WHITE PAPER: Technical Overview of the Probabilistic Method for Calculation of the Minimum Detectable Concentration of a Contaminant Radionuclide in Soil when Scanning Land Areas with GPS-Based Gamma Radiation Survey Systems

BACKGROUND

Since the publication of the Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) (NRC, 2000), use of global positioning systems (GPS)-based gamma radiation survey (gamma survey) techniques has become prevalent for characterizing radiological soil contamination in outdoor environments. These systems automatically record gamma radiation levels with thallium-doped sodium iodide NaI(Tl) scintillation instruments (NaI detectors) and corresponding geospatial coordinates with GPS receivers. Determination of the minimum detectable concentration (MDC) of a contaminant radionuclide in soil while scanning (scan MDC) with GPS-based gamma survey systems requires consideration of changes in detection efficiency as the NaI detector passes over a source of such contamination. This white paper summarizes a method that has been developed to generate scan MDCs with a freely accessible database interface (online calculator) provided by Environmental Restoration Group, Inc. (ERG) at the following internet address: http://www.ergoffice.com/ScanningMDC.aspx.

This method is referred to as the "probabilistic method" and involves use of the Monte Carlo N-Particle Extended (MCNPX) Transport code (LANL, 2011) to model instrument detection efficiency (number of photons detected per number of photons emitted) for various detector/source geometries. A large database of detection efficiencies has been modeled to represent a variety of gamma survey applications and potential scanning configurations (detector size, scan height, scan speed, and various sizes of contaminated soil volumes for a number of commonly encountered radionuclides). This database, along with certain modifications to the MARSSIM method for calculating scan MCDs, has been developed to make accessible to survey designers and regulators a reasonably wide range of calculated scan MDC values for the planning and design of GPS-based gamma surveys for outdoor land areas.

TECHNICAL DESCRIPTION OF THE PROBABILISTIC METHOD

The probabilistic method is detailed and evaluated at length in a peer-reviewed journal article that has been published in Health Physics (Alecksen and Whicker, 2016)[1]. This white paper provides a brief technical overview of the method for the benefit of users of the online calculator. It is limited in scope and detail, and users are referred to the Health Physics publication as cited in Footnote 1 for official documentation and any citation/referencing of the method or respectively generated scan MDC values[2].

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[1] Alecksen, T. and Whicker, R. 2016. Scan MDCs for GPS-Based Gamma Radiation Surveys. Operational Radiation Safety, Health Physics 111 (Supplement 2): S123-S132.

[2] Any citation/referencing of the probabilistic method as described in this white paper, or scan MDC values calculated with the ERG online calculator, should cite the Operational Radiation Safety/Health Physics journal article as referenced in Footnote 1.

The MCNPX modeling code is used for probabilistic simulation of photon interactions in media relevant to radiological surveys with GPS-based gamma scanning systems in outdoor environments (detector, air, contaminant radionuclide, and soil) based on various measurement geometries that may be encountered with this type of survey. Currently, scan MDC values based on the probabilistic method can be generated with the online calculator for two of the most commonly used detector types for this application (2 × 2 inch and 3 × 3 inch NaI crystal dimensions). The modeling for the probabilistic method considers detector counting efficiencies at a series of discrete lateral offsets relative to the center of a uniformly contaminated cylindrical volume of soil ("source") as shown in Figure 1. The detection efficiency at each offset geometry is used to calculate a numerical approximation of the total integrated detection efficiency of the detector as it passes over the source.

