Performance of Orbital Neutron Instruments for Spatially Resolved Hydrogen Measurements of Airless Planetary Bodies

David J. Lawrence,¹ Richard C. Elphic,² William C. Feldman,³
Herbert O. Funsten,⁴ and Thomas H. Prettyman³

Abstract

Orbital neutron spectroscopy has become a standard technique for measuring planetary surface compositions from orbit. While this technique has led to important discoveries, such as the deposits of hydrogen at the Moon and Mars, a limitation is its poor spatial resolution. For omni-directional neutron sensors, spatial resolutions are 1–1.5 times the spacecraft's altitude above the planetary surface (or 40–600 km for typical orbital altitudes). Neutron sensors with enhanced spatial resolution have been proposed, and one with a collimated field of view is scheduled to fly on a mission to measure lunar polar hydrogen. No quantitative studies or analyses have been published that evaluate in detail the detection and sensitivity limits of spatially resolved neutron measurements. Here, we describe two complementary techniques for evaluating the hydrogen sensitivity of spatially resolved neutron sensors: an analytic, closed-form expression that has been validated with Lunar Prospector neutron data, and a three-dimensional modeling technique. The analytic technique, called the Spatially resolved Neutron Analytic Sensitivity Approximation (SNASA), provides a straightforward method to evaluate spatially resolved neutron data from existing instruments as well as to plan for future mission scenarios. We conclude that the existing detector—the Lunar Exploration Neutron Detector (LEND)—scheduled to launch on the Lunar Reconnaissance Orbiter will have hydrogen sensitivities that are over an order of magnitude poorer than previously estimated. We further conclude that a sensor with a geometric factor of $\sim 100 \text{ cm}^2 \text{ Sr}$ (compared to the LEND geometric factor of $\sim 10.9 \text{ cm}^2 \text{ Sr}$) could make substantially improved measurements of the lunar polar hydrogen spatial distribution. Key Words: Planetary instrumentation—Planetary science—Moon—Spacecraft experiments—Hydrogen. *Astrobiology* 10, 183–200.

1. Introduction

ORBITAL NEUTRON SPECTROSCOPY has become a standard technique for remotely measuring planetary compositions from orbital distances (30–500 km). Orbital neutron spectroscopy relies upon galactic cosmic rays (GCR) that hit the surfaces of airless or nearly airless planetary bodies. When the GCR hit the planet, they initiate nuclear spallation reactions that liberate high-energy neutrons. These neutrons then downscatter in energy through a variety of elastic and inelastic collisions with planetary nuclei to create an equilibrium energy flux spectrum, $\Phi(E)$ (Fig. 1). This flux spectrum is typically divided into three broad energy ranges of fast, epithermal, and thermal neutrons. Fast neutrons have energies

from about 1 MeV to nearly the incident proton energy at the time of the GCR spallation reactions. Epithermal neutrons are medium-energy neutrons that span a wide energy range and typically have a flux that scales as $1/E$ (where E = neutron energy). The lowest-energy neutrons, thermal neutrons, are in thermal equilibrium with the planetary surface and have a Maxwellian energy distribution. All these features of an equilibrium neutron flux spectrum are illustrated in the modeled flux spectra shown in Fig. 1.

Thermal, epithermal, and fast neutrons from planetary surfaces are separately measured from orbit with standard neutron detection techniques (Feldman *et al.*, 2002b, 2004), and these measured neutrons carry information indicative of the underlying near-surface composition. For example,

¹Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland.

²NASA Ames Research Center, Moffett Field, California.

³Planetary Science Institute, Tucson, Arizona.

⁴Los Alamos National Laboratory, Los Alamos, New Mexico.

FIG. 1. Plot of modeled equilibrium neutron fluxes for a FAN material with various amounts of water added to the FAN soil. The fluxes are plotted as flux times energy to flatten out the power-law profile of the fluxes and better show the variation of epithermal neutrons with increasing water content.

because of their similar masses, epithermal neutrons lose their energy very efficiently in collisions with protons. Thus, a strong measure of hydrogen at a planetary surface is a decrease in the flux of epithermal neutrons (see Fig. 1). Epithermal neutrons have been used to measure the abundance of hydrogen at the lunar poles (Feldman *et al.*, 1998, 2000a, 2001; Lawrence *et al.*, 2006; Elphic *et al.*, 2007) from the Lunar Prospector (LP) spacecraft and at Mars (Feldman *et al.*, 2002a; Mitrofanov *et al.*, 2002) from the Mars Odyssey (MO) spacecraft. Thermal neutrons have been used to measure the abundance of neutron-absorbing elements iron, titanium, gadolinium, and samarium at the Moon (Elphic *et al.*, 2000, 2002; Feldman *et al.*, 2000b) as well as CO₂ at Mars (*e.g.*, Prettyman *et al.*, 2004). Fast neutrons carry information about iron and titanium (or, alternatively, average atomic mass) for nonhydrous silicate bodies (Maurice *et al.*, 2000; Gasnault *et al.*, 2001) as well as hydrogen at the Moon and Mars (Feldman *et al.*, 2000a, 2002a). New planetary neutron measurements are planned for the asteroids Ceres and Vesta on the NASA Dawn spacecraft (Prettyman *et al.*, 2003), for Mercury on the NASA MESSENGER spacecraft (Goldsten *et al.*, 2007), and for the Moon with the Lunar Reconnaissance Orbiter (LRO) spacecraft (Mitrofanov *et al.*, 2005, 2008). More details about specific orbital neutron spectroscopy measurements can be found in the above references. A good general reference for planetary neutron spectroscopy is Feldman *et al.* (1993).

Despite the fact that orbital neutron spectroscopy has become a standard remote sensing technique for measuring planetary composition, a significant drawback to this technique is that the mapping spatial resolution is quite broad. The reason for this broad spatial resolution is that all orbital neutron measurements to date have used omni-directional neutron sensors for which the full-width, half-maximum spatial resolution is ~ 1 – 1.5 times the altitude above the planetary surface. For the LP and MO missions, the optimum

spatial resolutions were 54 and 600 km (Maurice *et al.*, 2004; Prettyman *et al.*, 2004), respectively. As a consequence, many important science questions cannot be addressed with currently fielded instrumentation. For example, the LP Neutron Spectrometer (NS) identified enhanced hydrogen that is generally correlated with the locations of permanently shaded craters at the lunar poles. However, the spatial resolution of the LP data is too broad to resolve individual craters or deposits, all of which are smaller than 30 km in diameter. In response to this need, the LRO spacecraft is carrying a neutron sensor that will collimate the incoming epithermal neutrons in order to improve the spatial resolution of epithermal neutron measurements (Mitrofanov *et al.*, 2005, 2008).

Since spatially resolved orbital neutron spectroscopy is in its relative infancy, computational techniques and tools needed for detailed evaluation and validation of instrument performance are not sufficiently mature for most planetary neutron spectroscopy applications that require better spatial resolution than provided by omni-directional neutron spectrometers. There is no published study that evaluates in detail the detection and sensitivity limits of spatially resolved neutron measurements, and collimated field-of-view (FOV) measurements in particular. In this study, we have developed physics-based, statistics-driven methodologies for evaluating the sensitivity to hydrogen of orbital spatially resolved neutron measurements. Specifically, we have developed two complementary techniques for evaluating hydrogen sensitivity and spatial resolution: (1) an analytic approximation technique that we call the Spatially resolved Neutron Analytic Sensitivity Approximation (SNASA), and (2) a fully three-dimensional transport model technique. While the techniques presented here focus on spatially resolved epithermal neutron measurements as applied to hydrogen detection, these ideas are easily generalized for measurement of fast and thermal neutrons as well as gamma rays, which might use a collimated FOV and therefore have similar spatial response functions.

The organization of this paper is as follows. First, we describe the SNASA technique for determining the spatial resolution and hydrogen sensitivity for spatially resolved neutron measurements. Second, we describe a validation of the SNASA technique, using LP neutron data. Third, we apply the results of the SNASA technique to the case of the LRO collimated neutron instrument. Next, we describe a complementary three-dimensional technique for fully simulating the performance of spatially resolved neutron instruments. Finally, we discuss and summarize the results of this study.

2. The SNASA Technique for Determining Sensitivity and Spatial Resolution of Surface Hydrogen Deposits

2.1. General considerations

In this section, we present the SNASA technique for quantifying the hydrogen abundance sensitivity and spatial resolution of spatially resolved neutron instruments for a variety of scenarios with science-driven parameters, such as planetary surface composition and required spatial resolution, and mission-driven parameters, such as altitude, backgrounds, and data collection time. In practical terms, the results of this technique are also dependent on other pa-

FIG. 2. Geometric relationship of an ideal collimated neutron sensor where a cylindrically symmetric collimator of diameter x and height y surrounds a cylindrically symmetric neutron sensor. The opening half-angle for neutrons to enter the collimator from the nadir direction is given by θ .

rameters such as instrument size, structure, and composition; detection technique; and mission profile.

