LOCATION AND ACCESSIBILITY OF WATER ICE-BEARING PERMANENTLY SHADOWED REGIONS IN THE SOUTH POLAR REGION OF THE MOON. M. Lemelin1, 1Département de Géomatique appliquée, Université de Sherbrooke, Québec, Canada, J1K 2R1 (Myriam.Lemelin@USherbrooke.ca)

Introduction: The presence of water ice in permanently shadowed regions (PSRs) near the poles of the Moon as been inferred from a variety of remote sensing observations since the 1990s. Neutron spectrometers (e.g., Lunar Prospector Neutron Spectrometer-LPNS and the Lunar Exploration Neutron Detector-LEND) provided evidence for increased H within the upper meter of the regolith near the poles, while radar instruments (e.g., Clementine bistatic radar experiment, Mini-RF, and Mini-SAR) suggested the presence of water ice within the top meter of the regolith in certain PSRs [1-4]. Instruments operating from the far-ultraviolet (UV) to the near infrared (NIR) (e.g., the Moon Mineralogy Mapper – M3, the Lyman Alpha Mapping Project - LAMP, the Lunar Orbiter Laser Altimeter - LOLA) provided evidence for water ice at the surface [5-8]. However, these observations were either not spatially resolved within specific PSRs or were ambiguous as the signal detected could be due to other phenomena (e.g., wavelength-scale roughness, increased porosity, decreased space weathering) than water ice itself.

In 2009, the Lunar Crater Observation and Sensing Satellite (LCROSS) impacted into the PSR region of Cabeus crater near the south pole and provided direct evidence of the presence of water ice at this location. A shepherding spacecraft measured spectra of a plume of debris ejected by the impact and concluded that the concentration of water ice at the impact site was $\pm 5.6 \pm 2.9\%$ by mass [9]. In 2018, a study [10] of hyperspectral data acquired by M3 provided direct evidence of the presence of water ice at the optical surface (typically less than a few mm) in multiple PSRs, both in the north and south polar regions, based on the presence of spectral absorption features at 1.3, 1.5 and 2.0 μm, which corresponds to overtones and combination mode vibrations for H$_2$O ice. The vast majority of these spectral absorption features are co-located with extreme LOLA reflectance, LAMP “off” and “on” band ratio, and surface temperatures perpendicularly below the sublimation temperature of H$_2$O (110 K) [10].

Given these recent developments, it is now possible to identify specific PSRs where water ice has been detected at the surface and/or potentially at the subsurface. In preparation for the upcoming exploration of the polar regions, we can use this information to assess the accessibility of the water-bearing PSRs, and determine which one(s) should preferentially be explored. In this study, we conduct a spatial analysis to provide an integrated answer to the following questions: (1) In which PSRs has water been detected? (2) Is the water ice located at the surface, subsurface or both? (3) Where is it possible to safely land to access those water ice-bearing PSRs? (4) Is it possible to safely get from point A (landing site) to point B (water ice-bearing PSRs)? If multiple water ice-bearing PSRs are accessible, (5) which one(s) should preferentially be explored?

Datasets: To address these questions, multiple remote sensing datasets were used such as: the location of surficial water-ice detections from M3 data (Figure 4 in [10]), the location of potential subsurface water-ice by Mini-RF (Table S1 in [2]) and the location of PSRs available at a spatial resolution of 240 meters per pixel from 65-90°S [11]. The LOLA gridded Digital Elevation Model (DEM) data available at a spatial resolution of 20 meters per pixel from 80-90°S [12], illumination conditions modeled at a spatial resolution of 500 meters per pixel between 70-90°S [13], and Hydrogen content measured by Lunar Prospector [3] available at a spatial resolution of 0.5 degrees per pixel were also used.

