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Lunar Surface Thermal Analysis Roadmap

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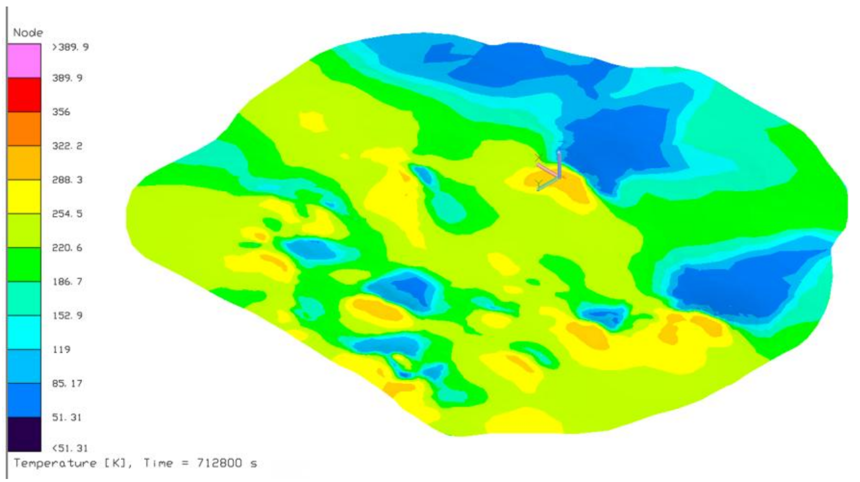
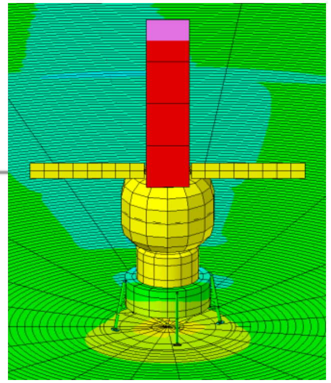
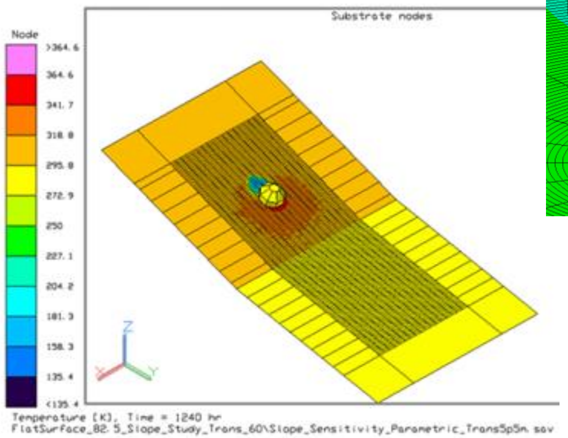
Introduction

- Much of NASA's institutional intuition regarding environment model development pace (i.e., model fidelity vs. time) is based on extensive experience with more predictable (orbital) environments.
- The extreme complexity and uncertainty inherent to lunar surface missions often requires a more complex, nuanced approach to thermal model development
- For lunar surface missions, con ops and environments are both complex and uncertain. Often, landing sites are not narrowed down to a short list until well after critical design review (CDR)
- **Because of this, defining what "bounding but reasonable" means for lunar surface analysis is almost always very challenging and situation-specific.**
- There are many ways to approach this problem. This work discusses some common lunar surface modeling methods and when they are likely to be most useful for different thermal system and mission design phases







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Lunar Surface Modeling Flow Chart

Project Phases & Milestones

Pre-Phase A	Phase A	Phase B	Phase C	Phase D	Phase E
Concept studies	Concept	Preliminary Design	Final Design & Build	Test, Verify, Validate	Operations

Milestones:
- Mission Concept Review (MCR)
- System Requirements Review (SRR)
- Preliminary Design Review (PDR)
- Critical Design Review (CDR)
- System Acceptance Review (SAR)
- Flight Readiness Review (L -<2 weeks)
- Launch

Trades: Architecture Feasibility → Requirements Generation → Design

Show requirements compliance: Bounding mission phases → All phases

Site specific analysis for mission planning

Reduced order models for trades
Early parametrics

Low fidelity assets
Bound worst hot/cold with conservativism

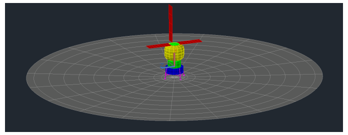
Reduced order models for trades
Detailed models for checking compliance

Correlated models for confirming ability to operate at planned site + Specifying operational limitations (e.g., location/time limits)

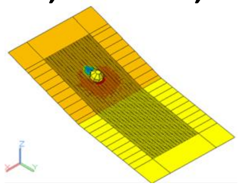
Meshed terrain models

Simple models: made with basic shapes

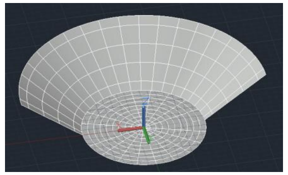
e.g., Disk model for flat regions, cold cases



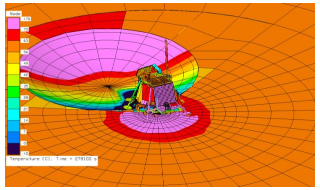
e.g., L-shaped model for general S. Pole, nominal, hot case



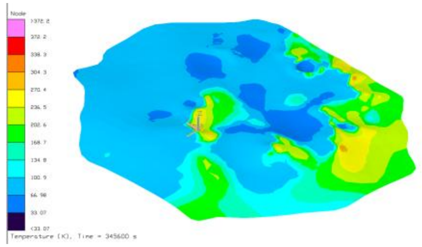
e.g., Stadium shape for hot cases



e.g., Disk with crater



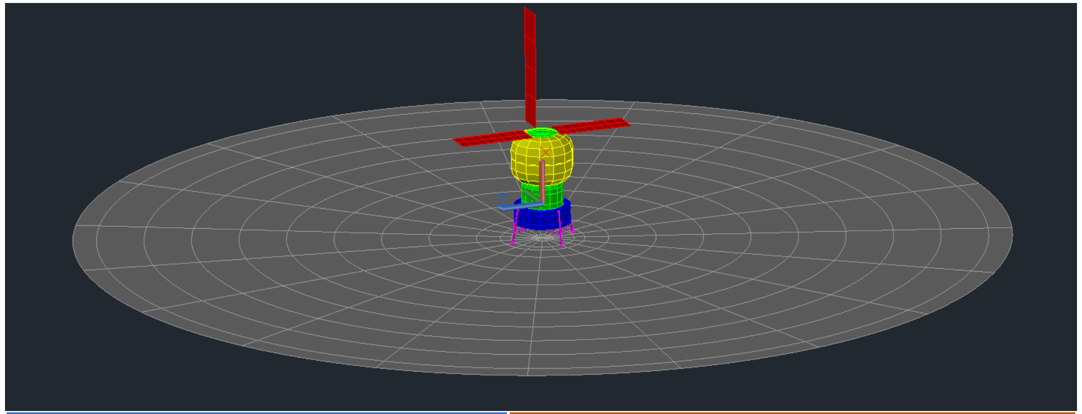
e.g., Meshed terrain model for site-specific analysis



Learnings From a Lunar Lander – Parts 1 & 2 (https://tfaws.nasa.gov/wp-content/uploads/TFAWS2025-TCP-I-01_Blue-Ghost-Lander_Sweeney.pptx)

1 Disk Model

- Composed of a flat disk, with a higher node density near the center to capture local effects and large enough to approximate the field of view to an infinite plane.*
- Transient models include regolith sublayers.
- Its utility is limited by the lack of options for capturing bounding cases due to terrain effects.



Pros	Cons
Easy to build	Does not accurately capture the terrain features emitting, reflecting, and blocking thermal energy.
Computationally efficient (less nodes than square ground)	Less useful for polar regions which have a higher density of tall terrain features.
	Generally, not recommended for estimating regolith sublayer temperatures (in non-flat regions) due to the lack of terrain influence and inaccurate solar access.
	Cannot capture accurate solar illumination timelines.

*Thermal Desktop's Idealized Planet can be used to model far field terrain whose temperature is negligibly impacted by the vehicle.

1 Disk Model

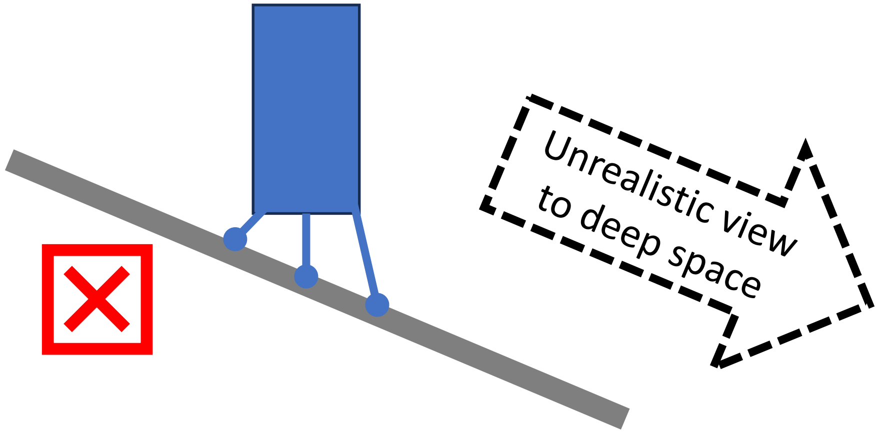
The following are example situations where the disk model may be useful for lunar surface thermal analysis

