IDENTIFICATION OF RISKS TO EVA CREATED BY AMBIENT LIGHTING CONDITIONS AT THE LUNAR SOUTH POLE

Cynthia H. Null[(1)], Mary K. Kaiser[(2)], Thomas E. Wolters[(3)], Jessica J. Marquez[(4)], A. Miranda Cooter[(5)], H. Charles Dischinger, Jr.[(6)]

[(1)]*National Aeronautics and Space Administration, Ames Research Center, C104, Moffett Field, CA, USA 94035, cynthia.h.null@nasa.gov*
[(2)]*National Aeronautics and Space Administration, Langley Research Center, MS125B, Hampton, VA USA 23681, mary.k.kaiser@nasa.gov*
[(3)]*National Aeronautics and Space Administration, Langley Research Center, MS125B, Hampton, VA USA 23681, thomas.e.wolters@nasa.gov*
[(4)]*National Aeronautics and Space Administration, Ames Research Center, MS262, Moffett Field, CA, USA 94035, jessica.j.marquez@nasa.gov*
[(5)]*National Aeronautics and Space Administration, Goddard Space Flight Center, Code 360, Greenbelt, MD 20770, ann.m.cooter@nasa.gov*
[(6)]*National Aeronautics and Space Administration, Marshall Space Flight Center, EV-74, Huntsville, AL, USA 32899, charles.dischinger@nasa.gov*

ABSTRACT

In the coming years, NASA's Artemis Campaign intends to return humans to the Moon, both to explore and to establish a permanent human presence. The targeted landing and habitation sites are near the Lunar South Pole (LSP). Compared to the middle latitudes where the Apollo landings occurred, the sun at the LSP is consistently low in the sky, creating a much more challenging visual experience.

The NASA Engineering & Safety Center (NESC) is working to characterize the extremes in ambient illumination that astronauts will encounter at the LSP, and to help programs characterize the lighting systems and glare protection that will be required to conduct safe surface operations. This paper will describe the LSP natural environments, and efforts to simulate that visual experience. It will also explain the risks derived from the lighting environment for the mission goals currently planned, and the kinds of new capabilities both in simulation techniques and in surface equipment that will be required to support those mission goals.

1. INTRODUCTION

Compared to the Moon's middle latitudes (where the Apollo landings occurred), the sun at the LSP is consistently low in the sky. At the sites being considered for the Artemis Campaign, the sun never exceeds seven degrees in elevation, and it is more often only one or two degrees above the horizon. As a result, the visual experience for the astronauts will be very different from that which the Apollo astronauts encountered. At the LSP, the sun will be in astronauts' field of view whenever they are oriented up-sun; when they face down sun, shadows will be extremely long and deep. The astronauts' visual systems will be stressed by high intensity light and glare, in quick juxtaposition with the need to adjust to extreme darkness. Because the human eye does not achieve such adaptations rapidly, highly capable lighting and eye-protection systems must be carefully designed. The NASA Engineering & Safety Center (NESC) is working both to characterize the illumination extremes that astronauts will encounter, and to help programs determine the lighting and glare protection systems that will be needed for safe surface operations.

This paper describes the natural environment at the LSP (and how it differs from that experienced by the Apollo astronauts). We then characterize the stresses it will present for the human visual system, given the system's capabilities and limitations. The paper also explores the challenges of creating high-fidelity simulations of the LSP's natural environment and the visual experience it creates. Finally, the paper will examine the risks created by the ambient lighting environment for the mission goals currently planned, and consider the kinds of new capabilities in simulation and surface equipment that will be required to support the design, planning, and training needed to meet those mission goals.

To capture and characterize these concerns, the NESC hosted a workshop in June of 2022, which brought together subject matter experts in:

- Artemis Campaign architecture and planning;
- Lunar natural environment;
- LSP terrain databases (including integration and enhancement techniques);
- Apollo experiences (including the personal recollections of Dr. Harrison Schmidt, the geologist-astronaut of Apollo 17);
- Human vision and physiology;

- Physical and CGI-based LSP terrain and lighting simulation technologies;
- Human-in-the-Loop (HITL) real-time simulation technologies.

Subsequent to the workshop, the NESC Team has conducted a number of site visits to NASA and other (military and industrial) simulation facilities, and continues discussions with Artemis managers regarding mission design and requirements.

