

Progress on the capabilities of the thermal simulation environment for moving objects on the lunar surface

ESTEWS 2026

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Agenda

- Overview: Lunar Simulation Environment for Thermal Analyses
- Lunar Surface Model
 - Thermal model
 - Adaptive Meshing
- Boulder Generation
- Validation
- Example Results
- Further Work

Lunar Simulation Environment for Thermal Analyses

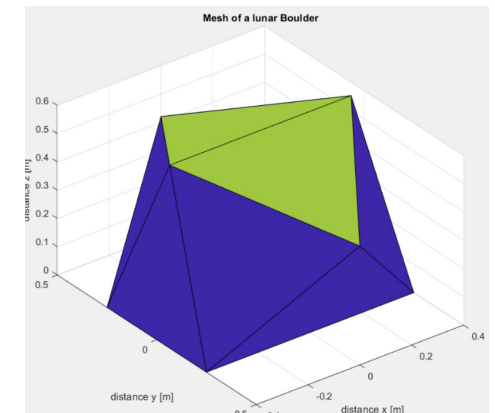
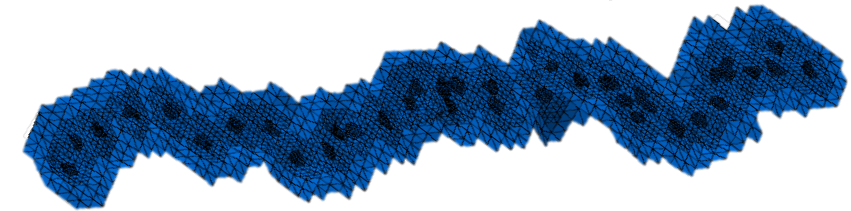
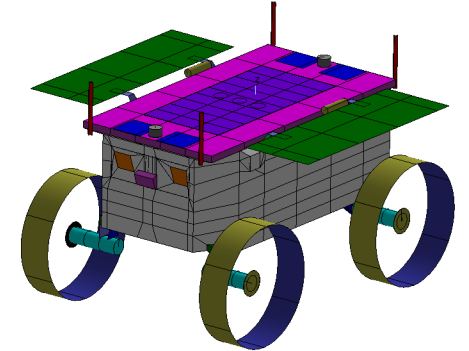
Overview

Purpose: Analysis of a moving ground system on the lunar surface

ESATAN-TMS based, written in MATLAB

Workflow:

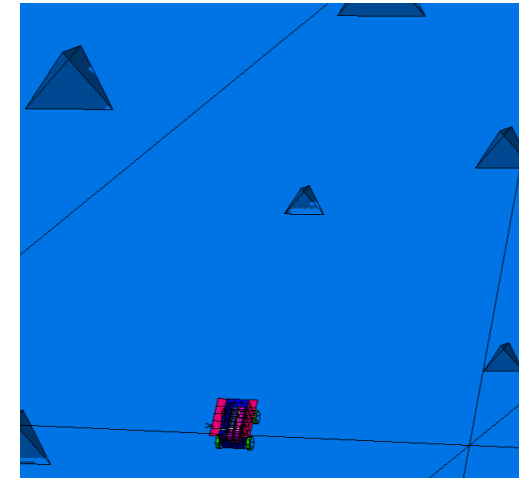
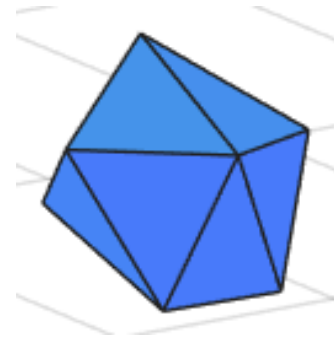
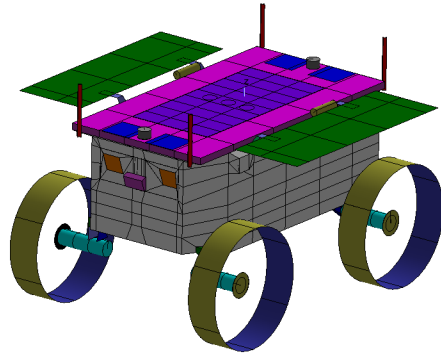
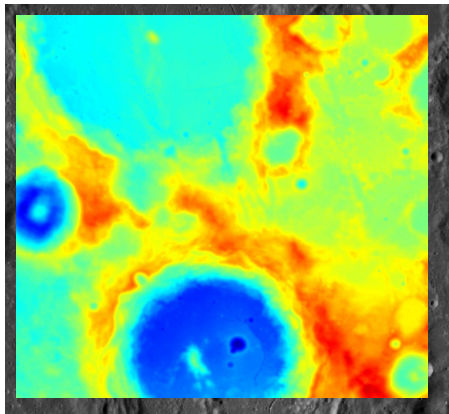
- Provide thermal model of a moving ground system (e.g. rover)
- Define mission path + timing on the lunar surface
- Define boulder settings
- Define simulation settings



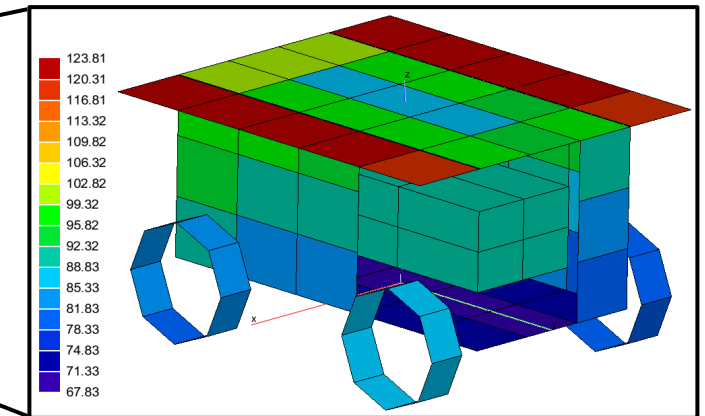
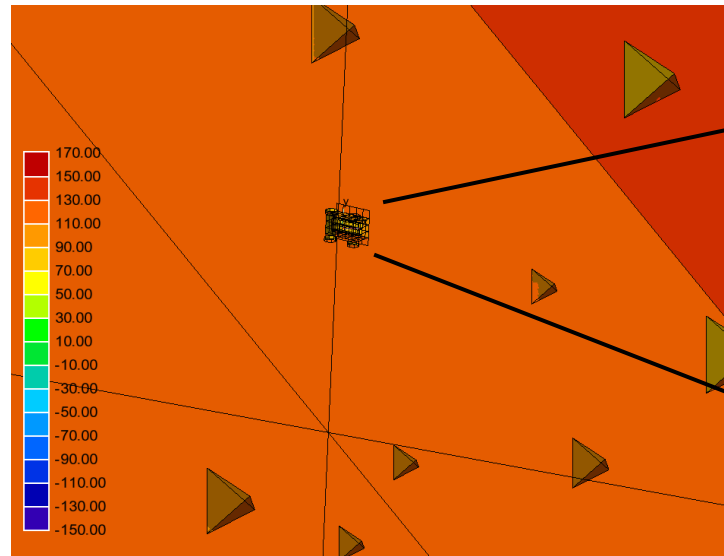
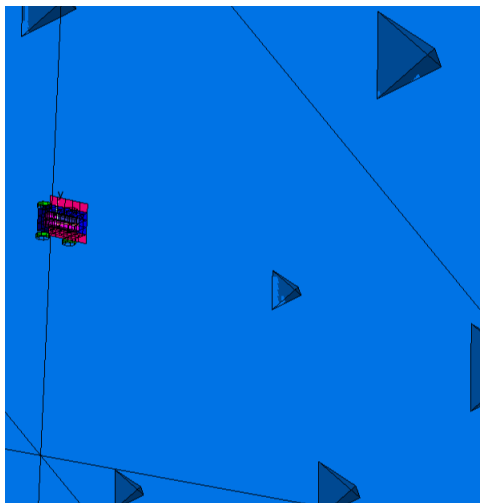
Lunar Simulation Environment for Thermal Analyses

Overview

- Three submodels:
 - Lunar surface: Topography based on SLDEM2015 data
 - Rover: Provided by user
 - Boulder: Generated by the environment



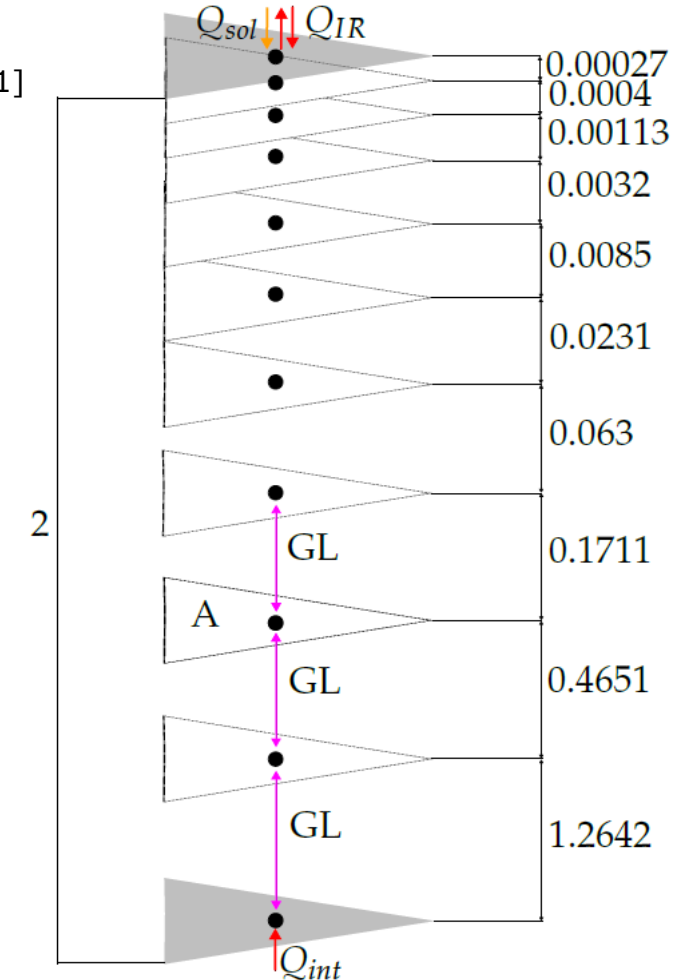
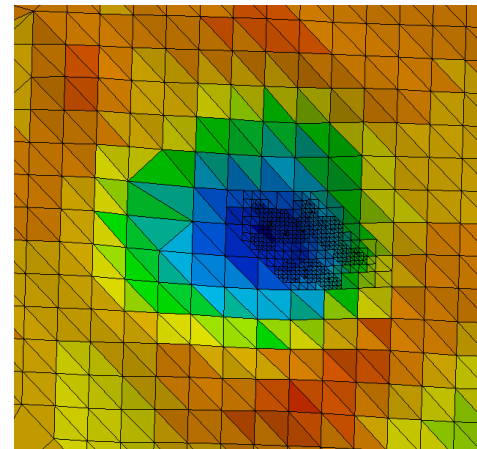
- Three submodels:
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Lunar Surface Model

