High-resolution mapping of lunar polar hydrogen with a low-resource orbital mission

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Abstract
Lunar permanently shaded regions (PSRs) are unique solar-system environments. Their low temperatures (<100 K) facilitate cold trapping of volatile materials over timescales comparable to the lifetime of the solar system. While much has been learned about these regions from orbital spacecraft, important missing information includes the spatial and depth-dependent distribution of bulk hydrogen concentrations in and around PSRs. We present two complementary mission scenarios where orbital neutron spectroscopy will provide significantly improved understanding of lunar polar bulk hydrogen concentrations. In the first mission concept, a six-month orbital mission will measure bulk hydrogen concentrations with sensitivity better than 50 ppm and a spatial resolution of order 20 km over the entire lunar South Polar region (poleward of 80ºS). Spatial reconstruction analyses of the returned data will improve the final spatial resolution to better than 10 km. The presence and burial depth (<25 cm) of subsurface deposits will be quantified with latitude-dependent sensitivities ranging from 50 to 350 ppm. The second concept envisions a few, very low altitude (<24 km) flyovers of one or more PSRs to quantify the hydrogen concentrations and spatial heterogeneities with a hydrogen sensitivity less than 200 and spatial scale size of 5 km. Both concepts can be combined in a single mission where full-coverage polar measurements are made with a hydrogen spatial resolution of 20 km, and higher spatial resolution measurements are made for a few strategically selected PSRs at the end of the mission.

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1. Introduction

Permanently shaded regions (PSRs) are unique and fascinating solar system environments. The type locations for PSRs are craters located at both poles of the Moon and Mercury. The interiors of these craters are not directly illuminated by sunlight and consequently maintain temperatures <100 K for geologically long periods of time.

One of the most important aspects of PSRs is that they serve as cold traps for volatiles, including water. Predictions dating back to the 1960s and 1970s proposed that lunar PSRs would have enhanced water concentrations [1,2]. Subsequent spacecraft and Earth-based measurements using various techniques (radar, neutron spectroscopy, spectral reflectance) have provided abundant evidence to support these predictions at both the Moon and Mercury [3–7]. The characteristics of PSRs and the processes that take place within them have implications for a variety of topics such as the origin and history of solar...
system volatiles [8], synthesis of organic materials [9], and in-situ resources for human exploration.

Despite being the subject of intensive Earth and spacecraft-based observations, many aspects of PSRs remain a mystery. Observations at Mercury show that there are significant amounts of water ice and other volatiles that are closely correlated with spatial and depth locations of volatile thermal stability [6,7,10–12]. In contrast, the spatial distribution and depth dependence of lunar polar hydrogen concentrations are not well correlated with locations of volatile thermal stability. For example, while surface frost has been observed in most lunar PSRs [13], bulk hydrogen concentrations do not appear to be uniformly enhanced within PSRs [14,15], and are not well correlated with locations of volatile stability expected by surface and subsurface temperatures in polar regions [16]. This qualitative difference between the lunar and mercurian PSRs, despite their similar environmental conditions (e.g., temperature, temporal stability), is not understood. Possible reasons for this Moon/Mercury PSR discrepancy are likely related to various volatile retention/removal processes, as well as volatile delivery sources and mechanisms.

Improved knowledge of the spatial and depth distribution of hydrogen concentrations would significantly advance our understanding of the processes and delivery sources. Specifically, the spatial distribution of hydrogen concentrations needs to be known at a spatial scale that is at least as small as the PSRs themselves. Such data could help determine if the source delivery mechanisms have occurred over a long time scale (e.g., via solar wind) and/or if volatiles were delivered through episodic events like cometary impact(s) [17]. Knowledge of the hydrogen concentration inside and outside PSRs will provide observational constraints to understand what environmental effects (e.g., surface and/or subsurface temperature) are strongly related to the current hydrogen distribution. Knowledge of the hydrogen burial to depths of tens of cm at a similar spatial scale can provide additional key constraints on various delivery and retention processes and time scales [18].

