Optimum Method to Determine Radioactivity in Large Tracts of Land - *In-situ* Gamma Spectroscopy or Sampling Followed by Laboratory Measurement

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**Abstract.** In the process of decommissioning contaminated facilities, and in the conduct of normal operations involving radioactive material, it is frequently required to show that large areas of land are not contaminated, or if contaminated that the amount is below an acceptable level. However, it is quite rare for the radioactivity in the soil to be uniformly distributed. Rather it is generally in a few isolated and probably unknown locations. One way to ascertain the status of the land concentration is to take soil samples for subsequent measurement in the laboratory. Another way is to use *in-situ* gamma spectroscopy. In both cases, the non-uniform distribution of radioactivity can greatly compromise the accuracy of the assay, and makes uncertainty estimates much more complicated than simple propagation of counting statistics. This paper examines the process of determining the best way to estimate the activity on the tract of land, and gives quantitative estimates of measurement uncertainty for various conditions of radioactivity. When the distribution of radioactivity in the soil is not homogeneous, the sampling uncertainty is likely to be larger than the *in-situ* measurement uncertainty.

**KEYWORDS:** Gamma spectroscopy, *in-situ*, uncertainty, soil, sampling

1. Introduction

A common measurement task is to determine the radioactivity concentration on lands that have been contaminated with radioactive material and have been remediated, or that are suspected of being contaminated. If the distribution of the radioactivity in the soil was well known, then it is a rather conventional task to evaluate the best method of measurement. Extracting a sample for laboratory measurement, or performing *in-situ* measurements of the entire container are well known and common methods.

But in practice, this convenient assumption of homogeneity is rarely the case. In both cases (*in-situ* measurement, and sampling followed by laboratory measurement) this non-uniform distribution of radioactivity greatly compromises the accuracy of the assay, and makes uncertainty estimates much more complicated than simple propagation of counting statistics. It is the purpose of this paper to show which of these methods is more accurate, and the appropriate use of each.

*In-situ* quantitative assay of the soil has historically been performed with a NaI or Ge detector on a tripod 1 meter from the soil surface [1]. The detector is used to perform a series of measurements in a pre-defined array. There are many choices of counting protocol that can be made, depending upon the level of accuracy needed, and depending upon the sensitivity and counting time desired. These include: detectors close to the surface or far away, distance between measurement locations in the array, and rectangular or triangular arrays.

With a uniform distribution of radioactivity in a known matrix the *in-situ* detector efficiency is easily determined with a few source measurements followed by simple mathematical manipulations [1], or with pure mathematical calibrations, e.g. MCNP[2] or ISOCS® [3, 4, 5, 6]. Since these calibrations assume uniform horizontal distribution of radioactivity, measurements where the radioactivity is not uniform will be in error. For a non-uniform distribution of radioactivity, the largest source of uncertainty is likely to be because a uniform reference calibration does not accurately represent the true efficiency. However, certain counting protocols which will be explored in this document can be shown to greatly reduce that uncertainty.

Alternatively, a series of soil samples can be taken and sent to the laboratory. If the sample is subsequently perfectly homogenized, properly prepared, and counted in a geometry where the
calibration is well known, the measurement uncertainty should be small. However, the accuracy of the land contamination radioactivity depends upon how well the laboratory sample concentration represents the field soil concentration. When the radioactivity on the land is not uniformly distributed, the largest source of uncertainty will very likely be the sampling uncertainty. Certain sampling protocols to be discussed later can be shown to greatly reduce that uncertainty.

So, given the choice of in-situ measurement of the soil with an imperfect gamma assay method, or extracting samples followed by a perfect laboratory assay, which will give a more accurate determination of the radioactivity concentration of the land?

2. Measurement Objectives

The first step in the process is to find out the true objectives of the measurement, and therefore the quality of the measurement that is required. This is a frequently overlooked step in the process. Rarely is the objective as simple as “what is the average concentration of radioactivity in that land area?” More likely it is something like “give me enough information to reliably categorize that land area as A, B, or C”.