Thermal model: General structure

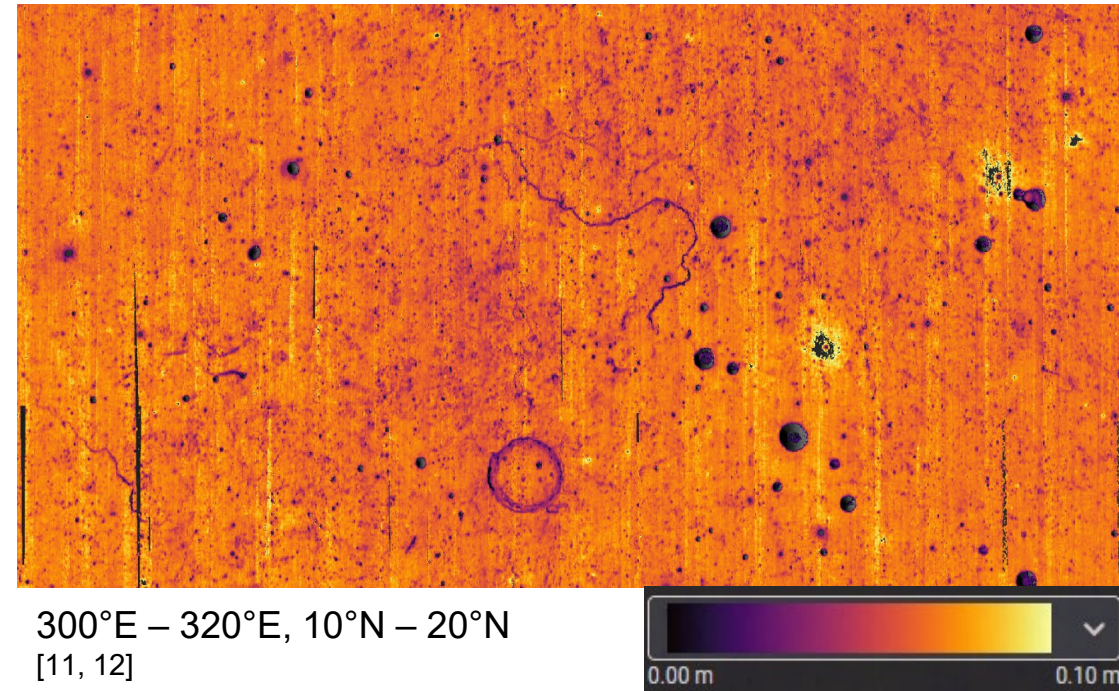
- Lunar surface model:
 - Two-layers: Upper 2 cm dust, denser regolith below [1]
 - 10 nodes in depth direction
 - GL between depth layers, no in-plane GL
 - Heat flux from lunar interior [2]
 - Initial temperature [3]
 - Triangle mesh



Lunar Surface Model

Hayne Model

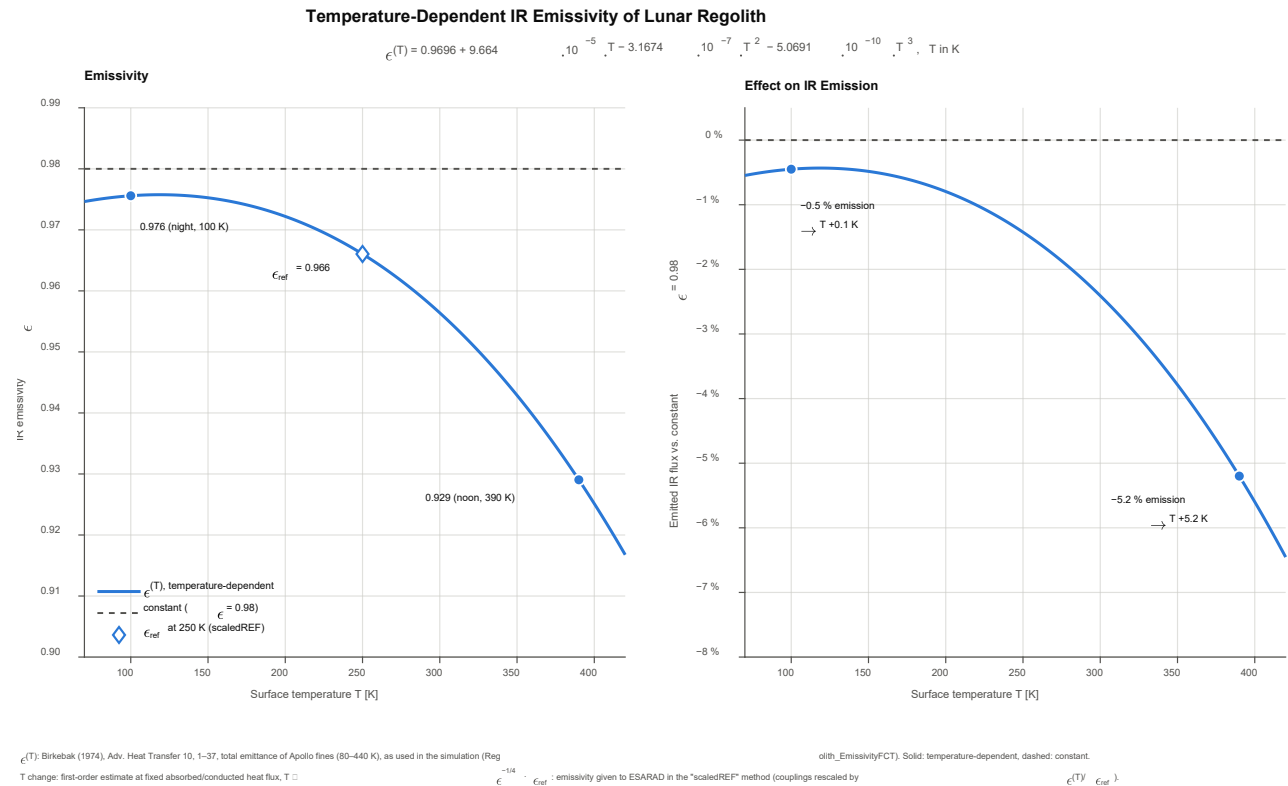
- Uses H-Parameter
- Thermal conductivity & heat capacity: $f(\rho_{reg})$
- ρ_{reg} is $f(H)$: $\rho_{reg}(z, H) = \rho_d - (\rho_d - \rho_s) \cdot e^{\frac{-z}{H}}$ [13]
- Value range:
 - $0.0 \text{ m} < H < 0.2 \text{ m}$
 - $\emptyset H = 0.06 \text{ m}$
 - Extreme H values only at fresh impact craters & regional pyroclastic deposits



Lunar Surface Model

Surface emissivity

- 2 options: Constant emissivity and temperature-dependent emissivity
- Constant emissivity:
Value defined by user
- Temperature-dependent emissivity

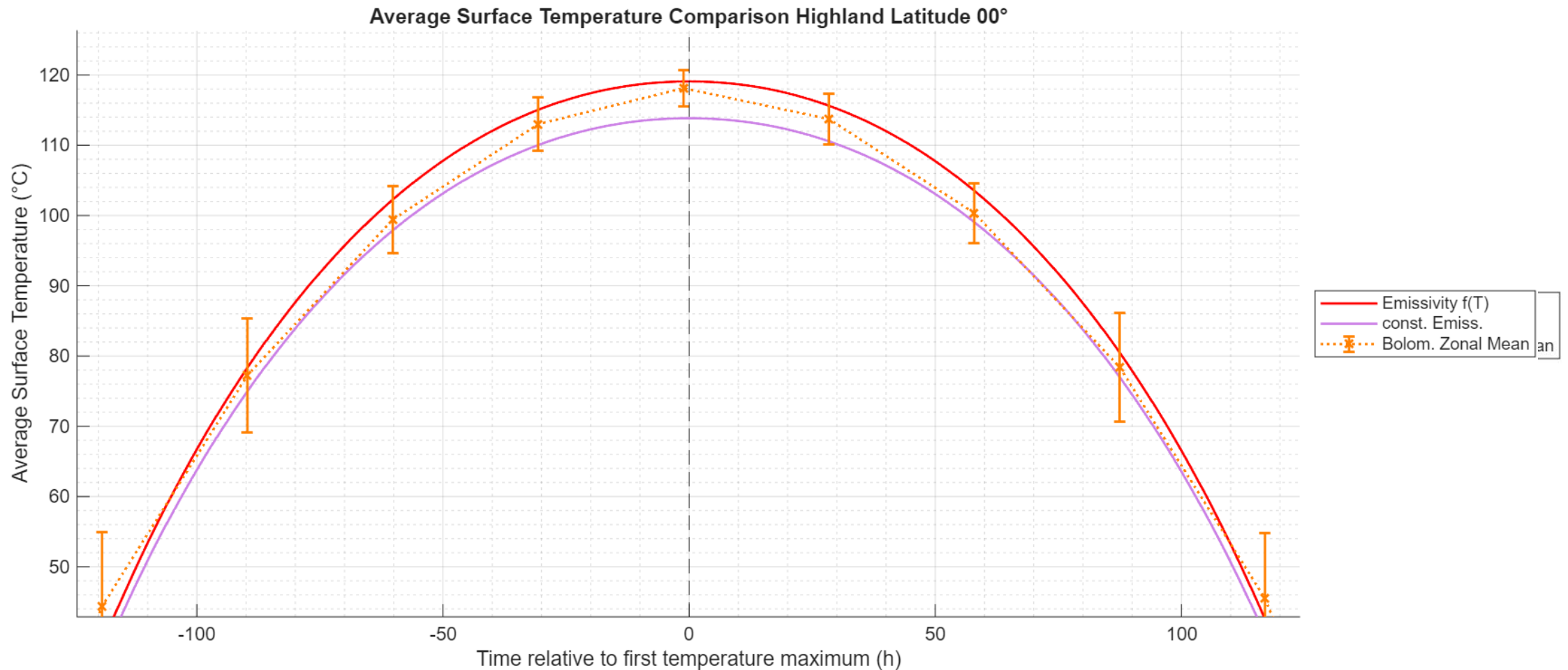


$$\epsilon(T) = 0.9696 + 9.664 \cdot 10^{-5} \cdot T - 3.1674 \cdot 10^{-7} \cdot T^2 - 5.0691 \cdot 10^{-10} \cdot T^3 \quad [7]$$

Lunar Surface Model

Surface emissivity

- 2 options: Constant emissivity and temperature-dependent emissivity



Lunar Surface Model

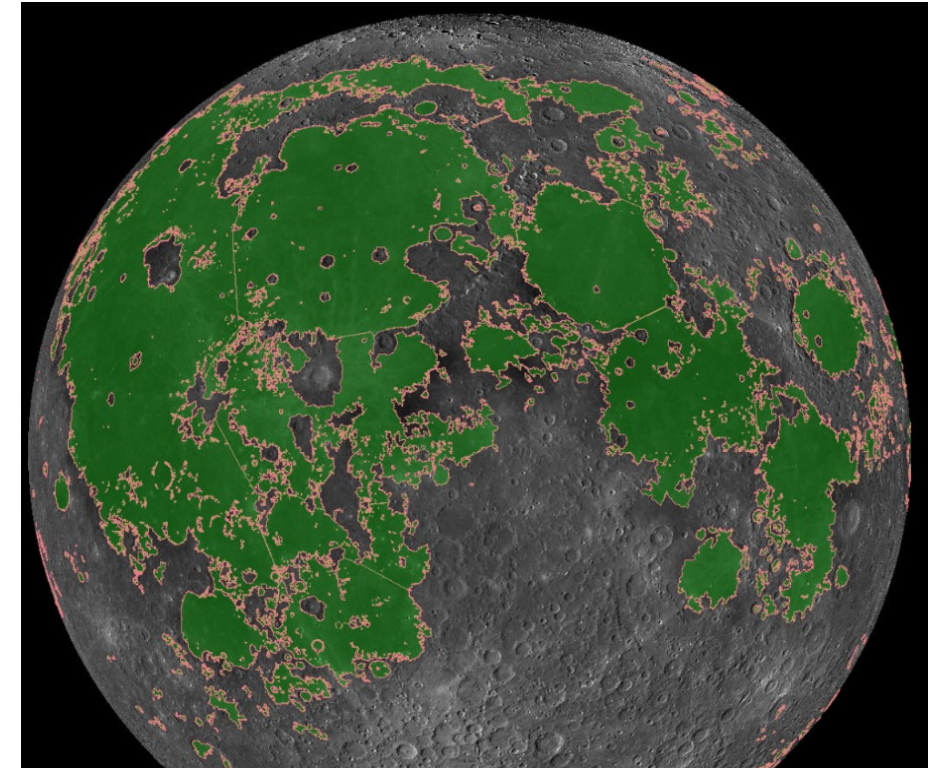
Surface solar absorptivity

- Mare / Highland distinction via Mare Boundary Map [14]
- Use correct thermo-optical properties of the lunar surface:

