Calibration and Validation of the Lunar Exploration Neutron Detector (LEND) Observations for the Study of the Moon’s Volatiles

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Abstract This paper reviews improved calibration methods for the Lunar Reconnaissance Orbiter’s (LRO) Lunar Exploration Neutron Detector (LEND). We cross-calibrated the set of LEND observations and models of its detectors’ physical geometry and composition against the McKinney Apollo 17 era measured neutron flux, Lunar Prospector Neutron Spectrometer (LP-NS) epithermal neutron observations, Earth-based Galactic Cosmic Ray (GCR) observations and altitude dependent models of the Moon’s neutron emission flux. Our neutron transport modeling of the LEND system with the GEometry ANd Tracking (Geant4) software package allows us to fully decompose the varying contributions of lunar, spacecraft and instrument dependent sources of neutrons and charged particles during the LEND mission. With this improved calibration, we can now fully predict every observation from the eight helium-3 detectors and the expected total and partial count-rates of neutrons and charged particles for the entirety of LEND’s now eight-plus year observation campaign at the Moon. The study has resulted in an improved calibration for...
all detectors. The high spatial resolution of LEND’s collimated and uncollimated sensors are illustrated using the neutron suppression region associated with the south polar Cabeus permanent shadowed region.

**Keywords** LRO · LEND · LP-NS · Lunar Neutrons · GCR Particles · Lunar Hydrogen · Orbital Sensing · Planetary Neutron Spallation

1 Introduction

Since the dawn of the space age over fifty years ago, the world’s space-faring nations have designed their lunar missions with a primary objective to understand the Moon’s surface water distribution (Clementine - Nozette et al. 1996, LPNS - Feldman et al. 1998, Kaguya - Kato M, et al., 2008, LRO - Mitrofanov et al. 2010a, Chandrayaan-1 - Pieters et al., 2009). This ongoing scientific quest continues to be driven by the critical role that efficiently extractable water and hydrogen-bearing volatiles will play as a resource for future manned missions to the surface, and potentially to supply missions into the solar system (Mendell W. ed. 1985). Absent such a resource, future missions will be severely constrained to their payloads, which will limit both the missions’ duration and their potential objectives. Thus, an understanding of the Moon’s spatial distribution of water and its budget remains high on the list of scientific priorities for future lunar missions. (Hubbard et al., 1998; Feldman et al., 2000; Boynton et al., 2004; Mitrofanov et al., 2007, 2008; Kato et al., 2008, and Andrews et al. 2014).

To derive the near-surface water distributions of the planets and the solar system’s small bodies, one of the most definitive remote sensing methods is to measure the neutron emission flux from orbit (LPNS, LEND, HEND, MONS - Maurice et al. 2011, Lawrence et al., 2014). Given adequate surface sampling, we can estimate both the spatial and near-surface depth distribution of hydrogen-bearing volatiles at up to 1 m, though, it must be noted that neutron techniques cannot discriminate water from other hydrogen-bearing c. Stratigraphy, geochemistry and surface temperature variations can also complicate the identification and quantification of hydrogen (Lawrence et al. 2011). Neutron studies also provide information about the Moon’s surface geochemistry, thus facilitating insights into its composition, as well as the origins and history of the Earth and our solar system (Gasnault et al., 2001). In particular, neutron techniques are highly applicable to the study of the Moon’s polar environment, where the highest concentrations of water are thought to exist. Neutron techniques are also advantaged over surface reflectance measurements which rely on reflected light which is in low supply at the poles. The technique is largely insensitive to surface temperature variation (Little et al., 2003; Lawrence et al., 2006) which can dramatically change in polar topography.

The history of nuclear experimental techniques as applied to lunar exploration goes back to the Apollo era. The first instrument to directly measure lunar neutrons was the Lunar Neutron Probe Experiment (LNPE) of Apollo 17
(Woolum et al., 1973, 1975), followed by the Lunar Prospector Neutron Spectrometer (LPNS), and finally the contemporary Lunar Reconnaissance Orbiter (LRO) mission with the Lunar Exploration Neutron Detector (LEND). From orbit, these instruments observe the Moon’s neutron emission flux and specially designed detectors integrate it over three large neutron energy ranges (thermal: \( E \leq 0.4 \) eV, epithermal: \( E \) from 0.4 eV to \( \sim 10 \) keV, and high energy: \( E \geq 100 \) keV). The intermediate epithermal energy range is particularly sensitive to hydrogen in the upper meter of regolith. MeV energy neutrons are created in the regolith as a result of nuclear interactions between incident Galactic Cosmic Rays (GCRs) and the lunar regolith. Neutron energies are moderated as the neutrons subsequently scatter throughout the upper layer of the lunar regolith. During this process, a fraction of the neutrons is emitted from the surface and can be measured by orbiting instrumentation. Hydrogen-bearing species within the regolith have a higher average neutron-scattering cross-section relative to most other regolith elements, so the rate at which neutron energies are moderated is primarily dependent on the concentration of hydrogen (H). Locations where the epithermal neutron emission flux is suppressed relative to a dry reference region potentially indicates the presence of hydrogen-bearing volatile deposits. Monte Carlo neutron transport modeling allows us to understand this complex process by simulating the production of neutrons in the regolith, the energy evolution and surface emission of these neutrons, and their interaction with the orbiting detectors and spacecraft subsystems.

Apollo 17’s LNPE observation was the first direct measurement of the lunar neutron density profile and was used by McKinney et al. (2006) to validate their Monte Carlo models of the lunar neutron emission flux. Similarly, the LPNE measurement is the critical baseline measurement by which we model and understand lunar neutron production, transport and detection, for the full range of LEND’s observational conditions.

The orbital neutron results to date provide tantalizing lines of evidence for water deposits in the form of water ice in the Moon’s PSRs. The LPNS determined that there is up to 4% suppression of the epithermal neutron flux that is maximized towards the Moon’s poles. This epithermal neutron flux suppression is thought to indicate the presence of water ice on the order of hundreds ppm (Feldman et al., 2001). However, the low spatial resolution of the LPNS (\( \sim 45 \) km) precluded direct observations of the PSRs (Feldman et al., 2001). Subsequent studies of the LPNS polar observations used image reconstruction techniques to estimate that concentrations up to several thousand ppm hydrogen may exist in some of the PSR’s (Elphic et al., 2007; Teodoro et al., 2010). Based on the promising LPNS findings, the LRO’s LEND instrument was designed to produce high-resolution maps of the Moon’s hydrogen at the poles and to measure the Moon’s radiation environment (Vondrak et al., 2010; Mitrofanov et al., 2010b). Early mission LEND observations found a direct spatial correlation of Neutron Suppressed Regions (NSRs) that are associated with the larger PSRs, though some PSRs inexplicably show no indication of
any significant concentrations of hydrogen (Mitrofanov et al., 2010a; Sanin et al. 2012; Mitrofanov et al. 2012; Boynton et al. 2012).

LEND’s complement of nine detectors includes the Collimated Sensor for EpiThermal Neutrons (CSETN) comprised of four collimated epithermal neutron detectors, one uncollimated Sensor for EpiThermal Neutrons (SETN), three Sensors of Thermal Neutrons (STN) and a Sensor for High Energy Neutrons (SHEN). LEND’s signature high spatial resolution instrument, CSETN, employs a neutron collimator made of neutron-absorbing materials to discriminate the influx of lunar neutrons, thus producing a nominal spatial resolution of 10 km diameter full-width-at-half-maximum (FWHM) from an orbital altitude of 50 km (Mitrofanov et al., 2008, 2010b).

However, a consequence of CSETN’s achieving such a high spatial resolution is that its observations are substantially degraded by low collimated neutron count rates and varying background contributions. CSETN’s low signal-to-noise ratio (SNR) arises from its relatively enhanced detection of scattered neutrons and charged particles, as compared to its lunar neutron detection rates. Comparable uncollimated sensors like LPNS and LEND’s SETN have higher SNR because their lunar neutron count rates are far higher than their background contributions. As a result, the performance of CSETN has been the source of contentious debate, yielding highly varying estimates of its collimated count rate.

The fact that the lunar and background flux contributions to CSETN have varied over the course of the mission and are difficult to model has led to several studies that have yielded substantially different estimates of CSETN’s signal and background count rates. More optimistic evaluations of the CSETN collimated rate originated from the LEND team, which estimated a prelaunch early mission collimated rate to be near 1.8 cps (Mitrofanov et al., 2008, 2010b) and in subsequence studies that rate was reduced to 0.8 ∼ 1.1 cps (Litvak et al., 2016, Livengood et al., 2017). More pessimistic views of the CSETN collimated rate have also been documented, in descending order: ≤ 0.25 cps (Eke et al., 2012); 0.2 cps (Lawrence et al., 2010); and ‘negligible’ (Teodoro et al. 2014). The most pessimistic views are directly dismissed by the detection of several neutron suppressed regions that are directly correlated to permanently shadowed regions in LEND’s H maps (Mitrofanov et al., 2010b, Boynton et al., 2012, Sanin et al. 2012, 2016). In the LPNS maps, the permanently shadowed regions are not independently resolved, although in the LPNS low-altitude mapping phase its average altitude is more than 15 km lower than CSETN’s (Teodoro et al., 2014).

Perhaps the more important claim is that the background contributions to CSETN have not been adequately quantified so that an accurate CSETN map of the spatial distribution of hydrogen can be derived (Lawrence et al. 2015). The key point being that an accurate understanding of background contributions to the detectors for the entire mission is needed, but has not been derived to date. To address the large discrepancy in CSETN count rate estimates, a detailed description of its signal sources coupled with a systematic
validation of CSETN’s performance and a quantification of its signal sources is necessary.

Motivating this research is the need to fully quantify all signal contributions to the LEND detectors to establish that we have properly calibrated data for the entire mission. Most importantly, we validate our calibration by predicting the expected total and partial count rates for every observation of each detector for the full range of operational, instrumental, altitude and solar conditions. This is the first study of LEND’s calibration to include such a validation of its results. Independent and highly precise Monte Carlo (MC) models, developed for each of LEND’s detectors, factor the independent configurations of detector materials, geometries, efficiency variations and operational constraints to yield a detailed understanding of the LEND’s observations. We use the GEometry ANd Tracking (Geant4) toolkit for all of our neutron transport modeling (Allison J. et al., 2006).