The project manager planning the measurement campaign must try to find out as much as possible about the desired measurement objectives so an optimum measurement strategy can be developed. Examples of things to inquire about include:

- Desired accuracy of the land area concentration; frequently a function of the level of activity and the type of nuclide
- Decision points where the land area is categorized into the appropriate group
- Acceptable Confidence Level for placing the land area in the correct category
- Timing – when are the results needed
- Cost – how much labor can be expended; what kind of equipment can be used; what is the cost penalty for an incorrect decision
- Accessibility – are all portions easy to access, can people or equipment be easily moved
- Past measurements or other knowledge – what are the possible nuclides to expect, the range of activity expected, the level of uniformity expected, ...

3. Measurement Strategy

The proper development of a measurement strategy can only happen after first knowing the Measurement Objectives, and by then understanding how the uncertainty in the measurement result changes due to the many possibilities of performing it.

The two primary measurement possibilities are in-situ measurement of the entire tract of land via gamma spectroscopy, and extracting soil samples from the land area for subsequent laboratory analysis. Each one of these methods has both good and bad points, which the program manager must understand well enough to design the most practical method that meets the agreed-upon Measurement Objectives.

3.1 In-situ Measurements

- Generally restricted to only gamma measurements
- Detection levels usually quite good since the measured volume quantity is very large
- Low energy or low abundance gammas may be problematic at low activity levels
- Can be performed with NaI or LaBr scintillators or Ge semiconductor detectors
- Instruments with poor energy resolution may have interference problems from NORM or other radioactivity in the soil
- Radioactivity from nearby ongoing remediation or storage may cause interference unless collimated detectors are used
- Instantaneous results can be used to guide future measurements in the area
- Expensive and sometimes fragile equipment must be used under field conditions
• Efficiency calibrations easily done with mathematical methods, even for collimated detectors
• No radioactive waste generated
• Measures all radioactivity there, including that in soil, vegetation, rocks, moisture, etc. that are commonly removed for laboratory analyses
• Taking multiple measurements in an array can reduce the uncertainty and provide evidence of uniformity, or the lack of it

3.2 Soil Sampling followed by Laboratory Measurements

• Extracting samples from areas of unknown radioactivity is required, with the appropriate level of safety protection
• The process of extracting samples can be physically dangerous
• Obtaining a representative sample from certain ground conditions may be difficult, e.g. large rocks, crevices between rocks, bogs or marshes, very wet soil, heavy root layers, …
• Samples must be packaged and shipped to laboratory
• Chain of custody of sample and matching to the proper geographical location must be established
• Can perform chemical separation on sample for removal of interferences and use optimum sample geometry for alpha, beta, and gamma assay
• Sample preparation other than for simple gamma spectroscopy is generally rather expensive
• Sample preparation generally removes items [rocks, vegetation, sticks, …] that are truly part of the environment
• Detection levels can be quite good since sample geometry is high and counting times can be long
• Results not generally available for weeks to months
• Samples must be disposed as radioactive waste
• Taking multiple samples and analyzing them separately can establish the uncertainty and can provide evidence of uniformity, or the lack of it.

3.3 Uncertainty Estimation

If the land area is known or can be assumed to be uniformly contaminated, then the measurement is a simple task. Either use a simple calibration method for the field in-situ method, or take a few random samples back to the laboratory. Under these idealistic conditions the measurement uncertainty will generally be dominated by counting statistics, which are well understood and easily handled by conventional methods.

For uniform geometries of well-known matrices, efficiency calibrations are rather easy to perform. Mixtures of radioactive calibration sources distributed in a simulated soil-like matrix have long been used successfully. More recently, mathematical calibrations like MCNP [2] and ISOCS® [3, 4, 5, 6] have been used and accepted by the user community for both calibration of large geometries like here and for laboratory geometries. They are especially convenient to use and when the matrix is something other than water – e.g. soil, concrete, rocks, asphalt, ...

