A PROPOSED PRESSURIZED ROVER TRAVERSE FROM CLAVIUS CRATER TO THE LUNAR SOUTH POLE

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Summary: A pressurized rover traverse path is proposed between a potential Moon base at Clavius crater and the lunar South Pole (~1040 km). Detailed orbital imaging and topography analysis and path planning confirm a viable route.

Introduction: Arguments have been presented for the importance for NASA's Artemis Program to establish a base on the Moon [1,2], and Clavius crater has been proposed as a good off-polar candidate site [3-5] **(Fig.1)**. Preliminary work suggested that a trafficable traverse route – the *Northwest Passage* – exists between Clavius and the lunar South Pole [3,4,6], but a detailed path had yet to be established. In this study, we identify a viable primary path and local alternate options for this *Northwest Passage* **(Fig.2).**

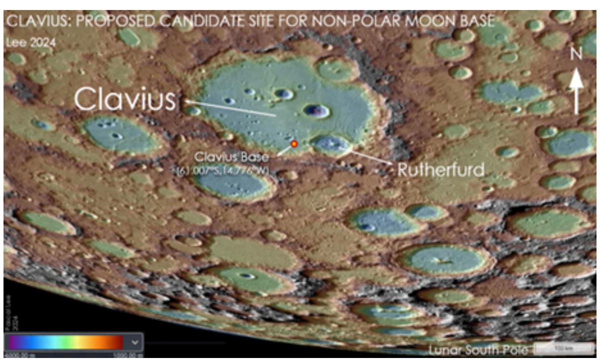

Figure 1. Clavius Crater, Base & Topography. *Location map of Clavius crater highlighting the proposed location of a Clavius Base [2] and a topographic corridor toward the lunar South Pole.*

Approach: ***Data****.* The present study examined several lunar data sets: a) high resolution visible imaging from NASA's Lunar Reconnaissance Orbiter (LRO) Camera (LROC) with spatial resolutions of ~100 m/pxl for the Wide Angle Camera (WAC) and ~0.5 m/pxl for the Narrow Angle Cameras (NACs); b) terrain elevation and slope from LRO's Lunar Orbiter Laser Altimeter (LOLA) with a horizontal resolution of 20 m to 50 m. The data were analyzed via three lunar data visualization and mapping tools: ACT NASA LRO/LROC Lunar QuickMap, NASA ARC/JPL Moon Trek, and Google Moon.

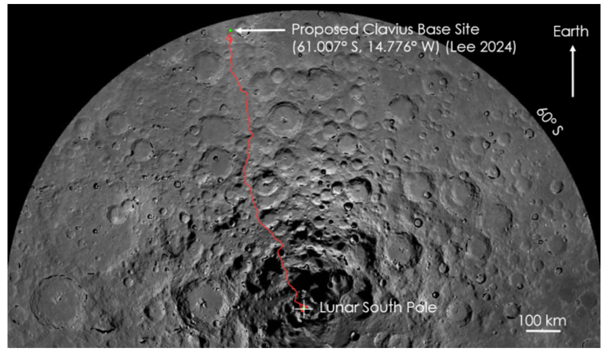

Figure 2. Overall Traverse Route. *Proposed "Northwest Passage" traverse.*

Operational Constraints*.* Two key operational constraints were considered in path planning: 1) steep slope avoidance; 2) obstacle avoidance.

Steep slope avoidance: Slope is an essential consideration for EVA, both on foot and in rover operations [7]. Based on the slope requirements and/or performance for i) the Apollo Lunar Roving Vehicle (LRV) [7,8] designed for up to 25° slopes [9], but with 20° as empirical operating limit [10], ii) the Lunar Chariot [11], iii) the Lunar Electric Rover (LER) designed for up to 35° slopes [12], iv) the Artemis Lunar Terrain Vehicle (LTV) designed for up to 20° slopes [13], and v) the JAXA-Toyota Lunar Cruiser pressurized rover designed for up to 20° slopes [14], a never exceed slope, S_{NE}, of 20° is a conventional limit. In the present study, a safe operational maximum slope, S_{max}, of 13° and a conservative never exceed slope S_{NE} of 17° were adopted.

