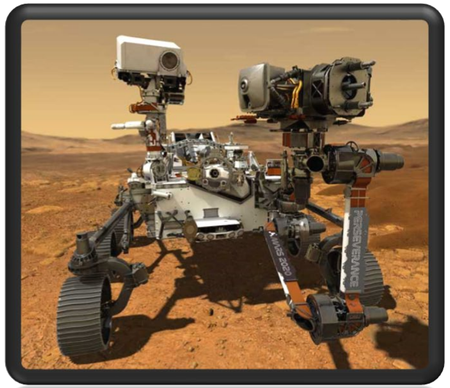
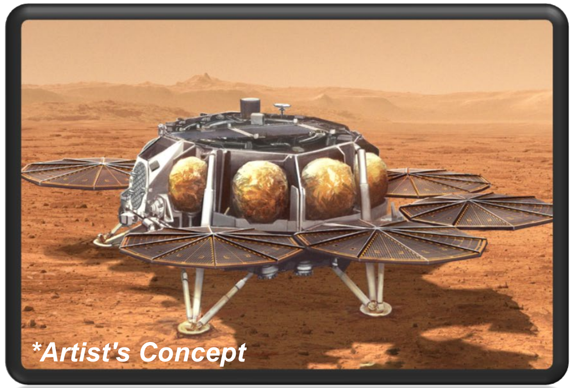
Phoenix
Landed: 2008
Landed Mass: 350 kg
Power Source: Solar Array
BOM Energy Generation Capability: 1800 Wh/sol

Curiosity
Landed: 2012
Landed Mass: 900 kg
Power Source: MMRTG
BOM Energy Generation Capability: 2800 Wh/sol

Insight
Landed: 2018
Landed Mass: 360 kg
Power Source: Solar Array
BOM Energy Generation Capability: 4500 Wh/sol



Perseverance
Landed: 2021
Landed Mass: 1000 kg
Power Source: MMRTG
BOM Energy Generation Capability: 2800 Wh/sol



Sample Return Lander
Planned Landing: 2030
Landed Mass: ~2300 kg
Power Source: Solar Array
BOM Energy Generation Capability: ~7500 Wh/sol

Architecture Drivers: Mission Con-Ops

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SC Launch → **Cruise** *(Two Year Duration)* → **EDL** → **Surface** *(Up to 235 sols)*

SC Launch	Cruise	EDL	Surface
Pre-Launch, *Launch*, *Post-Launch*	*Commissioning*, *Cruise*, *Approach*	*Entry*, *Descent*, *Landing*	*Commissioning*, *Tube Transfer*, *MLS Launch*

Key Power Subsystem Functions and Activities

SC Launch
- Battery supports loads prior to cruise solar array deployment
- Electronics inhibit unsafe activities prior to launch vehicle separation
- Electronics support key post-launch releases and deployments, including array deployment

Cruise
- Cruise solar array supports loads when sunlit
- Battery supports loads during peak load transients and off-sun events
- Electronics support autonomous SC behavior (nominal and off-nominal) throughout conjunction

EDL
- Battery supports loads after cruise stage separation
- Electronics support key EDL pyro and prop firing events
- Electronics electrically isolate cruise stage and lander prior to cable-cut

Surface
- Lander solar array deploys supports loads when sunlit
- Battery supports loads during peak load transients and night
- Electronics support key post-landing releases and deployments
- Electronics support lander low power sleep mode

Electronics regulate power bus, distribute switched power, and support key SC communication and fault management functions throughout mission

Architecture Drivers: Environments

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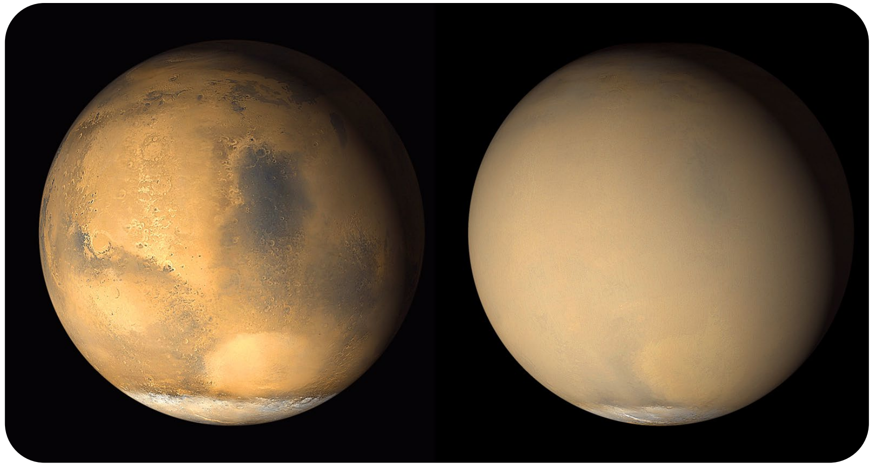
Cruise Phase:

- Low temperature space environment drives the need for high survival heat power, particularly for propulsion systems (ex: EDL prop system and MAV)

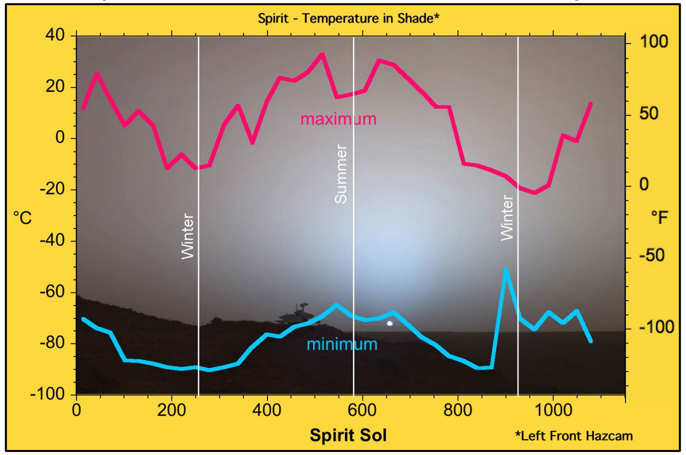
Surface Phase:

- Dust environment drives need for large solar array surface area
- Low night temperatures drive the need for high survival heat (ex: MAV), and drives the battery design
  - Battery cell section needs to trade power/energy density vs. low temperature performance

Onset of Mars Global Dust Storm (NASA/JPL-Caltech/MSSS)



