HLS

Lunar Surface Crater Thermal Effects on Lander Radiator Performance

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Study Purpose

<u>Problem Statement:</u> Lunar surface craters smaller than the spatial resolution of surface meshes used in typical Lunar surface thermal models (10 to 60 meters per pixel) may impact the accuracy of thermal model extrema predictions.

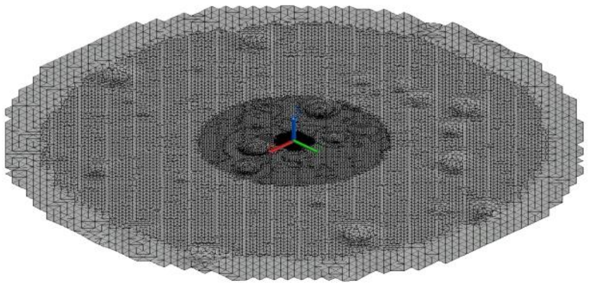
<u>Study Goal:</u> Investigate the thermal sensitivity of representative lander systems with realistic thermal surface orientations in bare and cratered terrain environments at relevant Artemis mission locations

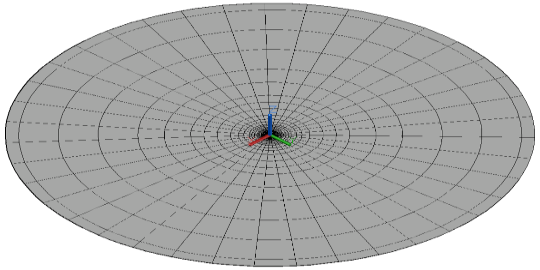
<u>Summary:</u> This thermal analysis task investigates the impact of lunar surface craters on lander radiator performance by comparing heat rejection capability results between bare and cratered terrain environments. This study examines external body-mounted lander radiator thermal performance across varying lander heights (5.5m, 20m, 50m) and radiator orientations (horizontal, 45º tilted, and vertical) at two representative Artemis mission latitudes (-89.5ºS and -82.5ºS), spanning from the Shackleton Connecting Ridge to Mons Mouton Plateau.

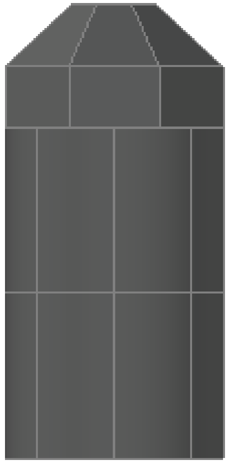
Model Overview

- **Analyzed 12 total cases;** 2 latitudes x 3 lander heights x 2 ground plane types
  - Latitudes = -89.5ºS, -82.5ºS
    - Range of Artemis sites (Shackleton Ridge to Mons Mouton Plateau)
  - Lander heights = 5.5m, 20m, 50m
  - Flat terrain with craters and without craters
- **Height variable reduced order lander model with three radiator orientations**
  - Representative of existing vehicles in terms of height, optical properties, external surface temperatures, and radiator placement
- **Assumptions:**
  - Assessing only body mounted radiators (single-sided)
  - Not including thermal impacts from far field terrain (mountains, valleys, etc.)[1,2]
  - Max crater diameter of 50m adjacent to landing origin
  - Lander is not placed within a crater

Submodel	Nodes
CRATER_SURFACE	22183
FLAT_SURFACE	1444
RADIATOR_HORIZONTAL	2
RADIATOR_TILTED	16
RADIATOR_VERTICAL	16
STRUCTURE	26


CRATER_SURFACE


FLAT_SURFACE

RADIATOR_HORIZONTAL
RADIATOR_TILTED
RADIATOR_VERTICAL

STRUCTURE

Versions: Thermal Desktop = 6.3 Patch 27, Model = Crater_v1e_WJG

Lunar Thermal Environment

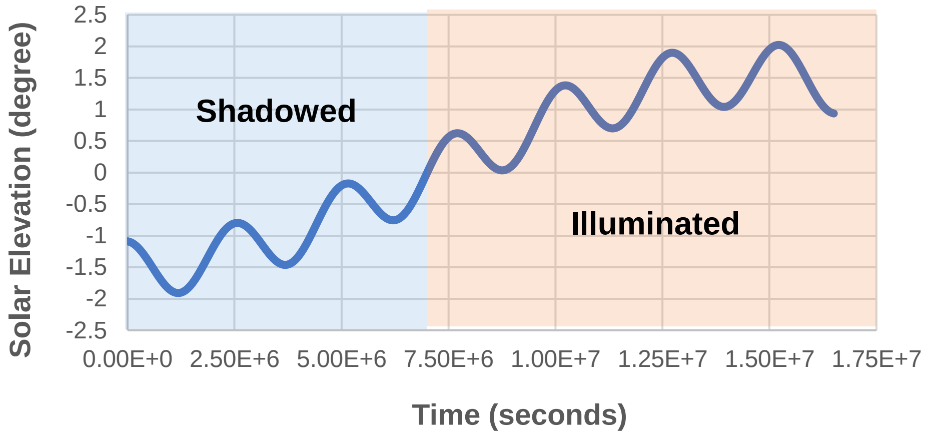
(applied identically for both crater and flat surface submodel runs)

- **Lunar environment defined using the Human Landing System (HLS) Lunar Thermal Analysis Guidebook (LTAG), Design Specification for Natural Environments (DSNE), and JPL Horizons data [3,4,5]**
  - Subsurface layers initialized via 10-year model run[3]
  - Time varying and location dependent solar vector paths[5]
    - Transient runs capture shadowed and illuminated periods
  - Constant worst case hot solar flux of 1415 W/m²
  - Solar diameter (subtended) angle (0.53º)[3]
  - Surface IR emissivity[6] and solar absorptivity[7]
    - Highland directional α_s (polar)[7] (angle dependent)
  - Surface density[8,9] and specific heat[10] (depth dependent)
  - Surface thermal conductivity (depth & temperature dependent)[9]

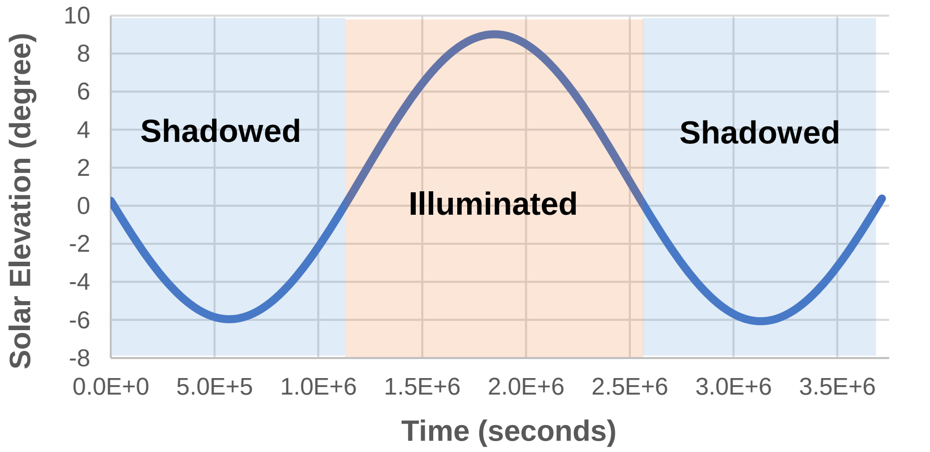
- **Selected candidate Artemis landing site latitudes**
  - -89.5ºS, Initializer (6/1/16 to 6/1/26), Transient (6/1/26 to 12/9/26)
  - -82.5ºS, Initializer (11/3/16 to 11/3/26), Transient (11/3/26 to 12/16/26)

- **Not included in thermal model**
  - Subsurface ground heat flow (~0.018 W/m²)[11]
  - Impacts from regolith dust deposition onto external surfaces
  - Thermal impacts from far field terrain
  - Earthshine (0 to 0.15 W/m²) and eclipses (~hours)[3]

-89.5ºS Case, Solar Transient

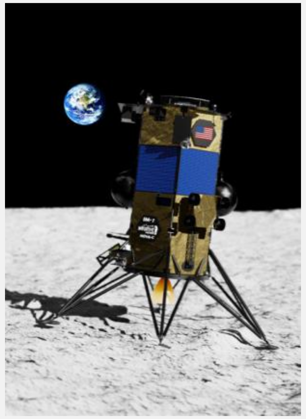


-82.5ºS Case, Solar Transient



Lunar Lander Survey

- **Historical, currently available, and in-development Lunar landers vary in design, size (height), and employ different radiator surface placements and orientations**
  - Three representative lander heights and radiator orientations were selected for inclusion in this study
    - *Lander heights = 5.5m, 20m, 50m; radiator orientations = horizontal, 45º tilted, and vertical*

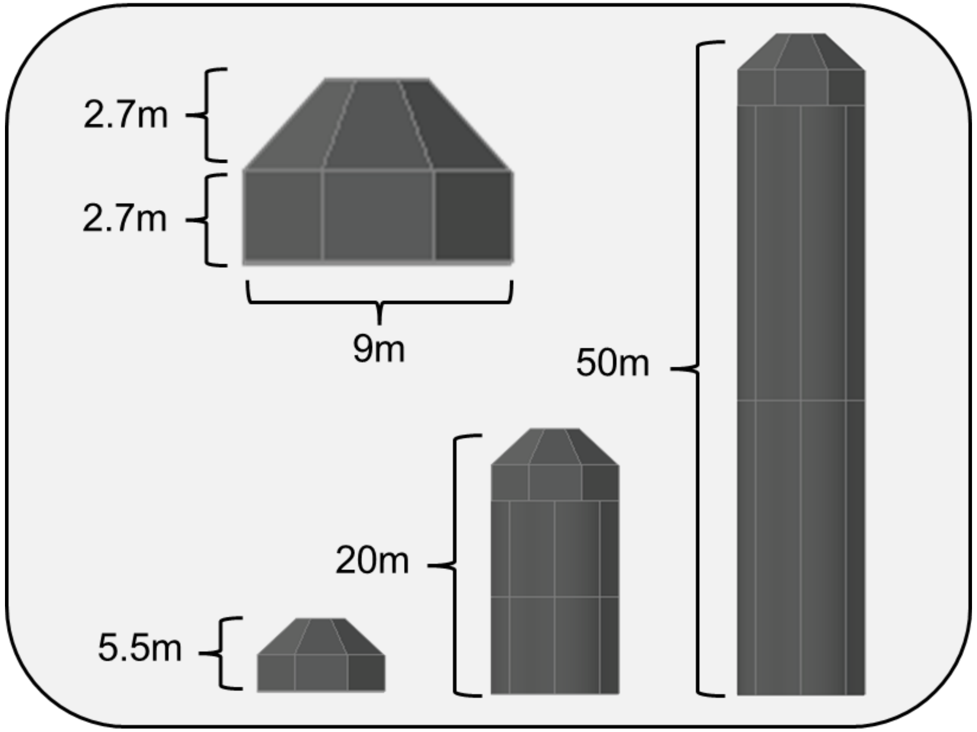
Firefly Blue Ghost[12]	**Intuitive Mach. NOVA-C[13]**	**Apollo LEM[14]**	**Blue Origin Mk1[15]**	**Blue Origin Mk2[16]**	**SpaceX Starship[16]**
Height: ~2m	**~4m**	**~7m**	**~8m**	**~15m**	**~50m**
					

[12] "Fireflyspace.com, 2025. https://fireflyspace.com/wp-content/uploads/2025/01/BGM1-Component-Graphic-vJan14-2025a.png, [13] "NOVA-C | Intuitive Machines," Intuitive Machines, 2024. https://www.intuitivemachines.com/nova-c, [14] "NASA's Apollo 11 Lunar Module (Basic Facts)," Apollo11Space, Dec. 08, 2019. https://apollo11space.com/nasas-apollo-11-lunar-module-basic-facts/, [15] Wikipedia Contributors, "Blue Moon (spacecraft)," Wikipedia, Nov. 21, 2025., [16] Astralytical, "SpaceX's Starship vs Blue Origin's Blue Moon: Who's landing first?," Substack.com, Mar. 18, 2024. https://astralytical.substack.com/p/spacexs-starship-vs-blue-origins (accessed Nov. 29, 2025).

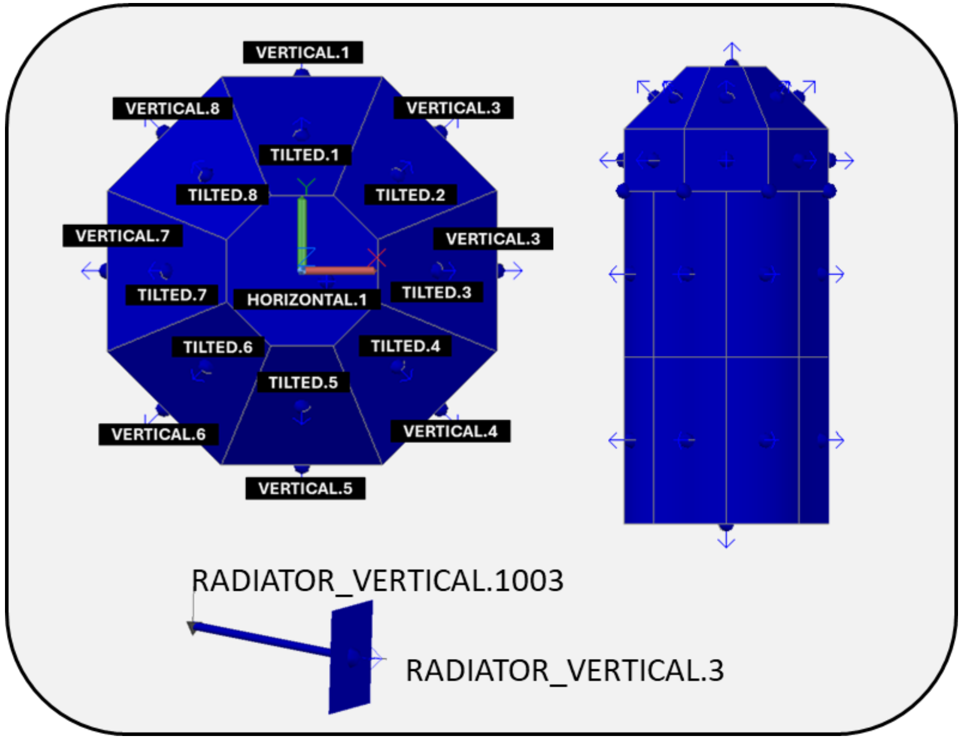
Lander Submodel

- ***Analyzed three** lander heights (5.5m, 20m, 50m)* **and** *radiator orientations (horizontal, 45º tilted, and vertical)***
- **Reduced order lander model with diffusion node surfaces connected to boundary nodes via conductors**
  - Radiator temperature set at 283K (10ºC) and structure temperature set at 293 K (20ºC)
  - Material set as Al 6061-T6 with all surfaces covered in Z93 (0.16 solar absorptivity, 0.92 IR emissivity)
  - Each radiator surface has an external surface area of $10m^2$