Obstacle avoidance: Obstacles range in size from regional-scale obstacles (e.g., large craters, mountain ranges) to local scale obstacles (e.g., boulders, cliffs, steps, rough patches). Among local scale obstacles, lunar surface terrain features, positive or negative in relief, likely to exceed a pressurized rover's ground clearance must be avoided. Considerable experience with obstacle avoidance in traverse planning and implementation exists from rover missions on the Moon and Mars, and also from terrestrial expeditions across rocky deserts and polar regions viewed as planetary analogs [15,16].

Path Planning. The traverse planning strategy adopted in this study entailed the following five key steps: 1) draw a bee line between the start and end points of the traverse to establish an initial shortest "as the crow flies" traverse axis; 2) identify any key waypoints - *e.g.*, science targets, narrow trafficable corridors, logistics hubs, strategic sites - between the start and end points, on and off the bee line; 3) identify optimal departure or approach paths for the start and end points, and for the key waypoints along the way, taking into account steep slope and obstacle avoidance constraints; 4) establish path segments connecting concecutive waypoints, taking into account the same constraints as in 3); 5) iterate between steps 3 and 4 as needed until a final optimized traverse path is achieved. In this study, the initial traverse bee line was drawn between the *Clavius Base* site at 61.007°S, 14.776°W inside Clavius crater [3-5] and the lunar South Pole. Key waypoints identified along the way were *Clarke Junction* (61.418°S, 15.247°W) and *Kubrick Junction* (62.144°S, 15.473°W) near the south rim of Clavius crater, and *Endurance Junction* (89.357°S, 42.201°W) on the lunar western nearside ~10 km from the lunar South Pole, *i.e.*, ~10 km from the south rim of Shackleton crater. The maximum slope allowed, S_{max}, was set at 13° and the never exceed slope, S_{NE}, at 17°, with an intermediate maximum slope set at 15°.

Results: The Clavius-Lunar South Pole traverse, or *Northwest Passage*, is divided into three sections: a) Clavius South Rim Access; b) *Traverse Corridor*; c) South Pole Access.

Clavius South Rim Access. To depart from/return to *Clavius Base* towards/from the south rim of Clavius crater, the Clavius South Rim Access traverse path includes two segments: i) a single, 14.23 km-long bee line between *Clavius Base* and *Clarke Junction*, located *inside* Clavius crater at the base of its southern rim; and ii) three slope-dependent alternate path options between *Clarke Junction* and *Kubrick Junction*, located in the highlands *outside* the south rim of Clavius crater **(Figs. 3 & 4; Table 1)**. Path 1 has the shallowest maximum slope of 13° and a driving distance between *Clarke Junction* and *Kubrick Junction* of 31.36 km. Path 2 has the steepest maximum slope of 17°, reducing the driving distance between *Clarke Junction* and *Kubrick Junction* to 24.49 km, *i.e.*, by 6.87 km compared to Path 1.

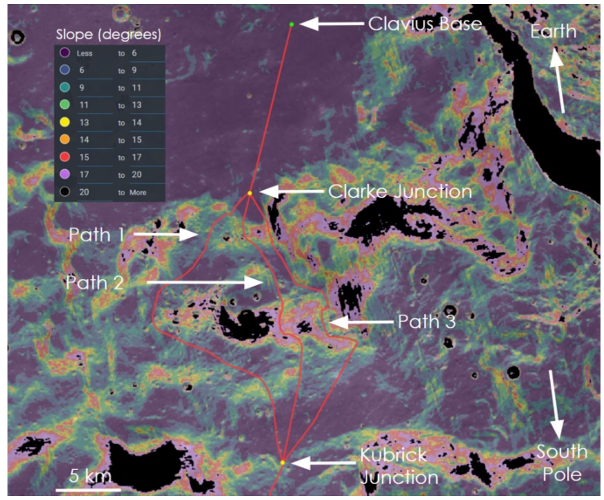

Figure 3. Clavius South Rim Access Paths. *Three path options between Clarke Junction and Kubrick Junction are identified in this study.*

