The Oxford 3D Thermophysical Model with application to the Lunar PROSPECT Mission

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Overview: To investigate potential in situ near surface volatiles that might be present in the lunar Polar regions, the European Space Agency (ESA) is developing the PROSPECT instrument package to fly to the South Polar region of the moon on-board Russia's Luna-27/Luna Resurs mission, which is scheduled to launch in the early 2020s [1,2]. PROSPECT will consist of a drill (ProSEED) that will collect samples from the regolith at depths of up to 1 m below the lunar surface and transfer them into a miniaturised chemical laboratory (ProSPA), where samples will be heated to 1000° C in the presence of different reagent gases to extract a range of different volatile species including water. For 8 study landing sites of the Luna-27 mission, to investigate the depth at which water ice is likely to be stable we have modelled the lunar surface and subsurface (<2.5 m) temperatures using the new Oxford three-dimensional thermophysical model. These sites have been identified as of specific interest as potential candidate sites for Luna 72/Luna Resurs, in part due to proximity to permanently shadowed areas and/or proximity to topographic features resulting in local shadowing of the site.

Oxford 3-D Thermophysical Model: One dimensional thermophysical models are poor predictors of the lunar polar surface and subsurface temperatures due to the importance of shadowing and scattering at high latitudes. To accurately model the surface and subsurface temperatures at the lunar poles requires a 3-D thermophysical model (3DTM). A new 3DTM that includes a discreet subsurface exponential density profile, surface shadowing and scattering effects has been developed at Oxford University to simulate the lunar surface and subsurface temperatures to account for these environmental effects at the poles [3,4,5]. The Oxford 3DTM combines the one-dimensional subsurface heat flow from the Hayne model [5] and the 3-D shadowing and scattering effects used in standard 3DTMs such as the Paige and Vasavada models [3,4]. To compute the shadowing and scattering effects the Oxford 3DTM uses the LOLA topography and albedo datasets. However, since the LOLA albedo measurements are performed using a 1064.4 nm laser the albedo values are scaled to represent the broadband solar albedo value using the method described in [5]. All other thermophysical modelling parameters are taken from [5].

There is currently no in situ data for the Polar regions to compare to our modelled values, so the simulations have been compared to measurements from the Lunar Reconnaissance Orbiter's Diviner Lunar Radiometer instrument ("Diviner") for validation [6].

The central location of each site studied is given in Table 1. The sites were simulated at 3 different resolutions (4 ppd, 16 ppd and 128 ppd - pixels per degree). Each model simulation was kept to ~2 hours in simulation time on a standard desktop personal computer by adapting size of the area simulated to that shown in Table 2.

Site	Latitude	Longitude
1	-79.30	-56.00
2	-80.56	-37.10
3	-81.24	68.99
4	-81.35	22.80
5	-84.25	-4.65
6	-84.33	33.19
7	-85.33	-4.78
8 *	-82.70	33.50

Table 1 : Study landing sites of the PROSPECT mission

Resolution	Latitude buffer	Longitude buffer	Simulation size	Surface element size
4ppd	4.00°	20.00°	~ 245 km	~ 8 km
16ppd	2.00°	10.00°	~ 122 km	~ 2 km
128ppd	0.15°	0.75°	~ 9 km	~230m

Table 2 : Area of simulated region around each study landing site for each resolution used.

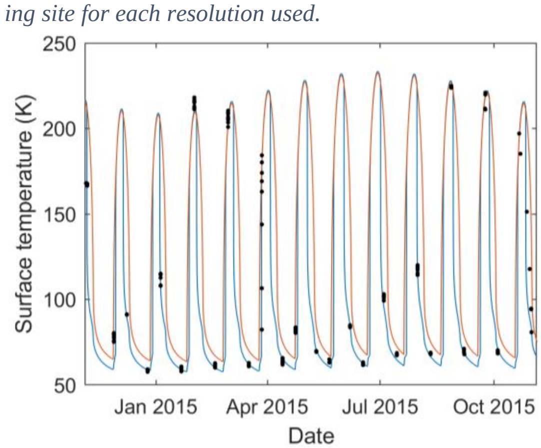

Figure 1 : Blue line is the 3D modelled surface temperature including shadowing and scattering, orange line is a 1D thermal model for the same location not including shadowing and scattering. Black dots are Diviner measurements at site 8. There are multiple Diviner measurements at each time due to the simulation surface elements covering multiple Diviner pixels.

