South Pole Lunar Lighting Studies for Driving Exploration on the Lunar Surface

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Abstract— **NASA's Artemis lunar missions will face new exploration challenges due to inherently low sun angles in the lunar south pole region. Whereas the Apollo missions were afforded sunlight for approximately 8 to 50-degrees above the horizon, sunlight for the next lunar missions will only be 1 to 2-degrees about the horizon. With this low angle, long shadows and high contrasts of light and dark areas will be faced by the crew and remote teleop operators while exploring the lunar surface. With this in mind, NASA developed an integrated virtual Lighting and Navigation Simulation to understand these challenges. Two studies have been conducted in this Lunar South Pole environment to evaluate the effects of natural and artificial lighting on driving and navigating a lunar rover across the surface. Early NASA studies, such as this, are used to aid in developing techniques and explore concepts of operations to promote mission success and crew safety. In the Phase One development evaluation, six astronauts were teleported to ten different lighting conditions. For each location, drivers were to drive to an imaginary target approximately 200-meters straight ahead and provide subjective feedback on their ability to drive under the given lighting conditions. Phase Two, a more operational study, four astronauts and a remote operator tested five different Artemis lunar mission scenarios. Results indicated sun direction at such low angles, especially when driving a high speed, can severely impact the crew's ability to safely drive the rover. In the up-sun situation, with the sun directly in the driver's eyes and compounded long shadows, the consistent preference among drivers was to initiate a tacking strategy of approximately +/- 20 to 30-degrees to improve visibility. This maneuver does require more time and rover energetics. Conversely, driving down-sun required the crew to tack as well to avoid the shadow of rover blocking the terrain. Less appreciated is how the surrounding landscape is lit. Traveling into shadowed areas, especially while facing a lit terrain beyond the shadowed area, drivers enter at their own risk due to pupil contraction making artificial lights useless. Additionally, the constant transitioning between dark and light areas are mentally taxing to the crew and natural navigational references such as the stars are invisible and therefore unusable. Slope and depth magnitude are very difficult hazards to judge when approaching a shadowed crater. This naturally leads to slower driving speeds than originally anticipated. As for observing scientifically interesting features, assessing them accurately varies greatly by the lighting condition. In most cases, the task can be completed, but the strategy is to use the sun to one's advantage. Crew workload distribution in the cockpit for driving operations was split amongst crew. The driver primarily focused attention on visual terrain (80%) but referenced displays approximately 20% of the time, while the co-pilot/navigator generally provided directional cues to the driver. These natural lighting conditions present significant challenges for safe rover operations; however, early studies having given investigators a "first-look" into understanding of how operating on the South Lunar Pole can be accomplished.**

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1. INTRODUCTION

NASA's Artemis lunar missions will face new exploration challenges due to inherently low sun angles in the lunar south pole region. Whereas the Apollo missions were afforded sunlight for approximately 8 to 50-degrees above the horizon, sunlight for the next lunar missions will only be approximately 1 to 2-degrees about the horizon. With this low angle, long shadows and high contrasts of light and dark areas will be faced by the crew and remote rover operators while exploring the lunar surface. With this in mind, NASA developed an integrated Extravehicular Activity (EVA)-Lunar Terrain Vehicle (LTV) Lighting and Navigation Simulation to understand these challenges. Since early 2020, the Exploration Development Mission Directorate (ESDMD) Strategy and Architecture Office (SAO) Human-in-the-Loop (HITL) test team has been developing an integrated EVA-LTV lighting and navigation simulation to understand these lighting challenges and being to develop techniques and explore concepts of operations that promote mission success and crew safety (Figure 1). Two studies have been conducted in this Lunar South Pole virtual environment to evaluate the effects of natural and artificial lighting on driving and navigating a lunar rover across the surface. The purpose of these early NASA studies is used to aid in developing techniques and explore concepts of operations to promote mission success and crew safety. In the Series One development evaluation, six astronauts and six engineers were teleported to ten different lighting conditions. For each location, drivers were to drive to an imaginary target approximately 200-meters (m) straight ahead and provide subjective feedback on their ability to drive under the given lighting conditions. With a more operational Series Two study, two teams of two astronauts and a remote operator tested five different Artemis lunar mission scenarios. These natural lighting conditions present significant challenges for safe rover operations such as assessing and avoiding terrain hazards, navigating and performing science exploration tasks; however, these studies having given investigators a first look understanding of operating on the South Lunar Pole.

Figure 1. A simulated view of astronauts with a rover on the lunar South Pole.

2. STUDY GOALS AND LIMITATIONS

The objective of these studies was two-folded: 1) to develop a simulation environment of the Lunar South Pole region to evaluate the effects of natural lighting conditions on conducting LTV traversing operations over a variety of different terrains and 2) to gain an understanding of how these different natural lighting conditions and terrain types which crewmembers will face on the lunar surface and their ability to conduct driving operations of a lunar rover. The outcome of these evaluations was to develop operational concepts governing nominal traverse characteristics while driving a lunar rover.

Some of the limitations of the virtual simulation environment is terrain resolution. The simulation is based on the highest fidelity terrain Digital Environment Model (DEM) and imagery know to-date from the Lunar Reconnaissance Orbiter (LRO) at a pixel resolution of 5m per pixel. However, without higher resolution terrain data from the surface, simulation developers, along with scientists established the smaller terrain details at a finer resolution of 20 centimeters (cm) per pixel based on statistical density and distribution models. Today, these models are continuously being refined and incorporated into the simulation for rock and crater densities and distributions on such terrain aspects as crater depth-to-diameter ratios, boulder properties and distribution around crater rims and so forth. During the first study, the natural lighting model was a single source; however, with the upgrade of the virtual engine, the current natural lighting model multipath which, according to lighting experts, is more realistic in nature. Eye adaption has also been improved since the first study was performed. Refinement of the LTV propulsion motors and terramechanics models have also improved over time. It should be noted these models are for a government reference LTV and may or may not represent the actual Artemis LTV vendor concept.

