

Lunar Thermal Analysis Guidebook (L-TAG):

Lunar Surface 3D Terrain Modeling

Carlos Gomez, Brian Hamill, Greg Schunk
NASA/Marshall Space Flight Center

&

Lisa Erickson
NASA/Johnson Space Center

Presented By
Lisa Erickson

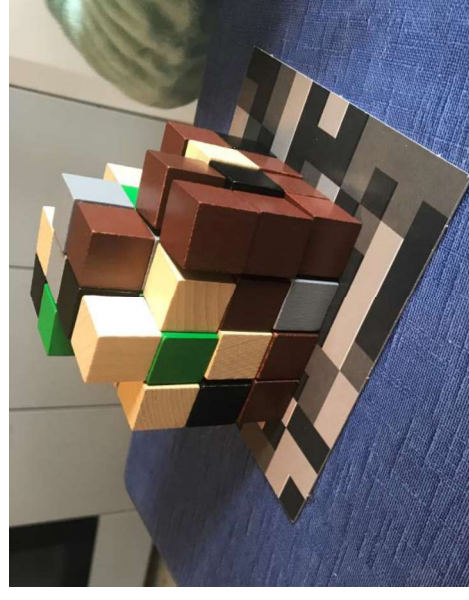


Thermal & Fluids Analysis Workshop
TFAWS 2022

September 6th-9th, 2022
Virtual Conference

Accessing LRO Digital Terrain Data

- Lunar surface meshes can be constructed using digital elevations models (DEMs) of the surface
- DEMs specify average elevation for squares – bounded by constant LAT/LON lines¹
- Lunar Surface DEMs are:
 - Derived from Lunar Reconnaissance Orbiter's Lunar Orbiter Laser Altimeter (LOLA) elevation data
 - Provided as Gridded Data Record DEMs (GDRDEMs) – DEMs projected onto a x-y map¹



Visualization of DEMs - a block world²

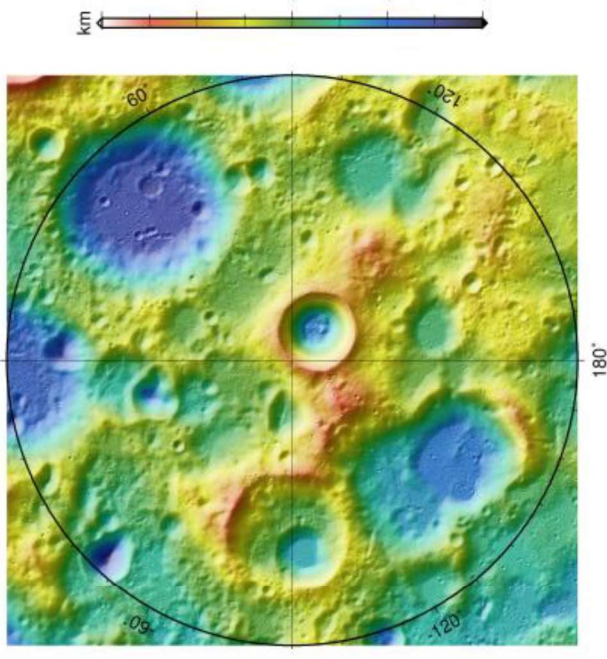
¹ "GDRDEM – Gridded Data Record Shape Map" https://ode.rsl.wustl.edu/moon/pagehelp/Content/Missions_Instruments/LRO/LOLA/GDR/GDRDEM.htm

² https://commons.wikimedia.org/wiki/File:Minecraft_board_game_blocks_01.jpg

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Lunar South Pole, -87.5° to the pole
by the LRO LOLA Science Team
LDEM_875S_5M 5 m/px



GDRDEM where pixel = elevation³

¹ "GDRDEM – Gridded Data Record Shape Map" https://ode.rsl.wustl.edu/moon/pagehelp/Content/Missions_Instruments/LRO/LOLA/GDR/GDRDEM.htm

² https://commons.wikimedia.org/wiki/File:Minercraft_board_game_blocks_01.jpg

³ LOLA Gridded Data Record Shape Map 87.5S 5m https://ode.rsl.wustl.edu/moon/indexproductpage.aspx?product_idgeo=21746070

Where to Find DEMs?

New Feature ☆ An optional user login has been added to ODE. It's free and simple to use! Through this feature, users can save product searches, map searches, and product details pages! Past can history and viewed product detail pages are accessible, as well. Click the anonymous user icon in the ODE banner above or click [here](#) to create an account. Additional user account information is found in the [ODE help](#) or email us at ode@wunder.wustl.edu with questions.

WELCOME TO THE LUNAR ORBITAL DATA EXPLORER

The PDS Geosciences Node Lunar Orbital Data Explorer (ODE) provides search, display, and download tools for the PDS science data archives of the Lunar Reconnaissance Orbiter (LRO), the Gravity Recovery and Interior Laboratory (GRAIL), the Clementine, the Lunar Prospector, the Lunar Orbiter, and the Indian Space Research Organisation's Chandrayaan-1 missions to Earth's moon. Choose one of the above tabs to start using ODE.

- Data Product Search**
Search for orbital science products across missions, instruments, and data sets via time, location, and product ids.
- Additional Tools**
• [LUNAR ORBITER](#)
• [LUNAR PROSPECTOR](#)
• [PRODUCT TIME COVERAGE](#)
- Data Set Browser**
Browse through the orbital data set files stored in the PDS archives
- Download Cart**
Download products added to the cart from the product search
- What's New**
See what's new with ODE
- Help & Resources**
Access the ODE Help, find additional resources, and see what's coming
- Available Data Sets**
A full list of mission, instrument, and product types available in Lunar ODE
- Download Cart**
Download products added to the cart from the product search

The Lunar Orbital Data Explorer is produced by the PDS Geosciences Node at Washington University in St. Louis. Send comments and questions to jds@wunder.wustl.edu.

LUNAR DATA SET BROWSER

Planetary science data stored in PDS is organized by data sets. A [data set](#) is a collection of related data products, usually products acquired by a particular instrument and processed in a certain way. The data set also includes all documentation and supporting materials needed to understand and use the data products.

The **Data Set Browser** allows the user to view data set contents that are currently cataloged in the ODE system. Expand the data set tree to view the contents of the available data sets.

Top Level: Start

Mission

- LEO
- CHL-CORR
- SJU
- GRAIL
- CLEM
- LP
- LQ
- ARC-E-NBAO

Instrument

- DLEE
- LAMP
- LEND
- LOLA
- LSOC
- MRE-RO

<https://ode.rsl.wustl.edu/moon/index.aspx>

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Top Level	Mission	Instrument	Data Set
Start	LEO	LOLA	LEO-LLOLA-16-GDR-V1.0
Start	LEO	LOLA	LEO-LLOLA-2-EDR-V1.0
Start	LEO	LOLA	LEO-LLOLA-3-RDR-V1.0
Start	LEO	LOLA	LEO-LLOLA-4-GDR-V1.0
Start	LEO	LOLA	LEO-LLOLA-5-SHADR-V1.0

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Top Level	Mission	Instrument	Data Set	Volume	Modify Date
Start	LEO	LOLA	LEO-LLOLA-16-GDR-V1.0	LEOLOL_1XXX	2022-06-10T16:29:11.076

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Top Level	Mission	Instrument	Data Set	Volume
Start	LEO	LOLA	LEO-LLOLA-16-GDR-V1.0	LEOLOL_1XXX

Folder/File	KB	Modify Date
browse	Directory	2011-12-05T17:14:53.000
calib	Directory	2016-01-12T10:21:40.341
catalog	Directory	2021-09-10T12:31:59.131
data	Directory	2022-06-02T08:09:00.042
document	Directory	2020-09-15T06:35:14.855
extras	Directory	2011-12-05T20:09:40.000
geomatky	Directory	2016-03-14T10:57:52.552
index	Directory	2011-12-05T20:13:03.000
label	Directory	2020-06-09T14:38:22.235
areadme.txt	10	2016-03-03T14:37:01.675
errata.txt	111	2022-06-02T09:14:20.599
vsides.txt	2	2015-12-14T15:34:56.044

<https://ode.rsl.wustl.edu/moon/index.aspx>

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Start	LEO	LOLA	LEO-LLOLA-16-GDR-V1.0	LRLOLOL_1XXX
Path in Volume	data	lola_gdr		

Folder/File	KB	Modify Date
lola_gdr	Directory	2019-09-05T14:07:21.291
lola_radr	Directory	2018-02-23T09:44:02.302
lola_rdrf	Directory	2022-06-10T09:18:14.158
lola_shadr	Directory	2022-03-02T08:53:43.548
slidem2015	Directory	2015-09-10T16:08:52.358

Lunar Orbital Data Explorer

LUNAR DATA SET BROWSER

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Start	LEO	LOLA	LEO-LLOLA-16-GDR-V1.0	LRLOLOL_1XXX
Path in Volume	data	lola_gdr		

Folder/File	KB	Modify Date
lola_gdr	Directory	2019-09-05T14:07:20.807
lola_radr	Directory	2019-09-05T14:07:21.284

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Path in Volume	data	lola_gdr		

Folder/File	KB	Modify Date
lola_gdr	Directory	2019-09-05T14:07:21.284
lola_radr	Directory	2019-09-05T14:07:21.284

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Start	LEO	LOLA	LEO-LLOLA-16-GDR-V1.0	LRLOLOL_1XXX
Path in Volume	data	lola_gdr		

Folder/File	KB	Modify Date
lola_gdr	Directory	2019-09-20T14:41:37.323
lola_radr	Directory	2019-09-20T14:41:38.815
lola_rdrf	Directory	2019-09-20T14:41:39.873

<https://ode.rsl.wustl.edu/moon/index.aspx>

Where to Find DEMs?

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Top Level	Mission	Instrument	Data Set	Volume
Start	LRO	LOLA	LRO-LLO-LA-16-GDR-V1.0	LROLOL_1xxx

Path in Volume

data lol_sdr polar float.img

Folder/File	KB	Modify Date
Idam_50n_1000m_float.img	25,645	2015-11-17T12:28:01.288
Idam_50n_1000m_float.lib	4	2015-12-30T10:41:53.902
Idam_50n_3000m_float.img	2,850	2015-11-17T12:28:01.368
Idam_50n_3000m_float.lib	4	2015-12-30T10:41:53.915
Idam_50s_1000m_float.img	25,645	2015-11-17T12:28:01.552
Idam_50s_1000m_float.lib	4	2015-12-30T10:41:53.927
Idam_50s_3000m_float.img	2,850	2015-11-17T12:28:01.668
Idam_50s_3000m_float.lib	4	2015-12-30T10:41:53.950
Idam_45n_100m_float.img	3,317,761	2016-08-31T20:58:45.174
Idam_45n_100m_float.lib	5	2016-09-07T16:25:09.791
Idam_45n_200m_float.img	879,441	2016-08-31T20:58:45.122

Idem_875s_10m_float.img	920,273	2017-06-02T11:06:02.237
Idem_875s_10m_float.lib	5	2017-06-02T11:07:50.772
Idem_875s_20m_float.img	230,069	2017-06-02T11:07:53.182
Idem_875s_20m_float.lib	5	2017-06-02T11:07:50.796
Idem_875s_5m_float.img	3,681,092	2017-06-02T11:05:44.986
Idem_875s_5m_float.lib	5	2017-06-02T11:05:41.917

<https://ode.rsl.wustl.edu/moon/index.aspx>

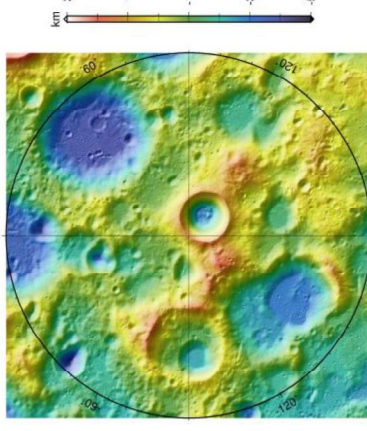
LDEM_875S_5M

LRO LOLA Gridded Data Record Shape Map (GDRDEM) (Derived Data)

Product Description and Data Set Documents (click to show)

Browse Meta Data Label Map Context

Browse Image - the image below is not the actual data product
Lunar South Pole, -87.5° to the pole
 by the LRO LOLA Science Team
 LDEM_875S_5M 5 m/px



Add Product to Cart

Remove Product from Cart

Cart & Download Help

Aspera Connect Browser Plug-in Option

Only available for data hosted by the PDS Geosciences Node.

Note: Installing the browser plug-in will require restarting the browser.

Download All Product & Derived Files with Aspera

Aspera Download Help

PDS Product Files

Derived Files

Product Files & Labels

KB

Idem_875s_5m_float.img

3,681,092

Product Data File

Idem_875s_5m_float.lib

5

Product Label File

Referenced Files

KB

Idam01_colocat

4

Map Projection File

DEM in _float.img format

Instructions for parsing DEM data

Converting LRO DEMs to Mesh

- Two steps:
 1. Convert DEM → Point Cloud (using Python)
 2. Convert Point Cloud → triangular mesh (using MeshLab)
- Note: These steps can be performed multiple ways
 - e.g., A DEM in .tiff format it can be converted using QGIS to a 3D model and meshes can be manipulated in Blender
 - <https://www.youtube.com/watch?v=eZZ2MVLZN4o>
 - <https://www.youtube.com/watch?v=-ubDqXZtdJE>

Step 1: Convert DEM → Point Cloud

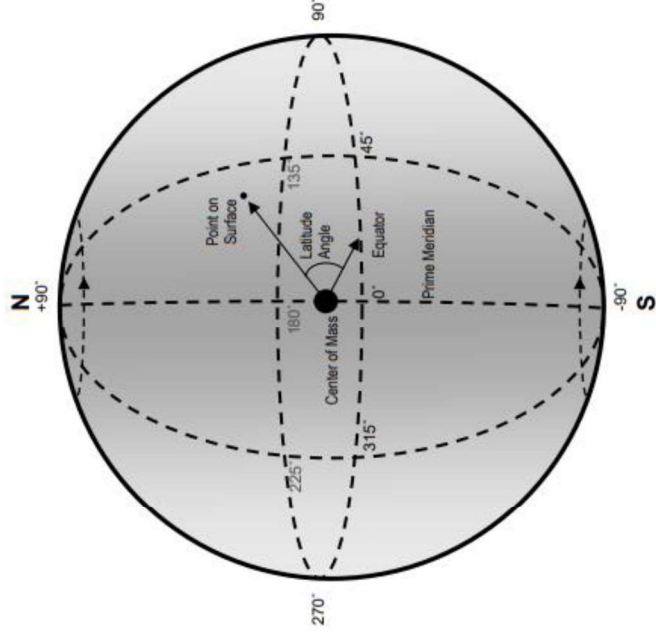
- Read `ldem_xxx_float.img`
 - The `ldem_xxx_float.lbl` file gives data structure to assume when uncompressing the data
 - `SAMPLE_TYPE = PC_Real` means float or 'f'
 - The total number of samples is `LINES*LINE_SAMPLES`
 - The `dsmap_polar.cat` states how to parse the file one sample at a time

```
data_file = io.open(input_file, 'rb')
raw_data = data_file.read()
datas = struct.unpack_from('f'*LINES*LINE_SAMPLES, raw_data)
i = 1 # sample coordinate
j = 1 # line coordinate
for val in datas: #range(0, len(datas)+1):
    # Xmap, Ymap = I, J converted to Cartesian coordinates
    # with 0,0 at center, N = total number of lines
    Xmap = (i - N/2. - 0.5)*MAP_SCALE
    Ymap = (j - N/2. - 0.5)*MAP_SCALE
    # radius from center of map to pixel I, J in meters
    Rmap = (Xmap**2. + Ymap**2.)*0.5
    # elevation from DEM
    Elevation = val*SCALING_FACTOR*1000 # in meters
    # Convert DEM coordinates to spherical coordinates
    # (S. Hemisphere)
    # (LAT, LON, ro) = ([degrees], [degrees], [m])
    LON = 90+math.atan2(Ymap, Xmap)*180/math.pi
    LAT = -90 + 180/math.pi * 2*math.atan(0.5 * Rmap/1737400)
    ro = (val*SCALING_FACTOR+OFFSET)*1000
    i = i + 1
    # Check if finished sampling a line
    if i == LINE_SAMPLES+1:
        j = j+ 1 # increment line coordinate
        i = 1 # reset sample coordinate
    if i*j == LINES*LINE_SAMPLES:
        print(all lines parsed)
```

Sample Python code for reading the DEM

Step 1: Convert DEM → Point Cloud

- Use spherical to cartesian conversion to convert from (LAT, LON, radius) to (x,y,z)



```
# Convert spherical to cartesian coordinates
# (x,y,z) = ([m],[m],[m])
x = r0 * math.cos((LAT) * math.pi/180) * math.cos(LON * math.pi/180)
y = r0 * math.cos((LAT) * math.pi/180) * math.sin(LON * math.pi/180)
z = r0 * math.sin((LAT) * math.pi/180)
```

Sample Python code for Spherical to Cartesian Conversion

Figure 1. Planetocentric coordinates are expressed as right-handed coordinates with the origin at the center of mass of the body.

