Can we measure soil density with radiometrics?

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SUMMARY

Current practice in radiometric data analysis seems to have largely ignored using the Compton scattered gamma rays to characterise the very near surface, the soil horizon. The emphasis is upon the line spectra from radioisotope decay and removing or stripping out the scattered radiation from the parent and daughter product line source radiation for geochemical analysis. These radiation lines in the gamma spectrum are the gamma rays that do not interact with the other elements in the soil. Only the scattered radiation provides us with a means to characterise physical properties so the soil. Thus, if we want to infer soil density then we should analyse the scattered gamma radiation from the Compton spectrum as it is done with borehole density tools. With borehole tools a strong and calibrated-known gamma source is used to normalise the Compton gamma count. In the case of airborne radiometric we have robust procedures to calculate the in-situ source radiations strength already in place. Numerical modelling of gamma radiation with GEANT4 to examine the possibility of measuring soil density via radiometrics on an airborne platform indicates it is possible. However, leached soil horizons and very saturated mediums may reduce the density estimate accuracy substantially.

Key words: Gamma Ray, Soil Density, Radiometrics

INTRODUCTION

To measure density normally a sample is taken, and a gravimetric method s is used. With airborne mapping taking sample is snot practical and soil density tends to come from sparse and limited sample on the near-surface in different horizons and then extrapolating these spare measurements by association with similar interpreted soil lithologies. To measure density without taking a sample generally requires a radioactive gamma source, usually a radioisotope such as Cs-137 or Co-60. However, any method to measure rock density using a strong gamma radiation source from the air isn't an acceptable solution. So, could we not use natural radioactive as our gamma source?

In a measurement of the natural radiation spectrum, we have all elements of the gamma-gamma density technique except the source strength is not known. Over the decades we have become better at estimating K, U, Th from gamma spectra, but do not use the scattered radiation in a meaningful way. So, if we have a good estimate of the gamma source properties might we be able to analyse the scattered radiation in a meaningful way? A method of measuring density without a radioisotope is proposed whereby the source of gamma radiation is the normally present natural radioactive background. It works by comparing the relative intensities of direct and scattered gamma rays from natural radioisotopes of K, U and Th elements. With a suitable large gamma detector measuring over an area estimates of soil density may be obtained if we look at scattered radiation in the Compton regime of scattering verses primary source of gamma rays. The probability of scatter per unit distance travelled is proportional to the electron density. As the average number of protons and neutrons (the heaviest components of matter) is equal to the number of electrons the amount of scattering is proportional to the mass-density of the material. This is the basis of gamma-gamma density measurement: related electron density to nucleonic density.

It seems unreasonable to not use the scattered gamma radiation portion of our gamma spectrum in some useful way for characterising the earth surface. However, even in in borehole logging the natural Compton spectrum is generally regarded as "noise". Within a radioactive whole-space the scattered gamma ray spectrum shape is independent of density because the scattered radiation from adjacent volumes equilibrates with respect emission and absorption so that the spectrum is the same in all directions and places within the volume. On the surface of a material with radioactive elements the overlying air is inert with respect to sources of radiation. Therefore, scattered Compton gamma rays measured in a shielded downward looking detector should detect the scattered gamma rays from the soil-earth predominantly as well as the gamma rays that pass without collision through the earth to the detector.

FEASIBILITY OF USING NATURAL RADIATION TO MEASURE DENSITY

To use natural radioactivity as a source of gamma rays to measure material density by looking at direct and scattered gamma rays. This is achieved by measuring the ratio of gamma rays in the 300-1200 keV energy region (the

Compton Band) versus the number of gamma rays that reach the detector without any scattering (the Peak band, or direct counts – gamma rays that travelled without interacting with any of the rock material). The natural gamma rays start randomly throughout the rock and emit in random directions. Only a small fraction of the total makes their way to the gamma detector. For instance, numerical simulations (using GEANT4 software) show that of a starting number of 1 million natural gamma rays only 30,000 arrive via scattering or directly into the detector. Gamma rays in the energy band of 200-1200 keV form part of the "Compton region" and the direct rays form a "peak" in the gamma ray energy spectrum. As the direct gamma rays start off with well-defined energies due to radioactive decay, when un-scattered they arrive at the detector with the same energy.