3. TEST EQUIPMENT

For the studies, several pieces of hardware were employed which included a video wall with LTV cockpit, a display for navigation, a hand controller. Several virtual simulation elements were used to model a government reference lunar rover, lunar surface terramechanic, South Pole lunar lighting, and a South Pole lunar terrain. Over the period of the studies, the lighting and terrain models were updated from the original Graphics for Exploration (EDGE) virtual model to the UnReal 5.2 virtual model for improved accuracy especially in the lighting model.

The System Engineering Simulator (SES) Video Wall

The video wall at Johnson Space Center (JSC) is located in Building 16 in the SES facility. The wall consists of ten 140-centimeter (cm) borderless Light Emitting Diode (LED) monitors arranged in a 2 x 5 matrix with an approximate horizontal field of view of 120-degrees (Figure 2). A single seat mockup rover cockpit is located approximately 1 meter from the center monitors with a single 38cm display for navigation and a single CH-Product 3-axis hand controller (Figure 3). The hand controller includes four buttons, one center top hat switch with two LEDs. Rationale for this type of joystick was with the extra degree of freedom in the yaw direction gave engineers a way to incorporate the crabbing function without relying on display software. Mapping for the hand controller was the same for both studies (Figure 4 and Table 1).For the later study, the cockpit was upgraded to a dual seat cockpit with two 38cm displays (Figure 5). At the test station, the test conductor can "teleport" the test subjects to different terrain locations with different lighting conditions, control the sun, control the vehicle lights, record all the objective simulation data, and record all test conditions.

Figure 2. The SES Video Wall for the Series One Study.

Figure 3. The CH-Product 3-axis hand controller.

Table 1. *CH-3 Product Joystick Functional Mapping*

Controller Direction	Element Motion	Function
Forward	Push Controller Forward	Vehicle will move forward While in Cruse Control bumping stick forward quickly will add 0.5 kph to speed
Backward	Push Controller Back	Vehicle will move backward While in Cruse Control bumping stick backward quickly will subtract 0.5 kph to speed
Lean Right	Push/Lean Controller to the Right	Vehicle goes sideways to the right (wheels at 90º)
Lean Left	Push/Lean Controller to the Left	Vehicle goes sideways to the left (wheels at 90º)
Twist Right	Yaw/Twist Controller to the Right	Turns vehicle to the right. Can rotate/pivot on vehicle Z-axis
Twist Left	Yaw/Twist Controller to the Right	Turns vehicle to the left. Can rotate/pivot on vehicle Z-axis
Silver Switch	Cruise Control and Steering Mode	UP- Cruise Control (On/Off) DOWN-Steering Mode Ackermann Crab Mode
White Button	White Button on lower left of Controller Head	Park Brake
Castle Switch	Castle Switch center of Controller Head	Camera Lens Control: UP- Zoom In DOWN- Zoom Out
Center Black Top Hat Button	Top Hat Button center left side on Controller Head	Camera Control: UP- Tilt Camera Down RIGHT- Pan Camera Right LEFT- Pan Camera Left DOWN- Tilt Camera Up

Table 1. *CH-3 Product Joystick Functional Mapping*

Controller Direction	Element Motion	Function
Red Trigger	Red Trigger center of grip below Controller Head	Momentary Break (Not Shown in Figure)

Figure 4. The SES video wall upgraded for the Series Two Study.

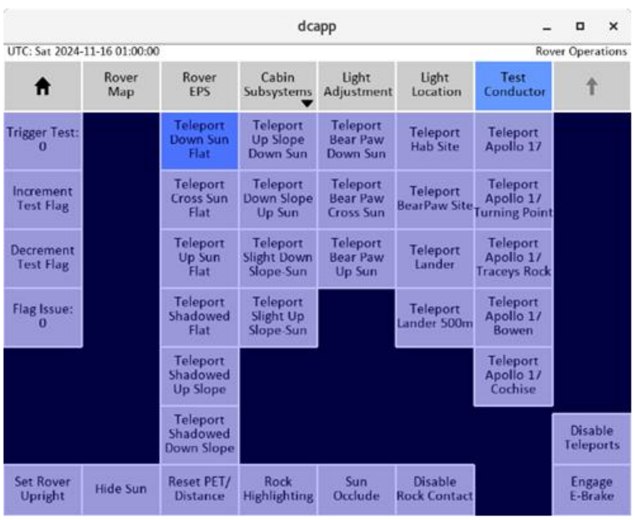


Figure 5. Test conductor screen.

The Simulated Vehicle

The notional government reference lunar rover modeled in the simulation could traverse forward and backwards, had a turning radius of 0-degree (i.e., can turn in place), was able to crab (i.e., move perpendicular to the direction the nose is pointing), could travel at speeds up to 15 kilometer per hour (kph), and could traverse slopes of +/- 20-degree (up-, down- and cross-slope) (Figure 6).

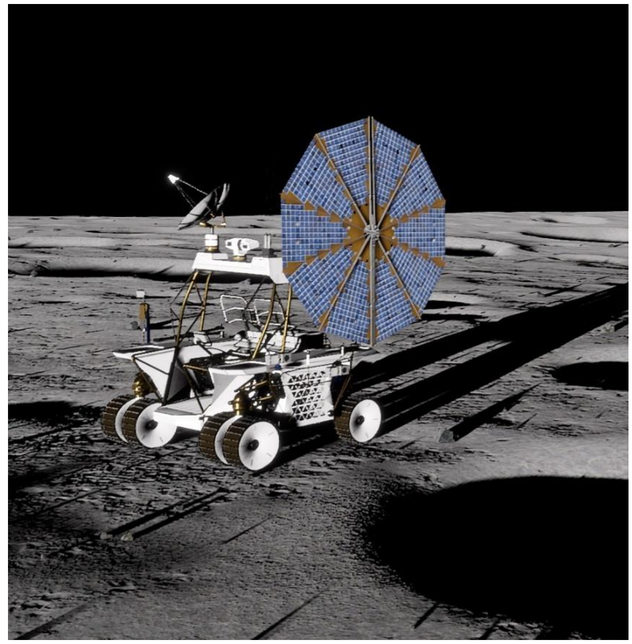
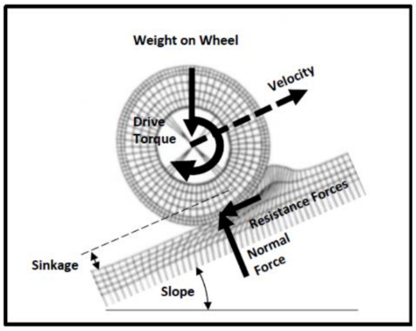


Figure 6. The virtual lunar rover vehicle.