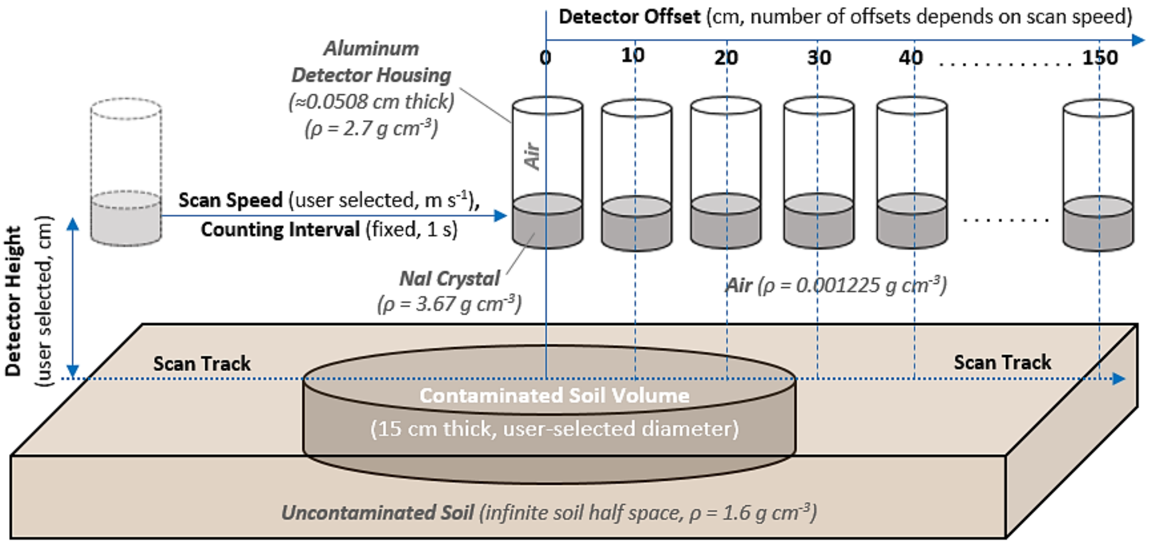

Figure 1: Annotated diagram of basic parameters/assumptions for probabilistic MCNPX modeling of NaI detection efficiency and calculation of scan MDCs for GPS-based gamma survey systems [adapted from Alecksen and Whicker (2016)].

This and other basic parameters and assumptions of MCNPX modeling and calculation of scan MDC values with the probabilistic method are depicted in Figure 1. MCNPX code selections include "analog" and "detailed physics" models, along with "pulse height tally" to simulate photon interactions in the NaI crystal. The absolute counting efficiency (ϵ) of the detector (ratio of photons detected per photons emitted from the source) is assumed to be represented by the pulse height tally. The user-selected radionuclide of interest in the contaminated soil volume (source) is assumed to contain any decay products (as applicable) in equilibrium with the parent. Other modeling assumptions and details are described in Alecksen and Whicker (2016).

Currently, the depth of contamination below the ground surface is limited to 15 cm (approximately 6 inches), but a strategic range of source diameters have been modeled as shown in Table 1. This allows the user to easily approximate a continuous curve of scan MDC values as a function of "hot spot" size (diameter) which can help survey designers make informed decisions on appropriate scan system parameters depending on the expected nature of contamination (e.g. small spills versus broadly dispersed windblown contamination, both of which may be present at a given site depending on location and site history).

Table 1: Input parameters included in the MCNPX-modeled detection efficiency database.

Detector Type	Radionuclide	Source Diameter (cm)		Detector Height (cm)	Detector Offset (cm)
2 x 2 inch NaI	^{226}Ra	20	300	10	0 to 150 in 10-cm increments
3 x 3 inch NaI	^{137}Cs	56	800	30	
	^{60}Co	100	1400 (infinite)	46	
	^{241}Am	150		100	
	^{232}Th	200			

GPS-based scanning systems provide a continuous series of discrete point estimates of the average count rate measured while scanning along a given scan path (sometimes referred to as a scan track). Successive readings are typically generated and recorded every 1 second. The distance over which the count rate is measured depends on scan speed. The probabilistic method assumes that each individual count rate reading is based on a counting interval that is statistically equivalent to an "observation interval" as described in MARSSIM, and this counting interval represents a 1-second scaler count[3]. The relative position of the fixed 1-second counting interval in relation to the source while scanning is independent of both scan speed and the horizontal dimensions (diameter) of the source of soil contamination.

As illustrated in Figure 1, discrete detector efficiency values are modeled at 10-cm offset increments from a starting point positioned directly over the center of the source to a final distance that depends on scan speed over the 1-second counting interval[4]. A large database of detection efficiencies has been modeled in this manner for all combinations of scanning scenario parameters shown in Table 1 to enable scan MDCs to be calculated for common detector types, contaminant radionuclides in soil, and various scan geometry configurations. Calculation of the scan MDC for a user-specified combination of Table 1 scan parameters is based on the radionuclide concentration in soil as calculated with the following equation (Equation 1):

$$S = \frac{C}{r * \epsilon * k * \rho * V} \qquad \text{(Equation 1)}$$

Where

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[3] Scan MDCs based on 1-second scaler counts are applicable to surveys performed with ratemeters provided that the data output interval is the same (every second), and the scan speed is slow enough or the size (diameter) of the source is large enough for the ratemeter to reach the minimum detectable count rate (MDCR) above background during any counting interval as the detector passes over the contaminated soil volume.

[4] The maximum scan speed currently included in the algorithm for calculation of scan MDCs is 1.5 m s^{-1}. This value is at the upper end of the range of typical walking speeds (PSU 2005; Knoblauch et al. 1996). Since the counting interval for GPS-based scan systems is assumed to be 1 second, 150 cm is currently the maximum modeled detector offset.

