Accessibility Data Set for Large Permanent Cold Traps at the Lunar Poles

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Abstract Many large cold traps exist at both lunar poles where temperatures never exceed 110 K annually, allowing the preservation of water ice. Much has been learned about these regions from orbital measurements, but in situ access is needed to truly understand the abundance, distribution, texture, and chemistry of volatiles that might be present in the regolith. We systematically studied the accessibility of the larger cold traps to wheeled vehicles from nearby staging areas. We calculated minimum energy routes for 20 north pole cold traps and 39 south pole cold traps >50 km² in area. At each, accessibility metrics were determined for paths into and out of the cold trap and for round trip paths that return to the same location. We found that 55 of the 59 cold traps are readily accessible without exceeding 25° slopes. Smaller cold traps are generally more accessible than larger ones, with certain exceptions. The accessibility data set is presented graphically, in tabular form, and as ArcGIS shapefiles, all of which can be used to inform site selection and mission planning for future scientific and resource-focused activities.

Plain Language Summary There are certain areas at the poles of the Moon which are cold enough to host ice deposits, but they have never been studied directly by robots or astronauts. In this study we determined how easy or difficult it would be for wheeled vehicles to get into and back out of coldest areas at the poles, which are found in topographic lows that sometimes have high slopes all around. We found that most of the cold areas can be driven into and back out of safely to nearby staging areas that have enough sunlight to recharge batteries. The smaller cold areas are generally easier to access, but some of the larger ones have safe, fast routes, especially for entry.

1. Introduction

The past decade has culminated in a significant new understanding of lunar polar volatiles (summarized by Lawrence, 2017) and an active water cycle on the Moon (Benna et al., 2019; Farrell et al., 2019; Li & Milliken, 2017), but many outstanding questions remain. Robotic spacecraft and humans will need direct access to cold trap regions at the poles in order to dramatically improve lunar volatile research and economic prospecting going forward. High-resolution time-resolved spacecraft observations now give a firm understanding of shadowing (Hayne et al., 2020; Kloos et al., 2019; Mazarico et al., 2011) and temperature conditions (Hayne et al., 2020; Williams et al., 2019) at the polar regions, advancing from theoretical predictions by Watson et al. (1961) and Arnold (1979). These data tell us where ices could exist. Remote sensing from orbit has produced conflicting estimates of where water ice does exist and how much there is, particularly in the upper meter (cf., Campbell & Campbell, 2006; Fa & Eke, 2018; Spudis et al., 2013; cf., Mitrofanov et al., 2010; Teodoro et al., 2014). Most satellite instruments are limited by spatial resolution and wavelength-dependent penetration beneath the regolith surface, which, for example, may explain some differences between neutron spectroscopy data (Teodoro et al., 2014), the Lunar Crater Observation and Sensing Satellite experiment (Colaprete et al., 2010), and shorter wavelength reflectance data (e.g., Li et al., 2018). As well, direct exposures of ice have not been observed in optical, long-exposure Lunar Reconnaissance Orbiter Narrow Angle Camera imagery. Faced with these limitations, Cannon and Britt (2020) drew on geologic processes, surface ages, and thermal environment data to develop a Terrain Type classification and an Ice Favorability Index (IFI) that predict where ices should exist and should be accessible in the upper several meters of the regolith column. The highest IFI values are mostly found in large permanent cold traps, which are the focus of this study.
Lunar cold traps are inherently challenging environments to access and operate in. Being permanently blocked from direct sunlight (which characterizes the surface of all cold traps) makes solar power impractical unless tall towers are erected, or long lengths of cable are laid. Lack of or only partial sight lines to Earth make communications difficult and probably require relay satellites. Tribocharging on equipment becomes an issue and must be mitigated to prevent buildup of high voltages (Rhodes et al., 2020). Because cold traps are found in topographic lows, they are often bounded by steep slopes that complicate wheel-based traverses (Bickel & Kring, 2020). Some craters that host cold traps like Amundsen feature flat, partially lit floors (Lemelin et al., 2014; Qiao et al., 2019) such that the partially lit region could be used for staging into the shadowed area. For the most part though, access must be gained from locations higher up above the rims of the crater or depression hosting the cold trap.

