Environmental Calculations for a Lunar Landing Site

Benjamin Paul Coffman
Environmental Calculations for a Lunar Landing Site

by

Benjamin Paul Coffman

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Honors Capstone Director: Dr. Matthew Turner

Modeling, Simulation and Analysis Research Engineer

Student (signature) Date 4-24-18

Director (signature) Date 4-23-18

Department Chair (signature) Date 4-23-18

Honors College Dean (signature) Date 4-30-18
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Student Name (printed)

Date
4-24-18
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Abstract

With the space race expanding into the private sector, the number of planned space missions is rapidly increasing. Each mission is a complex system of interlocking pieces which work together to accomplish a common goal. One thing that each mission must deal with is the environmental constraints that will be placed on the design of the spacecraft. Possible environments include the launch vehicle, transport vehicle, space, the moon, or Mars. A hot topic in the space industry is the possibility of placing a human colony on a terrestrial body other than Earth. The two locations most discussed for this endeavor have been the moon or Mars.

The Lunar Analysis and Sampling for Exploration and Research (LASER) Mission has been designed by The University of Alabama in Huntsville’s Integrated Product Team with scientific assistance from The College of Charleston. This mission’s goal is to “conduct science while in orbit of the moon and on the surface as well as gather samples for return to Earth in the South Pole Aiken Basin area of the moon” (“LASER Academic Announcement of Opportunity” 3). To accomplish this mission, there will be an orbiter in a path around the moon, a lander on the surface of the moon, a rover traversing the surface of the moon, and a Launch Ascent Vehicle (LAV) for returning the collected samples from the lander and rover.

This paper will focus on the functions of the lander and will benefit any future mission to the surface of the moon. This project will provide a means for considering different landing sites by generating temperature and power profiles for the mission depending on the longitude and latitude of the proposed landing site. The calculations necessary for achieving these results will be automated using Microsoft Excel and presented in a visually pleasing and easy to use format.
**Introduction**

The objective of the LASER mission is to “develop and design a mission to the south pole of the moon (near Shackleton Crater) to obtain surface and subsurface samples for return to Earth (LASER Mission Plan 2). In order to accomplish this mission, three spacecraft shall be designed: the orbiter, LAV and lander. The mission also includes a rover which shall disembark from the lander once on the surface of the moon.

Each spacecraft was assigned a role to fulfill. The orbiter will achieve a 100 km circular polar orbit and then conduct in-orbit science investigations over the course of the mission. The orbiter has a projected 2-year lifetime and will spend the first part of the mission transporting the lander and LAV after exiting the SLS payload fairing. These components all fit together as shown below in Figure 1.

![Figure 1: Assembly in Payload Fairing](image)
After detaching from the orbiter, the lander must achieve a soft landing at the landing site as determined by The College of Charleston. It will collect surface and subsurface samples at the landing site and will also accommodate the LAV and rover. The LAV will accommodate the lunar samples and transport them from the lander to the orbiter by achieving an orbit around the moon. It must have a 1-year lifetime. The rover will exit the lander and travel to a number of locations as specified by The College of Charleston. It will collect samples throughout its journey and return to the lander in order to transfer the samples to the LAV (“LASER Mission Plan” 3).

This project was performed in partnership with the lander design team, but it also impacted the LAV. The lander is designed with a space in the center for the LAV be housed in as shown in Figure 2 below. The design intent of this is for the lander to heat the LAV in order to maintain the LAV’s fuel within a specific temperature range. Extreme temperatures would cause the fuel to become unstable.

Figure 2: Lander/LAV Schematic

Figure 3 below does a good job of summing up the entirety of the lander’s mission. In Phase 0, the lander will be housed in the payload fairing of the SLS as it launches from Earth. In Phase 1, the lander will be attached to the orbiter as it enters its orbit of the Moon. Phase 2 will
consist of the lander detaching from the orbiter, descending to the moon’s surface, and landing successfully. Finally, Phase 3 will mark the end of the lander’s mission as the LAV launches and terminates the lifespan of the lander.