Lander Dimensions



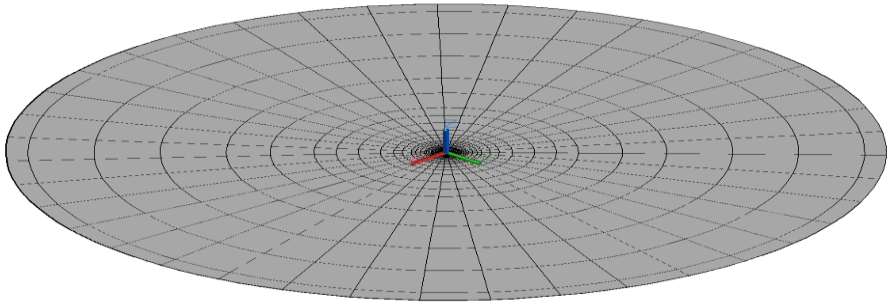
Radiator Node Map & Conductor Diagram



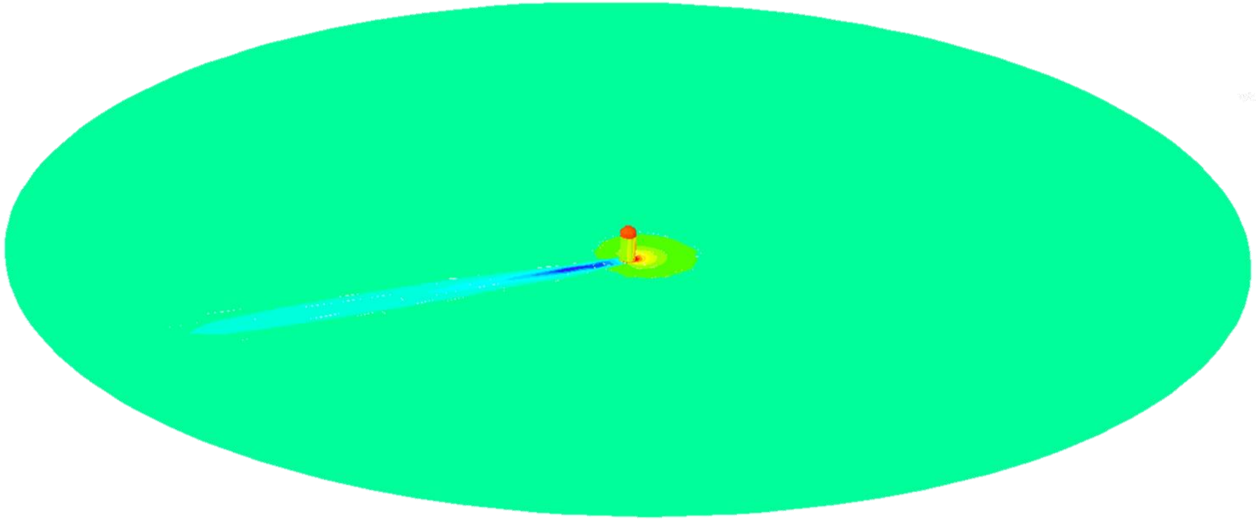
Flat Surface Submodel

- **Used section 9.3.1.3 “radiant energy: cylinder to ground plane exchange” from the LTAG to size the flat ground plane[3]**
  - Origin ground slope = 0º
  - Max Lander height = 50m
  - Lander radius = 4.5m
  - Surface radius = 325m

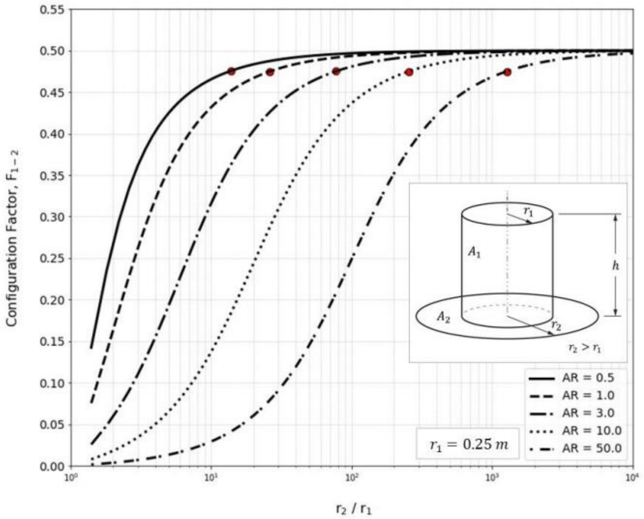
Flat Surface Element



Flat Surface Thermal Result Timestep*



LTAG Section 9.3.1.3[3]



$$(r_2/r_1)_{\Delta 5\%} \cong 12.63(AR) + 0.943$$

*visual only, temperature color scale not provided

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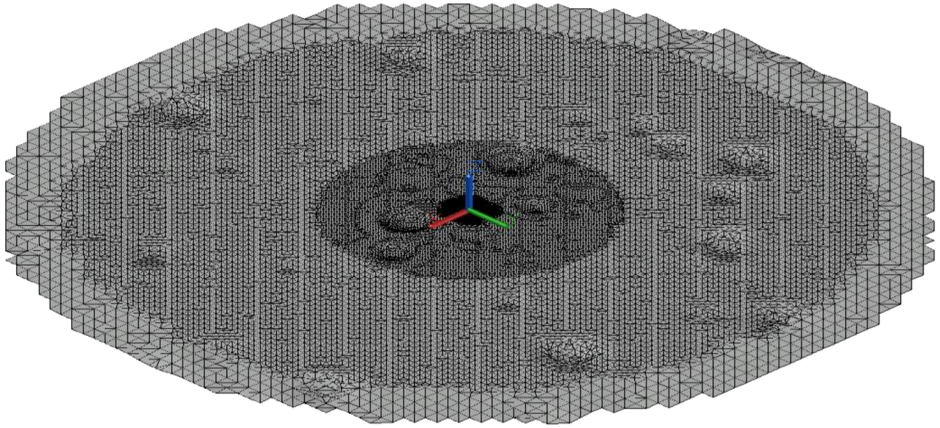
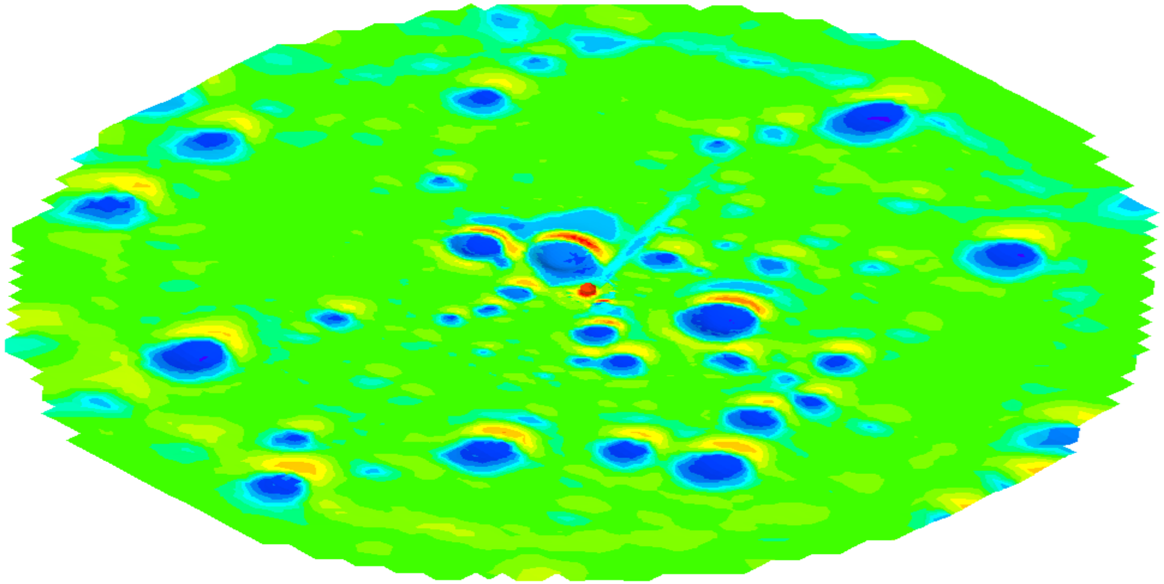
Crater Surface Submodel

- **Generated a flat surface mesh with a crater distribution**
  - Origin ground slope = ~1.5º (varies)
    - Influenced by small craters from synthcrater
  - Max crater diameter at surveyed Artemis candidate sites = 50m
  - Radius = 325m

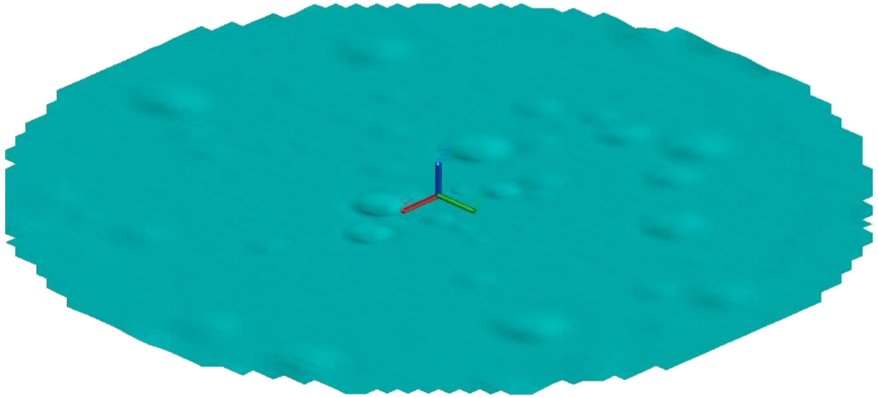
Crater Surface Mesh View



Crater Surface Thermal Result Timestep*



Crater Surface Shaded View



*visual only, temperature color scale not provided

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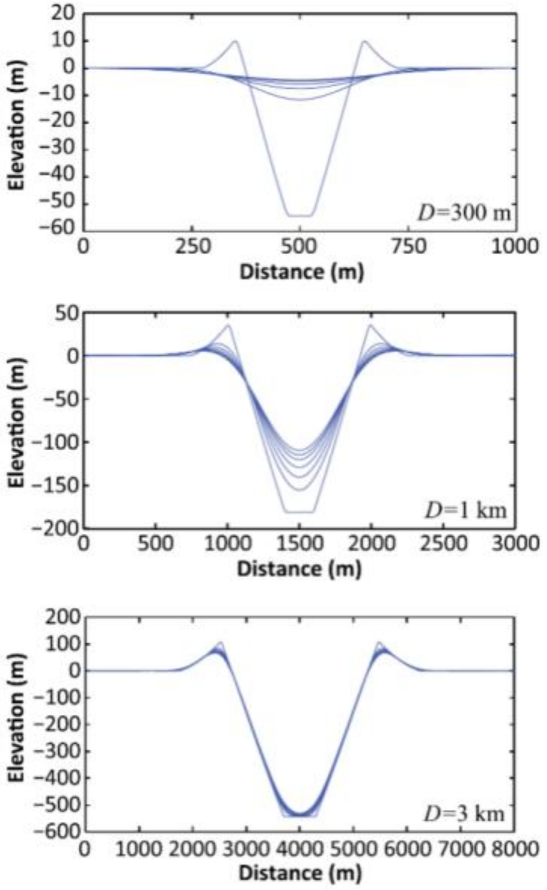
Synthetic Crater Distribution Generation

- **Utilized a Lunar Navigation Maps (LuNaMaps) project developed program that generates synthetic crater populations and places them onto a flat point cloud[17-19]**
- The synthcrater program generates craters with realistic diameters, depths, and ages as specified in planetary science literature and NASA's DSNE
  - Craters are embedded in "age order," and each new crater impact considers the previous topography so any coincident or overlapping crater will alter the topography of the underlying crater and terrain

Progressive Crater Degradation[19]



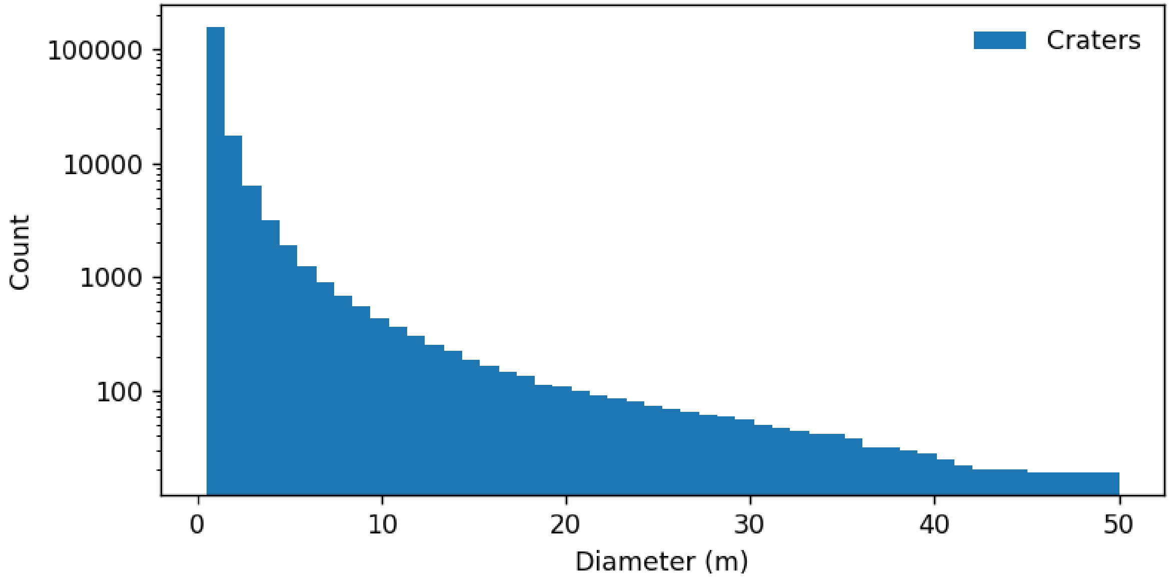
DSNE Crater Distribution Characteristics[4,19]