One of the best techniques for remotely measuring bulk hydrogen concentrations on planetary surfaces is neutron spectroscopy. Neutron spectroscopy is highly sensitive to low hydrogen concentrations, and is therefore well suited for making such measurements at the Moon. While various attempts have been made to improve our knowledge of the hydrogen spatial distribution on the Moon (e.g., [14,15,19]), there remain significant uncertainties regarding the spatial distribution at scales of <50 km (e.g., [20–23]). In addition, very little is known about hydrogen burial within PSRs except broad burial depth limits [24] and some spatial information of burial depths near the Moon’s South Pole [18].

The topic of this study is to present two variants of a low-resource orbital mission concept that can achieve significant improvements in our knowledge of the lunar polar hydrogen distribution. A better knowledge of the polar hydrogen spatial and depth distribution will provide key input to studies of PSR volatile processes by isolating individual craters that host enhanced hydrogen concentrations. In addition, data from such a mission will be valuable for future landed missions that seek to target landing sites with volatile enhancements [25].

2. Planetary neutron spectroscopy and lunar polar hydrogen measurements

Planetary neutron spectroscopy is the standard technique for quantifying hydrogen concentrations on planetary surfaces [26]. Neutrons are created by nuclear spallation reactions when high-energy cosmic rays strike the surface of an airless or nearly airless planetary body. The energies ($E_n$) of the resulting neutrons are typically divided into three ranges of fast ($E_n > 0.5$ MeV), epithermal ($0.5$ eV $< E_n < 0.5$ MeV) and thermal ($E_n < 0.5$ eV) neutrons. Hydrogen is uniquely suited for moderating neutrons due to its comparable mass, which allows a highly efficient momentum transfer during elastic collisions. This causes the number of epithermal neutrons to be strongly reduced where hydrogen is present, such that epithermal neutron flux measurements provide a highly sensitive measure of a soil’s hydrogen content. Fast-neutron fluxes are also sensitive to the hydrogen content in a planetary soil, but because their effective penetration depth differs from that of epithermal neutrons, comparisons of fast and epithermal neutron measurements can provide information about the burial depth of hydrogen enhancements [7,18].

Polar hydrogen enhancements were first measured on the Moon using the Lunar Prospector Neutron Spectrometer (LP-NS) [3]. The LP-NS was an omnidirectional detector whose spatial resolution of ~45 km (obtained at an altitude of 30 km; [27]) was sufficiently broad that hydrogen enhancements within specific PSRs could not be resolved. Nevertheless, Lunar Prospector (LP) measurements of epithermal and fast neutrons have been used to show that bulk hydrogen enhancements in Shackleton crater at the Moon’s south pole likely reach to the surface [18], which is in contrast to other polar regions where the hydrogen enhancements are likely buried by tens of cm of drier material [24].

Higher spatial resolution information was obtained from LP-NS data using spatial reconstruction analyses. These analyses remove the smoothing effects of the LP-NS spatial response to the limits allowed by the statistical uncertainties of the data [14,19,28]. These types of spatial reconstruction analyses have been conducted with a variety of datasets, including astrophysical observations [29], as well as other planetary neutron and gamma-ray measurements of Mars and the Moon [30,31]. For the lunar polar neutron data, an additional physical constraint – the amount of allowed hydrogen as a function of permanent shade – was coupled to the reconstruction analyses to provide more robust and physically reasonable results. These studies demonstrated that the measured LP-NS data are consistent with a hypothesis in which hydrogen is enhanced in some PSRs, but not uniformly across all PSRs [14,19,28].

To obtain higher spatial resolution measurements, the Lunar Reconnaissance Orbiter spacecraft carried a collimated neutron detector known as the Lunar Exploration Neutron Detector (LEND), which had the goal of quantifying hydrogen concentrations at a spatial resolution...
3. Lunar PLANe mission concept

In this section, we describe the requirements and basic details of a mission concept called the Lunar Polar Low-Altitude Neutron Experiment (PLANe). This mission can be accomplished with various implementations, so specific details are not discussed. However, for any implementation, the required mission and instrumentation resources are sufficiently low that a small spacecraft can satisfy the requirements. The Lunar PLANe mission has only a few driving requirements: types of neutron measurements, required sensitivity and accumulation time, and the mean altitude required to achieve the desired spatial resolution.