Figure 3: In-Flight Concept of Operations

The landing site as determined by The College of Charleston is located on the western rim of the Nishina crater at the coordinates 45.45 S 172.45 W as shown in Figures 4 and 5 below. This location was chosen firstly due to it being on the far side of the moon. This makes this mission unique to past missions as all previous landings have taken place on the side of the moon nearest to Earth. This location also has scientific interest because it displays impact melt and relatively unaltered exposed mantle. This characteristic makes the location especially well suited to the study of the effects of Late Heavy Bombardment by meteoroids (“Team Lander S.H.A.R.K. Mission Concept Study”).
Figure 4: Landing Site Coordinates

Figure 5: Landing Site Topography
The importance of the landing site is that each set of coordinates on the moon will have a different temperature and power availability profile. In order to determine the available power for the lander, it was necessary to calculate the variation of the solar irradiance over one lunar month. These solar irradiance values then drive the amount of power the lander is able to produce. Additionally, the length of the lunar night at the specific landing site will determine the requirements for battery power and/or a form of low power mode where all but the crucial systems are turned off while the lander is in darkness. The calculations for solar irradiance will be discussed in the methods section.

This paper utilizes the power and thermal calculations as discussed in order to contribute to the design of the LASER mission. By providing precise and iterative data on the environment, it is then possible to calculate the systems necessary for a successful mission. This includes the maximum possible power supply, the variation of the power supply, the necessary area of solar panels to be included in the structural design, and the thermal protection required of the lander design. These calculations can also be applied to any future lunar mission at any landing site due to the user-friendly nature of the calculations.
Methods

The Microsoft Excel spreadsheet created for this project was intended for use with the LASER mission but was designed so that it can be easily adapted for any future lunar mission. First, the operations of the “Calculations” section of the sheet may be explained. The first action performed by the spreadsheet is that it will iterate the position of the sun over the moon by one degree of longitude, beginning at zero and continuing up until 360. The latitude will be automatically populated based on the sun’s path around the moon. This path has angle five degrees north of the equator as shown in Figures 6 and 7 below. The moon rotates around the earth at a five-degree angle and the earth can be said to rotate around the sun at a relatively even angle (Saraf, Arun et al. 9873).

Figure 6: Path of Earth and Moon Around the Sun
Based on this information, the latitude ($\delta$) for each iteration is equivalent to $5/90$ of the longitude ($\lambda$) as shown in Equation 1 below.

**Equation 1:**

$$\delta = \lambda \ast \frac{5}{90}$$

The time will also be calculated from the longitude for each iteration. One lunar month lasts approximately 28 earth days, or 672 hours while the longitude covers a total of 360 degrees per rotation. The time ($t$) can be calculated for each iteration as shown in Equation 2 below.

**Equation 2:**

$$t = \lambda \ast \frac{672 \text{ hours}}{360 \text{ degrees}}$$

The time will be displayed from cell A5 through cell A366, longitude in cells B5-B366 and latitude in cells C5-C366 as shown in Figure 8 below.
The spreadsheet requires that the user provides the longitude and latitude of the landing site. In cells A2 and B2, the landing site coordinates can be input as shown in Figure 6 below. North is the positive direction on the y-axis while east is the positive direction on the x-axis. The coordinates shown in Figure 9 correspond to the landing site of the LASER mission, 45.45° S 172.45° W.

Once the landing site has been entered, the spreadsheet will calculate the solar zenith angle (θ) for each iteration. The solar elevation angle (α) is the angle between the horizon and the path of the sun to the landing site as shown in Figure 10 below. Likewise, the solar zenith angle is the angle formed between the vertical axis rising from the landing site and the path of the sun to the landing site (“Elevation Angle”).

![Figure 8: Time, Longitude and Latitude](image)

<table>
<thead>
<tr>
<th></th>
<th>Time (hr)</th>
<th>Longitude (E)</th>
<th>Latitude (N)</th>
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<td>7</td>
<td>3.7</td>
<td>2</td>
<td>0.11</td>
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<tr>
<td>8</td>
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<td>3</td>
<td>0.17</td>
</tr>
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<td>9</td>
<td>7.5</td>
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</tr>
<tr>
<td>10</td>
<td>9.3</td>
<td>5</td>
<td>0.28</td>
</tr>
</tbody>
</table>

![Figure 9: Input Landing Site Coordinates](image)

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Landing Site Longitude (E)</td>
<td>Landing Site Latitude (N)</td>
</tr>
<tr>
<td>2</td>
<td>-172.45</td>
<td>-45.45</td>
</tr>
</tbody>
</table>
The equation for the solar elevation angle can be calculated using the landing site longitude ($\Lambda$), the landing site latitude ($\Delta$), and the longitude and latitude of the sun’s current position. This relationship is shown in Equation 3 below (Woolf 3).