But this idealistic situation of a uniform matrix and a uniform distribution of radioactivity within the matrix is rarely the case. It is unusual for the matrix at a particular site to be well known in composition, but rather it commonly varies from location to location. The in-situ density also varies with location. It is even more unusual for the radioactivity to be homogeneously distributed laterally within the measurement area.

Consequently any efficiency calibration, source-based or mathematics-based, will be wrong when any of these non-calibrated conditions exist. This is true for both laboratory measurements of the sample and for in-situ measurements. For in-situ measurements, this deficiency of the generic calibration used to accurately represent the exact conditions in the container under measurement is most likely the major contribution to the uncertainty of the in-situ measurement. For laboratory measurements, the sample preparation normally should transform the sample into the proper form to that was used for the measurement instrument calibration. However to translate those laboratory results into area
concentration results requires propagation of laboratory uncertainty [normally small] and the sampling uncertainty [can be quite large].

For the conditions expected to be encountered, what is the in-situ measurement uncertainty? And if samples are extracted, what is the sampling uncertainty?

To help answer questions like this, a new feature to the ISOCS efficiency calibration software has been developed that allows uncertainty computations to be performed where there is incomplete knowledge of an accurate representation of the sample. The ISOCS Uncertainty Estimator (IUE) software [7, 8, 9, 10] can also simulate various non-uniform distributions in large sources, and then compute the resulting uncertainty in the efficiency calibration. The software also has a feature that simulates various sampling methods. The IUE software can then be used to create various non-homogeneous distributions in the soil, and then to estimate both the calibration uncertainty and the sampling uncertainty.

3.3.1 ISOCS Uncertainty Estimator – Overall Operation

IUE has been developed to improve the quality of the gamma spectroscopy uncertainty estimate, to improve the ease of generating these uncertainty estimates, and to document how they were generated.

The user first runs the ISOCS efficiency calibration software in the normal manner to compute the normal reference efficiency for the sample being measured. This efficiency file has encoded within it the inherent uncertainty in the ISOCS efficiency calibration method – i.e. 4-8% depending upon energy. As with most efficiency calibrations, this assumes the calibration model is a perfect representation of the sample.

The ISOCS calibration process requires defining the sample with various parameters. Some of these might be well known and do not vary appreciably; e.g. the detector height above the ground. Other parameters [or most in many situations] are “not well known” [NWK], e.g. the soil composition, soil density, vertical radioactivity distribution profile, non-radioactive overburden, etc. It is these “NWK” parameters that contribute to the uncertainty in the calibration efficiency. This is equally true for source-based calibrations and mathematical calibrations. For each NWK parameter, the user is required to provide to the IUE software an estimate as to how much that parameter varies. This can be determined, for example, by measuring a group of soil samples for density, or by consulting the literature for typical density and range, or just by making educated guesses. The parameters that can be varied include dimensional parameters [diameter, distance, thickness, density, …], as well as material composition of each item in the model.

For each NWK parameter, the user provides upper and lower limits [e.g. maximum and minimum density] and a distribution form that the parameter values within those limits are assumed to follow. As an example of this distribution form, if the values were determined by a series of measurements, then the limits can be assigned to represent 1 standard deviation, 2 standard deviations, or 3 standard deviations. If the values are just known as limits, then they could be assigned a uniform distribution function [all values equally probably] or a triangular distribution function [zero probability beyond the limits increasing linearly to the maximum probability in the middle].

The IUE software then assigns a value to each of these NWK parameters following the probabilities defined by the distribution function for that parameter. The efficiency is computed for that model. This process is repeated a large number of times until adding more models doesn’t change the result. The software then computes the model-to-model uncertainty for each energy, which will then be combined with the calibration uncertainty and the counting statistics uncertainty. If the radioactivity within the object to be measured is distributed in a non-uniform manner, then IUE can be used to examine various non-uniform distributions to estimate that portion of the Total Measurement Uncertainty [TMU].

