VIPER

National Aeronautics and Space Administration

NASA

An Overview of Mission Planning for the VIPER Rover

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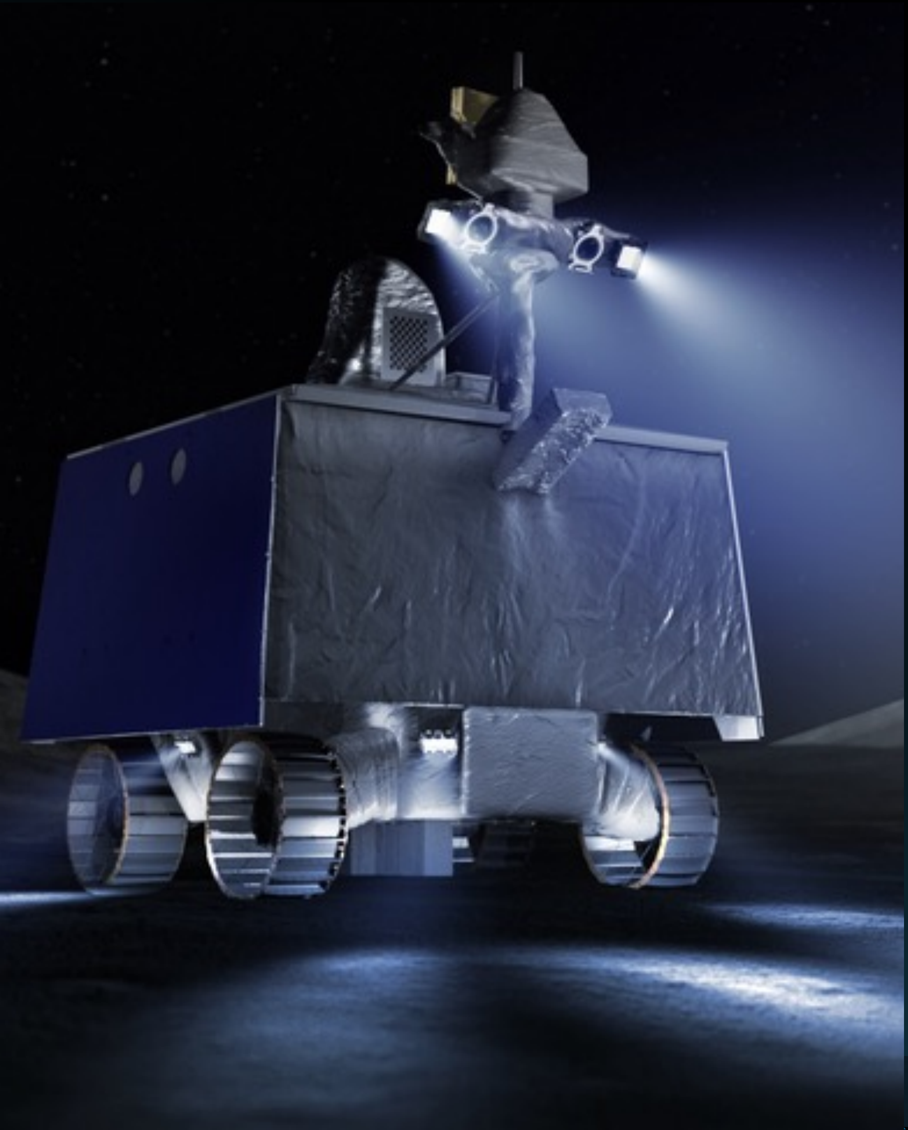
Why VIPER?



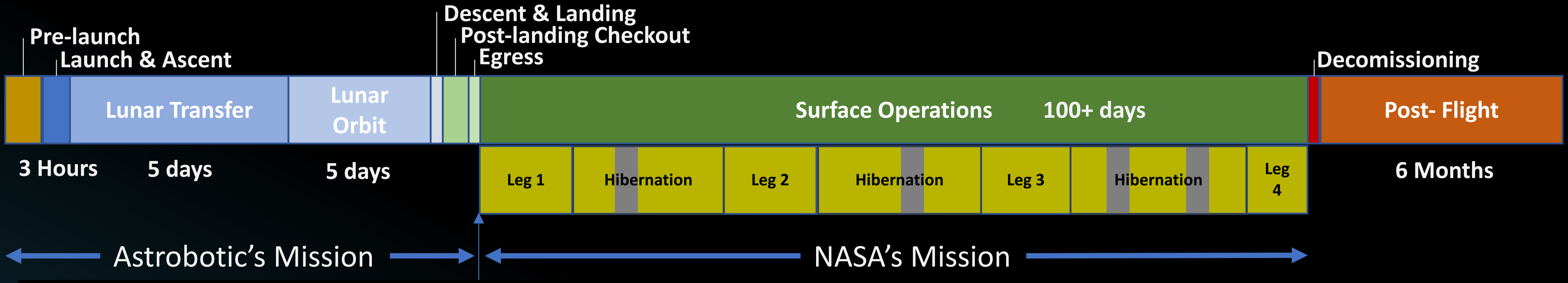
Lunar Polar Volatiles

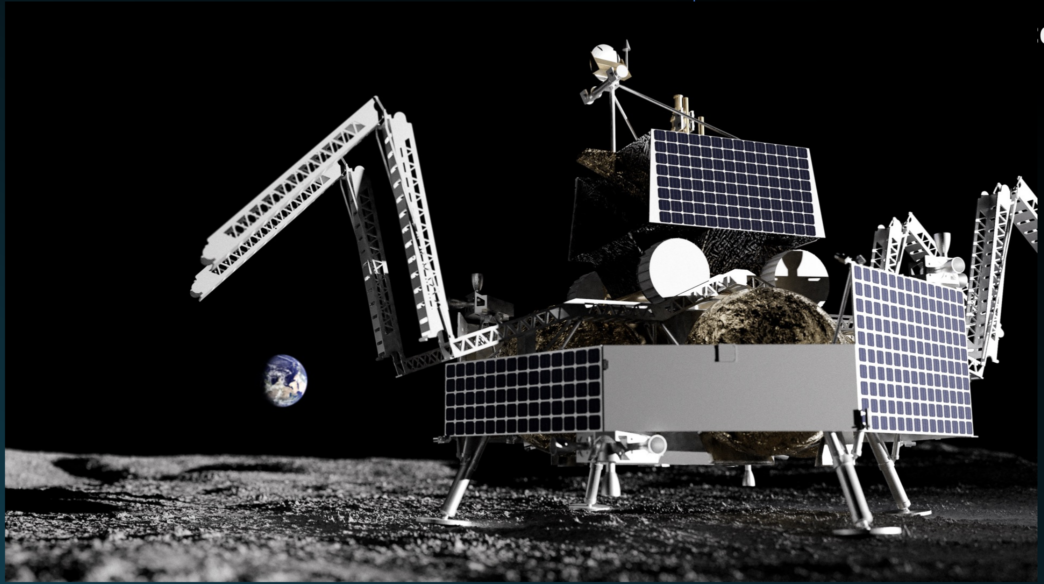
- frozen water, methane … (liquid or gas at room temp)
- detected from orbit by remote sensing
  Clementine, Lunar Prospector, LRO, LCROSS, Chandrayaan-1 …

VIPER will …

- make direct measurements of polar volatiles
- characterize their physical state & composition
- characterize horizontal & vertical distribution at scales relevant to potential extraction processes
- provide ground truth for orbital datasets used to create lunar resource maps

Overall Mission Plan





- VIPER delivered to moon under Commercial Lunar Payload Services (CLPS) contract
- Astrobotic's Griffin lander
- Will launch on Falcon Heavy
- VIPER is a payload until it's on the surface

This talk focuses on the surface operations phase

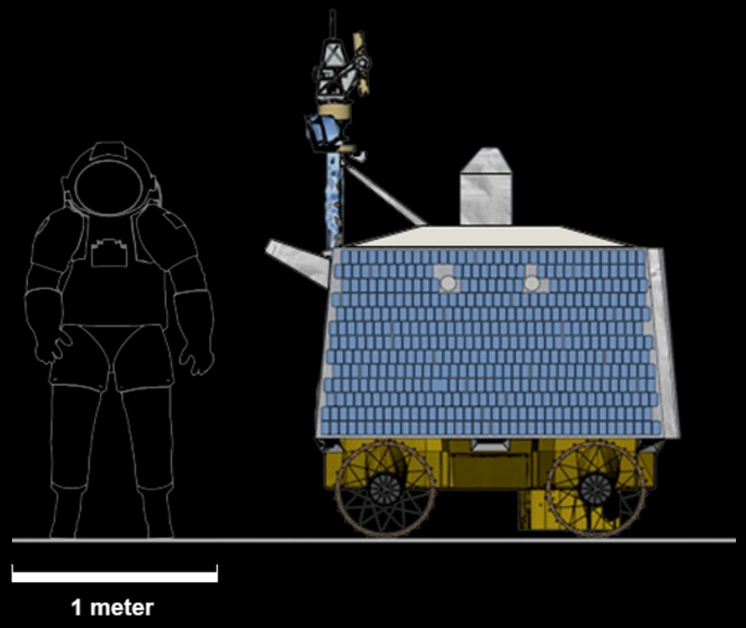
Innovation

Automated route planning approaches for lunar polar conditions

★	Site Analysis	Designed for evaluating and eliminating landing site options
★	Strategic Planning	Designed for optimizing mission productivity and minimizing risk
	Tactical Planning	Route planning inside small areas to optimize information gain

The science and ops teams will select the baseline from among the options

Key Engineering Specs



- Solar-powered rover
  - Working endurance in shadow (w/drill): ~9.5 hrs
  - Endurance in min power mode: 50 hrs
- Line-of-sight to Earth radio comms
  - Teleoperated from the ground
- Mission Duration: 100+ earth days
- Driving
  - Distance Travelled (goal): 20 km
  - 1 cm/s average speed
  - 10 cm/s when moving (waiting 90% of time)
  - 15 deg slope limit
  - Can negotiate 10 cm obstacles