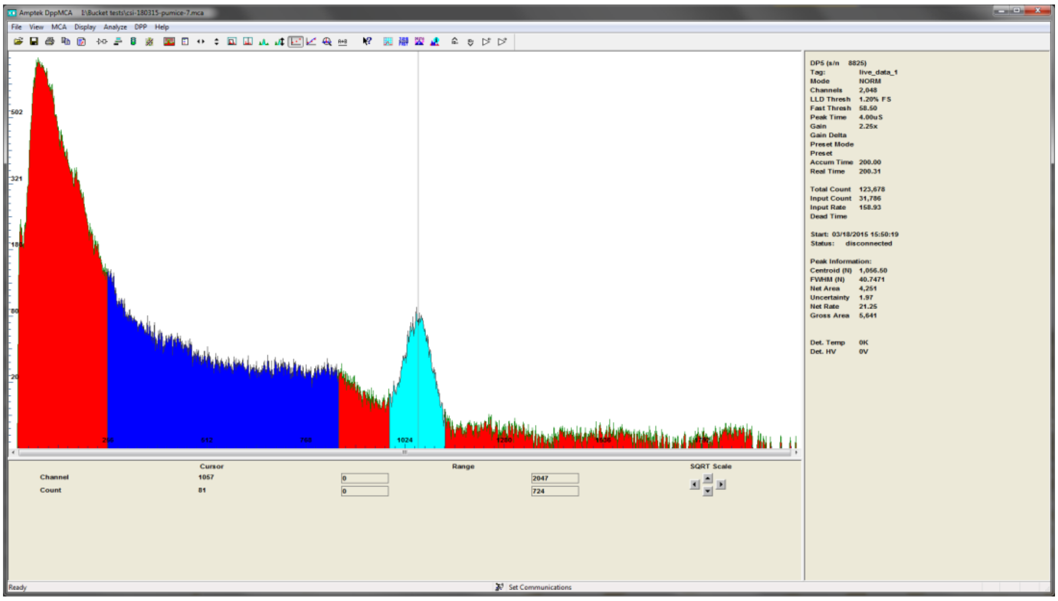

Figure 1. Example of Gamma energy spectrum of cement with CsI:Na detector. The K40 direct arrival Peak is light Blue and the Compton region is dark blue. The direct arrivals do not interact with the rock before reaching the gamma sensor and is used as a measure of natural radioactive intensity. Gamma rays from the Compton region have bene scattered by the rock and so are a measure of the rocks ability to scatter gamma rays. The raio of the blue areas might indicate the density of rock.

A ratio formed from the number of scattered gamma rays versus the number of un-scattered gamma rays can provide a measure of rock density. The rationale is:
The intensity (or number) of gamma rays in the 0.2 to 3 MeV energy band that make their way to the detector can be approximated by:

$$I_p = I_0\, e^{-k\rho} \qquad (1)$$

Where k is constant based upon average path length and the interaction cross section (independent of atomic number, Z). Thus, density (ρ) is the main factor in determining intensity if the radionuclides are distributed uniformly through the material (and then K represents the average path length). The initial intensity, I0, is representative of the concentration of naturally occurring radionuclides. Many gamma rays that are scattered (ie have lost energy) also find their way to the detector and this number is proportional to the intensity of the fraction scattered (which 1 minus the faction not scattered):

$$I_{C1} = \beta I_0(1 - e^{-k\rho}) \qquad (2)$$

Where the factor β scales the intensity so that it is a factor of the number scattered gamma rays that make it to the detector, and it is inversely affected by density in that at zero density there are no scattered gamma rays. Thus with a perfect detector the ratio of gamma rays detected within the Compton band versus the counts within the radionuclide peak bands would be approximately proportional to density.

However, the detector is not perfect and the Intensity in equations (1) and (2) need to be modified to include the efficiency of gamma capture in the detector. In many scintillators of modest diameter (25-60 mm), the ratio of 1.5 MeV gamma rays that are properly registered by their light pulse amplitude as in the 1.5MeV energy range (full capture) is only 30-60% depending upon the material of the detector. As many gamma rays are only partially captured by the detector only a fraction, g, register as the correct energy and the others register as lower energy gamma rays, mostly in the Compton band. Thus, not only is the number of direct gamma rays underestimated, but the remainder are added to the Compton band in addition to the gamma rays scattered within the rock.

