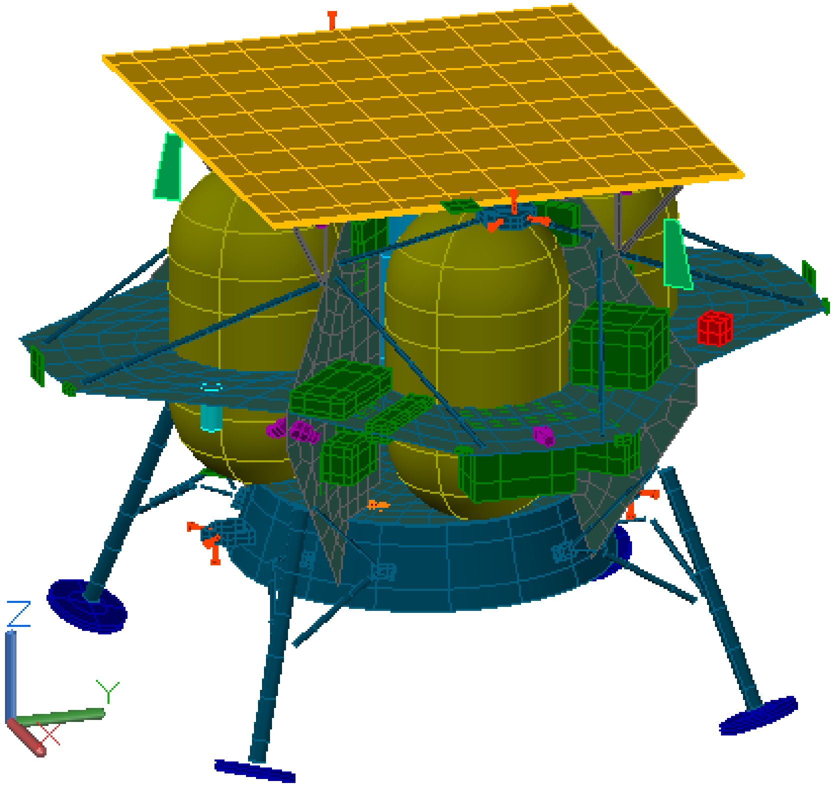
Thermal Environment Modeling Practices for the Descent Trajectory of Lunar Landers