	Freshest Craters		Degraded Craters		
Fraction of population	0.5%	2.5%	17%	30%	50%
Crater Characteristics	Very steep slopes, pronounced blocks, ejecta, optically immature	Steep slopes, blocks common	Moderate slopes, most blocks on rim	Gentle slopes, rim mostly eroded	Very gentle slopes, no rim
Typical depth/diameter ratio	0.12-0.2+	0.12-0.2	0.1-0.15	0.07-0.1	<0.07
Max. Wall Slope	35°+	25-35°	15-25°	10-15°	<10°

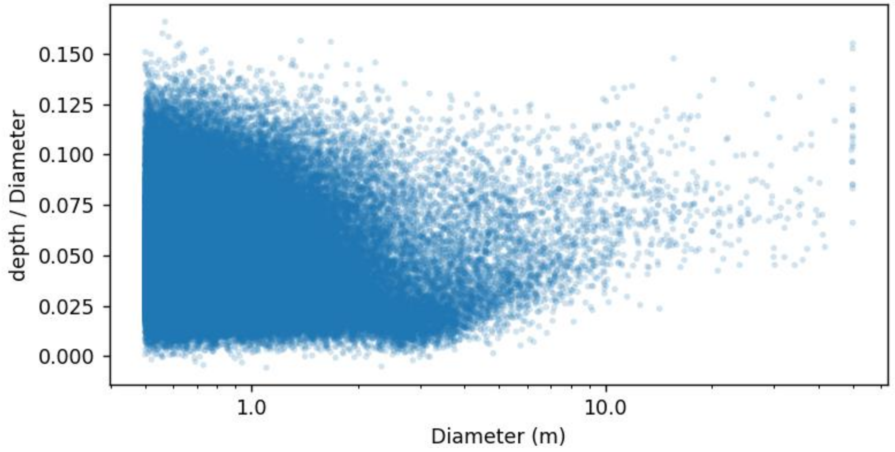
Crater Distribution Results

- **Synthcrater Input Parameters:**
  - Max crater diameter = 50m
    - Based on inspection of craters inside candidate Artemis landing sites
  - Min crater diameter = 0.5m
  - Point cloud size = 700m x 700m

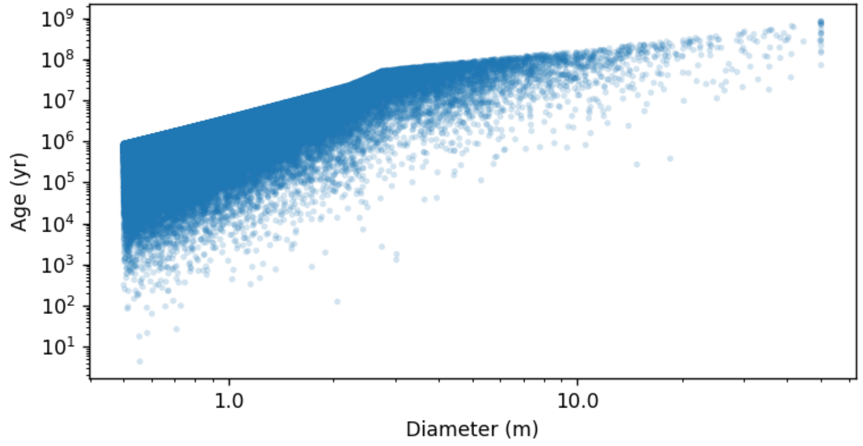
Crater Diameter vs Count



Crater Diameter vs Depth/Diameter



Crater Diameter vs Age



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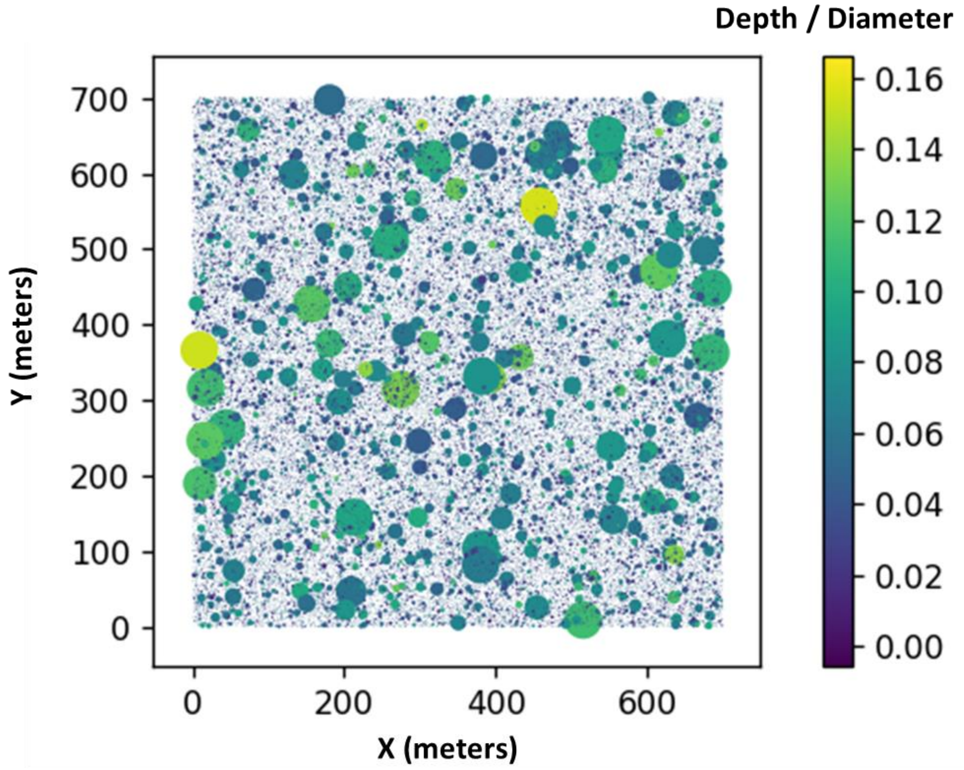
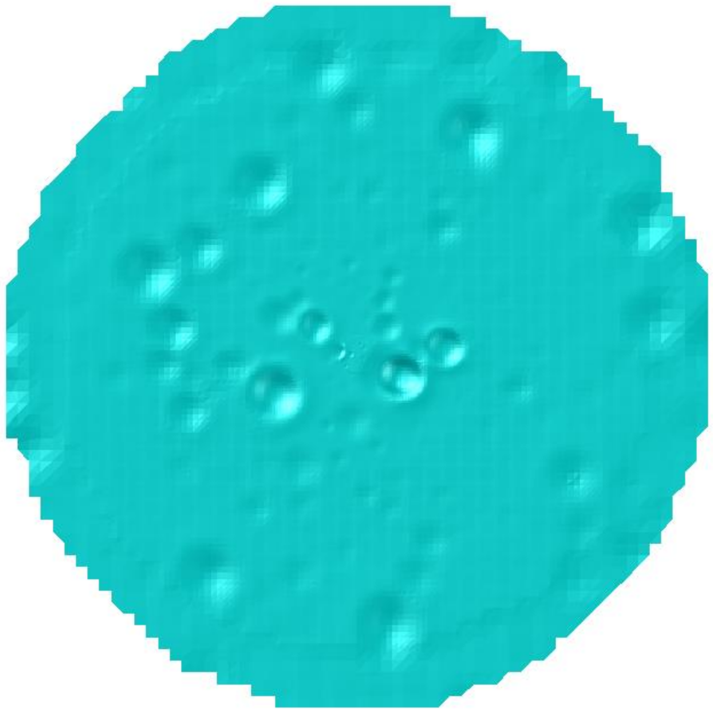
Resulting Crater Spatial Data

- **Used Lunar terrain meshing process to convert synthcrater point cloud to a reduced mesh usable by Thermal Desktop**
  - ~0.5 meter per pixel resolution within 15 m from origin, progressively less spatial resolution beyond origin to reduce node count

Synthcrater Point Cloud

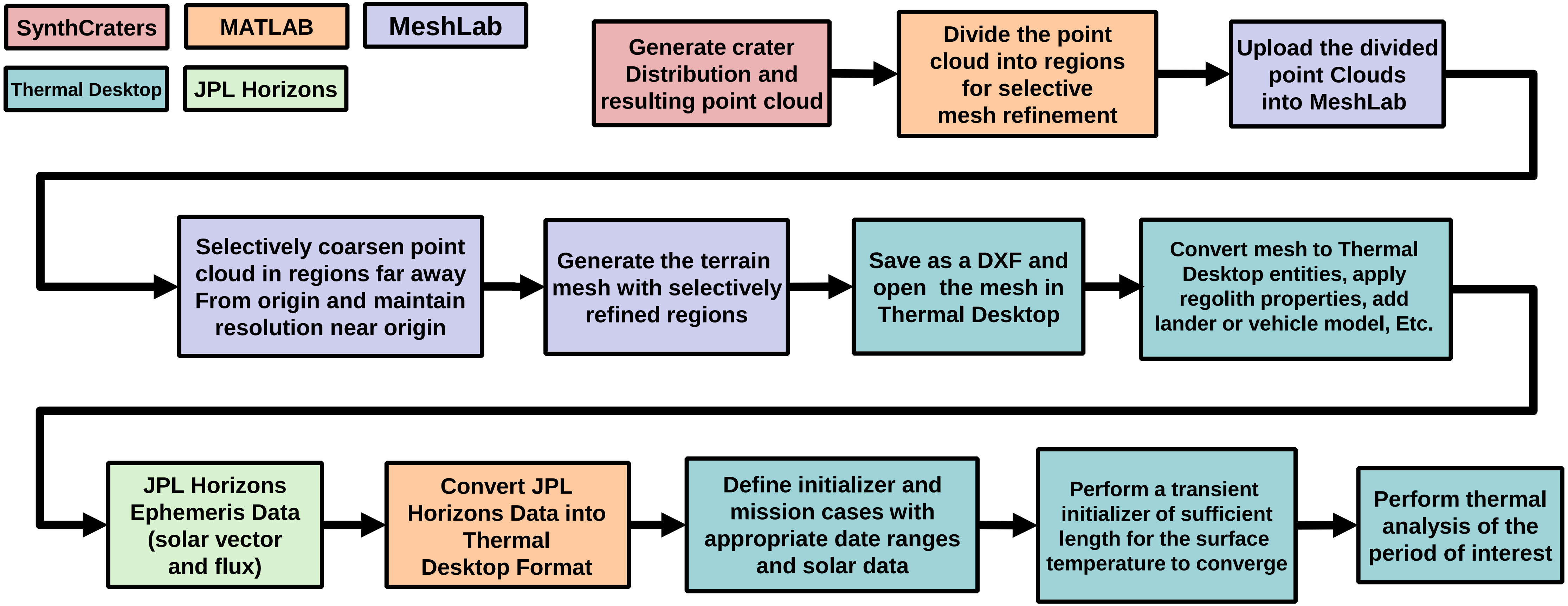


Reduced Mesh, Shaded View



Terrain Modeling Process Overview

- The process below is a modified version of what was developed for revision 2 of the HLS LTAG



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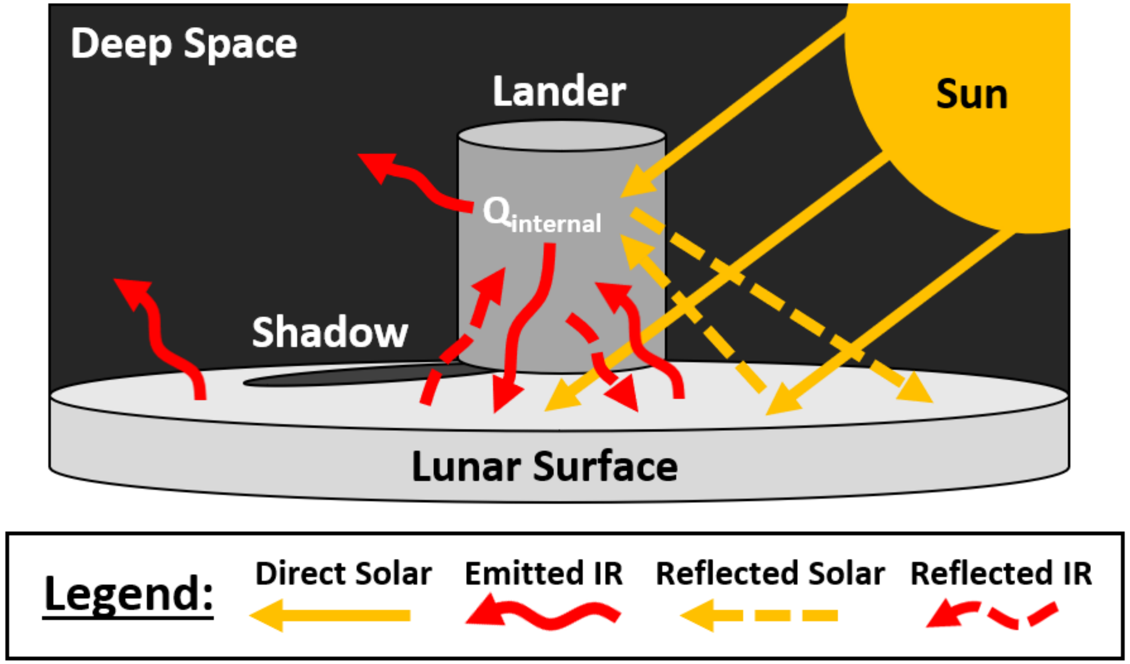
Results: QFLOW Query

- **Used Thermal Desktop post processing feature QFLOW to query the heat flow from the radiator surfaces to the environment**
- To capture the environmental heating rates incident upon the radiator surfaces in the QFLOW calculations, the input is *from* the internal boundary node *to* the accompanying radiator surface diffusion node
  - Boundary nodes are set at a constant temperature (283 K) and are connected to the radiator surface diffusion nodes via a high conductance conductor (10,000 W/K)