The simulation consists of a multi-body dynamic model developed using MultiBody Dynamics (MBdyn) software and the Johnson Space Center Engineering Orbital Dynamics (JEOD) [1] group, a representative electrical power system model developed using the General-Use Nodal Network Solver (GUNNS) software [2], rock contact model developed using Pong, and a simple terramechanics model. The multi-body dynamics model consists of individual dynamic models for rover chassis, suspensions, and wheels. These dynamic models are integrated with the contact modelling package (Pong) to determines the normal force and tractional force on each wheel. The representative electrical power system model consists of models for solar array, solar array regulator, batteries, constant power load for rover hotel load, and motor-gearing modules for propulsion and steering. The terramechanics model calculates compression resistance and bulldozing resistance on each wheel based on the wheel-soil interaction [3,4,5,6,7]. It also contains a simple rolling resistance to account for non-soil frictional resistance (Figure 7). The terramechanics model are currently in validation phase, which will be a useful model in future engineering analysis. These models are integrated together to simulate the driving dynamics and power consumption of the rover during traverse. In addition, the virtual vehicle has a full lighting and camera array (Figure 8 and Figure 9).



Modeling Soil Reaction as a Nonlinear Spring

$$P = \frac{W}{A} = kz^n$$

$$k = \frac{k_c}{b} + k_\phi$$

$$\text{Therefore: } \frac{W}{A} = \left(\frac{k_c}{b} + k_\phi\right) z^n$$

W = normal force on the wheel
A = contact surface
z = soil sinkage
n = exponent of sinkage
b = wheel width
k_c = modulus of cohesion
K_ϕ = modulus of friction

Figure 7. A diagram of a rover wheel and soil resistance along with the soil reaction formula.

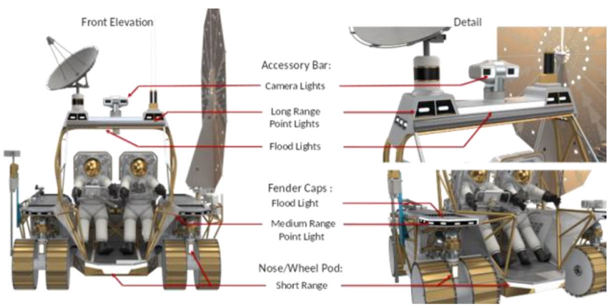


Figure 8. The vehicle's lighting positions.

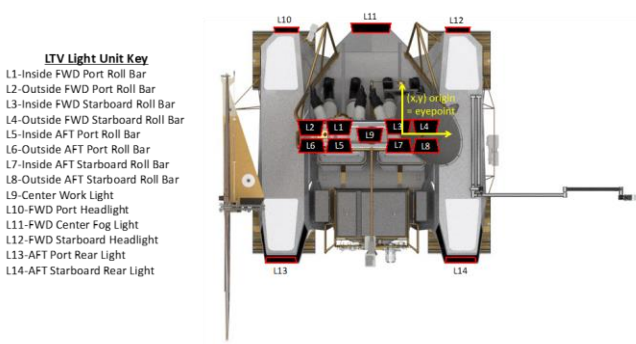


Figure 9. The vehicle's light unit locations.

The Virtual In-Situ Resource Utilization (ISRU) Unit

Only used in Study Series Two, this conceptual ISRU device measures 6.18m tall and 17.82m in length (Figure 10). The unit has simulated tanks, solar panels, radiators and a stowage unit. The unit involves using local resources to support exploration, instead of shipping those same resources from Earth. These units will become extremely important of the lunar architecture as humans venture on longer lunar missions. The inclusion of this unit was to add more realism to the crew for a 360-degree inspection task.

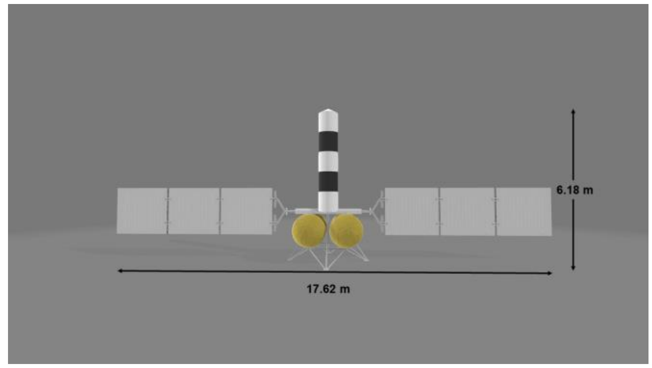


Figure 10. The virtual ISRU unit.

The Simulated South Pole Lunar Terrain

The lunar terrain incorporated into the simulation includes a high-fidelity representation of the 16 November 2024 lunar day with the South Pole lunar sun elevation of 1.2-degree and a notional 500m radius landing area approximately 17 kilometer (km) from the lunar south pole, as well as a 500m radius area inside the Bear Paw, approximately 8.9km west from the landing site (Figure 11). Bear Paw is a high-fidelity representation of a notional exploration site located near Shackleton crater rim approximately 7.7km away from a notional Artemis Base Camp (ABC) (Figure 12) (Universal Polar Coordinate System (UPS) (UPS [-4,795, -9,607] / Latitude -89.6459, Longitude -153.4739). The base camp location is where a surface habitat is stationed approximately 17km from the lunar south pole and 9km from the rim of Shackleton Crater (UPS [-11,331, -12,204] / Latitude -89.4398, Longitude -134.17). Connecting the Artemis Base Camp with Beera Paw is an area known as Ridgeline. Ridgeline is a 500m wide corridor between ABC and Bear Paw along a "least cost" energy path. Truth data for the terrain was based on 5m/pixel Digital Environment Model (DEM) data and 1m/pixel high-resolution imagery from the Lunar Reconnaissance Orbiter (LRO). This terrain was then augmented using randomization scripts with sub-resolution features, such as rocks and craters, based on statistical models provided by JSC Astromaterials Research and Exploration Science Division., Goddard Fight Center (GFC) and the Jet Population Laboratory (JPL) [8]. (Figure 13).