Previous studies have looked at traverses in single locations or groups of locations near the poles, but the accessibility of cold traps has yet to be assessed in any systematic way. Lemelin et al. (2014) developed a ranking system to down-select sites for missions focused on in situ study and sample return of volatiles. They produced maps and provided a number of hand-selected traverses as case studies. Speyerer et al. (2016) developed an optimized traverse-planning algorithm based on terramechanics (Bekker, 1956; Carrier et al., 1991; Terzaghi, 1943) and lighting conditions and applied it to a case study on the highly illuminated rim of Shackleton crater. Heldman et al. (2016) outlined a notional traverse at Haworth crater for the Lunar Prospector mission, which has since been reformulated as the Volatiles Investigating Polar Exploration Rover. Cunningham et al. (2017) created an advanced energy path planning algorithm and applied it to the Malapert region at the south pole. Basilevsky et al. (2019) also investigated Mons Malapert, in this case the topography and trafficability with eyes toward a possible operating base. Sargeant et al. (2020) used boulder tracks to assess the bearing capacity of regolith in permanently shadowed regions and found that it is modestly higher than regolith elsewhere. Bickel and Kring (2020) applied the same techniques to polar sunlit regolith and found similar bearing capacities to equatorial regions. These results give confidence that vehicles could drive in polar terrains and potentially down into cold trap regions without modifying their designs. However, the Sargeant et al. (2020) study was limited to latitudes less than ~75°, which leaves open the possibility that higher-latitude cold traps could have somewhat different properties. But which cold traps are most accessible? What routes provide the lowest-energy entry and egress from each cold trap, both for one-way traverses and repeated round trips from the same staging area?

Here, we systematically calculate the accessibility of 20 large cold traps near the Moon’s north pole and 39 at the south pole to build up a new data set to inform future scientific and economic activities. We locate well-lit, flat areas surrounding these cold traps for landing and/or staging then apply an energy-based cost function for traversing from these areas into the cold traps and back out again. Using Dijkstra’s algorithm, we calculate the lowest cost paths from staging areas to cold traps and determine different accessibility metrics for each path. The results provide a practical guide for exploring and prospecting volatiles at the lunar poles, and the techniques used are applicable to smaller cold traps than those studied here, or other scientific and economic regions of interest.

2. Methods

2.1. Cold Trap Locations

We follow Williams et al. (2019) and Hayne et al. (2020) in classifying cold traps as regions that are permanently <110 K annually. Larger cold traps like those studied here (>50 km²) are spatially resolvable over multiple ~250-m pixels in Diviner data (Williams et al., 2019), while smaller microcold traps are inferred based on shadowing and thermal models (Hayne et al., 2020). The reason that not all permanently shadowed regions are cold traps is due to energy reradiated from nearby illuminated slopes, and therefore, we suggest that studies of volatiles should focus on cold traps rather than permanently shadowed regions. For this study, the largest cold traps from 80°–90° latitude at both lunar poles were selected (Figure 1 and Tables S1–S2 in the supporting information) based on Diviner data from Williams et al. (2019). We gave each cold trap a unique identifier, with a two-letter code for the pole (NP = north pole, SP = south pole) and four-letter code that refers to the host crater in the case where it is named (e.g., Sverdrup crater = SVER) or is left as UN## for unnamed features.
2.2. Identifying Staging Areas

Larger cold traps are generally not suitable environments for landing and deploying infrastructure (such as an outpost) for reasons described above. An exception is battery-powered robotic spacecraft that could land directly in cold trap regions and carry out short-duration missions. However, our focus here is sustained exploration such as deep drilling and prospecting, or long-lived rovers that can visit multiple cold traps. In these cases, an area near the cold trap is required with favorable illumination conditions and safe terrain, with one or more viable paths into and back out of the cold trap. For example, one could imagine a small outpost established at a staging area that is occupied by humans for part of the year and from which robotic and/or human-operated vehicles are driven back and forth into the cold trap for scientific or economic activities. Or a long-lived polar exploration rover could traverse into a cold trap to take measurements then drive back out where it could recharge and move on to the next region.

To identify such staging areas, we used illumination (Mazarico et al., 2011) and topographic slope data at 40-m resolution from the Lunar Orbiter Laser Altimeter (LOLA) instrument (Smith et al., 2010) on board the Lunar Reconnaissance Orbiter. A circular boundary with a 30-km radius was placed around the target location identified within the cold trap (described below). Then, filters were applied to locate regions with >33% illumination (i.e., receives direct sunlight at least a third of the time throughout the 19-year lunar precession cycle) and <10° of topographic slope (Figure S1). These are generic values based on a useful duty cycle and low enough slopes to allow landing and infrastructure development but could be adjusted for more specific applications. We did not filter based on Earth visibility (i.e., direct communications) for the results shown here, but this could be applied to further discriminate staging areas, especially for nearside locations. Random points were drawn from these potential staging areas, as described below. Some of these points fell on crater rims or intercrater plains, while others were located on flat, illuminated areas on crater walls themselves, or even inside of the host crater/depression in some cases.