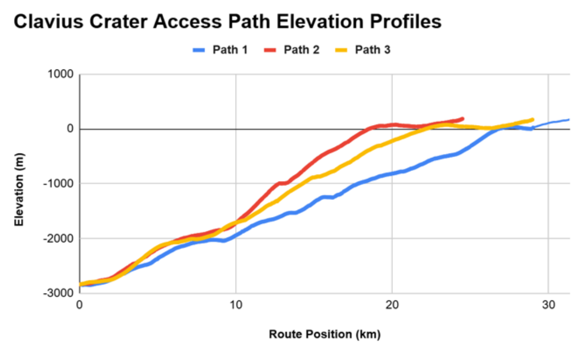

Figure 4: Elevation Change Along Clavius South Rim Access Paths. *Route position starts from Clarke Junction (left) and ends at Kubrick Junction (top). Elevation change is ~3000 m.*

Table 1. Clavius South Rim Access Path Data

Path (Clavius Jct - Kubrick Jct)	Path 1	Path 2	Path 3
Maximum Slope S_{max}	13°	17°	15°
Driving Distance (km)	31.36	24.49	29.04
Extra Distance *vs* Path 1 (km)	0	-6.87	-2.32

Path 3 provides an intermediate option with a maximum slope of 15° and a driving distance of 29.04 km, reduced by 2.32 km from the Path 1 option. Although these path options involve trade-offs between slope and driving distance, all three show that traversing the south rim of Clavius crater, with its ~3,000 m of elevation difference **(Fig.4)** and frequent slope changes along the way **(Fig. 5)**, is within anticipated rover capabilities.