Methods: To address the questions regarding the location and accessibility of water ice-bearing PSRs in the lunar south polar region, a spatial analysis was conducted in ArcGIS for the south polar region (80-90°S). To (1) determine in which PSRs water ice has been detected and to (2) determine if the water ice is located at the surface, subsurface or both, the shapefile of PSR locations was imported. PSRs smaller than the spatial resolution of the M3 data ($280 \times 280$ m) were discarded. The figure showing the M3 detection of surficial water-ice was also imported and georeferenced. The latitude and longitude values of potential subsurface water ice detection by Mini-RF were also added. Each PSR was manually checked to see if it is co-located with an M3 and/or a Mini-RF detection.

To determine (3) where it is possible to safely land in the perspective of accessing water ice-bearing PSRs, the LOLA DEM and the modeled illumination conditions were added. The slope was calculated from the LOLA DEM and the modeled illumination conditions were added. The slope was calculated. Any pixel where the slope is steeper than 10 degrees was excluded from the analysis.

To (4) determine if it is possible to safely get from a potential landing site to a water ice-bearing PSR, the distance between locations identified as “safe to land” in (3) and water ice-bearing PSRs identified in (1) was calculated. Any pixel where the slope is steeper than 10 degrees were excluded from the analysis.

Finally, to (5) determine which water ice bearing PSRs should preferentially be explored, the total area in these PSRs that are characterized by navigable slopes (i.e., $<10^\circ$) were calculated and their H content was taken into consideration.
Results: A total of 282 PSRs larger than 280 × 280 m are identified as having water ice at the surface based on M3 detections and/or potentially water ice at the subsurface based on Mini-RF data. For 255 PSRs, water ice has only been detected at the surface by M3 (although this does not exclude that it is also present at the subsurface). For 19 PSRs, water ice is inferred to be present only below the surface. For 8 PSRs, water ice has been detected at the surface and is inferred to be present below the surface (Fig. 1a).

Sites here considered to be safe for landing (i.e., that have slopes <10° and that are illuminated at least 45% of the time) correspond to flat surfaces outside large craters from 80-85°S, while they mostly correspond to crater rims poleward of 85°S.

Calculation of the shortest distance from these sites to water ice-bearing PSRs, by navigating only on slopes shallower than 10 degrees, reveal that it is indeed possible to traverse from a potential landing site to some of the water ice-bearing PSRs. While this is true for many PSRs, only 71 of them have accessible terrain that is at least 1 km², ensuring that a rover would have sufficient flat terrain to rove and potentially find water ice. These 71 PSRs are all PSRs for which water ice has been detected at the surface only (although they might also have water ice at the subsurface). Only three of these 71 PSRs are located within 1 km of a potential flat and illuminated landing site (between ~82-85°S), but their hydrogen abundance is not especially high (45-117 ppm).

When the search radius is extended to 1-2 km away from a potential landing site, seven water ice-bearing PSRs become accessible. Four of them are distributed at various longitudes between 84-87°S and their hydrogen abundance is again not especially high (59-113 ppm), while three of them are located around Shackleton crater (Fig. 1b) and have higher hydrogen abundances (143-150 ppm). These three PSRs are relatively isolated from other water-ice bearing PSRs when navigable terrain is restricted to slopes shallower than 10 degrees.

Conclusion: While numerous PSRs contain surface (and perhaps subsurface) water ice, few of them are characterized by relatively large navigable terrain, and even fewer of them are located within 2 kilometers of a potential landing site based on the constraints used herein. The few sites that have been identified are isolated from other nearby PSRs because of a slope constraint. Future work will relax and tighten the landing site and rover constraints (based on specific mission scenarios) on the accessibility of water ice-bearing PSRs. Accessible water ice-bearing PSRs will then be ranked according to their priority in response to specific mission goals.

Figure 1. Water ice-bearing PSRs within 80-90°S. a) blue: surface water ice detected by [10], red: subsurface ice inferred by [2], green: surface and potential subsurface ice detected. b) accessible water ice-bearing PSRs with at least 1 km² of flat terrain. Three PSRs (1-3) are within 2 km of a potential landing site (not shown here).