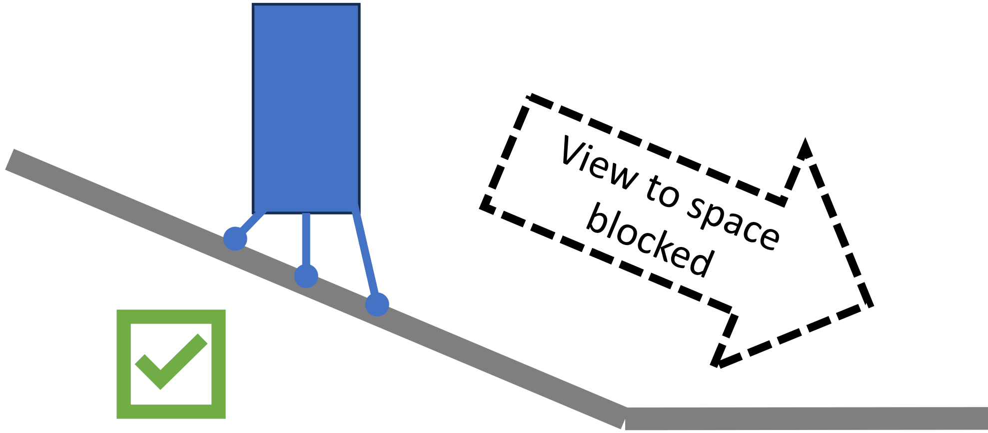
a) **Early radiator size estimates during concept studies, with the addition of terrain performance degradation factors. Generally steady-state is acceptable for preliminary studies.**

b) **Used up to PDR or phase B if the thermal system is**
- **Only required to survive flat featureless lunar environments (such as lunar mare or some parts of Connecting Ridge)**
- **Proven to not be sensitive to any potential terrain features (e.g., a large lunar lander far from terrain)**

c) **Used up to critical design review or phase C for cold cases such as inside a PSR, on top of a tall terrain feature during lunar night, cold biased lunar sunset, etc.**
- **Note these cases may require special modifications. For example, a PSR case would benefit from a rim to block deep space, and modeling lunar night on a hill may also require under sizing the ground plane to capture the negative horizon elevation angle (matching realistic view factor to space).**

Note, tilting the disk model can be used to achieve more accurate local temperatures when modeling a lunar asset on a slope. ***However, it is not an accurate way to account for terrain effects.*** *Large, three-dimensional terrain will take up a larger percent of a radiator's field of view and block the comparatively colder view to deep space.*





1 Disk Model

Modeling Methods:

- Node Type:

  Ground plane nodes should be calculated diffusion nodes rather than boundary nodes to capture the mutual interactions between the vehicle and the lunar surface.

- Disk Sizing

  Ground plane sizing recommendations can be found in the Lunar Thermal Analysis Guidebook (LTAG), section 9.3. *NOTE: The equations found in section 9.3.1.3 are known to be erroneous (e.g., under conservative) and will be fixed in the next revision of the LTAG. The un-simplified equations are correct.*

- Discretization

  Radial and azimuthal discretization near the center of the disk should be sufficiently high to capture the shadow and reflected heat from the lunar asset. Far-field discretization, outside the influence of the lunar asset can be very coarse

- Subsurface heating

  A geothermal heat flux (about 0.0090 to 0.045 with a global average of 0.018W/m^{2}K) is imposed on the top layer of lunar regolith from radioisotopes in the crust. Temperatures in shadowed craters are sensitive to ground heat flux.

- Approximating terrain effects

  One way to roughly approximate the effect of terrain is to apply an external heat flux or degrade heat rejection capability using values obtained from terrain studies. See "Lunar South Pole Terrain Effects on Radiator Performance" (https://ntrs.nasa.gov/citations/20250007546) and "Lunar Latitude and Terrain Radiator Sensitivity Study" (https://ntrs.nasa.gov/citations/20240011168)

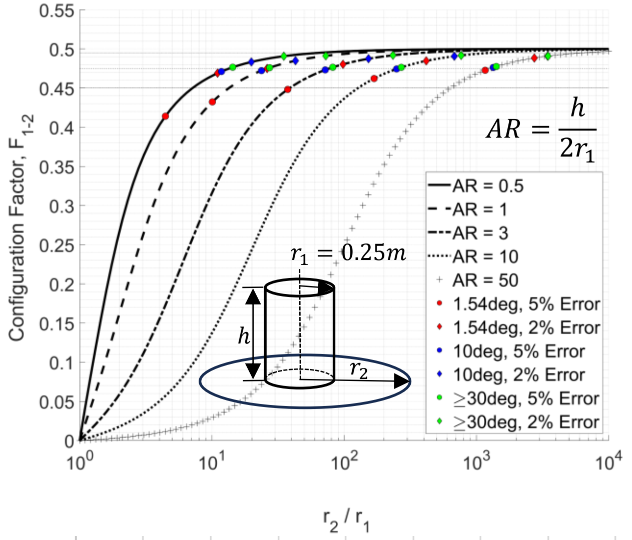
- Tilting

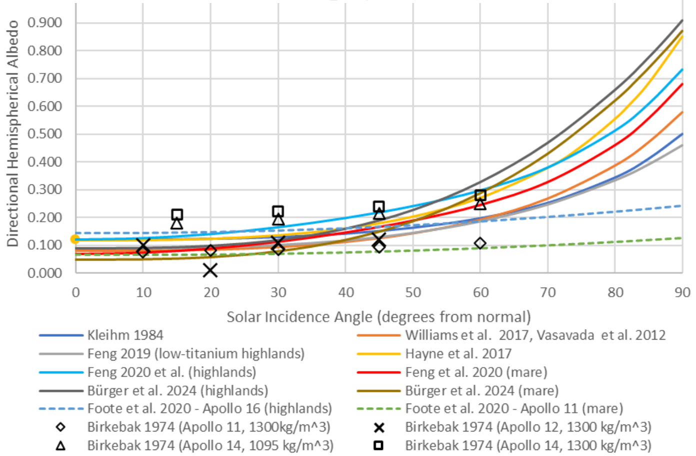
  One way to roughly approximate the effect of slope on the local terrain temperature is to either tilt the terrain toward the sun or increase the maximum solar elevation angle. Typically, the slope angle is selected to match the maximum operational slope requirement for the given lunar surface element. However, this method results in an incomplete picture of the thermal environment that would be expected on a sloped surface and should be used with caution.

- Optical Properties

  Optical properties can have a significant impact on ground temperatures. The impact to surface assets varies. Many models have used the lunar surface normal albedo values that were reported in the DSNE Rev I, which is incorrect. The albedo varies based on incident sun angle. Due to the uncertainty in albedo at high incidence angle DSNE Rev J will present piecewise functions bounding these albedos. Note that setting the lunar surface albedo to an artificially high value will result in hotter ground temperatures, however, this is not a substitute for including terrain effects.

>10°Elevation Angle, 5% Error in Q_{IR}: $r_2 = 28.21 AR r_1$





Directional hemispherical albedos models derived from fitting thermal models to LRO Diviner data plotted against laboratory measured Apollo albedos from Birkebak 1974 and the semi-empirical functions from Foot et al. 2020 (based on laboratory measurements).

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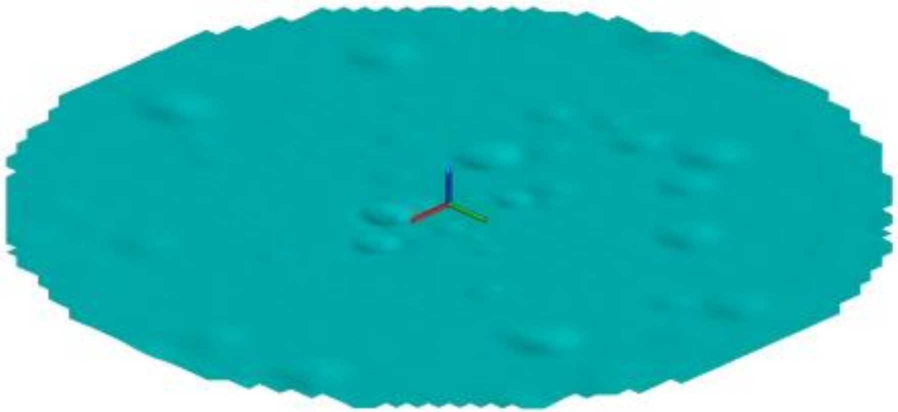
2 Disk Model + Features

- The addition of small surface features such as boulders and craters to the disk model, allows for isolating and assessing the total impact of these features, but it carries many of the same drawbacks as the featureless disk model
- While this method can be useful for performing dedicated studies, it is of limited use for modeling a flight-like environment unless the landing site is relatively flat and known to lack large terrain features



Pros	Cons
Allows for assessing sensitivity to small terrain features	Does not accurately capture the effect of larger scale terrain features
Computationally efficient (depending on feature density)	Generally, not recommended for estimating regolith sublayer temperatures (in non-flat regions)
	Not able to assess the compounding effects of both large and small terrain features
	Cannot capture accurate solar illumination timelines.

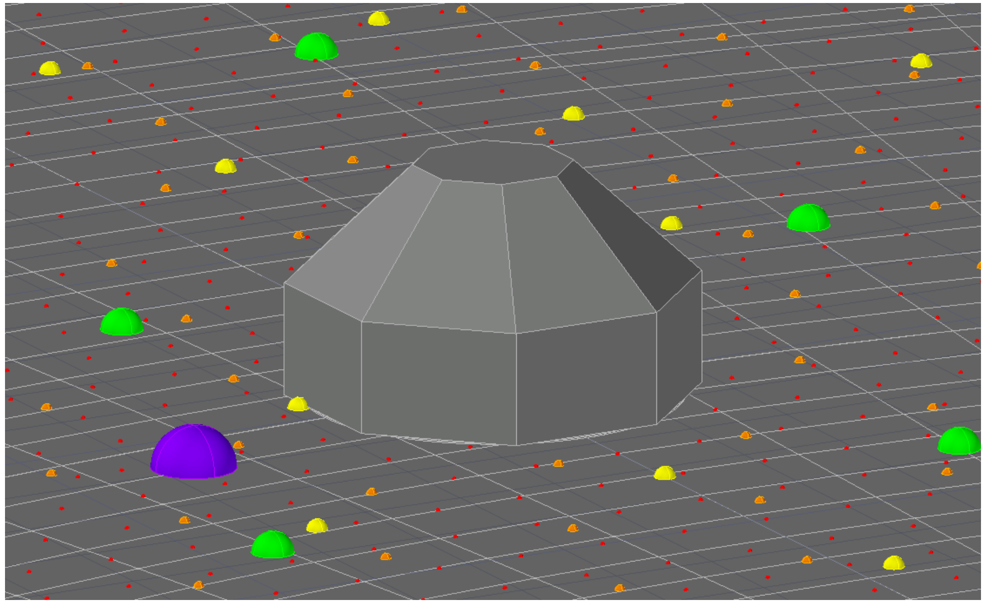
2 Disk Model + Features

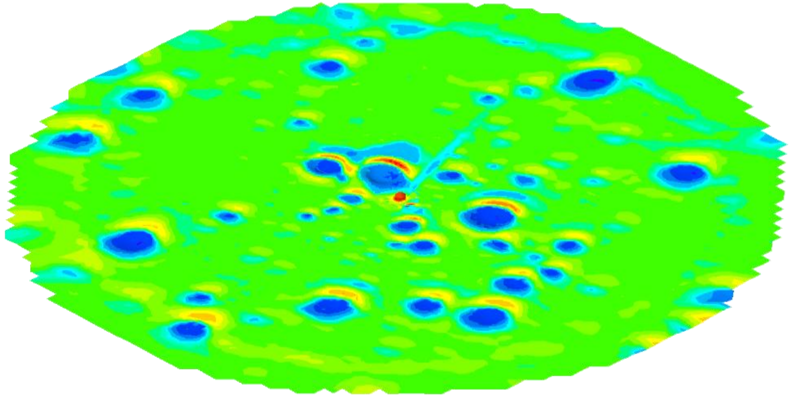
The following are situations where the disk model with features may be useful for lunar surface thermal analysis