Spirit Measurements of Surface Temperature (NASA/JPL-Caltech/Cornell/NMMNH)



Architecture Drivers: High Peak Load Demand

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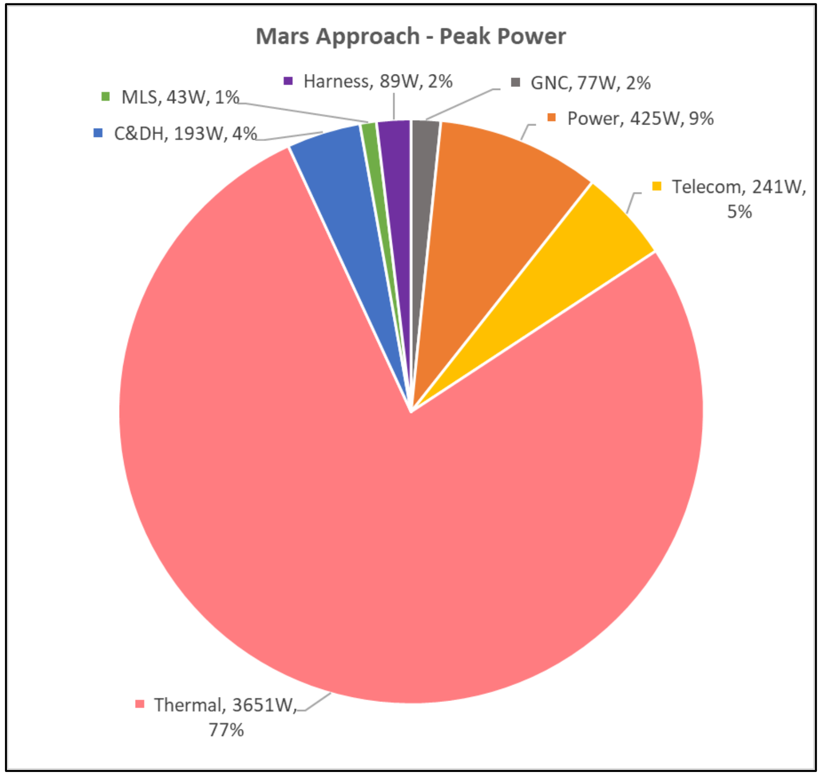
- SRL relies on electrical heater power, whereas past large Mars missions (Curiosity and Perseverance) relied on their nuclear MMRTG (~2 kWth) to provide survival heating
  - To reduce the number of power switching slices, there's a heavy reliance on thermostatically controlled heaters
  - Alternative options for heater power distribution were explored, but heritage hardware option was selected, primarily for programmatic reasons
  - Drives high transient peak powers (ex: >3.6 kW of heater power in the Mars Approach mode)
- Critical events like EDL (8 vs.12 landing engines) and MAV launch drive high peak loads of > 2.5 kW

Example: Peak Power During Mars Approach
(Total Power of 4.7 kW dominated by Heater Loads)



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Architecture Drivers: Power Source

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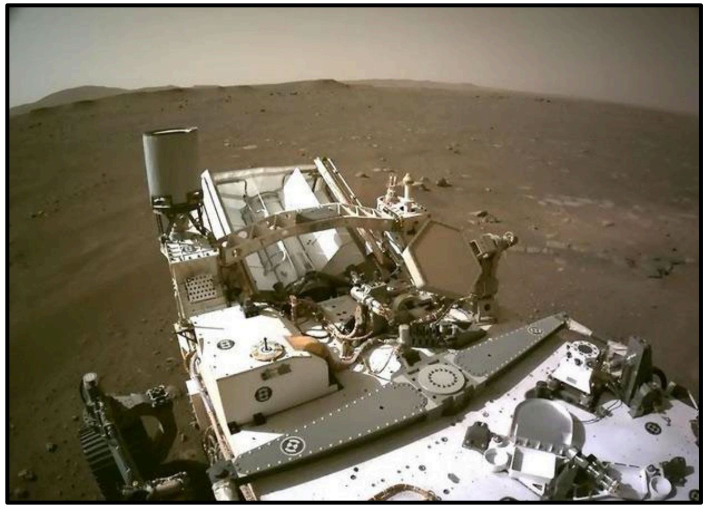
- Major driver for a solar-powered lander (vs. MMRTG) was accommodation challenges
  - MMRTG requires substantial support hardware (thermal cooling, structural support, clear access for late install, etc.)
  - Fitting both an MMRTG and the Mars Ascent Vehicle (MAV) proved challenging
- Cost and material availability were also considerations in the solar vs nuclear trade
- Relatively short surface mission duration is key enabled for solar-powered lander
  - <1/2 years for SRL, vs ~2 years for Curiosity/Perseverance
  - Surface mission constrained to avoid global dust storm season

Perseverance MMRTG (NASA/JPL-Caltech)



Architecture Drivers: Other Key Drivers

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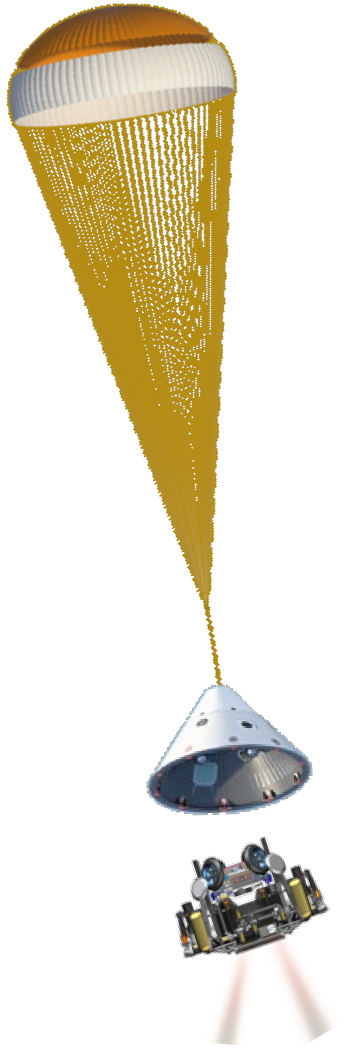
- **Flagship/Class A Reliability:** Lowest risk tolerance, very high priority mission, very high complexity (NPR 8705.4A) → single fault tolerance
- **Fault Protection and Autonomy:** Cruise conjunction, surface sleep mode, undervoltage/dead bus recovery responses
- **Deployments and Release Mechanisms:** High number of time-sensitive pyro and release device firings (ex: EDL, MAV Launch)
- **Deadfacing:** Electrical isolation of interfaces after separation events (and preventing fault propagation)
- **Programmatic:** Budget, schedule, staffing, development risk