2.3. Cost Function and Accessibility Metrics

The cold traps are often vast areas (Tables S1–S2), and clearly, some parts of them will be more or less desirable and more or less accessible. We identified a notional target location within each cold trap to constrain the problem of which specific region to focus on. This target location was calculated using the maximum IFI value (Cannon & Britt, 2020) within the cold trap, filtered to areas with <10° slope. In some cases, this automated procedure led to target locations on small plateaus halfway up the rim of a large crater: In these instances, we manually readjusted the target location to a safer area on the crater floor.

We used Dijkstra’s algorithm to identify optimal paths between the staging areas and cold trap target locations. Dijkstra’s algorithm computes the shortest or lowest cost path between nodes on a graph. To construct the graph, we created nodes at the cold trap target location, 250 random points drawn from within the potential staging areas and 4,749 additional random points for a total of 5,000 nodes on the graph. Delaunay triangulation was used to construct the graph itself. We used the energy model from Speyerer et al. (2016), which was based on earlier work by Terzaghi (1943), Bekker (1956), and Carrier et al. (1991), to calculate the cost of moving from one node to the next. This model is based on the total tractive energy (which takes topographic slope into account) of a 700-kg wheeled vehicle moving at constant velocity, multiplied by the
distance traveled. We assume here that slopes >25° are not traversable. The Lunar Rover Vehicle on Apollo 15–17 was rated for a maximum slope of 25° (Costes et al., 1972), and this is also close to maximum traversed slopes by Mars rovers (Arvidson et al., 2017). It is possible that a different type of vehicle (e.g., legged or rolling) could traverse steeper slopes than this, but in this case the wheel-based tractive energy model would no longer apply.

Multiple metrics were calculated to address the question of how “accessible” each cold trap is, which is a subjective concept. We first used Dijkstra’s algorithm to find the lowest-energy path between each of the 250 random points in the potential staging areas and the cold trap target location. This was done in both directions, because wheel torque differs substantially going downhill versus uphill (Bekker, 1956; Carrier et al., 1991; Speyerer et al., 2016; Terzahi, 1943). We then assessed the most efficient (lowest energy) down-hill paths, uphill paths, and round trip paths (which must return to the same location). For each of the 500 paths calculated per cold trap (250 each way), we also calculated the total geographic distance and maximum slope along the route. In some cases, there may be shorter or shallower paths that differ from the lowest-energy routes because of tradeoffs in distance versus slope. Finally, a “relative accessibility score” was calculated to compare the 59 cold traps in this study. To do this, we calculated the ranks of all nine metrics (energy, distance, and slope for each of downhill, uphill, and round trip) from 1 (worst) to 59 (best). The total accessibility score is the sum of the nine ranks, such that higher scores equate to greater accessibility (minimum value of 9, maximum of 531).

### 2.4. Rover-Scale Terrain Features

How well do the coarser resolution orbital-measured slopes used here compare to real terrain on the ground at the scale of a rover or human vehicle? The LOLA gridded elevation model used has a 40 m/pixel resolution, and a small fraction of the points in the grid are interpolated rather than directly sampled (Gläser et al., 2013). While it is true that there could be locally rougher terrain and higher slopes that are not captured by the LOLA data set, the lowest cost path at local scales is still most likely to be found along the lowest cost path determined from orbit, assuming self-affine topography. Previous studies have all relied on this type of LOLA data for their analyses (Cunningham et al., 2017; Heldman et al., 2016; Lemelin et al., 2014; Speyerer et al., 2016). Of course, hazard cameras on board a rover or human perception will still be needed to navigate around local terrain hazards such as slopes or boulders.