Instruments operate together while driving and stationary

Drill (1m)

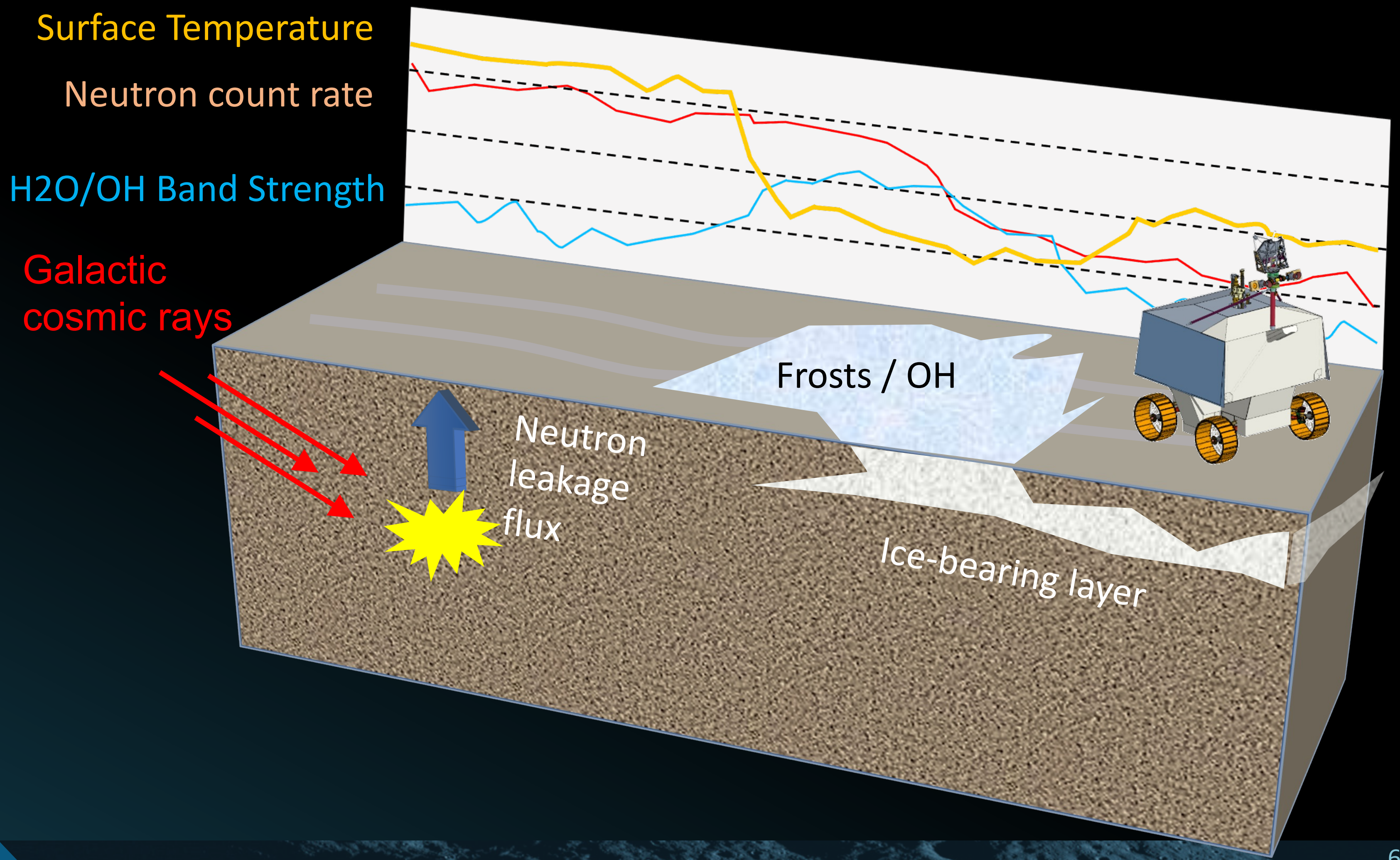
brings material to surface

Spectrometers

- Neutron
  subsurface hydrogen-bearing compounds
- Near-IR
  surface composition, incl. drill tailings
- Mass Spec
  identifies subliming gasses

Cameras

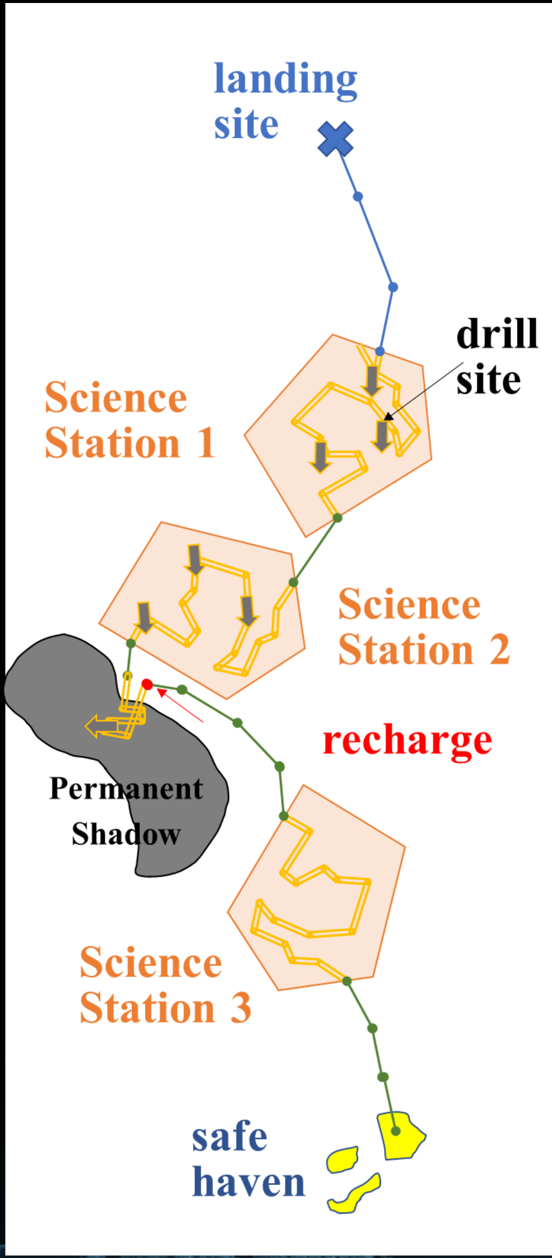
- Downward
  sees surface and drill tailings
- Stereo pair on mast
  geological context, navigation



Science Station: A Virtual Measurement

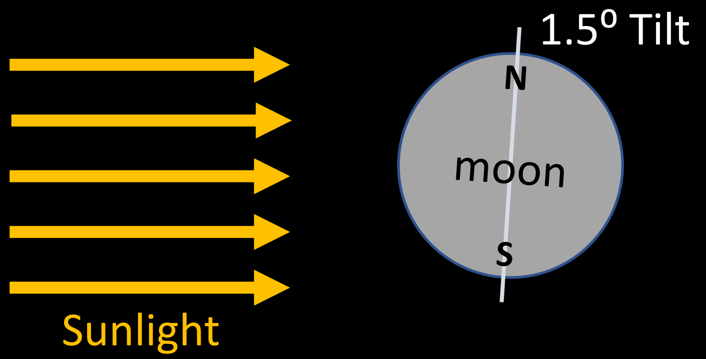
- Goal: Estimate total volatiles in top meter of a 3800 m^2 area
- Integrates data from all instruments
- Resource need case: 5% water ice => O2 for crew of 4 for 1 year
- 10-15% area coverage is adequate statistics for estimate
- Corresponding linear coverage is 224-335 m of driving
- Drill 3 times to 1m depth to ground truth prospecting data
- Full mission success requires a min of 6 science stations (want more)
- Science stations must be placed across a variety of thermal environments

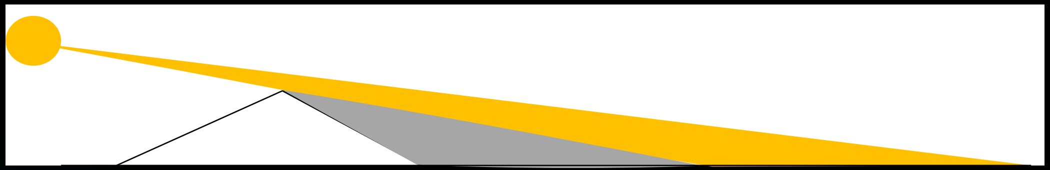
The core planning problem is the placement of these science stations