Mare regions: $\alpha = 0.93$ [8]

Highland regions: $\alpha = 0.84$

- Region of mission identified via path coordinates



Lunar Quickmap, © Applied Coherent Technology 2026

Lunar Surface Model

Surface solar absorptivity

- 2 options: Constant absorptivity or angle-dependent absorptivity

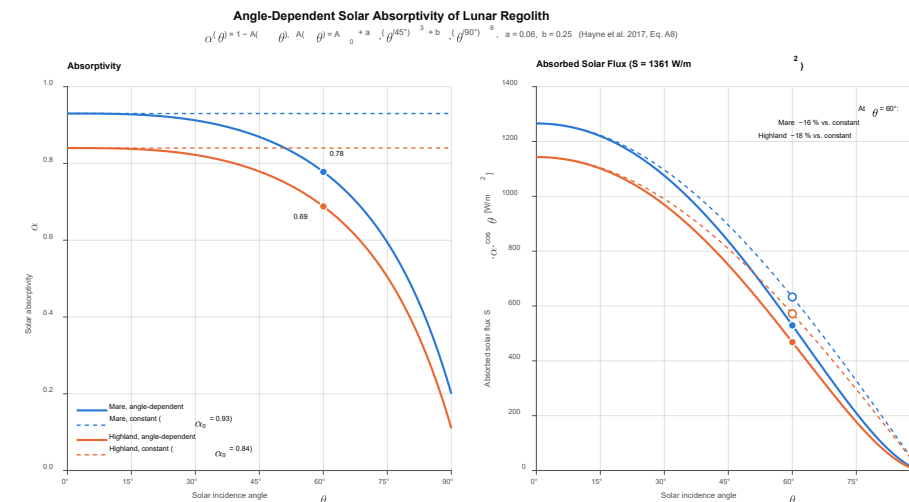
- Constant absorptivity:

Value defined by user for Mare regions and for Highland regions

- Angle-dependent absorptivity:

Via albedo: $A(\theta) = A_0 + a \cdot \left(\frac{\theta}{45\text{deg}}\right)^3 + b \cdot \left(\frac{\theta}{90\text{deg}}\right)^8$ with $a=0.06$, $b=0.25$ [Keihm, 1984]

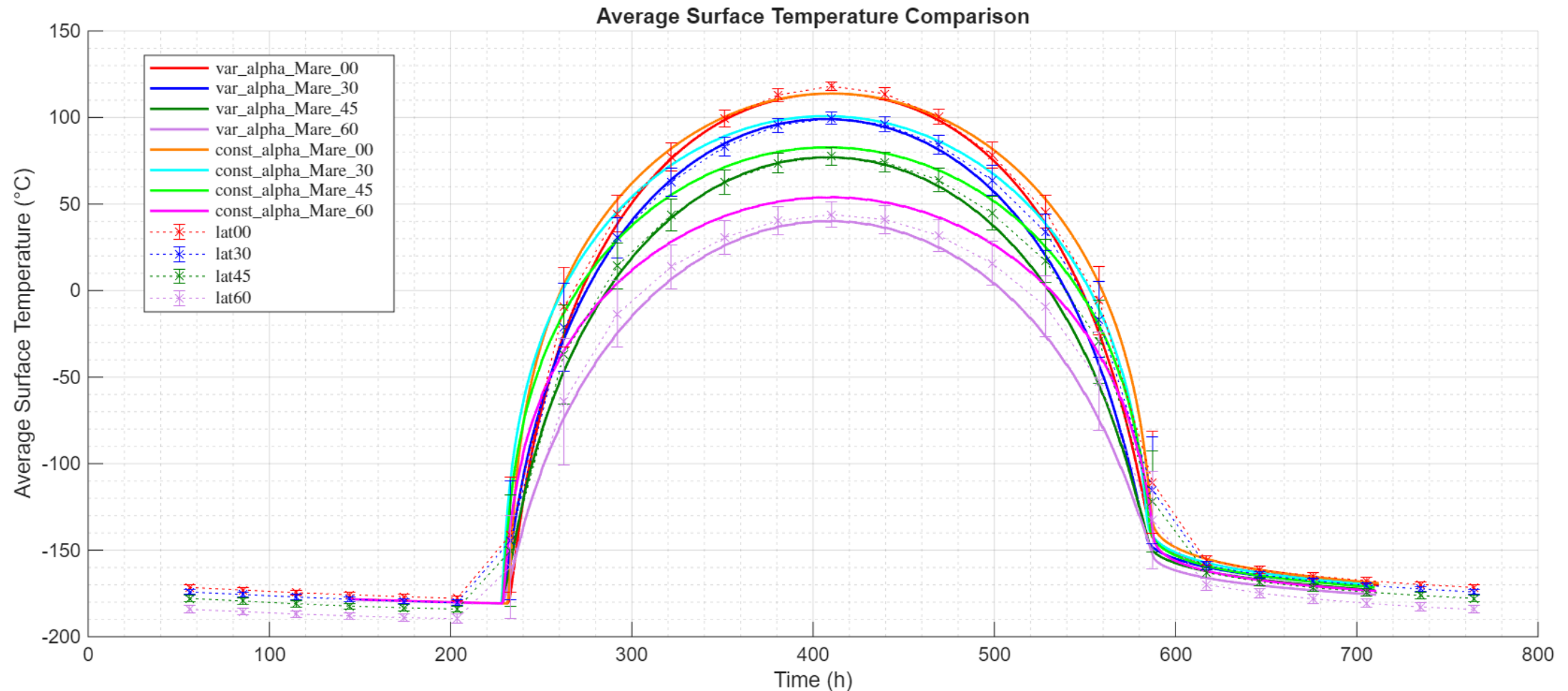
A_0 from constant absorptivity value



Lunar Surface Model

Surface solar absorptivity

- 2 options: Constant absorptivity or angle-dependent absorptivity



Lunar Surface Model

Initial Temperatures

- Initial temperature depends on latitude via

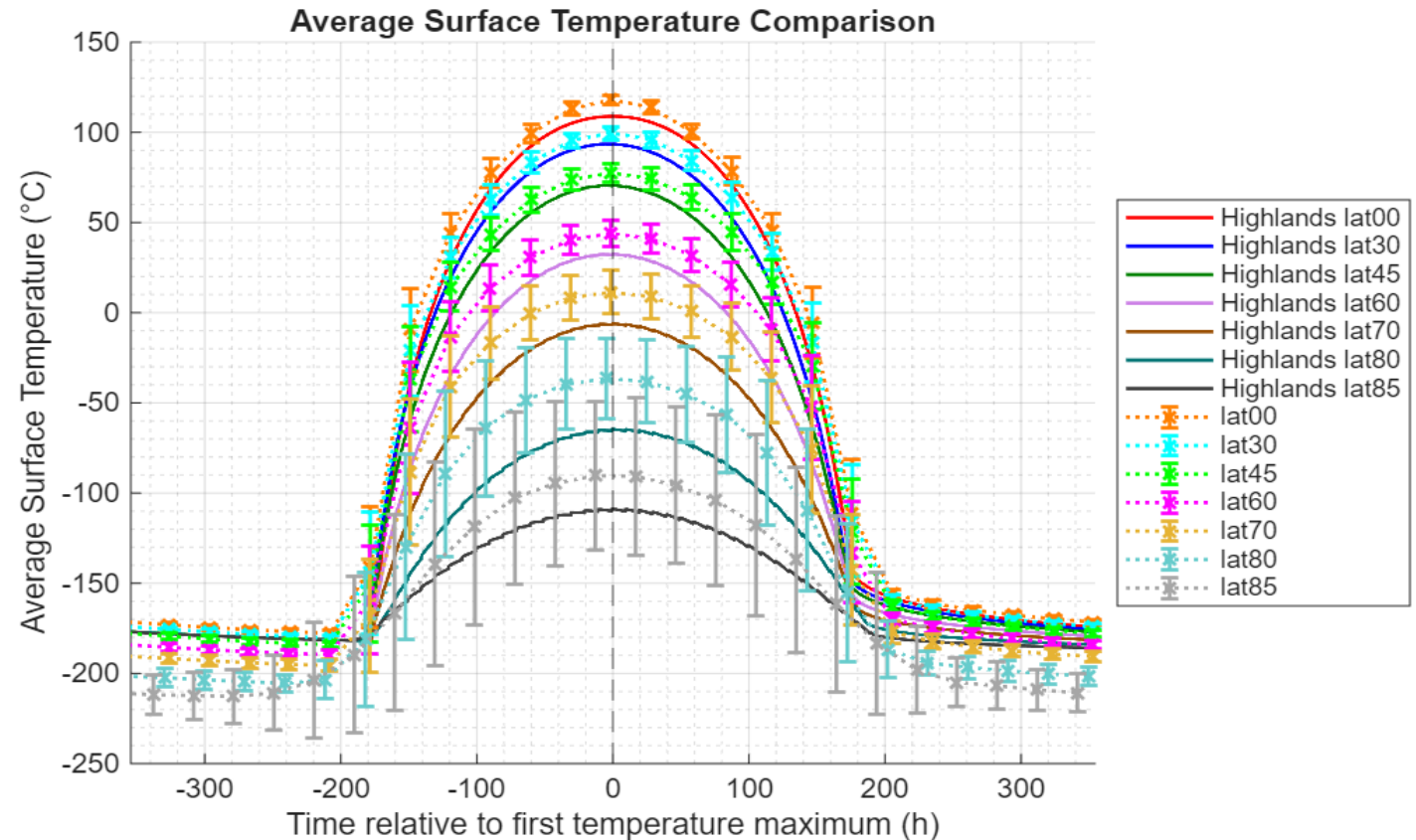
$$T = T_{ref} \cdot \cos(\varphi)^{\frac{1}{4}} \quad \text{with } T_{ref} = 255 \text{ K}$$

