Penumbra Heating Using Thermal Software System (TSS) v17

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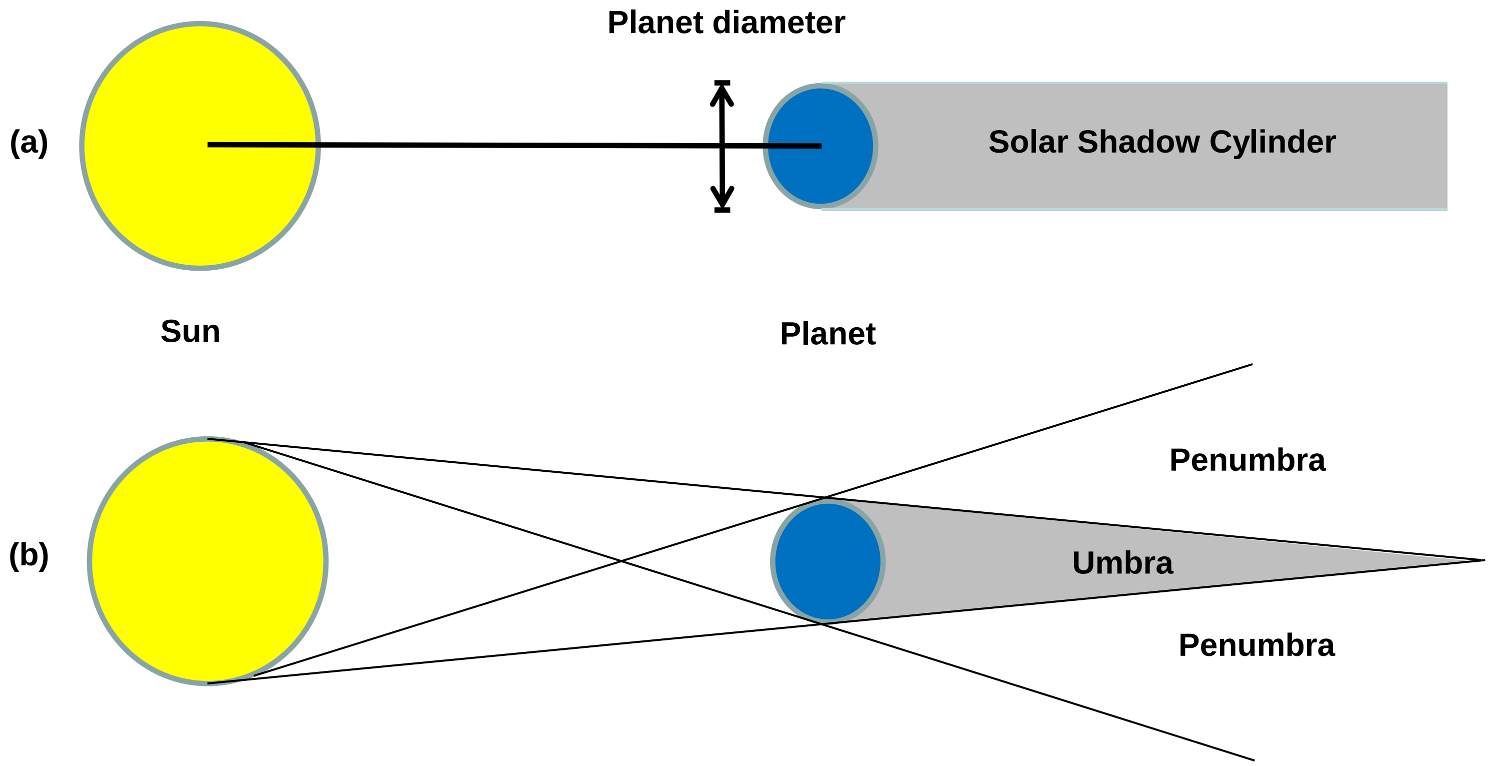
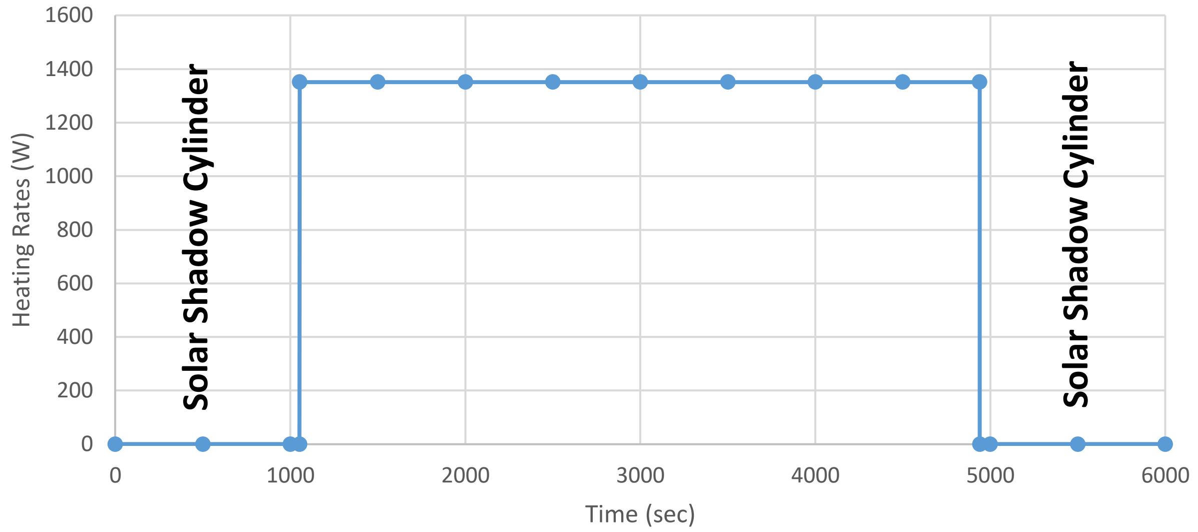
Introduction