Alex Szerszen, Jacobs MSFC ES22

08-26-2019

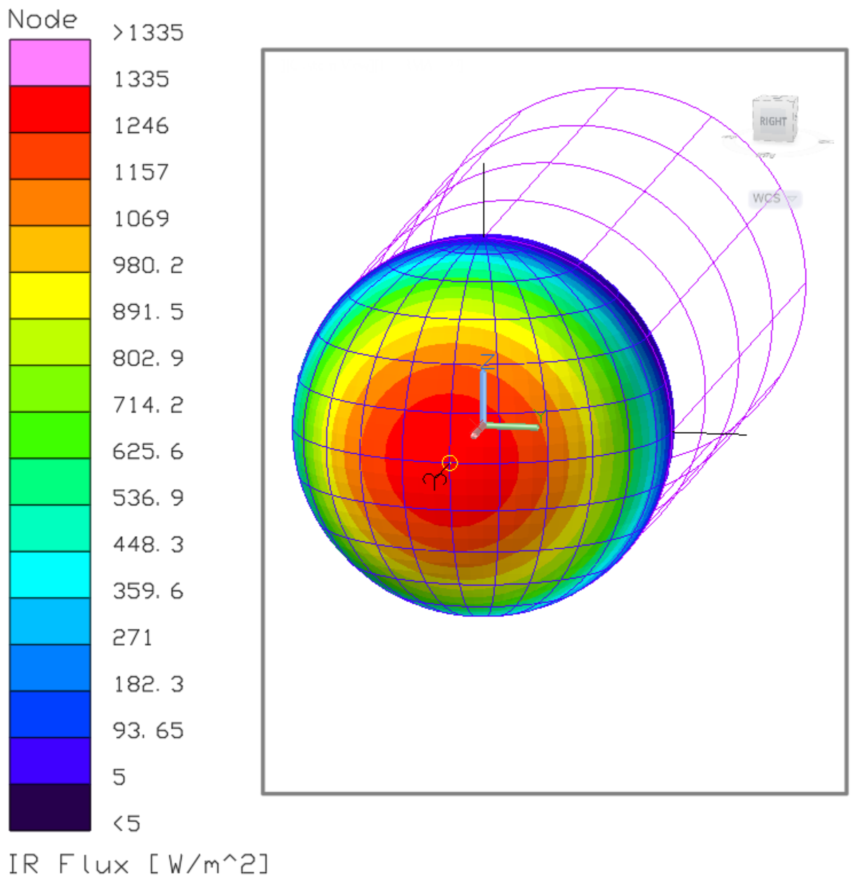
Introduction

- This presentation will discuss only one method of modeling the thermal environment for descent trajectories in Thermal Desktop.
- The descent in arguably the most critical point in any lander mission
- The descent phase presents a unique thermal environment compared to the rest of the mission (launch, earth orbit, transit, moon orbit, descent, surface operation)
    - View factor to space decreases
    - Main thruster firing and plume add additional heat
    - All electrical components operating at max power level.
- Heat loads must be modeled properly to ensure that the lander doesn't fail catastrophically



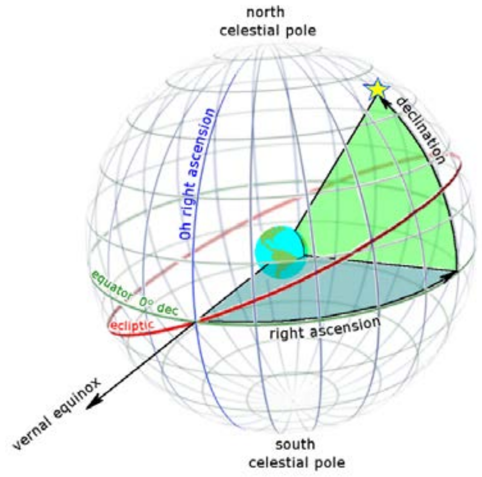
Defining Thermal Environment

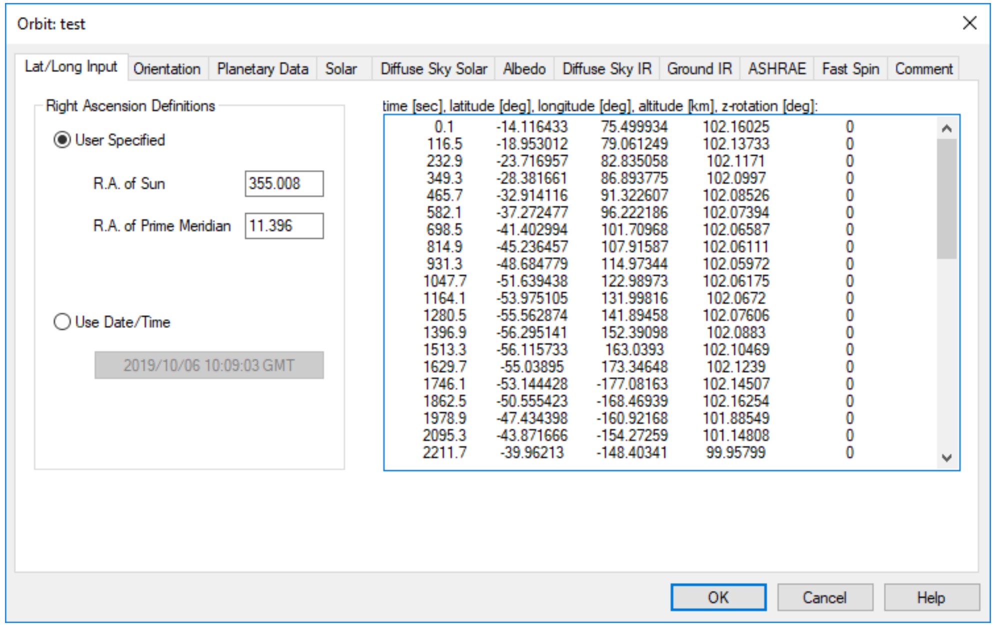
- There are several parameters that control and set the spatial time and location of the moon.
  - Right Ascension of the Sun
  - Right Ascension of the Prime Meridian
  - Earth's Moon's planetary data
    - Radius, gravitational mass, inclination, sidereal period, and mean solar day
  - Ground IR (seen to right)
- Moon-centered J2000 reference frame



