Meshed Lunar Terrain Thermal Model Building Short Course

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Thermal & Fluids Analysis Workshop

TFAWS 2026

August 31 – September 4, 2026

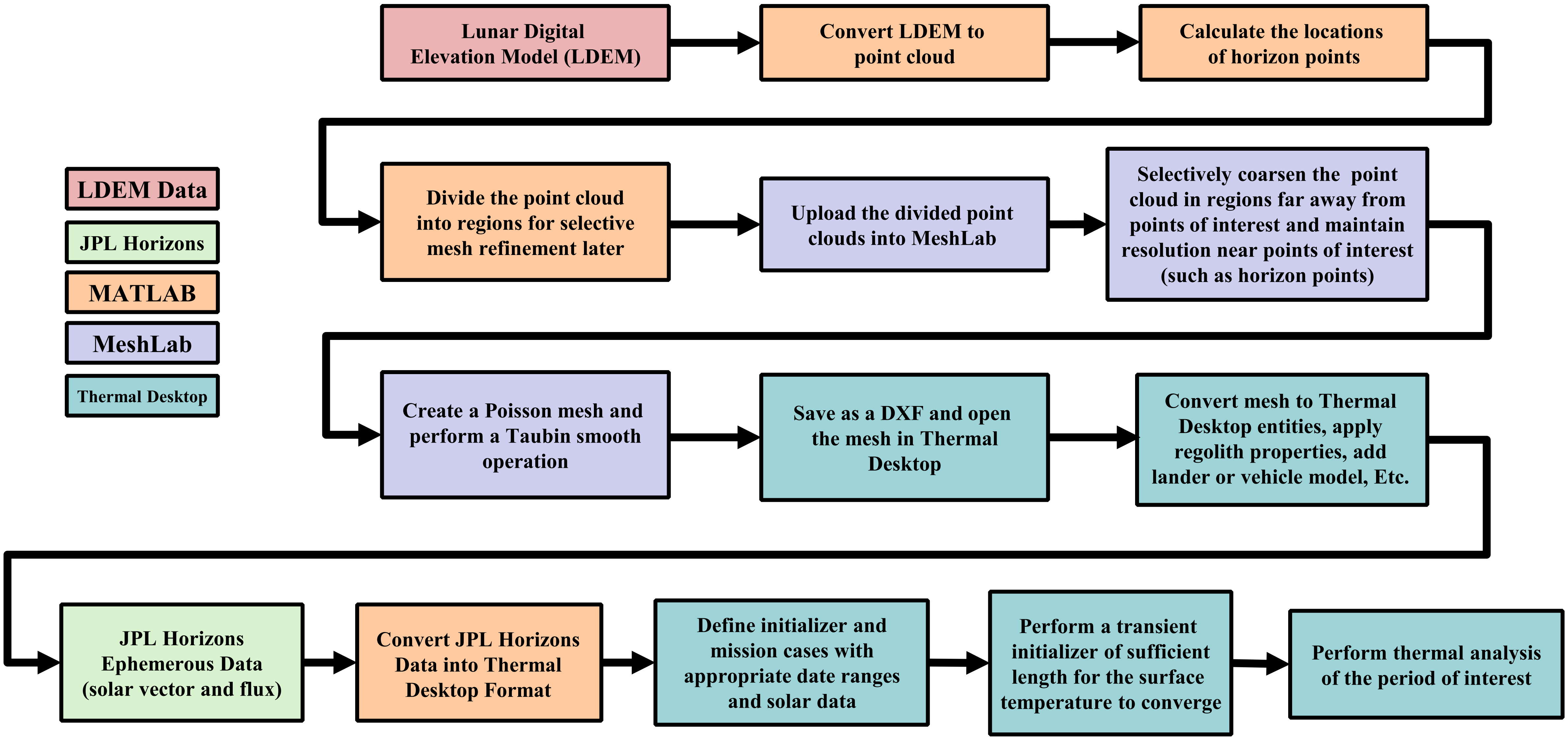
NASA Marshall Space Flight Center

Huntsville, AL

Terrain Modeling Process Overview

- This procedure describes one method for using lunar digital elevation models (LDEMs) to build detailed meshed terrain models of the lunar south pole in Thermal Desktop.
- Data sources include:
  - LDEMs from the Lunar Orbiter Laser Altimeter (LOLA) instrument, packaged into rasterized polar stereographic projections
  - JPL Horizons provides ephemerous data, used to track the position of the sun as a function of time from the perspective of the lunar surface
- Software tools include:
  - MATLAB
  - MeshLab
  - Thermal Desktop
- The procedure and code used here are applicable only to south polar locations. If a method for building terrain thermal models closer to the equator is desired, the same general procedures apply. However, the ideal (less distorted) map projection for such locations is the cylindrical projection (LOLA GDR Cylindrical projection information), so the code must be modified to accommodate cylindrical LDEMs.

Terrain Modeling Process Overview



Lunar Data Processing in MATLAB

This section describes the process of converting Lunar Digital Elevation Maps (LDEM) into a format that can be read imported int MeshLab

LDEM Download

- Go to: https://pgda.gsfc.nasa.gov/products/90
- Download the lunar digital elevation model titled:

  LDEM_60S_60MPP_ADJ.TIF

- This is a 60 meter/pixel terrain elevation model of lunar surface south of the 60°S latitude line
- The map is a polar stereographic projection
- For more detail and context on these maps, see the following publication:

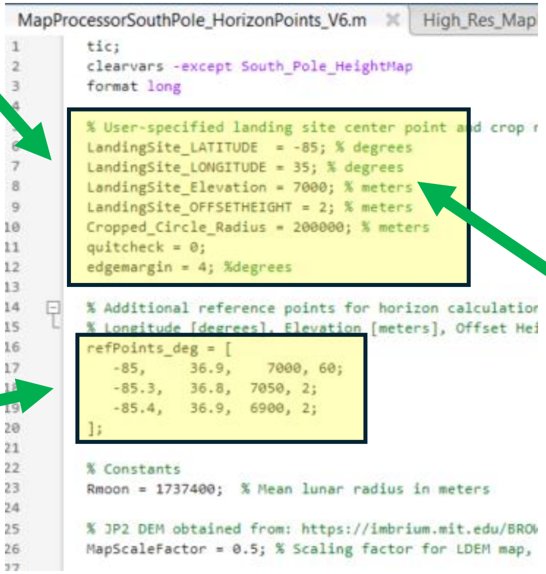
Barker et al., 2023 Planet. Sci. J., 4, 183. https://doi.org/10.3847/PSJ/acf3e1

LDEC_80S_20MPP_ADJ.TIF - LOLA Digital Elevation Counts (LDEC, number of LOLA spots per pixel)
LDEM_80S_20MPP_ADJ.TIF - LOLA Digital Elevation Model (LDEM) giving surface height (in meters)
LDEM_80S_20MPP_ADJ_EFFRES.TIF - LDEM effective resolution (in meters)
LDEM_80S_20MPP_ADJ_ERR.TIF - LDEM surface height error (in meters)
LDEM_80S_20MPP_ADJ_HILL.TIF - LDEM hillshade (45 deg altitude, 45 deg azimuth)
LDSM_80S_20MPP_ADJ.TIF - LOLA Digital Slope Map (LDSM, in degrees)
LDSM_80S_20MPP_ADJ_ERR.TIF - LDSM slope error (in degrees)

LDEC_60S_240MPP_ADJ.TIF - 131M
LDEM_60S_240MPP_ADJ.TIF - 210M
LDEM_60S_240MPP_ADJ_EFFRES.TIF - 248M
LDEM_60S_240MPP_ADJ_ERR.TIF - 255M
LDEM_60S_240MPP_ADJ_HILL.TIF - 93M
LDSM_60S_240MPP_ADJ.TIF - 247M
LDSM_60S_240MPP_ADJ_ERR.TIF - 248M
LDEC_60S_120MPP_ADJ.TIF - 463M
LDEM_60S_120MPP_ADJ.TIF - 785M
LDEM_60S_120MPP_ADJ_EFFRES.TIF - 1000M
LDEM_60S_120MPP_ADJ_ERR.TIF - 1016M
LDEM_60S_120MPP_ADJ_HILL.TIF - 354M
LDSM_60S_120MPP_ADJ.TIF - 972M
LDSM_60S_120MPP_ADJ_ERR.TIF - 1001M
LDEC_60S_60MPP_ADJ.TIF - 1.5G
LDEM_60S_60MPP_ADJ.TIF - 2.9G
LDEM_60S_60MPP_ADJ_EFFRES.TIF - 3.9G
LDEM_60S_60MPP_ADJ_ERR.TIF - 4.0G
LDEM_60S_60MPP_ADJ_HILL.TIF - 1.4G
LDSM_60S_60MPP_ADJ.TIF - 3.8G
LDSM_60S_60MPP_ADJ_ERR.TIF - 3.9G
LDEC_75S_30MPP_ADJ.TIF - 489M
LDEM_75S_30MPP_ADJ.TIF - 2.7G
LDEM_75S_30MPP_ADJ_EFFRES.TIF - 3.8G
LDEM_75S_30MPP_ADJ_ERR.TIF - 3.8G
LDEM_75S_30MPP_ADJ_HILL.TIF - 1.3G
LDSM_75S_30MPP_ADJ.TIF - 3.6G
LDSM_75S_30MPP_ADJ_ERR.TIF - 3.7G

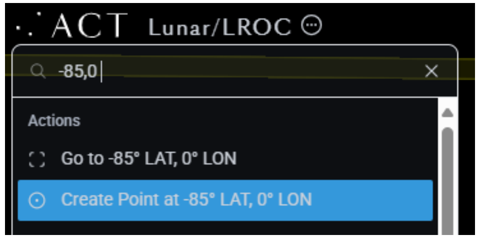
Convert the LDEM to a Point Cloud and Identify Horizon Point Clouds

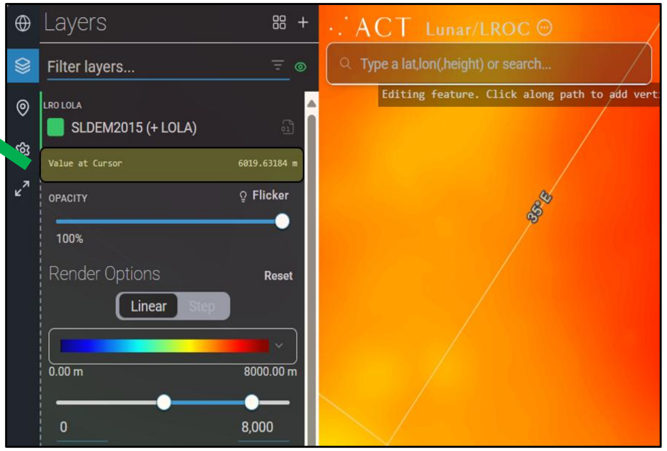
- With the JP2 LDEM in the file path, enter a latitude [degrees], longitude [degrees], local elevation [meters], surface offset height [meters], and map crop radius [meters] for the center point of the area of interest....and then run the code: MapProcessorSouthPole_HorizonPoints_V4.m
  - **Note offset height is height at which the horizon points are calculated.** For best results, this should be set to the height of a critical component on the vehicle of interest (such as radiator height or the top of the vehicle)
  - **Note horizon points are the most distant points in the point cloud that are visible from a given location of interest.** Horizon points may be close or far away depending on observer location and local topography
  - Multiple points of interest for horizon calculation can be provided if applicable. This is useful when capturing the terrain of a traverse or region of interest.
  - Local elevation for each point of interest specified is required and can be obtained via LROC QuickMap (https://quickmap.lroc.im-ldi.com/)
- The code will output a point cloud of the location with the user defined radius and also the locations of horizon points



Obtain Site Elevation

https://quickmap.lroc.im-ldi.com/





(Optional) Download High Resolution LDEM and Generate Point Cloud

- If higher resolution terrain data is desired in the immediate vicinity of the location of interest, this data can be incorporated in the final point cloud that is sent to MeshLab
- Download a 10m/pxl dataset from: https://pgda.gsfc.nasa.gov/products/90
- In the High_Res_MapProcessorSouthPole_V4.m code:
    - Enter the latitude and longitude previously specified for the larger point cloud, include a crop radius (defining the size of the zone where higher refinement data is desired)
    - Ensure the LDEM file name is correctly entered into the code
    - The output of this code is a LDEM that can now be included in the larger point cloud when combined in Mesh Lab.

LDEC_80S_20MPP_ADJ.TIF - 1.3G
LDEM_80S_20MPP_ADJ.TIF - 2.6G
LDEM_80S_20MPP_ADJ_EFFRES.TIF - 3.8G
LDEM_80S_20MPP_ADJ_ERR.TIF - 3.7G
LDEM_80S_20MPP_ADJ_HILL.TIF - 1.3G
LDSM_80S_20MPP_ADJ.TIF - 3.6G
LDSM_80S_20MPP_ADJ_ERR.TIF - 3.7G
LDEC_83S_10MPP_ADJ.TIF - 415M
LDEM_83S_10MPP_ADJ.TIF - 4.8G
LDEM_83S_10MPP_ADJ_EFFRES.TIF - 7.5G
LDEM_83S_10MPP_ADJ_ERR.TIF - 7.5G
LDEM_83S_10MPP_ADJ_HILL.TIF - 2.5G
LDSM_83S_10MPP_ADJ.TIF - 7.1G
LDSM_83S_10MPP_ADJ_ERR.TIF - 7.0G

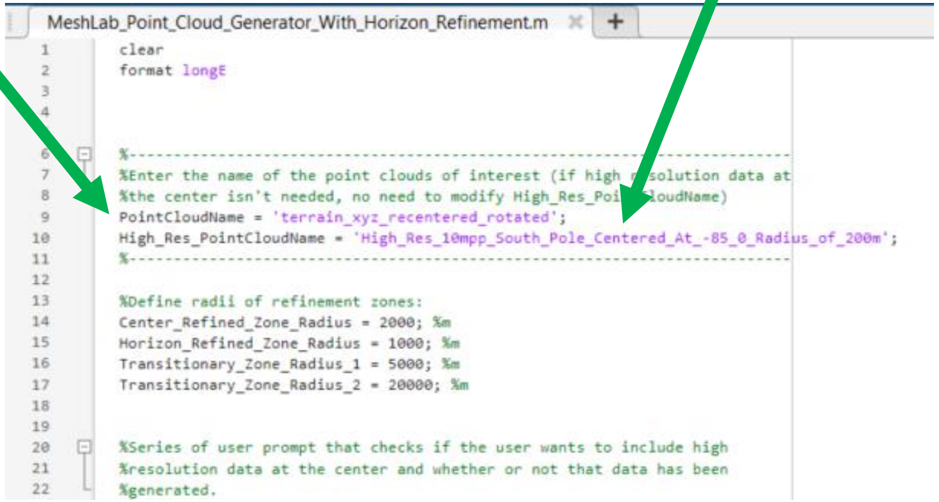
```
tic;
clearvars
format long

%NOTE: The high resolution data used in this code is only available south
%of the -83deg latitude line.


% User-specified landing site and crop radius
LandingSite_LATITUDE   = -85; % degrees
LandingSite_LONGITUDE  = 0; % degrees
LandingSite_Elevation  = 0.00; % meters
Data_Resolution = 10; %meters per pixel
%Make sure all of the above match the data input in the Map Processor for
%the coarse data
High_Res_Crop_Radius = 100; %meters


% Constants
Rmoon = 1737400;  % Mean lunar radius in meters
Map_Offset = 0; % meters

%Read the high resolution .tiff file, store the heigh map, x pixel numbers,
%and y pixel numbers.
t = Tiff('LDEM_83S_10MPP_ADJ.tiff','r');
A = read(t);
close(t)
A = single(A) + Rmoon;
```

Use MATLAB to Divide the Point Cloud into Refinement Regions

- To achieve higher mesh density near points of interest (horizon points and the center) and lower density far from points of interest, the point cloud must be selectively refined to reflect this. For this variable refinement to be reflected in the final mesh, the point cloud must also have variable refinement. To refine different parts of the point cloud differently, the point cloud must be divided into regions and saved to separate text files.
- The MeshLab_Point_Cloud_Generator_With_Horizon_Refinement_V4.m code takes the point cloud previously generated, divides it into an optional highly refined zone, a central zone, a horizon zone, two successive transition zones, and a coarse far field zone.
- These six point clouds are saved as txt files that can be uploaded into MeshLab

MapProcessorSouthPole_HorizonPoints_V4.m

High_Res_MapProcessorSouthPole_V4.m



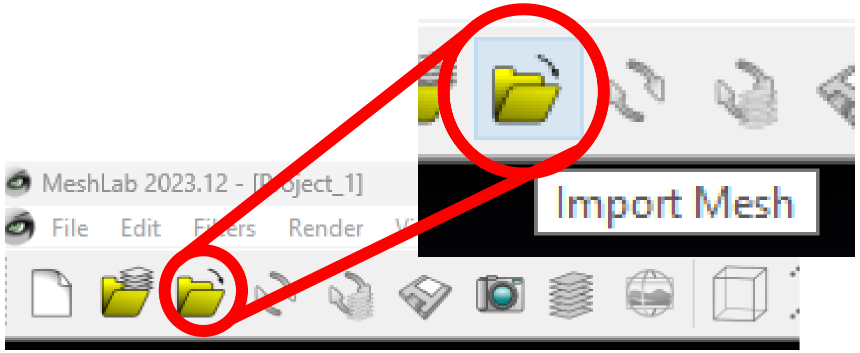
Lunar Terrain Meshing in MeshLab

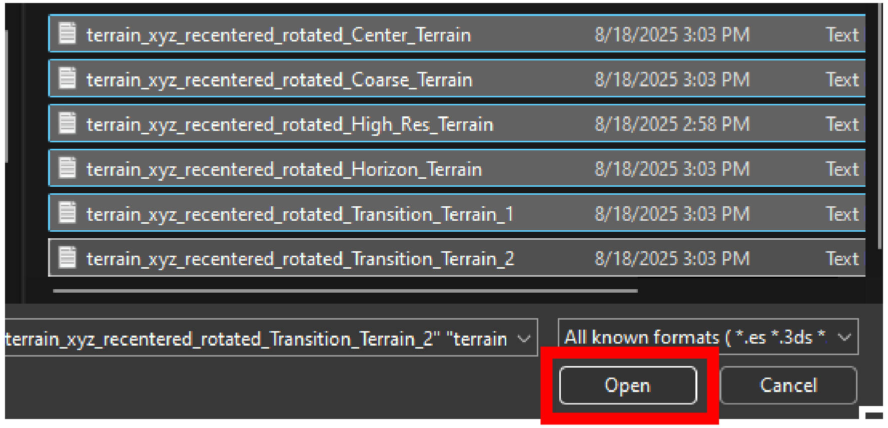
This section describes the process of converting the point clouds output by MATLAB into meshes that can be imported into Thermal Desktop

WARNING: MeshLab has no “undo” capability

Save often and be careful

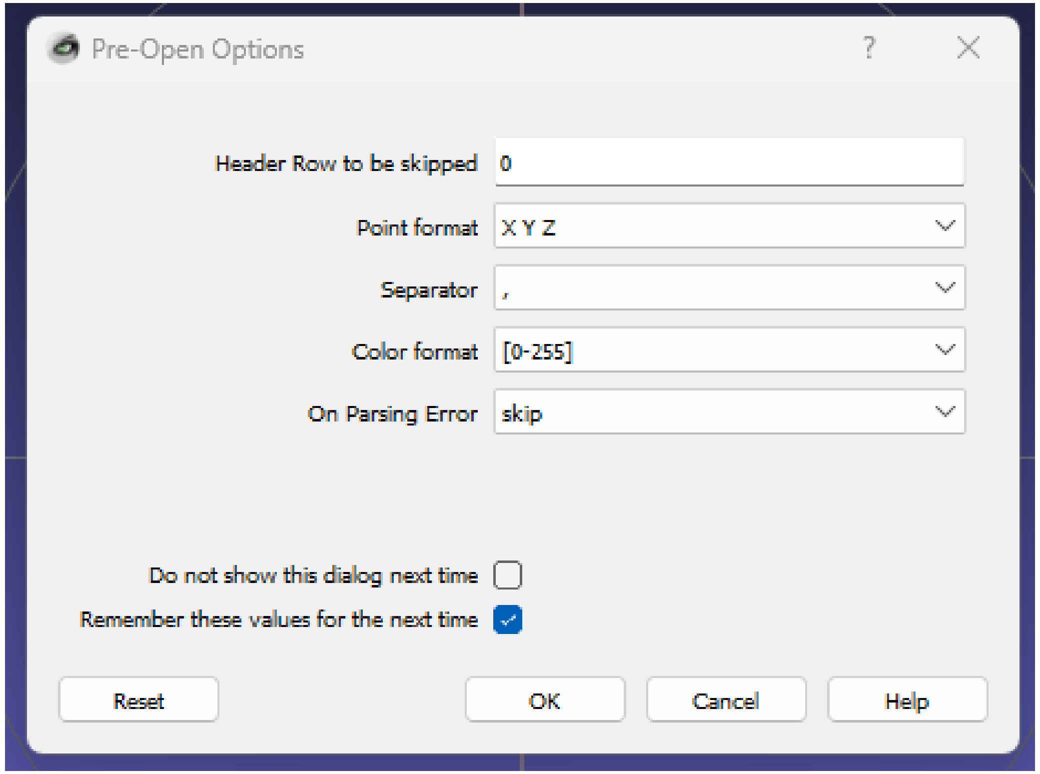
Import Point Clouds





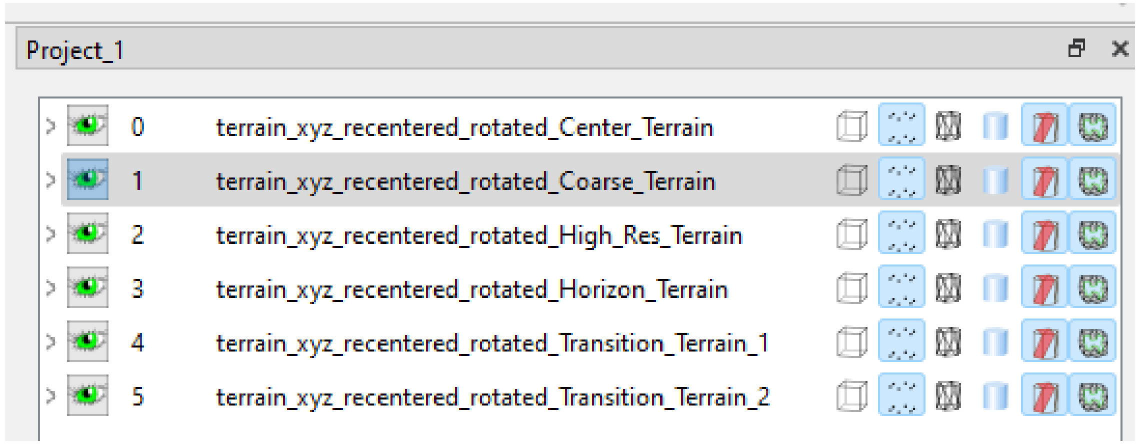
- After opening MeshLab (https://www.meshlab.net/) , select the Import Mesh icon
- Navigate to the point cloud txt files generated in the previous steps
- Select all the point clouds and open them

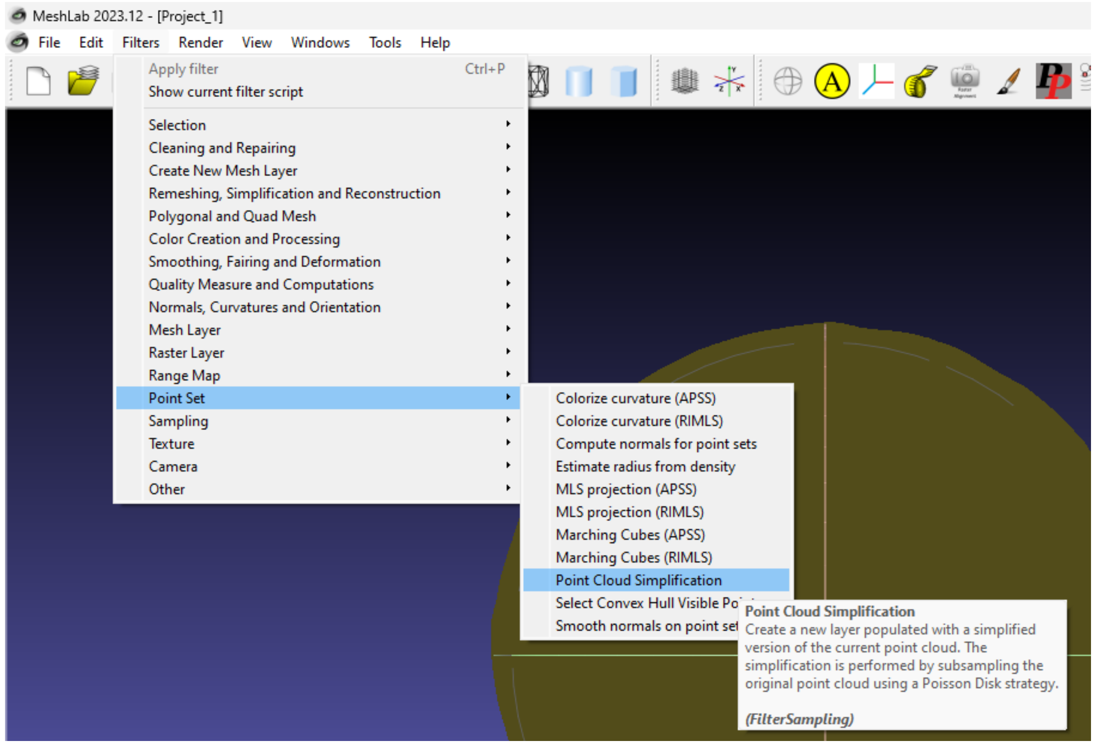
Import Point Clouds



- Ensure the “Pre-Open Options” are as shown to the left, and select OK
- Note the separator should be set to “,”. The default separator may be set to “;”
- This window will appear for all point clouds you selected