<https://lunar.gsfc.nasa.gov/library/LunCoordWhitePaper-10-08.pdf>

Step 1: Convert DEM → Point Cloud

- Reduce size of Point cloud file by selectively outputting points
- Points are outputted to .xyz file with format:

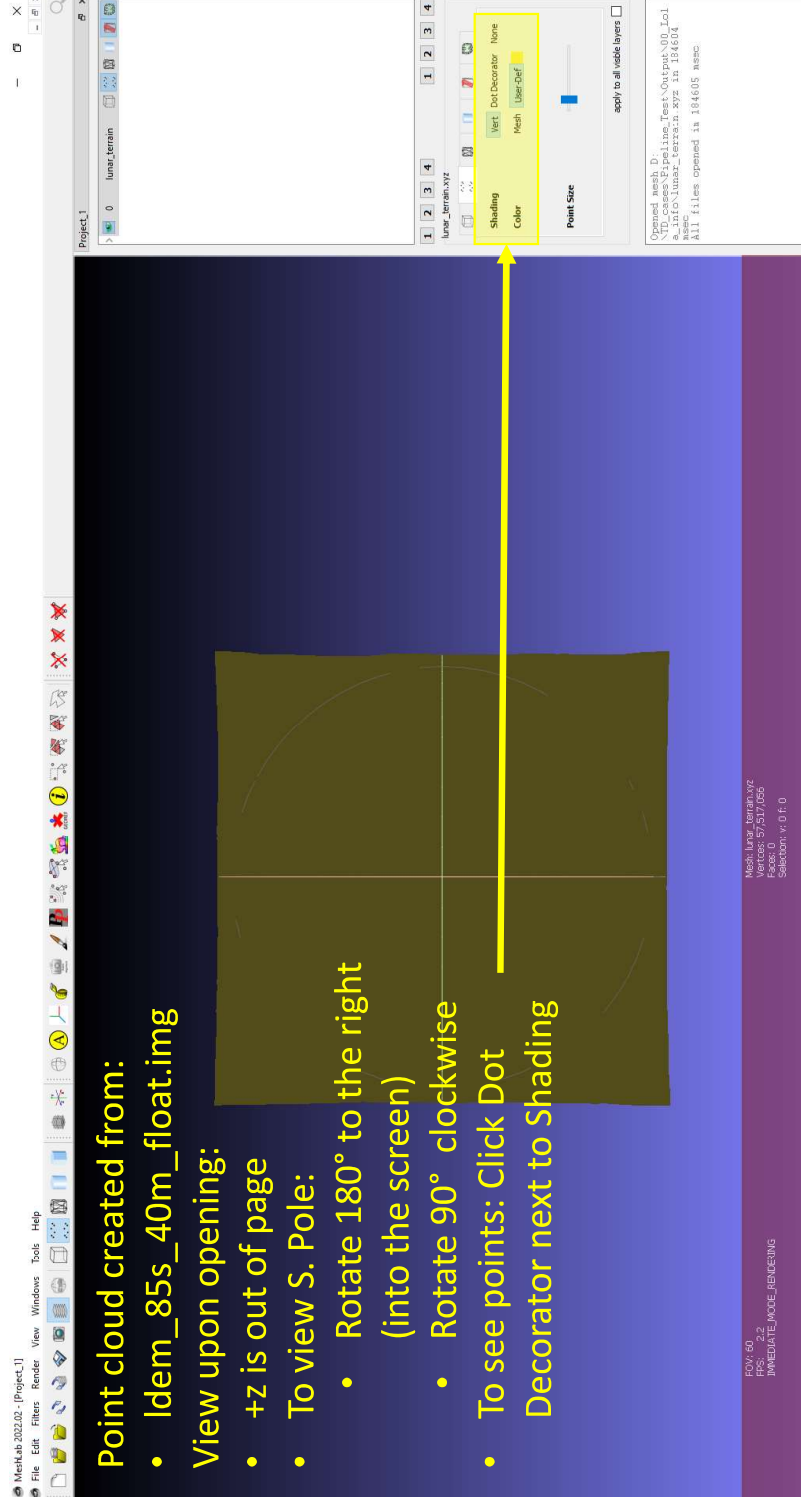


```
lunar_terrain_40m_boundbox.xyz - Notepad
File Edit Format View Help
128433.873095 32592.4653867 -1731275.74671
128433.873592 32632.1795374 -1731264.59408
128432.458443 32671.9400888 -1731255.92606
128431.445556 32711.5989535 -1731241.89612
128430.341495 32751.2339385 -1731226.63672
```

```
datas = struct.unpack('f'*LINES*LINE_SAMPLES,raw_data)
i = 1 # sample coordinate
j = 1 # line coordinate
for val in datas: #range(0,len(datas)+1):
# Xmap,Ymap = I,J converted to Cartesian coordinates with 0,0 at center
Xmap = (i - N/2. - 0.5)*MAP_SCALE
Ymap = (j - N/2. - 0.5)*MAP_SCALE
# radius from center of map to pixel I,J in meters
Rmap = (Xmap**2. + Ymap**2.)*0.5
# elevation from DEM
Elevation = val*SCALING_FACTOR**1000 # in meters
# Convert DEM coordinates to spherical coordinates (S. Hemisphere)
# (LAT, LON, ro) = ([degrees],[m])
LON = 90+math.atan2(Ymap,Xmap)*180/math.pi
LAT = -90 + 180/math.pi * 2*math.atan(0.5 * Rmap/1737400)
ro = (val*SCALING_FACTOR+OFFSET)*1000
# Convert spherical to cartesian coordinates
# (x,y,z) = ([m],[m],[m])
x = ro * math.cos((LAT) * math.pi/180) * math.cos(LON * math.pi/180)
y = ro * math.cos((LAT) * math.pi/180) * math.sin(LON * math.pi/180)
z = ro * math.sin((LAT) * math.pi/180)
output_str = str(x) + " " + str(y) + " " + str(z)+"\n"
# Only output points within the box
if (x <= xTL): # xTL = box top left x coordinate
if (x >= xBR): # xBR = box bottom right x coordinate
if (y >= yTL): #yTL = box top left y coordinate
if (y <= yBR): # yTL = box bottom right y coordinate
fid_xyz.write(output_str)
i = i + 1
# Check if finished sampling a line
if i == LINE_SAMPLES+1:
j = j + 1 # increment line coordinate
i = 1 # reset sample coordinate
if i*j == LINES*LINE_SAMPLES:
print(all lines parsed)
```

Sample Python code for creating point cloud from DEM

Point Cloud Example: 40m DEM 85S to 90S



Point cloud created from:

- Idem_85s_40m_float.img

View upon opening:

- +z is out of page
- To view S. Pole:
 - Rotate 180° to the right (into the screen)
 - Rotate 90° clockwise
- To see points: Click Dot Decorator next to Shading

MeshLab 2022.02 - [Project_1]
File Edit Filters Render View Windows Tools Help

FOV: 90
FPS: 2.2
IMMEDIATE/MODE_RENDERING

Mesh: Lunar_torada.xyz
Vertices: 57,517,055
Faces: 0
SubMeshes: 1, 0 f, 0

Project_1
lunar_torad...
0 lunar_torad...

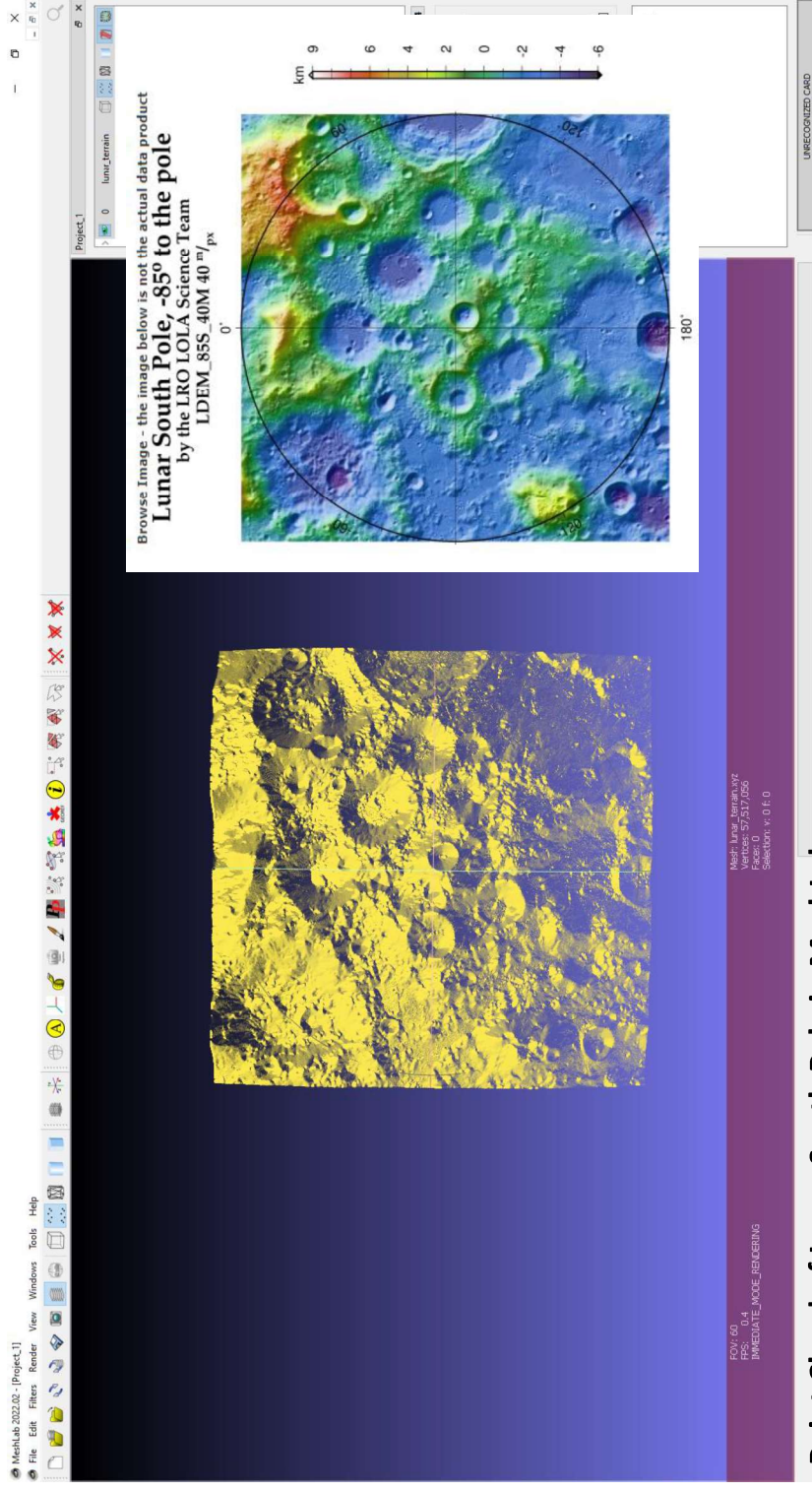
Shading: None
Dot Decorator: None
Mesh: User Def

Point Size
apply to all visible layers

Opened Mesh D:
NTD_Cases\Pipeline_Test\Output\00_Lo1
a_initio\Lunar_toradn.xyz in 194604
All files opened in 184605 msec

Point Cloud of Lunar South Pole in MeshLab

Point Cloud Example: 40m DEM 85S to 90S



Point Cloud of Lunar South Pole in MeshLab

LOLA Gridded Data Record Shape Map 85S 40m https://ode.rsl.wustl.edu/moon/indexproductpage.aspx?product_idgeo=21746067

Step 2: Point Cloud → Triangular mesh

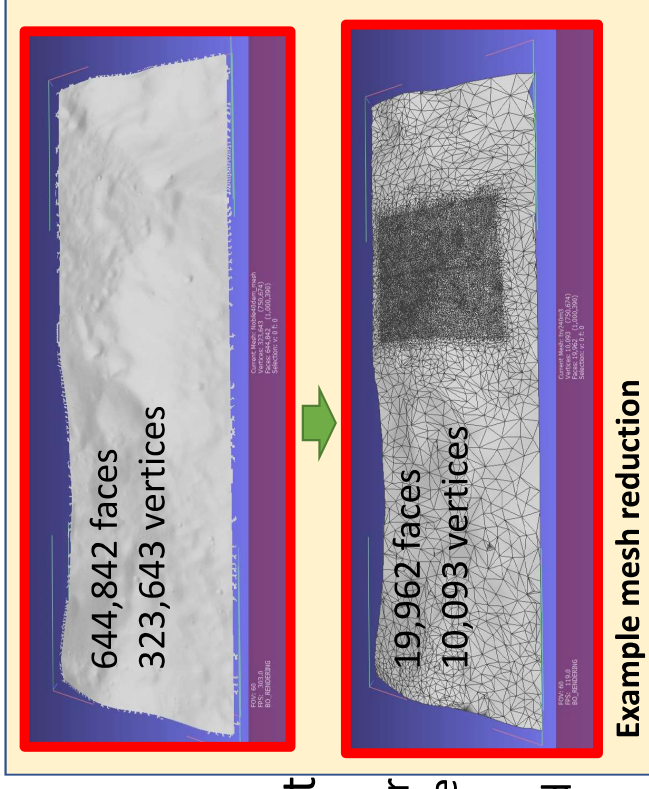
1. Open the lunar_terrain.xyz file in MeshLab.
2. Compute normal of mesh vertices that would be made from the xyz points
 - Filters > Point Set > Compute normal for point sets
 - use default of 10 neighbors
3. Construct the mesh (2 ways to do this)
 - Filters > Remeshing, Simplification, and Reconstruction > Screened Poisson Surface Reconstruction
 - Example settings (gave elements 100m in size from the 40m DEM):
 - Reconstruction Depth: 10 -- Increasing this decreases mesh element size.
 - Min Number of Samples: 1
 - use Default for the rest
 - Filters > Remeshing, Simplification, and Reconstruction > Ball Pivoting
4. **Mesh Reduction (simplify/cleanup mesh)**
5. Export resulting mesh to an .stl file
 - File> Export Mesh As
 - Unselect Materialize Color Encoding

Mesh reduction

1. If meshed with Poisson Surface Reconstruction remove the extra triangles made when constructing mesh
 - Filters > Selection > Select Faces with edges longer than use ~150 or 200
 - Click on triangle with the x over it to remove these faces
2. Clean up edges
 - Filters > Cleaning and Repairing > Remove isolated pieces (wrt Face Num.)
3. Mesh reduction options
 - Filters > Remeshing Simplification and Reconstruction > Simplification: clustering dissemination
 - Best to do this incrementally from outside in, detailed mesh will be in the center
 - Filters > Remeshing Simplification and Reconstruction > Quadratic Edge Collapse Decimation
 - MeshLab will only apply this to whole mesh
 - Remove
4. Locally increasing mesh density
 - Filters > Remeshing Simplification and Reconstruction > Subdivision Surfaces: Midpoint

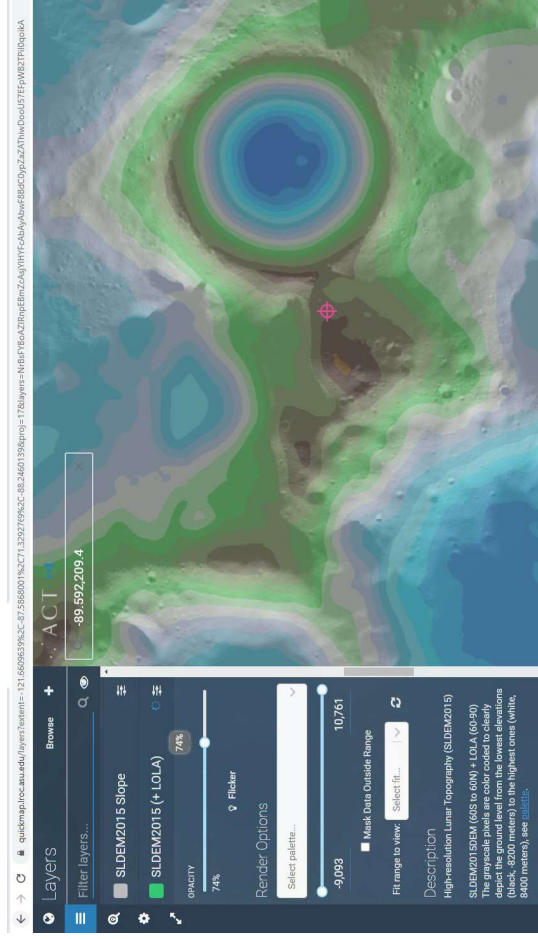
Mesh reduction

1. If meshed with Poisson Surface Reconstruction made when constructing mesh
 - Filters > Selection > Select Faces with edges longer
 - Click on triangle with the x over it to remove these
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 - Filters > Cleaning and Repairing > Remove isolated
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 - Filters > Remeshing Simplification and Reconstruction > Simplification > clustering
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Example: Point Cloud → Triangular mesh

- Area around 89.592S and 209.4E (-150.6W)¹

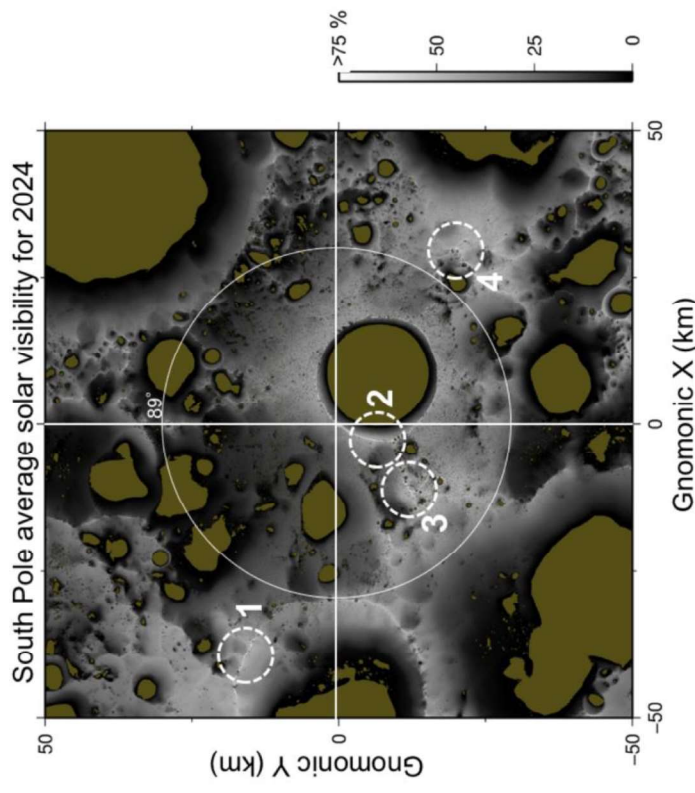


Example location shown in “Lunar QuickMap” website

<https://quickmap.lroc.asu.edu/query?extent=-121.0589468%2C-88.5101578%2C72.6825193%2C-89.1820632&proj=17&features=209.4000000%2C-89.5920000&selected=0&layers=NrB5FYBoAZIRnpEBmZcAsjYIHVFcAbAyAbwF8BdJAdeTpgDoAOAJknyNICIAmAOxwBzAKYAFFPgWEAKKcK4AulGhcAxB5CeKdG6Uq5KsGTRKAThYgUHFHGOIE0BRVDTcXA-r1A>