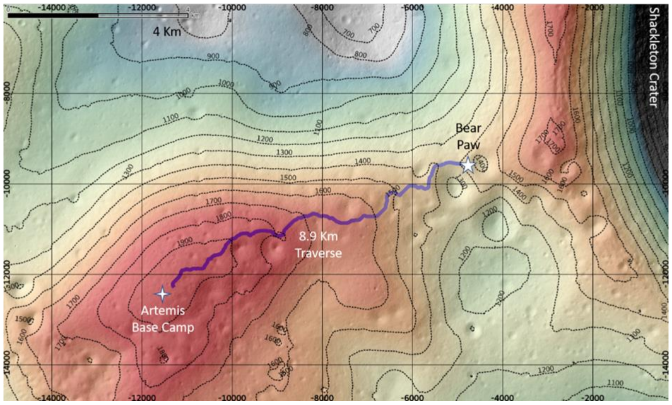


Figure 11. Top-down view of the simulated terrain, noting the Artemis Base Camp and Bear Paw areas with an 8.9km corridor between them.


Figure 12. Screen capture of Artemis Base Camp terrain (notional surface habitat on the right).


Figure 13. Screen capture of Bear Paw terrain.

The Simulated Natural Lighting Environment

The original South Pole lunar lighting environment was developed using the EDGE simulation model. EDGE modeled the environmental lighting using a directional infinite light source providing 127,000 lux of illumination to represent the light from the sun and incorporates Illuminating Engineering Society (IES) profiles for modeling the luminous flux of the artificial lights mounted on the LTV (Figure 14). Contributions to the illumination from reflections off surfaces including Earth shine are currently not being modeled in Engineering DOUG (Dynamic Onboard Ubiquitous Graphics) or EDGE, nor are shadows from light sources other than the sun. [8,9] The pupillary response in EDGE is currently modeled using an exposure value that computed from a center weighted adapting luminance and key value. [10,11] Limitations observed using a direct lighting model from EDGE and a seven-hour test session with Apollo 17's Dr. Harrison "Jack" Schmitt in May 2022, Dr. Schmitt provided information about ejecta distributions around the craters, surface soil coloration and sun size and brightness characterizes notability light backscatter or the reflective of bouncing lighting, especially with craters, proved a more realistic lunar environment [12]. This information prompted developers move to a more robust virtual multiple path lighting modeling engine of UnReal 5.2. The model is based on Virtual Shadow Maps (VSM) with a resolution of 16k x 16k (k-thousands) pixels (Figure 15). VSM delivers consistent, high-resolution motion picture quality shadowing using Nanite Virtualized Geometry, Lumen Global Illumination and Reflections and World Partition features. These models allow for the approximation of multipath (or bounce) lighting while maintaining real time performance. To check out the new simulation upgrades, another opportunity arose with Apollo 16's Brigadier General (Ret.) Charlie Duke (May 2023) who also devoted to a 7-hour virtual video wall session. Brig. Gen. Duke noted the regolith buildup around the base of the rocks was needed to accurately represent what he had observed during his Apollo 16 mission. Both men complemented the simulation capability stating one of the lighting conditions (down-sun, up slope) was analogous to their Apollo missions. Other additions included modeling Earth Shine, more realistic up-sun glare, and a pupillary response to the up-sun glare (Figure 16). With all the upgrades and additions, the South Pole Lunar Simulation was renamed to the Lunar Lighting and Mobility Analysis (LLAMA) simulation.


Figure 14. The simulated EDGE South Pole Lunar environment.

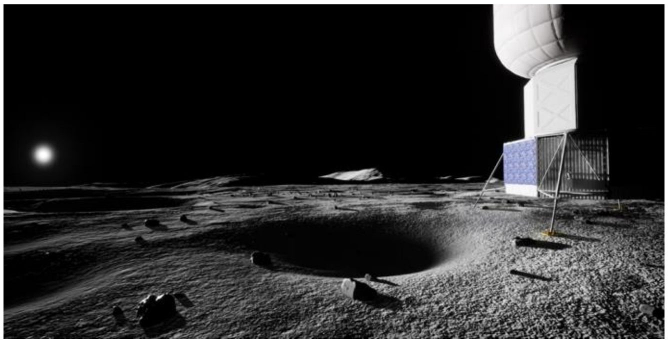


Figure 15. The simulated UnReal 5.2 South Pole Lunar environment.

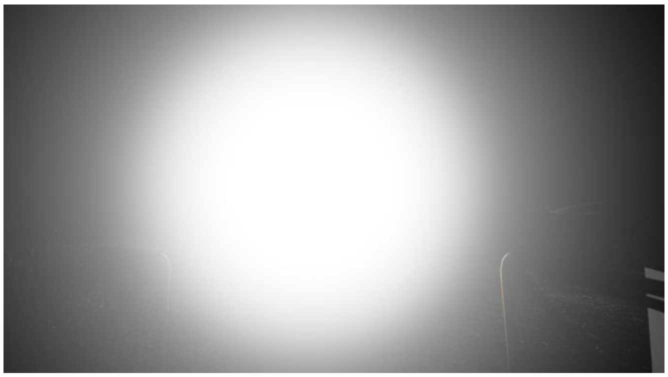


Figure 16. Up-sun glare upgrade for the Series Two Study.