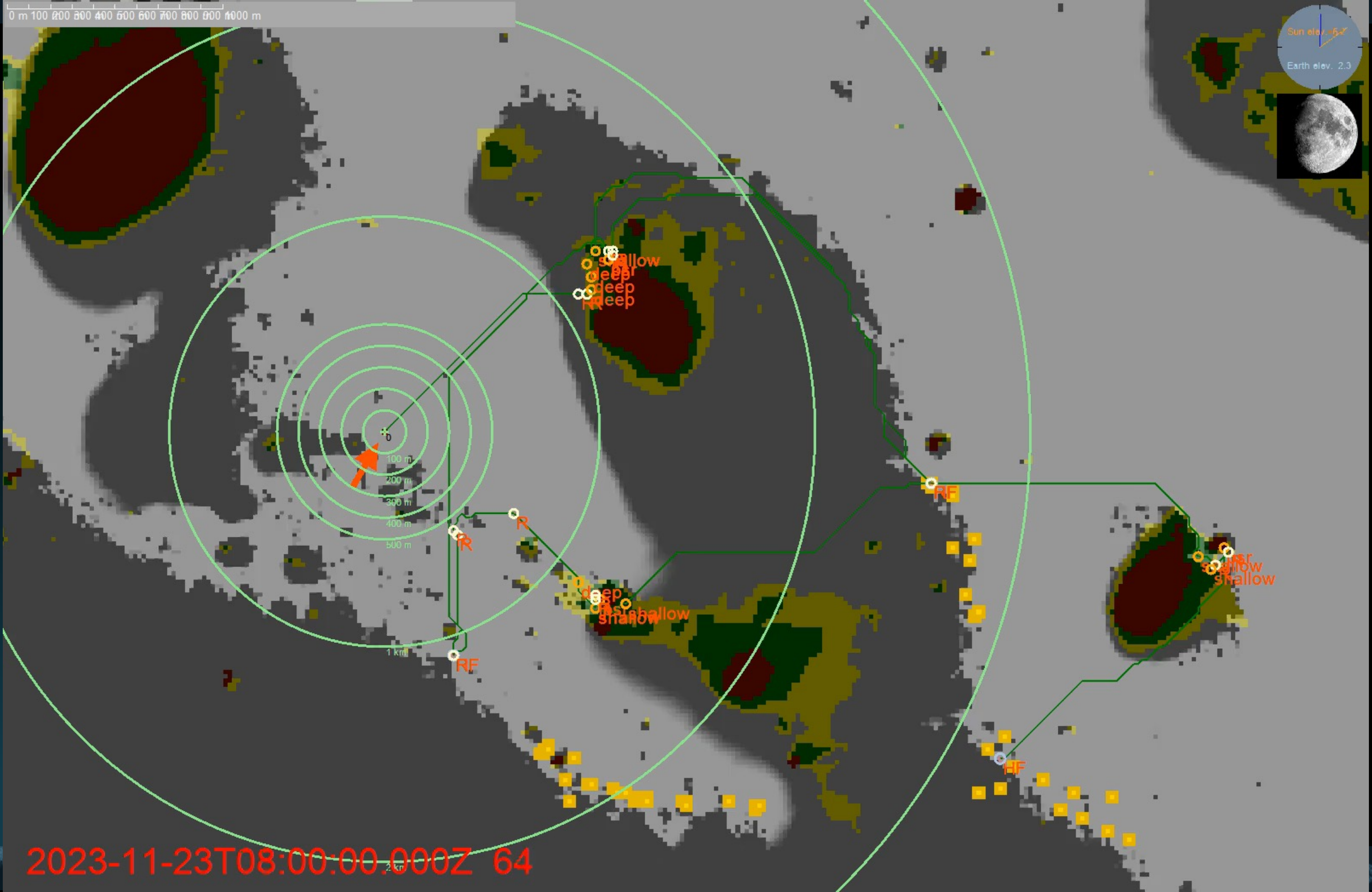
Why are solar power and DTE comms strong constraints?

- At the poles, the sun casts long shadows
- Similar radio shadows are cast from a line-of-site radio link to ground stations
- Sun and radio shadows move at speeds <u>similar to </u>VIPER's average speed
- So …





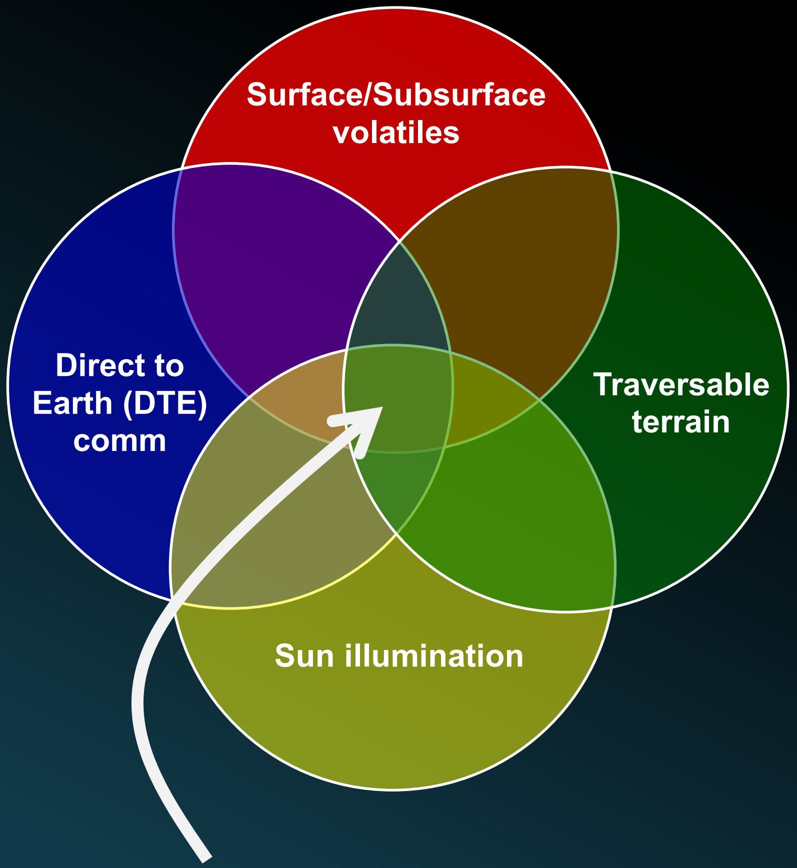
Traverses must be timed to avoid moving shadows



0 m 100 200 300 400 500 600 700 800 900 1000 m
Earth elev. 2.3
100 m
200 m
300 m
400 m
500 m
1 km
shallow
deep
R
RF
HF
2023-11-23T08:00:00.000Z 64

Site Selection: Where to land the rover?

Requirements



Mission sites must meet all four criteria

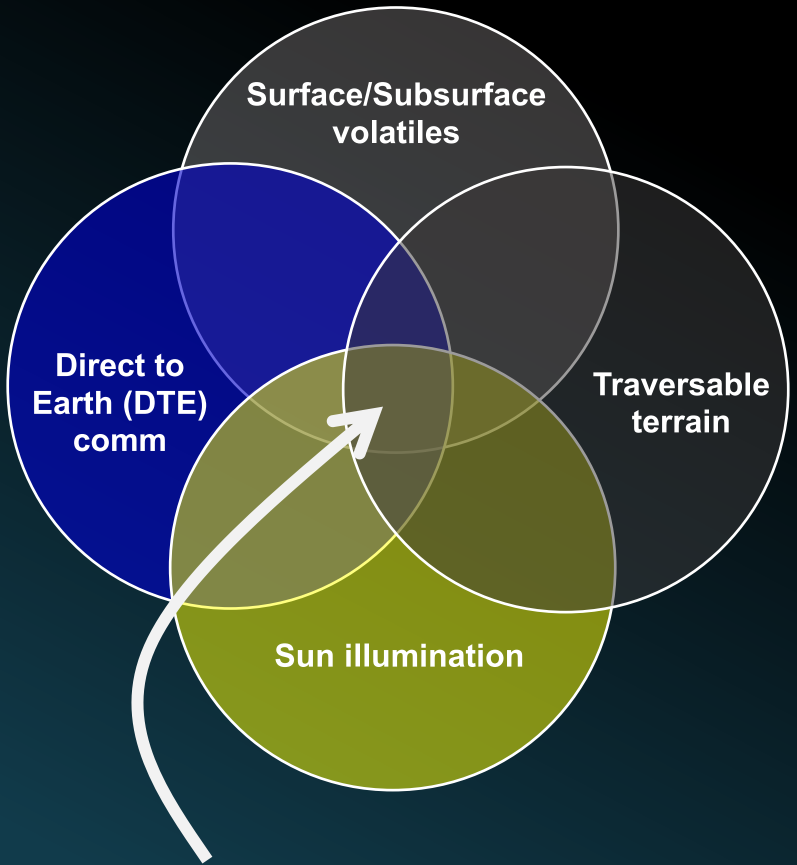
Preferences

Access to permanent shadow in craters of a variety of ages

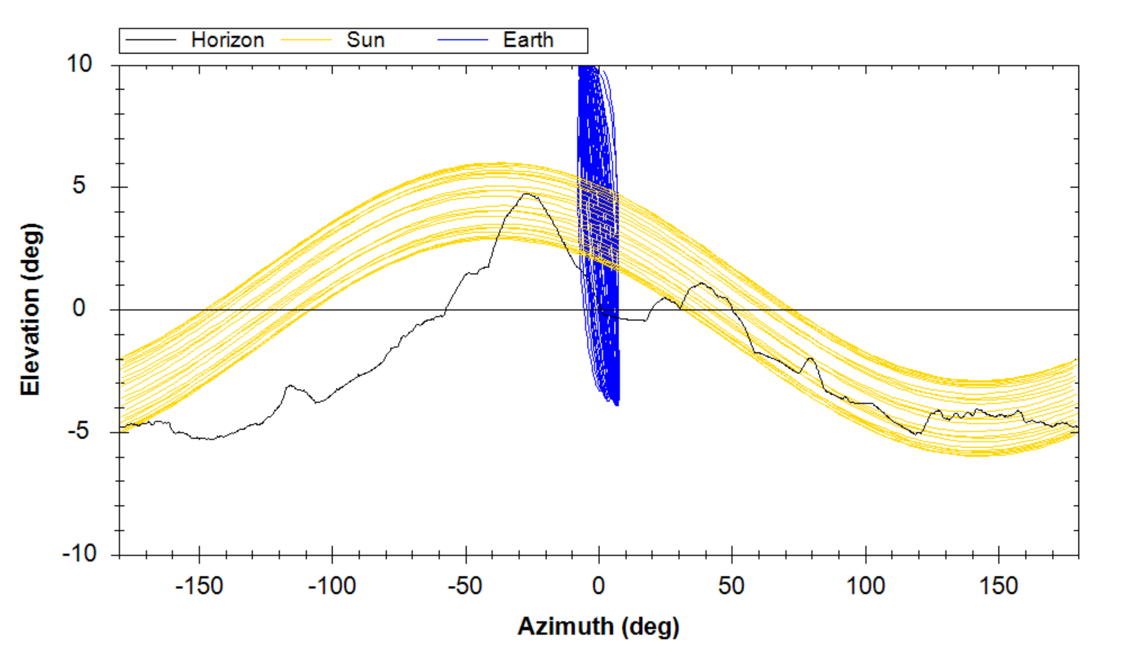
★ Support a multi-lunar-day mission

Site Selection: Where to land the rover?