- Typical Thermal Analysis Orbital Heating uses a Solar Shadow Cylinder, shown in below (a).
- Actual case is penumbra (partial shadow) and umbra (full shadow), see (b).



Introduction (continued)

- Heating rates for 1 square meter satellite
  - Starts in Solar Shadow Cylinder
  - Solar Pointing z-axis
  - LEO, 762 km circular orbit
  - Ends in Solar Shadow Cylinder

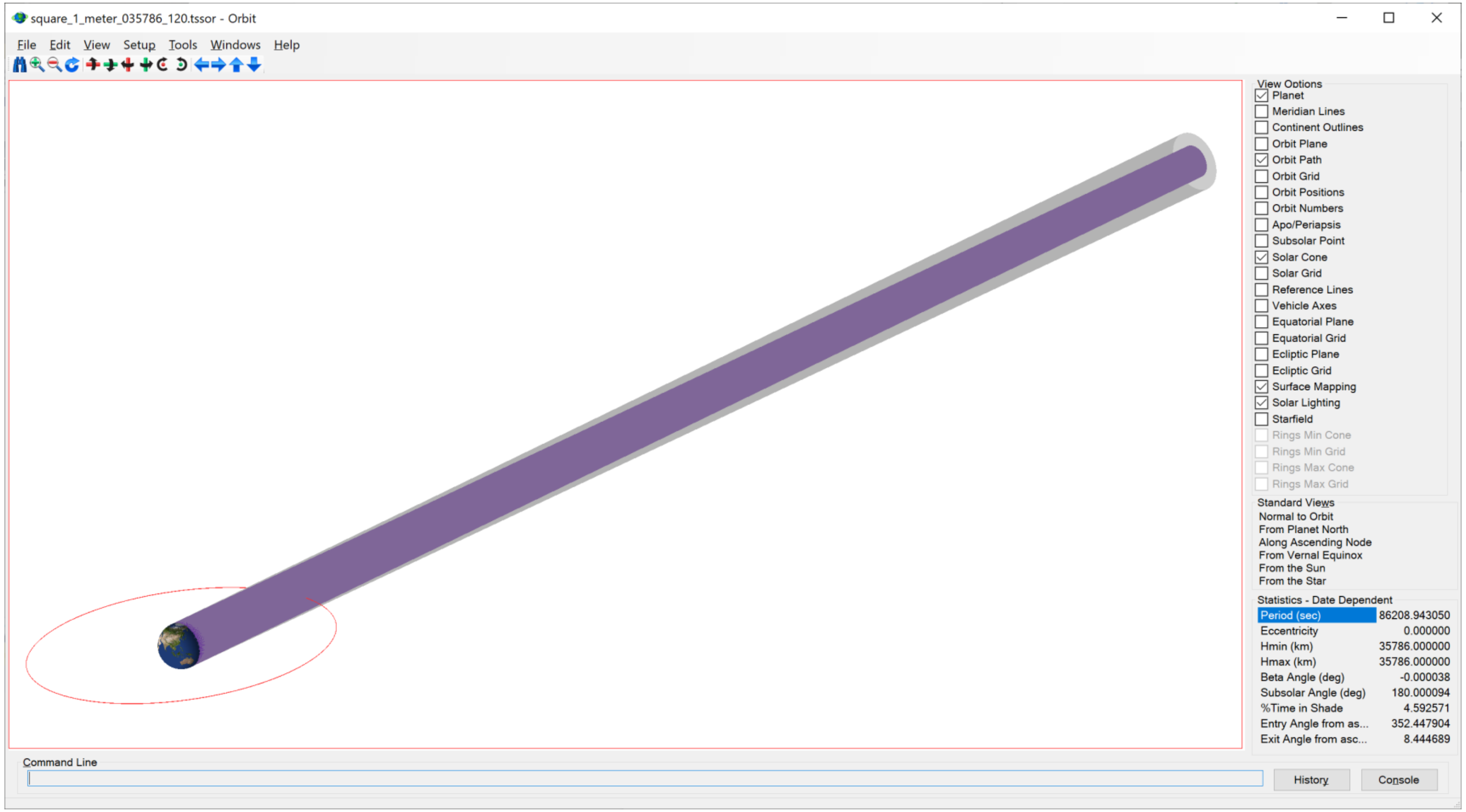


- Heating array (default) output
  - Time array, #1. Heat Array, #2
  - Initial position in shadow, value 0.
  - Time 1052.76 to 1053.76 exit Solar Shadow Cylinder, linear increase between 0.0 and 1351.4 Watts
  - Opposite at 4938.87 to 4939.87
  - User can set transition time.

```
C
C--- TIME-VARIABLE HEAT RATE TABLES
C
  1      =     $ TIME ARRAY
         0.00000,  499.94619,  999.89239, 1052.76274, 1053.76274,
       1499.83858, 1999.78477, 2499.73097, 2999.67716, 3499.62335,
       3999.56955, 4499.51574, 4938.86930, 4939.86930, 4999.46193,
       5499.40813, 5999.35432
C
  2      =     $ HEAT RATE ARRAY FOR NODE: MAIN.1
         0.0000,    0.0000,    0.0000,    0.0000,    1351.4
         1351.4,    1351.4,    1351.4,    1351.4,    1351.4
         1351.4,    1351.4,    1351.4,    0.0000,    0.0000
         0.0000,    0.0000
```

Introduction (cont.)

- Three dimensional view of Umbra (purple) and Penumbra (grey).
- Orbit (red circle) is GEO, 35786 km
- Length of Penumbra and Umbra is 30.7 Earth diameters (approximately the Moon's distance)
- Antumbra is much farther than Moon.



Methods

- Test cases for penumbra crossing.
- The start location of the test cases is at the Autumnal Equinox.
- Shown are the Ecliptic and Equatorial Planes.
- Table 1 shows the circular orbit altitude (km) and Penumbra Crossing times for LEO, GEO and Moon's orbital distance.

