Ground Slope Effects on Lander Radiator Performance

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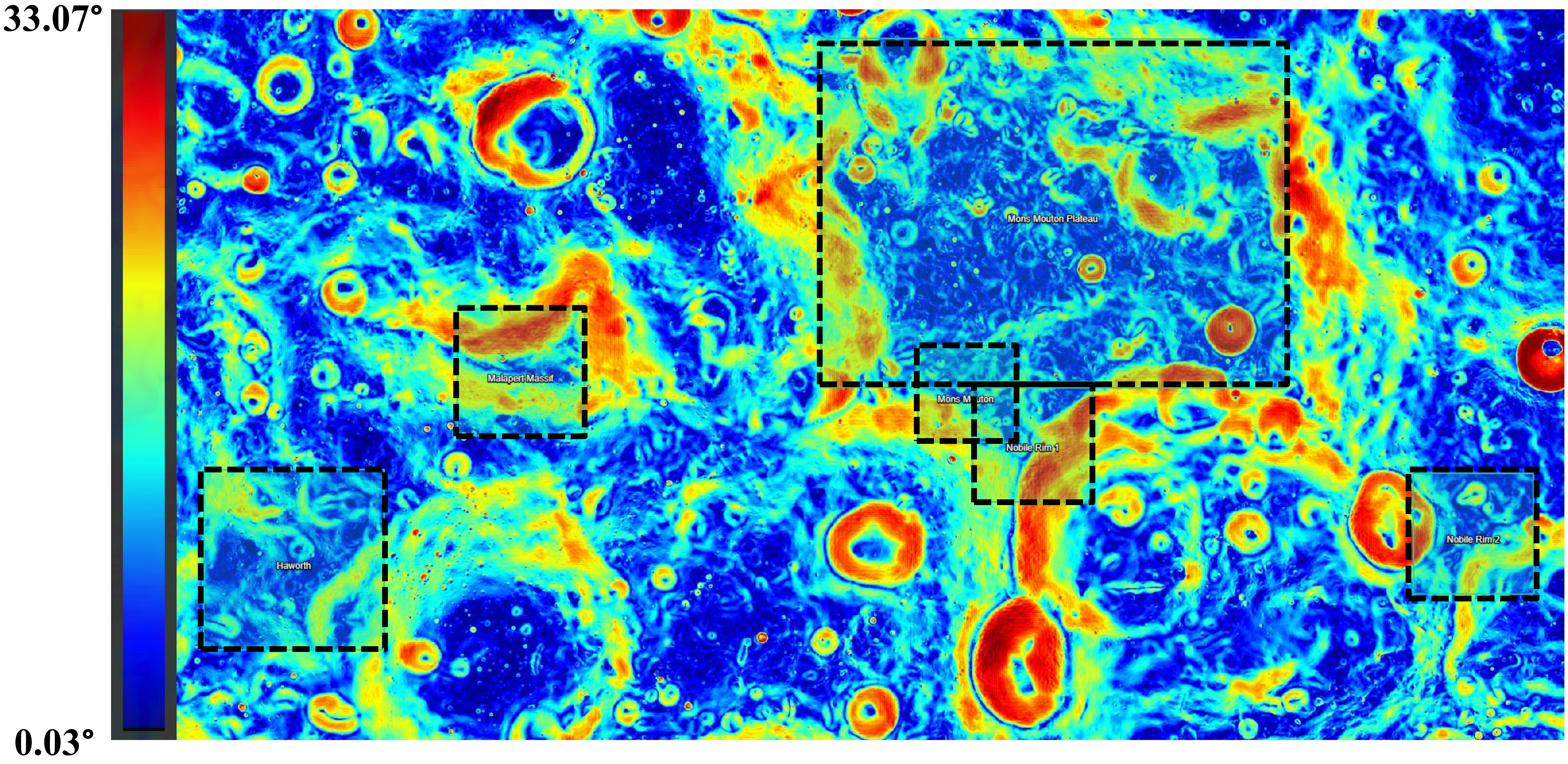
Lunar Slopes



LROC Quickmap Terrain Slope: Possible Slopes of Several Artemis Candidate Landing Regions in Boxed Areas

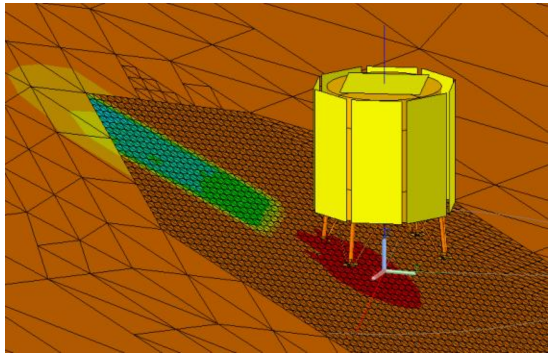
https://quickmap.lroc.im-ldi.com/layers?prjExtent=-102304.3834861%2C47834.4123314%2C218729.8775751%2C209496.2767565&stack=3388%2C3927&selectedFeature=%40%40user-defined%2CvFGiA&proj=17&defs=N4IgzGAckgXKAnAhgOwOYFM4G0AMA6XAJgDYBOaAFgBoJCB2ARjLPrAF1qRl0MAFJABsMAFxFZYIAEaCArhgC0CDABMQXAPYAHJAGMAliICecRgF8uYMkXpxQ2vYZOxzZoA

Background: Past Slope Studies

- Site specific studies have shown slopes significantly reducing heat rejection for 5m tall landers

W. Birmingham, W. Grier, and L. Erickson, “Lunar South Pole Terrain Effects on Radiator Performance,” TFAWS, 2025. https://ntrs.nasa.gov/citations/20250007546

Produced W/m² drop in radiator heat rejection for hot cases at 9 sites



Reduction in Radiator Heat Rejection Due to Terrain

Dusty White Paint

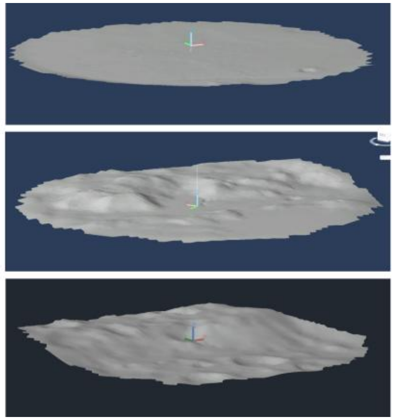
Location \ Radiator Orientation	Gravity Aligned Horizontal (W/m^2)	Gravity Aligned Vertical (W/m^2)	Terrain Aligned Horizontal (W/m^2)	Terrain Aligned Vertical (W/m^2)
Malapert Massif	71	124	348	233
Mons Mouton Plateau	55	147	340	220
Mons Mouton	-38*	67	241	152
Noble Rim 1	50	105	319	226
Nobile Rim 2	52	89	223	145
Slater Plain	52	110	259	164
de Gerlache Rim 2	36	113	299	173
Peak Near Cabeus B	23	111	288	173
Haworth	17	140	321	211

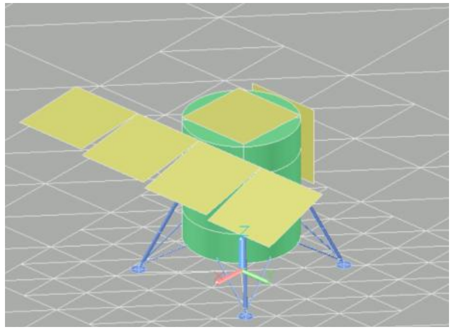
* At this specific location, the sun disappears behind the horizon during peak solar heating for the detailed terrain model but not for the flat terrain model. This results in the flat terrain model being the worse case *specifically for the dust covered case* due to the dust causing increased sensitivity to solar heating

W. Birmingham, G. Schunk, and B. Evans, “Lunar Latitude and Terrain Radiator Sensitivity Study,” TFAWS 2024. https://ntrs.nasa.gov/citations/20240011166

Produced % drop in heat rejection from sparse and dense mountains

- Flat Terrain Sample:
  - Apollo 11 terrain is used for this case.
  - Very flat and featureless (closest approximation to an infinite plane).
- Sparse Mountainous Terrain Sample:
  - Apollo 15 terrain is used for this case.
  - Tall mountains define the horizon with flat terrain in the immediate vicinity. Nearby mountains rise ~3km above the lander location.
- Dense Mountainous Terrain Sample:
  - A map of local standard deviation from mean height identified a highly mountainous section of terrain in a mid-latitude zone on the far side of the moon.
  - This location is in close proximity to very tall mountains, rising ~5km above the lander location. The lander sits in the bottom of a bowl (i.e. the horizon elevation is positive in all directions).





10° C Radiators

Ideal, Flat Terrain, Horizontal Radiator Heat Rejection (Control): 210W/m2	Flat Terrain: Percent Radiator Heat Rejection Decrease Due to Tilt Alone	Sparse Mountainous Terrain: Percent Radiator Heat Rejection Decrease Due to Terrain and Tilt	Dense Mountainous Terrain: Percent Radiator Heat Rejection Decrease Due to Terrain and Tilt
Horizontal Radiator	N/A	6%	30%
5° Eastward Tilt	1%	9%	33%
10° Eastward Tilt	8%	17%	46%
15° Eastward Tilt	14%	25%	55%
20° Eastward Tilt	21%	34%	68%

Problem: Identifying General Bounding Cases

Preform study to answer the following questions:

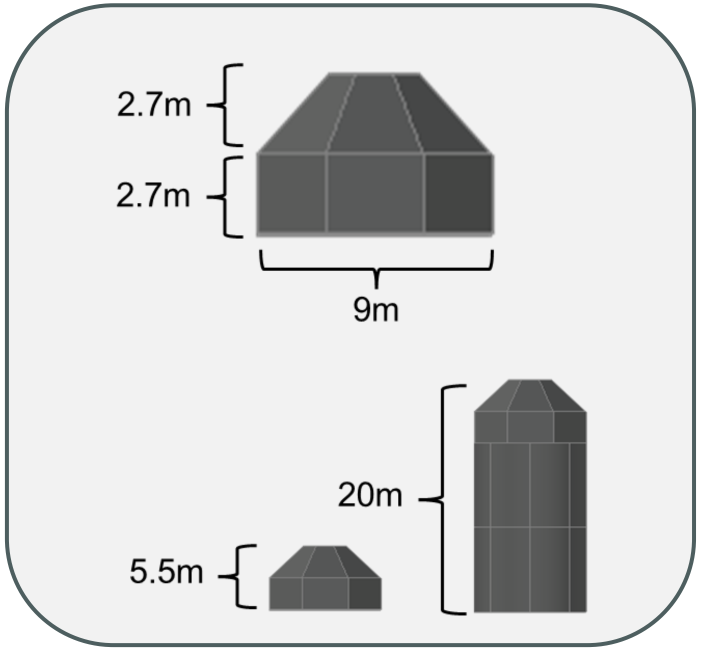
1) Can steady state analysis be used to identify the worst case?
2) What is the worst-case distance for vehicles near local slopes?
3) Are there cases where we can neglect a 'nearby' slope?

Approach: Examine the drop in radiator heat rejection from slopes

Study #1: Small-lander/rover

Study #2: Tall lander

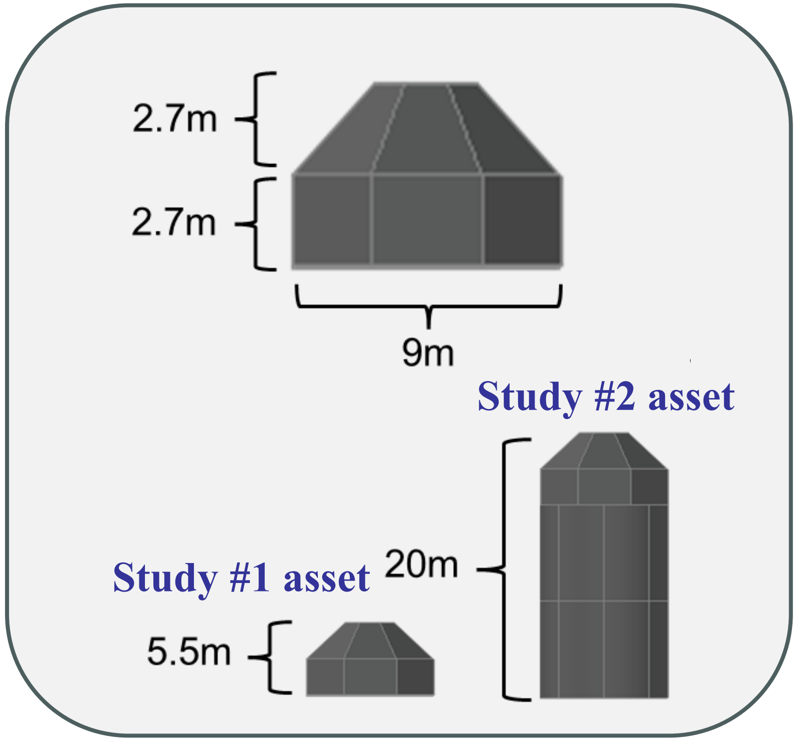
Asset Dimensions



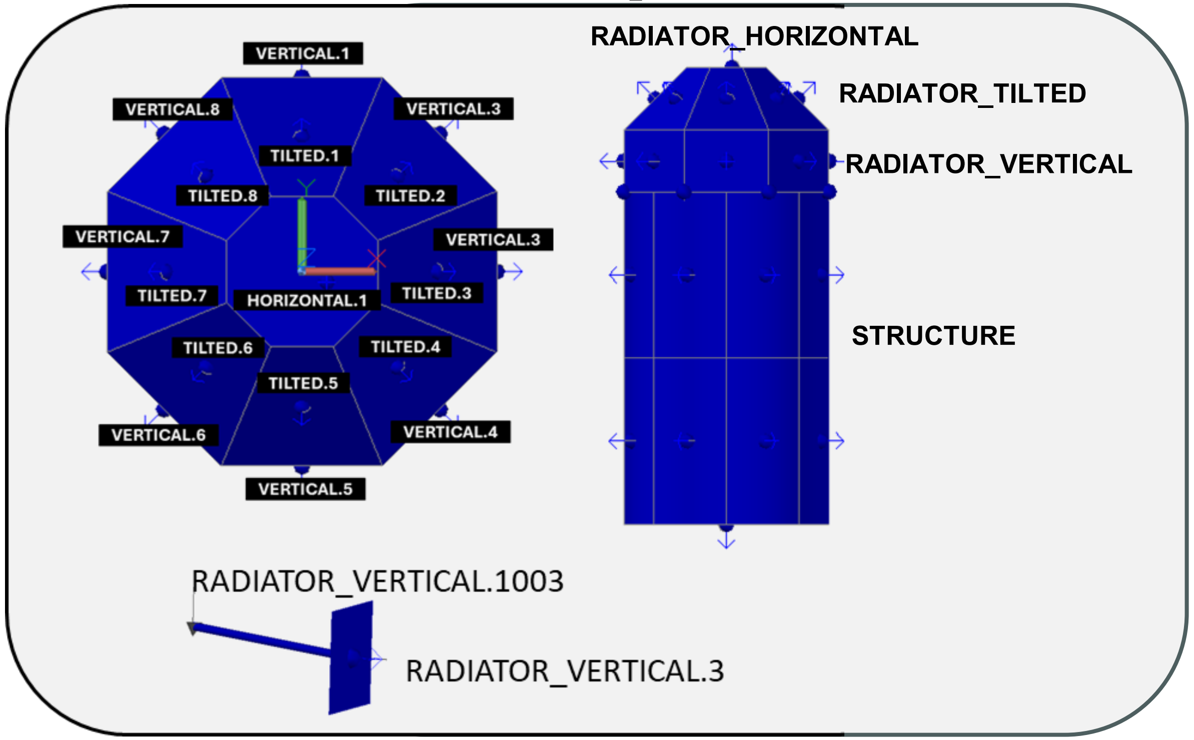
Model Overview: Asset

- Representative reduced order lander from [3] modeled in Thermal Desktop.
  - 17 body mounted radiators, each with a $10m^2$ surface area and horizontal, 45º inward-tilted, or vertical orientation.
  - Material set to Al 6061-T6 with all surfaces covered in Z93 (0.16 solar absorptivity, 0.92 IR emissivity).
  - Radiator set at 283K (10ºC) and structure set at 293 K (20ºC).
- Diffusion node surfaces connected to boundary nodes via conductors.