Requirements



Mission sites must meet all four criteria

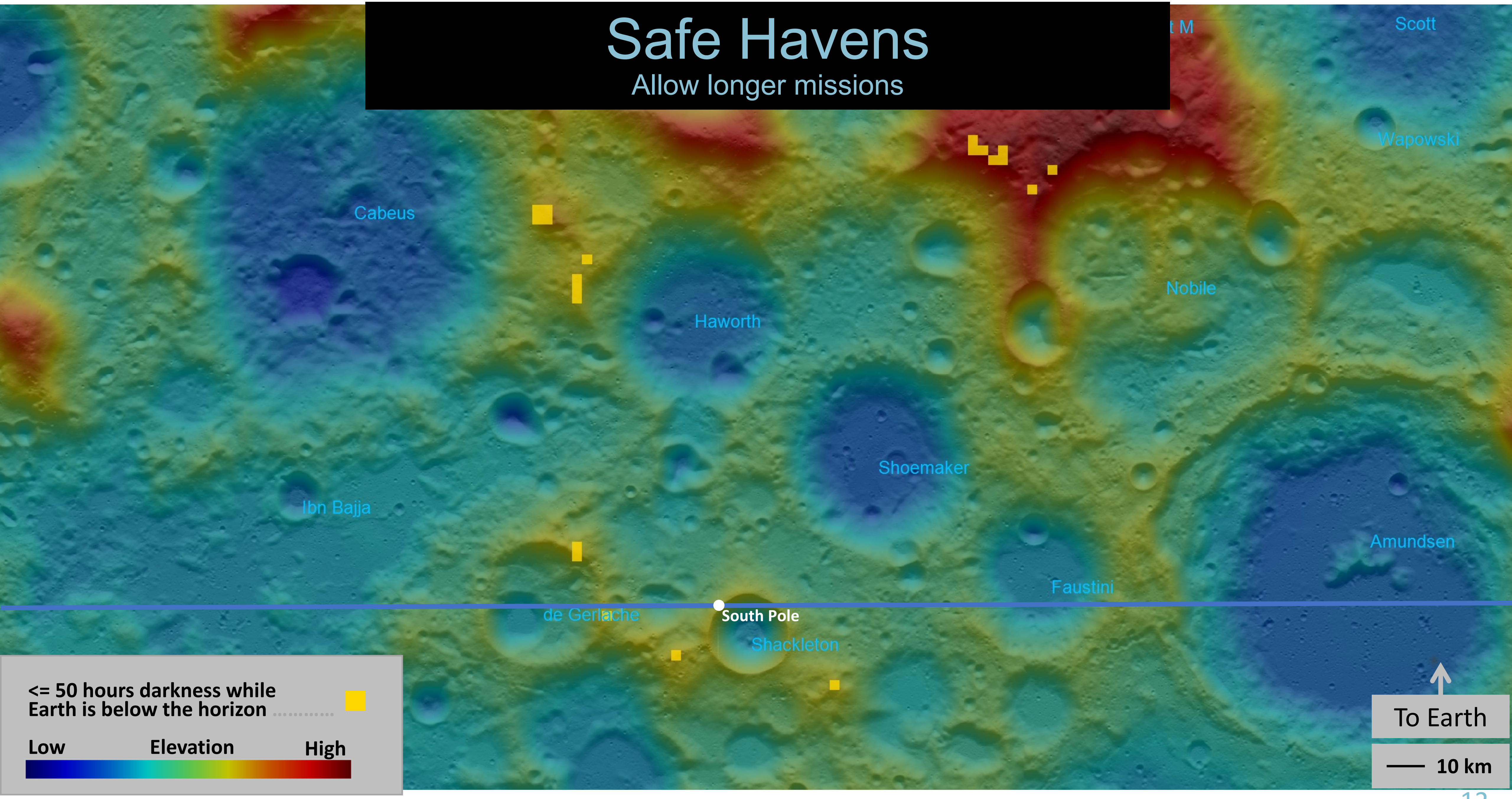


Question: How much is the Sun up while the Earth is down?

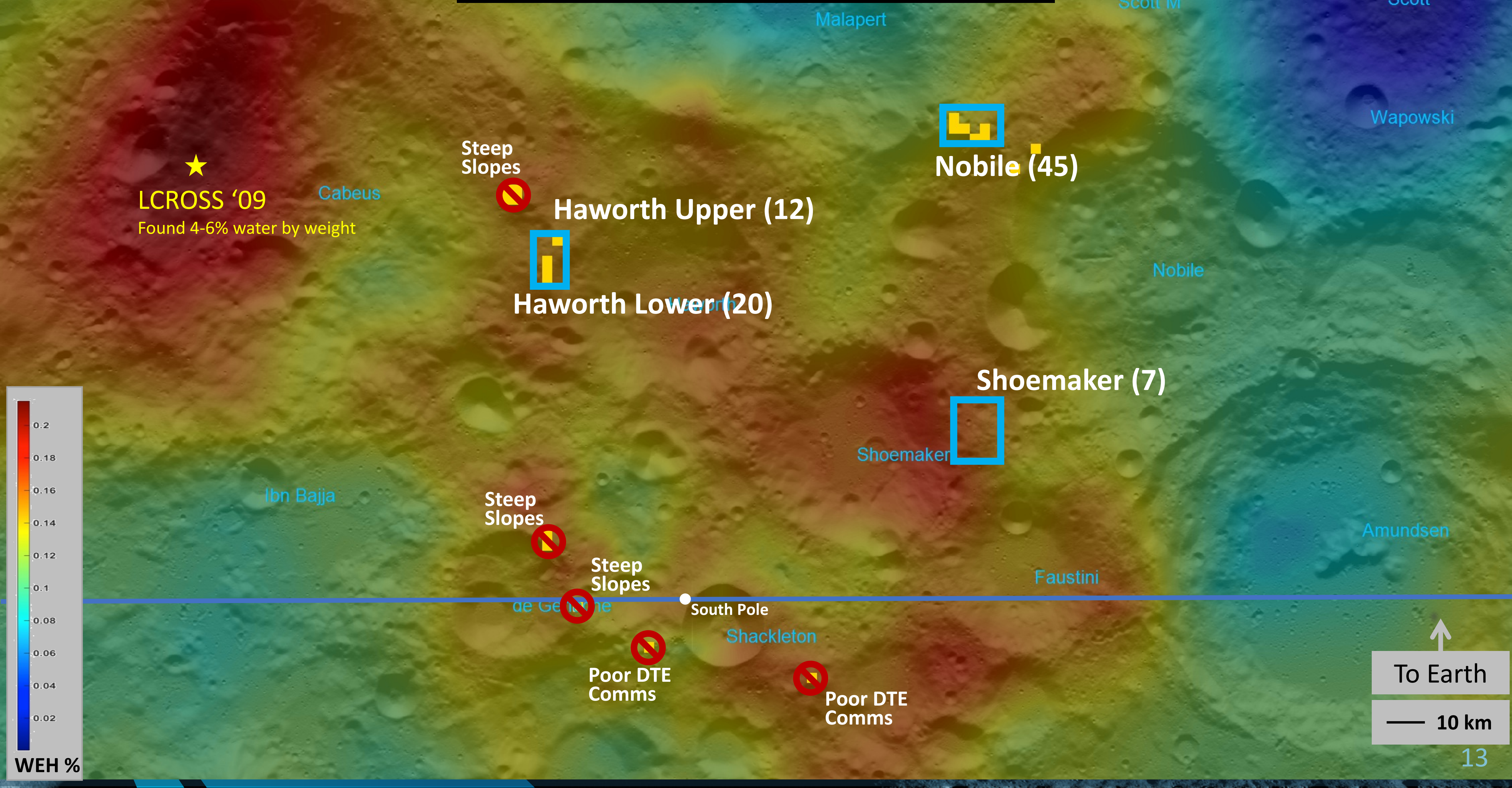
- Earth is below the horizon ½ the time
- Locations with < 50 hrs of shadow during these periods each month are relatively rare
- We call those locations Safe Havens