2. THE ARTEMIS CAMPAIGN

The Artemis Campaign is a robotic and crewed Moon exploration program led by NASA, along with three international partner agencies (the European Space Agency, or ESA; the Japan Aerospace Exploration Agency, or JAXA; and the Canadian Space Agency, or CSA). The program also includes the collaboration of additional government and private spaceflight entities; by December of 2022, twenty-three countries and one territory had signed the Artemis Accords.

Although the Artemis program was formally established in 2017, many of its components (such as the Orion spacecraft) were developed during the Constellation program, which ran from 2005 to 2010. Besides the Orion spacecraft, the principal components of the near-term Artemis missions include the Space Launch System (SLS), the Lunar Gateway outpost, the commercial Human Landing System (HLS), and next-generation EVA suits and rovers.

Artemis I, the successful uncrewed test of the SLS and Orion, was completed in November of 2022. The Orion capsule entered a polar distant retrograde lunar orbit, which it maintained for about six days before returning to Earth. Artemis II is tentatively scheduled for late 2024; its crew of four will perform extensive testing in Earth orbit before being boosted into a free-return trajectory around the Moon; this mission will be the first crewed mission to leave low-Earth orbit (LEO) since 1972.

Artemis III, tentatively planned for late 2025, will be the first crewed lunar landing. Two of the crew will spend ~6.5 days on the surface, performing at least two EVAs. Artemis IV (2028 or later) will be the first mission to utilize the Gateway station. Artemis V (no earlier than September 2029) will be the first mission to include the Lunar Terrain Vehicle (LTV), which will expand the astronaut's range of exploration during EVAs to ~20 km from the landing site.

The NESC focused its assessment on these early missions (specifically, Artemis III-V). While NASA and its partners intend to conduct additional missions in an ongoing Lunar campaign, these missions' goals (*e.g.*, extended operations in Permanently Shadowed Regions) and capabilities (*e.g.,* a Pressurized Lunar Rover that might employ synthetic vision systems) are yet to be defined.

While the precise landing sites for the Artemis missions have not yet been determined, NASA has identified 13 candidate landing regions (Fig. 2-1), all of which are within 6° of the LSP. The selection criteria include but are not limited to illumination at the landing site along with the potential for science. Specifically, scientists wish to conduct research into Permanently Shadowed Regions (PSRs) to look at the content of frozen volatiles, including water ice.

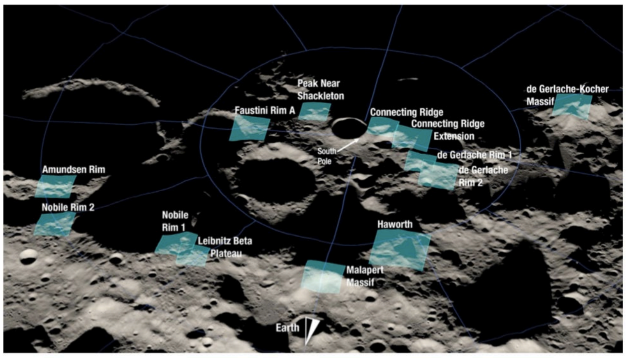


Figure 2-1. Candidate landing regions for the Artemis missions, all of which are within 6° of the LSP

These landing regions contain multiple areas suitable for executing a landing. Within these areas are multiple sites that meet the criteria for executing the science objective of the Artemis III mission. A down-selection to three regions is scheduled for later this summer. Site selection will continue as the focus on these regions is refined.

Although the terrain and lighting conditions at the LSP are more extreme than those encountered at the Apollo missions' more equatorial sites, it is nonetheless informative to examine the experience of astronauts on those earlier EVAs to understand the challenges they faced with ambient lighting, and to consider how these challenges will be exacerbated for the Artemis crews.

3. LESSONS LEARNED FROM APOLLO

When people hear of the Artemis Campaign, they tend to respond that humans are (finally) returning to the Moon. This is true, of course, but what people often fail to appreciate is how much more challenging the Artemis missions will be. The Apollo programs selected nearside, equatorial landing sites because these were the easiest locations to access (in terms of energy expenditure) and the easiest for logistics and safety (*e.g.*, direct line of communication, manageable range of temperatures, reasonable sun angles for the relatively short mission durations). The challenges the Apollo program faced were daunting enough, given President Kennedy's goal of "landing a man on the Moon and returning him safely to the Earth" before the end of the 1960s.

