ANALYSIS OF LRO DIVINER LUNAR SOUTH POLAR OBSERVATIONS USING AN ADVANCED HIGH-RESOLUTION THERMAL MODEL David A. Paige[1] dap@moon.ucla.edu, Erwan Mazarico[2], Tyler Powell[1], Lior Rubanenko[1], Mai Tran[1], Emily Foote Smith[1], Jean-Pierre Williams[1], Matthew A. Siegler[3], [1]Department of Earth, Planetary and Space Sciences, UCLA, Los Angeles, CA 90095; [2]NASA Goddard Space Flight Center, Greenbelt, MD; [3]Planetary Science Institute, Tucson AZ.

Introduction: The south polar region of the moon is a key target for future scientific exploration. The rugged south polar topography creates a diverse range of thermal environments whose temperatures exhibit extreme spatial and temporal variability. The thermal diversity of the region presents opportunities for cold-trapping of volatiles as well as challenges for surface and subsurface exploration.

Diviner Dataset: The LRO Diviner Lunar Radiometer Experiment has acquired an extensive set of thermal emission observations of the south polar region[1,2]. Diviner maps of bolometric brightness temperature have been produced with a ~250m covering a range of local times and seasons[2]. The Diviner data provide a valuable picture of polar thermal behavior, but the spatial resolution of the instrument and LRO's orbital coverage necessarily limits the completeness of the thermal database for investigating the thermal stability of volatiles and for planning future surface missions.

Thermal Model Approach: Thermal models use physics-based parameterizations to simulate the dominant processes responsible for determining the temperature of the surface and subsurface as a function of time. The results can be used to predict or postdict surface and subsurface temperatures, as well as observable emitted and reflected radiation to space. Lunar polar thermal models are challenging to implement because scattered solar and infrared radiation by topography dominate the surface energy balance of shadowed polar regions. The ray-tracing thermal model used by Paige et al, (2010)[1] successfully reproduced Diviner bolometric temperature observations of the lunar south polar region at a spatial resolution of 500m. In this study, we use a significantly more advanced version of the model that incorporates new LRO data and new insights gained from studying these data over the past ten years.

Topographic Dataset: The Paige et.al. (2010) model used south polar topography measured by the JAXA Selene orbital laser altimeter experiment[3]. The new model uses topography derived from the LRO LOLA instrument at a spatial resolution of 50 m, which represents a one hundred-fold improvement in topographic point density[4]. The new south polar topography covers the region within 150 km of the south pole has been processed to significantly reduce slope artifacts due to mismatched orbital tracks.

Roughness Parameterization: The Paige et al (2010) model represented the surface of the south polar region as a triangular mesh consisting of smooth facets with isotropic solar reflection and thermal emission characteristics. The model accounted for topographic shadowing and multi-order solar reflection and emission by large-scale topography. Subsequent goniometric measurements of the bi-directional reflectance of Apollo samples[5], and bi-directional and multi-spectral thermal emission from the lunar surface[5] have shown that the lunar surface exhibits strong anisotropic reflection and emission characteristics, particularly at high incidence angles. These can be traced largely to the effects of small-scale topographic roughness, which results in strong thermal contrasts on centimeter or smaller length

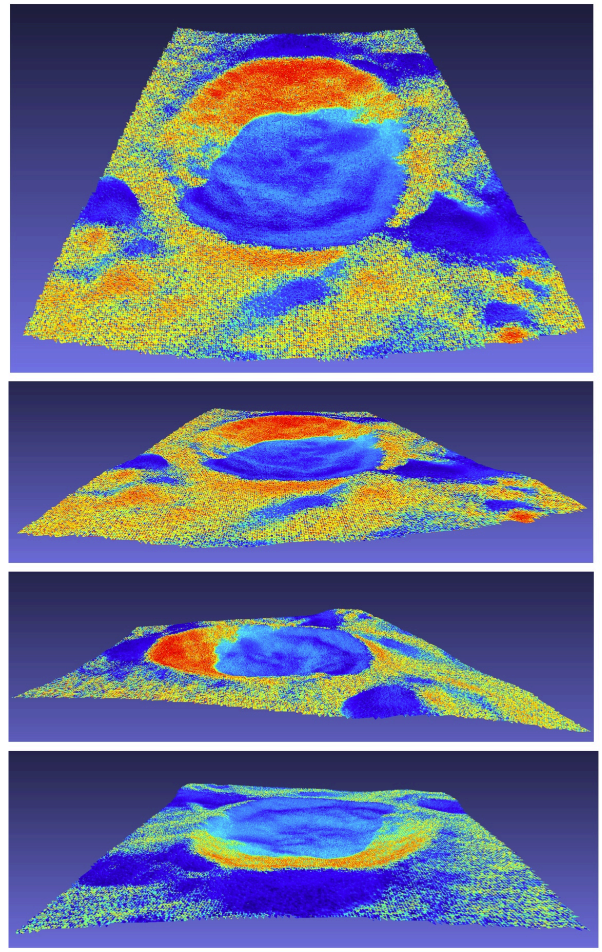

Fig. 1. Four views of an instantaneous snapshot of calculated surface temperatures for a roughened sub-faceted model representation of the south polar crater Wiechert J (85.6°S, 177.0°W).