S = source concentration in soil in picocuries per gram (pCi g^{-1})
C = photon count rate in counts per minute (cpm)
ϵ = MCNPX modeled detection efficiency in photons detected/photons emitted
k = radionuclide (plus decay progeny) emission rate in photons emitted per disintegration
ρ = soil density (g cm^{-3})
r = conversion factor of 2.22 disintegrations per minute per pCi
V = volume of the source (cm^{-3})

The efficiency parameter in Equation 1 is based on a series of discrete detector efficiencies as depicted in Figure 1 (up to a 150 cm offset from the center of the source). The objective is to determine the total detection efficiency during the 1-second counting interval, and the number of individual discrete detector efficiencies considered depends on user-selected scan speed (assumed to be constant). Assuming that NaI detector efficiency varies continuously as a function of distance from the center of the source, the total detector efficiency over the distance traveled during the counting interval is mathematically described by the integral:

$$\epsilon_t = \frac{1}{x_e - x_s}\int_{x_s}^{x_e} \epsilon(x)\, dx \qquad \text{(Equation 2)}$$

Where

ϵ_t = total detector efficiency in photons detected per photons emitted over the distance x_s to x_e
x_s = starting location of the counting interval
x_e = ending location of the counting interval
$\epsilon(x)$ = detector efficiency (γ_d/γ_e) as a function of distance x from the center of the source

Because the modeled efficiencies are discrete values rather than a known continuous function of distance traveled by the detector during the counting interval, the function is numerically approximated by treating the detection efficiency between each incremental offset as an area and using trapezoidal summation to calculate the total integrated efficiency. The total detection efficiency is obtained by substituting the trapezoidal summation for the integral of the continuous function in Equation 2:

$$\epsilon_t = \frac{\Delta x}{2(x_e - x_s)}\sum_{i=s}^{e-1}(\epsilon_i + \epsilon_{i+1}) \qquad \text{(Equation 3)}$$

Where

ϵ_t = total detection efficiency ($\gamma_{detected}/\gamma_{emitted}$) over the distance x_s to x_e
x_s = starting location of the counting interval
x_e = ending location of the counting interval
s = discrete index of point (x, ϵ) at start of counting interval
e = discrete index of point (x, ϵ) at end of counting interval
Δx = change in distance x between discrete points.

Another key parameter in Equation 1 is the photon count rate. To obtain a scan MDC, this variable is based on the minimum detectable count rate (MDCR) that is statistically distinguishable from that due to expected ambient background radiation for the detector type and land areas to be surveyed. As with the MARSSIM method, an *a priori* estimate of the likely background count rate for a given detector at the site in question is necessary. The MCNPX code does not consider background radiation. The MDCR is calculated with Equation 4 as adopted from the MARSSIM method (NRC, 1998 and 2000):

$$MDCR = \mathrm{d}' * \sqrt{b_i} * \frac{60}{i} \qquad \text{(Equation 4)}$$

Where

MDCR = minimum detectable (net) count rate in cpm
b_i = number of background counts in the counting interval
d' = the index of sensitivity based on Type I and Type II decision errors.
i = the counting interval in seconds

The index of sensitivity (d’) in Equation 4 is based on statistical probabilities associated with a normal (Gaussian) data distribution. This statistical parameter modifies the MDCR to limit false positive and false negative decision errors on source detection. Appropriate limits on decision errors are selected by the user and the web-based interface for the probabilistic method database queries a corresponding value of d’ based on values published in Table 6.5 of MARSSIM (NRC, 2000). The index of sensitivity applies to counts observed by an “ideal observer” during an “observation interval” as described in MARSSIM, as well as the counts recorded by a GPS-based scanning system during a 1-second counting interval. In either case the NaI detector will behave the same in response to terrestrial gamma radiation in outdoor environments, and the counts from a properly functioning instrument can be expected to follow a Poisson data distribution that closely approximates a normal data distribution.

Because GPS-based surveys are not amenable to “pausing” every time a 1-second reading is high enough to suggest a potential source, more conservative limits on decision errors are appropriate when survey objectives include detection of small hot spots. Based on common statistical and regulatory conventions, “false positive” and “false negative” error rates of 5% each may be considered acceptable for this scenario in terms of maximizing correct detection of contamination when present, yet minimizing false positive readings. The latter consideration (false positives) is important as returning for additional (e.g. slower or static) measurements at every location where a single 1-second reading exceeds the MDCR is generally not realistic. However, if more broadly dispersed soil contamination is expected, a more lenient error rate on false positives (e.g. 60%) may be appropriate for *a priori* estimation of the scan MDC as spatial “clustering” of “positive” count rates will usually provide clear retrospective evidence of true contamination on larger spatial scales.

