

Thermal Environment Modeling Practices for the Descent Trajectory of Lunar Landers

Alexander Szerszen

Jacobs Space Exploration Group, MSFC, ES22

ABSTRACT

With the current push to send landers back to the moon, properly modeling the thermal environment for the descent is critical. Descent in this paper is described as: descending from low lunar orbit to touch down on surface. There are several challenges during this period, including: many electronics (such as battery, avionics, transponder, etc...) have higher heat loads due to higher power levels, a significant portion of the view factor to space has been blocked out by the moon making heat rejection less efficient, components that normally do not have direct line of sight to the sun may get exposure due to the lander rotating to align for descent, and thruster firing will dump more heat into the lander. All of these factors combine during the most critical phase of a lander mission make it essential that the thermal environment has been properly set up during design and analysis. This paper presents one method of setting up the thermal environment during descent in Thermal Desktop and will also include some tips and tricks.

INTRODUCTION

This paper presents one method of modeling descent trajectories in the thermal modeling program Thermal Desktop. A full comprehensive discussion on descent modeling methods is not included. The descent is arguably the most critical point in any surface-landing mission and it is essential that every aspect be modeled accurately. Any small overlooked detail can mean disaster for a lander on final descent and the transient nature of descent makes modeling it all that more difficult.

During the course of a lander mission, the lander will experience different environmental phases such as launch, earth orbit, transit from earth to moon, moon orbit, descent, and surface operations. From phase to phase, certain components may have different heat loads or duty cycles depending on the nature of each phase. For example, during transit, the communications system might operate on a several hour duty cycle at a moderate power level whereas during descent, the communications system would likely operate for the entire descent at a high power level. The difference in these heat loads can sometimes be significant and, due to the critical nature of descent, it is important that the thermal modeler check all applied heat loads during descent and ensure that they are outputting at the proper level. The modeler must also make sure that all thrusters are running at the proper times during the descent and that the correct orientation is achieved during the simulation (a tip on how to check this will be discussed later).

EXTERNAL ENVIRONMENT SETTINGS

When modeling a thermal descent case in Thermal Desktop, there are several parameters that control and set the spatial time and location. For the current method, modeled after Astrobotic's descent trajectory, a terrestrial heating rate case was used. For the terrestrial case, the parameters specified were Right Ascension of the Sun, Right Ascension of the Prime Meridian, Earth's Moon's planetary data, and Ground IR. The Right Ascension of the Sun and the Right Ascension of the Prime Meridian are used to determine the position of the moon relative to the sun or the time of year and position of orbit. The Right Ascension of the Sun and Prime Meridian were determined using a moon-centered J2000 reference frame. Earth's moon's planetary data section contains inputs such as the body's radius, gravitational mass, inclination, sidereal period, and mean solar day and it can be either user defined or auto populated by Thermal Desktop for all planets in our solar system.

SIMULATION INITIALIZATION

When setting up the initial conditions for the descent case, it is important that one makes sure that either the results are initializing from a relevant case (usually an orbit case) or that there is enough simulation time before the descent starts to ensure that proper initial conditions have been reached. For the descent discussed here, modeled after Astrobotic's descent trajectory, the case was initialized from an orbit case and was initialized from an orbital average of 100 km. After the case ran, the results were then used as an initial condition for the surface simulation (not discussed here).

EFFECT OF DESCENT ON VIEW FACTORS

When starting the descent, the lander is designed to switch its attitude control from having the solar panels constantly facing the sun to having one section of the lander constantly facing the moon. This will significantly increase the radiative sink temperature for the section of the lander facing the moon that will house the ground sensors and possibly some telemetry components. If any of these components also increase the power usage during descent, they could possibly experience peak temperatures and they must be modeled accurately to ensure that all components remain within their prescribed temperature limits. An example of Astrobotic's lander's orientation from the perspective of the moon during descent can be seen below in Figure 1.