89.5920000&selected=0&layers=NrB5FYBoAZIRnpEBmZcAsjYIHVFcAbAyAbwF8BdJAdeTpgDoAOAJknyNICIAmAOxwBzAKYAFFPgWEAKKcK4AulGhcAxB5CeKdG6Uq5KsGTRKAThYgUHFHGOIE0BRVDTcXA-r1A

K4AulGhcAxB5CeKdG6Uq5KsGTRKAThYgUHFHGOIE0BRVDTcXA-r1A



Landing Site Regions of Interest on Lunar surface²

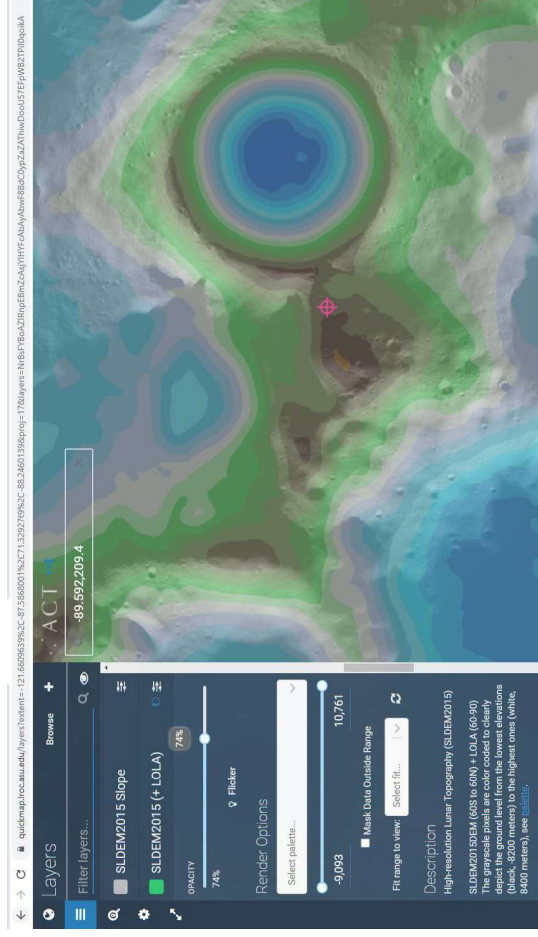
¹ Location considered by “Optimized traverse planning for future polar prospectors based on lunar topography” <https://ttu-ir.tdl.org/bitstream/handle/2346/86274/CES-2020-288.pdf?sequence=1&isAllowed=y>
² M. Smith, “Human Lunar Exploration” NASA Advisory Council Human Exploration & Operations Committee, May 2019, <https://www.nasa.gov/sites/default/files/atoms/files/20190528-nac-heoc-smith-v5b.pdf>

Start Demonstration

The next few slides summarize the demonstration which gives an example on how to create a lunar surface mesh from a point cloud in MeshLab.

Example: Point Cloud → Triangular mesh

- Area around 89.592S and 209.4E (-150.6W)



Example location shown in “Lunar QuickMap” website

[https://quickmap.lroc.asu.edu/query?extent=-121.0589468%2C-88.5101578%2C72.6825193%2C-](https://quickmap.lroc.asu.edu/query?extent=-121.0589468%2C-88.5101578%2C72.6825193%2C-89.1820632&proj=17&features=709.4000000%2C-89.5920000&selected=0&layers=NrBsfYBoAZIRnpEBmzCAsjYIHVFcAbAyAbwF8BdJAdeTpgDoAOAJknyNICIAmAQxwBzAKYAFFgWEAKKcK4AulGHCxgHsCeKdG6Uq5KsGTRKAThYgUHFHGOIE0BRVDTcXA-r1A)

[89.1820632&proj=17&features=709.4000000%2C-](https://quickmap.lroc.asu.edu/query?extent=-121.0589468%2C-88.5101578%2C72.6825193%2C-89.1820632&proj=17&features=709.4000000%2C-89.5920000&selected=0&layers=NrBsfYBoAZIRnpEBmzCAsjYIHVFcAbAyAbwF8BdJAdeTpgDoAOAJknyNICIAmAQxwBzAKYAFFgWEAKKcK4AulGHCxgHsCeKdG6Uq5KsGTRKAThYgUHFHGOIE0BRVDTcXA-r1A)

[89.5920000&selected=0&layers=NrBsfYBoAZIRnpEBmzCAsjYIHVFcAbAyAbwF8BdJAdeTpgDoAOAJknyNICIAmAQxwBzAKYAFFgWEAKKcK4AulGHCxgHsCeKdG6Uq5KsGTRKAThYgUHFHGOIE0BRVDTcXA-r1A](https://quickmap.lroc.asu.edu/query?extent=-121.0589468%2C-88.5101578%2C72.6825193%2C-89.1820632&proj=17&features=709.4000000%2C-89.5920000&selected=0&layers=NrBsfYBoAZIRnpEBmzCAsjYIHVFcAbAyAbwF8BdJAdeTpgDoAOAJknyNICIAmAQxwBzAKYAFFgWEAKKcK4AulGHCxgHsCeKdG6Uq5KsGTRKAThYgUHFHGOIE0BRVDTcXA-r1A)

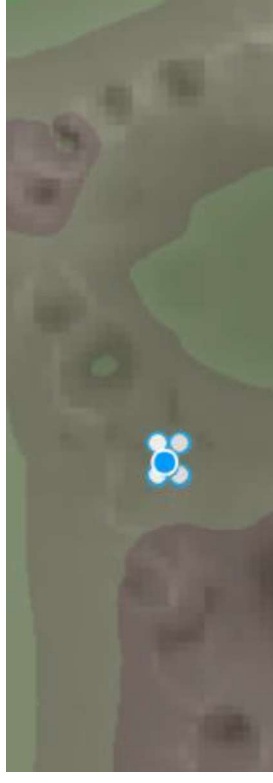
For simplicity limit the box size:

top_left = [-89.59183, -149.59296

top_right = [-89.59775, -151.06213]

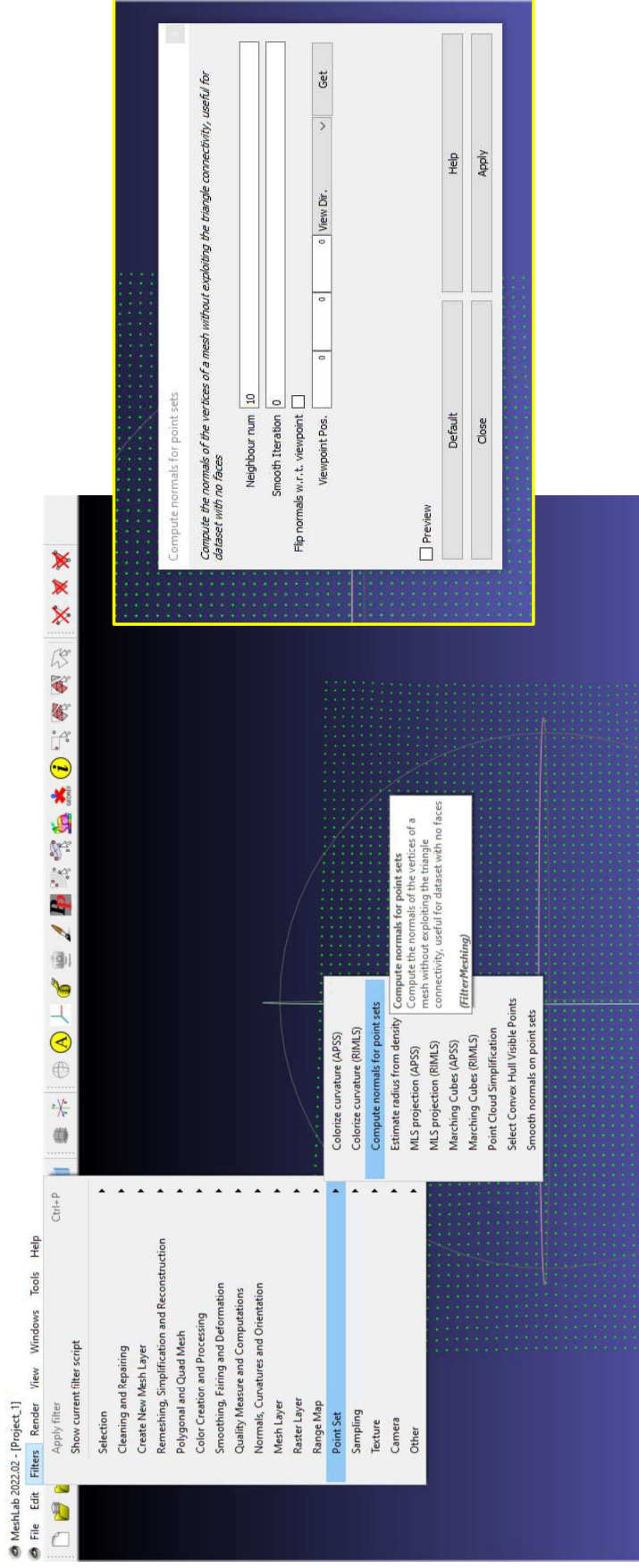
bottom_right = [-89.59053, -151.58538

bottom_left = [-89.58441, -150.12331]



Example: Point Cloud → Triangular mesh

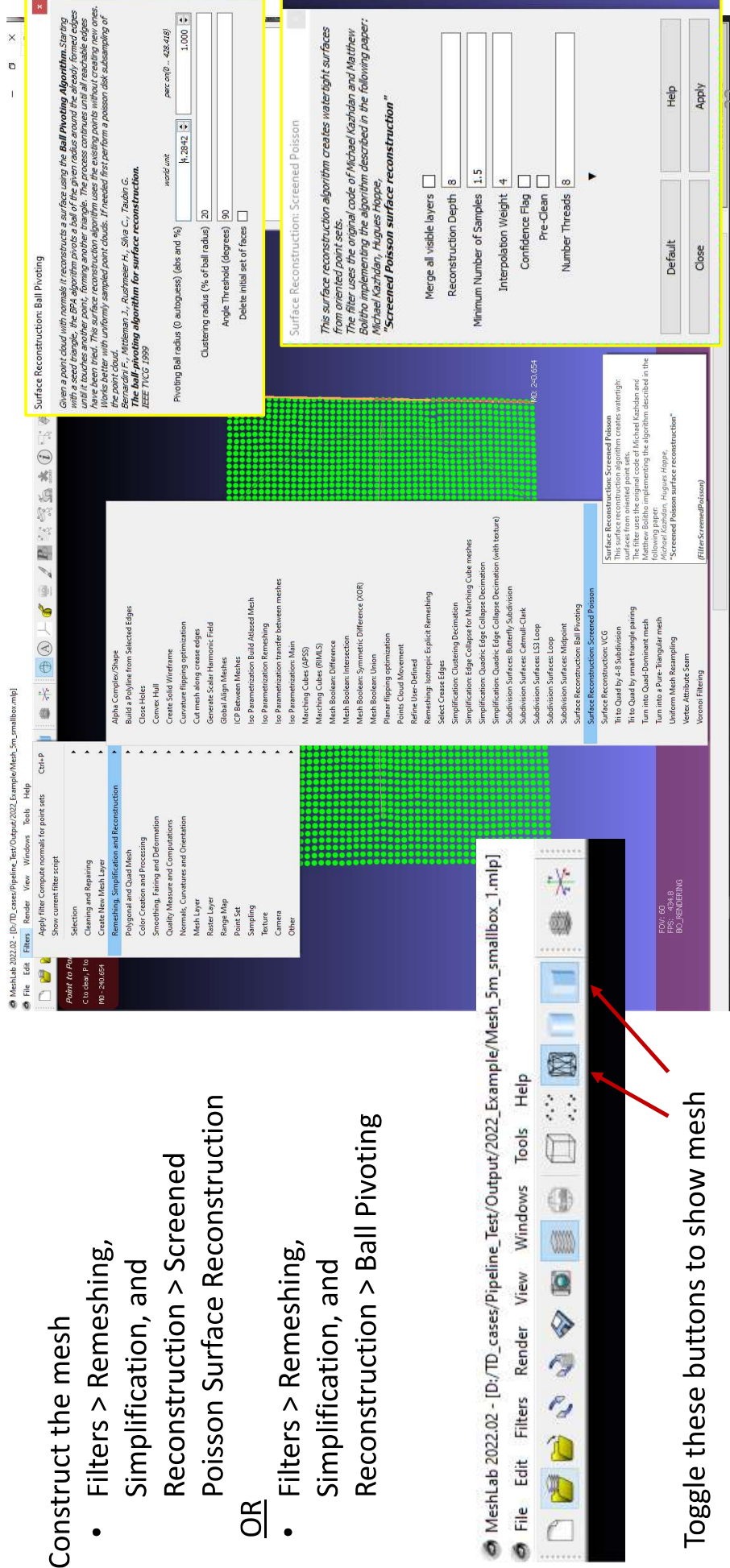
2. Compute normals of mesh vertices
 - Filters > Point Set > Compute normal for point sets



Example: Point Cloud → Triangular mesh

3. Construct the mesh

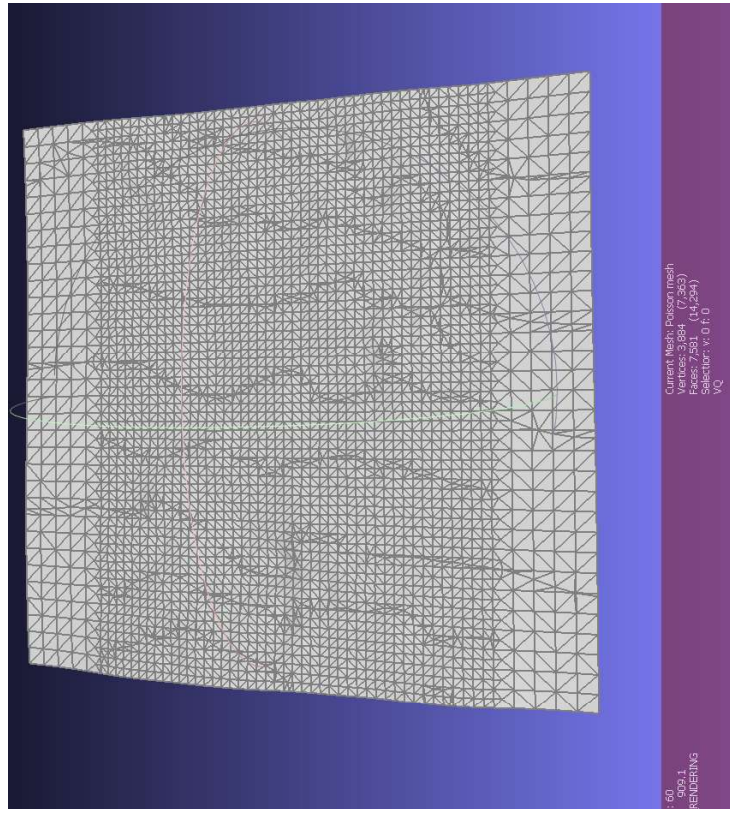
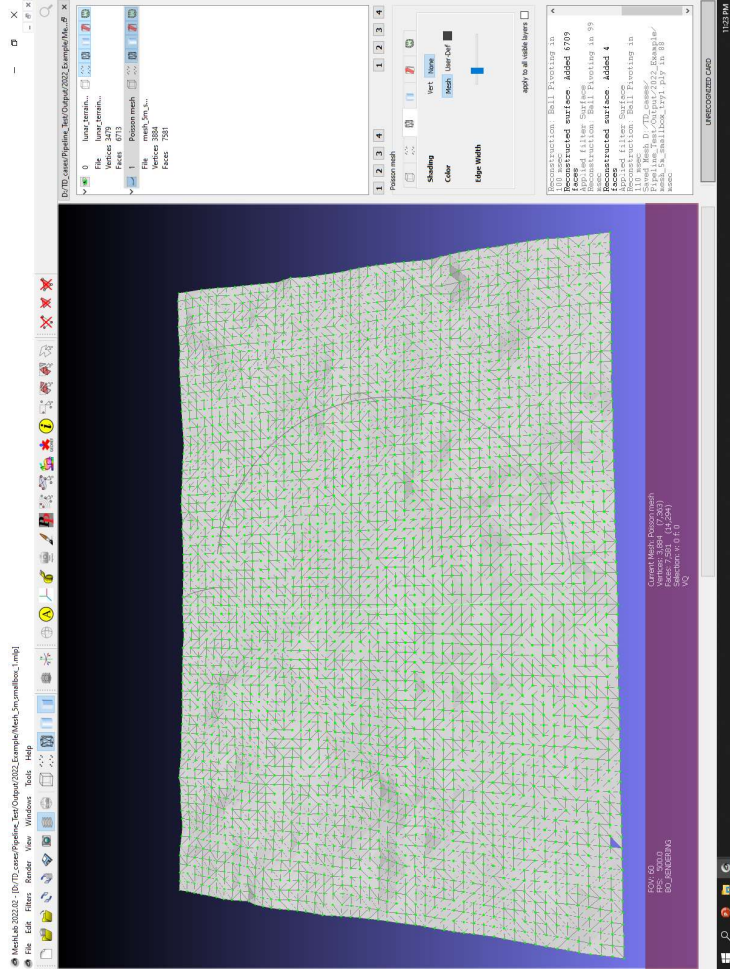
- Filters > Remeshing, Simplification, and Reconstruction > Screened Poisson Surface Reconstruction
- OR
- Filters > Remeshing, Simplification, and Reconstruction > Ball Pivoting



