Maps of Primary Radiation Dose Around the Lunar South Pole: Preliminary Assessment of Artemis Landing Sites. P. H. Phipps[1,2,3], T. J. Stubbs[2], M. D. Looper[4], H. E. Spence[5], and L. W. Townsend[6] [1]University of Maryland, Baltimore County, Baltimore, Maryland, USA (email: phphipps@umbc.edu), [2]NASA/GSFC, Greenbelt, Maryland, USA, [3]CRESSTII, NASA/GSFC, Greenbelt, MD, USA, [4]The Aerospace Corporation, El Segundo, CA, USA, [5]University of New Hampshire, Durham, New Hampshire, USA, [6]University of Tennessee, Knoxville, TN, USA.

Introduction: The Moon has a harsh radiation environment that poses significant challenges to future science and exploration activities. Exposure hazards from space radiation are primarily due to galactic cosmic rays (GCRs) and solar energetic particles (SEPs) that are incident at the lunar surface from all directions. The Lunar Reconnaissance Orbiter's (LRO) Cosmic Ray Telescope for Effects of Radiation (CRaTER) instrument has been observing space radiation around the Moon since 2009 [1]. The CRaTER observations show a steady GCR flux with intermittent SEP events that have much higher fluxes. During solar minimum, the GCR flux is higher, while the SEP events are less common. On the other hand, during solar maximum, the SEP events have are more frequent and the GCR flux is lower. This is due to variations in solar activity. GCRs have characteristic energies spanning from 1 MeV to 10s of GeV [2]. SEPs, however, have much lower energy ranges of 50 keV to 100s of MeV.

The level of exposure at a given location on the Moon is dependent on the amount of space radiation incident from above the local horizon (Figure 1). This means that radiation dosage depends on the surrounding terrain for any location on the surface, so it can vary substantially from point to point. Previously, we have considered radiation exposure around simple lunar craters that are representative of the types of landforms that will be encountered by future landed missions [3]. However, in this study we have used digital elevation models (DEMs) of the Moon to map out radiation doses within 10º of the lunar South Pole (Figure 2), which includes the candidate landing sites for the Artemis III mission [4].

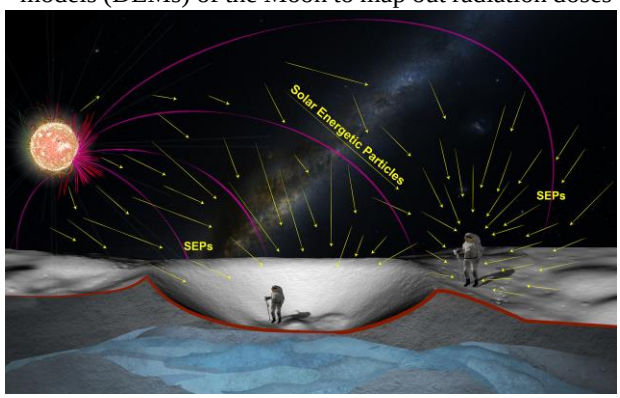


Figure 1 Illustration of how natural shielding from surrounding terrain effects radiation exposure at the lunar surface in and around a crater during a solar energetic particle (SEP) event. Inside the crater, the high elevation of the crater walls blocks SEPs incident at shallow angles.

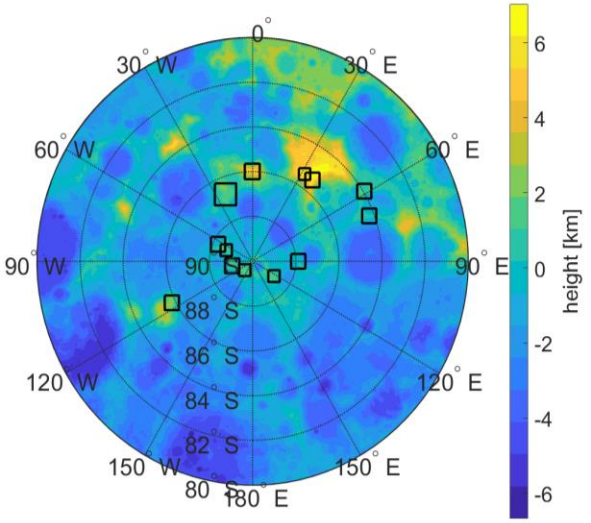


Figure 2 Height map from 128 ppd LOLA DEM. The black rectangles are the Artemis III candidate sites.