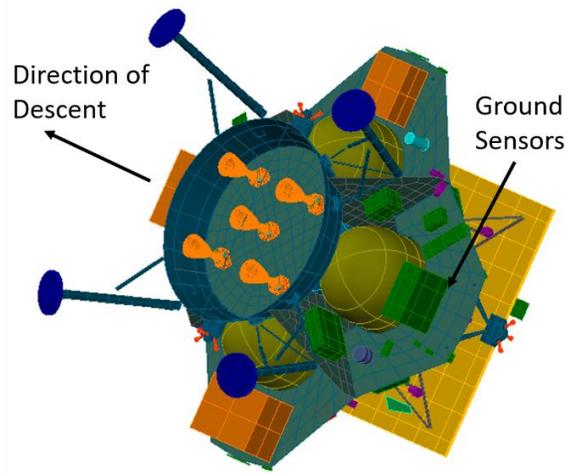


Figure 1. View of Astrobotic Lander from perspective of moon.

BUILDING A THERMAL DESKTOP MODEL: Defining Orbit

The Astrobotic descent case proved challenging to build primarily because, in Thermal Desktop (V6.0), there is no built in option to point the vehicle towards (or away from) the velocity vector for terrestrial heating rate cases². To get around this, time-dependent vehicle rotations had to be entered as symbols into Thermal Desktop. For this case, no velocity vectors or vehicle rotations were available to the author to orient the lander, only the latitude, longitude, and altitude versus time. As a result, custom MatLab code was written to determine the individual vehicle rotation per time step based on the change in latitude, longitude and altitude. The code works by taking the change in latitude, longitude and altitude per each time step and then determining the rotation in Cartesian coordinates necessary to keep the vehicle “perpendicular” to the moon. The method allows for any number of rotations of the lander to orient itself and it will always simplify back down to three base rotations as will be described later.

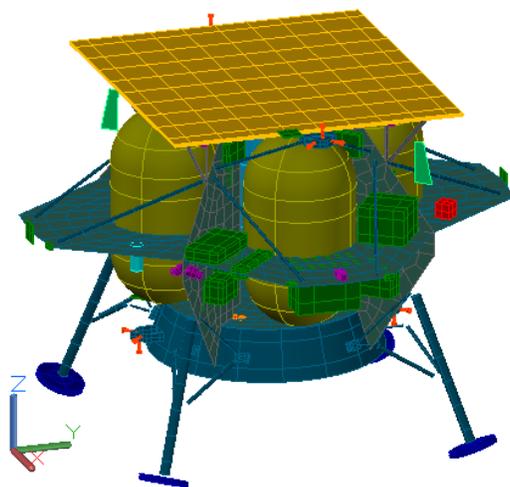


Figure 2. Astrobotic Lander in Thermal Desktop with coordinate system reference

When building a descent model (terrestrial heating rate case) in Thermal Desktop, the first step is to determine the right ascension of the sun (or declination) and the right ascension of the prime meridian (or right ascension). The declination is defined as the “angle from the equatorial plane, positive towards the north pole” while the right ascension is defined as “the angle measured in the equatorial plane from the Vernal Equinox. The angle is measured counter-clockwise using the right-hand rule about the north pole of the planet.” Both terms are input in degrees and with these; the location of the sun relative to the moon is defined.

For the current example, moon centered Cartesian coordinates of the sun were given to the author from the navigation team. With the coordinates of the sun with respect to the moon, it is a simple trigonometry problem to calculate the declination and right ascension.

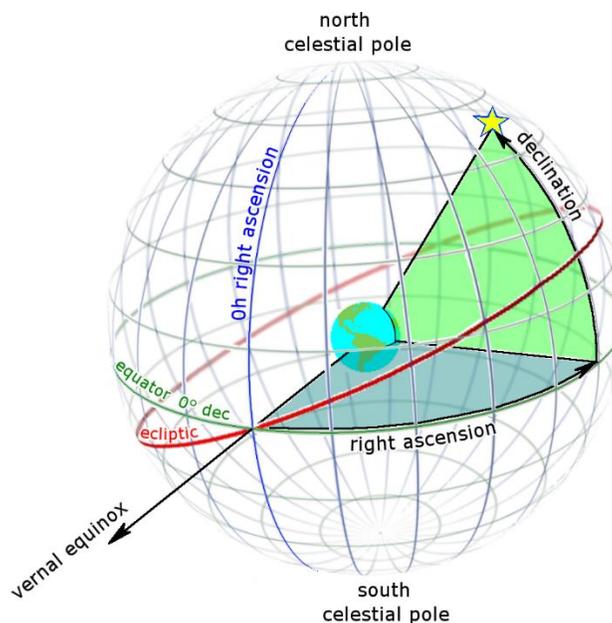


Figure 3. Image of Declination and Right Ascension⁴

The next step is to ensure the format of the latitude, longitude, and altitude data is in the proper format. The lander descent data was given in terms of radians in a spherical coordinate system. To be compatible with Thermal Desktop, the data was converted into degrees.