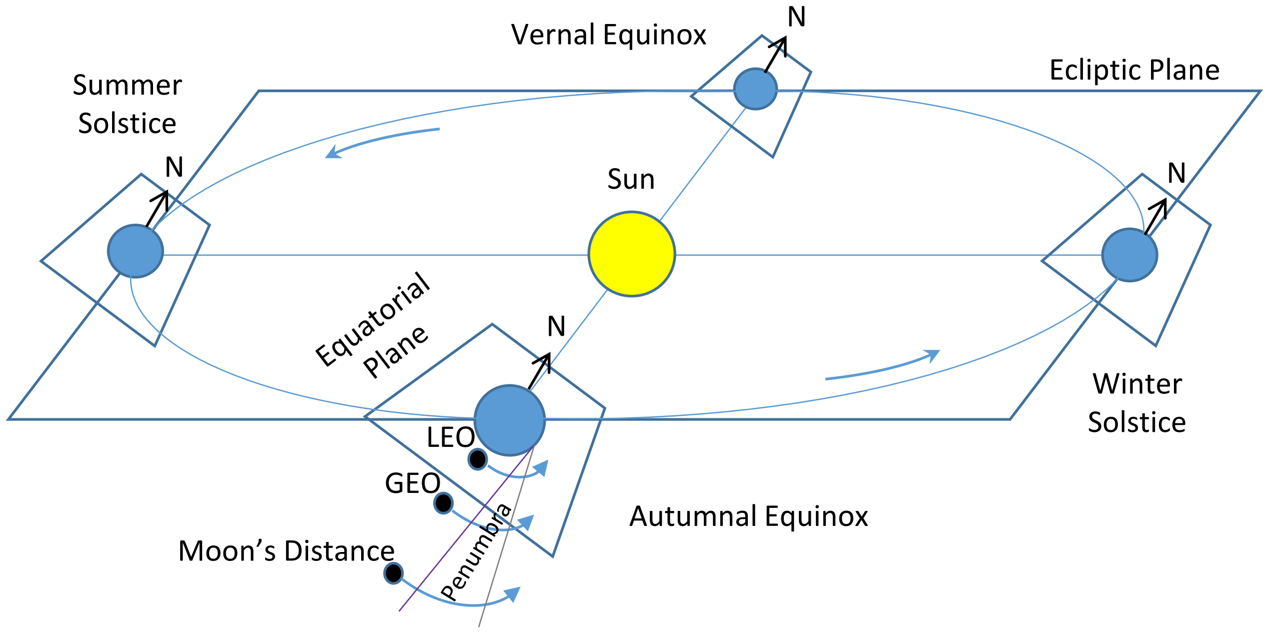


Table 1. Orbital Penumbra Crossing Time for LEO, GEO, and Moon's Orbital Distance

Orbit type	Circular Orbit Altitude (km)	Penumbra Crossing Time (mm:ss.ss)
LEO	762	00:08.90
GEO	35786	02:08.40
Moon's orbital distance	384399	64:46.15

- The Penumbra crossing times are show in the figure from LEO to Moon’s distance. High Earth Orbit (HEO) begins beyond GEO.