Safe Havens

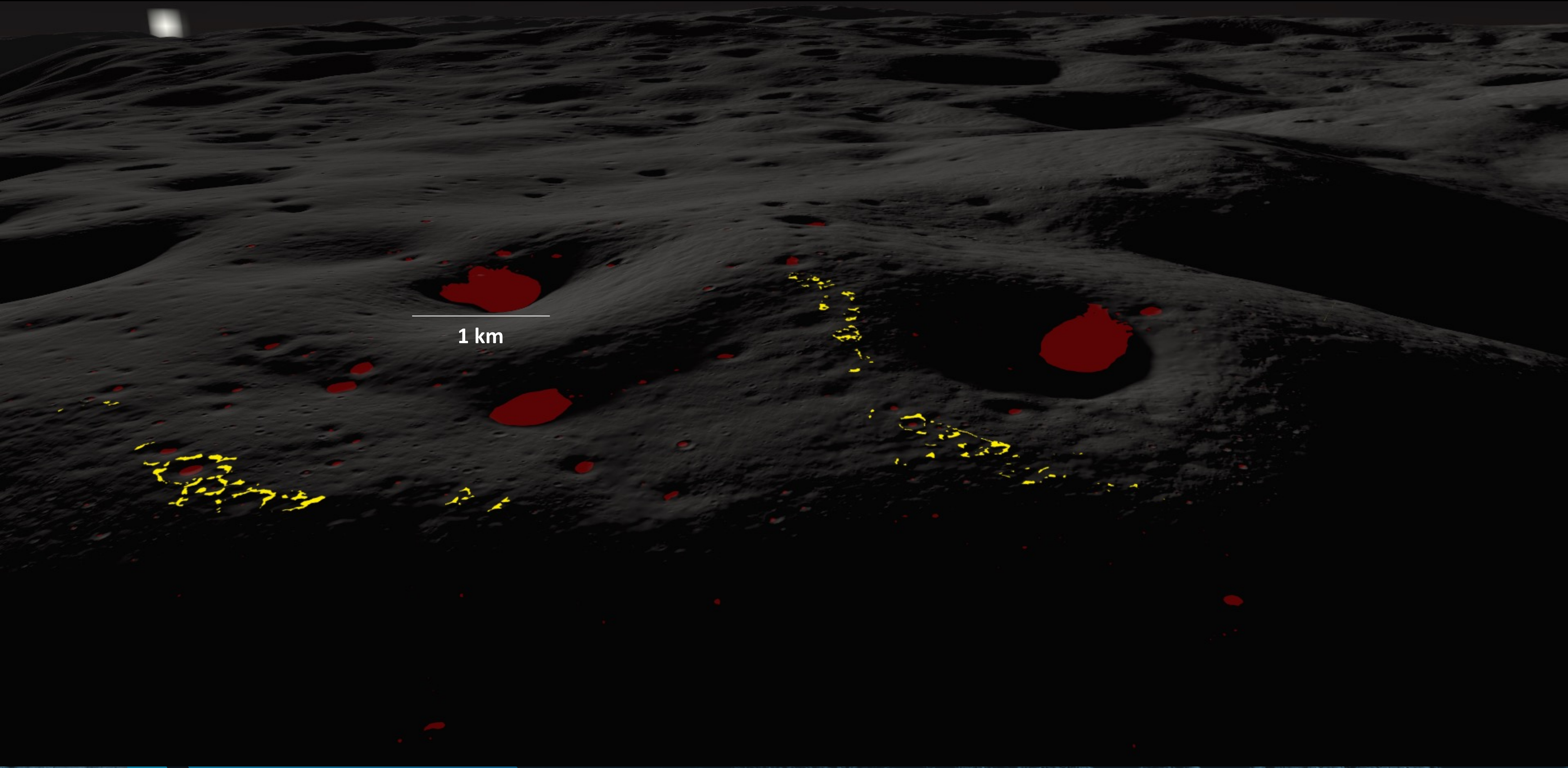
Allow longer missions



Focused on Three Areas

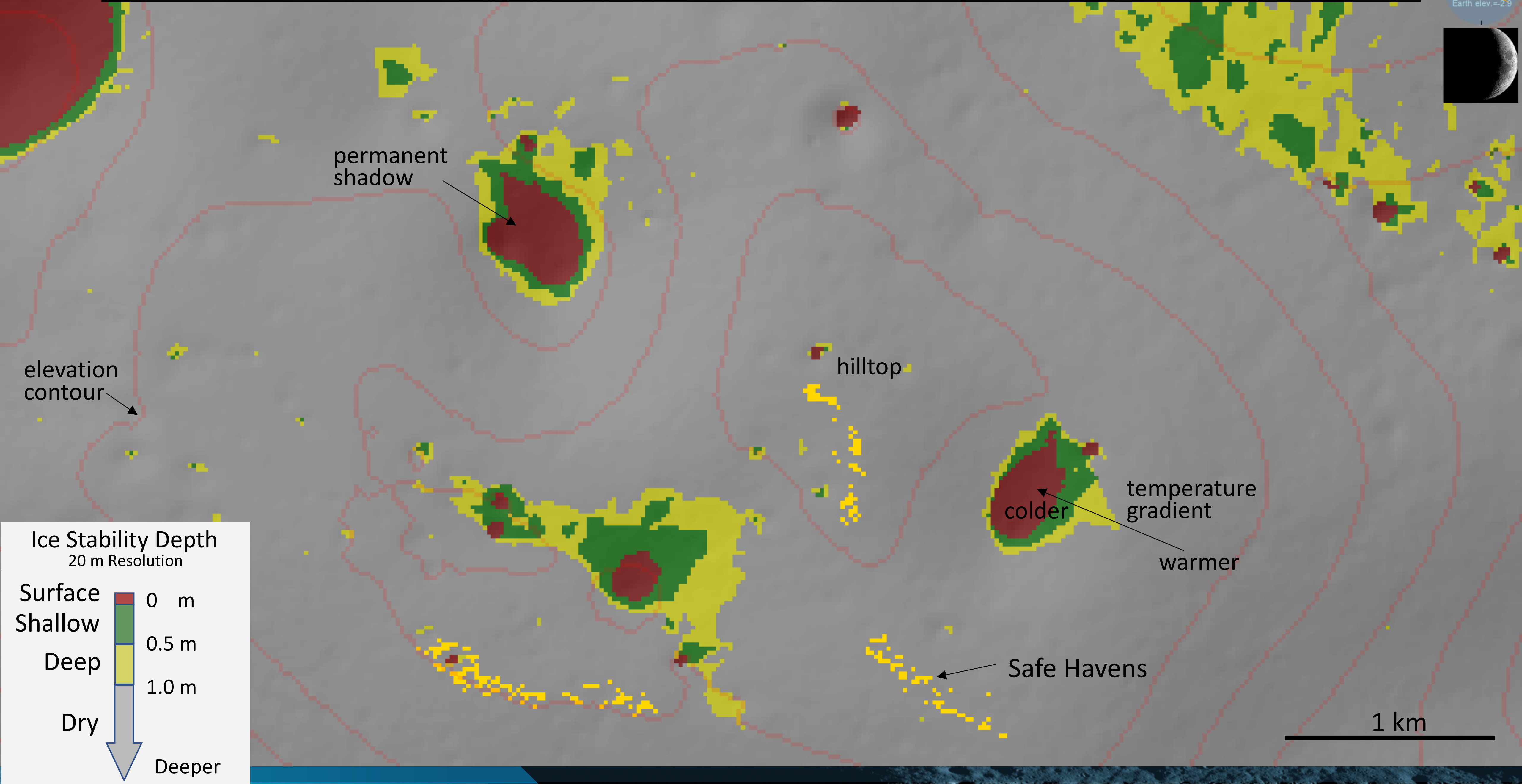


Nobile Site Overview

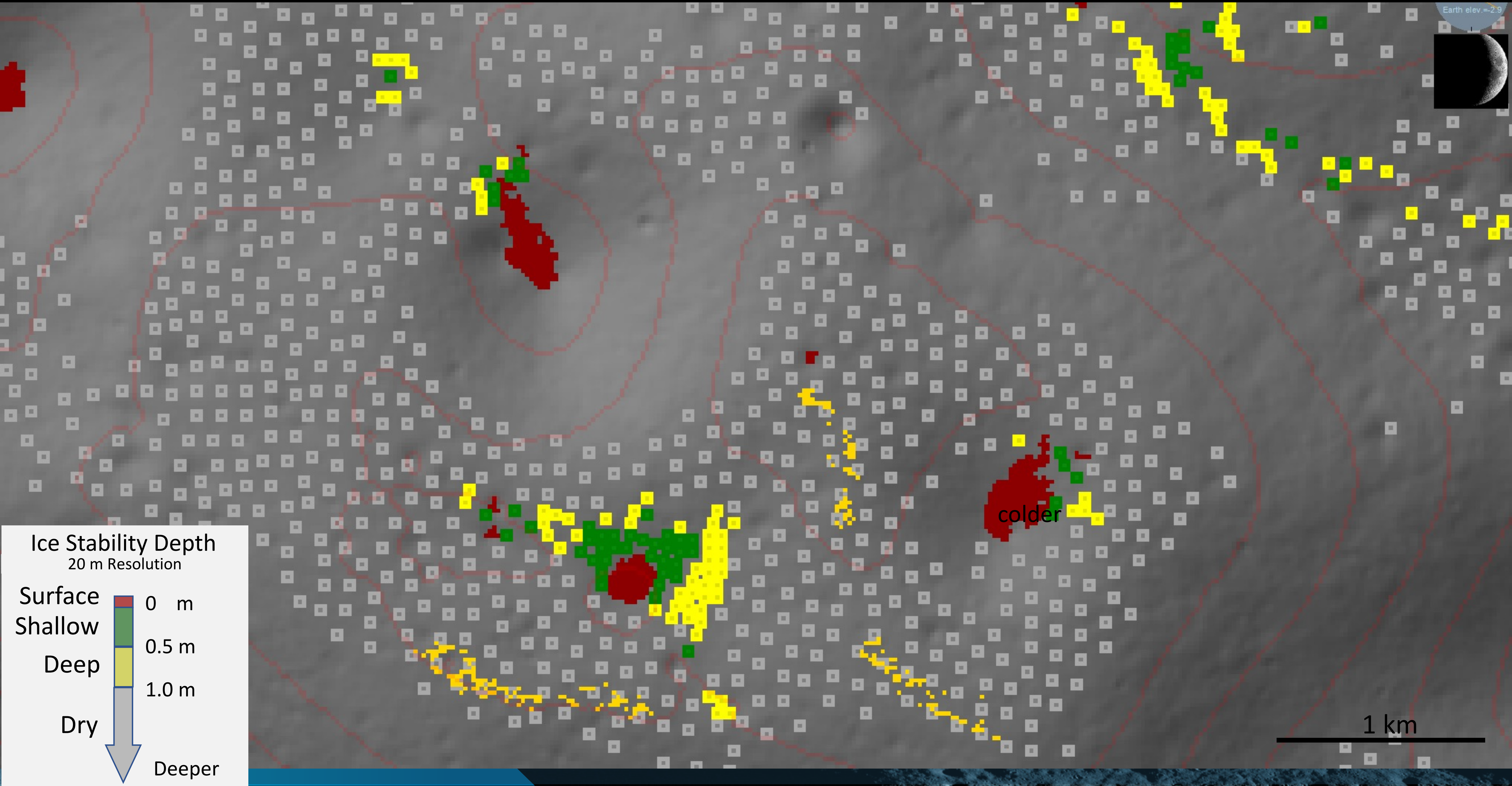


Traverse Planning for Site Selection

Thermal modeling divides terrain into regions



The regions are divided into candidate Science Stations



Traverse Planning Algorithm #1: Traveling Salesman

Goal

- Support evaluation / elimination of candidate landing sites
- Search is sound and complete – if no solutions are found, then none exist

