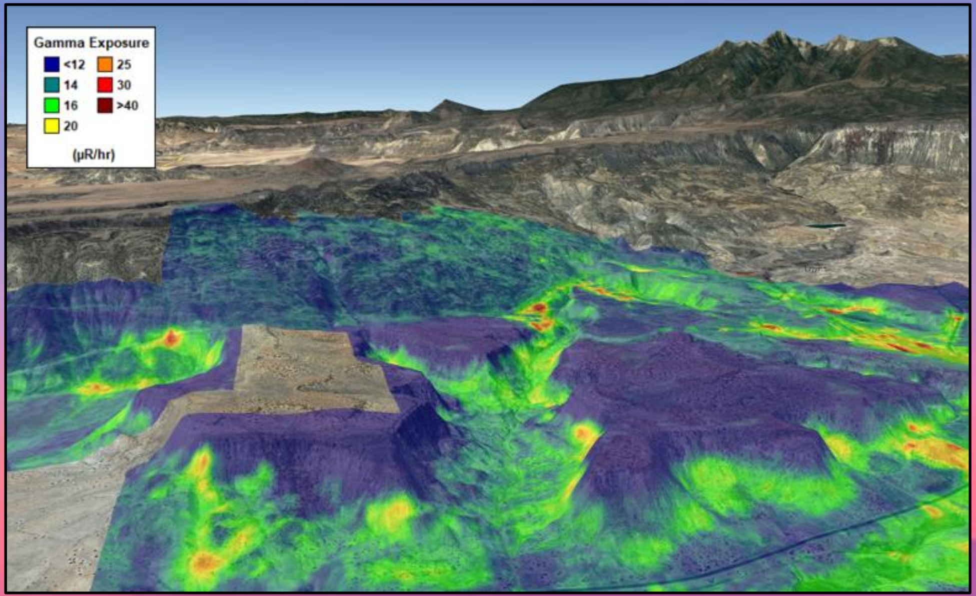
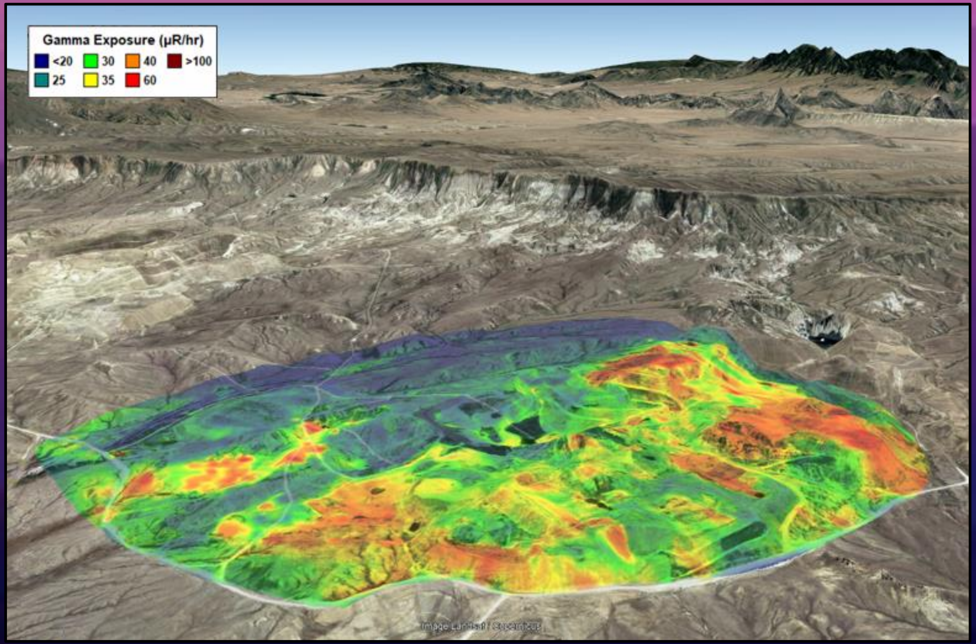
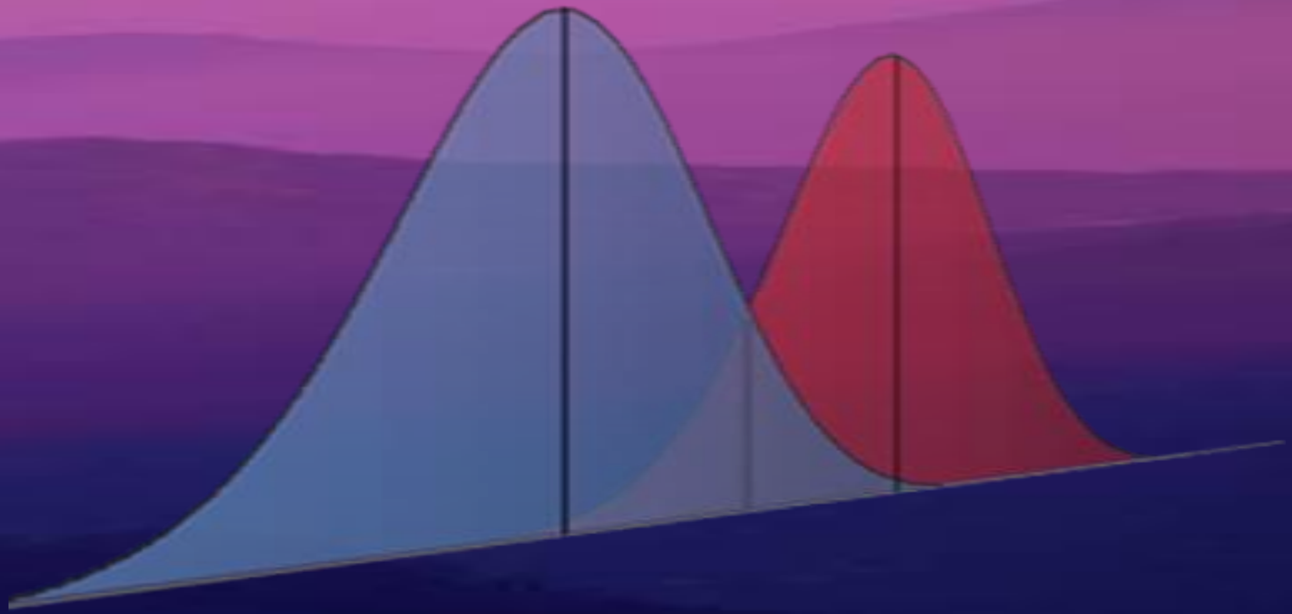