3.3.2 IUE Data Entry Method
The user first points the software to one of the intermediate files created in the normal process of performing an ISOCS efficiency calibration. This file contains all the physical parameters of the normal [assumed perfect] calibration model.

The user is then presented with a series of screens showing all the parameters from the calibration model, and given an opportunity to make each of them a variable parameter. If that parameter is to be varied, then the user enters for each parameter the minimum value, the maximum value, and the distribution function to be used. Two examples of these screens are shown below as Figures 1 and 2.

In the case where the variable parameter is a material, the user enters a series of discrete materials, along with a weighting factor denoting the likelihood of that particular material being present.

All input parameters are stored in a file, and available as a printed report for the project record.

3.3.3 Calculational Methodology

The method used in this software is Probabilistic – all variables are assumed to vary randomly, but in a manner as described by their individual probability distribution function. All variables [except a few that are noted elsewhere] are assumed to vary independently from others, to the extent that it is physically possible.

Using these rules, the IUE software creates the files for a series of ISOCS calibration models. A random process is used to generate values for each NWK parameter, according to the probability distribution function rules and limits defined by the user. These values are combined to create an ISOCS model. A large number of these models are created and checked for validity.

The IUE software then computes the efficiency for a large number of energies using each of the valid random models. The IUE software now contains an array of efficiency values at each energy. For each energy, the IUE software then computes the mean efficiency, and the standard deviation of those efficiency values at that energy. This standard deviation now represents the uncertainty from the combined effect of all the NWK parameters.

This uncertainty is then combined with the basic ISOCS calibration uncertainty and embedded within the efficiency calibration. When this efficiency calibration is used to analyze a sample, this total calibration uncertainty is propagated with counting statistics uncertainty and other uncertainties for the final total measurement uncertainty.
3.3.4 Other Software Features

For measurements situations that use multiple detectors, the software allows the user to specify how many detectors, and determine their placement around the object. Therefore it can be used to calibrate or estimate uncertainty from common field measurement systems like box or truck counters, or in-situ soil measurements.

For measurement situations that use rotating samples, the software allows the user to specify this, and to define how many discrete steps are used to simulate a continuous rotation. For measurement situations that use scanning detectors, the software allows the user to specify this, and define how many discrete steps are used to simulate a continuous scan. This allows the software to be used to calibrate and estimate uncertainty for common drum measurement systems.

Some measurement situations have non-uniform sample concentration. Several of the ISOCS sample shapes [templates] allow non-uniform distributions, including “hot spots”. The IUE software expands that by allowing a multiple [or variable] number of hotspots and the size of the hotspots [fixed or variable] to be included in the model.

Although most of the variables are treated as independent variables, a few of them can be inter-dependent. A common example is sample height in a container, sample density, and sample weight. The weight is typically the most well known parameter, as it is rather easy to determine. The IUE software lets the user enter the weight as a variable parameter and then it computes either sample height or sample density.

The software computes the arithmetic mean efficiency and standard deviation, as well as the geometric mean efficiency and standard deviation. For measurement situations where attenuation is the dominant factor, the values are more likely to be in a log-normal pattern, where the geometric values are more relevant.

The IUE software also operates in a Sensitivity Mode, where only 1 parameter is varied at a time. This provides the user with feedback as to which of the parameters are the major contributors to the total uncertainty, thus allowing the user to concentrate data collection resources on those dimensions that are most important.

The IUE software can also simulate the extraction of a portion of the measured object and compute the “representativeness” or uncertainty of that sample. This process only works on those ISOCS templates that have “hot spots” of non-uniform radioactivity. The user specifies the sample type [core or grab], specifies the sample volume to be extracted and how many sub-samples will make up the total sample extraction volume. The IUE Sampling program then simulates extraction of these samples from the same objects that were used for the previously described in-situ uncertainty analysis. This is done multiple times using random sampling locations from each of the objects. The software computes the fraction of the radioactive source within each sample as compared to the amount in the object. Then the uncertainty is computed from the total population of samples.