Power Subsystem Architecture Overview

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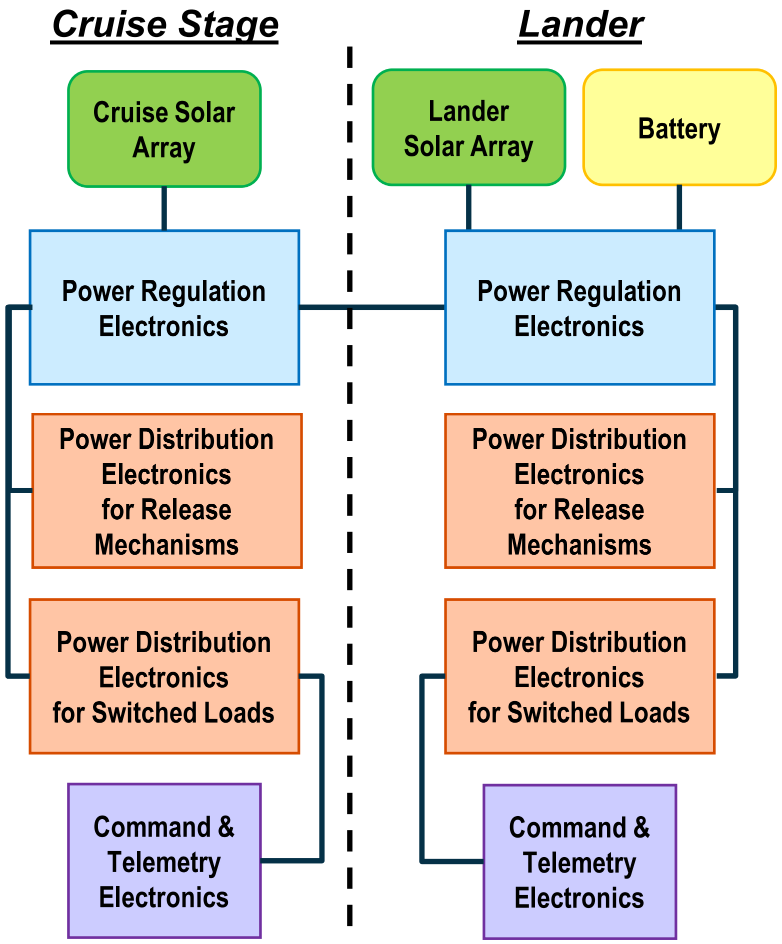
Single fault tolerant architecture with the following key functions:

- **Power Generation:** Cruise solar array provides power during the Cruise Phase and lander solar array provides power during the Surface Phase
- **Energy Storage:** Secondary (rechargeable) battery provides power during off-sun maneuvers in cruise, EDL, and over night on surface
- **Power Regulation:** Direct energy transfer (DET) architecture with solar array string switching and the battery on the bus (i.e. bus voltage driven by battery voltage/SOC)
- **Power Distribution:** Switched power provided to SC subsystem and payload loads, including release mechanisms and propulsion valves
  - Also provides safety inhibited power buses
- **Command and Telemetry:** S/C communication interface for health status and control, as well as fault management functions



Power Subsystem Hardware Overview

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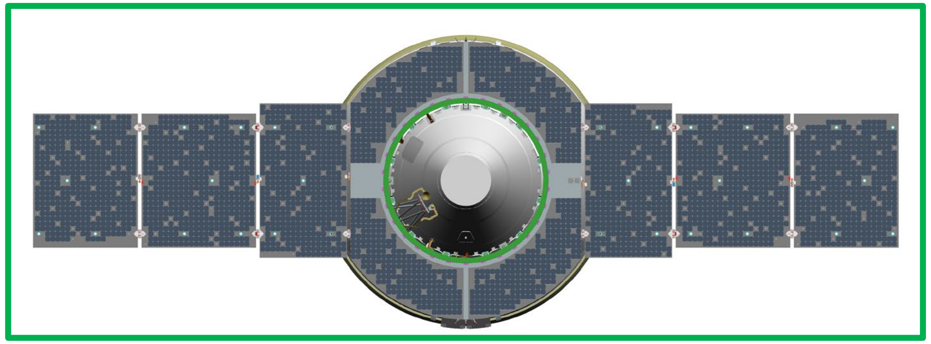
Power Generation:
- Lockheed Martin-provided cruise solar array
- Northrop Grumman UltraFlex lander solar array comprised of five Insight-sized wings

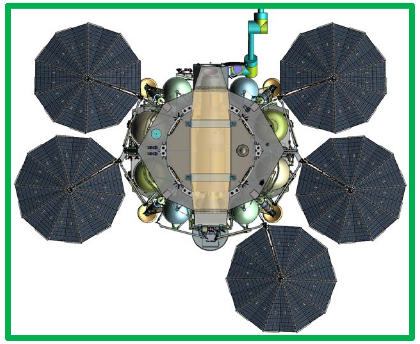
Energy Storage:
- ABSL 8s96p Li-ion secondary battery with LG Chem MJ1 18650 small cells (no cell balancing required)

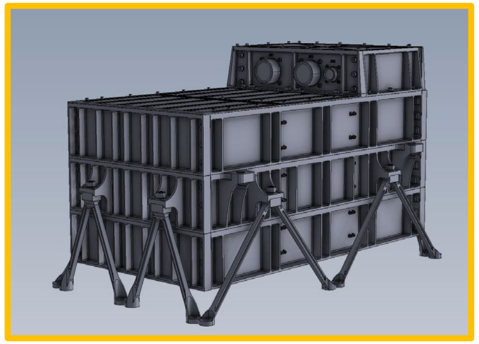
Power Regulation:
- Power Bus Controller (PBC)
- Solar Array Interface Slice (SAIS)
- Power Junction Slice (PJS)
- Power/Pyro Slice (PPS)

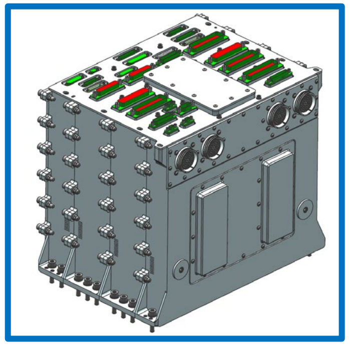
Power Distribution:
- Power Switch Slice (PSS)
- Guidance Interface Driver card (GID)
- Pyro Firing Slice (PFS)
- Deployment Power Switch Slice (DPSS)