Detection Sensitivity for Digital, GPS-Based Gamma Surveys

Tyler Alecksen and Randy Whicker

Presented by: Patrick Hendrickson
Environmental Restoration Group, Inc.



Introduction

- Terrestrial gamma radiation surveys important for licensing/decommissioning of uranium recovery facilities under NRC and Agreement State regulations and guidance.

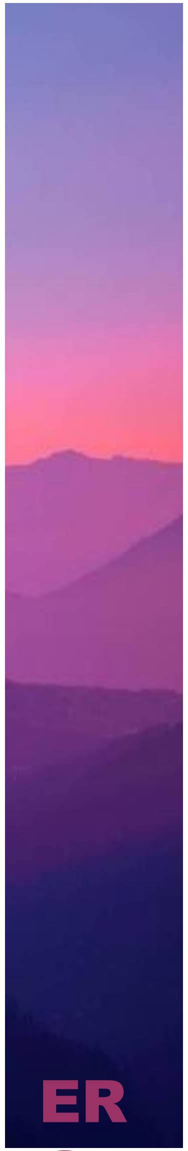
- Also important to address abandoned uranium mines under EPA and DOE Office of Legacy Management programs.

- Regulatory guidance from the Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) (USNRC, 2000) commonly cited by these agencies.

- Under MARSSIM guidelines, gamma surveys at uranium sites must be sensitive enough to detect Ra-226 in surface soils at concentrations at or below regulatory release criteria.

- MARSSIM provides a method for calculation of the minimum detectable concentration (MDC) in soil while scanning (scan MDC) with a traditional manual technique of listening to audible count rate output ("clicks") to detect hotspots in real-time while scanning.

- However, modern digital, GPS-based gamma surveys and retrospective data analysis have largely replaced the traditional survey approach described in MARSSIM.



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MARSSIM-based scan MDCs

- The scan MDC as described in MARSSIM has the following limitations:
  - Intended only for survey planning purposes based on the traditional manual scanning technique.
  - Applies to a single observation interval (e.g., 1-2 seconds) at a discrete location.
  - Highly complex to calculate for a project-specific set of scanning parameters:

MARSSIM scan MDC Calculation Approach:

Calculate the probability of interaction in the detector

$$Fluence\ rate \approx \frac{1\ \mu R/h}{(E_\gamma)\ (\mu_{en}/\rho)_{air}} \approx \frac{1}{(400)\ (0.0296)} = 0.0844$$

$$P = 1 - e^{(\mu/\rho)_{NaI}\ (x)\ (\rho_{NaI})} = 1 - e^{(0.117\ cm^2/g)(5.1\ cm)\ (3.67\ g/cm^3)} = 0.89$$

Calculate detector sensitivity using manufacturer data

$$cpm/\mu R/h,\ 400\ keV = (900) * \frac{0.0750}{0.0396} = 1{,}700\ cpm/\mu R/h$$

Calculate the minimum detectable count rate for **ideal surveyor**

(1) b_i = (4,000 cpm)*(1 sec)*(1 min/60 sec) = 66.7 counts

(2) MDCR = (1.38)*(√66.7)*(60 sec/1 min) = 680 cpm

(3) $MDCR_{surveyor}$ = 680/√0.5 = 960 cpm

Use ratio to convert MDCR to exposure

$$Minimum\ detectable\ exposure\ rate = \frac{960\ cpm}{350\ cpm/\mu R/h} = 2.73\ \mu R/h$$

Use Microshield® to calculate arbitrary soil concentration

$$(5\ pCi/g) * (1.6\ g/cm^3) * (1\ \mu Ci/10^6\ pCi) = 8E{-}6\ \mu Ci/cm^3$$

Use Microshield and MDCR exposure to calculate scan MDC

$$Scan\ MDC = (5\ pCi/g) * \frac{2.73\ \mu R/h}{1.307\ \mu R/h} = 10.4\ pCi/g$$

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MARSSIM-based scan MDCs

- Calculation of MARSSIM-based scan MDCs not practical for most users:
  - overly complex, requires special expertise
  - requires expensive Micro-Shield® software
- Instead, survey planners have previously cited scan MDC values from Table 6.7 in MARSSIM, even though these values apply only to a fixed set of scan parameters:
  - background count rate = 10,000 cpm (for 2” x 2” NaI detector)
  - detector height = 10 cm
  - scan speed = 0.5 meters/second
  - hotspot size = 56 cm diameter
  - false positive proportion = 60%

