From Counts to Confidence: An IP-Respecting Calibration Framework and Standards for Commercial Space GRNS That Affords Decision-Ready Lunar Resource Products. T.S.J. Gabriel[1], [1]U.S. Geological Survey, Astrogeology Science Center (2255 N. Gemini Rd., Flagstaff, AZ 86001, USA. tgabriel@usgs.gov).

Introduction: Gamma-Ray and Neutron Spectroscopy (GRNS) data collected at the Moon is key to lunar resource prospecting efforts. GRNS is among the most effective tools for detecting Th- and H-rich substrates and for constraining bulk elemental composition in the top tens of centimeters to a meter of the lunar surface. However, unique deep space GRNS challenges can negatively impact chemical estimates and quantitative resource assessments. Furthermore, the paucity of standards with respect to calibration, validation/cross-validation, and contract language represents additional hurdles to producing decision-ready geospatial products.

As commercially developed and operated civil space missions expand, commercially derived GRNS data may increasingly underpin early-stage resource evaluation, site triage, and strategic planning. However, GRNS signals are unavoidably shaped by the materials and geometry of the host spacecraft in ways that are in stark contrast to more common sensing systems. Structural masses, fuel tanks and cooling loops, batteries, radioisotope thermoelectric generators, and shielding all influence neutron and gamma ray transport. Thus, for most GRNS instruments, a full understanding of the spacecraft system may be necessitated for robust quantitative interpretation and high-quality inference.

Vendors and customers face choices in how GRNS verification and validation is handled. For vendors, well-documented, verified, validated, and cross-validated products may be minimum viable products. For customers, contracts may explicitly require third-party traceable and validatable datasets, setting a high bar for transparency and repeatability, akin to exploration science missions. Historically, however, GRNS cross-validation issues still arose in these settings due to several factors. This is compounded by the bespoke nature of deep space GRNS architectures and the lack of standardized requirements, including those aligned with NASA Procedural Requirements (NPR) 7120.5 Phase A-E lifecycle.

In a commercialized deep space environment, contract structures and programs may afford calibration activities to be managed and validated internally or validated by a third party under non-disclosure agreements. Calibration information may be shared selectively across an entity's own business units, or with its partners and customers. However, robust verification and validation with trusted parties or via standardized and recognized processes may improve net perceived product value. A tailored calibration framework that addresses intellectual property (IP) concerns could provide an avenue for ensuring lunar resource and science product fidelity, while reducing contract friction.

Background: Neutrons and gamma rays produced in the lunar regolith by cosmic-ray interactions and natural radioactivity (in the case of the Th^{232} series) can constrain geochemistry. However, GRNS data are subject to unique dependencies (see Figure 1). Neutrons and gamma rays interact with, or are products of interactions with, the spacecraft, which influences counting data. Given faint distal sources and potentially short integrations, poor accounting of spacecraft effects can impact and bias estimated deposit tonnages. Careful domain expert work involves incorporating spacecraft materials in nuclear transport models [e.g., 1,2] and benchmarking against calibration measurements. Within transport simulations, source particles interact with the spacecraft, instrument, and lunar regolith, allowing instrument response and background to be characterized.

Measurements are also influenced by detector altitude, spacecraft attitude, geochemical and geotechnical assumptions, and the methodologies used to account for these factors, perform inference, and map project results. Background-only integrations are sensitive to the variable source background and its interaction with the spacecraft (Figure 1, right). Two teams may model these effects differently, causing cross-validation challenges. At high altitudes, topography-free assumptions may be sufficient, whereas in ultra low-altitude concepts, the assumption may introduce biases depending on the sensor spatial response. This may potentially impact steep slopes and crater floors differently, biasing inference in certain terrains. At the rover scale, nearby boulders may also bias counting statistics and geochemical inferences.

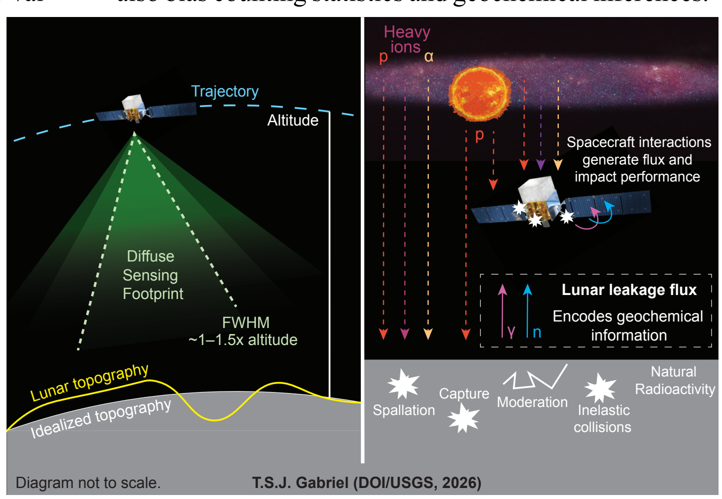

Figure 1: Depiction of GRNS measurements, showing sensing area altitude dependency (left) and sources of signal and background (right).