Approach: Divide planning into …

1. Select a sequence of visits to candidate science stations
2. For the best sequence, plan the route inside each science station by hand

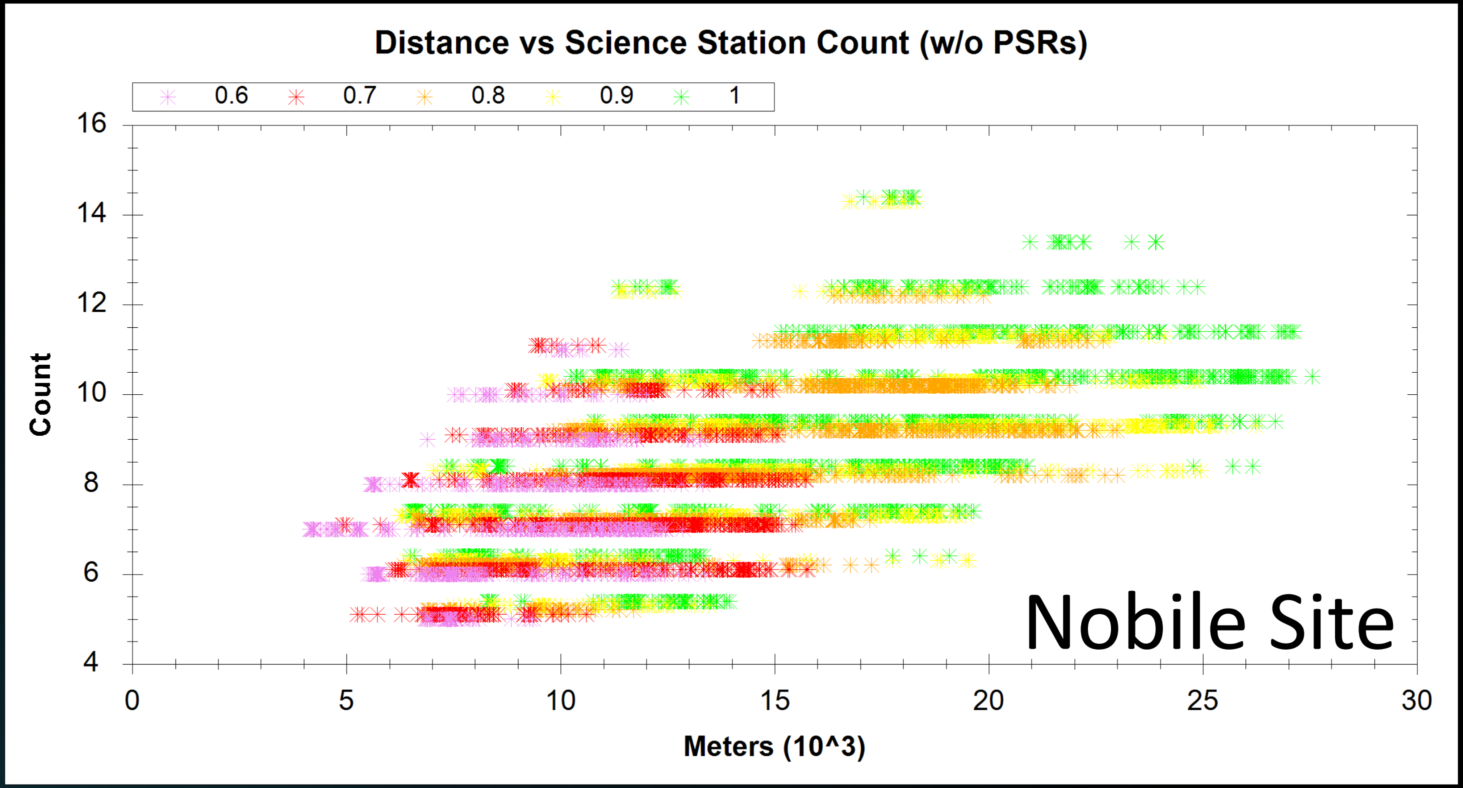
Step #1 is a cost-constrained traveling salesman problem

- Visit a subset of the cities (science stations), not all of them
- Each city has a score (all candidate science stations have equal value)
- Maximize the sum of the city scores (maximize the number of science stations visited)
- Drives between cities have a cost (which models time)
- Don't exceed a total cost (the time Earth is above the horizon at the site)
- with time window constraints
    - Science station visits must occur in sun (except for entry into permanent shadow)
    - Drives must occur in sun

Execution variance

Comparing Sites by the Traverses They Support

- This formulation of the problem can be solved completely for this scale of traverse
- This algorithm generated families of traverses for the Nobile, Haworth and Shoemaker sites
- The Nobile site was chosen
- We've moved to a more sophisticated algorithm for strategic planning
- Described next



Strategic Traverse Planning

SHERPA

- SHERPA (System Health Enabled Real-time Planning Advisor) is an artificial intelligence (AI) decision support system for robotic space missions that is based on formal decision making under uncertainty.
- Supports planning for systems with degrading or faulty components.
- Provides:
  - Interfaces to solvers / policies;
  - Use case infrastructure;
  - Model, telemetry, and data products management;
  - Unit and end-to-end testing framework;
  - Visualization tools;
  - Benchmarking and statistics facilities.

SHERPA is the first AI system based on formal decision making under uncertainty to be used on a space mission

Team

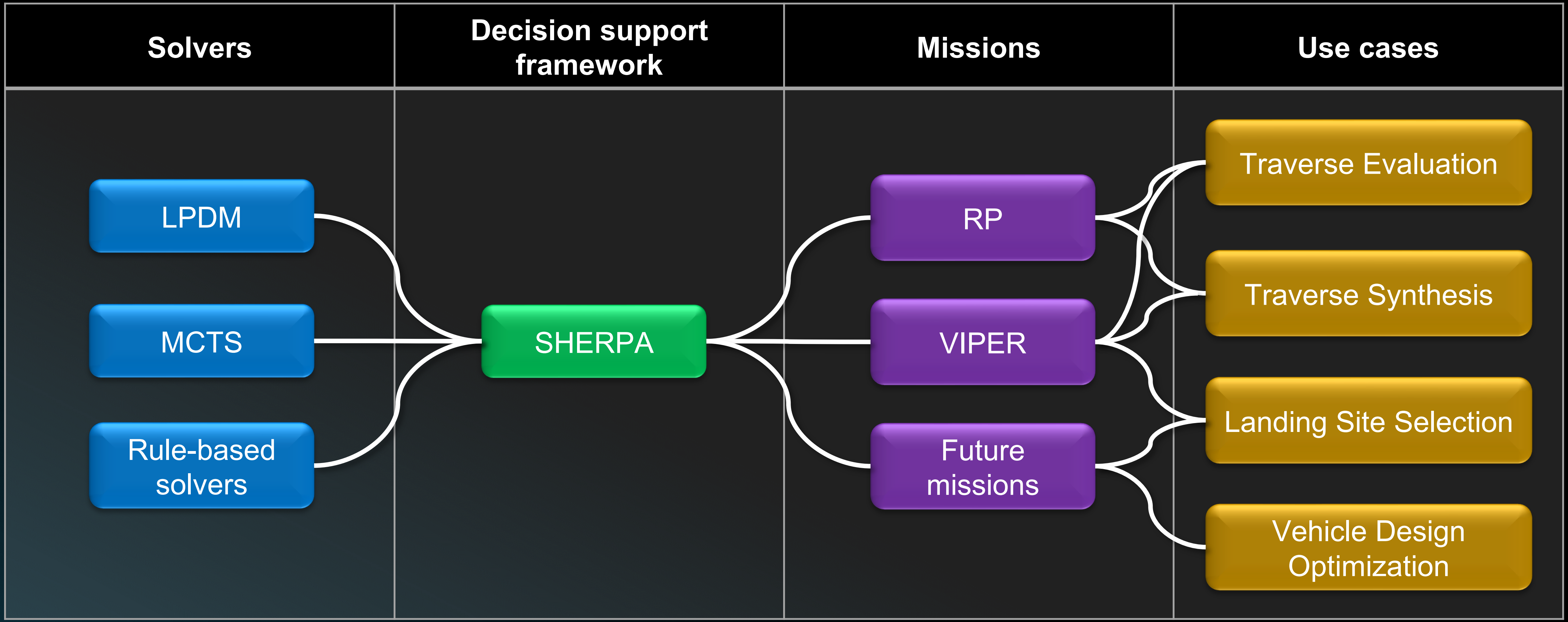
- Edward Balaban (NASA Ames, lead)
- Somrita Banerjee (Stanford)
- Zachary Booth (UC Santa Cruz)
- Thomas Cannon (UC Santa Cruz)