To illustrate the method, we use a neutron spectrometer that consists of a collimator that defines the FOV for epithermal neutrons coupled to a neutron sensor, which is a standard omni-directional neutron spectrometer. The collimator technique is straightforward to understand and can be well applied to the SNASA technique. It is also the basis for several recently proposed neutron instruments and will be flown in lunar orbit on LRO (Mitrofanov *et al.*, 2005, 2008).

Figure 2 shows the general concept for a neutron spectrometer with a collimated FOV for epithermal neutrons. A collimator made from an epithermal neutron-absorbing material is placed in front of a neutron sensor to restrict the neutrons from entering the sensor from side angles. The collimating material can be made from a standard neutron-absorbing material such as ^{10}B enriched boron carbide (B_4C) since ^{10}B has a very large thermal and epithermal neutron absorption cross section. The neutron sensor can be one of a variety of types. A standard neutron sensor that has extensive spaceflight heritage is a ^3He gas proportional counter (Hahn *et al.*, 2002; Feldman *et al.*, 2004).

For simplicity, we consider a cylindrical collimator whose angle of view projects to a circular FOV at the planetary surface. The full-width, full maximum (FWFM) of the FOV, D_{FOV} , is defined geometrically by the aspect ratio of the collimator and the distance, H , of the sensor to the planet (see Figs. 2 and 3):

$$D_{\text{FOV}} = \frac{2x}{y} H \quad (1)$$

Here x and y are the diameter and height of the collimator, respectively. In addition to neutrons that transit the colli-

FIG. 3. (Side view) Geometric relationship of the collimated sensor to a planetary surface. The FWFM field of view, D_{FOV} , is defined by the opening half-angle and the height, H , of the sensor above the planetary surface. (Top view) Geometric illustration of a hydrated deposit within a collimated neutron sensor FOV. Region 1 represents a hydrated soil deposit located within the FOV that has a size less than the FOV of the collimated instrument and WEH abundance of w_1 . Region 2 represents a region that is within the FOV of the collimated instrument but has a different WEH value of w_2 . The collimator FOV is given by the diameter of region 2. Region 3 is the region outside the collimated FOV and extends to the visible limb of the planet. Higher-energy neutrons from region 3 can penetrate the collimator and are considered background neutrons.

imator without striking a collimator wall, background neutrons from all angles with sufficient energy to pass through the collimator material can also be detected by the neutron sensor. Both the collimated and background neutrons are accounted for in the SNASA technique.

2.2. Develop analytic method for calculating hydrogen sensitivity

Before describing the components of the SNASA technique, we will first generally describe the epithermal neutron flux—and therefore the measured counts—at the entrance of either an omni-directional neutron spectrometer or a neutron spectrometer with improved spatial resolution as a function of hydrogen abundance. When measuring hydrogen by

using epithermal neutrons, the average water-equivalent hydrogen (WEH) weight fraction, w , of an area viewed by the spectrometer is related to the measured epithermal neutron counts $C(w)$ associated with that area: (Feldman *et al.*, 1998)

$$C(w) = R(w)C(0) \quad (2)$$

where

$$R(w) = \frac{1}{1 + 61w} \leq 1 \quad (3)$$

$R(w)$ represents the count rate ratio between a region with w weight fraction WEH and zero WEH. Equation 3 was determined empirically via neutron transport modeling in Feldman *et al.* (1998). In principle, the counts $C(0)$ for epithermal neutrons emitted from a completely dry surface can be determined through neutron transport modeling (*e.g.*, Lawrence *et al.*, 2006; McKinney *et al.*, 2006). However, in practice there are often normalization uncertainties with such techniques. Thus, if the particular situation permits, *in situ* normalization can be obtained through empirical measurements of known sources. For example, on the Moon, immature regions are known to have the least amounts of solar wind-implemented hydrogen (*e.g.*, Johnson *et al.*, 2002); therefore, measured epithermal neutron data over such regions provide a good approximation of, and an absolute lower bound to, $C(0)$. For Mars neutron data, an absolute normalization was determined from measurements over the known composition of the thick, wintertime CO_2 polar cap (Feldman *et al.*, 2003; Prettyman *et al.*, 2004). Equations 2 and 3 form the foundation for the quantitative evaluation of spatially resolved hydrogen measurements with the use of the SNSA technique.

2.2.1. Problem setup. Collimated instruments have a specified FOV, which for our purposes we have defined as circular on the planetary surface having a diameter D_{FOV} . Figure 3 shows a diagram of a simplified scenario. D_{FOV} represents the collimated FOV seen by an instrument from orbit and defined by Eq. 1. We have simplified the scenario for illustrative purposes by defining a circular hydrated deposit represented by the blue shaded region 1 and located at the center of the FOV. The counts $C_1(w_1)$ of epithermal neutrons from this region follow Eq. 2. Since we are interested in a minimum sensitivity estimate, we limit our discussion to cases in which the hydrogen deposit is smaller than the FOV, since the best spatial resolution and sensitivity are required for these cases. Region 2 represents an annular region that has a lower abundance of hydrogen with counts $C_2(w_2)$. Maximum contrast between regions 1 and 2 is obtained when $w_1 \gg w_2$. The cumulative counts from within the FOV are therefore $C_{\text{FOV}}(w_1, w_2) = C_1(w_1) + C_2(w_2)$.

Counts from region 3 are due to neutrons that originate from all areas of the planetary surface beyond the FOV of the collimated spectrometer but are within the view of the spacecraft. Specifically, this includes all regions from the outer edge of the FOV to the limb of the planetary object. Neutrons from region 3 can be detected if they have sufficient energy to pass through a collimator wall and be de-

tected by the neutron sensor. We define the total counts of neutrons from region 3 as the background counts C_{back} .

When using Fig. 3 as a measurement scenario, the total measured neutron counts consist of the counts measured within the FOV plus the background counts detected from neutrons that penetrate the collimator material:

$$C(w_1, w_2) = C_{\text{FOV}}(w_1, w_2) + C_{\text{back}} \quad (4)$$

In developing our analytic expression for hydrogen sensitivity, our goal is to express the measured hydrogen abundance of the deposit in region 1 relative to the dry FOV counts, $C_{\text{FOV}}(0,0)$, along with other factors that account for hydrogen abundances, background neutrons, and FOV coverage effects. The next four subsections describe how these various terms are determined.

2.2.2. Background from outside the FOV. The background neutrons represented by C_{back} are high-energy epithermal and fast neutrons and come from all directions, including the planetary surface and spacecraft. For this study, we ignore neutrons backscattered from the spacecraft because they depend uniquely on the spacecraft design and the location of the neutron spectrometer on the spacecraft. Modeling of neutron transport through spacecraft materials (Lawrence *et al.*, 2009) has shown that spacecraft backscattered neutrons are a non-negligible background. Nevertheless, these backscattered neutrons can be estimated with the appropriate modeling and can be easily incorporated into the overall neutron sensitivity estimate (*e.g.*, Section 4.1.3).

Planetary background neutrons arrive from all locations of the planetary surface visible to the spacecraft, including beyond the collimated FOV, and their flux at the spacecraft is altitude dependent. We therefore assume that their flux at the spacecraft has no dependence on hydrogen abundance at the spatial scale of the collimated neutron measurements (although their flux may have compositional variations on spatial scales of an omni-directional detector). Second, the background neutrons, which are fast neutrons and higher-energy epithermal neutrons that can penetrate the collimator, are detected with lower efficiency than the epithermal neutrons from within the FOV, so the background count rate is proportional to the total measured neutron count rate through a scale factor: $C_{\text{back}} = f_{\text{back}} C(0,0)$. The scale factor f_{back} depends on the specific construction (material type, thickness, size) of the collimator, neutron sensor, and spacecraft. With use of the definition of C_{back} and Eq. 4, the background counts can be expressed in terms of the FOV counts and f_{back} as

$$C_{\text{back}} = C_{\text{FOV}}(0,0) \left(\frac{f_{\text{back}}}{1 - f_{\text{back}}} \right) \quad (5)$$

2.2.3. Background from inside the FOV. As previously stated, the epithermal neutron counts detected from within the FOV (see Fig. 3) can be separated as the counts from the hydrated region 1 plus the counts from a drier region 2. For the sake of simplicity, we assume here that only region 1 has hydrogen and is represented by $C_1(w_1)$, while region 2 is completely dry ($w_2 = 0$) and is represented by $C_2(0)$:

$$C_{\text{FOV}}(w_1, 0) = C_1(w_1) + C_2(0) \quad (6)$$

This expression with no hydrogen in region 2 and w weight fraction WEH in region 1 (compared to region 2 having a nonzero but lower amount of hydrogen than region 1) provides the maximum measurement contrast between the hydrated and nonhydrated regions and represents the optimum scenario for detecting small-area hydrogen features. This scenario should be applicable, for example, to hydrous deposits at the Moon that lie within the dry boundaries of fully shadowed craters. Also note that the scenario depicted in Fig. 3 is an idealized situation, and in reality a full set of measurements will be comprised of multiple passes over a given region where a true hydrogen deposit may or may not be centered on the FOV on any given pass. The situation in Fig. 3, therefore, illustrates the situation when multiple-pass data can be binned such that a deposit is centered in the FOV. The results of a detailed simulation that considers a realistic observation scenario are compared to our analytic treatment in Section 5.

