Ground truth and lunar global thorium map calibration: Are we "there" yet?

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Introduction No lunar science issue is more important than the calibration of the global-surface thorium data set obtained by Lunar Prospector [1]. Of all the elements amenable to analysis by orbital gamma-ray spectrometry, Th should be the easiest to determine. Also (and not coincidentally — radioactivity is exploited in the orbital measurements), Th is one of the three main sources of radioactive heat, and strongly correlates with the other two (K and U). Th is almost ideally incompatible during igneous differentiation. In high-K KREEP, Th and U are enriched over CI chondrites by a factor (~750×) greater than for any other element (Ba, ~570×, is third) [2]. Since Th is also cosmochemically refractory (i.e., coherent with other refractory lithophile elements, including the major elements Al and Ca), by constraining Th atop (and indirectly within) the lunar crust, we go a long way towards constraining the whole-Moon composition.

The Problem Despite the advantages of Th as a target for orbital gamma-ray spectrometry, calibration of the lunar Th data has proven difficult. The problem comes at the low end of the range. Early calibrations were based on an over-simplistic assumption that the low end could be addressed by setting as Th = 0 µg/g the cell with the statistically lowest counting rate [1, 3] (it should be noted that the authors of these early calibrations admitted the approach was bound to be imperfect, at the low end of the range). Basically the same calibration was used for [4]. Comparison with samples, including lunar meteorites (lunaites) [e.g., 5, 6, 7], and also statistical arguments [5, 6], showed these early calibrations to be seriously in error. Briefly stated, the statistical argument is as follows: the very large number of cells at low Th, and the inevitable statistical scatter among these data, resulted in a "0" that was the artificial tip of a statistical tail, i.e., several sigmas (and thus somewhat over 1 µg/g of apparent Th) below the vast majority of cells that, in reality, have essentially the same Th. Recently, Prettyman et al. [8] produced an improved calibration, but only for a high-altitude, low spatial resolution (5°×5° cells) data set. In the latest release of high spatial resolution (0.5°×0.5° cells) data [9], the calibration of [4] was rescaled to conform to that of Prettyman et al. [8]. The calibration of [8] has average surface Th concentration = 1.57 µg/g, lower by 0.65× compared to the concentration implied by the previous [3, 4] calibrations.

Ground Truth: Still Not Very Well Matched

Lunar meteorites. The recent discovery of two relatively KREEP-rich meteoritic regolith breccias, SaH 169 [10] and Y-983885 [11], has slightly alleviated the degree to which the spectrum of lunaite polymict breccia compositions implies a need for a large proportion of the surface to have very low (~0.3-0.4 µg/g) Th concentrations. In Fig. 1, the green sample spectrum is based mainly on regolith samples; several individual impact melt breccias and fragmental breccias are averaged to count as just two (very low Th) samples. The three Apollo and Luna ~pure highland sites are conservatively included, even though we know they sampled the relatively KREEP-rich near side.

It is becoming increasingly clear that lunaites are a significantly biased population, with the bias probably favoring Th-rich (and mare) source terrains. More work is needed on physical modeling of the impact flux as a function of position on the Moon. The most recent published work on this problem (for the modern Earth-Moon distance) is three decades old. The 0^{th} order conclusion from the most authoritative such study [12] was that the near side/far side bias is negligible. Nonetheless, both [12] and earlier [13] found a that the Moon's leading hemisphere (i.e., the hemisphere centered at 90°W) has a higher accretion rate, by a factor of 1.2 [12] to 1.8 [13]. There may also be a significant bias in favor of low latitude [13, 14]. A more modern study [15], but one that only simulated Earth-Moon distances out to 0.6× the modern value, extrapolates to suggest a strong, remarkably localized bias in favor of low latitude and longitudes of ~10-40° and 70-100°W (along with two roughly antipodal areas). By any calibration of the Th data, the most Th-rich regions are between 10°E and 70°W and 15°S and 60°N. A 10-40°W, near-equatorial bias would almost precisely match the most extremely Th-rich large area of the Moon. A more generic bias toward low latitudes and the leading hemisphere would still favor the broader Procellarum-Imbrium region of high Th.

In any event, the ratio of mare to highland lunaites is clearly significantly higher than the 1:5 ratio of mare to highland surfaces on the Moon. At this writing, 10 different known lunaites consist predominantly of mare material (most recently: LAP02205 and PCA 02010). Depending upon pairing assignments, particularly with respect to small Dhofar fragmental and impact melt breccias, the number of discrete highland meteorites is ~16 to 20. Even allowing for extreme vagaries in the still small-number statistics, it seems clear that a real bias exists in favor of mare samples. The bias might be partly a result of strength screening [cf. 16], but it seems best to assume that at least in part it reflects the bias toward the general Procellarum region previously suggested by (admittedly primitive) physical modeling [11-14]. If so, agreement between the low end of the Prettyman et al. [8, 9] calibration and the "pure samples" ground truth is not as satisfactory as Fig. 1 would otherwise suggest.

