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Transient Thermal Model and Analysis of the Lunar Surface and Regolith for Cryogenic Fluid Storage

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Abstract

A transient thermal model of the lunar surface and regolith was developed along with analytical techniques which will be used to evaluate the storage of cryogenic fluids at equatorial and polar landing sites. The model can provide lunar surface and subsurface temperatures as a function of latitude and time throughout the lunar cycle and season. It also accounts for the presence of or lack of the undisturbed fluff layer on the lunar surface. The model was validated with Apollo 15 and Clementine data and shows good agreement with other analytical models.

Introduction

Future missions to the Moon will include long duration habitation of the lunar surface. During those periods, cryogenic propellants and fluids for life support will require provisions for long term, low boil-off storage. To prevent excessive boil-off of these cryogenes, insulation techniques and low-heat-loss supports need to be designed and evaluated. Furthermore, passive or active heat removal systems may be required depending on the thermal environment of the surrounding.

In this analysis a model was developed to predict the time dependent lunar surface temperatures at polar and near polar locations. The thermal environment was defined during day and night periods. The day time temperatures are fairly straight forward to calculate but night time temperatures are a function how much heat is stored in the subsurface, how well the heat is transferred into and out of the regolith, and the internal heat generation of the planet. Due to seasonal variations, polar locations can have periods of constant sun light during the summer that can last many months followed by constant night time conditions for the remainder of the year; except, some high elevations, such as crater rims, can experience constant daylight (ref. 1) during 70 percent of the winter.

The lunar cycle lasts 656 hr, which is 27 Earth days. The Apollo (ref. 2) missions measured surface temperatures at 20° and 26° N latitude that ranged from 102 to 384 K with an average of 254 K. The monthly range was ± 140 K. There are no accurate temperature measurements of the polar regions but Clementine data (ref. 3) just suggests that it is less than 200 K. Analytical models of Vasavada, et al (ref. 4) have predicted day time surface temperatures at 85° N latitude of 225 K, while the nighttime predictions were 70 K.

This analysis first develops a transient thermal model of the regolith and compares it with empirical data from the Apollo 15 and 17 missions and the long-wave infrared survey of the lunar surface by the Clementine spacecraft. This served to validate the thermal model, permitting its use for the predictions of surface temperatures and heat leaks into cryogenic propellant and life support tanks in support of the Exploration Systems Architecture Studies.

Description

Surface and Subsurface Thermal Properties

The geometric, thermal, and radiative properties used in the thermal model are shown in figure 1. The regolith was modeled to a depth of 0.62 m of which the first 2 cm were modeled with different properties,

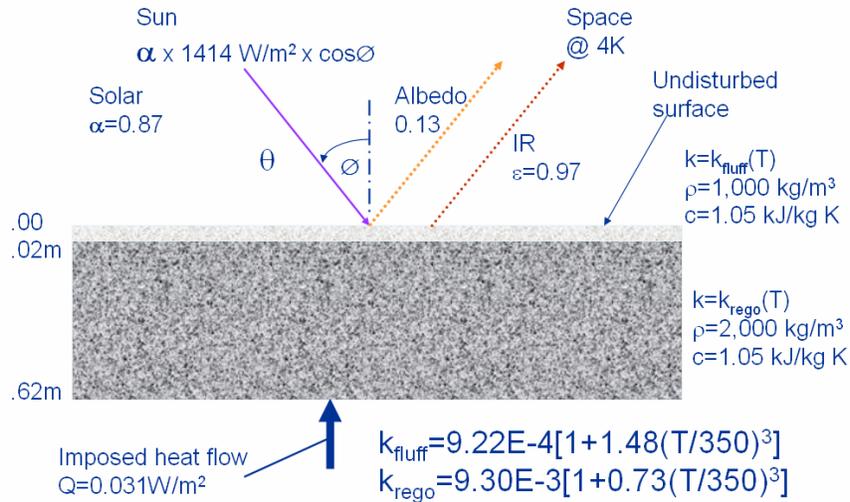


Figure 1.—Thermal characteristics of lunar surface.

which is called fluff. The fluff has a density of about $\frac{1}{2}$ that of the underlying regolith. In the evacuated fluff, the heat transfer is mainly due to particle to particle radiation and therefore its thermal resistance is highly temperature dependent. An effective emissivity of 0.7 used to represent the fluff gave temperature results consistent with Apollo 15 data. Later, the model was improved so that time dependent properties as defined by Mitchell and de Pater (ref. 5) and Cremers and Birkebak (ref. 6), which are shown at the bottom of figure 1, were used.

The heat load on the surface is the product of the solar insolation of 1414 W/m^2 , the cosine of the Sun's angle of incidence, and the surface's solar absorptivity of 0.87 (ref. 7). A fraction of solar insolation, varying from 0.07 to 0.15 (ref. 3) depending on terrain, is reflected from the surface. A "moonshine" value of 0.13 is used herein. The Moon has a black body temperature of 274 K (ref. 8) which is 20 K warmer than the Earth and emits heat with an infrared emissivity of 0.97 (ref. 9). The bulk thermal inertia $(k\rho c)^{-\frac{1}{2}} = 0.019 \text{ m}^2\text{s}^{\frac{1}{2}}\text{KJ}^{-1}$ was determined by Smith and West (ref. 10) and from that a specific heat $c = 1053 \text{ J/kgK}$ can be extracted (ref. 9). Bastin (ref. 11) reports a bulk thermal inertia value of $0.025 \text{ m}^2\text{s}^{\frac{1}{2}}\text{KJ}^{-1}$ which is about 30 percent higher than the value reported by Smith and West. The effect of thermal inertia on the lunar surface temperatures as reported by Bastin (ref. 11) is shown in figure 2. Due to the low density and the low thermal conductivity of the fluff layer, the bulk thermal inertia of the fluff is about 25 percent higher than that of the underlying regolith. Thus, a landing site where the fluff has been partly blown away from rocket exhaust will have night time surface temperatures higher than the undisturbed areas. This could create substantial variations in predicted vs. actual surface temperatures on vehicle elements.