**Equation 3:**

$$\sin \alpha = (\sin \delta \times \sin \Delta) + [\cos \delta \times \cos \Delta \times \cos (\Lambda - \lambda)]$$

As displayed in Figure 11, the solar zenith angle is the complement of the solar elevation angle. Therefore, the equation for the solar zenith angle can be derived as shown below in Equation 4.
Equation 4: \[ \cos\theta = (\sin\delta \times \sin\Delta) + [\cos\delta \times \cos\Delta \times \cos(\Lambda - \lambda)] \]

The atmosphere of the moon can be considered a vacuum for these calculations (Dunbar). This assumption greatly simplifies the calculations for solar irradiance (I) and temperature (T). Solar irradiance is defined as the power per unit area received from the Sun. This value will change based on the landing site and oscillate based on the time of day. Knowledge of the exact solar irradiance is crucial when choosing a landing site as it will dictate how much power will be available for the lander to use at any specified time. Likewise, it will drive the consideration of solar panels and batteries in the design of the lander. Neglecting mass of the atmosphere, the equation for solar irradiance is as follows in Equation 5 such that “i” is equal to the solar irradiance constant (“Solar Radiation” 11). The solar irradiance constant is generally accepted to be 1366 W/m². (“Glossary of Solar Radiation Resource Terms”).

Equation 5: \[ I = i \times \cos\theta \]

The temperature at the landing site was calculated as a function of solar irradiance. These calculations rely solely on the heat coming directly from the sun and neglects the heat absorbed by the surface of the moon and irradiated off during the lunar night. The calculations have been determined to be reliable by comparing the results to readings taken from the Diviner mission. These readings will be presented and analyzed in the Results section. Equation 6, found below, was used to relate solar irradiance to temperature such that “\(\sigma\)” is equal to the Stefan Boltzmann constant, or 5.67 x 10⁻⁸ W/mK⁻⁴ (Luciuk 1).

Equation 6: \[ I = \varepsilon \sigma T^4 \]
In order to simplify the calculations, the moon is considered to be a blackbody with emissivity ($\varepsilon$) of 1 thus reducing Equation 6 to yield Equation 7. Equation 7 has also been manipulated in order to isolate temperature on one side of the equation.

**Equation 7:**

$$T = \frac{i^{0.25}}{\sigma}$$

Unfortunately, the raw solar irradiance values do not provide an accurate representation of the power that will be available to the lander. This is due to the fact that the solar rays will not always be normal to the solar panels and due to the efficiency of the solar panel itself. In order to maximize the time spent with the sun’s rays normal to the solar panel, it is necessary to determine the tilt of the solar panels ($\phi$) according to Equation 8.

**Equation 8:**

$$\phi = \Delta \pm 25$$

The sign of this equation will be determined by the direction that the collector is facing. “It is important to note that a positive tilt angle in the northern hemisphere means that the collector is tilted facing south, while negative tilt angle in the northern hemisphere means that the collector is tilted facing north” (Idowu 7). Likewise, a positive tilt angle in the southern hemisphere means that the collector is facing north, while negative tilt angle in the southern hemisphere means that the collector is tilted facing south. If this protocol for solar panel tilt is followed, then the light angle efficiency can be maximized at 70%. The efficiency of the solar panel itself will vary depend on the solar panel selected by the design team. The solar panels selected for the LASER mission had an efficiency of 44.5%. These efficiencies can be entered in to the Excel spreadsheet in cells C2 and D2 as shown in Figure 12 below. The solar zenith
angle, theoretical irradiance, actual irradiance and temperature values will subsequently be populated in columns D-G as shown in Figure 13 below.

![Figure 12: Efficiency Input Cells](image)

![Figure 13: Solar Zenith Angle, Theoretical Irradiance, Actual Irradiance and Temperature](image)

360 rows of data will be shown in the Excel spreadsheet for each column. In order to provide the user with a more measurable output, certain values are pulled and displayed in the upper right-hand corner of the spreadsheet. The “MAX” function is used to display the maximum theoretical and actual solar irradiance in cells F2 and F3, respectively. Likewise, the “AVERAGE” function is used to display the mean theoretical and actual solar irradiance in cells G2 and G3, respectively. See Figure 14 below for reference. The second sheet of this Excel file, titled “Graphs,” is used to visually present the data. These charts will be discussed in the subsequent Results section of the paper.

