

Power Hibernation for Low-Cost Solar Powered Lunar Missions

CLPS Survive the Night Technology Workshop

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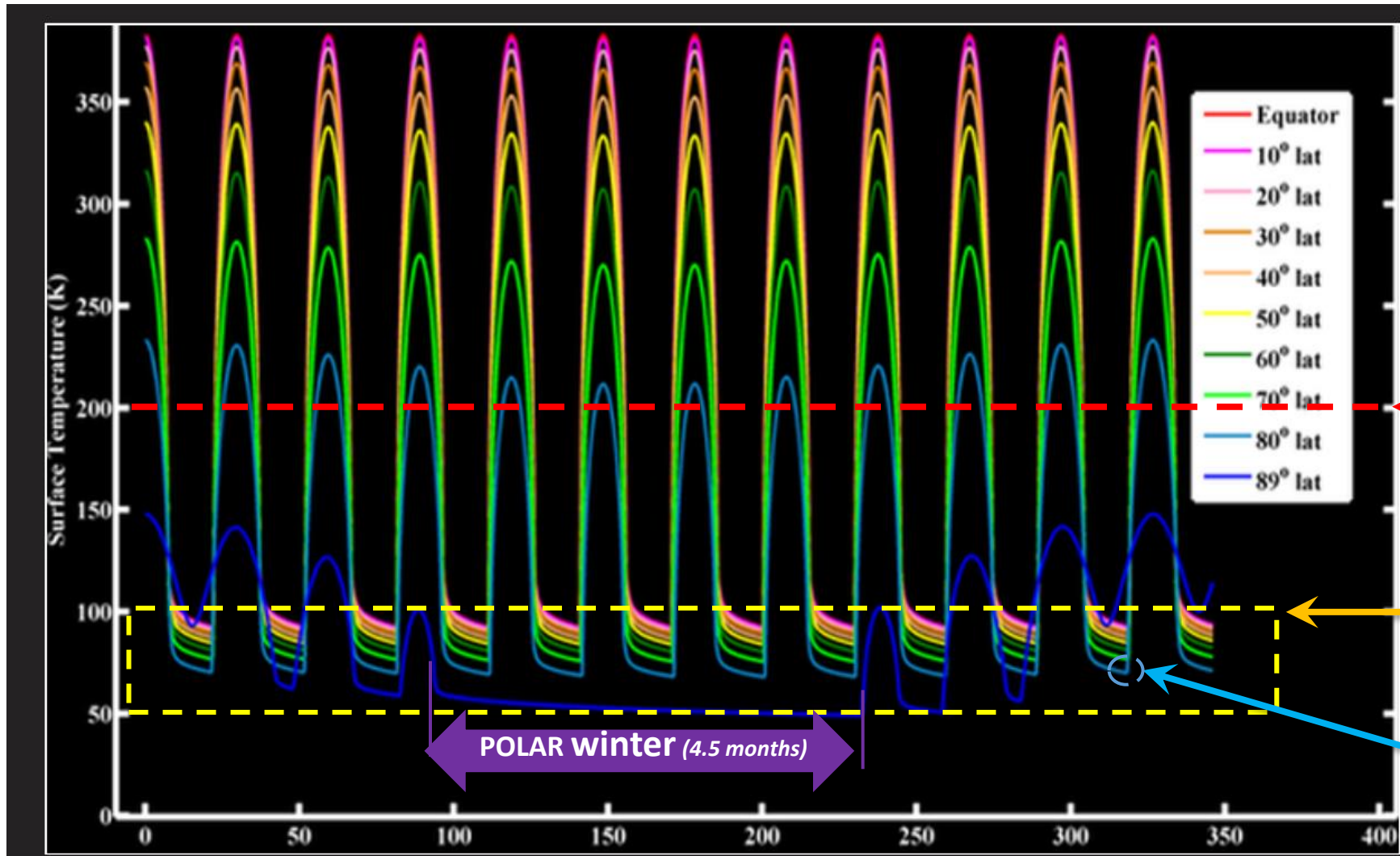


The Extreme Lunar Environment

LRO DIVINER: Lunar Day/Night Temperature Range by Latitude



Thermal model calculations of monthly & annual lunar surface temperature variations at various latitudes



- **Day:** 150-400 K highs based on latitude
- **Night:** 50-100 K lows *all latitudes*
 - Duration (non-polar): ~354 hrs (~14.75 Earth days)
- **Lunar Polar Winter:** Sun is below horizon for ~4.5 months

Li-ion battery approx. freeze temperature

Lunar night is extremely cold everywhere

Lunar dawn

Lunar Power Hibernation Approach

- **Aimed at low-cost solar powered spacecraft (CLPS missions)**
- **Intended to extend the mission capability beyond a single lunar cycle**
 - Passively surviving the lunar night
 - Reactivate power at lunar dawn
 - Progressively restore full functions
- **Hibernation minimizes design impact on existing spacecraft**
 - Enable multiple lunar cycles while minimizing redesign and development costs
 - Changes limited to dawn mode functions in the power system
 - Minimize impact on system size and payload capacity
- **Make what spacecraft we have work (still needs tech development)**

Lunar Power Hibernation Approach

Hibernation is enabled by a Li-ion cell's ability to survive extreme cold

- Tests show 18650 Li-ion cells can passively tolerate multiple freeze/thaw cycles
- Remove battery from main bus shutting down all power until dawn
- Dawn illumination of PV arrays triggers a “dawn mode” restart sequence

Why 18650 Li-Ion cells for cryo-tolerant batteries?