To accomplish the primary hydrogen concentration measurement, the detection and quantification of epithermal neutrons are required. Information about hydrogen burial is accomplished with the detection and quantification of fast neutrons. For this study, our baseline neutron sensor is a borated plastic (BP) scintillator. BP has extensive spaceflight heritage, including on the LP, Mars Odyssey (MO), Dawn, and MESSENGER missions [39–42]. We baseline a BP sensor that has similar characteristics to the MESSENGER Neutron Spectrometer (NS; Fig. 1a), which provided robust measurements of both epithermal and fast neutrons around Mercury [7]. The BP portion of the MESSENGER NS is a 10 cm × 10 cm × 10 cm cube of borated plastic read out by a 51-mm photomultiplier tube (PMT). The full NS included two lithium glass scintillators and PMTs, and had a mass of 4.9 kg. The Lunar PLANe BP-only sensor (Fig. 1b) and associated electronics would have lower mass and power requirements than the MESSENGER NS. The sensor size can be easily scaled up or down to accommodate different mission/spacecraft parameters.

Because the uncertainties of planetary neutron measurements are limited by statistical uncertainties, the sensitivity and accumulation time requirements are coupled parameters. Larger detectors provide higher neutron count rates and can reach the required spatial resolution and hydrogen concentration sensitivities in shorter times. However, larger (or multiple) detectors require more spacecraft resources (mass, volume, and power), which can increase other mission resource requirements. Based on experience from prior missions as well as expectations from future missions, reasonable mission durations for a lunar orbital spacecraft are on the order of six months to a year. Both LP and MESSENGER demonstrated the ability to make robust polar hydrogen measurements in this amount of time. Therefore, the sensor size used for MESSENGER is a good candidate size for the Lunar PLANe mission concept.

The final driving requirement is the required mean altitude that enables the high spatial resolution measurement. Ideally, low-altitude measurements of both lunar poles would be made from a polar orbit with a single mission. However, because of the non-uniform lunar gravity field, such an orbit would require significant maintenance, which in turn significantly increases the
spacecraft propulsion and operational resources. In contrast, achieving low altitudes over just one pole via an elliptical orbit provides an inherently more stable orbit that requires significantly less maintenance. Since the South Pole contains some of the largest PSRs, we have therefore chosen an elliptical orbit with a periapsis at the Moon’s South Pole.

The altitude requirement is driven by the need to make measurements that spatially resolve hydrogen concentrations within the largest PSRs. The largest South Pole PSRs have diameters ranging from 20 to 40 km. To spatially resolve the hydrogen within these locations, we need an improvement by a factor of 1.5–2 from the spatial resolution of 45 km obtained by LP [27]. This leads to the requirement for a mean altitude of 15–20 km over the primary PSRs at the South Pole. Improved spatial knowledge of the hydrogen concentration by additional factors of at least 1.5–2 can be obtained through the type of spatial reconstruction algorithms that have been used on prior orbital neutron and gamma-ray data (see [43]). Thus, ultimate spatial resolutions smaller than 10 km can be obtained.

We finally note that this mission concept assumes a multi-month mission duration for which high statistical precision measurements across the entire pole can be derived. However, this multi-month duration requirement limits the lowest altitude that can be obtained. A complementary mission concept that can obtain higher spatial resolution measurements through even lower altitudes, but at the potential cost of lower precision, is to use a large-area detector for a small number of very-low altitude polar passes. We investigate this mission concept in Section 6.

4. Orbit plan for lunar PLANE concept

To illustrate the mission proof-of-concept, we have designed a lunar orbit profile that meets the requirements for <25-km-altitude flyovers of the South Pole and mission duration of at least six months. To carry out the calculations of an example trajectory, we use the following assumptions and boundary conditions: 1) the Earth–Moon transfer is accomplished using a standard Hohmann-like transfer; and 2) the spacecraft is dropped off in a 100 km altitude circular polar orbit and additional propulsion is used to place the spacecraft in a 20 km by 200 km polar orbit with periapsis at the South Pole. For simplicity, we assume impulsive maneuvers that are achievable with standard chemical propulsion with the understanding that higher-efficiency systems (e.g., solar electric) may achieve better performance at the expense of additional trajectory and mission operations complexity. The lunar gravity field is modeled using a 50 × 50 gravity model, which compares well with the high-resolution 100 × 100 and 160 × 160 models. Earth and Sun perturbations are explicitly included. A lunar South Pole terrain map is used for altitude calculations. Finally, station keeping is accomplished using single maneuvers, which are assumed to be instantaneous. Views of the orbit trajectory are shown in Fig. 2, where Fig. 2a shows the Earth–Moon transfer, and Fig. 2b shows the portions of the low-altitude passes less than 20 km as seen on a map of the lunar South Pole. The ΔV required to enter the final orbit is around 900 m/s, which is similar to other previous lunar polar orbital missions (e.g., [44]).