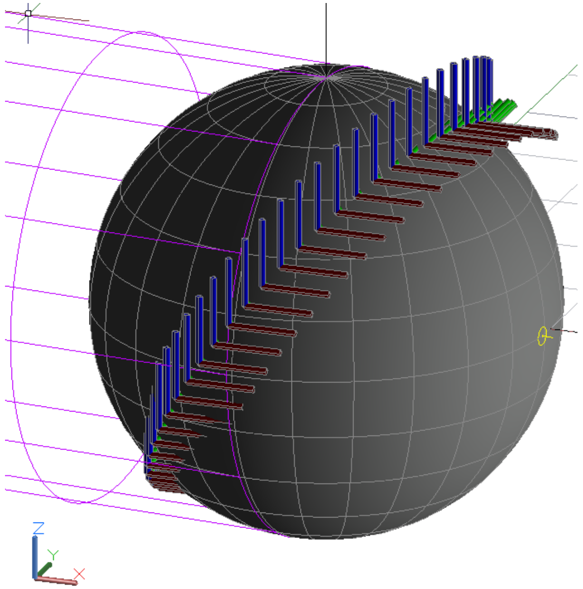
Building Thermal Desktop Model

- Terrestrial heating rate case used
- Right Ascension of sun and right ascension of prime meridian are the first inputs needed
  - Determined using moon-centered coordinates of sun in Cartesian
- Latitude, longitude and altitude versus time control the location of the lander for each time step



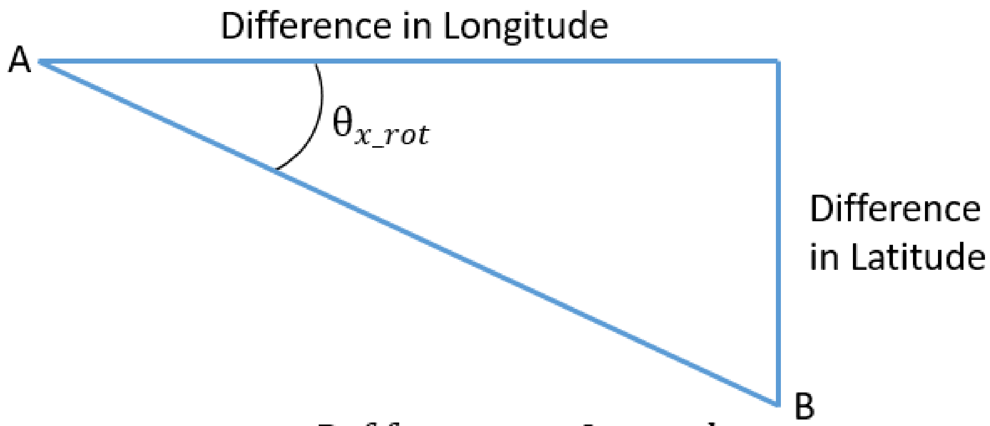


0.1	-14.116433	75.499934	102.16025	0
116.5	-18.953012	79.061249	102.13733	0
232.9	-23.716957	82.835058	102.1171	0
349.3	-28.381661	86.893775	102.0997	0
465.7	-32.914116	91.322607	102.08526	0
582.1	-37.272477	96.222186	102.07394	0
698.5	-41.402994	101.70968	102.06587	0
814.9	-45.236457	107.91587	102.06111	0
931.3	-48.684779	114.97344	102.05972	0
1047.7	-51.639438	122.98973	102.06175	0
1164.1	-53.975105	131.99816	102.0672	0
1280.5	-55.562874	141.89458	102.07606	0
1396.9	-56.295141	152.39098	102.0883	0
1513.3	-56.115733	163.0393	102.10469	0
1629.7	-55.03895	173.34648	102.1239	0
1746.1	-53.144428	-177.08163	102.14507	0
1862.5	-50.555423	-168.46939	102.16254	0
1978.9	-47.434398	-160.92168	101.88549	0
2095.3	-43.871666	-154.27259	101.14808	0
2211.7	-39.96213	-148.40341	99.95799	0