Toggle these buttons to show mesh

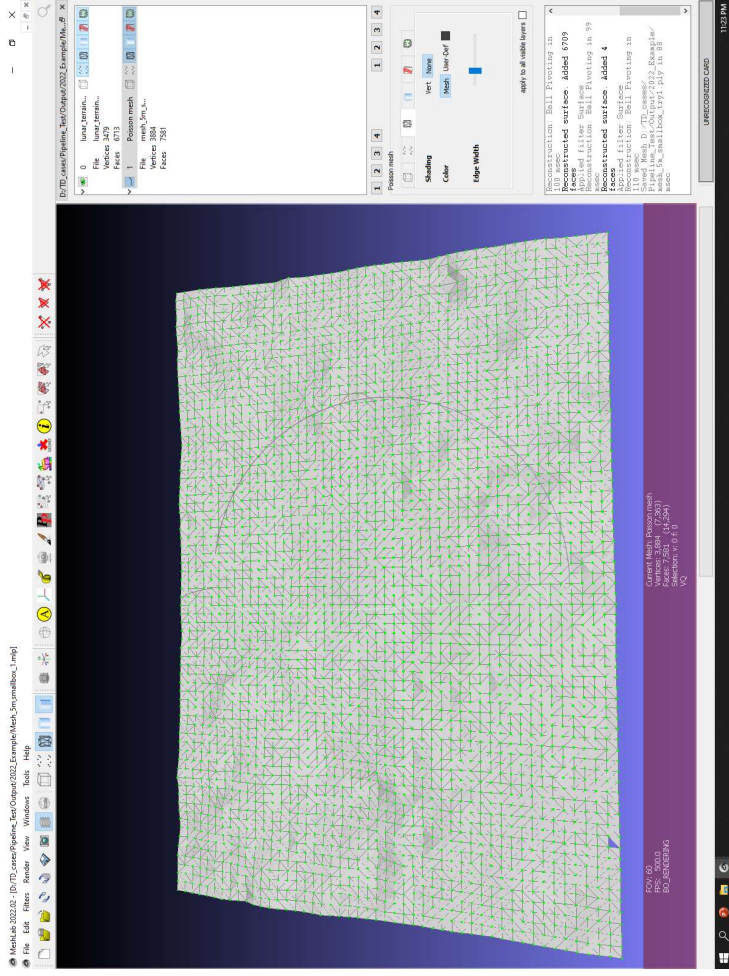
Example: Point Cloud → Triangular mesh

- Ball Pivoting
- Screened Poisson Surface Reconstruction

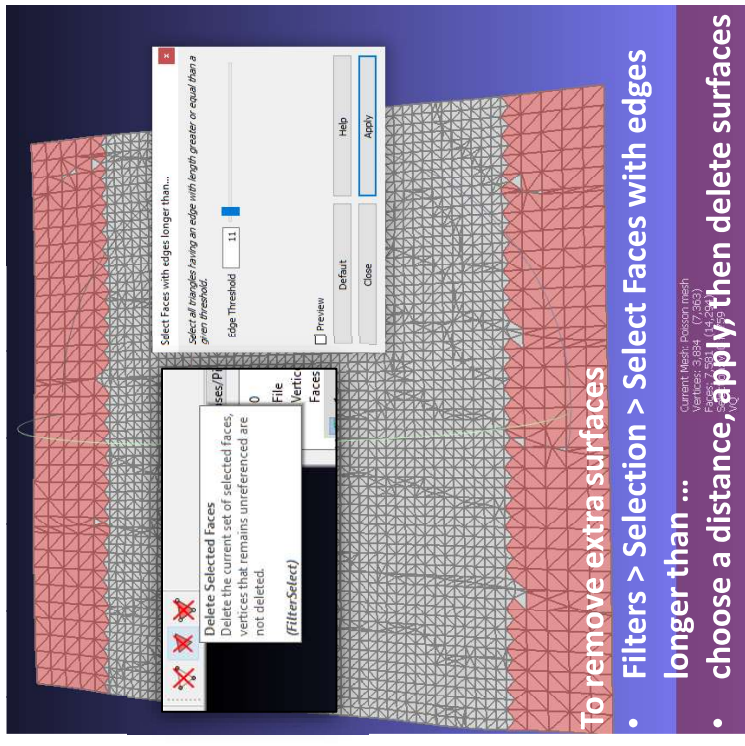


Example: Point Cloud → Triangular mesh

- Ball Pivoting



- Screened Poisson Surface Reconstruction

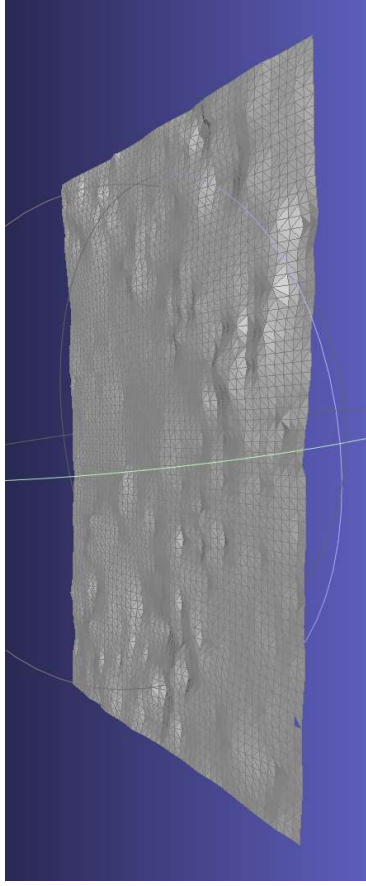


To remove extra surfaces

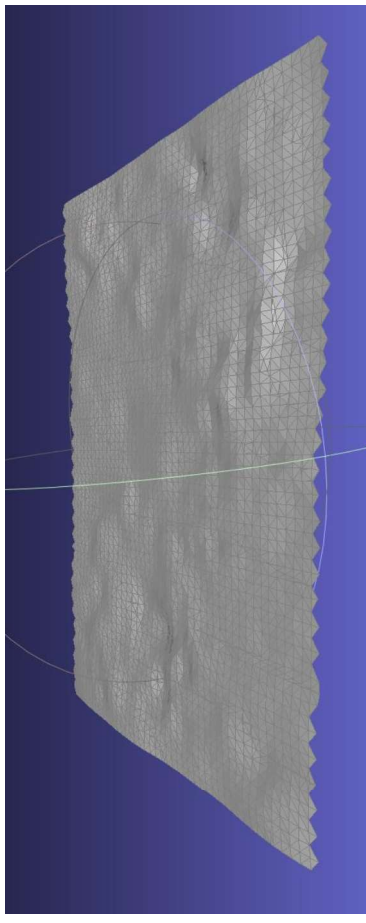
- Filters > Selection > Select Faces with edges longer than ...
- choose a distance, apply then delete surfaces

Example: Point Cloud → Triangular mesh

- Ball Pivoting



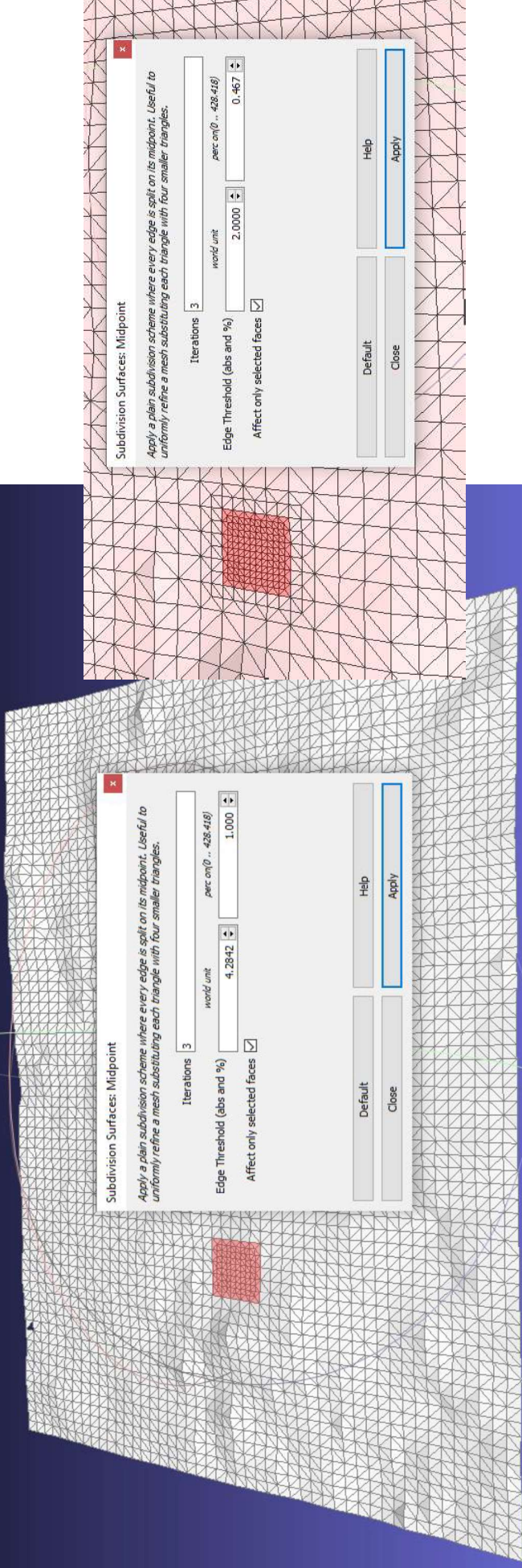
- Screened Poisson Surface Reconstruction



Example: Point Cloud → Triangular mesh

Increase mesh density in a particular area

- Filters > Remeshing Simplification and Reconstruction > Subdivision Surfaces: Midpoint



Example: Point Cloud → Triangular mesh

Export or Load Points to determine where you are.
-10793.587 -6170.1987 -1738833.6 → -89.5903 -150.2454
-10761.428 -6122.6631 -1738827.9 → -89.592 -150.3625

```
"lunar_terrain_5m_smallbox_ball_pivoting3_picked_points.pp - Notepad
File Edit Format View Help
<DOCTYPE PickedPoints>
<PickedPoints>
<DocumentData>
<DateTime date="2022-08-15" time="05:11:30"/>
<UserName="Irrerick1"/>
<DataFileName name="lunar_terrain_5m_smallbox_ball_pivoting3.stl"/>
<TemplateName name="new Template"/>
</DocumentData>
<point y="-6170.1987" active="1" name="new point" z="-1738833.6" x="-10793.587"/>
<point y="-6122.6631" active="1" name="new point" z="-1738827.9" x="-10761.428"/>
</PickedPoints>
```

Point Name	X	Y	Z	active
new point	-10793.6	-6170.2	-1738833.6	<input checked="" type="checkbox"/>
new point	-10761.4	-6122.66	-1738833.06	<input checked="" type="checkbox"/>

Mesh: lunar_terrain_5m_smallbox_ball_pivoting3.stl
Vertices: 3646
Faces: 7041
Clipping Near: 0.61

Opened mesh D:\TD_Cases\3_Examples\lunar_terrain_5m_smallbox_ball_pivot1.ng3.stl in 187 Assoc
All files opened in 210 Assoc
-6151.64492 -1738831.250000
[666.402]
Selected: new Mesh:0
Sketched: none PickedPoints

Example: Point Cloud → Triangular mesh

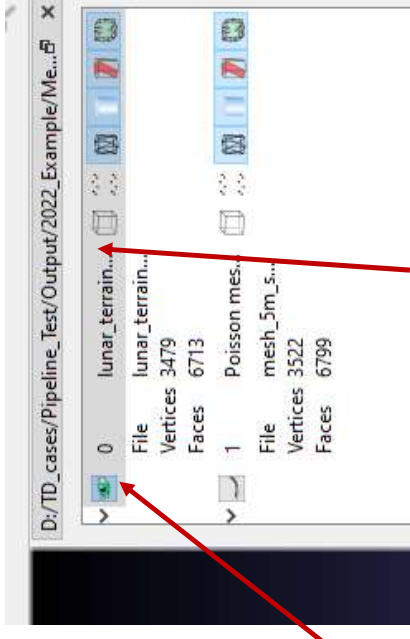
3. Export mesh:

- File > Export mesh as
- Select .stl extensions

Reload last saved layer (instead of undo)



Toggle these buttons to show mesh



Show or hide mesh

Operations (e.g.,
filtering & selection
will be performed on
highlighted one)

End Demonstration

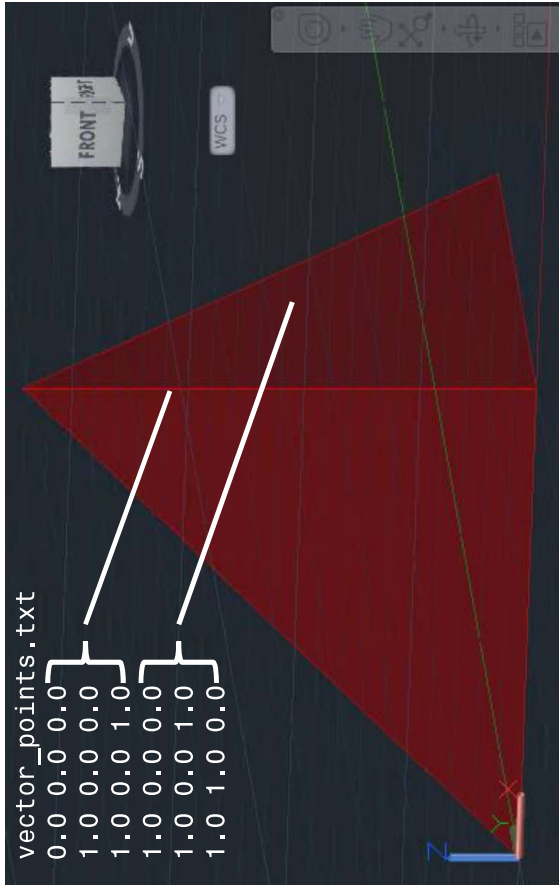
Import Mesh into Thermal Desktop

- Three steps:
 1. Convert .stl file to a list of mesh vectors (that describe each triangle)
 2. Run an AutoCAD VBA script to create mesh elements from these vectors
 - Requires AutoCAD VBA module to be installed
 - <https://knowledge.autodesk.com/support/autocad/downloads/caas/downloads/content/download-the-microsoft-vba-module-for-autocad.html>
 3. Convert AutoCAD mesh to TD mesh elements and add surface properties

See: Human Landing System Lunar Thermal Analysis Guidebook Section 9.5.1.3: Importing Meshes
https://ntrs.nasa.gov/api/citations/20210010030/downloads/HLS-UG-001%20Lunar%20Thermal%20Analysis%20Guidebook%20Baseline_STI.pdf

Step 1: Convert .stl file to Mesh Vectors

- Each triangular surface is described by 3 vectors
 - Each vector is defined its vertices
- Goal:
 - Write vectors to a .txt file, which will be read by AutoCAD in step 2
- Use Python package numpy-stl to
 - extract vectors from the .stl file
 - output vectors to vector_points.txt



AutoCAD Surface Elements



Step 1: Convert .stl file to Mesh Vectors

Example method to create `vector_points.txt`:

```
# Installed modules.
import numpy as np
from stl import mesh

# Read in the surface mesh.
s_mesh = mesh.Mesh.from_file(input_stl_full)

# Generate output text file.
f = open(filepath, 'w')

# Iterate through vectors of .stl file
for i in range(0, len(s_mesh.vectors)):
    # Iterate through 3 points of a vector
    for j in range(0, len(s_mesh.vectors[0])):
        # Iterate through x y z of each point
        outstr = '' # initialize output string
        for k in range(0, len(s_mesh.vectors[0][0])):
            outstr = outstr + str(s_mesh.vectors[i][j][k])
            if k < (len(s_mesh.vectors[0][0]) - 1):
                outstr = outstr + ' '
            else:
                outstr = outstr + '\n'
        # Write to output file
        f.write(outstr)
f.close()
```