Point Cloud Simplification

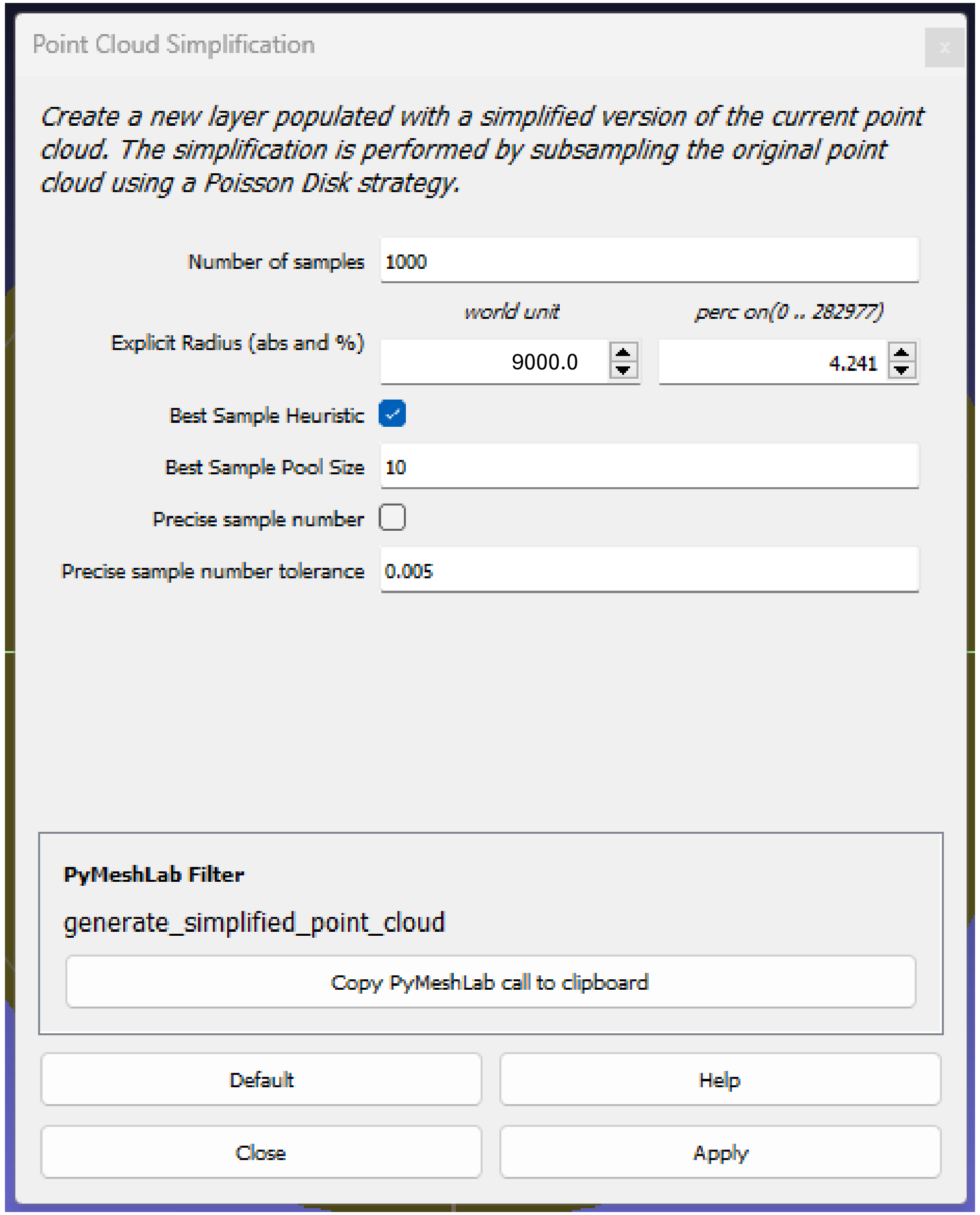




- In this step, almost every point cloud is “simplified” (made more sparse)
- In the project window, select the point cloud you want to simplify
- Navigate to the following to use the “Point Cloud Simplification” function :

  Filters->Point Set->Point Cloud Simplification
- The slide to follow will include a table of settings to use for each point cloud

Point Cloud Simplification

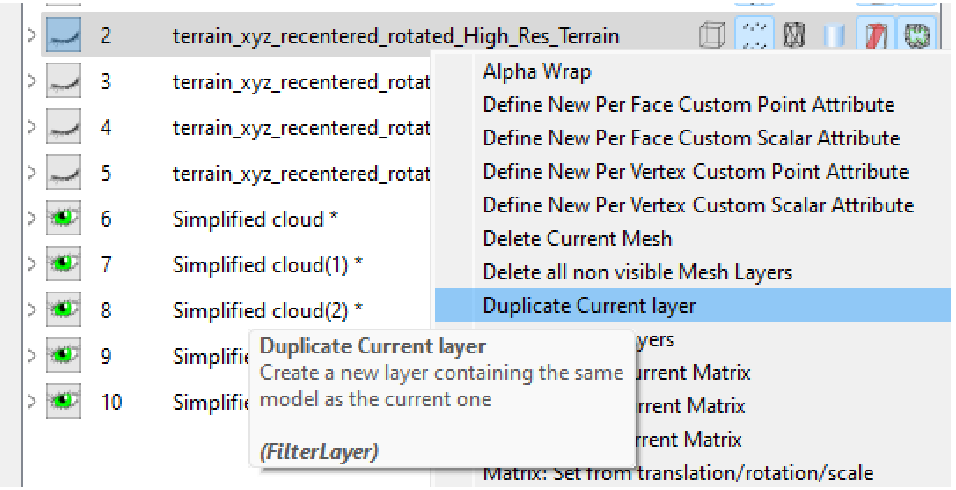


- The only parameter that needs to be edited for each point cloud simplification is the Explicit Radius (world unit)
- The table below summarizes good explicit radius settings to use for each. The world units are in meters
- Note these are just guidelines. **A larger explicit radius will result in a coarser mesh**, so if more or less mesh refinement is desired, these settings should be revisited
- Also note the ratios of explicit radii are ideal for preventing errors with meshing. **If a change is made to any one of these radii, the other radii should be changed to preserve the ratios used here**

Point Cloud	Explicit Radius (world unit)
Coarse Terrain	9000
Transition Terrain 2	3750
Transition Terrain 1	2250
Horizon Terrain	750
Center Terrain	150
High Resolution Terrain	N/A (Do not simplify)

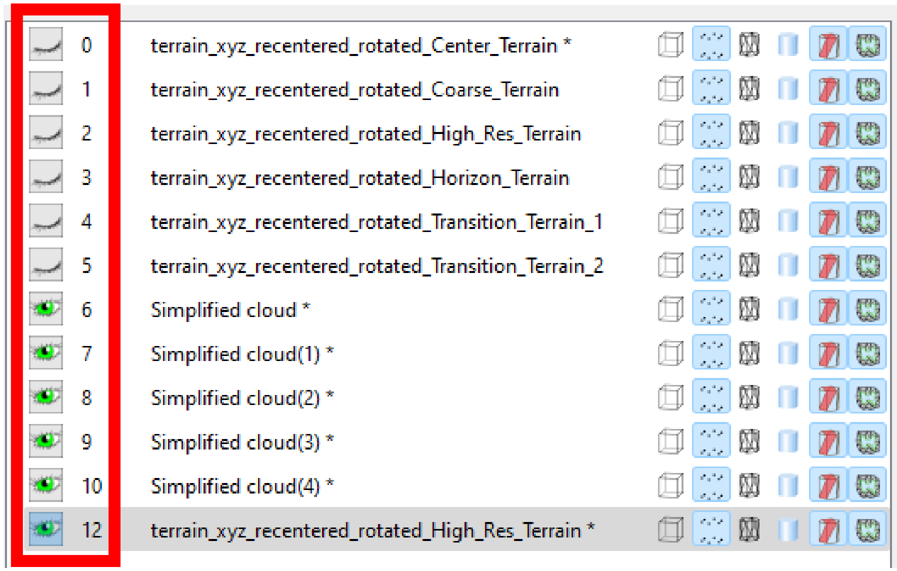
- Select Apply when finished
- Repeat until all point clouds are simplified according to the radius setting shown in the table

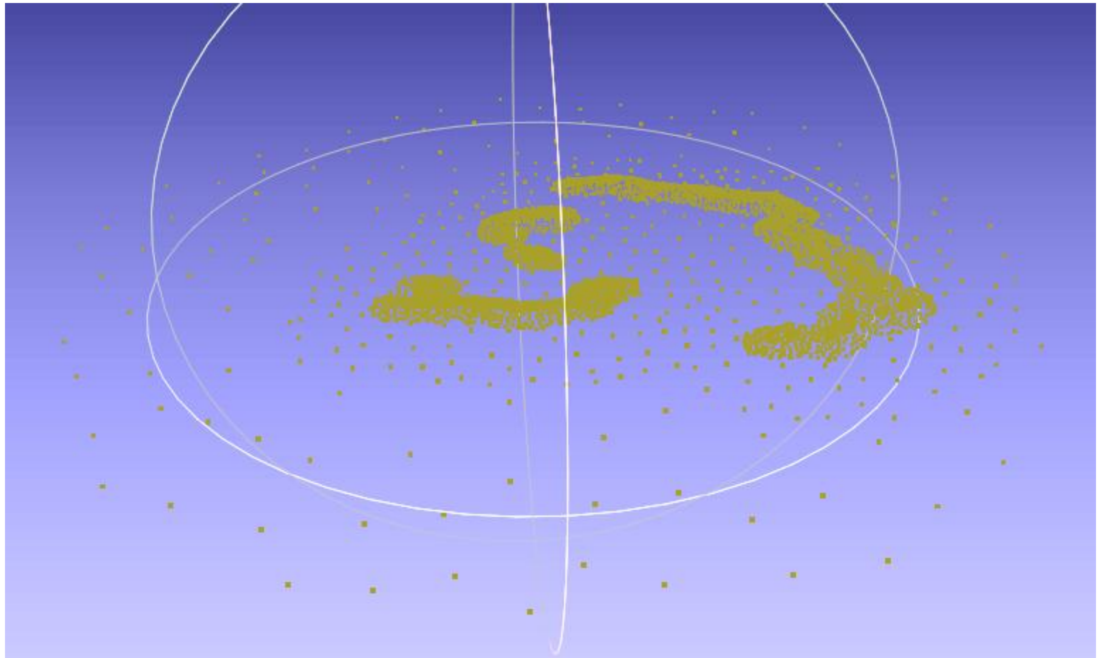
Point Cloud Simplification



- For any point clouds that you don't simplify, it is recommended that you duplicate to avoid deleting this point cloud prematurely
- Right click the high-resolution terrain point cloud and select "Duplicate Current Layer"

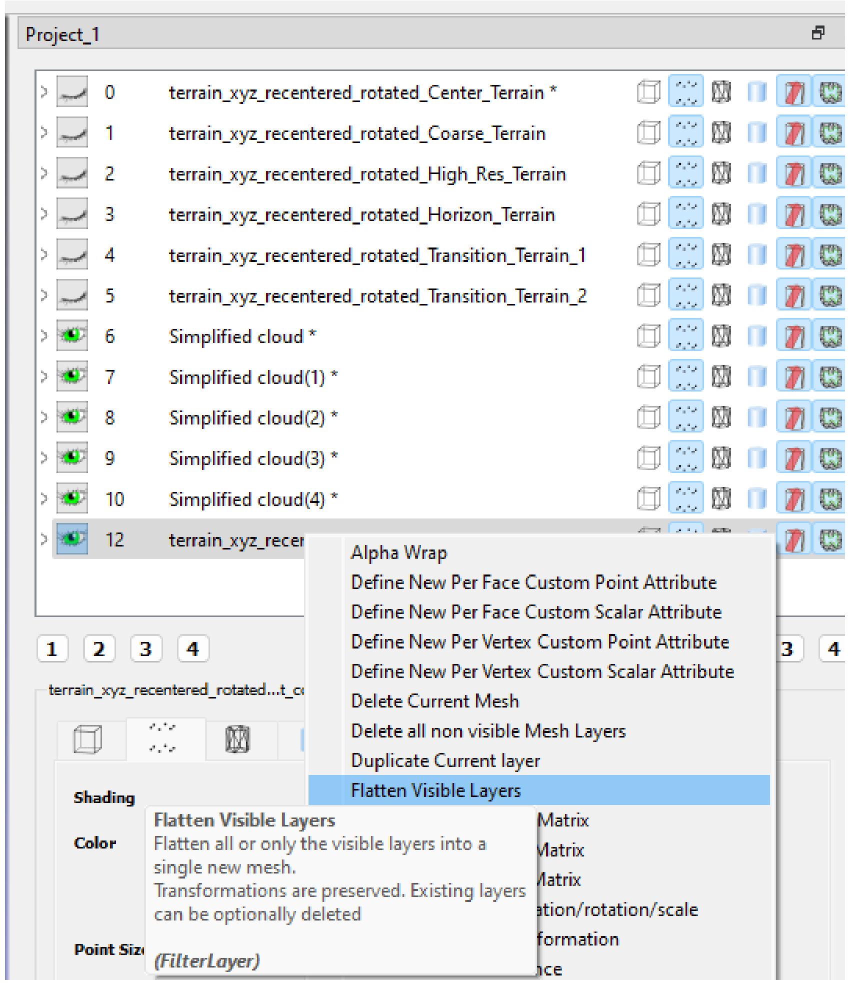
Point Cloud Flattening



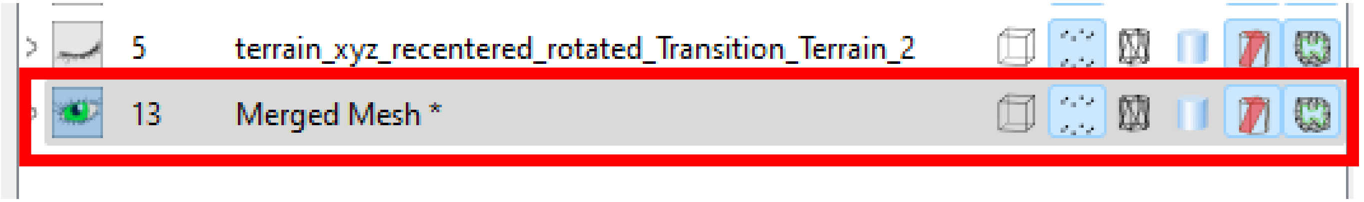


- In the Project window, turn off the visibility of all the original point clouds by selecting the green eye, and only leave the visibility of the new point clouds on
- Your visible point clouds should look something like the image to the bottom left (exact appearance will vary by location)

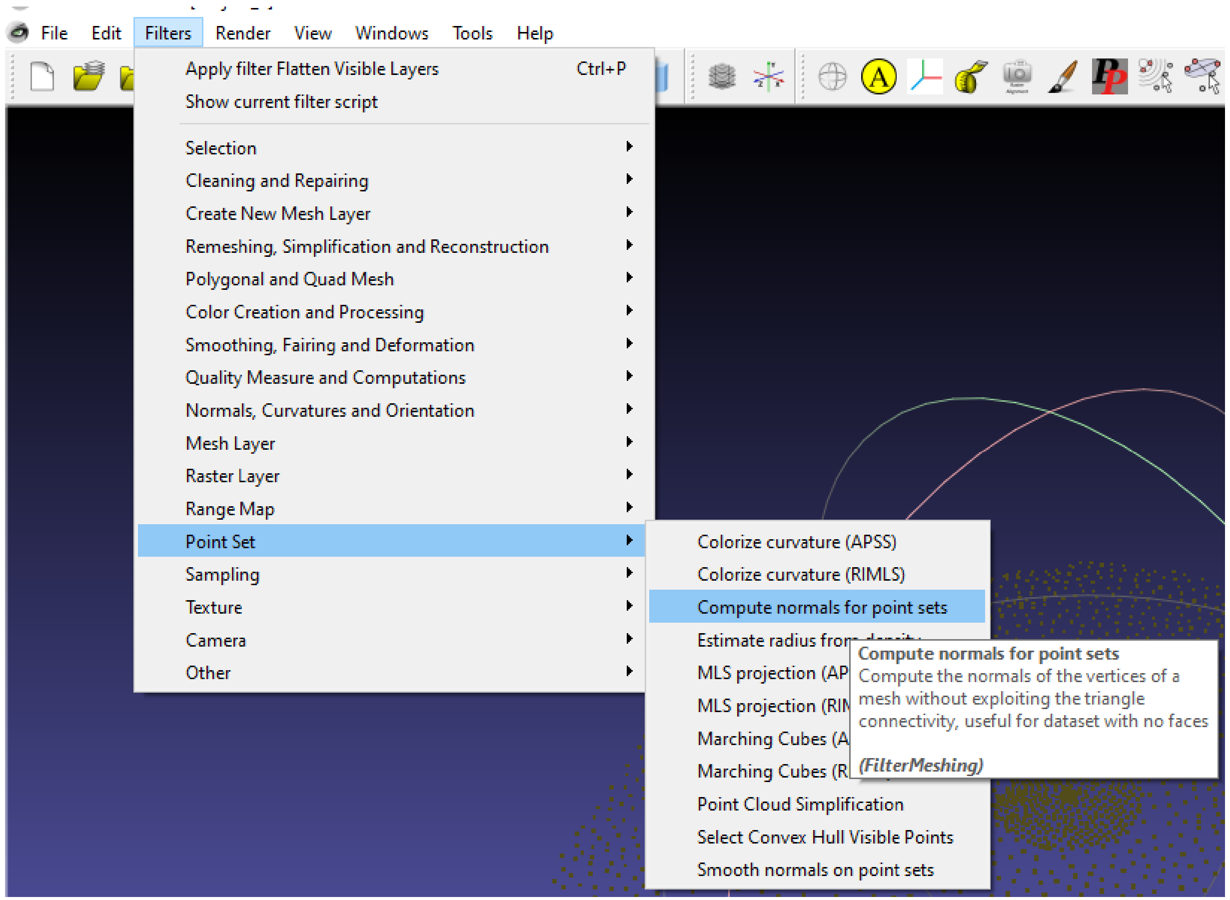
Point Cloud Flattening



- Right click any one of the visible point clouds, and select “Flatten Visible Layers”
- A “Flatten Visible Layers” window will appear. Use the default settings, select Apply and Close
- All the simplified and duplicated point clouds that were left visible will merge into a single layer called “Merged Mesh *”



Calculate Point Cloud Normal Unit Vectors

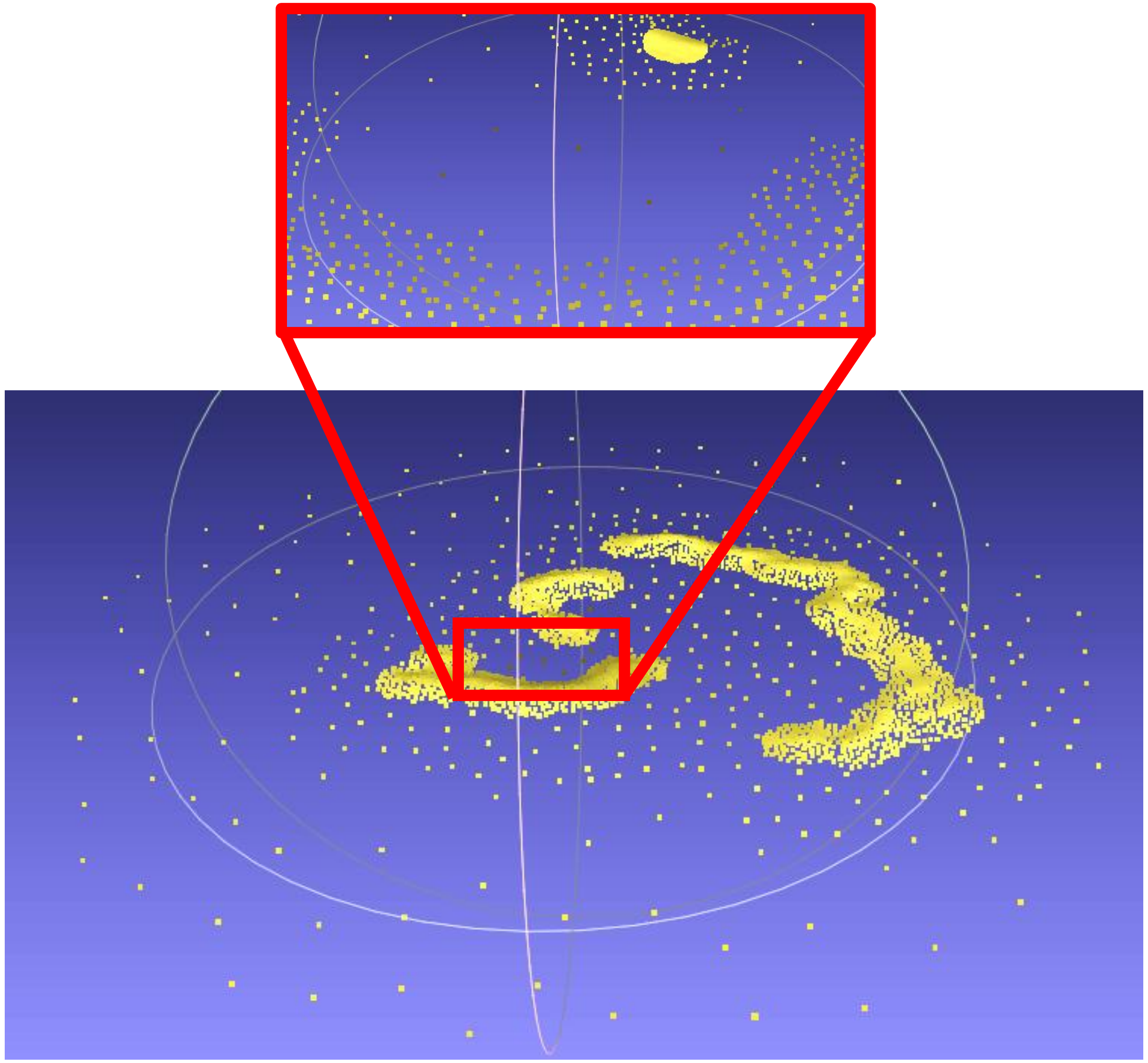


- In the project window, select the "Merged Mesh" point cloud
- Navigate to the following:

  Filters->Point Set->Compute normal for point sets

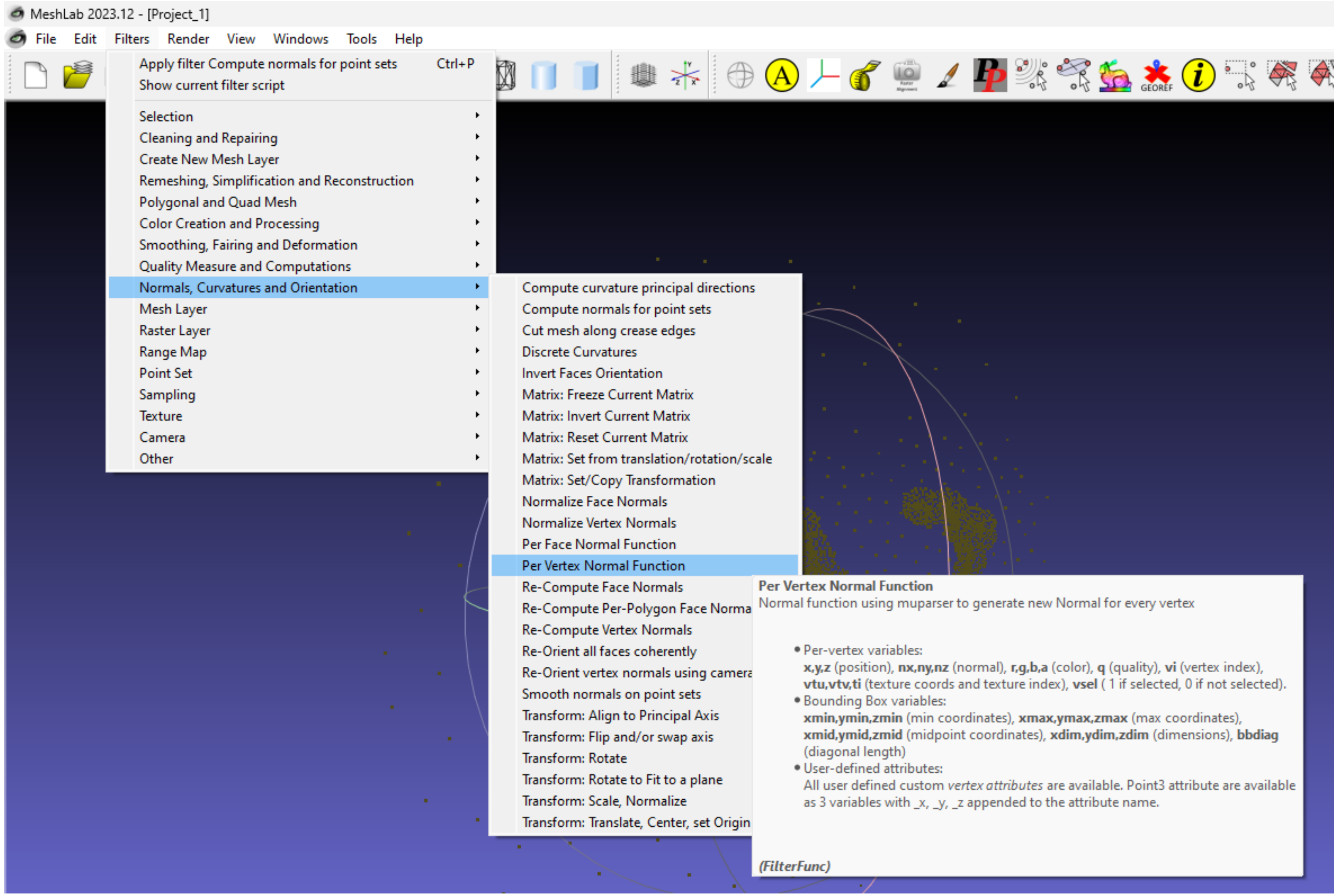
- A settings window will appear. Keep the default settings, select Apply, and then select Close