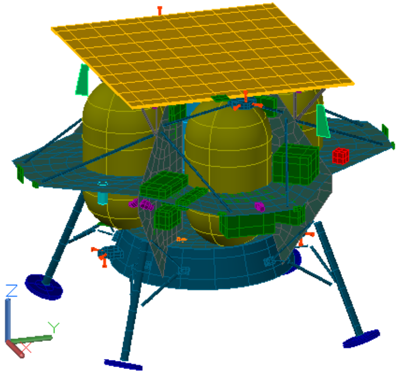


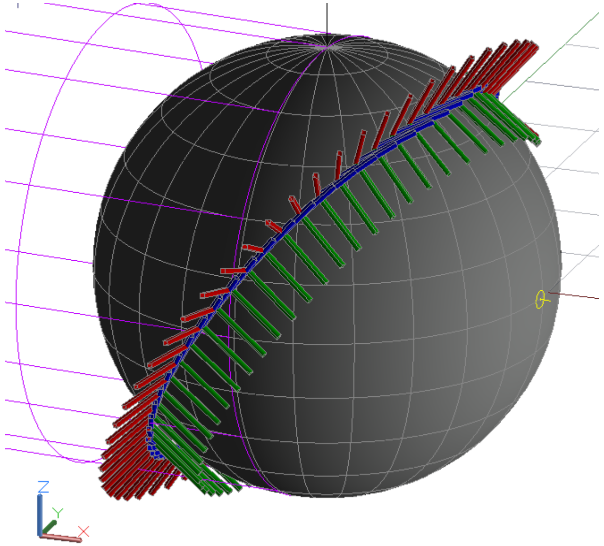
Building Thermal Desktop Model

- Rotate along Z-axis by longitude plus value of R.A. of the prime meridian
  - Result: X-axis of lander points through Z-axis of moon
- Rotate along Y-axis by value of latitude
  - Result: X-axis of lander points through center of moon
- Rotate along X-axis by the inverse tangent of change in latitude over change in longitude.
  - Result: Z-axis of lander points along velocity vector



$$\theta_{x\_rot} = \tan^{-1}\left(\frac{Difference\ in\ Latitude}{Difference\ in\ Longitude}\right)$$





Additional Rotations Required

- If more than 3 rotations are desired, then the use of rotation matrices is required.
- Rotation matrices allow the conversion of any number of rotations down to 3 base rotations.
- To do this you:
  - Rotate lander by any number of rotations at each time step
  - Obtain a 3X3 matrix for each time step
  - Equate the 3X3 matrix at each time step to the base rotation matrix seen below

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

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

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

$$R(i) = I_3 * R_z\big(Longitude(i)\big) * R_y\big(Latitude(i)\big) * R_x\left(\theta_{x_{rot}}(i)\right) * R_y\left(135°\right)$$

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

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

2-Argument Arctangent

- Equate the final matrix at each time step to the base rotation matrix below and solve for theta (θ), phi (ϕ), and psi (ψ)
- 2 solutions for both phi and psi
  - Must use 2-argument arctangent

