Reconstruction of the Spatial Distribution of Surface Activity Concentration for an In-Situ, Gamma-Ray, Truck-borne Survey

by

François Marshall, B.Sc.

A thesis submitted to the
Faculty of Graduate and Postdoctoral Affairs
in partial fulfillment of the requirements for the degree of

Master of Science in Medical Physics

Ottawa-Carleton Institute for Physics
Department of Physics
Carleton University
Ottawa, Ontario
September, 2014

©Copyright
François Marshall, 2014

Abstract

In 2012, three test detonations of a radiological dispersal device (RDD) were performed at the experimental proving ground of Defence Research and Development Canada (DRDC) in Suffield, Alberta. These were the first outdoor detonations of a radioactive source in an outdoor environment. The purpose of these exercises was to characterize the effects of an RDD in the uncontrolled environment, so as to properly model the contamination as it would likely appear in the real situation of a terrorist attack. For example, wind transport affects the plume deposition distribution. A number of government research teams were involved in the experiments.

The RDD source was ^{140}La . A suite of in-situ instruments were set up to monitor the blast dynamics and the plume deposition distribution. The Nuclear Emergency Response Team (NERT) of Natural Resources Canada performed two mobile surveys of the plume distribution to reconstruct a map of the spatial distribution of surface activity concentration at the time of the blast. One of these was an airborne survey, which involves using detectors of thallium-activated sodium iodide ($\text{Na}(\text{Tl})$) to measure the count rate of gamma emissions from the distributed source. The survey provides a detailed map of the surface activity concentration, but only based on estimations associated with large spatial resolution. To improve on this, the truck-borne survey is essential because its sensitivity is confined to a more localized area of space, and its detection system is directional (it is called a directional spectrometer). With four standing crystals of $\text{NaI}(\text{Tl})$, this detection system offers data that, with the aid of Monte Carlo, can be used to reconstruct an averaged measure of the local surface activity concentration around the survey path of the truck.

Using the Electron Gamma Shower code of the National Research Council of Canada (EGSnrc), the sensitivity of the truck-borne spectrometer was determined for finite disc sources of successively increasing size. The asymptote value of the sensitivity was used in a conversion factor to scale all the count rate values of the truck path into average values of the surface activity concentration. The result of

the analysis was a map of the surface activity concentration for a dataset from on June 6th, 2012. The surface activity concentration decreases from 140 kBq/m² to 20 kBq/m² over $\mathcal{O}(1)$ km of ground zero.

A spatial deconvolution technique was developed in order to simultaneously make use of the count rates from all the crystals of the directional spectrometers in a sample of the survey path. EGSnrc simulations were performed for a static array of truck-borne spectrometers and 20 m $\times$ 20 m pixel sources to determine the array responses for pixel sources at different regions of space in a 120 m $\times$ 120 m field of interest. Then, the system function for this setup was assumed to be linear. By fitting the survey-path array response with these individual, simulated, array responses, the relative importance of those regions of space could be reconstructed for the true distribution. The result of this analysis was a pixelized map of surface activity concentration for a field of interest around the survey path. The reconstructed distribution is in agreement with the reconstruction from the spatial averaging method, but has better spatial resolution.

In this thesis, after introducing the RDD experiment, results from the truck-borne spectrometer surveys will be shown for both the spatial averaging and the spatial deconvolution methods.

This dissertation is dedicated to my supervisor, Dr. Laurel Sinclair, for her generous support throughout the degree. Also, it is dedicated to Dr. Alain Bellerive, whose support has been instrumental in my proress. Finally, it is dedicated to my family and friends for their support.

Acknowledgments

I would like to acknowledge my supervisor, Dr. Laurel Sinclair, for her excellent advice, and for her encouragement to pursue innovative approaches. Also, particular thanks to members of the NERT for allowing me to participate in their activities and to conduct: data analysis meetings; field work; training; a conference, and exercises. I would like to thank the following members of the NERT: Dr. David McCormack; Nina Plouffe; Dr. Audrey MacLeod; John Buckle; Richard Fortin; Dr. Henry Seywerd; Maurice Coyle; Doug Oneschuk; Reid van Brabant; Brad Harvey; Alain Grenier; and John Carson.

I am also grateful to my nominal co-supervisor, Dr. Alain Bellerive; he organized meetings to ensure that the work was progressing.

I would like to thank Dr. Dave Rogers for his instruction of the EGSnrc course of winter 2013, as well as the Carleton faculty who taught my graduate courses from in 2012 and 2013.

In the Carleton University department of physics, the system and networks administrator, Bill Jack, was crucial in helping with the use of the Carleton computer cluster to run EGSnrc in batch mode with the use of a script to iterate over several input files.

