National Aeronautics and Space Administration

VIPER

Generalizing Lunar Vehicle Thermal Analysis Lessons Learned from VIPER

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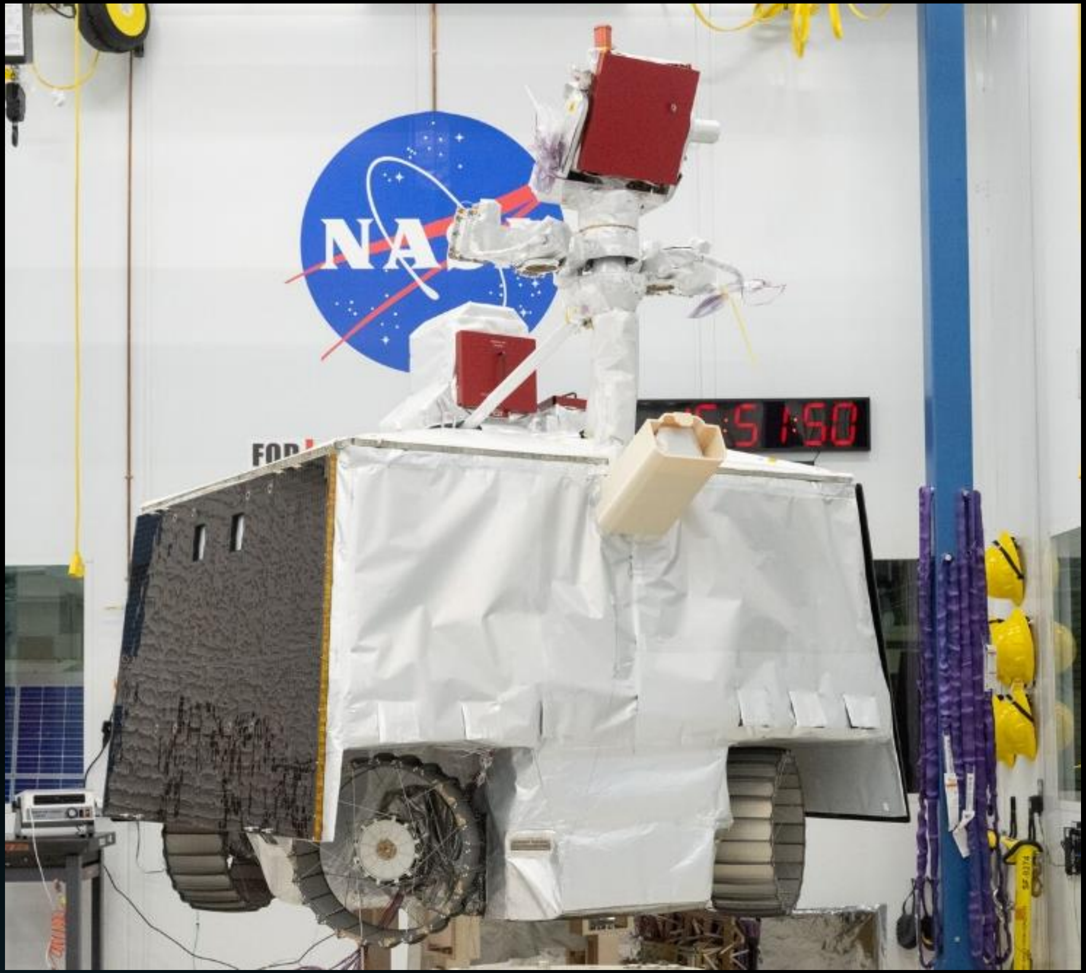
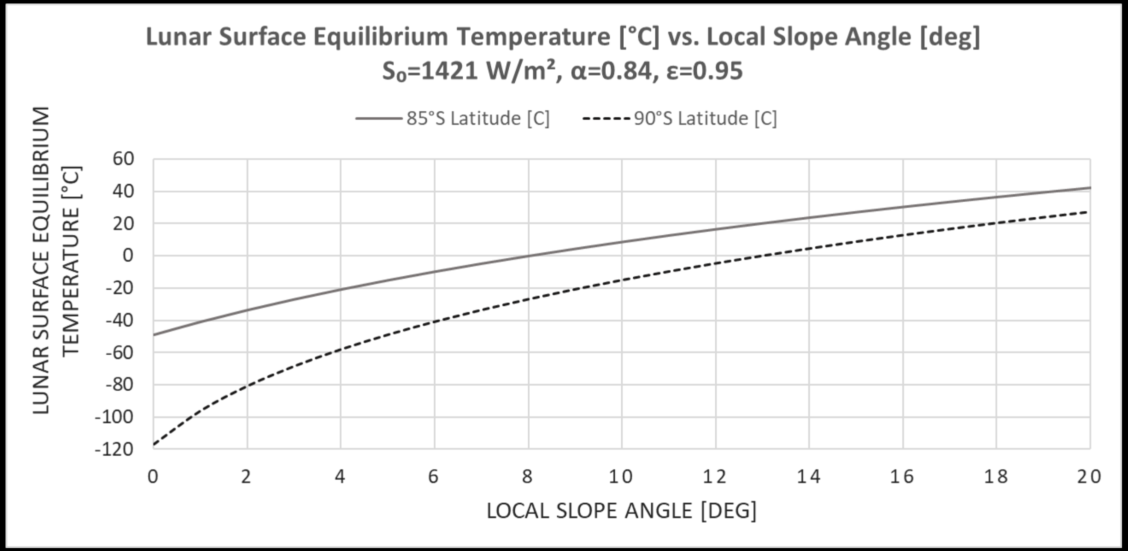
What is VIPER?

- Volatiles Investigating Polar Exploration Rover (VIPER)
- Robotic rover designed for resource prospecting of the lunar south pole
- “Science lab on wheels”: mass spectrometer, near-infrared spectrometer, neutron spectrometer, and one-meter drill
- Seeks out water ice and other frozen volatiles on the lunar surface – particularly in areas known as “permanently shadowed regions” (PSRs)
- Sophisticated power generation, imaging, mobility, communication, thermal management, and navigation systems
- Assembly completed in June 2024; all environmental testing completed and successful (vibe, acoustic, TVAC, loads) in May 2025!

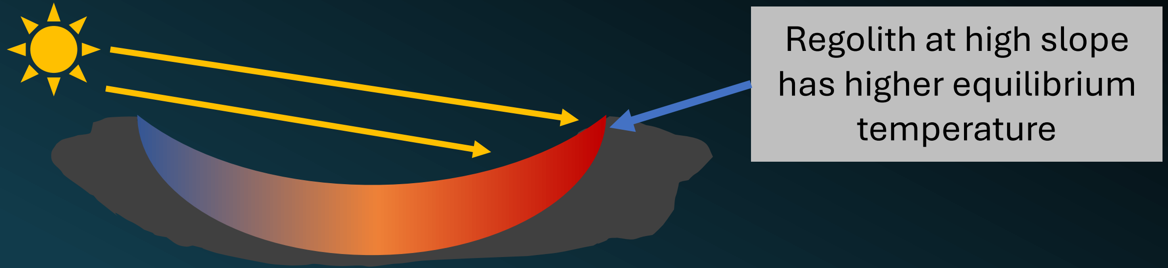


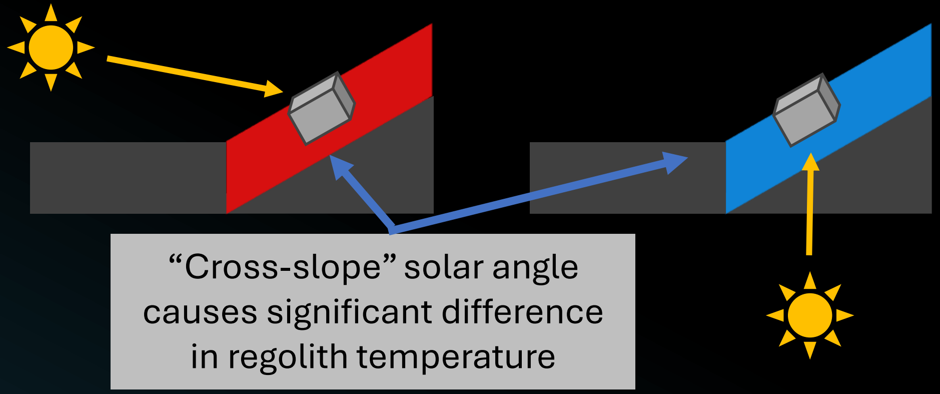
Lunar South Pole Environment Basics

- Lunar south pole thermal environment is driven mainly by three factors
  1. Solar elevation angle
  2. Cross-slope solar angle: angle of alignment between sun and slope
  3. Local slope angle
- High solar elevation angle imparts more flux onto top-mounted radiators
- Hot lunar regolith causes significant IR heat load
- Increased alignment between solar vector and slope normal vector increases regolith temperature