Calculate Point Cloud Normal Unit Vectors



- Navigate around the point cloud. Note that the brightly colored side of the dots indicates the direction of the normal vector (a bright dot means you're looking at what MeshLab considers the "top" of the surface)
- Inevitably there will be dots with normals that are flipped in the wrong direction. Sometimes there are only a handful of problem nodes (as pictured here). Sometimes most or all of them are incorrect. Incorrect normal vector orientations will be dark when viewed from the top down
- These normal vectors must be selected and reversed (continued on the next slide)

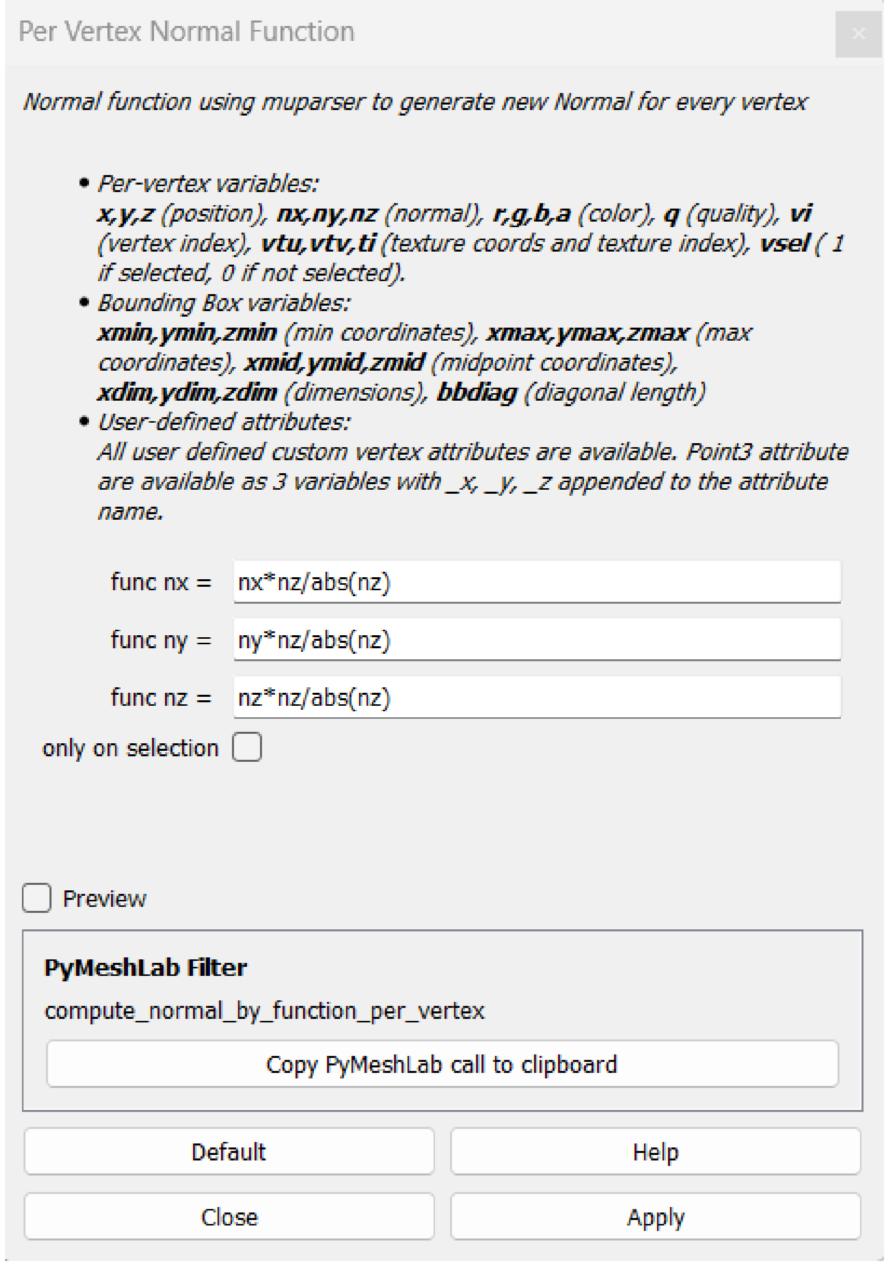
Calculate Point Cloud Normal Unit Vectors



Navigate to:

Filters->Normals, Curvatures, and Orientation->**Per Vertex Normal Function**

Calculate Point Cloud Normal Unit Vectors



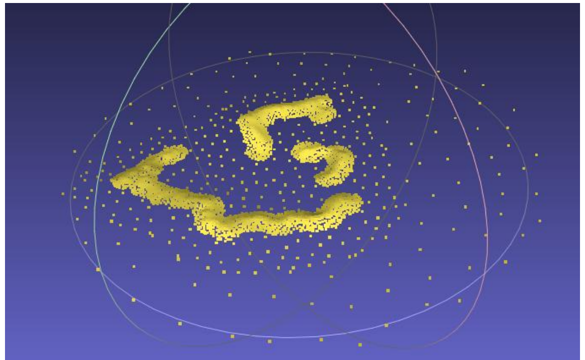
- In the Per Vertex Normal Function window, ensure there is NO check next to "only on selection" (as shown to the left)
- The following functions will automatically flip the normal vector if it is found to be facing the wrong way (toward the center of the moon):

func nx = **nx*nz/abs(nz)**

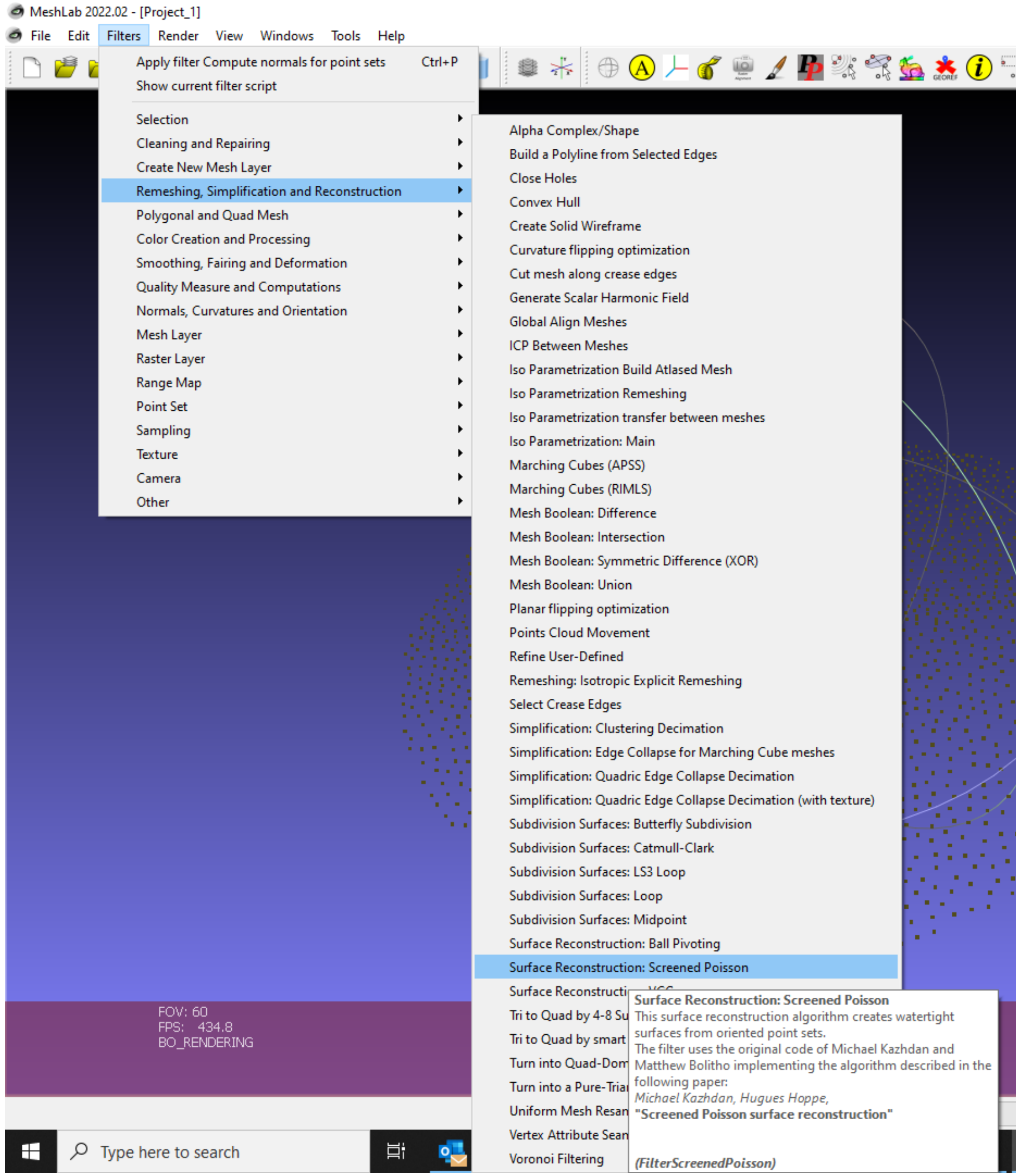
func ny = **ny*nz/abs(nz)**

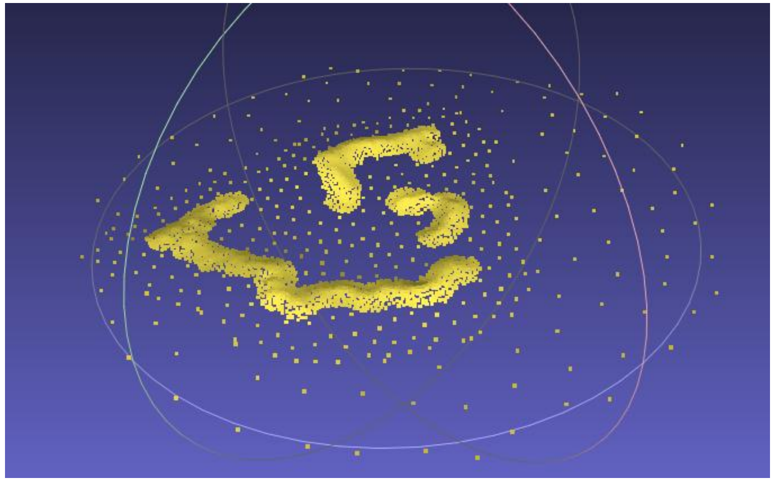
func nz = **nz*nz/abs(nz)**

- Copy these functions into the respective text boxes as shown to the left
- Select Apply and inspect the point cloud. All the points should now appear bright yellow when viewed from the top and dark yellow when viewed from the bottom.



Meshing

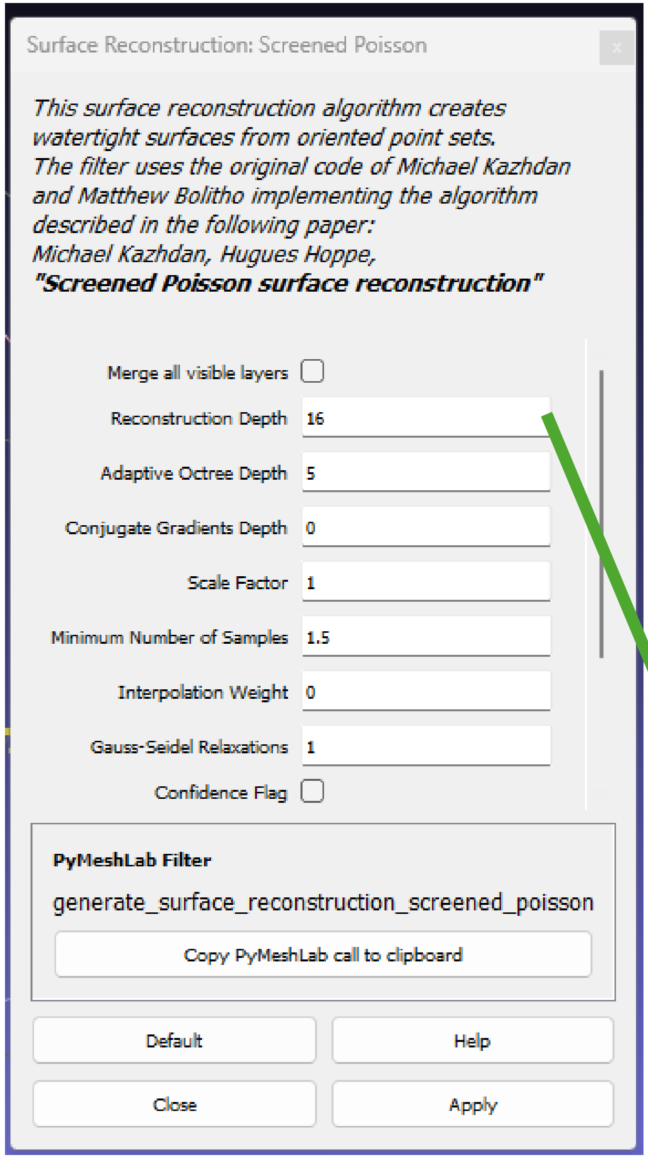




- Now that you have a merged point cloud with normal vectors facing the correct direction, the surface can be meshed
- With the “Merged Mesh” in the project window selected, navigate to the following:

  Filters->Remeshing, Simplification, and Reconstruction->Surface Reconstruction: Screened Poisson

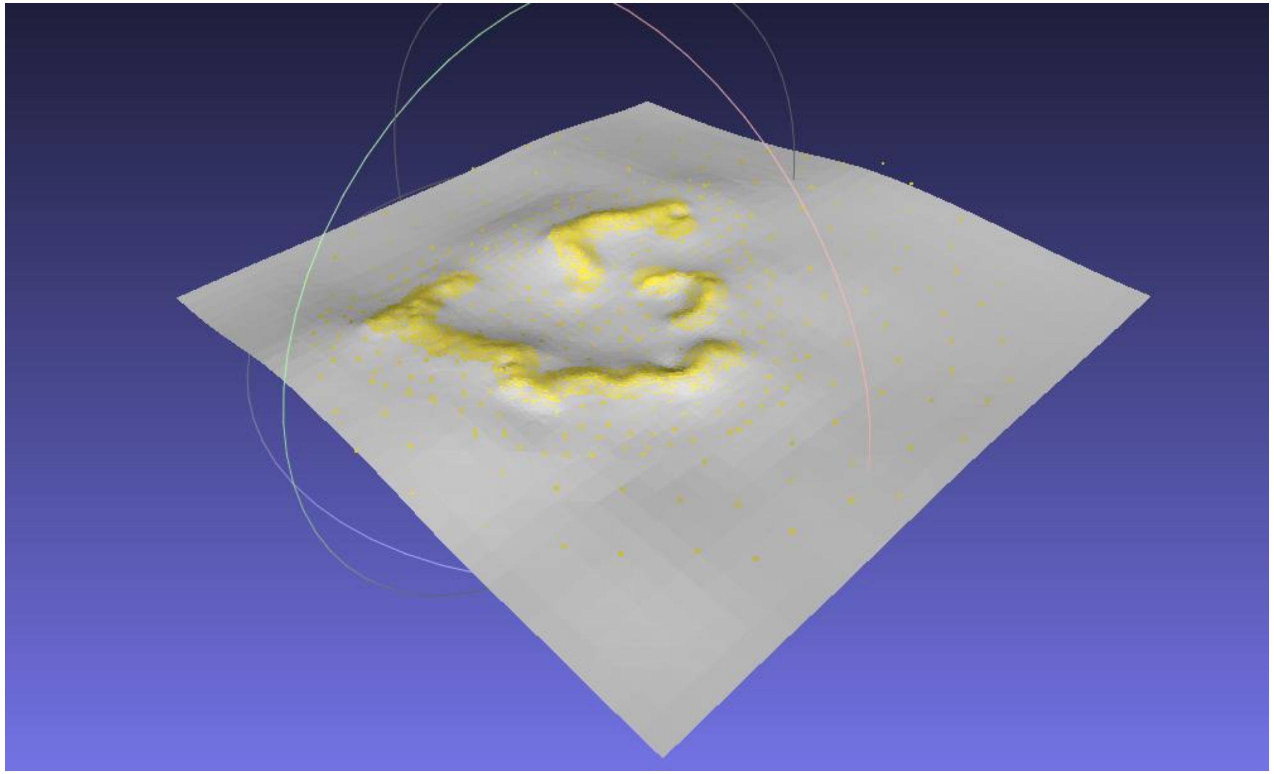
Meshing



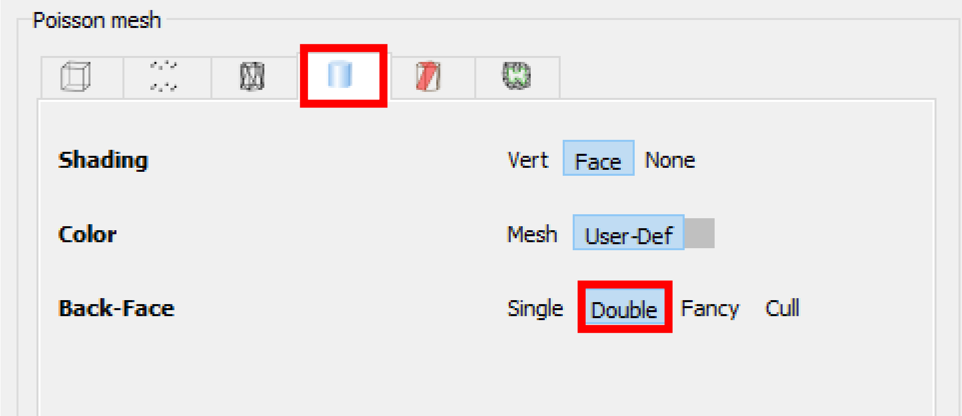
17 Should be standard for powerful workstations

- In the "Surface Reconstruction: Screened Poisson" window, select the down arrow to view more advanced settings and enter the following :
  - Reconstruction Depth = 16 or 17 (17 is better but may take significantly longer)
  - Interpolation Weight = **0**
  - Scale Factor = 1
  - Gauss-Seidel Relaxations = 1
- Leave all other settings default
- Select Apply and once it is finished calculating, select Close

Mesh Inspection

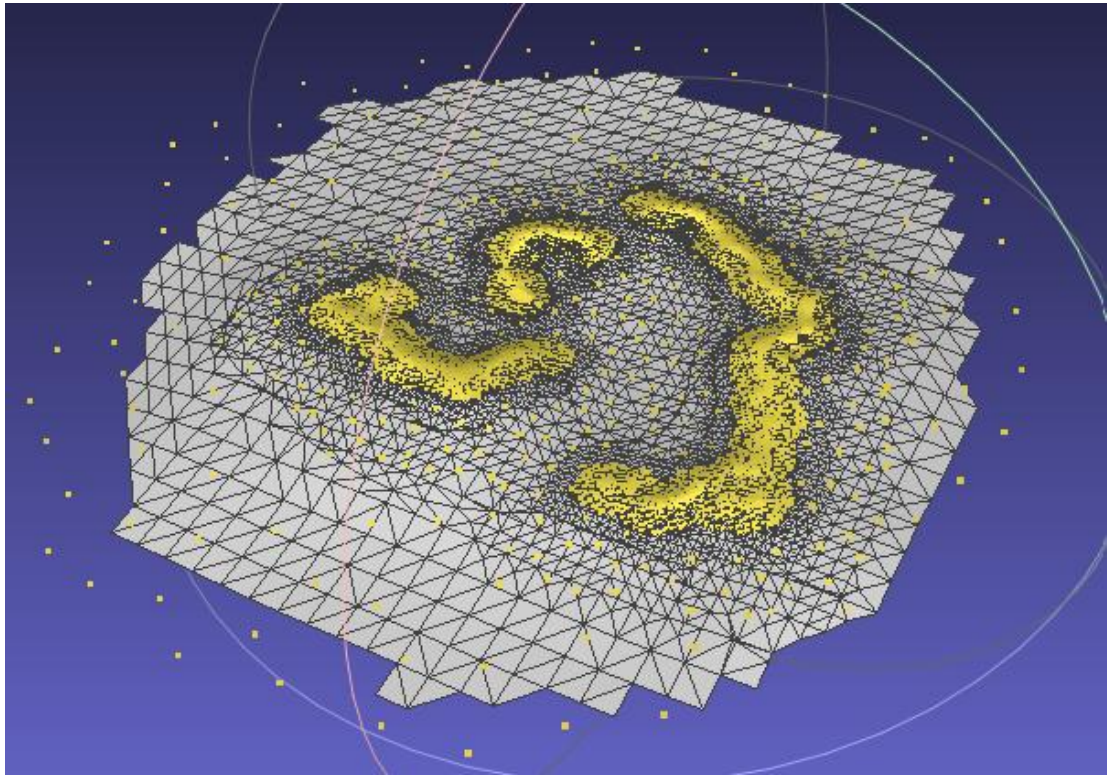


- With “Poisson mesh” selected in the project window, look below the project window to the view settings
- Navigate to surface settings as shown below, and select “Double” for Back-Face (This will allow you to see the mesh better)



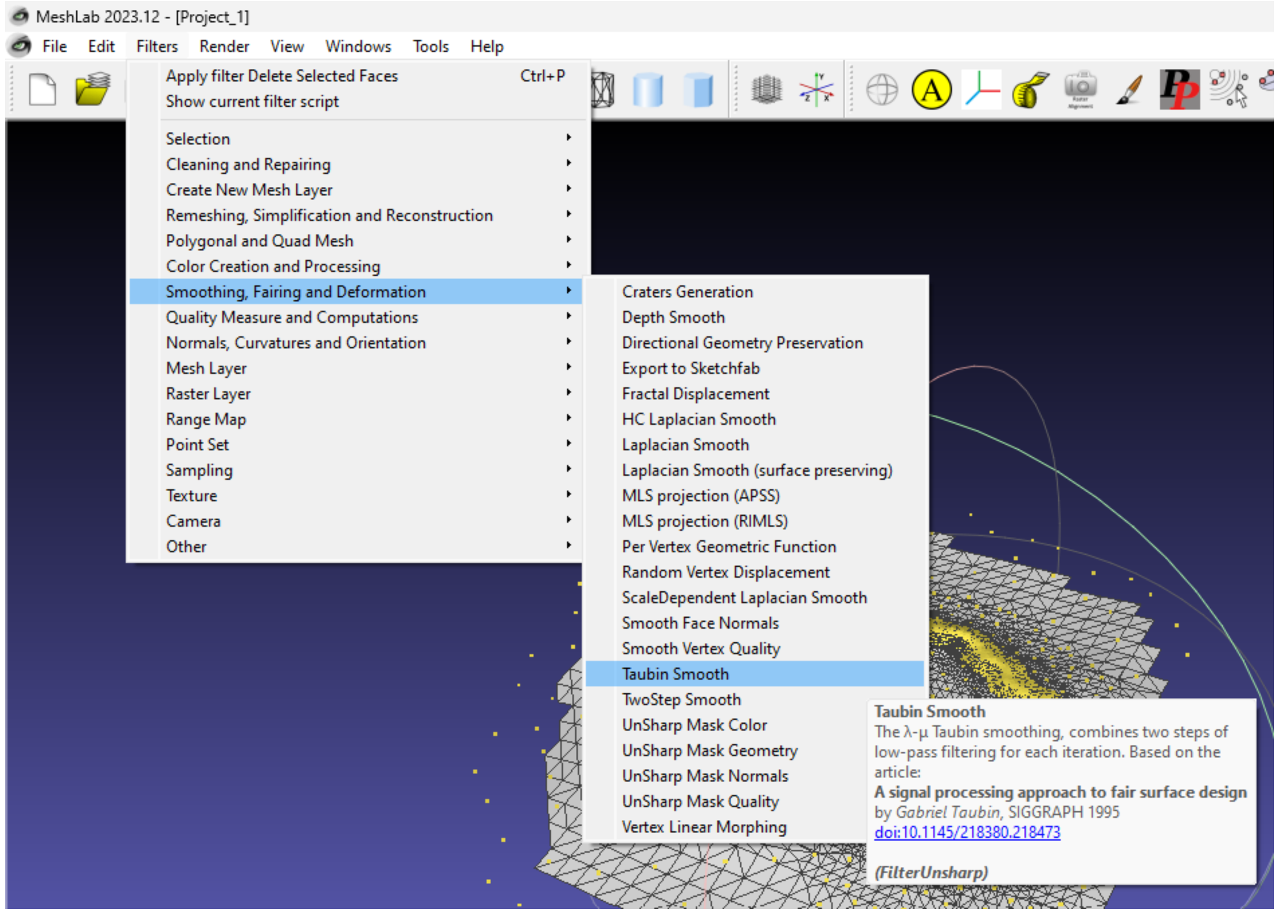
- Inspect the mesh for obvious abnormalities. The mesh should look similar to the mesh shown on the left

Mesh Trimming



- In the top toolbar, first select **Wireframe** to better view mesh elements, and then select the **Select Faces in a rectangular region** tool to allow for selection of individual mesh elements
- Looking at the point cloud as a visual reference, carefully select and delete (hit the delete button on your keyboard) the erroneous corners of the mesh and any parts of the mesh that are not likely to influence the lunar surface asset in your thermal desktop model
- **Be careful not to delete too much. A mesh element may not be in the direct FOV of your lunar asset, but it may still have an indirect thermal influence over your vehicle (e.g. a hill that's not visible from the perspective of your lunar asset may be blocking the sun from warming a hill that *is* in your asset's FOV)**
- Depending on the mesh, you may be able to get away with deleting more or fewer mesh elements. The goal of deleting elements is to have a more efficient Thermal Desktop model that doesn't analyze unnecessary terrain
- An example of a trimmed mesh is shown to the left