### Table 1

#### Accessibility Metrics for North Polar Cold Traps

| Cold trap ID | Minimum energy down (joules) | Minimum energy up (joules) | Minimum energy round trip (joules) | Dist. (km) | Maximum Slope (deg) | Best distance (km) | Best max slope (deg) | Score |
|--------------|------------------------------|----------------------------|-----------------------------------|-----------|---------------------|-------------------|---------------------|-------|
| NP_UN04      | 3.4E+05                      | 1.2E+06                    | 1.6E+06                           | 15.0      | 22                  | 15.0              | 17                  | 397   |
| NP_UN05      | 7.7E+05                      | 1.1E+06                    | 1.8E+06                           | 16.8      | 13                  | 16.8              | 13                  | 392   |
| NP_UN01      | 4.8E+05                      | 1.1E+06                    | 1.6E+06                           | 17.0      | 19                  | 17.0              | 17                  | 355   |
| NP_UN02      | 4.6E+05                      | 9.8E+05                    | 1.4E+06                           | 14.4      | 19                  | 14.4              | 19                  | 354   |
| NP_UN03      | 6.4E+05                      | 1.1E+06                    | 1.8E+06                           | 18.4      | 22                  | 18.0              | 16                  | 343   |
| NP_HEVE      | 5.0E+05                      | 1.6E+06                    | 2.2E+06                           | 21.0      | 22                  | 21.0              | 15                  | 332   |
| NP_UN07      | 4.3E+05                      | 1.4E+06                    | 1.9E+06                           | 18.2      | 24                  | 18.2              | 19                  | 299   |
| NP_FIBI      | 5.8E+05                      | 1.2E+06                    | 1.9E+06                           | 19.1      | 24                  | 19.1              | 18                  | 284   |
| NP_UN06      | 5.1E+05                      | 1.2E+06                    | 1.8E+06                           | 16.9      | 22                  | 16.9              | 22                  | 275   |
| NP_UN08      | 9.3E+05                      | 1.5E+06                    | 2.6E+06                           | 24.6      | 16                  | 24.2              | 16                  | 267   |
| NP_ROZW      | 7.2E+05                      | 2.0E+06                    | 2.7E+06                           | 26.8      | 20                  | 26.8              | 13                  | 266   |
| NP_NANF      | 5.5E+05                      | 1.7E+06                    | 2.2E+06                           | 21.0      | 20                  | 21.0              | 20                  | 249   |
| NP_HERM      | 6.3E+05                      | 2.0E+06                    | 2.6E+06                           | 27.0      | 19                  | 27.0              | 16                  | 236   |
| NP_ROZI      | 4.8E+05                      | 2.0E+06                    | 2.4E+06                           | 24.0      | 25                  | 24.0              | 19                  | 233   |
| NP_LENA      | 7.3E+05                      | 2.3E+06                    | 3.2E+06                           | 32.8      | 21                  | 32.8              | 13                  | 216   |
| NP_NANA      | 7.3E+05                      | 2.3E+06                    | 3.0E+06                           | 30.0      | 23                  | 30.0              | 18                  | 170   |
| NP_ROZU      | 5.5E+05                      | 2.2E+06                    | 2.8E+06                           | 27.3      | 25                  | 27.3              | 20                  | 159   |
| NP_HERA      | 6.8E+05                      | 3.1E+06                    | 3.8E+06                           | 36.4      | 25                  | 36.4              | 23                  | 86    |
| NP_SYLV      | 1.0E+06                      | 3.2E+06                    | 4.2E+06                           | 40.7      | 24                  | 40.7              | 22                  | 69    |

Note: Distance and slope metrics are given for round trip routes. Italicized entries have no paths with a maximum slope <25°. The “score” column gives the sum of ranks for all nine metrics calculated (Table S3 and Data Set S3).
3. Results

The accessibility data set is presented in both tabular and graphical form. Tables 1 and 2 list some key accessibility metrics for each of the 59 cold traps. Figure 1 is color coded with the relative accessibility score. The supporting information contains significant additional data: Tables S1–S2 list the locations and sizes of the cold traps, Table S3 contains the rankings of all nine accessibility metrics that are used to calculate the relative accessibility score; Figures S2–S60 show maps of each target location, the cold trap boundary, and the lowest cost, lowest distance, and lowest slope paths (when these differ); Data Sets S1–S2 are ArcGIS shapefiles for the cold traps (polygons with attributes for each accessibility metric); and Data Set S3 contains the raw data and the calculations of the rankings.