![Figure 14: Maximum and Average Solar Irradiance](image)

Figures 15 and 16 are shown below in order to provide a holistic view of the spreadsheet and give better reference as to the visual presentation.
### Figure 15: Columns A-D

<table>
<thead>
<tr>
<th>Time (hr)</th>
<th>Longitude (E)</th>
<th>Latitude (N)</th>
<th>Solar Zenith Angle (degrees)</th>
</tr>
</thead>
<tbody>
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<td>134</td>
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<tr>
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<td>1</td>
<td>0.06</td>
<td>134</td>
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<tr>
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<td>0.11</td>
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<tr>
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<td>135</td>
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<td>9.3</td>
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</tr>
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<td>0.39</td>
<td>135</td>
</tr>
</tbody>
</table>

### Figure 16: Columns E-G

<table>
<thead>
<tr>
<th>Theoretical</th>
<th>Maximum Solar Irradiance (W/m²)</th>
<th>Average Solar Irradiance (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual</td>
<td>967</td>
<td>298</td>
</tr>
<tr>
<td></td>
<td>301</td>
<td>93</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Theoretical Irradiance (W/m²)</th>
<th>Actual Irradiance (W/m²)</th>
<th>Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>-296</td>
<td>#NUM!</td>
</tr>
<tr>
<td>-953</td>
<td>-297</td>
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<td>-956</td>
<td>-298</td>
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</tr>
<tr>
<td>-958</td>
<td>-298</td>
<td>#NUM!</td>
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<td>#NUM!</td>
</tr>
<tr>
<td>-964</td>
<td>-300</td>
<td>#NUM!</td>
</tr>
<tr>
<td>-965</td>
<td>-301</td>
<td>#NUM!</td>
</tr>
</tbody>
</table>
Results

The spreadsheet will output three graphs which serve as a visual representation of the data calculated for the landing site. The first graph, as shown on the following page in Figure 17, represents the theoretical solar irradiance over one lunar month for the landing site.

![Figure 17: Theoretical Solar Irradiance vs Time](image1.png)

The second graph, shown below in Figure 18, mimics the distribution of the theoretical solar irradiance. However, since it is showing the actual available irradiance, the graph is significantly scaled down to almost a third of its original magnitude.

![Figure 18: Actual Available Power vs Time](image2.png)
The difference between Figures 17 and 18 is due to the light angle and solar panel efficiencies. Figure 18 is a representation of how much power can be harvested for each square meter of solar panels given any time over any lunar month whereas Figure 17 is a representation of how much solar irradiance would be incident to a normal plane at the landing site given any time over any lunar month. Thus, Figure 18 was the primary contributor to power considerations. However, the calculations for Figure 17 provided a stepping stone for the temperature calculations. The results of these calculations are displayed graphically below in Figure 19.

![Surface Temperature Over One Month](image)

**Figure 19: Surface Temperature vs Time**

The temperature calculations operated under the assumption that surface temperature is a function of solar irradiance only. Due to this, it was necessary to establish a minimum temperature for the landing site. Figure 19 reflects this by setting a minimum value for the y-axis at 100 K. This value came from the Diviner Lunar Radiometer experiment.

Diviner is a radiometer used for mapping solar reflectance and infrared emission that was hosted on board the Lunar Reconnaissance Orbiter (LRO). It collected approximately one-
quarter trillion calibrated radiance measurements of the moon over the course of five and a half years. Diviner measured the incoming solar flux as well as the outgoing thermal emission which were then used to approximate surface temperature as shown below in Figure 20.

Figure 20 differs from Figure 19 in that it uses local time for the x-axis as opposed to lunar hours. Additionally, the Diviner data provides a better representation of the cooling effects of the dark hours. The core of the graph, however, validates the calculations performed for the LASER mission. The landing site of 45.45 S 172.45 W corresponds to the readings at a latitude of 45 degrees or the yellow markers in Figure 20. The average readings for Diviner show a maximum temperature of 350 K while the maximum calculated temperature from the Excel spreadsheet is slightly above 350 K. However, this correlates appropriately to the slight standard deviation in correlated values that was shown to be as high as 30 K (Williams, J P).
This being said, the Diviner mission results serve as validation for the calculations performed in this project as the temperature values match up with a reasonable level of accuracy. Additionally, since the temperature calculations were founded off the power calculations, the Diviner data also confirms the results of the solar irradiance results. This gives the user great confidence in the data provided by the Excel spreadsheet about any specific landing site.
Discussion

The calculations performed for this project were essential to the success of the LASER mission planning. The temperature and power data were necessary for decisions made by the thermal, power and structural subsystems.