Mesh Refinement

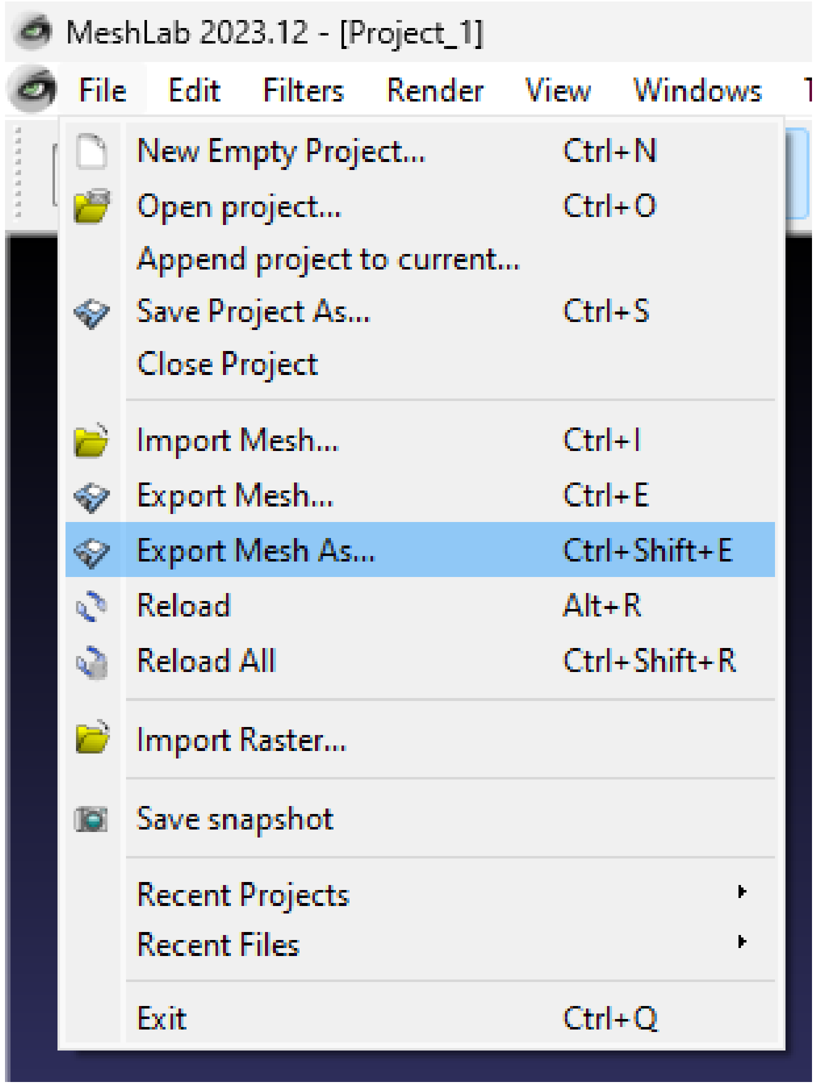


- With the Poisson Mesh selected in the Project window, navigate to the following:

Filters-> Smoothing, Fairing and Deformation-> **Taubin Smooth**

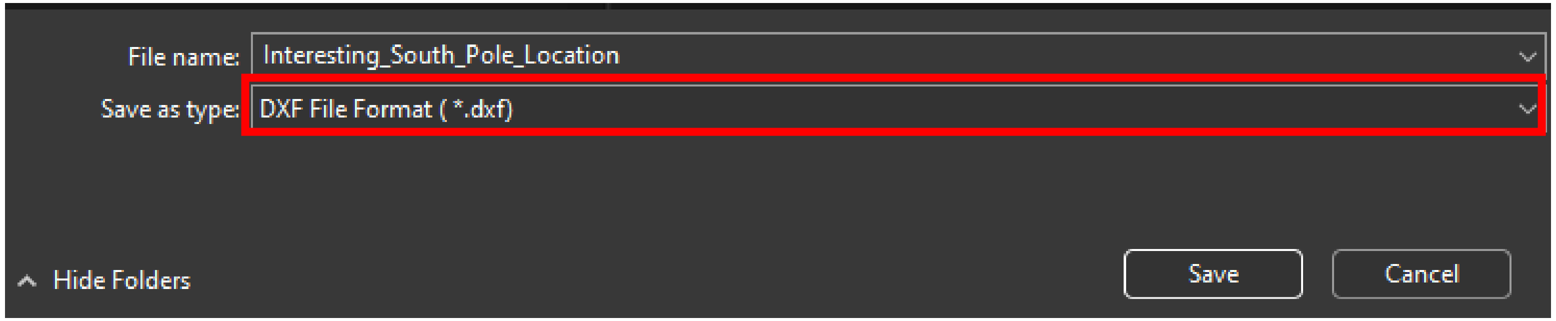
- A Taubin smooth will greatly improve the quality of mesh elements without sacrificing the accuracy of the surface
- A window will appear. Keep the default settings, select Apply, then Close

Exporting the Mesh



- **With the "Poisson mesh" selected in the project window**, Navigate to the following:

  File->Export Mesh As…
- In the Save window, enter a file name, and **for "Save as type:" select DXF**



- Keep the default settings in the "Choose Saving Options for:" window, and select OK
- You now have a terrain mesh that can be imported into AutoCAD/Thermal Desktop

Note: Don't close MeshLab until you've inspected the mesh in AutoCAD. Sometimes it will unexpectedly save a corrupted version of the DXF, and the DXF may need to be saved again

JPL Horizons Data Processing

This section describes the process of gathering solar vector and flux data from JPL Horizons for the surface site of interest and converting it into a format useable by Thermal Desktop

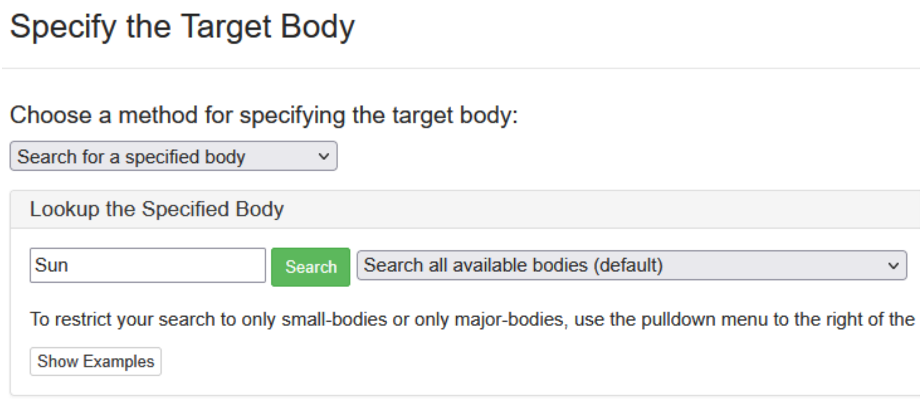
JPL Horizons Data Processing: **Solar Vector**

- Go to the JPL Horizons web interface found here:

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

- **For solar vector data, the Ephemeris Type to "Observer Table"**

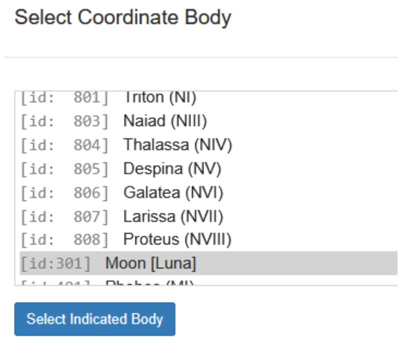
- For Target Body, select "Edit" If the target body is set to something other than the sun
  - Select "Search for a specified body" in the drop-down menu
  - Type "Sun" into the search box, and hit "Search"
  - Sun should be automatically selected and return you to the main settings page



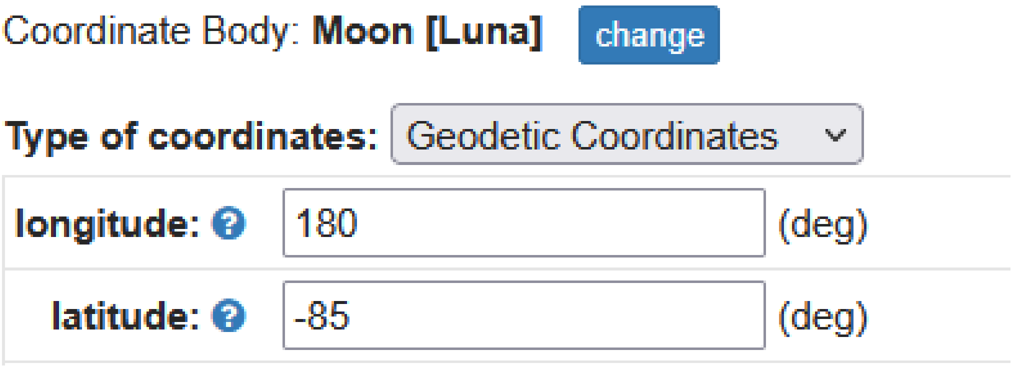
JPL Horizons Data Processing: **Solar Vector**

- For Observer Location, select "Edit"

- Under "Choose a method:" select "Specify Coordinates" from the drop-down menu



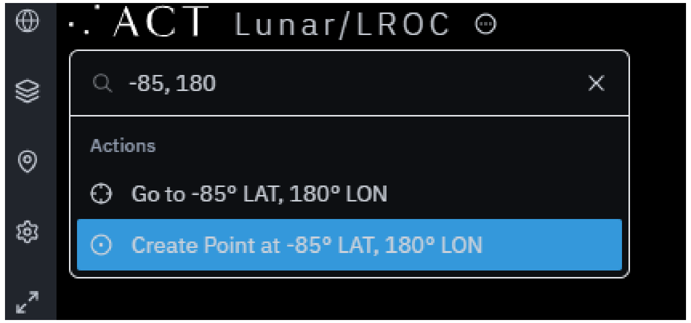
- For Coordinate Body, select "Change" if it isn't set to Moon already
  - Scroll all the way down to "Moon [Luna]" (it's close to the bottom of the list) and hit "Select Indicated Body"

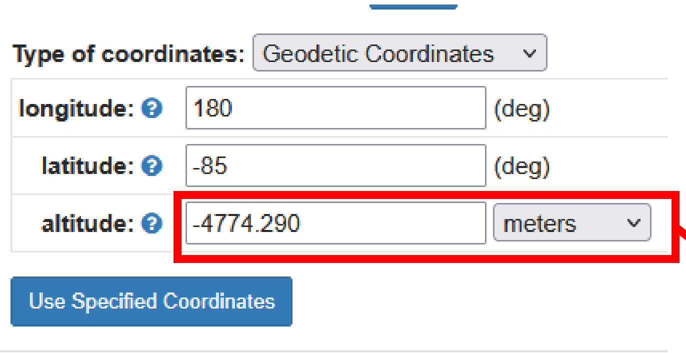


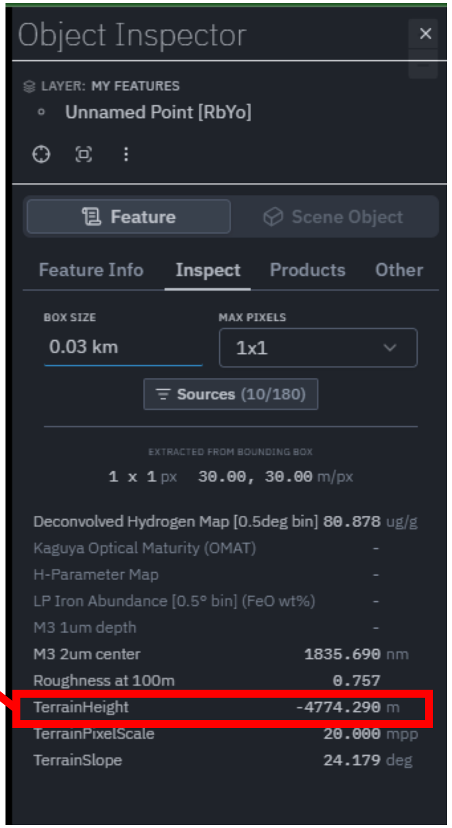
- Under Type of coordinates, select "Geodetic Coordinates" from the drop-down menu
- Enter the longitude and latitude of interest
  - South pole latitudes are negative
  - If you're like me, you like to enter Latitude then Longitude – they are in reverse order here
- **Continued on the next slide….**

JPL Horizons Data Processing: **Solar Vector**

- To find altitude, use LROC Quickmap. Go to the following link:
  - https://quickmap.lroc.im-ldi.com
- Enter the latitude and longitude into the search bar, separated by a comma, and select "Create Point"
- In the Object Inspector window on the right, navigate to the "Inspect" tab
- Copy the TerrainHeight, navigate back to JPL Horizons, and enter this into the "altitude"
- **Ensure the units are set to meters in JPL Horizons!**
- Select "Use Specified Coordinates"







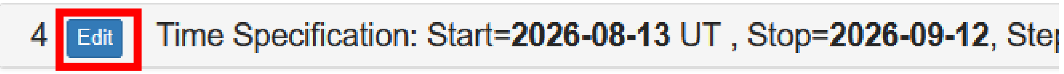
JPL Horizons Data Processing: **Solar Vector**

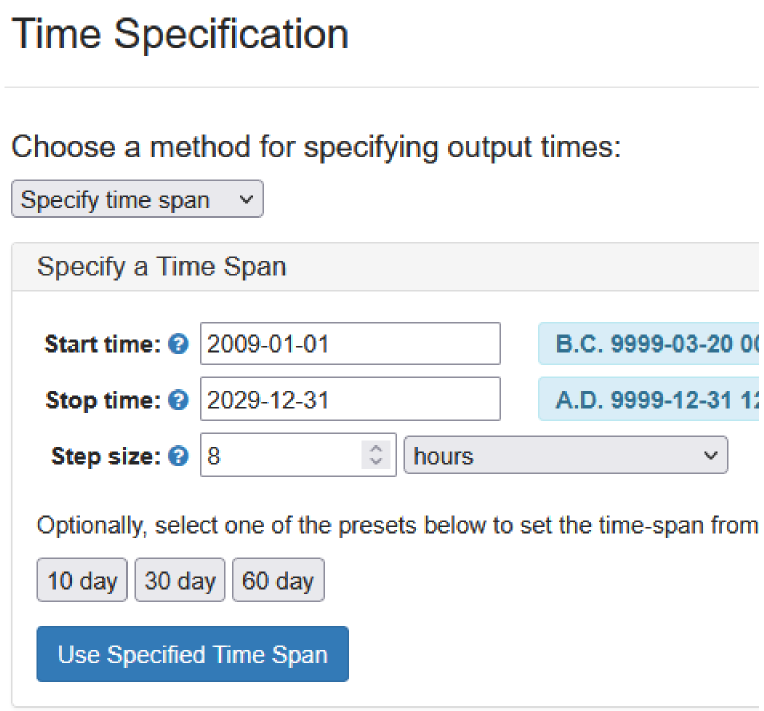
- For Time Specification, select "Edit"

- Enter a start and stop time that makes sense for your analysis:
  - The maximum transient initializer time span typically needed for subsurface temperatures to converge to a steady pattern is 20 years. However, for some sites and for some cases where perfect temperature stability is not needed, sometimes only 1 year of initializer data is acceptable.
  - The time span used for individual hot or cold cases varies significantly depending on the length of the phenomenon you are attempting to capture. The maximum is 28 days, but runs on the order of ~20 hours are more common.

- Set step size **units to hours** and enter an appropriate step size:
  - Multi-year transient initializer can typically be run with time steps on the order of 24 hours
  - Shorter single hot case or cold case runs can typically be run with 1-8 hour time steps depending on how long the case is and how many sharp transitions in solar access occur during the case.

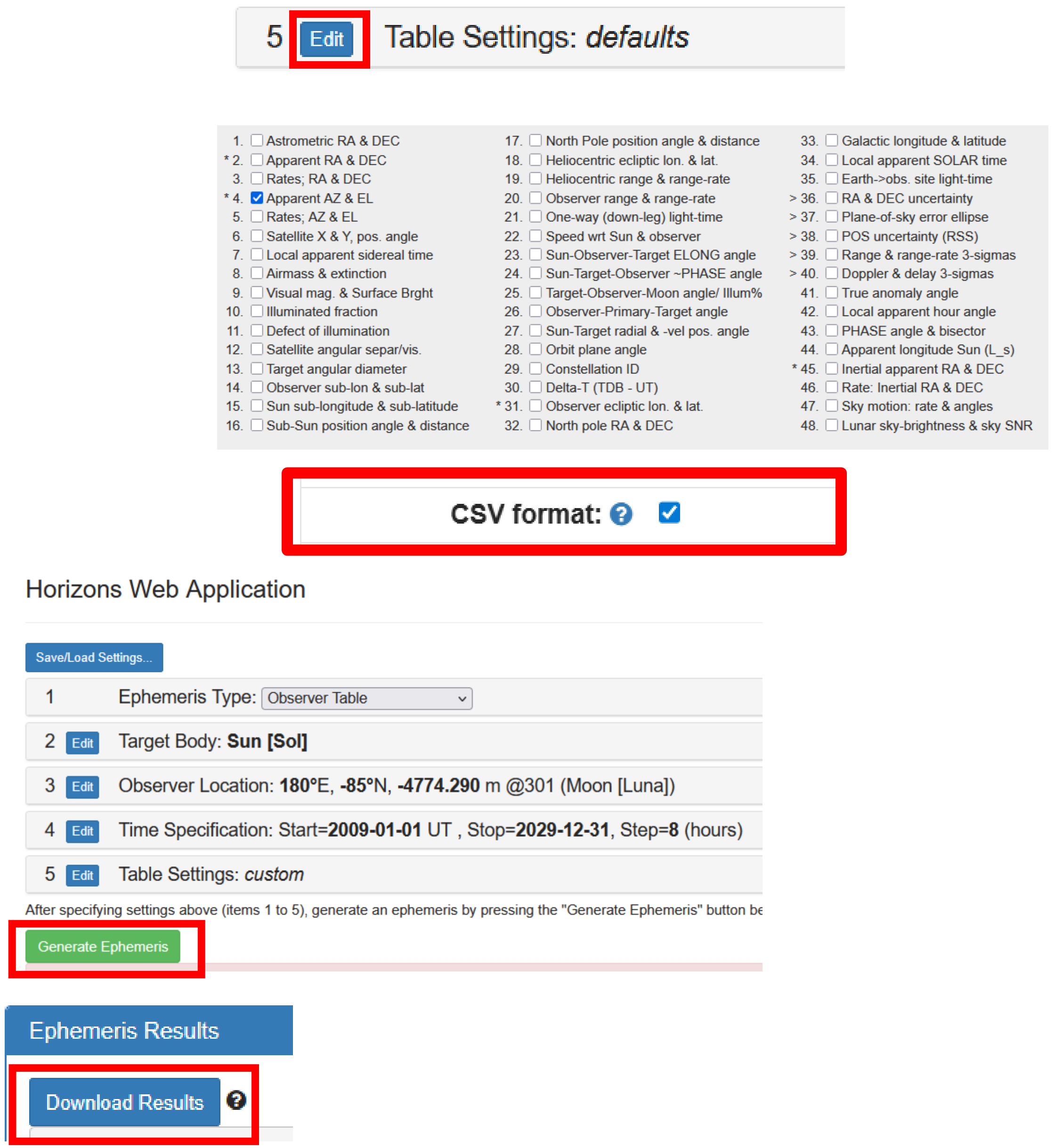
- Select "Use Specified Time Span"





JPL Horizons Data Processing: **Solar Vector**

- For Table Settings, select “Edit”
- Uncheck all boxes except “Apparent AZ & EL”
- Scroll down to “Additional Table Settings” and ensure “CSV format” is selected.
- Select “Use Specified Settings”
- In the main window, select “Generate Ephemeris”
- Select “Download Results” and save to a convenient location with a memorable file name



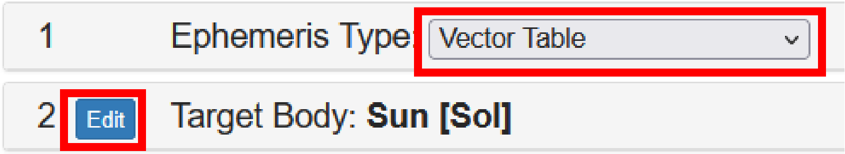
JPL Horizons Data Processing: **Solar Flux**

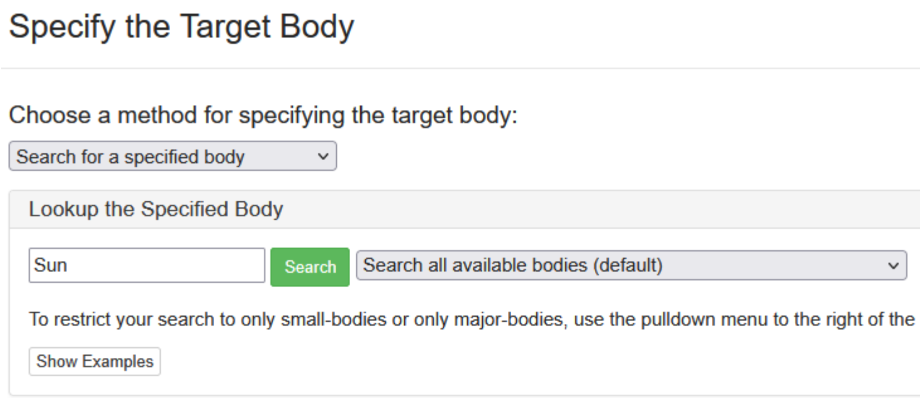
- Keep the existing instance of JPL Horizons open or go to the JPL Horizons web interface found here:

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

- **For solar flux data, the Ephemeris Type to "Vector Table"**

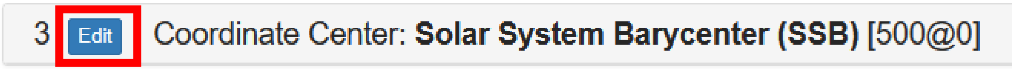
- For Target Body, select "Edit" If the target body is set to something other than the sun
  - Select "Search for a specified body" in the drop-down menu
  - Type "Sun" into the search box, and hit "Search"
  - Sun should be automatically selected and return you to the main settings page

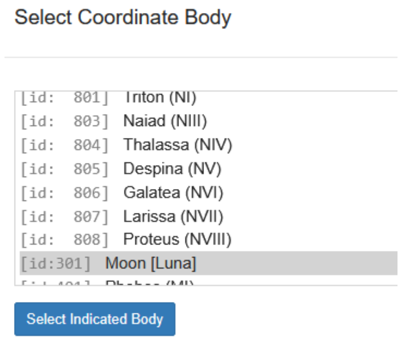


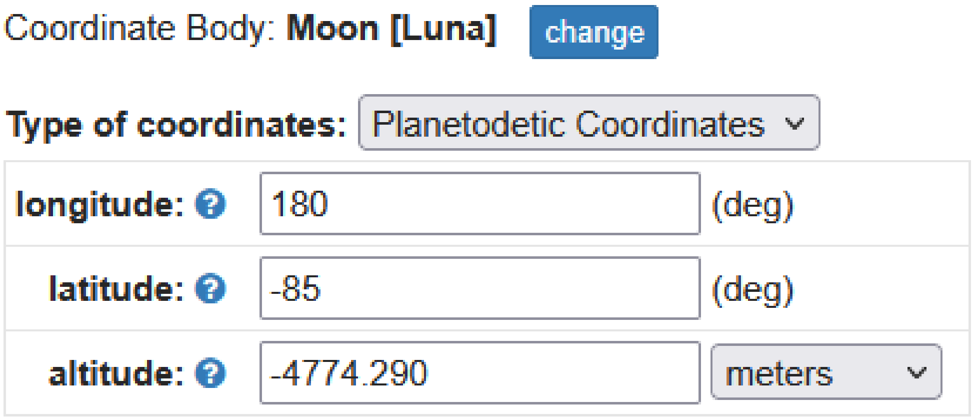


JPL Horizons Data Processing: **Solar Flux**

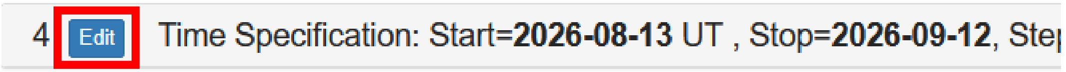
- For Coordinate Center, select “Edit”
- Under “Choose a method:” select “Specify Coordinates” from the drop-down menu
- For Coordinate Body, select “Change” if it isn’t set to Moon already
  - Scroll all the way down to “Moon [Luna]” (it’s close to the bottom of the list) and hit “Select Indicated Body”
- Under Type of coordinates, select “Planetodetic Coordinates” from the drop-down menu
- **Enter the same lat, long, and altitude used to generate solar vector data (ensure units are set to meters for altitude)**