Matters compound as no two vehicles are the same, outside of proliferated architectures, and critical factors that influence GRNS performance may change along a program's lifetime. These represent major hurdles for GRNS teams. Precision and spatial response may need to be described through concept design and guaranteed by proposal submission but may be compromised or challenged by late changes in vehicle architecture, vendor, or CONOPS requirements. For example, the placement of power systems can be highly impactful on the performance and viability of GRNS systems.

An IP-Respecting GRNS Calibration Framework: Considering the calibration of a GRNS instrument within a framework, instead of an all-or-nothing approach, may enable commercial viability for GRNS, the reduction of contract friction, and the production of high-quality resource products for decision makers.

IPR-Tiers
Tier 0: Telemetry & Enhanced Description
Tier 1: Spacecraft Materials
Tier 2: Response & Calibration Information
Tier 3: Verification, Validation, Cross-Validation

Tiers of an IP-Respecting Calibration Framework.

Tier 0 includes basic information, such as standard telemetry (e.g., timestamps, quaternions, modes, gains, temperatures) as well as GRNS-specific enhanced instrument descriptions (e.g., live-time correction) that describe when, where, and how data were acquired and processed. Tier 1 includes descriptions of spacecraft materials that can be as detailed as necessary for the application. In the case where limited IP is preserved and maximum transparency is necessary or required, detailed Tier 1 information may include full chemical descriptions, locations, masses, and densities of spacecraft subcomponents. Where preservation of IP is required or where a broader description sufficiently secures a product's value to the end-user, directional density distributions or bulk descriptions of material volumes may be sufficient and would encode fewer sensitive design details. In instances where two missions with similar architectures, but with IP barriers between them, the impact of minor deviations in spacecraft architectures may be examined with broad material descriptions.

Tier 2 includes directional and energy-dependent response functions of the instrument and/or the instrument-plus-bus system, as determined from direct measurement or simulation. These outputs from nuclear N-particle transport codes and experiments can be made available in Tier 2 without exposing instrument configuration or transport input files. This demonstrates instrument response, and thus the resolution and uncertainties in geochemical inference maps used in resource evaluations. Incorporating Tier 2 information within the proposal in a federal contract environment could help avoid downstream friction (see practical example in [3]). However, a tension between strict pre-submission solicitation requirements, unknown detector isolation accommodations during submission, and late-evolving vehicle architectures remain a challenge.

Tier 3 includes verification, validation, and cross-validation products. These include detailed data from cruise phase measurements and potentially co-located and/or co-temporal measurements with other sensors for cross-validation. Appending the propulsion schedule, fuel information, and attitude configuration aids in the interpretation of results. For orbital missions, integration over reference terrain supports comparability.

Flexible Applications: The tiered framework accommodates a range of customer and vendor strategies:

Internal corporate use: A single company with multiple business units (e.g., manufacturing, space operations, analysis, and resource product development) can use IP-R Tiers to selectively share calibration artifacts internally. This can streamline internal integration and reduce development redundancy.

Business-to-business: Two or more companies collaborating on prospecting activities or data agreements can leverage IP-R Tiers or similar structures as contractual language for defining expectations, reducing ambiguity, and increasing the value of shared products.

"Go-it-alone" commercial operations: Keeping calibration entirely internal may be relevant in specific contexts, where only processed products or limited derivatives are released. In such cases, the framework can help structure internal calibration workflows, product lines, and data valuation models for internal customers.

Federal contracts: In government-contracted scenarios, tiered calibration commitments, including as part of NPR 7120.5 contracts, may reduce contract friction, clarify deliverables, and align expectations. This could afford improved assessments of a product's competitiveness and the data's long-term archival value.

In any situation, addressing the unique challenges to lunar GRNS applications would help secure data products at a fidelity and standard necessary for quantitative resource and geochemical assessments. IP-R Tiers are an example framework that can be used to improve GRNS agreements and activities between the diverse multi-party relationships that are increasingly prevalent in lunar exploration and reconnaissance.

Acknowledgments: Support recognized from the Space Resources & Hazards Section at the U.S. Department of Interior, U.S. Geological Survey Astrogeology Science Center. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

References: [1] Kulesza et al. (2022). MCNP® Code Version 6.3.0: Theory & User Manual, LA-UR-22-30006 (9/2022). [2] Agostinelli et al. (2003). *NIMPR-A*, 506(3): 250–303. [3] Lawrence, et al. (2010). *Astrobiology,* Mar;10(2):183–200.