In general, the epithermal counts from the dry region 2 are proportional to the total FOV counts for a completely dry FOV:

$$C_2(0) = f_{\text{epi}} C_{\text{FOV}}(0, 0) \quad (7)$$

The scale factor, f_{epi} , is given as

$$f_{\text{epi}} = \frac{C_2(0)}{C_1(0) + C_2(0)} \quad (8)$$

and depends on the relative solid angles of region 1 and 2 as well as the relative response (including response effects due to spacecraft altitude and angle-dependent detector efficiency) of the neutron sensor to the two regions. An example of how f_{epi} is calculated for a specific detector configuration is provided in Section 4.1.4.

2.2.4. Derive $C_{\text{FOV}}(w, 0)$ in terms of $C_{\text{FOV}}(0, 0)$. By using the relation of Eq. 2 for region 1 along with Eqs. 6 and 7 for a fully dry region, the counts from the hydrated region 1 can be expressed as

$$C_1(w_1) = R(w_1)C_1(0) = R(w_1)C_{\text{FOV}}(0, 0)(1 - f_{\text{epi}}) \quad (9)$$

With the above relations, the full expression for $C_{\text{FOV}}(w, 0)$ is then

$$C_{\text{FOV}}(w, 0) = C_{\text{FOV}}(0, 0)[R(w_1)(1 - f_{\text{epi}}) + f_{\text{epi}}] \quad (10)$$

2.2.5. Derive signal-to-noise and hydrogen sensitivity expression. In practice, the ability to distinguish one region from a neighboring region within the measurement statistics enables one to determine the measurement sensitivity for a given spatial resolution. In this problem, the spatial resolution is defined by D_{FOV} . Thus, the fundamental neutron measurement of interest is the difference in counts ΔC , between a FOV that has w_1 weight fraction hydrogen in region 1 versus a completely dry ($w_1 = 0$) region 1: $\Delta C(w_1, 0) = C(0, 0) - C(w_1, 0)$, where $C(w_1, 0) < C(0, 0)$ because the presence of hydrogen decreases the epithermal neutron emission according to Eqs. 2 and 3. Using the expressions given in the sections above, we can express $\Delta C(w_1, 0)$ as

$$\Delta C(w_1, 0) = C_{\text{FOV}}(0, 0)(1 - f_{\text{epi}}(1 - R(w_1))) \quad (11)$$

Since the statistical uncertainty for total measured counts C is $\sqrt{C}$, the total uncertainty for ΔC can be derived with the use of known statistical relations (Bevington and Robinson, 1992) and the expressions defined above:

$$\begin{aligned} \sigma_{\Delta C}(w_1, 0) &= \sqrt{\sigma_{C(0,0)}^2 + \sigma_{C(w_1,0)}^2} \\ &= \sqrt{C(0,0) + C(w_1,0)} \\ &= \sqrt{C_{\text{FOV}}(0,0) \left[1 + 2 \left(\frac{f_{\text{back}}}{1 - f_{\text{back}}} \right) + R(w_1) + f_{\text{epi}}(1 - R(w_1)) \right]} \end{aligned} \quad (12)$$

The signal-to-noise is defined as $S_n = \Delta C / \sigma_{\Delta C}$ and, using Eqs. 11 and 12, takes the form

$$S_n(w_1, 0) = \frac{\sqrt{b_{\text{FOV}}(0,0)\tau(1 - f_{\text{epi}})(1 - R(w_1))}}{\sqrt{1 + 2 \left(\frac{f_{\text{back}}}{1 - f_{\text{back}}} \right) + R(w_1) + f_{\text{epi}}(1 - R(w_1))}} \quad (13)$$

Here, $b_{\text{FOV}}(0,0)$ is the counting rate for a completely dry region within the FOV, and τ is defined as the total counting time for a given measurement. Equation 13 can be solved for $R(w_1)$, the hydrated-to-dry counting-rate ratio, which we denote as R^* , since it is a value directly calculated with instrument viewing parameters:

$$R^* = 1 + \frac{1}{b_{\text{FOV}}(0,0)\tau(1 - f_{\text{epi}})} \left[\frac{S_n^2}{2} - S_n \left(\frac{S_n^2}{4} + \frac{2b_{\text{FOV}}(0,0)\tau}{(1 - f_{\text{back}})} \right)^{1/2} \right] \quad (14)$$

From Eq. 3, the WEH abundance required to achieve a particular value of signal-to-noise is

$$w_1 = \frac{1 - R^*}{61R^*} \quad (15)$$

2.2.6. Use of hydrogen sensitivity relation. Equation 14 gives an analytic expression of the measured neutron counting ratio between a hydrated and dry region, which can then be directly translated into hydrogen abundance. This expression contains quantities that can be determined in a straightforward manner. For example, the FOV counting rate for a given detector system can be calculated by using a Monte Carlo transport calculation, or it can be estimated with use of geometric relationships and a few known empirical values. The counting time, τ is determined via a known mission scenario. The background factors, f_{epi} and f_{back} , are determined via known properties of the detector system. Finally, the desired signal-to-noise can be specified based on the degree of certainty required for a given measurement. A typical value used for a 99% degree of uncertainty is $S_n = 3$ (Bevington and Robinson, 1992). For more robust measurements, S_n can be set to larger values of 4 or 5. In summary, Eqs. 14 and 15 provide a closed-form, analytic expression of the hydrogen sensitivity for a collimated neutron detector.

3. Validation of SNSA Technique with LP Thermal Neutron Measurements

Before discussing the SNSA technique as applied to a collimated neutron detector, we address here the use of

existing Lunar Prospector Neutron Spectrometer (LP-NS) data to validate the SNSA technique. To carry out such a validation, a data set where surface compositional abundances are independently known is required. Such independent knowledge does not exist for LP epithermal neutron measurements of lunar hydrogen abundances. However, LP thermal neutron data can serve as a validation proxy for epithermal neutrons. The reasons for this are four-fold. First, as mentioned in Section 1, thermal neutrons are sensitive to the presence of neutron-absorbing elements gadolinium, samarium, iron, and titanium. Gadolinium and samarium are incompatible rare earth elements that closely track thorium abundances in lunar soils (Haskin and Warren, 1991). Iron and titanium have been mapped with high spatial resolution with the use of Clementine spectral reflectance (CSR) data (Lucey *et al.*, 2000). The CSR data sets can thus serve as a “ground truth” for iron and titanium abundances. Second, the spatial response of the LP-measured thermal neutrons is sufficiently similar to that of epithermal neutrons (Maurice *et al.*, 2004) so that thermal neutrons can adequately represent epithermal neutrons for the purpose of a validation. Third, because the thermal neutron counting rate decreases with increasing iron and titanium abundances (Feldman *et al.*, 2000b), measured thermal neutrons can be used to mimic the effect of hydrogen on epithermal neutrons. Finally, there exist multiple locations on the Moon where thermal neutron reductions are smaller than the FWHM spatial response of the NS, which is the Moon’s horizon at 30 km altitude, or ~600 km. Further, such locations are relatively isolated in regions of higher thermal neutron counts. These regions thus serve as good test cases for a validation.

To carry out the validation, a ground truth relationship must be established between surface thermal neutron counts predicted from CSR-measured iron and titanium abundances and those measured from orbit using the LP-NS. Figure 4 shows a plot of global CSR-derived $[\text{Fe}] + 2.36[\text{Ti}]$ abundances versus thermal neutron counting rates. The CSR-derived abundances are combined to equalize the effect of neutron absorption, where the thermal ($E = 0.025$ eV) ab-

sorption cross section of iron and titanium is 2.58 and 6.11 barns, respectively. The factor of 2.36 is the ratio of the two cross sections. The iron and titanium data sets were smoothed with the thermal neutron spatial response to enable a proper comparison between the CSR and thermal neutron data sets.

To reduce thermal neutron variations from gadolinium and samarium and keep only variations from iron and titanium, data in Fig. 4 were restricted to regions with thorium abundances less than 1.5 ppm (Lawrence *et al.*, 2003). At high iron and titanium values, Fig. 4 shows a reasonable correlation with thermal neutrons. For this analysis, we assume this correlation holds for all iron and titanium values, although at low iron/titanium abundances the thermal neutron counts respond primarily to the composition of other elements in the regolith that have variable (and, for this analysis, unknown) relative abundances.

Next, seven locations on the Moon were identified that satisfy the criteria of being isolated counting-rate reductions with sizes smaller than the LP-NS FWHM spatial response. These seven regions are listed in Table 1 along with their sizes, locations, and associated values for f_{epi} (see Section 4.1.4 for how f_{epi} is calculated). For the case of LP-NS, $f_{\text{back}} = 0$ since there is no collimator, and neutrons out to the horizon are detected in the omni-directional FOV.