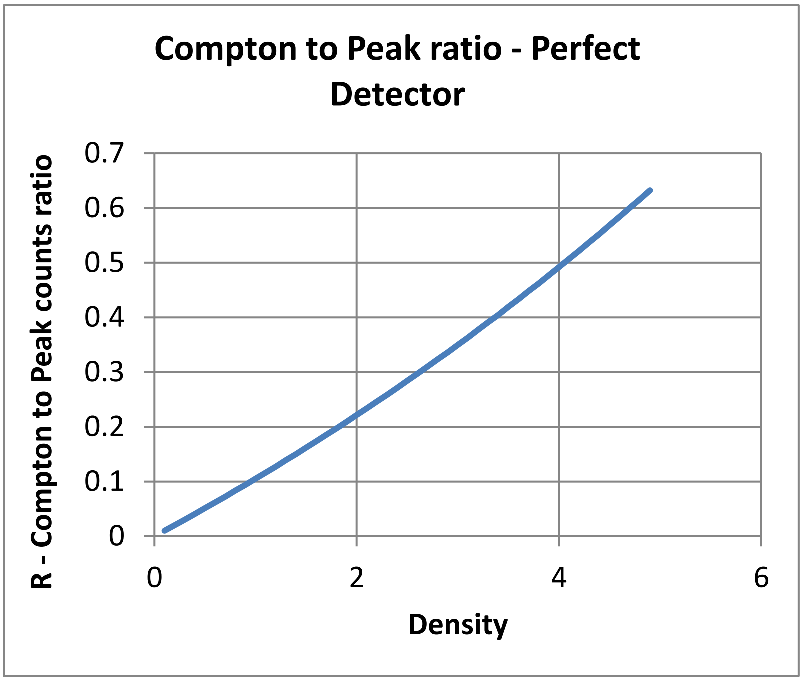

Figure 2. Relative number of Compton gamma rays versus direct gamma rays with a perfect detector. That is one that registers all incoming gamma rays at the correct energy. Most detectors capture a fraction correctly and the rest of the gamma rays are measured as less than full energy due to scattering in the crystal with the loss or escape of a partially absorbed gamma ray.

The modifications to 1 and 2 are:

$$I_p = gI_0\, e^{-k\rho} \tag{3}$$
$$I_C = \beta I_0(1 - e^{-k\rho}) + (1-g)\, I_0\, e^{-k\rho} \tag{4}$$

The ratio of (3) and (4) can provide a measure of the influence of density as the normalisation of the two quantities removes the effects of radionuclide concentration and the other terms are largely constant.

$$R = \frac{I_C}{I_p} = \frac{\beta I_0(1 - e^{-k\rho}) + (1-g)\, I_0\, e^{-k\rho}}{gI_0\, e^{-k\rho}} \tag{5}$$

$$R = \frac{\beta\,(1 - e^{-k\rho}) + (1-g)\, e^{-k\rho}}{g\, e^{-k\rho}} \tag{6}$$

The ratio R is now non-zero at zero density because the detector will produce a fraction of Compton gamma rays even with a uniform source of mon-energetic gamma rays into the detector. Most detectors and scintillator materials with diameters of 30-60 mm will have a value of g between 0.3 and 0.7 (the peak to Compton ratio of the detector).

To obtain good precision approximately 50,000 gamma rays need to be collected to reduce statistical variations in gamma counting.

$$e = \sqrt{\frac{1}{N_c} + \frac{1}{N_p}} \tag{7}$$

Where Nc and Np are the number of gamma rays counted from Compton and the Peak areas of the gamma spectrum. Typically, the number in the Peak area, Np, is the smaller number for normal rock densities and typical gamma detector performance. For example, with R=3 and 50,000 gamma rays counted the relative error in estimating R is approximately e=1%. With a relative error in R of 1% the precision of density measurement could be +/- 0.05g/cc.

This is likely too much to hope for from even a large airborne radiometric detector, but indicates that even several thousand gamma rays may be able to provide useful information about density changes.