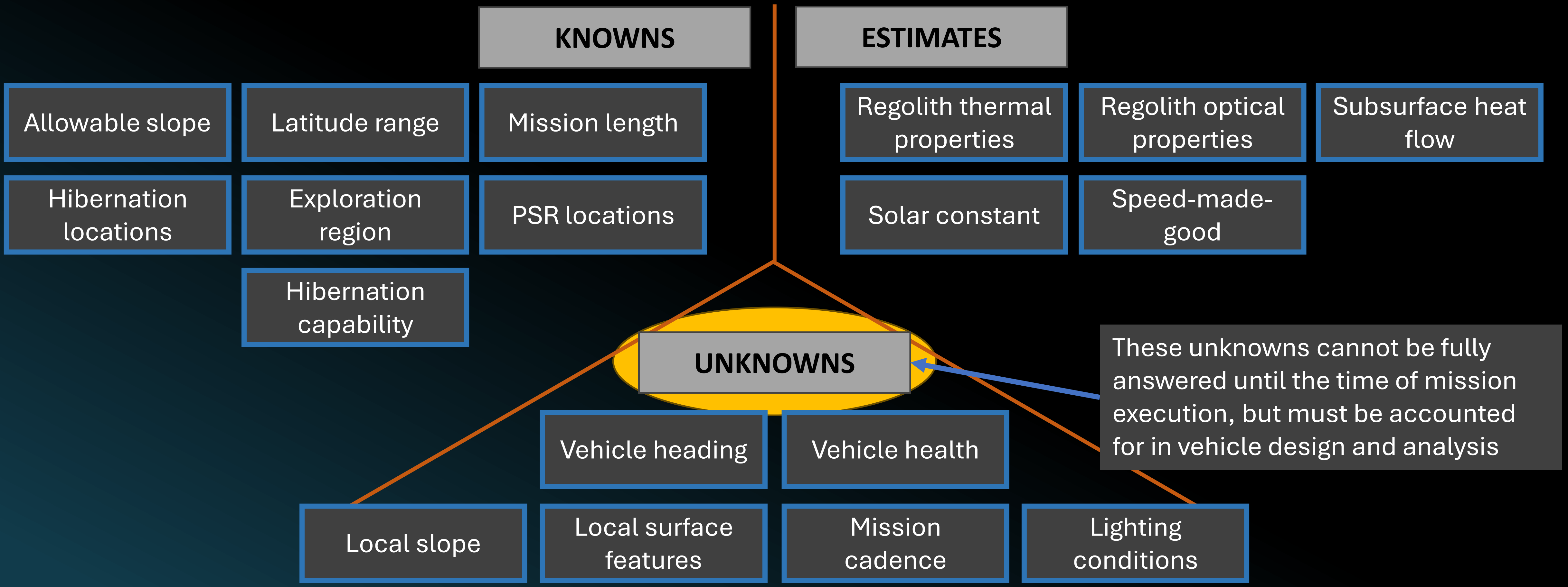
Lunar surface equilibrium temperature vs. Local slope angle





Constraining Lunar South Pole Environment

How do you constrain environments for a constantly-moving mission?



Thermal Issues

Early VIPER thermal development proved to be challenging

- Incredibly large (and complex) operational envelope
- Impossible to anticipate/analyze every environment and pose combination
- Unknown initial conditions
- Unknown cadence and timing
- Expectation that traverse plans will change during execution
- Rover state/health can override operational priorities

In short: a thermal analyst's worst nightmare!

Ultimately:

- How can we assure rover operation on the lunar surface?
- How can we assure anomaly resolution capability on the lunar surface?

Thermal Issues - Mitigation

How can these concerns be mitigated?

- Incredibly large (and complex) operational envelope
  - →*But we don't plan on using most of it in "nominal" operation*
- Impossible to anticipate/analyze every environment and pose combination
  - →*But we do know what is optimal for our vehicle*
- Unknown actual traverse profile
  - →*But we can analyze bounding cases*

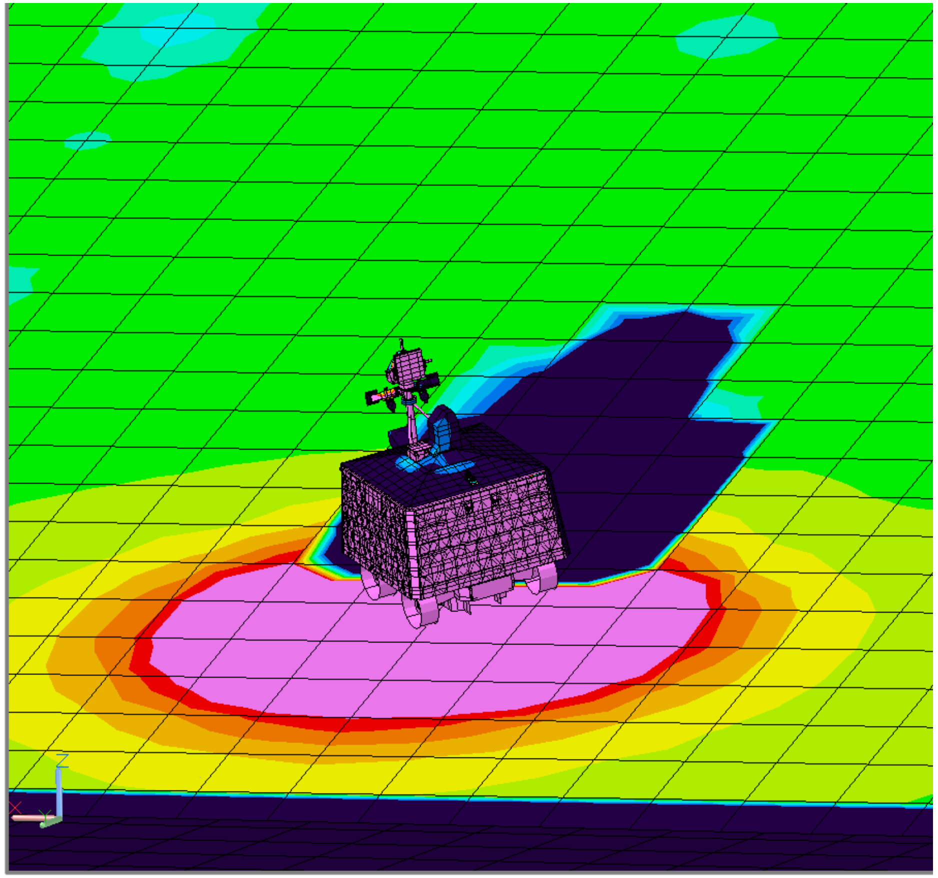
Solution: Work backwards rather than forwards – develop thermal analysis frameworks that allow mission planning around known-safe capabilities and optimal mission execution.

→What might these frameworks look like?

Framework 1: Tolerable Entrenched Time (TET)

TET Top-Level Summary

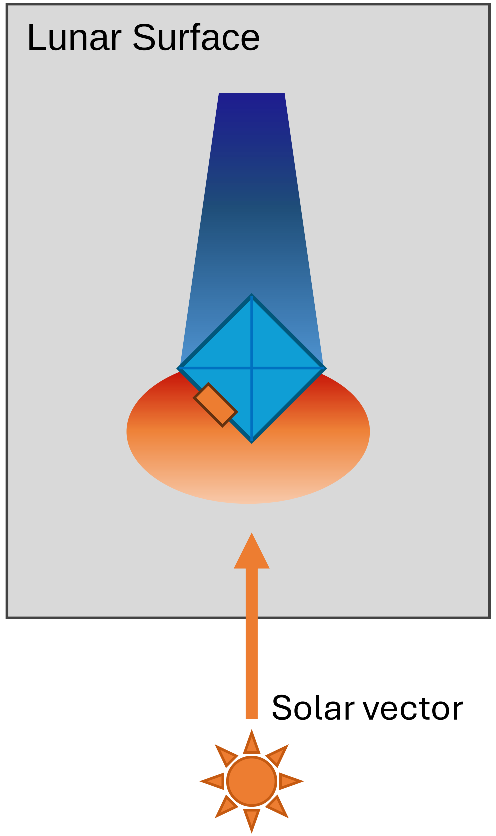
- Framework is tolerable to mission planning changes and mobility faults
- Conservative results – if we got stuck in a bad situation (i.e. entrenched in regolith), how long could we survive?
- For VIPER – TET driven by vehicle speed, parking/idling time, and safe-haven limitations on the lunar south pole



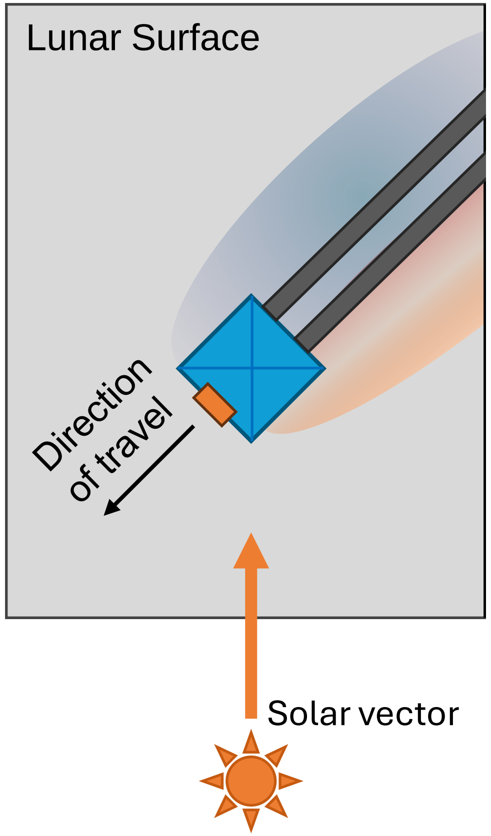
Thermal analysis showing hotspot on sunlit side of VIPER

TET Driving Factors

- Early VIPER thermal analysis identified operationally significant difference in temperatures for **roving** vs. **parked** cases
- Parking causes hotspot of regolith to develop in front of vehicle due to reflected energy
- Both regolith and exterior temperatures increase over several hours before reaching steady-state
- **Thermally advantageous to be "on the move"** - lines up with VIPER concept of operations
- Getting stuck could lead to environmentally-driven overheating - but how long could the rover be stuck?
  - Work backwards to find an answer