`s_mesh = mesh object`

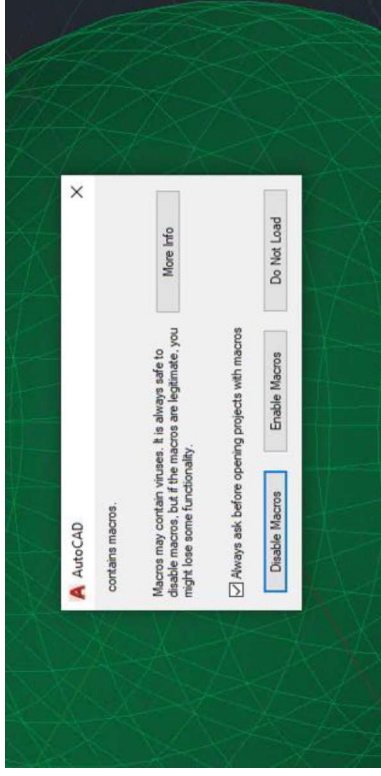
`s_mesh.vectors` contains
a list of all mesh vectors

an individual vector can be
accessed with the object
`s_mesh.vectors[i][j][k]`

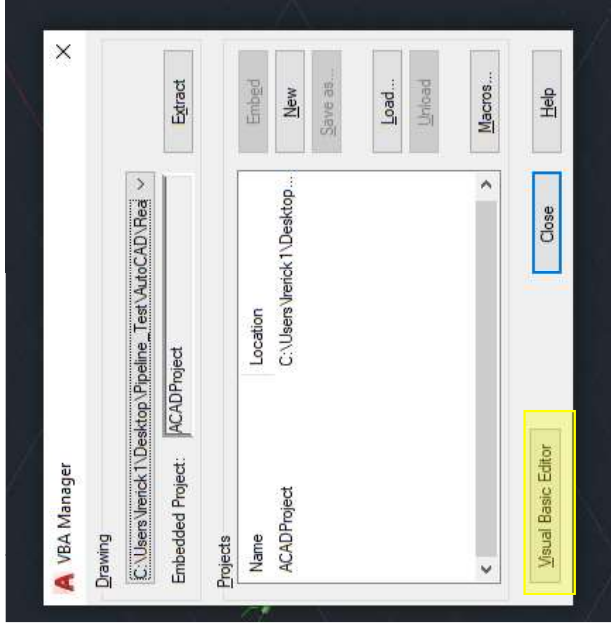
Python code outputting mesh vectors

Step 2: Create AutoCAD surface mesh

- To open VBA editor:
 - Type VBAMAN
 - Click Visual Basic Editor



AutoCAD file with VBA code will prompt to enable macros



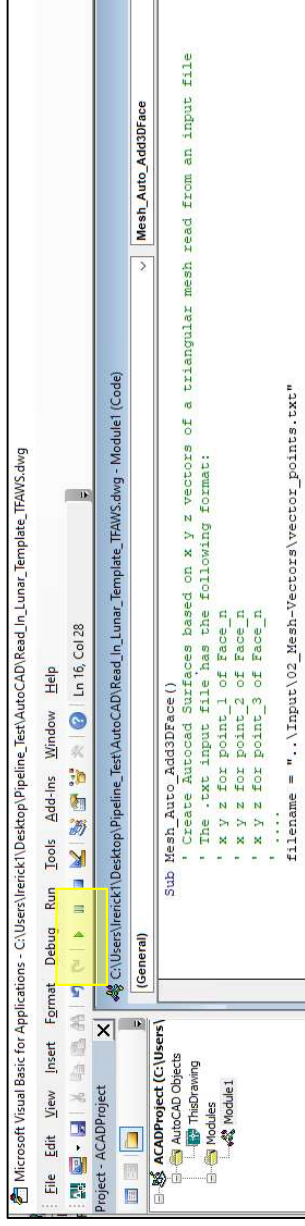
AutoCAD VBA Manager

Step 2: Create AutoCAD surface mesh

- Example code to create surface mesh is given in the Human Landing System Lunar Thermal Analysis Guidebook
 - Search for: Mesh_Auto_Add3DFace
 - Filename = sets input directory
 - Add3DFace(pt0, pt1, pt2, pt3) creates the triangular element
 - For a Quad element would input Add3DFace(pt0, pt1, pt2, pt3)
- In the VBA editor press the green play button to run the script

Add3DFace Method (ActiveX)
Creates a 3DFace object given four vertices.
Supported platforms: Windows only
Signature
VBA: RetVal1 = object.Add3DFace (Point1, Point2, Point3 [, Points4])
object Type: Block, ModelSpace, PaperSpace

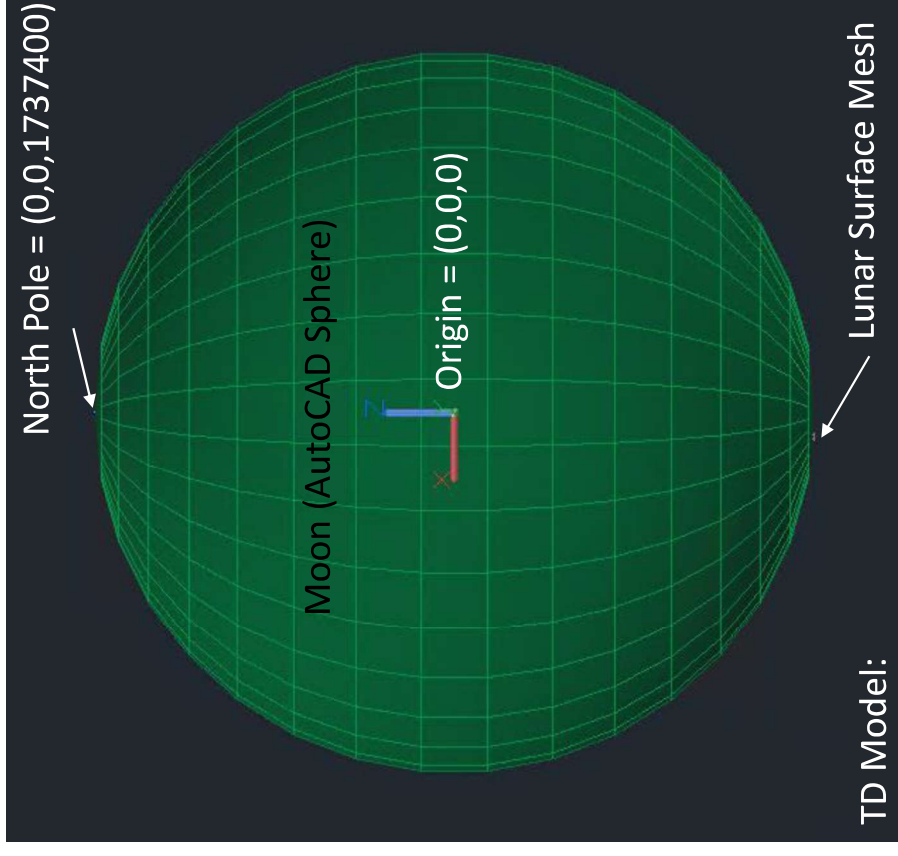
AutoCAD Add3DFace Method help:
<https://help.autodesk.com/view/OARX/2022/ENU/?guid=GUID-E125323B-7DC2-4174-AEA9-DAAEA0E683D9>



AutoCAD VBA editor

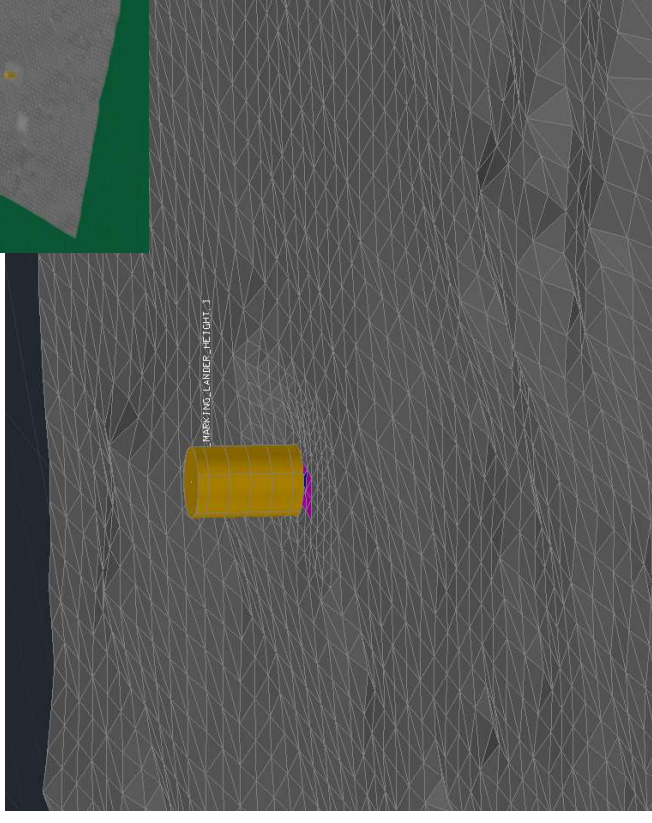
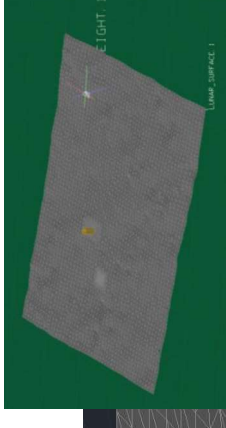
Step 3: Convert AutoCAD mesh to TD mesh

- Highlight the ground the select:
 - Thermal > FD/FEM Network > Convert AutoCAD Surface to Nodes/Elements
- Zoom in, mesh will be far away from origin
 - Show a node label if needed to see it
- Use properties described earlier



Step 4: Placing object on surface

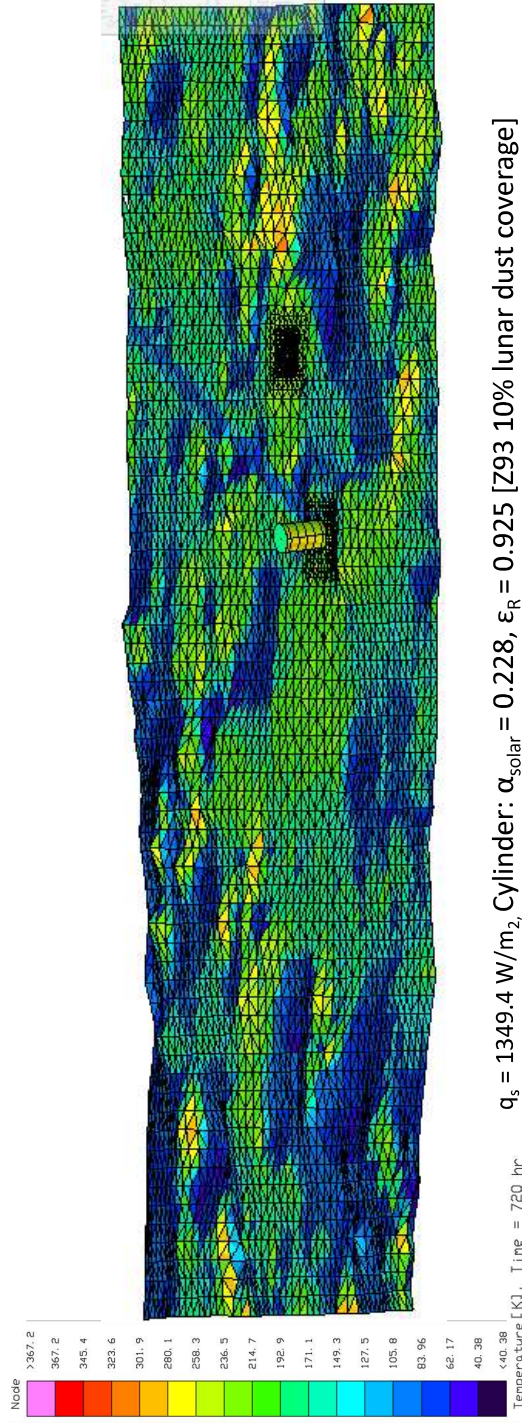
- A simple approach for static objects:
 - Attach your object to an articulator placed at the center of a triangle
 - Calculate normal vector out of triangle's surface
 - $\vec{n} = \vec{AB} \times \vec{AC}$
 - Where \vec{AB} and \vec{AC} are vectors describing 2 of the triangle's edges
 - Use right hand rule to pick them such that \vec{n} points in the desired direction
 - Calculate point x distance away from triangle's center along normal vector
 - Place a temporary node at that point
 - Grab +z articulator grip point and move it to the temporary node.
- Alternative approach:
 - Place object on a square
 - Attach center of square to articulator
 - Specify articular rotations
 - Order of rotations matching TD articulators:
 - Rotate about z axis
 - Rotate about transformed y axis
 - Rotate about transformed x axis



**Example: Cylinder 1 m above meshed terrain
(h=12 m, r=4 m)**

Example: Cylinder on Meshed Terrain

- Area around 89.592S and 209.4E (-150.6W)
- Orbit: 2010-Sep-21 00:00 to 2010-Oct-21 00:00
- Ground is initialized for 5 years prior to run



Example: Effect of Far-field Terrain

- Used geometry to check if terrain features could shadow terrain at point P



- Predict if an target object at point P could be shadowed by a blocking object at point P_H located θ degrees away.
 - Estimate θ as difference between latitudes, assuming at some point the target and blocking objects are aligned.
- Know radius of moon, r , height of blocking object, H , height of target object H_T (e.g. terrain elevation at P), solar elevation angle, α , and θ .
- Calculate height of shadow at point P , y .
 - Shadow cast by H at point P_H = shadow cast by H_T on a flat plane at a distance d away from target point P .
- Note: Sunlight is imperfectly collimated ($\pm 0.5^\circ$), to 'correct' $+0.5^\circ$ to max solar elevation angle at P .

By Trig relations:

$$z = H \sin(\alpha) \tan(\alpha)$$

$$h_f = h_p - c - z \text{ estimated flat plane height}$$

$$d = r \sin(\theta) \text{ distance from } P_H \text{ to } P$$

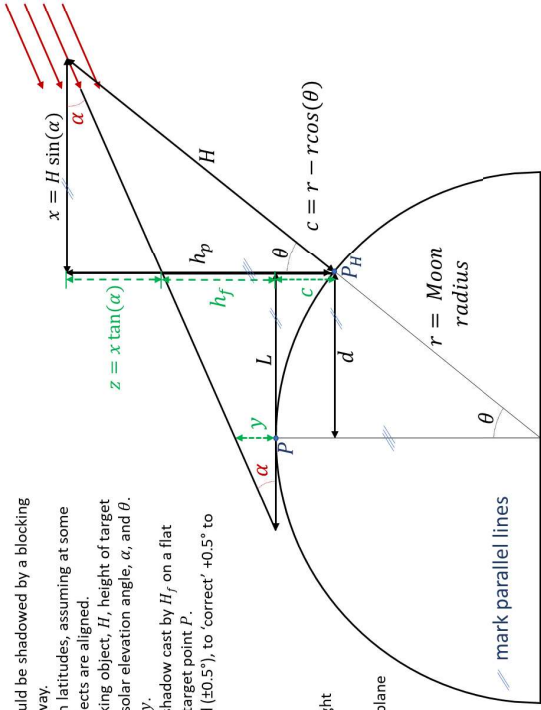
$$L = h_f / \tan(\alpha) \text{ length of shadow on flat plane}$$

By similar triangles:

$$\frac{y}{h_f} = \frac{L-d}{L}$$

$$y = \left(\frac{L-d}{L} \right) h_f$$

$$\text{if } y > H_T \text{ target is shadowed}$$

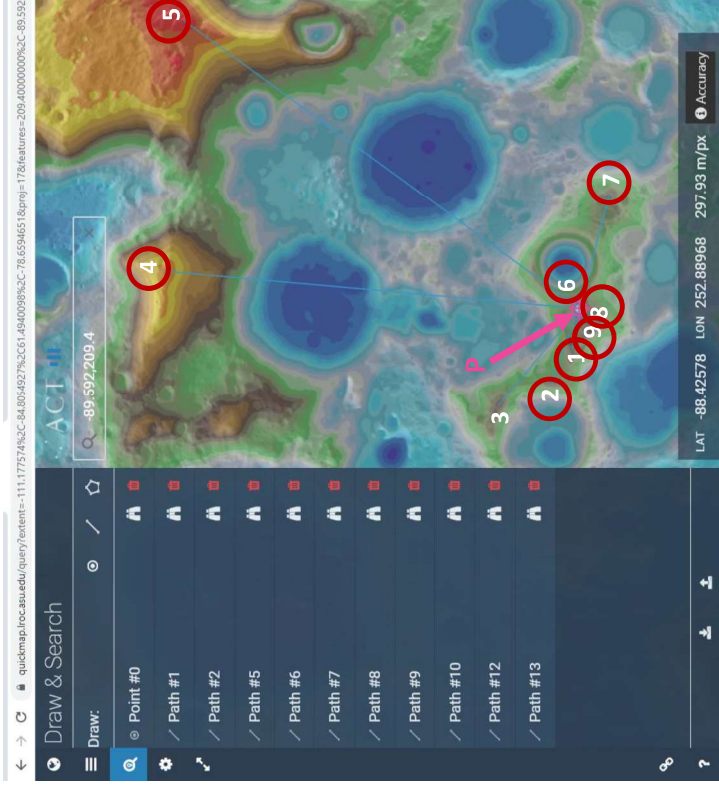


Note: sunlight is imperfectly collimated ($\pm 0.5^\circ$), this estimate can be improved by checking for shadowing from a range of elevation angles $0 < \alpha \leq \alpha_{max} + 0.5$. Time in shadow may be short.