Subsurface temperature measurements taken during the Apollo 15 and 17 missions showed that the regolith temperature increases with depth. The regolith temperature profiles as reported in (ref. 2) are shown in figure 3. This thermal gradient is interpreted as a heat flow from the interior equivalent to 0.031 W/m^2 (ref. 2) and has an uncertainty of ± 20 percent. This imposed heat flow of 0.031 W/m^2 from the lunar surface was used in the model, as shown in figure 1.

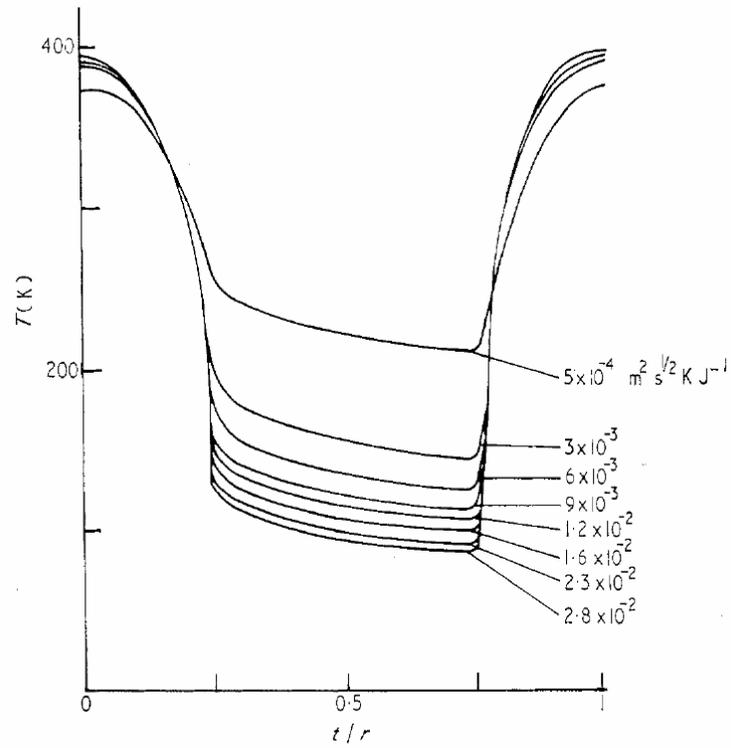


Figure 2.—Equatorial lunar surface temperatures as a function of normalized time and bulk thermal inertia (ref. 11).

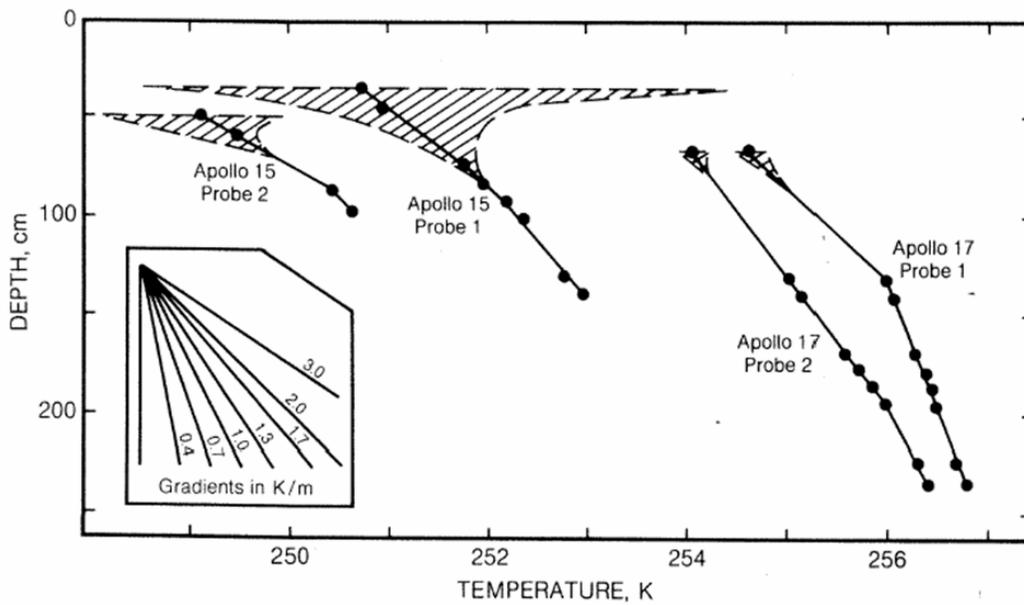


Figure 3.—Regolith temperatures with daily variations versus depth (ref. 2).

Finite Difference Model

A finite difference model was generated using the Thermal Analyzer System (TAS) by Harvard Thermal. Figure 4 shows the surface model dimensions as 100 by 100 m with a 5 by 5 m grid. A 10 by 10 m patch in the center has a more refined grid and represents the landing zone. The thickness of the fluff and the depth of the regolith are meshed as shown in figure 5. The first 0.02 m thick layer is the fluff.