To better understand the ΔV and maneuver requirements for different orbit altitudes, we carried out a study where we varied the upper and lower-altitude boundaries that control the station keeping maneuvers. We used three cases where the boundary altitudes were 10 and 25 km, 10 and 20 km, and 13 and 17 km. Table 1 lists these cases along with the respective cumulative station keeping usage, the number of required maneuvers, and the number of days between maneuvers. The most restrictive case (bounding altitudes of 13 km by 17 km) is incompatible with the operations for a low-resource mission, as it would require a maneuver cadence of less than one day. Even the medium boundary case (10 km by 20 km) requires maneuvers with a cadence of less than three days. For this study, we have therefore adopted the 10 km by 25 km altitude bounding case, which needs a station-keeping maneuver roughly every five days, and has a total station-keeping ΔV requirement of ~50 m/s.

Once in orbit, the ideal operational scenario is for the spacecraft to be nadir pointed, which provides a constant...
viewing geometry that minimizes the need for viewing geometry corrections to the neutron measurements. However, nadir pointing is not required as corrections for non-constant viewing geometries have been accomplished in similar mission scenarios [7,27]. Nevertheless, in such scenarios, knowledge of the full spacecraft attitude is required.

Altitude values for the example trajectory are shown in Figs. 3 and 4. Fig. 3 shows all altitudes poleward of 80ºS versus time for the 180-day mission trajectory. These altitudes poleward of 80ºS are shown as a histogram in Fig. 4, where analogous altitudes from the LP mission are also shown. The mean altitude for the Lunar PLANE mission is 18 km with an altitude spread (25th to 75th percentile) of 5 km. In contrast, the LP mission has a mean altitude of 33 km with a larger altitude spread of 12 km.

5. Performance estimates for lunar PLANE mission concept

We estimate the performance of the Lunar PLANE concept using two complementary techniques. The first technique uses a semi-analytic statistical-significance approach that was developed and used by Miller [45] and Miller et al. [18,35] for planetary neutron data. The second technique uses a full mission simulation, which was developed for the analysis of MESSENGER NS data [7,46].

The statistical-significance technique compares neutron count-rate decreases due to enhanced polar hydrogen to count-rate values in non-polar, non-hydrogen-rich regions. Specifically, for a given pixel size and associated accumulation time, this technique quantifies the count-rate decrease that can be measured with a given statistical significance. The dominant source of measurement uncertainties is assumed to be the Poisson statistics. The hydrogen sensitivity is derived using counts-to-concentration relationships given by Feldman et al. [3] and Lawrence et al. [24].

To obtain the expected accumulation times and total counts across the South Pole, we use the six-month trajectory discussed in Section 3 combined with the instrument response for the MESSENGER NS [7]. For the purpose of this study, we require a single-pixel statistical significance that has the Poisson-statistics equivalent of three sigma. Contours of surface hydrogen sensitivity are shown in Fig. 5 for epithermal and fast neutrons. Contours of hydrogen sensitivity for buried hydrogen based on fast neutron measurements are shown in Fig. 6. The epithermal neutron sensitivities are shown for pixel sizes of 15 km and the fast neutron sensitivities are shown for pixel sizes of 30 km.