4. Large Tract of Land Uncertainty Calculation

4.1 Homogeneous distribution example – in-situ measurement

For this scenario, there is an area of soil that could potentially be considered as contaminated. The soil area assumed here was 60m x 60m for a total area of 3600 square meters. Due to past actions at the site, the soil is assumed to be contaminated. A single release event caused this entire contamination event, therefore we shall assume that the radioactivity has a uniform horizontal distribution over the small measurement area. The vertical contamination profile is exponential in depth distribution with the radioactivity reducing to 37% at between 3 and 6 cm. There is a wind-blown layer of uncontaminated sand on top with a depth of from zero to 2cm, but most of it is 1cm. The density varies between 1.4 and 1.8 g/cc. The soil composition is also variable across the site and ranges from
wet sandy material at a density of around 1.8 g/cc down to soil mixed with decayed vegetation at densities of 1.0. The soil composition was estimated to be normal soil approximately 50% of the area, mostly sand approximately 25% of the time, and soil and decayed vegetation about 25% of the time.

The ISOCS detector was on a temporary vertical support that wasn’t very reproducible and therefore the detector-ground distance varied from 80 to 120 cm. The detector also wasn’t always kept vertical and varied in angle from +30° to -30°.

The nuclides of interest for this site are Am-241 at 60 keV, Uranium-235 at 185 keV, and Uranium-238, using the Pa-234m daughter at 1001 keV.

There are 6 uncontrolled variables in this problem. What uncertainty should be assigned to the combination of all these variables when doing an in-situ assay? To answer this question the above data were used with IUE in the Uncertainty Analysis mode. A triangular distribution was assumed for each variable. The program created several hundred mathematical calibrations which were analyzed for standard deviation. Table 1 shows the 95% CL uncertainty estimate. The first row in the data is when all the parameters were allowed to vary as described above. From the IUE Sensitivity Analysis results [not shown here], the user knew that thickness of the sand overburden was a big factor, and wanted to hypothetically explore what would happen if he would more accurately determine it. The next row shows the result of the re-calculation. Still not satisfied, the user evaluated the improvement by classifying the soil type in the vicinity of the detector, which removes the composition variable and reduces the density variable; this gives the results in the last row.

<table>
<thead>
<tr>
<th>Condition</th>
<th>95% CL at 60keV</th>
<th>95% CL at 1001keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>All items variable</td>
<td>61%</td>
<td>31%</td>
</tr>
<tr>
<td>After fixing the sand overburden depth</td>
<td>31%</td>
<td>19%</td>
</tr>
<tr>
<td>After fixing the soil composition under the detector</td>
<td>22%</td>
<td>15%</td>
</tr>
</tbody>
</table>

4.2 Non-homogeneous distribution of radioactivity in large land tract – in-situ measurement

4.2.1 Description of land contamination scenario

This exercise is intended to illustrate the usefulness of the IUE software to optimize a counting geometry, and then to assign an uncertainty to the efficiency calibration for that optimum geometry. For this scenario, there is an area of soil that could potentially be considered as contaminated. The soil area assumed here was 60m x 60m for a total area of 3600 square meters. Due to past actions at the site, there are isolated areas that are contaminated, however the bulk of the land area is not contaminated. Walk-over surveys have shown that the size of the contaminated areas are small – 1m² is assumed for this experiment. The contamination is assumed to be in a layer extending from the surface down to 15cm.

Measurements are needed to assess the average radioactivity of the 3600 m² area for the purpose of comparison of the average soil activity per gram to release limits. One method of assay is to perform in-situ gamma spectroscopy, positioning the detector several meters from the ground and repeating this measurement in a grid pattern over the entire area. The average in-situ concentration is the average of all the individual analyses. An alternate method would be to extract a group of samples from random locations for subsequent laboratory analysis. The average laboratory concentration is determined from analysis of a portion of the composite of the multiple extracted samples.
The nuclides of interest have energies of approximately 60 keV, 200 keV, and 1000 keV. What is the optimum in-situ counting geometry if the purpose is to minimize the total uncertainty of the activity concentration?