Asset Dimensions

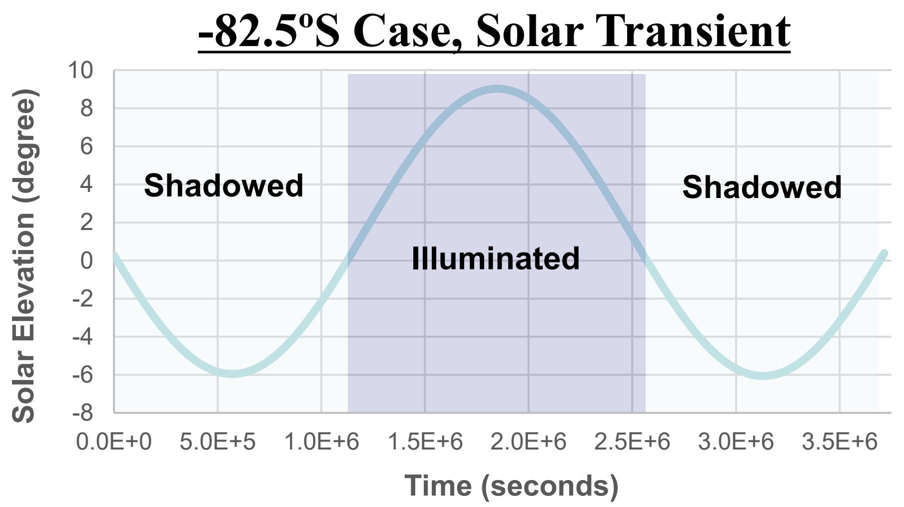


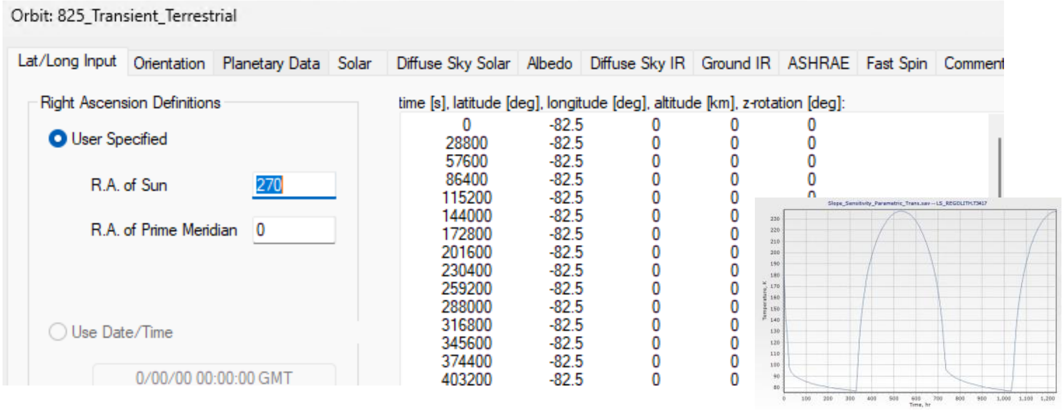
Radiator Node Map & Conductor



Model Overview: Environment

- Selected Latitude: -82.5ºS
  - Steady state: Since the asset is symmetric, performed for one sun angle (elevation = 9.02º, azimuth = directly facing the slope)
  - Transient: For simplicity, performed with a terrestrial orbit configured for summer (R.A. of Sun = 270). Initialized with a steady state case, run for 1240 hours, 8hr timestep
- Lunar environment defined using the Human Landing System (HLS) Lunar Thermal Analysis Guidebook (LTAG), Design Specification for Natural Environments (DSNE), and JPL Horizons data [4,5,6]
  - Constant worst case hot solar flux of 1415 W/m²
  - Solar diameter (subtended) angle (0.53º)[4]
  - Surface IR emissivity[5] ε = 0.95
  - Surface solar absorptivity[2,7]
    - Highland directional α_s (polar)(angle dependent)
  - Surface density[8,9] and specific heat[10] (depth dependent)
  - Surface thermal conductivity (depth & temperature dependent)[9]
  - Subsurface ground heat flow (~0.018 W/m²)[11]



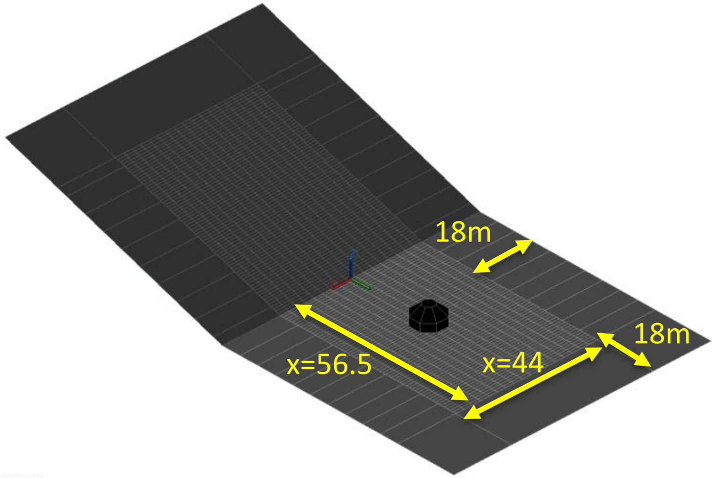


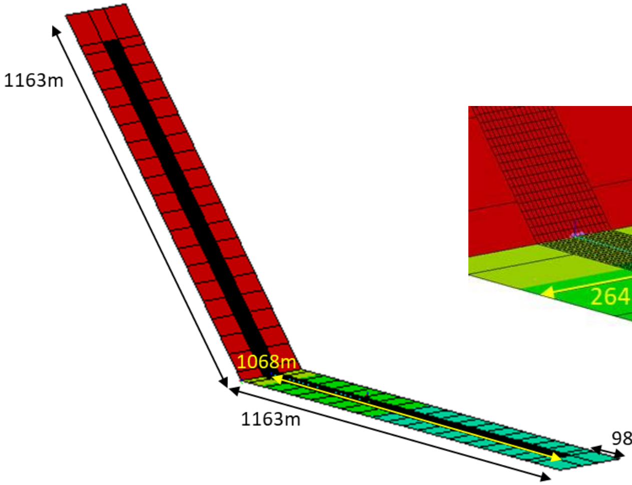
Model Overview: Lunar Surface

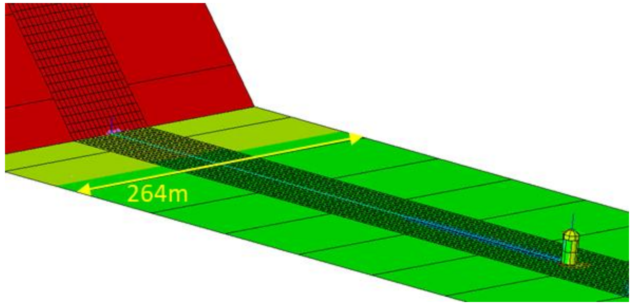
- Size ground to capture 1) the effect of the vehicle on the surface, 2) the effect of the surface on the vehicle, and 3) fill the space between the lander and the slope.
  - The minimum allowed size of the detailed center size was calculated using LTAG equation 9.3.1.4[4] to capture #2*: $r_{Ground\ S} \cong r_{asset}(1.77ln(AR) + 5.85))$
  - The minimum allowed size of the entire ground size was selected using LTAG equation 9.3.1.4[4] to capture #1*: $r_{Ground\ L} \cong r_{asset}(12.63(AR) + 0.943)$

- **Study #1: 5.5m tall asset (aspect ratio AR = 0.56)**
  - **Total Size:**
    - **74.5m long (y direction)**
    - **80m wide ground (x direction)**
  - **Detailed section**
    - **44m wide (x direction)**
    - **56.5m long (y direction)**
  - **Required shooting 50k rays per node, 3.35% error target, and 0.0001 bij cutoff* output to SINDA**

- **Study #2: 20m tall asset (aspect ratio AR = 2.23)**
  - **Total Size:**
    - **1163m long (y direction) to model asset 1km from slope**
    - **264m wide ground (x direction)**
  - **Detailed section**
    - **68m wide (x direction)**
    - **1068m long (y direction) to model asset 1km from slope**
  - **Required shooting 500k rays per node, a 1% error target, and 1e-7bij cutoff** output to SINDA**
    - **A couple cases needed to be re-run with 1million rays to smooth out the horizontal radiator's predictions**





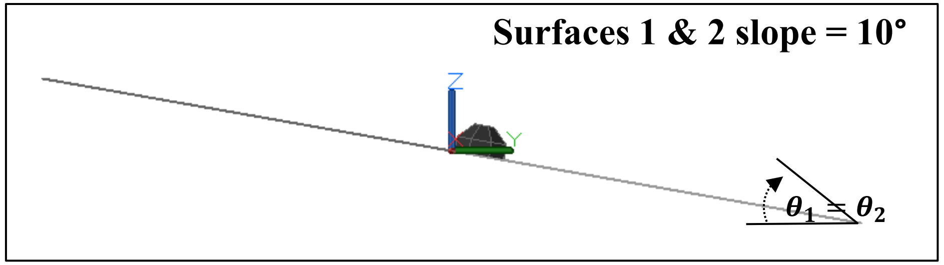


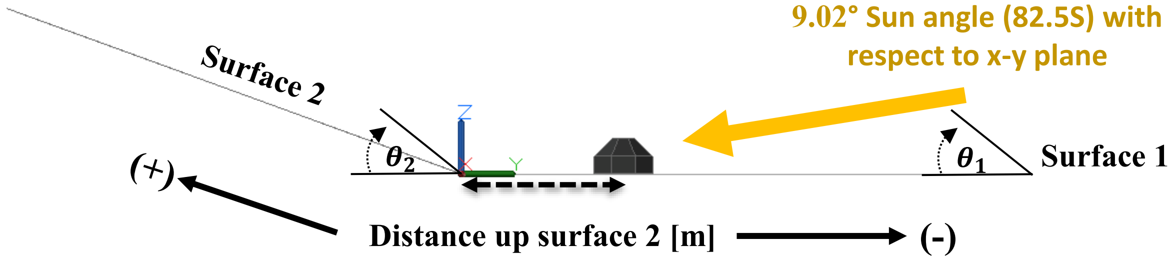
***The baseline release of [4] gives the ground radius that results in a 5% difference in the overall field of view of the geometry when the ground is a disk as opposed to an infinite plane $\left|(F_{1-2})_{r_2/r_1\to\infty} - F_{1-2}\right| = 0.05$ (which is equivalent to $F_{1-2} / (F_{1-2})_{r_2/r_1\to\infty}$ =90%). This may be too small in some cases.**

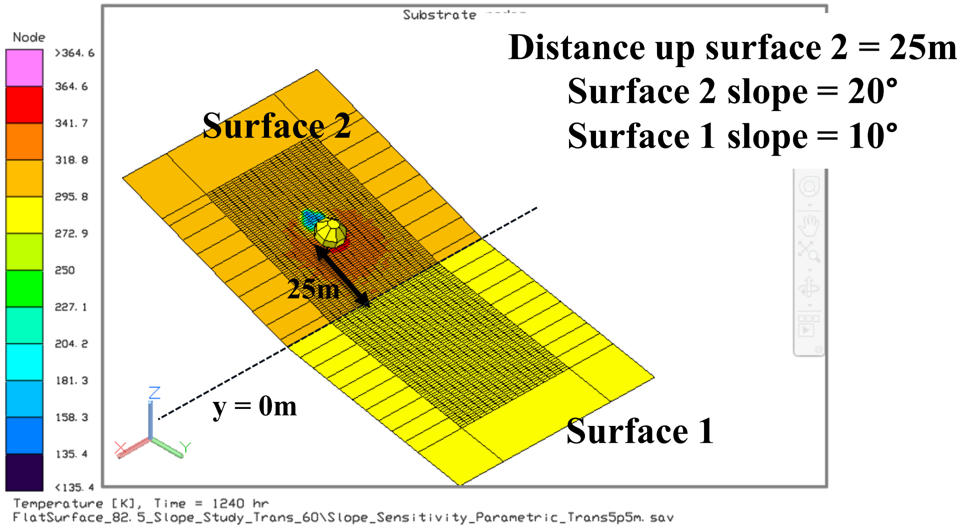
****bij cutoffs were selected with a sensitivity study with 70K rays shot for Study #1 and 500k rays shot for Study #2. The # of rays shot impacted this sensitivity.**

Study #1: 5.5m tall asset

- Predict radiator heat rejection, varying the asset's location and ground slopes.
  - Assets are not expected to travel to slopes >20°[17-18]
  - Assume max slope asset can approach is 30°
  - Distance up surface 2: ±25m
- **Cases set reflects desire to see:**
  - Can a steady state analysis be used to capture the worst case?
  - What is the worst case – overall, and for each radiator orientation?
  - Can you bound the worst case with a single tilted surface?







Study #1: Can Steady State Capture Worst Case:

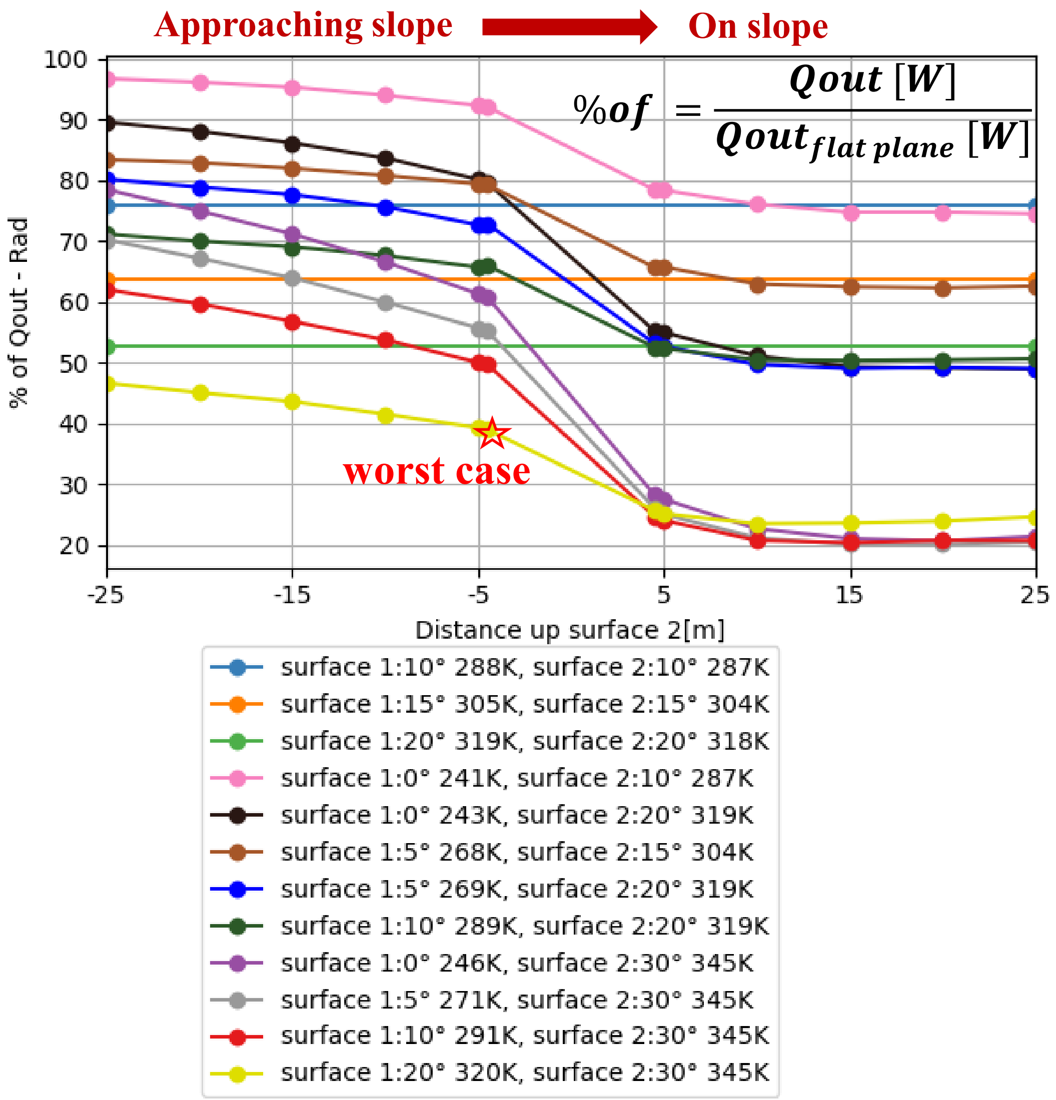
- Yes – for this study. Individual panel steady state worst cases rejected 1% - 12% less heat (13 to 74W)
  - Largest Δ: vertical +x facing panel, 2nd largest Δ: vertical 45º from slope facing panel
- Note: Worst cases identified by the steady state and transient parametric sweeps were close but not identical.
  - Transient results at steady state worst case location within: 2% except the sun facing tilted panel which predicts 14% more heat rejection