Figs. 5 and 6 illustrate a few key points. First, for pixel sizes (15 km) smaller than the altitude-limited spatial footprint, hydrogen sensitivities of < 50 ppm are achieved across the entire pole using epithermal neutrons. Thus, the primary factor that will affect spatial resolution is the distribution of spacecraft altitudes. In addition, these excellent statistical precisions will enable robust spatial deconvolution studies to be carried out as has been done for other high-statistics datasets (e.g., [43]). Second, the fast neutron sensitivities provide a guide for how well the hydrogen-burial measurements can be accomplished. Because the fast neutron count rate is over a factor of six lower than the epithermal neutron count rate ([7]), the fast neutron results in Fig. 5b and Fig. 6 use a pixel size that is four times larger in area than for epithermal neutrons. These figures show that the fast-neutron-derived concentration sensitivity is roughly a factor of six larger than that for epithermal neutrons. However, even with these sensitivities ( < 350 ppm H for regions poleward of 80ºS), we could detect and quantify surface expressions of hydrogen with a sensitivity that is a factor of four better than the surface hydrogen that was reported present at Shackleton crater ([18]). Finally, Fig. 6 shows the sensitivity of hydrogen-rich layers buried under hydrogen-poor layers that are 10 and 20 cm thick. As seen, for all cases we can detect buried hydrogen concentrations...
greater than 350 ppm. As an example, this type of performance would easily allow the quantification of hydrogen concentrations of the type reported in Cabeus crater by LCROSS (3–10 wt%) under tens of cm of dry soil [4].

For the second complementary technique to assess the Lunar PLANE performance, we have carried out a full mission simulation using a hypothetical hydrogen spatial distribution to demonstrate the type of hydrogen concentration map that would be returned by the mission. For this technique, we use neutron transport modeling tools described by Lawrence et al. [7,46] and derive a time-series count rate for a nominal six-month mission using the trajectory described in the prior section. For each accumulation-time interval, randomized uncertainties account for the Poisson statistics. We assume that all time-dependent corrections have been properly carried out (e.g., variable viewing geometry and instrument parameters, variable cosmic rays, etc.; [27]). The simulated time series count rate is then mapped on the lunar surface in an identical manner to what is done for measured data. Because the phase space for variable burial depths is quite large, here we only assess the ability of the simulated measurements to spatially resolve hydrogen within PSRs.

To complete the simulation, we assume a model hydrogen spatial distribution. For this assumed distribution, we use the spatially reconstructed neutron count rate map of Teodoro et al. [23]. This map (Fig. 7) was derived using the Pixon spatial-deconvolution technique, and had additional constraints that allowed larger hydrogen concentrations inside PSRs compared to concentrations outside PSRs. This map is directly constrained by the LP data such that when it is smoothed by the LP spatial footprint, the resulting

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**Fig. 5.** Hydrogen concentration limits for a 180-day Lunar PLANE mission mapped on regions poleward of 80°S. (a) Concentration limits for hydrogen extending to the surface based on epithermal neutrons. Limits are derived for pixels with a size of 15 km. The red contour corresponds to 30 ppm. (b) Concentration limits for hydrogen extending to the surface based on fast neutrons. Limits are derived for pixels with a size of 30 km. The red contour corresponds to 200 ppm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

**Fig. 6.** Hydrogen concentration limits for hydrogen buried under dry lunar soil for a 180-day Lunar PLANE mission mapped on regions poleward of 80°S. (a) Concentration limits for hydrogen buried under 10 cm of dry soil as measured with fast neutrons. (b) Concentration limits for hydrogen buried under 20 cm of dry soil as measured with fast neutrons. In both cases, limits are derived for pixels with a size of 30 km, and the red contour corresponds to 200 ppm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
The map matches the LP-NS data. The locations for four of the largest PSRs are noted on Fig. 7.

Fig. 8 shows the mapped count rates when the time-series count rate is mapped for latitudes poleward of 80ºS. Fig. 8a shows the raw count rate map and Fig. 8b shows a map when the count rate is smoothed with a spatial footprint of 14 km using the techniques of Maurice et al. [27]. Such smoothing is done to dampen the scatter due to the Poisson uncertainties. In both maps, multiple PSRs are clearly spatially resolved.

In contrast to the Lunar PLANE simulation, Fig. 9 shows the measured LP epithermal neutron count rate, both as a raw, unsmoothed map (Fig. 9a) and as a smoothed map with a spatial footprint of 25 km (Fig. 9b). The comparison between the measured LP data and simulated Lunar PLANE data shows that if the hydrogen spatial distribution were

![Fig. 7. Spatially reconstructed map of LP-NS epithermal neutron count rates based on the analysis of Teodoro et al. [42,43]. Locations of prominent PSRs are labeled.](image)

![Fig. 8. Maps of simulated Lunar PLANE epithermal neutron count rates poleward of 80ºS in units of counts per second (cps). (a) Raw, unsmoothed count rates; and (b) smoothed count rates.](image)
what is given by Fig. 7, then the Lunar PLANE data would clearly resolve separate PSRs, whereas the measured LP data do not. Further, the simulated map of Fig. 8 is consistent with the spatial resolution performance described by the statistical-significance technique.