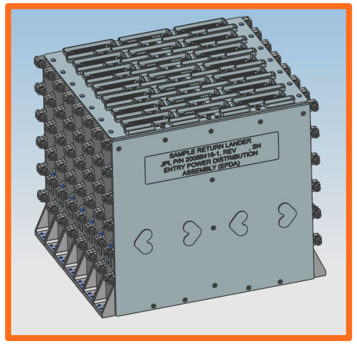
Command and Telemetry:
- MSAP/MSL Remote Engineering Unit (MREU)
- Telemetry Mux Card (TMC)

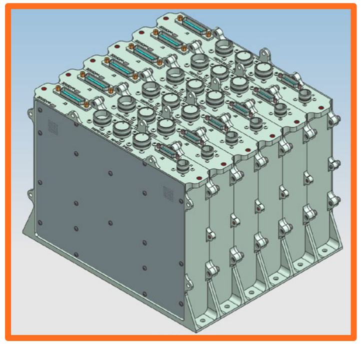


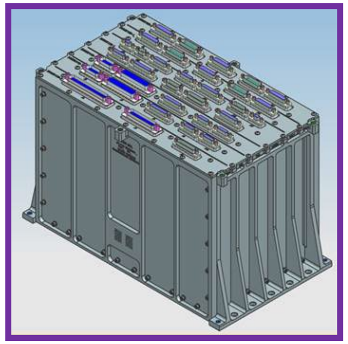












SRL Power Subsystem Functional Block Diagram

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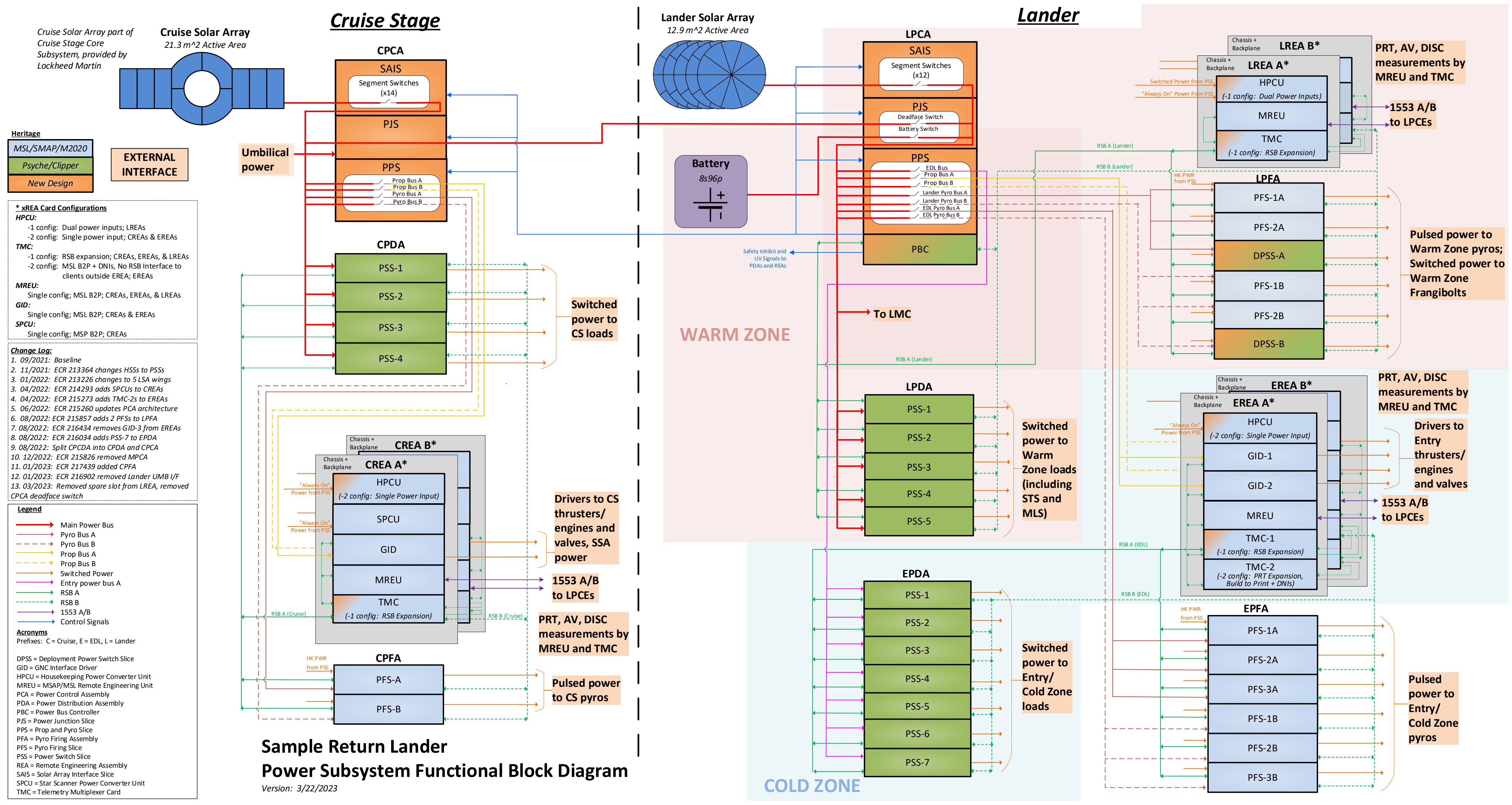

Leveraging Heritage…While Expanding Capabilities for a New Mission

Heritage		New Mission
Power electronics from the MSL/M2020, SMAP, Psyche, and Europa Clipper project	→	Modifications to electronics for SRL-specific needs (ex: higher power than previous missions)
Battery cell technology used on the Europa Clipper project	→	Larger assembly capacity and modified thermally-isolated packaging design for Mars surface environment
Ultraflex solar array wing design from Phoenix and Insight projects	→	Updated cell technology, strengthened mechanical design for higher wind loading

Heritage hardware does not equal heritage architecture; challenge is adapting designs to new mission-specific needs and environments