To carry out the validation of the SNSA technique, the counting-rate ratio R (Eq. 2) is used to compare “ground truth” to the SNSA prediction. Figure 5 gives an example of how the comparison is carried out. Figure 5a is a CSR iron map ($0.5^\circ \times 0.5^\circ$ pixels) of the Moscoviense region, and Figures 5b and 5c are unsmoothed and smoothed thermal neutron maps of the same region, respectively (Maurice *et al.*, 2004). The unsmoothed thermal neutron map shows the data set used for calculating total thermal neutron counts; the smoothed thermal neutron map shows a higher signal-to-noise version of the thermal neutrons, but with a broader (smoothed) spatial response that allows the thermal neutron features to be clearly delineated. The mean $[\text{Fe}] + 2.36[\text{Ti}]$ value within Moscoviense (indicated by the center circle) is 18.9 wt % (titanium map is not shown). Using the correlation in Fig. 4, these abundances translate to a “ground truth” thermal neutron counting rate of 549 counts per 32 seconds. Based on the total number of collected measurements in this region (86), the total “ground truth” counts are 47,218. To mute compositional variations when using background counts, four equivalent-sized regions were selected, which are shown by the outer circles in Fig. 5 as background regions. The total counts in each region are determined by calculating the total counts in each circle and scaling the number of measurements to be equivalent to the number of measurements in the center circle (the SNSA model as given in Eqs. 13 and 14 assumes that the signal and background regions have the same counting time). The total counts in each background region are: 62,254, 66,854, 63,011, and 59,824. By combining measurements from the four background regions, a “ground truth” mean value of $R_{\text{GT}} = 0.761$ and a standard deviation $\sigma_{R_{\text{GT}}} = 0.039$ (see Table 1) are obtained. Here, the standard deviation represents variances in R_{GT} mostly due to residual compositional differences in the background regions.

The “prediction” of R_{GT} , R^* , (Eq. 14) is determined via the total measured counts in the central region $[C(w,0) = 49,851]$

FIG. 4. Plot of thermal neutron counts versus lunar global $[\text{Fe}] + 2.36[\text{Ti}]$ for locations where $[\text{Th}] < 1.5$ ppm. A linear fit is shown for $[\text{Fe}] + 2.36[\text{Ti}] > 13$ wt %.

TABLE 1. LOCATIONS USED FOR SNASA VALIDATION

Location	Location	Size (km)	f_{epi}	$[\text{Fe}] + 2.36[\text{Ti}]$	R_{GT}	$\sigma_{R_{\text{GT}}}$	R^*	σ_{R^*}	$1 - R_{\text{GT}}/R^*$
Moscoviense	27°N, 148°E	225	0.09	18.9	0.761	0.039	0.783	0.028	0.028
Tsiolkovsky	21°S, 129°E	135	0.23	18.0	0.777	0.034	0.894	0.052	0.131
Grimaldi	9°N, 64°W	130	0.24	27.2	0.714	0.018	0.655	0.025	-0.090
Ley	42°N, 155°E	60	0.58	11.0	0.865	0.039	0.821	0.099	-0.054
Lyot	50°S, 85°E	132	0.24	15.4	0.892	0.034	0.889	0.046	-0.003
Dewar	3°S, 166°E	114	0.29	8.5	0.828	0.030	0.816	0.045	-0.015
Kohlschutter	14°N, 154°E	53	0.62	7.0	0.868	0.027	0.946	0.080	0.083

Listed sizes are the diameters taken from the iron enhancement measured with the $0.5^\circ \times 0.5^\circ$ CSR iron data.

and the total counts in the background regions $[C(0,0) = 62,254, 66,854, 63,011, \text{ and } 59,824]$. Since uncertainties in the thermal neutron counts have been shown to be mostly Poisson (Maurice *et al.*, 2004), here the uncertainties in each region are assumed to be the square root of the total number of counts. A signal-to-noise, S_{tr} , is calculated by $\Delta C/\sigma_{\Delta C}$; and, as with R_{GT} , mean and standard deviation values are determined: $R^* = 0.783$, $\sigma_{R^*} = 0.0281$ (see Table 1). The procedure described above was carried out for

the seven lunar locations, and results for all locations are shown in Table 1. In all cases, the relative differences between R_{GT} and R^* (last column in Table 1) are less than 15%. Figure 6 shows a plot of R_{GT} versus R^* . The correlation coefficient is 0.74, which is a moderate correlation. In summary, this validation analysis has shown that the SNASA model can reproduce measured LP thermal neutron data to within a relative difference of 15%, which provides better confidence in the SNASA technique.

FIG. 5. Regional maps of the Moscoviense region on the Moon. (a) shows CSR-derived iron abundances on $0.5^\circ \times 0.5^\circ$ pixels; (b) shows raw, unsmoothed thermal neutron data; (c) shows smoothed thermal neutron data. The circles show regions where total counts were derived. The center circle is the high iron/low thermal neutron region, and the outer circles are the four background regions.

FIG. 6. R^* versus R_{GT} for the seven selected regions of thermal neutron reductions due to high iron and titanium abundances. The error bars represent variability due to different total counts in the background regions.

4. Application of SNSA Technique for Lunar Poles

4.1. Spatially resolved hydrogen measurements in lunar polar regions

Here, we discuss application of the analytic model of Section 2 to the Lunar Exploration Neutron Detector (LEND) that is part of the NASA Lunar Reconnaissance Orbiter (LRO) mission scheduled to launch in June 2009. Details of the LEND instrument are described in Mitrofanov *et al.* (2005, 2008). We use these details to estimate LEND's sensitivity to hydrogen at its optimum proposed spatial resolution, using the SNSA framework. To utilize Eqs. 14 and 15, it is necessary to derive the LEND count rate from a dry FOV, $b_{FOV}(0,0)$, and the terms τ , f_{back} , and f_{epi} . Our estimates of these quantities are described below.

Before proceeding further, we provide a brief description of the LEND spectrometer, using the information given in Mitrofanov *et al.* (2005, 2008). Figure 7 shows our best understanding of the LEND sensor and collimator configuration. The full LEND instrument consists of four sensor/collimator packages. The collimator is bilayered with polyethylene on the outside and B_4C on the inside. Since the B_4C density and ^{10}B enrichment have not been specified, we assumed a density of 2.5 g/cm^3 and a 95% ^{10}B enrichment (with ^{10}B being the boron isotope having a large thermal neutron capture cross section). The geometry of the collimator given in Fig. 7 is estimated based on Mitrofanov *et al.* (2005, 2008), although the following analysis does not depend on the precise dimensions.

The neutron sensors are 5 cm diameter 3He proportional counters with a gas pressure of 20 atm (Mitrofanov *et al.*, 2005). Using our knowledge of typical 3He neutron sensors, we show in Fig. 7 our assumed configuration for the 3He counter. Specifically, we used a cylindrical sensor 5 cm in diameter with 1.5 cm dead spaces at each end for wire attachments and housing. Based on conversations with 3He manufacturers (Johnson, 2006), 1.5 cm is a minimum length for a dead space with typical lengths being 2–2.5 cm. To block out thermal neutrons and only measure epithermal

FIG. 7. Geometry model used for a single LEND telescope. The complete LEND detector consists of four such telescopes. Dimensions and materials used in the neutron transport response calculation are given in the figure.

neutrons, the 3He counter is surrounded by a layer of Cd, which absorbs neutrons with energies less than 0.4 eV. For our model, we used a Cd thickness of 0.063 cm, which is the same thickness used for the LP 3He epithermal neutron sensor (Feldman *et al.*, 2004).

4.1.1. Estimate $b_{FOV}(0,0)$ for LEND. Using this information about the sensor and collimator, we estimated the count rate $b_{FOV}(0,0)$ of epithermal neutrons from dry ferroan anorthosite (FAN) soil expected for LEND. We used two estimation methods as a check of consistency: the first method is based on simple scaling arguments by comparing LEND with the LP neutron spectrometer and its lunar measurements, and the second method is based on neutron transport calculations of the neutron flux from the surface to the sensor as well as neutron transport calculations of the sensor/collimator sensitivity.

For the estimate using scaling arguments, $b_{FOV}(0,0)$ can be determined from the average measured LP counting rate $b_{LP}(0,0) = 21$ counts per second (cps) for dry FAN soil (Lawrence *et al.*, 2006):

$$b_{FOV}(0,0) = b_{LP}(0,0) \times S_{FOV} \times S_{Pressure} \times S_{Area} \times S_{Dead} \quad (16)$$

Here, S_{FOV} is the ratio in integrated neutron flux between the omni-directional LP sensors and the collimated sensors, $S_{Pressure}$ is the ratio of counts between the 10 atm 3He in the LP sensors and 20 atm 3He in the LEND sensors, S_{Area} is the ratio of cross-sectional areas between the LP sensors and

the LEND sensors, and S_{Dead} is the fractional reduction in LEND counts due to the ^3He dead layer in the ^3He sensors relative to the LP sensors. Note that LP flew during solar minimum, and LRO is expected to fly during solar minimum so that we expect a similar GCR flux and, therefore, similar neutron flux emitted from the lunar surface. However, since LEND will operate in a different solar cycle than LP, the precise GCR flux will depend on solar modulation conditions for our current solar cycle. Therefore, the GCR flux used here may be slightly different than the GCR flux present during the operating LRO mission.