Section 9.3.2 "Human Landing System Thermal Analysis Gradebook" HLS-UG-001

Example: Effect of Far-field Terrain

- Used geometry to check if terrain features could shadow terrain at point P



case	Target		Block		Target		Block		H _T [m]		Target location shadowed?
	Lat	Lon	Lat	Lon	Lat	Lon	H _T [m]	H [m]			
1	-89.592	209.4	-89.4591	-137.052	1465	5246	yes				
2	-89.592	209.4	-89.3081	-113.824	1465	1691	yes for elevation <1.36°				
3	-89.592	209.4	-89.0099	-92.9862	1465	1425	No				
4	-89.592	209.4	-88.6715	-67.9055	1465	1798	yes for elevation <0.22°				
5	-89.592	209.4	-85.9757	2.72545	1465	5140	yes for elevation <0.11°				
6	-89.592	209.4	-85.2456	36.6487	1465	6749	yes for elevation <0.12°				
7	-89.592	209.4	-89.7476	-157.942	1465	1996	Yes				
8	-89.592	209.4	-88.8017	123.906	1465	1641	yes for elevation <0.03°				
9	-89.592	209.4	-89.5403	-150.05	1465	1646	yes				

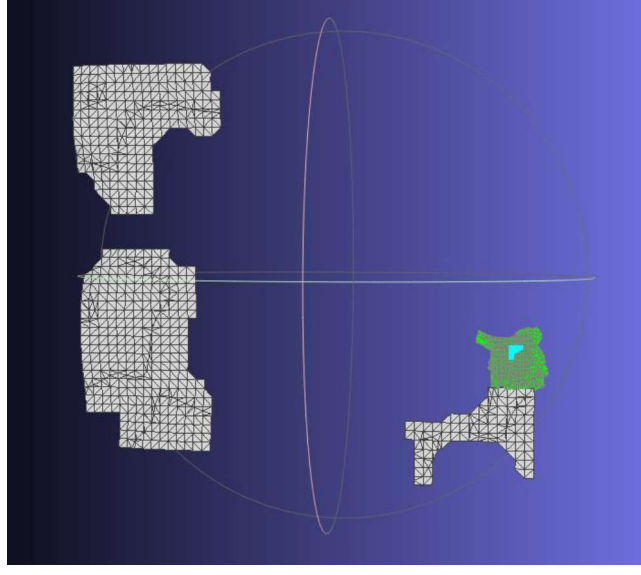
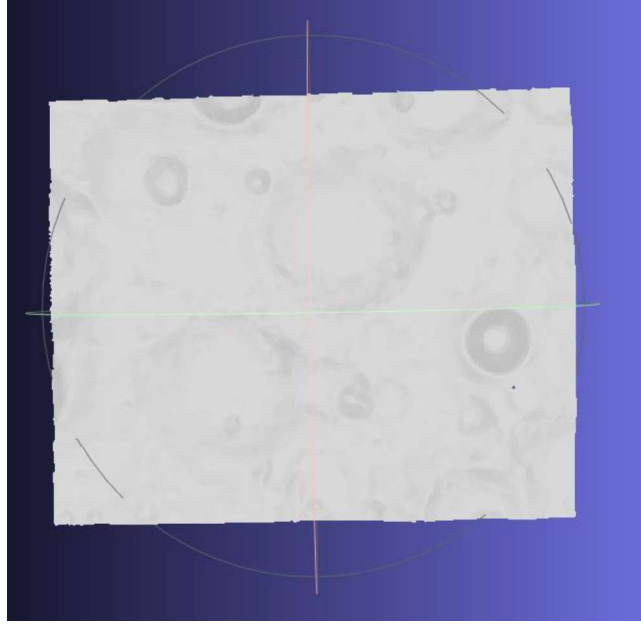
Total days where elevation angle is $\leq 0^\circ = 169$

Total days where elevation angle is $\leq 0.22^\circ$ and $> 0^\circ = 190$

Closer hills could negate impact of farther hills

Example: Effect of Far-field Terrain

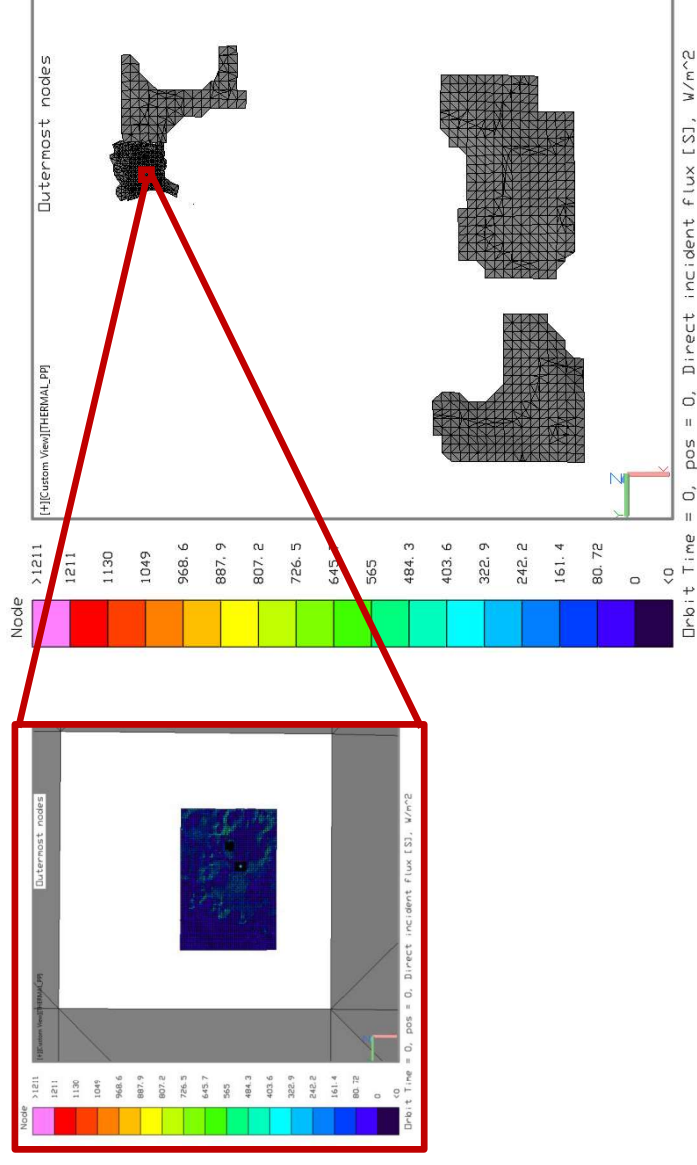
- Meshed large terrain & removed elements at low elevations



LAT/LON Bounds:
top_right = [-84.76164, 35.20046, 6116.21] top_left = [-85.49455, -19.77071, 2310.69]
bottom_left = [-87.93420, -120.80487, -865.08] bottom_right = [-87.05400, 110.14100, -1390.71]

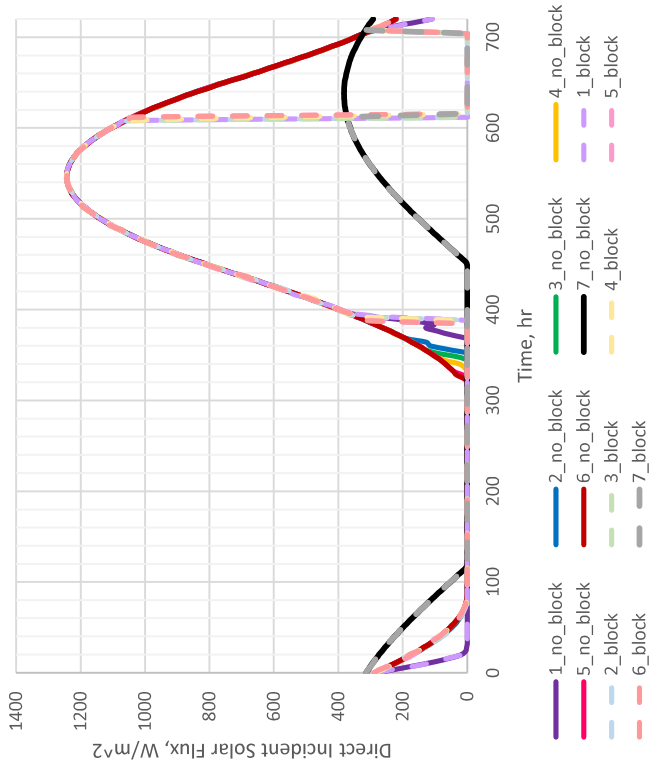
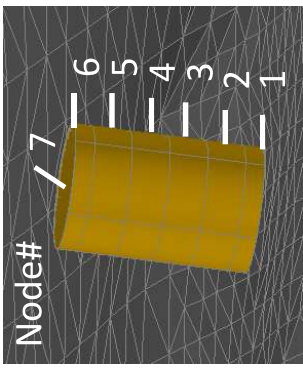
Example: Effect of Far-field Terrain

- Added far-field terrain to TD model
 - set active = none to act as a reflector/blocker
- Compared results with and without far-field terrain blockers

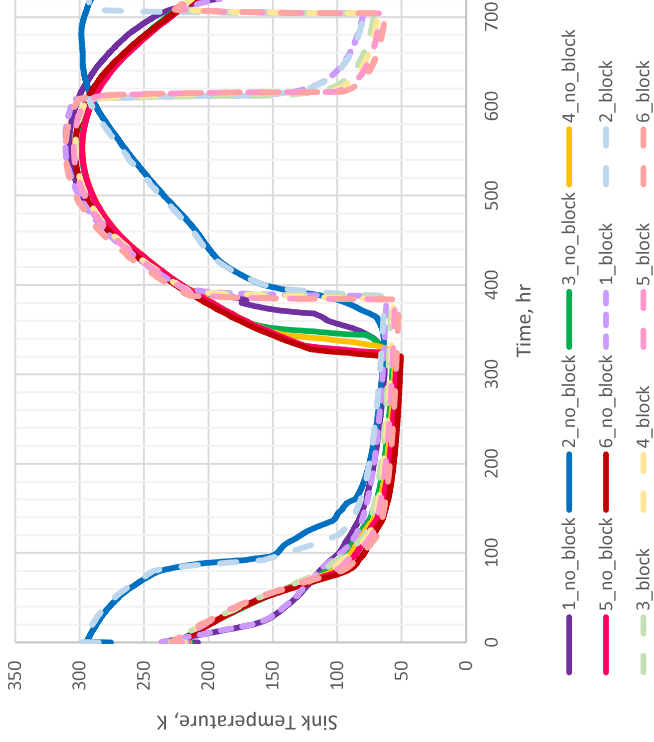


Ground temperatures

- Far-field terrain blocked solar rays from hitting cylinder



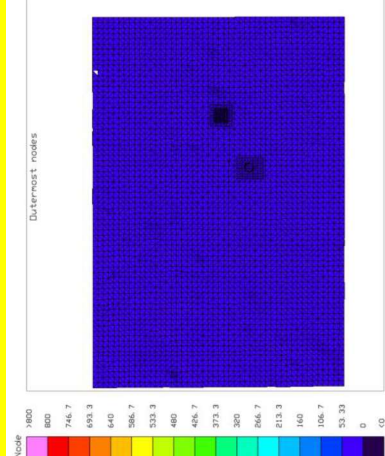
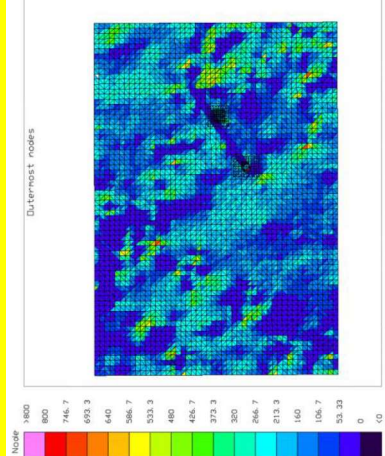
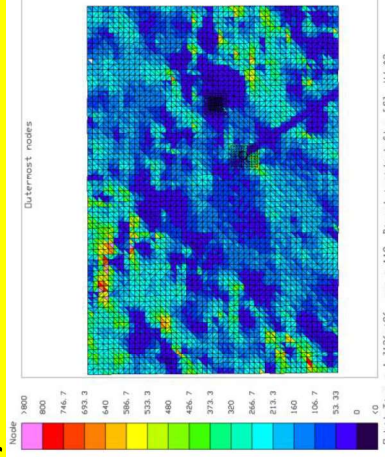
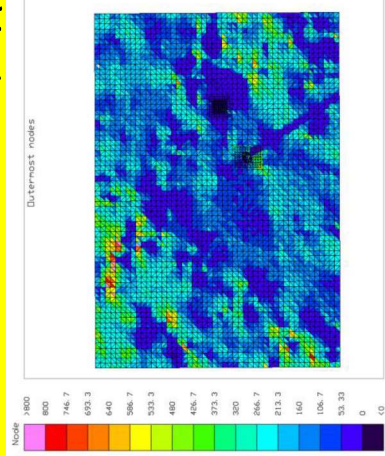
Direct Incident Solar flux



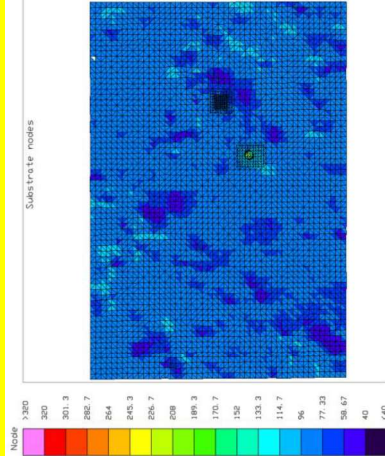
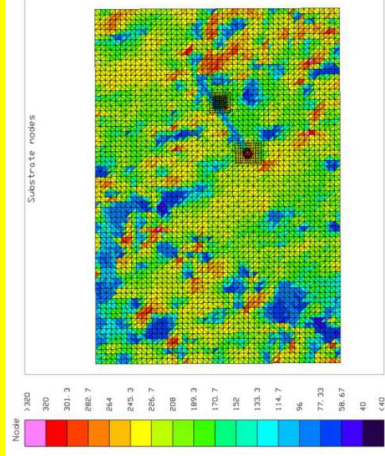
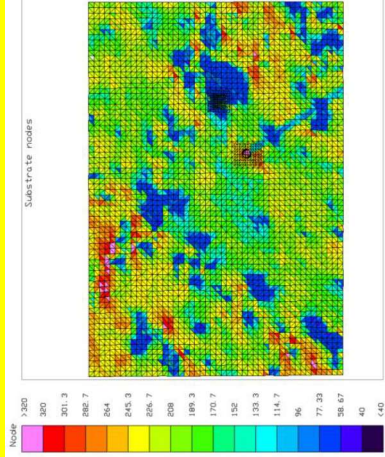
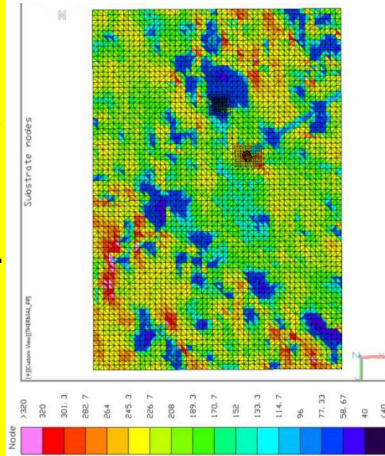
Sink Temperatures

Example: Effect of Far-field Terrain

Direct Incident Solar Flux, $W/(m^2K)$



Ground Temperatures, K



[481 hrs] without far-field terrain

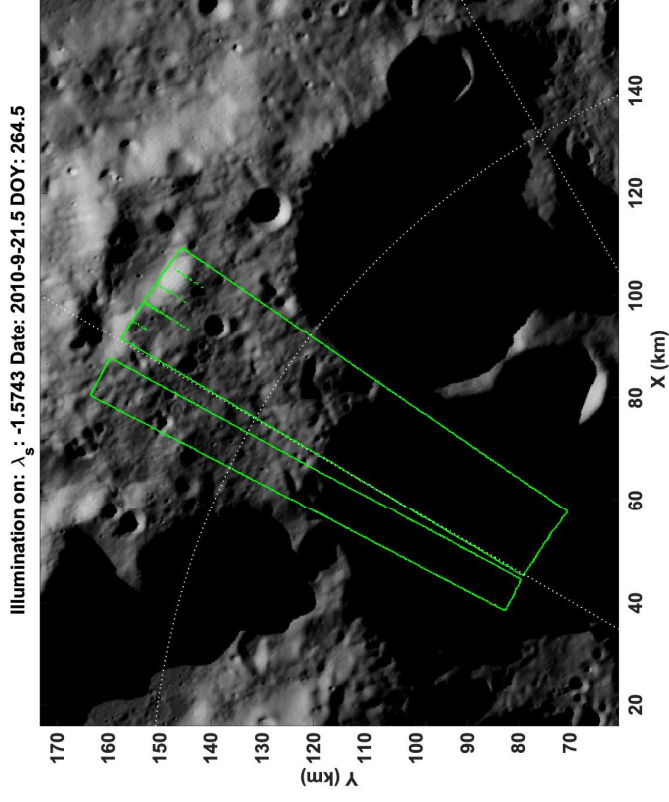
with far-field terrain

[650-652 hrs] without far-field terrain

with far-field terrain

Comparison to Diviner Data

- Goal: Check Thermal Desktop ground temperature predictions with LRO DIVINER data [250m × 250m resolution]
- Comparison Date / Time: 2010-09-21 12.76 hours
- Nobile location:



Comparison to Diviner Data

- Comparison:

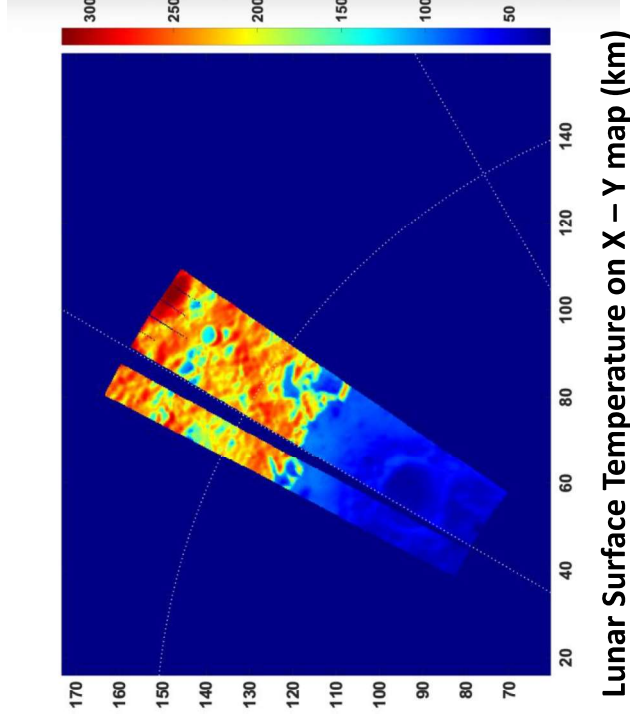
- 1) Received DIVINER Tbol from Pierre Williams for Comparison Date / Time: 2010-09-21 12.76 hours

Tbol = Bolometric brightness temperature (measures spectrally integrated radiative flux from surface)

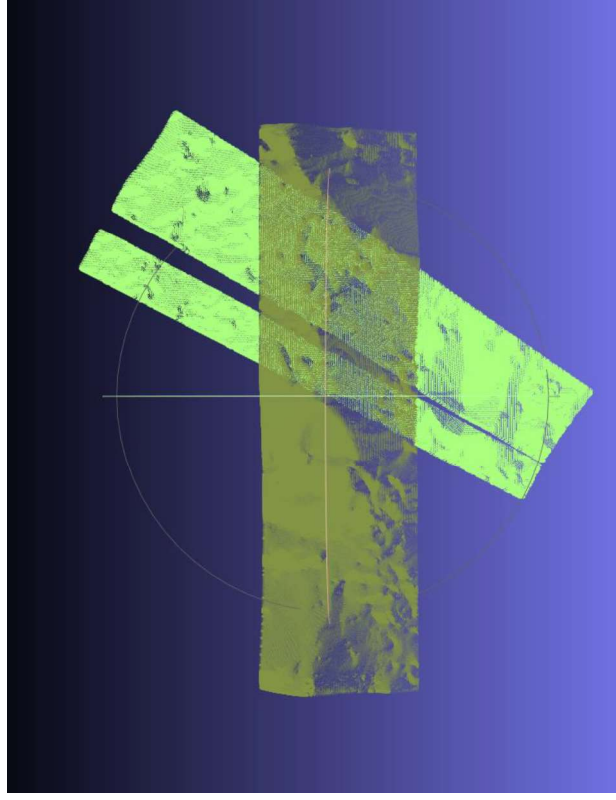
Paige et al. "Diviner Lunar Radiometer Observations of Cold Traps in the Moon's South Polar Region" & Gläser and Gläser "Modeling near-surface temperatures of airless bodies with application to the Moon" showed polar region good agreement of Tbol to model surface temperatures.