Yet despite the Apollo missions' more benign environment (benign being a very relative term), many of the challenges the Apollo astronauts encountered will likewise plague their Artemis colleagues. Consider, for example, two aspects Neil Armstrong noted about the Lunar environment just moments after making his "one small step" pronouncement:

> *"I can pick it [the lunar dust] up loosely with my toe. It does adhere in fine layers like powdered charcoal to the sole and the sides of my boots… It's quite dark here in the shadow and a little hard for me to see if I have good footing. I'll work my way over to the sunlight here without looking directly into the sun."* [1]

Thus, during his first five minutes on the surface of the Moon, Commander Armstrong recognized what would become documented as two of the most significant operational challenges for lunar missions: dust and ambient lighting. NASA has dedicated and talented colleagues addressing the lunar dust issue. Hence, this study focuses primarily on the issue of lunar ambient lighting.

In terms of dealing with the ambient lighting, Commander Armstrong had two advantages the Artemis astronauts will lack. First, given the relative lack of rocks and craters in the Sea of Tranquility, the largest shadows were those of the Lander. Hence, it didn't take much movement for him to exit these shadows, which were partially illuminated by reflected light. In a later section, we will discuss how much more extensive and dark the shadows in the LSP region will be. Second, it was relatively easy for Armstrong to avoid looking at the sun; the sun's elevation was already at 14° at the start of his EVA.

While there isn't a single Apollo mission that had natural environment characteristics as daunting as those of the proposed Artemis landing zones, Apollo 16 (which explored the Descartes highlands) was the most similar in terms of surface features *(i.e.,* the spatial and size distributions of rocks and craters). In terms of Sun elevation, the closest match to those expected at Artemis sites was encountered during the first EVA of Apollo 12. When the EVA commenced, the sun was 7.5° above the horizon (its zenith would be 9.5° at the end of the four-hour excursion). Fig. 3-1 shows the low sun angle encountered during EVA-1. While cameras cannot exactly replicate human perception of the scene, Commander Pete Conrad's initial words capture what the camera cannot: "Boy, that sun is bright… it's just like somebody's got a super-bright spotlight." [2]

Apollo 12, Ocean of Storms, EVA 1, 19 November 1969, frames A12-46-6738 to 6740 : Apollo 12 landing site

Figure 3-1. The sun behind Apollo 12's Lunar Module, as photographed during EVA 1

Transcripts from EVA-1 indicate the low sun angle was a source of difficulty throughout the excursion. In addition to burning out the sensor in the color video camera that was inadvertently pointed at it, the sun interfered with several EVA operations, requiring adjustments in positioning and procedures [2].

All subsequent Apollo mission encountered more benign sun angles during their EVAs; Apollo 16, for example, conducted EVAs with sun elevations between ~22° and ~49°. Nonetheless, astronauts on all the Apollo missions noted issues with the ambient illumination, from difficulties judging distances to not recognizing previously seen terrain features on subsequent EVAs (*i.e.,* when the new sun angle created different shadowing and apparent color).

It is also informative to examine the Apollo EVA suit (see Fig. 3-2), and the technologies it afforded to deal with lunar ambient lighting. First, there were no lights mounted anywhere on the suit. This seemed reasonable to designers, given that all missions were conducted during "daylight" hours, and in fully-illuminated terrain, meaning terrain lacking widespread shadows.

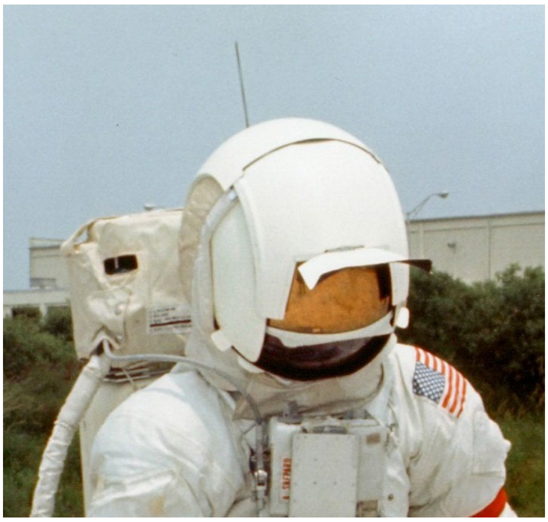


Figure 3-2. EVA suit used for Apollo missions

There were, however, multiple mechanisms the astronaut could use to attenuate the lunar sunlight. Most notably, the suit helmet was equipped with a gold-plated secondary visor that significantly dimmed visible light. (Note: there were other optical coatings on the primary visor to attenuate UV and IR wavelengths and protect eyesight. The gold plating was intended to dim visible light.) There were also cap-visor and side baffles that could be extended to block the sun's rays. However, while these eye-protection systems proved generally adequate for the Apollo missions, they will not suffice for the challenges the Artemis missions will present.