Lorne Erhardt, from DRDC-Ottawa, led the trials. D. Quayle, from Health Canada, and A.R. Green, from DRDC-Suffield, were instrumental in making the RDD trials run. The whole NRCan Nuclear Emergency Response team carried out the data collection of mobile surveys: L. Sinclair, R. Fortin, J. Buckle, H. Seywerd, R. van Brabant, M. Coyle, B. Harvey, M. McCurdy and special guest J. Rollings from Health Canada.

The DRDC Canadian Safety and Security Program funded the RDD trials under the project number, CRTI 07-0103RD. My research affiliate salary was a CSSP-funded community development project.

In addition, I would like to acknowledge the help of fellow graduate students at

Carleton who listened to presentations, and offered comments and advice: Paul Prior; Sarah Cuddy-Walsh; Simin Razavi; Leila Lukhumaidze. Marc Chamberlain helped with the installation of computer software.

Finally, a special thanks to my family and friends.

Statement of Originality

In the Suffield experiments, some of the field data were obtained by the Nuclear Emergency Response Team. Participants of the NERT were: L. Sinclair, R. Fortin, J. Buckle, H. Seywerd, R. van Brabant, M. Coyle, B. Harvey, M. McCurdy and J. Rollings. The field data of the NERT includes the airborne and truck-borne datasets, as well as the SAM 940 handheld measurements for ground truth. In lieu of participating in the data acquisition at the Suffield experiments, I participated in an emergency response exercise at the Darlington nuclear power plant, using a similar survey system. Dr. Laurel Sinclair, Richard Fortin, Dr. Henry Seywerd, and myself were involved in setting up the truck calibration experiment at the Shirley's Bay branch of Defence Research and Development Canada, in Ottawa. I helped to monitor the fluctuations of the spectrum being acquired in the RadAssist live-time display, and to set up the equipment for the experiment.

Dr. Sinclair devised the method of spatial averaging, which involved using the infinite plane method for discs of large radii to extract an asymptote from Monte Carlo data. The method followed from calculations of the surface activity concentration that were performed for xenon-133 along the west coast of Canada, in the aftermath of Fukushima [1]. My contribution was to create a detailed representation of the directional spectrometer in EGSnrc. Using different truck-borne systems, Dr. Sinclair and I performed independent analyses to examine the dependence of the reconstructed distribution on different systematic effects, such as the differences between a spherical and rectangular gross-count detection system, or alternative models of the truck that produced good agreement with the true response of the directional system. Her code was based on the “tutor7pp.cpp” tutor code of EGSnrc, while mine was also based on this example. I determined the level of uncertainty present due to ambiguity of the truck mass distribution, and I conducted analyses to determine the variation of the fit value of the sensitivity asymptote in response to modifications of the fitting range for the sensitivity equation.

Dr. Sinclair devised a spatial deconvolution method, which involved treating the surface activity concentration of every pixel of an image as a free parameter in a fit. I suggested a formalism for this method, based on the notation of [2]. Lag correction is standard for analyses of mobile, in situ, geophysical surveys; however, averaging the

spatial coordinates and the crystal responses of the truck-borne, directional spectrometers was Dr. Sinclair's idea. In this analysis, I had the responsibility of comparing my reconstruction of the spatial distribution of surface activity concentration with Dr. Sinclair's version for this same reconstruction. As with the infinite plane calculation, the extent of the experimental uncertainties was examined. Discussion of this comparison is reserved for [3]. In addition to the systematic uncertainties caused by ambiguity in the truck mass distribution, I conducted other simulations, in which the level of subtracted background or the spatial positioning of averaged truck-borne spectrometers was varied. It was my idea to use asymmetric errors to characterize the uncertainty, since the MIGRAD errors broke down for bound parameters in the least-squares fit. This calculation was based on the proposed analysis of [4], and Dr. Sinclair decided that MINOS should be used to complement MIGRAD. This is the standard MINUIT method for determining errors, which copes with the constraints of tightly-bound parameters.