4. STUDY DESIGNS

Series One Study Design and Procedures

This testing utilized six astronaut and six engineering subjects with mobility and/or flight operations backgrounds. Subjects were to drive ten different lighting and terrain scenarios (Figure 17) (Up-sun, flat terrain, 90-degree Cross-sun, flat terrain, Down-sun, flat terrain, fully shadowed, flat terrain, Up-sun, slight up slope (7-degree), Down-sun slight down slope (7-degree), Up-sun, down slope (15-degree), Down-sun up slope (15-degree), fully shadowed up slope (15-degree), and fully shadowed down slope (15-degree)). Moreover, two vehicle lighting conditions were tested – without vehicle lights and with vehicle lights.

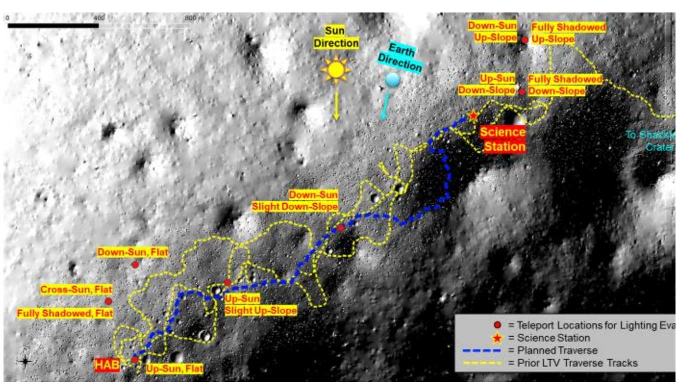


Figure 17. The ten driving scenarios.

Using the Displays and Control Application (DCApp), the test conductor would "teleport" the LTV to one of the ten different sun-facing and terrain locations (Figure 18). At each location, the test subject was asked to face a specific direction relative to the sun and drive to an imaginary target approximately 200m straight ahead. With the driving task complete, the subject would provide subjective feedback on his/her ability to drive under the given lighting condition. The subjective feedback was providing corresponding task acceptability and capability assessments for each natural lighting condition. Of note, while one mitigation for managing a harsh natural lighting condition might simple be to reposition/reorient oneself and/or the rover so that the sun and artificial lights could be used more advantageously, there were circumstances under which this was not possible (e.g., due to terrain obstacles, hardware malfunctions, etc.). Thus, by requiring subjects to provide feedback in all sun-facing orientations, investigators could better capture the full breath of challenges or the lack thereof. This was collected for each of the ten scenarios.

Figure 18. Test conductor "teleporting" a subject.

Series Two Study Design and Procedures

Using five longer Artemis scenarios with a distance ranging from 275m to 2,597m under similar South Pole lunar lighting conditions, four astronaut subjects were employed for this within subject designed study with various flight backgrounds (Figure 19). Scenarios included the crew's first day on the Moon, several scientific sites on a 35m crater located at Bear Paw, a communication outage site near the notional Artemis surface habitat, a crater field activity near the surface habitat, and an inspection task on Connecting Ridge at a ISRU site (Table 2). Each day scenario took approximately 4-hours to complete. At the beginning of each test session, test subjects were briefed on the rationale and objectives of the study, as well as the subjective and objective data metrics which were collected after each session. Subjects were then given familiarization time in the video wall and virtual reality (VR) environments to get familiar with the terrain, lighting, and rover characteristics (Figure 20). Using the same task acceptability rational as in Series One, each subject gave an acceptability score and feedback after the session was completed.

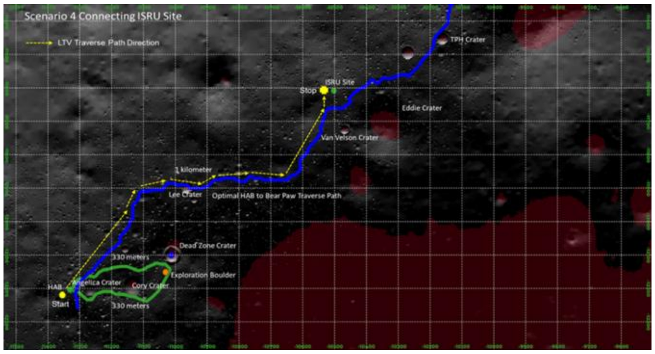


Figure 19. Example of a traverse plan.

Table 2. *Series Two Test Scenarios*

No.	Scenario	Description
1	Bear Paw	At Bear Paw, crew will exploration the Crater of Misery (COM) (a 35-meter in diameter large crater) by taking samples and photographing the area. They will then proceed onto Tanner Boulder to pick up chip samples and photograph. Finally navigate through the Crater Field on Infinite Sorrows (CFIS). The sites are in shadowed lighting areas; however, comm coverage is good. the approximate total distance of the traverse is 660 meters. Will be run twice to test remote ops versus crew driving.
2	HAB DeadZone Site	At the HAB site, the crew will be exploring at Dead Zone Crater where they will be taking samples and photos. The crew will then proceed on foot to a nearby Exploration Boulder collect a chip sample from the boulder and photograph the area. Communications at Dead Zone crater is an issue and the site is in total shadow when the crew is in the crater. Crew will also collect samples in Cory Crater. Total traverse distance is approximately 660 meters. Will be run twice to test remote ops versus crew driving.
3	HAB Site Crater Hopping Site	At the HAB site, crew will be exploring and traverse to multiple crater sites in the Fields of Quick and Easy Solutions (FQES) where they photograph and retrieve 3 small scientific payloads and stow them on the rover. Total traverse distance in approximately 2.2 km. Will be run twice to test remote ops versus crew driving.
4	In-Situ Resource Utilization unit (ISRU) inspection and parts pickup	Crew will travel approximately 1 kilometer (km) to inspect an ISRU unit on Connecting Ridge from the HAB. Once at ISRU the crew will have the rover do a 360-degree visual inspection of the unit. Then in VR will do a closer inspection and photograph the unit. Next, they will pick up several small parts packages to bring back with them on the rover. Finally, the crew will pick up a few rock samples near unit. Will be run twice to test remote ops and crew driving.
5	Crew First Day on Moon	At the lander site, the crew has arrived on the Moon and the rover recorded the event for MCC. The rover is 500 meters from the site to protect it from any FOD produced by the lander. The crew will descend the Starship Lunar Lander from the elevator approximately 50 meters high and traveling 0.25 meters/second. This will take approximately 3 minutes and 20 seconds. Once on the surface, the crew will first acquire a contingency sample (rocks), do a visual inspection of the lander, then will setup the Artemis flag, and do photography. Once the rover has arrived, crew will inventory the tools on the rover and visually inspected the rover for any damage. Getting aboard the rover, the crew will proceed to Chip Boulder and collect Chip samples. Then on their return trip to the lander, will survey the Abyss of Eternal Loneliness (AEL) Crater. Will be run twice for with different remote ops delays. Total traverse is 1.2 km.