The first and most important area of the descent heating rate case is accounted for with the right ascension, declination, and latitude, longitude and altitude versus time. Figure 4 presents an example of the Thermal Desktop interface for the terrestrial heating rate case and can be seen below with the primary inputs that shape the descent.

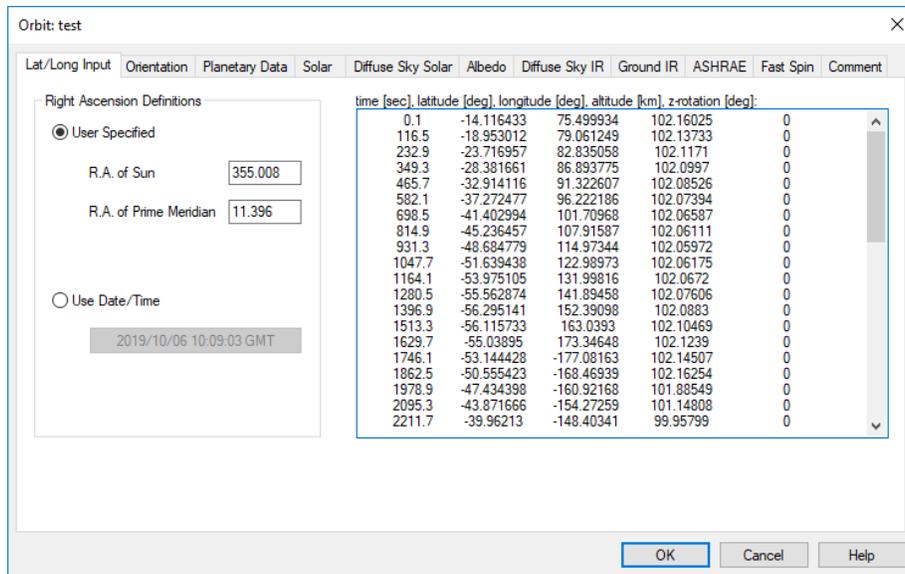


Figure 4. Image of Thermal Desktop orbit interface

With the above data entered, an orbit similar to the one displayed on the left of Figure 5 below can be obtained. The latitude, longitude and altitude of the lander versus time will now be correctly simulated but the orientation of the lander is not taken into account yet. For the two images below in Figure 5, the sequence of coordinate systems around the moon represent each time step in the descent and the orientation of the coordinate systems corresponds to the lander's orientation and coordinate system in Figure 2.