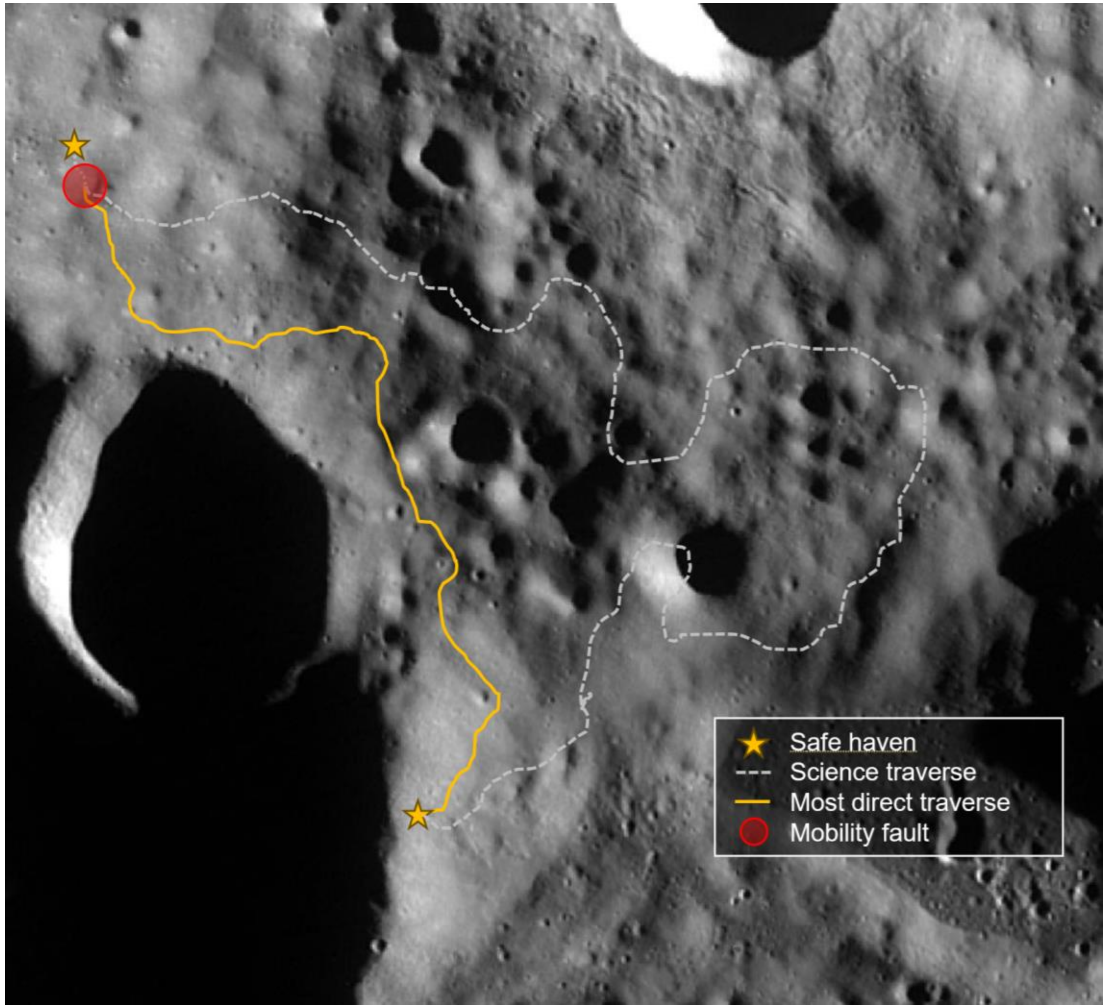
"Parked" lunar surface thermal gradient



"Roving" lunar surface thermal gradient

TET Methodology

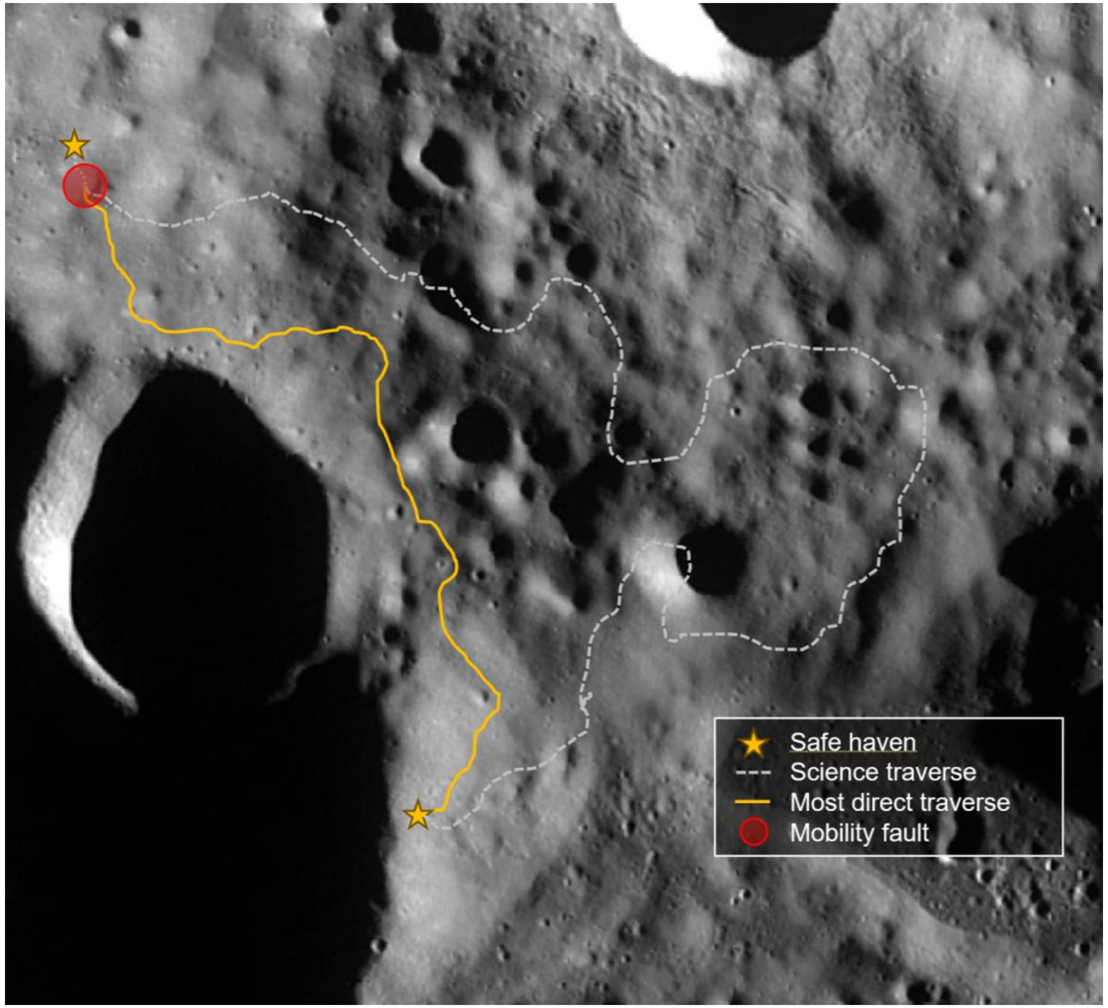
- Need to define how long an “off nominal” scenario could last to define vehicle design/analysis
- For VIPER, seasonal variability in safe-haven darkness periods eventually causes need to traverse between two hibernation locations
- If mobility fails between two safe-havens, eventually it becomes impossible to reach new safe-haven before nightfall (and loss-of-vehicle occurs)
- Creates a “ticking clock” scenario – if rover becomes stuck, a finite amount of time exists to get unstuck before the traverse is impossible



Example traverse (not to scale)[1]

TET Methodology

- TET methodology relies on advanced traverse planning capability (calculating reasonable traverse timelines)
- Monte Carlo simulation of traverses could identify shortest possible time between hibernation sites
- Maximum allowable traverse timeline could be performed via lighting analysis (or other methods)
- Difference between maximum allowable and shortest time informs how long a rover would need to tolerate environmentally-reflected heating
- TET is highly dependent on rover "class"
  - This methodology becomes much easier for rovers with stringent and relatively short traverse durations (e.g. crewed vehicles)



Example traverse (not to scale)[1]

Framework 2: Contingency Mode(s) (CM)