-> at 00° : $T_{init} = 255 \text{ K}$

-> at 60° : $T_{init} = 214 \text{ K}$

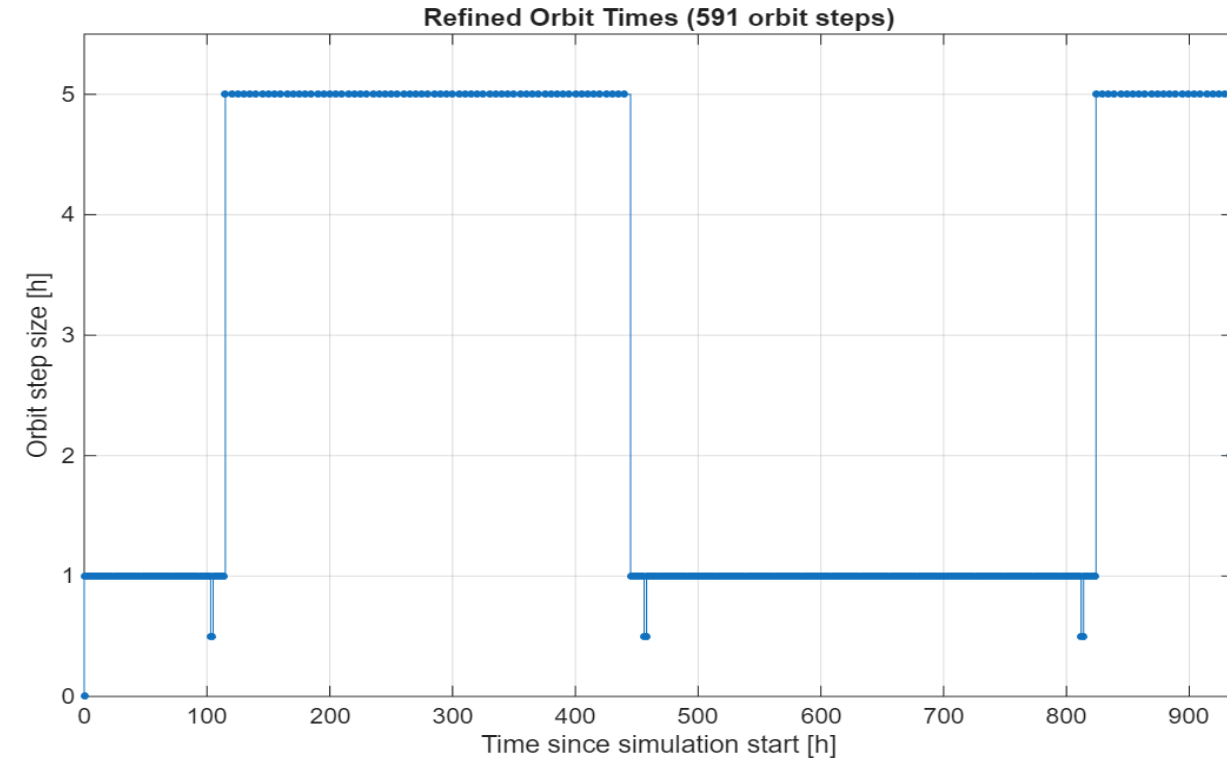
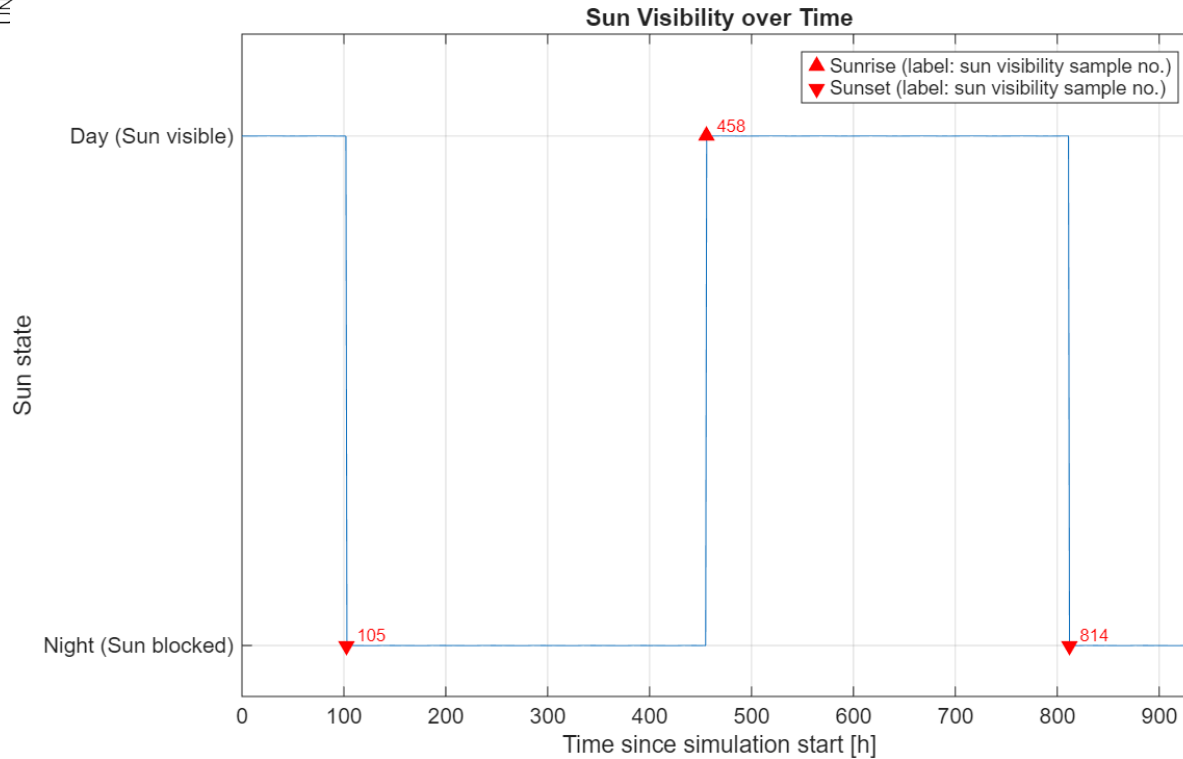
-> at 85° : $T_{init} = 139 \text{ K}$

- After initialization: Swing-in 1 via a simplified surface mode



Lunar Surface Model

Temporal refinement



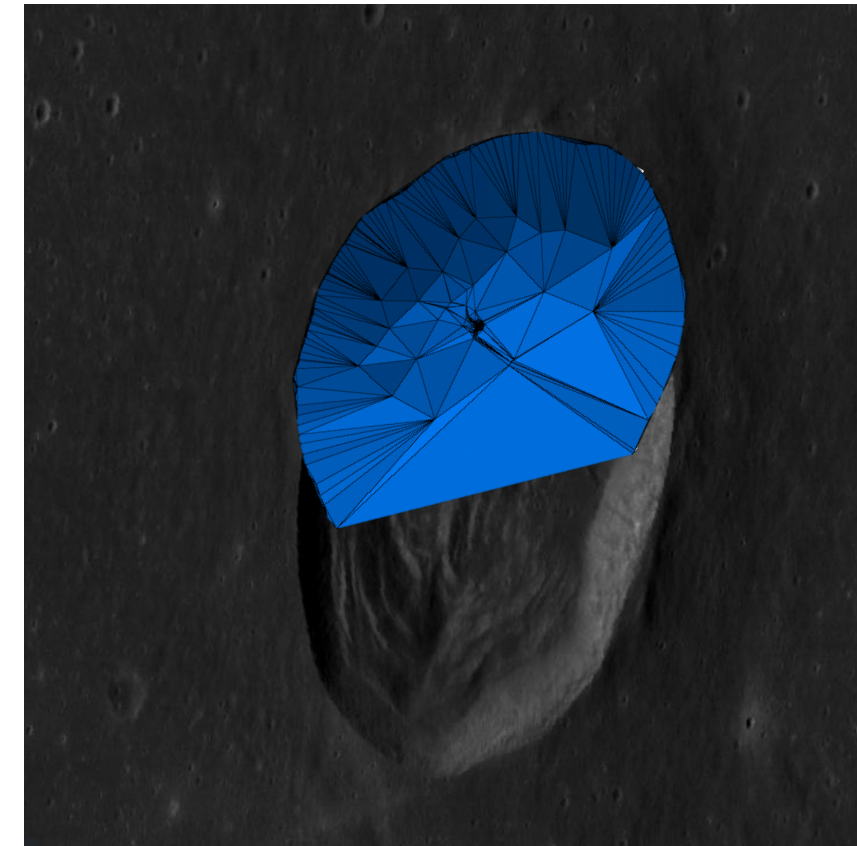
Lunar Surface Model

Adaptive meshing

Problem: Computation time vs. result accuracy

Relevant meshing distance depends on topography around rover

- Surface to be meshed = area within visible horizon
ray casting from each waypoint → New mesh
 - ray tracing yields view factors to surface elements
 - Elements refined based on view factor threshold
 - Custom refinement in rover vicinity
- surface mesh with high resolution near the path
- considering topographic features
- generally decreasing with distance

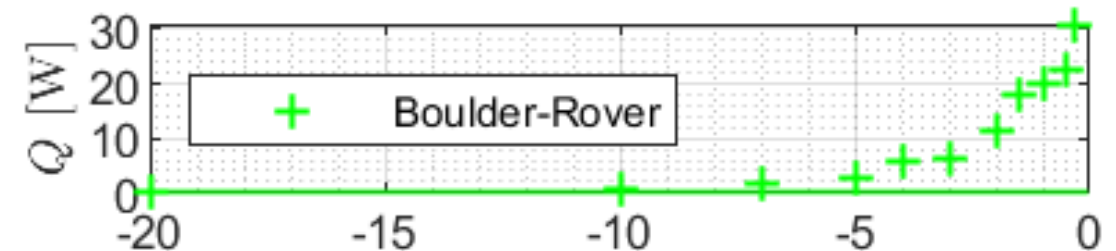
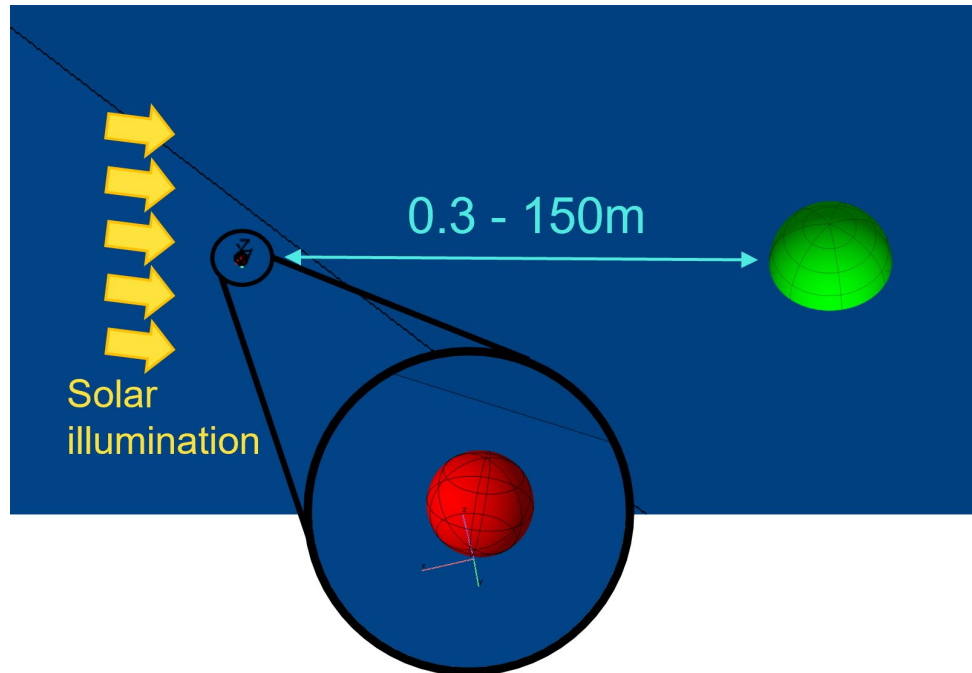


Boulder on the lunar surface

Placement

Why are local surface features relevant?