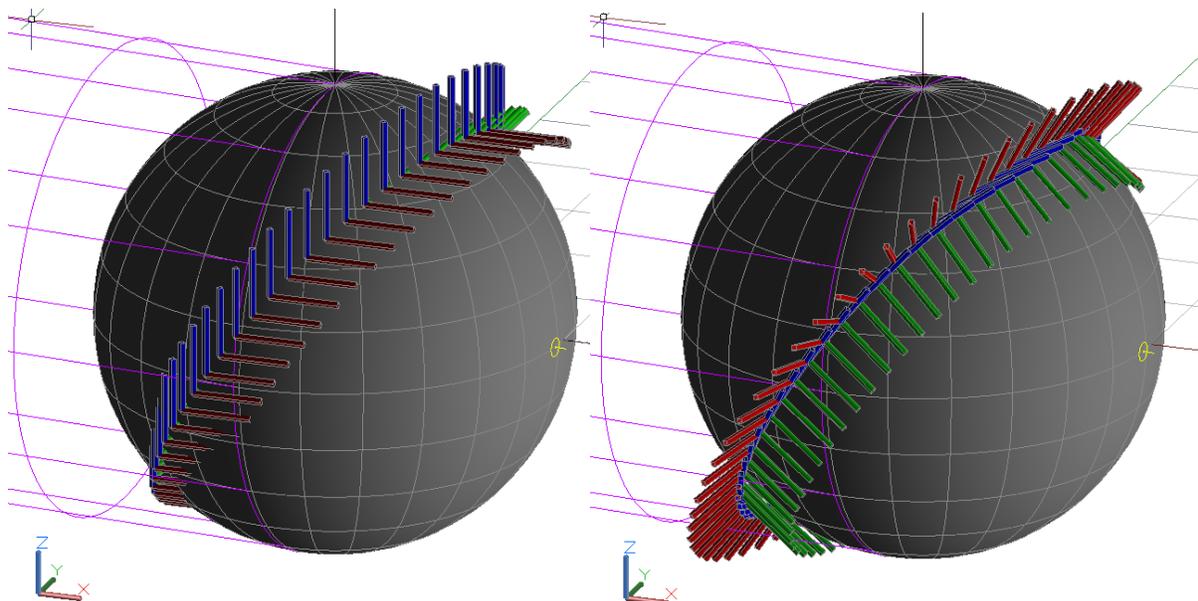


Figure 5. Images of lander orientation during descent.

BUILDING A THERMAL DESKTOP MODEL: Defining Orientation

For the case of the Astrobotic descent, the bottom of the lander faces the velocity vector with a 45 degree cant towards the surface so that the landing sensors have their required view of the surface in order to track altitude, an example of this orientation can be seen in Figure 1. For the model, the +Z-axis extends through the top of the lander and the +X-axis extends out the center of the avionics deck.

To ensure this orientation, several rotations per time step are required and only three additional rotations are allowed in Thermal Desktop currently. The first two rotations can be taken directly from the latitude and longitude. If the lander is then rotated along the Z-axis by the lander's longitude plus the value of the right ascension at each time step, the X-axis will point through the moon's Z-axis. The right ascension angle is added into the Z-axis rotation because the right ascension defines the subsolar longitude in Thermal Desktop. If the lander is then rotated along its Y-axis by the lander's latitude at each time step, the lander's X-axis will always point through the center of the moon instead of just through the moon's Z-axis. At this point the rotation about the X-axis is needed to ensure that the Z-axis points along the velocity vector. To do this, the difference in latitude and longitude between two time steps is taken and used to calculate the angle of decline (or incline) between the two points. Figure 6 below shows how this can be done.

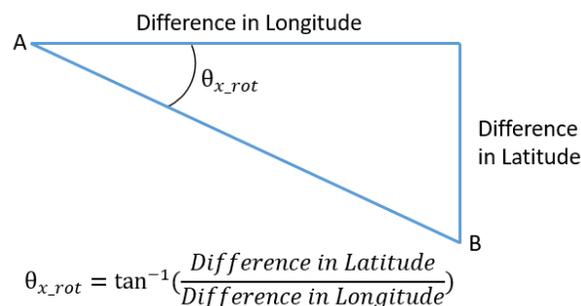


Figure 6. Depiction of how the X-axis rotation was determined

The difference in degrees between latitude and longitude is being used here as a length and the actual distances can be calculated with the known radius and altitude but those additional calculations are unnecessary. When looking at the lander points normal to the moon, the altitude and curvature of the descent become irrelevant so that just the angle of decline (or incline) between points is pertinent.

If just a trajectory like the one seen on the right of Figure 5 is desired, then no further calculations are required. However, if additional rotations are required as is the case with the Astrobotic lander's descent, then rotation matrices must be employed to account for additional rotations in order to input the data into Thermal Desktop. A rotation matrix is a matrix that is used to perform a rotation in Euclidean space. Rotation matrices are needed to simplify any extra rotations down to three base rotations.

$$R_x(\theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \theta & -\sin \theta \\ 0 & \sin \theta & \cos \theta \end{bmatrix}$$

$$R_y(\theta) = \begin{bmatrix} \cos \theta & 0 & -\sin \theta \\ 0 & 1 & 0 \\ \sin \theta & 0 & \cos \theta \end{bmatrix}$$

$$R_z(\theta) = \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Figure 7. Rotation matrices about the three axes

From the example seen on the right of Figure 5, it can be seen that the orientation needed by Astrobotic is not yet achieved. The +Z-axis (blue arrow) is pointing along the velocity vector when it should be pointing away from the velocity vector and the +X-axis (red arrow) is pointing away from the moon when it should be pointing towards the planet with a 45 degree cant away from the velocity vector.