CM Methodology

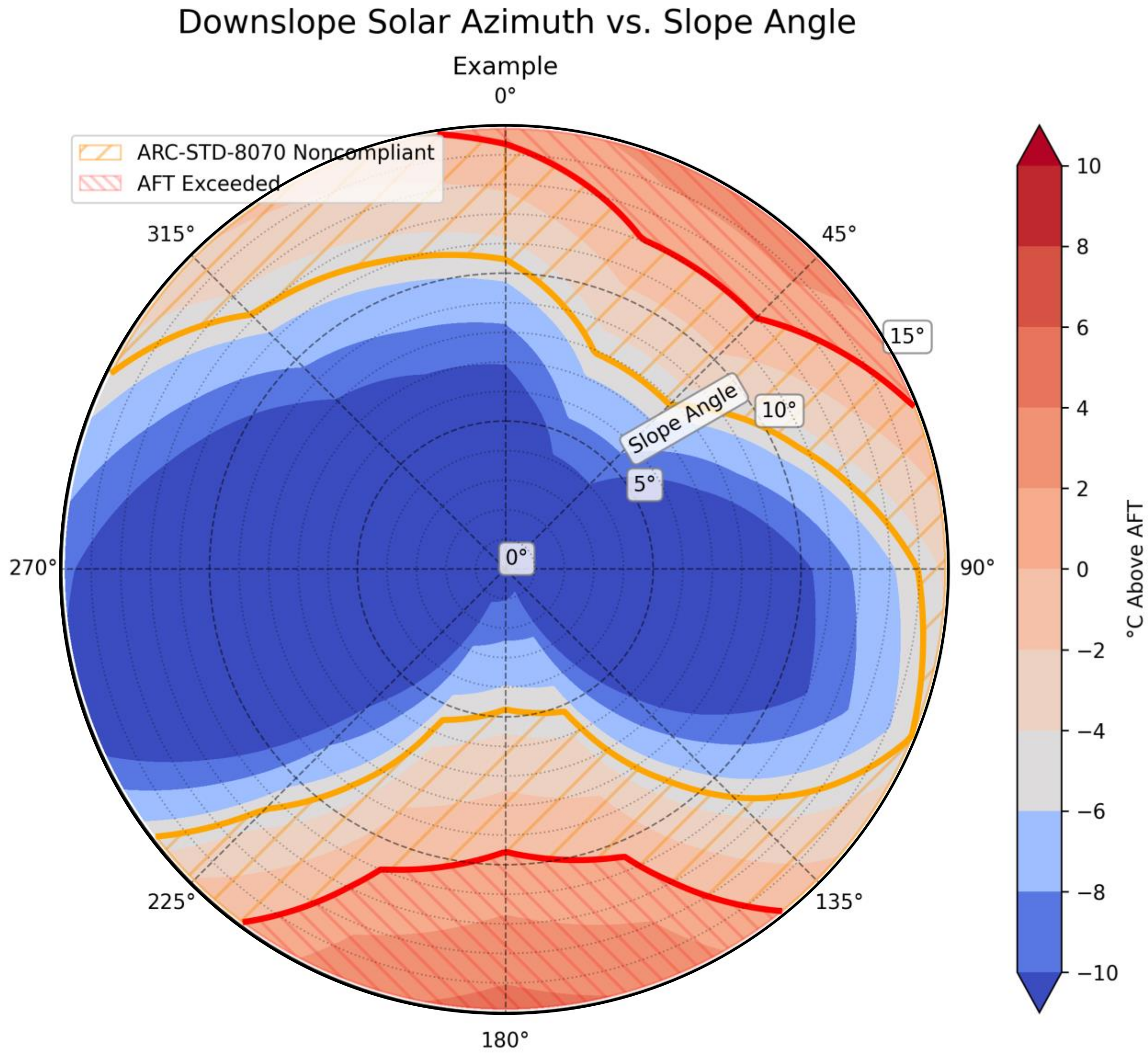
- “Contingency Mode” framework examines rover operations from a point of vehicle modalities
- Framework mainly relies on bifurcating “nominal” and “contingency” rover operations
- Underlying mechanism is applying different restrictions to different operational modes
  - Nominal operations may be limited to specific environments, slopes, times of day
  - Contingency operations may allow worse environments but require fewer capabilities
- Prevents designing for the absolute worst-case environment, but predicated on rigorously defining concept of operations early

Nominal Operations	Contingency Mode
• Science instruments powered • Consistent speed-made-good • Low allowable slopes • Etc.	• Minimum equipment powered • Worst-case environment • Full traversable envelope • Etc.

Framework 3: Unlimited Operations Envelope (UOE)

UOE Top-Level Summary

- UOE framework generates single chart with "worst-case" TMS performance
- Conservative results – if everything was working against us, what could the vehicle still do?
- Defines zones where <u>any operation</u> can be performed - regardless of environment or operational state
- Traverses are planned around a known-safe envelope and additional analysis can be performed if that envelope must be exceeded
- "Expandable" framework – similar chart can be made for multitude of operational states or environmental limitations



Example unlimited operations envelope (not representative of VIPER)

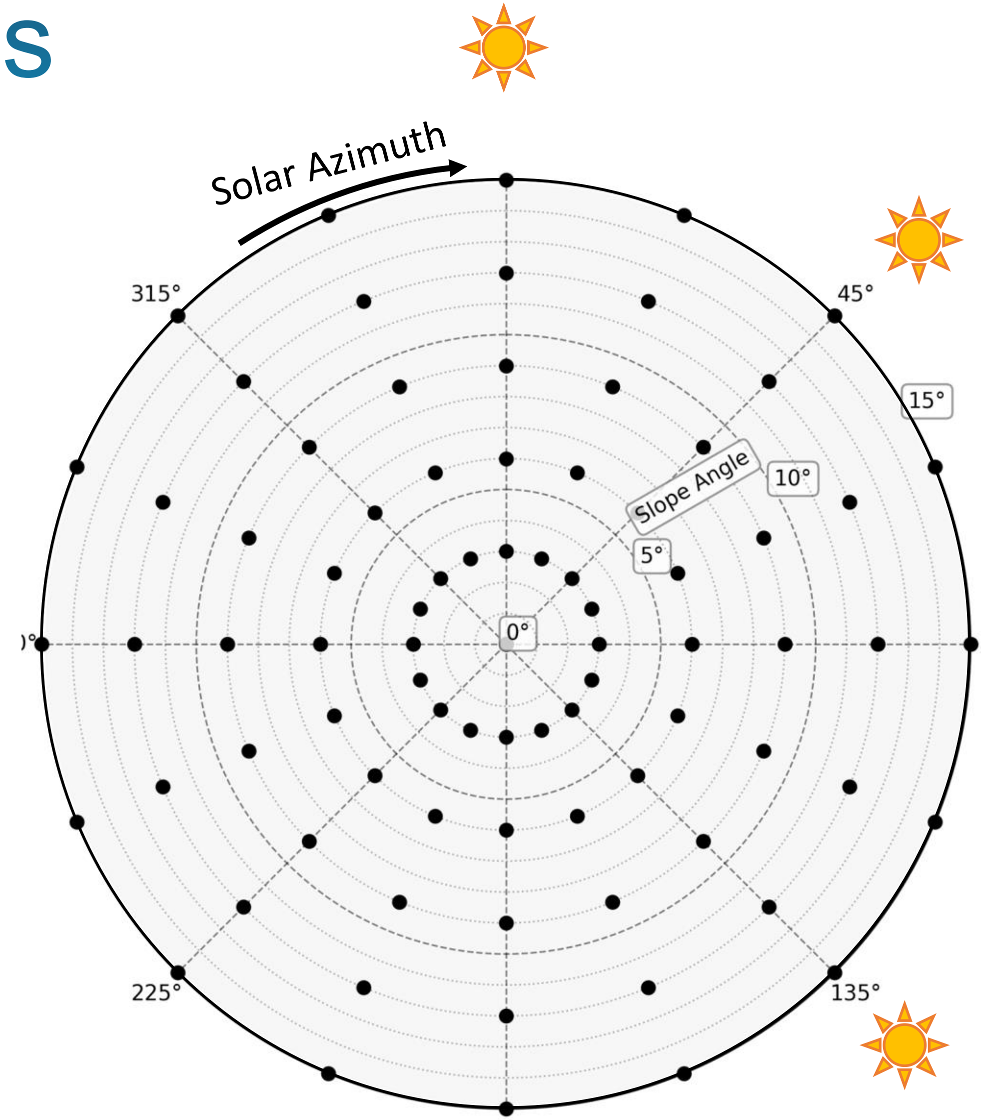
Methodology & Assumptions

Assumptions:

- All cases are steady-state
- Maximum solar elevation angle for mission timeline
- Sun is always aligned to slope to create hottest regolith plane
- VIPER is in its highest power-draw state
  - Thermal team's convention assumes maximum *sustained* dissipation
  - Intent that mission planners should not have to worry about tracking component power states

Methodology:

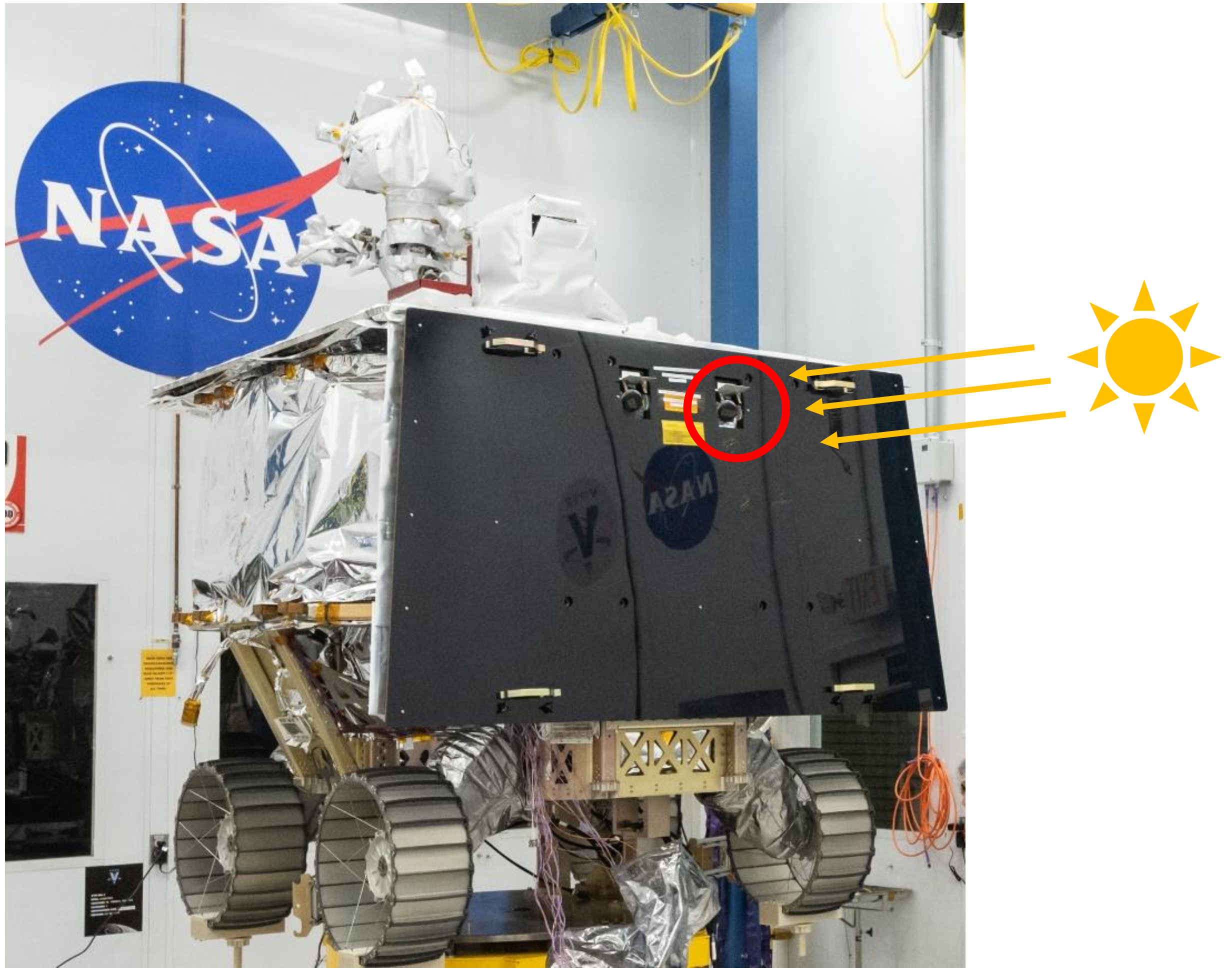
- Run a set of sunlit steady-state cases covering 360° solar azimuth range for slopes increasing from 0° (flat terrain) to highest allowable slope (15° for VIPER)
- Cases run every 22.5° solar azimuth angle and 3° slope from 0°-15°
  - 96 total steady-state cases