The solar panels are the sole source of power for this mission, therefore the solar irradiance calculations were crucial for determining available power for the spacecraft. Due to the low levels of solar irradiance, it was necessary to maximize the area of solar panels on the lander. In order to accomplish this, the octagonal rim of the lander structure was lined with solar panels designed to fold outward. This flower petal-based structure can be seen below in Figure 21. Each diagonal petal has an area of 2.89 m$^2$ while each panel on a straight edge has an area of 2.83 m$^2$. This gives a total surface area of 20.043 m$^2$ for the solar panels. One drawback to the design is that one solar panel had to be sacrificed in favor of a ramp. This ramp is necessary for the rover to drive up, allowing it to place its lunar samples into the top of the LAV using a robotic arm.

![Figure 21: Solar Panel Schematic](image)
The power provided by the solar panels was deemed to be sufficient during the daytime. However, at nighttime there is no incoming solar irradiance and therefore no source of power. Some power from the daytime can be stored in batteries. However, batteries are extremely heavy and the amount of batteries necessary to get the lander through the night at full capacity would have an exceedingly high mass. Additionally, the cold of the nighttime also necessitated an increase in power consumption in order to heat the lander and the LAV. Despite only being needed for half of the time, the thermal system would take up 28% of the power. This jump can be seen in the power profile displayed in Figure 22 below.

![Power Profile](image)

**Figure 22: Lander Power Profile**

This realization resulted in two decisions: first, all non-essential systems will be put into sleep mode during darkness; secondly, the original plan for thermal control by traditional means was replaced by a radioactive heating unit (RHU). The RHU provides thermal energy via the
radioactive decay of Plutonium-238. This provides an alternative to the traditional heater which would require power to be input in order to operate.

The lack of power availability as shown by the spreadsheet calculations increased the need for batteries in order to be able to operate at night. However, the inclusion of an RHU allows for mass and conservation. The need for more batteries is eliminated, which is crucial for mass purposes. An RHU has a mass of roughly forty grams, whereas a typical battery has a mass greater than ten kilograms (“Team Lander S.H.A.R.K. Mission Concept Review”).

The environmental calculations performed by this spreadsheet allowed the structural, power and thermal subsystem teams to make important design decisions. Solar panel area was maximized, power usage was minimized, and alternative forms of heating were explored.
Conclusion

The program developed by this project is applicable to much more than just the LASER mission. On December 11, 2017, President Trump signed Space Policy Directive 1 that makes a goal of national space policy to return to the moon. According to President Trump, space is “the next great American frontier” (Northon).

America is not the only nation with its eyes set on the moon. China’s Chang’e 4 mission is similar to the LASER mission in that it is a lunar lander mission that intends to land on the far side of the moon in the South Pole – Aitken Basin region. In addition to this mission, planned to launch at the end of 2018, the Chang’e 5 mission is another lunar sample return mission scheduled to launch in 2019 (Williams, David).

Russia is another nation that has plans in place to put a spacecraft on the moon in the near future. Luna-25 is the first planned launch for the next wave of Russian space exploration. This lunar lander mission is scheduled for 2018 and will be followed by Luna-26 and Luna-27. These missions are scheduled to launch in 2019 and 2020, respectively (“Russian Moon Exploration Program”).

International governments are not the only parties interested in exploration of the Moon. The space race is beginning to transition to the private sector, with Elon Musk’s Space-X and Jeff Bezos’s blue origin being the most recognizable. There are also numerous smaller companies pursuing a landing on the lunar regolith. According to its website, Moon Express’s mission is to “redefine possible by returning to the moon and unlocking its mysteries and resources for the benefit of humanity.” Their ultimate goal is to establish a lunar research outpost and begin to harvest the moon for water and useful minerals (“Redefining Possible”).
High levels of interest in the moon make this project applicable to the real world today. This spreadsheet automates the process of calculating temperature and solar irradiance distributions for any potential landing site on the moon and is backed up by data recorded by the Diviner mission. In the past, reaching the moon has always been a mammoth milestone for leading nations around the globe. Soon, however, the Moon will be within reach of everyone.
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