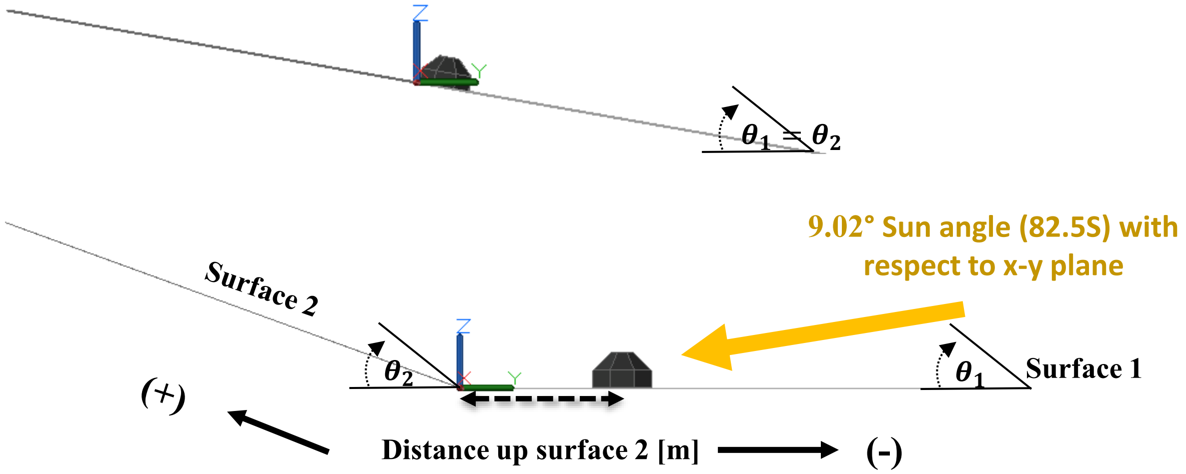
Heat rejection comparison: Red<Orange<Yellow<Green<Blue, (-) Q indicates a TSINK > T radiator
N – faces sun, S – faces slope, E – faces +x, SE – faces 45° away from slope, NE – faces 45° away from sun,

	$Q = \varepsilon\sigma A\left(T_{rad}^4 - T_{sink}^4\right)$ [W]	TILTED	VERT	HORIZ	TILT_N	TILT_NE	TILT_E	TILT_SE	TILT_S	VERT_N	VERT_NE	VERT_E	VERT_SE	VERT_S	Total
Steady State (SS)	Worst case Surface 1 slope [°]	20	20	0	10	5	20	0	0	5	0	20	0	0	20
	Worst case Surface 2 slope [°]	30	30	20	20	20	30	30	30	20	20	30	30	30	30
	Worst case Distance up surface 2 [m]	-4.5	-5	4.5	25	25	-4.5	-4.5	-5	20	20	-5	-4.5	-15	-4.5
	Worst case [W]	12312	-757	2214	369	851	1776	1545	1496	-2413	-1566	317	714	1198	13869
Transient (Trans)	Worst case Surface 1 slope [°]	20	20	0	0	5	20	0	0	5	5	20	20	0	20
	Worst case Surface 2 slope [°]	30	30	20	20	20	30	30	30	20	20	30	30	30	30
	Worst case Distance up surface 2 [m]	-5	-4.5	4.5	25	20	-4.5	-4.5	-5	20	25	-5	-4.5	-15	-5
	Base case (with no slope) [W]	20078	12396	2977	1291	1780	2934	3173	3216	-590	272	2217	2608	2938	35450
	Worst case [W]	12547	-464	2214	382	878	1801	1596	1522	-2397	-1512	360	788	1213	14343
	Worst case at steady state worst case location [W]	12601	-430	2214	436	880	1801	1596	1522	-2397	-1487	360	806	1213	14361
	Value at Surface 1 & Surface 2 at 20° slope (Trans)	14595	2096	2237	492	983	2000	2751	2777	-1974	-1138	594	1483	2310	18929
Comparisons	ΔQ Base - Worst case value (Trans)	7531	12860	763	909	902	1132	1576	1693	1806	1784	1856	1820	1726	21108
	ΔQ Base-Worst case value (SS)	7766	13153	762	922	928	1157	1627	1720	1822	1837	1900	1894	1741	21582
	ΔQ Base - Worst case value (Trans) at SS worst case location	7477	12826	763	855	900	1132	1576	1693	1806	1758	1856	1803	1726	21089
	ΔQ Base - Value at Surface 1& Surface 2 at 20° slope (Trans)	5483	10299	739	799	796	934	422	439	1384	1409	1623	1125	628	16522
	ΔQ Worst case Trans - Worst Case SS	235	294	0	13	27	25	51	26	16	54	43	74	15	474
	ΔQ Worst Case - Worst case at Worst case SS location (Trans)	-54	-34	0	-54	-2	0	0	0	0	-25	0	-17	0	-19
	ΔQ Worst case - value for both surfaces at 20° slope (Trans)	-2048	-2560	-23	-110	-105	-198	-1154	-1254	-423	-374	-234	-695	-1098	-4586
	% |diff Q Worst case Trans - Worst Case SS|	2%	63%	0.0%	3%	3%	1%	3%	2%	1%	4%	12%	9%	1%	3%
	% |diff Q Worst Case - Worst case at Worst case SS location (Trans)|	0.4%	7%	0.0%	14%	0%	0.0%	0.0%	0.0%	0.0%	2%	0.0%	2%	0.0%	0.1%
	% |diff Q Worst Case - Value at Surface 1& Surface 2 at 20° slope (Trans)|	16%	552%	1%	29%	12%	11%	72%	82%	18%	25%	65%	88%	91%	32%

Study #1: What is the overall worst case?

- On a 20° slope approaching a 30° slope
- If surface 2 was ≤20°:
  - 25m up on surface 2 at 20°



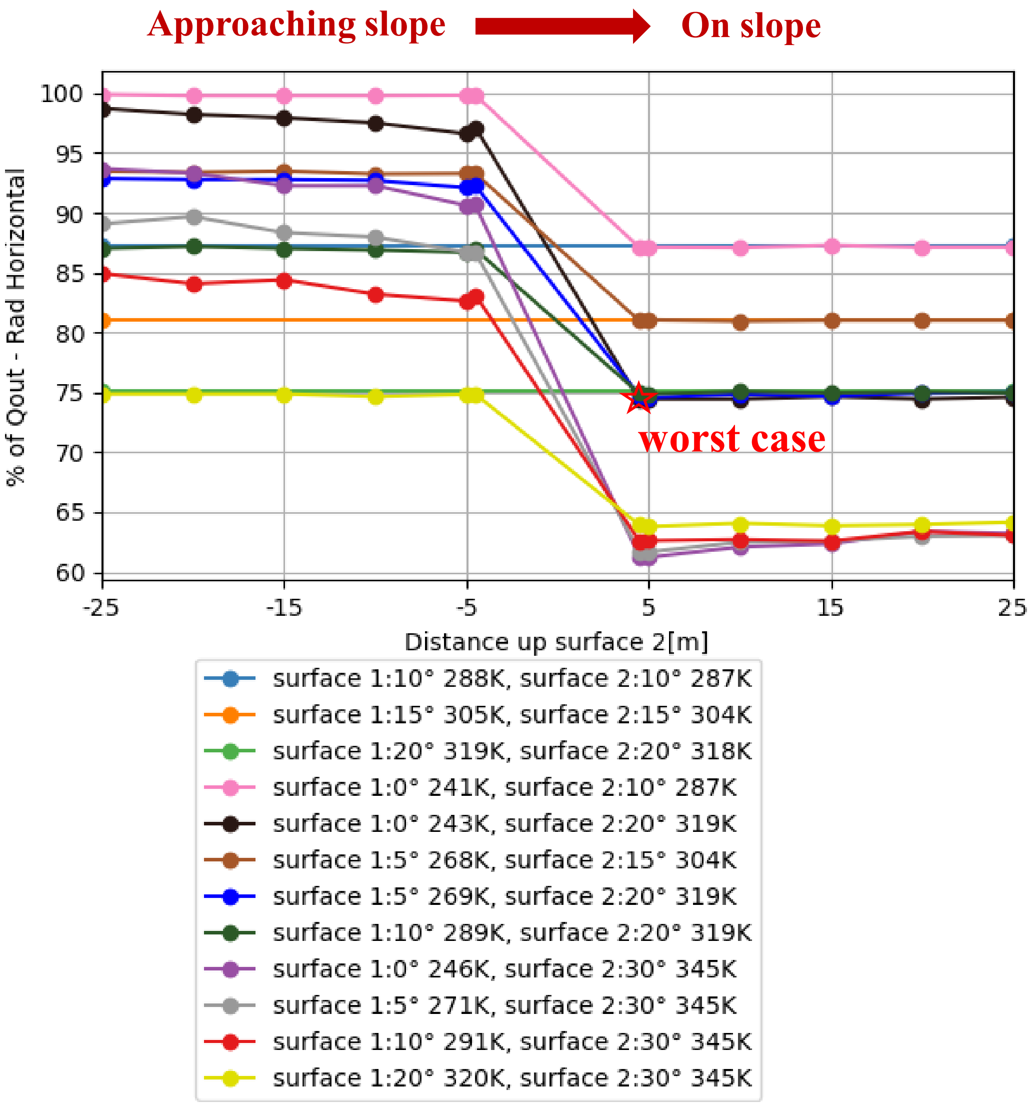


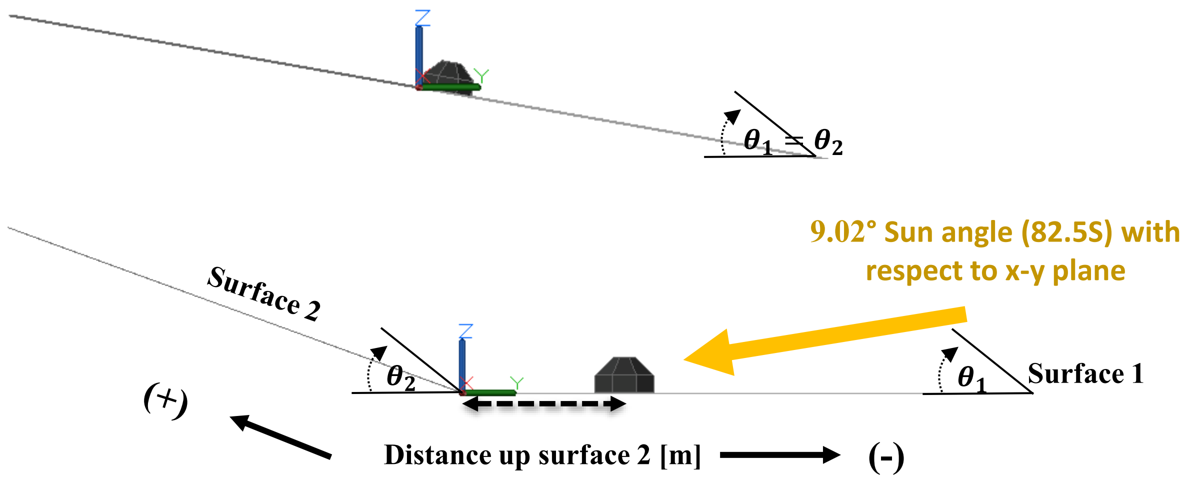
Study #1: What is the worst case per panel?

- Horizontal panels → slightly up 4.5m onto a 20º sloped surface near a flat ground (0º incline)
  - very close to the 'on a 20º slope just before a 30º slope' case
- If surface 2 was ≤20°:
  - ~>10m up on surface 2 where surface 1 is ~5-10º

$$\%of = \frac{Qout\,[W]}{Qout_{flat\ plane}\,[W]}$$

Heat rejection drops as % of Q rejected by the base case



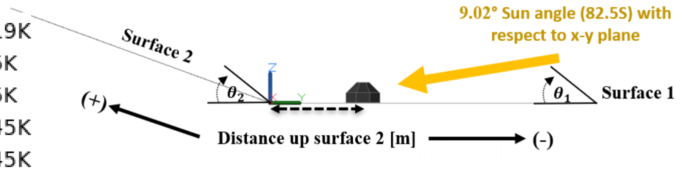


Study #1: What is the worst case per panel?

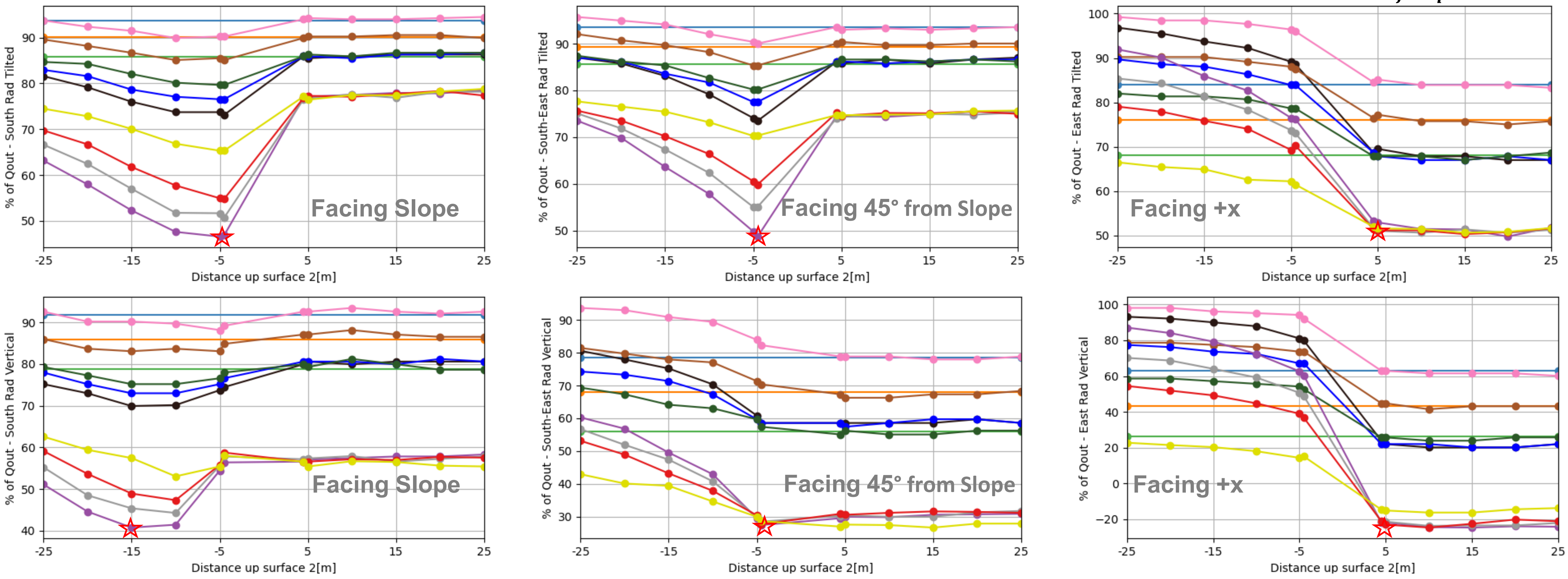
- Panels seeing the slope + panels not seeing the slope or sun → tends to be on a flat ground (0º incline) just before a 30º slope

- surface 1:10° 288K, surface 2:10° 287K
- surface 1:15° 305K, surface 2:15° 304K
- surface 1:20° 319K, surface 2:20° 318K
- surface 1:0° 241K, surface 2:10° 287K
- surface 1:0° 243K, surface 2:20° 319K
- surface 1:5° 268K, surface 2:15° 304K
- surface 1:5° 269K, surface 2:20° 319K
- surface 1:10° 289K, surface 2:20° 319K
- surface 1:0° 246K, surface 2:30° 345K
- surface 1:5° 271K, surface 2:30° 345K
- surface 1:10° 291K, surface 2:30° 345K
- surface 1:20° 320K, surface 2:30° 345K

☆ = worst case



$$\%of = \frac{Qout\ [W]}{Qout_{flat\ plane}\ [W]}$$



Approaching slope → On slope

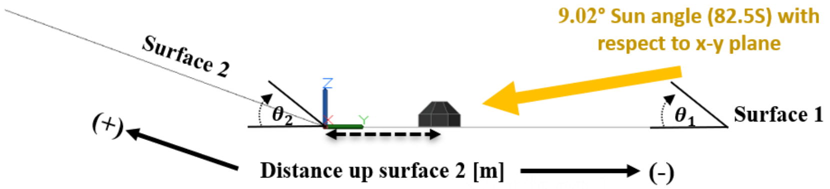
Study #1: What is the worst case per panel?