a) **Sensitivity studies performed during concept definition, to determine the surface feature sizes the TCS is sensitive to**

b) **Used up to critical design review or phase C if the thermal system is only required to survive very flat lunar environments or is proven to not be sensitive to any large terrain features (hills, large craters, etc.)**

c) **Modified version used up to critical design review or phase C for cold cases such as inside a PSR, on top of a tall terrain feature during lunar night, etc.**





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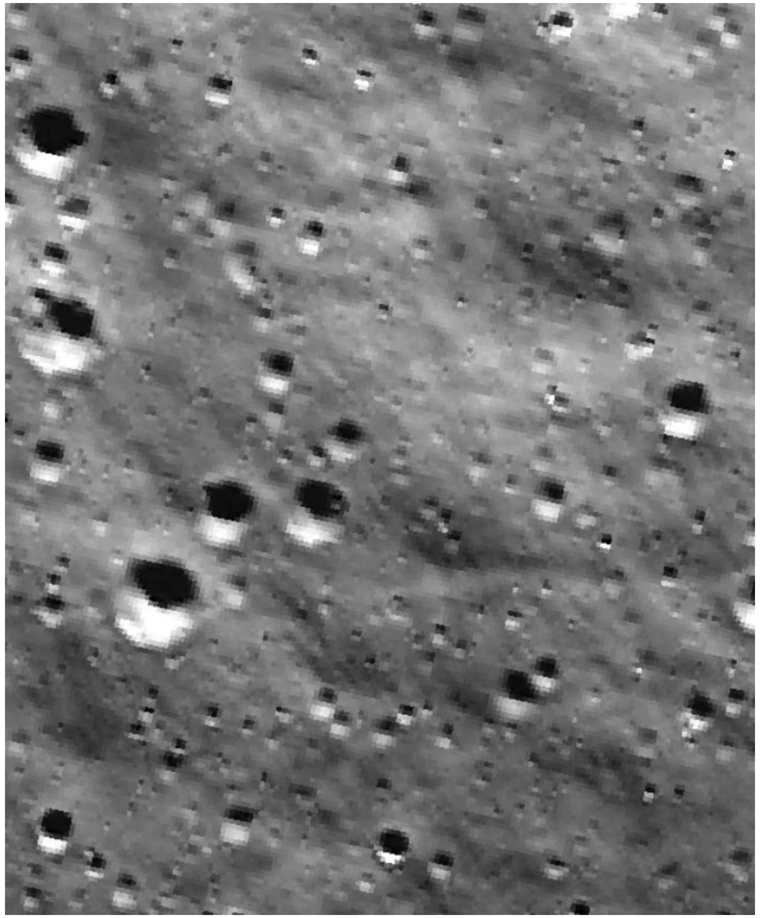
2 Disk Model + Features

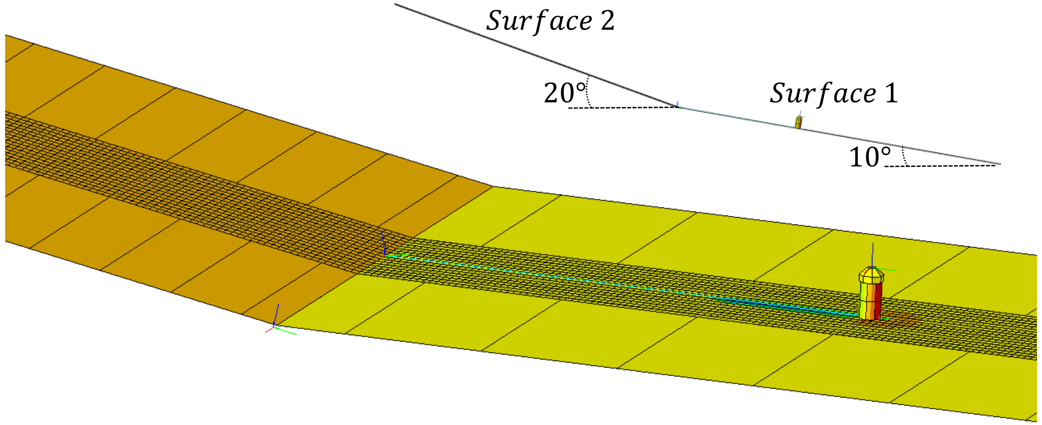
Modeling Methods:

- The same methods for modeling the featureless disk apply here
- Rocks may be modeled using primitives such as solid hemispheres or solid hemi-ellipsoids.
  - Note that regolith covered in small rocks is currently believed to contribute negligibly more thermal energy compared to bare diffusive regolith
  - Typically, the greatest impact from rocks will come from individual interactions with one or more large rocks
- Craters can be modeled using paraboloids
  - Addition of craters will require a more complicated collection of primitives (more than just a single disk) to integrate the crater with the rest of the ground plane
  - Ranges of crater diameters to use can be found by looking at Narrow Angle Camera (NAC) imagery of prospective landing sites in LROC Quickmap (quickmap.lroc.im-ldi.com) and using tools to measure diameter
  - Crater depth can then be obtained using crater aspect ratios found in section 3.4.1.2 in the Cross-Program Design Specification For Natural Environments (SLS-SPEC-159 or DSNE)
    - LuNaMaps sythcrater program can also be used to autogenerate terrain with crater distributions from DSNE.



3 L Model

- Composed of two flat surfaces to represent an asset nearing a slope.
- Like the disk model, has a higher node density near the center to capture local effects and large enough to approximate the field of view to an infinite plane.
- Estimates possible terrain effects from nearby slopes.
  - Requires knowing possible range of slopes for surface 1 and surface 2.
- Steady state runs can predict worst case radiator heat rejections
- Fairly broadly applicable across design phases and landing regions. However, the simplified slope results in a model that may may not bound worst case terrain effects.



Pros	Cons
Captures effects of nearby slopes.	May not bound the actual worst case hot condition at some landing sites (e.g., not sufficient for approaching a stadium shaped hill).
Run much faster than meshed terrain models	Large case matrix needed to capture hot cases for all vehicle components (vary sun angles, vehicle pointing & placement)
Easy to adjust slopes to 0° also capture cold PSR case.	Cannot capture accurate solar illumination timelines.

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3 L Model

The following are situations where the L model may be useful for lunar surface thermal analysis

a) **Pre-CDR rapid turn-around design analysis cycles (e.g., sensitivity studies, design trades).**

b) **Showing requirements compliance through CDR and Verification & Validation if the thermal system is only required to approach simple slopes - e.g., does not approach a stadium type of slope.** *NOTE: work is currently ongoing to create a validated simple thermal model that bounds the worst hot case for possible HLS landing sites*

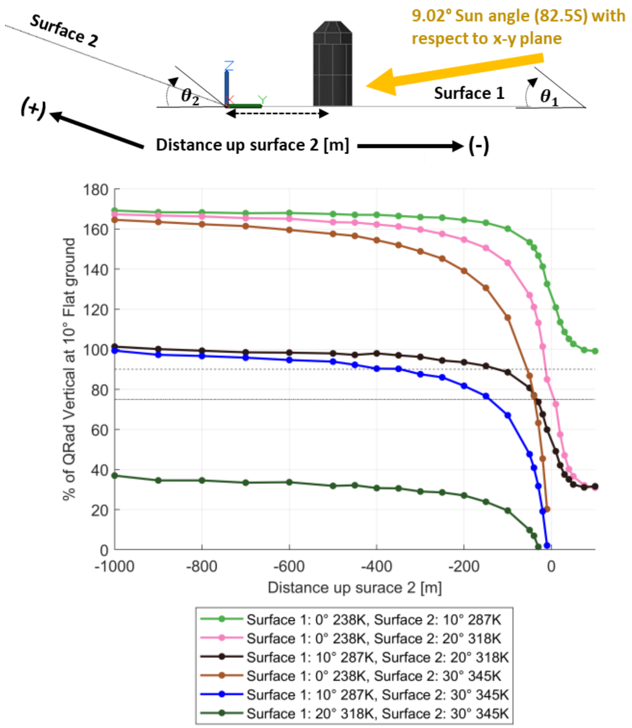
c) **Use with validated thermal system model for quick turn around analysis during flight**

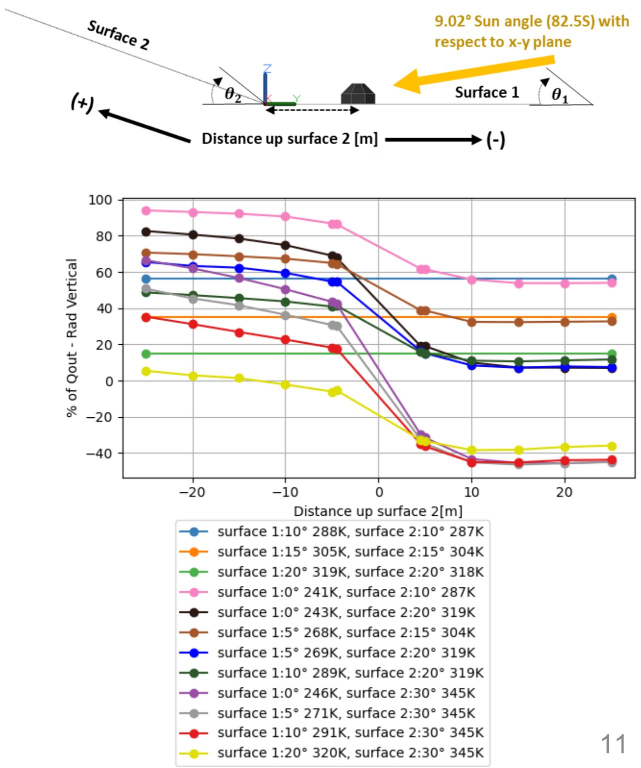
Use of the L-model request identifying worst case positions with respect to the slope – this depends on vehicle height.