Of particular concern will be radiation exposure to biological targets, such as astronauts. Therefore, we use targets composed of water (H_2O) surrounded by 1 mm-thick aluminum shielding as a proxy for a space suited astronaut on the Moon. We consider radiation exposure during the worst case scenarios for both GCRs and SEPs. For GCRs, this is at solar minimum when shielding from the heliospheric magnetic field is reduced. For SEPs, we selected the infamous event from October 1989, which is considered to be the worst case SEP event for biological damage [5].

Methods: We use Geant4 Monte Carlo simulations [6] to compute the dose response for spherical targets composed of water (H_2O), as a proxy for biological systems. These simulated targets are surrounded by shells of aluminum of varying thickness to approximate the influence of artificial shielding from space suits, rovers, and habitats. The doses from primary space radiation (in centi-Gray [cGy] are determined by convolving these dose responses with proton fluence spectra of October 1989 SEP event and solar minimum for GCRs) [7]. GCR spectrum comes from O'Neill (2010). The 1989 SEP spectrum comes from fits to the spectrum retrieved from OLTARIS [7].

To determine the effect of terrain at the lunar surface, we use the 128 pixel per degree (ppd) Lunar Orbiter

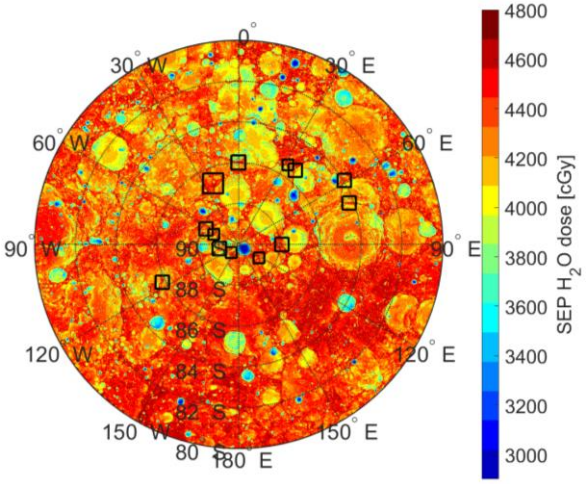


Figure 3 SEP proton dose radiation map using 128 ppd LOLA DEM. The black rectangles are the Artemis

Laser Altimeter (LOLA) DEM (0.235 km per pixel). Measuring the local horizon for each location on a grid we calculate the solid angle of the visible sky. Together with the Geant4 dose response and the GCR and SEP fluence spectra, this gives the dose received at each surface point.

Discussion and Conclusions: Figure 4 shows the results for the Artemis III candidate sites. The South Pole covering all proposed Artemis III landing sites is shown in Figure 3. Figure 4 shows each individual Artemis III candidate site.

Radiation intensities from SEP events are much larger than from GCR events and occur over much shorter time scales. The SEP events are also much more sporadic. Thus, acute radiation exposure can be expected to occur during SEP events. The mean radiation exposure for the total South Pole is 0.265±0.019 cGy for GCRs over a 30 day period and 4275±301 cGy for SEPs from October 1989 event. The maximum dose is 0.32 cGy for GCRs and 4800 cGy for SEPs (Figure 3).