- **Panels seeing the sun →** tends to be 20 to 25m up onto a 20º slope near a surface with a lower incline (~5-10º).

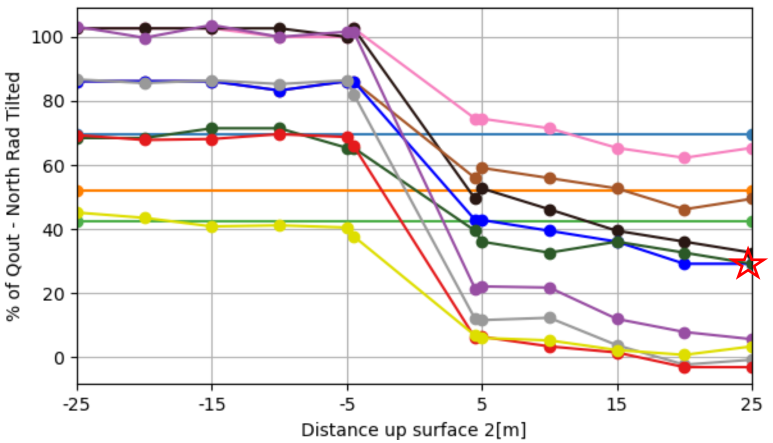
$$\%of = \frac{Qout\,[W]}{Qout_{flat\ plane}\,[W]}$$

☆ = worst case

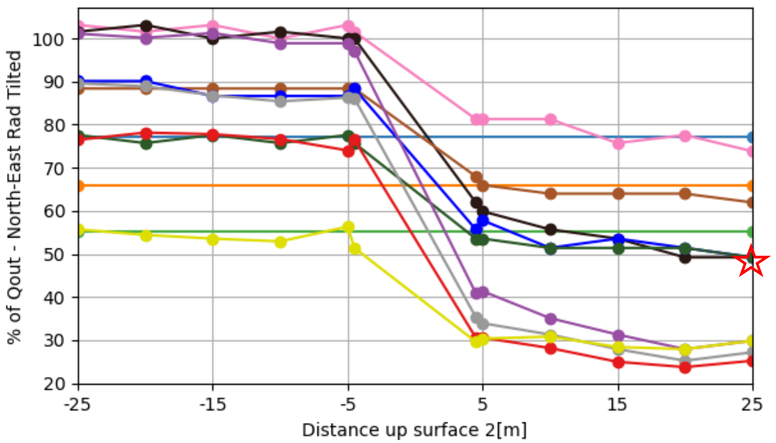
- surface 1:10° 288K, surface 2:10° 287K
- surface 1:15° 305K, surface 2:15° 304K
- surface 1:20° 319K, surface 2:20° 318K
- surface 1:0° 241K, surface 2:10° 287K
- surface 1:0° 243K, surface 2:20° 319K
- surface 1:5° 268K, surface 2:15° 304K
- surface 1:5° 269K, surface 2:20° 319K
- surface 1:10° 289K, surface 2:20° 319K
- surface 1:0° 246K, surface 2:30° 345K
- surface 1:5° 271K, surface 2:30° 345K
- surface 1:10° 291K, surface 2:30° 345K
- surface 1:20° 320K, surface 2:30° 345K



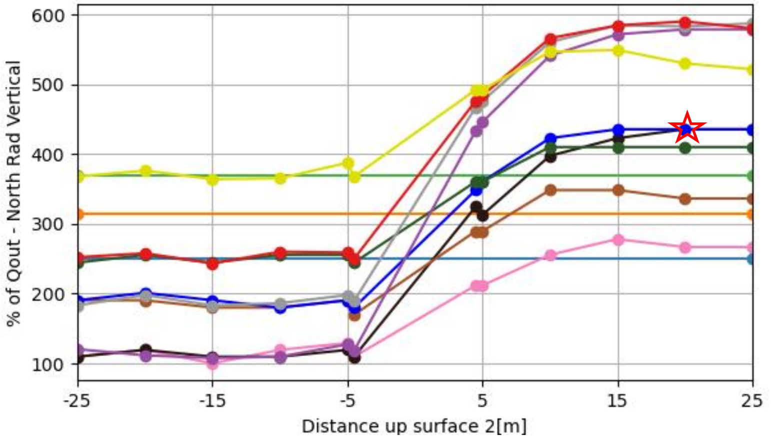
Facing Sun

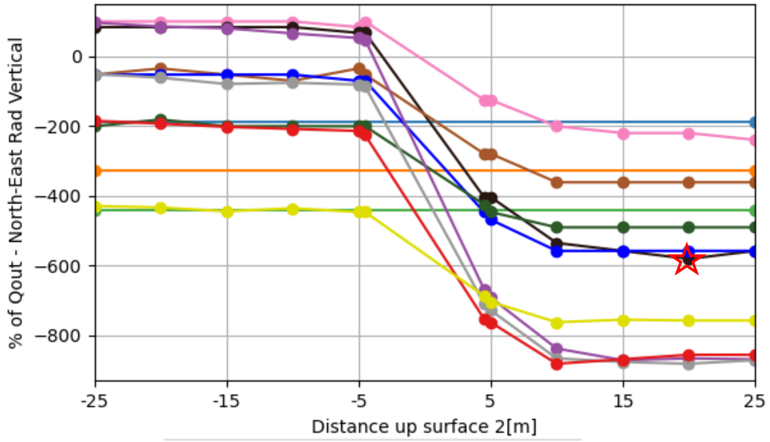


Facing 45° from Sun



Approaching slope → On slope





Study #1: Can we neglect a ‘nearby’ slope?

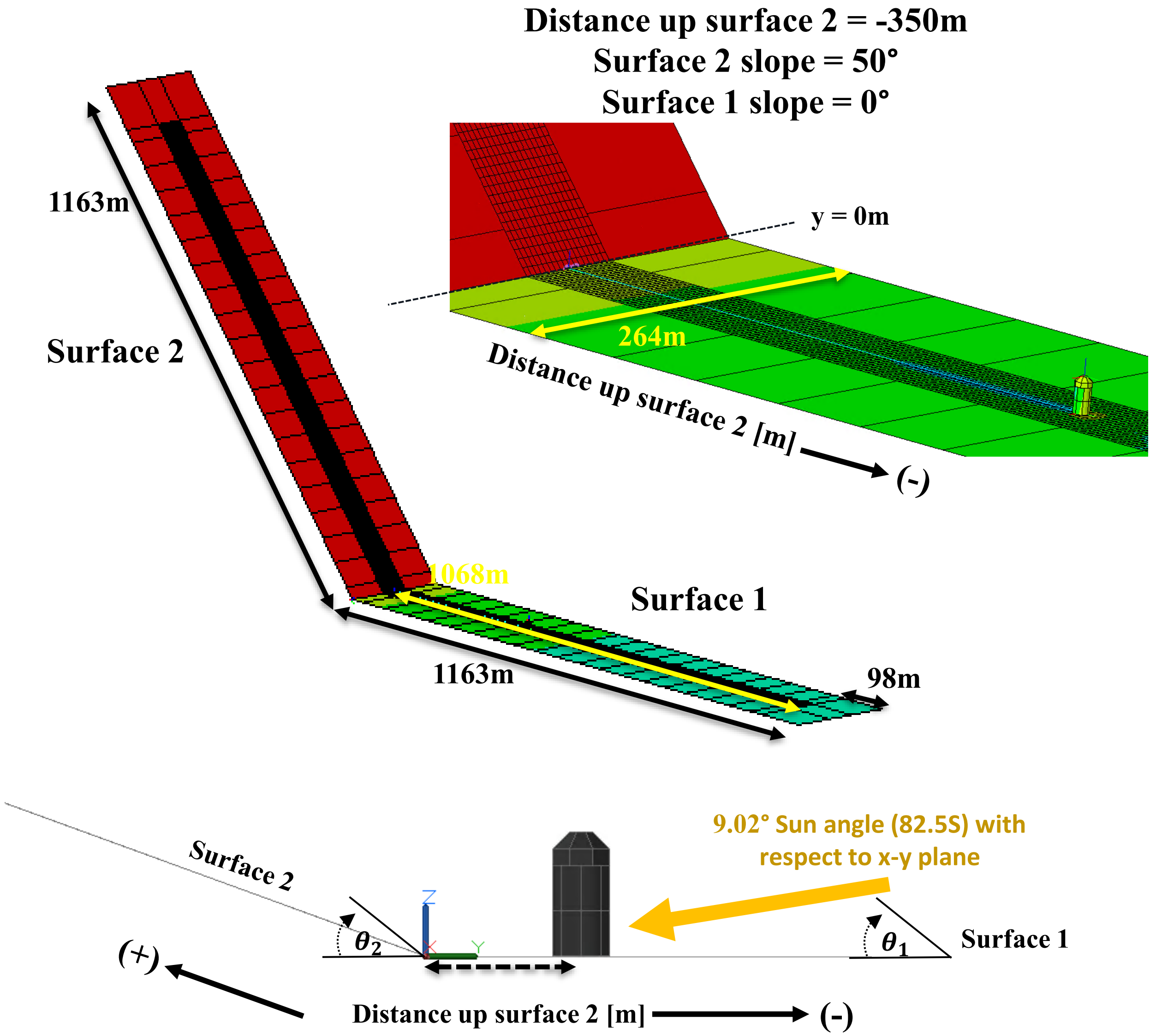
- In most cases, no.
  - Results show a slope and using a flat-tilted (i.e., \ shaped) ground overall significantly overpredicting heat rejection
    - 32% of total & 82% of slope facing 45º tilted radiators
    - 8% of total & 17% of slope facing 45º tilted radiators if max slope was 20º
    - However, the worst-case of the horizontal radiator on the _ shaped ground, was within 1% of that predicted with the \ shaped ground

Heat rejection comparison: Red<Orange<Yellow<Green<Blue, (-) Q indicates a TSINK > T radiator
N – faces sun, S – faces slope, E – faces +x, SE – faces 45° away from slope, NE – faces 45° away from sun,

	$Q = \varepsilon\sigma A\left(T_{rad}^4 - T_{sink}^4\right)$ [W]	TILTED	VERT	HORIZ	TILT_N	TILT_NE	TILT_E	TILT_SE	TILT_S	VERT_N	VERT_NE	VERT_E	VERT_SE	VERT_S	Total
Transient (Trans)	Worst case Surface 1 slope [°]	20	20	0	0	5	20	0	0	5	5	20	20	0	20
	Worst case Surface 2 slope [°]	30	30	20	20	20	30	30	30	20	20	30	30	30	30
	Worst case Distance up surface 2 [m]	-5	-4.5	4.5	25	20	-4.5	-4.5	-5	20	25	-5	-4.5	-15	-5
	Base case (with no slope) [W]	20078	12396	2977	1291	1780	2934	3173	3216	-590	272	2217	2608	2938	35450
	Worst case [W]	12547	-464	2214	382	878	1801	1596	1522	-2397	-1512	360	788	1213	14343
	If surface 2 was ≤20°, Worst case Surface 1 slope [°]	0	-5	0	0	-5	-5	0	0	-5	-5	0	-20	0	0
	If surface 2 was ≤20°, Worst case Surface 2 slope [°]	20	15	20	20	15	15	20	20	15	15	20	0	20	20
	If surface 2 was ≤20°, Worst case Distance up surface 2 [m]	25	20	4.5	25	20	20	-5	-5	20	25	15	-25	-10	25
	If surface 2 was ≤20°, Worst case [W]	14268	1084	2214	382	878	1966	2383	2366	-2397	-1512	484	1483	2078	17600
	Value at Surface 1 & Surface 2 at 20° slope	14595	2096	2237	492	983	2000	2751	2777	-1974	-1138	594	1483	2310	18929
	ΔQ Worst case - value for both surfaces at 20° slope (Trans)	-2048	-2560	-23	-110	-105	-198	-1154	-1254	-423	-374	-234	-695	-1098	-4586
	% |diff Q Worst Case - Value at Surface 1& Surface 2 at 20° slope (Trans) |	16%	552%	1%	29%	12%	11%	72%	82%	18%	25%	65%	88%	91%	32%
	ΔQ Worst case - value for both surfaces at 20° slope (Trans)	-327	-1013	-23	-110	-105	-34	-368	-411	-423	-374	-110	0	-232	-1329
	% |diff Q Worst case if max allowed slope was 20º- Value at Surface 1& Surface 2 at 20° slope (Trans) |	-2%	-93%	-1%	-29%	-12%	-2%	-15%	-17%	18%	25%	-23%	0%	-11%	-8%

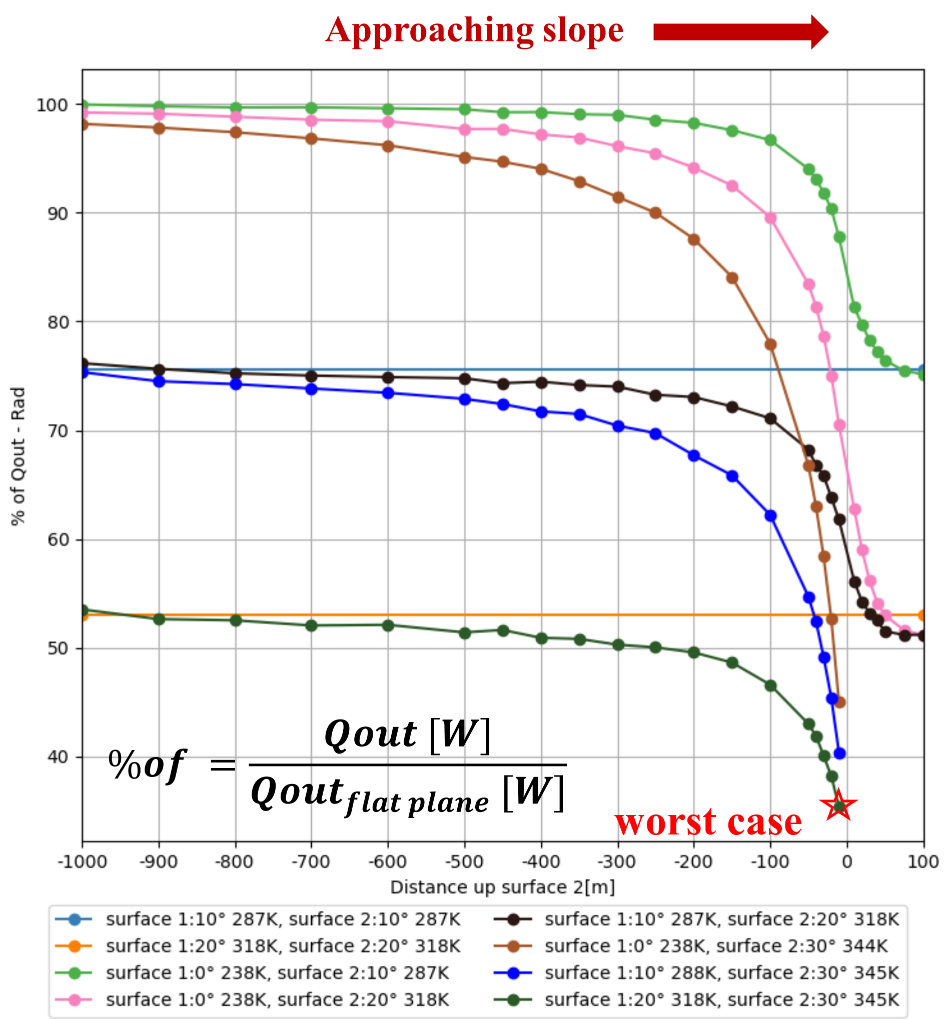
Study #2: 20m tall asset

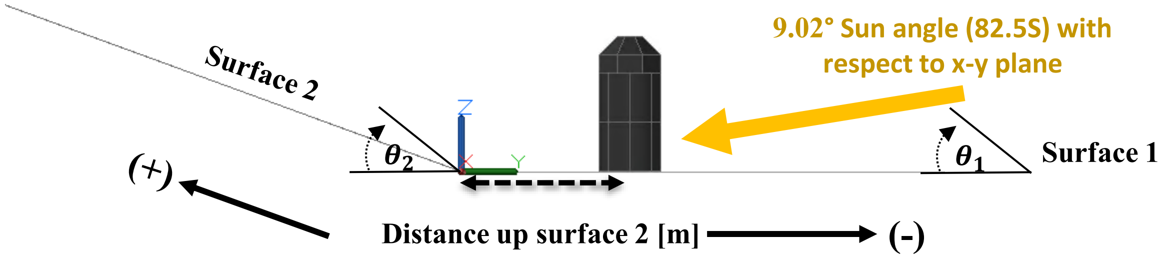
- Predict radiator heat rejection, varying the asset's location and ground slopes.
  - Assets are not expected to travel to slopes >20°[17-18]
  - Assume max slope asset can approach is 30°
  - Distance up surface 2: ±100m
  - Only ran steady state cases
- **Cases set reflects desire to see:**
  - What is the worst case – overall, and for each radiator orientation if the asset can approach a max slope of 30°?
  - Can you be far enough away from a slope for its impact to be neglected when sizing radiators?