Example for body mounted vertical radiators 20m tall vs 5m tall landers:

$$\%of = \frac{Qout\ [W]}{Qout_{flat\ plane\ with\ 10°\ tilt\ to\ sun}\ [W]}$$

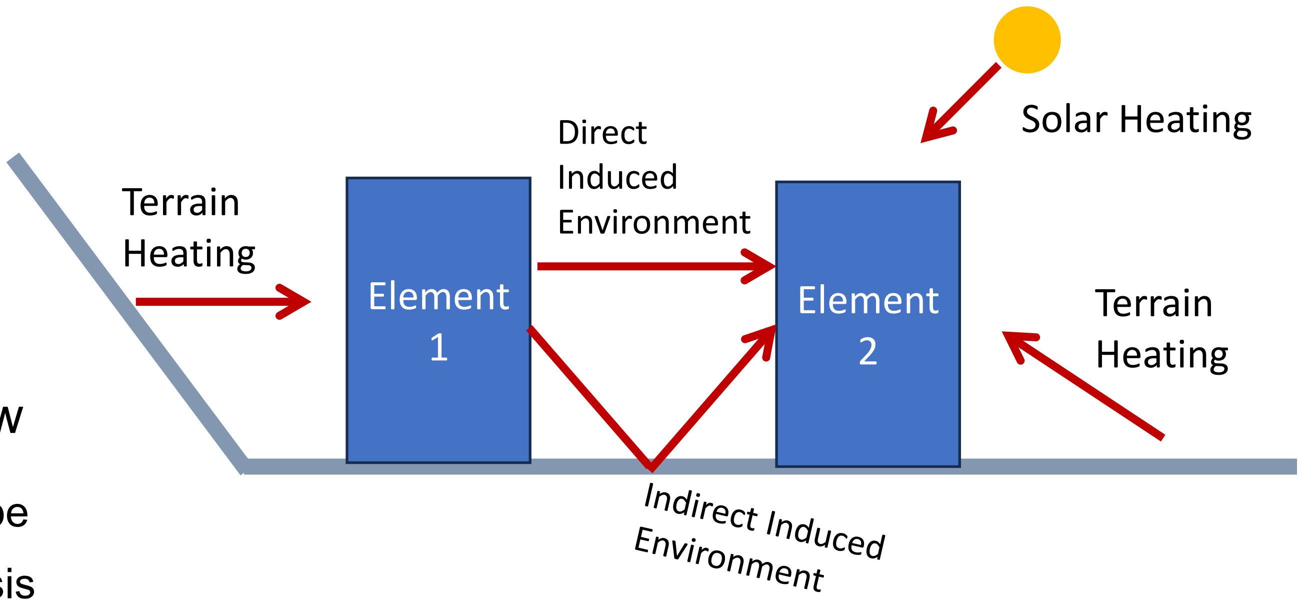
$$\%of = \frac{Qout\ [W]}{Qout_{flat\ plane}\ [W]}$$





3.5 Induced Environments Model

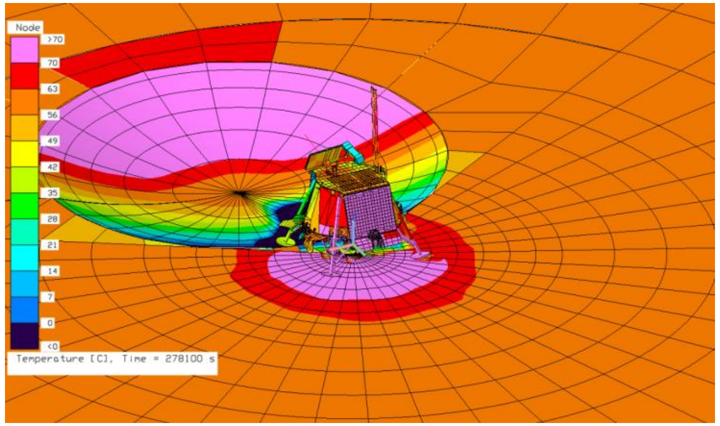
- Composed of a simplified lunar surface model (such as the L-model), and is specifically optimized to assess thermal environments mutually induced by two or more lunar assets
- This kind of model is essential for any mission involving two or more lunar surface assets in close proximity to each other
- Applicability at design phases depends on how bounding the base lunar surface model is:
    - A validated lunar surface model that is known to be bounding of all prospective landing sites or exploration regions can be used for design analysis up to CDR
    - Using an unvalidated surface model carries risk when used for design assessments though it is still valuable for performing sensitivity studies
- A moonbase (formerly EHP) thermal team is currently constructing a cross-program Lunar Induced Thermal Environments Model (LITEM) to assess induced environments from multiple Artemis lunar surface assets.



Pros	Cons
Important for understanding potentially driving induced environments	Designing an appropriately validated simplified lunar surface model is complex and time consuming
Computationally efficient	Cannot capture accurate solar illumination timelines

4 L Model + Features

- Small surface features (e.g., boulders, craters) can be added to the L-model to capture more terrain effects.
- Useful for studies to:
  - Assess sensitivity to possible surface features (e.g., small to large rocks/craters).
  - Identify worst cases and/or operating limits (e.g., go-no-go, thermal clocks) near different sized surface features.
- Fairly broadly applicable across design phases depending on the application and expected landing region. However, the simplified slope results in a model that may may not bound worst case terrain effects.
  - Sensitivity analysis to rocks/craters may show that they do not need to be included for worst case analysis.



Learnings From a Lunar Lander – Parts 1 & 2 (https://tfaws.nasa.gov/wp-content/uploads/TFAWS2025-TCP-I-01_Blue-Ghost-Lander_Sweeney.pptx)

Pros	Cons
Able to capture the effects of small terrain features and simple slopes.	May not bound the actual worst case hot condition at some landing sites.
Run much faster than meshed terrain models	Large case matrix needed to capture hot cases for all vehicle components (vary sun angles, vehicle pointing & placement)
Easy to adjust slopes to 0° also capture cold PSR case.	Cannot capture accurate solar illumination timelines.

4 L Model + Features

The following are situations where the L model with features may be useful for lunar surface thermal analysis

a) Sensitivity studies to determine scale of impact features have on the thermal system

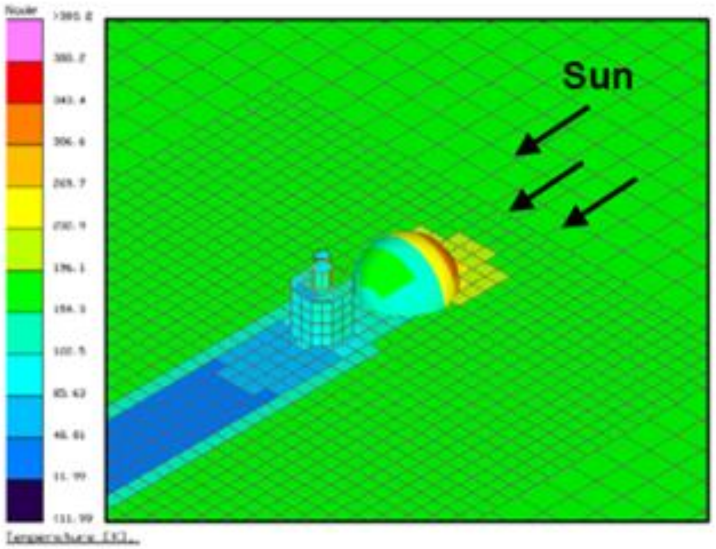
- **Including: impacts of realistically sized craters and rocks individually or combined.**

If features are determined to be required to capture the worst case:

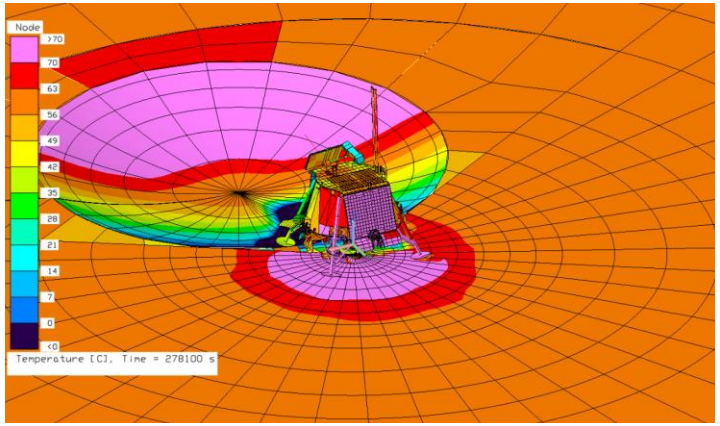
b) Pre-CDR rapid turn-around design analysis cycles (e.g., sensitivity studies, design trades),

c) Showing requirements compliance through CDR and Verification & Validation if the thermal system is only required to approach simple slopes - e.g., does not approach a stadium type of slope. *NOTE: work is currently ongoing to create a validated simple thermal model that bounds the worst hot case for possible HLS landing sites*

d) Use with validated thermal system model for quick turn around analysis during flight