Thermal Radiation Exchange



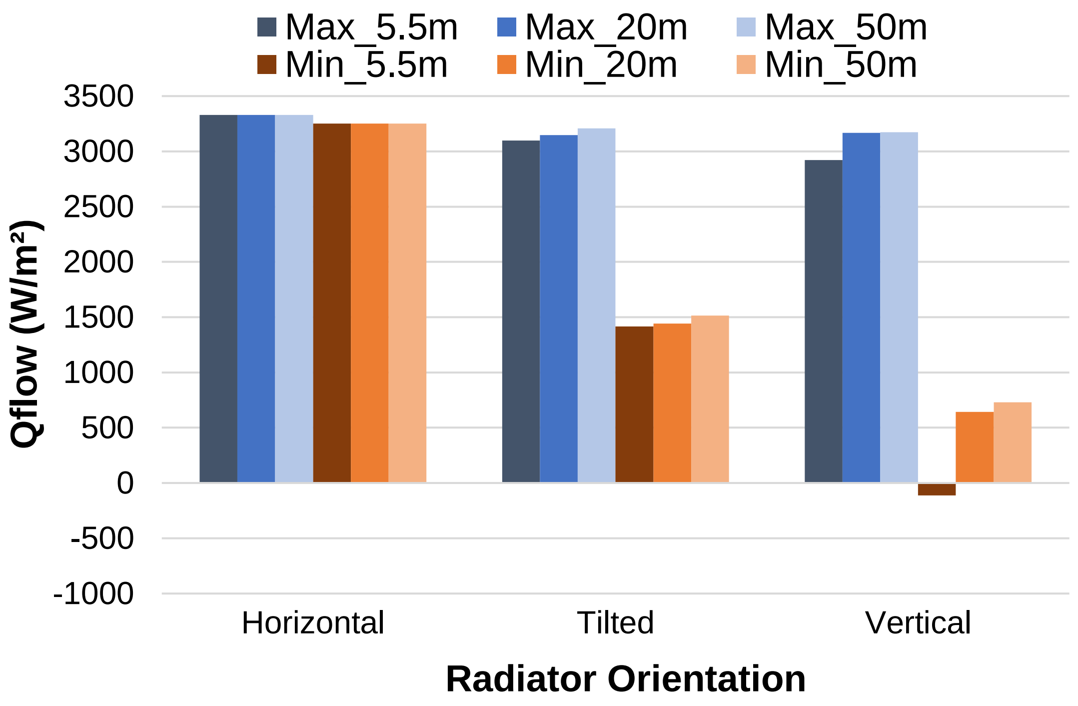
Radiator Nodal Associations

Diffusion Node	Boundary Node
RADIATOR_HORIZONTAL.1	RADIATOR_HORIZONTAL.1000
RADIATOR_TILTED.1	RADIATOR_TILTED.1001
RADIATOR_TILTED.2	RADIATOR_TILTED.1002
RADIATOR_TILTED.3	RADIATOR_TILTED.1003
RADIATOR_TILTED.4	RADIATOR_TILTED.1004
RADIATOR_TILTED.5	RADIATOR_TILTED.1005
RADIATOR_TILTED.6	RADIATOR_TILTED.1006
RADIATOR_TILTED.7	RADIATOR_TILTED.1007
RADIATOR_TILTED.8	RADIATOR_TILTED.1008
RADIATOR_VERTICAL.1	RADIATOR_VERTICAL.1001
RADIATOR_VERTICAL.2	RADIATOR_VERTICAL.1002
RADIATOR_VERTICAL.3	RADIATOR_VERTICAL.1003
RADIATOR_VERTICAL.4	RADIATOR_VERTICAL.1004
RADIATOR_VERTICAL.5	RADIATOR_VERTICAL.1005
RADIATOR_VERTICAL.6	RADIATOR_VERTICAL.1006
RADIATOR_VERTICAL.7	RADIATOR_VERTICAL.1007
RADIATOR_VERTICAL.8	RADIATOR_VERTICAL.1008

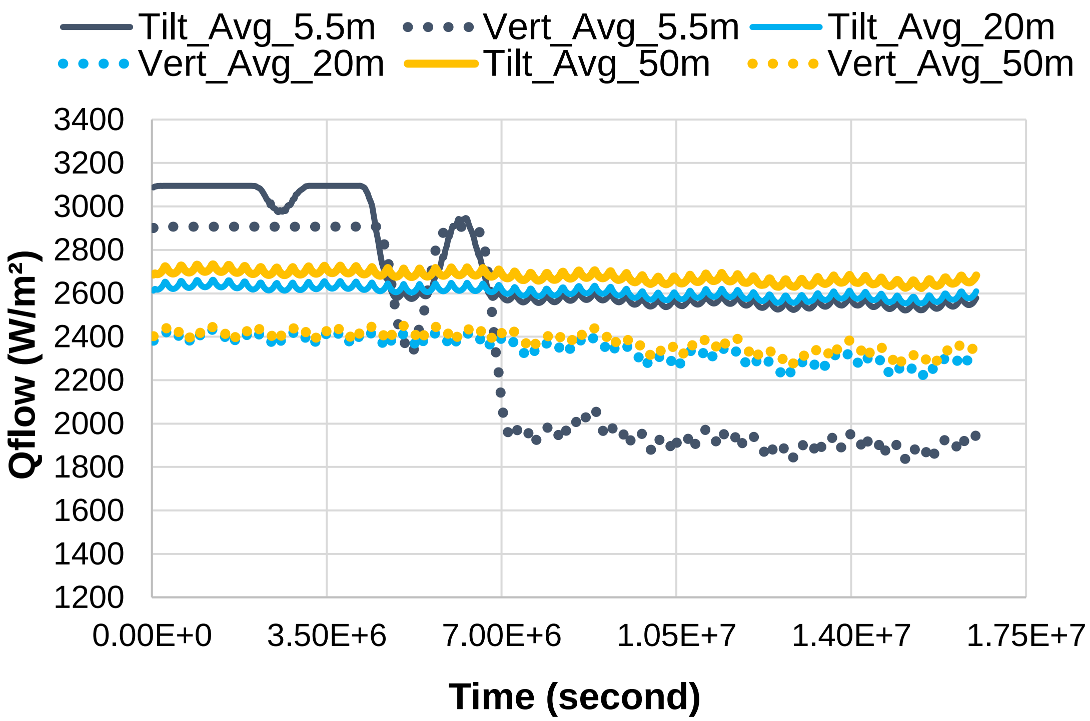
Results: -89.5ºS Flat Surface

- **Heat rejection capability trend: *Horizontal > Tilted > Vertical and 50m > 20m > 5.5m***
  - Radiator orientation impacts heat rejection capability much more than height from Lunar surface
  - Maximum and minimum heat rejection capability occurs during shadowed (night) and illuminated (day) periods respectively
  - Individual vertical radiators for a 5.5m lander height have periods (up to ~55 hours) of negative heat rejection capability

Max & Min Heat Rejection (single panel)

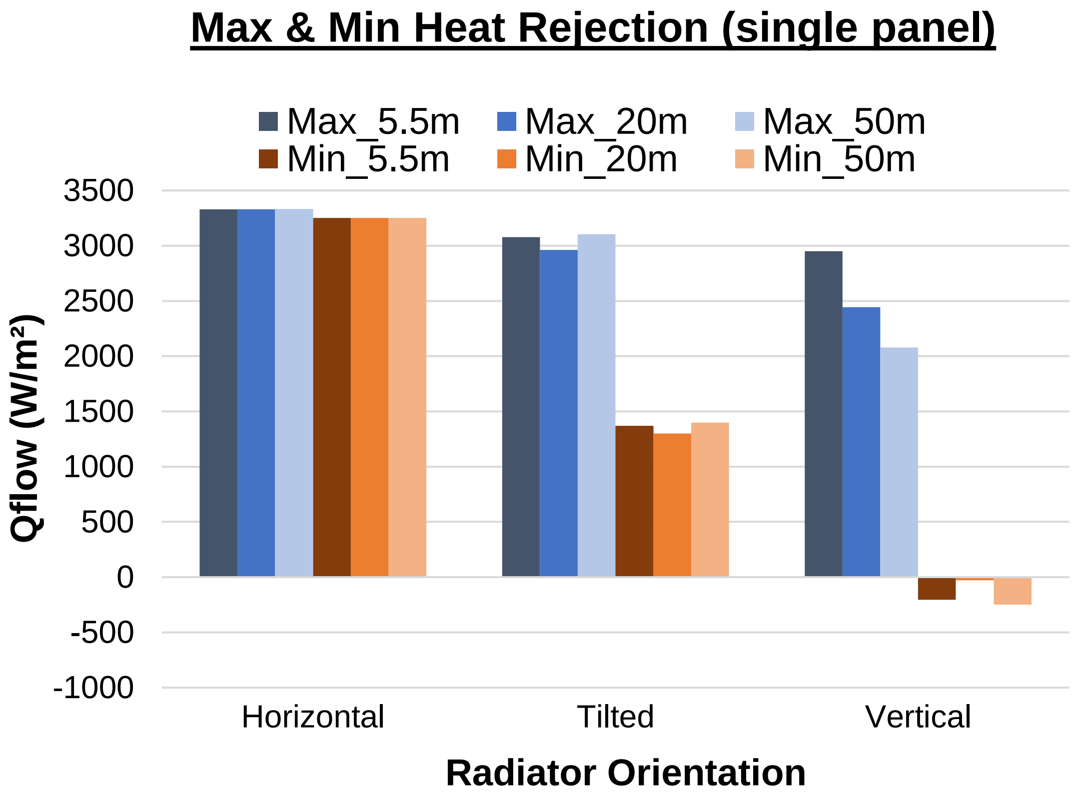


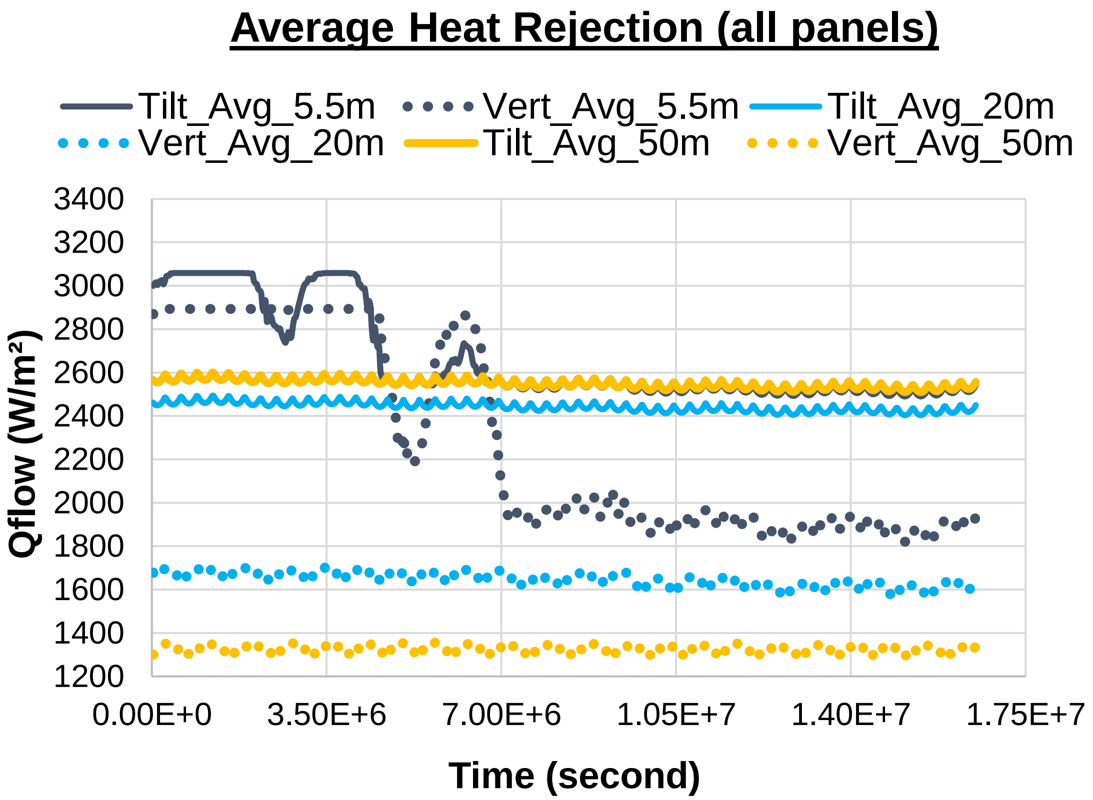
Average Heat Rejection (all panels)



Results: -89.5ºS Crater Surface

- **Heat rejection capability trend: *Horizontal > Tilted > Vertical, radiator orientation impacts dependent on view factor to craters***
  - Relative to -89.5ºS flat surface, titled and vertical radiators experience reduced heat rejection capability
  - Individual vertical radiators have periods (up to ~105 hours for 50m height) of negative heat rejection capability
  - Maximum heat rejection is significantly reduced for vertical radiators at 20m and 50m lander heights