4.2.2 Computation plan

From an IUE Sensitivity analysis, it was determined that the largest contribution to the uncertainty is the number and location of the radioactive hotspots on the ground. Therefore, to identify the non-uniformity contribution to the total uncertainty, all other items were considered “well-known” and were not varied. The only source parameter varied was the number of 1m² radioactive hotspots in the 3600m² survey area. The hotspots were distributed over a 120m x 120m area to simulate a large contaminated zone, but the survey area being measured is only the central 60m x 60m area. Figure 3 illustrates the measurement conditions, and is shown with 9 detector locations covering the survey area.

The counting geometry variables that were investigated are:
- elevation of the detector from the surface
  - 1m, 3m, and 10m
- detector locations per 60m x 60m area
  - 9, 16, and 49 locations
- grid shape
  - rectangular and triangular grid patterns
- number of hotspots per 3600m²
  - varying between 3 and 100
- primary energy of nuclide
  - 60, 200, 1000 keV

The rectangular grid pattern placed the detectors at 10, 20, and 30m intervals. This means that there was a measurement for each 100, 400, and 900 square meters of land area, respectively. A triangular grid pattern was computed so that each detector would have the same amount of land area. Table 2 shows the distance from each detector to its nearest 4 neighbors for rectangular spacing and nearest 6 neighbors for triangular spacing.

<table>
<thead>
<tr>
<th>Number of detectors</th>
<th>Rect. Spacing</th>
<th>Tri. Spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 detectors per 3600m²</td>
<td>30m</td>
<td>32.56m</td>
</tr>
<tr>
<td>16 detectors per 3600m²</td>
<td>20m</td>
<td>21.97m</td>
</tr>
<tr>
<td>49 detectors per 3600m²</td>
<td>10m</td>
<td>10.99m</td>
</tr>
</tbody>
</table>

Computations of the in-situ uncertainty were performed using IUE for all important combinations of the variables. For each computation condition, a large series of land contamination models was generated, each with the specified number of hotspots but in different randomly chosen locations. IUE then computed the efficiency for each detector for the sum of all the hotspots, and then computed the average efficiency for the three energy values. Data were recorded for the mean efficiency and relative standard deviation for each of the computations.

4.2.3 Computation results

For this measurement scenario, the uncertainty is dominated by geometrical factors, rather than attenuation, therefore there was very little difference between the 3 energies. The 200 keV results are shown graphically in Figure 4 and throughout the rest of this document; the 60 keV uncertainty is about 20% higher and the 1000 keV uncertainty is about 10% lower than the values presented here.
The left graph of Figure 4 shows the uncertainty vs. the number of hotspots in the 3600 square meter area for the 3 rectangular grid spacings at 3 different detector elevations – 1, 3, and 10 meters. The graph on the right shows the same information but with triangular grid spacing.

Figure 4  In-situ soil measurement uncertainty under various distance and deployment configurations

Observations from these in-situ simulated measurements:

• The uncertainty as a function of the number of hotspots generally follows the square-root function – as the number of hotspots per unit area increases a factor of 4, the uncertainty is reduced a factor of 2.

• Decreasing the grid spacing is helpful in reducing the uncertainty when the detector is close to the ground; for 1m elevation, going from 30m to 20m [going from 9 to 16 measurements] reduces the uncertainty an average factor of 1.6; decreasing the grid spacing from 30m to 10m [from 9 to 49 measurements] reduces the uncertainty just about a factor of 3. But if the detector is at 10m elevation, there is essentially no change in uncertainty due to reduced grid spacing. See Table 3 for details.

• Elevating the detector from the ground is very helpful in reducing the uncertainty, especially with wide detector grid spacings. For the 30m spacing, going from 1m to 3m elevation reduces the uncertainty an average factor of 3 and going from 1m to 10m elevation reduces the uncertainty a factor of 10. For the 20m spacing, the uncertainty is reduced a factor of 3 and 7. For the 10m spacing, the uncertainty reduction is now down to 2 and 3.5. See Table 4 for details.