Table 6.7 NaI(Tl) Scintillation Detector Scan MDCs for Common Radiological Contaminants[a]

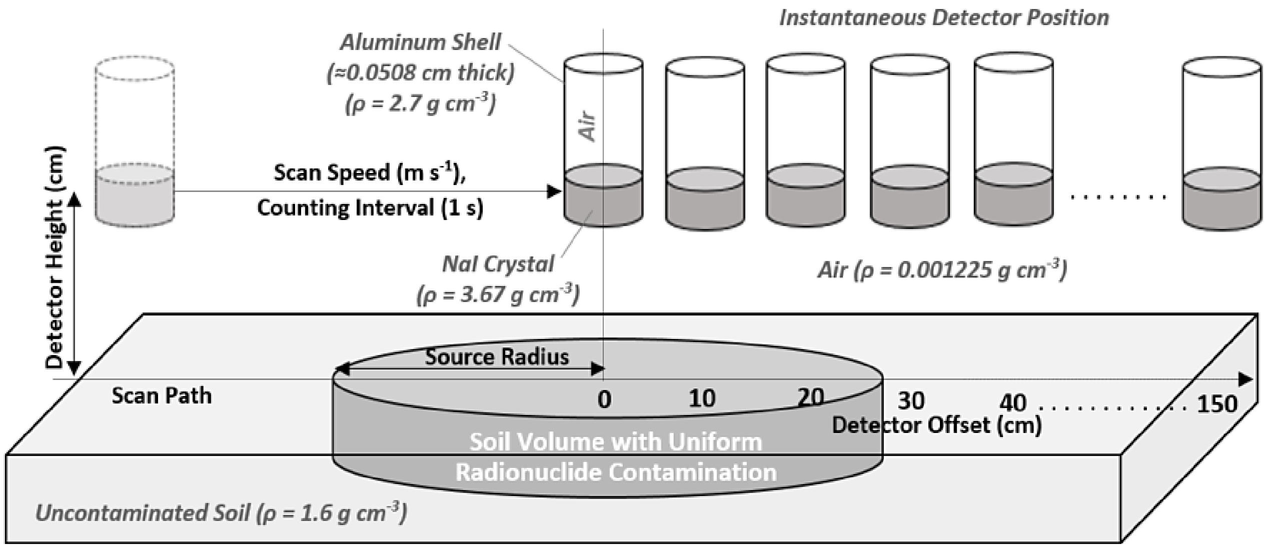
Radionuclide/Radioactive Material	1.25 in. by 1.5 in. NaI Detector		2 in. by 2 in. NaI Detector	
	Scan MDC (Bq/kg)	Weighted cpm/μR/h	Scan MDC (Bq/kg)	Weighted cpm/μR/h
Am-241	1,650	5,830	1,170	13,000
Co-60	215	160	126	430
Cs-137	385	350	237	900
Th-230	111,000	4,300	78,400	9,580
Ra-226 (in equilibrium with progeny)	167	300	104	760
Th-232 decay series (Sum of all radionuclides in he thorium decay series)	1,050	340	677	830
Th-232 (In equilibrium with progeny in decay series)	104	340	66.6	830
Depleted Uranium[b] (0.34% U-235)	2,980	1,680	2,070	3,790
Natural Uranium[b]	4,260	1,770	2,960	3,990
3% Enriched Uranium[b]	5,070	2,010	3,540	4,520
20% Enriched Uranium[b]	5,620	2,210	3,960	4,940
50% Enriched Uranium[b]	6,220	2,240	4,370	5,010
75% Enriched Uranium[b]	6,960	2,250	4,880	5,030

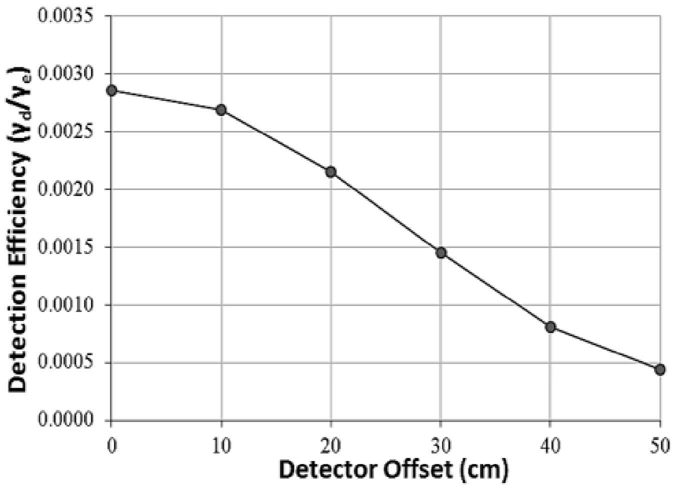
Probabilistic Method for Calculation of Scan MDCs

- In 2016, ERG published a “Probabilistic Method” for calculation of scan MDCs specifically for digitally recorded, GPS-based gamma surveys:
  - ❑ *Alecksen, T. and Whicker, R. 2016. Scan MDCs for GPS-Based Gamma Radiation Surveys. Operational Radiation Safety, Health Physics 111 (Supplement 2): S123-S132.*
- ERG hosts a companion scan MDC calculator online, freely available for public use at:
  - ❑ *https://ergoffice.com/erg-calculator/*
- The Probabilistic Method and companion scan MDC calculator enable survey planners and regulators to easily calculate scan MDCs for common radionuclides of interest across a wide range of potential scanning parameters (e.g., detector type, height, scan speed, etc.).
- Does not require specialized expertise or expensive modeling software for calculations.
- More appropriate method to simulate detector response to a source while scanning.