Lunar Surface: ESCG-4470-08-TEAN-DOC-0219



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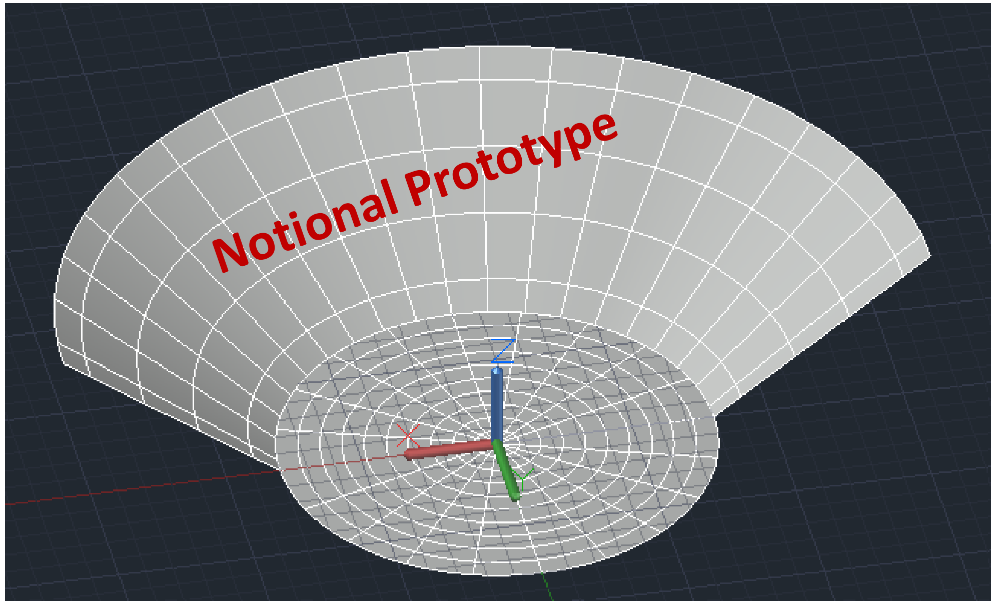
New Simplified Model Coming

- Currently, there is an HLS-funded task to identify the hottest possible landing scenario for HLS and build a simplified model that captures this environment.

- In this task, we will parameterize and sort hundreds of thousands of landing scenarios, characterize the TSINK and incident infrared energy at the hottest site with a detailed model (see the slides to follow), and recreate the environment with TD primitives to match the environment of the detailed model

- The outcomes of this task will be:
  - A model similar to the L-model that can capture even more extreme hot landing site environments
  - A simplified model that can be used up to CDR due to validation against terrain data

- Preliminary studies have suggested that the final simplified model may be shaped like an amphitheater



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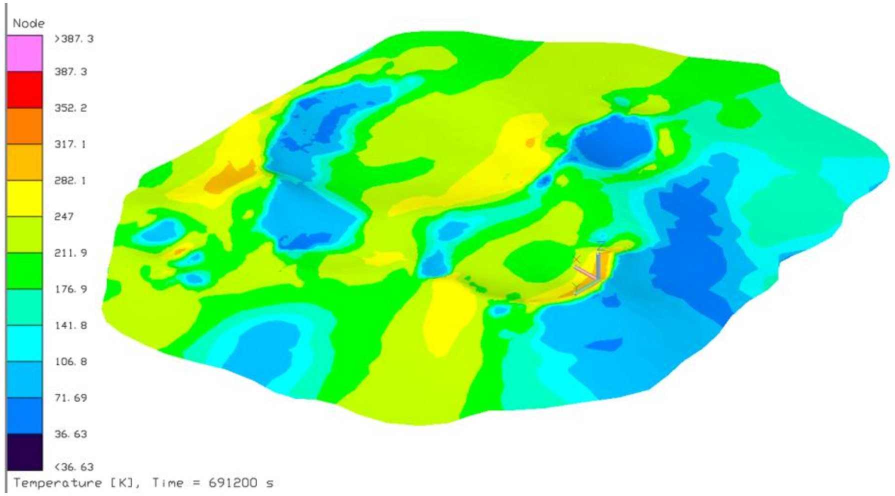
5 Detailed Terrain Model

- When the list of prospective landing sites is sufficiently narrowed, it may be advantageous (or even necessary) to use more flight-like meshed terrain models
- Terrain models can be very informative when attempting to understand the exact timeline and worst cases expected during the mission
- Use of these models may even be an essential activity for certification of flight readiness (COFR)
- ***It is not recommended that this kind of model be used for early design iterations when model speed and agility are needed***



Pros	Cons
Provides high accuracy, site-specific thermal environments	Very computationally expensive – not ideal for design analysis cycles
Captures accurate solar illumination timelines	Not ideal when the list of prospective landing sites is long or incomplete
With improved model building work-flows, creating a model from scratch is now a 2-hour task (less with practice)	Unnecessary detail for simpler environments (e.g. flat equatorial locations)

5 Detailed Terrain Model

The following are situations where detailed terrain models may be useful for generating thermal environments

a) **Used during concept development (if the list of sites is narrowed early enough) to determine sensitivity to nearby terrain features**

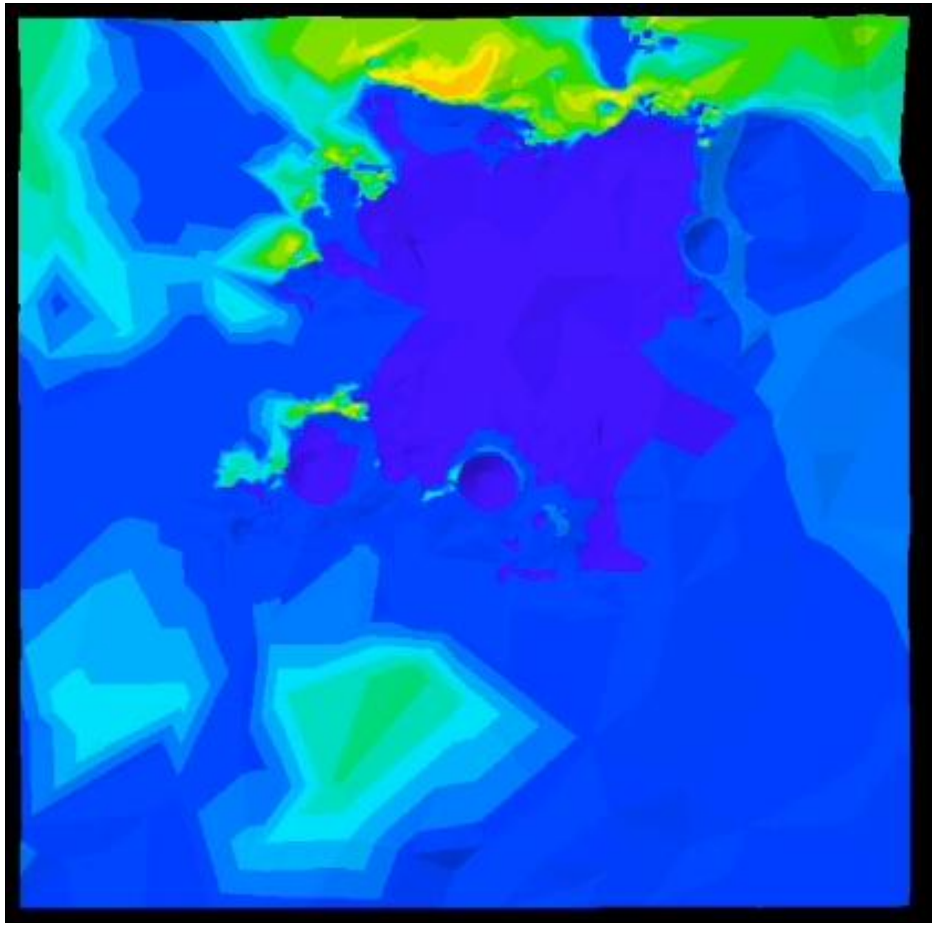
b) **Used up to critical design review or phase C (if landing sites are narrowed) as a source of truth from which to base bounding simplified models (i.e. building simplified models that match or bound the TSINK found at the landing site(s))**

c) **Used at COFR to verify the thermal system can operate at the desired landing site and surface stay**

   Regardless of requirements language, it is always very informative to run a terrain model prior to launch and ensure the landing site environments are bounded by any previous modeling efforts

d) **Used for mission integrated analysis for EVA planning**

e) **Used with simplified thermal system model for thermal analysis during flight to assess unexpected thermal environments**



5 Detailed Terrain Model

The method described here is based on the method described in the LTAG, but with some changes/improvements. In summary, this procedure takes lunar digital elevation models (LDEMs) and converts them to meshed surface models in Thermal Desktop

- MATLAB is used to convert lunar digital elevation models (LDEMs) to a point cloud (a list of x,y,z coordinates) that is centered around the lat and long of interest.
- The end goal of this process is a variable density mesh with higher mesh density at the site of interest and at the horizon (as viewed from the site). MATLAB is also used to identify horizon points and subdivide the data into sections where higher density is preserved
- MeshLab is used to ingest the subdivided point cloud, compute normal vectors, and construct a mesh using a Screened Poisson algorithm
- AutoCAD can ingest the dxf mesh output by MeshLab, and Thermal Desktop can convert AutoCAD surfaces to TD surfaces
- The mesh can then be coded with regolith optical properties, thermophysical properties, and sublayer discretization using insulation nodes (using recommendations described in the LTAG)
- To model smaller features that aren't captured in LDEM data, there are two general approaches:
  - Use the same methods described in sections 2 & 4 to manually add features to terrain models
  - Use ultra high-resolution (~1mpp) shape from shading data (if accessible) to mesh smaller terrain features (this process isn't described here and may require additional tools like COMSOL)