- Can increase IR flux onto transiting object (by up to 330% [3])
- Cast shadows

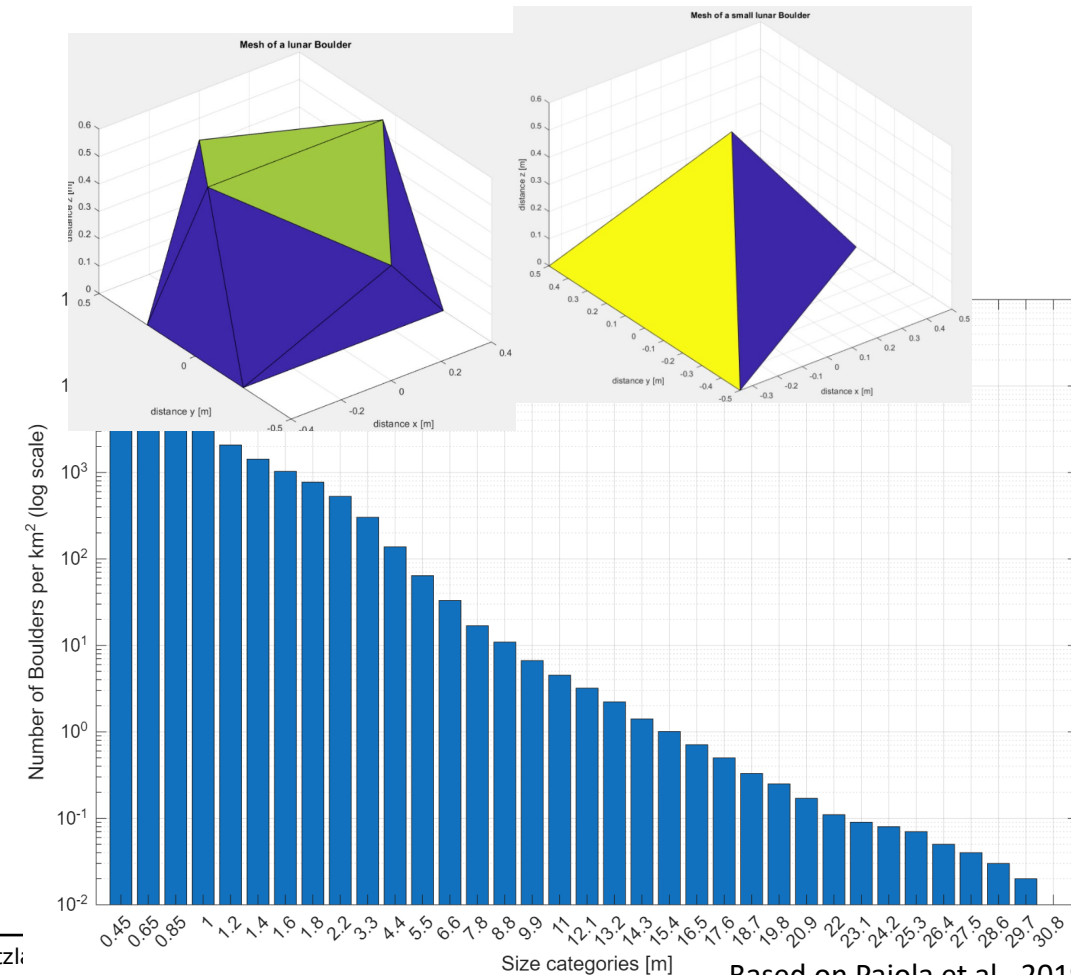


Boulder on the lunar surface

Placement

Why are local surface features relevant?

- Can increase IR flux onto transiting object (by up to 330% [3])
- Cast shadows
- Options for placement and size of boulders:
 - Manually
 - Stochastically
- boulders eliminated if view factor < threshold
- boulder shapes defined as two distinct shapes including random component



Boulder on the lunar surface

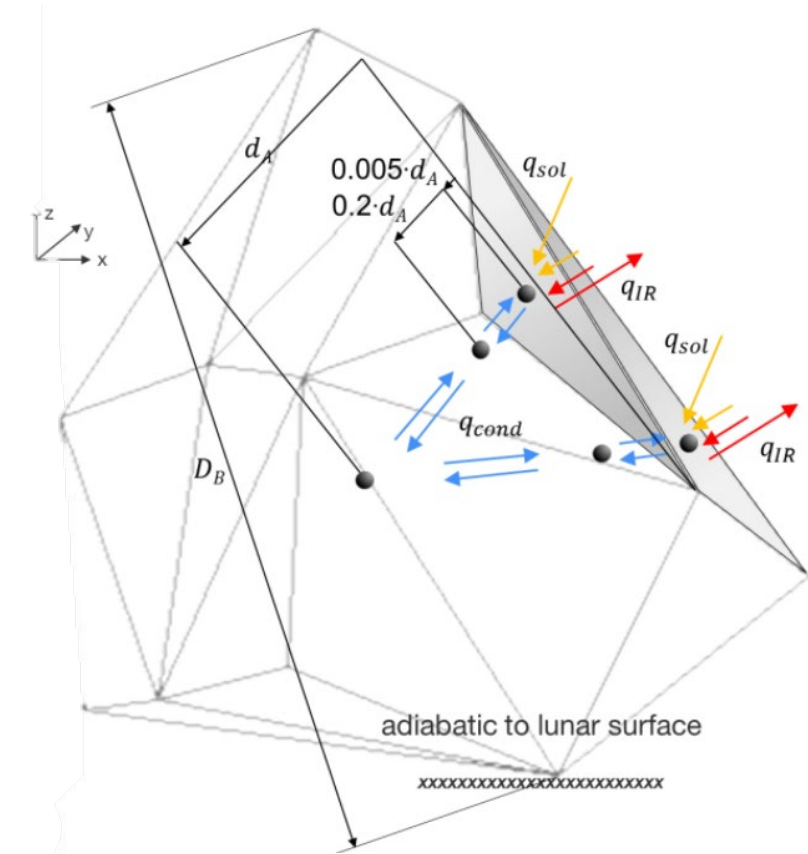
Thermal model

Thermal model according to Hager, 2013:
surface nodes,
one intermittent node per surface node,
one central node

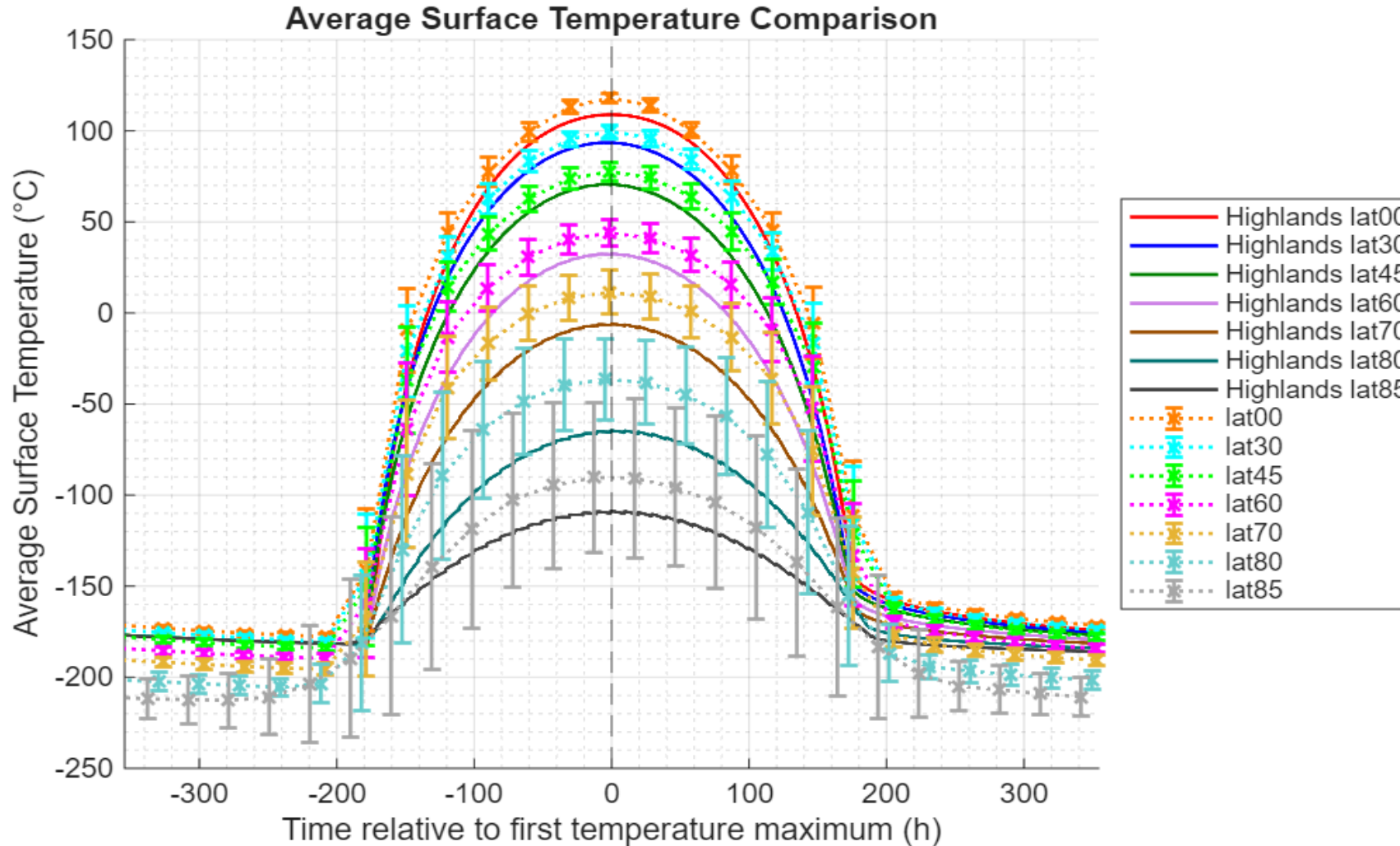
Boulder material: Anorthosite / Basalt / Breccia

→ Density, thermal conductivity, spec. heat capacity
based on Apollo samples + terrestrial Anorthosite

Thermooptical properties: same options as regolith



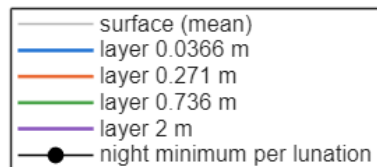
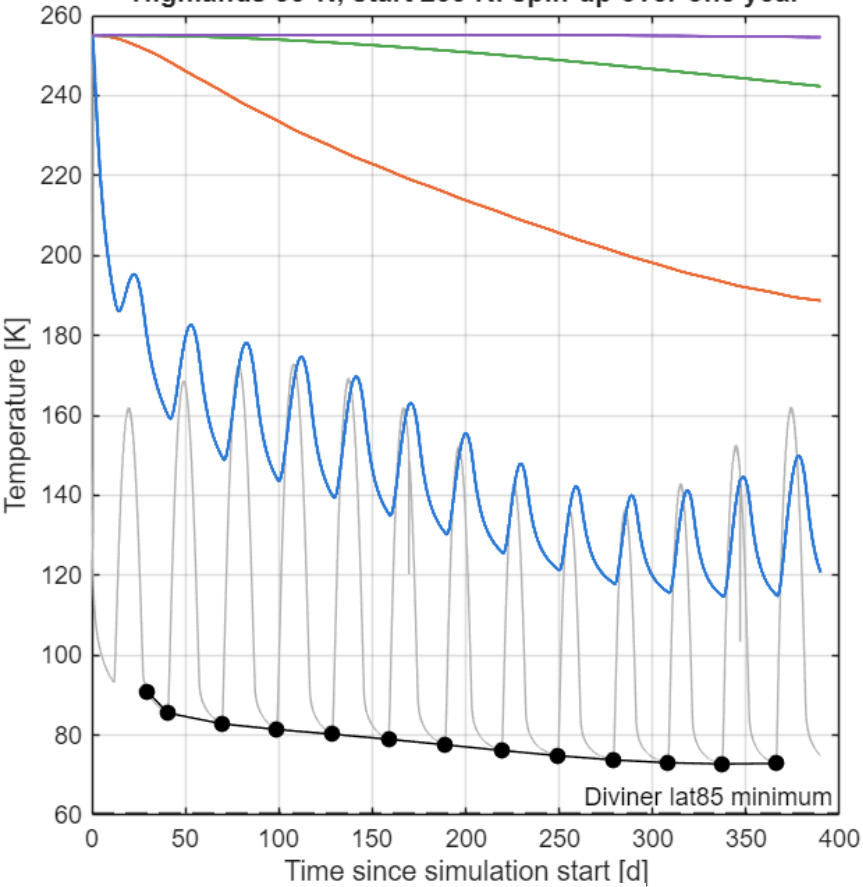
Hager, 2013