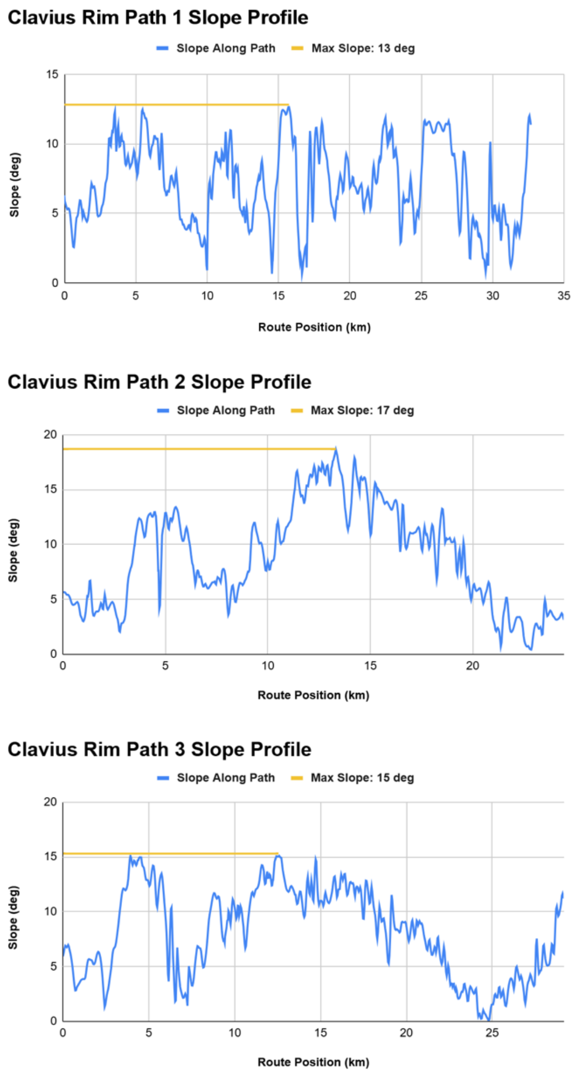

***Figure 5: Slope Change Along Clavius South Rim Access Paths. Top**: Path 1; **Middle**: Path 2; **Bottom**: Path 3.*

Traverse Corridor. From *Kubrick Junction* to *Endurance Junction*, a single, 962 km-long traverse path is identified - designated the *Traverse Corridor* - that minimizes slopes, circumvents regional and local obstacles, and enables science and resource areas of interest to be accessed via "exit ramps" or bifurcations. From North to South, the traverse path passes east of Blancanus crater (diameter D~107 km), then west of Gruemberger (D~95 km), then between Kaproth (D~119 km) and Moretus (D~114 km), then east of Casatus (D~110 km), then west of Newton (D~79 km), then west of Newton A (D~64 km), then between Cabeus A (D~40 km) and Cabeus B (D~62 km),

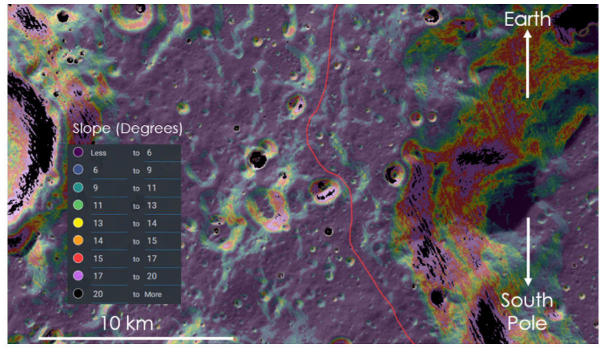

***Figure 6. Traverse Corridor**. Sample section of the Traverse Corridor west of Newton crater (right). Note slopes at ~50 m resolution are < 6°.*

then west of Cabeus (D~99 km) whose H_2O ice-rich permanently shadowed region (PSR) was impacted by NASA's LCROSS (Lunar Crater Observation and Sensing Satellite) [17], then north of De Gerlache (D~34 km) before reaching Endurance Junction. Much of the *Traverse Corridor* has slopes < 6°, at least at the horizontal scale of LRO LOLA data, *i.e.*, ~20 -50 m **(Fig. 6)**.

South Pole Access. Four path options are identified between *Endurance Junction* and the lunar South Pole: Paths 1A (S_{max}=15°) and 1B (S_{max}=17°) attain the pole from the nearside, *i.e.*, Shackleton's west side; Paths 2A (S_{max}=15°) and 2B (S_{max}=17°) reach the pole from the farside, *i.e.*, Shackleton's east side **(Fig. 7) (Table 2)**.

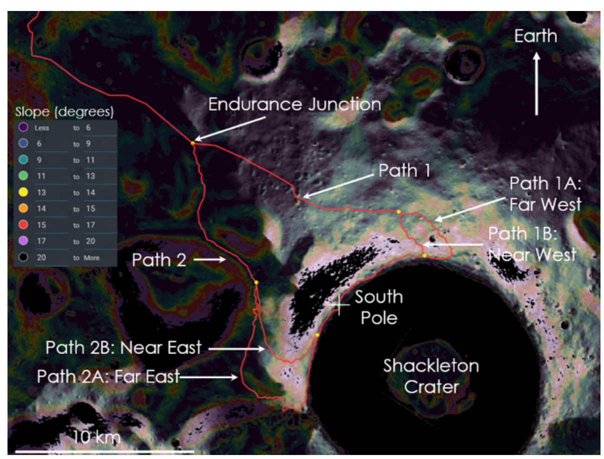

***Figure 7. South Pole Access Paths.** Four path options are identified from Endurance Junction.*

Table 2. South Pole Access Path Data

Path (Endurance Jct - S. Pole)	1A	1B	2A	2B
Maximum Slope S_{max}	15°	17°	15°	17°
Driving Distance (km)	40.58	35.90	44.57	31.77
Extra Distance *vs* Path 1A (km)	0	-4.68	+3.99	-8.81