6. Very low altitude, multiple PSR flyover mission scenario

The spacecraft $\Delta V$ requirements ($> 900$ m/s) for the Lunar PLANE orbital mission scenario is sufficiently large that for small spacecraft (e.g., CubeSats), such $\Delta V$ might not be easily obtainable without the Lunar PLANE spacecraft being placed in the proper orbit by a larger spacecraft. In addition, there might be a need to acquire better spatial resolutions than can be obtained from the orbital mission described in Sections 3 and 4. Specifically, while spatial reconstruction of data from the orbital mission could return spatial resolutions better than 10 km, actual measurements with a spatial resolution better than 10 km may be required for some strategic locations. On the basis of these considerations, we investigate the broad requirements for a complementary mission scenario where a NS would make a few, very low altitude ($\sim 5$ km) measurements over one or more polar PSRs. While the $\Delta V$ requirements for such a scenario would likely be significantly lower than for a full orbital mission, determining a detailed mission design is beyond the scope of this study. Rather, using broad bounding conditions, we investigate the mission and instrument parameters that are needed to achieve meaningful measurements with a few low-altitude passes.

Because the neutron measurement is count-rate limited, the primary parameter that drives measurement performance is the sensor effective area (the sensor efficiency times the physical sensing area). Secondary parameters of importance are the spacecraft altitude and velocity. The altitude determines the geometric spatial resolution in the limit of infinite statistics. Spacecraft velocity determines the accumulation time per spatial-resolution element, which constrains the achievable hydrogen sensitivity.

The primary objective of this analysis is the following: given a spacecraft velocity and required spatial resolution element, what sensor effective area is required to make a hydrogen measurement of a given concentration sensitivity? In regards to spacecraft velocity, we assume two bounding conditions of nominal orbital velocity for a two-hour orbital period (1.5 km/s), and a velocity equivalent to the Moon’s escape velocity (2.4 km/s). For the spatial resolution requirement, we want the measurement to clearly quantify if a given large PSR ($> 20$ km diameter) has enhanced hydrogen concentrations, and to quantify the hydrogen spatial heterogeneities, if any exist, across the PSR. To obtain multiple measurements across a PSR, we therefore require a spatial resolution ranging from 5 to 10 km. Finally, in regards to hydrogen sensitivity, reports of inferred PSR hydrogen concentrations range from a few hundred ppm to upwards of a few weight percent water.

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**Fig. 9.** Maps of measured LP-NS epithermal neutron count rates poleward of 80ºS. (a) Raw, unsmoothed count rates; and (b) smoothed count rates.

**Fig. 10.** MESSENGER NS epithermal neutron data versus fraction-of-$2\pi$ solid angle subtended by the planet Mercury on the sensor. These representative data were taken on 28 August 2014. The gray line is fitted to the linear trend and has a slope of 107.9 cps per solid angle and an offset of ~2.6 counts per second.
equivalent hydrogen (WEH) [3,4,14,24,28,34]. Thus our required hydrogen sensitivity requirement is between 200 and 300 ppm.

Because the NS count rate is such a key parameter, its dependence on altitude, or equivalently Moon solid angle, needs to be clearly understood. Fig. 10 shows measured epithermal neutron count rates from the MESSENGER NS as a function of the fraction-of-2π solid angle for a representative day in 2014. The overall trend is due to the solid angle subtended by Mercury onto the NS sensor. Smaller scale variations are due to orientation changes of the MESSENGER spacecraft [7]. When the overall trend is fit with a linear function, we can extrapolate count rates for lower altitudes.

