ESTIMATES OF SOLAR MODULATION POTENTIAL TO SUPPORT LUNAR EXPLORATION AND VOLATILES PROSPECTING WITH THE NEUTRON SPECTROMETER SYSTEM.

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Introduction: Multiple spacecraft will explore the south pole and other high-interest areas of the Moon in the next decade (e.g., VIPER, Astrobotic Peregrine Mission-1, and MoonRanger) [1, 2, 3]. These spacecraft will each carry a Neutron Spectrometer System (NSS), part of a suite of instruments designed to characterize the distribution and abundance of volatiles (e.g., water ice) in the top ~1 m of the lunar surface [4]. NSS measures neutron count rates in two energy ranges: thermal (E < ~0.4 eV) and epithermal (~0.4 eV < E < ~100 keV). These neutrons are produced through the interaction of galactic cosmic rays (GCRs) with nuclei in the subsurface. The abundance of these two neutron populations at the lunar surface varies primarily as a function of subsurface geochemistry (e.g., wt.% H and neutron absorbing materials) and the flux of GCRs.

At energies <~1 GeV, the GCR flux in the Earth-Moon system has been shown to vary with solar cycle. Modeled differential flux spectra of GCRs can be parameterized by a single time-dependent factor called the solar modulation potential, φ [5, 6]. Constraining φ (and therefore the flux of GCRs) is critical for interpretation of NSS data and can greatly enhance the instrument's ability to guide spacecraft operations in near real-time.

Here we compare three methods for generating φ values. The first method is to infer φ from near real-time neutron count rates measured at neutron monitoring stations around the world. The second method uses direct measurements of GCRs from the Advanced Composition Explorer (ACE) Cosmic Ray Isotope Spectrometer (CRIS) instrument to generate φ using the relationships developed by Slaba and Whitman [7]. Finally, de Wet et al. demonstrated a method for using absorbed dose rates from the Lunar Reconnaissance Orbiter (LRO) Cosmic Ray Telescope for the Effects of Radiation (CRaTER) instrument to estimate φ [8]. Past studies have used variants of the three methods to show how the different measurables relate to the observed and effective GCR flux seen at the Moon [e.g., 9, 10, 11].

Method 1: Neutron count rates measured as recently as the last ~2 minutes are available for stations around the world at https://www.nmdb.eu. We use data from four stations with low rigidity and historical data going back at least to the peak of Solar Cycle 23: Thule, Inuvik, Fort Smith, and Terre Adelie. To convert these to φ, we fit cubic polynomials between average monthly neutron count rates and φ values from the last 70 years from Usoskin et al. [12] (e.g., Fig 1). We compute mean values of φ from neutron count rates measured at all four stations (Fig 2A, 2C).

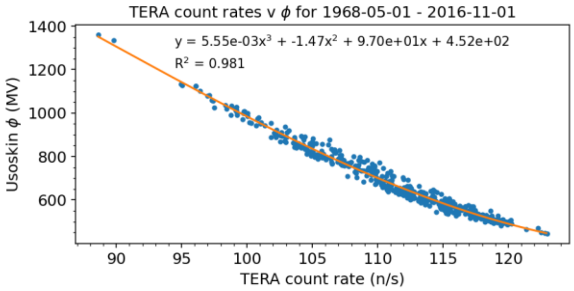

Figure 1. Neutron count rates from the Terre Adelie station in Antarctica versus φ from [12]. A cubic polynomial fit to the data can be used to estimate φ for terrestrial neutron count rates measured during future lunar missions.

Method 2: Fluxes of cosmic rays with Z=5 up to Z=28 are available from the ACE Science Center (https://izw1.caltech.edu/ACE/ASC/level2/index.html) and were compared to modeled fluxes by Slaba and Whitman to estimate φ [7]. They found φ could be estimated from the measured flux by:

$$\varphi(F_{\mathrm{ACE}}, a, b) = [b - a*\ln(F_{\mathrm{ACE}})]^2$$

where F_{ACE} is the integrated flux for a particular ion and a and b are fit parameters. We compute φ from ACE/CRIS integrated oxygen flux data (Fig 2A, 2C).

Method 3: Lineal energy transfer (LET) spectra from LRO CRaTER can be used to estimate absorbed dose rate [8]. Using a radiation transport model, de Wet et al. developed a response function to infer the solar modulation potential from the absorbed dose rate [8]. The dose rates are available at https://crater-web.sr.unh.edu/ and must be filtered to include only measurements with coincidence in the three CRaTER detector pairs and increasing LET between the detectors pairs.

Values of φ computed from the three methods described here are shown in Fig 2A and 2C. The corresponding integrated omnidirectional GCR proton flux, computed using the formulation from Castagnoli and Lal [6], is shown in Fig 2B and 2D.