We successfully validate our LEND detector models by directly comparing each detector’s total Monte Carlo-predicted count rate with its total raw count rate as observed during the nearly nine-year course of the LRO/LEND mission. Our result (see Figure 1) shows excellent agreement between the predicted and total raw detector count rates for the full range of solar activity, altitude, observing geometry, and instrumental and operational conditions for the suite of LEND detectors. Systematic low-rate excursions of the raw rates from the predicted rates are because of detector efficiency variation, see Section 2. Section 2 provides a full description of the LEND detectors, the sources of signals detected by LEND, the factors that cause the signal to vary as well as the methods to correct the data from each detector. We determine the SNR and information properties of the LEND channel spectra to derive the optimal channel sets by which we integrate the observations. We fully validate each detector’s independently-derived calibration by presenting a detailed review and comparison of its predicted and raw count rates. Section 3 validates our calibration by reviewing lunar maps derived from each detector. We also demonstrate the respective upper-bound spatial resolutions of the CSETN and SETN detectors using the neutron suppression region (NSR) at Cabeus crater. Section 4 provides a discussion of the science results and Section 5 reviews our conclusions.

2 2 Methods: Calibration of the LEND Observations

To quantify the complete set of signals that contribute to the LEND data, each detector must be independently modeled and understood in the context of its physical geometry and the full-range of its observing conditions. In this section we systematically assemble our detector MC models and compare them to a series of important benchmarks. The section begins with an overview of the LRO spacecraft and LEND instrument and is followed by the details of our physical models. The set of LEND lunar and background signals are described along with the varying altitude and solar factors that principally
modulate the LEND signals. In Section 2.3.1 our models are compared to the ground-truth results of the Apollo 17 era LNPE experiment, which defines the standard for regolith neutron density as a function of depth. That study, coupled with the McKinney et al. (2006) prediction of the expected energy distribution of neutron emission flux from the Moon, provides the baseline measurement against which we compare our results. We then couple those studies with Earth-based neutron measurements, which are highly correlated to the LEND detector count rates and which allow us to characterize the solar-cycle dependent GCR influx at 1 astronomical unit. We derive the variation in the expected neutron emission flux and then normalize and compare our results to the LPNS era observations.

Altitude-dependent calibrations are derived from the individually-modeled detector performance predictions, which allow us to identify individual sources and calculate the predicted count rate contributions from scattered neutrons and charged particles. We also reconcile an error in the detector efficiency previously defined for the LEND SETN detector (Litvak et al., 2016). The section concludes with tables that explicitly define the calibration methodology and provides figures to compare the total predicted count rates with the measured total raw count rates for each detector. The supplemental on-line materials describe the details of several supporting studies as well as show a complete description of the calibration methods. We justify our use of channels 7 to 15 to integrate CSETN observations by evaluating the SNR and sensitivity of the neutron detectors as measured by the information entropy of their channel spectra. Detailed signals of charged particles and lunar neutrons signals in the CSETN channels is discussed in Sec. 2.5.
2.1 Description of LEND instrument

Each of LEND’s eight identical $^3$He proportional counters has outer dimensions of 7.7 cm in length and 5.1 cm in diameter and is designed to measure the count rates of the Moon’s thermal and epithermal neutrons. In addition, there is one fast neutron detector, SHEN, made from a scintillation stilbene crystal. Four of the $^3$He detectors are collimated and designed for the detection of epithermal neutrons (CSETN1 – CSETN4). There are also an uncollimated $^3$He epithermal neutron detector (SETN) and three omnidirectional $^3$He counters designed as thermal neutron detectors (STN1 – STN3). Using the information given by (Mitrofanov et al., 2008) and Litvak et al., 2012, 2016, we constructed the independent detector models of SETN, CSETN, STN and SHEN as shown in Figure 2. Each neutron detector consists of a 0.5 mm thick cylindrical aluminum container with a 5 cm inner diameter and has a 5 cm active length with a 1.25 cm inactive dead zone at each end. The detectors are loaded with 20 atm pressure of $^3$He gas at a density of 0.0027 g/cm$^3$. The CSETN collimator consists of polyethylene layers lined with $^{10}$B on the inside surface. In our model we assume a density of 0.95 g/cm$^3$ of pure $^{10}$B powder for the inner layer (100% enrichment) and a density of 0.948 g/cm$^3$ for the polyethylene. To block thermal neutrons of energies less than 0.4 eV, both the sides and the top of SETN are wrapped in a 0.5 mm thick Cd foil. CSETN has a 0.5 mm thick Cd foil covering only the top of each detector.

The STN detectors have no Cd covering and are thus sensitive to both thermal and epithermal neutrons. Calibrations for STN1 and STN2 are the same as for the STN3, they are not discussed in this paper; neither is the calibration for the fast neutron detector SHEN.

2.2 LRO and LEND Modeling

An LRO spacecraft model (Figure 2) was built to investigate the potential contribution of scattered neutrons and secondary particles generated from the spacecraft. The masses of the major components of the spacecraft are as follows: spacecraft body – 2.54 cm thick foam-filled honeycomb aluminum panels, 135 kg; fuel tanks: titanium fuel tank, ~ 76 kg; fuel – hydrazine (N$_2$H$_4$) with quantity varying during the course of mission; fuel tank support – 1.15 cm thick, 94.5 cm high, 52 cm radius cylindrical aluminum support, ~ 87 kg; LOLA, LAMP and LROC casing - 2.54 cm thick, foam-filled honeycomb aluminum panels, ~ 19 kg. The total mass in this MC simulation is 617 kg. The total dry mass of LRO is 1018 kg where the 400 kg mass locate such as the solar panels, gimbals, reaction wheels are far away from the LEND detectors which give negligible influence to the LEND signals. Thus those items were removed from our model. Simulations show that the impact of fuel mass variation to the detector rates is insignificant; the fuel quantity at the beginning of the commissioning phase was 268.5 kg.
The complete LEND assembly consists of four CSETN detectors (yellow), one epithermal detector – SETN (green), three thermal neutron detectors – STN1 (gray), STN2 (red), STN3 (blue), and one fast neutron detector – SHEN (white). The CSETN detectors are surrounded by layers of collimation materials: – polyethylene (gray) with their inner surface lined with 10B (blue). Right: LEND is a fixed nadir-pointing instrument located at the lower left of the LRO spacecraft as shown in the figure above. Since STN3 and STN1 are the sensors closest to the body of the LRO spacecraft, they have a higher background rate than the other LEND sensors.

Our LEND and LRO spacecraft models were built to investigate the signals detected by the LEND $^3$He detectors (Figure 2). We defined foam-filled honeycomb aluminum panels for the spacecraft body and casings, titanium for the fuel tank, and used varying quantities of hydrazine fuel to check for its background contributions to the LEND data over the different phases of the LRO mission. In this simulation model, the total mass of the LRO spacecraft during the commissioning phase is 617 kg.

2.3 Signal sources detected by LEND

The signals detected by the LEND originate from GCR interactions with the Moon and the LRO spacecraft, as described in Table 1. The two independent variables to consider in this discussion are the GCR flux and spacecraft altitude, which are the primary factors that influence LEND’s signal variation. Lunar neutrons (LN) emitted from the surface may be detected directly by the $^3$He detectors, or they may be detected after scattering from the spacecraft or the collimator assembly. For CSETN, the collimated proportion of the total signal is the primary signal for understanding lunar hydrogen. Scattered lunar neutrons originate as higher energy neutrons which down-scatter in energy to a detectable energy range. Secondary neutrons originate from lunar neutrons interacting with the spacecraft or the collimator. The secondary neutrons are induced by energy of MeV to hundreds of MeV lunar neutrons then emitted isotropically. Thus the secondary neutrons have to be separated from lunar neutrons in the altitude correction.

All signals that originate from GCR interactions with the spacecraft are background signals. GCR are primarily protons and alpha particles and can
Table 1 Sources of signals detected by the LEND $^3$He sensors can be categorized into the components shown in this table.

| Source | Remarks |
|--------|---------|
| **Signal** | Lunar neutrons - direct hits and scattered neutrons |
| | Scattered and secondary neutrons induced by lunar neutrons interacting with the spacecraft and the LEND assembly. |
| | Flux $\propto \left( \frac{R}{R+L} \right)^2$ |
| | $R$: Moon radius |
| | $L$: altitude |
| | Lunar neutron emission angular distribution corrections. |
| | Proportional to the lunar neutron flux, considered as a part of the lunar neutron signals. |

| Background | GCR charged particles (mainly protons and $\alpha$-particles) and secondary particles induced by GCR particles interacting with LRO spacecraft, LEND assembly |
|-----------|--------------------------------------------------------------------------------------------------|
| | Secondary charged particles induced by lunar neutrons. |
| | Proportional to the open sky solid angle $\Omega$. Cruise phase open sky solid angle is estimated to be $\sim 3\pi$ for CSETN and $2\pi$ for SETN (instead of $4\pi$) since the LEND detectors are partially blocked by the LRO spacecraft. |
| | Proportional to the lunar neutron flux. |

be directly detected by the LEND detectors. GCR can also interact with the spacecraft and the LEND instrument to produce neutrons and charged particles. Charged particles can also be produced by lunar neutrons that interact with the spacecraft and the LEND instrument.

The intensity of all of the signals detected by the LEND $^3$He sensors is a function of the solar cycle, which governs the emission flux of lunar neutrons as well as the background signals produced by the spacecraft. The solar modulation potential (SV) which characterizes the modulation of GCRs as they pass through the heliosphere on their way to the Earth-Moon system, varies with the 11-year solar cycle. The solar modulation potential has been used to quantify the GCR conditions at 1 astronomical unit since 1951 (Usoskin et al., 2005). Figure 1 illustrates the modulated count rates of all LEND sensors as the solar potential has ranged from solar minimum near 2009 to solar maximum in 2014 and its returning to minimum. LEND count rates are maximized when the GCR flux was high in 2009 and some of its detectors show 30–40% lower count-rates in 2014. The systematic low-rate excursions of the raw rates
from the expected rates are due to detector efficiency variation which is caused by the biweekly spacecraft station-keeping operations.

Altitude variation complicates the signal analysis because it causes variation in the LRO’s solid angle to the Moon. Since the detected lunar neutron emission flux is proportional to its solid angle, the count rates due to lunar neutrons increases as altitude decreases. However, since the intensity of the GCR background produced by the spacecraft is inversely related to its solid angle, the count rate from GCR background processes decreases with altitude. Thus, for a given elliptical orbit, the lunar neutron flux is high and the GCR background is low when the spacecraft is at low altitude. The inverse holds true when the spacecraft is at high altitudes. The problem is especially important for CSETN detectors because while the total count rate may be nearly invariant throughout the orbit, the fraction of the total rate that is due to GCR backgrounds can vary in inverse proportion to the lunar neutron signal.