Study #2: What is the overall worst case?

- On a 20° slope approaching a 30° slope
- If surface 2 was ≤20°:
  - 100m up on surface 2 at 20°



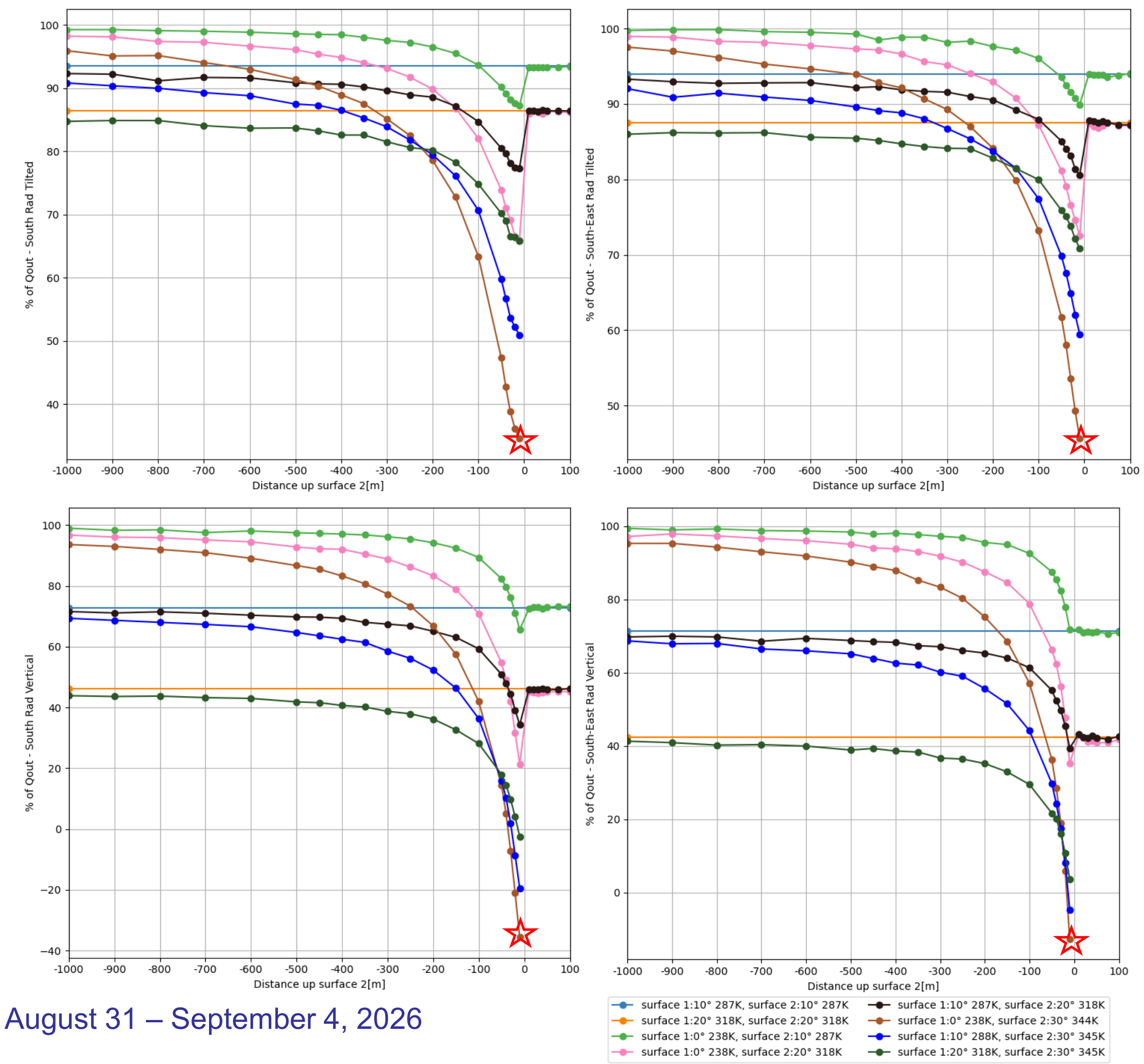


Study #2: What is the worst case per panel?

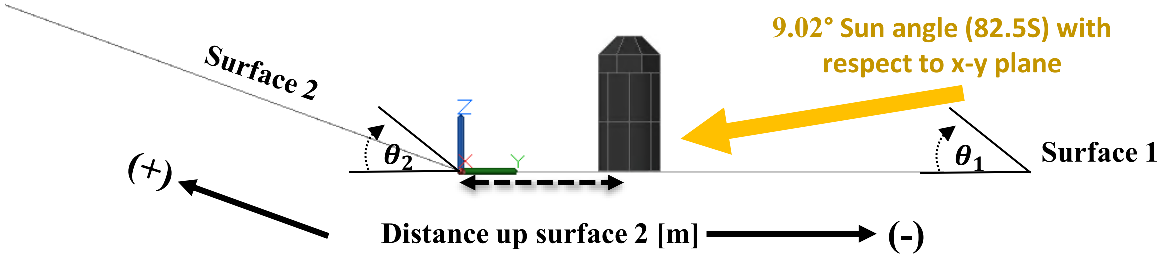
- Panels seeing the slope→ on flat ground (surface 1 = 0°) just before a 30° slope
- If surface 2 was ≤20°:
  - Just before the 20° slope

☆ = worst case

Approaching slope



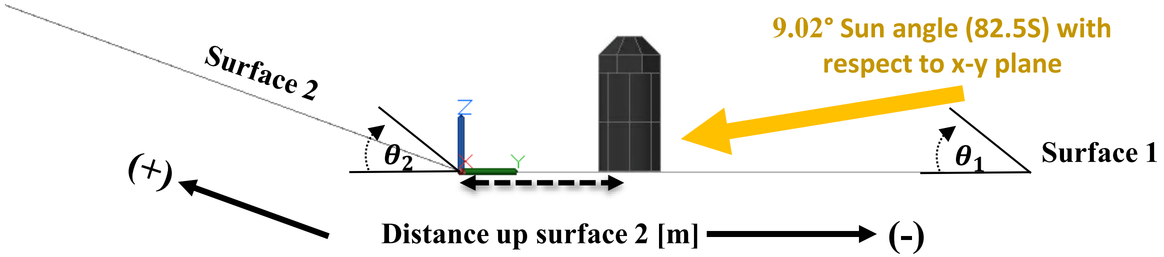
$$\%of = \frac{Qout\ [W]}{Qout_{flat\ plane}\ [W]}$$



Study #2: What is the worst case per panel?

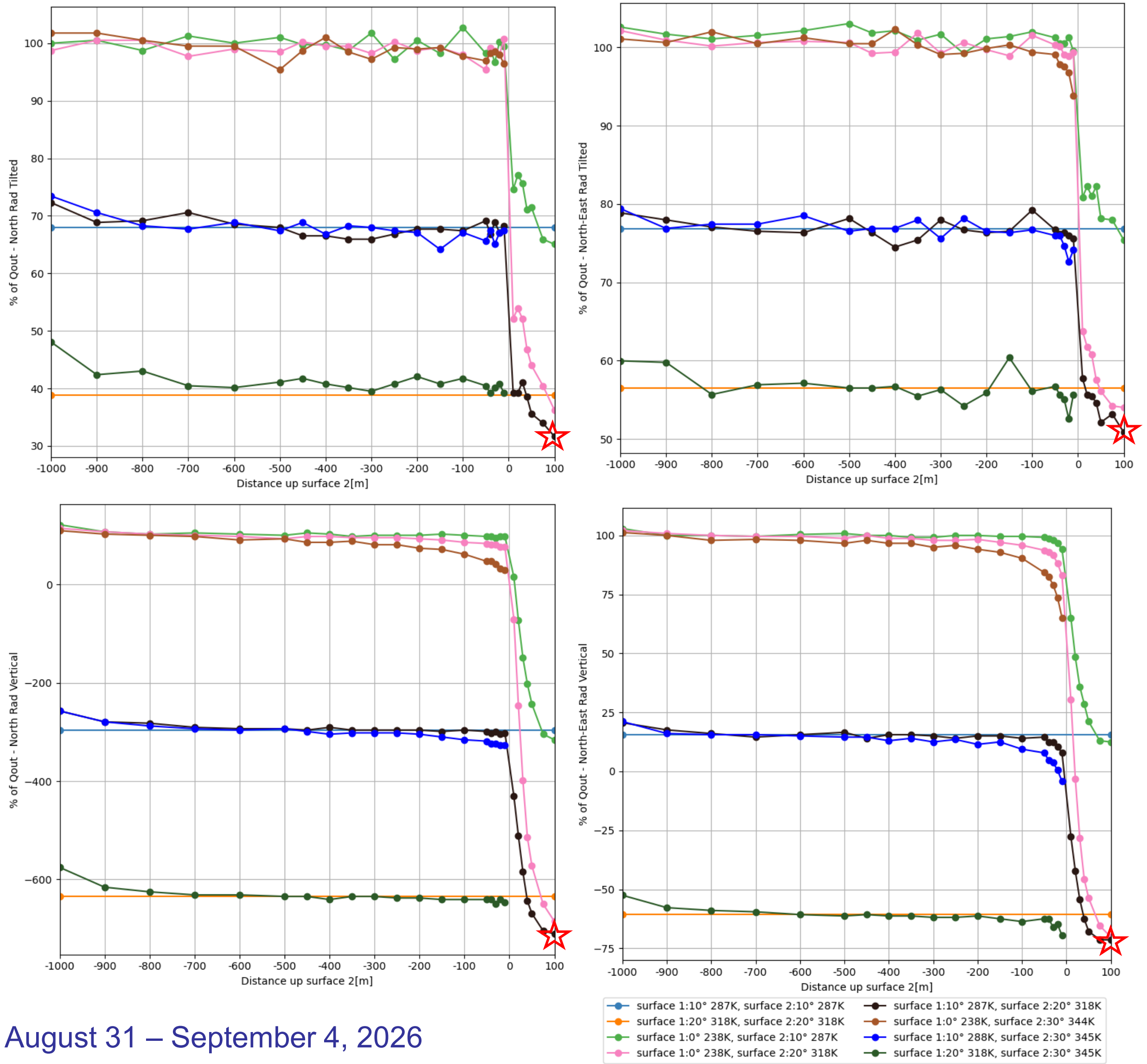
- <u>Panels seeing the sun</u>→ 100m up onto a 20º sloped surface 2 where surface 1's slope is 10º
- If surface 2 was ≤20°:
  - unchanged

$$\%of = \frac{Qout\ [W]}{Qout_{flat\ plane}\ [W]}$$



☆ = worst case

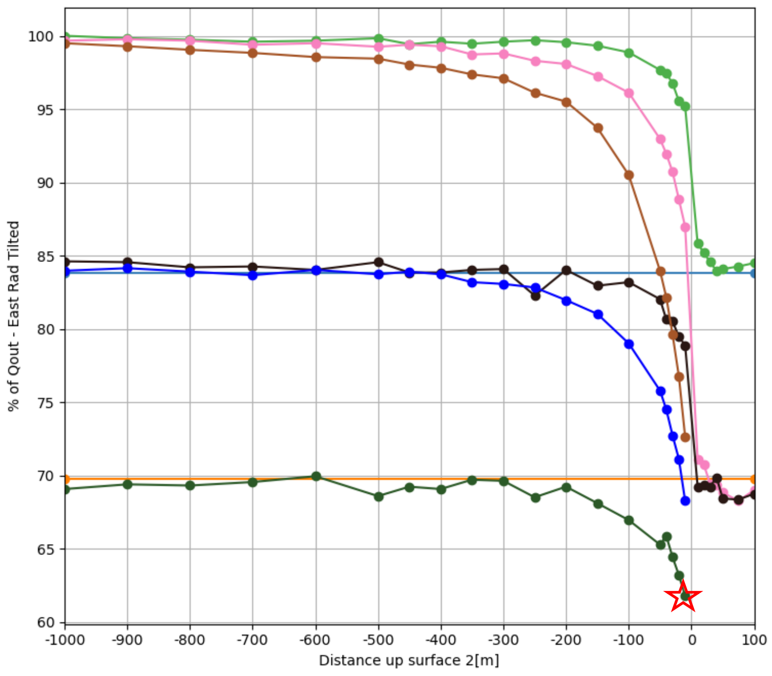
Approaching slope



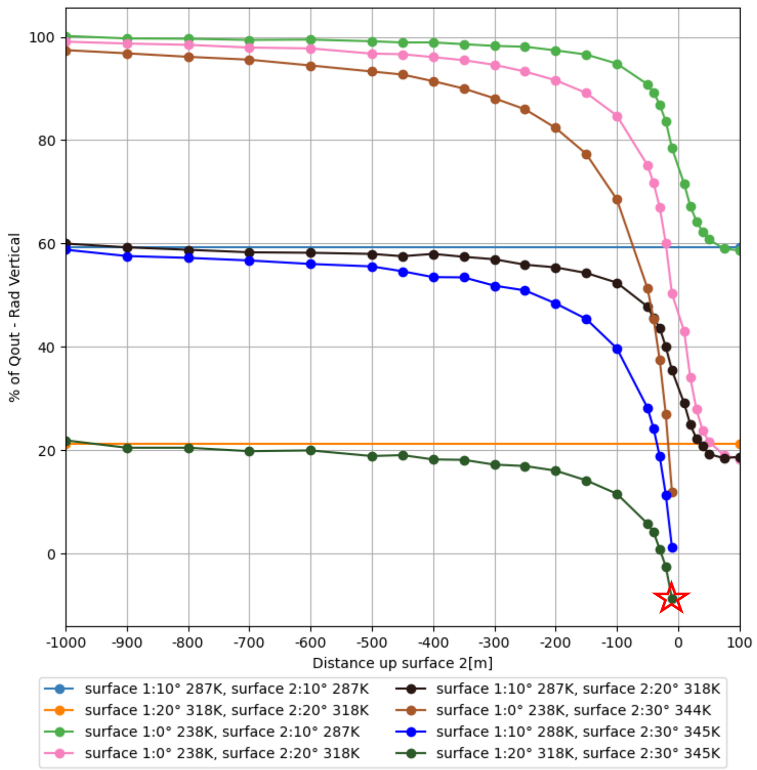
Study #2: What is the worst case per panel?