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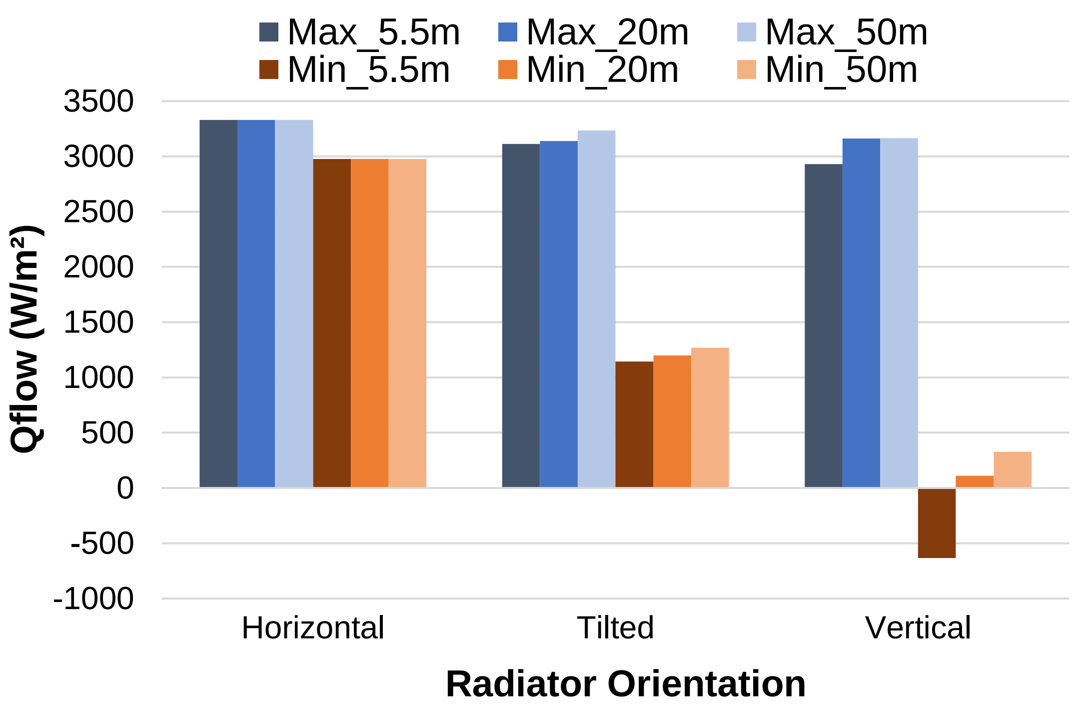
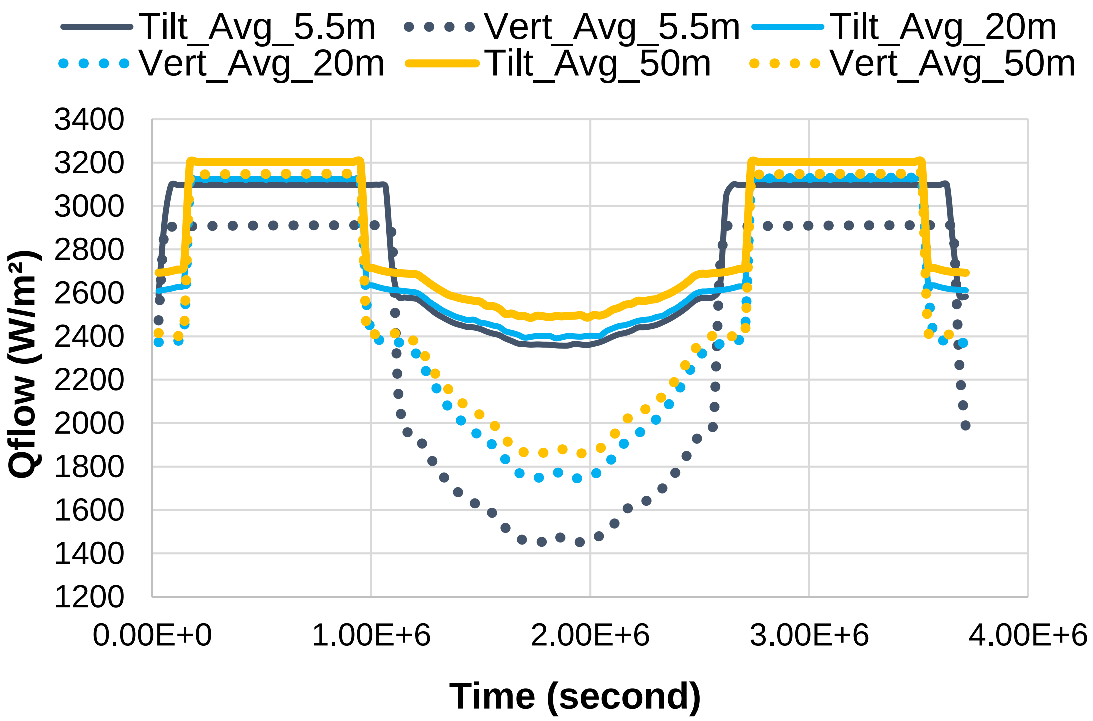
Results: -82.5ºS Flat Surface

- **Heat rejection capability trend: *Horizontal > Tilted > Vertical and 50m > 20m > 5.5m***
  - Heat rejection capability for -82.5ºS flat surface is less than -89.5ºS flat surface for all orientations and lander heights
  - Individual vertical radiators for a 5.5m lander height have periods (up to ~125 hours) of negative heat rejection capability

Max & Min Heat Rejection (single panel)



Average Heat Rejection (all panels)



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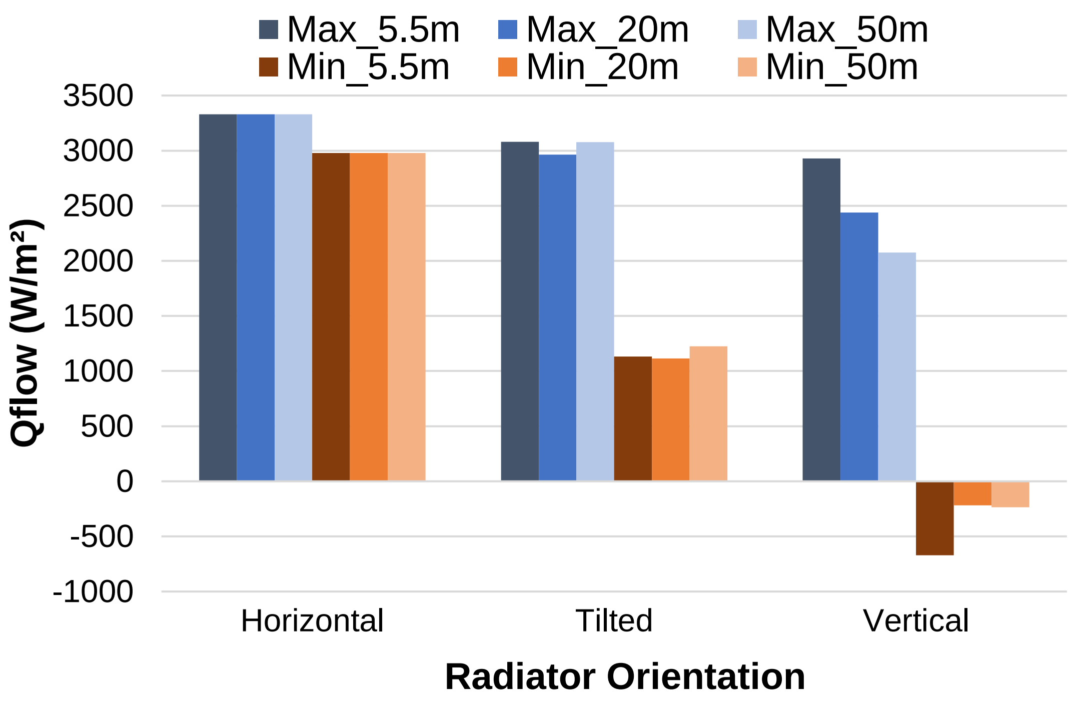
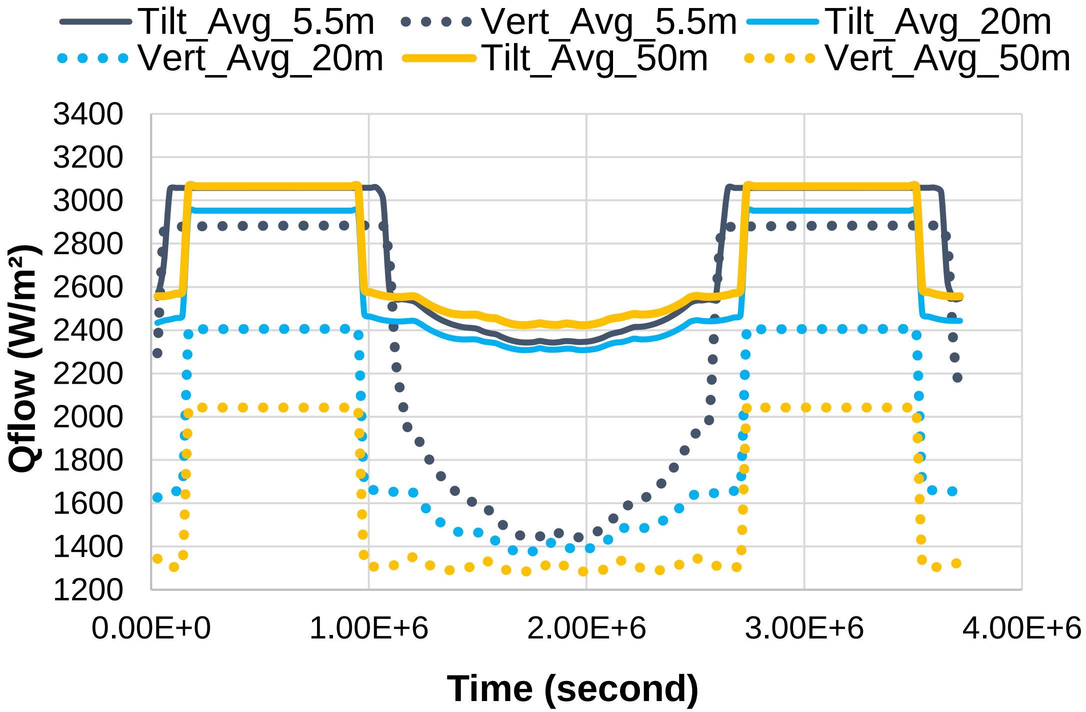
Results: -82.5ºS Crater Surface

- **Heat rejection capability trend: *Horizontal > Tilted > Vertical and 50m > 20m > 5.5m***
  - Relative to -82.5ºS flat surface, titled and vertical radiators experience reduced heat rejection capability
  - Individual vertical radiators have periods (up to ~125 hours for 5.5m height) of negative heat rejection capability
  - Maximum heat rejection is significantly reduced for vertical radiators at 20m and 50m lander heights

Max & Min Heat Rejection (single panel)



Average Heat Rejection (all panels)

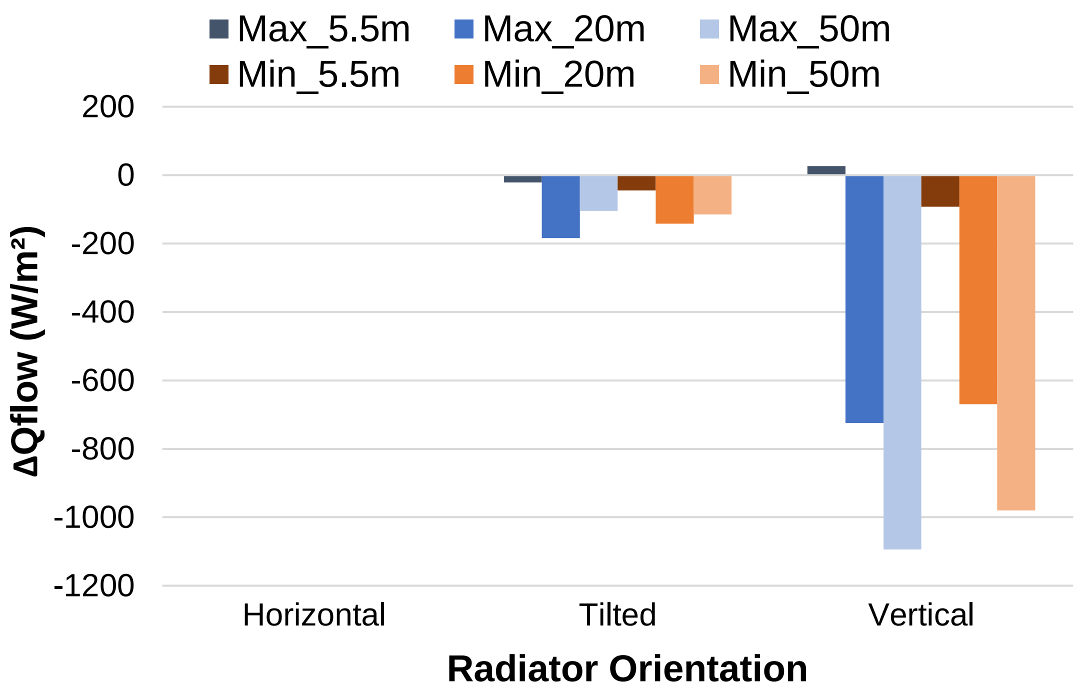


Comparison: -89.5ºS Flat vs Crater

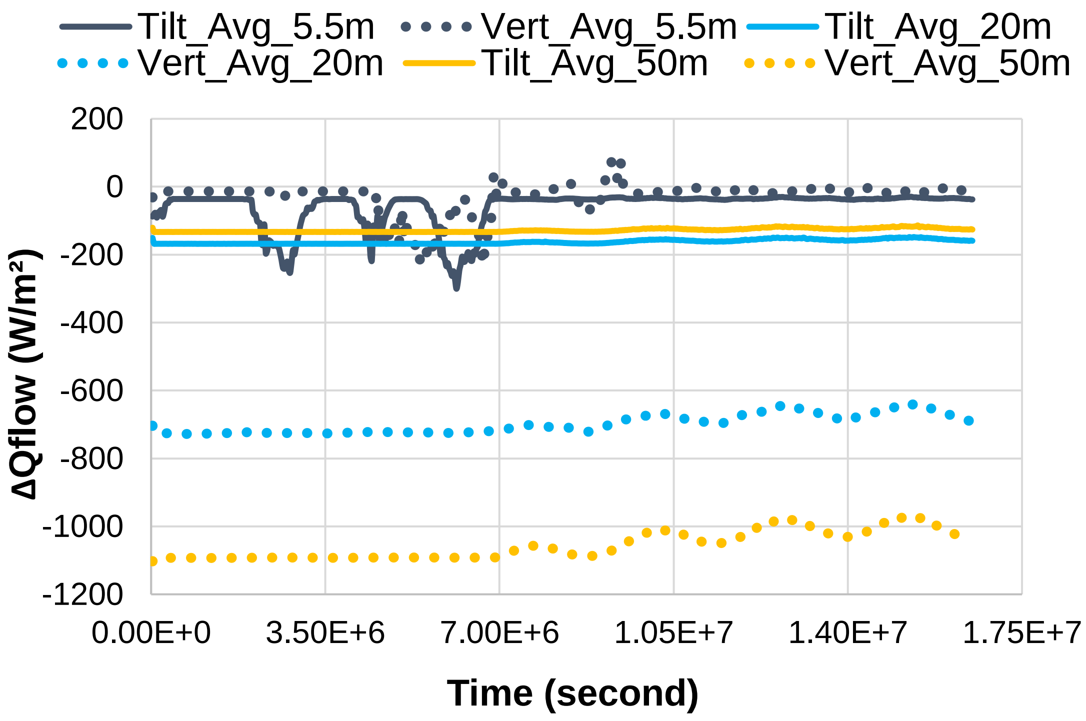
- Horizontal radiators are unaffected by craters and are the best orientation in terms of heat rejection capability
- Tilted radiators experience moderately reduced rejection capability, with 20m lander height being the worst case
- Vertical radiators experience significantly reduced rejection capability and performance degrades as lander height increases

$$\Delta Q_{flow} = Q_{flow_{crater}} - Q_{flow_{flat}}$$

Max & Min Heat Rejection (single panel)