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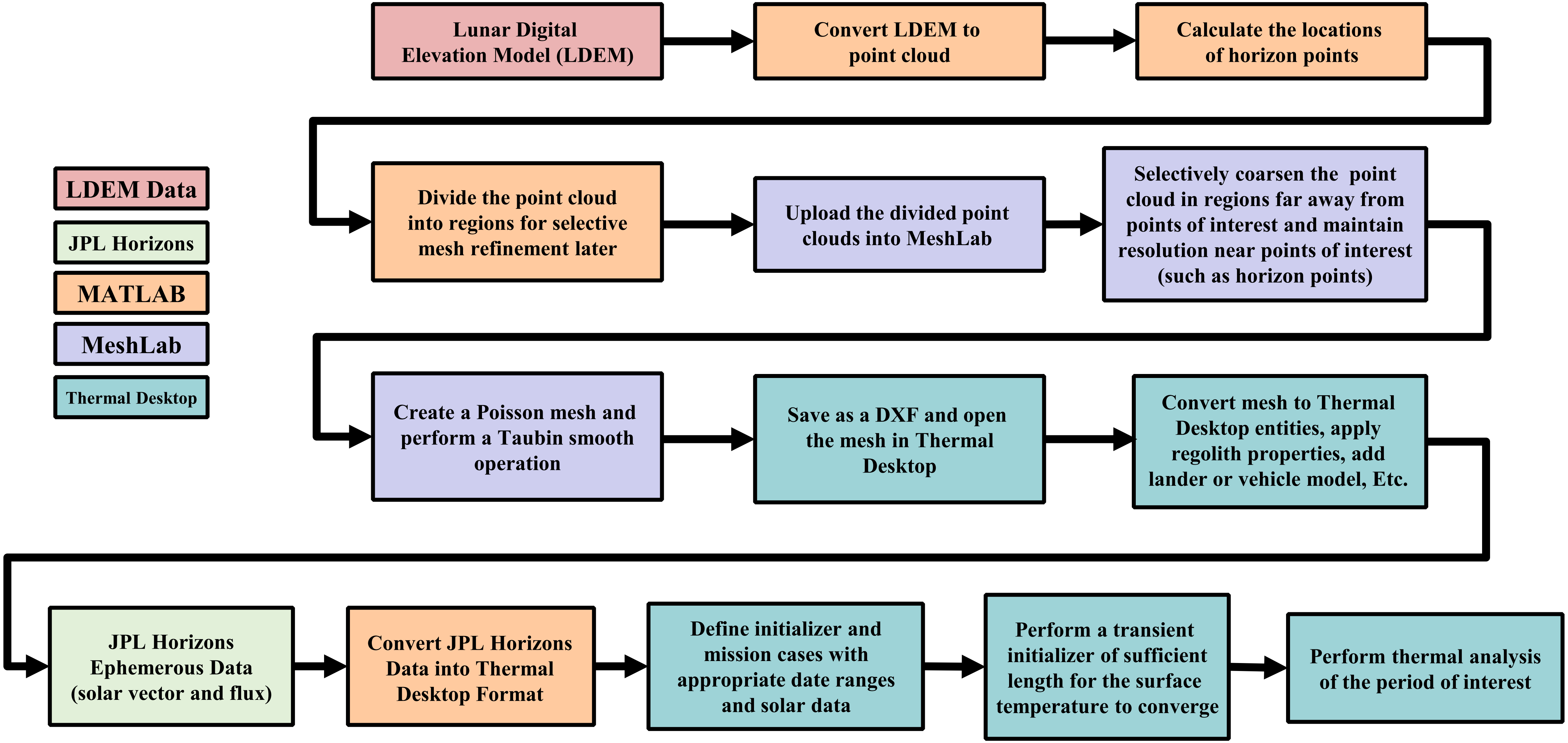
5 Detailed Terrain Model



5 Detailed Terrain Model

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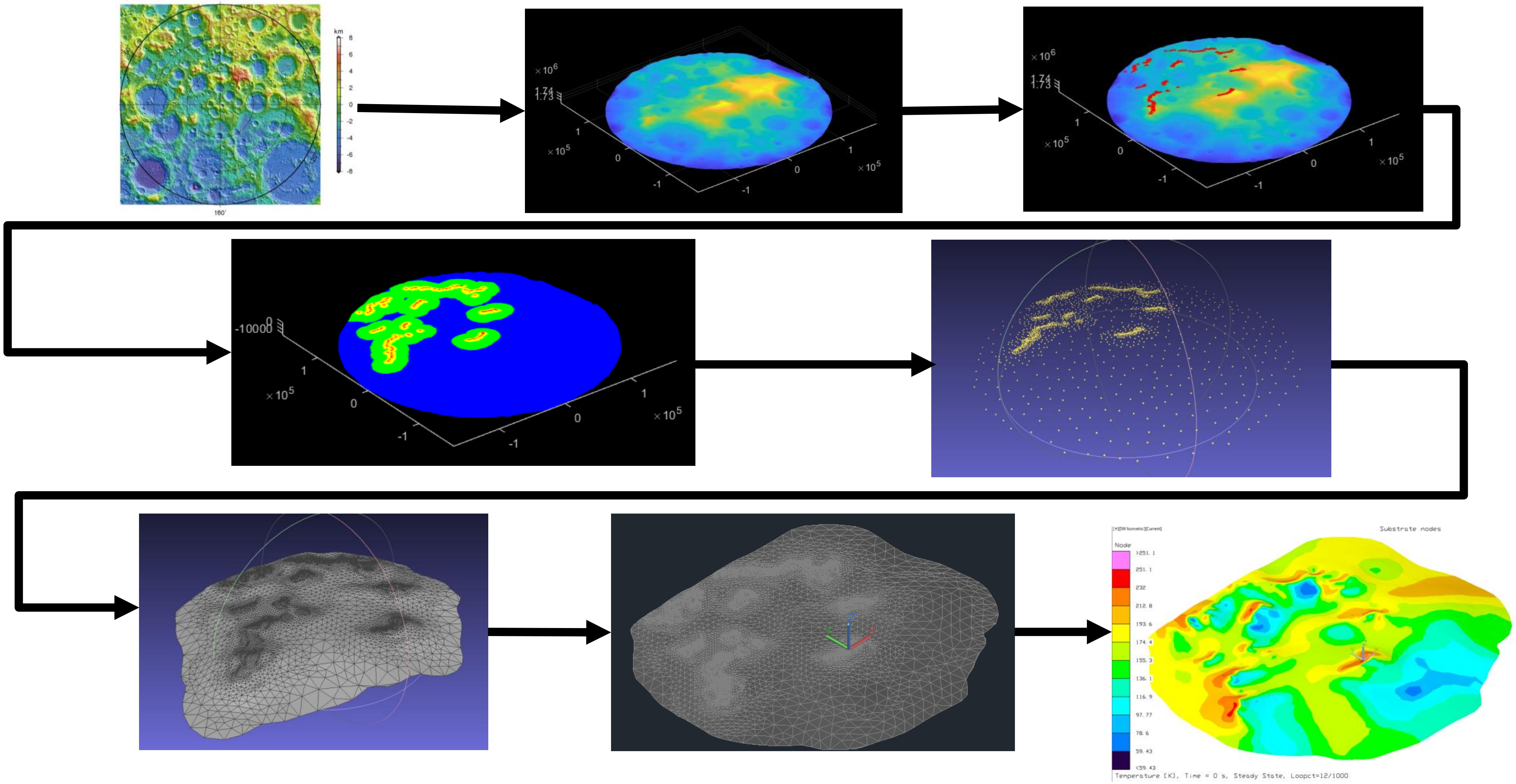

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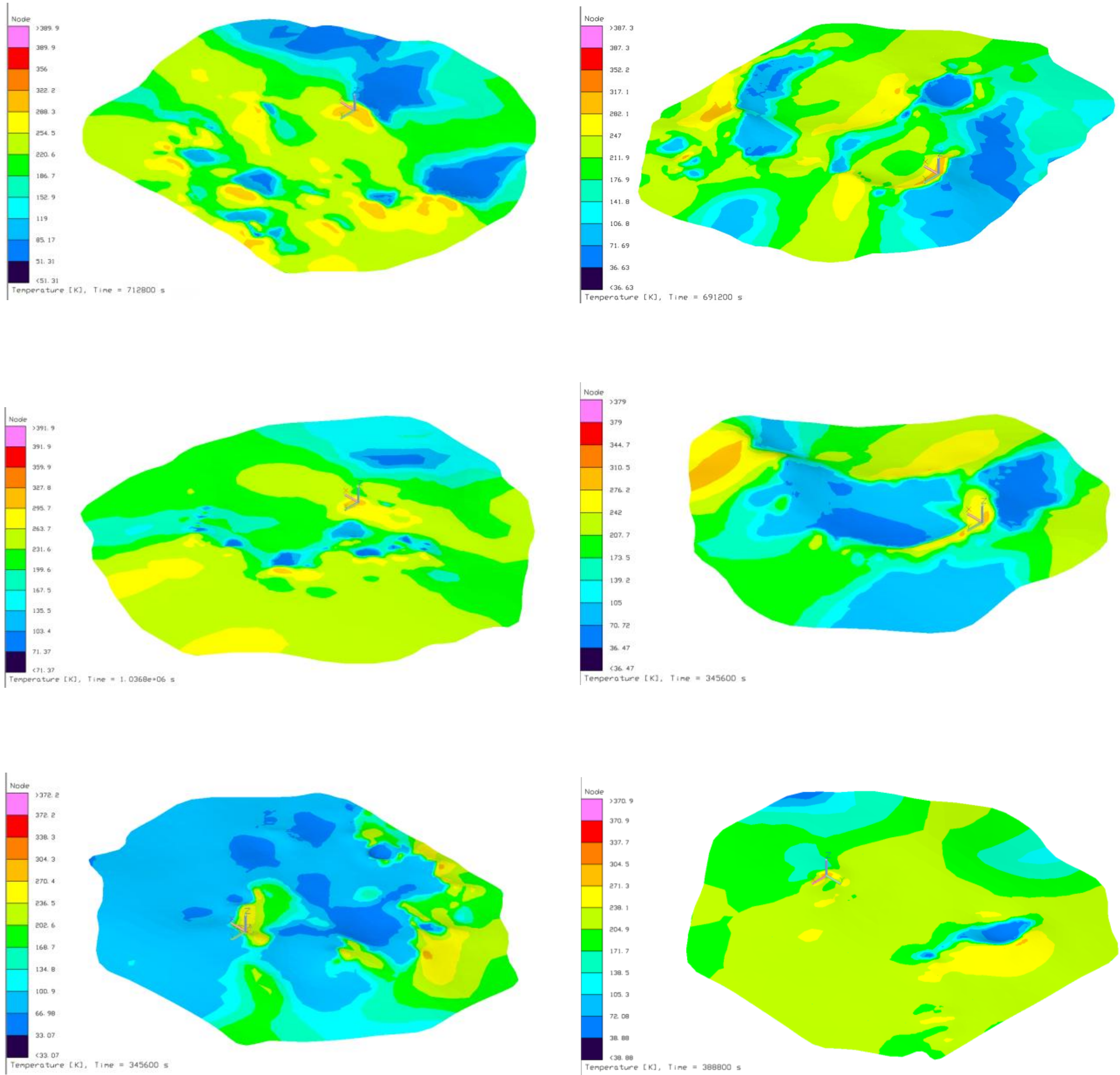
5 Detailed Terrain Model