The required count-rate reduction for a given hydrogen concentration, w (given in units of weight fraction WEH), is obtained from the relation of Feldman et al. [3] where w is related to the epithermal neutron count-rate ratio, R, of a wet region to a dry:

\[ R = \frac{C(w)}{C(0)} = \frac{1}{1 + 61w} \]  

Here, C(w) and C(0) are the epithermal neutron count rates in wet and dry regions, respectively. Eq. 1 allows fractional count rate changes to be determined for any specified hydrogen sensitivity. We assume that the dominant source of uncertainties is Poisson statistics, thus the fractional uncertainty, f, for a given measurement is \( f = 1/\sqrt{N} \), where N is the total counts in the measurement of interest. Because the flyby measurements will be a track of multiple values, we require that each measurement for a given spatial resolution element be made with a three-sigma precision. In this case, the fractional measurement precision is required to be \( f = (1 - R)/3 \). This relation determines the required number of total counts for a given hydrogen sensitivity. Finally, the spacecraft velocity fixes the amount of time, \( \tau \), for each spatial resolution element. The total counts can then be expressed by:

\[ N = C_{NS}m\tau, \]  

where \( C_{NS} \) is the count rate for a single NS module, and m is the number NS modules required to achieve the required sensitivity.

The results of the sensitivity calculation are shown in Fig. 11 for the two different bounding spacecraft velocities of 1.5 km/s and 2.4 km/s, where the required number of NS modules is plotted versus hydrogen concentration. This figure shows that for a lunar orbit velocity (1.5 km/s), hydrogen sensitivities of 200 to 300 ppm with spatial resolution sizes on the order of 5–10 km can be achieved with the effective-area equivalent of one to three NS modules. For the faster 2.4 km/s case, 200-ppm hydrogen sensitivity at 5 km altitude requires slightly more than four NS modules, but higher sensitivities and larger footprints can be obtained with fewer than three NS modules. While larger than the nominal MESSENGER NS sensor size (100 cm² sensor area), a sensor with a larger area of 200–400 cm² can still be accommodated within small spacecraft. In particular, a mission with this performance would easily detect and locate a hydrogen enhancement with a concentration greater than 500 ppm and a spatial scale size of 5 km. Such a measurement is sufficiently robust to provide strong constraints on understanding various hypotheses for the processes driving the delivery and retention of polar hydrogen enhancements. Finally, because the fast-neutron count rate is significantly lower than the epithermal neutron count rate [7], the fast neutron flyby measurements will not achieve the same spatial resolution performance as the epithermal neutrons. A fast-neutron measurement from a four-module NS would detect a hydrogen enhancement with a concentration around 1000 ppm at a spatial scale of 30 km.

7. Summary and conclusions

Understanding the hydrogen concentrations at the lunar poles is an important planetary science objective and can address multiple open questions in studies of lunar science, solar system PSRs, as well as provide information for future solar-system exploration. In particular, better quantification of the spatial and depth distribution of lunar polar hydrogen concentrations is needed. Planetary neutron spectroscopy is the best way...
to make such measurements from orbit, and improved spatial distribution information can be acquired through measurements at lower spacecraft altitudes than has previously been accomplished.

We have presented two complementary mission scenarios that can accomplish these measurements. The first is an orbital mission that has an elliptical lunar orbit with a periapsis at the South Pole. This mission can achieve improved spatial resolution by roughly a factor of two compared to prior measurements. Spatial reconstruction algorithms can improve this spatial resolution by an additional factor of two or more. The orbital mission would orbit the Moon for approximately six months and use existing, high-heritage instrumentation.

The second mission scenario uses a few, very low altitude passes (\( \sim 5 \text{ km} \)) over one or more PSRs. With a sensor size that can still be accommodated on a small spacecraft, robust measurements of hydrogen concentrations with \( <10 \text{ km} \) spatial resolution can be made for a set of strategically targeted PSRs at one or both lunar poles. Such measurements would provide critical constraints towards improving our understanding lunar polar volatiles and the processes that operate within permanently shaded regions.

Finally, an alternative approach is to combine both mission concepts. An orbiting spacecraft could map polar hydrogen deposits at the 20 km spatial scale, followed by a period of \( <5 \text{ km} \) passes over strategically chosen PSRs. This approach not only returns targeted measurements over high-value PSRs, but also provides for experimental validation of the spatial deconvolution techniques that would be applied to the full-coverage data. With this scenario, the NS would be sized to accomplish the final low-altitude measurement. One benefit of using a larger NS for the 15–20 km spatial-resolution measurements is that these measurements could be accomplished more quickly than when using a smaller NS. For example, if a four-module NS was used for this combined mission scenario, the orbital mission could be completed within three months, and a robust set of \( <5 \text{ km} \)-altitude measurements could be carried out during the final days of operation.

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References