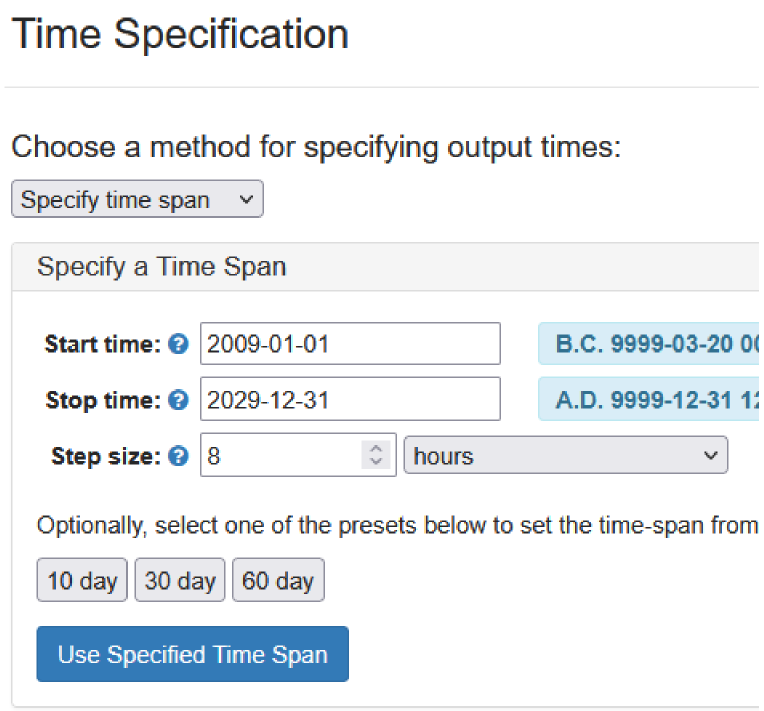




JPL Horizons Data Processing: **Solar Flux**

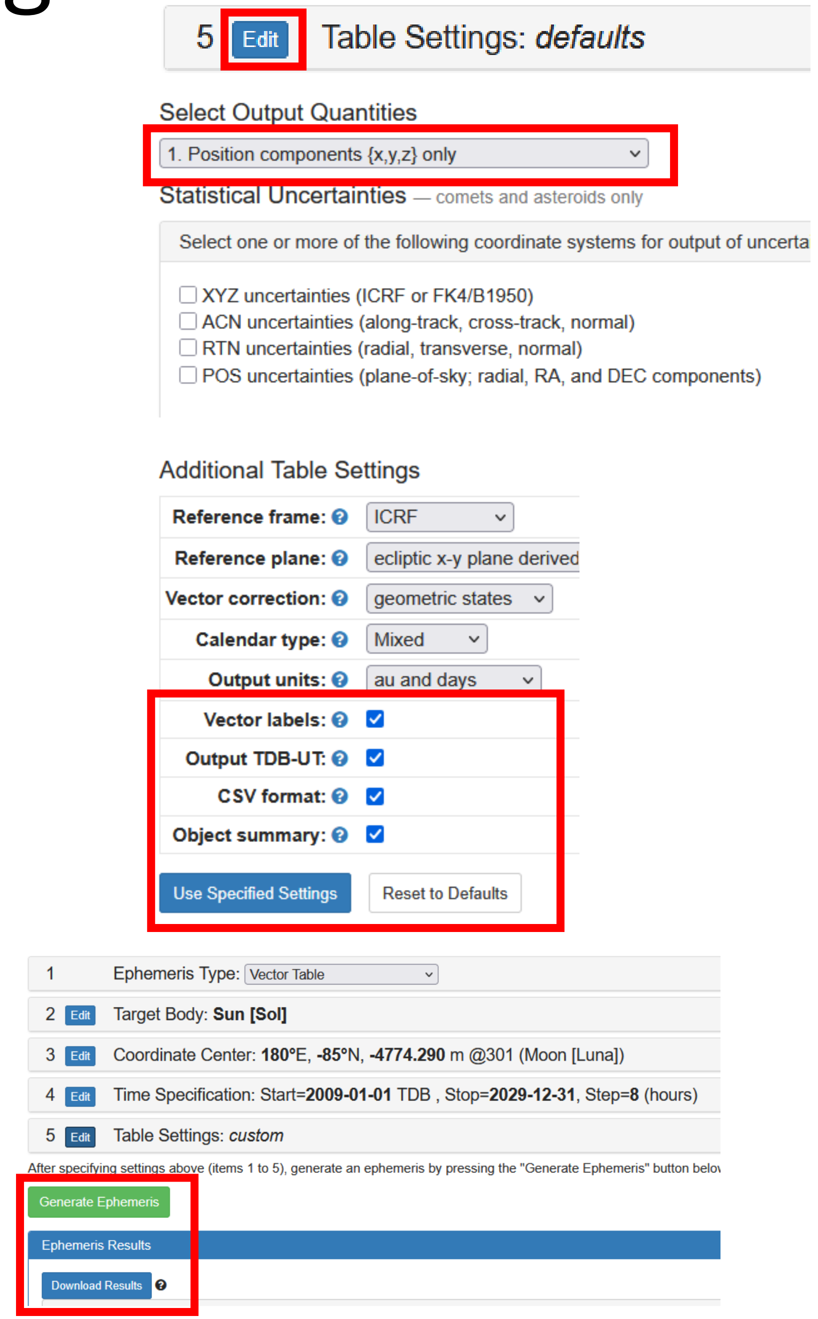


- For Time Specification, select “Edit”
- Set step size **units to hours** and enter the same start time, stop time, and step size used to calculate solar vector
- Select “Use Specified Time Span”



JPL Horizons Data Processing: **Solar Flux**

- For Table Settings, select "Edit"
- Under Select Output Quantities, select "Position components {x,y,z} only" from the drop-down menu
- Scroll down to "Additional Table Settings"
    - Switch units to "au and days"
    - Select all boxes
- Select "Use Specified Settings"
- In the main window, select "Generate Ephemeris"
- Select "Download Results" and save to a convenient location with a memorable file name



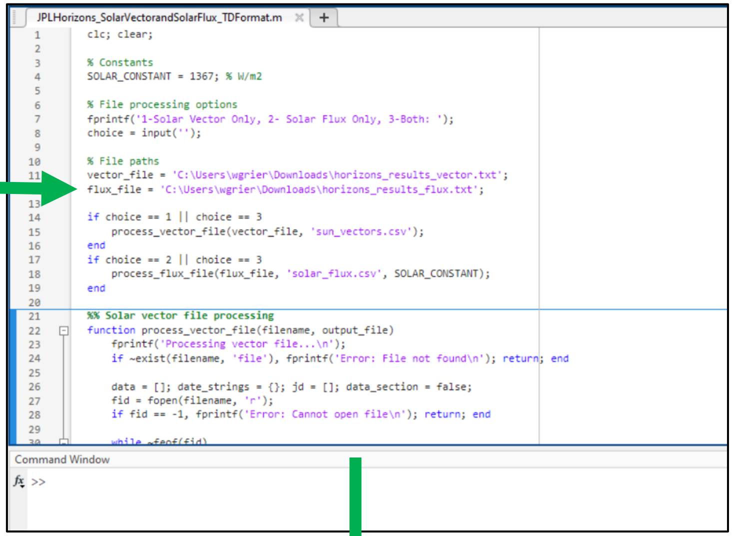
JPL Horizons Data Processing: **MATLAB**

- Open the Matlab code: JPLHorizons_SolarVectorandSolarFlux_TDFormat.m

- Enter the file names and paths to both the vector and flux files into the MATLAB code

- Run the code – this should output:
  - CSV **vector** file with data that can be directly copied into the "Vector Input" tab in Thermal Desktop's **orbit editor**
  - CSV **flux** file that can be copied directly into **Solar flux vs Time Table** under the "Solar" tab in TD's orbit editor

Specify .txt location and Execute Matlab



Matlab File Name:
JPLHorizons_SolarVectorand SolarFlux_TDFormat.m

Open Vector and Flux Files

Date	Seconds	Sun_i	Sun_j	Sun_k	Planet_i	Planet_j	Planet_k	Ratio
10/23/2026 0:00	0	-0.04156	0.993523	0.105757	0	0	-1	1.001
10/23/2026 1:00	3600	-0.05039	0.993117	0.105732	0	0	-1	1.001
10/23/2026 2:00	7200	-0.05921	0.992633	0.105701	0	0	-1	1.001
10/23/2026 3:00	10800	-0.06803	0.992072	0.105663	0	0	-1	1.001
10/23/2026 4:00	14400	-0.07685	0.991433	0.105619	0	0	-1	1.001
10/23/2026 5:00	18000	-0.08565	0.990716	0.105569	0	0	-1	1.001
10/23/2026 6:00	21600	-0.09445	0.989922	0.105512	0	0	-1	1.001
10/23/2026 7:00	25200	-0.10325	0.98905	0.105449	0	0	-1	1.001
10/23/2026 8:00	28800	-0.11203	0.988101	0.105379	0	0	-1	1.001
10/23/2026 9:00	32400	-0.12081	0.987075	0.105303	0	0	-1	1.001
10/23/2026 10:00	36000	-0.12958	0.985971	0.105221	0	0	-1	1.001
10/23/2026 11:00	39600	-0.13833	0.98479	0.105133	0	0	-1	1.001
10/23/2026 12:00	43200	-0.14708	0.983532	0.105038	0	0	-1	1.001
10/23/2026 13:00	46800	-0.15581	0.982197	0.104936	0	0	-1	1.001
10/23/2026 14:00	50400	-0.16453	0.980785	0.104828	0	0	-1	1.001
10/23/2026 15:00	54000	-0.17324	0.979297	0.104714	0	0	-1	1.001
10/23/2026 16:00	57600	-0.18194	0.977732	0.104594	0	0	-1	1.001

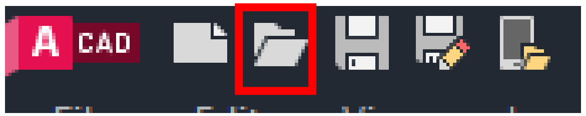
Date	Seconds	SolarFlux_W_m2
10/24/2009 0:00	0	1384.328
10/25/2009 0:00	86400	1383.75
10/26/2009 0:00	172800	1383.114
10/27/2009 0:00	259200	1382.474
10/28/2009 0:00	345600	1381.88
10/29/2009 0:00	432000	1381.385
10/30/2009 0:00	518400	1381.039
10/31/2009 0:00	604800	1380.891
11/1/2009 0:00	691200	1380.985
11/2/2009 0:00	777600	1381.357
11/3/2009 0:00	864000	1382.037
11/4/2009 0:00	950400	1383.035

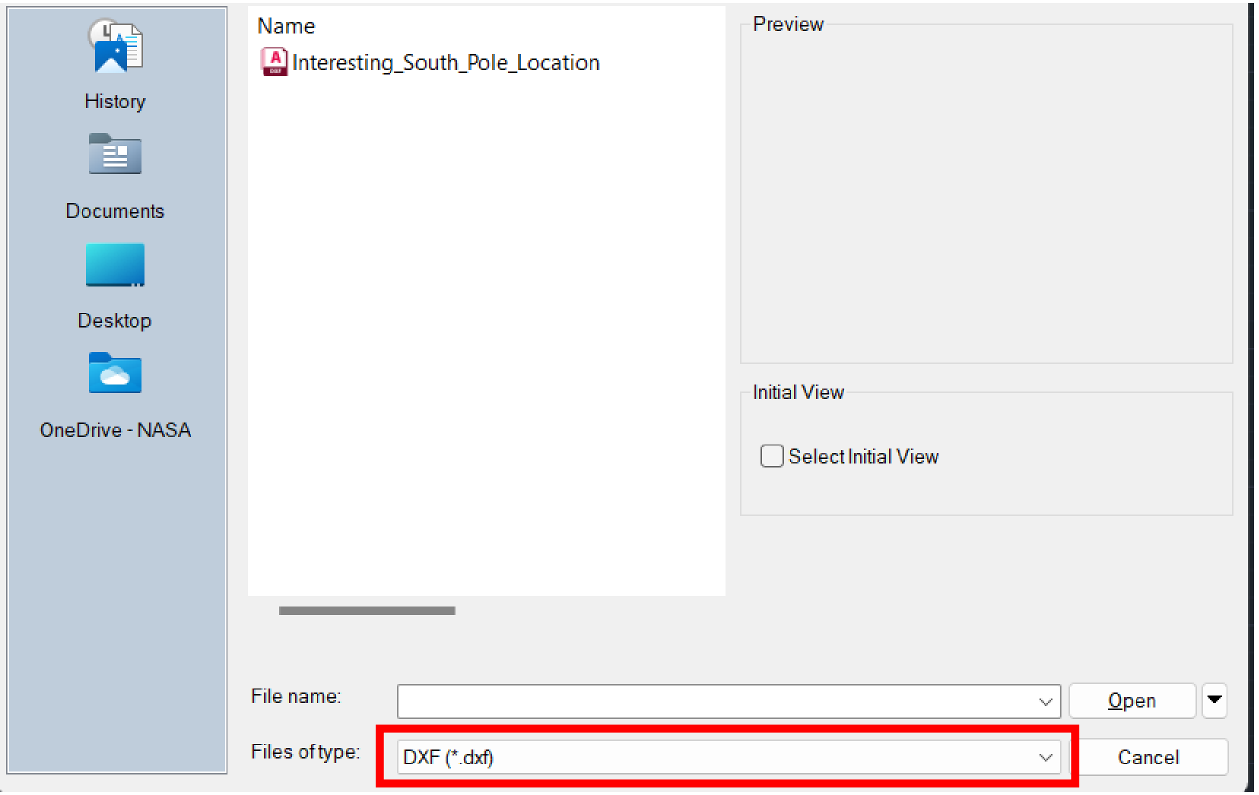
Lunar Terrain Thermal Analysis in Thermal Desktop

This section describes the process of building and running the final Thermal Desktop model.

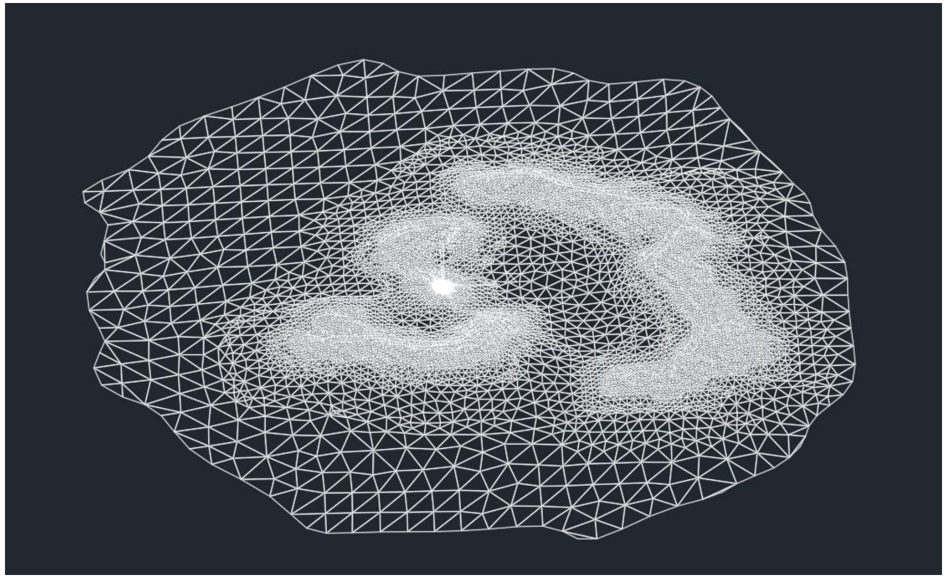
Note these instructions were created using version 6.3 of Thermal Desktop

Importing the Mesh



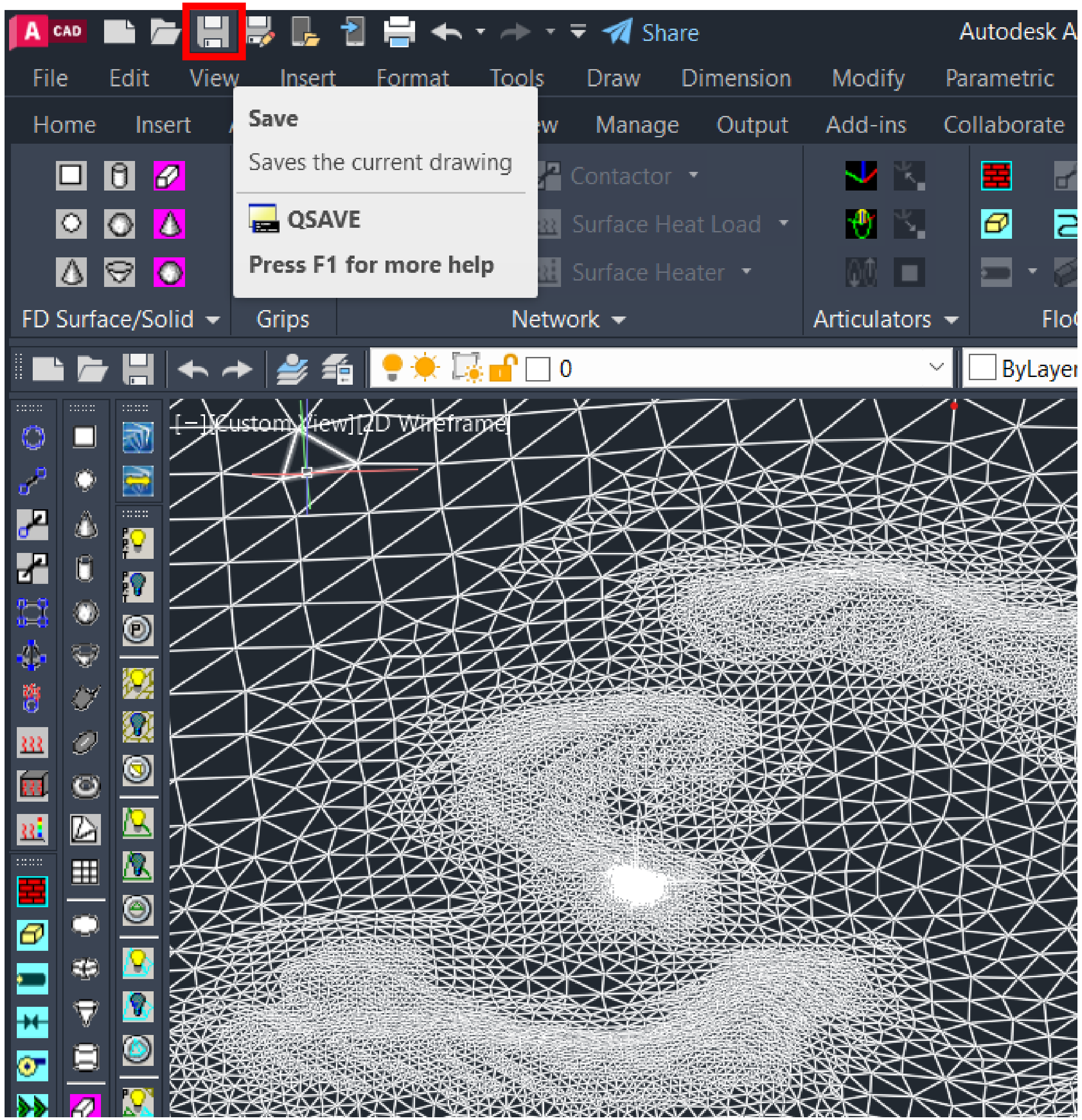


- **Open AutoCAD/Thermal Desktop***
- Select the “Open” icon in the upper lefthand corner
- Navigate to the DXF file that was exported from MeshLab (ensuring the “File of type” is set to DXF) and Open
- Zoom out to view/Inspect the mesh.



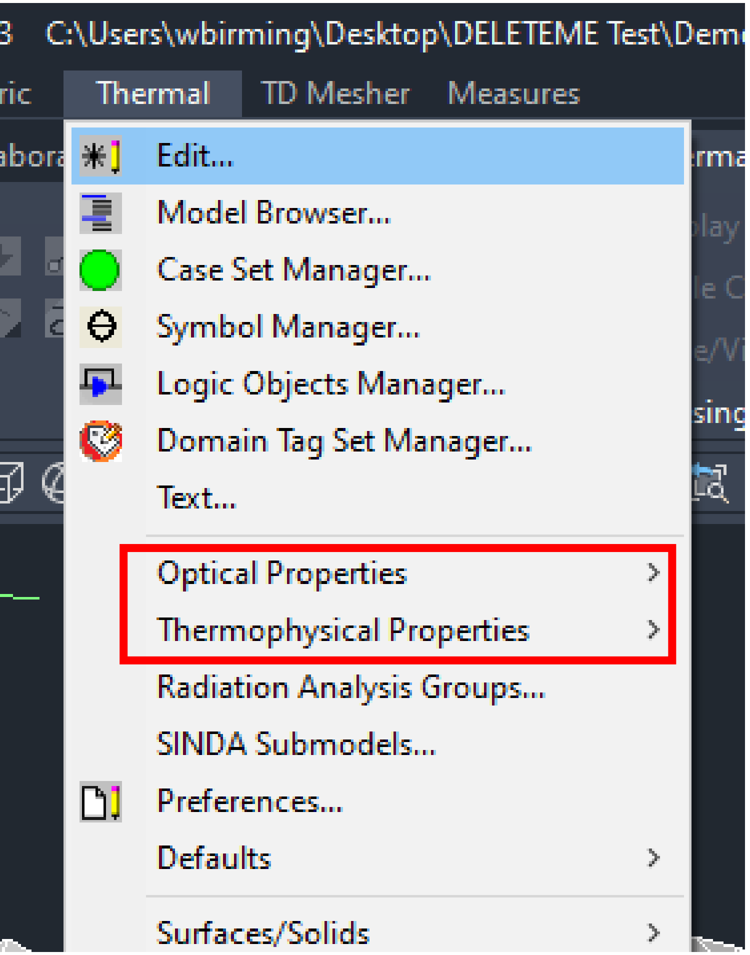
*Note: Don’t close MeshLab until you’ve inspected the mesh in AutoCAD. Sometimes it will unexpectedly save a corrupted version of the DXF, and the DXF may need to be saved again

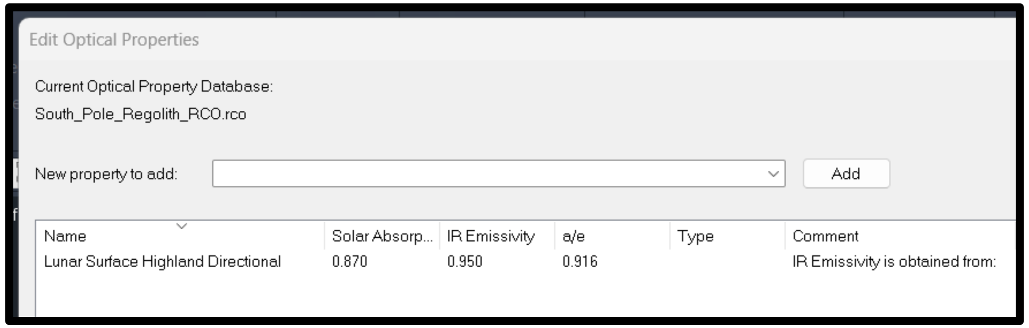
DWG Conversion



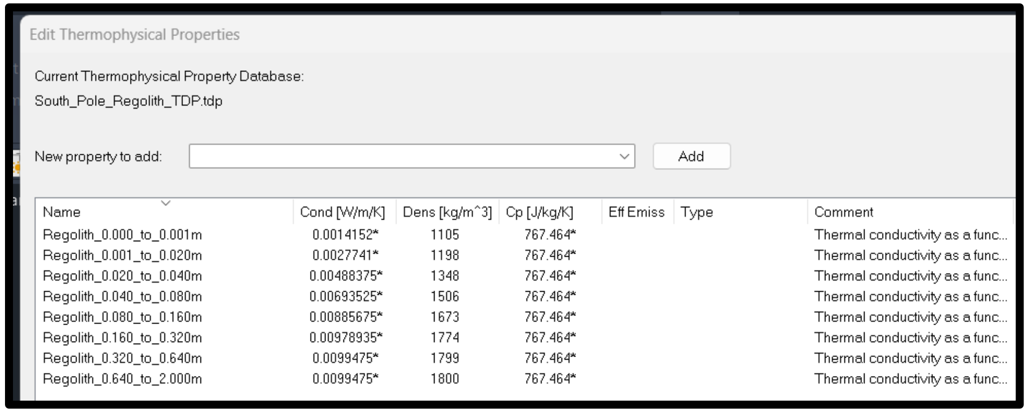
- **Go ahead and select the Save Icon to save As a .dwg file. (Among other things, this step makes your TD model recoverable in the event of a crash)**

Property Files





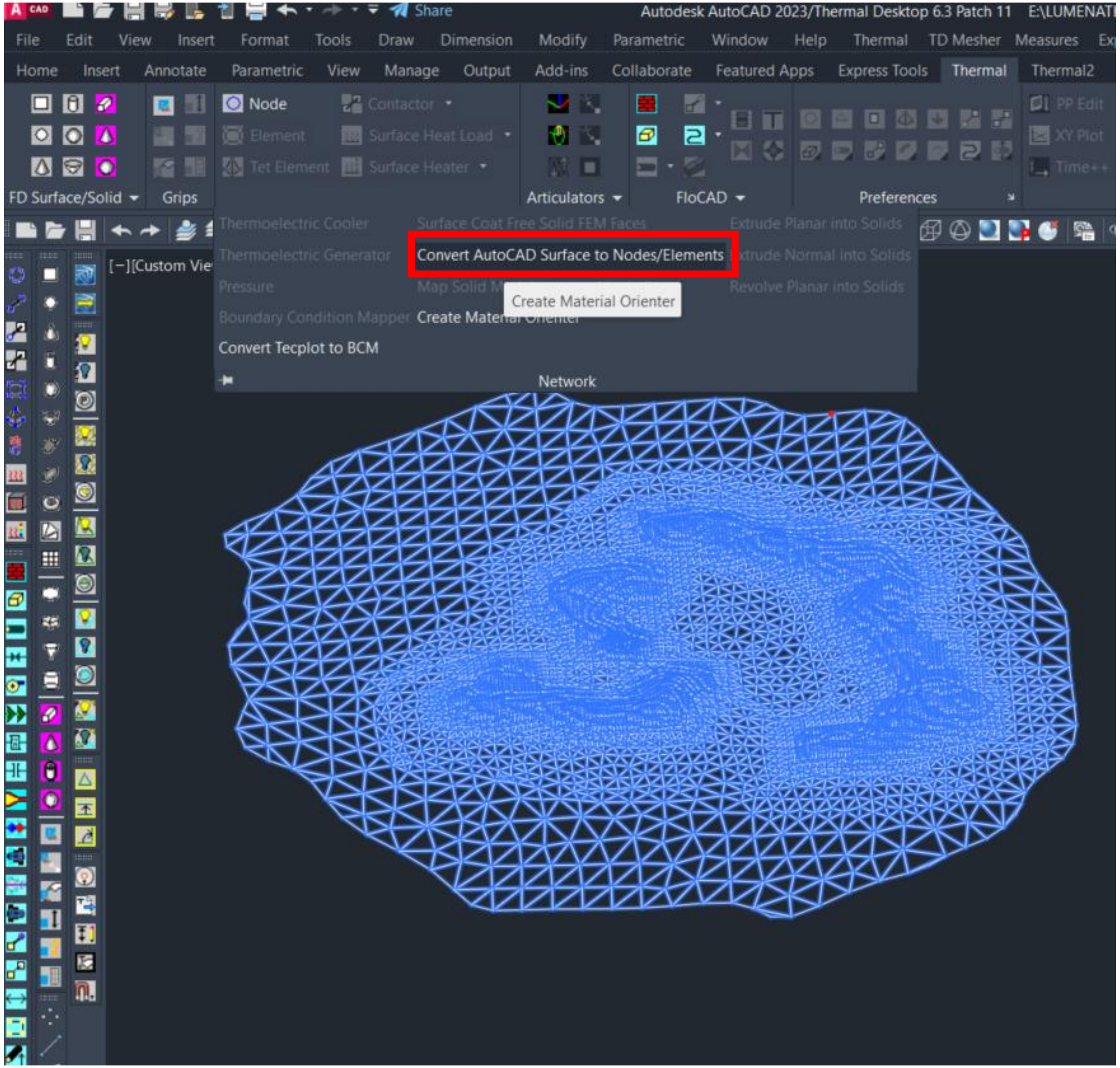
Name	Solar Absorp...	IR Emissivity	a/e	Type	Comment
Lunar Surface Highland Directional	0.870	0.950	0.916		IR Emissivity is obtained from:



Name	Cond [W/m/K]	Dens [kg/m^3]	Cp [J/kg/K]	Eff Emiss	Type	Comment
Regolith_0.000_to_0.001m	0.0014152*	1105	767.464*			Thermal conductivity as a func...
Regolith_0.001_to_0.020m	0.0027741*	1198	767.464*			Thermal conductivity as a func...
Regolith_0.020_to_0.040m	0.00488375*	1348	767.464*			Thermal conductivity as a func...
Regolith_0.040_to_0.080m	0.00693525*	1506	767.464*			Thermal conductivity as a func...
Regolith_0.080_to_0.160m	0.00885675*	1673	767.464*			Thermal conductivity as a func...
Regolith_0.160_to_0.320m	0.00978935*	1774	767.464*			Thermal conductivity as a func...
Regolith_0.320_to_0.640m	0.0099475*	1799	767.464*			Thermal conductivity as a func...
Regolith_0.640_to_2.000m	0.0099475*	1800	767.464*			Thermal conductivity as a func...