Probabilistic Method for Calculation of Scan MDCs

- Probabilistic Method based on modeled detection efficiency as the detector passes over a contaminated soil volume source (hotspot):





- Monte Carlo N-Particle Extended (MCNPX) software (LANL, 2011) used to model 4,520 combinations of different scanning parameters (e.g., detector type, radionuclide, source radius, detector height, detector offset, etc.).
- Modeled efficiency results stored in a relational database used by the scan MDC calculator.

Probabilistic Method for Calculation of Scan MDCs

- Probabilistic Method simplistic, combines integrated detection efficiency as the detector passes over a source with the Minimum Detectable Count Rate (MDCR) as defined in MARSSIM:

Probabilistic Method Approach

$$S = \frac{C}{r * \epsilon * k * \rho * V}$$

S = source concentration in soil in Becquerel per kilogram (Bq kg^{-1})

C = photon count rate in counts per minute (cpm), defined at the MDCR (see below)

ϵ = MCNPX modeled detection efficiency in photons detected/photons emitted

k = radionuclide gamma emission rate in photons emitted per disintegration

ρ = soil density (kg cm^{-3})

r = conversion factor of 60 disintegrations per minute per Bq

V = volume of the source (cm^{-3})

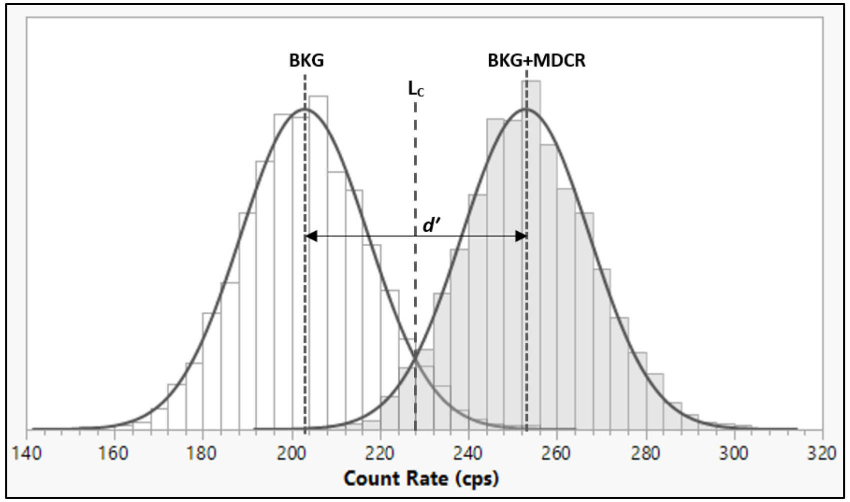
$$C = MDCR = \mathrm{d}' * \sqrt{b_i} * \frac{60}{i}$$

MDCR = minimum detectable (net) count rate in cpm

b_i = number of background counts in the observation interval

d' = the index of sensitivity based on Type I and Type II decision errors.

i = the observation interval in seconds



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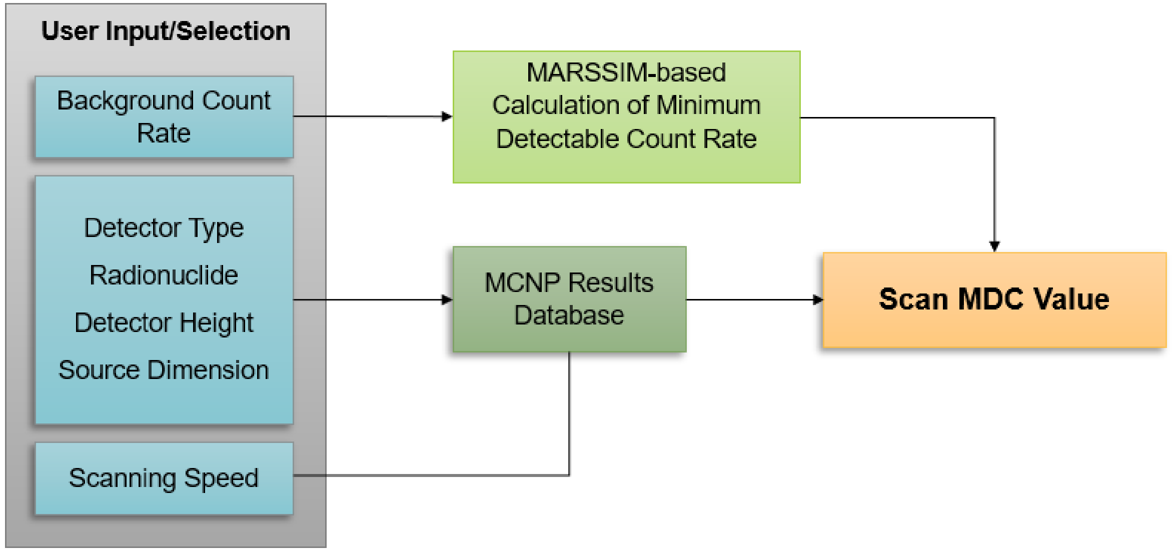
Probabilistic Method for Calculation of Scan MDCs

- Summary of Probabilistic Method and companion scan MDC calculator approach:



- Accounts for scattered photons from volumetric sources, avoids reliance on sensitivity values based on detector response to point sources.
- For small hotspots and low-energy photon emissions, generally produces higher scan MDCs than MARSSIM Table 6.7 values given identical scanning parameters.
- For larger hotspots and broadly dispersed soil contamination, generally produces lower scan MDCs than MARSSIM Table 6.7 values given identical scanning parameters.