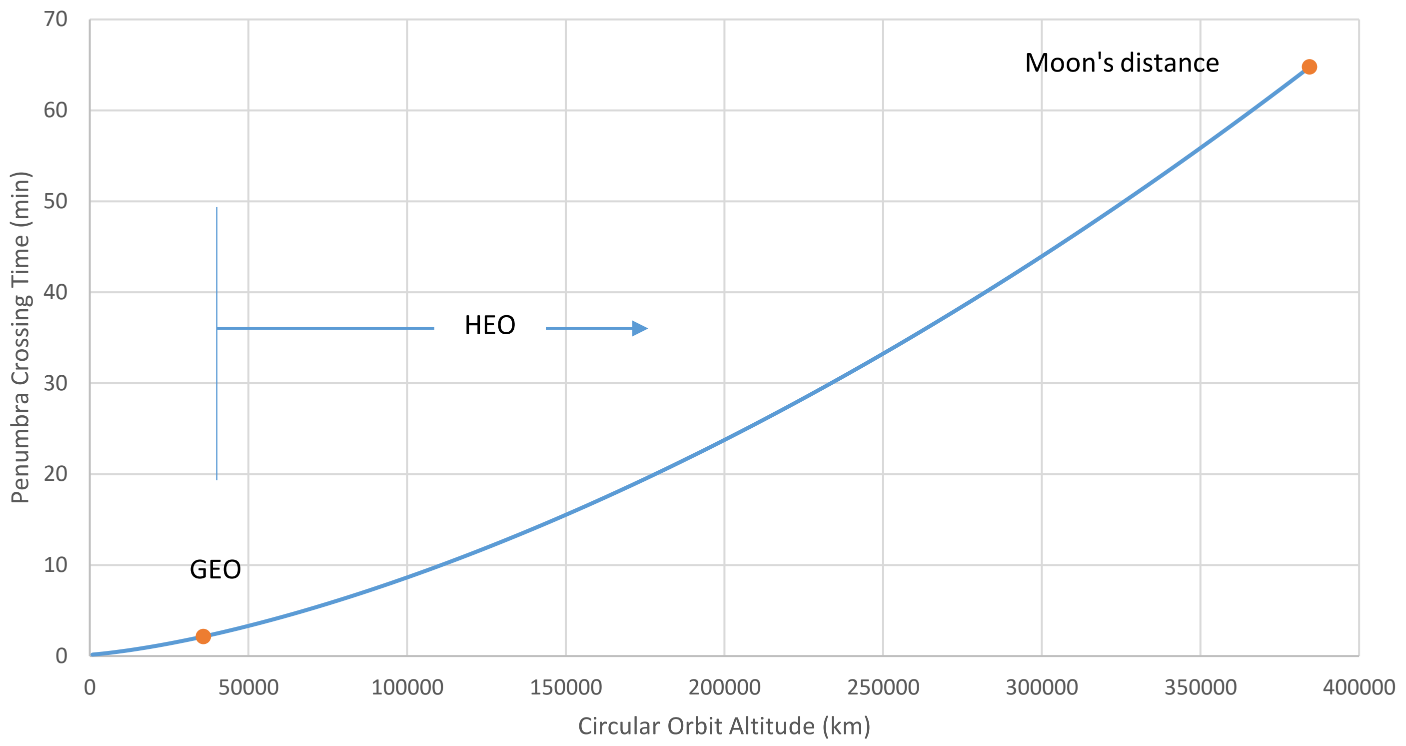


Figure 5. Penumbra Crossing Time vs Altitude for Circular Orbit

Results (continued)

- Figure 6, 7, and 8 show actual heat flux (blue) and linear interpolated flux values (orange) during the Penumbra crossing.