Table 2. *Series Two Test Scenarios*


Figure 20. Crew driving the rover in the video wall.

Methodology and Data Collection

For both series of studies, a task acceptability scale was used by the subjects. Task acceptability is the ability to complete a task effectively, efficiently, and reliably without significant discomfort, exertion, fatigue, or avoidable inefficiencies, and without risk of injury to self or damage to equipment/vehicle [13,14]. The Acceptability Scale was developed by NASA's Exploration Analogs and Mission Development (EAMD) project during analog field testing in 2008 [14] is based on a 10-point Likert scale (1-10) where the scale is divided into five distinct categories with two numerical ratings within each category to discriminate preferences (Figure 21). The scale was designed, in part, from the Cooper-Harper Quality Handling Scale to have a scale that could quantify how the acceptability of the logistic operations by the subject using a simple scale. Likert scale data can be considered as either interval or ordinal depending on the presentation of the rating scale to the subject [15]. The Acceptability rating scale is interval because only the rating category, e.g., totally acceptable, acceptable, etc. has a label and descriptor, each individual rating does not have a label. A reasonable interpretation of this scale by a subject is that the distance between the data points along the scale are equal [15]. This is reinforced by the constant width of the scale itself. Interval data can be analyzed with descriptive statistics. The individual acceptability ratings will be analyzed to provide minimum, maximum, and median acceptability using a 95% confidence interval for each timeline task. Additionally, both individual and subject consensus ratings for each of the task/session was collected.

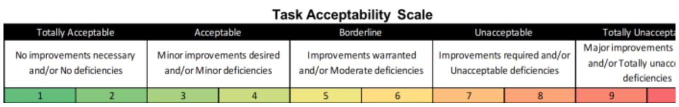


Figure 21. The EAMD Acceptability Rating Scale.

Subjective workload was only collected in Series 2 study. As a hypothetical construct, workload represents the cost incurred by a human operator to achieve a particular level of performance [16]. Demands of a certain task is created by the task objectives, duration, structure, and by the human and/or system resources that are provided. For example, mental workload is the difference between cognitive demands of a particular task and the operator's attention resources. [17, 18]. In order to test workload, many researchers state that subjective ratings may come close to actually tapping the essence of workload [16, 17]. The rationale for subjective data in the practical advantages such as, ease of implementation and being non-intrusiveness to collect. One of these standard workload methods is the NASA-Task Load Index (TLX). The TLX has been used in numerous successful multitask contexts such as real [14] and simulated flight tasks [19, 20, 21, 22, 23, 24] and remote-control vehicles [16]. Developed by Hart and Staveland [16], the NASA-TLX uses six dimensions to assess mental workload: mental demand, physical demand, temporal demand, performance, effort and frustration [17]. Definitions of the NASA-TLX dimensions can be seen in Table 3. Twenty step bipolar scales are used to obtain ratings for each dimension. A score from 0 to 100 is obtained on each scale [16, 17]. The operator is required to pair comparison between which dimension is more relevant to the workload across all pairs of six dimensions [17]. To combine the six individual ratings into a global score, a weighting procedure is used. The weighting procedure takes the number of times a dimension is chosen as more relevant the weighting for that dimension scale is calculated. An overall workload score from 0 to 100 is obtained for each rated task by multiplying the weight by the individual dimension scale score, summing across the scales, and dividing by 15 (the total number of paired comparisons) [17]. With the NASA-TLX showing a high correlation with performance, an Analysis of Variance (ANOVA) can be carried out on these performance measures in order to check the existence of performance differences associated with workload [17].

Table 3. *NASA-TLX Rating Scale Definitions**

Title	Endpoints	Descriptions
Mental Demand	*Low/High*	How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
Physical Demand	*Low/High*	How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
Temporal Demand	*Low/High*	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
Performance	*Good/Poor*	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
Effort	*Low/High*	How hard did you have to work (mentally and physically) to accomplish your level of performance?
Frustration Level	*Low/High*	How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

*Hart, S.G. & Staveland, L.E. (1988). "Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research," Human Mental Workload, P.A. Hancock & N. Meshkati (Eds.), pp. 239-250. Amsterdam: North Holland Press 1988.

The objective data collected was the same for both studies. Objective data collection included, total distance in meters, average speed in kilometers and/or meters per second, time in seconds, frequency of rock contact, brake usage, frequency of rover as a communication relay, and frequency of the lander as a communication delay, location of EVA, etc. will be assessed (Table 4). All simulation data is recorded at a tenth of a second for both the video wall and the EVA VR sim.

Table 4. *Simulation Objective Data Collected*

Data Units	Data	Data Description
In meters (m)	Distance	The total meters the crew drove the rover for a specific task
In Kilometers per hour (kph)	Average Speed	The average speed the crew drove the rover for a specific task
Seconds	Moving Time	The average moving time the crew drove the rover for a specific task
Seconds	Stationary Time	The average stationary time the crew stopped the rover for a specific task
Seconds	Total Drive Time	The total drive time the crew drove the rover for a specific task
Frequency of Contact	Rock Contact	Frequency of Contact during a specific task

5. Results and Discussion

Natural Lighting

Under natural lighting conditions, sun direction, especially when driving at higher speeds can be a serious impediment to traversing safely. The South Pole lunar terrain is literally littered with craters and boulders everywhere to a point there is no way to drive around all the terrain features. Though not at the lunar South Pole, the Apollo 17 rover crew noted: *"… that in the real world when you drive the Rover (Lunar Roving Vehicle LRV) you are continually avoiding rocks, holes, and craters. Some you can see and some you can't quite see.* [25] (Figure 22) Crews stated it would be easy to damage the vehicle as hazards are often difficult to see in the lighting conditions being faced. Moreover, they noted it was difficult to judge the magnitude of the hazard accurately (Figure 23). For instance, is this an easy little crater I can driving through or a deep crater that could high-center the vehicle. This was observed by the Apollo 16 rover crew reporting: "[Going down sun] *is really grim. I* (Young) *was scared to go more than 4 or 5 kilometers per hour. Going out there looking dead ahead, I couldn't see Craters. I could see the rocks all right and avoid them. But I couldn't see the craters."* [26]. Slopes and depth were observed by the subjects as very difficult to judge when approaching. This naturally leads to slower driving speeds than originally anticipated.