S_{FOV} . To determine S_{FOV} , an expression derived by Prettyman *et al.* (2006) is used for the differential flux onto a detector orbiting at an altitude H above a spherical planet of radius R_m (see Fig. 8):

$$\phi(\mu)d\mu = \Phi(\mu)G(\mu)d\mu, \text{ where} \\ G(\mu) = R_m / \sqrt{R_m^2 - (1 - \mu^2)(R_m + H)^2} \quad (17)$$

Here, ϕ is the neutron flux at the detector, Φ is the surface flux from the planet, and $\mu = \cos(\theta)$ is the direction cosine at the spacecraft relative to the vector defined by the spacecraft and the lunar center of figure. Note that Prettyman *et al.* (2006) derived this expression for gamma rays that have straight-line trajectories. Here, we are interested in epithermal neutrons, which we also assume to have straight-line trajectories. This assumption, however, breaks down for lower-energy thermal neutrons that travel on ballistic trajectories (Feldman *et al.*, 1989). While not strictly true for the Moon, (see Lawrence *et al.*, 2006), we assume that the surface flux is isotropic so that $\Phi(\mu) = \Phi$. With this assumption, the total integrated flux is

$$\phi = \int_{\mu=\mu_{\min}}^1 \Phi G(\mu) d\mu \\ = \frac{\Phi \ln[2(q\mu + \sqrt{(\mu^2 - 1)q^2 + 1})]}{q} \Big|_{\mu=\mu_{\min}}^1 \quad (18)$$

FIG. 8. Geometry for transporting neutrons from the surface of the Moon to the spacecraft.

where $q = (R_m + H)/R_m$. For the omni-directional LP neutron sensor at the Moon ($R_m = 1738$ km) at an altitude approximately equivalent to the LRO orbit ($H = 50$ km), $\mu_{\min}$ is

$$\mu_{\min} = \sqrt{1 - \left(\frac{R_m}{R_m + H}\right)^2} = 0.235 \quad (19)$$

The full angular opening of the LEND collimator is $\sim 12^\circ$ so that for LEND $\theta_{\max} = 12^\circ$ and $\mu_{\min} = 0.978$. With use of Eq. 18, the ratio of integrated neutron flux for LEND to LP due to their differing FOVs is then

$$S_{\text{FOV}} = \frac{\phi_{\text{LEND}}}{\phi_{\text{LP}}} = \frac{0.022}{2.02} = 0.0109 \quad (20)$$

S_{Pressure} and S_{Dead} . Using MCNPX models of ^3He neutron sensors with different pressures, we determined that $S_{\text{Pressure}} = 1.25$ and $S_{\text{Dead}} = 0.76$ relative to the LP neutron spectrometer. Therefore, while the LEND ^3He pressure is twice that of the LP neutron spectrometer, the lower efficiency that results from its larger dead layer yields a net decrease in LEND efficiency of $S_{\text{Pressure}} \times S_{\text{Dead}} = 0.95$ relative to LP.

S_{Area} . The cross-sectional area of each LP-NS sensor is 114 cm^2 . The total cross-sectional area for the LEND sensors is $4 \times \pi \times (2.5)^2 = 78.5 \text{ cm}^2$. S_{Area} is therefore $78.5/114 = 0.69$.

Based on scaling arguments of LEND relative to the LP neutron spectrometer, the total estimated LEND counting rate for dry FAN soil within its FOV is

$$b_{\text{FOV}}(0, 0) = b_{\text{LP}}(0, 0) \times S_{\text{FOV}} \times S_{\text{Pressure}} \times S_{\text{Area}} \times S_{\text{Dead}} \\ = 21 \times 0.0109 \times 1.25 \times 0.69 \times 0.76 \\ = 0.15 \text{ cps} \quad (21)$$

We now estimate $b_{\text{FOV}}(0, 0)$, using a full neutron transport calculation. First, we carried out a neutron transport calculation of the LEND efficiency in a manner that is similar to what was done for the LP-NS sensors (Lawrence *et al.*, 2002, 2006). Specifically, using MCNPX, we propagated plane wave neutrons onto the LEND sensor of Fig. 7. These neutrons had energies ranging from 0.25 eV to 10 MeV and incident angles θ ranging from 0° to 90° . For azimuthal angles, ϕ (see Fig. 8), we assumed azimuthal symmetry. Using Eq. 17 of Lawrence *et al.* (2002) with a calculated flux from a FAN-type soil (Lawrence *et al.*, 2002, 2006), we calculated the angular response of the LEND sensor by averaging the sensor efficiency over all neutron energies.

This angular response is shown in Fig. 9, with a linear scale shown in Fig. 9a and log scale shown in Fig. 9b. Note that, in Fig. 9b, the response has a local minimum for angles just beyond the collimator angle where the path length through the collimator is the greatest. This response gradually increases for larger angles where the path length through the collimator decreases. The model statistical uncertainty is approximately $\pm 5\%$. As expected, the angular FWHM is $\theta_{\text{FWHM}} = 24^\circ$, which agrees with the collimator's geometrical half-width, full-maximum of 12° . At an altitude of $H = 50$ km, the corresponding FWHM spatial resolution is $2 \times H \times \tan(0.5 \times \theta_{\text{FWHM}}) = 21$ km. To derive the estimated counting rate $b_{\text{FOV}}(0, 0)$ of epithermal neutrons from dry FAN, we used the same algorithms for LEND as were used for validating LP

FIG. 9. (a) Modeled angular relative response of a single LEND telescope as a function of incident angle, where incident angle is defined in Fig. 2. Note that the FWHM response is $\sim 24^\circ$ and thus corresponds with the geometry shown in Fig. 7. The error bars are the statistical uncertainties of the Monte Carlo model and have a magnitude of $\sim 5\%$. (b) Same modeled response function as in (a), but now the response is plotted as a log scale to illustrate the response behavior beyond the main FWHM peak. The minimum response occurs at narrow angles where neutrons travel the longest path length through the collimator. However, for wide angles, the response increases as neutrons travel shorter lengths through the collimator.

neutron measurements (Lawrence *et al.*, 2006 and references therein) to obtain $b_{\text{FOV}}(0,0) = 0.18$ cps. These algorithms account for the full neutron transport from the lunar surface to the spacecraft, along with spacecraft motion and non-isotropic neutron flux from the lunar surface.

This value of $b_{\text{FOV}}(0,0) = 0.18$ cps derived by using a validated neutron transport calculation compares well with the value of $b_{\text{FOV}}(0,0) = 0.15$ cps derived earlier by using simple scaling arguments alone. However, the value $b_{\text{FOV}}(0,0) = 0.18$ cps derived here is significantly different from the values stated in Mitrofanov *et al.* (2008), which range from 0.29 to 0.9 cps and are factors of 1.6 and 5 times the value derived here. Specifically, these cited in Mitrofanov *et al.* (2008) were determined by using a simple scaling approach (0.29 cps), a numerical estimate with a simple cylindrical design

(0.32 cps), and a collimator “optimization program” (0.9 cps). Mitrofanov *et al.* (2008) do not provide sufficient details (similar to what we have given above) to evaluate their approach for any of these calculations. Furthermore, the cited values are not self-consistent, and the large discrepancies between the values are not explained.

One possible source of the larger epithermal neutron counts given by Mitrofanov *et al.* (2008) is the higher energy component that can successfully transit a collimator wall and be detected. However, by definition, these epithermal neutrons are background neutrons because they did not originate from within the instrument FOV. Alternately, if they are considered as part of the valid epithermal signal and not an epithermal background, then the actual instrument FOV is wider than the FOV defined simply by the collimator geometry, which thus reduces the spatial resolution of the instrument.

4.1.2. Estimate τ for LEND. For a realistic mission scenario, the dwell time τ of the spacecraft over an individual spatial pixel on the planetary surface is needed to use Eqs. 13–15, and we expect that the dwell time is dependent on the specific orbit of the spacecraft and the size of the spatial pixel. For a polar orbiting spacecraft, the mission-integrated dwell time $\tau(\lambda)$ of a spacecraft over fixed location of the planetary surface is a strong function of latitude λ and follows $\tau(\lambda) \propto [\cos(\lambda)]^{-1}$. This function has a singularity at the poles and rapidly decreases with decreasing latitude or, alternately, increasing distance from the poles. When using this as the basis for quantifying the dwell time over a pixel of finite size, the polar singularity provides a false metric for the dwell time because in a perfectly polar orbit the spacecraft always crosses a polar pixel, independent of the spatial size of the pixel. In contrast, for all other pixels, the number of orbits before revisit is strongly dependent on the pixel size. Therefore, by selecting the polar pixel to define the dwell time, we arrive at an answer that is meaningless except for the polar pixel itself. Mitrofanov *et al.* (2008) used 3×10^4 seconds for the estimated LRO time coverage of a 10 km diameter spot at the lunar pole, assuming a spacecraft in an ideal polar orbit for 1 year.