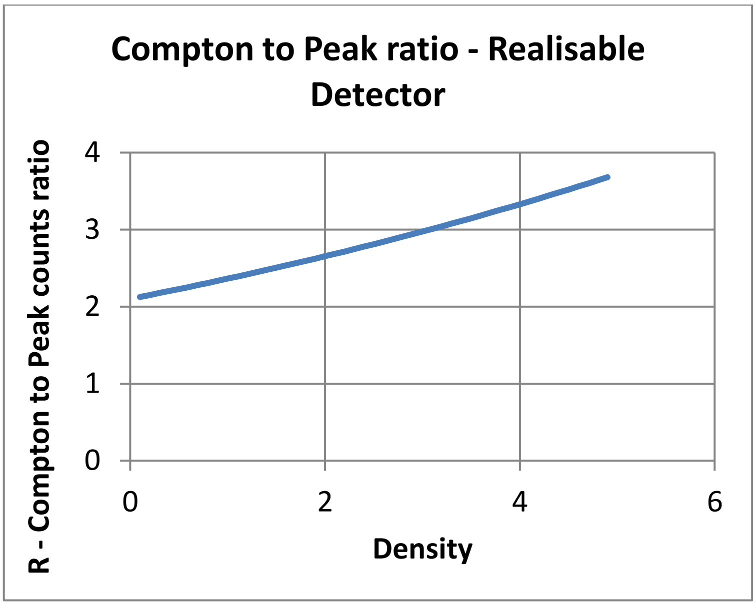

Figure 3. Relative number of Compton gamma rays versus direct gamma rays with a detector such scintillator made of CsI with a 40mm diameter. For this type of detector only 40% of the incoming gamma rays at 1.5 MeV are correctly measured with respect to energy. The rest will be distributed in the spectrum as lower energy gamma rays.

Laboratory tests using 35 cm dia x 35 cm high buckets of concrete with different aggregates to simulate rock were used to test the idea (Figure 4). The buckets had pumice (low density), sand (medium density) and iron ball bearings (high density) aggregates plus some potassium salts added to produce natural K40 gamma radiation (1460 keV). The average densities of the buckets are: pumice – 1.6, cement – 2.1 , iron – 2.6; thus a span of 1 g/ccThe corresponding estimates of g (which is the detector peak-to-Compton efficiency) for thesdetectors was estimated to be 0.35 respectively due to the diameter and density. The R – Compton-to-Peak ratio data shows the expected change with R versus density and expected zero density intercepts are similar to that in Figure 3 with the appropriate values of g. These laboratory tests provide hope where there was none before: density does change the gamma spectrum Compton to K40-peak ratio.

Within the range of densities of common rock formations, from 2 to 3.5, the R curve will be fairly linear and the constants k and g may be estimated empirically with calibration pits or calibration boreholes. Alternatively for a configured system the R versus density may calibrated with test samples in a laboratory, test pits of controlled density or against boreholes logged with active source methods.

Whilst it is possible to make a model with Monte-Carlo methods the detector response and then perform data inversion, it would appear to offer little benefit to being able to measure density as the ratio R calculation removes the need to calculate concentrations of natural radionuclides. Some compensation for Compton scattered gamma rays originating from U and Th being added to the peak of K40 decays would need to be incorporated into the calculation of R.

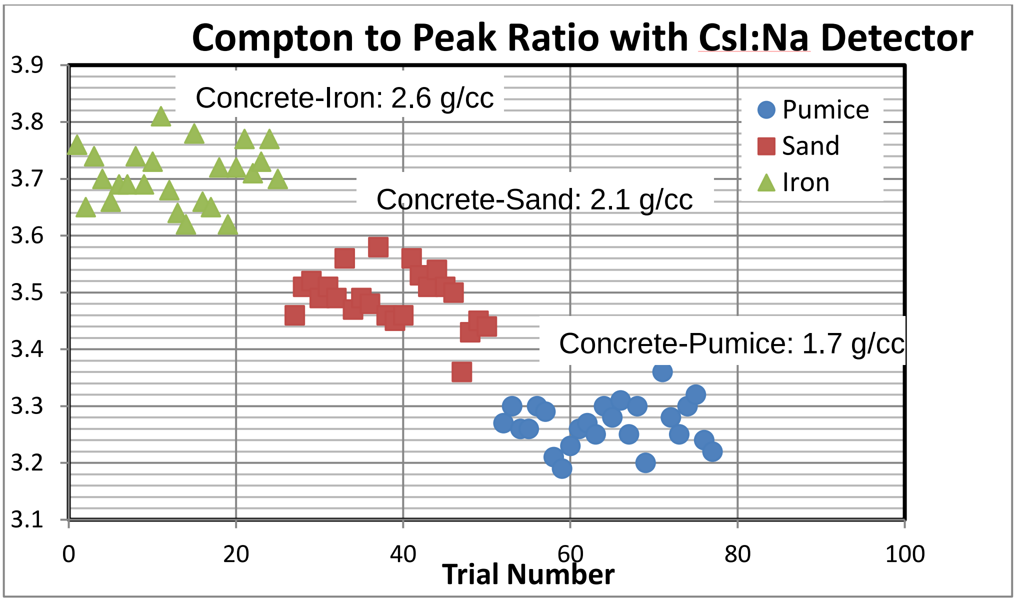

Figure 4. Laboratory tests with buckets of concrete with different aggregates. These measurements were flawed with respect to testing the hypothesis of whether we can use natural radioactivity for in-situ density. Measurement within boreholes due to the limited size of the samples allowed too many gamma rays to escape without a compensating number to enter into the sample. However, the air-surface boundaries of the material in a bucket demonstrates in a physically realisable way that we can measure differences in density from the natural gamma spectrum if the conditions are right