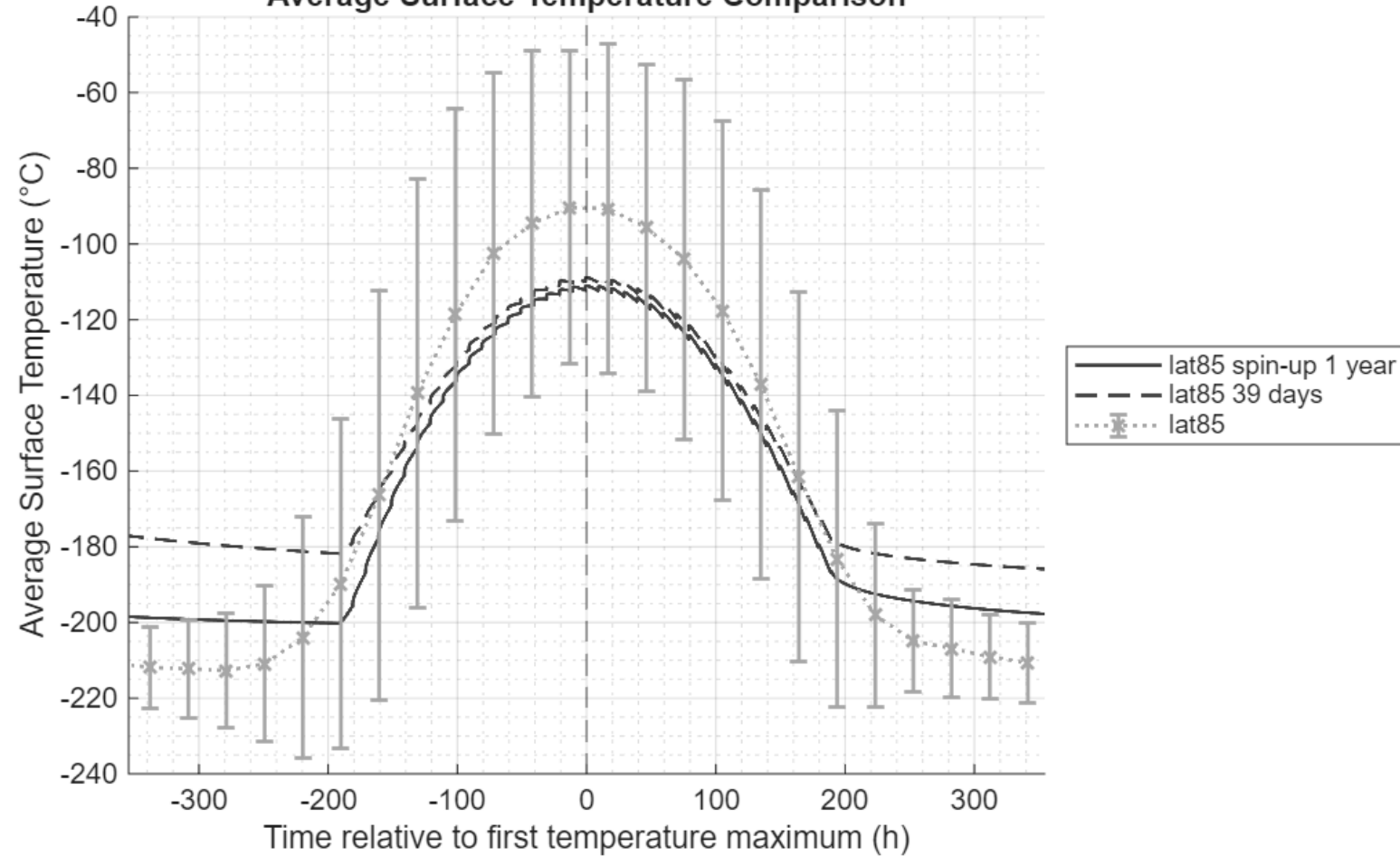
Validation

Night temperature

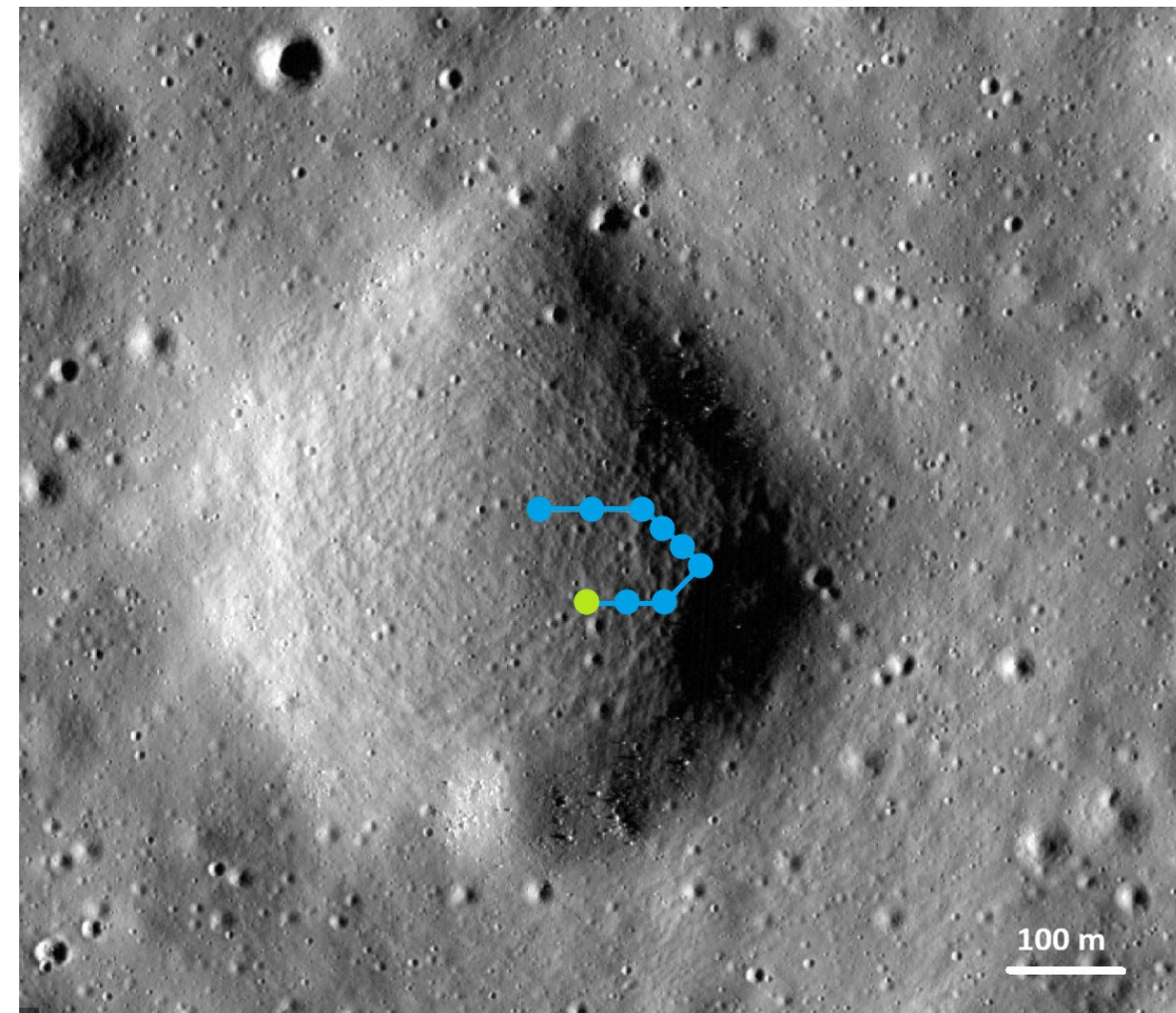
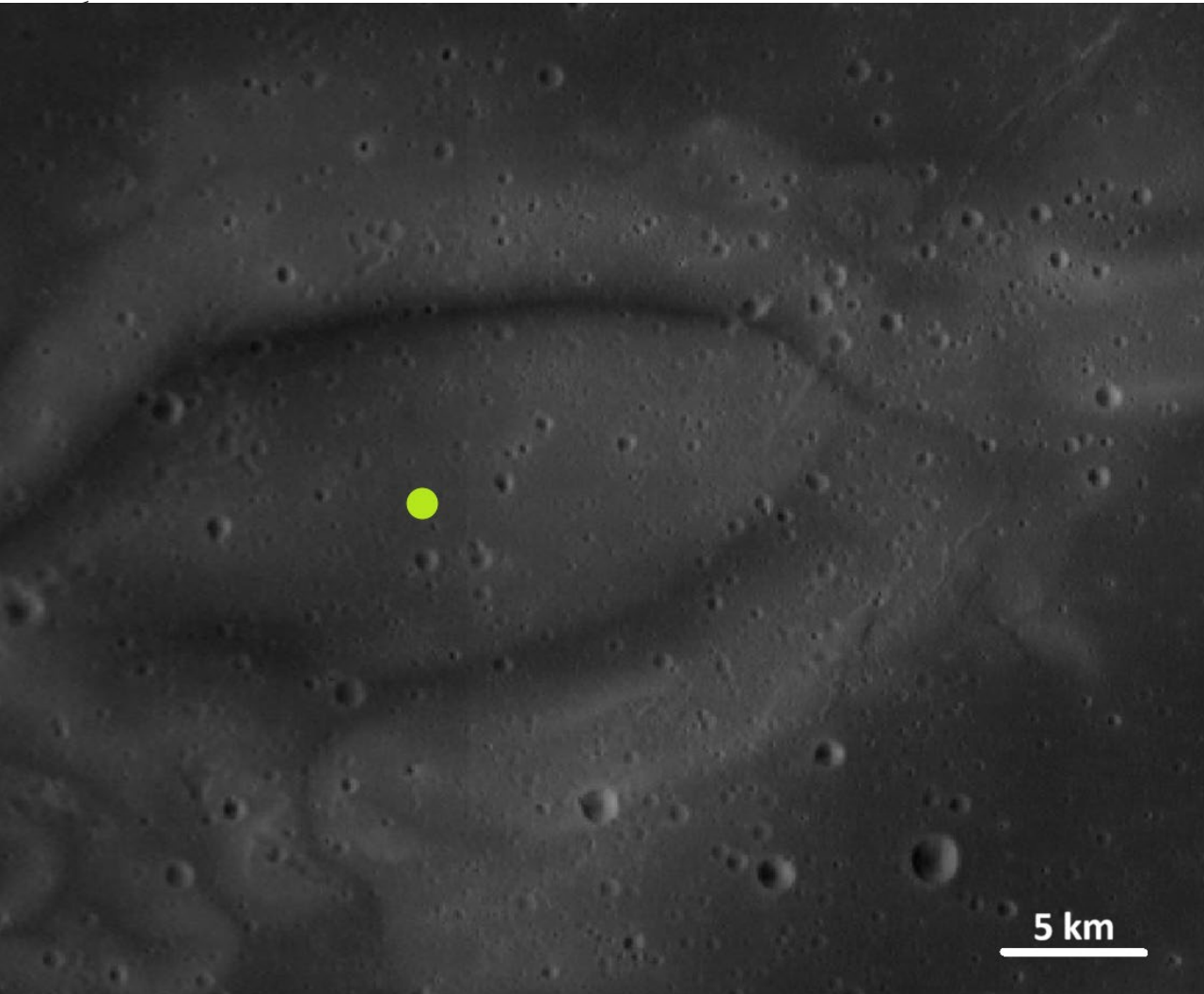
Highlands 85°N, start 255 K: spin-up over one year