- Open TDP and RCO Files containing all the properties needed for the lunar terrain analysis (future steps will be much easier if this is done now)
- The basic properties used for this analysis are shown to the left (note lander-specific properties can be added later if desired)

Conversion to Thermal Desktop



- Select the entire mesh
- Under “Network” select “Convert AutoCAD Surface to Nodes/Elements

Notes on Regolith Properties

- **Thermal conductivity as a function of temperature and density is obtained from:**

Martinez, A., & Siegler, M. A. (2021). A Global Thermal Conductivity Model for Lunar Regolith at Low Temperatures. Journal of Geophysical Research: Planets, 126, e2021JE006829. https://doi.org/10.1029/2021JE006829

- **Density as a function of depth is obtained from:**

Vasavada, A. R., Bandfield, J. L., Greenhagen, B. T., Hayne, P. O., Siegler, M. A., Williams, J., & Paige, D. A. (2012). Lunar equatorial surface temperatures and regolith properties from the Diviner Lunar Radiometer Experiment. Journal of Geophysical Research: Planets, E12. https://doi.org/10.1029/2011je003987
&
Hayne, P. O., Bandfield, J. L., Siegler, M. A., Vasavada, A. R., Ghent, R. R., Williams, J.-P., ... Paige, D. A. (2017). Global Regolith Thermophysical Properties of the Moon from the Diviner Lunar Radiometer Experiment. Journal of Geophysical Research: Planets, 122, 2371–2400. https://doi.org/10.1002/2017JE005387

- **Specific heat as a function of temperature is obtained from:**

Woods-Robinson, R., Siegler, M. A., & Paige, D. A. (2019). A Model for The Thermophysical Properties of Lunar Regolith at Low Temperatures. Journal of Geophysical Research: Planets, 124, 1989–2011. https://doi.org/10.1029/2019JE005955

- **IR Emissivity is obtained from:**

Hayne, P. O., Bandfield, J. L., Siegler, M. A., Vasavada, A. R., Ghent, R. R., Williams, J.-P., ... Paige, D. A. (2017). Global Regolith Thermophysical Properties of the Moon from the Diviner Lunar Radiometer Experiment. Journal of Geophysical Research: Planets, 122, 2371–2400. https://doi.org/10.1002/2017JE005387

- **Directional Solar Absorptivity is obtained from:**

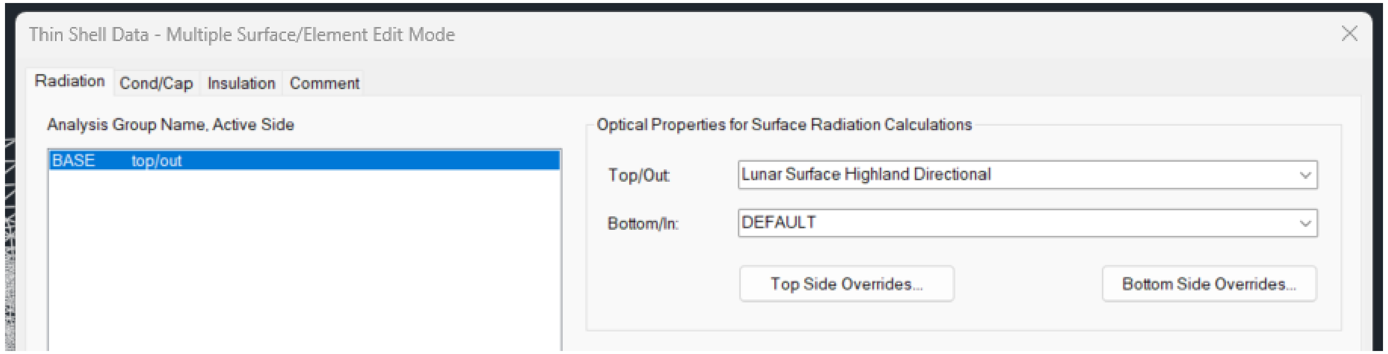
Feng, J., Siegler, M. A., & Hayne, P. O. (2020). New Constraints on Thermal and Dielectric Properties of Lunar Regolith from LRO Diviner and CE-2 Microwave Radiometer. Journal of Geophysical Research: Planets, 125, e2019JE006130. https://doi.org/10.1029/2019JE006130

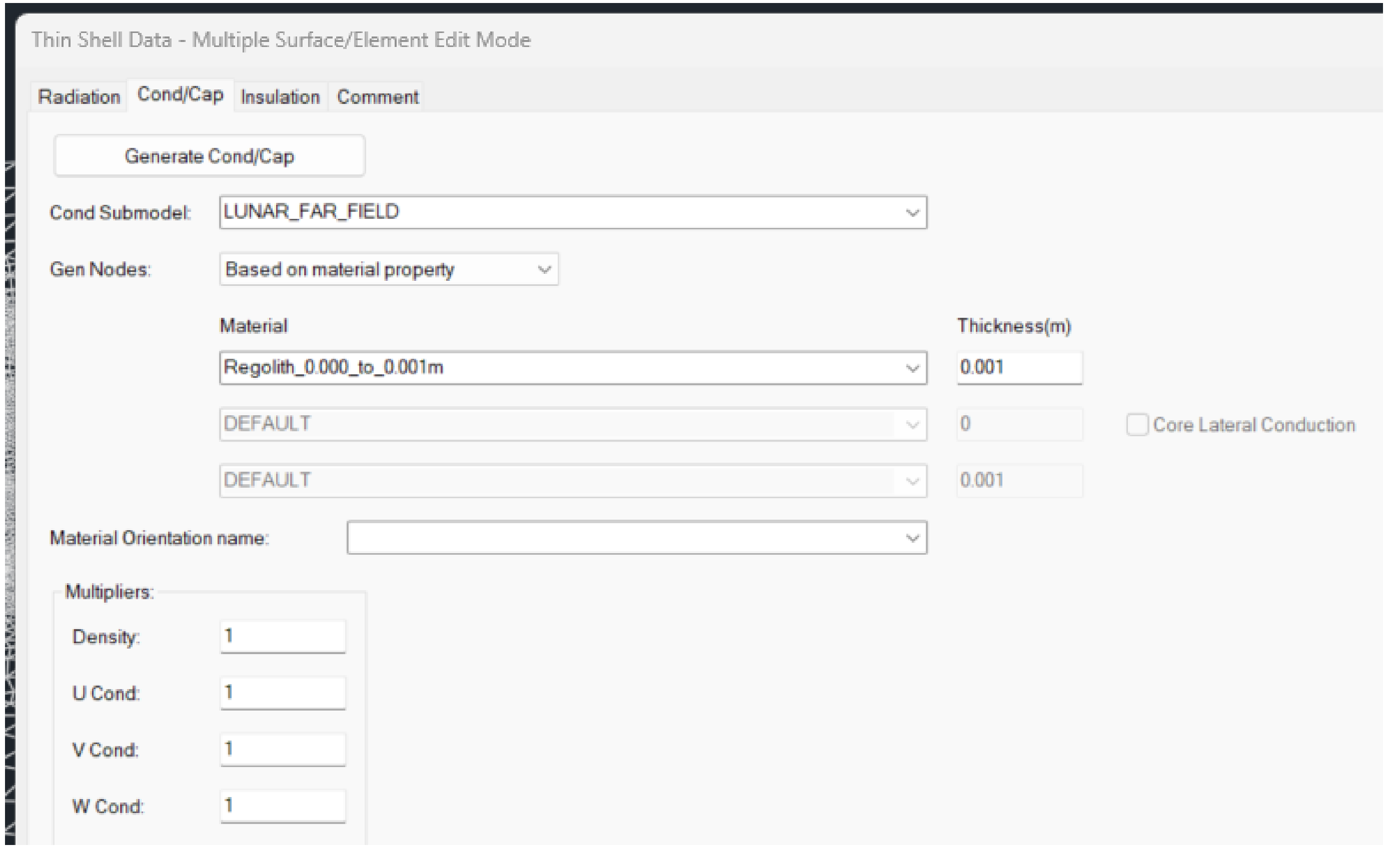
The regolith properties used in this example were obtained from the sources listed to the left

For help applying these sources to your analysis (or selecting better sources for your specific situation), consult one of the following:

- The Cross-Program Design Specification for Natural Environments (DSNE) or SLS-SPEC-159
- The Lunar Thermal Analysis Guidebook (LTAG) or HLS-UG-001
- Contact the LUMENATE team:
  - Lisa Erickson (lisa.erickson@nasa.gov)
    NASA / JSC / EC611
  - Will Grier (will.j.grier@nasa.gov)
    NASA / LaRC / D206
  - Will Birmingham (william.j.birmingham@nasa.gov)
    NASA / MSFC / EV34

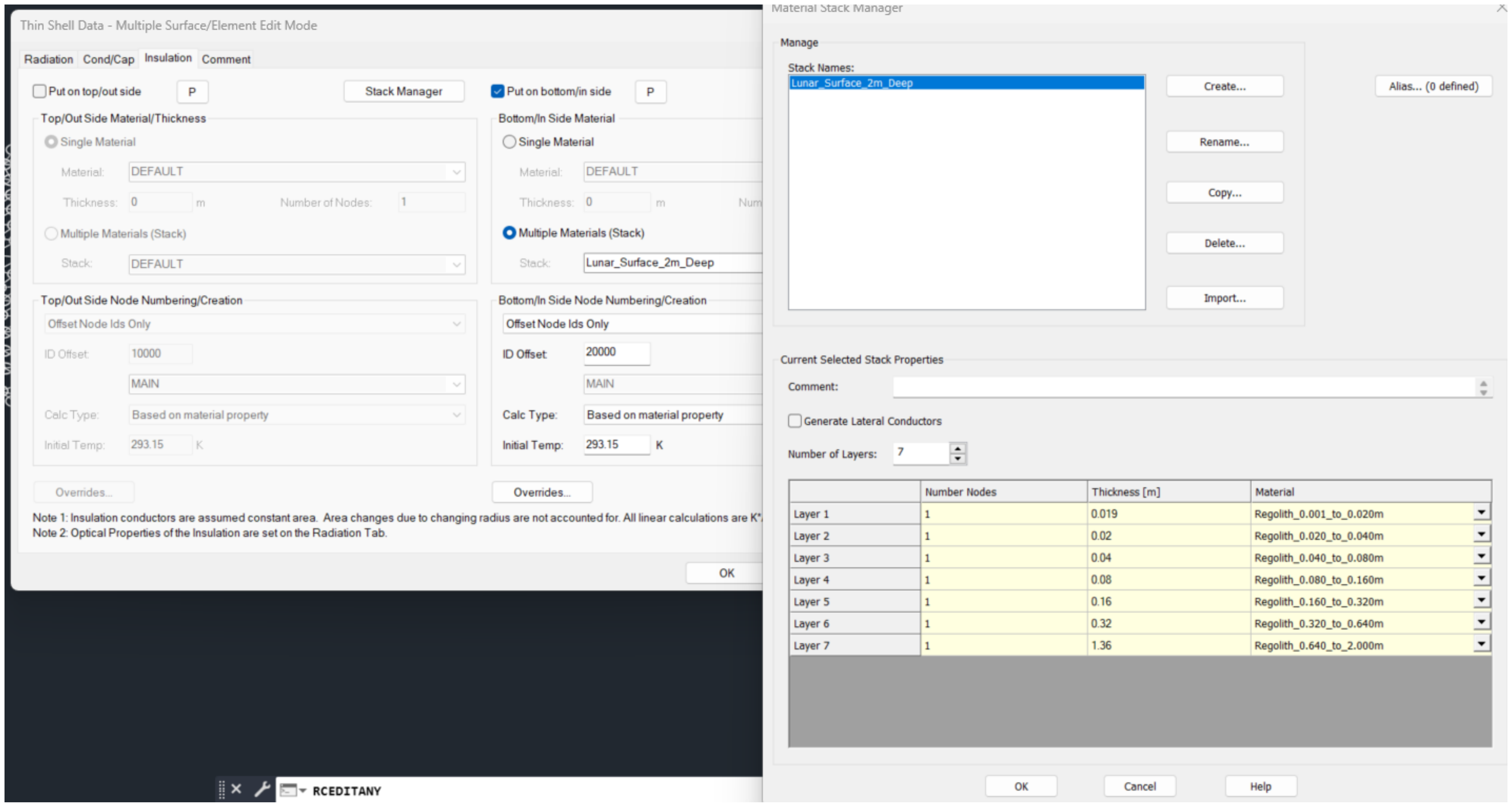
Regolith Properties





- If care was taken in MeshLab to ensure normal vectors pointed up, the Top/Out will be the active side to which optical properties should be applied (as shown to the left). **However, be sure to double-check this**
- Define optical and thermophysical properties as shown
- For Cond Submodel, Define a new submodel such as: LUNAR_FAR_FIELD

Regolith Properties

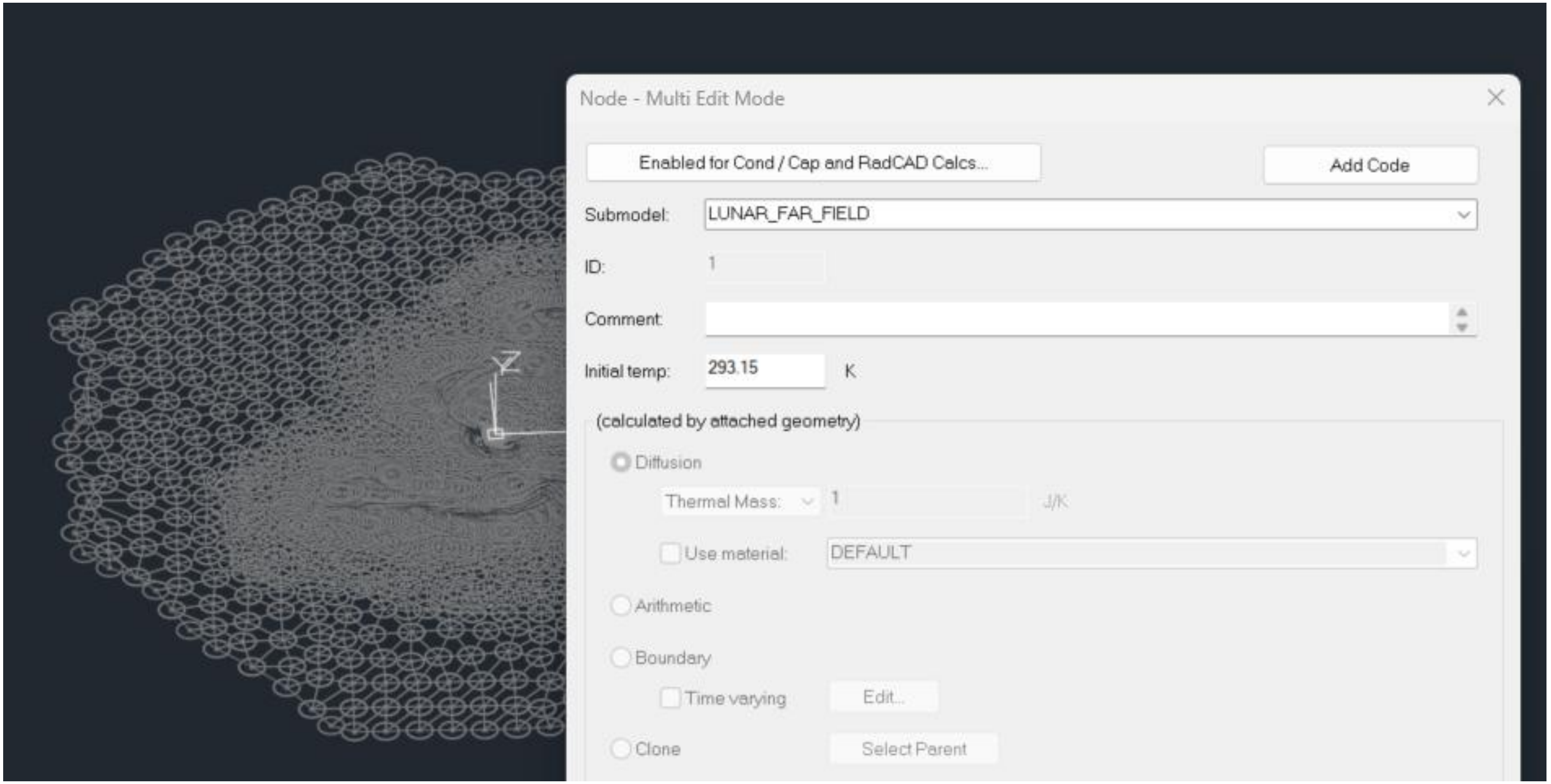


- Navigate to the Insulation Tab
- The methodology here presented, uses insulation layers to model subsurface regolith. Seven layers are used here as shown to the left.
- (Note this window is accessed by selecting the Stack Manager button under the Insulation Tab)
- Apply the insulation stack to the down-facing side
- Set up the insulation stack as shown to the left

A version of the layer specifications that can be copied and pasted directly into the Material Stack Manager:

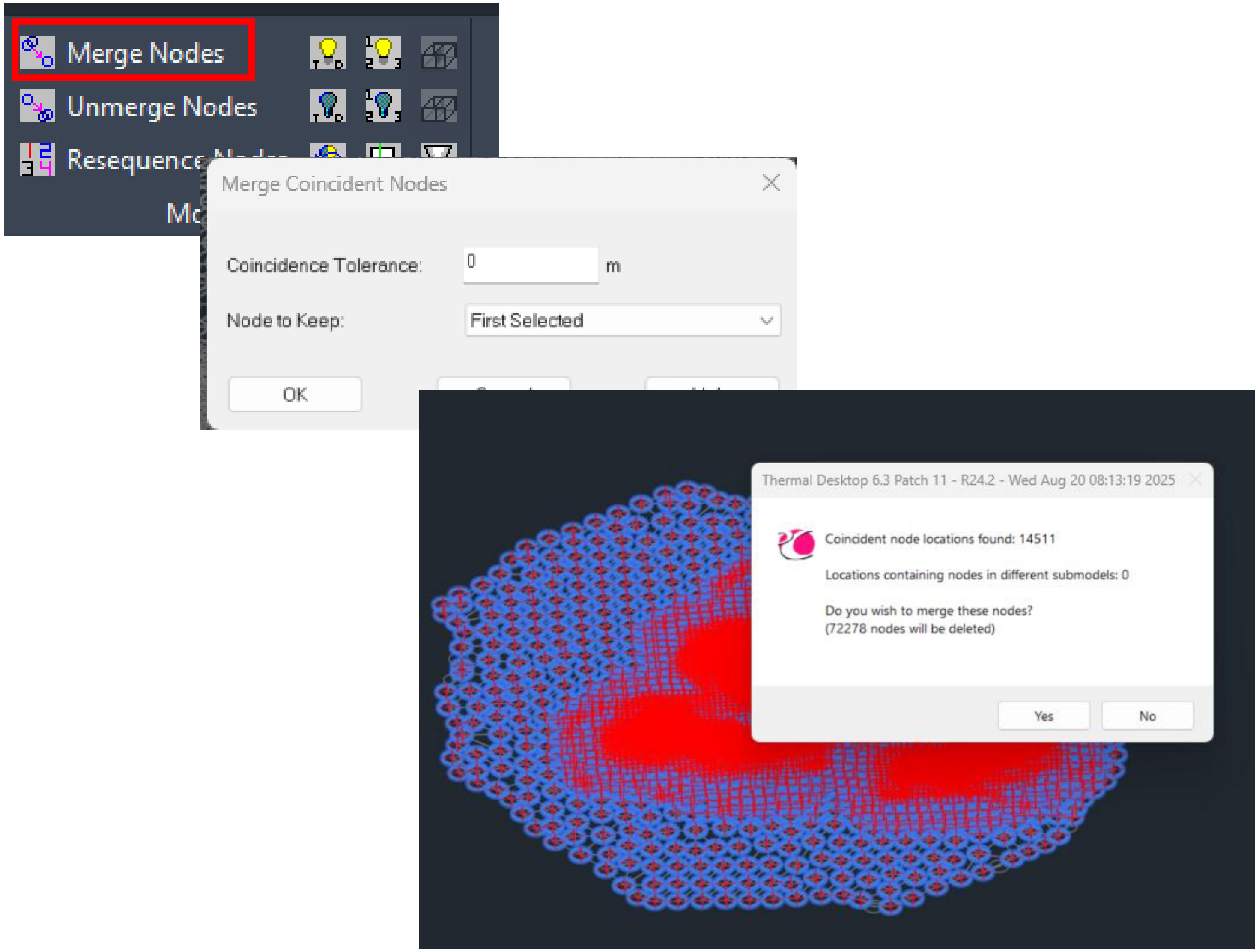
1	0.019	Regolith_0.001_to_0.020m
1	0.02	Regolith_0.020_to_0.040m
1	0.04	Regolith_0.040_to_0.080m
1	0.08	Regolith_0.080_to_0.160m
1	0.16	Regolith_0.160_to_0.320m
1	0.32	Regolith_0.320_to_0.640m
1	1.36	Regolith_0.640_to_2.000m

Submodel Assignment



- Select all nodes and edit
- Change the submodel to something recognizable such as “LUNAR_FAR_FIELD”
- Select OK

Merge Nodes

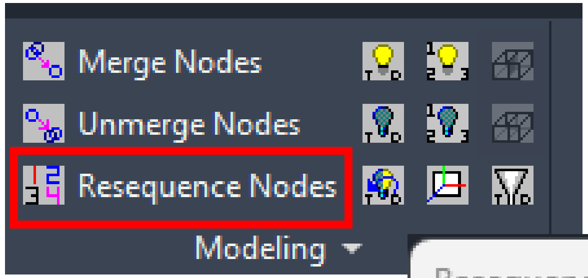


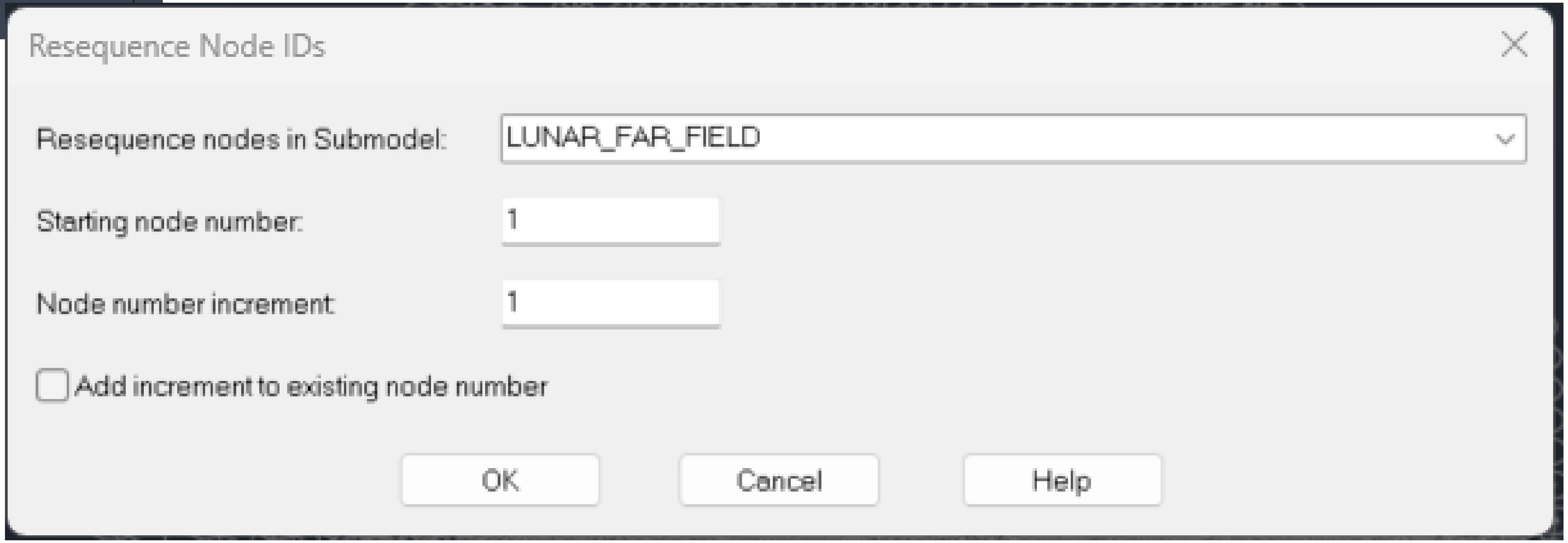
- Select all nodes
- Select Merge Nodes
- Select OK then Yes