Power Bus Regulation Architecture

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- A bus regulation trade study was performed based on heritage architectures; primarily comparing direct energy transfer (DET) vs. converter-based topology
- A DET architecture with solar array segment switching was selected based on driving criteria
  - Power goes directly from the solar array and/or battery to the loads
  - There is no power conversion between the power source/storage and the loads (and therefore no conversion losses)
  - Power bus voltage is driven by the battery voltage (which varies as a function of SOC)
  - Solar array operating point is also driven by battery voltage (i.e. not typically operating at array Pmp)

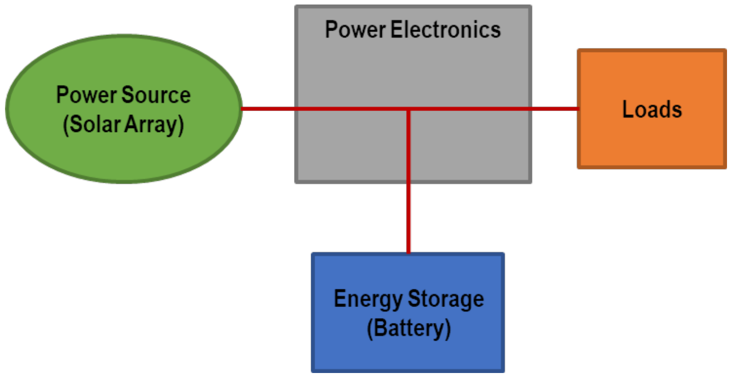
DET architecture with battery on the bus and SA segment switching provides a robust solution to varying load and environmental conditions while limiting overall complexity

SRL Power Bus Regulation Trade Study

Selected Option

Trade Discriminator	Block Redundant Segment Switching (SMAP Heritage)	Internally Redundant Converter-Based (Europa Heritage)	Internally Redundant Segment Switching (SMAP + Europa Heritage)	Identified as Mission Driver?
Surface Power Efficiency				X
Cruise Power Efficiency				
Mass				X
Volume				X
Power Dissipation				X
Redundancy / FCR Approach				
Heritage and Complexity				
Required Modifications				
Parts				
BTE				
Applicability to MMRTG				

Direct Energy Transfer Architecture



Power Bus Regulation Architecture: Control Approach

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- SA power regulation is managed by the PBC
  - The PBC switches SA segments on/off based on the demand of the load; if load < demand, power is left on the array (i.e. no shunting)
  - The SA segment switches are accommodated in the SAIS
- The PBC also manages the battery through a CC/CV charge management approach
  - Battery/bus voltage and battery charge current are selectable in flight
- Single fault tolerance is achieved by each of the 3 PBC FCRs/FPGAs executing its own control loop, with the output being triple majority voted on the SAIS

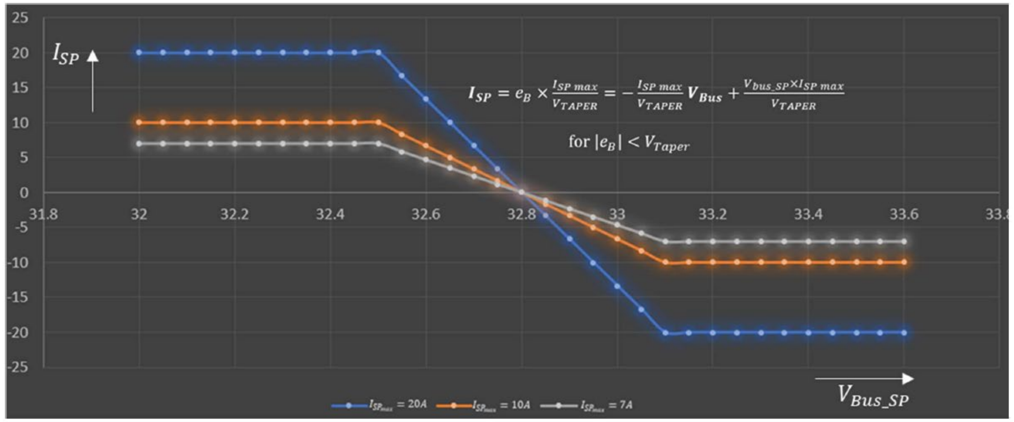
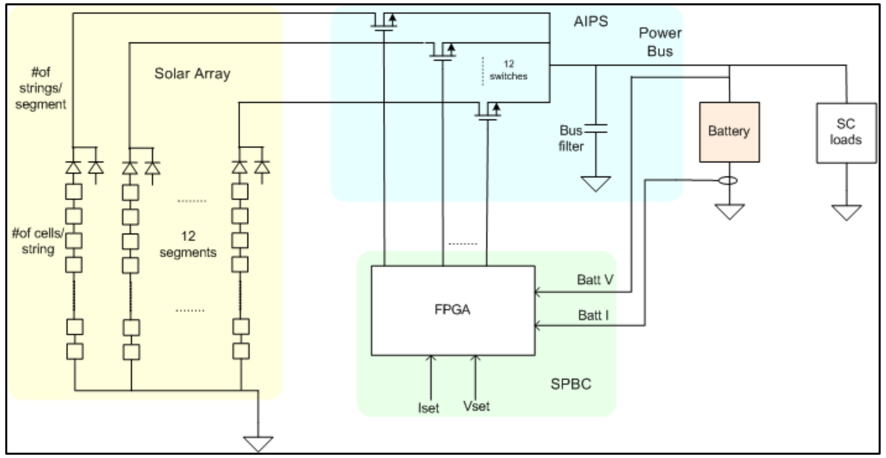
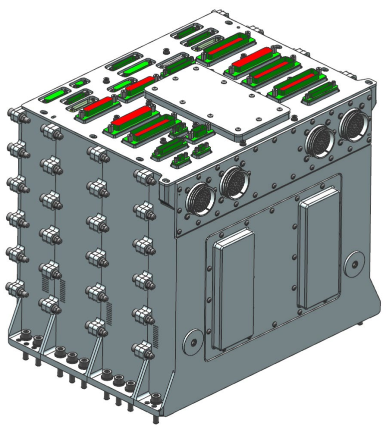


Figure 8: Battery current as a function of configurable battery current setpoint

Bus Control Approach



PCA



Power Bus Regulation Architecture: Electronics-SA Interface

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- The PCA implements segment switching with fine and coarse control, with segments turned on/off based on load in a binary counter approach
  - Three fine control bits are mapped to small SA segments (few strings)
  - Nine coarse control bits are mapped to large SA segments (many strings)
- **Cruise SA:** 14 circuits are split across the static and deployed panels
- **Lander SA:** Each wing (up to six) has 12 circuits, with one circuit from each wing getting mapped to a SAIS segment switch
  - Allows all wings to have the same string/circuit layout
  - Maintains robustness in differing conditions across the wings (i.e. failed wing, imbalanced dust loading, etc.)