The vast majority of even the largest cold traps were found to be readily accessible by wheeled vehicles, and cold trap size was a good but not perfect predictor of accessibility. Overall, 55 of 59 cold traps (93%) had at least one entry and egress path with <25° maximum slope. The four that did not were all located in fresh craters with uniformly high slopes around their entire walls, presenting no easy paths in or out. These

| Table 2 |
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| Accessibility Metrics for South Polar Cold Traps |
| Cold trap ID | Minimum energy down (joules) | Minimum energy up (joules) | Minimum energy round trip (joules) | Distance (km) | Maximum slope (deg) | Best distance (km) | Best maximum slope (deg) | Score |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| SP_UN14 | 2.4E+05 | 8.6E+05 | 1.2E+06 | 11.2 | 18 | 11.2 | 12 | 496 |
| SP_UN18 | 2.8E+05 | 7.7E+05 | 1.0E+06 | 9.9 | 18 | 9.9 | 14 | 486 |
| SP_UN03 | 3.8E+05 | 1.1E+06 | 1.5E+06 | 14.3 | 16 | 14.3 | 13 | 457 |
| SP_UN17 | 1.7E+05 | 8.4E+05 | 1.0E+06 | 9.6 | 18 | 9.6 | 17 | 453 |
| SP_UN16 | 4.2E+05 | 1.0E+06 | 1.4E+06 | 14.6 | 21 | 14.6 | 13 | 446 |
| SP_UN19 | 1.7E+05 | 8.6E+05 | 1.0E+06 | 9.6 | 23 | 9.6 | 18 | 440 |
| SP_SLAT | 2.0E+05 | 9.0E+05 | 1.1E+06 | 11.4 | 23 | 11.4 | 18 | 417 |
| SP_UN20 | 4.2E+05 | 9.7E+05 | 1.8E+06 | 16.7 | 15 | 16.7 | 15 | 407 |
| SP_UN10 | 3.5E+05 | 1.1E+06 | 1.5E+06 | 14.4 | 18 | 14.4 | 17 | 403 |
| SP_UN04 | 4.4E+05 | 1.4E+06 | 1.8E+06 | 17.8 | 19 | 17.8 | 14 | 390 |
| SP_UN07 | 6.1E+05 | 1.7E+06 | 2.3E+06 | 15.9 | 21 | 15.9 | 15 | 389 |
| SP_UN15 | 2.8E+05 | 1.4E+06 | 1.6E+06 | 15.8 | 23 | 15.8 | 17 | 381 |
| SP_WIEC | 4.4E+05 | 1.6E+06 | 2.1E+06 | 19.3 | 23 | 19.3 | 12 | 380 |
| SP_NEFE | 3.7E+05 | 1.7E+06 | 2.0E+06 | 19.2 | 24 | 19.2 | 15 | 350 |
| SP_UN09 | 6.6E+05 | 1.8E+06 | 2.6E+06 | 18.2 | 22 | 18.2 | 16 | 345 |
| SP_UN02 | 6.7E+05 | 1.6E+06 | 2.3E+06 | 21.9 | 16 | 21.9 | 14 | 327 |
| SP_WI2 | 4.1E+05 | 1.4E+06 | 1.5E+06 | 14.4 | 24 | 14.4 | 23 | 322 |
| SP_UN01 | 4.4E+05 | 1.5E+06 | 2.0E+06 | 23.5 | 24 | 22.5 | 16 | 306 |
| SP_UN21 | 3.2E+05 | 1.7E+06 | 2.1E+06 | 20.9 | 22 | 20.9 | 19 | 277 |
| SP_NOBI | 7.2E+05 | 2.0E+06 | 2.7E+06 | 26.2 | 21 | 26.2 | 16 | 249 |
| SP_SCOT | 4.5E+05 | 2.0E+06 | 2.4E+06 | 23.0 | 23 | 23.0 | 20 | 232 |
| SP_UN11 | 4.6E+05 | 2.0E+06 | 2.5E+06 | 24.2 | 24 | 24.2 | 19 | 210 |
| SP_FAUS | 3.7E+05 | 2.1E+06 | 2.5E+06 | 25.2 | 23 | 25.2 | 22 | 204 |
| SP_UN05 | 8.7E+05 | 2.2E+06 | 3.2E+06 | 30.4 | 25 | 30.4 | 16 | 198 |
| SP_SHOE | 3.3E+05 | 2.2E+06 | 2.5E+06 | 26.6 | 23 | 25.9 | 22 | 193 |
| SP_CABB | 4.3E+05 | 1.8E+06 | 2.7E+06 | 28.4 | 22 | 28.4 | 21 | 187 |
| SP_WI1 | 3.7E+05 | 2.2E+06 | 2.5E+06 | 24.5 | 25 | 24.5 | 24 | 177 |
| SP_SVER | 6.8E+05 | 2.3E+06 | 3.1E+06 | 30.8 | 18 | 30.8 | 18 | 160 |
| SP_UN06 | 4.5E+05 | 1.9E+06 | 3.6E+06 | 36.3 | 24 | 36.3 | 21 | 134 |
| SP_UN12 | 1.3E+06 | 3.0E+06 | 4.3E+06 | 42.3 | 18 | 42.1 | 18 | 128 |
| SP_DEGE | 7.8E+05 | 2.2E+06 | 3.0E+06 | 28.8 | 25 | 28.8 | 22 | 118 |
| SP_AMUN | 1.2E+05 | 3.0E+06 | 4.2E+06 | 40.9 | 20 | 40.9 | 19 | 106 |
| SP_CAB1 | 7.4E+05 | 3.1E+06 | 3.9E+06 | 38.2 | 20 | 38.2 | 20 | 104 |
| SP_HAWO | 7.3E+05 | 2.4E+06 | 3.2E+06 | 31.0 | 24 | 31.0 | 23 | 90 |
| SP_IDLL | 35.3 | 30 | 55 |
| SP_CAB2 | 2.2E+06 | 3.8E+06 | 6.0E+06 | 61.4 | 22 | 61.4 | 22 | 50 |
| SP_SHAC | 40.9 | 35 | 41 |
| SP_UN13 | 1.3E+06 | 4.3E+06 | 5.7E+06 | 55.0 | 25 | 55.0 | 25 | 27 |
| SP_UN08 | 54.3 | 33 | 23 |