Model Accuracy: We will present an overview of modelling results from all 8 sites and provide the 16 ppd resolution for site 8 as an example in this abstract. Figure 1 shows the comparison between the Diviner measured surface temperature and the modelled surface temperature for the element that contains the central location of site 8. As can be seen in Figure 1 the 3DTM is in good agreement with the Diviner measurements with the absolute temperature deviation being typically less than 5 K. Where the absolute temperature deviation is defined as being the time averaged absolute difference between the modelled temperature and the Diviner measured temperature.

The modelled temperature deviates from measured Diviner surface temperatures greatest during sunrise and sunset when the surface temperature is changing rapidly. During these periods the modelled temperature deviation from the Diviner measurements can be ~10 K due to a timing or geometry error where the modelled temperature changes slightly earlier or later than the Diviner temperature. This deviation is likely due to the model only simulating the sun as a point source.

The absolute model deviation from Diviner surface measurements is also high in regions that are in near permanent shadow such as pole facing shallow slopes and surface elements on the boundary of permanently shadowed regions. For many of these areas the model of the sun as a point source and the discrete simulation grid causes the model to treat them as permanently shadowed, even though they are only partially shadowed during the summer. This can cause deviations of > 30 K and as such modelled temperatures in these regions should be treated with caution. The absolute temperature deviation from Diviner surface measurements for the 16 ppd simulation of site 8 can be seen in Figure 2.

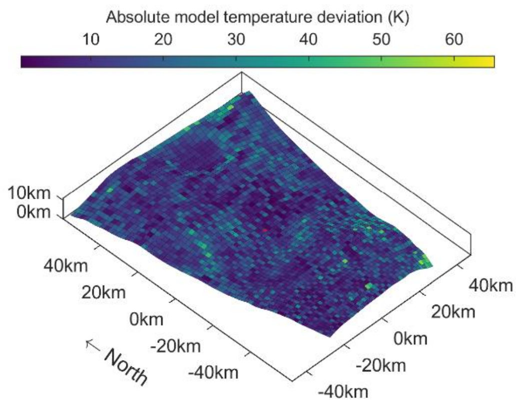

Figure 2 : Absolute difference between Diviner surface temperature measurements and 3DTM surface temperatures at site 8. Red dot shows center of site 8.

Ice Stability Depth: Despite the limitations of the model outlined above, it is still possible to make deductions on the ice stability in these regions. From the thermal model it was possible to define the depth required to drill to reach subsurface temperatures where water ice is expected to be stable by assuming water ice is stable if the temperature remains below 112 K throughout the seasonal cycle [3]. The minimum stable ice depth can be calculated as the depth required to drill to get to a subsurface layer that has a stable temperature < 112 K.

The minimum stable ice depth for site 8 is shown in Figure 3, which shows there are large regions where ice is not stable at any depths and in those locations where ice is stable the minimum ice stability depth is relatively shallow (< 0.5 m). Across all landing sites it was found the simulated minimum constant temperature typically occurs at a depth of ~ 0.5 m. These results show that, assuming careful selection of landing site. The current design depth of the PROSPECT drill (~1 m) should be sufficient to sample trapped water ice.

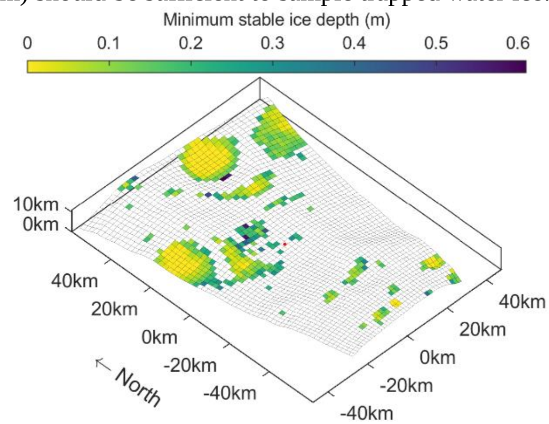

Figure 3 : Minimum depth of stable water ice for region surrounding site 8.

Conclusions: Depths at which ice would be expected to be stable are generally near the surface (< 0.5 m), so the choice of landing site location and the precision landing capability of the lander are essential given the engineering constraints on the sampling system.

There is an obvious correlation between the illumination fraction and the volatile stability conditions. Luna-27/PROSPECT will therefore have a trade-off to select a site that will satisfy both critical power/operations requirements and science objectives of the PROSPECT mission.

Acknowledgements: We would like to thank the UK Science and Technology Facilities Council, the Leverhulme Trust, the UK Space Agency and the European Space Agency for supporting this work.

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