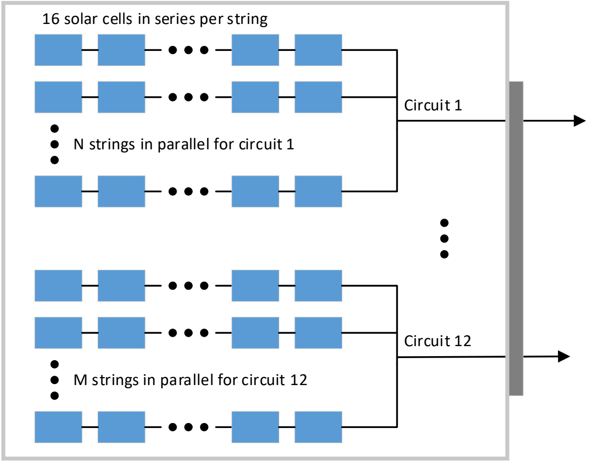
PBC Segment Map Excerpt

Internal u[k] bits 23-16	Coarse Switches												Fine			
	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
00000000b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
To	0	0	0	0	0	0	0	0	0	0	0	0	. . .			
00001111b	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
0001xxxxb	0	0	0	0	0	0	0	0	0	0	0	1	x	x	x	x
0010xxxxb	0	0	0	0	0	0	0	0	0	0	1	1	x	x	x	x
0011xxxxb	0	0	0	0	0	0	0	0	0	1	1	1	x	x	x	x
0100xxxxb	0	0	0	0	0	0	0	0	1	1	1	1	x	x	x	x

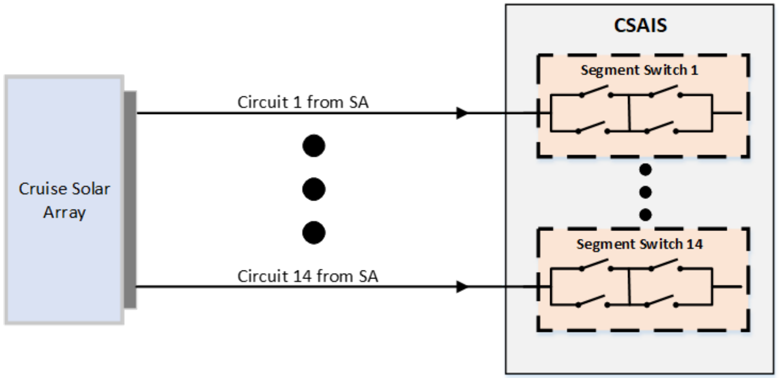
SRL Segment Definition

	Cruise SA	Lander SA
# Fine Control Segments	3	3
Fine Segment Sizes	1.2A, 1.8A, 3A	4x 7.2A, 2x 7.8A, 3x 8.4A
# Coarse Segments	14	12
Coarse Segment Sizes	4A, 6A, 11A	11x 20A

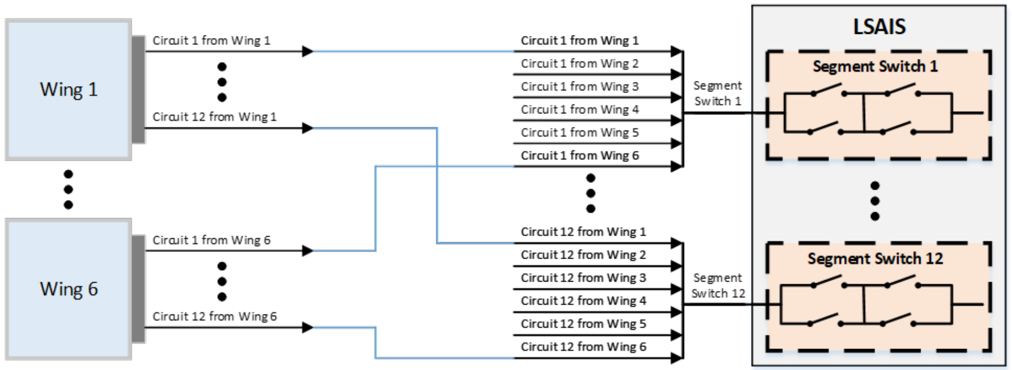
LSA Wing



CSA Circuit to Segment Mapping



LSA Circuit to Segment Mapping (6 Wings Shown)



Cruise Power Generation

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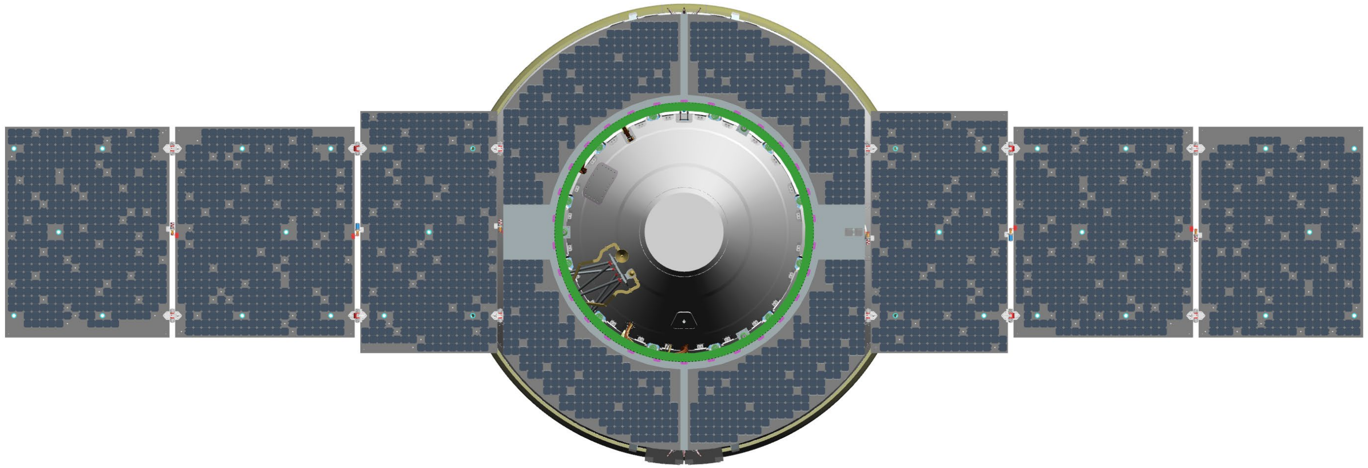
- The cruise solar array is delivered by Lockheed Martin (LM) as part of the Cruise Stage contract
- The baseline design consists of a static assembly and two deployed wings using AzurSpace 4G32 solar cells, with a total active area of ~21 m^2
- Given high power requirements and limited available volume, an optimized design is implemented using mixed string lengths
  - 2,000 W at 0.95 AU (hot case)
  - 2,450 W at 1.65 AU (cold case)
- The array will be comprised of 14 circuits to interface with the power control electronics