We next relate our LEND models to solar potential and altitude, the primary sources of LEND’s signal variation during the mission as illustrated in Table 1. A set of independent models of the LEND detectors’ count rates can be defined as:

\[ C_{\text{Total}}(SV, Alt) = C_{\text{LN}}(SV, Alt) + C_{\text{GCR}}(SV, Alt) + C_{\text{2nd}}(SV, Alt) \quad (1) \]

where \( SV \) is the solar modulation potential in MV (mega-volts) and \( Alt \) is the orbit altitude in km, \( C_{\text{Total}} \) is the total count rate of the detector \( C \) (i.e. SETN, STN1 – 3, CSETN1 – 4), \( C_{\text{LN}} \) is the lunar neutron count rate, including the scattered and secondary lunar neutrons, \( C_{\text{GCR}} \) is the count rate for GCR particles and their induced secondary particles, And \( C_{\text{2nd}} \) is the count rate from secondary charged particles induced by lunar neutrons. We discuss the variation in these contributions as a function of solar modulation potential and altitude in the sections below.

2.3.1 Lunar Neutrons

The Apollo 17 Lunar Neutron Probe Experiment (LNPE) has provided a unique set of in situ measurements that show the production of neutrons in lunar soil bombarded by GCR (Woolum et al., 1973, 1975). The LNPE measurements are the neutron source for the McKinney, et al. (2006) study, which derived the lunar neutron surface flux as a function of neutron energy. The LNPE measurements and the McKinney models define the critical references for the GCR source and lunar neutron calculations presented in this paper. We derive key calibration correction coefficients as described below.

We use an analytical model by Castagnoli and Lal (1980) and Masarik and Reedy (1996) for GCR proton and alpha particle energy spectra as a function of solar modulation potential which has been widely accepted and was used by McKinney et al., (2006) to evaluate neutron production in the Moon’s subsurface. The \( 4\pi \) GCR flux \( J \text{ (particle/(MeV/n)/cm}^2/\text{sec)} \) is given by:
Table 2 Parameters of (Castagnoli and Lal, 1980) GCR proton and alpha particle energy flux.

| Particle | A (1/cm²·sec·MeV) | a (MeV) | b (MeV⁻¹) | γ |
|----------|-------------------|---------|-----------|----|
| Proton   | 1.24 × 10⁶        | 780     | 2.5 × 10⁻⁴ | 2.65|
| α-particle | 2.26 × 10⁸     | 660     | 1.4 × 10⁻⁴ | 2.77|

\[
J(E,\Phi) = A \frac{E(E + 2m_p c^2)(E + \chi + \phi)^{-\gamma}}{(E + \Phi)(E + 2m_p c^2 + \phi)} \tag{2}
\]

where \(A(1/cm²·sec·MeV)\) is a normalization factor, \(E(MeV/n)\) is the kinetic energy of GCR nuclei, \(\phi(MV)\) is the solar modulation potential, \(m_p(MeV/c^2)\) is the proton mass, \(c\) is the speed of light, \(\chi = a \cdot e^{-bE}\), and the parameters \(A, a, b, \) and \(\gamma\) are given in Table 2.

A series of reconstructed monthly values of the solar modulation potential from July 1936 through December 2009 (Usoskin et al., 2011) suggests that the solar modulation potential at the Apollo 17 epoch was about 470 MV. The neutron density profiles derived from MCNPX Monte Carlo simulations for solar modulation potential in the range of 550 to 600 MV are found in McKinney (2006). Our Geant4 simulation of lunar neutron production using the Apollo 17 landing site soil chemical composition shows good agreement with the results in McKinney et al. We tracked the α, Li particles generated from the \(^{10}\)B neutron capture reaction and their traces as registered on a Triafol TN thin film, using the same configuration of LNPE in situ measurements. Our MC model shows a good fit to the Woolum’s LNPE track density measurement, illustrated in Figure 3. The peak of the track density profile appears at depth 150 g/cm². We used the solar modulation potential of the Apollo 17 epoch 470 MV with total lunar neutron flux 4.35 neutrons/cm²·sec as a reference point to cross-calibrate the orbital \(^3\)He neutron results from LPNS and LEND epochs in the following sections. The MC simulation gives a higher track number density than the measurement from LNPE because the kinetic energies of some emitted α and Li particles are not high enough to register track marks on the Triafol TN film.

2.3.2 Backgrounds: GCR Charged Particles and Secondary Particles

GCR charged particles are the primary source of the LEND detectors’ background signals. Neutrons induced by GCR interactions in the spacecraft (Mitrofanov et al., 2010b; Litvak et al. 2012, 2016; Sanin et al., 2017) contribute a small fraction of the total background signals. To estimate the background signals triggered by GCR charged particles, we analyzed the observations during the LRO lunar insertion phase (altitude ranging from 2,500 km to 30 km) and evaluated observations during the periods of several major solar coronal mass ejection (CME) events (e.g. – Jan. 23, 2012, July 14, Sept. 2, 2014 and Sept. 6, 10, 2017). Since an elliptical orbit was maintained during the LRO orbital insertion period, extreme end-member GCR induced background and lunar
neutron count-rate conditions result because the Moon’s solid angle varied to the greatest extent. The LEND detectors have different sensitivities to the energy distributions of neutrons and changed particles. Protons with energies below 20 MeV cannot penetrate through the 2 mm thick aluminum wall of LEND’s He detectors. The CSETN collimator prevents protons of energies lower than 200 MeV from entering CSETN’s He detectors. SETN and STN are more sensitive than CSETN to most solar coronal mass ejection events since the solar wind protons’ energies are usually less than 200 MeV. For example, while both STN2 and SETN detected the July 14, 2014 CME particles, the CSETN detectors were insensitive to that event because the proton energy was on the order of tens of MeV. However, STN2, SETN and the four CSETN detectors all observed the January 23, 2012, September 2, 2014 and September 10, 2017 CME events at the same time because the flux of protons exceeded hundreds of MeV.
2.4 Corrections for Solar Potential Modulation and Altitude Variation

2.4.1 Solar Modulation Potential

Neutrons emitted from planetary objects are proportional to the GCR flux with an inverse correlation between the GCR flux and solar activity. Neutron monitors from McMurdo, Antarctica (Bieber et al., 2005) and Oulu, Finland (Usoskin et al., 2005, 2011) show the inverse relationship between the GCR flux and solar activity. A high neutron count rate indicates a high GCR flux when the solar modulation potential is low. Since the GCR flux spectra are very similar at the Earth and lunar orbits, they can be considered to be equivalent in comparing orbital neutron detections to different epochs in the solar activity cycle. The long-term solar modulation parameter (Usoskin et al., 2011) reconstructed from the Oulu Cosmic Ray Station ground-based monthly data is given by:

\[ SV = 36432.2 - 148.0 \times C + 0.00207 \times C^2 - 9.892 \times 10^{-8} \times C^3 \quad (3) \]

Where \( SV \) is the solar modulation potential in MV and \( C \) is Oulu’s normalized neutron count rate. We used 2-hour smoothed Oulu neutron data to correct the LEND observations for solar modulation potential. The correction is necessary to standardize each detectors’ observations collected during the mission to a common GCR level. For our calibrations, we standardize the observations to 260 MV which occurred in late 2009 (Usoskin et al., 2011) during the LRO commissioning phase.

2.4.2 Altitude and Angular Sensitivity

None of the LEND sensors are completely omnidirectional detectors, specifically their detection efficiencies vary as a function of neutron incident angle. The uncollimated sensors, SETN and STN have a higher detection efficiency to neutrons entering from the cylindrical side of the detectors than from the circular faces. Thus, the SETN and STN count rates are not simply proportional to the neutron flux when the spacecraft changes its altitude. Neutrons emitted from the Moon’s surface have an angular distribution of approximately \( \cos^{3/2} \theta \) (Lawrence et al., 2006) for low energy neutrons and \( \cos \theta \) for high energy neutrons, where \( \theta \) is the angle from the surface normal, as illustrated in Figure 4. Since, thermal and low energy epithermal neutrons experience many collisions prior to their departing from the Moon’s surface, they closely follow a theoretical angular distribution of \( \cos^{3/2} \theta \). The high energy neutrons escape from the surface isotropically because they generally originate at shallower depths, and encounter very few or zero collisions with the lunar regolith nuclei before escape and thus have a \( \cos \theta \) distribution. We used energy-dependent lunar neutron angular distributions to calculate the LEND detector count rates at different altitudes and solar modulation potentials. The energy-dependent angular distribution is particularly important for calibrating the CSETN detectors because out-of-collimation signals are mainly contributed by high energy
Angular distributions of leakage neutrons from the Moon’s surface. black: $E < 1 \text{keV}$, red: $1 \text{keV} < E < 1 \text{MeV}$, and blue: $E > 1 \text{MeV}$. Dashed fine lines are the curve fits.

neutrons ($E \geq \text{keV}$). The incident angular distribution in the LRO frame of reference, $f(\theta)$, can be expressed as the angular distribution $f(\theta')$ as measured from the ground, by the relationship:

$$\theta = \arcsin[\sin \theta' \times \left( \frac{R}{R + L} \right)]$$  \hspace{1cm} (4)$$

We converted the $f(\theta')$ derived from the Monte Carlo simulation to the angular distribution $f(\theta)$ at a given altitude $L$ to calculate the theoretical count rates for each LEND detector. Figure 5 shows the energy and angular probability density function (PDF) of CSETN’s detected neutrons. Neutrons detected by CSETN detectors within the collimation angle are mainly epithermal neutrons. The non-collimated neutrons are higher energy neutrons that have been attenuated by the collimators. The altitude correction for a LEND detector count rate is a product of the detector’s angular sensitivity and the lunar neutron angular distribution at a given altitude $L$, and not proportional to the lunar neutron flux as described in (Litvak et al., 2012, 2016). The altitude variations of each LEND detector lunar-neutron count rates normalized to the observation at 50 km altitude are shown in Figure 6. The uncollimated sensors SETN and STN have a similar response to the change in altitude that decreases more rapidly than that of the CSETN because of different angular sensitivities of the sensors. The SETN and STN detected neutrons come in from large incident nadir angles while the CSETN is more sensitive to the neutrons approaching within collimation.
Fig. 5 Energy and angular probability density function of neutrons detected by CSETN at 50 km altitude. As shown in the figure, high energy (fast) neutrons primarily are scattered by the collimator so that their energies are reduced to the detectable epithermal and thermal energy range.

Fig. 6 Simulated altitude-dependent variation of the normalized lunar neutron count rates for the CSETN (blue), SETN (orange) and STN3 (grey). Note that the CSETN altitude variation differs from the uncollimated sensors SETN and STN3. We use these altitude variation curves as the baselines for the LEND’s altitude adjustments.
2.5 Observations from $^3$He Channel Spectra

Since the sources of the LEND $^3$He detector signals have different energy distributions, their contribution to the count rates in the detectors’ sixteen-channel spectra varies by channel number. For example, background signals from GCR, secondary charged particles and $\gamma$-rays tend to appear in the detectors low output channels, while the proton and tritons created from neutron capture in the $^3$He detectors mainly appear in the upper channels. Early in the mission, the LEND SNR was improved by integrating over the upper spectral channels, 9 to 15 (Litvak et al., 2012). That study considered the higher lunar (SNR) of CSETN’s upper spectral channels to define the set of channels over which all of the LEND $^3$He detectors are integrated. Based on the discussion earlier in this section, we postulated that the range of valid channels should vary for each detector, and because the uncollimated sensors, SETN and STN1-3 have higher lunar neutron count rates, they should have a higher SNR and allow the integration of more channels. Our study resulted in the following modifications to our processing of the detector channel spectra as compared to Litvak et al., 2012:

A. Extend the CSETN usable spectral channels to 7 to 15, inclusive

B. Extend the SETN and STN1-3 channels to 0 to 15, inclusive.

Based on our study, two additional channels (7,8) are included from the CSETN detectors, thus increasing the detector count rates. For the SETN and STN1-3 sensors, the integration of all spectral channels has increased their respective count rates and the new analysis methods have also facilitated the recovery of over six years of SETN and STN1-3 observations.