To better understand why the ambient illumination of the LSP region will prove so daunting to EVA operations, it is helpful to review the capabilities and limitations of the human visual system with regards to adapting to illumination levels.

4. THE HUMAN VISUAL SYSTEM

Even on Earth, vision is the most dominant of human senses. During lunar EVAs, this dominance is increased due to the fact other senses are diminished or absent. EVA astronauts are unable to hear, smell, or taste the external environment; touch and proprioception are limited or altered by the EVA suit. It is thus critical to understand how the human visual system will be able to adapt to the ambient lighting of the LSP.

Ambient light passes through the iris and lens of the eye, and focuses on the retina that lines the back of the eyeball. The human retina contains two classes of receptor cells: rods and cones. The rods respond purely to the intensity of light, thus supporting monochromic vision. The three types of cones (which selectively respond to short-, medium-, and long-wavelength visible light) work in concert to support chromatic vision. (Note: ~1% of humans, primarily female, possess a fourth type of cone, affording them better color discrimination. Conversely, about 8% of males and 0.5% of females exhibit some degree of color vision deficiency caused by a lack of full functionality of one or more of their cone types. Astronauts have their vision tested and can be assumed to have fully functional color vision.)

Rods and cones are not distributed equally or evenly across the retinal surface. As shown in Fig. 4-1, cones are densely packed in the central area of the retina; this enables humans' sharp *foveal* vision, which extends ±10°. Rods, in contrast, are sparse in this central region, but become more densely packed in the peripheral regions. [4] (Note: Each eye has a "blind spot" in the area of the optic nerve, which lacks any receptors. Because of binocular vision, eye movements, and the human brain's perceptual processing, this gap has minimal functional significance.)

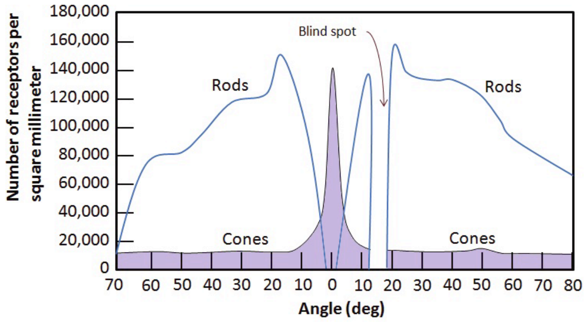


Figure 4-1. Distribution of receptors (rods and cones) across the human visual field (right eye).

Upon exiting the retina, the neuron excitations of the rods and cones feed two separate visual pathways in the lateral geniculate nuclei (LGN): the Magnocellular (M) and Parvocellular (P), respectively. The M pathway is primarily responsible for the perception of movement, gross depth, and brightness discrimination. The P pathway is necessary for the perception of color, form, and fine detail. [3]

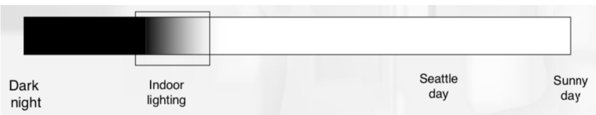
It is almost more correct to say that there are two human visual systems: The M pathway that is concerned with *Where* (*i.e.,* the depth and motion of monochromatic "blobs" in the visual scene); and the P pathway that is concerned with *What* (*i.e*., the form, color, and details of objects inspected with foveal vision). Because the capabilities of these two systems vary depending on the brightness of the visual scene, it is important to consider if ambient lighting conditions are adequate to support both of these systems. (Note: For completeness, we must note that there is a third pathway – the Koniocellular, or K – that processes input from the short-wavelength "blue" cones. The function of this pathway is not fully understood; it likely plays a role in color perception, but may also influence circadian entrainment, and aid integration of somatosensory and proprioceptive information with visual perception. Still, most functional vision can be explained by the mechanisms of the M and P pathways.)