- <u>Panels not seeing slope or sun</u>→ on 20º slope just before a 30º slope.
- If surface 2 was ≤20°:
  - ~100m up on surface 2 at 20°

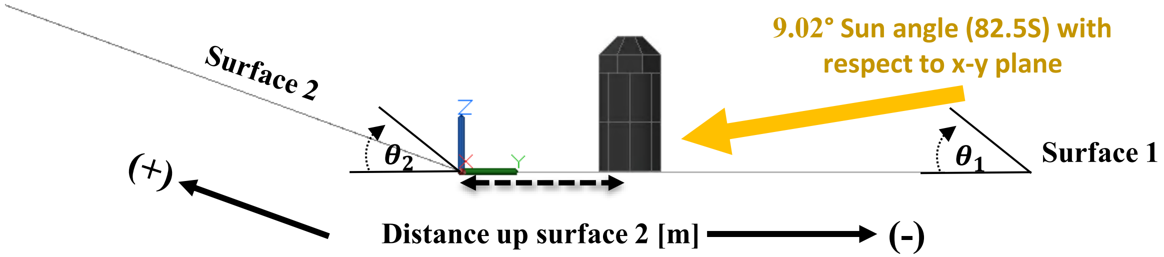
☆ = worst case



Approaching slope

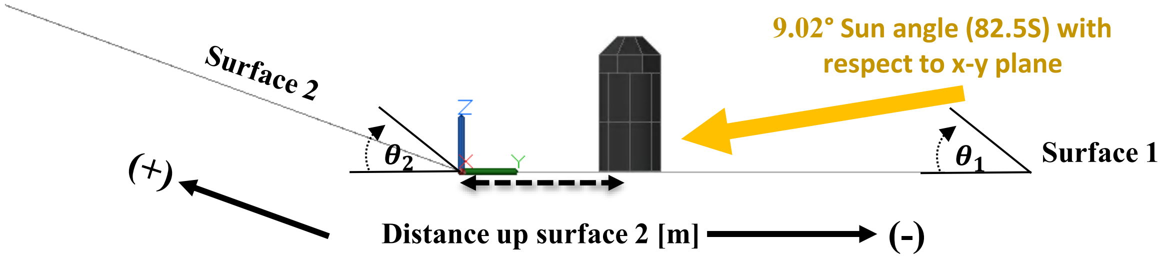


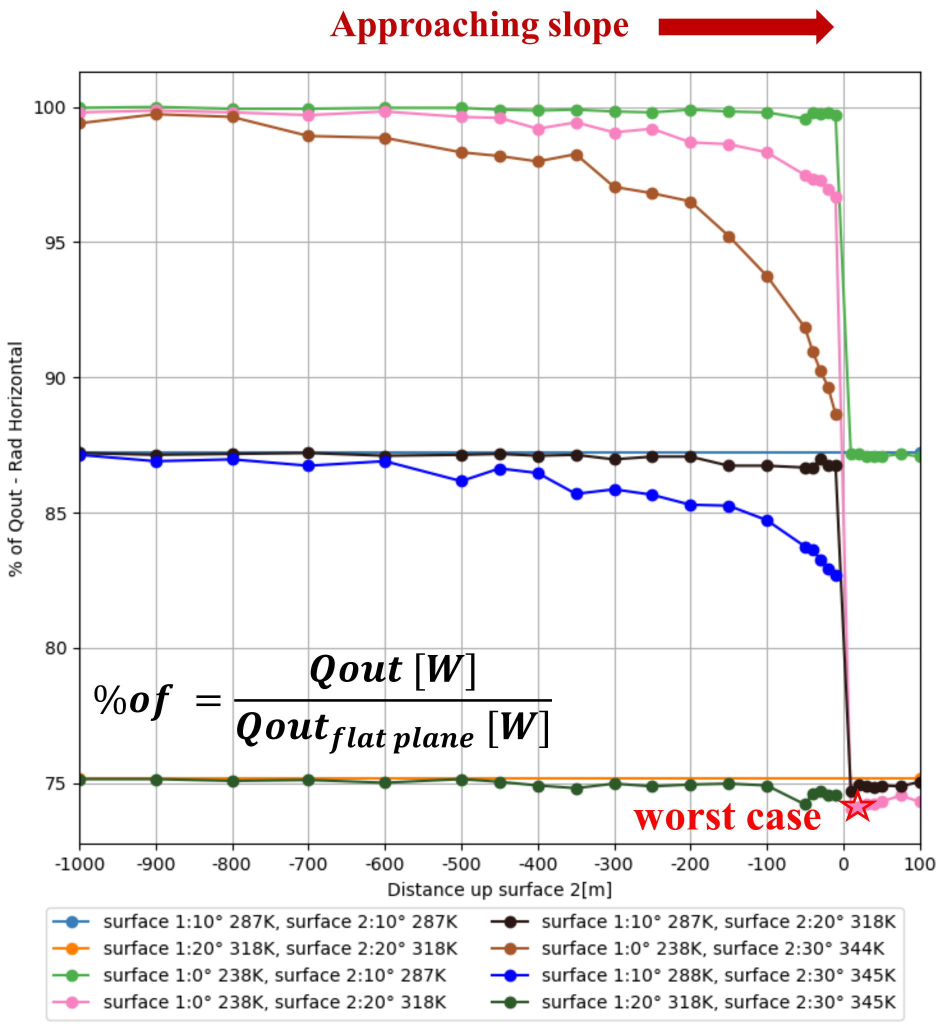
$$\%of = \frac{Qout\ [W]}{Qout_{flat\ plane}\ [W]}$$



Study #2: What is the worst case per panel?

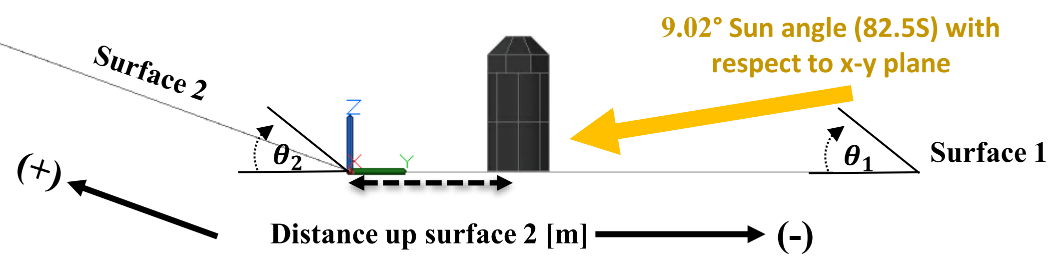
- Horizontal panels→ it was slightly up onto a 20° sloped surface where surface 1's slope is 10
- If surface 2 was ≤20°:
  - unchanged





Study #1: Can we ‘neglect’ a nearby slope?

- No, if a radiator is sized assuming a flat-tilted ground unexpected slopes >100m away can cause significant drops in heat rejection.
- Vertical panels facing the slope are most impacted.



Distance up surface 2 where $Q_{out} \leq 90\% \, Q_{out}$ when $\theta_1 = \theta_2 = 10^\circ$

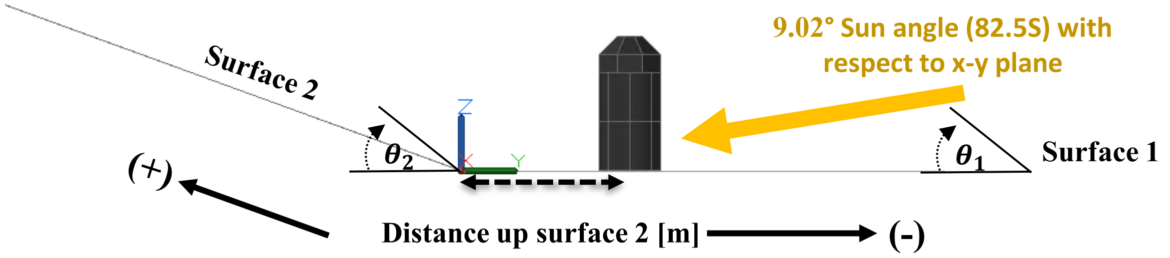
θ_1 [°]	θ_2 [°]	Total [m]	Total of Tilted Radiators [m]	Total of Vertical Radiators [m]	Horizontal Radiator [m]	Sun facing Tilted Radiator [m]	45° from Sun facing Tilted Radiator [m]	East (Not sun or slope) facing Tilted Radiator [m]	45° from Slope facing Tilted Radiator [m]	Slope facing Tilted Radiator [m]	Sun facing Vertical Radiator* [m]	45° from Sun facing Vertical Radiator** [m]	East (Not sun or slope) facing Radiator [m]	45° from Slope facing Vertical Radiator [m]	Slope facing Vertical Radiator [m]
0	10	All $>0.9Q_{@10^\circ}$	All $>0.9Q_{@10^\circ}$	All $>0.9Q_{@10^\circ}$	All $>0.9Q_{@10^\circ}$	All $>0.9Q_{@10^\circ}$	All $>0.9Q_{@10^\circ}$	All $>0.9Q_{@10^\circ}$	All $>0.9Q_{@10^\circ}$	All $>0.9Q_{@10^\circ}$	60	72	All $>0.9Q_{@10^\circ}$	All $>0.9Q_{@10^\circ}$	All $>0.9Q_{@10^\circ}$
0	20	-4	4	-13	6	6	7	5	On Slope | -78	On Slope | -122	21	15	-2	-45	-83
10	20	-49	-9	-123	4	-5	-3	-3	On Slope | -45	On Slope | -94	-952	-46	-39	-159	-214
0	30	-56	-68	-56	All $>0.9Q_{@10^\circ}$	All $>0.9Q_{@10^\circ}$	All $>0.9Q_{@10^\circ}$	-17	-208	-282	All $>0.9Q_{@10^\circ}$	All $>0.9Q_{@10^\circ}$	-26	-131	-193
10	30	-209	-136	-345	All $>0.9Q_{@10^\circ}$	All $>0.9Q_{@10^\circ}$	All $>0.9Q_{@10^\circ}$	-47	-226	-312	-957	-434	-116	-463	-547
20	30	All $<0.9Q_{@10^\circ}$	All $<0.9Q_{@10^\circ}$	All $<0.9Q_{@10^\circ}$	All $<0.9Q_{@10^\circ}$	All $<0.9Q_{@10^\circ}$	All $<0.9Q_{@10^\circ}$	All $<0.9Q_{@10^\circ}$	-382	-717	All $<0.9Q_{@10^\circ}$	All $<0.9Q_{@10^\circ}$	All $<0.9Q_{@10^\circ}$	All $<0.9Q_{@10^\circ}$	All $<0.9Q_{@10^\circ}$

***Radiators only absorb heat when $\theta_1 = \theta_2 = 10°$ and $\theta_1 = \theta_2 = 20°$. ** Radiators only absorb heat when $\theta_1 = \theta_2 = 20°$.**
On Slope = all tested locations on the slope had Q> Q_{out} when $\theta_1 = \theta_2$
Distances > than 100m, a typical margin of error for landing[17] are shown in red.

Study #1: Can we neglect a nearby slope?

E.g., on a 10º slope less than 209m away from a 30º slope Total $Q_{out} \leq 90\% \, Q_{out\ at\ 10º}$

E.g., on a 20º slope less than 717m away from a 30º slope $Q_{out} \leq 90\% \, Q_{out\ at\ 10º}$



Distance up surface 2 where $Q_{out} \leq 90\% \, Q_{out}$ when $\theta_1 = \theta_2 = 10º$

θ_1 [°]	θ_2 [°]	Total [m]	Total of Tilted Radiators [m]	Total of Vertical Radiators [m]	Horizontal Radiator [m]	Sun facing Tilted Radiator [m]	45° from Sun facing Tilted Radiator [m]	East (Not sun or slope) facing Tilted Radiator [m]	45° from Slope facing Tilted Radiator [m]	Slope facing Tilted Radiator [m]	Sun facing Vertical Radiator* [m]	45° from Sun facing Vertical Radiator** [m]	East (Not sun or slope) facing Radiator [m]	45° from Slope facing Vertical Radiator [m]	Slope facing Vertical Radiator [m]
0	10	All >0.9$Q_{@10°}$	All >0.9$Q_{@10°}$	All >0.9$Q_{@10°}$	All >0.9$Q_{@10°}$	All >0.9$Q_{@10°}$	All >0.9$Q_{@10°}$	All >0.9$Q_{@10°}$	All >0.9$Q_{@10°}$	All >0.9$Q_{@10°}$	60	72	All >0.9$Q_{@10°}$	All >0.9$Q_{@10°}$	All >0.9$Q_{@10°}$
0	20	-4	4	-13	6	6	7	5	On Slope | -78	On Slope | -122	21	15	-2	-45	-83
10	20	-49	-9	-123	4	-5	-3	-3	On Slope | -45	On Slope | -94	-952	-46	-39	-159	-214
0	30	-56	-68	-56	All >0.9$Q_{@10°}$	All >0.9$Q_{@10°}$	All >0.9$Q_{@10°}$	-17	-208	-282	All >0.9$Q_{@10°}$	All >0.9$Q_{@10°}$	-26	-131	-193
10	30	**-209**	-136	-345	All >0.9$Q_{@10°}$	All >0.9$Q_{@10°}$	All >0.9$Q_{@10°}$	-47	-226	-312	-957	-434	-116	-463	-547
20	30	All <0.9$Q_{@10°}$	All <0.9$Q_{@10°}$	All <0.9$Q_{@10°}$	All <0.9$Q_{@10°}$	All <0.9$Q_{@10°}$	All <0.9$Q_{@10°}$	All <0.9$Q_{@10°}$	-382	**-717**	All <0.9$Q_{@10°}$	All <0.9$Q_{@10°}$	All <0.9$Q_{@10°}$	All <0.9$Q_{@10°}$	All <0.9$Q_{@10°}$

*Radiators only absorb heat when $\theta_1 = \theta_2 = 10°$ and $\theta_1 = \theta_2 = 20°$. ** Radiators only absorb heat when $\theta_1 = \theta_2 = 20°$.

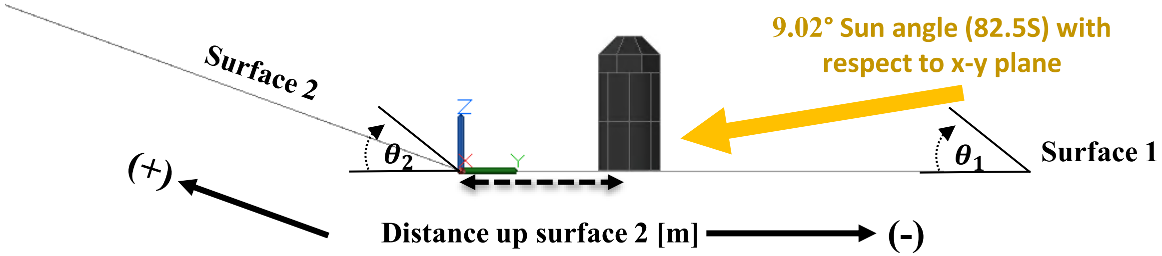
On Slope = all tested locations on the slope had Q> Q_{out} when $\theta_1 = \theta_2$

Distances > than 100m, a typical margin of error for landing[17] are shown in red.

Study #1: Can we neglect a nearby slope?