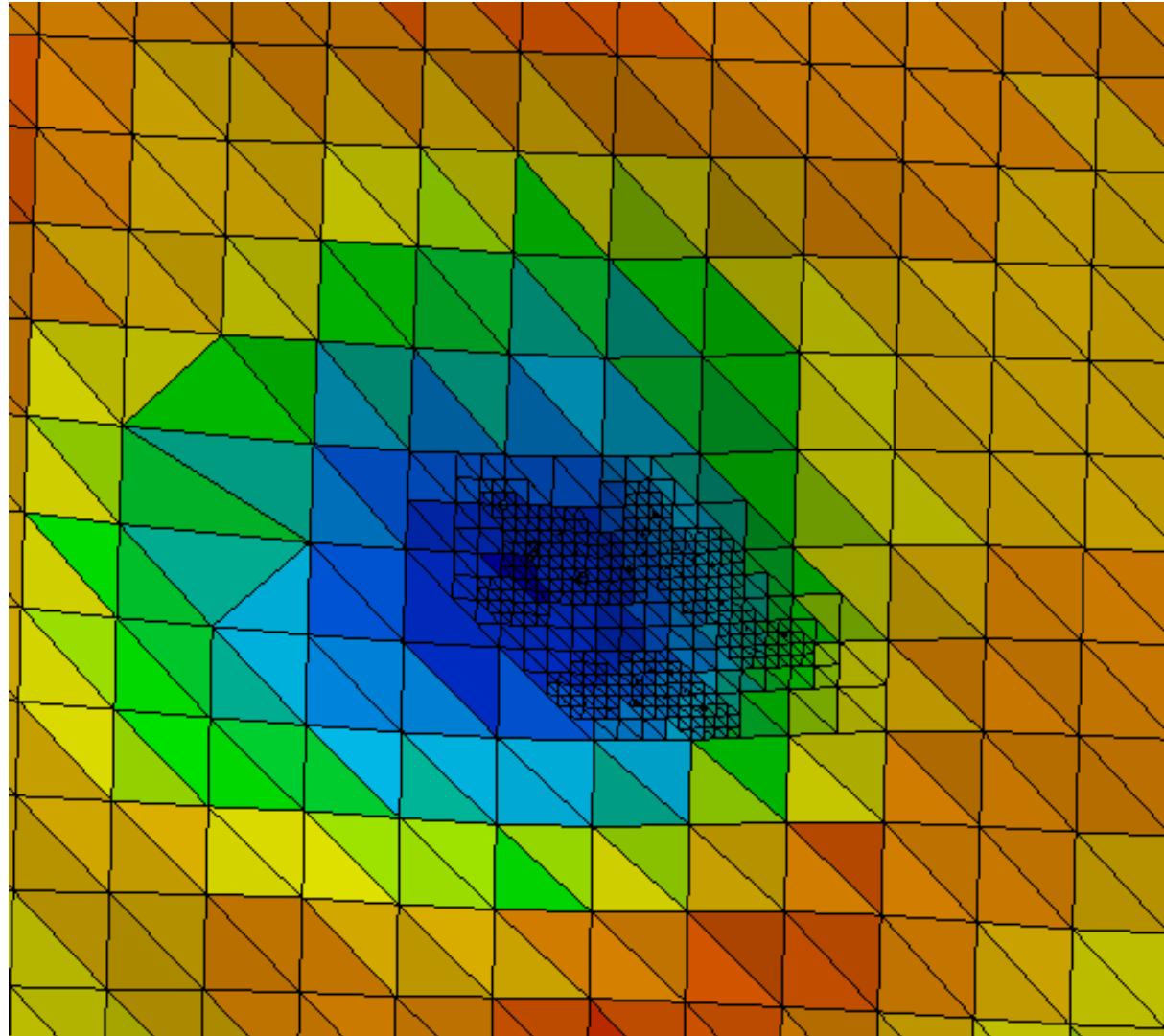
Average Surface Temperature Comparison



Complete Simulation

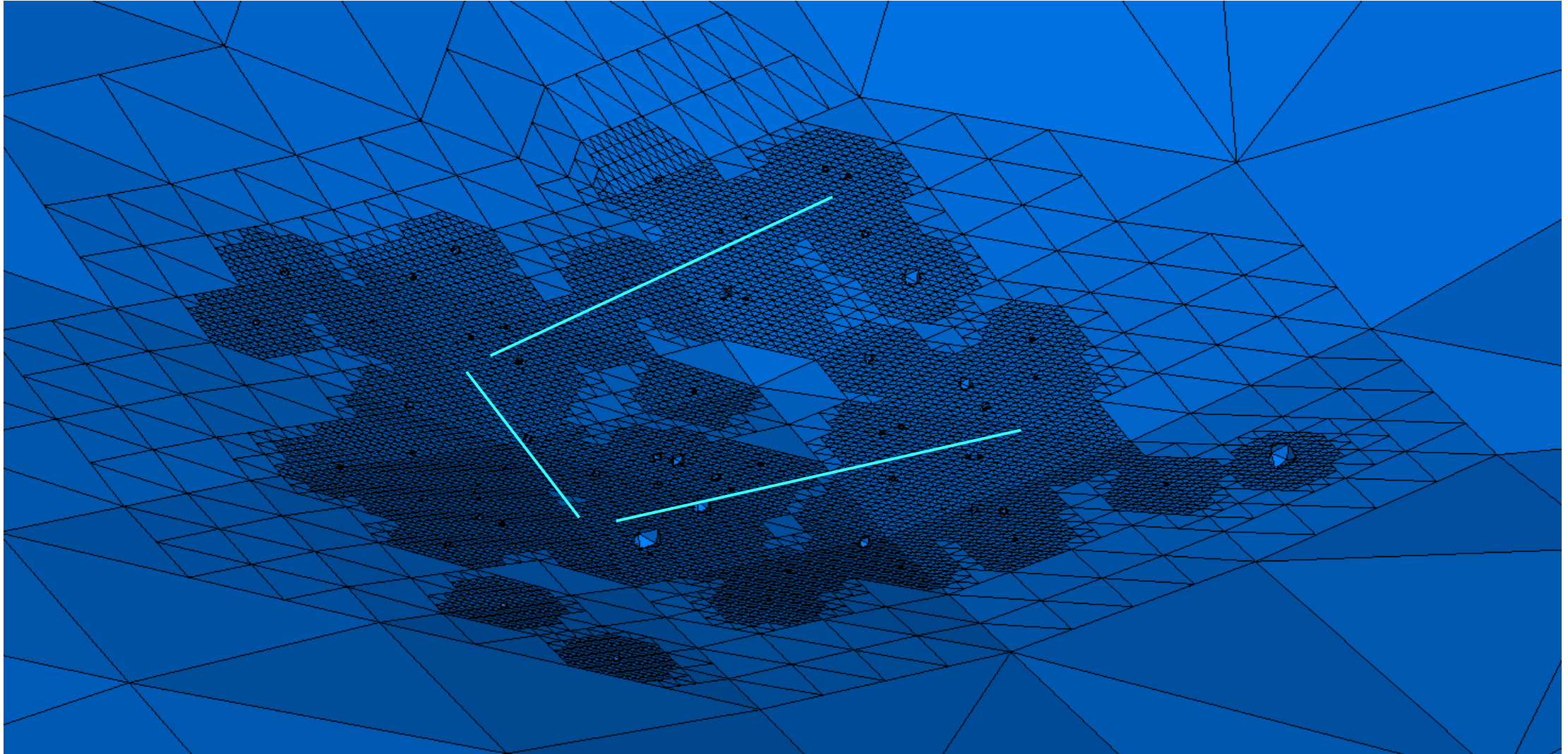


Complete Simulation

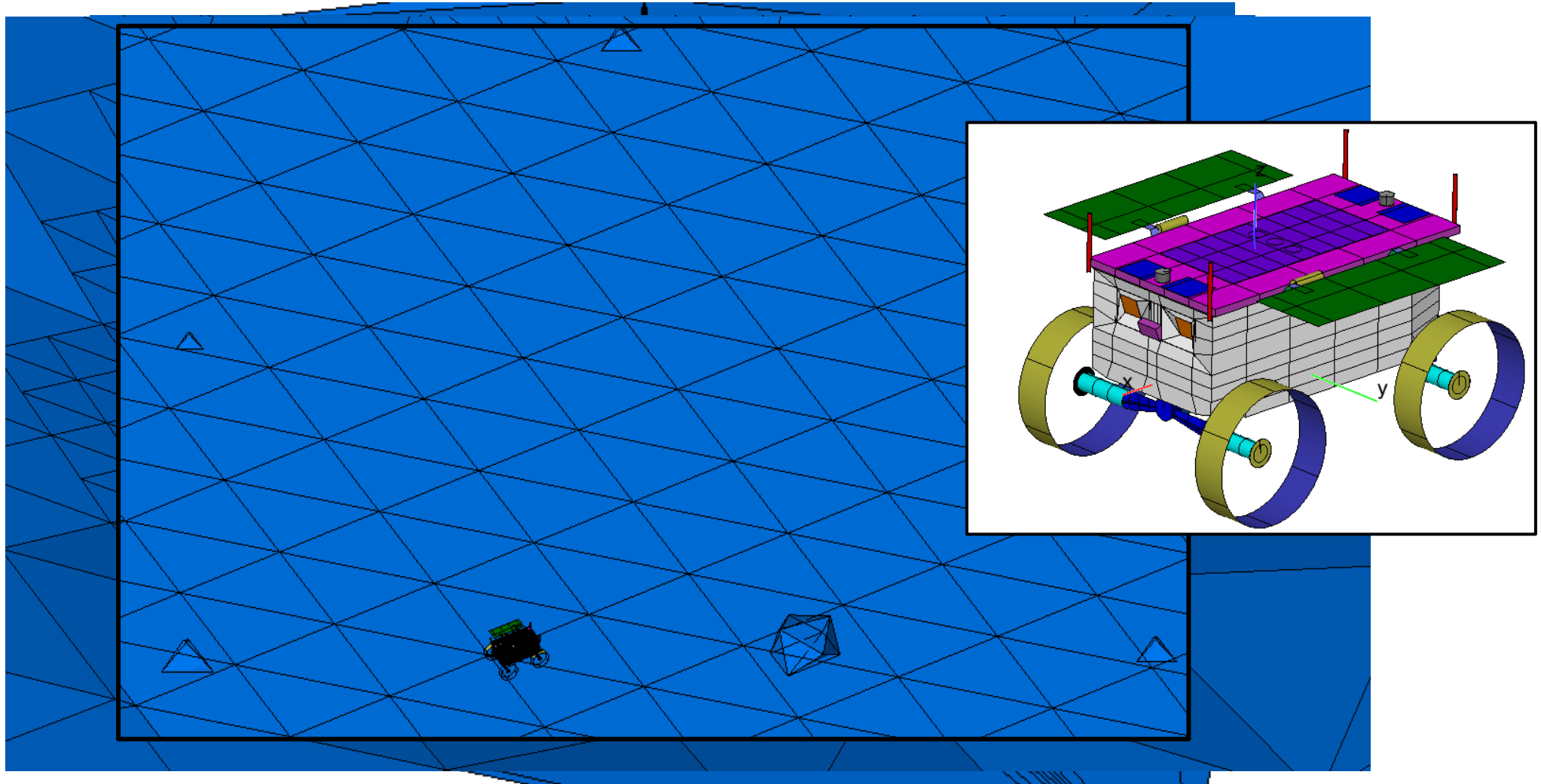


Complete Simulation

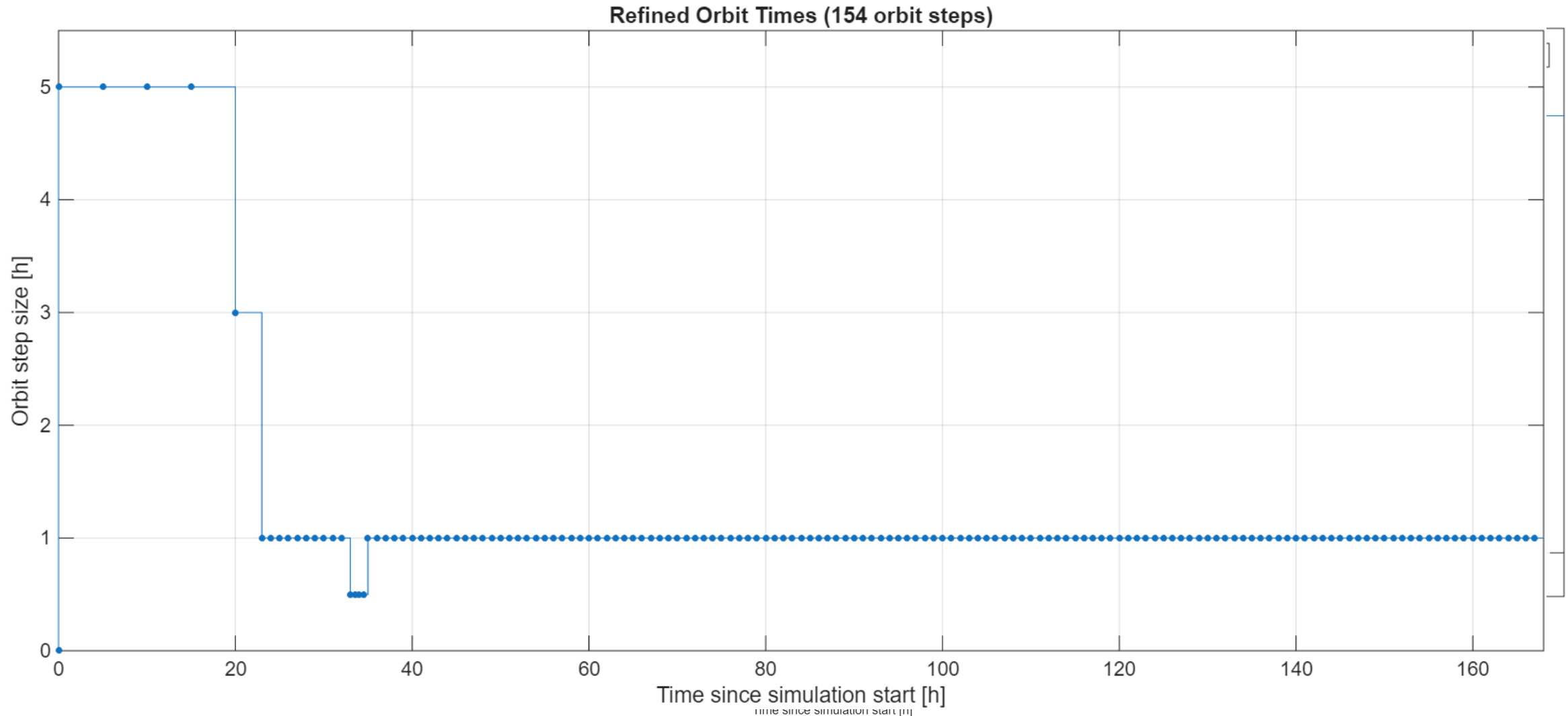
Mission Path



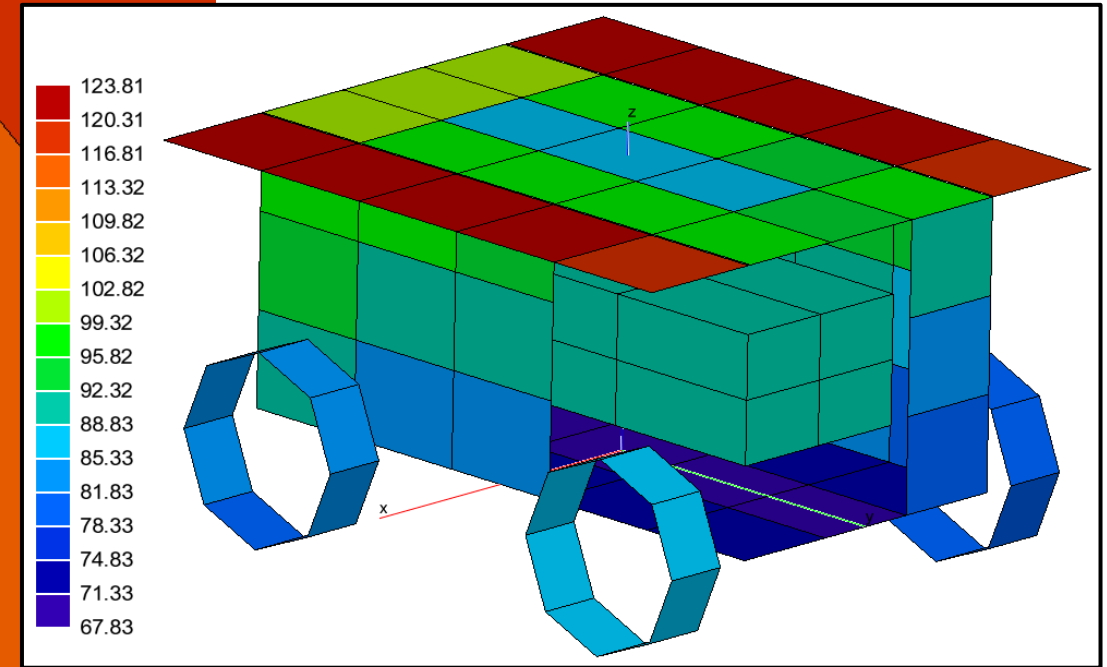
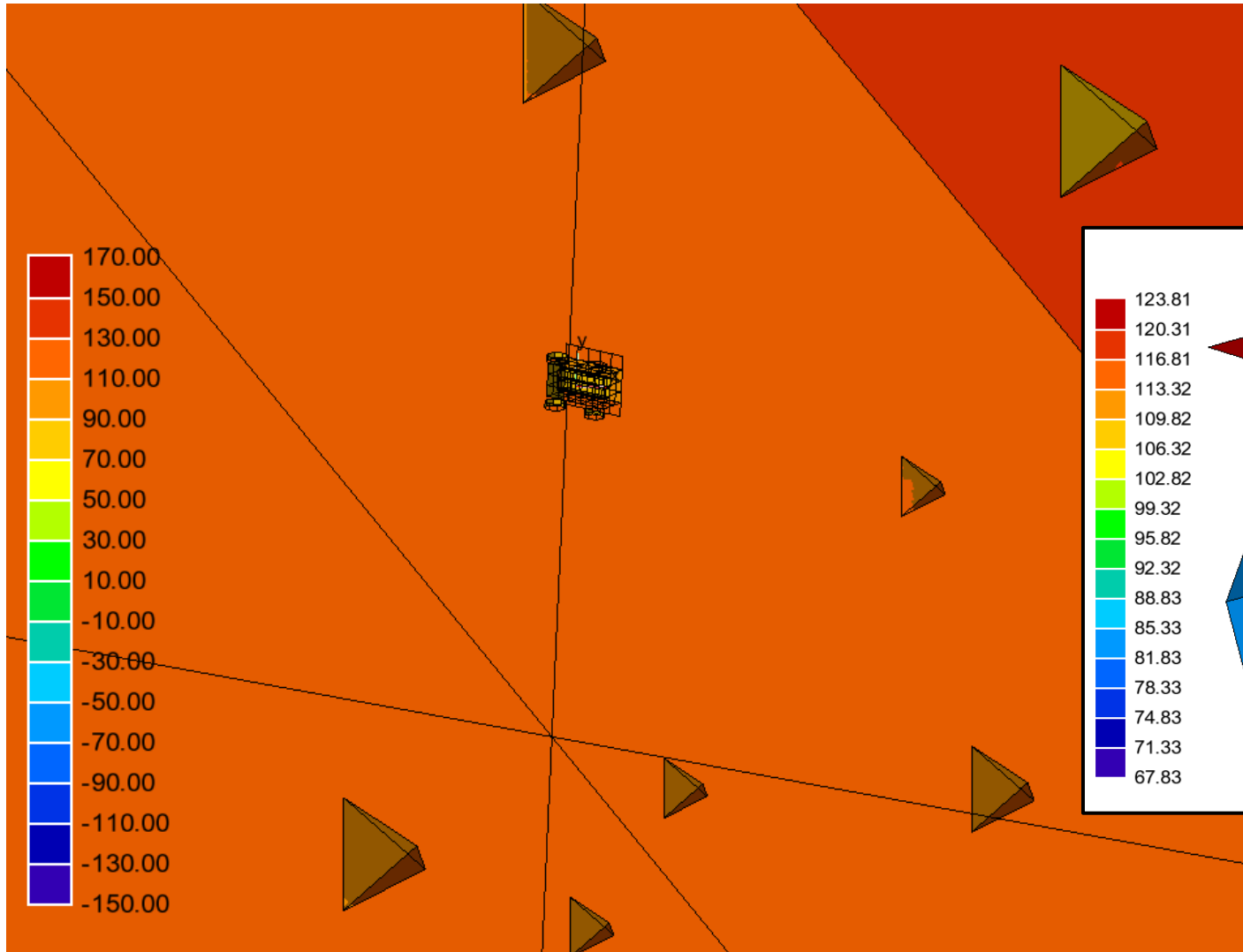
Complete Simulation



Complete Simulation



Complete Simulation



Problems we ran into

- Monte-Carlo ray tracer used an unseeded RNG -> node IDs at locations not reproducible
- Visibility domain: Convex-hull horizon also meshes hidden terrain (intended, as a shadow and IR source). But: Horizon sectors narrower than DEM pixels -> dense, regular mesh of hidden terrain far out
- Overlapping boulder zones -> Too many boulders at overlapping certain locations

Further Work

Vision: Assist surface missions with thermal predictions

- Of the actual lunar surrounding (at future waypoints)
- Of future thermal state of a rover
 - ➡ pathfinding & path optimization

- Introduction of local topographic features from rover vision data
- Thermal Watchdog
- Integration into pathfinding

Publication currently pending. GIT access on request.

A thermal simulation environment for moving objects on the lunar surface

Questions? Opinions?

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