With this basic understanding of human visual processing, it becomes more apparent why the ambient illumination on the lunar surface presents such a challenge. The human visual system is tasked with interpreting stimuli across a range of illumination levels, and that range is incredibly broad (and bimodal) on the lunar surface.

Consider light intensities here on Earth. In principle, intensities can range across nine orders of magnitude. That is, a piece of pure-white paper can be a billion times brighter in full high-desert sunlight than on a moonless night. But, in fact, in any given lighting environment, intensity typically ranges over two to three orders of magnitude. The human visual system calibrates its dynamic range to match ambient light levels.

A representation of this recalibration is shown in Fig. 4-2. If a person is outside in Seattle on a cloudy day, their visual system adapts to that range of illumination (which, as mentioned, spans at most three orders of magnitude). If the person then enters a windowless building, their visual system will adjust to that level of ambient lighting. Both environments support full visual capability (*i.e.,* both rod- and cone-based vision, but only once the person has adapted to that environment's ambient illumination.

(a)



(b)

Figure 4-2. Graphic representation of the shift in human eye's luminance sensitivity to cope with changes in ambient illumination from a cloudy day (a) to a building's interior lighting (b)

Humans have three mechanisms to adapt to changes in illumination. First, the eyes' pupils can contract or expand in diameter (from ~2 to ~8 mm) to allow more or less of the available light to enter the eye. (This is analogous to adjusting the aperture on a camera.) The pupil can accomplish this adjustment in seconds (taking slightly longer to expand than contract), and it shifts the eye's "sensitivity window" by about two orders of magnitude. Examining Fig. 4-2, one can see that this would be the level of adaptation needed to shift from a sunny to cloudy day, making it a fully adequate adaptation mechanism for partly cloudy terrestrial days when the sun dodges in and out of the clouds.

The second adaptation mechanism involves the rods and cones adjusting their sensitivity to light. Cones can adjust more quickly (~10 minutes), but have a smaller adaptation range – in low-light environments, humans are unable to perceive color and fine detail. The rods take longer to adjust (up to 30 minutes for maximal sensitivity), but have a much greater range (*i.e.*, they can provide "night vision"). Note that the times required for these adjustments are well attuned to the daylight-dusk-dark and dark-dawn-daylight progressions humans experience on Earth.

The third adjustment the human visual system can make to changes in ambient illumination is the manner in which our visual system weighs input from the M and P pathways. Roughly speaking, scotopic vision dominantly weighs the M pathway and drives vision in low-light conditions; photopic vision weighs the P pathway more heavily and functions in high illumination environments. Illumination conditions that provide excellent support for both pathways are termed mesopic. (Note: Human factors experts describing lighting conditions and the resultant functional vision tend to use the terms photopic, mesopic, and scotopic, while physiologists and vision scientists focus more on the underlying neural pathways, M and P.)

The critical aspects to consider regarding how the human visual system processes stimuli and adjusts to the level of illumination are:

- The human visual system can function across the wide range (nine orders of magnitude) of illumination encountered in the terrestrial environment; but at any given time, the system is calibrated to function at the current level of ambient illumination (which only varies 2-3 orders of magnitude);
- To adapt to a different level of illumination takes time. Fast (pupil-based) adaptation can occur within seconds, but only shifts the calibration window a few orders of magnitude; larger adaptations take far longer.
- These larger adaptations can alter the degree to which information from the two visual processing streams are utilized.
- Because the P pathway cannot function at low levels of illumination, humans' ability to discern color and fine detail may be compromised in these environments, yet actions dependent on information from the M pathway can continue.

- The human visual system did not evolve to function in environments containing both extremely bright and extremely dark areas of illumination within a single visual scene. As will be discussed in Section 6, such scenes will be commonly encountered at the LSP.