Overall Traverse. The complete *Northwest Passage* traverse from Clavius Base to the Lunar South Pole stretches a driving distance ranging from 1032.5 km to 1052.2 km (**Fig. 2**). Slope distribution analysis along this route shows that 98.6 percent of the traverse remains at or below 13°, while the entire traverse remains within a 15° slope limit (at least at the horizontal resolution of LRO LOLA data). This result suggests that a pressurized rover should be able to, with adequate autonomy and strategic caching of supplies, complete the journey. **Table 3** indicates the duration of the 1-way traverse *vs* driving speed, idle time, and *speed made good* (SMG) (total distance driven divided by total duration of journey) along the 1042 km traverse path. If driven non-stop at an average of 14.5 kph, the total distance could be covered in 3 Earth days. With 12h idle time each day, the traverse could still be completed in 3 days by driving 12 hours at 28.9 kph. With 6h idle time each day and driving at 24.8 kph, the traverse is completed in 7 days, *i.e.*, half the nominal sunlit time of a lunar day (not taking into account shadowing near the poles).

Table 3. Clavius Base – South Pole Drive Time

1-Way Traverse	Speed (kph)	Drive Time (d)	SMG* (kph)
Non-Stop	14.5	3.0	14.5
Fast Drive 12h/dy	28.9	3.0	14.5
Slow Drive 6h/day	24.8	7.0	6.2

*SMG = Speed Made Good

Discussion. In **Table 3**, the driving speeds and daily idle times imply SMGs of 6.2 to 14.5 kph. Such SMGs would be reasonable once a known safe and trafficable route has been established. During the NASA Haughton-Mars Project's *Northwest Passage Drive Expedition* in the Arctic, 496 km were traversed on sea-ice in 8 days, *i.e.,* with a SMG of only ~2.58 kph, but the journey was an initial traverse into unknown terrain with no advance caching of supplies or self-driving capability, and included multiple pauses for real-time scouting, resupply runs, repairs, science, and extended periods of loss of visibility due to weather [15,16]. On smooth sea-ice, peak speeds of ~35 kph were achieved, and limited from exceeding that value only due to the danger of amplifying sea-ice pressure waves. Thus, the speeds in **Table 3**, which are below 35 kph, are not unreasonable, especially given assumptions of advance scouting, pre-traverse supplies caching, self-driving capability, and no weather delays.

Although the traverse from *Clavius Base* to the lunar South Pole appears readily feasible, caution must be exercised given the resolution limits of the LRO LROC and LOLA data. Local scale obstacles such as boulder fields or small scarps are not resolved and could complicate traverse implementation by forcing unplanned detours. Furthermore, the study did not yet account for other critical factors in traverse planning for which data is available such as terrain roughness, solar illumination - especially across frequently shadowed terrain around the pole -, or direct-to-Earth (DTE) communication coverage, each of which could affect path selection and traverse tempo.

Conclusion: This study proposes a viable pressurized rover traverse path for the *Northwest Passage* between Clavius crater and the lunar South Pole that appears feasible on the basis of terrain obstacle avoidance and steep slope avoidance using LRO data. Clavius' South Rim and the lunar South Pole, which bracket the *Traverse Corridor*, both present multiple access path options that remain within practical and safe slope tolerances anticipated for a pressurized rover (~20°). The full traverse path maintains slopes ≤ 13° except on the outer rim of Shackleton crater where slopes of up to 15° have to be tackled. Once established, the *Northwest Passage* could be traversed by pressurized rover in just a few days, thus allowing a rapid transit between *Clavius Base* and the lunar south polar region.

Future Work: Future work will entail examining solar illumination and DTE communication conditions along the path, and modifying it as needed to optimize both. Optimal timing of the traverse during the lunar day will also need to be determined, for instance to minimize dwell time in shadowed regions. Strategic locations for establishing caches of supplies or safe havens also need to be identified based on pressurized rover autonomy and range. Exit ramps and bifurcations to access science and resource areas of interest will also need to be mapped in detail. Together, these enhancements will evolve the current traverse concept into a baseline for mission planning.

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