Average Heat Rejection (all panels)

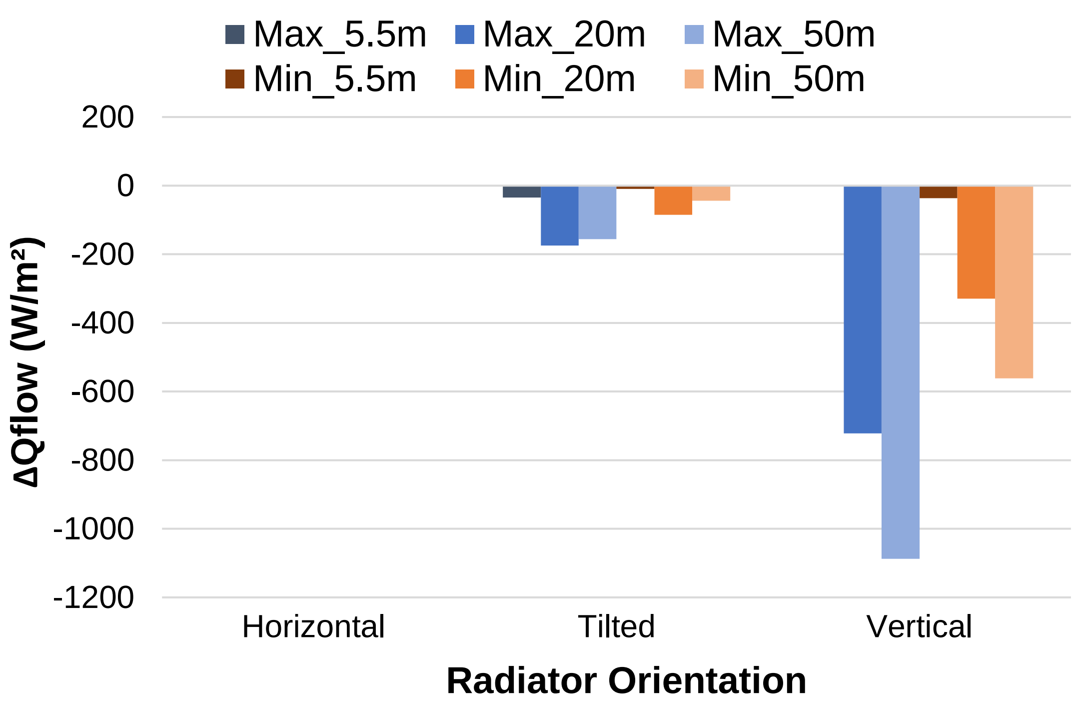


Comparison: -82.5ºS Flat vs Crater

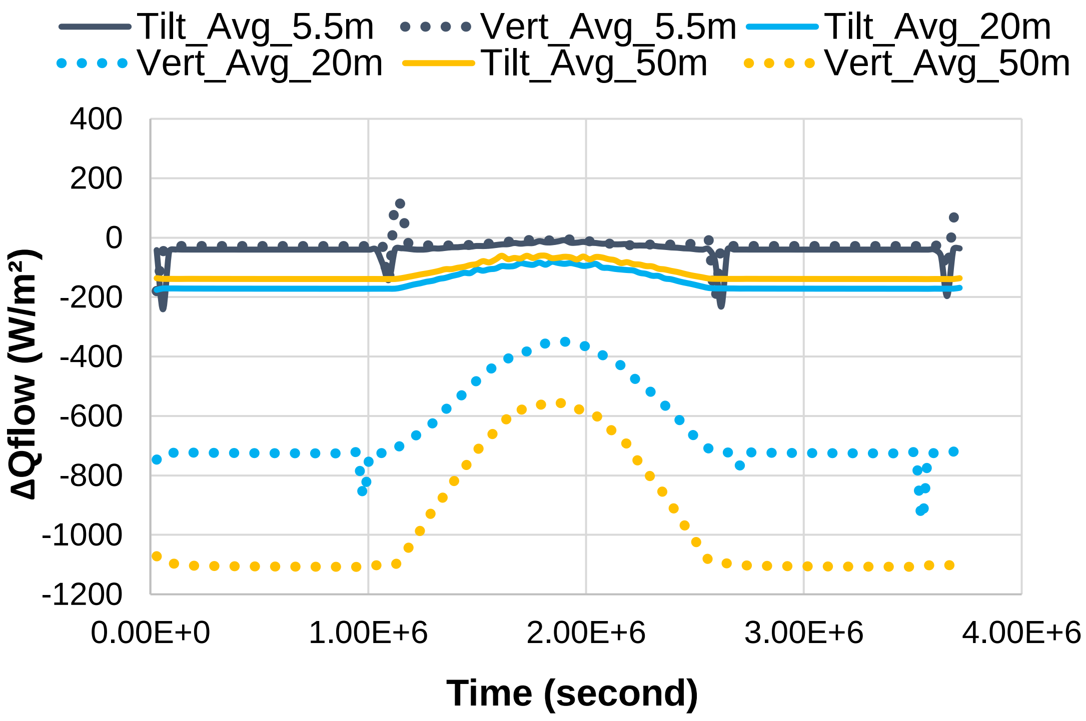
$$\Delta Q_{flow} = Q_{flow_{crater}} - Q_{flow_{flat}}$$

- Observed trends are similar to the -89.5ºS comparison case:
  - Horizontal radiators are unaffected by craters and are the best orientation in terms of heat rejection capability
  - Tilted radiators experience moderately reduced rejection capability, with 20m lander height being the worst case
  - Vertical radiators experience significantly reduced rejection capability and performance degrades as lander height increases
- Craters have less of an effect on performance in the worst-case hot environment when compared to -89.5ºS

Max & Min Heat Rejection (single panel)



Average Heat Rejection (all panels)



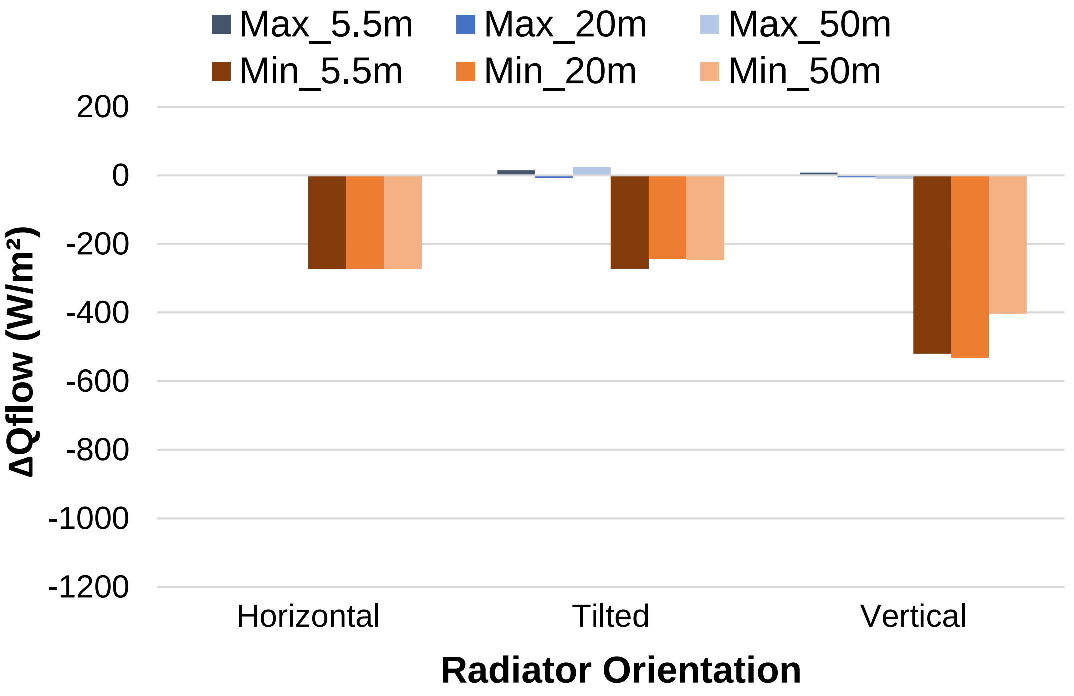
Comparison: -89.5ºS vs -82.5ºS

- Observed trends are similar between the compared cases:
  - Heat rejection capability degrades as latitude increases
- Changes in latitude result in less performance degradation when craters are included in the ground plane
  - Trend is more significant for tilted and vertical radiators

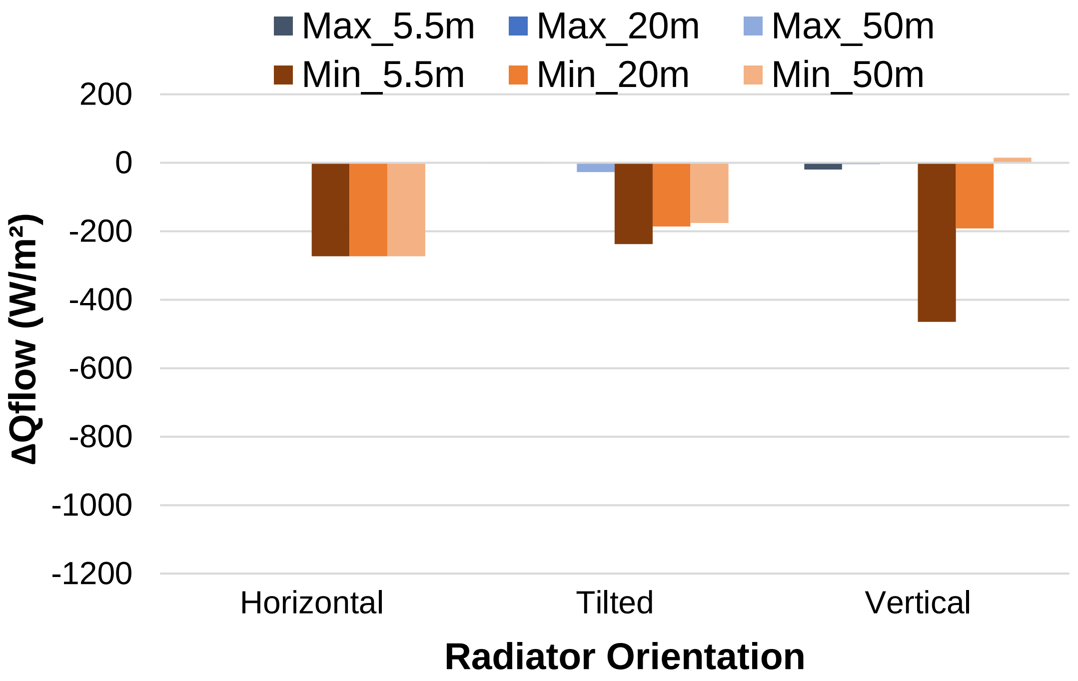
$$(1)\Delta Q_{flow} = Q_{flow-82.5°S\_flat} - Q_{flow-89.5°S\_flat}$$

$$(2)\Delta Q_{flow} = Q_{flow-82.5°S\_crater} - Q_{flow-89.5°S\_crater}$$

(1) Flat, Max & Min Heat Rejection (single panel)



(2) Crater, Max & Min Heat Rejection (single panel)



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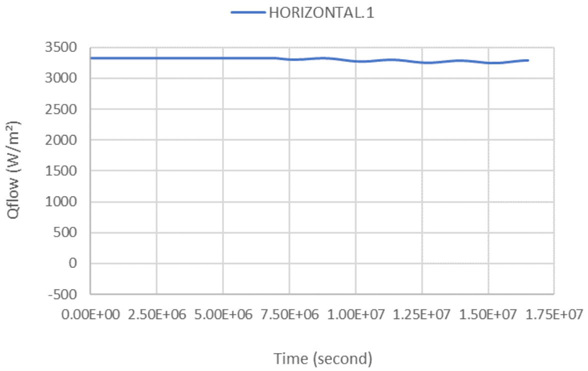
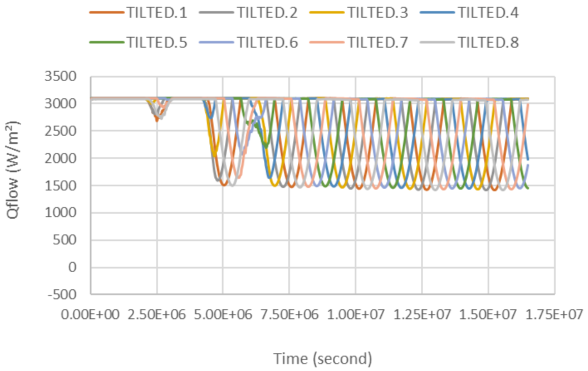
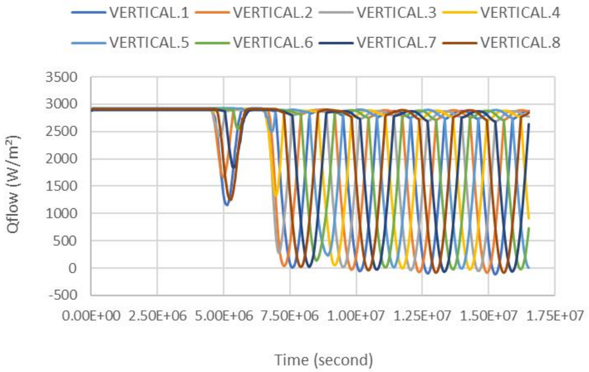
Transient: -89.5ºS Flat Surface

Lander Height (meter)

5.5 m







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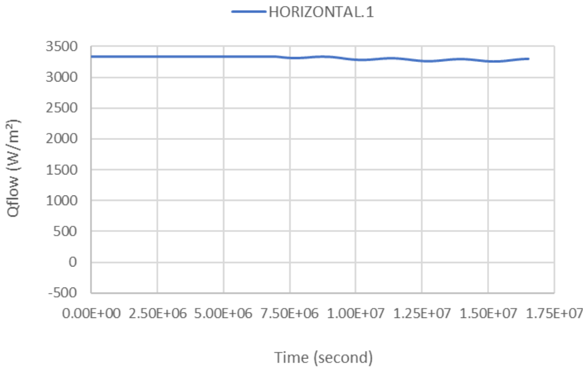

