Radiation Dose Around The Lunar South Pole Near the Candidate Landing Sites for the Artemis III Mission.
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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 rate of GCR flux with intermittent SEP events that have much higher fluxes. During solar minimum the GCR have a higher flux rate while the SEP events are less common. On the other hand, during solar maximum the SEP events have a higher rate but 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].

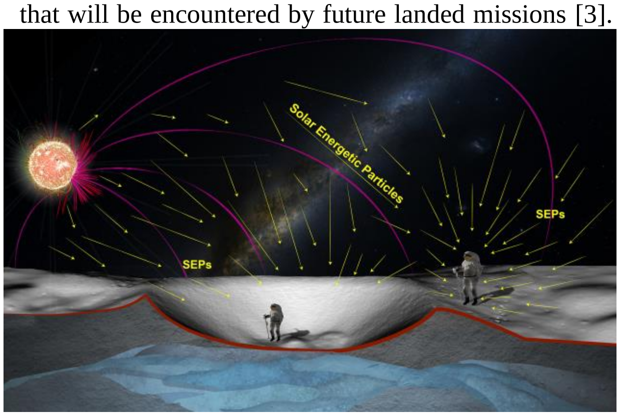

Figure 1 Illustration of how natural shielding from surrounding terrain effects radiation exposure at the lunar surface in and around a crater during a solar energetic particle (SEP) event. Inside the crater, the high elevation of the crater walls blocks SEPs incident at shallow angles.

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 (indicated by black boxes) [4].

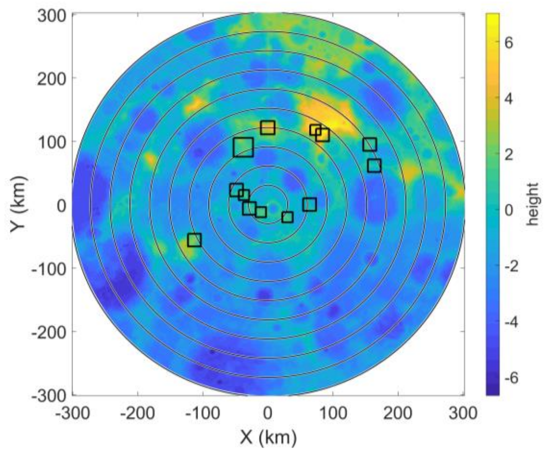

Figure 2 Lunar South Pole height map (64 ppd LOLA DEM) with candidate Artemis III landing sites.

We use targets composed of water (H_2O), as a proxy for biological systems. These targets are surrounded by shells of aluminum of varying thickness to approximate the influence of localized shielding from space suits, rovers, and habitats. To determine the doses from primary space radiation (e.g., in centi-Gray [cGy]), we convolve the Geant4-computed dose responses with representative worst case events, SEP spectra for the October 1989 event and solar minimum for GCRs [4]. Of particular concern will be radiation exposure to biological targets, such as astronauts.

Methods: We use Geant4 Monte Carlo simulations [5] to compute the dose response for spherical targets compute the dose response for spherical targets composed of water (H_2O), as a proxy for biological systems. These targets are surrounded by shells of aluminum of varying thickness to approximate the influence of localized shielding from space suits, rovers, and habitats. To determine the doses from primary space radiation (in cGy), we convolve the Geant4-computed dose responses with representative worst case events (October 1989 SEP event and Solar Minimum for GCRs) [6].

To determine the topographical affect at the lunar surface we use the 64 pixel per degree (ppd) Lunar