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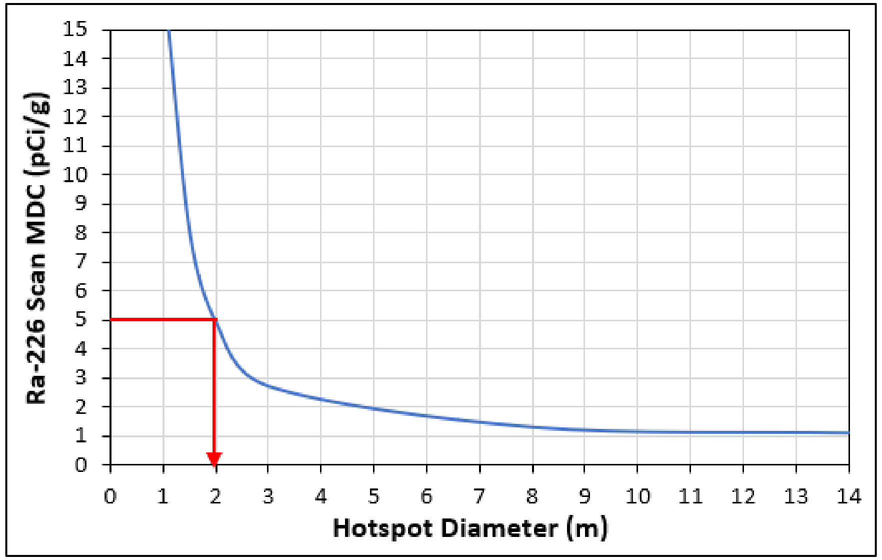
Probabilistic Method for Calculation of Scan MDCs

- **How can the Probabilistic Method benefit the uranium recovery industry?**

Example Application:

- ➢ 10 CFR 40, Appendix A, Criterion 6 specifies soil release criteria for unrestricted use.
- ➢ Release criterion for Ra-226 in surface soil (0-15 cm) is an average of 5 pCi/g above background for any 100 m^2 area.
- ➢ Curve of scan MDCs for digital gamma survey data as a function of hotspot size generated with Probabilistic Method and companion online scan MDC calculator (example graph shown).



- ➢ This curve shows that the specified gamma survey method can detect Ra-226 at 5 pCi/g above background for a hotspot as small as 2 meters diameter (areal extent of 3.14 m^2).
- ➢ This survey assessment tool shows that the sensitivity of the specified gamma survey method (detector type, height, scan speed, etc.) meets the data quality objectives (DQOs) for the final status survey.

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Validation of Statistical Basis for Probabilistic Method

- Revision 1 of NUREG-1507 (USNRC, 2020) states that the MDCR equation does not apply to a posteriori (digitally recorded) scan data.

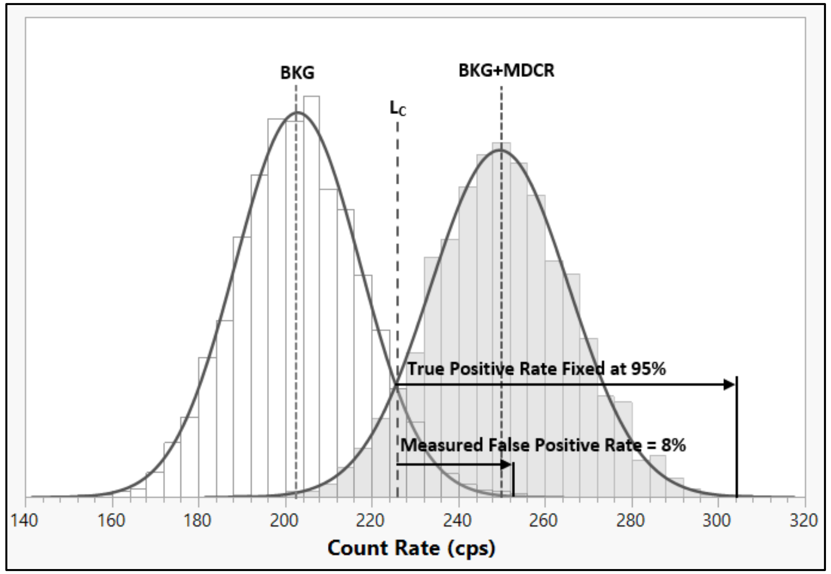
- In 2023, ERG published the results of empirical testing to determine whether the use of the MDCR in the Probabilistic Method is a statistically valid application of the MDCR concept for digitally recorded gamma survey data:

  - *Alecksen, T. and Whicker, R. 2023. Retrospective Detection Sensitivity for GPS-Based Gamma Radiation Surveys. Health Physics Volume 124, No. 6: 451-461; June 2023.*

- Results indicate that digital data distributions for 1-second scaler counts of background and a Ra-226 soil reference source precisely follow the statistical basis for the MDCR.

- Slight difference in the measured versus expected false positive error rate (3%) was due to slight differences in variance between the two data distributions.

- These findings indicate that the Probabilistic Method can be used to calculate valid scan MDCs on both a prospective (a priori) and retrospective (a posteriori) basis.