Figure 22. An Apollo crewmember driving the LRV up-sun. Note the visor is down. [curiosity NASA]

Figure 23. Crewmember driving over the simulated South Pole lunar terrain.

In the up-sun case, it is difficult to see what is in front of the vehicle when staring directly into the sun. Long shadows from every rock in front of the vehicle compounds the issue as it is difficult to tell which rocks are significant obstacles and which one are not (Figure 24). This was very apparent to the Apollo 17 rover crew with Gene Cernan stating: "*Driving up-Sun … was a degraded mode of driving. It was very bright. Everything that you were looking at was effectively washed out."* [25] Additionally, driving down-sun with the vehicle's long shadow in the center of the driver's field-of-view (FOV) can be hazardous to the crew as well (Figure 25). Apollo 16 reported: " *I don't recommend driving in zero phase* (down sun). *When you got to a ridge, you couldn't tell if* *it was a drop off, or whether it was a smooth, shallow ridge."* [26] With both sun direction cases, the crew would tack the vehicle's direction to the left and right to avoid any hazardous in front of them due to a bight, glaring sun (up-sun) for casting a long shadow (down-sun). This was a consistent preference to traverse in the cross-sun direction due to challenges with looking directly up-sun and down-sun. Apollo 16 noted: "*Driving cross-Sun was no problem. You could s everything, At least you could avoid* [any hazards]*."* [26] Tacking in this case, mean driving the vehicle either to the left or right of center approximately +/- 20 to 30-degrees. The Apollo rover crews tacked "*a lot of times*." This maneuver requires more time and rover energetics; however, will likely be safer to the crew and the vehicle (Figure 26).

Figure 24. A subject driving up-sun.

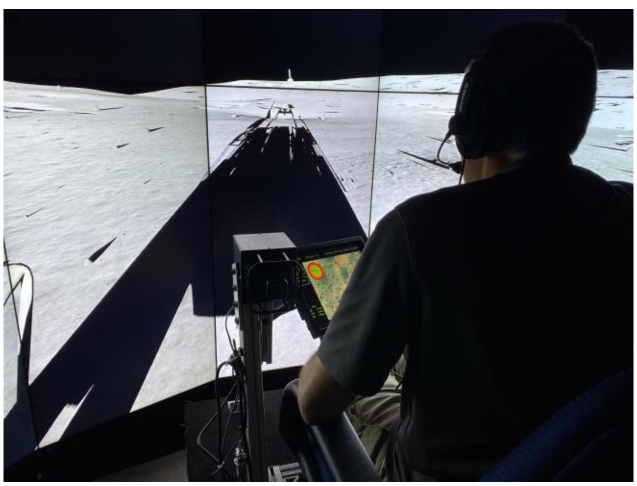


Figure 25. A subject driving down-sun.

Figure 26. A subject driving cross sun.

Staring into the sun is an obvious hazard, but less appreciated is how bright the surrounding landscape is when lit. If lit terrain is in view, pupil contraction is such that artificial lights on the vehicle are ineffective. This was very apparent during Series 2 study with the upgraded up-sun element. For the traverse studied, the repeated transitioning between dark and light became mentally taxing and hazardous to the rover crew. They noted the "best" or safest route, as opposed to least energy and distance planned traverse, which as tested, might be to use the most lit path, especially if the direction of travel is primarily cross-sun or fully shadowed with strong artificial vehicle lights to support longer-range navigational distances. Subjects did indicate several simple solutions to aid in the up-sun condition such as a sunshade or helmet visor. The Apollo 15 rover crew noting this during their technical crew debrief stating: "[I] *put* [my] *visor partially down, the hard, opaque, outer visor … and it really helped, particularly driving up-sun. You can drive right straight into the Sun with that visor down. But with the visor up, it's pretty tough going driving into the Sun*." [26] Apollo 17 had the same observation: *"… When you drove up-Sun you and a capability to either shielding your eyes with the hard-cover visor or your hand. As soon as you did that, you had absolutely distinct and perfect vision as to what was ahead of you. It was a case of being able to have the right geometry of the Sun versus your direction of driving*." [25] Also being considered was driving using a video camera view. A non-design solution was to have a crewmember egress the vehicle and walk alongside to help guide the driver.

Shadowed areas are so dark (especially when facing lit terrain beyond the shadowed area) that one enters these areas at one's own peril (Figure 27). Solutions for this lighting situation could be employing are sensing devices such radar or Light Detection and Ranging (LiDAR). As for the ability to notice scientifically interesting features, the accuracy varies greatly by the lighting condition the vehicle is in. In most cases, the task can be completed; however, a tactical strategy of using the sun to one's advantage, depending on terrain, improved the visual accuracy significantly. All these lighting conditions reported above would affect the accuracy and speed of any teleoperations from Earth.

Figure 27. A subject driving into a shadowed area.

Furthermore, there were some lighting conditions studied that were unacceptable regardless of artificial lights which must be pro-actively avoided. One lighting condition example is driving up-sun on a slight up-slope such that the terrain is shadowed due to the slope while the sun is shining into one's eyes at the level one is seated in the vehicle (Figure 28).