To determine the set of optimal channels by which we integrate the CSETN signals we compared the CSETN SNR to the detector sensitivity. The detector SNR is determined as the ratio of summed lunar neutrons (pink), $P_{LN}$ to summed background (blue) $P_{Bck}$, $P_{LN}/P_{Bck}$, as shown in Figure 8 (blue), using the integration of channels from n to 15 in x-axis, where n systematically increases between 0 and 15. We find that the product of SNR and information sensitivity for CSETN4 and SETN show the optimal channels to be used for analyzing CSETN and SETN data. We use signals of channel 7 to 15 for all CSETN. Since SETN lost pulse height discrimination (PHD) capability in May 2011, we have no better options than using the sum of all channels for analyzing SETN data.

We extend the relationship established for radar and radio studies, which shows the reduction in the information content of radar scattering and radio observations as the detectors SNR is diminished (Liu et al., 2018; Zhang et al., 2010). Those studies used the information entropy to describe how the average information carrying capacity of those detectors varies with SNR. Our study considers the average information content of the LEND detectors channel spectra as a function of their expected count rates. The study systematically analyzed combinations of spectral channels based on their SNR and information entropy. The channel set combinations were defined because of the increased lunar neutron signals in the high spectral channels.
Fig. 7 The expected CSETN-4 (top) and SETN (bottom) detector channel distribution of total, background and lunar neutron (LN) counts.

It must be stated that the detected counts in a given $^3\text{He}$ detector channel cannot be identified as signal or background, we use the expected distribution of observation count-rates to characterize the detector sensitivity using the average information entropy of lunar neutrons at differing count rates. The information entropy $H$ characterizes the average diversity of information given the average distribution of symbols in a sequence of known symbols (observation counts). The distribution of expected count-rates is derived from a large number of observations simulated from a Poisson distribution at a given average count-rate. The highest spectral channel entropy occurs when the average detector count rates are highest and the count rates are uniformly distributed. The spectral channel entropy is lowest when the count-rates are low and relatively increased numbers of observations have 0 counts. Entropy is defined as $H = -\sum_{i=0}^{\infty} p_i \log(p_i)$ (Shannon et al., 1948), where $p_i$ is the fraction of observations from the lunar neutron count-rate distributions (orange) plot from Figure 8.

We scaled the Figure 7 lunar signals and backgrounds for the CSETN4 and SETN detectors using their respective mission averaged count rates [2.93 and 14 cps]. From the scaled Figure 7 distributions, we systematically summed the lunar neutron and background count-rates for channel sets summed between $n$ and 15, where $n$ varies from 0 to 15, yielding a series of average count-rates $LN$ and $BKG$. Given the sets of average count rates and a Poisson random number generator we determined the fraction of times $p_i$, that observations
were 0, 1, 2, 3 .. i counts. The probability distribution of observation counts is normalized to 1.0 by dividing the distribution by the total simulated observations. Figure 8 shows the inversely related normalized plots of SNR and information entropy sensitivity as a function of the LN and BKG channel sums. The plots of products of SNR and Entropy show the optimal balance of high SNR and high information entropy sensitivity. We selected channel 7 as the lower channel boundary for CSETN’s detector integrations, because CSETN4 has one of the highest average count-rates and CSETN’s inboard sensors 1 and 2, have lower SNR than CSETN4 so the intersection point for the full system is likely to be to the right of channel 7.

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The respective SETN plot in Figure 8 indicates that the optimal channel set should span 11 to 15 because of the high SNR in those channels. However, SETN’s loss of PHD capability in May 2011 precludes the possibility of integrating channels 11 to 15 after that time. After May 2011 all counts were accumulated in channel 0. We can however integrate all fifteen channels for the full mission and justify it given SETN’s SNR is high for all spectral channels. By an equivalent method, STN2 is now recovered from its PHD failure in 2011. With this approach both SETN and STN2 are now restored to ongoing scientific operations and all eight-plus years of each detectors observations are available for mapping.
A secondary validation study for CSETN in Section 3.3 shows the Pearson correlation coefficient improved to 0.723 in a comparison of split detector mapping studies. We integrated spectral channels 7 to 15 and compared CSETN maps prepared from CSETN 1 and 3 vs CSETN 2 and 4. Pearson correlation coefficient $r$ was derived in the top four degrees of latitude, as compared to similar studies derived from the archived CSETN observations in the Planetary Data System (PDS).

2.6 Ground Calibrations of LEND at the Joint Institute for Nuclear Research (JINR), Dubna, Russia

In this section we review the SETN and CSETN detection angular efficiency and, in particular, correct some of the earlier conclusions of the LEND ground calibration studies made at the Frank Laboratory of Nuclear Physics (FLNP) of the Joint Institute for Nuclear Research (JINR) in Dubna, Russia (Mitrofanov et al., 2016). The objective of this study was to evaluate the angular efficiency of the LEND detectors and to benchmark the ground calibration of the angular efficiency. After the experimental tests were complete, it was concluded that the SETN detector had a 25% lower detection efficiency than the CSETN detectors. Due to the misinterpretation of experimental results, the calibration of CSETN was incorrectly scaled to the incorrect SETN standard (Litvak et al. 2012, 2016).

Upon re-evaluation of this test, our models indicate that the discrepancy in the measured efficiencies is attributed to the solid angle of the source. In the JINR experiment, a 7.6 cm radius spherical $^{252}$Cf source was placed only 1.5 m from the LEND instrument. Using our MC study, we were able to show that when the location of the source is moved to a distance of 25 m, the apparent efficiency difference between SETN and CSETN is eliminated. When the source is close by as in the JINR study, the CSETN appears to have a higher detection efficiency than SETN because there is a greater angular range through which incident neutrons can be scattered into the detectors. Details of these measurements and the relevant MC simulations are available in the supplemental online materials.

2.7 Detector Calibration and Validation Methods

2.7.1 Benchmarking SETN and LPNS with Monte Carlo simulations and observations at LP Epoch and LRO Epoch

In this section we compare the LEND detectors to neutron detectors that had different designs, orbital configurations and that operated during different phases of the solar cycle. SETN is located at the far side of the LEND assembly and away from the LRO spacecraft, so the impact of scattered neutrons and secondary particles from the spacecraft on SETN measurements are minimized.
Table 3 Specification for the LP-NS and LEND/SETN $^3$He proportional counters.

|                             | LP-NS | SETN |
|-----------------------------|-------|------|
| Diameter (cm)               | 5.7   | 5.1  |
| Active Length (cm)          | 20    | 5    |
| Volume (cm$^3$)             | 510.35| 102.14|
| Pressure (atm)              | 10    | 20   |
| Housing Material            | Stainless Steel | Aluminum |
| Cd Foil (mm)                | 0.63  | 0.5  |
| $^3$He Density (Pressure) Correction* | 1     | 1.68 |
| Inactive Length             | 1.25  | 1.25 |

compared to CSETN and STN detectors. We use the lunar leakage neutron spectra from dry ferroan anorthosite (FAN) soil from the Apollo 17 landing site to predict the SETN count rates at solar modulation potential 260MV, which LEND experienced in October 2009, (Usoskin et al., 2011), 425MV in January 1998 (Lawrence et al., 2006), and 470MV in December 1972 (McKinney et al., 2006) corresponding to the solar environment during the LRO, LP, and Apollo 17 epochs.

The LP-NS and SETN $^3$He detector information is given in (Feldman et al., 1999, 2004; Lawrence et al., 2006; and Mitrofanov et al., 2005, 2008) and is summarized in Table 3. LP-NS consists of a pair of $^3$He detectors and the LEND instrument has eight $^3$He detectors. We first benchmark the LP-NS epithermal neutron detector and the SETN with the neutron emission spectrum from dry FAN soil.

* Values obtained from Geant4 simulations.

We use the same estimation method as Lawrence et al (2009) to compare the count rate ratio of two different $^3$He detectors. For omnidirectional sensors, the count rate ratio of SETN to LP can be expressed as:

$$SETN = LP \times S_{Pressure} \times S_{Volume} \times S_{Dead} \times S_{Geometric}$$  \hspace{1cm} (5)

where $S_{Pressure}$ is the ratio of count rates due solely to pressure differences between the 10 atm $^3$He detector (LP-NS) and 20 atm $^3$He detector (SETN), $S_{Volume}$ is the volume ratio, which compares the LP-NS and SETN $^3$He active zone volumes, and $S_{Dead}$ is the efficiency reduction correction contributed by the inactive zone. We use $S_{Volume}$ instead of $S_{Area}$ used in Lawrence (2009) because LP-NS and SETN are not thin targets. The effective target thickness varies as a function of the incident angle of the neutrons bombarding the sensor. This volumetric approach addresses both cross-section projection and target thickness factors. Using Geant4 modeling of $^3$He sensors with different pressures for both LP-NS and SETN, we concluded that the ratio of count rates between detectors with 20 atm and 10 atm is characterized by $S_{Pressure} = 1.68$. We choose $S_{Dead} = 1$, since LP-NS and SETN detectors have the same inactive length of 1.25 cm on each end. $S_{Geometric}$, the detector orientation and geometric correction coefficient, is approximately 1.15.