Note: Distance and slope metrics are given for round trip routes. Italicized entries have no paths with a maximum slope <25°. The “score” column gives the sum of ranks for all nine metrics calculated (Table S3 and Data Set S3).
included Hermite A crater at the north pole and Idel'son L crater, Shackleton crater, and unnamed feature SP-UN08 at the south pole. Figure 2 shows a plot of the total accessibility score versus size of the cold trap. There was a wide spread in scores for the smaller cold traps (<200 km²); however, if the grouping of fresh, high-sloped craters (orange shaded region in Figure 2) is excluded, then a trend emerges of decreasing accessibility with increasing cold trap size due to greater driving distances required. The average distance of the lowest-energy routes (round trip) was 24 km. This gives a round trip driving time of ~1.8 hr assuming a constant speed of 13 km/hr that the LRV was rated for (Costes et al., 1972). The average maximum slope along the lowest-energy routes was 21°.

Most cold traps had paths with gentler slopes than the lowest-energy option. Out of the 59 cold traps, 55 had one or more routes where the maximum slope was lower than that encountered along the lowest-energy route (Tables 1 and 2 and Figures S2–S59). For example, the Wiechert crater cold trap at the south pole had a maximum slope of 23° along the most energy-efficient round trip route (19.3 km long) but had an alternative, less efficient route with a maximum slope of only 12° (37 km long). In these cases, the distances were generally much longer, but this trade could be favored for certain vehicles, which are not safe to operate at moderate to high slopes (15°–25°). Only 9 out of 59 cold traps featured a route that was modestly shorter than the lowest-energy option, trading this against higher slopes. For example, the Shoemaker crater cold trap had an alternate round trip route that saved 0.7 km on the most energy-efficient one.

Driving energy was universally greater for uphill paths than downhill paths, but there was a wide range in the magnitude of this difference. The downhill paths were always lower energy because vehicles can coast downhill and maintain a constant velocity with little to no torque applied. On average, the lowest-energy uphill path required 236% more energy than the downhill path. Some of the larger cold traps had a much more pronounced difference: The enormous Shoemaker and Faustini crater cold traps had some of the most energy-efficient entry paths of all (Table 2) but featured egress paths requiring ~500% more energy. The uphill routes generally determined the location of the lowest-energy round trip routes (which must return to the same staging location). Many cold traps had a lower energy downhill path than that used in the round trip (Figures S2–S59), but the best uphill path was generally the same as that in the round trip route. Thus, if a vehicle only needs to descend but not climb back out, different cold traps become more favorable than those highlighted by the total accessibility score (Figure 1).