5. LSP SUFACE FEATURES

The LSP surface is not totally unknown. It is an area that has seen more impacts than the rest of the Moon, creating mountain ranges and a multitude of large craters. This cratering produces the PSRs, the areas where the science teams are especially interested in collecting data. The expectation from the bombardment that occurred at the LSP is that there should be more rocks and small craters than at the Apollo sites due to the ejecta. In terms of surface features, the area has thus far shown itself to be most similar to the highland terrain explored in the Apollo 16 mission, a scene from which is shown in Fig. 5-1. [3]

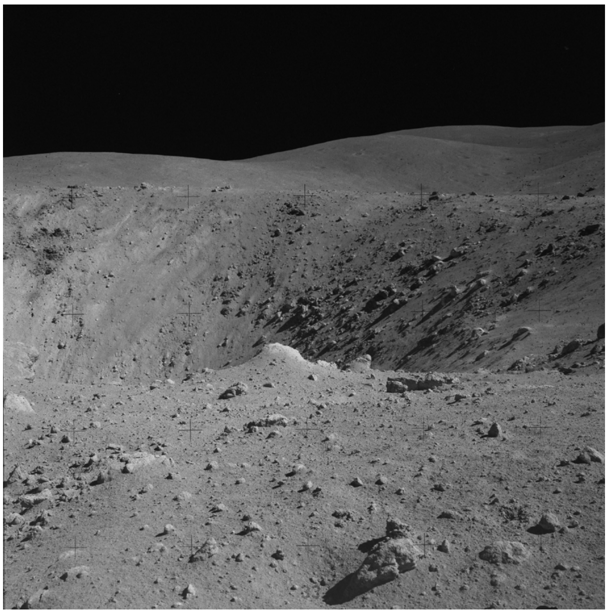


Figure 5-1. Apollo 16 Highlands Terrain at North Ray Crater.

The Lunar Reconnaissance Orbiter (LRO), which provides a resolution of 5m imagery as well as terrain elevation data, has proven the highlands similarity to be true (at least down to its resolution limits). Further analysis of imagery and, in particular, the movement of shadows in multiple images of the same sites, has provided a capability to determine size and position of boulders and craters smaller than 5m down to about 1m. Emerging distributions follow previously established distributions as laid out in the Cross-Program Design Specification for Natural Environments (DSNE) [6]. The distribution of rocks and small craters at the LSP is being attributed to its age. The bombardment happened early in the Moon's development, and it has been hypothesized that subsequent eons have allowed sufficient time for the accumulation of regolith to bury most of the ejecta and made the small craters into a hummocky, or humpy, surface.

6. LSP AMBIENT ILLUMINATION

The LSP lighting environment, like everywhere on the Moon, is influenced by the lack of atmosphere. This prevents attenuation or scattering as would be experienced on the Earth, and leads to a highly dynamic illumination range. Further, because the sun elevations for the LSP regions being considered never exceed 7°, and most of the time are at or around 2° elevation, the sun will never be out of view for half of the horizon when it is available for illumination. As previously discussed, the closest analog to LSP ambient illumination that astronauts have experienced was during the first EVA of Apollo 12 (Fig. 6-1).

Secondary illumination will be available, but has not yet been fully characterized for the landing regions under consideration for Artemis III. Such illumination sources include: reflected light from sources such as the Earth (especially when it is full); other natural surfaces such as mountains and large rocks that may catch and reflect sunlight (albedo); and human-made objects such as landers, rovers, suits and (eventually) supply and habitat structures. Examples of types of reflective illumination are shown in Fig. 6-2 and Fig. 6-3.

Figure 6-1. Apollo 12 Landing Site Panorama during EVA-1, with the Sun at 7.5° elevation. Note the illuminated area (or halo) around the astronaut's shadow, which is in the opposite direction of the sun; this is retro-reflectance.

Figure 6-2. A close up from the Apollo 12 panorama, highlighting the halo around the astronaut's shadow created by retro-reflectance.

Figure 6-3. Apollo 17 Boulder Shadow with some light reflected from nearby surfaces.

LSP illumination, when combined with surface features, will need to be accommodated for the astronauts on the surface both in terms of light intensity and glare protection as well as illumination when entering or working in shadowed areas. At best, there will be a patchwork of highly lit areas where intensity and glare will affect the astronauts' visual field, interspersed with dark patches or totally dark areas where little to no light assists their ability to see. Supplemental lighting will be needed, particularly for walking and driving tasks, and will be most important when transitioning from extreme brightness to total darkness.

7. SIMULATING THE LSP ENVIRONMENT

Simulating the LSP environment is challenging and requires a variety of approaches to cover the range of characteristics that need to be modeled, evaluated, or tested. Physical simulation, involving surface analogs to regolith and rocks along with various lighting approaches, are needed in order to: test hardware for illumination characteristics, develop methods for execution of lunar surface activities, and perform task training with lighting intensities that will mimic the challenges and physiological responses to the lighting conditions at the LSP.