- 2) Used DEM to determine x, y, z of DIVINER Tbol

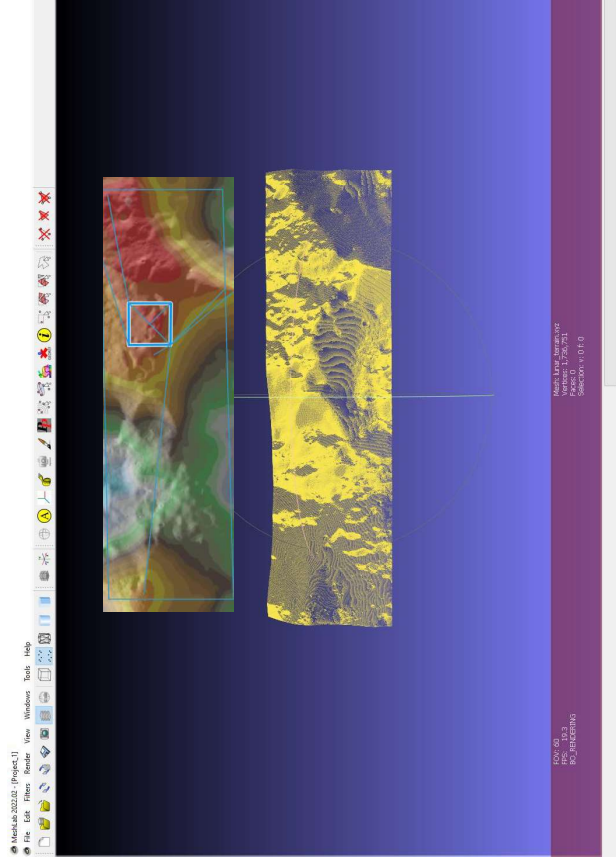
- 3) Used TD to interpolate node temperature to Tbol points



Comparison to Diviner Data



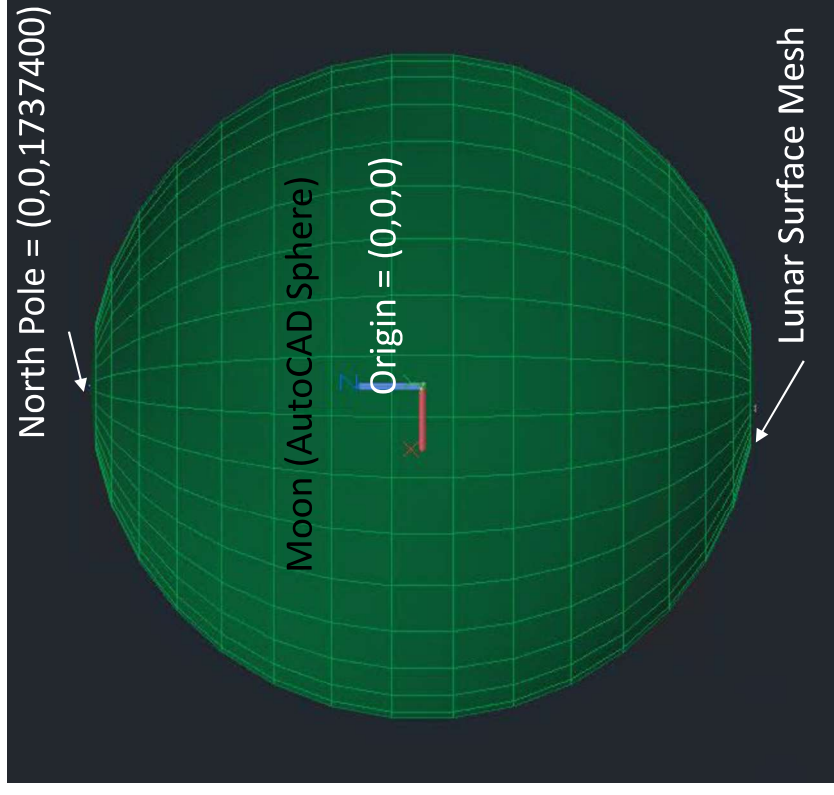
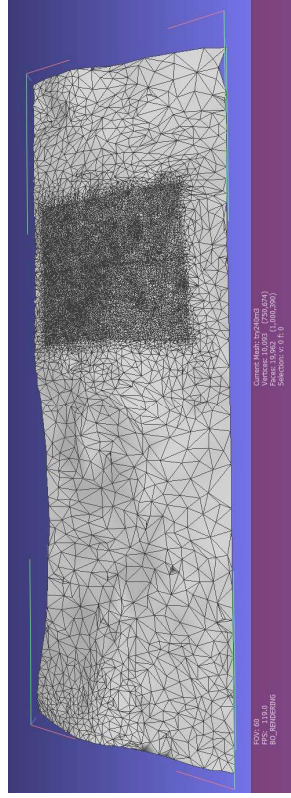
DEM points (tan) & Diviner Points (green)



Point cloud (yellow) & Elevation from Lunar QuickMap Website

Comparison to Diviner Data

- Analysis Method:
 - 1) Create point cloud from 40m x 40m DEM
 - 2) Mesh in MeshLab use “Screened Poisson Surface” method
 - 3) Reduce mesh & import it into Thermal Desktop



Dense region element sizes are ~250m

Comparison to Diviner Data

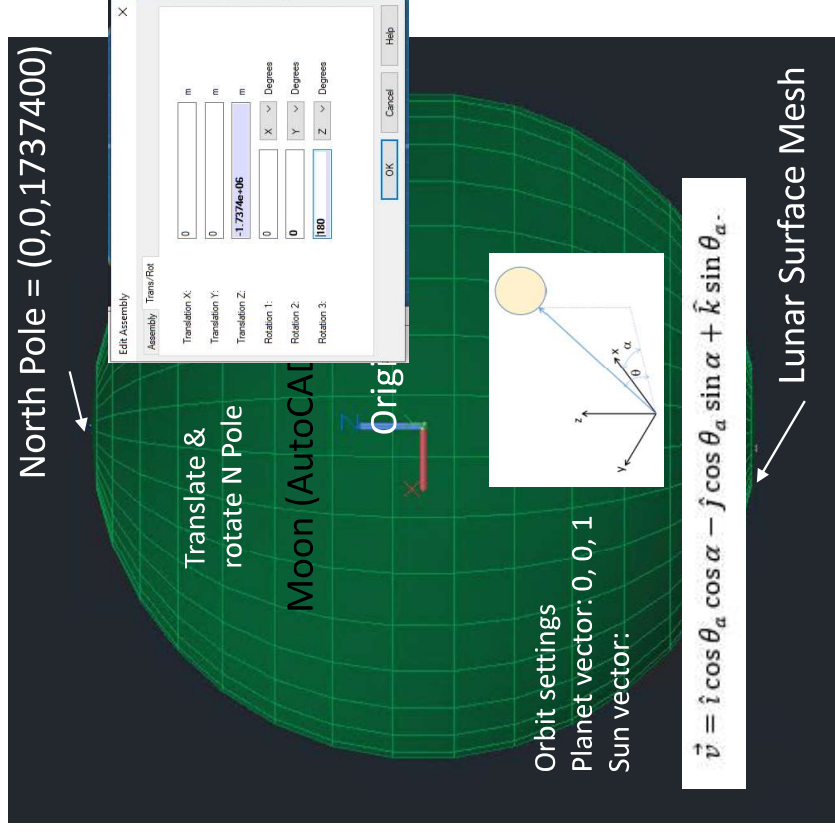
- Analysis Method:
 - 4) Obtain sun azimuth and elevation angles from JPL horizons database for comparison date to 5 yrs prior (angles are with respect to local zenith)
 - 5) Match origin in model with Horizon's assumed origin

JPL Horizons settings:

```

Current Settings
Ephemeris Type [change] : OBSERVER
Target Body [change] : Sun [Sol] [10]
Observer Location [change] : Topocentric @301 [Moon] [ 0°00'00.0"E, 90°00'00.0"N ]
Time Span [change] : Start=2010-09-21, Stop=2010-09-22, Step=30 m
Table Settings [change] : QUANTITIES=4,13
Display/Output [change] : default (formatted HTML)
    
```

Date (UT)	HR:MN	Azi (e-approx)	Elev	Ang-diam
2010-Sep-21 00:00		152.6407	-1.5625	1906.840
2010-Sep-21 00:30		152.6343	-1.5628	1906.844
2010-Sep-21 01:00		153.1473	-1.5630	1906.844
2010-Sep-21 01:30		153.4613	-1.5630	1906.847
2010-Sep-21 02:00		153.6551	-1.5634	1906.849
2010-Sep-21 02:30		153.3068	-1.5634	1906.852
2010-Sep-21 03:00		134.1624	-1.5633	1906.854
2010-Sep-21 03:30		134.4160	-1.5633	1906.857
2010-Sep-21 04:00		134.6695	-1.5633	1906.860
2010-Sep-21 04:30		134.7226	-1.5642	1906.862
2010-Sep-21 05:00		135.1368	-1.5644	1906.865
2010-Sep-21 05:30		135.4804	-1.5646	1906.866
2010-Sep-21 06:00		135.6946	-1.5647	1906.871
2010-Sep-21 06:30		135.3075	-1.5649	1906.874
2010-Sep-21 07:00		136.1348	-1.5651	1906.876
2010-Sep-21 07:30		136.4934	-1.5653	1906.881
2010-Sep-21 08:00		136.9530	-1.5654	1906.884
2010-Sep-21 08:30		137.0262	-1.5655	1906.886
2010-Sep-21 09:00		137.4520	-1.5657	1906.891
2010-Sep-21 09:30		137.7128	-1.5659	1906.893
2010-Sep-21 10:00		137.6454	-1.5660	1906.895
2010-Sep-21 10:30		138.3290	-1.5663	1906.902
2010-Sep-21 11:00		138.4736	-1.5663	1906.910
2010-Sep-21 11:30		138.7272	-1.5665	1906.914
2010-Sep-21 12:00		138.9868	-1.5666	1906.918
2010-Sep-21 12:30		139.2344	-1.5668	1906.922



Comparison to Diviner Data

- Analysis Method:
 - 6) Supply a time varying solar constant
 - Used JPL WebGeocalc (Spice) to determine distance from sun at specified dates
 - output: Orbiting body range (km)
 - Calculated solar constant at these distances

Solar flux is proportional to inverse square of distance to sun

$$q_s = I_b \frac{A_p}{S^2} \rightarrow q_s \propto \frac{1}{S^2}$$

A_p = projected area of sun

I_b = black body intensity

S = distance to sun

Can use $q_s = 1367 \text{ W}/m^2$ at 1 AU (149597870.7 km) to find q_s at other distances

$$q_{s,2} = \frac{q_{s,1} S_1^2}{S_2^2}$$

<https://wgci.jpl.nasa.gov:8443/webgeocalc/#OrbitalElements>

Comparison to Diviner Data

To use TD to interpolate node temperature to Tbol points:
Thermal > Export Map Data to Locations

To output temperatures at nodes in TD mesh:
Thermal > Export Information



Comparison to Diviner Data

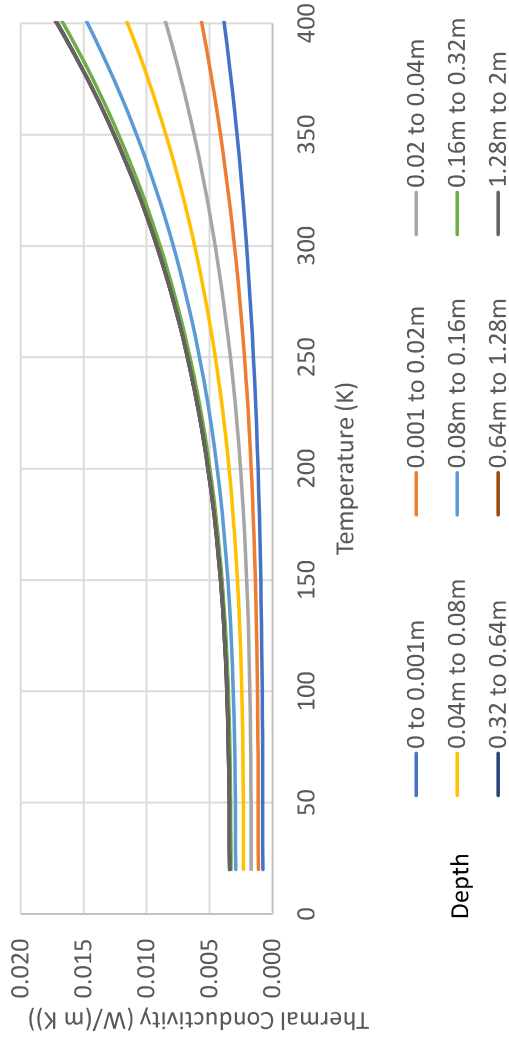
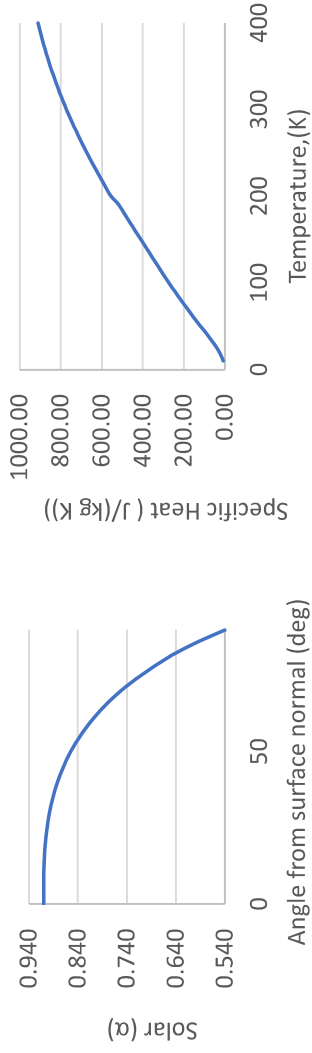
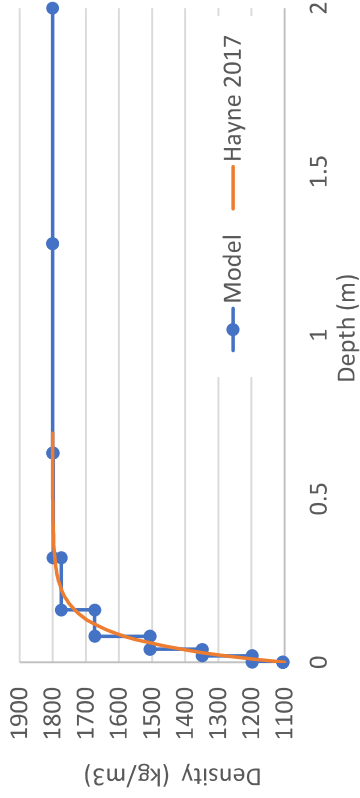
Model 1:

- Solar Flux 1421 W/m²
- Lunar Surface
 - 9 layers, 2m deep, increasing density
 - α = angular dependent, Feng 2019¹
 - $\epsilon = 0.97$

Interior Heat Flux = 0.018 w/m²

k & ρ = Hayne 2017 (better when >100K)²

c_p = Woods-Robinson 2019³



¹ Feng et al., "Lunar Regolith Properties Constrained by LRO Diviner and Chang'e-2 Microwave Radiometer Data," 2019.