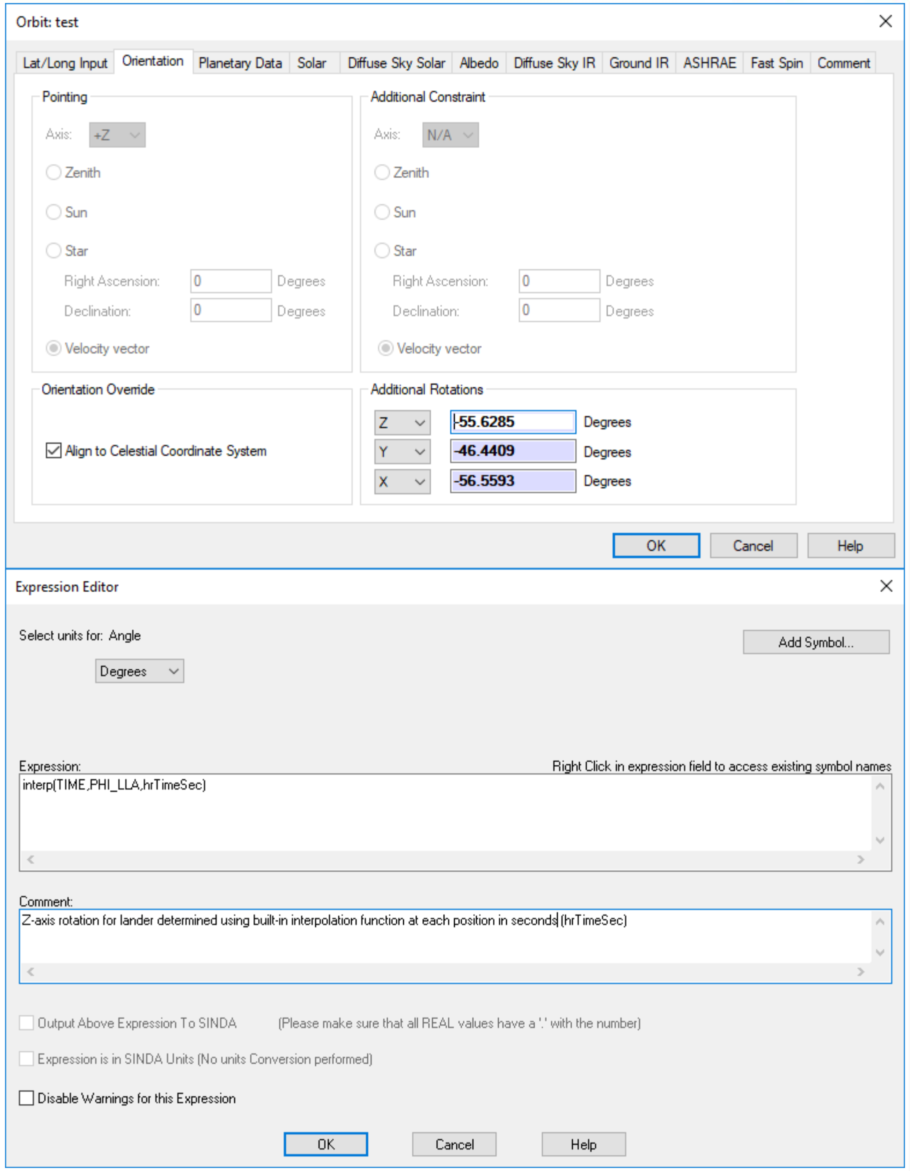
$$\theta = asin(-r_{31})$$
$$\phi = atan2(r_{21}, r_{11})$$
$$\psi = atan2(r_{32}, r_{33})$$

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

$$R = R_z(\phi) * R_y(\theta) * R_x(\psi)$$
$$= \begin{bmatrix} cos\theta\ cos\phi & sin\psi\ sin\theta\ cos\phi - cos\psi\ sin\phi & cos\psi\ sin\theta\ cos\phi + sin\psi\ sin\phi \\ cos\theta\ sin\phi & sin\psi\ sin\theta\ sin\phi + cos\psi\ cos\phi & cos\psi\ sin\theta\ sin\phi - sin\psi\ cos\phi \\ -sin\theta & sin\psi\ cos\theta & cos\psi\ cos\theta \end{bmatrix}$$

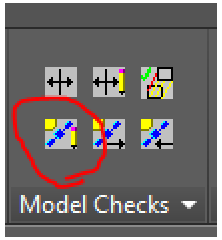
Building Thermal Desktop Model

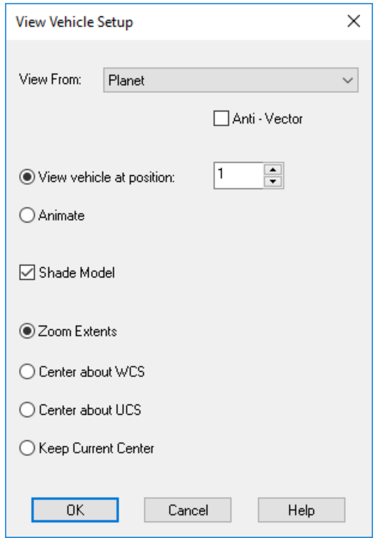
- Add in the additional rotations on the orientation tab for terrestrial heating rate cases
- Select “align to celestial coordinate system”
- Create array symbols for theta, phi, and psi in the symbol manager
- Interpolate between time steps of heating rate case