Former team members

- Tomer Arnon (Alfred University)
- Saylor Brisson (Stanford)
- Jennifer Chang (Ohlone College)
- Sophia Eichholz (NYU)
- Sarah Feng (Los Altos High School)
- Alex Gao (Gunn High School)
- Miguel Garcia (Skyline College)
- Leyton Ho (Palo Alto High School)
- Logan Kilpatrick (Harvard)
- Chandler Kilpatrick (UPenn)
- Robert Moss (Stanford)
- Molly O’Connor (NASA Ames)
- Nobel Truong (UC Berkeley)

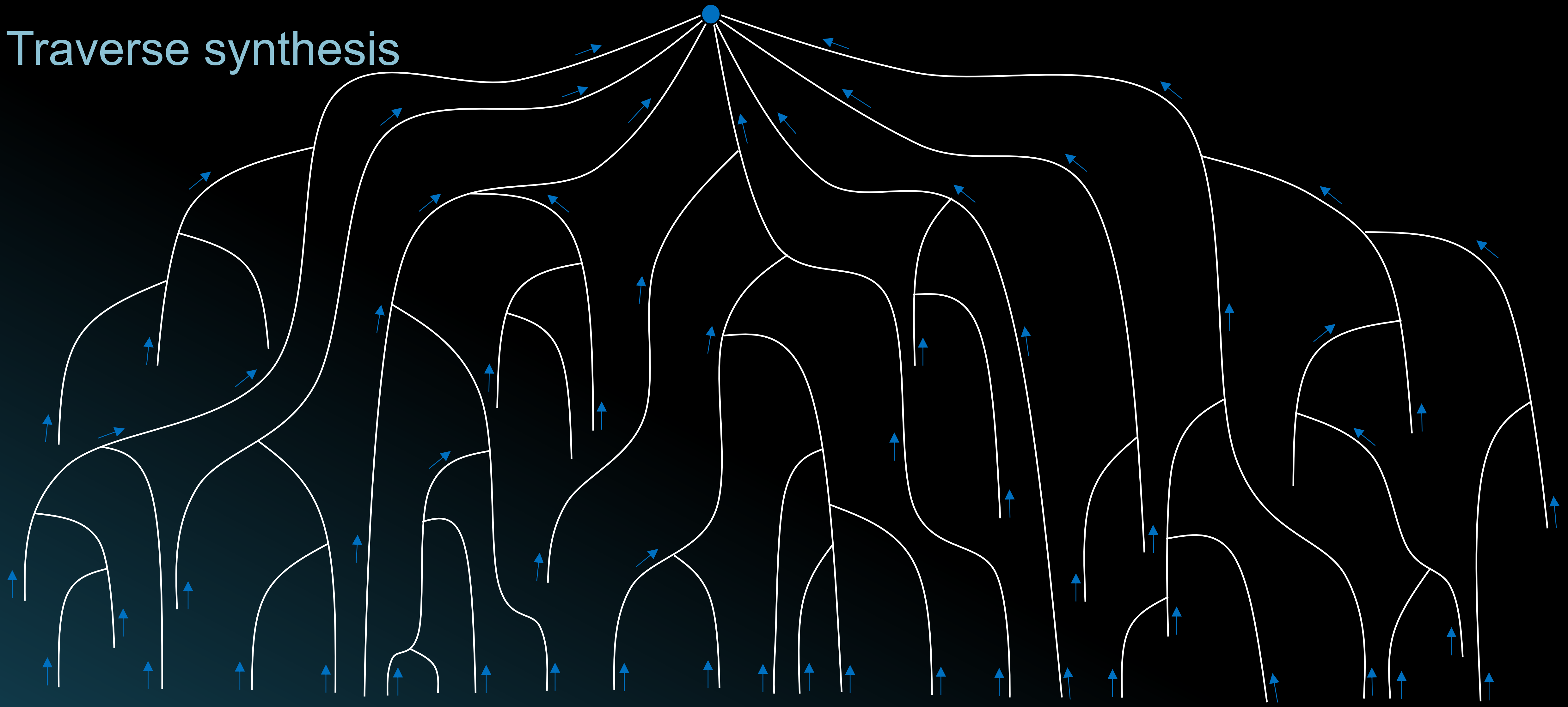
Special thanks to our colleagues on VIPER System Engineering, Science, and Mission Systems for providing support, suggestions, and data instrumental to the development of SHERPA

SHERPA Architecture



- Currently, the primary strategic-level solvers in SHERPA are those for Markov decision processes (MDPs) and partially observable Markov decision processes (POMDPs).
- MDPs and POMDPs are general mathematical frameworks for reasoning under uncertainty.

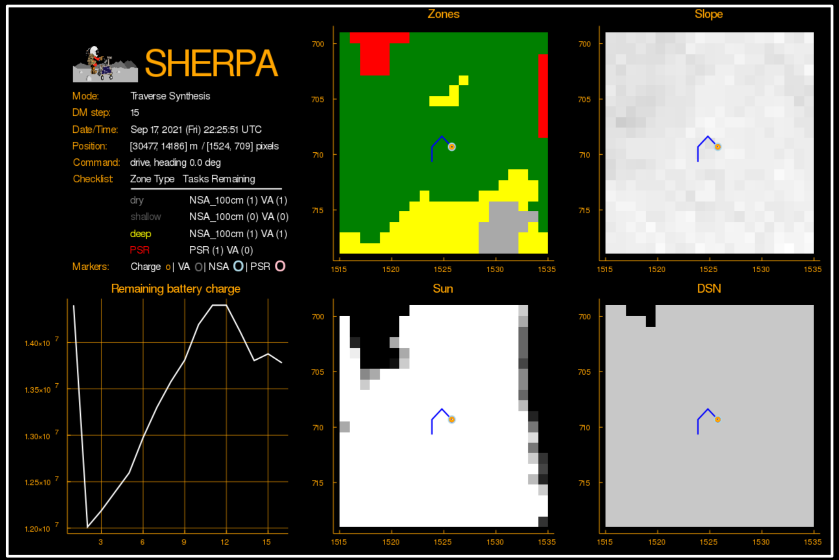
Traverse synthesis



- Numerous stochastic mission scenarios are executed and a policy tree is constructed on their basis
- Execution outcomes are propagated from the leaf nodes through the intermediate nodes, all the way up to the root node
- Action with the best strategic outcome is then selected at the root node (current state)

Traverse Synthesis development timeline

- Version 0:
  - Generated traverses for Resource Prospector (precursor to VIPER). A simpler problem, as that mission was being planned for a single lunar day.
  - Problem formulated as a POMDP, with single-level reasoning performed by the Large Problem Decision Making (LPDM) POMDP solver.
  - Action space consisted of short-duration driving operations (rails or prospecting) in a particular direction and drilling activities.



Version 0 graphical user interface

Version 1:

- Reformulated as an MDP for VIPER, with strategic-level reasoning performed by the Monte Carlo Tree Search (MCTS) MDP solver.
- MCTS reasons sequentially over macro-actions describing either operations on the way to a PSR or operations on the way from a PSR to a safe haven. Detailed tactical-level reasoning is performed within macro-actions.

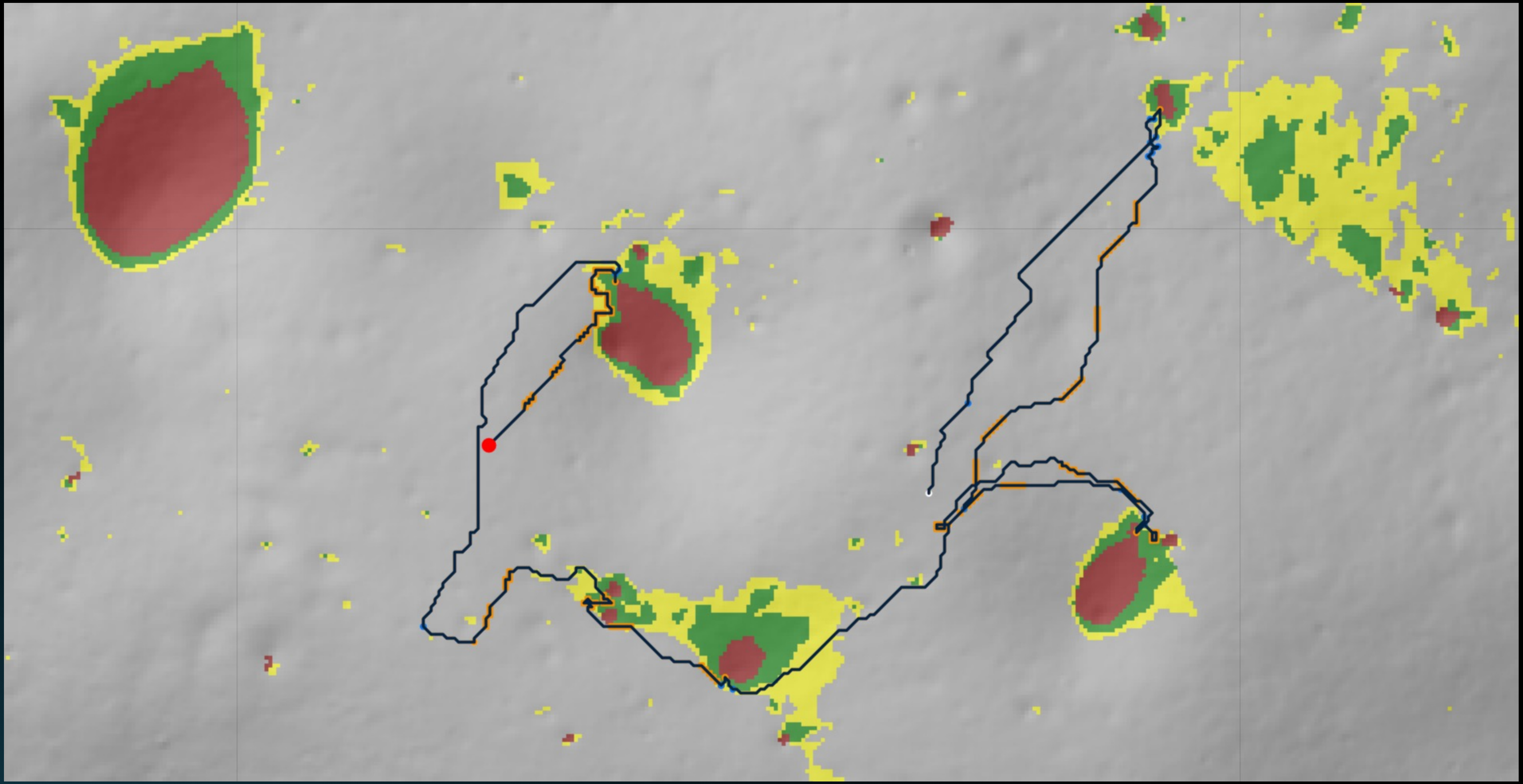
Version 2 (in development):

- Reformulated as a two-stage process: (1) approximate, but fast strategic-level sequential reasoning by MCTS and (2) a detailed tactical-level traverse refinement process once a general strategy has been determined.
- The refinement process includes assignment of science station polygons and computation of robust intra-target paths.