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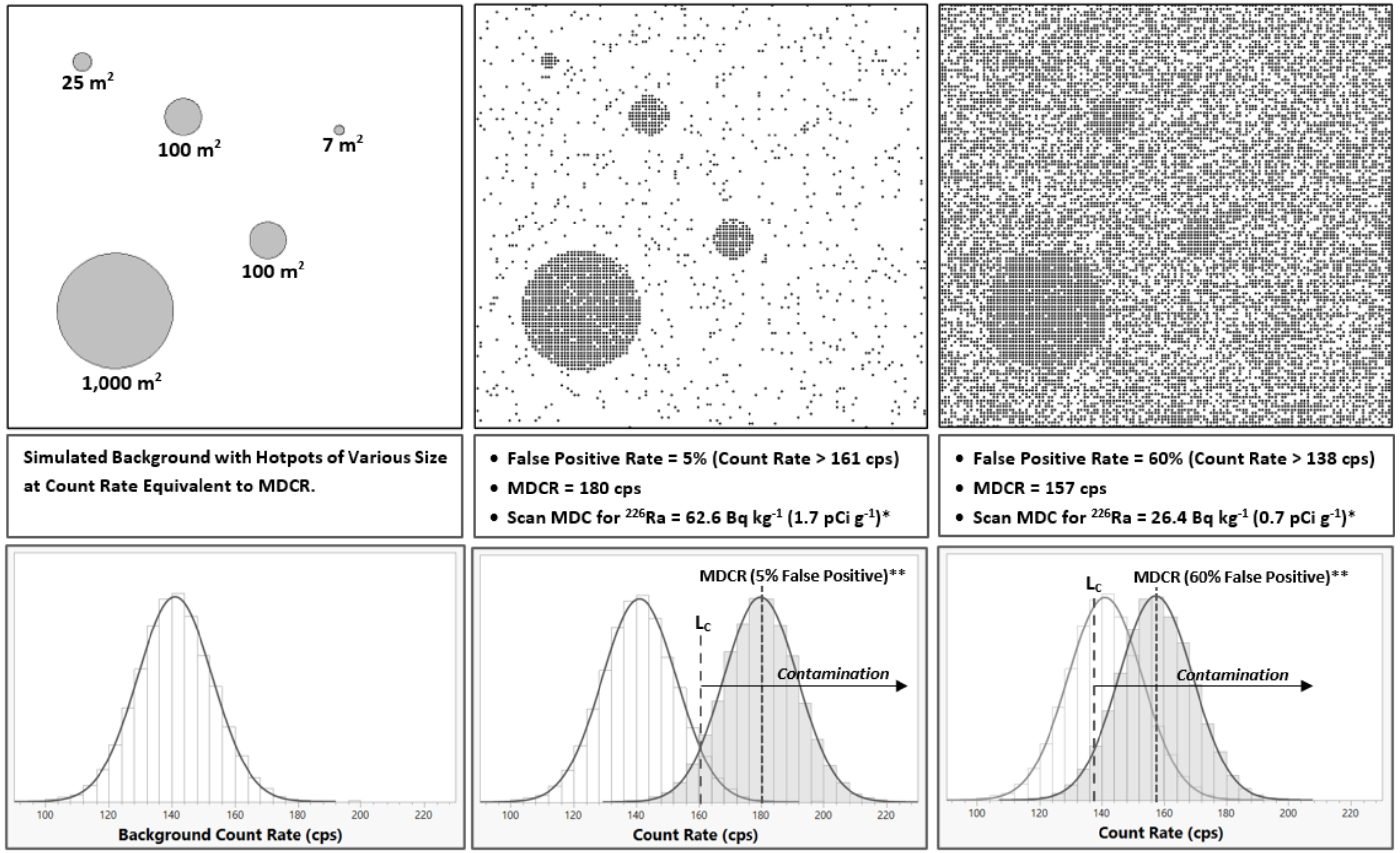
Retrospective Detection Sensitivity for Digital Gamma Surveys

- ERG's 2023 publication also describes retrospective quantification of scan sensitivity metrics based on spatial autocorrelation (clustering) of multiple scan readings in excess of the MDCR.

  - This figure illustrates the distributional meaning of the false positive error rate and implications for identification of hotspots of various size.

  - For larger hotpots, spatial clustering of data in excess of the MDCR justifies a higher tolerance for false positive errors, resulting in more realistic (lower) scan MDCs. However, high false positive conditions reduces ability to detect smaller hotspots.



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Effects of Nearest Neighbor Averaging on Detection Sensitivity

- Under the central limit theorem, post-processing of digital gamma survey datasets based on nearest neighbor averaging preserves mean values for the background and source distributions but reduces variance and overlap.

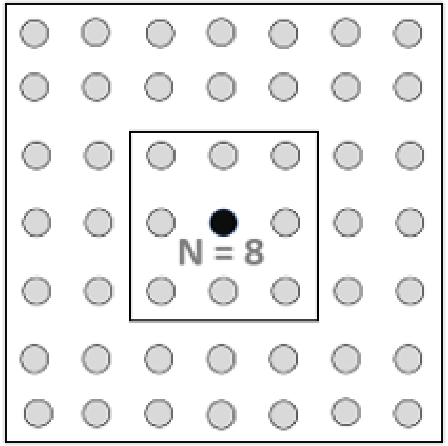
- This permits modification of the MDCR equation to account for reductions in variance depending on the number of nearest neighbors used in the averaging.