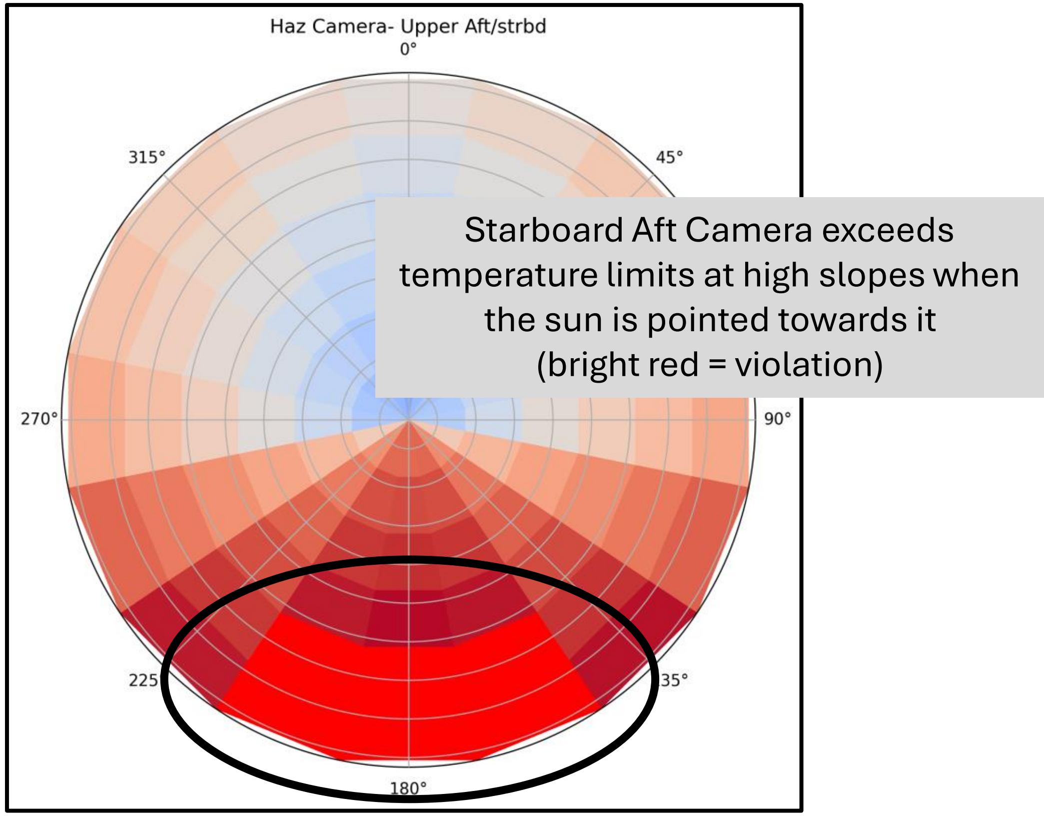


Solar azimuth case matrix for a single slope (each dot represents one case)

Methodology

- Examine temperature limit violation per-component

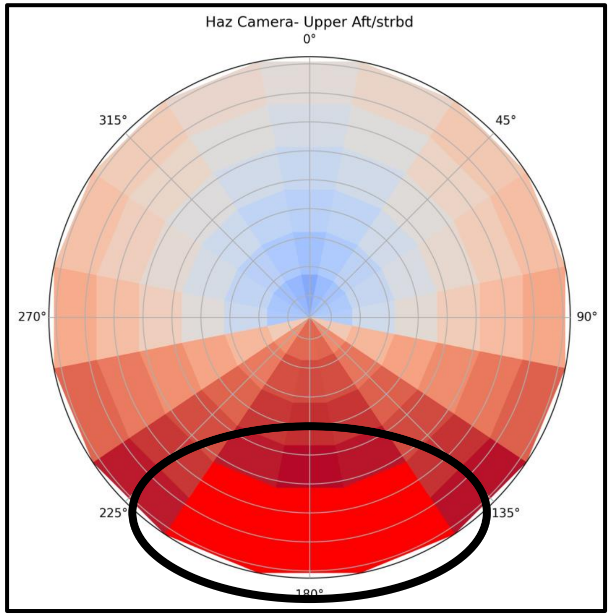


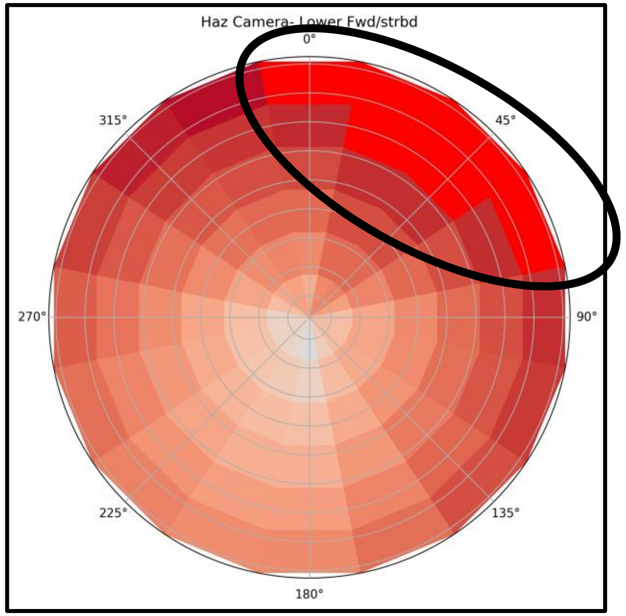


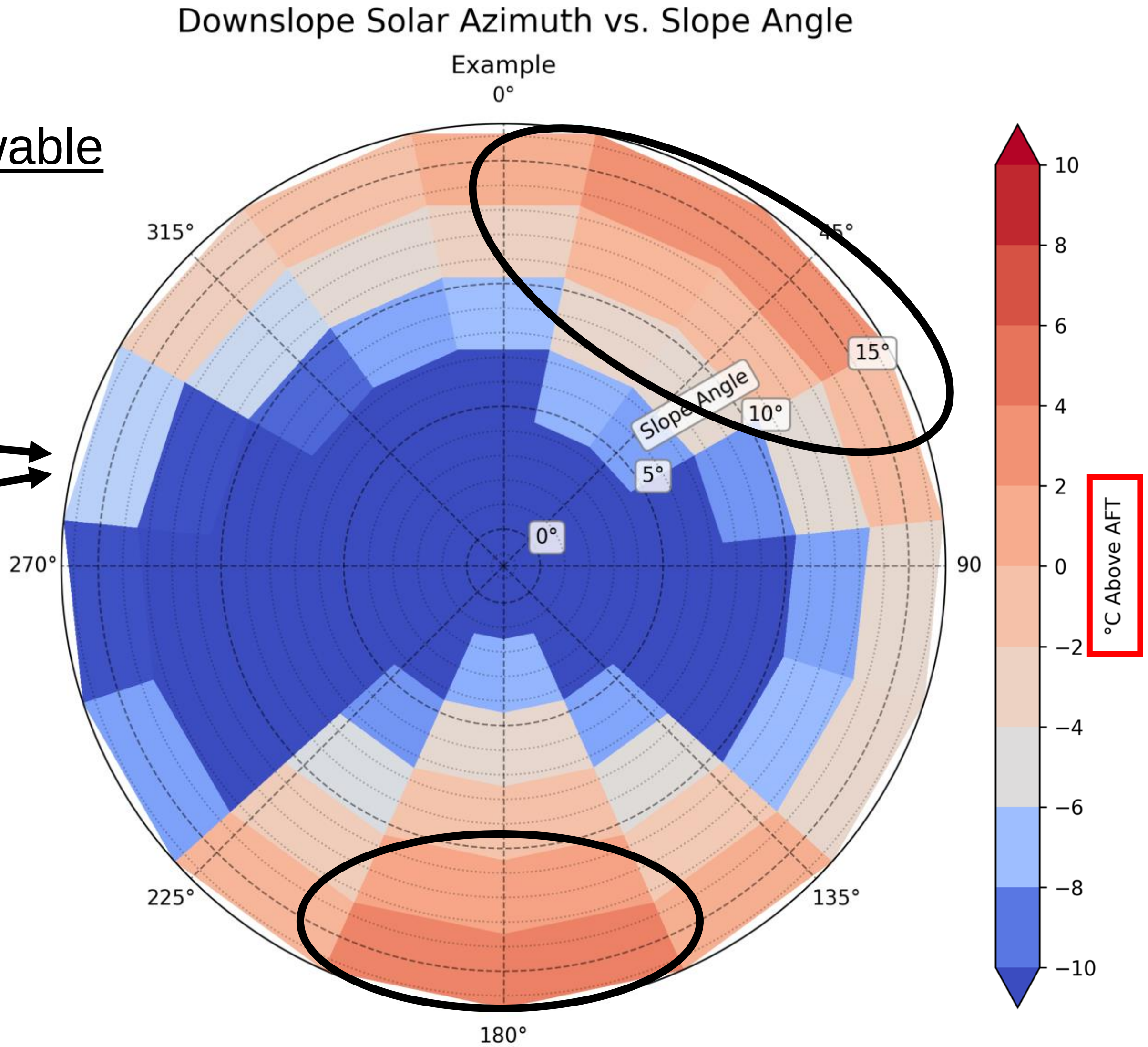
Starboard aft camera temperatures vs. solar azimuth and slope