- Widely used for both small and large spacecraft batteries
- Voltage drops to zero when frozen (~ 200 K)
- Recovers when returned to operational temperatures
 - Recovered state of charge
 - Cells tested in a vacuum successfully recovered.
- What about other formats?
 - Similar cylindrical formats (such as 21700, 22700, 26650, etc.) may be viable

Lunar Power Hibernation Approach

Dawn Mode recovery is enabled by Cryo-Electronics:

- All systems need to be Cryo-Tolerant
 - Passively survive the extreme cold
- Key Power circuits must be Cryo-Operable
 - Cold-start at cryogenic temperatures
 - Provides stable operation down to 50 K

Dawn Mode Power Functions

- Prevents PV Array Overvoltage
- Stable operation on solar array output alone
 - Battery is initially frozen and isolated (low power quality environment)
- Pre-Heat to bring avionics and battery up to temperature
- Pre-Charge Battery to match bus voltage
- Reconnect battery and bus

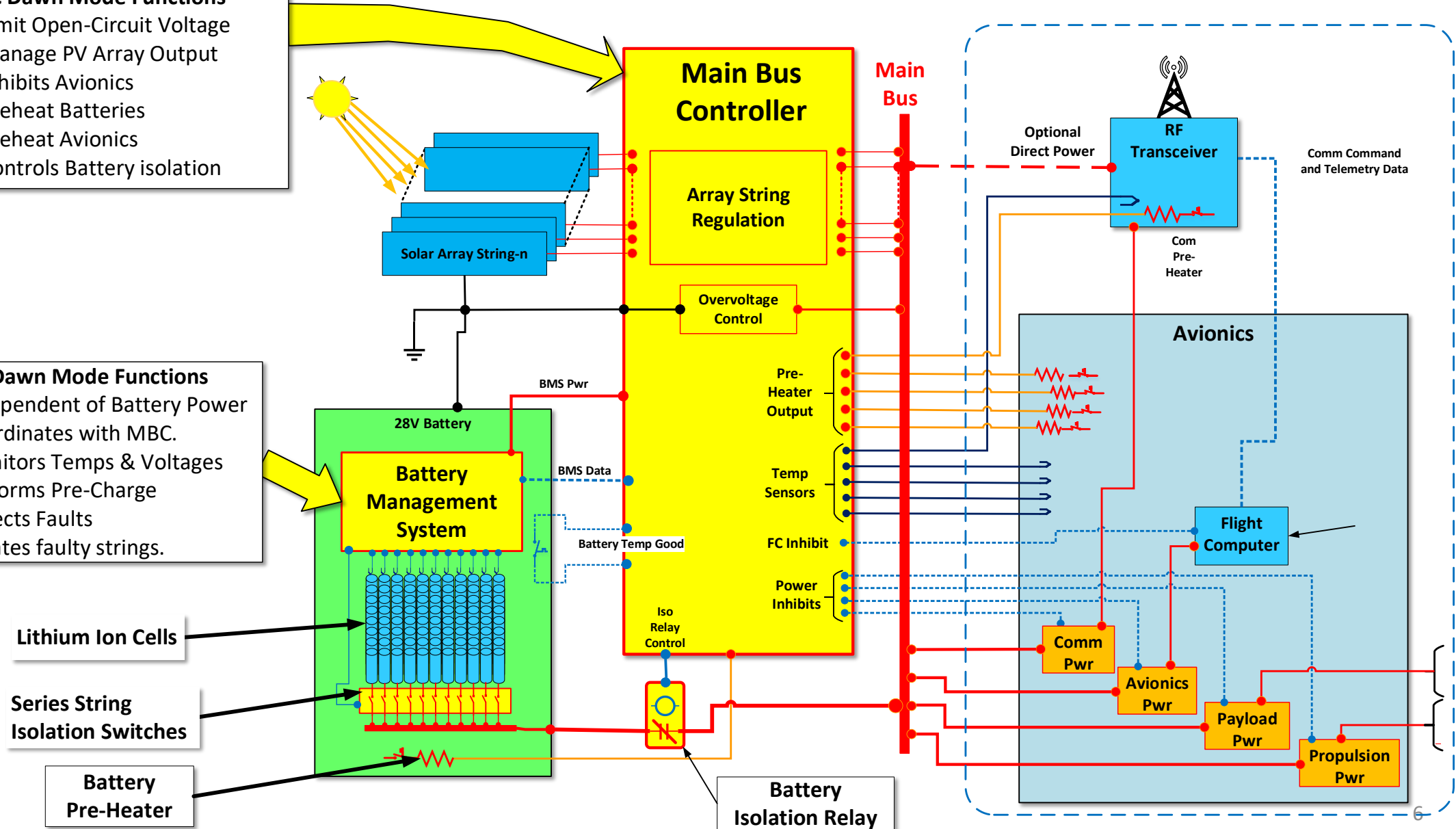
Lunar Power Hibernation: Dawn Mode

MBC Dawn Mode Functions

- Limit Open-Circuit Voltage
- Manage PV Array Output
- Inhibits Avionics
- Preheat Batteries
- Preheat Avionics
- Controls Battery isolation

BMS Dawn Mode Functions

- Independent of Battery Power
- Coordinates with MBC.
- Monitors Temps & Voltages
- Performs Pre-Charge
- Detects Faults
- Isolates faulty strings.



Cryo-Tolerant Batteries for Hibernation

- **Prior cryogenic 18650 tests raised a number of questions**
 - How many freeze/thaw cycles can be tolerated?
 - What are potential degradation mechanisms?
- **The Li-ion cell freeze/thaw process is not well understood**
 - Why do they survive despite dire expectations?
 - Can we exploit the cryogenic conditions for safety?

Cryo-Tolerant Electronics for Hibernation

Cryo-tolerant electronics are capable of tolerating cryogenic temperature cycles without degradation

- Most avionics need only tolerate the cold
- Cryo-Tolerance is primarily a device and circuit packaging issue
- Managing coefficient of thermal expansion (CTE) is key
 - Common Fiberglass Reinforced Printed Circuits have limited tolerance of cryo-temps (limited cycle life)
 - Small devices and circuits have lower CTE stress
 - High-reliability techniques emphasize matching CTE
- Managing the internal thermal environment to minimize thermal stress
 - Maintain flat thermal gradients
 - Minimize thermal rate of change
 - Note: Lunar environment changes a few degrees per hour

Cryo-Operable Electronics for Hibernation

Cryo-operable electronics are capable of cold starting and stable operation in cryogenic temperatures

- All semiconductor properties shift with temperature
- Understanding thermal effects on semi-conductor and transistor architecture are key to cryo-operability