- In general, improves spatial resolution and retrospective identification of hotspots.

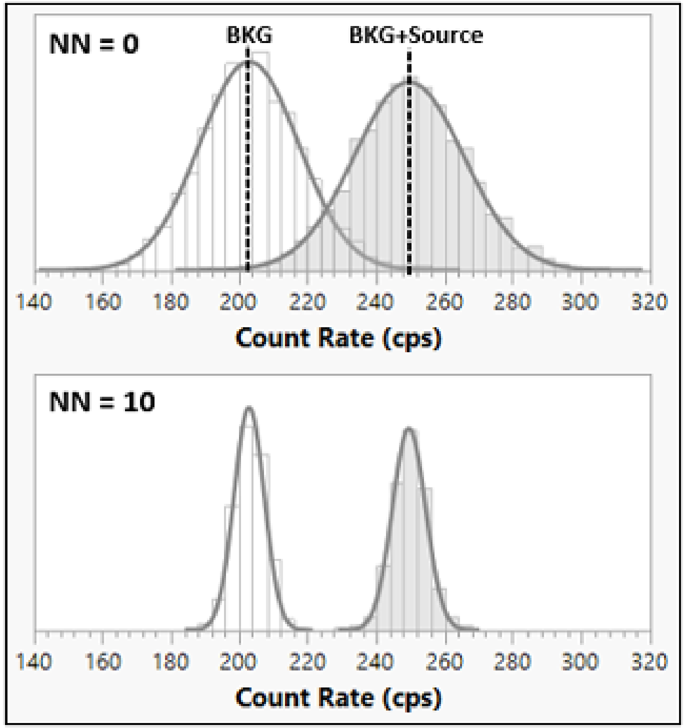
- Limitations include potential to obscure small hotspots, and applicability only to nearest neighbor averaged datasets.

$$MDCR = \frac{d' * \sqrt{b_i} * 60}{i * \sqrt{N+1}}$$

Where N = number of nearest neighbor data points used for averaging, with replacement.



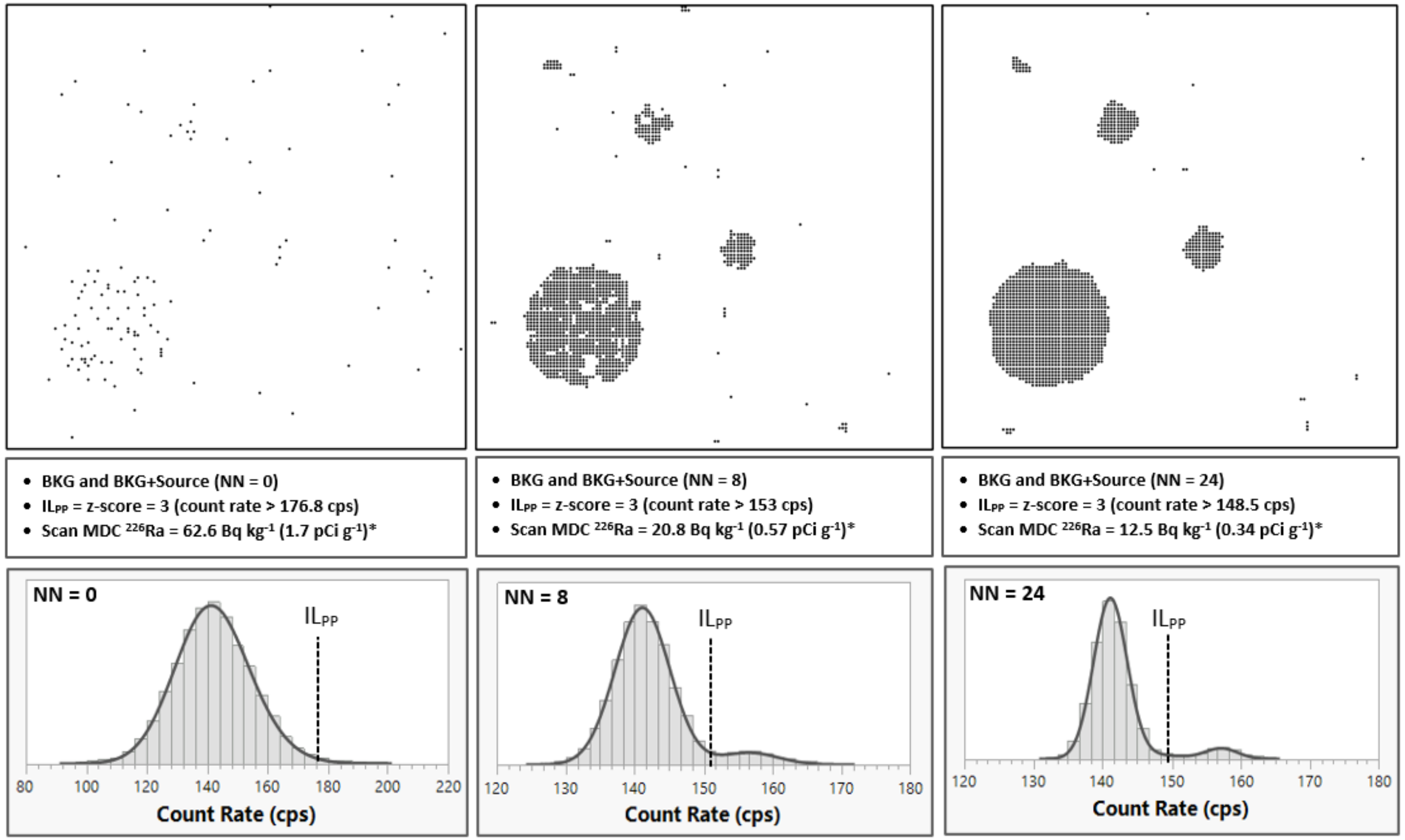
Nearest neighbor averaging example.