Methodology

- Combine limit violations relative to individual allowable temperature, keeping maximum upper deviance





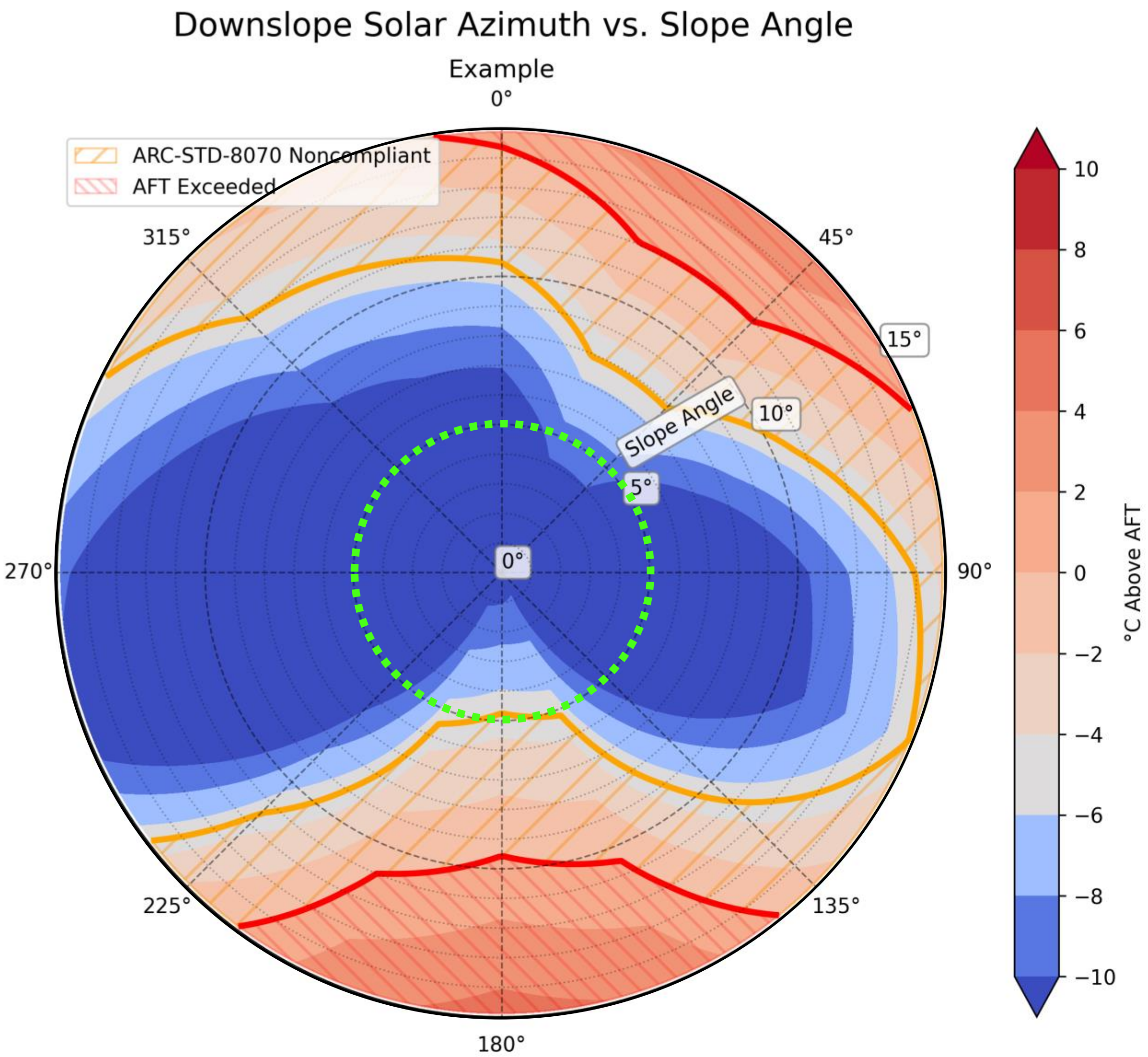


AFT-exceedance-normalized component chart (example)

Results

With the resulting example chart, some insights are readily gained:

- Below any 5° slope, any operation allowed for any length of time (green circle)
- Sun on port side (270° azimuth) is preferable for operations
- Further insights can be gained by extending this analysis framework:
  - What is the thermally “limiting” component?
  - How does speed affect temperatures
  - What is good terrain to change modes?
  - Much more

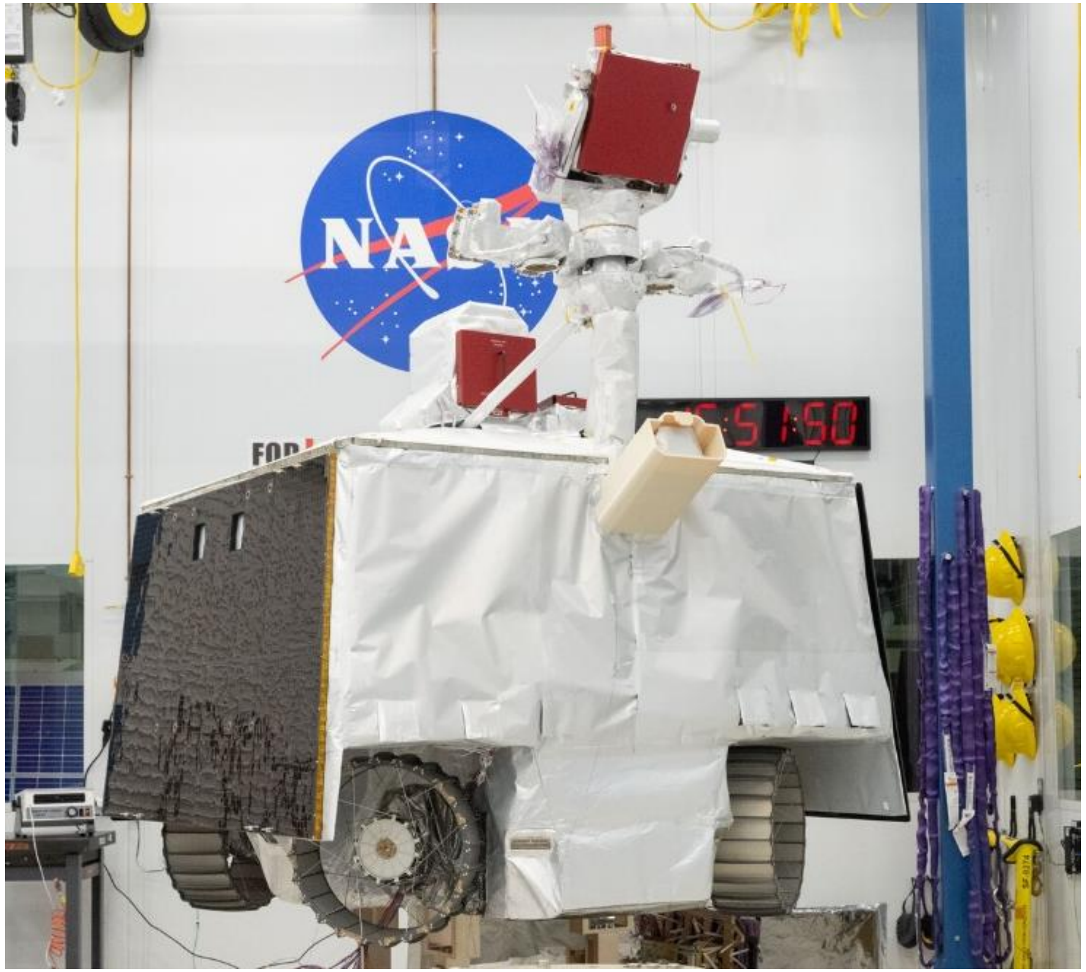


Final unlimited operations envelope (example)

Conclusion

Summary and Conclusions

- Thermal analysis for lunar vehicles is incredibly complex due to dynamic capabilities of such vehicles
- Thermal analysts are faced with many unknown variables that cannot be resolved before mission execution
- It is often easier to work backwards to find a limiting factor than work forwards to answer open-ended questions
- By examining lunar vehicle missions holistically, it becomes easier to identify analytical frameworks that better ensure mission success



Questions?

References

[1]Lunar QuickMap, Online Software Package, Ver: bd5649a4@ 2024-09-30T15:32:03.034Z, Applied Coherent Technology Corporation, Herndon, VA, 2025.

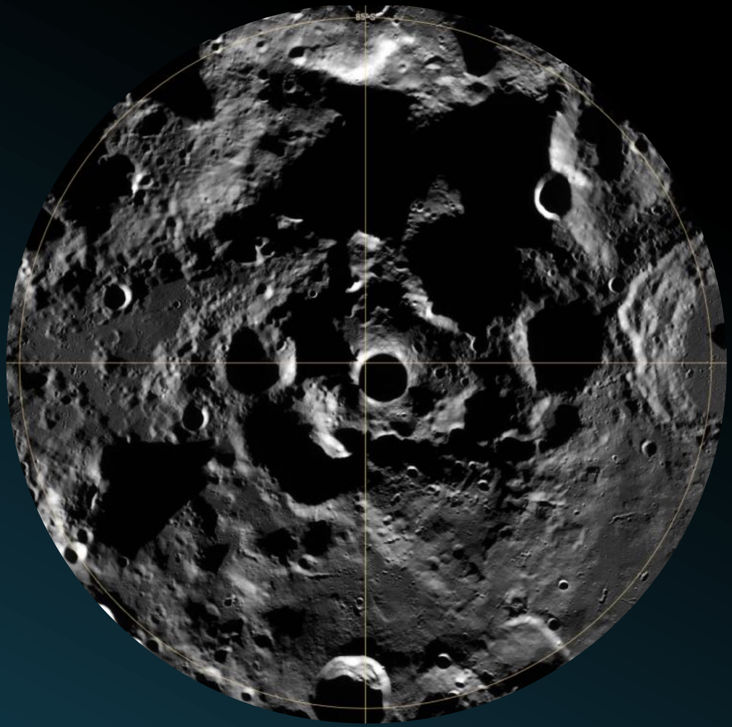
[2]Williams, J.P., Paige, D.A., Greenhagen, B.T., and Sefton-Nash, E., “The global surface temperatures of the Moon as measured by the Diviner Radiometer Experiment,” *Icarus*, Vol. 283, 2017, pp. 300–325.