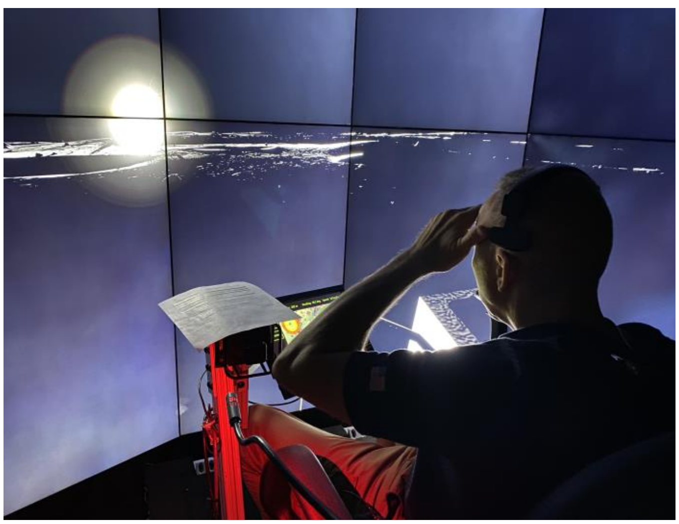


Figure 28. A special lighting situation with the subject looking up sun on a slight up-slope where he is in the sun while the bottom of the vehicle is in shadow.

Artificial Lighting

The rover had 14 lighting units all around the vehicle in order to assist the crew while driving and was only studied in Series One. Crew stated the vehicle lights did not project as far as desired for long-range navigation and hazard avoidance as was tested in fully shadowed areas. They additionally, noted they could not safely enter into a shadowed area from a well-lit area without some type of artificial light. During the times the crew drove in fully shadowed areas, they wanted a directable spotlight to aide in picking out hazards.

Workload

Crew workload while driving, was only collected during the Series Two study. The crew observed that at driver primarily focused their attention on the visual terrain approximately 80%, but who reference their display approximately 20% of the time while driving over the lunar terrain to a pre-determined destination. The co-driver/navigator would provide general directional/navigational cues to the driver while tending to provide scientific observations or handling the communication links to Houston Mission Control (Figure 29). Each crewmember used a different version of the terrain map to complement what they were accomplishing (Figure 30). For example, the driver used a slope map with a more localized view to aid in maneuvering around obstacles. The co-driver/navigator used several different maps depending on what activity they were supporting at the time. If communications were needed, the co-driver/navigator would use the terrain's communication coverage map. However, if the co-driver/navigator was supporting the driver in getting through rough terrain, they would use a terrain map that showed the "big picture" of the planned traverse versus the driver's more localized view. This was confirmed by the Apollo 17 rover crew indicating: *"…The driving tasks as termed to workload was comparable in certain kinds of trips. The guy in the left seat is going to pay attention to the driving task. It's a continuous requirement to watch where you're going, The duty cycle of the controller (driver) is almost 100 percent*." [25]

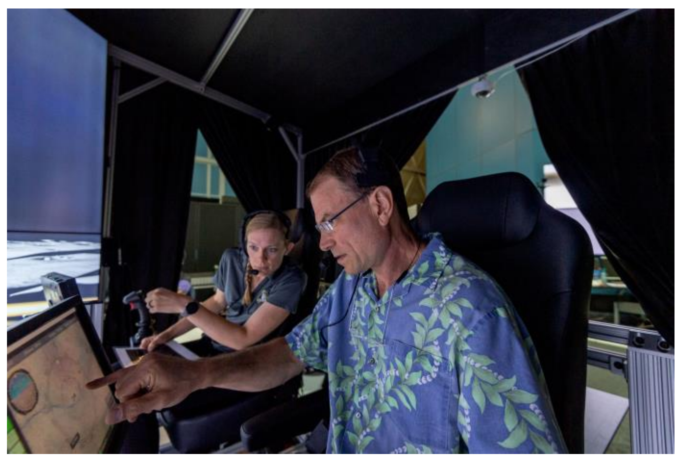


Figure 29. The crew showing a division of workload within the rover cockpit.

Figure 30. The two displays in the rover cockpit with the driver's display showing a local view, while the co-driver/navigator's display shows a "big picture" view.

6. CONCLUSIONS

Visible light in extremely confounding in the lunar South Pole environment. With the sun angle at the South Pole approximately 1.5 to 2-degrees above the horizon, natural lighting becomes a major challenge to a crew exploring the Moon with a rover. Though the tested traverse was a trade between vehicle power balance, it was not the best from a mission operational viewpoint. Contrast between light and shadowed areas tend to make the shadows areas even darker. This, in turn, makes hazard identification and avoidance quite challenging. Planning of traverses should consider the sun angle and crew visibility while driving.
Given the known challenges from driving in a lighting hazard condition (up or down-sun for example), more attention will need to be paid to traverse planning that optimizes the lighting and communication coverage over the route.

Virtual reality simulations are a useful tool [27, 28, 29, 30, 31] for understanding what a crew could face at the lunar South Pole in regard to natural lighting and terrain. The Apollo rover crew noted: *"… the* [LRV] *simulator was great … for driving on the lunar surface. We (Irwin and Scott) both thought that was a very useful simulation. It really made us feel at home once we got to the Moon. It made us familiar with the sequence of craters we'd encounter … and their relative positions."* [26] NASA's Lunar Lighting and Mobility Analysis (LLAMA) simulation is an attempt to gain general knowledge of the hazardous and conditions a crew could face. For the subjects who participated in these two series of studies, they reported the simulation capability was impressive and was essential to familiarization and demonstrate to anyone, crew, engineers, trainers, who is seriously working any type of South Pole lunar operations, especially with mobility vehicles. In order to understand the environment, we will be putting the crew into, it is paramount for us to have some visual and sensorial experience to base engineering decisions as a frame of reference. A simulation, such as the one developed by NASA, makes it easier for an engineer to understand why lights need to have more intensity making approval from a Program Manager for the additional hardware more sustainable. Additionally, the usefulness of the simulation for crew training while driving in different lighting conditions, shadows, and challenging washout scenarios are all things that crew have read or heard about, but being in the VR environment provided them useful context and would be an excellent utility in the initial stages of conceptual operation design, and hardware development and crew training.

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