- **NOTE: The number of nodes after merging should be less than 10,000. If it's significantly more than 10k, you will likely have to revisit the "Point Cloud Simplification" step in the MeshLab tutorial.**
- **This example shows a mesh with too many nodes! It was not made using the recommendations in the table, and the mesh had to be remade.**

Resequence Nodes

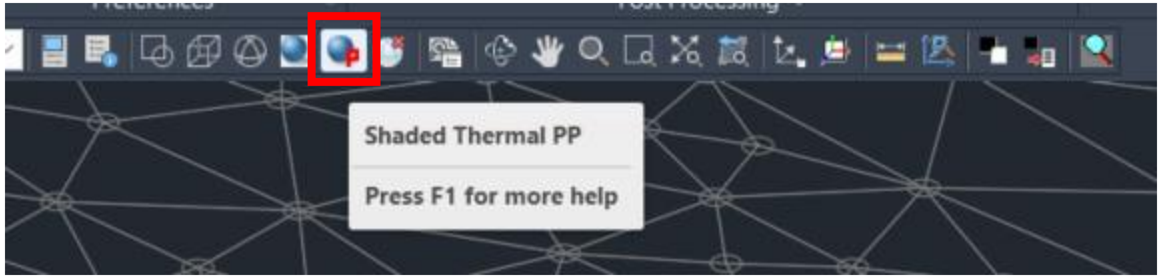
- Select all nodes
- Select Resequence Nodes
- Set the Starting node number to 1 and select OK

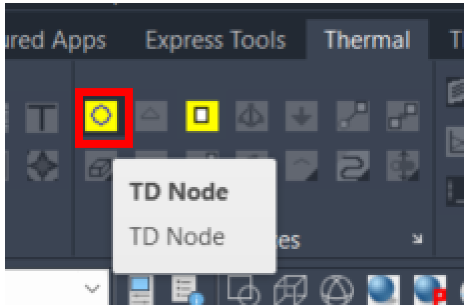


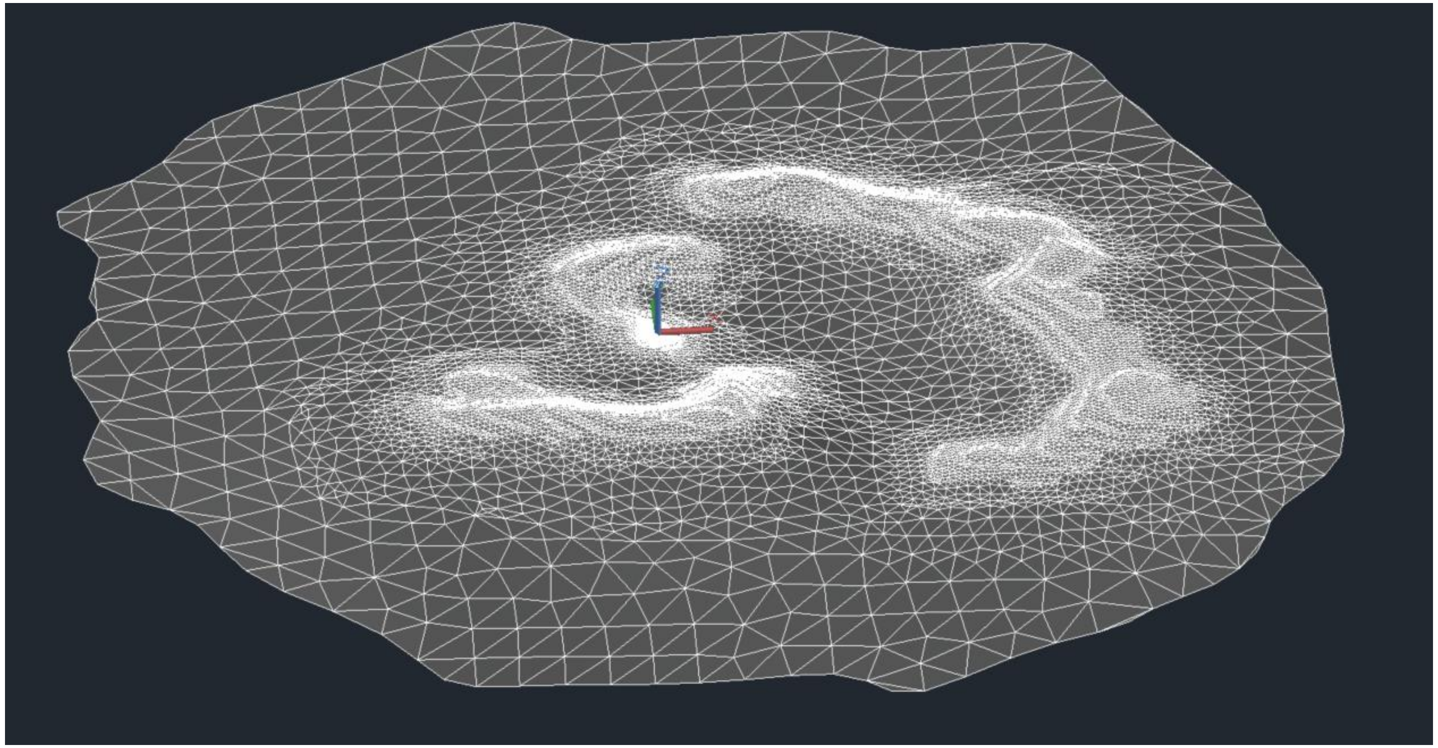


View Settings

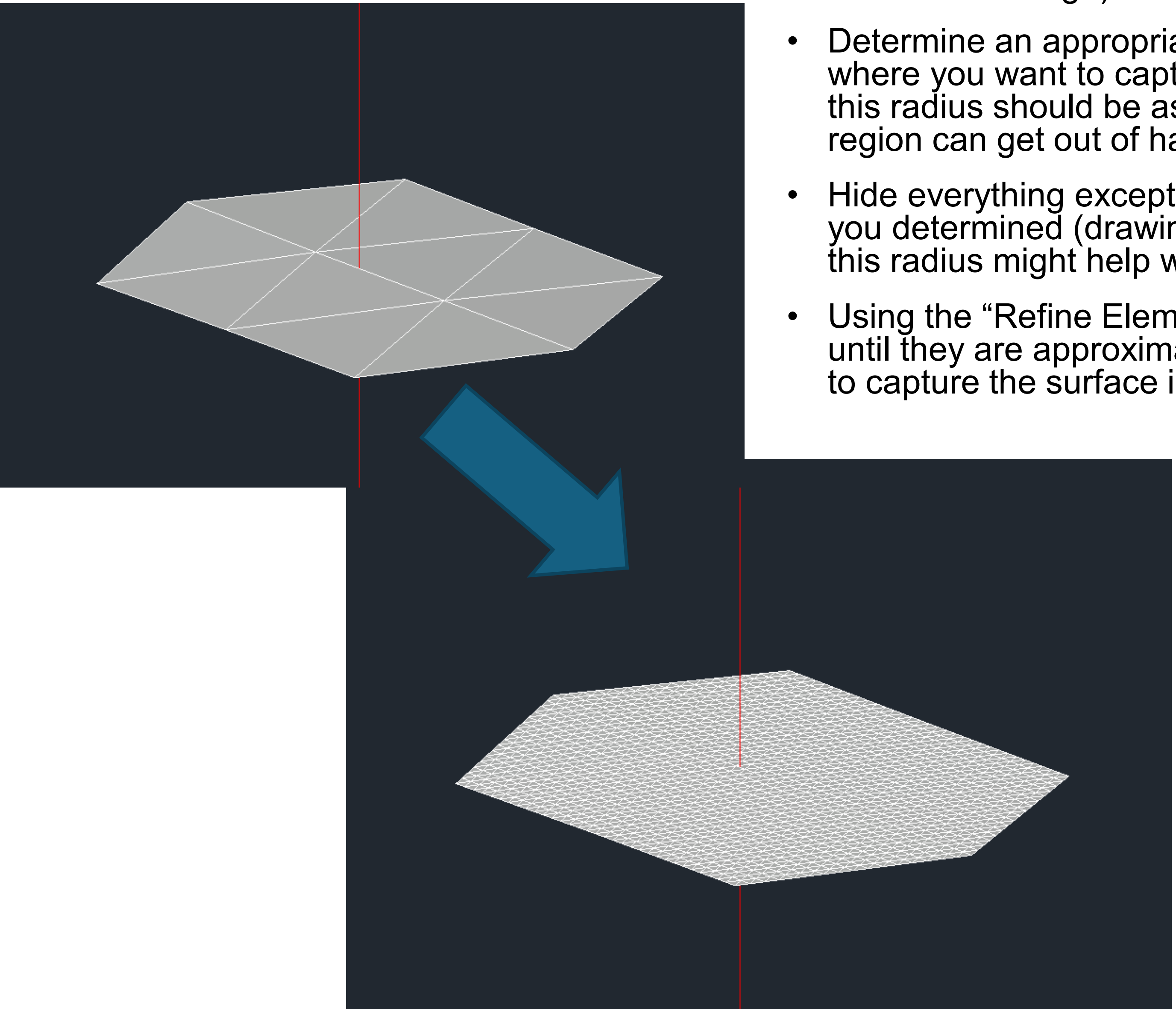
- Select the “Shaded Thermal PP” option from the upper toolbar to better view and select the mesh
- Select TD Node to turn off node visibility (the nodes slow down viewing significantly)
- Your model should look similar to the model shown below



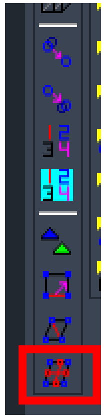




Center Mesh Refinement

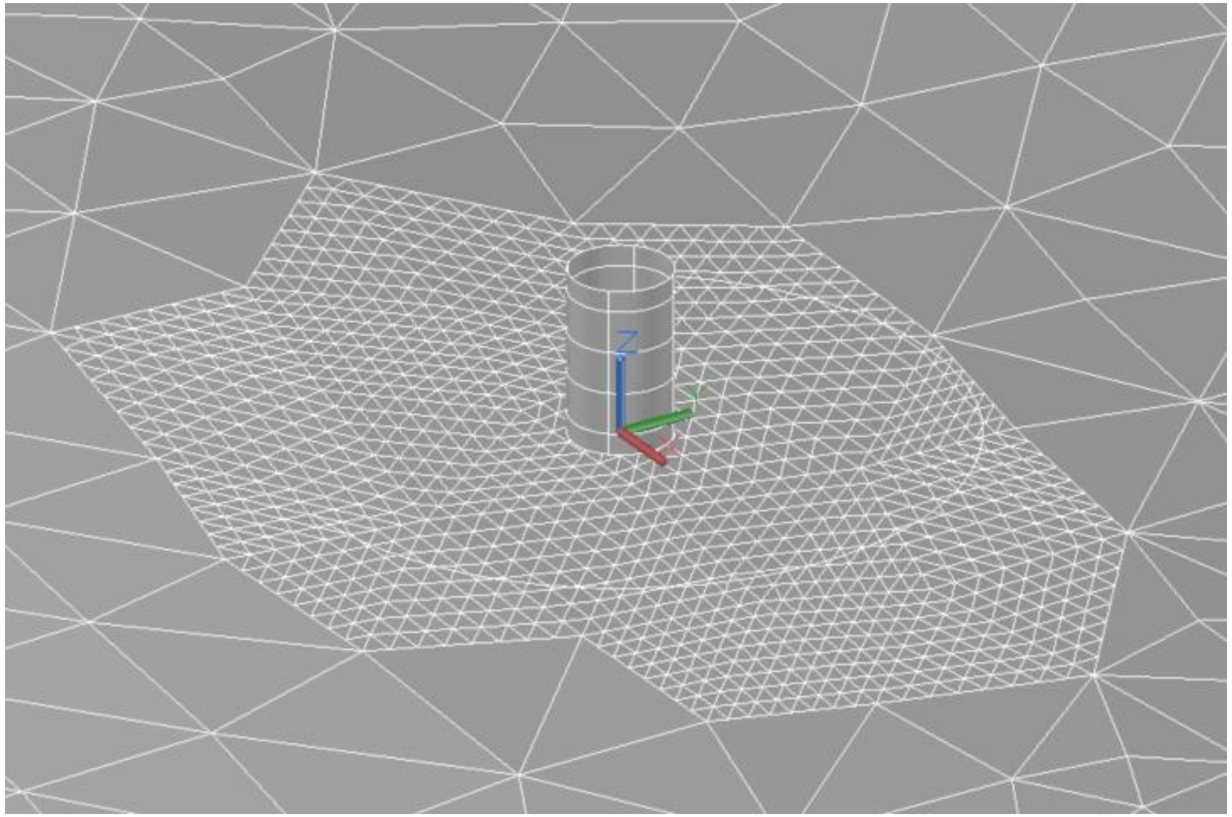


- Zoom into the origin of the world coordinate system (this is where your lunar asset will go)
- Determine an appropriate a “refinement radius” around your vehicle where you want to capture shadows and heat reflections better (NOTE: this radius should be as small as possible! The number of nodes in this region can get out of hand quickly)
- Hide everything except the mesh elements that are within the radius you determined (drawing an **AutoCAD** circle centered at the origin with this radius might help with his process)
- Using the “Refine Elements” tool, continue to divide these elements until they are approximately 1m on the sides (this is normally sufficient to capture the surface interactions of a small to mid-sized)



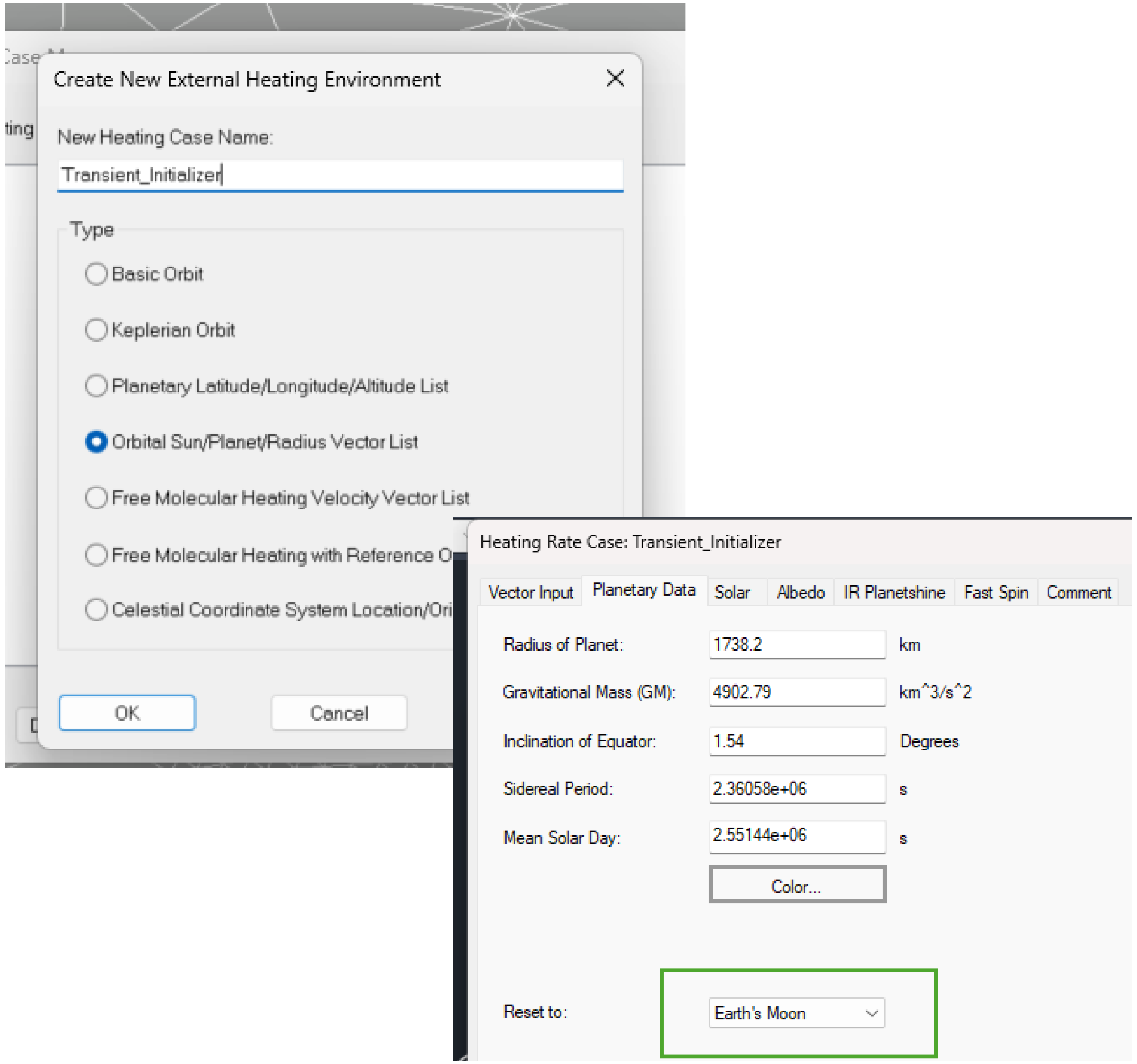
- **Once refinement is complete:**
  - **Edit the surfaces to have a new conduction submodel such as “LUNAR_NEAR_FIELD”**
  - **Using the Model Browser, select List By-> Surfaces/Solids, select Lunar_Near_Field, select “Display Only”**
  - **Select all the nodes, and edit the nodes to have a new submodel such as “LUNAR_NEAR_FIELD”**
  - **Merge the new nodes**
  - **Resequence the new nodes**

Lunar Asset Model



- Now a model of the lander can be copied into the model
- A simple cylinder is used for this example
- (Note: ensure that the **AutoCAD** units are the same between the two models before attempting to copy elements from one model to another)

Orbit Definition



- Create a new orbit in Thermal Desktop using the “Orbital Sun/Planet/Radius Vector List” orbit type

- **Refer to the “Solar Vector” and “Solar Flux and Subtended Angle” Sections in this manual for instructions on how to use JPL Horizons and MATLAB code to build vector list orbits in Thermal Desktop. The solar flux data is used to make the solar flux a function of time.**

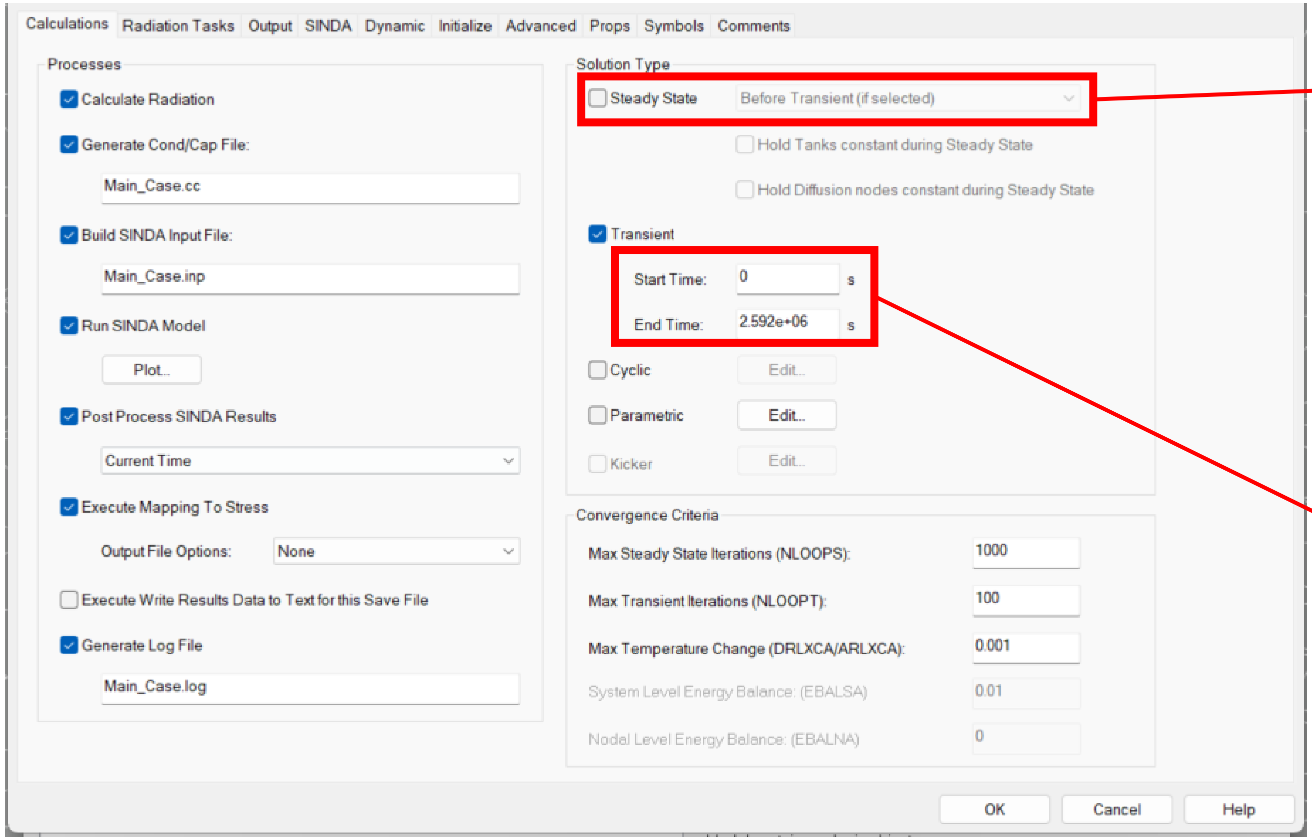
- You will be creating two orbits:
  1. Transient Initializer: A long multi-year transient case, the end of which will be used as the initial condition for the main case. This can use a very coarse time step (1 – 2 days is generally an acceptable range)
  2. Main Case: the single lunar day or surface stay that you’re interested in. This should use a much finer time step (1-6 hours is generally acceptable). Generally the more dynamic the shadow environment is expected to be, the finer the time step should be.

- Refer to the LTAG (section 9.2.4) to better understand how long to run the transient initializer. Anywhere from 1 to 20 years can a good amount of time to ensure the top layer of the regolith is converging to a consistent temperature.