- Currently, there is an HLS-funded task to validate detailed terrain models against DIVINER data
- Previous work has confirmed that bounding hot optical properties can be used to bound maximum summer DIVINER data, but this task will attempt to define region-specific correlation parameters that result in DIVINER-accurate temperatures
- The outcomes of this task include:
  - A better understanding of how different correlation parameters (optical properties, thermophysical properties, etc.) vary regionally
  - Improved confidence in the validity of detailed terrain models as a tool for design certification



Steady State vs Transient Lunar Surface Analysis

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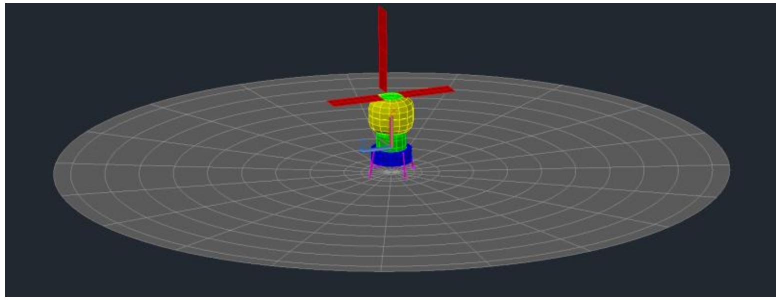
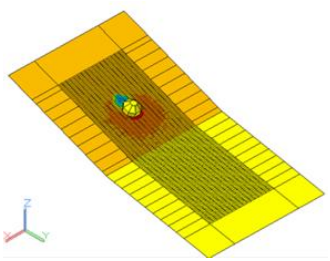
Steady State	
Advantages	**Disadvantages**
Computationally Efficient	Does not capture accurate solar heating
Better for early concept studies when model efficiency is needed	Inadequate to assess time-dependent thermal events (night survival time, traverse time before cooling, etc.)
May be sufficient for design iterations at some hot well-lit locations (when transient impact from regolith thermal mass is less critical)	More prone to surface temperature inaccuracies
No need to model regolith sublayers	Inadequate to assess sublayer temperatures

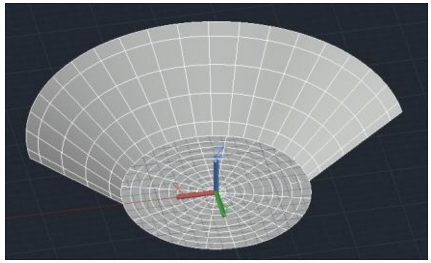
Transient	
Advantages	**Disadvantages**
Can capture accurate solar illumination timelines when coupled with an accurate horizon model	More computationally expensive, especially if initialized to sublayer temperature stability
Accounts for thermal mass of the regolith	Limited utility when transient thermal events driven by con-ops are ill-defined
Accounts for thermal mass of the habitation/vehicle	Limited utility when landing sites and the natural environment assumptions are ill-defined
Highly accurate solar position data easily accessible through JPL horizons	May be unnecessary detail for early concept studies
Required for site and date-specific analysis	
Can capture time-dependent thermal events (night heat leak rates, lunar morning warm up, etc.)	

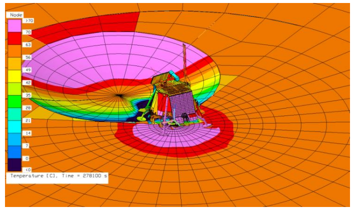
Conclusion

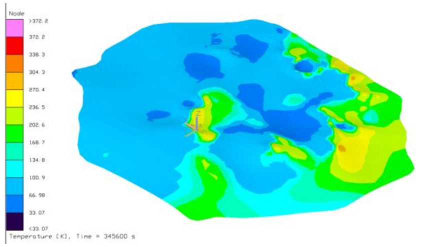
- The uncertainty and complexity of lunar landing site thermal environments will always carry a risk that the true worst case is missed. This is compounded by the need for simple, highly efficient models during early design cycles.
- However, some of this risk can be mitigated through strategic selection of simplified bounding lunar surface models and more detailed accurate surface models
- The 5 model categories discussed here are:
    1. Disk Model: Typically, only used for highly notional concept studies except when the lunar environment can be accurately represented with a perfectly flat plane
    2. Disk Model + Features: A good tool for highly notional concept studies when sensitivity to small features is a concern
    3. L Model: An improved simplified models that can likely be configured to yield bounding environments that include terrain. (Note an improved version of this model that is more likely to be bounding may result from an HLS landing site investigation activity)
    4. L Model + Features: A further improved simple terrain model that can be used when sensitivity to small features is a concern
    5. Detailed Terrain Model: A highly accurate (though computationally expensive) way to model a single landing site or exploration region





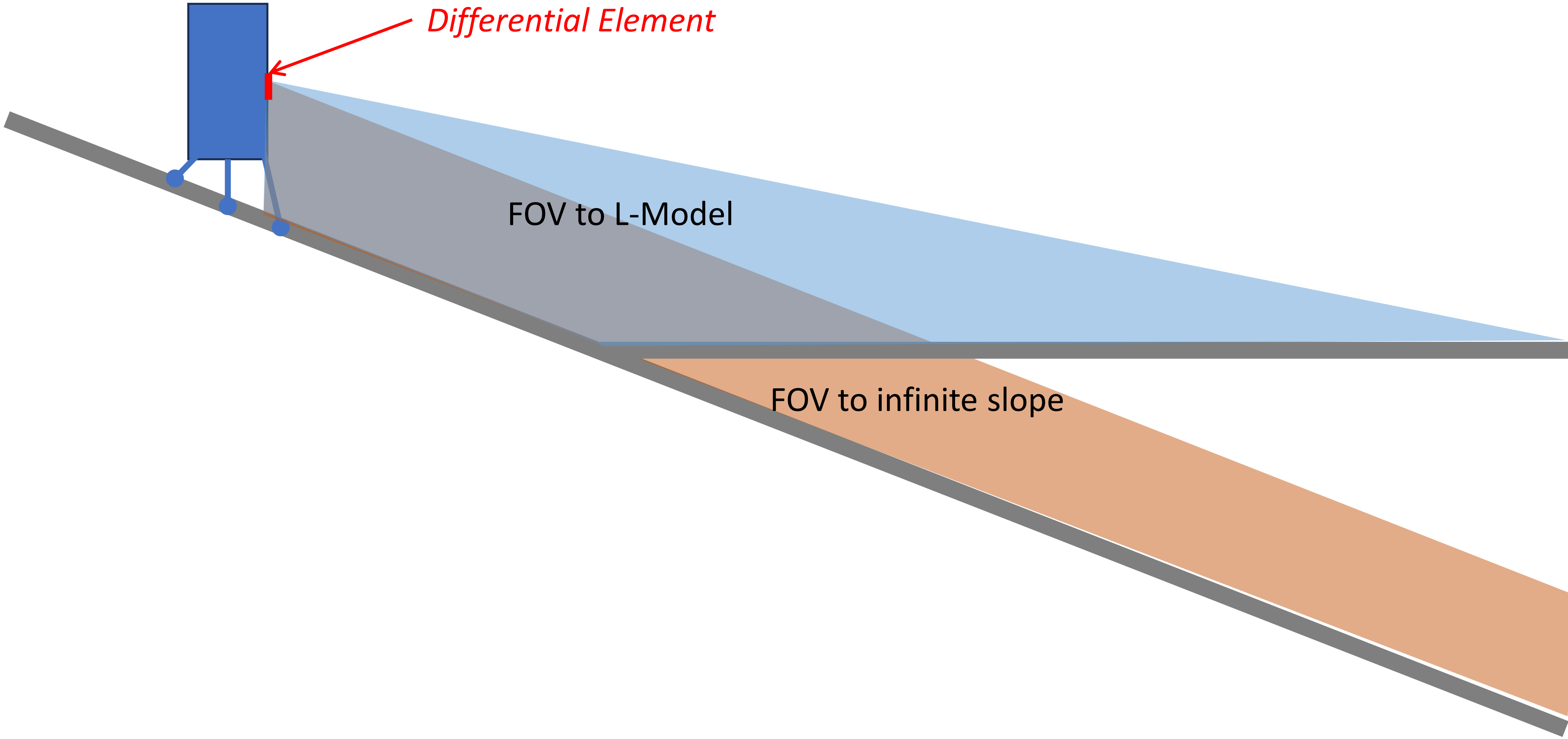






Backup

FOV to Space Comparison



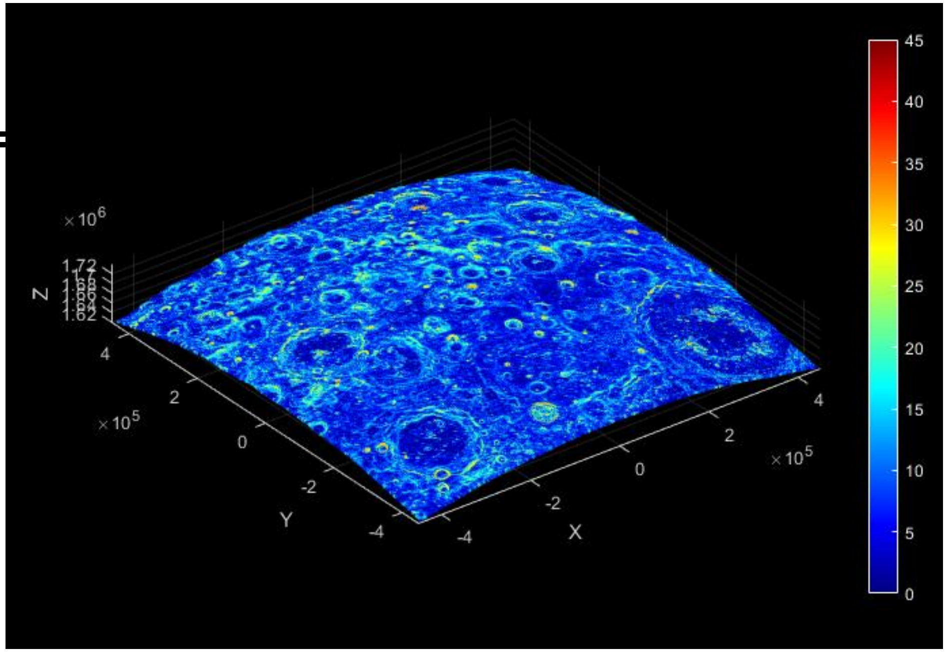
Lunar Surface Slope Map

- Built a MATLAB code that calculates point clouds and curvature corrected surface normals from 60m resolution lunar digital elevation maps