Lockheed Martin SRL Cruise Solar Array



Surface Power Generation

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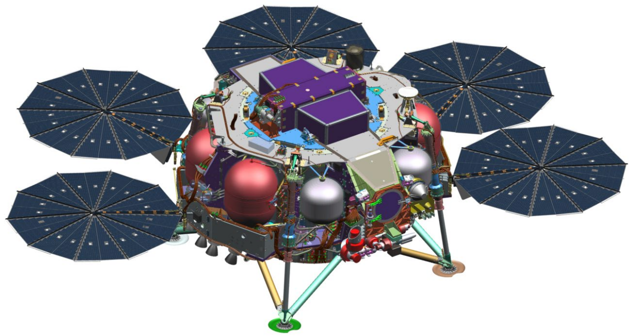
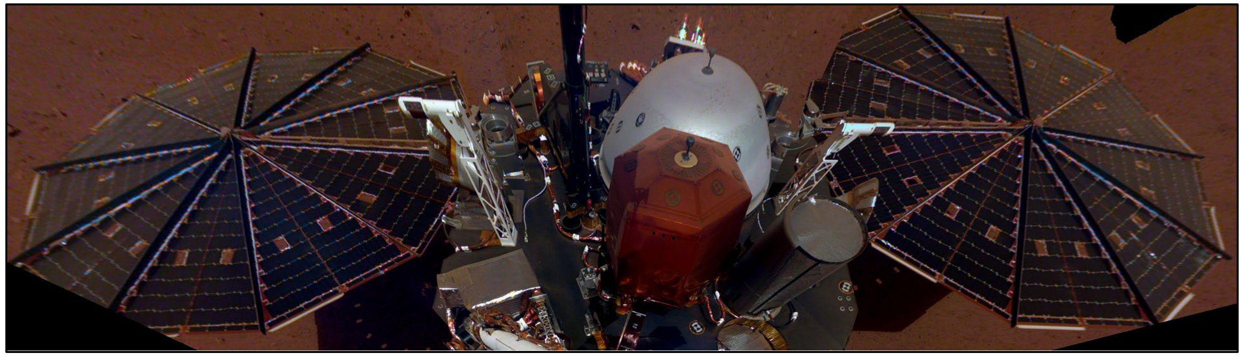
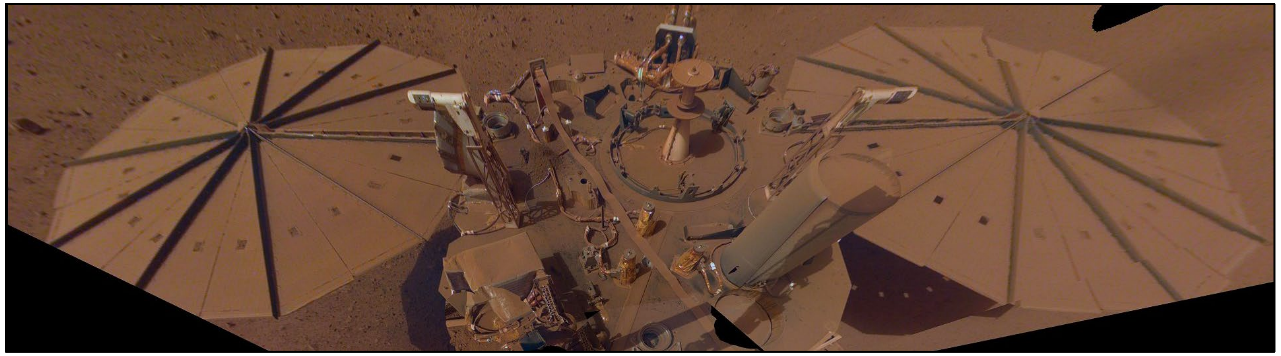
- Lander solar array is built by Northrop Grumman and is comprised of five deployable 2.19 m diameter UltraFlex wings, with a total estimated active area of 12.9 m^2
    - SC is being designed to be capable of handling six wings if needed
- Array is based on Insight heritage with modifications to account for the different environment (ex: longer string lengths due to hotter max surface temperatures, structurally stiffer due to increased wind loading)
- Baseline cell technology = SolAero ZTJ-Omega solar cells
- Generates ~7.5 kWh/sol on Mars at BOM, clear skies
- Each wing contains 12 circuits, with circuits from each wing getting combined into a single segment at the power electronics
- Large solar array area is driven by Mars surface dust environment

Lander Solar Array (Deployed)



Insight Dust Accumulation





Energy Storage

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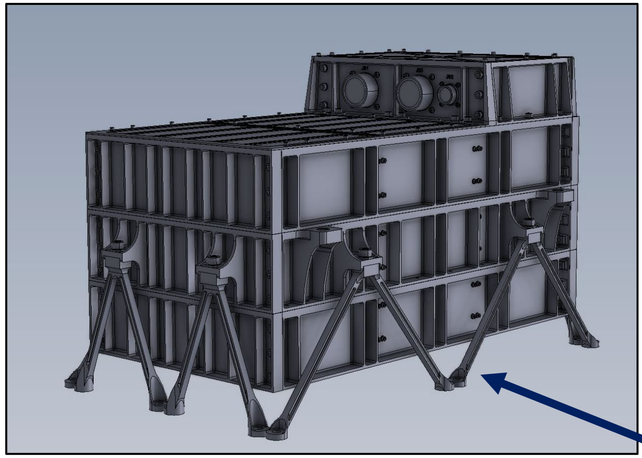
- Energy storage is provided by a single 8s96p Lithium-ion secondary (i.e. rechargeable) battery
  - Unlike prior lander Mars missions, there are no thermal batteries
- Battery is built by ABSL using LG Chem MJ1 18650 small cells (no cell balancing required, fault containment is at the string level)
- Battery cell selection and packaging design drivers included the thermal environment, power capability, and energy capacity
- A high power/energy density cell was selected with a thermally isolated structural design plus survival heaters to maintain the battery within preferred temperature range of 0C to 30C