[3]Hamill, B.D., Schunk. R.G., and Erickson, L.R., “Human Landing System Lunar Thermal Analysis Guidebook,” HLS-UG-001, 2021.

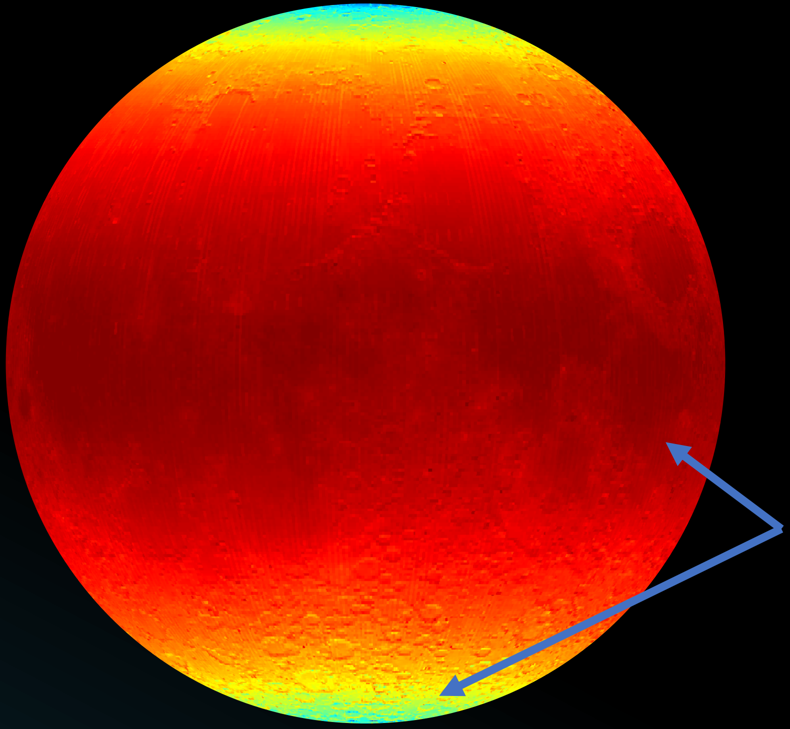
Backup

Lunar South Pole Environment

- Lunar south pole generally implied to be region between 85°S and 90°S latitudes
- Thermal environment changes with landing location (latitude), time of year, time of day, far-field terrain (mountains), near-field terrain (boulders, craters) – extremely complex environment



Lunar south pole terrain (85°S to 90°S)[1]



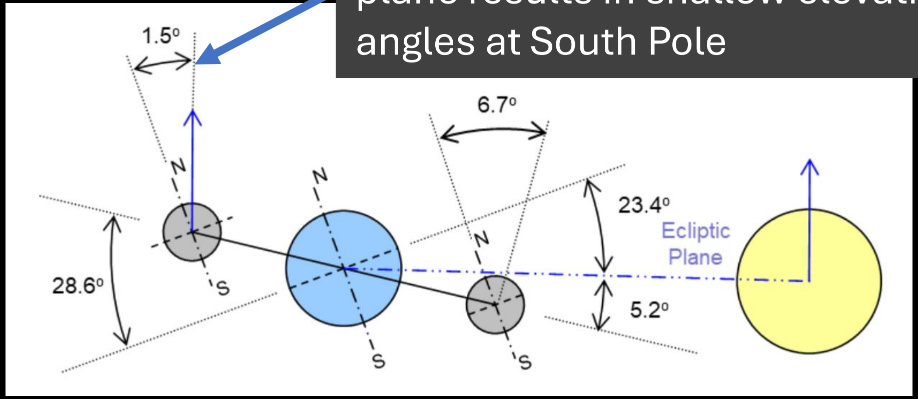
Latitude dependence of global maximum temperature

Global maximum temperatures of the lunar surface (nearside)[1,2]

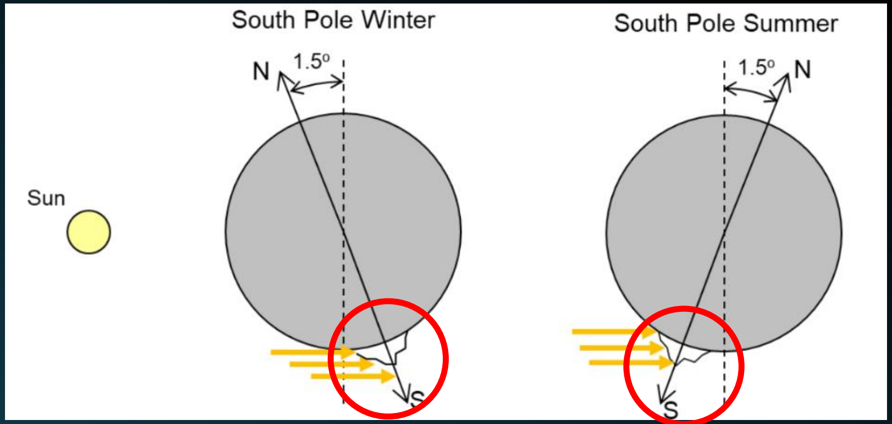
Lunar South Pole Environment

- Due to low angle relative to ecliptic plane, solar elevation angle will always be very low in polar regions
- Slow lunar rotation means that extreme temperatures will be experienced for long periods of time
- Due to polar topography, several locations exist where shadowed/night periods are reduced greatly from typical ≈14 days – known as "safe havens"

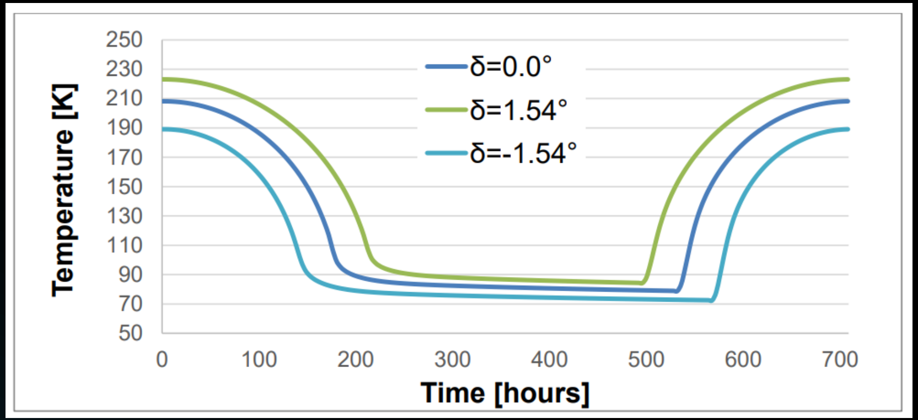
Low angle relative to ecliptic plane results in shallow elevation angles at South Pole



Lunar orbit[3]



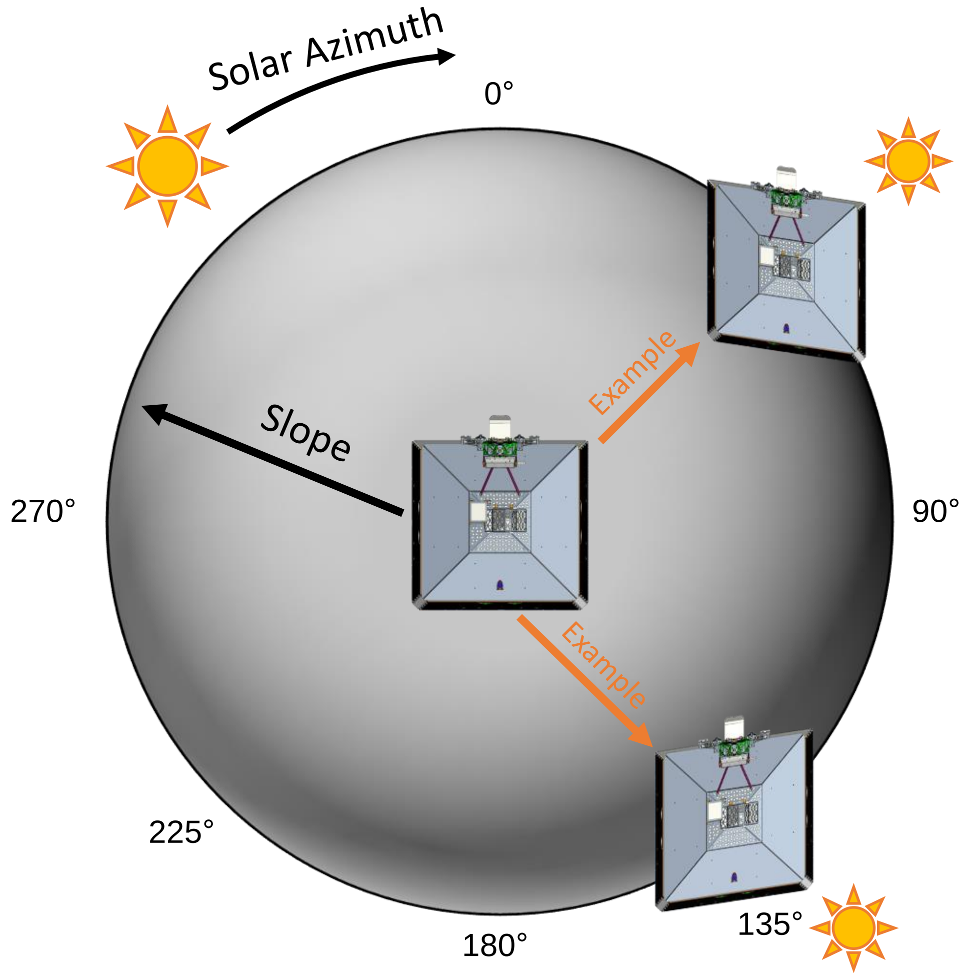
Lunar south pole geography causing safe havens[3]