A more representative and complete approach is to quantify $\tau(\lambda)$ for all pixels except the two polar pixels. In practice, we must include several other considerations. First, the dwell time generally follows $[\cos(\lambda)]^{-1}$ but in a stepwise way in which the steps are larger for larger spatial pixels. Second, a polar orbit at the Moon will drift in inclination because of the Moon’s nonspherical gravitational field from mascons that are still not fully mapped. LRO is expected to drift by 0.5° in the first year of the mission (Saylor, 2005), which corresponds to ~ 15 km at the lunar surface. Third, a real mission will not have a 100% duty cycle because data will be lost due to solar particle events, data drop outs, corrupted data, and other reasons. For LP, the duty cycle was 86% (Lawrence *et al.*, 2004) and likely represents an optimum value because the LP mission operated during solar minimum when the occurrence of solar particle events was at a minimum.

$\tau(\lambda)$ can be estimated by using the LP mission profile. The goals of the LP mission were to carry out mapping of lunar composition from a polar orbit with a particular emphasis on the lunar polar regions (Binder, 1998). Thus, LP spacecraft orbital data provide a test case for determining the optimum collection time per unit surface area. Figure 10 and Table 2

show the number of seconds per 10 km pixel taken from the 30 km, low-altitude portion of the LP mission. The 30 km orbit only lasted ~ 7 months (Lawrence *et al.*, 2004), so the times in Fig. 10 and Table 2 have been scaled to 1 year to enable a direct comparison to be made with the nominal 1-year LRO mission. The maximum time of 6700 seconds is over a factor 4 less than the value of Mitrofanov *et al.* (2008). We also note that, as expected, these times follow a $[\cos(\lambda)]^{-1}$ dependence. We expect that the main reason for the discrepancy between our times and the Mitrofanov *et al.* (2008) value of 3×10^4 seconds is that Mitrofanov *et al.* likely used an ideal polar orbit, computed the value at the singularity τ (90°), and did not consider the inclination drift of the LRO orbit. Since the LP mission was designed to carry out lunar polar mapping with no other constraints on the mission, the measurements here represent a best-case situation regarding mapping times.

4.1.3. Estimate f_{back} for LEND. To determine f_{back} , the background counting rate from detected neutrons originating from locations at the planetary surface beyond the collimated FOV must be determined. With the same LEND instrument model and MCNPX simulations that were used to derive $b_{\text{FOV}}(0,0)$, we determined $b_{\text{back}} = C_{\text{back}}/\tau = 0.09$ cps. For this estimate, we ignored backscattered neutrons from the spacecraft, which may represent a significant additional background. As a consequence, the background estimate here represents a best-case scenario. Combining b_{back} and $b_{\text{FOV}}(0,0)$, we determined that the LEND signal-to-noise ratio is $0.18/0.09 = 2$, which is significantly better than the Mitrofanov *et al.* (2008) signal-to-noise estimate of 0.75. Because of the reasons described earlier (see Section 4.1.1), we will use our value of b_{back} , recognizing it may represent an optimum (minimum) value that does not include other backgrounds such as backscattered neutrons from the spacecraft structure. With b_{back} determined, Eq. 5 gives $f_{\text{back}} = 0.333$. If the background values from Mitrofanov *et al.* (2008) were used, then $f_{\text{back}} = 0.57$.

FIG. 10. Lunar Prospector collection times for 10×10 km sized pixels as a function of latitude, where the times from the 30 km LP orbit are scaled to 1 year. Data for the north pole are shown as a solid line and data from the south pole are shown as a dashed line. The dotted line shows a $[\cos(\lambda)]^{-1}$ dependence scaled to the lowest latitude point and demonstrates that the counting times scale as $[\cos(\lambda)]^{-1}$.

4.1.4. Estimate f_{epi} for LEND. f_{epi} represents the fractional background within the FOV that is due to a dry region surrounding a hydrated region and is defined by Eq. 8. The value for f_{epi} is calculated by using the two-dimensional response of the collimator sensor configuration at a given spacecraft altitude. Because we assumed azimuthal symmetry, the one-dimensional response of Fig. 9 was rotated to achieve a two-dimensional response. Figure 11 demonstrates how f_{epi} is determined by using three-dimensional mesh plots that represent various sizes of hydrous deposits within a 20 km diameter FOV. The mesh denotes the full FOV response, and the shaded region is the portion of the FOV response coming from a hydrated region that has various diameters. f_{epi} is then the ratio in volume of the shaded to mesh regions. This fraction of f_{epi} versus the diameter of the hydrated region is plotted in Fig. 12. In particular, for a 10 km diameter hydrated region (*i.e.*, the intended best-case LEND spatial resolution) at an altitude of 50 km, f_{epi} has a value of 0.54.

4.1.5. Estimated sensitivity for LEND. When all the values derived in Sections 4.1.1–4.1.4 (see Table 3) are put together, Eqs. 14 and 15 can be used to obtain hydrogen sensitivity estimates for a variety of latitudes. Table 4 lists these results for latitudes ranging from 85° to 90° . For these estimates, we assumed a 3σ detection (*i.e.*, $S_n = 3$), which should be considered marginal (a 4σ or 5σ detection limit would be more robust). Table 4 also lists the signal-to-noise (using Eq. 13) that would be obtained for a hydrated feature that has 100 ppm hydrogen from our estimated counting rates. Finally, equivalent LEND sensitivities given by Chin *et al.* (2007) and Mitrofanov *et al.* (2008) are listed in Table 4 and show a large discrepancy (over an order of magnitude) relative to the estimates derived here for all latitudes.

Figure 13 illustrates the type of scaling analyses that can be easily carried out with Eqs. 14 and 15, where the WEH 3σ sensitivity for a 10 km diameter deposit is plotted versus sensor geometric factor for three different latitudes. Here, geometric factor is defined as $g = A\Omega$, where A is the detector area and Ω is the subtended solid angle. For the LEND sensor,

$$\Omega = \int_0^{2\pi} \int_1^{\cos 12^\circ} d\phi d \cos \theta \quad (22)$$

such that $g = 10.9 \text{ cm}^2 \text{ Sr}$. From Fig. 13, it can be seen that, to obtain the sensitivity required by LEND of 100 ppm (0.09 wt % WEH) near the pole (Chin *et al.*, 2007), the geometric factor

TABLE 2. COUNTING TIMES FOR 10×10 KM SIZED PIXELS AS A FUNCTION OF LATITUDE FROM THE LUNAR PROSPECTOR 30 KM ORBIT PHASE, WHERE THE COUNTING TIMES ARE SCALED TO ONE YEAR

Location	Counting time per 10 km pixel (sec)
90°	6700
89°	3400
88°	1500
87°	900
86°	680
85°	500

FIG. 11. Two-dimensional response of the LEND instrument (mesh) and fractional response due to counts coming from a region 1 (solid). The response from region 1 is shown for different diameters of (a) 5 km, (b) 10 km, (c) 15 km, and (d) 20 km.

FIG. 12. Value of f_{epi} as a function of region 1 diameter.

would need to be $\sim 420 \text{ cm}^2 \text{ Sr}$, which is almost a factor of 40 larger than the current size. In terms of detector area, this corresponds to a size of just over 3000 cm^2 , or a sensor scale size of greater than 55 cm on a side.

5. Three-Dimensional Transport Modeling to Estimate Hydrogen Sensitivity

5.1. Description of three-dimensional modeling technique

In contrast to the analytic approximation technique described in Section 2, another way to estimate counting rates of orbital neutron detectors is to develop and run a full three-dimensional simulation of the entire neutron creation, transport, and detection processes. Feldman *et al.* (1989) derived a general expression for the neutron counting rate, b , as measured by a neutron sensor in orbit about a planet:

$$b = \frac{1}{2\pi} \int d\varphi_H \int d\mu_H \int dK_H \frac{\mathbf{V}_T \cdot \hat{\mathbf{n}}}{|\mathbf{V}_H|} A \varepsilon(K_D, \mu_D, \varphi_D) \Phi(K_H, \mu_H, \varphi_H) \quad (23)$$

TABLE 3. LIST OF PARAMETERS USED FOR THE APPLICATION OF THE SNSA TECHNIQUE TO THE LEND INSTRUMENT

Parameter	Value	Remarks
$b_{\text{FOV}}(0,0)$	0.18 counts per second	Use modeled value (Section 4.1.1)
τ	6700, 900, 500 seconds	Values from Table 2 for 90°, 87°, and 85° latitude
f_{back}	0.33	Value from instrument modeling. Value from Mitrofanov <i>et al.</i> (2008) would be $f_{\text{back}} = 0.57$. (Section 4.1.3)
f_{epi}	0.54	Assumes a 10 km diameter feature within the LEND FOV (Section 4.1.4)

Here, $\mathbf{V}_T = \mathbf{V}_S + \mathbf{V}_H$ is the total neutron velocity in the spacecraft frame of reference, $\mathbf{V}_S$ is the spacecraft velocity, $\mathbf{V}_H$ is the neutron velocity at orbit altitude H , $A\epsilon$ is the area (A) efficiency (ϵ) response of the neutron sensor evaluated at neutron kinetic energy K_D and angles ϕ_D and θ_D relative to the neutron sensor, and $\hat{n}$ is the unit vector normal to the neutron sensor. Φ is the energy- and angle-dependent surface neutron flux as transported to an orbital altitude H . The total counting rate is an integral over the polar ($\mu_H = \cos\theta_H$) and azimuthal (ϕ_H) angles, and neutron energy K_H at orbit.