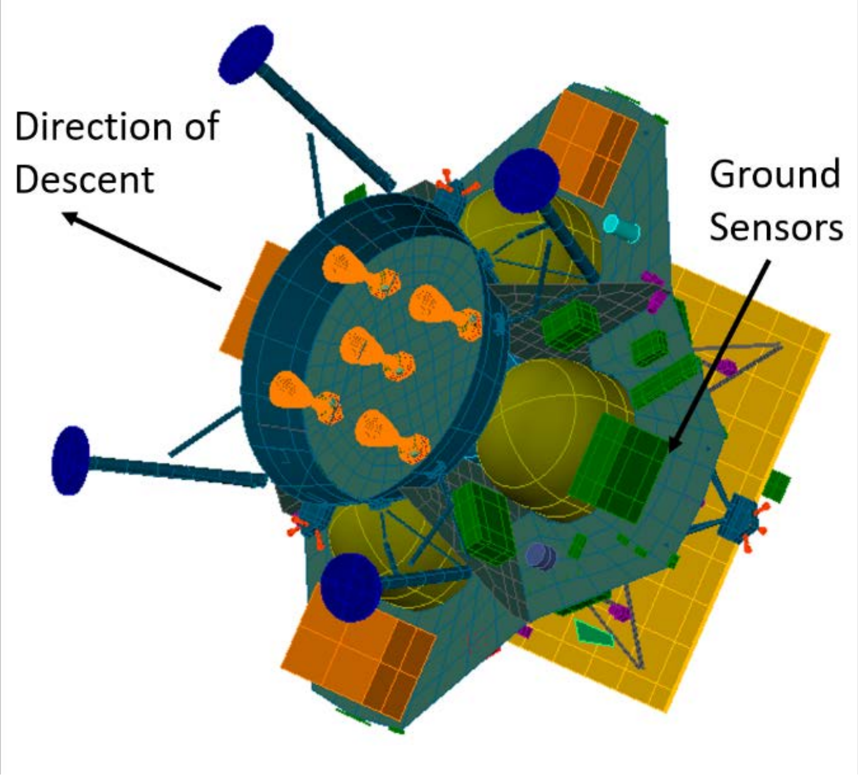


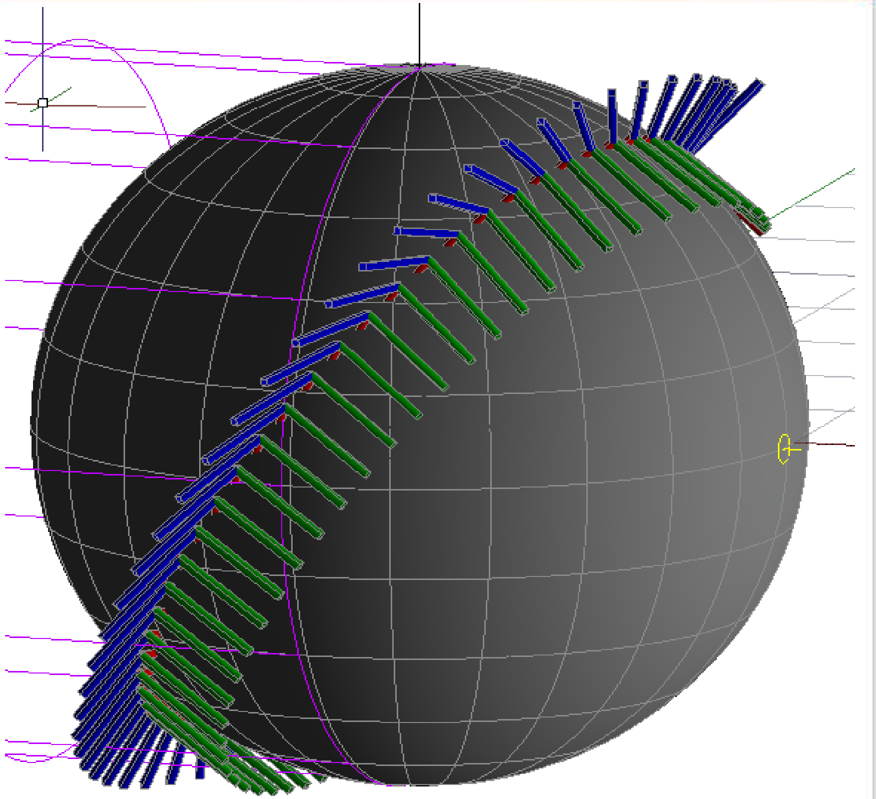
Quality Checks

- Two methods to check that the lander is properly oriented at each time step
  - Display the orbit in the heating rate case manager
  - View the lander from the planet









Conclusion

- 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 one way to obtain the desired results but is very versatile and easy to use if more detailed rotations are required.

Questions?

- Questions?
- Comments?
- Other ways of achieving desired effects?