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The Effect of VIPER Headlights on Lunar Surface and Subsurface Temperatures

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Summary: Upcoming lunar missions will introduce light flux to regions shielded from direct sunlight; we investigate the thermal effects on the lunar surface and subsurface from these lights.

Introduction: Permanently shadowed regions (PSRs) at the lunar poles are a consequence of the nearly perpendicular orientation of the lunar spin axis to the ecliptic plane. PSRs do not see direct sunlight and harbor extremely cold environments where temperatures can be below 20K [1,2]. These extreme environments are of interest due to their ability to host a variety of volatile species over geologic timescales. Cold traps are regions that limit sublimation rates of volatiles to under 1 kg m^{-2} Gya^{-1} [3]. For water ice, this rate corresponds to a temperature near 110K, and for CO_2 ice this is near 55K [4], though regions at these temperatures do not alone indicate the presence of volatiles [5,6].

Aiming to inform questions on the distribution and origin of lunar volatiles, NASA's Volatiles Investigating Polar Exploration Rover (VIPER) is slated to land near the lunar south pole in late 2024. The extreme topography of the south pole and the objectives of the mission necessitate illumination during rover traverses. These needs are addressed by the inclusion of the NavLights (among other luminaires), which consist of two forward facing light fixtures on gimbals with elevation and azimuth angle control. The introduction of artificial light flux from the NavLights in PSRs is unprecedented, highlighting the need for an analysis of the effects on surface and subsurface temperatures. Unintentional energy flux to the surface may alter the stability of volatiles in and near PSRs. Here, we address possible thermal effects that lights may have on the upper 1 m of lunar regolith.

Methods: We use our 1D thermal finite element model, which solves for temperatures from the 0 to 1m depth with a resolution of 1cm. For lunar regolith thermophysical properties, we use the specific heat capacity and depth-dependent density models from [7], the geothermal flux from [7] and [8], and the thermal conductivity model from [9] to account for the ultracold temperatures of the south pole. There are three different cases evaluated in this study, two of which are determined by equilibrium surface temperature, while the last case is chosen to represent a PSR condition. Surface temperatures of 100K and 50K are selected for the first two cases. For the PSR case, the temperatures are determined by evaluating the equilibrium condition given zero surface flux; this corresponds to a surface temperature of 24K. The thermal variation with depth for each case is determined by solving for the equilibrium condition given by the surface temperature. For the sake of brevity, Cases 1, 2, and 3 refer to the cases of 100K, 50K, and 24K initial surface temperatures. The illumination footprint (see Figure 1) is dependent on the orientation and design of the luminaires. We consider the flux from the NavLights, focused 1m directly in front of the rover, corresponding to an elevation angle of 60.95º below the horizon, and a 0º azimuth angle. We do not consider the spectral absorbance of the surface at the specific wavelengths of the NavLights.

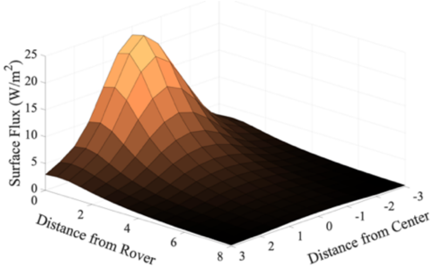

Figure 1: NavLight surface flux, fixture elevation angle of -60.95º, azimuth of 0º

VIPER Analysis: During the VIPER mission, the NavLights will be used for only brief periods of illumination. Nominal use will be flashes under 100ms in sunlit regions and near 1s in shadowed regions, with the off-nominal maximum being 5s. The design maximum of the NavLights is 10s [10], though this is beyond even off-nominal usage. Applying our model, we find that nominal light usage leads to temperature increases of 0.1K or below. Durations of 1s, 5s, and 10s lead to temperature increases less than 1K across the lighting area for all cases, while temperature changes are negligible in the subsurface. For each duration tested, Case 3 sees the highest temperature increases, which under the center of light increases 0.6K over 5s (Figure 2). Along with other operational mitigations, low lighting durations for the VIPER mission mitigate the heat transfer to the surface, which limits interference with science activity like volatile prospecting. The thermal effect of the NavLights within designed use is minimal.

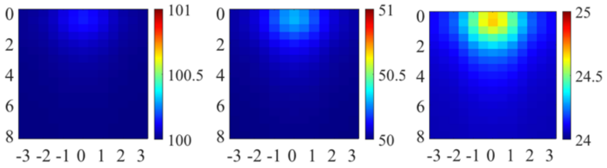

Figure 2: Cases 1, 2, and 3 surface temperature maps after 5s X-axes and y-axes are distances from the center of the rover and the rover itself, respectively, in meters.