The relative orientation of the LP-NS and LEND detectors in orbital impacts neutron detection. Lunar Prospector is a spin-stabilized spacecraft with
its spin axis oriented normal to the ecliptic plane and a rotational rate of 12 rpm, whereas LRO is a 3-axis stabilized and mostly nadir pointing platform. In the reference frame of LP-NS, the spin axis is pointed in the nadir direction near the poles and is parallel to the ground surface near the equator. LEND instruments are always aligned with the nadir direction, except during spacecraft slews. Using the LP-NS count rate of 21.7 cps (Lawrence et al., 2002, 2010) as a reference to estimate the SETN count rate at the LP epoch, we have:

\[
\text{SETN} = LP \times S_{\text{Pressure}} \times S_{\text{Volume}} \times S_{\text{Dead}} \times S_{\text{Geometric}} = 21.7 \times 1.68 \times 0.2 \times 1.15 = 8.38 \text{ cps at 30km altitude, LP Epoch}
\]

Monte Carlo simulation shows that the neutron flux during the LRO epoch is \(\sim 1.4\) times the flux during the LP epoch, assuming the solar modulation potential is 550MV at the LP epoch and 260MV at the LRO epoch. The LP-NS and SETN counting rates during the LRO epoch become:

\[
\text{LP} = 21.7 \times \left(\frac{R_{\text{Moon}} + H_1}{R_{\text{Moon}} + H_2}\right)^2 \times F(SV)
\]

\[
= 21.7 \times \left(\frac{1737 + 30}{1737 + 50}\right)^2 \times 1.4 = 29.7 \text{ cps LP-NS at 50 km altitude, LRO Epoch}
\]

\[
\text{SETN} = 8.38 \times \left(\frac{1737 + 30}{1737 + 50}\right)^2 \times 1.4 = 11.5 \text{ cps SETN at 50 km altitude, LRO Epoch}
\]

\(R_{\text{Moon}}\): Moon radius, \(H\): altitude, and \(F(SV)\): neutron flux ratio

The simulation using dry FAN soil neutrons with a total neutron flux of \(3.96 \text{n/cm}^2 \cdot \text{sec} (0.94 \text{n/cm}^2 \cdot \text{sec in 0.4 eV – 1 keV})\) gives LP-NS count rates of 30.22 cps in the equatorial region and 28.87 cps in the polar region with the global average of 29.53 cps whereas the SETN count rate is 9.48 cps under the same conditions. The simple scaling evaluation of the count rate ratio LP-NS to SETN \(\sim 2.58\) is in good agreement with the Geant4 simulations \(\sim 2.84\), within 10% deviation. The SETN count rate during the commissioning phase was found to be \(\sim 12.7\) cps based on the Monte Carlo calculations and the averaged LP-NS epithermal neutron detector low altitude observations. The Monte Carlo simulations show that 10% of SETN’s signals are neutrons scattered by the collimator although the field of view diminished because the collimation materials prevent some neutrons from being detected by SETN (Figure 9). Taking the LRO spacecraft velocity into consideration, the uncollimated sensors detected more neutrons on front side of the spacecraft than on the backside. Figure 9 shows the azimuthal angular distributions of the detected neutrons, orange lines present the boundary conditions of a stationary LRO at 50 km altitude and the blue lines are with LRO traveling at 1.6 \(\text{km/sec}\) in the \(-X\) direction.
2.7.2 Solar Modulation Potential and Altitude Adjustments

Since solar modulation potential and altitude are independent factors that influence the LEND detector count rates each observation must be simultaneously corrected using the equations below.

The model components $C_{LN}(SV, Alt)$, $C_{GCR}(SV, Alt)$, and $C_{2nd}(SV, Alt)$ in Eq. 1 can be written as

$$C_{LN}(SV, Alt) = C_{260MV50km} \times Coef_{SV} \times Coef_{Alt}$$  \hspace{1cm} (8)$$

$$C_{GCR}(SV, Alt) = Flux_{GCR} \times Coef_{GCR} \times (\Omega_C - |\sin(0.5 \times \arcsin(\frac{1737}{1737 + Alt}))|)^2$$  \hspace{1cm} (9)$$

$$C_{2nd}(SV, Alt) = Flux_{LN} \times Coef_{2nd}_{SV} \times \left(\frac{1737}{1737 + Alt}\right)^2$$  \hspace{1cm} (10)$$
Table 4 LEND observation corrections to the solar modulation potential of 260 MV and 50 km orbital altitude. All LEND correction methods share the same Coeff\textsubscript{GCR-SV}, and Coeff\textsubscript{2nd-SV} coefficients. The parameters are shown in the table, where Coeff = $P_0 + P_1 \cdot SV + P_2 \cdot SV^2 + P_3 \cdot SV^3$.

| Coeff\textsubscript{GCR-SV} | Coeff\textsubscript{LN-SV} |
|-----------------------------|--------------------------|
| $P_0$                       | 2.09                     |
|                             | 1.584                    |
| $P_1$                       | -0.0055                  |
|                             | -0.003                   |
| $P_2$                       | $5.4 \times 10^{-6}$     |
|                             | $2.91 \times 10^{-6}$    |
| $P_3$                       | $-1.86 \times 10^{-7}$   |
|                             | $-9.03 \times 10^{-10}$  |

Table 5 Solar modulation potential and altitude correction parameters for lunar neutrons.

| Coeff\textsubscript{SV} | Coeff\textsubscript{Alt} |
|--------------------------|--------------------------|
| SETN, STN                | CSETN1                   |
| P0                       | 0.747                    |
|                           | 0.847                    |
| P1                       | 0.063                    |
|                           | 0.00265                  |
| P2                       | $-2.4 \times 10^{-8}$    |
|                           | $-1.19 \times 10^{-8}$   |
| P3                       | $4.21 \times 10^{-10}$   |
|                           | $1.73 \times 10^{-8}$    |
| P4                       | $-4.46 \times 10^{-11}$  |
|                           | $-8.42 \times 10^{-12}$  |

Table 6 Detector dependent coefficients – $C_{260MV50km}$, $F_{\text{GCR}}$, $F_{\text{LN}}$, and $\Omega$. (a): When LRO travels in the +X direction, STN1 faces the front. (b): When LRO travels in the -X direction, STN2 faces the front.

| $F_{\text{GCR}}$ | $F_{\text{LN}}$ | $\Omega$ |
|------------------|-----------------|----------|
| SETN             | CSETN1          | CSETN2   |
| 1.75             | 1.85            | 1.95     |
| 0.95             | 0.55            | 0.76     |
| 0.5              | 0.6             | 0.75     |
| 0.5              | 0.6             | 0.5      |

$C_{260MV50km}$

| SETN | CSETN1 | CSETN2 | CSETN3 | CSETN4 | STN1 | STN2 | STN3 |
|------|--------|--------|--------|--------|------|------|------|
| 15.11| 0.58   | 0.52   | 0.55   | 0.58   | 36.0(a) | 29.50(a) |
|      |        |        |        |        | 31.0(b) | 22.0(b) |

$F_{\text{GCR}}$ and $F_{\text{LN}}$ are the number of GCR proton and the Lunar neutron per cm$^2$–sec respectively.

To illustrate the successful decomposition of the LEND detector observations during the mission, we show the full and partial count rates of the SETN, CSETN4, and STN3 observations as a function of SV and Alt in Figure 10. The predicted and observed total count rates of SETN, STN1, STN2, STN3 and CSETN4 match very well and are shown in Figure 1. In May 2011, SETN and STN2 lost the pulse height discrimination capability. The new calibration algorithm enables us to recover observations of the SETN and the STN2, since these two detectors have been only able to register integrated total count rates instead of signals of each individual channels since May 2011. To validate the calibration algorithm, we also compared the predicted count rates to the observations as a function of altitude. Figure 10 shows (left) the predicted count rates (dashed lines) and the observations (solid lines) of each LEND detector;
Fig. 10 The total count rates ($\Sigma_{\text{Ch0 to Ch15}}$) for SETN and STN detectors and the high channel count rates ($\Sigma_{\text{Ch7 to Ch15}}$) for CSETN detectors as a function of altitude during the commissioning phase.

and (right) CSETN4’s lunar neutrons, GCR particles, secondary particles and the total signal as a function of altitude. The lunar neutrons’ signal gradually decreases to higher altitudes whereas the GCR’s component increases resulting in a slow varying count rate in altitude for all CSETN detectors. The count rates of the SETN and STN detectors asymptotically decrease with altitudes because of the GCR components’ lower fraction of the total signal as compared to CSETN detectors.

2.8 LRO/LEND Operational Factors

A consequence of LEND’s long operational history is that there is the impact that LRO and LEND operations have systematically had on LEND’s observations and maps. Some of these effects, like SV and Alt, are quantified and accounted for, as discussed in this section. Other factors are not as well understood but are also discussed here.

Figure 12 shows LRO’s mapping mission as broken down into three operational phases: Commissioning, Science Mapping and Extended Mission. The 2.5 month Commissioning phase is characterized by an elliptical orbit with periselene in the south and aposelene in the north. The orbital inclination was maintained near 90° by regular station-keeping which continued until the
Fig. 11 Left column shows the expected total neutron count rates and contributions of lunar neutrons, secondary particles and GCR particles as a function of altitude for (Top) SETN, (Middle) STN3, and (Bottom) CSETN. Figures of the right column are the count rates as a function of the solar modulation potential.

Table 7 Table of LRO/LEND mission phases and times. LRO Time (second) = 0 at 00:00:00 2001-01-01

| LRO Mission Phase | Start: LRO Time | Start: Julian Date |
|-------------------|-----------------|-------------------|
| Commissioning     | 268102088       | 2009-07-01        |
| Science           | 274736160       | 2009-09-15        |
| Extended          | 345316653       | 2011-12-11        |

end of the Science mapping phase. The Science mapping phase commenced in September 15, 2009 when the orbit was circularized near 50 km altitude, with periselene varying by latitude, but was mostly in the north. During the nearly 20-month Science mapping phase the polar-trajectory was maintained, so LEND had full polar coverage extending from July 1, 2009 to December 11, 2011. At the start of the series of LRO extended missions, the station-keeping maneuvers were curtailed and thus the orbital inclination dropped, ending LEND’s nadir-pointing coverage of the highest 3o of latitude.

Because of variations in LEND’s distribution of surface coverage by detector as well as in the distributions of regional altitude, adjustments need to be made to the data. The different CSETN’s detectors have different raw average count rates and operation timelines. When regular station-keeping maneuvers were curtailed at the start of the Extended mission, coverage ended near the
Fig. 12 Time profile of the (red) aposelene and (black) periselene of LRO: July 2009 to Sept 2017.

poles because of the diminishing orbital inclination which then precluded coverage of the top 3° of latitude. At that time, the periselene altitude was near the south pole, commensurate with the new elliptical orbit. The coverage hole arises where the region loosely defined by the top three degrees of latitude meets the lower latitudes. Small errors < 0.01 cps in LEND’s (CSETN) maps arise at the boundary because the coverage inside the high latitude region was collected under differing altitude, solar potential and operational conditions than the more equatorial surface immediately adjacent to it. Though the magnitude of the uncertainty is small, the coverage hole is reported here because it importantly bisects the permanently shadowed regions at the Haworth and Faustini PSR’s. The SOM reviews the corresponding figures of the average altitude distribution and coverage hole as derived for the SETN maps.