Distributional effects of nearest neighbor averaging.

Effects of Nearest Neighbor Averaging on Detection Sensitivity

- "Investigation levels" for post-processed datasets ("IL_{PP}") as described in NUREG-1507 can be applied to nearest neighbor averaged datasets. This enables identification of hotspots that exceed a specified IL_{PP} threshold.
- Improved resolution of hotspots due to variance reductions for background and source distributions proportional to the number of nearest neighbors used in the averaging.
- This technique generally improves retrospective identification of all but the smallest hotspots.



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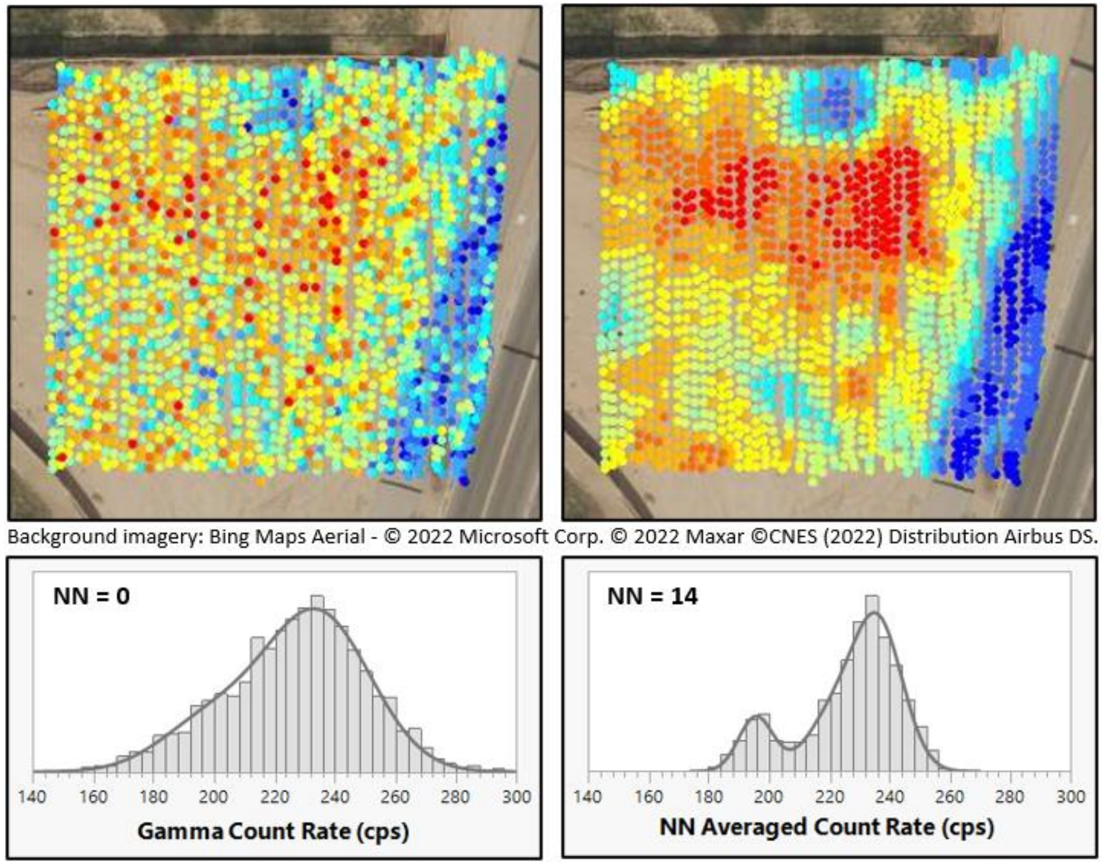
Effects of Nearest Neighbor Averaging on Detection Sensitivity

- An empirical demonstration of visual and distributional effects of nearest neighbor averaging is shown in the figure at right.
- Reduced variance improves visual resolution of subtle spatial patterns in the data.
- Reveals underlying bimodal distribution with two distinct populations of values.
- Similar effects possible with data interpolation techniques such as geostatistical kriging.



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Summary and Conclusions

- Gamma surveys at uranium sites must be sensitive enough to detect Ra-226 in surface soils at concentrations at or below regulatory release criteria.
- MARSSIM guidance for calculation of scan MDCs limited to prospective planning for the traditional, manual scanning technique of listening to audible count rate output to detect hotspots in real time while scanning.
- Modern digital, GPS-based gamma surveys and retrospective data analysis have largely replaced the traditional survey approach described in MARSSIM.
- ERG has published a Probabilistic Method for calculation of scan MDCs for digital, GPS-based gamma surveys (Aleckson and Whicker, 2016) and hosts a companion scan MDC calculator online (freely available for public use at: https://ergoffice.com/erg-calculator/).
- ERG has also published methods for retrospective quantification of scan MDCs based on spatial clustering of data that exceed the MDCR, and nearest neighbor averaging of macroscopic datasets to reduce variance and overlap in the background and source data distributions (Aleckson and Whicker, 2023).

Questions?

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

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