Uncertainties modeled for VIPER

- Traverse start time
- Initial battery charge
- Power draw
- SMG
- Activities duration
- DSN connection availability
- Solar Energetic Proton (SEP) events

Example strategic traverse



- Visits four PSRs (one per lunar day)
- 20+ km of driving, 20+ science stations

Traverse Evaluation

Traverse Evaluation use case

- In this use case, Monte-Carlo simulations are used to stress-test candidate traverses.
- SHERPA injects delays and faults during a traverse scenario execution and collects performance statistics, including mission success criteria satisfied.
- Delays and faults are injected based on their modeled probabilities:

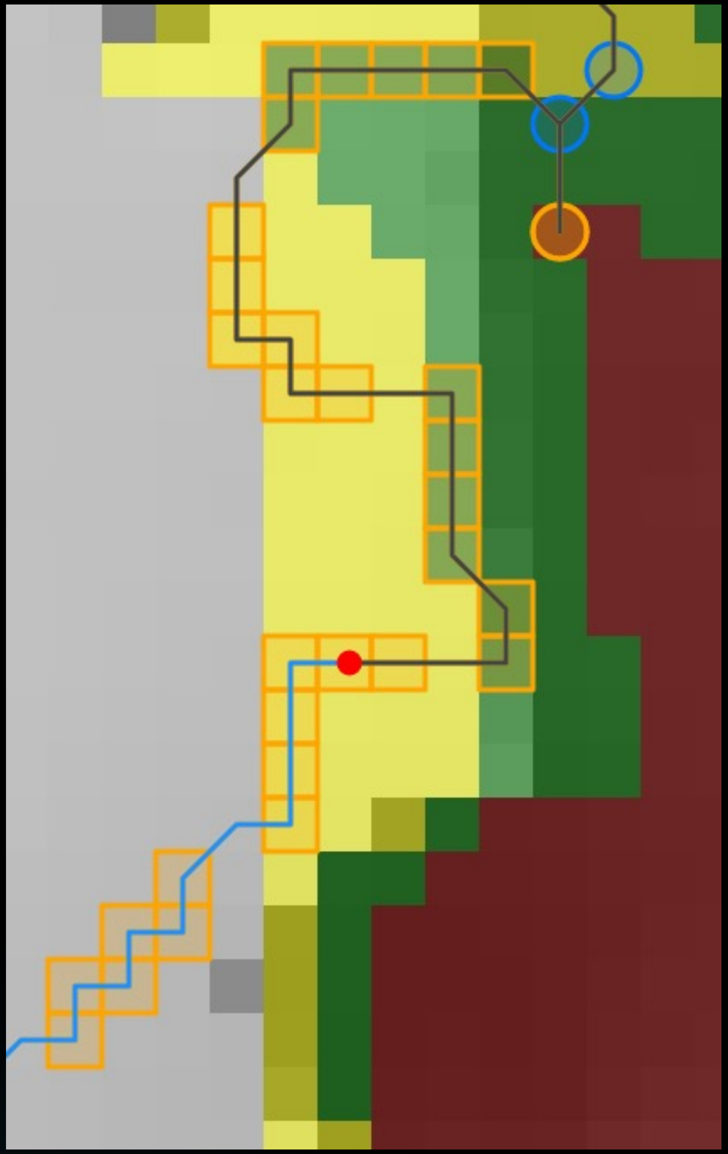
Variable	Distribution	Mean	Standard deviation
Start time	Gaussian (truncated): on-time and delays	planned start time	2 hours
Initial battery charge	Gaussian (truncated): max charge and lower	full charge	20% of full charge
Power draw	Gaussian (truncated): CBE and higher	CBE	20% of CBE
Effective speed	Gaussian (truncated): CBE and lower	CBE	20, 30, 40, and 50% of CBE
Activity duration	Gaussian (truncated): CBE and higher	CBE	20% of CBE

CBE — current best estimate of a value

- Scenario execution policies are intended to represent human operator decisions.

Scenario execution policies

- If running behind nominal schedule, certain optimizations are performed to try to catch up:
  - recharge periods are minimized, whenever possible;
  - drill operations in shallow and PSR stations are shortened.
- Science stations departure is always at the pre-planned time, with optional activities dropped if necessary.
- If a sun shadow is encountered when running ahead of the nominal schedule, the rover will wait until either the shadow moves away from the path or we catch up with the schedule.
- If a sun shadow is encountered when running behind the nominal schedule, the rover will attempt to go

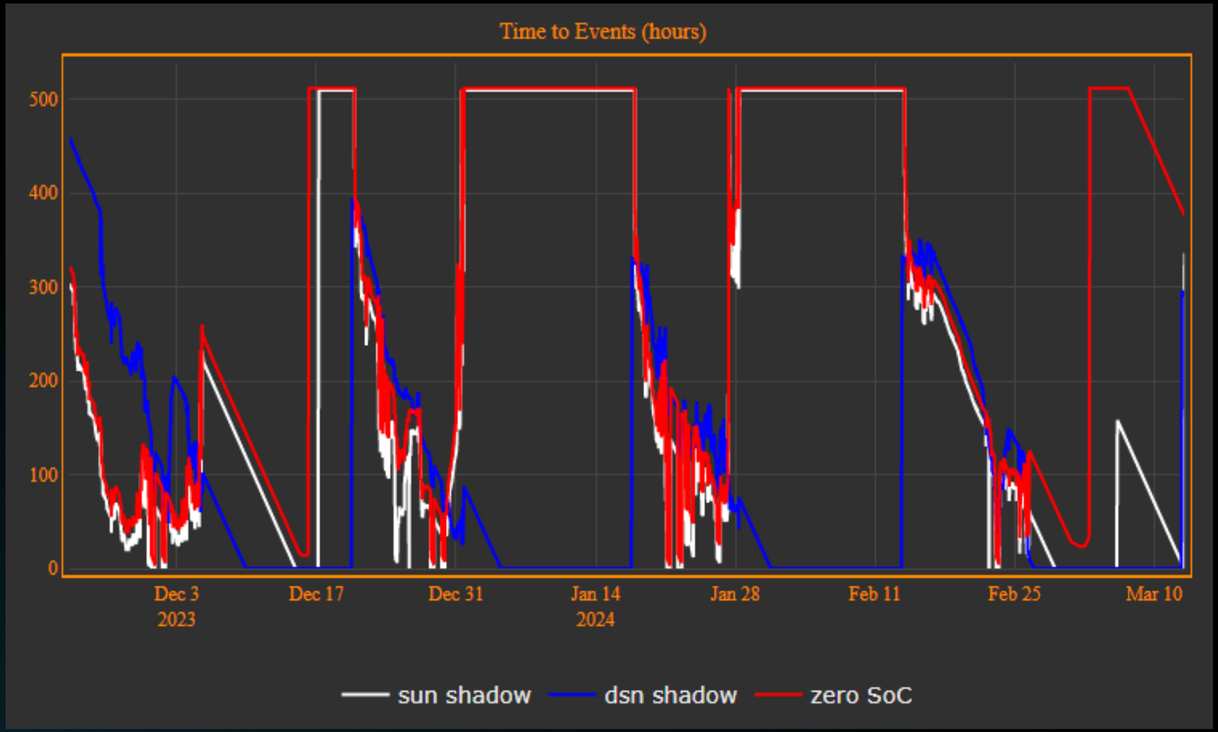


Metrics computed

- Completion fraction
- Full mission success fraction
- Duration to full success (avg)*
- First lunar day stations (avg)*
- First lunar day PSRs (avg)*
- Visited stations (avg)*
- Visited PSRs (avg)*
- Duration, Earth days (avg)*
- Normalized duration vs expected (avg)*
- Odometry (avg)*
- Normalized science score vs max possible (avg)*
- Time to sun shadow, hours (min, avg)*
- Time to DSN shadow, hours (min, avg)*
- Time to 0 SoC, hours (min, avg)*

* Standard deviation is also computed

- DSN shadow events count (avg)*
- DSN shadow cumulative duration, hours (avg)*
- DSN dropout events count (avg)*
- DSN dropout cumulative duration, hours (avg)*
- ISR distance accrual (by type), meters (avg)*
- SEP event statistics



Thank you!
Questions?

Backup

Macro-actions

- Class A macro-actions describe activities on the way to a PSR entry window, as well as the activities inside the PSR.
- Class B macro-actions encompass activities on the way from a PSR to one of the safe havens.
- Traverse Synthesis v1 computes detailed intra-target paths and determines locations and layouts of science stations.
- Traverse Synthesis v2 routes approximate paths through as many locations of interest as possible but leaves detailed path computations and science station assignment to Traverse Refinement.