3 Results

In this section, we further validate our calibration methods by cross-comparing cylindrical projection and south-polar stereographic maps that are prepared from the SETN, CSETN and STN3 detector data. We first review the baseline observation metrics used in the study. A review of the full-mission SETN,
Table 8 Table of observations for each detector and LRO mission phase. Total 1-sec observations for CSETN 1 to 4, SETN and STN3. STN2 (not shown) failed during the science mission (May 2011)

| Detector | Commissioning | Science | Extended | Total |
|----------|---------------|---------|----------|-------|
| CSETN-1  | 6.1489×10^6  | 3.6309×10^7 | 0        | 4.2457×10^7 |
| CSETN-2  | 6.1498×10^6  | 3.7326×10^7 | 0        | 4.3476×10^7 |
| CSETN-3  | 6.1504×10^6  | 3.6460×10^7 | 1.4156×10^8 | 1.8417×10^8 |
| CSETN-4  | 6.1513×10^6  | 4.7079×10^7 | 1.2958×10^8 | 1.9282×10^8 |
| SETN     | 6.0165×10^6  | 4.6953×10^7 | 1.3674×10^8 | 1.8972×10^8 |
| STN3     | 5.9712×10^6  | 3.9594×10^7 | 0        | 4.5565×10^7 |

Table 9 Table of LEND instrument operations, LRO time = 268102088 corresponds to calendar date: 2009-07-01T00:48:08

| Detector | LRO Time Start | LRO Time End | Julian Date, End | Span (Yrs) |
|----------|----------------|--------------|------------------|------------|
| CSETN-1  | 268102088      | 3.21×10^8    | 2011-03-02 20:00:33 | 1.67       |
| CSETN-2  | 268102088      | 3.29×10^8    | 2011-05-31 15:20:25 | 1.91       |
| CSETN-3  | 268102088      | Ongoing      | Ongoing          | > 8.46     |
| CSETN-4  | 268102088      | Ongoing      | Ongoing          | > 8.46     |
| SETN     | 268102088      | Ongoing      | Ongoing          | > 8.46     |
| STN3     | 268102088      | 3.29×10^8    | 2011-05-24 00:00:47 | 1.90×10^7  |

CSETN and STN cylindrical projection maps shows our background reference region. The map of the thermal neutron flux, is defined by $STN = STN3 - 1.2 \times SETN$, where STN is a background subtracted map of the thermal neutron emission flux since our MC modeling indicates that the epithermal contribution to STN3 is 1.2 times the SETN count-rate. Polar-stereographic maps are reviewed for each set of detectors. The upper-bounds conditions for the spatial resolution of the SETN and CSETN detectors is derived from corresponding LOLA topographic cross-sections centered over the impact point of the Lunar Crater Observation and Sensing Satellite (LCROSS) (Smith et al., 2010, Colaprete et al. 2010). We do not include maps from the thermal STN1 and STN2 detectors because of the increased complexity of the analysis that is required for the Doppler detector studies.

As this paper is primarily an engineering study and focused on LEND data observation calibration, we do not convert the epithermal neutron count-rate maps to maps of hydrogen (H) content. H maps will be presented in an upcoming south-polar study (McClanahan et al., 2018). Detailed descriptions of the mapping methods are provided in the supplemental online materials. Metrics for the maps are expressed in units of counts per second. The epithermal neutron suppression of a region with count rate m in the map is determined by comparing this count rate to the reference rate established by the averaged epithermal neutron count rates b for the low-latitude highlands region at 50oS ≤ r ≤ 55oS latitude, 240oE ≤ r ≤ 300oE longitude. The neutron suppression is given by Supp % = \((1 - (m/b)) \times 100\). The hydrous region with count rate b was selected because of its moderate latitude, moderate epithermal neutron emission flux and position in feldspathic highlands terrain, Figure 13.
Fig. 13 Cylindrical maps of LEND background corrected count-rate and neutron suppression. (upper-left) SETN full-mission campaign observations mapped spanning July 2009 to September 2017. (upper-right) CSETN full-mission map spanning July 2009 to September 2017 (bottom-center) Thermal flux, STN is corrected for the contributions from epithermal neutrons by subtracting $1.2 \times$ SETN map from the STN3 map. Map units are in $\text{counts \cdot sec}^{-1}$. Neutron suppression percent (Supp%), is defined as $(1 - (m/b)) \times 100$, where $b$ is the averaged reference count-rate for $240^\circ E < r < 300^\circ E$ longitude and $50^\circ S < r < 55^\circ S$ and $m$ is the count-rate for the regions in the map. The dashed box indicates the location and region over which the reference rate $b$ is averaged.

Figure 13 shows cylindrical maps of the background subtracted SETN, CSETN and STN maps. The polar suppression of the epithermal neutron flux observed in the SETN and CSETN maps is consistent with the existence of near-surface concentrations of hydrogen-bearing volatiles. The magnitude of the neutron suppression is slightly lower in the north pole of the CSETN map because of the high average altitude (over 150 km) during the mission. The difference may be attributed to reduced SNR and/or sensitivity. The mafic mare is indicated by the low neutron emission flux (blue) area near the center of the STN thermal neutron map and corresponds to the high epithermal neutron emission flux region (red) in the CSETN map. Feldspathic highlands terrain is seen in the bright (red) regions of the SETN and STN maps.

3.1 SETN

Figure 14 shows a set of co-registered south-polar stereographic SETN maps derived from 8.5 years of fully-calibrated observations, above $75^\circ S$. Table 10 reviews the observation counts included each map. Figure 14A (upper-left) shows the SETN full-mission map. Independent low-altitude (SETN-Low)
Table 10 SETN full-mission, high-altitude and low-altitude map information.

| SETN SP Maps | No. of Observations | Ave. Alt. (km) |
|--------------|---------------------|---------------|
| SETN Low Alt.| 5.84 x 10^6         | 35.7 ± 1.8    |
| SETN High Alt.| 9.33 x 10^6         | 52.6 ± 1.3    |
| SETN All     | 1.52 x 10^7         | 46.2 ± 2.5    |

and high-altitude (SETN-High) maps are now derived by splitting the observations into two maps, as a function of altitude, Low ≤ 43 km and High > 43 km. The SETN-Low map is made possible by the recovery of the extended mission observations in 2012 to 2015, when LRO’s south polar periapsis was frequently below 40 km. Figure 14B shows the SETN-High south-polar map, which uses observations that averaged 52.6 ± 1.3 km altitude. Figure 14D shows the SETN-Low map that was produced from observations taken at an average of 35.7 ± 1.8 km altitude. Figure 14C shows the corresponding digital elevation map derived from the Lunar Reconnaissance Orbiter Laser Altimeter (LOLA), which gives a reference to south-polar features (Smith et al., 2010). Co-registered permanently shadowed regions that exceed 125 km^2 are outlined in white, as derived from a solar illumination model (Mazarico et al., 2011).

Since the SNR ratio of the SETN instrument is much higher than the CSETN instrument, the development of the SETN-High and SETN-Low maps, with their low statistical uncertainties provides a new analytical capability that was not possible in previous lunar neutron mapping studies. A review of the SETN-High map of the largest PSRs at the Cabeus, Haworth, Shoemaker, Faustini, Nobile and Wiechert craters show the expected reduced neutron suppression associated with those craters due to the increased altitude. The poleward-facing slopes (PFS) of Amundsen and Drygalski craters provide an excellent example of the suppression of the neutron emission flux on those slopes, in contrast to an enhancement of the flux on their corresponding equator-facing slopes (McClanahan et al., 2015). A relatively enhanced neutron flux is observed at the interiors of the larger craters at Schomberger, Newton, Schrödinger, Scott, Drygalski and towards the equator-facing slope of Amundsen. The greater neutron flux in these large low-slope crater basins may be due to the increased galactic cosmic-ray influx made possible by the surfaces’ greater solid-sky angles, geochemistry, regolith density or roughness variation (Feldman et al. 2001, McClanahan et al., 2015, Eke et al., 2015).

Validation of our calibration methods is also found in the location of the maximum neutron suppression points shown as yellow ‘+’ in the statistically independent SETN-High and SETN-Low maps, Figure 14. The SETN-High and SETN-Low maps both indicate that the maximum suppression occurs within the Faustini PSR at 86.98°S, 89.62°E and 86.89°S, 87.93°E, locations that are separated by 51.3 km.

The new low-altitude SETN map also provides several important advantages over the Lunar Prospector Neutron Spectrometer (LPNS) epithermal neutron flux map, which is available from NASA’s Planetary Data System (PDS) (Feldman et al., 1998). For the polar region above 75°S, the SETN-Low
Fig. 14 Fully-calibrated and background-subtracted LEND SETN omni-directional epithermal neutron count rate (CPS) south-polar stereographic maps above $75^\circ$ S. (A) SETN full-mission campaign observations mapped from July 2009 and now recovered to September 2017. (B) SETN high-altitude map composed of observations where the altitude is $> 48$ km. (D) SETN low-altitude map composed of observations where the altitude is $< 43$ km. (C) Co-registered LOLA digital elevation map in kilometers. Yellow names are large permanently shadowed regions with areas $> 125$ km$^2$. White names are large named craters. Red names identify the South Pole Aitken Basin and Highlands terrain. Permanently shadowed regions are outlined in white. Map units are in counts·sec$^{-1}$ and Sup%, epithermal neutron suppression % is defined as $(1 - m/b) \times 100$, where b is the background average count-rate in the region defined by $240^\circ$E $< r < 300^\circ$E longitude and $55^\circ$S $< r < 60^\circ$S) and m is the count-rate at a given map location. Average altitudes $\mu$ are shown at the bottom of each SETN map.

map includes $5.84 \times 10^6$ one-second observations taken at an average altitude of 35.7 km. The corresponding LPNS map includes $1.317 \times 10^5$ eight-second observations acquired within the region (Maurice et al., 2004). The LPNS observations were accumulated during its 3-month low-altitude campaign, where the average altitude was 30 km. The SETN-Low map now includes $\sim 44.3$ times the number of observations accumulated by LPNS over the same region, thus
the SETN-Low map benefits from significantly lower statistical uncertainties. In addition, since the SETN observation integration times are 1-sec rather than LPNS’ 8-sec integrations, the SETN observations are less spatially blurred by along-track motion. LRO’s present plan to circularize its orbital altitude above 50 km over the next several years will eventually curtail SETN’s low-altitude south-polar campaign. Also, LRO’s diminishing orbital inclination, which began in December 2011, effectively ended nadir-pointing observations of the top 3° near the poles, precluding nadir-pointing coverage of the large PSR’s at Haworth, Shoemaker, Shackleton and most of the Faustini crater.

3.2 CSETN

Figure 15 illustrates the fully-calibrated, high-resolution mapping of the CSETN observations, as presented in three south-polar stereographic maps above 82°S. Figure 15A illustrates the mapping of all calibrated observations from all four of CSETN’s detectors that were accumulated during the full mission between July 2009 and December 2017. Another important line of validation is to duplicate our map NSR detections by splitting the CSETN observations into statistically independent south-polar stereographic maps. Figure 15B (upper-right) is derived exclusively from the calibrated observations of CSETN detectors 2 and 4 (C2,4) and Figure 15D is derived exclusively from the calibrated observations of CSETN detectors 1 and 3 (C1,3). Both of the split mission maps, C1,3 and C2,4, show the independent detections of the four largest south-polar NSR’s (pink), which directly correspond to the Cabeus, Haworth, Shoemaker and Faustini PSR’s. The maps in the Figure 15 studies were produced using identical mapping methods and a 32 km diameter mapping kernel.