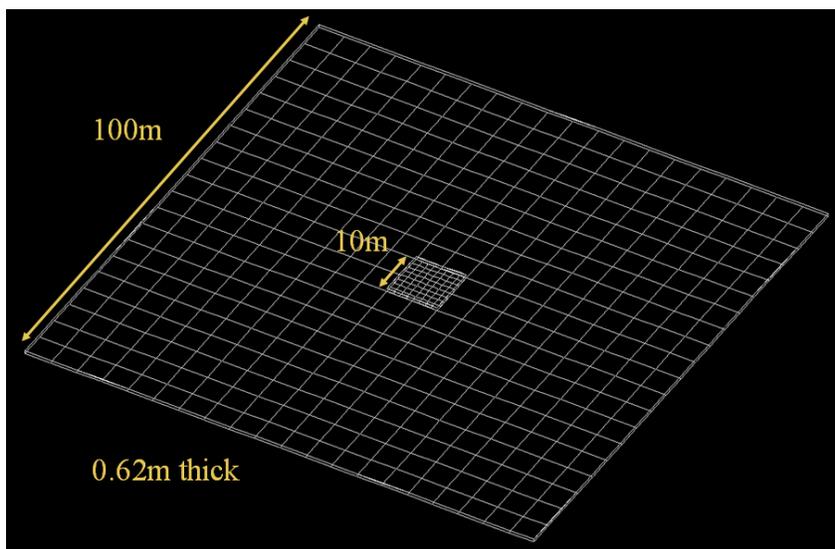


Figure 4.—Lunar surface finite difference model.

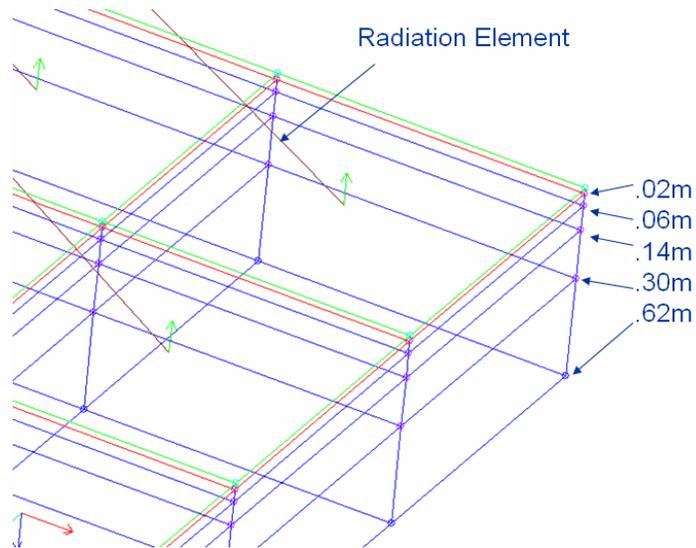


Figure 5.—Depth grid of regolith.

Results

First, the steady state temperature with the Sun at noon conditions and at zero latitude was solved and found to be 386 K. This is consistent with Apollo (ref. 2) temperature data and the Clementine data (ref. 3), which is shown below.

Next, a transient analysis was performed by varying the sun's heating load every 27 Earth days. TAS does not accommodate moving heat sources; therefore the variation in the Sun's heat load as a function of time was simulated by varying the flux magnitude with a sine function. The transient analysis was started at steady-state conditions and continued many months until the temperatures at the end of the period matched those at the beginning of the period, i.e., the temperatures just before sunrise equal those at sunrise. Typically it took 100 lunar cycles (months) to achieve this. The temperature at the end of these 100 cycles is then used as the initial conditions for further transient analyses.

The calculated surface temperatures for 3 lunar days at the equator are shown in figure 7. The results are similar to the Apollo 17 site data which had daily ranges of 102 to 384 K. The lunar cycle subsurface temperatures from the model are shown in figure 8; they compare well with the measured data reported in figure 2. The Apollo 17 data (ref. 2) shows a 280 K temperature swing on the surface, about 5 K at 0.3 m, and no significant variations at 70 cm with a mean temperature of 253 K at 1.38 m. Therefore the transient thermal model of the lunar surface and regolith shows good agreement with actual measurements taken during the Apollo missions.

Next the model was modified to predict the temperatures at polar and near polar locations. For these cases, the heat source representing the Sun is a node placed above the horizon at an angle relative to the surface that is a function of the Moon's obliquity and the latitude of the landing site and the season. The Moon's obliquity, 1.5° , is the angle (or tilt) between its axis of rotation and the ecliptic plane. It is shown in figure 9.

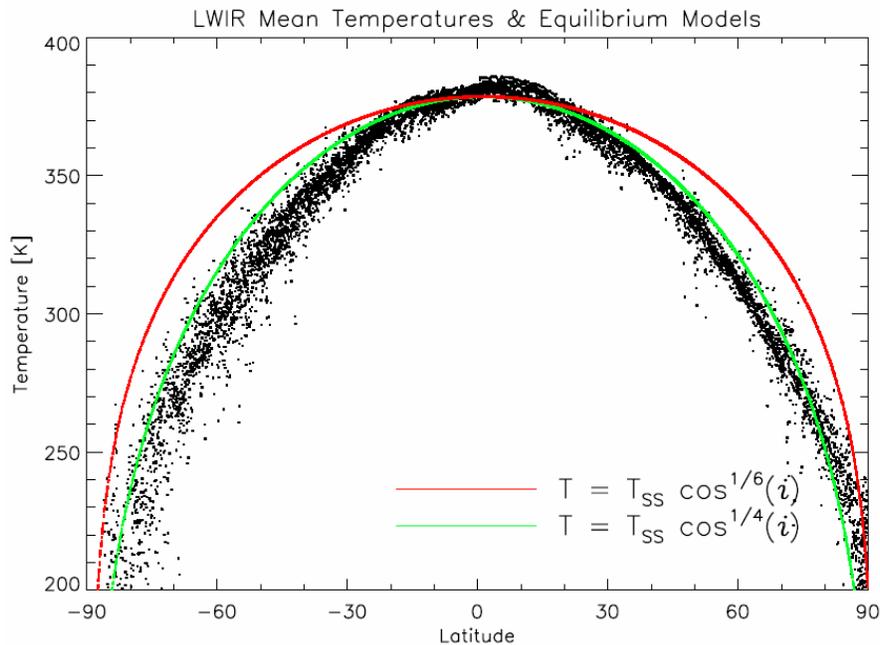


Figure 6.—Lunar surface temperature versus latitude (ref. 3).