To evaluate this integral properly, Feldman *et al.* (1989) derived various analytic expressions that account for (i) the neutron transport from the planetary surface to orbit, (ii) how gravity and the finite neutron lifetime affect that transport, and (iii) how the neutron velocity and sensor orientation affect the total neutron counting rate. Applications of this general integral for neutron data of the Moon (Elphic *et al.*, 2001, 2004; Lawrence *et al.*, 2002, 2006), Mars (*e.g.*, Prettyman *et al.*, 2004), and Mercury (Lawrence *et al.*, 2009) have been reported. A GCR-induced surface neutron flux is calculated by using the particle transport code MCNPX (Pelowitz, 2005). Figure 1 shows examples of neutron fluxes for a lunar FAN composition with varying amounts of added hydrogen. As reported by Lawrence *et al.* (2006), the polar angle dependencies of Φ have been shown to have a $\sqrt{\cos\theta}$ dependence for a large range of neutron energies; this polar angle dependence has been included in this model. It is generally assumed that Φ is azimuthally symmetric.

The neutron sensor response was calculated via MCNPX. Feldman *et al.* (2002b) gave an example of a response function calculation for the Mars Odyssey NS; Lawrence *et al.* (2002) gave an example of a sensor response calculation for the LP-NS sensors. In regard to lunar measurements, Elphic *et al.* (2001) described how these counting rates were determined for LP neutron measurements. Lawrence *et al.* (2002, 2006) used these calculations for model-based estimates of

LP neutron counting rates. In particular, the model absolute counting rates of Lawrence *et al.* (2006) agreed to within 10% of the measured counting rates, which validates the general model described here.

5.2. Application of three-dimensional modeling technique to lunar poles

For this study, the same techniques described in Elphic *et al.* (2001, 2004) and Lawrence *et al.* (2002, 2006) were used to evaluate the performance of the LEND sensor. For this model calculation, a simulated 300×300 km deposit field (Fig. 14) poleward of 85° at the Moon, having pixel sizes of 2×2 km, is used to evaluate the performance of a LEND-type detector. The “water deposit” regions have varying sizes from 5 to 20 km on a side in order to span the expected sizes of the larger hydrogen deposits near the lunar poles. The hydrogen value of 1 wt % WEH was chosen to reflect the current best estimate of lunar polar hydrogen abundances based on spatially deconvolved LP-NS data (Elphic *et al.*, 2007). In addition, 1 wt % WEH is over an order of magnitude larger than the quoted sensitivity for the LEND instrument for a 10 km diameter-sized region near the lunar pole (Chin *et al.*, 2007; Mitrofanov *et al.*, 2008). A detection should be clearly seen if the sensitivity estimates of Mitrofanov *et al.* (2008) are correct. Finally, the deposits are placed at varying distances from the lunar poles in order to see how detection sensitivity varies for different collection times (*e.g.*, see Fig. 10 for collection times).

To reflect a true measurement, we used LP exposure times for its 30 km altitude orbit mission phase and scaled those times to one year, which is the nominal duration for the prime LRO mission. The modeled altitude was also set to the expected LRO orbital altitude of 50 km instead of the 30 km LP orbit. Poisson uncertainties were added to the modeled counting rates to reflect the statistical uncertainties that are encountered in a real measurement.

TABLE 4. HYDROGEN SENSITIVITY LIMITS FOR 10×10 KM SIZED PIXELS AS A FUNCTION OF LATITUDE FOR THIS STUDY AND FOR ANALYSES BY CHIN *ET AL.* (2007) AND MITROFANOV *ET AL.* (2008)

Latitude	Hydrogen sensitivity, this study (ppm)	Hydrogen sensitivity, LEND team (ppm)	S_n of 100 ppm detection on 10×10 km pixel
90°	850	80	0.480
89°	1444	82.5	0.342
88°	3445	—	0.227
87°	8998	279	0.176
86°	32584	—	0.153
85°	No detection	726	0.131

The fourth column gives the signal-to-noise for a 100 ppm detection on a 10×10 km sized pixel based on Eq. 13.

FIG. 13. Water-equivalent hydrogen (WEH) sensitivity as a function of collimated neutron sensor geometric factor for a 10×10 km sized pixel. The three solid lines show the sensitivity for a 1-year polar mission at three different latitudes of 90° , 87° , and 85° . The LEND geometry factor of $10.9 \text{ cm}^2 \text{ Sr}$ is shown as a vertical line in the figure. If f_{epi} had a value of 0, then the dashed line shows the calculated sensitivity for 90° latitude. The horizontal, solid line shows the sensitivity limit for 1 wt % WEH.

Figure 15 shows the simulated raw counting rate for the LEND simulation after a 1-year nominal mission. The map is clearly noisy, and very little spatial contrast is seen. Orbital neutron data, however, are typically smoothed to enhance the signal-to-noise. Thus, Fig. 15b shows the results of Fig. 15a after a two-dimensional, Gaussian smooth has been applied. There is still significant noise in the map, but there do appear to be detections of larger deposits near the pole where counting times are the largest. To help better delineate deposit detections, Fig. 15c shows the map of 15b in units of signal-to-noise. Locations of 3σ detections are shown by the green contours (the same contours are shown in Fig. 15b). As seen, there are no statistically significant observations of 5 km and 10 km hydrous deposits. Only the most poleward 15 and 20 km features show significant detections. These results are consistent with the results from the analytic calculation of Section 4, which showed a 3σ detection limit of 850 ppm for a 10 km diameter-sized deposit near the pole. Further, the results of Fig. 15 are not consistent with a sub-100 ppm detection sensitivity, as claimed by Chin *et al.* (2007) and Mitrofanov *et al.* (2008). We therefore now have two different techniques that point to a significant discrepancy with the results of Chin *et al.* (2007) and Mitrofanov *et al.* (2008).

6. Discussion and Conclusions

6.1. Discussion

When the results from the two different techniques presented in Section 4 and 5 are compared, the results are similar and consistent. Furthermore, this agreement strongly supports the validity of the SNSA framework since the general three-dimensional modeling technique has been validated when using LP-NS data (*e.g.*, Lawrence *et al.*, 2006). Second, the SNSA technique provides for straightforward

FIG. 14. Simulated deposit field poleward of 85° . The squares show simulated locations of hydrated regions having 1 wt % WEH within a lunar FAN material. The regions outside the squares are a FAN material. The size of the squares are 5, 10, 15, and 20 km. The circle shows the location of 85° latitude.

scaling relationships (*e.g.*, Fig. 13), which are fundamentally sound because of its validation with LP neutron data as well as a good agreement between the SNSA and three-dimensional modeling techniques. Finally, both the SNSA and the full three-dimensional simulations show significant discrepancies with Chin *et al.* (2007) and Mitrofanov *et al.* (2008), in particular that the sensitivity of LEND is over an order of magnitude poorer than claimed.

Possible sources of discrepancy between the results presented here and the values cited in Chin *et al.* (2007) and Mitrofanov *et al.* (2008) include the following: (1) assumptions about counting time; (2) estimates of FOV counting rates; (3) treatment of the epithermal neutron background; and (4) treatment of the fast neutron background. We discuss each of these items in sequence.

In regard to counting time, we found a significant discrepancy of over a factor of 4 for the 90° latitude value that occurs at a singularity. Mitrofanov *et al.* (2008) did not give assumed counting times for lower latitudes, so it is possible that the discrepancy between assumed counting times may persist for lower latitudes as well. If the assumed counting times from Fig. 10 are increased by a factor of 4, the sensitivity at 90° latitude will be reduced to $\sim 0.3 \text{ wt } \%$ (or 330 ppm H), which narrows, but does not eliminate, the discrepancy.