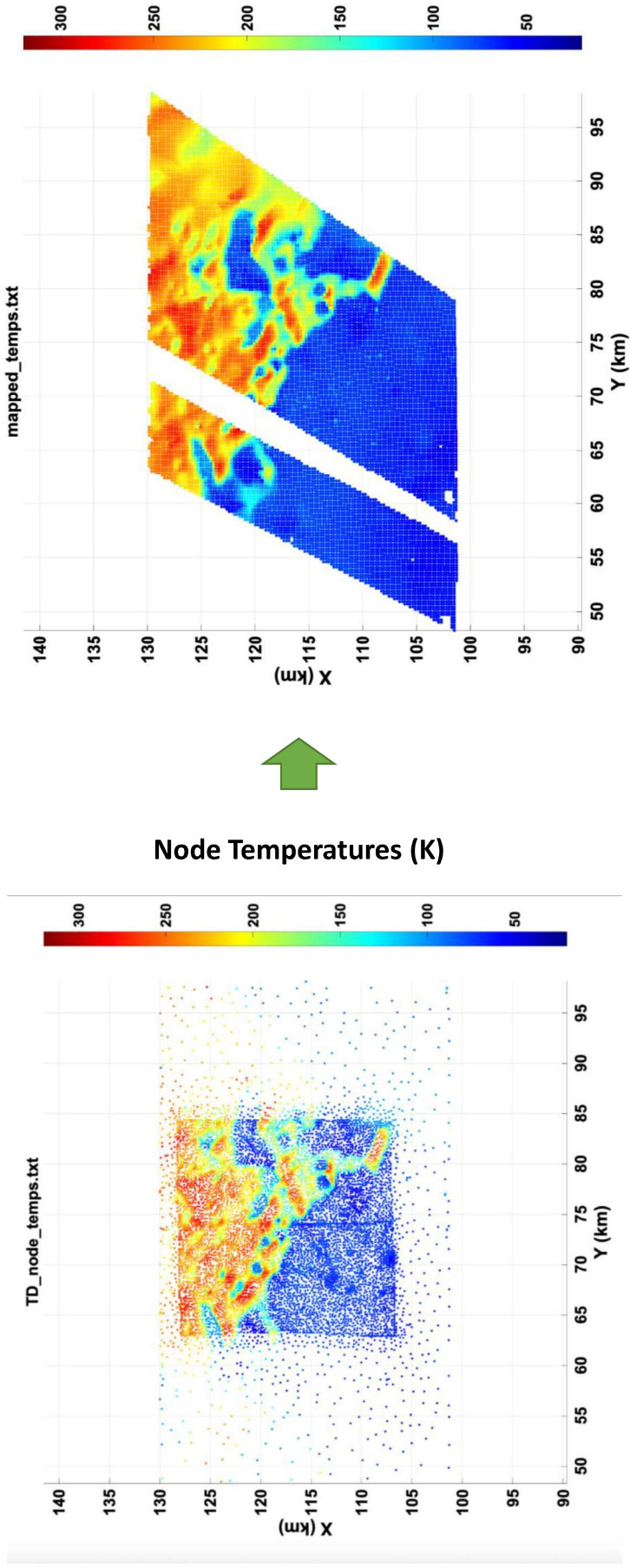
² Hayne et al., "Global Regolith Thermophysical Properties of the Moon From the Diviner Lunar Radiometer Experiment: Lunar Regolith Thermophysical Properties," 2017.

³ Woods-Robinson et al., "A model for the Thermophysical Properties of Lunar Regolith at Low Temperatures" 2019.

Comparison to Diviner Data

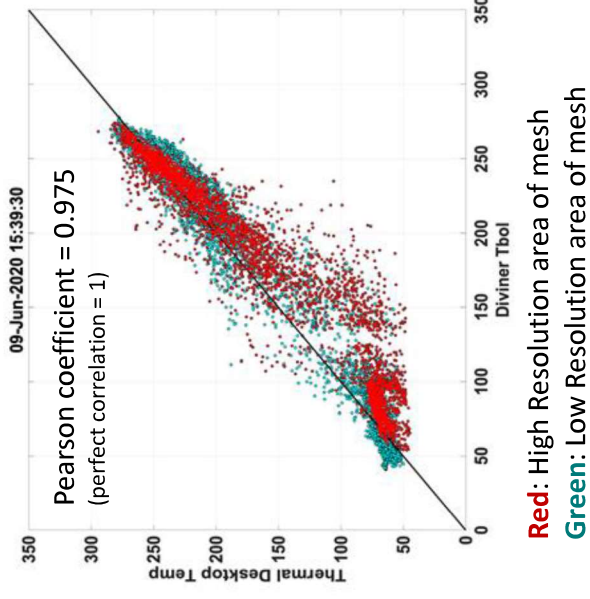
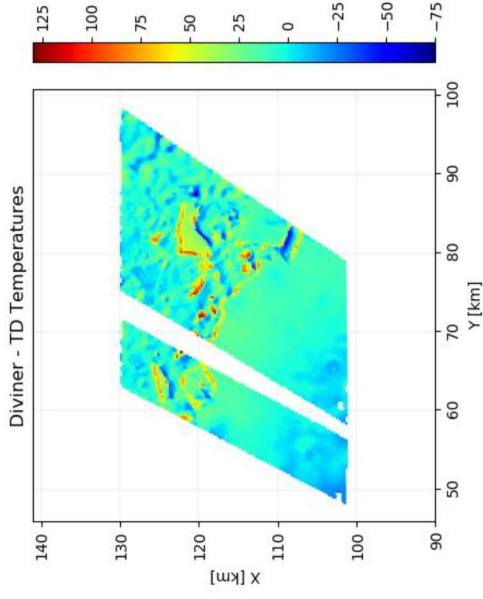
Comparison:

3) Used TD to interpolate node temperature to Diviner temperatures points (shown below)



Comparison to Diviner Data

- Results on par with comparison in P. Gläser and D. Gläser, “Modeling near-surface temperatures of airless bodies with application to the Moon” 2019.
- Hypothesize that scatter around 120-150K is largely due to mismatch in shadow boundaries from DEM mesh resolution
 - Gläser and Gläser found DEM resolution impacted how well the model’s shadow boundaries matched with Diviner temperatures.

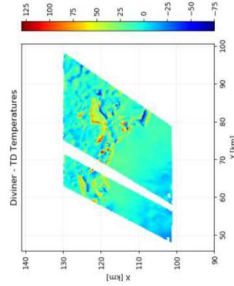
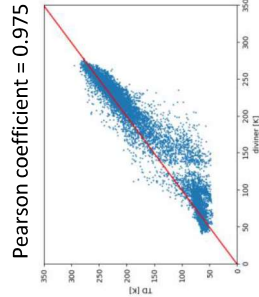


Comparison to Diviner Data – Property Sensitivity

- Repeated comparison with different ground properties

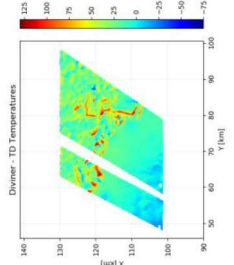
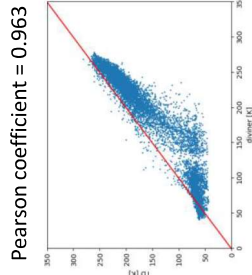
Model 1:

α = angular dependent, Feng 2019
 k & ρ = Hayne 2017
 c_p = Woods-Robinson 2019



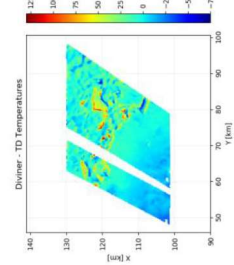
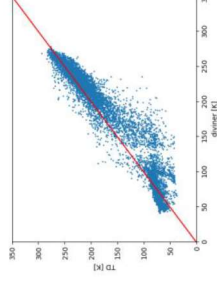
Model 2:

α = angular dependent, Feng 2020
 k & ρ = Hayne 2017
 c_p = Woods-Robinson 2019



Model 3:

α = angular dependent, Feng 2020
 k & ρ = Martinez and Siegler 2021
 • thickness of surface needed to increase from 0.001 m to 0.01 m for time step reasons
 c_p = Woods-Robinson 2019
 Pearson coefficient = 0.971



¹ Feng et al., "Lunar Regolith Properties Constrained by LRO Diviner and Chang'e-2 Microwave Radiometer Data," 2019.

² Hayne et al., "Global Regolith Thermophysical Properties of the Moon From the Diviner Lunar Radiometer Experiment: Lunar Regolith Thermophysical Properties," 2017.

³ Woods-Robinson et al., "A model for the Thermophysical Properties of Lunar Regolith at Low Temperatures", 2019.

⁴ Martinez and Siegler "A global Thermal Conductivity Model for Regolith at Low Temperatures", 2021.

⁵ Feng, M. A. Siegler, and P. O. Hayne, "New Constraints on Thermal and Dielectric Properties of Lunar Regolith from LRO Diviner and CE-2 Microwave Radiometer," 2020 – use full (not approximate) equation 8

Comparison to Diviner Data – Property Sensitivity

- Repeated comparison with different ground properties

Model 1:

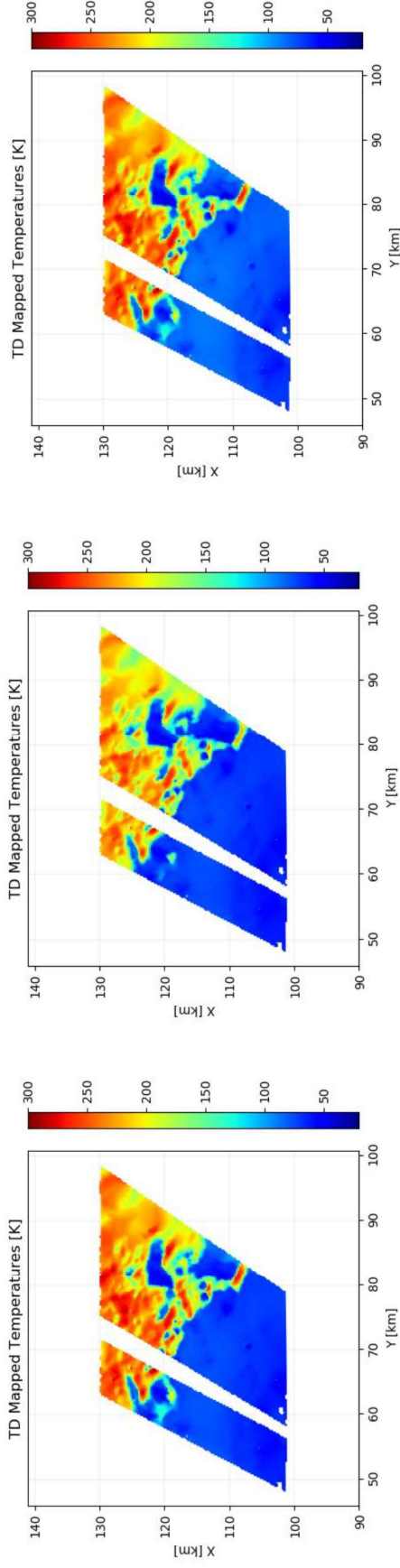
α = angular dependent, Feng 2019
 k & ρ = Hayne 2017
 c_p = Woods-Robinson 2019

Model 2:

α = angular dependent, Feng 2020
 k & ρ = Hayne 2017
 c_p = Woods-Robinson 2019

Model 3:

α = angular dependent, Feng 2020
 k & ρ = Martinez and Siegler 2021
 • thickness of surface needed to increase from 0.001 m to 0.01 m for time step reasons
 c_p = Woods-Robinson 2019



¹ Feng et al., "Lunar Regolith Properties Constrained by LRO Diviner and Chang'e-2 Microwave Radiometer Data," 2019.

² Hayne et al., "Global Regolith Thermophysical Properties of the Moon From the Diviner Lunar Radiometer Experiment: Lunar Regolith Thermophysical Properties," 2017.

³ Woods-Robinson et al., "A model for the Thermophysical Properties of Lunar Regolith at Low Temperatures", 2019.

⁴ Martinez and Siegler "A global Thermal Conductivity Model for Regolith at Low Temperatures," 2021.

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Comparison to Diviner Data – Property Sensitivity

- Repeated comparison with different ground properties

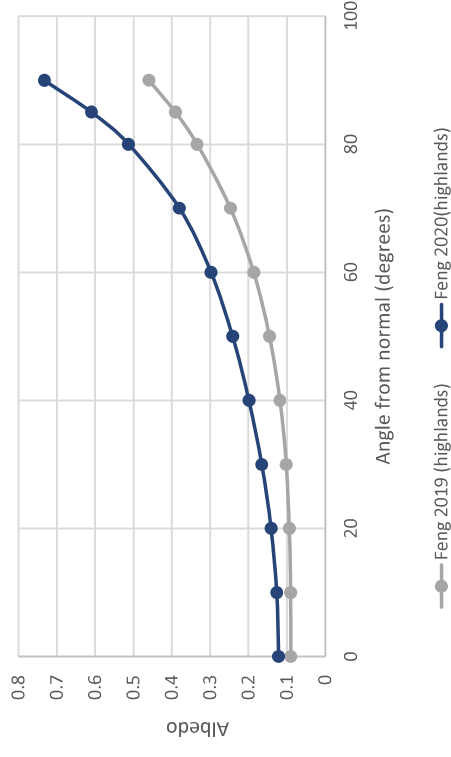
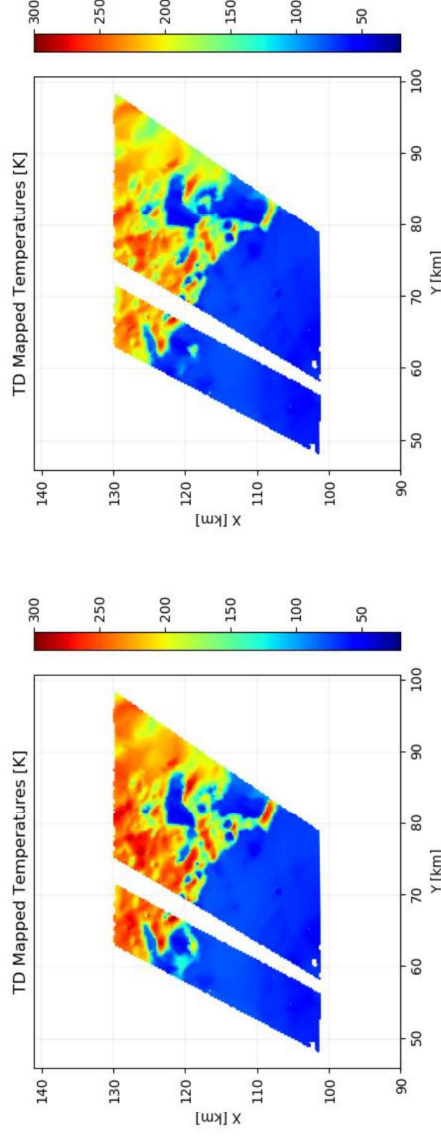
Model 1:

α = angular dependent, Feng 2019
 k & ρ = Hayne 2017
 c_p = Woods-Robinson 2019

Model 2:

α = angular dependent, Feng 2020
 k & ρ = Hayne 2017
 c_p = Woods-Robinson 2019

The differences in albedo caused a noticeable change in predicted surface temperatures.

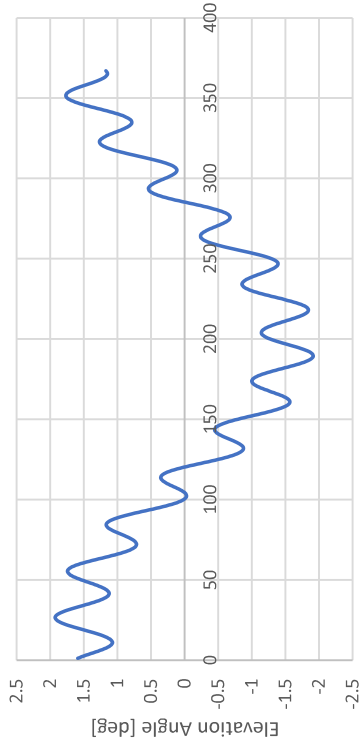


¹ Feng et al., "Lunar Regolith Properties Constrained by LRO Diviner and Chang'e-2 Microwave Radiometer Data," 2019.
² Hayne et al., "Global Regolith Thermophysical Properties of the Moon From the Diviner Lunar Radiometer Experiment: Lunar Regolith Thermophysical Properties," 2017.
³ Woods-Robinson et al., "A model for the Thermophysical Properties of Lunar Regolith at Low Temperatures," 2019.
⁴ Martinez and Siegler "A global Thermal Conductivity Model for Regolith at Low Temperatures," 2021.
⁵ Feng, M. A. Siegler, and P. O. Hayne, "New Constraints on Thermal and Dielectric Properties of Lunar Regolith from LRO Diviner and CE-2 Microwave Radiometer," 2020 – use full (not approximate) equation 8

Backup

3D Modeling example – Size the Terrain

- Obtain local elevation angles
 - Output from JPL Horizons
 - Max: 1.925107°



Time [Day] from 2009-Sep-21 to 2010-Sep-21

ssd.jpl.nasa.gov/horizons/app.html#/

Jet Propulsion Laboratory
California Institute of Technology

Solar System Dynamics

Home / Tools / Horizons System

Horizons System

Horizons Web Application

1 Ephemeris Type: Observer Table

2 **Edit** Target Body: Sun [Sol]

3 **Edit** Observer Location: 209.4°E, -89.592°N, 1.465 km @301 (Moon [Luna])

4 **Edit** Time Specification: Start=2009-09-21 UT, Stop=2010-09-22, Step=1 (days)

5 **Edit** Table Settings: custom

Generate Ephemeris

<https://ssd.jpl.nasa.gov/horizons/app.html#/>

Heat flux on body orbiting the sun

$$\text{Solid angle } \Omega_s = \frac{A_p}{S^2} = \frac{\pi R_s^2}{S^2}$$

Total black body emissive power in vacuum

$$E_b = \sigma T^4$$

Total emissive power related to intensity to intensity

$$E_b = \int_{\Omega} I_b \hat{n} \cdot \hat{s} d\Omega = \int_0^{2\pi} \int_0^{\pi/2} I_b \cos \theta \sin \theta d\theta d\psi = \pi I_b \rightarrow I_b = \frac{E_b}{\pi}$$

Solar constant

$$q_s = \int_{\Omega} I_b d\Omega = I_b \int_{\Omega} d\Omega = I_b \Omega_s = \left(\frac{E_b}{\pi}\right) \Omega_s = \frac{E_b \pi R_s^2}{\pi S^2}$$

$q_s = I_b \frac{A_p}{S^2} \rightarrow q_s \propto \frac{1}{S^2}$ solar flux is proportional to inverse square of distance to sun

Therefore, if q_s is known at one location we can find q_s at others

$$q_{s,1} S_1^2 = q_{s,2} S_2^2$$

$$q_{s,2} = \frac{q_{s,1} S_1^2}{S_2^2}$$