- The three test cases show that the heating is not linear and exhibits lower than linear heating initially and larger than linear heating new the end of the transition.

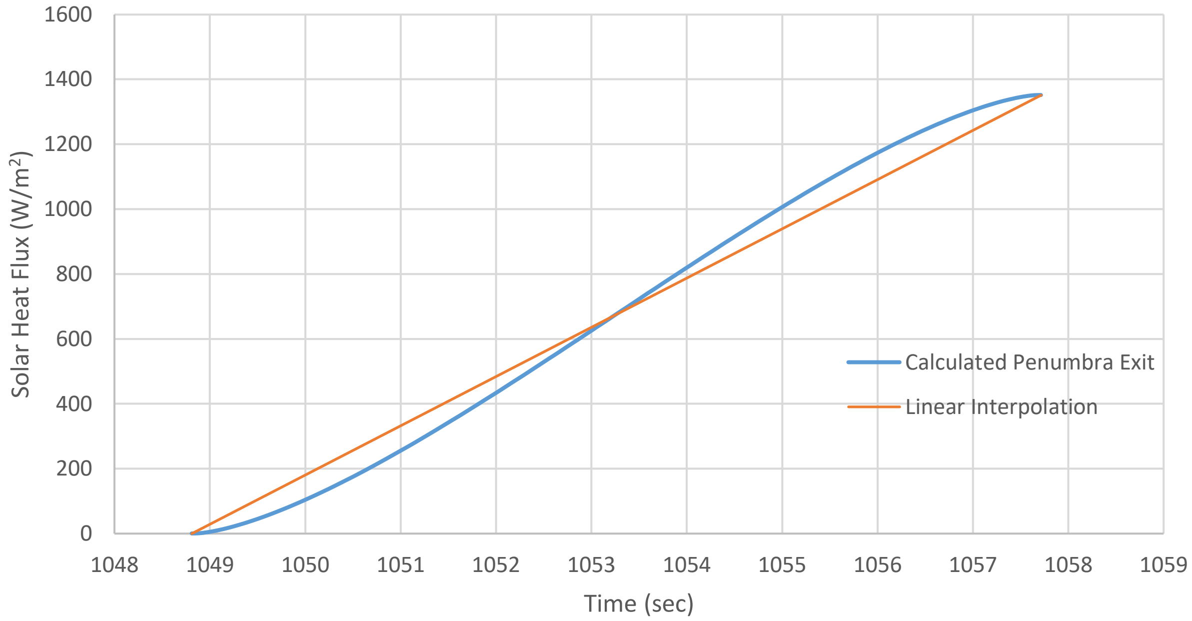


Figure 6. LEO Penumbra Exit Solar Incident Flux.