 - Example: SiGe changes from one conduction method to another
 - Transistor architectures can minimize sensitivity to temperature (Ex: GaN HEMT)

Circuit-level cryo-operability (400 K to 50 K)

- Many circuits use mixed technologies (Si, SiC, SiGe, GaAs, GaN) and transistor types and functions.
- Need to account for differing parameter changes for a wide temperature range
 - Flat response to temperature is ideal for circuit stability
 - Will likely need device level temperature compensation techniques

Summary of Technology Needs

Battery Technology (cell to battery level)

- Thorough characterization of the freeze/thaw process
- Electro-chemical and thermal-mechanical characterization and modelling
- Development of in-flight cell management and diagnostics
 - Thermal management
 - Detection of faults (if possible while in the frozen state)
 - Fault mitigation schemes

Electronics Technology (device & circuit level)

- Advanced device and circuit package materials and techniques
- Characterization testing of electronics at cryogenic temperatures
- Physics-informed modelling and simulation tools to exploit characterization data
- Temperature compensation techniques to assure stability

Current Research Projects

Current research under Space Technology Mission Directorate funding:

Battery Technology

- Two Early Career Faculty PIs investigating Li-ion freeze/thaw behaviors

Electronics Technology

- Early Career Faculty PI investigating Gallium-Nitride technology
- Lunar Surface Technology Research (LuSTR) Investigations
 - Silicon-Germanium technology
 - Back gate control for Silicon-On-Insulator temperature compensation
 - Investigating methods for improving circuit board cryo-tolerance

GRC Center Innovation Funding (assembly level work)

- Investigating multi-cell battery interactions through freeze/thaw process
- Developing cryo-operable power circuit

Infusion of Hibernation Technologies

Development of guidelines and design tools are needed to aid spacecraft and payload developers infuse new technology.

- **Cryo-Tolerant Battery design guidelines:**
 - Package batteries to ensure uniform thermal environment
 - Potential cold battery diagnostics and fault isolation
- **Cryo-Electronics design guidelines:**
 - Cryo-tolerant electronics device package and circuit level guidelines
 - Cryo-operable electronics data and engineering tools
 - Characterization data for devices and passive components for 400 K to 50 K
 - Utilize physics-informed modelling and simulation tools when possible

Next Step: Define a Lunar Power Hibernation technology demonstrator to allow the technologies to converge into an application.

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