Discussion: Terrestrial neutron measurements have the advantage of near real-time publication but are the least direct measure of the GCR flux discussed here. CRIS data are direct measurements of energy deposited by GCRs outside of Earth's magnetic field but are published only at the end of every Bartels' rotation (27 days). CRaTER data are also measurements of energy deposited by GCRs and have the advantage of being in the most similar environment to measurements made by NSS. However, the data are available only as often as LRO downlink is made through the Deep Space Network and calibrated data are published to the CRaTER website (~weekly).

There is general agreement between the φ values generated by the three methods at periods of low solar activity, but some significant differences exist during the peak of the last solar cycle (~2013-2016 in Fig. 2). Resolution of which method is the most appropriate to use for NSS could be provided by additional pre-flight characterization of the sensor's response to GCRs and in-flight measurements from the instrument's overload channel.

NSS operations during VIPER's planned 100+ Earth day mission will overlap the cadences of the three methods discussed here [1, 4]. The constraints offered through these methods will support near real-time interpretation of the water ice abundance around the rover during drives as well as at multi-day science station stops. Finally, a synthesis of the three methods will support subsequent interpretation of NSS data using detailed radiation transport modeling.

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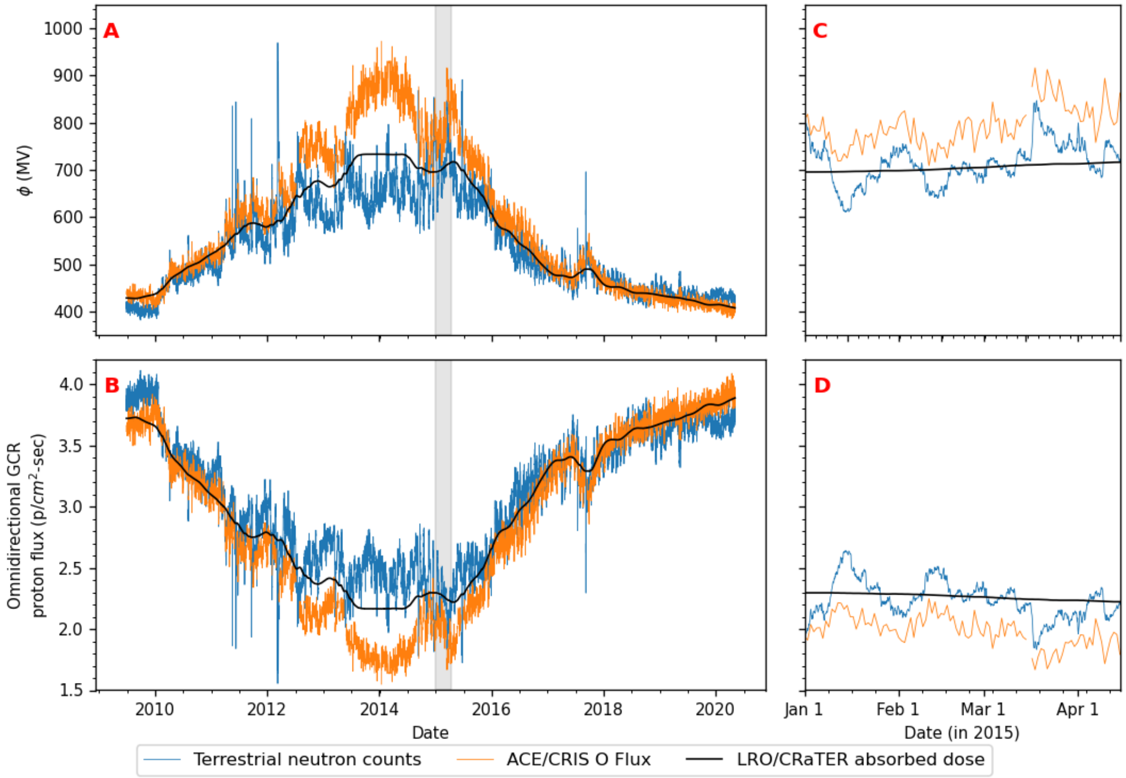

Figure 2. (A) Solar modulation potential as estimated from terrestrial neutron count rates (blue), GCR oxygen flux from ACE/CRIS (orange), and absorbed dose from the LRO/CRaTER instrument (black). Data are shown for most of the last solar cycle, starting with the launch of LRO in June 2009. (B) Omnidirectional GCR proton flux for the φ in (A), computed using the differential GCR flux spectrum formulation provided in [6] and integrated over 10 to 10^6 MeV. (C,D) Same as (A) and (B), but for a window during the peak of the last solar cycle (January to April 2015, gray vertical shaded areas in A,B) to show variability in solar modulation and the corresponding estimated proton flux for a VIPER-like mission duration (~100 days) [1]. VIPER is expected to be operating at the lunar south pole during the peak of the next solar cycle (~2024-2025).