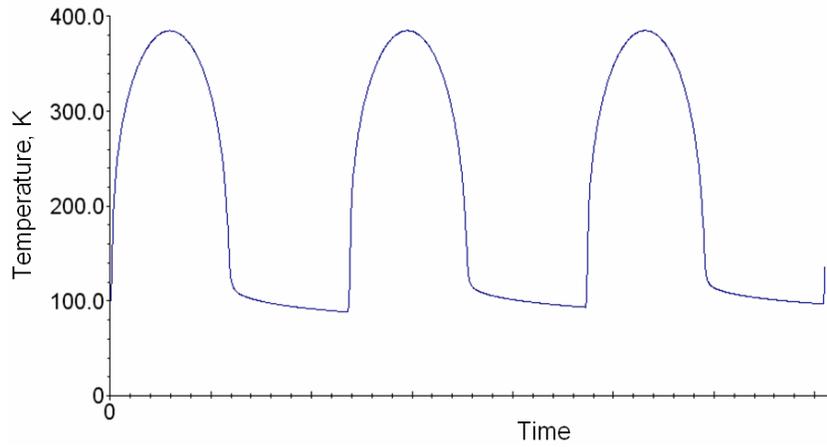


Figure 7.—Daily lunar equatorial surface temperatures.

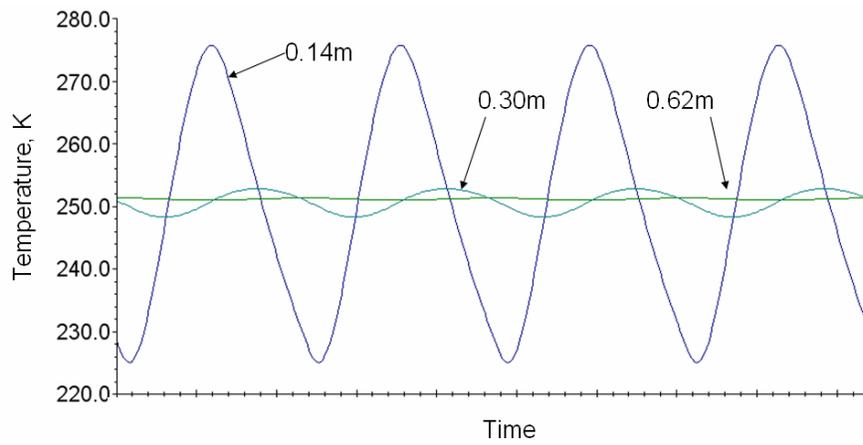


Figure 8.—Daily lunar subsurface temperatures.

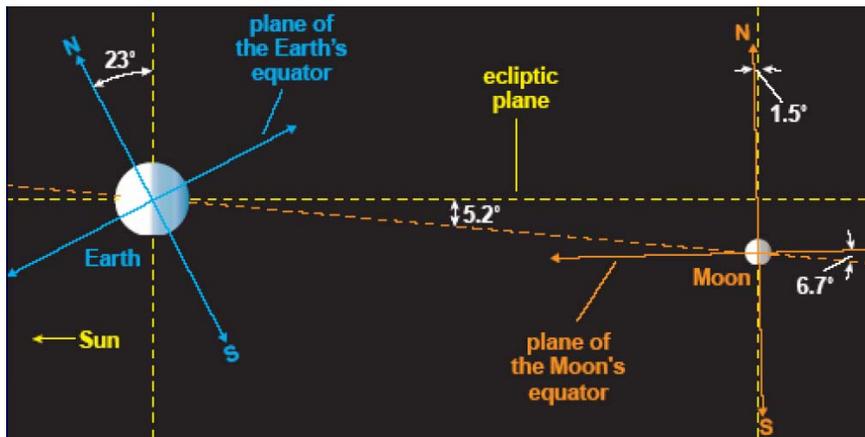


Figure 9.—Lunar obliquity (ref. 12).

Figure 10 shows an example of the Sun’s track relative to the horizon for a lunar day during the summer solstice when located at 88° N latitude. During this period there can be nearly constant daylight throughout the month, depending on the surrounding topography. The amplitude of sinusoidal variations is a function of the site’s latitude and the mean value is the Moon’s obliquity. Since TAS can not accommodate a moving heat source, it is reasonable to locate the heat source at the peak angle and then vary its heat flux as a function of time. Vasavada (ref. 4) performed an analysis at 0° and 85° N latitude which produced the results shown in figure 11. The equatorial results here agree well with the analysis results discussed previously in this report. For comparison purposes, this model was then modified to represent the 85° N latitude environment.