E.g., on a 20º slope less than 127m away from a 30º slope Total $Q_{out} \leq 90\%\ Q_{out\ at\ 20^\circ}$

E.g., on a 20º slope less than 143m away from a 30º slope $Q_{out} \leq 90\%\ Q_{out\ at\ 20^\circ}$



Distance up surface 2 where $Q_{out} \leq 90\%\ Q_{out}$ at $\theta_1 = \theta_2 = 20^\circ$

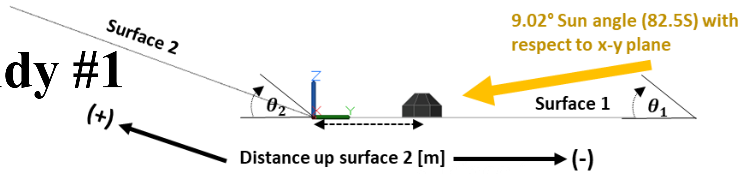
θ_1 [°]	θ_2 [°]	Total [m]	Total of Tilted Radiators [m]	Total of Vertical Radiators [m]	Horizontal Radiator [m]	Sun facing Tilted Radiator [m]	45° from Sun facing Tilted Radiator [m]	East (Not sun or slope) facing Tilted Radiator [m]	45° from Slope facing Tilted Radiator [m]	Slope facing Tilted Radiator [m]	Sun facing Vertical Radiator* [m]	45° from Sun facing Vertical Radiator** [m]	East (Not sun or slope) facing Radiator [m]	45° from Slope facing Vertical Radiator [m]	Slope facing Vertical Radiator [m]
0	10	All $>0.9Q_{@20^\circ}$	All $>0.9Q_{@20^\circ}$	All $>0.9Q_{@20^\circ}$	All $>0.9Q_{@20^\circ}$	All $>0.9Q_{@20^\circ}$	All $>0.9Q_{@20^\circ}$	All $>0.9Q_{@20^\circ}$	All $>0.9Q_{@20^\circ}$	All $>0.9Q_{@20^\circ}$	All $>0.9Q_{@20^\circ}$	All $>0.9Q_{@20^\circ}$	All $>0.9Q_{@20^\circ}$	All $>0.9Q_{@20^\circ}$	All $>0.9Q_{@20^\circ}$
0	20	All $>0.9Q_{@20^\circ}$	All $>0.9Q_{@20^\circ}$	75	All $>0.9Q_{@20^\circ}$	All $>0.9Q_{@20^\circ}$	All $>0.9Q_{@20^\circ}$	All $>0.9Q_{@20^\circ}$	On Slope | -39	On Slope | -74	50	51	All $>0.9Q_{@20^\circ}$	On Slope | -12	On Slope | -30
10	20	All $>0.9Q_{@20^\circ}$	All $>0.9Q_{@20^\circ}$	56	All $>0.9Q_{@20^\circ}$	61	All $>0.9Q_{@20^\circ}$	All $>0.9Q_{@20^\circ}$	All $>0.9Q_{@20^\circ}$	On Slope | -25	28	30	All $>0.9Q_{@20^\circ}$	All $>0.9Q_{@20^\circ}$	On Slope | -25
0	30	-14	-19	-15	All $>0.9Q_{@20^\circ}$	All $>0.9Q_{@20^\circ}$	All $>0.9Q_{@20^\circ}$	All $>0.9Q_{@20^\circ}$	-142	-193	All $>0.9Q_{@20^\circ}$	All $>0.9Q_{@20^\circ}$	All $>0.9Q_{@20^\circ}$	-55	-99
10	30	-26	-26	-30	All $>0.9Q_{@20^\circ}$	All $>0.9Q_{@20^\circ}$	All $>0.9Q_{@20^\circ}$	All $>0.9Q_{@20^\circ}$	-117	-174	All $>0.9Q_{@20^\circ}$	All $>0.9Q_{@20^\circ}$	-12	-80	-126
20	30	**-127**	-50	-519	All $>0.9Q_{@20^\circ}$	All $>0.9Q_{@20^\circ}$	All $>0.9Q_{@20^\circ}$	-17	-86	**-143**	All $<0.9Q_{@20^\circ}$	-962	-99	-347	-451

***Radiators only absorb heat when $\theta_1 = \theta_2 = 10^\circ$ and $\theta_1 = \theta_2 = 20^\circ$. ** Radiators only absorb heat when $\theta_1 = \theta_2 = 20^\circ$.**
On Slope = all tested locations on the slope had Q> Q_{out} when $\theta_1 = \theta_2$
Distances > than 100m, a typical margin of error for landing[17] are shown in red.

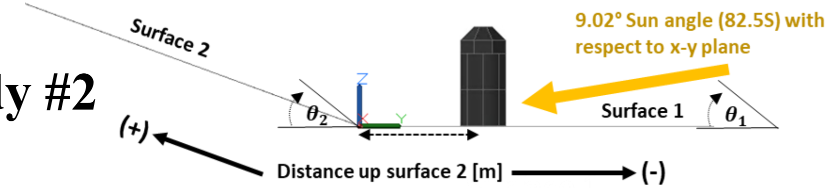
Summary of Conclusions

- Both Study #1 and #2 demonstrated that the presence of slopes, represented by a **_ shaped ground** should be considered when attempting to predict worst hot cases.
  - The overall worst case (i.e., minimum total heat rejection of all radiators) occurs just before the maximum slope the asset can encounter.
  - The per panel worst case depended on the panel's view of the slope or sun.
    - The horizontal panel's worst case was shortly up that max allowed slope of that the asset could be on (surface 2 = 20º) where surface 1 has a lower slope (0º for the 5.5m and 10º for the 20m tall lander)
    - Panels that saw the sun tended to have a worst case that was on the max slope the asset could be on (surface 2 = 20º), far enough on the slope that the heat rejection leveled off (25m for the 5.5m tall asset and 100m for the 20m tall asset). Surface 1 in these cases ranged from 5 to 10º.
    - Panels that saw the slope had a worst case on a flat ground (surface 1=0º) just before the max expected nearby slope (surface 2 = 30º).
    - Panels that saw neither the slope nor the sun (i.e., faced east) had worst cases just before the max expected nearby slope (surface 2 = 30º). Surface 1 in these cases ranged from 0º for the 5.5m tall asset to 20º for the 20m tall asset.
  - Study #1 and #2 showed that using a **\ shaped ground at** 20º for design purposes would significantly underpredict the total worst-case heat rejection if the max possible expected slope was 30º (32% for the 5.5m tall asset and 50% for the 20m tall asset).
- Study #1 showed that steady state cases can be used to predict worst case radiator heat rejections.
- Study #2 presented for each possible surface 1 and surface 2 configurations, distances where if an asset lands further away the degradation in heat rejection is ≤10% the heat rejected by a vehicle on a flat 10º, or 20º slope.

Study #1



Study #2



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“We acknowledge the use of imagery from Lunar QuickMap (https://lunar.quickmap.io), a collaboration between NASA, Arizona State University & Applied Coherent Technology Corp."

BACKUP – EXTRA DETAILS

Model Overview: Outputs

- Used SINDA subroutine TSINK1 to calculate sink temperatures in Kelvin

SINDA Logic Blocks

Logic implements the following equation to calculate average sink temperature (since each panel has the same area).

$$TSINK_{average} = \left(\sum_{i=1}^{i=\#\,Panels} TSINK^4_{panel\ i} \Big/ \#\ Panels \right)^{0.25}$$

User Code Edit

Enabled for Cond/Cap Calcs...

Comment:

Before/After Submodels | After all thermal submodels | Iteration Dependent (Variables 1)

Declarations (COMMON blocks, INTEGER, REAL):

Code:

```
        call CALC_TSINKS()
        call CALC_QOUTS()
        TFarGround = LS_REGOLITH.T294
        TFarGround_Slope = LS_REGOLITH_SLOPE.T294
```

User Code Edit

Enabled for Cond/Cap Calcs...

Comment:

Operations/Subroutine/Procedure | Subroutine Block

One node per radiator panel

```
SPELLOFF
C-------------------------------------------------------------

C-------------------------------------------------------------
F       subroutine CALC_TSINKS()
           call common

F           integer :: i
F           integer :: n_nodes
F           real :: Ts4
F           real :: Ts4sum
F           real :: Ts
F           real :: Gs
F           real :: Tsink_avg

C          Calculates average TSINK of reach panel - assume units are K
C          Horizontal Radiator ----------------------------------------------------------
F          Ts4sum=0.0
F          n_nodes = 1
F          do i=1,n_nodes
             call TSINK1('RADIATOR_HORIZONTAL',i,'none','R',1.0, Gs, Ts)
F            Ts4=Ts**(4.0)               ! Tsink to the 4th power
F            Ts4sum=Ts4sum+Ts4
F           end do
F             Tsink_avg=((Ts4sum/n_nodes)**0.25)
              TSINK_RAD_HORIZ = Tsink_avg
C          Tilted Radiator  ---------------------------------------------------------------
F          Ts4sum=0.0
F          n_nodes = 8
F          do i=1,n_nodes
             call TSINK1('RADIATOR_TILTED',i,'none','R',1.0, Gs, Ts)
F            Ts4=Ts**(4.0)               ! Tsink to the 4th power
F            Ts4sum=Ts4sum+Ts4
F           end do
F             Tsink_avg=((Ts4sum/n_nodes)**0.25)
              TSINK_RAD_TILT = Tsink_avg
C          Vertical Radiator ---------------------------------------------------------------
F          Ts4sum=0.0
F          n_nodes = 8
F          do i=1,n_nodes
             call TSINK1('RADIATOR_VERTICAL',i,'none','R',1.0, Gs, Ts)
F            Ts4=Ts**(4.0)               ! Tsink to the 4th power
F            Ts4sum=Ts4sum+Ts4
F           end do
F             Tsink_avg=((Ts4sum/n_nodes)**0.25)
            TSINK_RAD_VERT = Tsink_avg

             call TSINK1('RADIATOR_TILTED',1,'none','R',1.0, Gs, TSINK_RAD_TILT_N)
             call TSINK1('RADIATOR_TILTED',2,'none','R',1.0, Gs, TSINK_RAD_TILT_NE)
             call TSINK1('RADIATOR_TILTED',3,'none','R',1.0, Gs, TSINK_RAD_TILT_E)
             call TSINK1('RADIATOR_TILTED',4,'none','R',1.0, Gs, TSINK_RAD_TILT_SE)
             call TSINK1('RADIATOR_TILTED',5,'none','R',1.0, Gs, TSINK_RAD_TILT_S)
             call TSINK1('RADIATOR_VERTICAL',1,'none','R',1.0, Gs, TSINK_RAD_VERT_N)
             call TSINK1('RADIATOR_VERTICAL',2,'none','R',1.0, Gs, TSINK_RAD_VERT_NE)
             call TSINK1('RADIATOR_VERTICAL',3,'none','R',1.0, Gs, TSINK_RAD_VERT_E)
             call TSINK1('RADIATOR_VERTICAL',4,'none','R',1.0, Gs, TSINK_RAD_VERT_SE)
             call TSINK1('RADIATOR_VERTICAL',5,'none','R',1.0, Gs, TSINK_RAD_VERT_S)

F       end subroutine
C
```

Model Overview: Outputs

- Used SINDA subroutines QFLOWSET and QFLOW to get heat rejected by the radiators in Watts
  - Heat rejected by individual horizontal and vertical radiators was calculated using: $Q = \varepsilon \sigma A\left(T_{rad}^4 - T_{sink}^4\right)$

SINDA Logic Blocks

User Code Edit

Enabled for Cond/Cap Calcs...

Comment:

Operations/Subroutine/Procedure | Operations Block Post Build (TDPOSTBL)

Declarations (COMMON blocks, INTEGER, REAL):

Code:

```
C      Call CALL QFLOWSET(setid, 'smn1', list1, 'smn2', list2)

        CALL QFLOWSET(1, 'RADIATOR_HORIZONTAL_BOUNDARY', 0, 'RADIATOR_HORIZONTAL', 0)
        CALL QFLOWSET(2, 'RADIATOR_VERTICAL_BOUNDARY', 0, 'RADIATOR_VERTICAL', 0)
        CALL QFLOWSET(3, 'RADIATOR_TILTED_BOUNDARY', 0, 'RADIATOR_TILTED', 0)
        CALL QFLOWSET(4, 'STRUCTURE_BOUNDARY', 0, 'STRUCTURE', 0)
```

User Code Edit

Enabled for Cond/Cap Calcs...

Comment:

Before/After Submodels | After all thermal submodels | Iteration Dependent (Variables 1)

Declarations (COMMON blocks, INTEGER, REAL):

Code:

```
        call CALC_TSINKS()
        call CALC_QOUTS()
        TFarGround = LS_REGOLITH.T294
        TFarGround_Slope = LS_REGOLITH_SLOPE.T294
```

```
C-----------------------------------------------------------------
F      subroutine CALC_Qouts()
          call common

F          real :: qlin
F          real :: qrad

C          CALL QFLOWSET(1, 'RADIATOR_HORIZONTAL_BOUNDARY', 0, 'RADIATOR_HORIZONTAL', 0)
C          CALL QFLOWSET(2, 'RADIATOR_VERTICAL_BOUNDARY', 0, 'RADIATOR_VERTICAL', 0)
C          CALL QFLOWSET(3, 'RADIATOR_TILTED_BOUNDARY', 0, 'RADIATOR_TILTED', 0)
C          CALL QFLOWSET(4, 'STRUCTURE_BOUNDARY', 0, 'STRUCTURE', 0)

          CALL QFLOW(1, qlin, qrad, QOUT_RAD_HORIZ)
          CALL QFLOW(2, qlin, qrad, QOUT_RAD_VERT)
          CALL QFLOW(3, qlin, qrad, QOUT_RAD_TILT)
          CALL QFLOW(4, qlin, qrad, QOUT_STRUCT)

F      end subroutine
C
```

Study#2 Worst Case Heat Rejection Summary

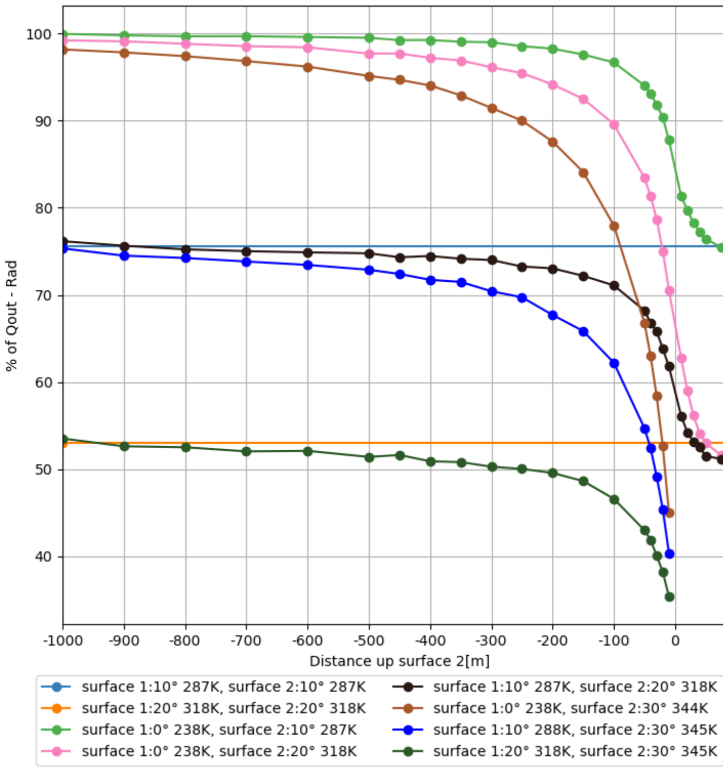
- Per panel worst case depends on direction – e.g., pointing to or away from the sun.
- Radiator tilt 45° verses vertical does not impact worst case configuration.