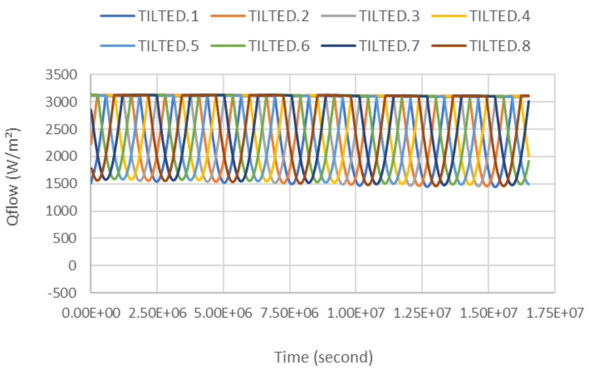

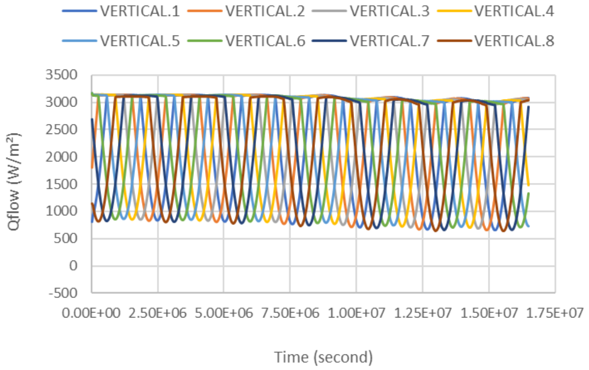

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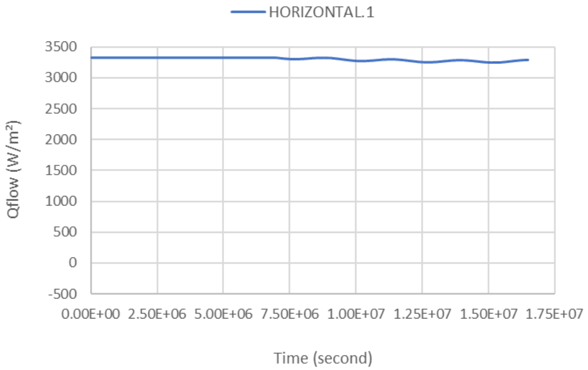
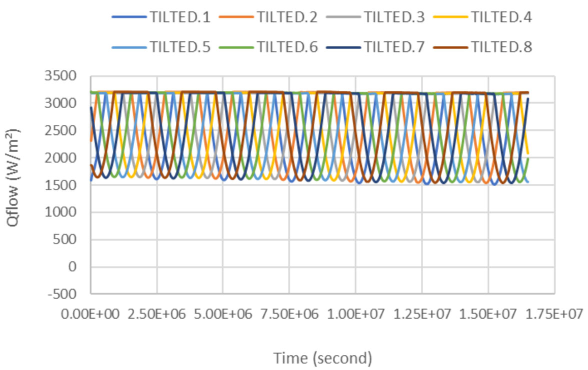
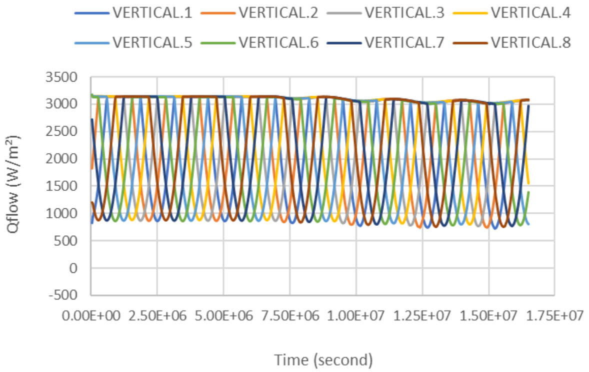


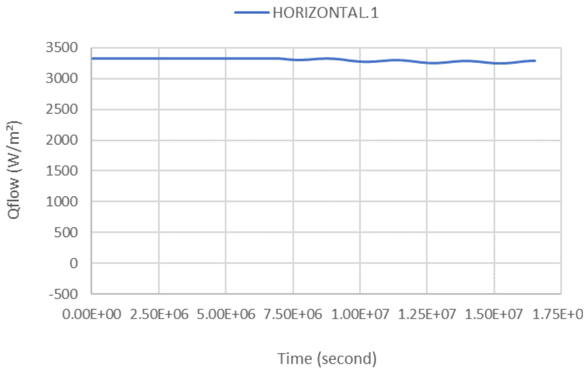


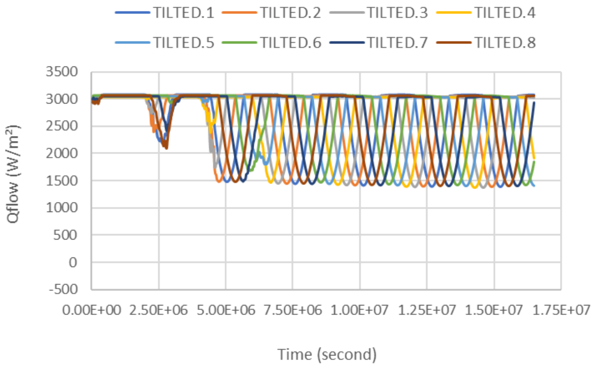


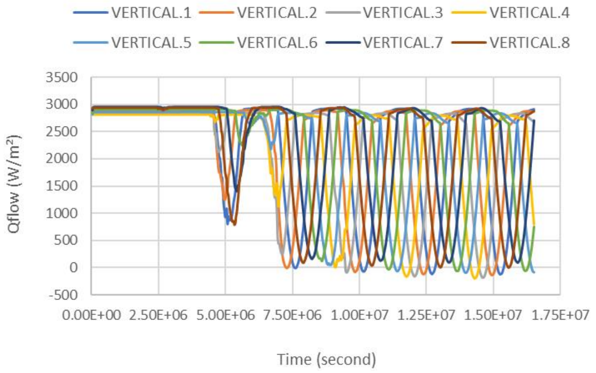
Transient: -89.5ºS Crater Surface

Lander Height (meter)

5.5 m







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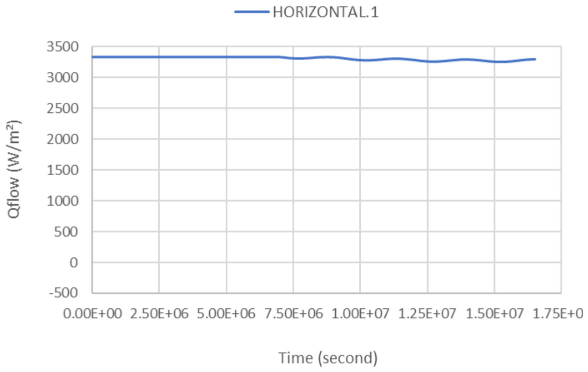

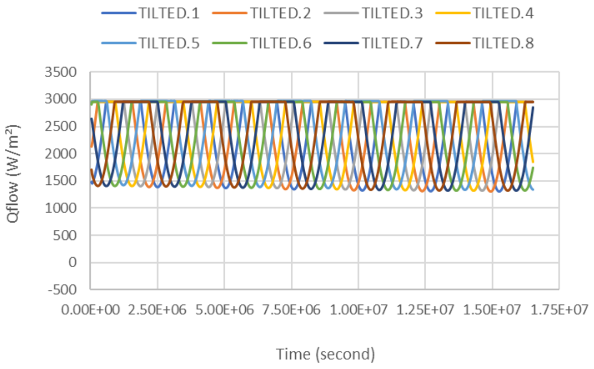

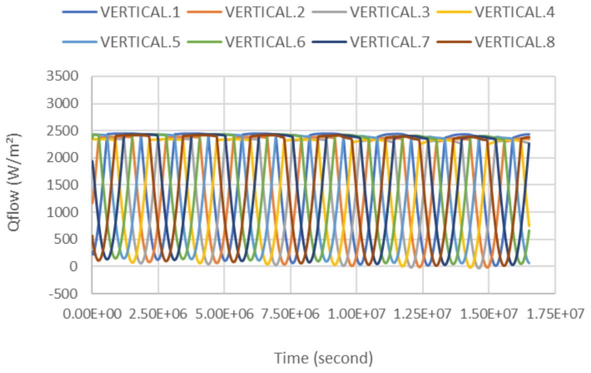

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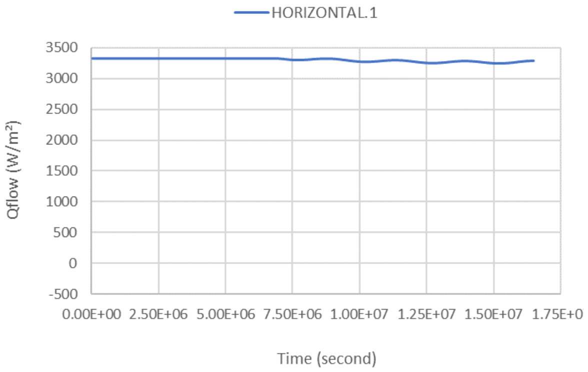

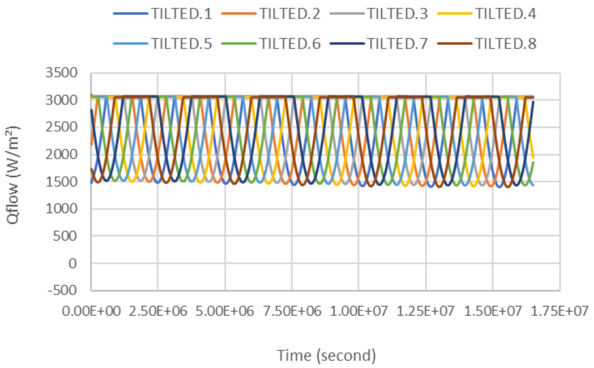

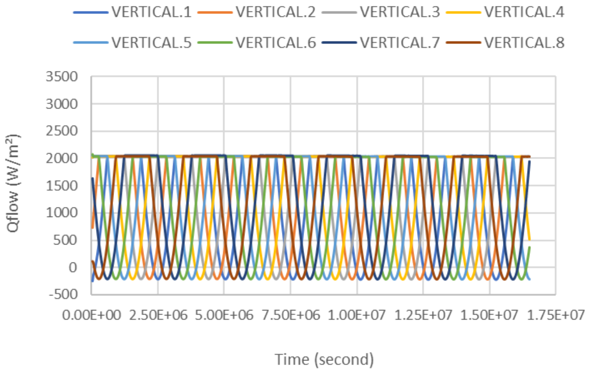

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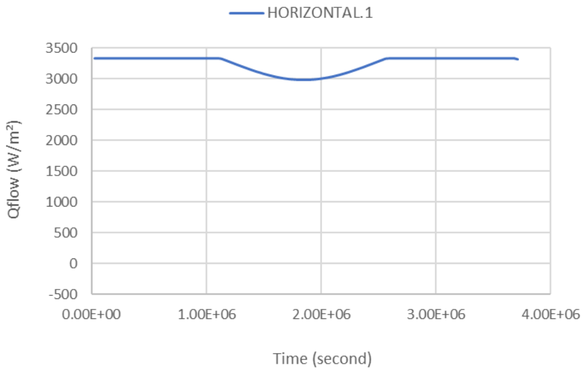
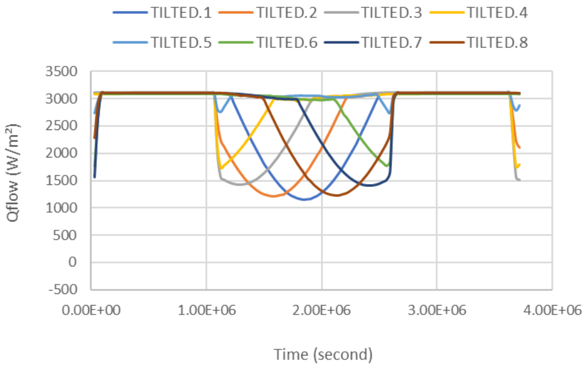
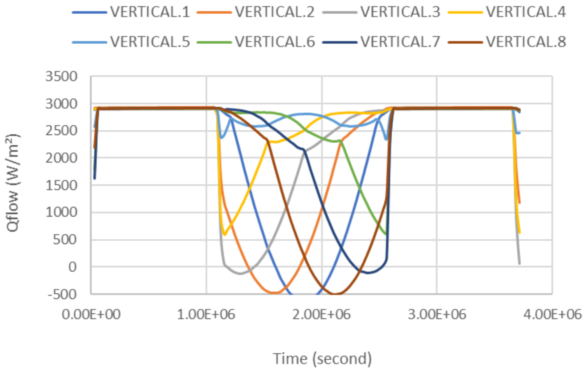
Transient: -82.5ºS Flat Surface

Lander Height (meter)

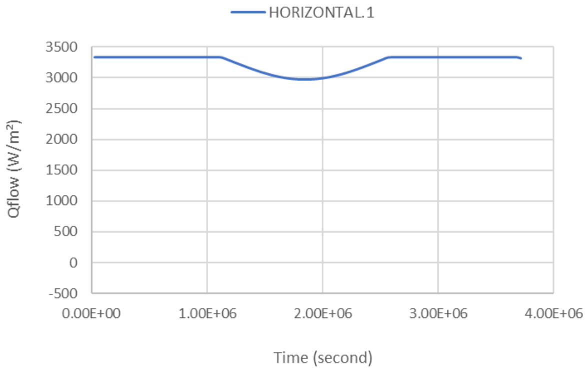
5.5 m

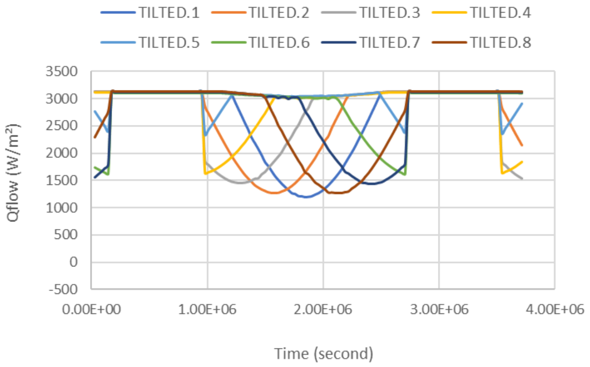


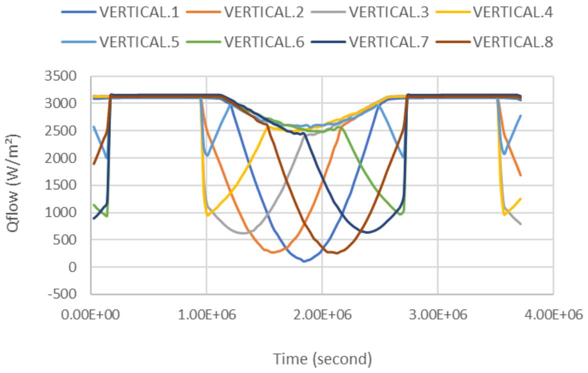




20 m







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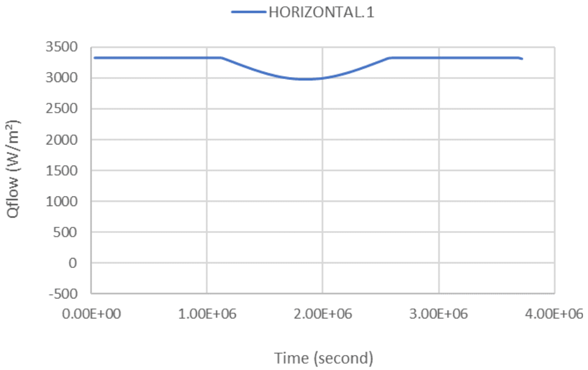