Figure 15C shows the spatial distribution of the statistical uncertainties and systematic errors to provide a high-resolution illustration of the measured CSETN errors. This illustration makes a stronger and spatially specific statement about the total uncertainties and errors, as compared to a map of the expected statistical uncertainties, which is determined simply by the square-root of the number of observations accumulated in a given region (Boynton et al., 2012). The statistical uncertainties shown in the Figure 15 maps are, from LRO’s polar orbiting trajectory, primarily latitude dependent. While the CSETN maps show excellent results, the spatial distribution of the errors in the map vary statistically by coverage and regionally by each detector’s relative contribution as well as the sensitivity variations with time since detector turn-on as described in section 2.2. Figure 15C is defined as the absolute deviation of the difference of the split detector maps, \( D = |C1,3 – C2,4| \). The subtraction eliminates lunar induced signals common to both maps, thus isolating statistical and systematic uncertainties. The difference map in Figure 15C also defines the upper-bounds conditions for the errors in the full-mission map, which then have the expected statistical uncertainties reduced by \( \sqrt{2} \), given the C1,3 and C2,4 coverage is combined.
Further validation of the detector-specific calibrations comes with a check of the location at which the maximum neutron suppression independently occurs in the C1,3 and C2,4 maps, which indicates that they occur at 84.58°S, 314.01°E and 88.04°S, 53.7°E, respectively, as indicated by the yellow ‘+’ in each map. These locations correspond to positions within the Cabeus and the Shoemaker PSR’s and have equivalent neutron suppressions of 27.9% and 29.4%, respectively. The full mission map, which integrates the observations from both maps suggests the maximum neutron suppression of 26.4% is reduced by averaging, and occurs in the Shoemaker PSR, thus indicating the location at which the greatest concentration of hydrogen-bearing volatiles is thought to occur in the Moon’s southern hemisphere. This statement assumes all of the neutron suppression entirely is attributable to hydrogen. That location is consistent with 1% WEH based on the regolith composition model of Lawrence et al. (2006).

Since the latitude trend in the Pearson correlation coefficient $r$, as measured between the C1,3 and C2,4 maps is coverage-dependent, it similarly diminishes with latitude. Above 86°S, $r = 0.724$ and $r = 0.48$ between 82°S and 86°S. Below 80°S, CSETN’s value as a high-resolution sensor becomes limited. Towards lower latitudes near 75°S, $r$ becomes negligible at $r = 0.048$. Figure 15C shows the spatial distribution of CSETN’s uncertainties (lower-left). The err % is derived by normalizing $D = C_{1,3} - C_{2,4}$— to to the averaged anhydrous reference count rate established for the background-subtracted CSETN full-mission map described in section 3.1.

3.3 SETN and CSETN Spatial Resolutions

Figure 16 quantitatively illustrates the spatial resolution properties of LEND’s SETN and CSETN epithermal neutron sensors. This study uses topographic cross sections to quantify two orthogonal transects of the Cabeus NSR at 311.3°E, 84.7°S that intersect at the impact site of the LCROSS mission’s Centaur rocket as mapped in Figure 16A (Marshal et al., 2012). The site was selected for this study because of ground-truth evidence of the existence of near surface concentrations of water ice at 5.4% by weight (Colaprete et al. 2010). The 100-km-wide Cabeus crater, centered at 84.9°S, 324.5°E, is also perhaps the most important and enigmatic of the south polar PSRs because of the strong line of neutron evidence from both LPNS and the LEND, that indicate that Cabeus maintains amongst the highest concentrations of water ice on the Moon (Feldman et al., 1998; Elphic et al., 2007; Mitrofanov et al., 2010a, 2012; Sanin et al., 2016). Siegler et al. (2016) have suggested that the high water-ice concentration in Cabeus may be explained if this crater had been the paleo-location of the Moon’s south pole, and that the pole location subsequently wandered to its present position near Shackleton crater, 89.9°S, 0.0°E. These conditions, plus the relative isolation of the Cabeus PSR away from the other large PSR’s, makes it an excellent location to evaluate the spatial resolution of the CSETN and SETN detectors.
Fig. 15 Fully-calibrated and background-subtracted LEND CSETN south-polar stereographic count rate maps from detector combinations above 82°S. Independent maps show the high correlation of the detected neutron flux for amongst detectors and the independent detection of neutron suppressed regions at the large permanently shadowed regions. 14A: (upper-left) CSETN full-mission map with all detectors (1,2,3,4) integrated. 14B: (upper-right) CSETN 2,4 full-mission count-rate map integrated from detectors (2,4) only. 14D: (lower-right) CSETN 1,3 full-mission count-rate map from detectors (1,3) only. 14C: (lower-left) Absolute deviation count rate map derived from the absolute value of the difference of the CSETN 13 and CSETN 24 maps. 14C thus shows the corresponding spatial distribution and upper bounds conditions for the combination of statistical and systematic errors. Outlines of the largest (area > 100km²) permanently shadowed regions are shown in white. Map units are in counts·sec⁻¹ and Sup%, suppression % is defined as ((b/m)−1) × 100, where b is the background-subtracted average count-rate in the region between 330°E and 30°E longitude and 55°S to 60°S and m is the count rate for various regions on the map. Note: longitude lines are only shown on the RMS error map.
We have systematically quantified the upper-bounds conditions for the spatial resolution of the SETN and CSETN instruments’ fields-of-view (FOV) by mapping their respective observations using two dependent conditions that impact the measure of the instruments’ spatial response. The SETN and CSETN maps are otherwise identically prepared. For SETN, we evaluate its two altitude-dependent maps SETN-Low and SETN-High, as shown in Figure 16. Theoretically, the SETN-Low map should show a greater amount of neutron suppression at the NSR’s because of the increased spatial resolution due to the reduced altitude as compared to the SETN-High map. As reported in Table 11 the mean altitude of the SETN-High map = 52.6 km and the mean altitude of the SETN-Low map = 35.7 km, show a 16.9 km altitude difference.

To study the CSETN response, the full mission map was prepared using both a high resolution 23-km diameter mapping kernel and a lower resolution 32-km diameter mapping kernel as used in Figure 16, which institutes a differing level of map smoothing. The 23 km mapping kernel approximates the Full-Width at Full-Maximum (FWFM) of the CSETN instrument at 50 km (Mitrofanov et al. 2010).

The upper bound conditions of the instruments’ spatial resolution are derived from convolution theory, which predicts that the measured width of the NSR in the map is related to the spatial resolution $f$ of the instrument by $w \times f$, where $w$ is the unknown spatial-width of the hydrogenated spot. The study assumes that the spot has a uniform internal hydrogen distribution in the upper meter, and that $f/2$ describes the spatial-width of the partial instrumental blurring of the NSR, on either side of spot $w$. To quantify the
spatial width \( w \), the suppression trend along each transect is least-squares fit to a Gaussian function and \( w \) is related to the fit standard deviation \( \sigma \), and its error. The spatial resolution is thus defined by its full-width at half-maximum, \((\text{FWHM}) = 2.35 \times \sigma\). If we assume that the PSR is uniformly hydrogenated along the profile, then the width \( w \) can be subtracted from the full width of the fit = \( 6 \times \sigma \), to derive the upper bounds estimate of \( f \).

Figure 16.B (middle) and 16C (right) each illustrate the instruments’ response to the Cabeus NSRs along the two orthogonal transects, the longitudinal transect is from A to A’ and the transverse transect is from B to B’. Three co-registered plots are shown for each transect. At the top is the corresponding LOLA topography cross-section in km for the transects of the Cabeus crater basin, with permanently shadowed region pixels shown in bold blue (Smith et al., 2010). The middle plots show the SETN measurements along the transects, as derived from the SETN-High (red) and SETN-Low (blue) epithermal neutron flux maps. The epithermal neutron suppression fraction shown in Figure 16 is defined in the positive domain as \( \text{Supp}\% = \left(1 - \frac{C(x)}{C(0)}\right) \times 100 \), where \( C(0) \) is the reference mean count rate of the anhydrous region \( r \) defined in section 3.1, and \( C(x) \) is the count rate at map location \( x \). Gaussian fits of the neutron suppression measurements with distance quantify the relative spatial responses to the Cabeus NSR.

SETN’s new calibration methods are further validated by the illustration of an improved spatial response in its SETN-Low vs. SETN-High map as shown in Table 11. Results from the A to A’ longitudinal transect show the expected altitude dependent improvement in the SETN-Low spatial responses where the SETN-Low data shows greater suppression magnitudes and narrower neutron suppression regions as compared to the SETN-High case. It is also shown that the SETN detection of the Cabeus NSR is asymmetric, being broader along the transverse transect. One possible explanation is that the NSR in the longitude profile is being sharpened by the enhanced neutron flux at locations 25 km and 140 km along the x-axis, which coincide with equator-facing slopes. The enhanced neutron flux on these surfaces may be governed by some combination of relatively anhydrous surfaces or a temperature-dependent enhancement in the neutron emission flux on those surfaces, because of their greater exposure to sun (Little et al., 2003, Lawrence et al., 2006). Thus, we quantitatively conclude that the spatial resolution of the SETN-Low map is improved relative to that of the SETN-High map, due to its exclusive use of low-altitude observations.

Strong evidence for CSETN’s superior spatial resolution, as compared to SETN, is shown by the direct comparison of their spatial response to the Cabeus PSR. Table 11 that the CSETN-23 km suppression response is narrower than the SETN-Low response by 33% and 74% in FWHM, for the longitude and transverse transects. Results show that the CSETN-23 km map has a 2.8% and 3.0% greater suppression magnitude for the two transects.