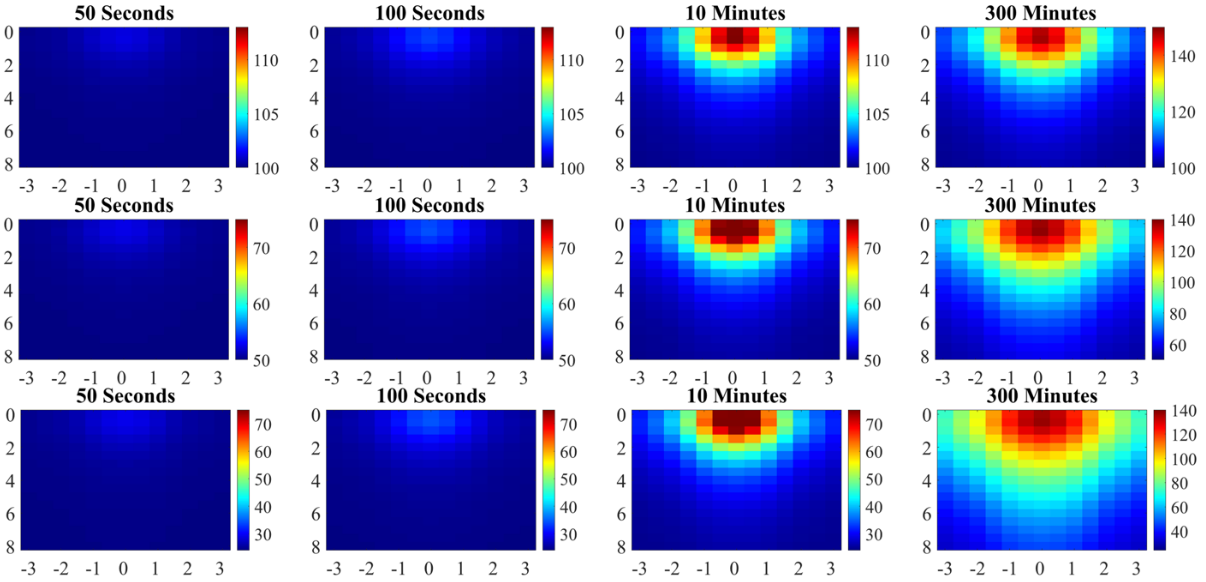

Figure 3: Cases 1, 2, and 3 surface temperature maps after 50 seconds, 100 seconds, 10 minutes, and 300 minutes. X-axes and y-axes are distances from the center of the rover and the rover itself, respectively, in meters.

Future Mission Lighting Scenarios: Future lunar missions to the lunar south pole may require longer duration illumination and may be less constrained by their power budgets to provide lighting. Possible scenarios are lunar base camps and active worksites which necessitate proper lighting for manned science and construction activities. For these scenarios, we extend simulations to 300-minute light exposures using the NavLight luminaires. Such durations will not occur during the VIPER mission as the nominal light use is near 1 second, but these results show the impact that relatively low light intensities (24 Wm^{-2} peak under the center of light) can have on the cold lunar surface over long timescales for future missions. We find that heating from these lighting conditions is increasingly significant for areas with cooler initial conditions, and initial surface heating rates are largely linear for an initial period. Shown in Figure 3, Cases 1, 2, and 3 see temperature increases of 13K, 28K, and 56K directly under the center of light over 10 minutes. Temperature increases fall off with distance. Over 300 minutes, surface temperatures approach 148K for case 1, and 139K for the cases 2 and 3 as shown in Figure 3. Each case reaches 120K after 16, 32, and 20 minutes, respectively. For all cases, temperature changes below 2cm are insignificant for the timescales tested.

Heating of this scale is important to characterize for future lunar missions, as this indicates that extended surface lighting may pose a risk to the stability of surface volatiles. Likewise, luminaires designed with long term lighting capabilities or high outputs can aid surface investigations with their ability to vaporize volatiles.

Conclusion: During mission operations, the VIPER NavLights lack the ability to significantly heat the lunar surface, and subsurface temperature increases will be negligible. Over nominal light usage, surface temperatures will see maximum increases of near 1K. This is due to the low lighting durations and other operational mitigations used to minimize heating and avoid interference with science activities.

In future lunar missions, extended periods of surface illumination will impact the stability of surface volatiles. Using VIPER luminaires as example hardware, 1 hour of similar light flux on the surface is enough to increase a range of surface temperatures (24K – 100K) to 120K. Over 5 hours, surface temperatures under the center of light may reach 140K and above, with subsurface heating being observed in depths up to 2cm.

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