Due to limits with display technology, computer-based LSP surface simulations lack the dynamic range to elicit physiological responses. However, such simulations are able to render what is seen so that things like the ability to navigate on the surface and avoid obstacles can be tested, sequences for deploying payloads can be developed, or collecting samples from PSRs can be rehearsed.

8. OPERATIONAL CHALLENGES

The ambient illumination of the LSP is extremely harsh, with the juxtaposition of extremely bright and extremely dark areas within a single visual scene. It is difficult to simulate this visual environment due to current limitations in display and lighting technologies. Likewise, it is difficult to simulate the gravitational-inertial environment astronauts will experience on the Moon. Thus, Artemis astronauts must perform tasks and operations during their missions without the benefit of training in a true high-fidelity simulator.

Thus, it is incumbent on mission designers, planners, and trainers to determine the best simulation capabilities to use for each operational task in order to maximize the fidelity of training during pre-mission preparation. As a part of the training, crewmembers must be fully informed of the limitations of each simulation so that they can anticipate critical differences they will encounter in the actual operational environment. Operational experiences must then be examined to determine how simulation tools can be improved.

Finally, given the extreme lighting conditions of the operational environment, it will be prudent to provide the crew with alternative "fallback" procedures to ensure safety and the best possible degree of mission success. For example, if it turns out that a display designed to be "daylight readable" is overwhelmed ambient illumination, astronauts will require another means to acquire the information needed to complete their task.

9. SAFETY ISSUES AND CONSIDERATIONS

Artemis astronauts will explore an entirely new lunar region with very different lighting characteristics than those experienced by previous astronauts. As described above, inherent lighting at the LSP is very dynamic and, without supplemental illumination and/or specialized visual aids, could result in a lack of situational awareness and/or the inability to see hands and feet during tasks or translations. This lack of visual awareness could cause trips and falls or damage to the suit from inadvertent misuse of tools, leading to permanent injury or death to crew.

While it is not possible to eliminate all hazards when exploring a new environment, it is vital to provide integrated, adaptable tools and associated training to the crew to mitigate the effects of dynamic lighting at the LSP. Tools to provide illumination or to control illumination should be designed to work together to contribute to the overall safety of the crew.

8. INTEGRATED SYSTEM REQUIREMENTS

As the crewed Artemis journey begins, it will be vital to ensure that tools and equipment provide an integrated and comprehensive approach to managing lighting while on the lunar surface. Such tools must work together, sharing resources, to mitigate glare as well as to illuminate shadows. Requirements for these tools should be top level and flowed down to suits, rovers, landers, and any other equipment used for exploration.

The procurement model used by the Artemis campaign makes the sharing of requirements especially challenging because, for example, lander and suit services will be provided by different vendors. Thus, if the suit community determines lighting needs could be met more efficiently and effectively by mounting area lights on the lander's exterior, it is currently unclear how such a "cross program" requirement could be levied. This integration is a current focus, within the Agency.

Similarly, it will be critical to ensure that techniques and technologies developed to deal with one aspect of the harsh LSP ambient lighting does not work at cross purpose to another. For example, unless the solutions are properly integrated, visors that attenuate a significant amount of visible light could greatly increase the brightness required from supplemental lights to illuminate shadowed regions.

9. CONCLUSION

When the Artemis missions return humans to the surface of the Moon, astronauts will need to cope with far more challenging ambient lighting condition than the Apollo missions encountered at the lower lunar latitudes. The sun, never higher than seven degrees above the horizon, will be a constant source of glare and create shadows that are incredible long and deep. Visual scenes will often contain a range of illuminations far greater than any viewed here on Earth, overwhelming the human visual system's ability to achieve a level of adaptation appropriate for all areas of the scene.

It is only by following an integrated and systematic approach to defining lighting and eye-protection design requirements that the Artemis team will be able to successfully explore the lunar surface and establish a permanent presence near the Lunar South Pole. All the Artemis programs must work in concert to develop tools and systems that are adaptable and coordinated. Only such an overarching lighting architecture will be able to fully support safe and effective EVA activities in the challenging ambient lighting conditions of the LSP.

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