During October 1989 event the radiation dosage at the lunar surface would be significantly larger than the 30 day radiation dosage limit. The limit is not exceeded for just GCR radiation dose. Dose limits vary by the system of the human body being considered, e.g., the lens of the eye, blood forming organs (BFO) or the central nervous system (CNS). If astronauts could seek the protection of shielding from lunar terrain then the radiation dosage can be significantly reduced. Therefore, for protection from SEP events, the shielding effect of surrounding terrain is an important consideration when selecting sites for permanent habitats, as well as for choosing routes and contingency planning during surface operations.

References: [1] Schwadron, N. A., et al. (2018) *Space Weather, 16*, 289–303. [2] Case, A. W., et al. (2013), *Space Weather*, 11, 361– 368. [3] Phipps et al. (2021), 52nd LPSC abstract 1500 [4] NASA Artemis III press release (August 2022) RELEASE 22-089. [5] Townsend, L., et al. (2018) LSSS, 23-39 [6] Allison, J., et al. (2006) IEEE Trans. Nucl. Sci., 53 (1), 270–278. [7] On-Line tool for the Assessment of Radiation In Space (OLTARIS), oltaris.nasa.gov

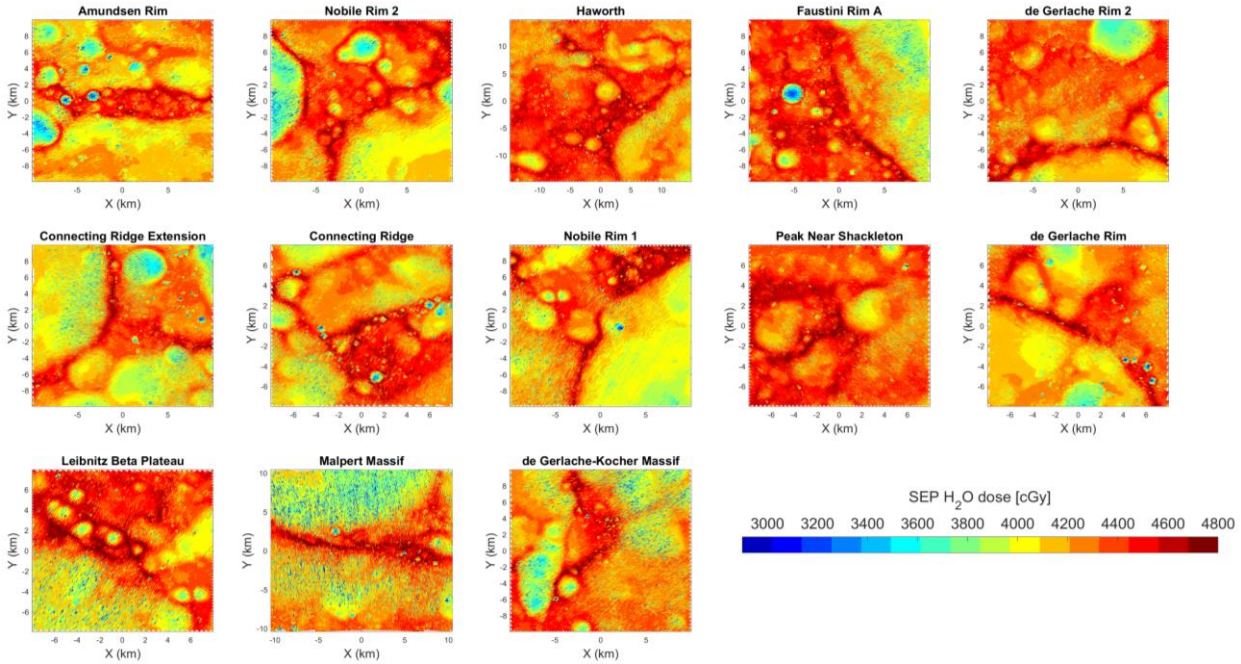


Figure 4 Maps of radiation dose at the Artemis III candidate landing sites for an astronaut with only their spacesuit for protection. Simulated for the worst case scenario for a biologically damaging SEP event (October 1989).