SRL Battery Characteristics

Cells per String	8
# Strings	96
Total Cells	768
BOM Capacity	235 Ah
EOM Capacity	201 Ah
Max Continuous Discharge	100 A
Max Pulsed Discharge	140 A

SRL Battery Configuration

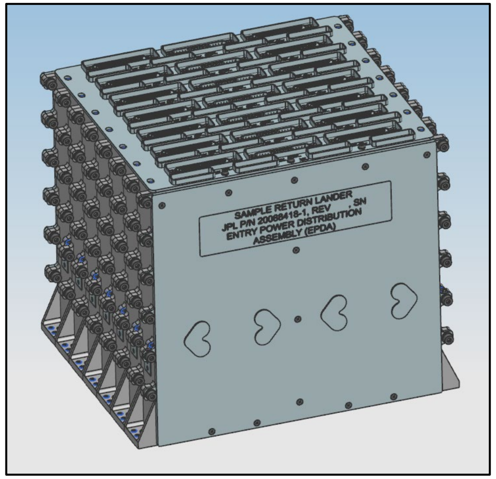


18650 Small Cells

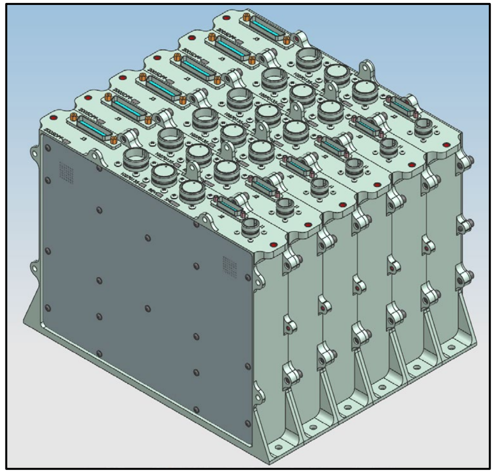
Power Distribution

- Switching electronics with high modularity are implemented to allow capability growth throughout the system development timeline with limited impact to the subsystem architecture
- **Power Switch Slice (PSS)**
  - Switches main bus power to loads
  - Europa Clipper/Psyche project heritage
  - Each PSS provides 26x 2A channels, 4x 5A channels, and 2x 10A channels
    - Channel = high side + low side switches
  - PSS has internally redundant switch control
  - Key features are resettable OCP for loads, load current telemetry, UV load shed capability, safety inhibited switches, and auto-turn on switches
- **Pyro Firing Slice (PFS)**
  - Used to fire Pyros/NSIs and NEAs with current-limited output channels
  - MSL/M2020 and SMAP heritage (build-to-print)
  - Parallel channels are used to fire NEAs, which require higher current
- **Deployment Power Switch Slice (DPSS)**
  - A new card is being developed for SRL for firing Frangibolts
  - Based on a modified PSS design

PSSs



PFSs



Pre-decisional information for planning and discussion purposes only.

Command and Telemetry Electronics

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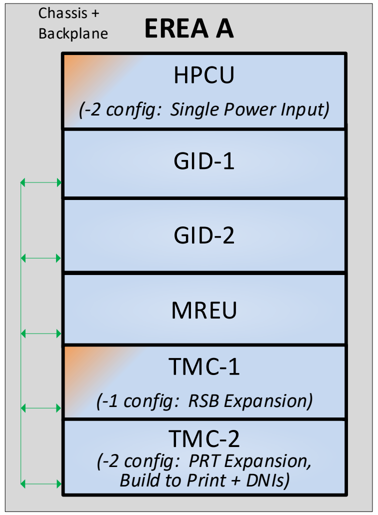
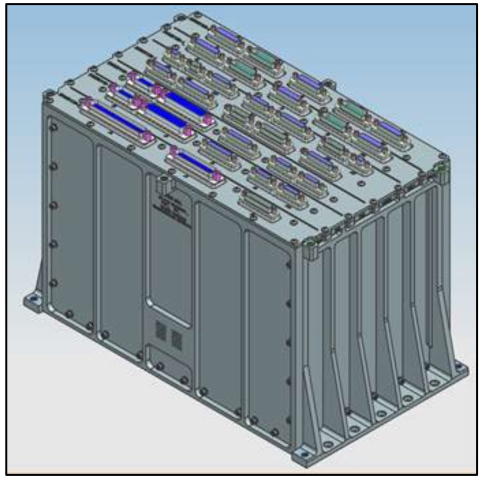
- **Remote Engineering Assemblies (REAs)**
  - ***MSAP/MSL Remote Engineering Unit (MREU):*** Critical autonomy and fault management functions; complements the main SC avionics/flight computer (separate assemblies)
  - ***Telemetry Mux Card (TMC):*** Telemetry collection and communications serial bus distribution hub
  - ***GNC Interface Driver (GID):*** Thruster and latch valve pulsed drivers
  - ***Housekeeping Power Converter Unit (HPCU):*** Secondary voltage conversion for the REA cards
  - ***Backplane:*** Distribution of power and communication among the cards
- The REAs are primarily heritage from past JPL missions (MSL/M2020, SMAP, etc.), with some targeted modifications
  - Allows the leveraging of heritage fault protection strategies and flight software, in addition to hardware



REA



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Summary

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- The NASA-ESA MSR campaign is an unprecedented multi-mission collaboration aiming to return samples from the Martian surface to Earth
- The SRL spacecraft would be the largest and highest power vehicle to land on another planet
- The power subsystem needs to leverage past heritage designs while also adapting hardware to the new driving demands of the mission
  - Diverse mission phases and con-ops
  - Challenging environmental conditions
  - Significant spacecraft load demands
- The power subsystem will be built upon the architectural lineage of JPL's past successful Mars surface missions, while advancing the design to accommodate the SRL’s multi-kW needs in an efficient manner
- The SRL power subsystem could serve as the basis for JPL’s large scale, flagship solar powered missions into the future

MSR Overview Video

https://www.youtube.com/watch?v=t9G36CDLzIg

Acknowledgement

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