To employ these additional rotations, one starts with an identity matrix then multiplies it by the rotation matrix for each axes being rotated about. Equation 1 below shows what was employed for the Astrobotic descent case.

$$R(i) = I_3 * R_z(Longitude(i)) * R_y(Latitude(i)) * R_x(\theta_{x_{rot}}(i)) * R_y(135^\circ) \quad (1)$$

To simply any number of additional rotations down to three rotations, take the final matrix obtained and equate it to a rotation matrix using three base rotations as is shown below in Equation 2.

$$R = R_z(\phi)R_y(\theta)R_x(\psi)$$

$$= \begin{bmatrix} \cos\theta \cos\phi & \sin\psi \sin\theta \cos\phi - \cos\psi \sin\phi & \cos\psi \sin\theta \cos\phi + \sin\psi \sin\phi \\ \cos\theta \sin\phi & \sin\psi \sin\theta \sin\phi + \cos\psi \cos\phi & \cos\psi \sin\theta \sin\phi - \sin\psi \cos\phi \\ -\sin\theta & \sin\psi \cos\theta & \cos\psi \cos\theta \end{bmatrix} \quad (2)$$

With the matrix above, it can be seen that solving for theta (θ) is simple whereas both phi (ϕ) and psi (ψ) have two solutions. To solve for phi and psi, one needs to use 2-argument arctangent as shown in the Equations 4 and 5.

$$\theta = \text{asin}(-r_{31}) \quad (3)$$

$$\psi = \text{atan2}(r_{32}, r_{33}) \quad (4)$$

$$\phi = \text{atan2}(r_{21}, r_{11}) \quad (5)$$

The conditions regarding how to use 2-argument arctangent are shown below in Figure 8. Once this is done, theta, psi, and phi can be obtained for each time step. This can be done by hand but MatLab also has 2-argument arctangent built into the software.

$$\text{atan2}(y, x) = \begin{cases} \arctan\left(\frac{y}{x}\right) & \text{if } x > 0, \\ \arctan\left(\frac{y}{x}\right) + \pi & \text{if } x < 0 \text{ and } y \geq 0, \\ \arctan\left(\frac{y}{x}\right) - \pi & \text{if } x < 0 \text{ and } y < 0, \\ +\frac{\pi}{2} & \text{if } x = 0 \text{ and } y > 0, \\ -\frac{\pi}{2} & \text{if } x = 0 \text{ and } y < 0, \\ \text{undefined} & \text{if } x = 0 \text{ and } y = 0. \end{cases}$$

Figure 8. Expression for 2-argument arctangent in terms of standard arctangent function.

With the base three rotations per time step solved for, one can then move back to Thermal Desktop and finish creating the heating rate case. To do this, create symbol arrays for time, theta, psi, and phi in the symbol manager, select the option “Align to Celestial Coordinate System” on the orientation tab for the terrestrial heating rate case, select the order of the additional rotations and finally use the “interp” function as an expression for each of the three additional rotations. Figure 9 gives an example of how this is done in Thermal Desktop.