scales[6]. The updated model incorporates these effects by dividing each ~50 meter mesh triangle into ~16 smaller triangles to create a continuous rough surface with a gaussian distribution of slope angles peaked at ~25°, which is required to reproduce Diviner multi-spectral thermal emission observations at lower latitudes[5]. In the new model, radiation fluxes are calculated for each individual sub-facet using ray tracing, which enables explicit determination of the ~16 sub-facet surface temperatures. The resulting anisotropic and anisothermal temperatures can be compared directly with angular and spectral observations made by Diviner from orbit. The net effect of this roughness is to "beam" low phase angle reflected and emitted solar energy from illuminated crater walls into the permanently shadowed regions, thus increasing their surface temperatures to be more consistent with Diviner observations (See Fig. 1).

Thermal Conduction Parameterization: The Paige et al., 2010 model utilized the Vasavada et al (1999)[7] two-layer parameterization of the density structure of the lunar regolith, with thermal and reflectance properties that were tuned to match Diviner bolometric brightness temperature measurements in illuminated regions at high-latitudes. The updated model uses the Hayne et al (2017)[8] regolith density structure and the Woods-Robinson et al. (2019)[9] temperature-dependent thermal properties parameterization, which have been shown to agree well with lunar soil measurements at cryogenic temperatures[10]. The model employs a 3-d conduction scheme developed by Powell (2019)[11] to calculate temperatures in the uppermost ~2 cm of the lunar surface. In this approach, the 16 triangular sub-facets used in the roughness parameterization described are assumed to be representative of the ~0.5 m length-scale roughness of ~50 meter triangle as a whole. To account for the fact that horizontal heat conduction cannot be neglected[5], the top three surface layers are represented as a space-filling tetrahedronal mesh that extends three layers below the rough surface. Below the third layer, the surface is assumed to be spatially isothermal and is represented by a conventional 1-d thermal model with parallel layers. This approach enables realistic calculations fine-scale surface temperature diversity as well as accurate sub-surface temperatures that track the areal averaged effects of fine-scale surface irregularities.

Parallel Implementation: The updated model is optimized for parallel computations on a high-performance computer cluster. The calculations proceed in four steps. The first step uses ray tracing to calculate the radiative interaction probabilities between all the facets. The second step optimally partitions the triangular mesh between the cluster computers based on mutual visibility. The third step calculates surface and sub-surface temperatures for all the facets and sub-facets as a function of time. The fourth step analyzes the output to produce diagnostic output and higher-level data products.

Model Outputs and Database: The output of the model can be used to predict direct and indirect insolation conditions as well as average surface and subsurface temperatures for specific ~50 meter regions as a function of time at ~0.5 Earth day intervals. Maps and time-lapse thermal movies can also be produce. Model outputs also enable calculations of the time-dependent thermal stability of potential surface and sub-surface volatiles. The model can also predict bolometric brightness temperatures and Diviner brightness temperatures at specified viewing geometries. A reference standard version of the model results will be available to the community in a publicly-accessible database.

Key Science Questions: The updated high-resolution model results in conjunction with Diviner data will enable us to address a number of key outstanding science questions. While the normal albedo near IR of the south polar region has been mapped by LOLA[12], the thermal properties of the south polar regolith in illuminated and permanently shadowed regions is currently unknown. We anticipate that the new model results provide new insights regarding the degree to which south polar surface and subsurface thermal properties are consistent with those observed at lower latitudes. Potential correlations between thermal state and thermal properties are of special interest as they may reveal the presence of surface or subsurface volatile deposits.

References: [1] Paige et al, Science 330, 479, 2010. [2] Williams et al., JGR Planets 124, 2019. [3] Akari et al, Science 232 897, 2009 [4] Zuber et al., Nature 11216, 2012. [5] Foote et al., Icaurs 336, 113456, 2020. [6] Bandfield et al., Icarus 248, 357, 201. [7] Vasavada et al., Icarus 141, 179, 1999 [8] Hayne et al., JGR Planets, 2017JE005387, 2017. [9] Woods-Robinson et al., JGR Planets, 2019JE005955, 2019. [10] Siegler et al. P24A-05, Fall AGU 2016. [11] Powell et al., P41C-3468, AGU Fall Meeting, 2019. [12] Lemelin et al., Icarus 273, 315, 2016.