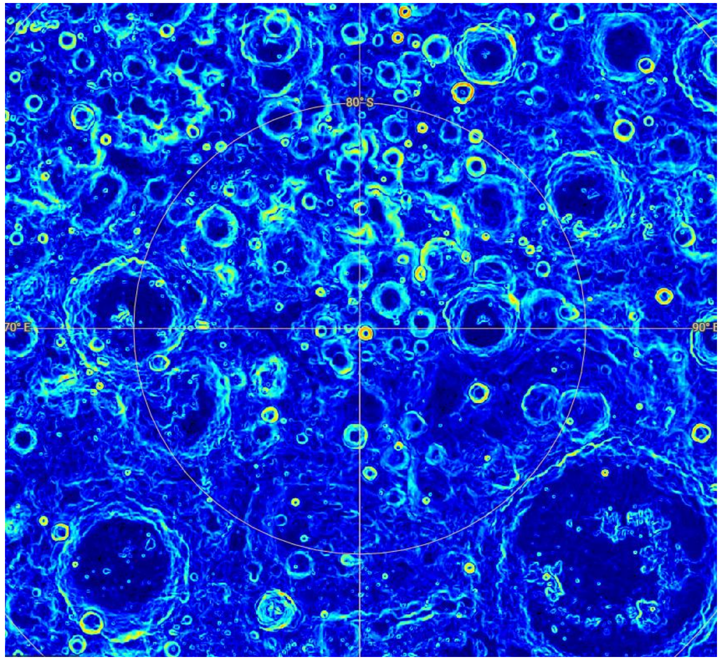
- The normals can be converted to surface slope and azimuth angle with simple trigonometry

- My data compares very well with QuickMap slope data, and (unlike QuickMap data) it allows me to calculate statistics

My MATLAB Code



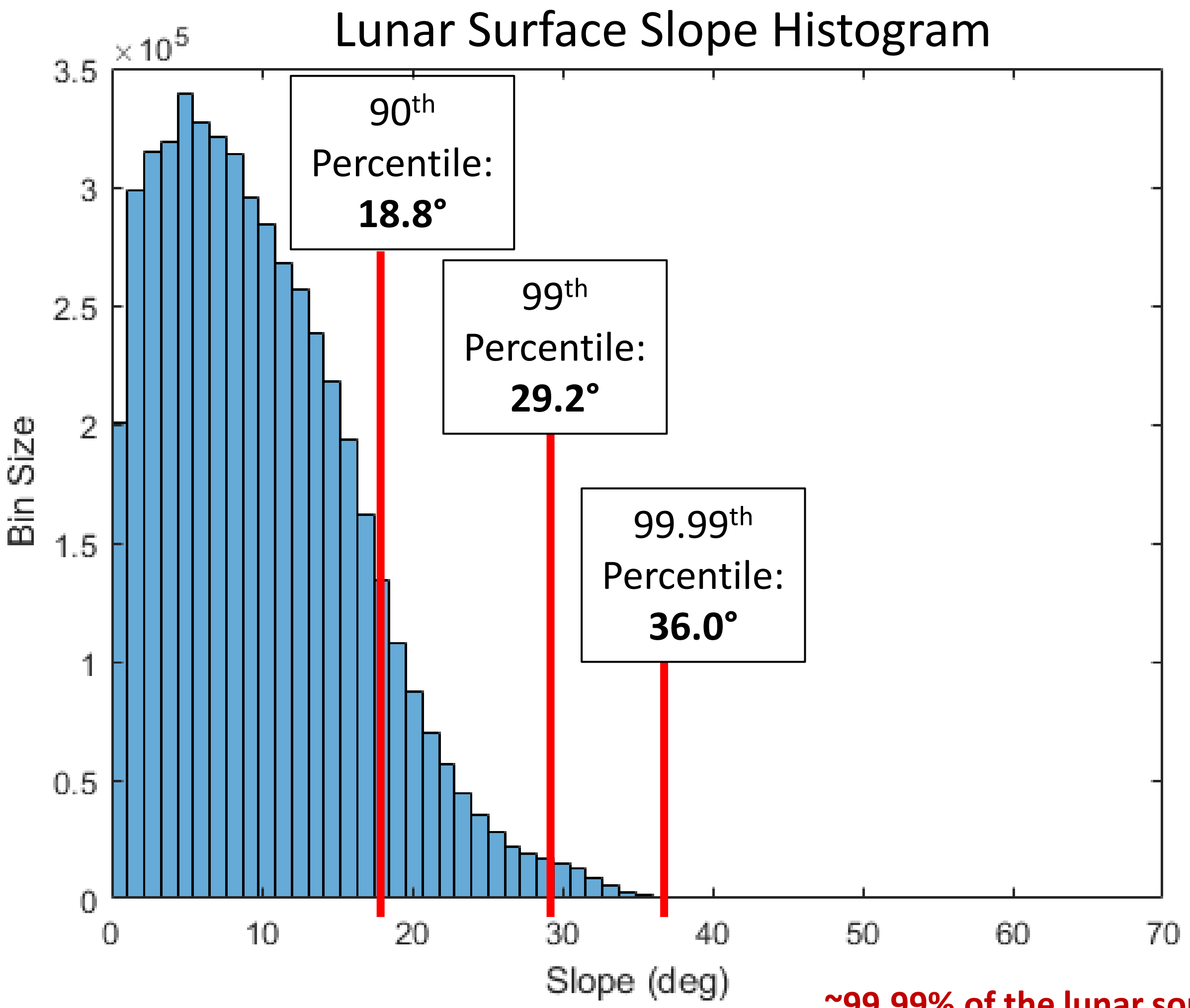
LROC QuickMap (Same color scale)



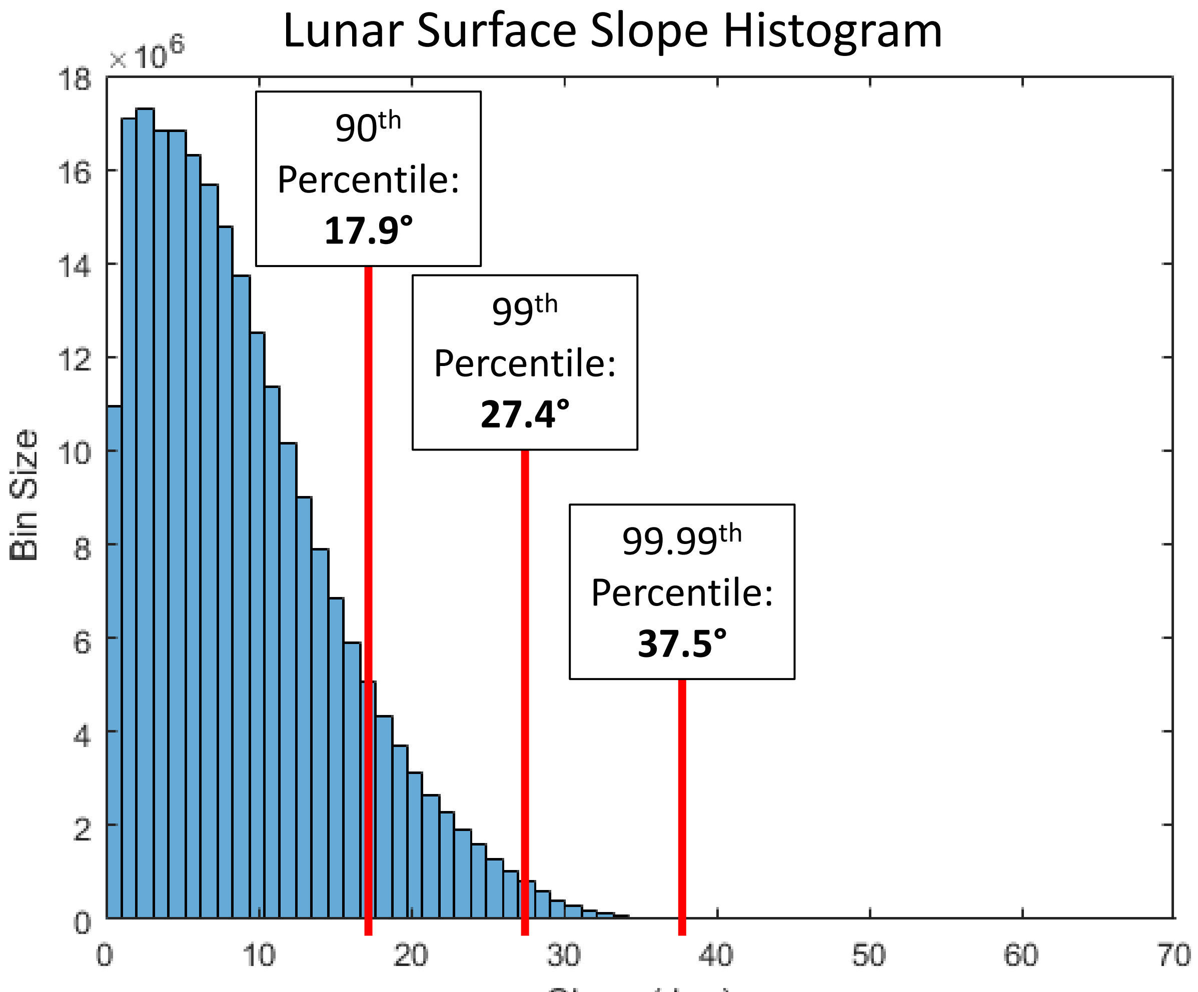
HLS

Lunar Surface Slope Map

-87.5° Latitude and Below



-75° Latitude and Below



~99.99% of the lunar south pole has a slope less than about 38°

~90% of the lunar south pole has a slope less than about 20°

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