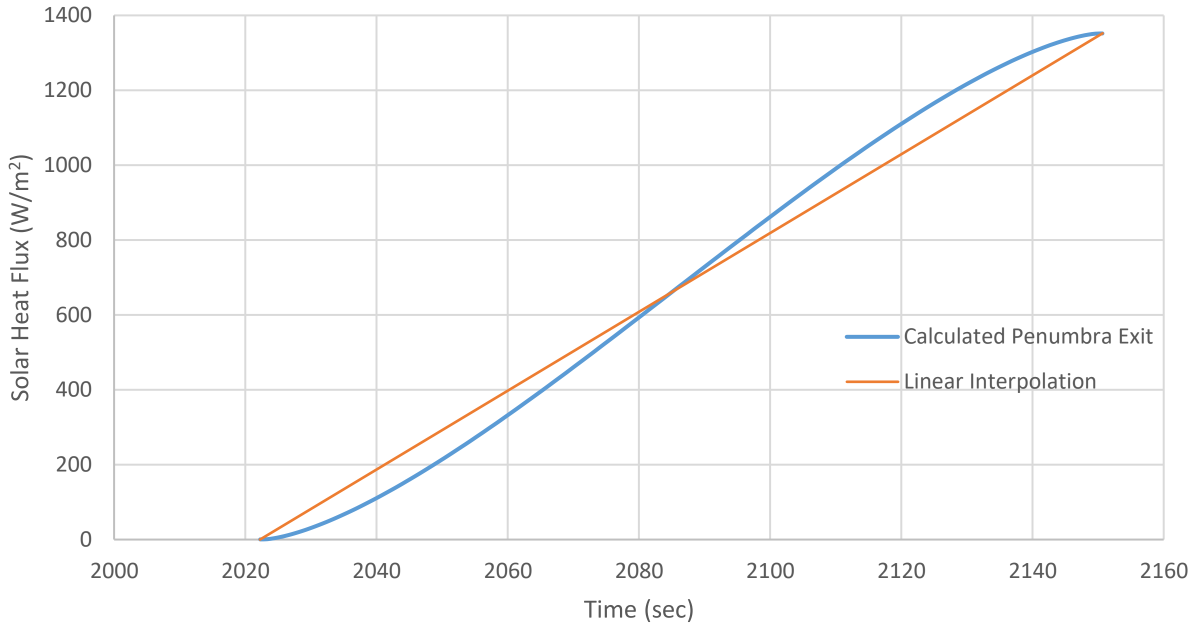


Figure 7. GEO Penumbra Exit Solar Incident Flux.

- Notice that the Moon’s Orbit distance has a similar pattern, although, on a percentage basis (to normalize the response between all cases) the Moon’s orbit distance crosses the linear interpolated line earlier.