4. Discussion

In general, we found that the 250 paths for each cold trap tended to converge on one or more branches or “highways” as they approached the target location in the cold trap (Figure S1). In theory, the number of these highways could be used as an additional constraint on accessibility, as those cold traps with multiple different options may be favorable to those with only one accessible route. However, it is not obvious how different or far apart two paths should be to count as separate options. Therefore, we leave this type of exercise for future work where more specific missions or operational concepts for a select number of locations are fleshed out.

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**Figure 2.** Plot of total accessibility score versus cold trap area. Red diamonds indicate cold traps with no viable paths using the energy model. Orange circle denotes very fresh craters; if excluded, a trend emerges of decreasing accessibility for larger cold traps.**

**Figure 3.** Oblique views of multiaccess plateaus (MPs) identified at the (a) north pole and (b) south pole. Cold trap boundaries outlined in white. Extent is 100 km per side.
4.1. Multiaccess Plateaus

We identified two flat, well-illuminated plateaus with efficient access to multiple nearby cold traps. The lunar north pole usually receives far less attention than the south, but many large accessible cold traps are located there. Figure 3a shows the example of NP-UN04, a degraded crater to the north of Rozhdestvenskiy U. It is one of the larger permanent cold traps at the north pole and has a higher accessibility score than all other northern cold traps. The access plateau (MP1) where the lowest-energy round trip path travels to for NP-UN04 is a flat expanse that also has access into the massive Rozhdestvenskiy U cold trap. Slater crater at the south pole (Figure 3b) is one of the largest cold traps to have a very high accessibility score (Figure 2 and Tables 2 and S2). The plateau (MP2) where the lowest-energy round trip path travels to is also close (~10–20 km) to two other high-accessibility cold traps (SP-UN18 and SP-UN19) and to Faustini crater (SP-FAUS), which has a very low energy entry path as described above. There is a relatively large flat area on this plateau (Figure 3b), close to points with illumination conditions as high as 56%, which could be significantly improved with modest towers.

4.2. Applications for Future Exploration

With over 50 permanent cold traps >50 km² in area at the lunar poles (Figure 1), space agencies and space mining companies are faced with an abundance of choice for where to launch scientific and resource prospecting missions. This option suite may not be fully appreciated, as many concept studies default to using Shackleton crater, which is not high in terms of ice favorability (Cannon & Britt, 2020) and has horrendous accessibility (Table 1). Wheeled vehicle access from nearby staging areas is an important metric among many others, and the comprehensive approach used here now allows for constrained maximization comparison between different cold traps. This accessibility data set can also be combined with previously developed techniques. Path planning algorithms from Speyerer et al. (2016) and Cunningham et al. (2017) take temporal lighting effects and battery charge into account and can therefore be used on the short segments of the paths here that are located in areas of partial sunlight. For example, if planning entry into and exit from a crater, those algorithms could be used to properly time the trips and make sure batteries can be recharged when the vehicle climbs back out. The round trip routes here are particularly significant for sustained operations from an outpost or base: For example, a swarm of autonomous excavation robots could carry icy regolith out of a cold trap to a nearby processing plant then descend back down, akin to pack mule routes. The one-way routes are better suited for initial exploration, particularly for long-duration rover missions.

5. Conclusions

We presented a new accessibility data set for large (>50 km²) permanent cold traps at both lunar poles. Dijkstra's algorithm was used to calculate the lowest-energy paths for a wheeled vehicle into and out of each cold trap to better lit staging areas nearby. Out of the 59 cold traps, 55 of them have both entry and egress paths with <25° maximum slope. Smaller cold traps were found to be generally more accessible in terms of round trip paths, but some of the largest south pole cold traps (e.g., Shoemaker and Faustini craters) have very favorable downhill paths for one-way trips. We also located flat, well-lit plateaus with access to multiple nearby cold traps. This data set can be used to inform site selection and traverse routes for future human and robotic exploration of volatiles at the Moon’s poles.

Data Availability Statement

Data sets for this research are available for free online (https://zenodo.org/record/3971095#.XyhJBNKjJAN) (Creative Commons Attribution 4.0 International, no access restrictions). The LOLA topography and illumination data sets (Mazarico et al., 2011; Smith et al., 2010) are available from the NASA Planetary Data Service and online (http://imbrium.mit.edu). A MATLAB implementation of Dijkstra's algorithm is available online (https://www.mathworks.com/matlabcentral/fileexchange/20025-dijkstra-s-minimum-cost-path-algorithm).

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