SIMULATION WITH GEANT4

Simulating the earths response to an airborne radiometrics is very large computational undertaking. So a considerably simpler numerical model was used with the earth represented as a solid sphere about 2m in diameter. GEANT4 was used to model the sphere at different densities and 100 million K40 gamma rays uniformly spread throughout the sphere volume. The gamma rays escaping the surface were assumed to all enter a gamma detector above the surface and the energy and other properties logged before constructing a high-resolution spectrum. An example gamma spectrum from, the simulations is presented in Figure 5.

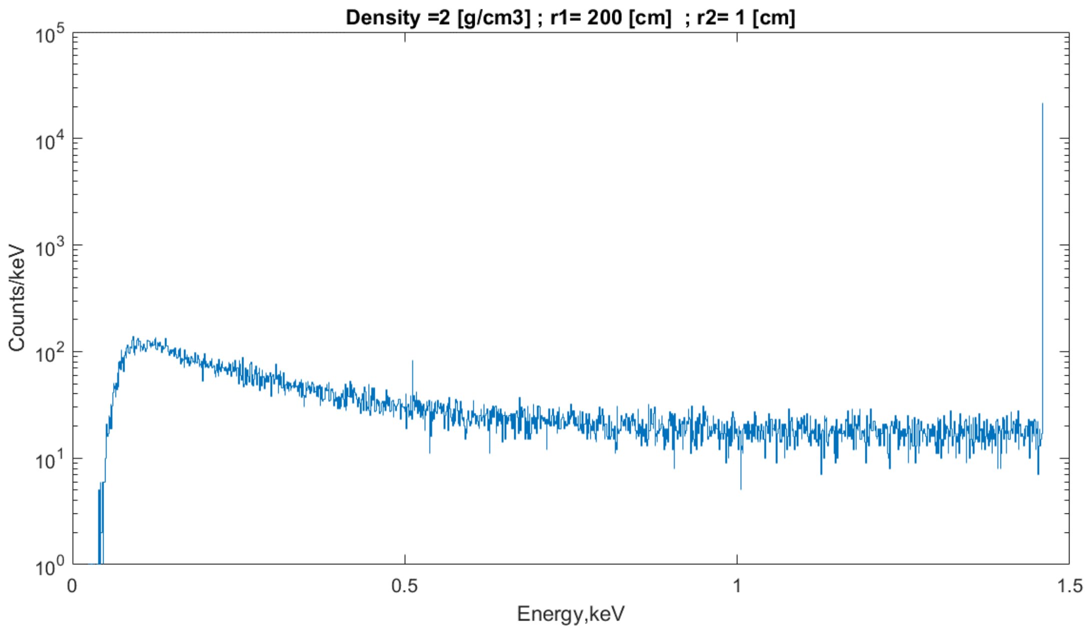

Figure 5. Example of simulated gamma spectrum from a solid sphere of 2m diameter.