Specific Sampled Sites. The low end of the [8, 9] calibration still seems to widely miss the mark when tested most directly, vs. regolith compositions for documented low-Th sampling sites. The worst case is Luna 24. The Th concentration of the Luna 24 regolith sample (from various positions along a 2 m core) is just 0.40 ± (1-σ) 0.08 µg/g, when averaged from many analyses among 7 source publications (including two very high-precision U determinations, converted into Th by assuming Th/U = 3.75). Excluding two Soviet sources, the average would be even lower: 0.36±0.05.

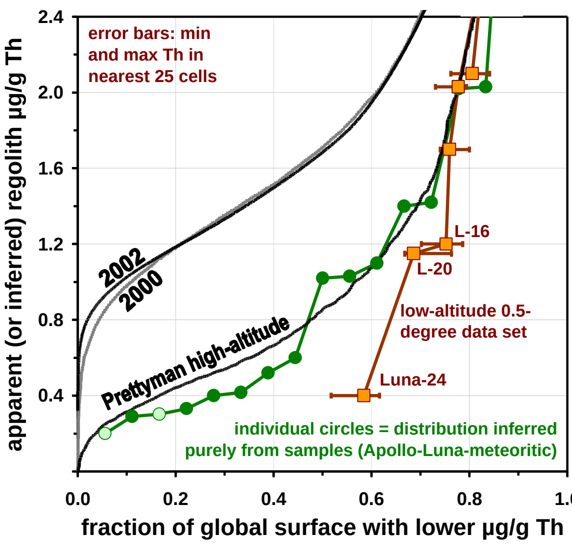

Fig. 1. Low-end comparison between three orbital Th calibrations [3,4,8] and two forms of ground truth.

Careful parsing of the low-altitude, 0.5-degree Th data set [4] shows that (unless and until the data set is subjected to some non-generic, region-specific recalibration), the count rate at the Luna 24 site will always be higher than the count rate for 58% of the lunar surface. Fig. 1 shows this result, with error bars that are conservatively based on the maximum and minimum Th levels reported [4] for the 25 cells (i.e., a 2-cell cushion in any direction) nearest the site. The discrepancy vs. the high-altitude [8] calibration, where the 58% coverage level occurs at Th = 1.02 µg/g, is very worrisome. The problem is not much alleviated if we draw a direct comparison to the high-altitude [8] calibration, where the site occurs almost precisely at the mid-point between two of the large 5°×5° cells. In terms of fraction of the Moon's surface at lower Th (in the [8] calibration), the southern 5° cell is at the 35% position, the northern 5° cell is at 54%, but the 0.5-degree data [4] (however calibrated) strongly suggest (barring some unusual sub-0.5°-scale heterogeneity) that the actual site's Th is far better matched by the northern cell than by the southern. In terms of actual concentrations, the simple average of the two relevant 5° cells [8] is 0.76 µg/g, i.e., high by a factor of ~1.9.

The sampled location with the next lowest Th is Luna 20, where the 6 most reliable sources indicate 1.11 ± 0.11 µg/g; for plotting purposes, lending partial credence to several lesser-known sources, 1.15 has been assumed. In the 0.5-degree Th data set [4], this site is at a higher Th level than 68.6% of the lunar surface. In the high-altitude 5°×5° calibration [8], the site is toward the SW corner of a cell with higher Th than 65% of the global surface; and the 0.5-degree data [4] (however calibrated) imply that the actual site's Th is probably higher than the mean for this 5°×5° cell. As a little bit of good news, the [8] calibration does nearly match the average regolith Th concentration at Luna 16 (as conservatively averaged, 1.20±0.15).

Another, no doubt related problem that has still not been completely fixed is the failure of the trend of ground truth vs. orbital data to extrapolate, as it surely should, towards 0 orbital Th at 0 sample Th. Instead (and even ignoring Luna 20 and/or Luna 24, although ignoring them relaxes the constraint), an offset of ~0.4-0.7 µg/g Th persists.

Conclusions: The Prettyman et al. [8] algorithm and its low-altitude descendant [9] have gone a long way towards correcting the lunar Th calibration. However, low-end Th data are probably still too high by a significant factor. Assuming the high end of the calibration is OK, the whole-Moon average surface Th is still being overestimated by a factor of 1.1 (or more).

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