Regarding $b_{\text{FOV}}(0,0)$, the results derived in Section 4.1.1 differ by up to a factor of 5 with the values of $b_{\text{FOV}}(0,0)$ cited in Mitrofanov *et al.* (2008). We further note that, since the value of $b_{\text{FOV}}(0,0)$ is used in both the SNSA and full three-dimensional modeling techniques, errors in our estimate of $b_{\text{FOV}}(0,0)$ would affect both these techniques equally. To see how the range of $b_{\text{FOV}}(0,0)$ values affects sensitivity, in the context of SNSA, we assume that $b_{\text{FOV}}(0,0)$ scales as detector area, which in turn scales as geometry factor, G , when the solid angle remains fixed. If the LEND geometric factor is scaled by a factor of 5 to account for a factor 5 higher $b_{\text{FOV}}(0,0)$ cited in Mitrofanov *et al.* (2008), the WEH sensi-

FIG. 15. (a) Raw simulated counting rate for 1 year of LEND data collection over the simulated deposit field of Fig. 14. (b) Smoothed counting rate from the simulated data of Fig. 15a. (c) Smoothed map of Fig. 15b converted into units of signal-to-noise. The green contours represent a signal-to-noise of 3.

tivity lowers to 0.27 wt % (or 300 ppm H) for 90° latitudes as shown in Fig. 10. If an assumed increased counting time is combined with an assumed increased counting rate, the 90° sensitivity decreases to 0.13 wt % (or 140 ppm H), which is still almost a factor of 2 larger than the values given by Mitrofanov *et al.* (2008).

In regard to the treatment of the epithermal neutron background, the dashed line in Fig. 13 shows a calculation of WEH sensitivity if the epithermal neutron background is neglected (*i.e.*, if $f_{\text{epi}} = 0$). A value of $f_{\text{epi}} = 0$ occurs if a hydrated deposit completely fills the FOV. If this effect were neglected, then the sensitivity would be reduced to 0.34 wt % WEH (380 ppm H), which by itself is not enough to resolve the discrepancy. However, if $f_{\text{epi}} = 0$, $b_{\text{FOV}}(0,0) = 0.9$ cps, and the counting times were a factor of 4 larger, the WEH sensitivity would be reduced to 0.058 wt % WEH (64 ppm H), which is lower than the value given by Mitrofanov *et al.* (2008).

Finally, we address the discrepancy in background fast neutrons that was estimated here as a value of 2 for the fast neutron-to-FOV signal-to-noise, which is significantly higher than the value of 0.75 in Mitrofanov *et al.* (2008). If a value of 0.75 is correct, then $f_{\text{back}} = 0.57$, and the hydrogen sensitivity would increase to 1.1 wt % (1200 ppm H) at the pole, which would result in a larger discrepancy between the sensitivity estimate of this study and the estimate of Mitrofanov *et al.* (2008).

In summary, the discussion above shows that three possible reasons for the sensitivity discrepancies may be different treatments of τ , $b_{\text{FOV}}(0,0)$ and f_{epi} . However, as described in Section 4.1.2, it is clear that the counting times given in Fig. 10 and Table 2 are almost certainly close to the times that will be obtained with the LRO mission. As discussed in Section 4.1.1, the agreement between the simple scaling estimate developed here and the full three-dimensional Monte Carlo simulations validated with LP data indicate that the value of $b_{\text{FOV}}(0,0)$ estimated by using these techniques is likely to be valid. Finally, it is clear, based on simple geometric reasoning (*e.g.*, Fig. 3 and Fig. 9), that the epithermal neutron background cannot be ignored. We therefore conclude that the WEH sensitivity estimates cited in Chin *et al.* (2007) and Mitrofanov *et al.* (2008) are substantially poorer than claimed.

As a final discussion point, we now consider what size neutron spectrometer would be appropriate for making spatially resolved neutron measurements of the lunar polar hydrogen deposits. Based on the most recent spatial deconvolution analysis of LP-NS data (Elphic *et al.*, 2007), probable values of WEH abundances in small regions (<10 km diameter) are ~ 1 wt %. We therefore adopt 1 wt % as a reasonable value for a WEH sensitivity target. Since the deconvolution analyses of Elphic *et al.* (2007) did not give unique results, the true abundances and locations of

hydrogen deposits are not currently known. Therefore, new spatially resolved measurements of polar hydrogen with a sensitivity of 1 wt % over most of the lunar polar regions (*i.e.*, poleward of 85°) would be a significant improvement over existing measurements. We note that, based on our analysis, the current LEND design can, at best, achieve sub-1 wt % sensitivity very near the pole but will miss this sensitivity target at its designed spatial resolution for most of the near-polar regions where polar hydrogen deposits have been observed (Feldman *et al.*, 2000a; Lawrence *et al.*, 2006).

If it is assumed that a collimated instrument has the same solid angle as the LEND instrument (to achieve the same spatial resolution at 50 km altitude), the required geometric factor to obtain 1 wt % WEH sensitivity poleward of 85° is $\sim 100 \text{ cm}^2 \text{ Sr}$. This is almost a factor of 10 larger than the LEND geometric factor. While this is a substantially larger geometric factor than LEND, an instrument can be designed in a straightforward manner with 8 ^3He neutron sensors, each with the same size as one LP ^3He sensor, which has an area of 114 cm^2 (Feldman *et al.*, 2004). Further, these sensors could be placed behind a neutron collimator where a total instrument mass would be comparable to the targeted mass (25 kg) of the LEND instrument (Mitrofanov *et al.*, 2005). Variations in mission scenarios, available instrument resources, and specific scientific requirements would, of course, drive the detailed instrument design. Therefore, while our analysis indicates that only a substantially larger instrument could achieve 10 km spatial resolution and 100 ppm H sensitivity, a reasonably sized collimated neutron instrument could be built that still provides dramatically new information about the lunar polar hydrogen deposits.

6.2. Conclusions

In this paper, we have derived and validated the SNASA analytic technique, using basic instrument design parameters for calculating hydrogen sensitivity of a collimated neutron sensor. SNASA enables accurate, rapid assessment of spatially resolved neutron sensor performance and can directly facilitate evaluation of design trade studies to optimize performance. The technique is easily generalized and applied to spatially resolved fast neutron, thermal neutron, and gamma-ray measurements. We further showed that the SNASA results are comparable to the results of a three-dimensional modeling technique that has been validated with LP orbital neutron data.

SNASA additionally allows straightforward scaling calculations to be carried out in order to make comparisons of instrument performance for various mission and measurement scenarios. We specifically compared our results to the hydrogen sensitivity claims of the LEND instrument on NASA's LRO mission. We found that the LEND sensitivity performance is over an order of magnitude poorer than claimed. Our analysis showed that a sensitivity of 1 wt % WEH at 10 km spatial resolution can be achieved for all locations poleward of 85° for an instrument with a geometry factor of $\sim 100 \text{ cm}^2 \text{ Sr}$.

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Abbreviations

cps, counts per second; CSR, Clementine spectral reflectance; FAN, ferroan anorthosite; FOV, field of view; FWF, full-width, full maximum; GCR, galactic cosmic rays; LEND, Lunar Exploration Neutron Detector; LP, Lunar Prospector; LP-NS, Lunar Prospector Neutron Spectrometer; LRO, Lunar Reconnaissance Orbiter; NS, Neutron Spectrometer; SNASA, Spatially resolved Neutron Analytic Sensitivity Approximation; WEH, water-equivalent hydrogen.

Reply to the release of new information from Mitrofanov *et al.* (2009a, 2009b) and McClanahan *et al.* (2010) in regard to the results of "Performance of Orbital Neutron Instruments for Spatially Resolved Hydrogen Measurements of Airless Planetary Bodies"

Since the original submission of this paper in June 2009, two releases of information relevant to the results of this paper have occurred. The first is a detailed description of the LEND instrument (Mitrofanov *et al.*, 2009a). After reviewing Mitrofanov *et al.* (2009a), we found no new information to change the conclusions of our study. A few minor replies are as follows: (1) The density of the neutron-absorbing ^{10}B material in the final LEND instrument was 1 g/cm^3 , whereas we assumed 2.5 g/cm^3 . Thus, the background rejection from the ^{10}B in the LEND flight instrument will be worse than in our analysis. (2) Final dimensions of the LEND epithermal neutron collimator are given in Mitrofanov *et al.* (2009a) and are very close to our assumed dimensions (Fig. 7). (3) Mitrofanov *et al.* (2009a) showed a comparison of the measured and modeled angular response of the epithermal neutron collimator, which is similar to our Fig. 9. However, Mitrofanov *et al.* (2009a) did not show the measured or modeled response at angles greater than 20° away from the nadir direction. These wide angles are critical for understanding the fast neutron background, which our analysis indicated is a key driver for statistically significant spatial resolution.

The second release of information from the LEND team provides initial results of flight data (Mitrofanov *et al.*, 2009b; McClanahan *et al.*, 2010), where the integral LEND epithermal neutron count rates in orbit about the Moon are reported to be 5 cps. Based on the discussion in Section 4.1, our analysis showed that the count rate for collimated neutrons from the lunar surface is likely in the range of 0.15–0.18 cps. Rounding up to 0.2 cps, the implied background count rate is 4.8 cps, which yields a collimated signal to isotropic background ratio of 0.04 and $f_{\text{back}} = 0.96$. When this value of f_{back} is used in Eq. 14, the SNASA technique implies that there is no statistically significant detection of collimated neutrons from the lunar surface of any features <10 km diameter for any hydrogen abundance at any latitude.

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Address correspondence to:

David J. Lawrence

MP3-E169

Johns Hopkins University Applied Physics Laboratory

11100 Johns Hopkins Road

Laurel, MD 20723

E-mail: David.J.Lawrence@jhuapl.edu

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