For GPS-based scanning systems, any potential counting interval will be random in the position of its occurrence relative to the source, and all potential counting interval positions have an equally low probability of occurrence. To help avoid calculation of scan MDCs that could result in ineffective survey design specifications (scan speed, detector height, detector size) as needed to meet survey objectives, the probabilistic method assumes that the end of the counting interval always occurs when the detector is directly over the center of the source. Of all possible counting intervals that could occur along a scan path that passes directly over the center of the source, and where the detector is at minimum positioned above some portion of the source during the interval, this particular interval is the most conservative as for any other ending position, a preceding or subsequent counting interval will always have equal or higher counts as the detector passes over the source. For a given scan speed, the total detection efficiency over this conservative counting interval is equivalent to that for a 1-second counting interval that begins with the detector positioned directly over the center of the source (as depicted in Figure 1) due to symmetry.

In cases where gamma survey objectives involve characterizing broadly dispersed soil contamination, the source will tend to have more uniform diffuse gamma fields that may approximate infinite plane source conditions. Under these conditions, the detection capabilities of the scanning system will differ from that of small hot spots. To model detection efficiency and scan MDCs with the MCNPX code for infinite plane source conditions, the diameter of the source area that represents such conditions was experimentally estimated to be approximately 14 meters based on iterative modeling of static detector response to increasing source diameters until associated static MDCs reached a plateau. Further details of infinite plane modeling and assumptions are provided in Alecksen and Whicker (2016).

In summary, Figure 2 provides a flow diagram that depicts the basic elements of the probabilistic method for calculating scan MDC values. The online scan MDC calculator automatically queries the appropriate detection efficiency database values based on user-selected parameters of detector type and height, scan speed, source diameter, and radionuclide, then calculates a corresponding MDCR and scan MDC (using Equations 1, 3 and 4).

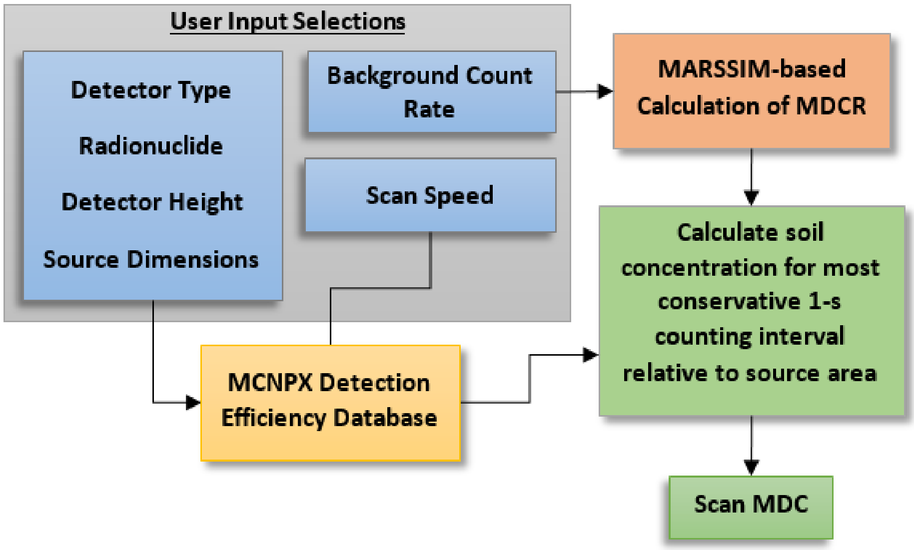

Figure 2: Flow diagram of the probabilistic method for modeling and calculation of scan MDC values.

The database interface (http://www.ergoffice.com/ScanningMDC) can be used to quickly generate scan MDC values for any combination of gamma survey design parameters indicated in Table 1. The database interface webpage is freely accessible to the public and is intended for use by survey designers and regulators. Additional gamma survey planning/design parameter selections (e.g. additional radionuclides, scan speeds, and possibly additional detector heights and detector sizes) may be added to the database in the future to allow calculation of scan MDCs for a wider range of gamma survey scenarios and objectives. Suggestions or special requests may be considered, and can be directed to Tyler Alecksen (tyleralecksen@ergoffice.com) or Randy Whicker (randywhicker@ergoffice.com) at Environmental Restoration Group, Inc. (ERG).

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