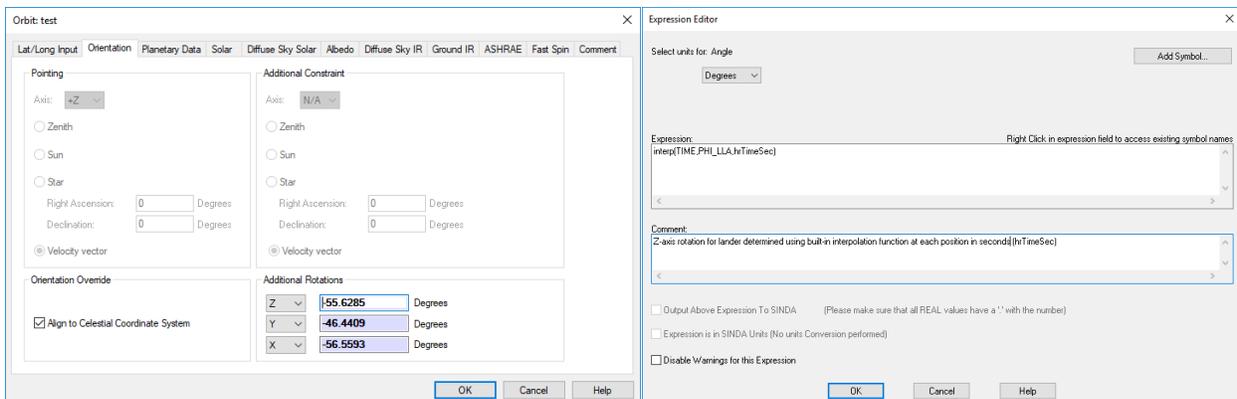


Figure 9. Images of Thermal Desktop orbit interface showing

With all this done, one can then obtain an orbit similar to the one shown in Figure 9. This orbital view is a good way to check that the lander rotations have been calculated and entered correctly. Another way to check the lander’s orientation during descent is to view the lander from the perspective of the moon in Thermal Desktop for each time step of the descent as

shown in Figure 1. Both methods should be checked to ensure that the lander is properly oriented for the entire descent.

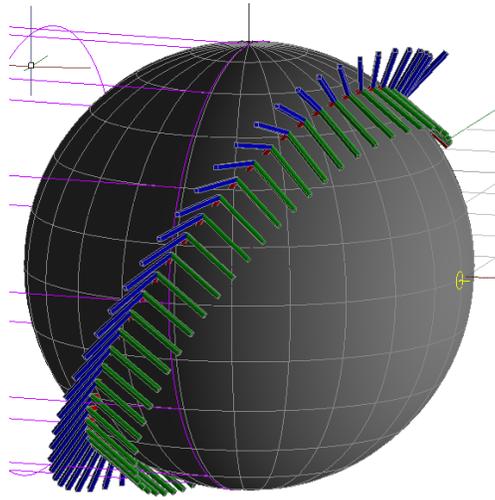


Figure 9. Image of final lander orientation during descent.

CONCLUSIONS

Modeling the thermal environment for a lander descent correctly is essential for a successful mission. This can be difficult due to the transient nature of a descent and the addition of new thermal conditions such as component heat loads, changing view factors/radiative sink temperatures, and thruster/plume heat loads. The method shown above is just one way to model the descent environment of a lunar lander but it is the best way the author has found and is easily modified if changes to the descent trajectory are made.

ACKNOWLEDGEMENTS

The author would like to acknowledge Stephanie Mauro and Brian O'Connor for their assistance and guidance in working in Thermal Desktop and helping to develop and check the descent heating rate case. The author would also like to acknowledge Astrobotic and their team for their counseling and guidance while working on the thermal analysis, specifically Jeff Hopkins for his tireless support and direction.

CONTACT

Alexander Szerszen works as a thermal analyst for Jacobs Space Exploration Group at Marshall Space Flight Center on the ESSCA contract. He has been helping perform thermal analysis on the Astrobotic Peregrine lunar lander since March 2018. He received his Master's in Engineering from North Carolina State University in 2017. He can be contacted at alexander.d.szerszen@nasa.gov and 256-961-3140.

References

1. Mauro, S. (2019). Challenges of Designing a Passive Thermal Control System for the Astrobotic Peregrine Lunar Lander.
2. *Modeling Vehicle with +Z pointing in direction of travel.* (2019, 07 23). Retrieved from CRTech User Forum:
<https://crttech.com/forum/viewtopic.php?f=2&t=405&sid=4722431850c879592137630c7a2b00ed>
3. Panczak, T. D., Ring, S. G., Welch, M. J., Johnson, D., Cullimore, B. A., & Bell, D. P. (2017). *Thermal Desktop User's Manual Version 6.0.* Boulder: C&R Technologies.
4. *Ra and dec on celestial sphere.* (2019, July 23). Retrieved from Wikimedia Commons:
<https://commons.wikimedia.org/w/index.php?curid=19907447>