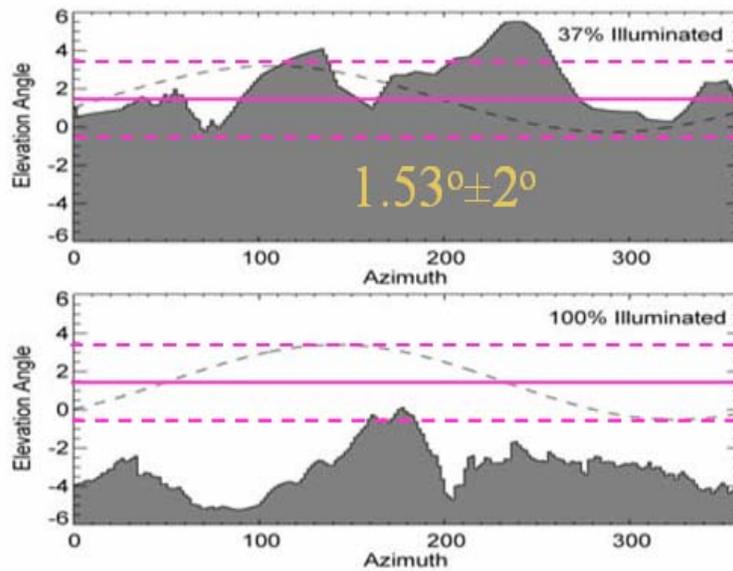


Figure 10.—Sun track on lunar horizon at 88° N latitude during a lunar day at summer solstice for different topographies (ref. 13).

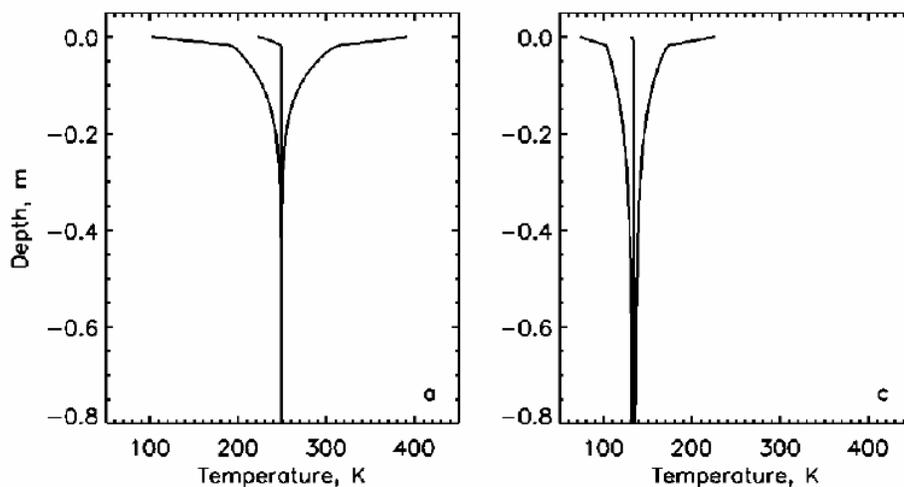


Figure 11.—Lunar surface and subsurface temperatures at 0° latitude (left) and 85° N latitude (right) (ref. 4).

As figure 10 shows, at high latitudes it is hard to determine how long the Sun will be visible during the month; furthermore it will vary with the season. Vasavada did not state what they used but if topography is ignored then the number of days of daylight during each month for various time of the year can be found by using the simple functions used to make figure 12. For 88° latitude, the summer solstice has about 24 days of sunlight during that month, whereas the winter solstice has only 9. Elevation is also important for object located above the surface. The example in figure 13 shows that an elevation of 500 m lowers the horizon 1.4° below the horizontal which will increase the length of the daylight hours on object. For this analysis at 88° latitude it was assumed that Sun is located 3.53° above the horizon and the day and night periods are equal. This is not a physically correct situation, although during the equinox the day and night periods are equal but at this time the Sun will only reach 2° above the horizon. While that is the case, note that for a flat level surface the horizon is the surface itself, thus elevation is not a factor when determining the solar heat load on a flat level surface.

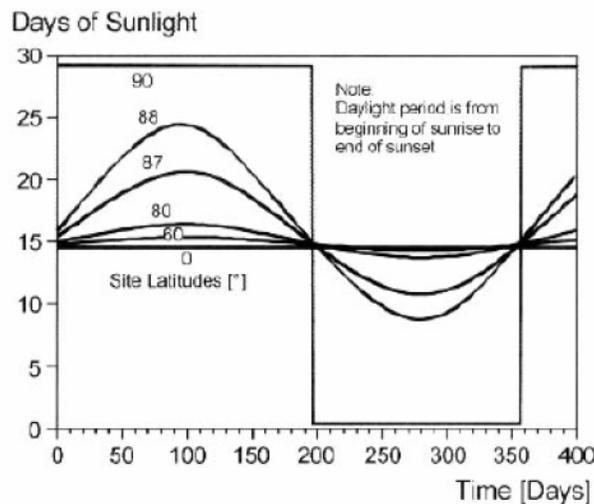


Figure 12.—Number of days of sunlight per month during the year for different latitudes (ref. 14).