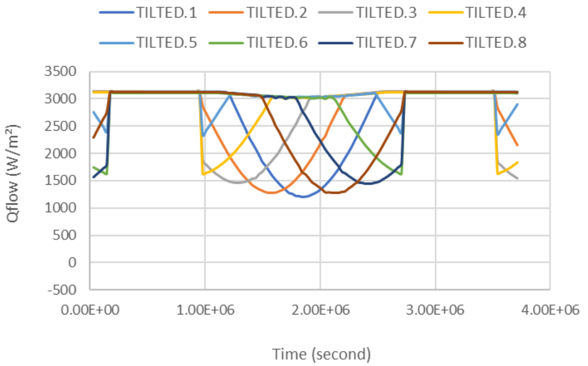

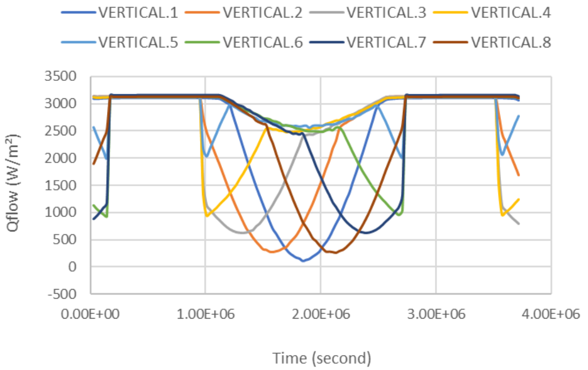

Transient: -82.5ºS Crater Surface

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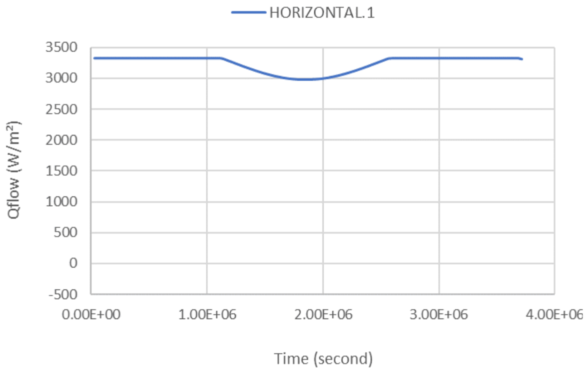
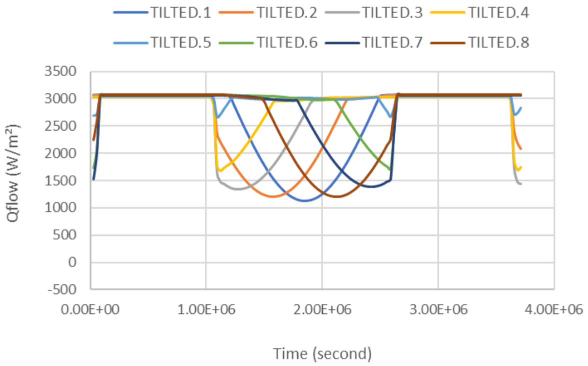
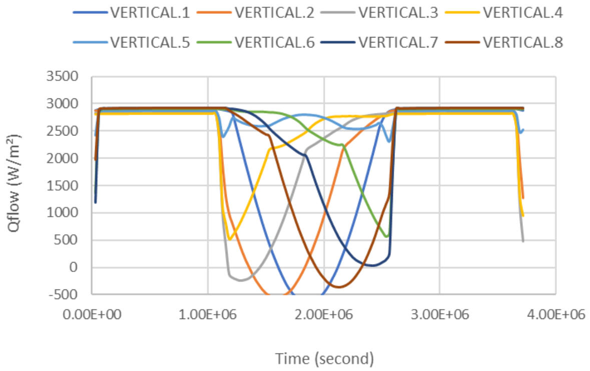
Lander Height (meter)

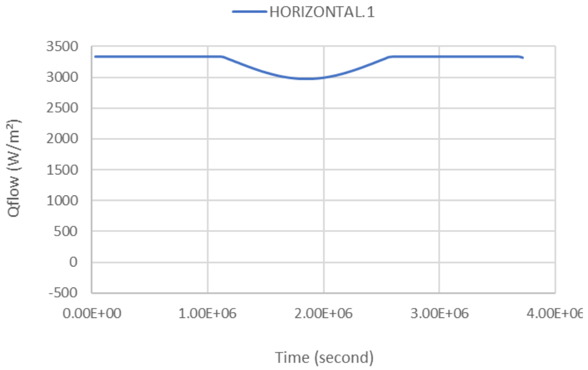
5.5 m

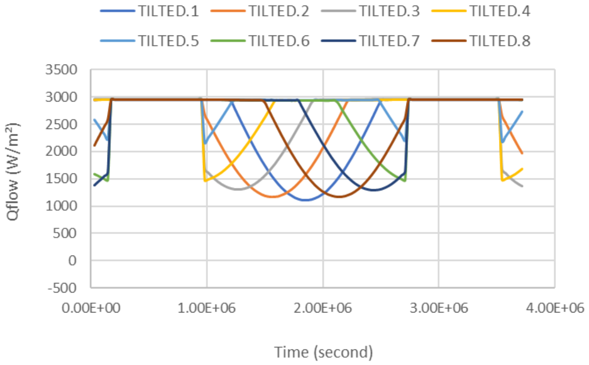


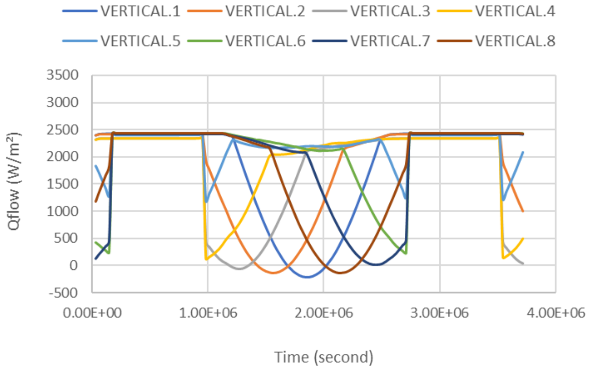




20 m







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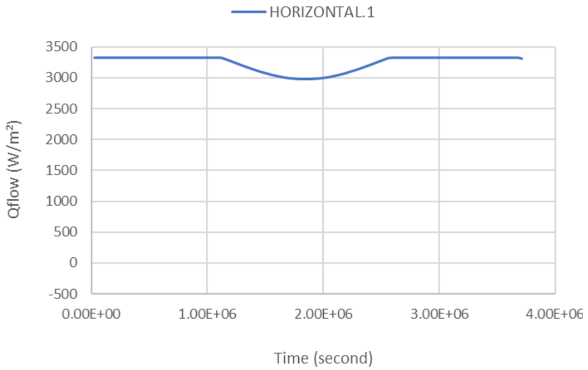
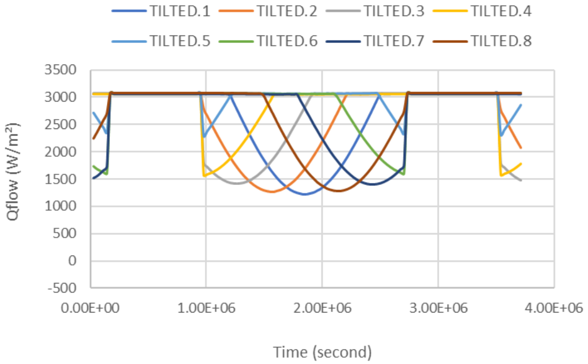
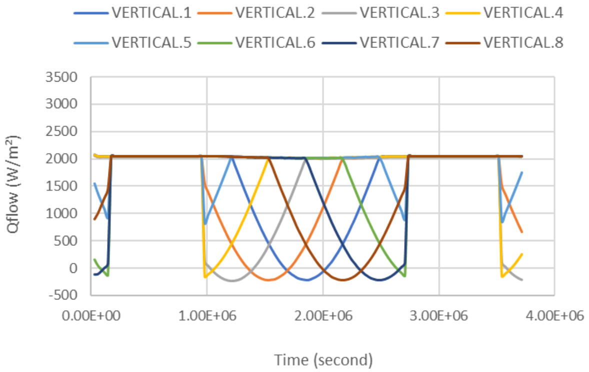
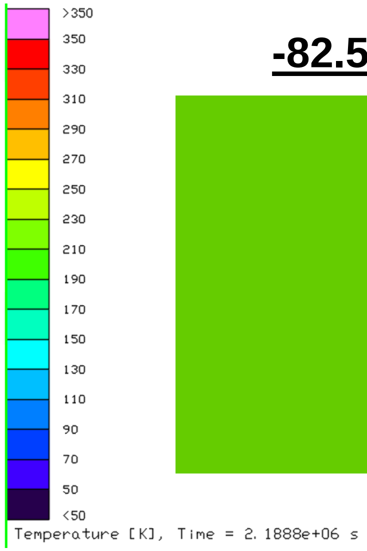




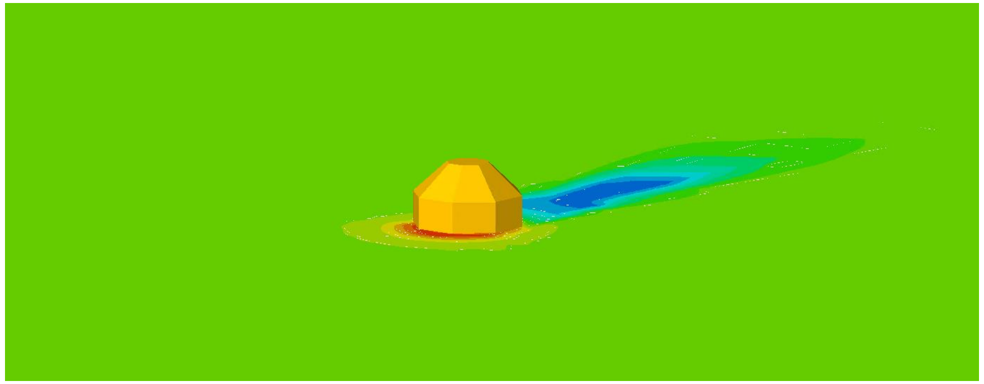


Findings: Crater Thermal Impacts

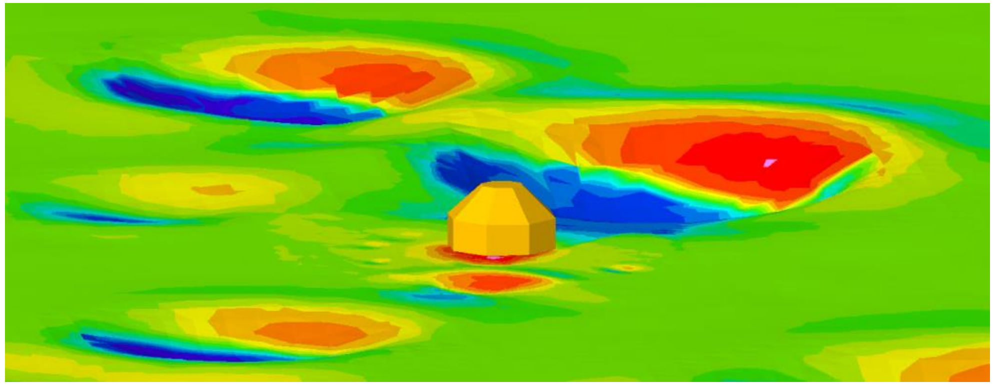
- **Small craters and sloped features of medium sized craters, that are not typically captured in Lunar surface meshes, impart additional environmental heating upon landed surface assets**
- **Crater induced ground slope variations increase the environmental heat flux incident upon the lander**
  - Localized ground slope differences caused by craters of all sizes creates areas with higher Lunar surface temperature
  - Hot crater regions contribute more heat flux than the cold crater regions subtract
  - The low solar elevation angle (at the poles) is more normal upon sloped crater features leading to elevated surface temperature
    - The incidence angle dependent solar absorptivity of the Lunar surface compounds this heating effect on sloped crater walls
- **When compared to a flat ground, craters significantly and moderately *degrade* the heat rejection performance of vertical and tilted radiators respectively, especially as lander height increases**
  - Horizontal radiators are largely unaffected



-82.5ºS Flat Surface, 5.5m lander height



-82.5ºS Crater Surface, 5.5m lander height



Findings: Heat Rejection Trends

- **Radiator heat rejection capability trends:**
  - Horizontal > tilted > vertical
  - 50m > 20m > 5.5m lander height
  - Flat terrain > cratered terrain
  - -89.5ºS > -82.5ºS

- **Radiator orientation impacts heat rejection capability much more than the other factors**
  - Horizontal and tilted radiators are largely unaffected by the presence of craters and changes in latitude
  - Vertical radiators are the most susceptible to performance degradation from the presence of craters and changes in latitude due to a large view factor to the terrain
    - The performance of vertical radiators in crater fields decreases (for worst case) as lander height increases
    - Individual vertical radiators in cratered terrain have extended periods of negative heat rejection capability at all lander heights
  - Tilted radiators perform similarly to horizontal radiators in the cold case, but performance drops by ~2/3 in worst case hot conditions (at all lander heights)

HLS

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