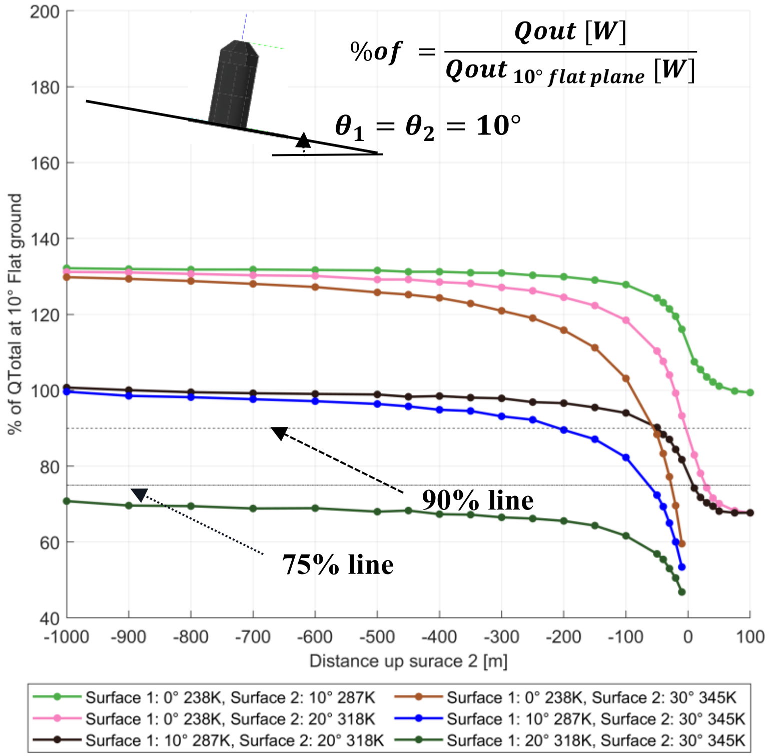
Steady State Heat Rejection Comparisons: (-) Q indicates a TSINK > T radiator
N – faces sun, S – faces surface 2 (slope), E – faces +x, SE – faces 45° away from slope, NE – faces 45° away from sun

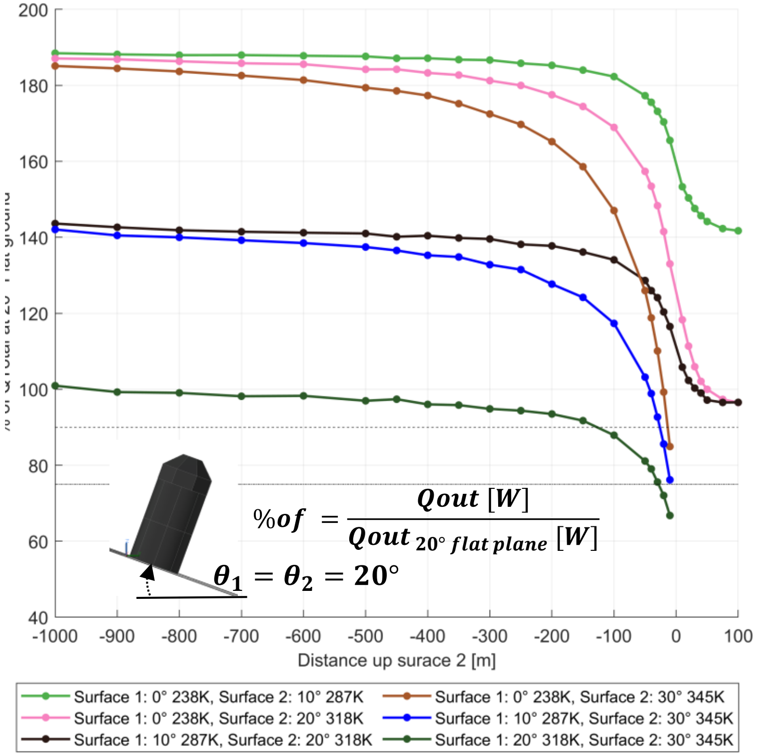
	$Q = \varepsilon\sigma A\left(T_{rad}^4 - T_{sink}^4\right)$ [W]	TILTED	VERT	HORIZ	TILT_N	TILT_NE	TILT_E	TILT_SE	TILT_S	VERT_N	VERT_NE	VERT_E	VERT_SE	VERT_S	Total
	Base value Slopes = 0°	20165	15121	2977	1297	1761	2936	3159	3166	188	898	2572	2653	2710	38263
	$\Delta Q_{\text{Base case - Worst case}}$	7518	16439	772	887	865	1121	1716	2071	1539	1541	2058	2990	3676	24715
	% $\lvert$diff $Q_{\text{Base case - Worst case}}\rvert$	37%	109%	26%	68%	49%	38%	54%	65%	820%	172%	80%	113%	136%	65%
Worst case – with restrictions: no slopes >30°, asset cannot be on slopes >20°	**Surface 1 slope**	20	20	0	10	10	20	0	0	10	10	20	0	0	20
	Surface 2 slope	30	30	20	20	20	30	30	30	20	20	30	30	30	30
	Distance up surface 2 [m]	-10	-10	10	100	100	-10	-10	-10	100	100	-10	-10	-10	-10
	Worst case value [W]	12647	-1318	2204	409	896	1814	1443	1096	-1351	-643	514	-337	-967	13548
	Value at Surface 1 & Surface 2 at 20° slope	14854	3201	2238	504	994	2050	2767	2736	-1205	-545	979	1128	1251	20293
	$\Delta Q_{\text{Worst case - value for both surfaces at 20° slope}}$	-2207	-4519	-33	-95	-98	-235	-1324	-1640	-146	-98	-465	-1465	-2218	-6745
	% $\lvert$diff $Q_{\text{Worst case - Value at Surface 1\& Surface 2 at 20° slope}}\rvert$	17%	343%	2%	23%	11%	13%	92%	150%	11%	15%	91%	435%	229%	50%
	Value at Surface 1 at 20° slope & Surface 2 at 30° =10m from surface 2	12647	-1318	2220	507	979	1814	2238	2086	-1228	-626	514	93	-65	13548
	$\Delta Q_{\text{Worst case - Value at Surface 1 at 20° slope \& Surface 2 at 30° =10m from surface 2}}$	0	0	-15	-98	-83	0	-795	-990	-123	-17	0	-430	-902	0
	% $\lvert$diff $Q_{\text{Worst case - Value at Surface 1 at 20° slope \& Surface 2 at 30° =10m from surface 2}}\rvert$	0%	0%	1%	24%	9%	0%	55%	90%	9%	3%	0%	128%	93%	0%
Worst case – with restrictions: no slopes >20°, asset cannot be on slopes >20°	**Surface 1 slope**	10	0	0	10	10	0	0	0	10	10	0	0	0	0
	Surface 2 slope	20	20	20	20	20	20	20	20	20	20	20	20	20	20
	Distance up surface 2 [m]	100	100	10	100	100	75	-10	-10	100	100	100	-10	-10	100
	Worst case [W]	14526	2771	2204	409	896	2004	2290	2088	-1351	-643	945	934	576	19584
	$\Delta Q_{\text{Worst case - value for both surfaces at 20° slope}}$	-327	-430	-33	-95	-98	-46	-477	-648	-146	-98	-34	-194	-675	-708
	% $\lvert$diff $Q_{\text{Worst case- value at Surface 1\& Surface 2 at 20° slope}}\rvert$	2%	16%	2%	23%	11%	2%	21%	31%	11%	15%	4%	21%	117%	4%

Study #1: Can we neglect a nearby slope?

- A _ shaped ground results in lower heat rejection than a \ shaped ground :
  - 0° slope, existing on a 10° or 20° slope would exceed a 10% Q margin*.
  - If the asset was designed for a 10° slope, landing on a 10° <209m from a 30° slope would exceed a 10% Q margin , landing on a 10° <49m from a 20° slope would exceed a 10% Q margin.
  - If the asset was designed for a 20° slope, landing on a 20° <127m from a 30° slope would exceed a 10% Q margin.
  - Note: the impacts to radiators with different orientations are different.
  - Note: % of Q values with respect to a 10° or 20° flat plane can be >100.



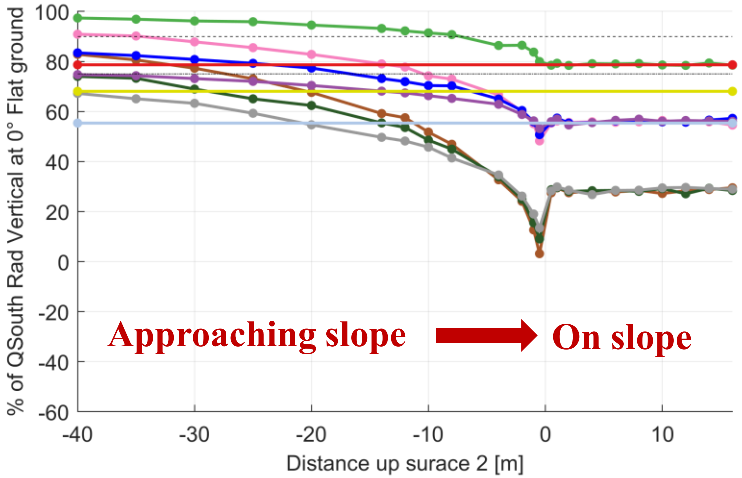




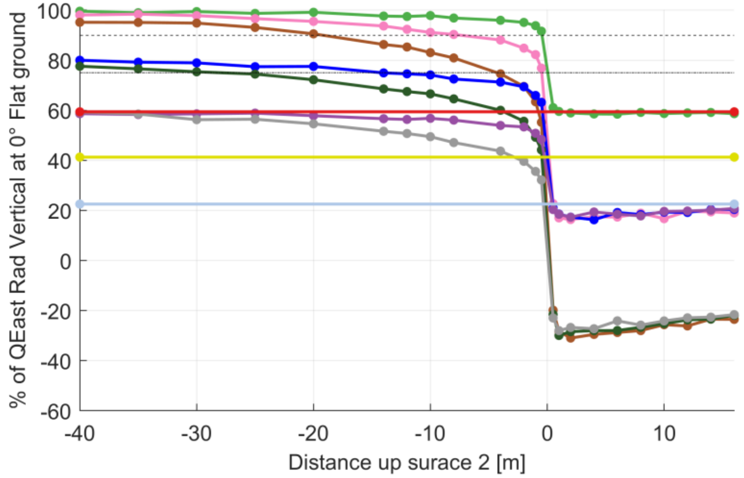
Extra Results: 1ft^2 Box

- When approaching a slope, the worst case tends to be:
  - South facing panel – close to but not yet on the slope
  - + x facing panel – a short distance up the slope
  - Sun facing panel – on the slope

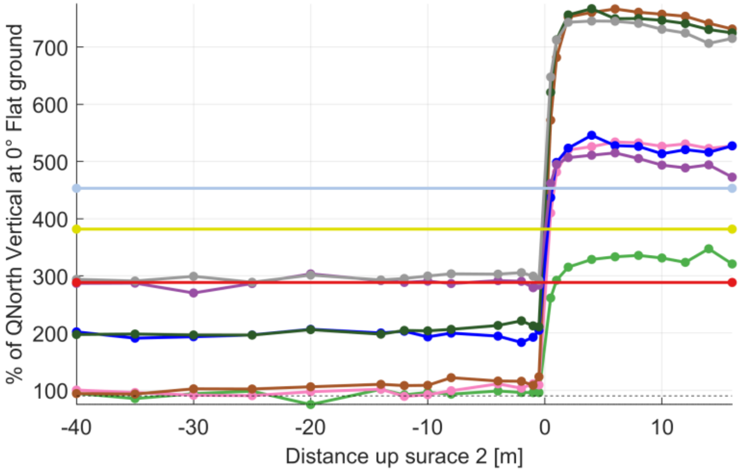
Facing Slope

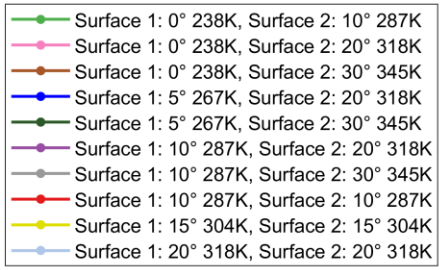


Facing +x

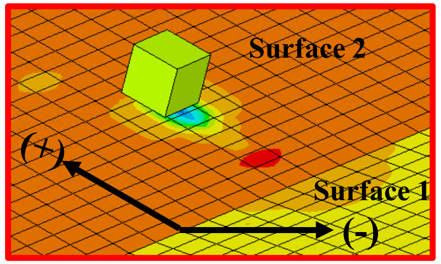


Facing Sun





$$\%of \;=\; \frac{Qout\,[W]}{Qout_{\,0°\,flat\,plane}\,[W]}$$

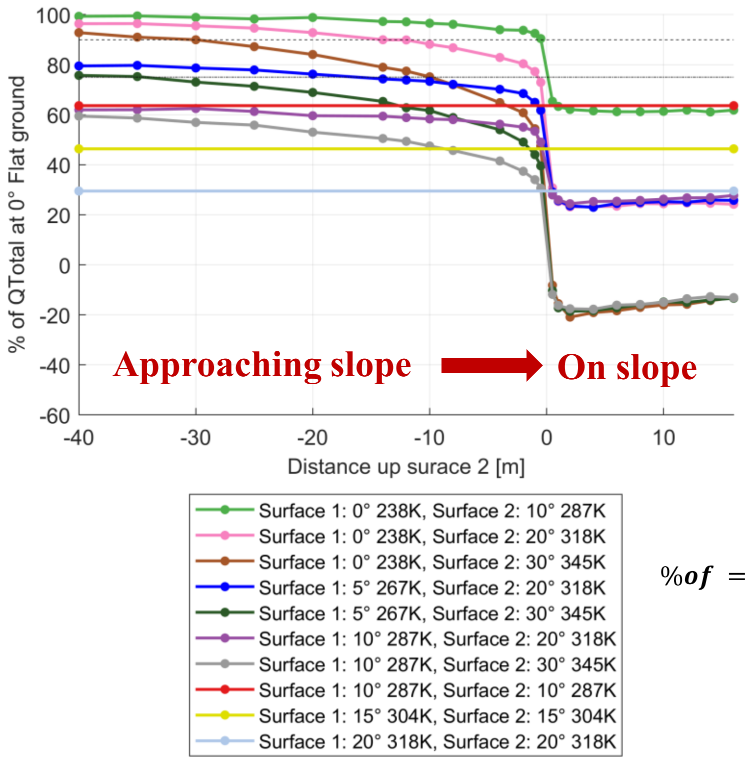


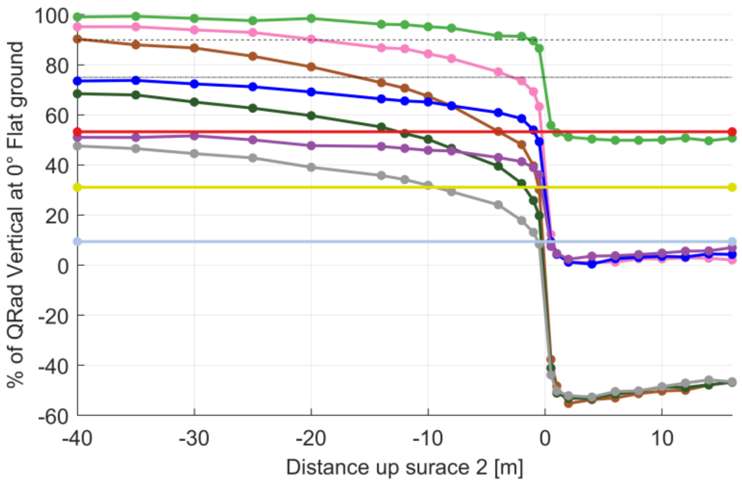
Distance up surface 2 [m]

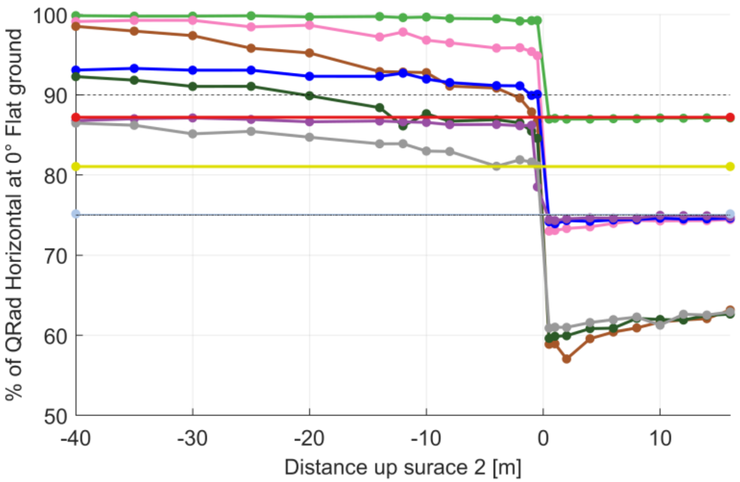
$$\%ofQNorth \;=\; \frac{Qin\,[W]}{Qin_{\,0°\,flat\,plane}\,[W]}$$

Extra Results: 1ft^2 Box

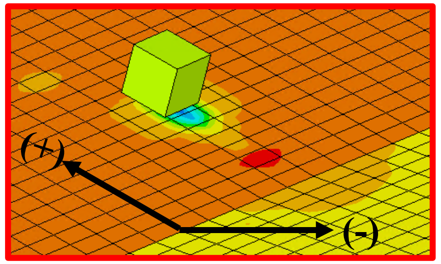
- When approaching a slope, the worst case tends to be:
  - Total – a short distance up the slope
  - All vertical panels – a short distance up the slope
  - Horizontal - a short distance up the slope







$$\%of = \frac{Qout\ [W]}{Qout_{0°\ flat\ plane}\ [W]}$$



Distance up surface 2 [m]