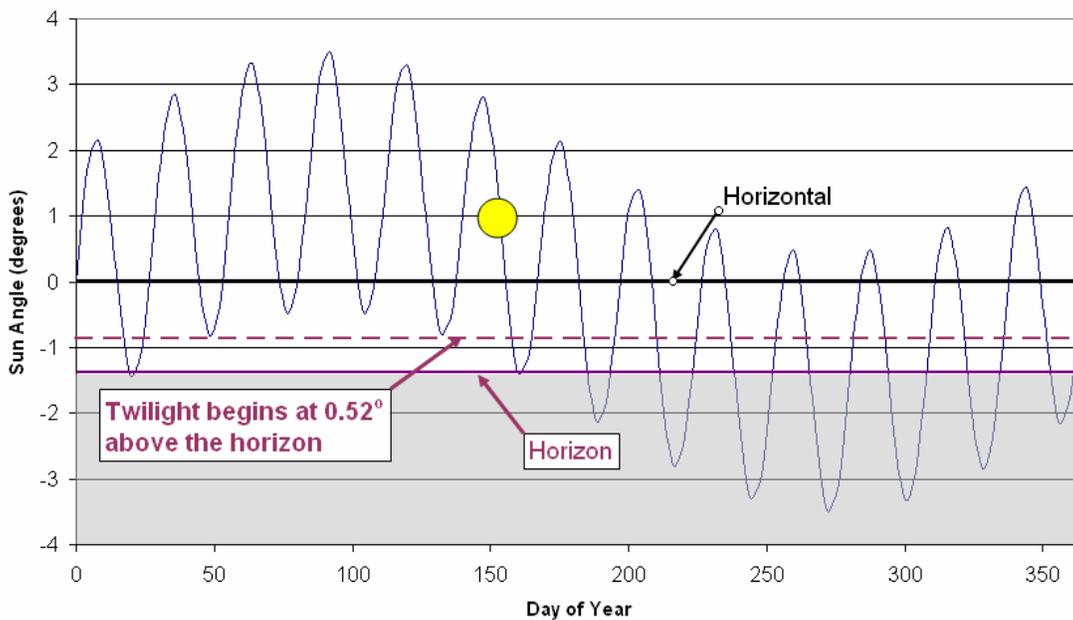


Figure 13.—Sun angle versus day of year at 88° N latitude and 500 m elevation.

With the Sun fixed at 3.53° the transient model was run for 100 lunar cycles. The last cycle produced the temperature profiles shown in figure 14. The data shows good agreement with figure 11, with minimum and maximum surface temperatures of 75 to 190 K and an at depth constant temperature of about 126 K. At depth, the Vasavada model was about 10 K warmer which could be caused by a longer daylight to night time period ratio. The model was also run without the fluff layer to see the affect of not having fluff present. The bottom half of figure 14 shows that maximum surface temperature remains the same but night time minimum temperatures are higher. Furthermore the temperature variations just below the surface are more extreme.

Following this model correlation, it was run at 90° south latitude mainly to see what will be the minimum temperatures reached after long periods of darkness. To be conservative the elevation was assumed to be zero. This provides a Sun angle with respect to time as shown in figure 15. In this case, daylight lasts half a year. However, lunar landing sites at the poles could be selected for maximum illumination periods. There are crater rims near the poles which are nearly “Peaks of Eternal Light” (ref. 15). For example, by choosing an elevation of 500 m there is nearly constant illumination, for an object above the surface, as shown in figure 16.

With a half a year of daylight and half a year of darkness the lunar surface and subsurface temperatures are shown in figure 17. The surface temperatures for the ‘with fluff’ and ‘without fluff’ cases are closer together than there were in figure 14 because the subsurface has much more time to cool off. There are also significant temperature variations at -30 and -62 cm, suggesting that a thicker model might be required. Further parametric studies should be done to determine the sensitivity of the temperatures relative to the thickness of the model. Note that after nearly 6 months of darkness, surface temperatures are still dropping and that temperature variations at -62 cm are nearly totally out of phase with the surface temperatures. A steady state analysis was also performed with no solar thermal load applied and the steady state surface temperature went to 27.4 K, which matches the temperature calculated by Head (ref. 19) when Earthshine and reflected radiation are not accounted for. When Earthshine and reflected radiation are included, Head predicts minimum temperatures in craters of 70 K.

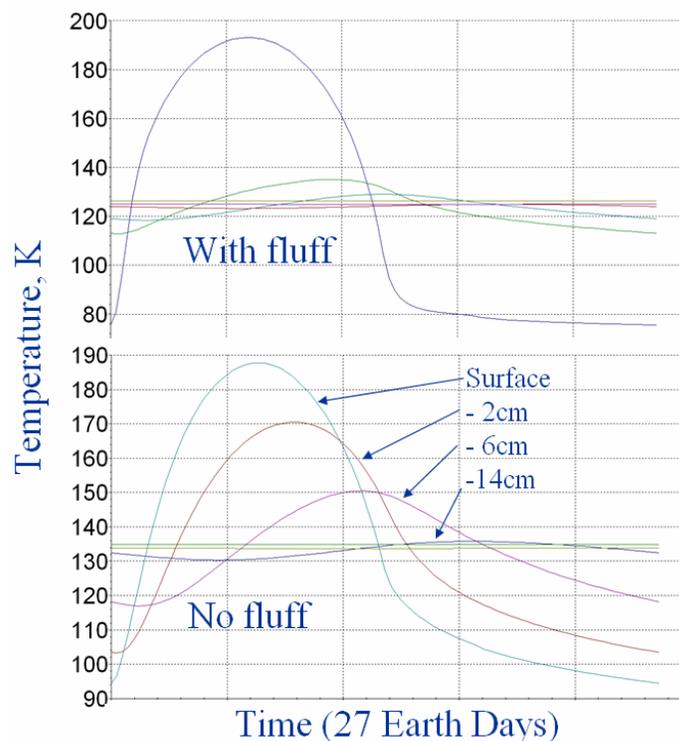


Figure 14.—Lunar surface and subsurface temperatures with and without fluff at 85° N latitude.