• Triangular grid spacing is also somewhat helpful at reducing the uncertainty when the number of hotspots per unit area is very low. For the cases with 3 hotspots per 3600m², the triangular grids had an uncertainty a factor of 1.5x lower than the rectangular grids, but when the hotspots were at 100/3600m², there was no improvement with triangular grids. See Table 5 for details.
The efficiency for each detector changes very little with any of the variables except as a normal function of energy and attenuation in soil. Therefore the techniques described here to improve uncertainty will not significantly harm the Minimum Detectable Activity for total area activity.

- The efficiency at 60 keV is a factor of 6 lower than 200 keV and the efficiency at 1000 keV is a factor of 1.5x lower.
- The efficiency is essentially the same at 1m and 3m detector elevation, and decreases about 20% at 10m. This slight [and probably insignificant] efficiency reduction is believed to be an artifact of the experiment due to the limited size of the source distribution area; in theory if the size of a planar source is very large, then there is no reduction in efficiency as the source-detector distance increases, except for air attenuation.
- With triangular grids, the 60 keV efficiency was 12% higher than for rectangular grids at 1m detector elevation, 3% higher at 3m elevation, and the same at 10m. For higher energies, the differences were smaller.

4.3 Non-homogeneous distribution of radioactivity in large land tract – sampling

The typical soil sampling method involves using a coring tool to extract a cylinder of soil from the surface down to the desired depth. Here we assumed it was a 10cm diameter core sampling down to 15cm depth. Multiple cores were taken and composited [mixed together] for laboratory analysis. The compositing, mixing, sub-sample extraction, and laboratory analysis were assumed to be statistically perfect operations. Figure 5 shows the results. The graph on the left shows that there is a significant reduction in the uncertainty as the number hotspots per unit area increases. There is also a significant reduction in the uncertainty as the number of samples are taken per unit area. Both of these follow the expected square root function – if there are 4x the number of samples or the number of hotspots then there is a 2x decrease in the uncertainty.

![Sampling uncertainty](image1)
![Fraction of samples with activity](image2)

Figure 5  Sample extraction uncertainty [left] and fraction of samples containing radioactivity [right] for various numbers of samples

For 10 hotspots per survey area, and 100 samples, the uncertainty is about 200%. If the number of samples is increased to 1000, then the uncertainty is reduced to about 60%. For comparison [see Figure 4], all of the in-situ uncertainties are less than 200%, and using 10m grid spacings at 1m detector elevation or 3m detector elevation with a 30m grid reduces all the in-situ uncertainty values to less than 60%.

Increasing the number of cores has both economic and practical consequences. The cores could be made smaller without statistical consequence here; for cores of 1cm and 10cm diameter, and for equal
numbers of samples, there was no statistical difference in the uncertainty. Taking 1cm diameter cores in soil is not mechanically practical, but 5cm diameter cores are common. But, it should be noted, that 1000 cores of 5 cm diameter would weigh nearly 1000 lbs.

Another major issue with sampling where the number of hotspots is low in comparison to the total size of the item is the low probability of any sample actually hitting an area with radioactivity. The graph at the right of Figure 5 indicates that nearly 1000 samples are needed to have a reasonably high probability of finding any portion of any hotspot in the laboratory samples – at 10 hotspots and 300 samples, nearly half of the samples will have zero activity even when radioactivity is present in the 60m x 60m area. For those cases, the area would be designated as clean, simply because none of the radioactivity was in the portion of the area that was measured in the laboratory.

4.4 Comparison between in-situ assay uncertainty and Sampling uncertainty

So, which is better -- in-situ assay of the soil, or extracting and assaying a portion? For the case with 10 hotspots in the survey unit, the in-situ measurements can achieve approximately 60% uncertainty with either 30m grid spacing and with the detector at 3m, or 10m grid spacing with the detector at 1m elevation.