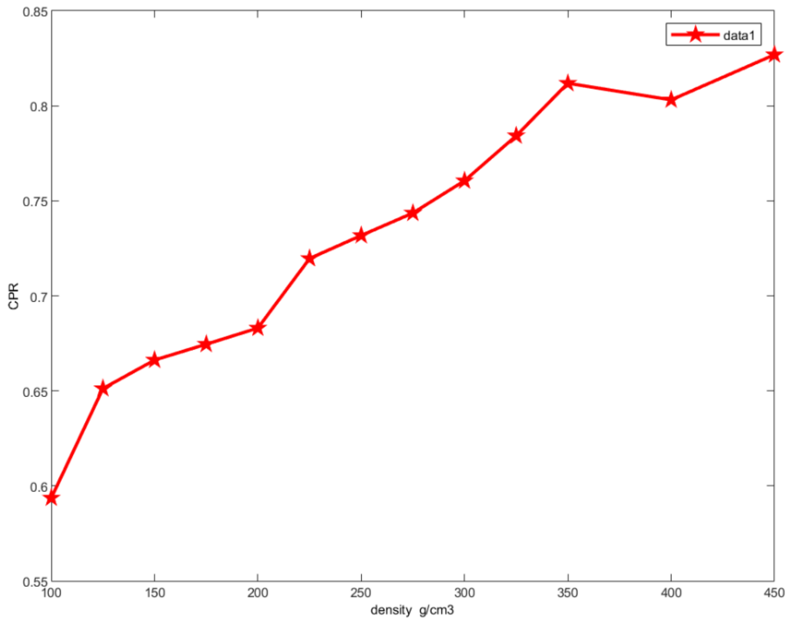

Figure 6. The Compton-to-Peak ratio of a 200 cm diameter sphere model with K40 distributed uniformly in the sphere. The trend is as anticipated fand so there is hope that it is possible tp use radiometrics to measure surface density from natural radiation

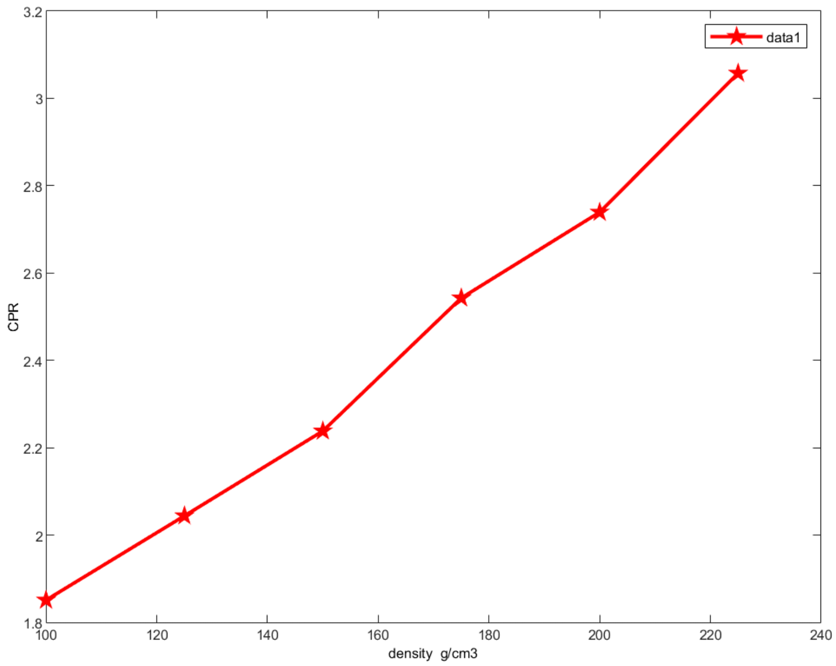

Figure 7. The Compton-to-Peak ratio with 15 cm of barren silica sopil (1.5g/cc) overlying a 200 cm diameter sphere model in Figure 6. The trend is the same but the numbers a vastly different. This is an exaggerated example of the violation of the assumption of uniformity within the soil horizon.

The resulting gamma spectrums and analysis of Compton-to-Peak in Figure 6 shows a strong trend of CPR increasing with Density as hypothesised. The simulation with a shallow cover of non-radioactive material in Figure 7 also shows that this CPR analysis methodology ha limitations in dealing with no-uniform soil horizons with significant differences in responses.

CONCLUSIONS

It might be feasible to measure soil density from the air. Physical models and numerical modelling indicate it is possible and perhaps even feasible to measure soil density from airborne radiometrics. Basic numerical and physical modelling seem to indicate that there is hope to measure near-surface or soil density. The number of gamma ray into impossible to gather and the effect would appear measurable. Departures from the assumptions used in the models is likely to be the biggest issue in practice. Leached soil horizons and saturated areas would seem to be an issue in accurate density estimates. These issues may be turned into our favour when analysing why apparently uniform areas have different Compton-to--Peak response: it may be due sot differing saturation of the soil with water, and that would be very good outcome to know for many people.

ACKNOWLEDGMENTS

I would like to acknowledge the enthusiasm of Dr Ida Hooshyari-Far and Dr Sepideh Rastin in looking at this idea years ago, with Dr Hooshyari-Far collecting many laboratory measurements and Dr Rastin for running the GEANT4 simulations on a large computing system in a timely manner. Additionally, I would like to acknowledge Dr Michael Carson for creating the GEANT4 models and modelling parameters.