Interestingly, a comparison of the CSETN data for the longitude and transverse transects shows the opposite asymmetry than was shown for the SETN study, with the width of the suppression response in the longitude case being
Table 11 Results of the spatial resolution study at Cabeus for SETN and CSETN. Column 1) Detector identity and mapping condition. Column 2) The measured maximum neutron suppression derived from the peak of the Gaussian fit. Column 3) the standard deviation sigma derived from the Gaussian fit. Column 4) The Full-Width at Half-Maximum (FWHM) of the fit = 2.35* (column – 3) Column 5) PSR adjusted FWHM’s. Assuming a uniformly hydrated spot diameter at Cabeus, \( w = 19 \text{ km} \), Full-Width at Full-Maximum (FWFM) = 6 × σ, then \( \text{FWHM}’ = ((σ × 6.) − 19.)/6. × 2.35 \).

| Det. ID & Cond. | Det. ID & Cond. | Long. A to A’ | Max Supp % | Sigma (km) | FWHM (km) | Adj FWHM (km) | Std. Error (%) |
|----------------|----------------|---------------|------------|------------|------------|---------------|---------------|
| SETN Low-Alt.  | Transverse, B to B’ |               | 6.50%      | 20.03      | 51.5       | 39.7          | 0.139         |
| SETN Hi-Alt.   |               |               | No Fit     | No Fit     | No Fit     | No Fit        | No Fit        |
| CSETN 23 km    |               |               | 21.0%      | 14.85      | 34.9       | 27.5          | 0.908         |
| CSETN 32 km    |               |               | 18.0%      | 15.32      | 36         | 28.6          | 0.524         |

broader. A possible explanation is that the equator-facing surfaces are not observed by the narrower CSETN field-of-view and are thus not a factor in the detected flux at the PSR. Further, the relatively broadened neutron suppression along the A to A’ transect into the Cabeus basin may indicate the presence of hydrogen-bearing volatiles in regions that are occasionally illuminated, which is indicated near 110 to 120 km along the x-axis and is observed by both SETN and CSETN. If the smaller neutron suppression is due to hydrogen in the illuminated regolith, it may be because of numerous small PSRs in the Cabeus basin or it may instead indicate buried ice or an icy mixture. Assuming that the neutron suppression is entirely attributable to hydrogen uniformly mixed in the regolith, then a baseline of 0.4% WEH is estimated for the location of maximum neutron suppression near the LCROSS impact.

The errors described in column 6 of Table 11 of this study are expressed in the units of the standard error of the residuals of the gaussian fit as compared to the cross-sections. Finally, the multi-detector demonstration reviewed here at the Cabeus NSR, coupled with the independent detections of the NSRs in the Cabeus, Haworth, Shoemaker, and Faustini regions as shown in C1,3 and C2,4 of Figure 15 clearly refute the early mission assertions that the CSETN collimated count-rate is ‘negligible’ and that the PSR detections at Shoemaker and the other large southern craters are simply due to ‘statistical noise’ (Eke et al., 2012; Teodoro et al., 2014; Mitrofanov et al., 2010; Sanin et al., 2016).

3.4 STN3

Figure 17 shows variations of the south polar stereographic maps corresponding to measurements from LEND’s uncollimated Sensor for Thermal Neutrons #3 (STN3). Because STN3 does not include a Cd cover, it is sensitive to neu-
Fig. 17 Fully-calibrated LEND STN3 omni-directional thermal neutron flux data from the south pole as polar stereographic count rate maps above 75°S. Left: STN3 map from July 2 2009 to May 2011; Right: STN thermal neutron map where \( STN = STN3 - 1.2 \times SETN \) removes epithermal neutron contributions scattered from the collimator. Permanently shadowed regions are outlined in white. Map units are in \( \text{counts} \cdot \text{sec}^{-1} \) and Sup\%, suppression \% is defined as \( \left( \frac{b}{m} - 1 \right) \times 100 \), where \( b \) is the background average count-rate in the region between 240°E and 300°E longitude and 55°S to 60°S and \( m \) is the count rate for the locations in the map.

3.5 Results Discussion

Both the CSETN full-mission map and the SETN-Low epithermal neutron flux maps indicate the presence of strongly suppressed NSRs which overlie the large south polar PSRs at Cabeus, Haworth, Shoemaker and Faustini craters. The CSETN data independently identifies all of the above regions as individual NSRs, while the SETN-Low and SETN-High maps can only clearly distinguish Cabeus, likely because it is more spatially isolated. The Cabeus NSR is only weakly detected in the SETN-High map.

Faustini crater’s NSR is far more prominent in this paper’s CSETN-Full, SETN-Full and SETN-Low maps than had been observed in prior LEND team
papers (Mitrofanov et al., 2010, Boynton et al., 2012, Sanin et al., 2016). The cause of this paper’s stronger Faustini NSR is attributed to the present use of observations that were excluded in prior studies because of their low detector efficiency right after instrument turn-on. Regular station keeping maneuvers reduced the coverage of the Faustini crater region because they occurred in orbital tracks near the 90°E and 270°E longitude lines that coincided with Faustini crater. Detector sensitivities in the available Faustini coverage were also likely degraded by the consistently low detector efficiencies after instrument turn on (Litvak et al., 2012; Boynton et al. 2012; Litvak et al. 2016). Faustini’s coverage is further degraded by the diminished orbital inclination during the extended mission, in which only parts of the Faustini crater were observed. The SETN-Low map also indicates that the strongest NSR occurs near the Faustini and Shoemaker craters rather than the Cabeus NSR. However, the magnitude of this suppression may be a function of the convolution of the close proximity of several nearby PSRs. Of the set of NSR’s – Cabeus, Haworth, Shoemaker and Faustini, CSETN and SETN maps are consistent in indicating Haworth has the weakest overall suppression of the four.

Stable and cryogenically cold maximum surface temperatures \(\leq 110\) K, as is found in the PSRs, are thought to define the primary conditions for the retention of water concentrations at the surface of the Moon. However, studies that balance the supply, formation and loss rates of water indicate that the optimal conditions for concentrations of water at the surface to exist are between 65 K and 110 K (Esterman, 1955, Watson et al., 1961; Arnold, 1979). This study’s CSETN and SETN maps confirm earlier LEND CSETN evidence that the NSR at Haworth is relatively weaker than the NSRs in the Shoemaker and Cabeus PSRs. The relatively weaker Haworth NSR may be related to its colder maximum temperature near 70 K as compared to the warmer Shoemaker and Faustini craters (Feldman et al, 2001; Boynton et al., 2012; Hayne et al., 2015). These regions will be studied further in McClanahan et al. 2018.

Theoretical studies of the neutron flux from hydrogenated lunar regolith have shown that the attenuation of the epithermal neutron flux due to H in the regolith should be associated with an increase in the thermal neutron flux (Hodges et al., 2002; Lawrence et al. 2006). The LEND STN maps of the south polar thermal neutron flux confirm the LPNS team’s prior findings of no corresponding enhancement in thermal neutron flux at any of the south-polar NSRs (see Figure 15). The implication of this result is that the NSR detections found by CSETN and indirectly by SETN and LPNS are only partially consistent with the presence of high concentrations of H. Theoretical studies of icy mixtures in the regolith, layering and surface frost have also shown that the interpretation of the neutron emission flux can in some cases be ambiguous because of regional geochemistry and temperature variations and the existence of surface frosts (Lawrence et al., 2006, Lawrence et al., 2011).

The independent SETN-Low and SETN-High maps shown in Figure 14 also indicate several NSR’s that overlie high-altitude ridges and slopes. These anomalous NSRs are located near the Sverdrup, Malapert, Amundsen and Weichert craters. In these cases, the neutron suppression phenomena may not
be attributed to concentrations of H in these illuminated regions, but instead may be due to the minimization of the solid-sky-angle available at the surface. The anomalous NSRs were first observed in Feldman et al., (2001). McClanahan et al., (2014) later speculated that they were associated with solid-sky-angle minimization as observed in LEND maps. The phenomenon was quantified in the LPNS observations by Eke et al., (2014). The neutron production in the regolith in these regions is relatively attenuated by sloped topography, which diminishes the regional solid-sky-angle and the corresponding influx of GCR.

4 Conclusions

In this study we showed that we can accurately predict the partial and total count-rates for observations by any of LEND’s $^3$He detectors for the full span of LEND’s now eight-plus year mission. In the course of the paper we systematically reviewed the design and development of our Geant4 detector models and validated them by comparing them to several established benchmarks, which included the Apollo 17 epoch Lunar Neutron Probe Experiment, and the McKinney et al., (2006) models of the Moon’s neutron emission flux during the Apollo 17 epoch and then evaluated LEND’s detectors against the results of the Lunar Prospector Neutron Spectrometer. Our results quantified the relative counts contributions from collimated neutrons, scattered lunar neutrons, GCR and secondary charged particles as a function of the expected ranges of solar modulation potential and altitude variations. The cross-validation method established here shows that we can normalize and compare the Moon’s neutron emission flux from different time periods, as well as compare differently configured $^3$He detectors. The comparison was made possible by the Oulu neutron monitor in northern Norway, European Union which allowed us to quantify the expected lunar emission flux as defined in units of solar modulation potential. The correction for altitude-dependent variations is folded into the model to adjust the partial lunar neutrons and GCR-dependent background contributions. Each detector’s spatial resolution is derived by modeling the detector’s physical geometry and factoring in altitude and GCR variations.

Our secondary line of validation entailed a review of several cylindrical and south-polar stereographic maps generated from the SETN, CSETN and STN3 detector data. The study yielded several important contributions to lunar neutron and hydrogen-bearing volatile research.

[1] New spectral integration methods for the period before and after May 2011 allow us to fully recover and combine six-plus years of SETN observations that were thought to be lost so that we can now calibrate and map all eight plus years of SETN observations.

[2] A new, low-altitude, SETN south-polar stereographic map for $\delta = 75^\circ$S is derived from the additional observations. The SETN low-altitude map with mean altitude 35 +/- 1.8 km is equivalent to the average altitude of the corresponding LPNS map and presently includes more than fifty-eight times the
number of observations that are available in the LPNS PDS products. A higher altitude south-polar stereographic map is derived for comparison.

[3] Our efforts restored the STN2 Doppler instrument to ongoing operations. The detector measures the thermal neutron flux and the dataset now spans over eight years of operations. Details of the new STN2 calibration methods and the specialized mapping methods will be reviewed in a subsequent paper.

[4] Using split detector maps (see Figure 15), we showed independent detections of neutron suppressed regions near the south pole that are strongly correlated with the positions of the PSRs at Haworth, Shoemaker and Faustini craters. The neutron suppressed regions are likely associated with high concentrations of hydrogen-bearing volatiles in the upper-meter of regolith.

[5] We reviewed the spatial distribution of the combined statistical and systematic uncertainties of the CSETN observations by mapping the absolute difference in the CSETN split detector maps (see Figure 15). The study is an important statement of the combined uncertainty in a given location which is designed to support future, more detailed investigations.

[6] The upper-bounds conditions of the SETN and CSETN spatial resolution were defined as 39.7 km and 19.1 km, respectively in a study of detected neutron emission flux along orthogonal transects (see Figure 16). The study was performed using the largest Cabeus PSR and the transects were centered on the LCROSS impact point, a ground truth location at which high concentrations of hydrogen-bearing volatiles were detected.

[7] Hydrogen-bearing volatiles appear to exist on the occasionally illuminated surfaces in the Cabeus crater basin, as indicated by the asymmetric spatial-widths derived from the CSETN data along orthogonal transects.

5 Conclusions

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