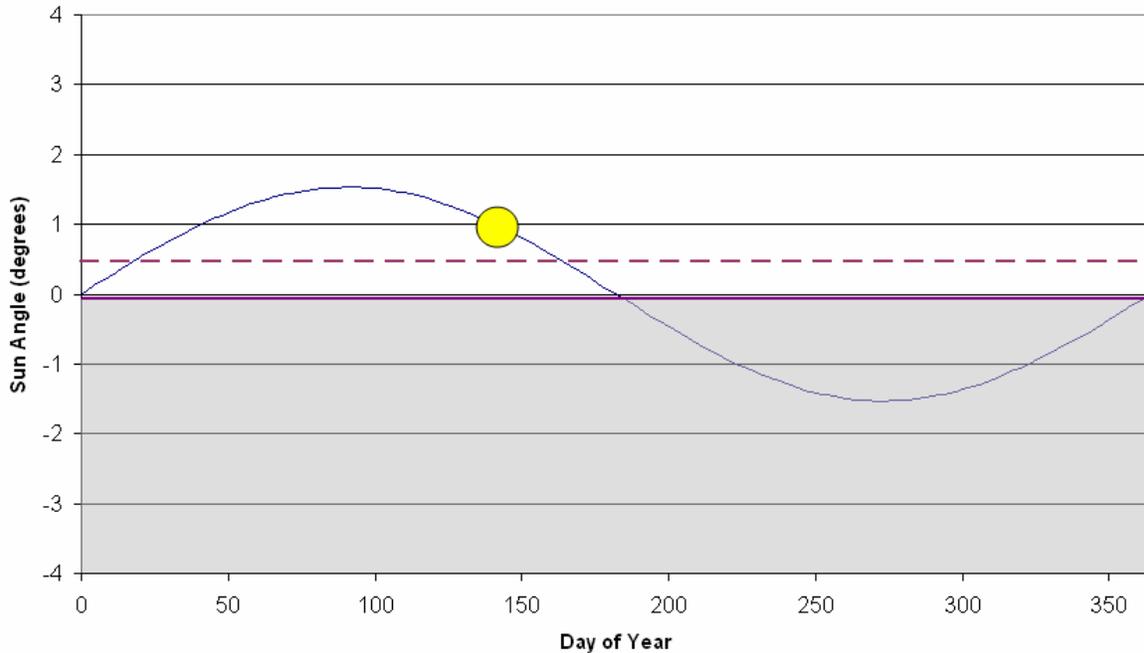


Figure 15.—Sun angle versus day of year at 90° S latitude, zero elevation.

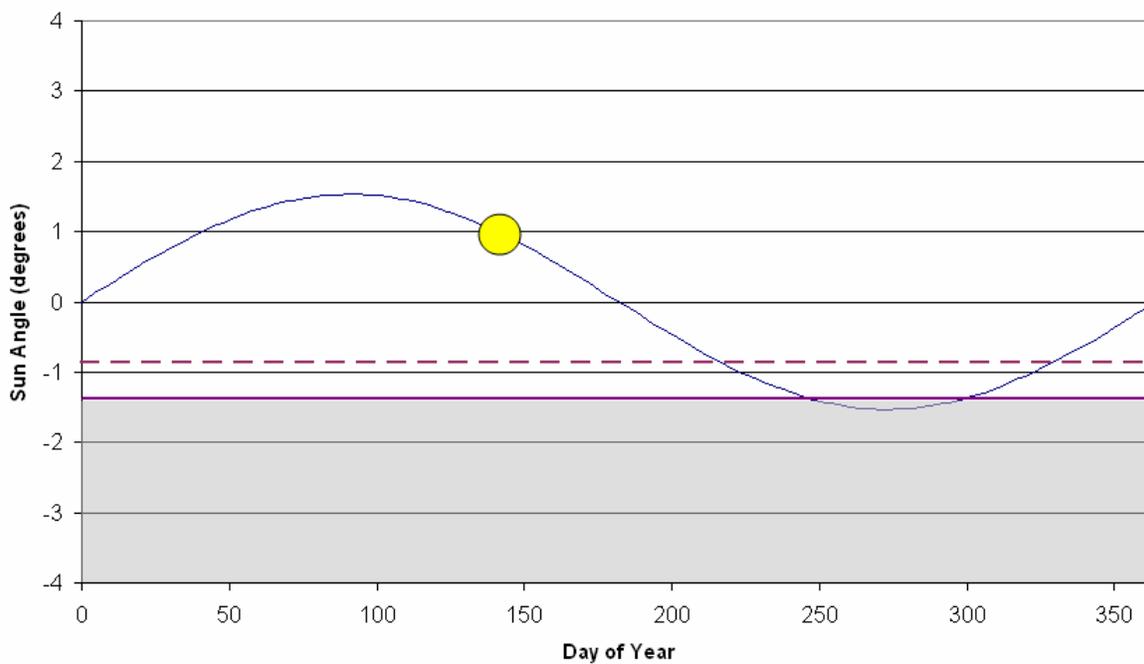


Figure 16.—Sun angle versus day of year at 90° S latitude, 500 m elevation.

When vehicle surfaces are exposed to temperatures below 100 K, its emissivity can drop significantly. When this happens the vehicle surface cannot radiate as efficiently and will not reach the low temperatures predicted by an analysis that does not account for temperature dependent radiative properties. Furthermore, there is an insufficient database of vehicle surface properties at temperatures below 100 K for the materials considered.