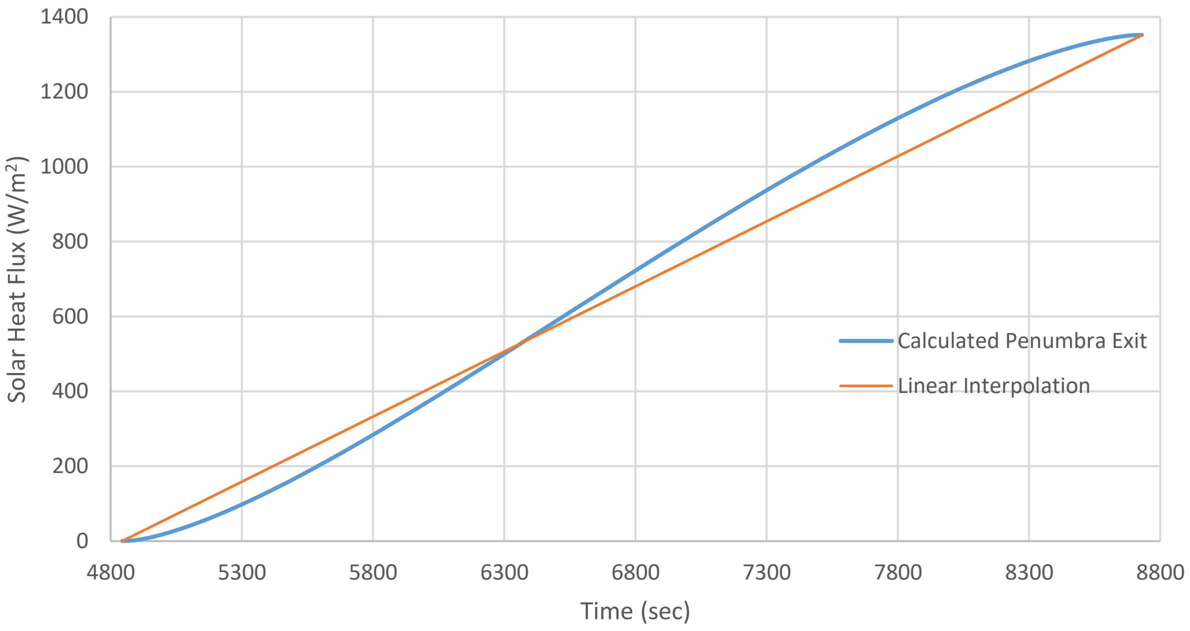


Figure 8. Circular Moon's Orbit Distance Penumbra Exit Solar Flux.

Results (cont.)

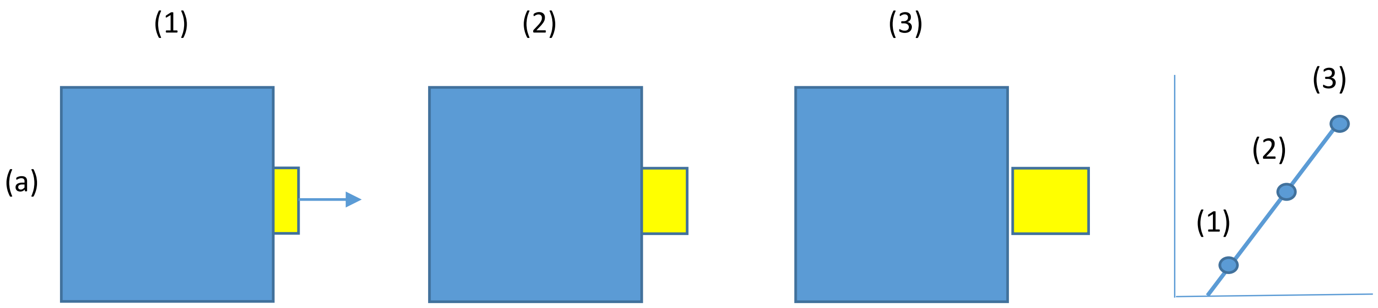
- The earlier crossing can be seen by looking at the total heating.
- The total heating increases compared to the linear interpolated value as the distance increases.

Table 2. Integrated Energy for LEO, GEO, and Moon's orbit distance Exiting Penumbra

Circular Orbit	Penumbra Calculations Total Energy (J)	Linear Interpolated Total Energy (J)	Difference (J)	Percent Difference
LEO	6,017.65	6,016.43	1.22	0.02%
GEO	87,090.76	86,764.01	326.75	0.38%
Moon's distance	2,719,124.00	2,625,924.71	93,199.30	3.43%

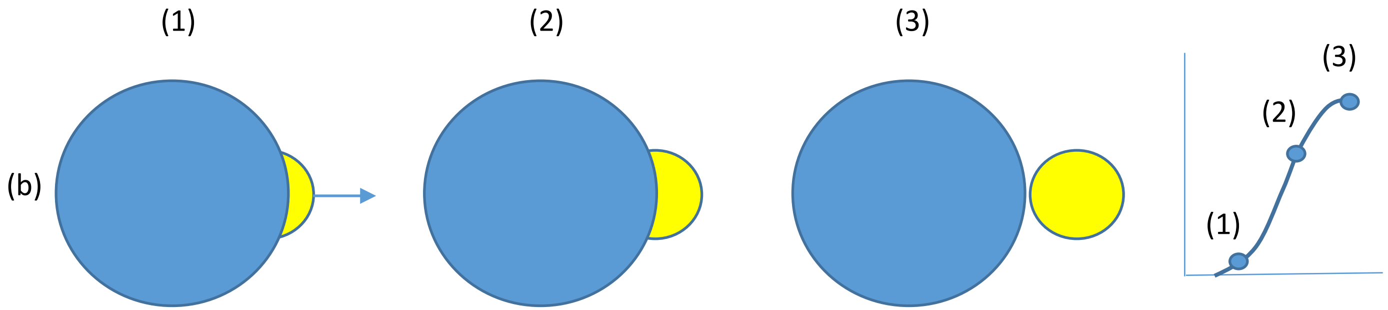
Results (cont.)