- Select “Earth’s Moon” under planetary data

Case Set Details

Calculations



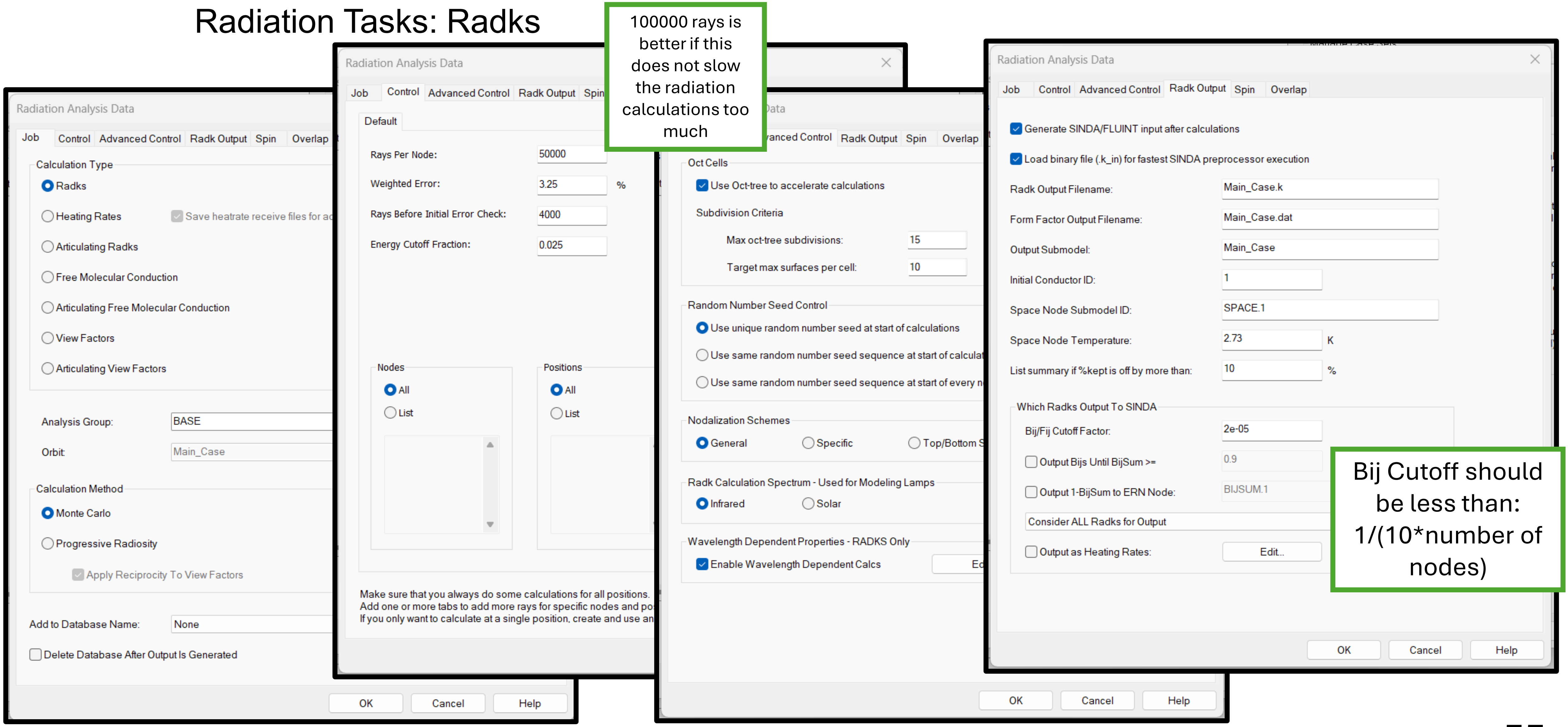
- For the transient initializer, consider turning on Steady State before Transient to likely reduce the number of years required for surface convergence
- For the main case, ensure this is off as this case should be initialized to the final time step of the transient initializer

- For both the transient initializer and the main case, ensure the start and stop times match the inputs of the vector list orbit

Case Set Details

The RADK calculation for both Case Sets are setup as shown below:

Radiation Tasks: Radks

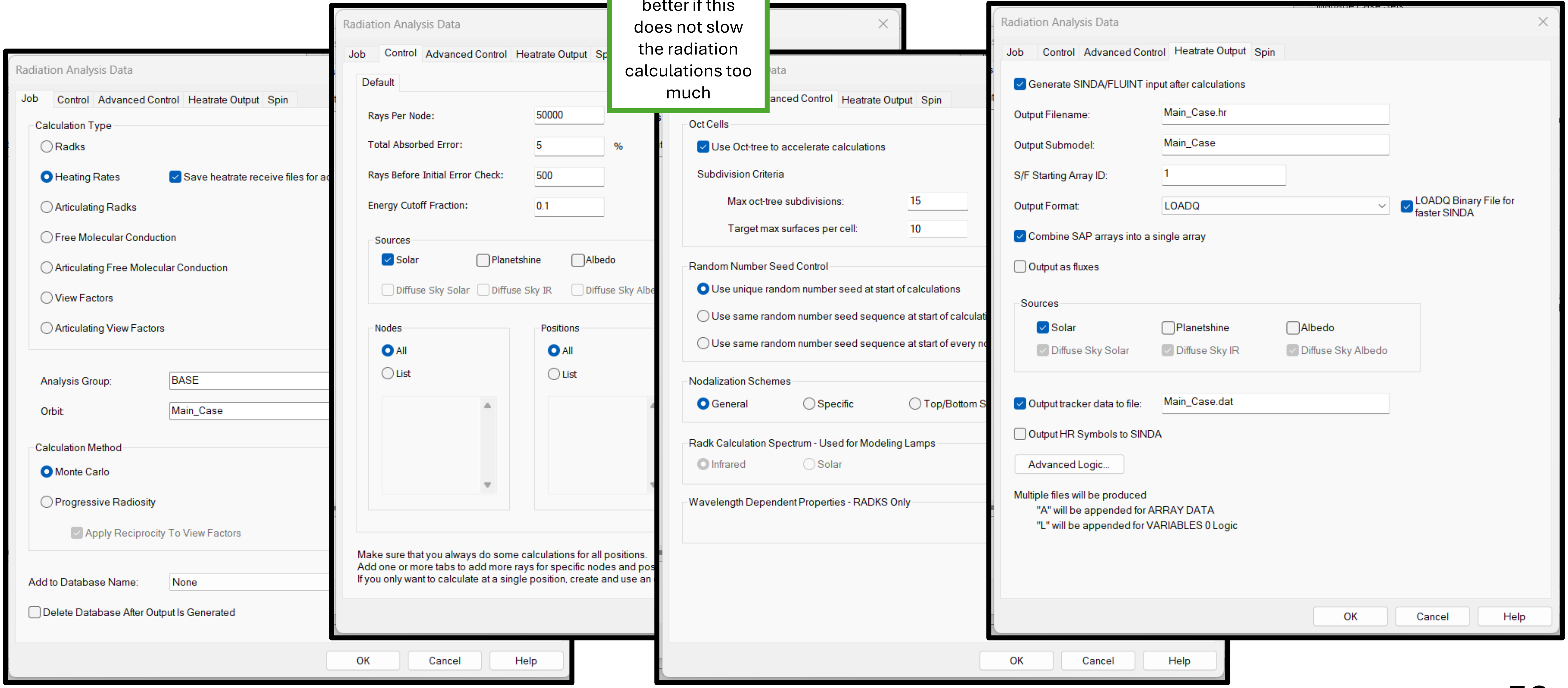


Case Set Details

The Heat Rate calculation for both Case Sets are setup as shown below:

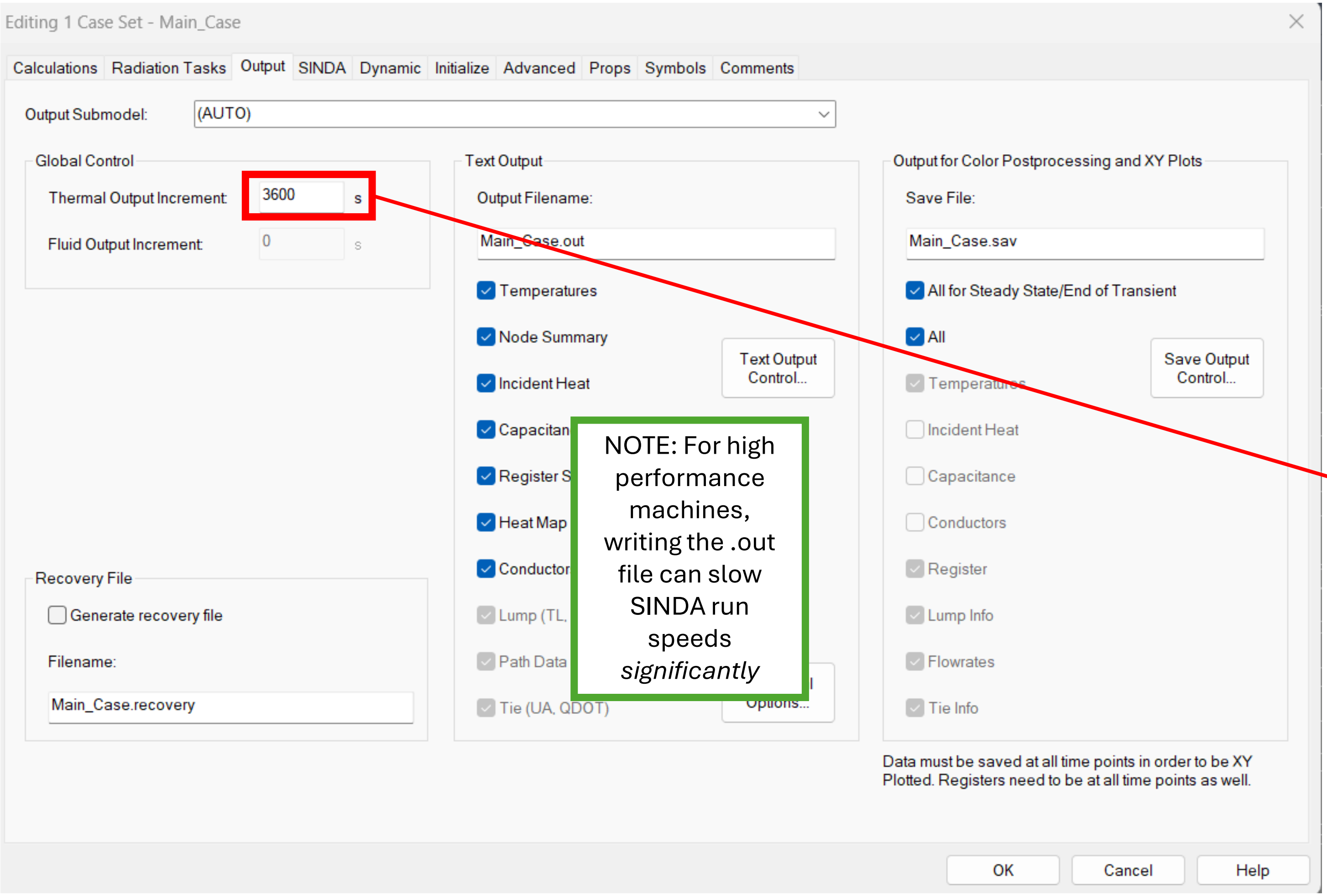
Radiation Tasks: Heat Rates

100000 rays is better if this does not slow the radiation calculations too much



Case Set Details

Output

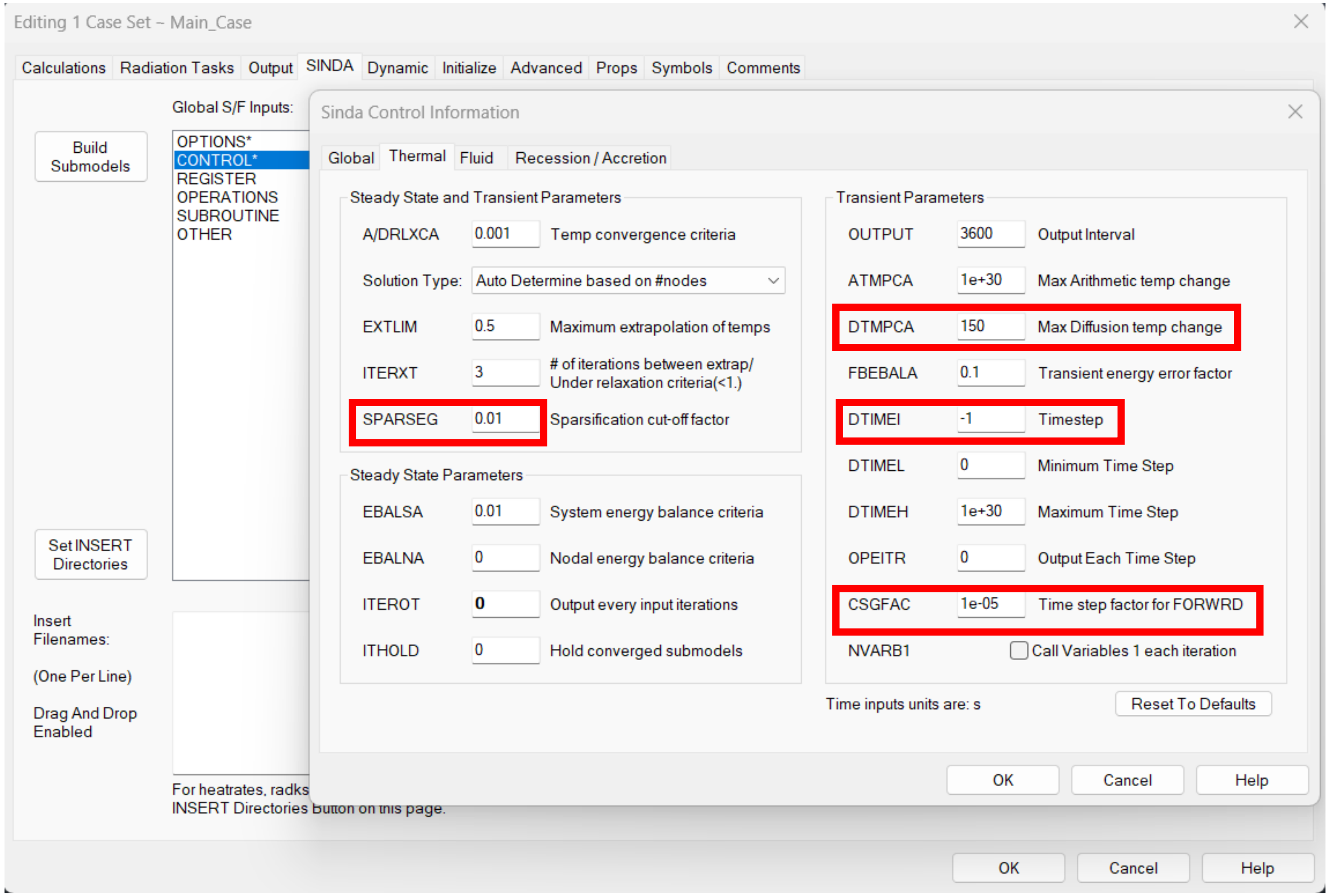


NOTE: For high performance machines, writing the .out file can slow SINDA run speeds *significantly*

- For both the transient initializer and the main case, ensure the output increment matches the time step used for the vector list orbit (or is at least larger than the vector list time step)

Case Set Details (OPTIONAL)

Sinda: Control-> Thermal

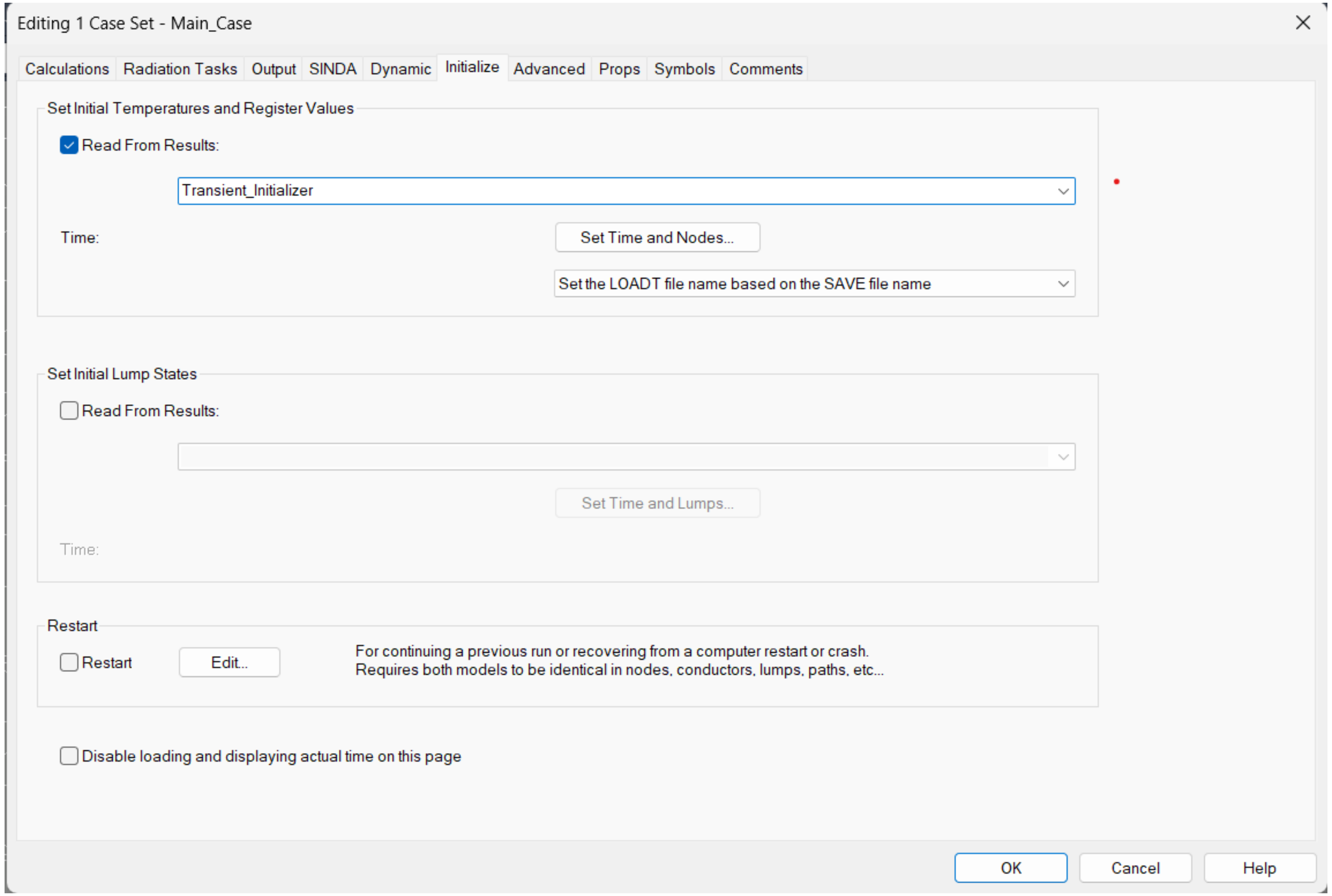


- Optionally, the SINDA thermal control parameters can be changed to improve speed.
- **These high-speed parameters should ONLY be used if the thermal model does not contain ANY heaters or logic objects**
- The red boxes to the left highlight the parameters that are changed from default settings to achieve higher speeds.

Credit to the Shawn Breeding MSFC, EV71 for recommending these settings and greatly improving terrain model speed

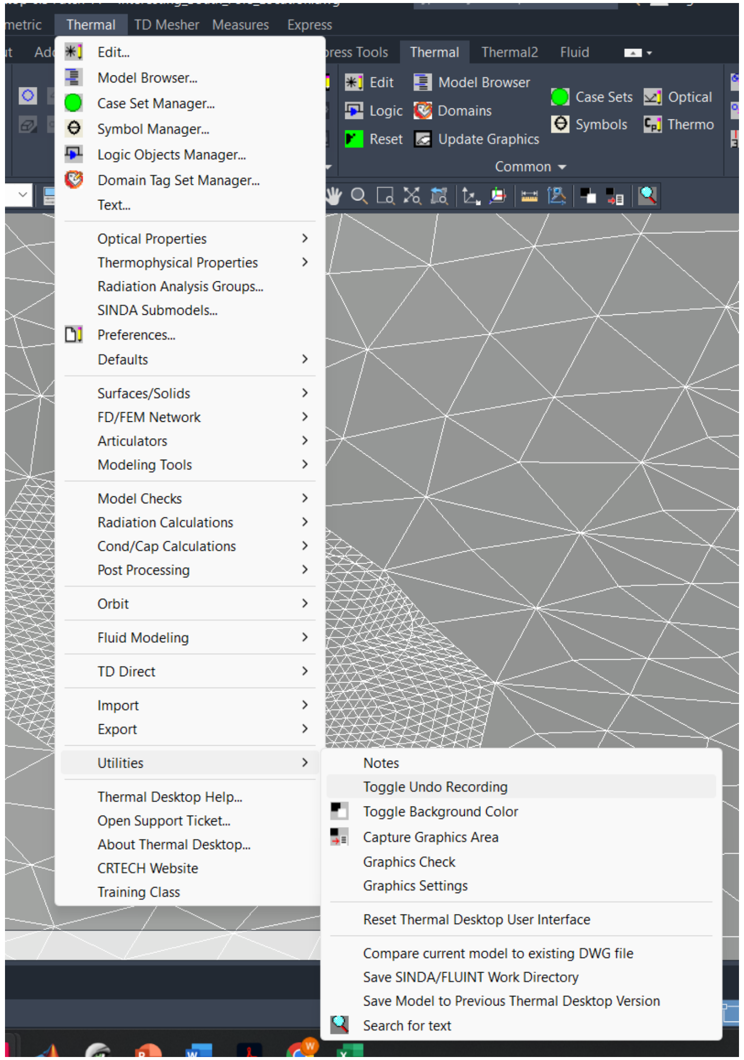
Case Set Details

Initialize



- The transient initializer should be run first and not be initialized to another save file
- The main case should be initialized to the final time step of the transient initializer

Memory

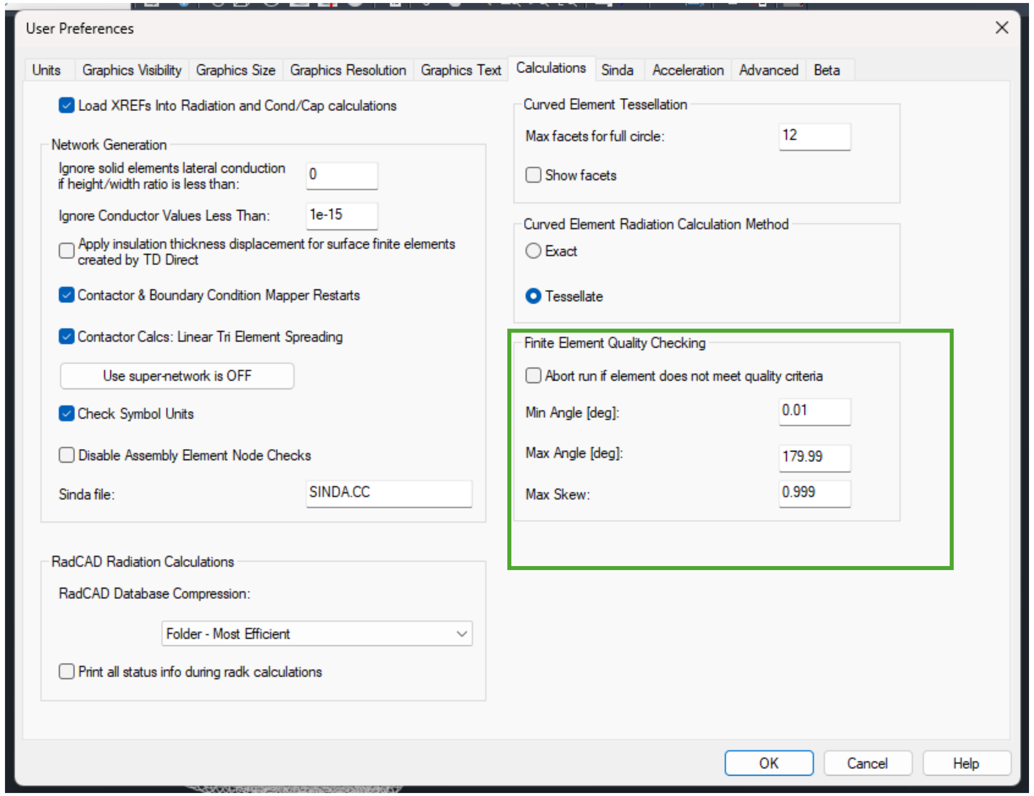


- A transient thermal model of this size run over so many time steps will take up a significant amount of memory. Ensure this model is run in a drive with 10’s of Gb prior to starting
- To help reduce the quantity of unneeded temporary data stored, navigate to:

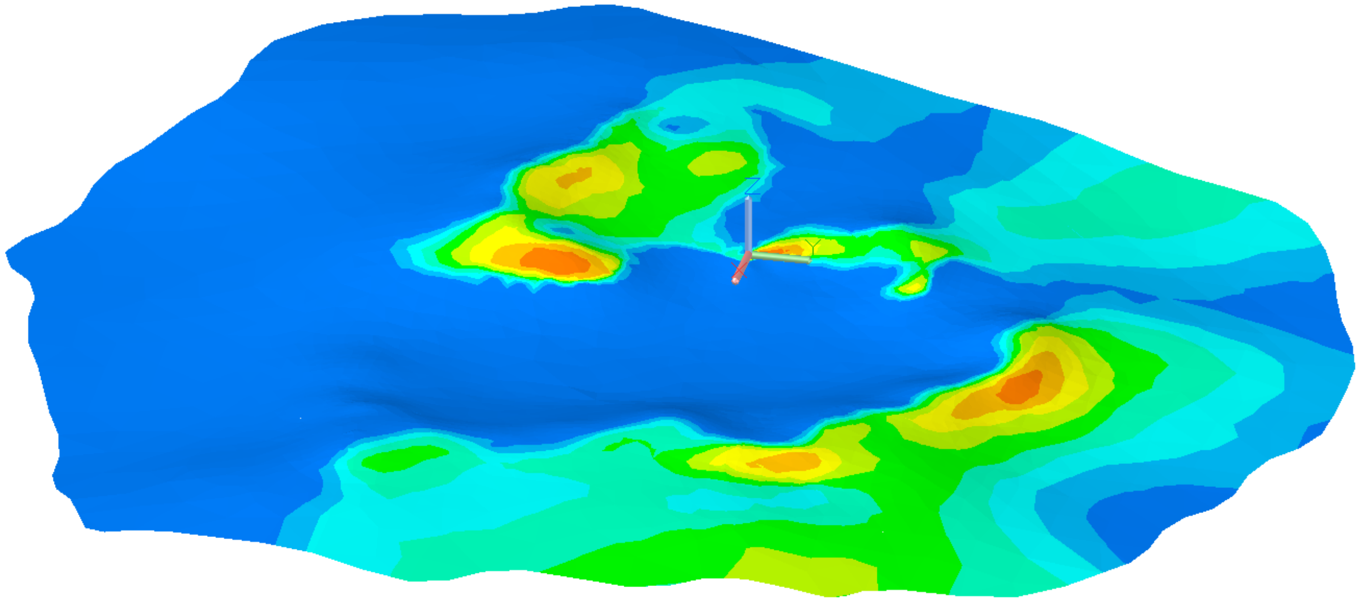
Thermal-> Utilities-> Toggle Undo Recording

Mesh Quality Check

- Sometimes, the mesh created by this process can result in elements that fail quality checks
- It is recommended that the model be run with default quality check settings
- However, if Thermal Desktop terminates a run due to elements that fail quality checks, you can investigate the mesh elements that failed the check. If these elements are far from and/or do not have a direct line of site to the central location, it is generally acceptable to ignore this problem and uncheck the “Abort run if element does not meet quality criteria” box under User Preferences -> Calculations



Run



- Run the transient initializer followed by the main case
- Inspect the final contour plots and post-process results