Diurnal lunar surface temperatures vs. solar declination angles predicted in Thermal Desktop[3]

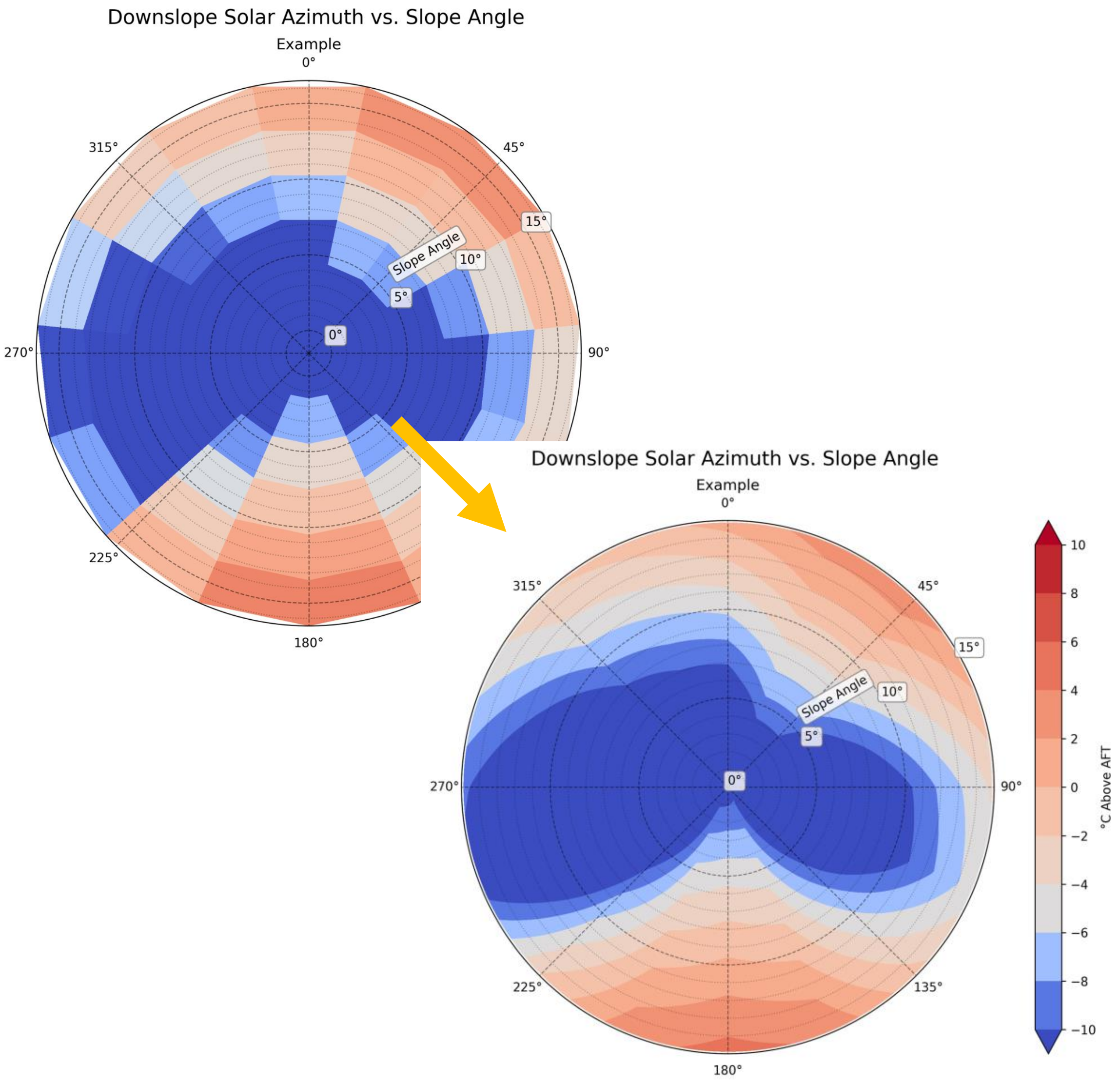
Reading Polar Slope/Azimuth Chart

- Heading → rover pointing direction
- Azimuth → sun angle relative to rover pointing direction
- Rover heading is always 0° (forward)
- Slope increases outward from center
- Sun is always downslope
  - Goal is to maximize solar angle relative to environment (biases results hot)
- “Rover on a hemisphere” (or bowl)



UOE Cubic Interpolation

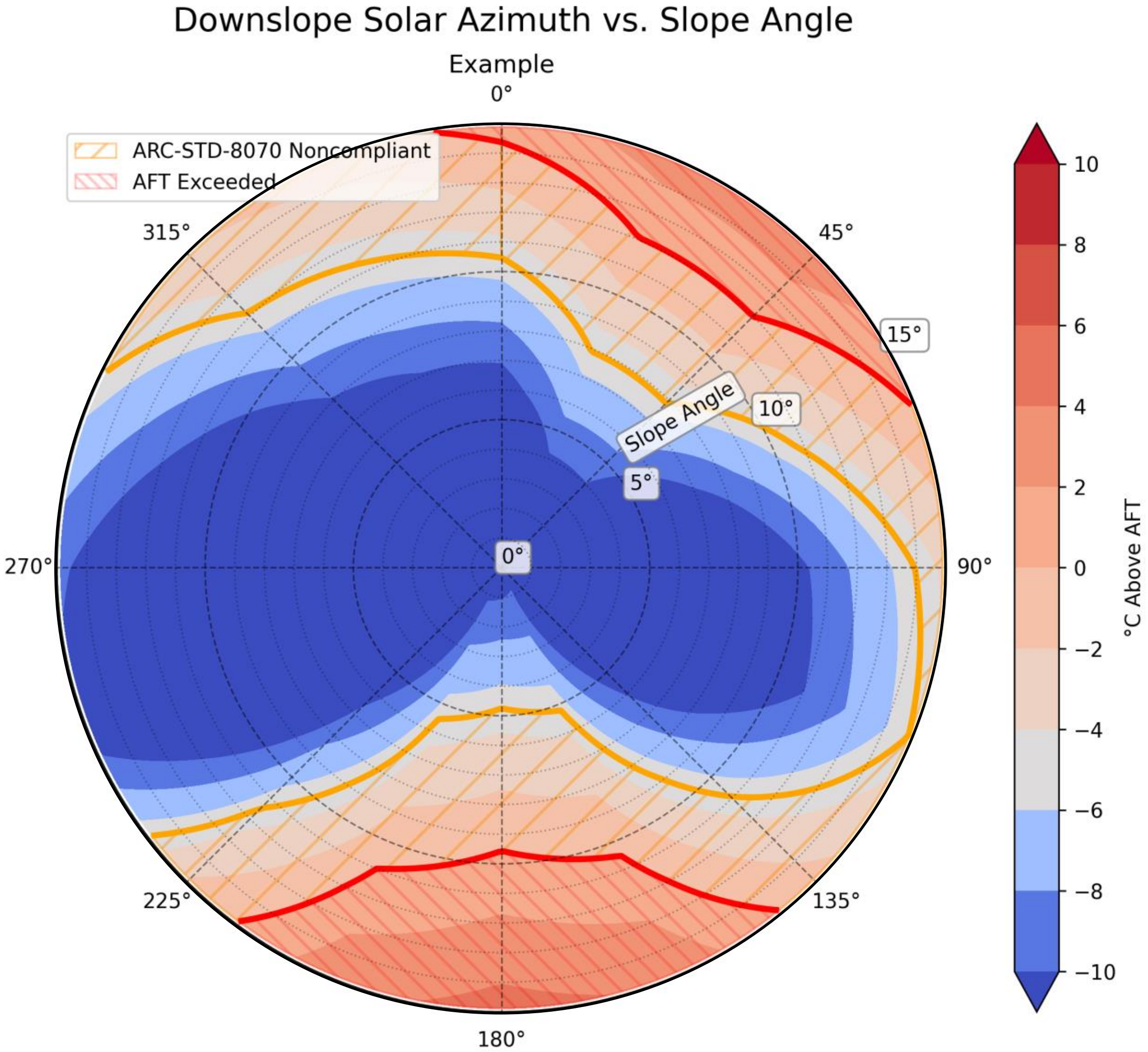
- Cubic interpolation effectively weights by the AFT exceedance of the component in each case nearest to or exceeding its margin
- Similar results could be obtained by running an increased number of cases. However, interpolation may offer a computationally “cheap” way of filling in gaps of data that adds to human intuition of chart



AFT-exceedance-normalized component chart with cubic interpolation (example)

UOE Styling

- Chart is stylized to aid with requirements management for VIPER
- VIPER binding requirements document is ARC-STD-8070, which specifies that 5°C margin be applied to analysis results
- Contour lines added to chart to clarify AFT violations in raw data vs. requirements compliance
- Similar contours/zones can be added for many helpful reasons
    - Highlight a specific component contributing to thermal violations
    - Depict specific slope and azimuth combinations preferable to operations
    - Draw attention to a zone highly impacted by a particular operation



Final unlimited operations envelope (example)