- For comparison, the linear transition can be modeled by two squares.
- While a more accurate approximation can be developed with circles.



Square Model (linear)

$$\dot{Q}_{linear}(t) = \dot{Q}_{max}\left(\frac{t - t_{start}}{t_{end} - t_{start}}\right)$$



Circle Model (sinusoidal)

$$\dot{Q}_{sinusoidal}(t) = \dot{Q}_{linear}(t) + A\sin(\theta(t) + \pi)$$

$$\theta(t) = 2\pi\left(\frac{t - t_{start}}{t_{end} - t_{start}}\right)$$

Results (cont.)

- The sinusoidal amplitude can be calculated using the absolute value of the maximum difference between the two curves.
- Simple example shows a value of 3.0.
- Table 3 shows the sinusoidal flux amplitude for our three test cases.
- The amplitude change is a function of altitude.
- The Moon's distance results in the Earth eclipsing surface having more curvature. This produces differences between the cases.

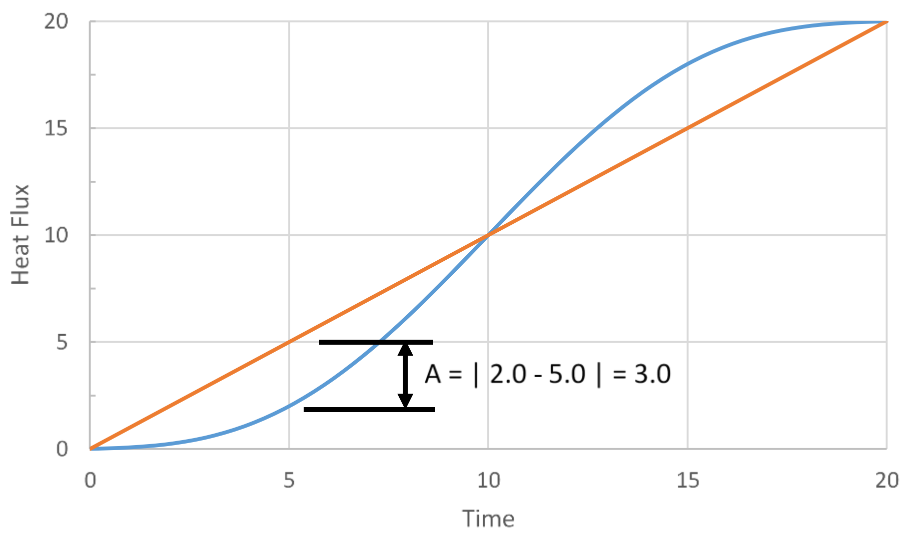


Table 3 Sinusoidal Heat Flux for Circular Orbits

Circular Orbit	Sinusoidal Flux Amplitude, A (W/m²)
LEO	81.982
GEO	83.880
Moon's orbital distance	101.085

Conclusions

- Thermal Software System v17 can determine penumbra heating that, as shown, is not a linear transition like the historic solar shadow cylinder.
- Future work will allow multibody calculations to determine penumbra heating for multiple bodies by finding and analyzing eclipses.
- A general methodology for calculating sinusoidal heat flux for circular orbits has been provided and compared to a linear interpolation for solar shadow cylinder transition.

Movies

- LEO, 8.90 seconds, actual speed/duration

Movies

- GEO, real-time 2:08 mm:ss, 2X speed, video time 1:04 mm:ss

Movies

- MEO, real-time 64:46 mm:ss, 60X speed, 1:05 mm:ss