Compare that to the sampling uncertainty of 200% when 100 samples are taken. Taking 1000 samples is about 60% uncertainty, and will weigh nearly ½ ton, and must be totally homogenized in order for there not to be a further increase in the sampling uncertainty from subsequent sub-sampling in the laboratory.

A further drawback of sampling for sparse a distribution like this is that unless a large number of samples is taken [1000 here] there is a high probability that no portion of any of the samples will actually hit the hotspots. For this 10 hotspot scenario, when 30 samples are taken 93% of the time there will be zero activity, and when 300 samples are taken, 46% of the time there will be zero activity shown in the laboratory analysis.

If there are 100 hotspots in the survey area, then the sampling uncertainty is about 110% if 100 samples are extracted and 60% for 30 samples. At 100 samples, 95% of the laboratory measurements will contain radioactivity, and at 30 samples 55% of them will contain radioactivity. For the same 100 hotspots, all in-situ measurements are less than 40%, even the simple 9-detector 1-meter elevation measurement.

5. Conclusion

It has been shown that for rather extreme non-homogeneous distributions, there are several reasonable easy to implement measurement strategies that can reduce the in-situ measurement uncertainty down to the <50% sd range.

- Increasing the detector elevation is the most effective; going from 1m to 3m is a factor of 3 improvement and going to 10m is a factor of 10 improvement for 30m detector spacing, but there is less improvement for closer detector spacings. With increasing elevation there is little reduction in efficiency and therefore detectability.
- Decreasing the distance between detector locations, thus increasing the number of measurement points per unit area is also helpful; Going from 30m grids to 10m grids gives about a factor of 3 uncertainty reduction at 1m elevation, but essentially no change at 10m elevation.
- Using triangular grids can also help, especially when at very few hotspots – at 3 hotspots per 3600m² this was a factor of 1.5 improvement, while there was no improvement over rectangular grids at 100 hotspots/3600m².

It has also been shown that for these same non-homogeneous distributions, any practical sampling strategy will have a considerably higher uncertainty, therefore even a perfect laboratory measurement
uncertainty must still be propagated with the high sampling uncertainty to properly state the activity of the land area.

As a commentary – is it really necessary to have a very low standard deviation? Probably not, since most measurements are performed to make a decision [e.g. above a pre-defined level or not] rather than to determine the actual activity. But what IS required is to accurately present the quality of the result so that the proper decision for that measurement of land area can be made. For example: if the measured activity for the nuclide of interest was a factor of 10 below the “decision limit” then even the quick and simple 30m grids with 9 measurements per 60x60m area would be adequate to prove that the area is “acceptable”, even if there was only 1 hotspot in the entire area. If most of the survey areas in the site are like this, then this simple geometry is an economical one to use. And for those few measurements that have results closer to the decision limit, those few survey areas could be recounted in a more precise method – perhaps with the detector elevated to 3m.

REFERENCES

[1] H. BECK, J DeCAMPO, C GOGOLAK; In-situ Ge(Li) and NaI(Tl) gamma-ray spectrometer; HASL-258; 1972
[7] F. BRONSON; The Uncertainty from Inhomogeneity; A Comparison between Gamma Spectroscopy of a Large Sample and Sampling Error; [in press] Presented at HPS Mid-Year Symposium, Jan 2007, Knoxville KY
[8] F. BRONSON, and V. ATRASHKEVICH; Measurement Uncertainty from In-Situ Gamma Spectroscopy of Non-homogeneous Containers and from Laboratory Assay; Proceedings of Waste Management 2007, Tucson AZ
[9] F. BRONSON; To Sample or Not to Sample – An Investigation Into the Uncertainty from Sampling Followed by Laboratory Analysis Versus In-situ Gamma Spectroscopy for Situations of Non-Uniform Radioactivity Distribution; Proceedings of Waste Management 2008, Phoenix AZ