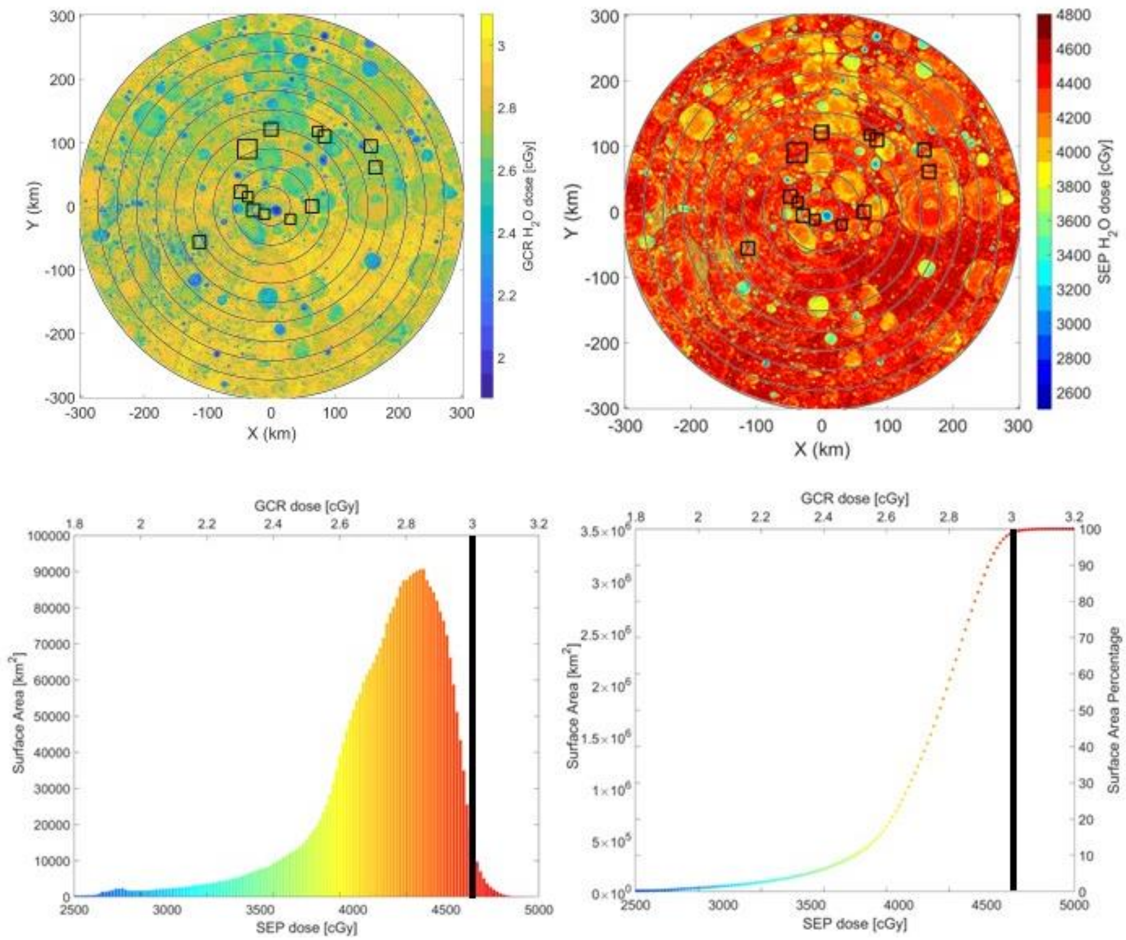

Figure 3 Maps and histograms of radiation dose within 10º of the lunar South Pole, where black rectangles indicate candidate landing sites for the Artemis III mission. (top left) GCR radiation dose at Solar Minimum. (top right) Worst case SEP radiation (October 1989 event). (bottom left) Radiation dose for GCRs and SEPs as a function of surface area [km^2], and (bottom right) the associated cumulative distribution; in both cases, the vertical line marks the dose for a flat surface (exposure over 2π steradians).

Orbiter Laser Altimeter (LOLA) DEM (0.47 km per pixel). Measuring the local horizon for each location on a grid we calculate the solid angle of the visible sky. This fraction can be multiplied by the dose response determined from the Geant4 convolution with SEP spectrum. This gives the dose received from SEP protons at each surface point.

Discussion and Conclusions: Figure 3 shows the results for 10º around the lunar South Pole covering all proposed Artemis III landing sites. The figure shows that the lunar terrain can provide shielding of up to 40% around lunar craters (*e.g.*, Shackleton) while most of the surface is shielding by around 0-10%.

Radiation from SEP events are much larger than GCR events and occur over much short time scales. The SEP events are also much more sporadic. Thus, acute radiation exposure can be expected to occur during SEP events. The most likely radiation exposure is 2.83 cGy for GCRs and 4396 cGy for SEPs. The maximum dose is 3.2 cGy for GCRs and 5000 cGy for SEPs (Figure 3).

During October 1989 event the radiation dosage at the lunar surface would be larger than the 30 day radiation dosage limit. The limit is not exceeded for just GCR radiation dose. Although, 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 effects 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] Allison, J., et al. (2006) IEEE Trans. Nucl. Sci., 53 (1), 270–278. [5] On-Line tool for the Assessment of Radiation In Space (OLTARIS), oltaris.nasa.gov