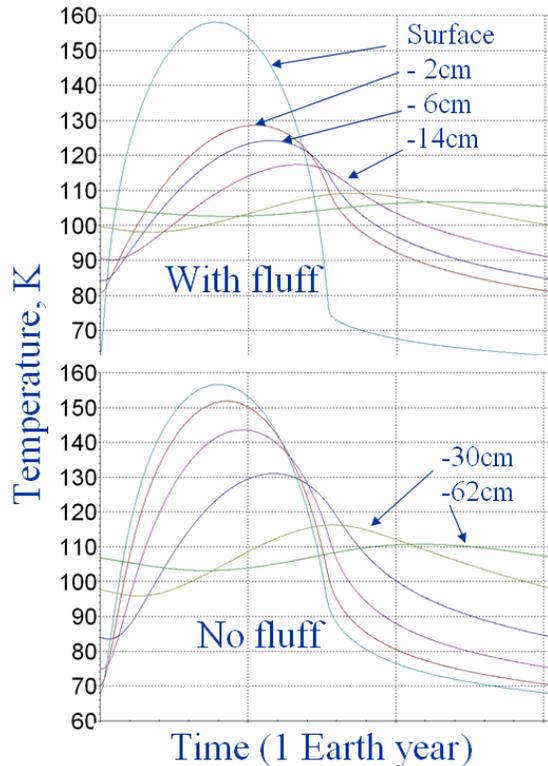


Figure 17.—Lunar surface and subsurface temperatures at 90° S latitude, zero elevation, with and without fluff.

South Pole Topology

It is very difficult to define the day and night periods throughout the year at the Polar regions. The topology of the region is complicated with basins 4 km deep and mountains 12 km high, which are not found on Earth. The South Pole is located within the South Pole Aitken basin (SPA) which is a large crater over 2500 km in diameter and averaging 12 km deep near the center of the basin. The pole is about 200 km inside the rim crest of the SPA. Because of its location inside the topographic low, the elevation of the South Pole is likely to be several kilometers below the mean lunar radius, resulting in zones of permanent shadow. As Clementine laser altimeter did not operate for lunar latitudes greater than 70°, there is no altimetry data for the polar regions. . . .’ (ref. 16) But elevation maps have been made using relatively little photographic data. These maps have been used to assess lighting conditions and to characterize Peak of Eternal Light. (ref. 17) These peaks will be permanently lit during the summer and will be in shadow for very short periods in the winter.

There is significant interest in the landing located on the rim of the Shackleton crater, which is within a few kilometers of the South Pole. As indicated in figure 18, the winter illumination periods can vary significantly with location and a proposed landing site might only be illuminated 50 percent of time. Furthermore, small changes in location or surface slope can have a significant effect. Shadowing from adjacent high terrain can make lighting intermittent, as indicated by figure 10, and the surface slope gradient can be large relative to the Sun angle, which is less than 1.5° at the pole. For example, if the surface slopes 1.5° towards the Sun the solar heating load will double, if it slopes 1.5° away from the Sun the solar heating load will be zero; and since the Sun moves horizontally across the horizon this angle of incidence will vary throughout the year.

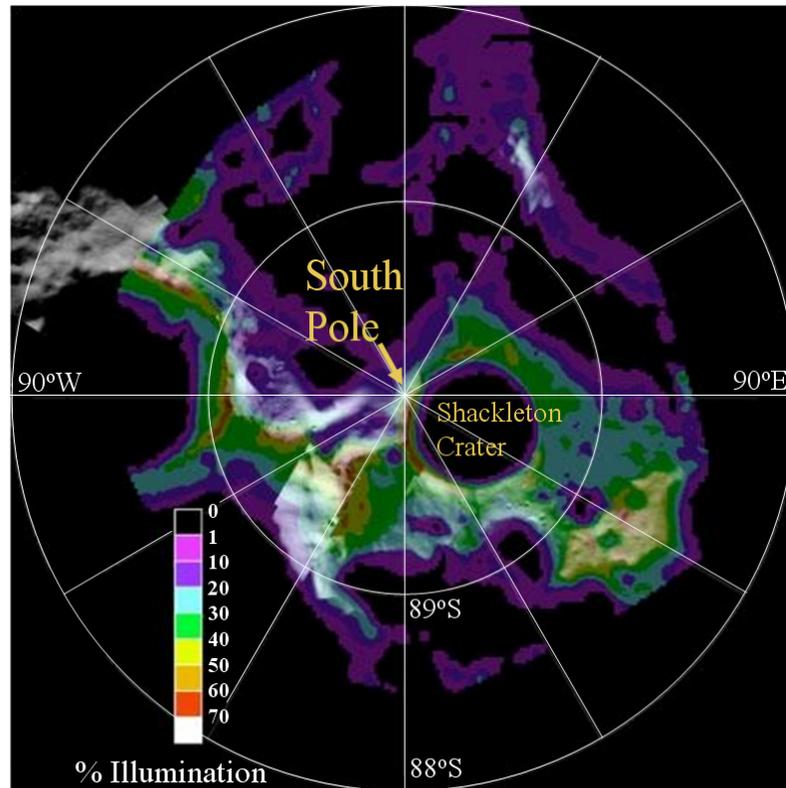


Figure 18.—Peak of Eternal Light on Shackleton Crater Rim (ref. 18).

When determining minimum temperatures after long periods of darkness, Earthshine and solar reflections from nearby peaks can be important. As discussed earlier, Head (ref. 19) showed when located inside of a crater and only heat from the lunar interior is accounted for, the steady state temperature is 28 K; but when Earthshine is included, the temperature rises to 38 K and after adding solar reflections from the crater rim it rises to 71 K. When just solar reflections are accounted for, the temperature is 70 K indicating that this is the dominating factor, i.e. adding Earthshine and interior heat only adds 1 K.

Conclusions

A thermal model has been developed which can be used to predict daily lunar surface and subsurface temperatures at any latitude throughout the year, if realistic illumination period data can be provided. It can also account for elevation and the presence of a fluff layer. The model was verified using Apollo and Clementine transient surface and subsurface temperature measurements taken at near-equatorial regions. It compares well with other analyses performed at 85° N latitude. The model was then extrapolated to predict the surface and subsurface temperatures at the lunar poles. This may be used to evaluate the thermal performance of vehicle surface elements used for the storage of cryogenic fluids at equatorial and polar landing sites.

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