Contents

Abstract	ii
Acknowledgments	v
Table of Contents	ix
List of Tables	xii
List of Figures	xiii
Nomenclature	xvi
1 Introduction	1
1.1 Context of the Radiological Dispersal Device	1
1.2 The Federal Nuclear Emergency Plan and The Nuclear Emergency Response Team	2
1.3 Mobile Surveys	5
1.3.1 Motivation	5
1.3.2 Directional Systems	5
1.4 Thesis Structure	9
2 Experimental Setup	10
2.1 Full-Scale Experiments for a Radiological Dispersal Device	10
2.2 Field Setup	11
2.3 The RDD Source	11
2.4 Field-Trial Measurement Systems	13
2.5 Airborne, Mobile Surveys	17
2.6 Truck-borne, Mobile Surveys	19

2.6.1	The Truck-borne Mobile Survey System	19
2.6.2	Interactions of Gamma Rays in NaI	24
2.6.3	Energy Resolution and Selection of Bounds on Photopeak Integration	28
2.6.4	Background Subtraction	28
2.6.5	Decay Correction	31
2.6.6	Lag Correction	32
2.6.7	Spatial Averaging	33
2.6.8	Response Maps	35
3	Reconstructing the Truck-borne, Directional Spectrometer in Simulation	39
3.1	Modelling the Directional Spectrometer in EGSnrc	39
3.2	Particle Sources	43
3.3	Photon Transport, Particle Scoring, and Generated Output	44
3.4	Obtaining an Accurate Model of the Simulated Truck Design using a Calibration Experiment	45
4	Reconstruction by Spatial Averaging: The Infinite Plane Approximation	56
4.1	The Infinite Plane Method	57
4.2	Determination of a Conversion Factor for Surface Activity Concentration	59
4.3	Systematic Uncertainties Affecting the Conversion Factor	64
4.4	Application to the RDD Datasets	68
5	The Spatial Deconvolution Method: Reconstructing the Local Distribution of Surface Activity Concentration	73
5.1	Theory: The Spatial Deconvolution Method	74
5.1.1	Setup of the Problem	74
5.1.2	Linear Systems	75
5.1.3	The Spatial Deconvolution Method	75
5.2	The Experimental Dataset	78
5.3	Monte Carlo Simulations of Template Sources	80
5.4	Implementation of the Method	81
5.5	Reconstruction of Artificial Source Distributions	84

5.5.1	Pixel Source Distributions	84
5.5.2	Rectangular Source Distribution	87
5.5.3	Extended Rectangular Source Distribution	91
5.6	Application of the Spatial Deconvolution Method to the Suffield Dataset of June 6th	96
5.6.1	Reconstruction for the Map of the Central Values	96
5.6.2	Statistical Uncertainties	98
5.6.3	Systematic Uncertainties	101
5.6.4	Net Systematic Uncertainties	106
6	Conclusion	109
6.1	The Infinite Plane Calculation	109
6.2	The Spatial Deconvolution Method	110
6.3	Comparison the Spatial Deconvolution Results with Results of the In- finite Plane Calculation	111
6.4	Further Improvements	113
6.5	Closing Comments	114
	List of References	116
	Appendix A EGSnrc Directional Spectrometer Geometry	119
	Appendix B Truck Designs in EGSnrc for the DRDC Experiments	124
	Appendix C Smearing Code for EGSnrc Pulse Height Distribution	127
	Appendix D Validation of the Method: Comparison with Theoretical Constraints	130
D.0.1	Limiting Bounds on the Sensitivity Profile: Efficiency Consid- erations	130

List of Tables

2.1	RSX-1 Specifications	21
2.2	Cross Sections of the Primary Interaction Mechanisms for 1.6 MeV Photons incident on NaI	25
2.3	NORM Peaks in the Background Spectrum	28
3.1	Material Properties of a Simulation RSX-1 Log	41
3.2	Parameter Selection for Photon Transport	44
3.3	Order of Events for the DRDC Calibration Experiment	48
4.1	Setup of EGSnrc for Simulations of Uniformly Populated Disc Sources of Isotropic Emitters	60
4.2	Amplitudes and Asymptotes for Fits of the Sensitivity Equation to the Best Two Truck Designs	64
5.1	Setup of EGSnrc Parameters for the Simulation of a Pixel Source . .	80
5.2	Setup of MIGRAD for Parameter Optimization	84
5.3	Reconstructed Surface Activity Concentrations for Pixel Sources . . .	87
5.4	Relative Importance of Design Setup Parameters for Reconstructing the Spatial Distribution of Surface Activity Concentration	101
A.1	Methods for Efficient Interface Crossing	120
A.2	Geometry Models for Directional Spectrometer	121
B.1	Design Details for the Best Estimate of the EGSnrc Truck Design . .	125
B.2	Design Details for the Best Estimate of the EGSnrc Truck Design . .	126
D.1	Results for Directional Spectrometer of Intrinsic Efficiency	131

List of Figures

1.1	Operations Site for the Unified Response Exercise (May, 2014)	3
1.2	Helicopter Employed for Unified Response Exercise (May, 2014) . . .	4
1.3	Sprinter Truck Employed for Unified Response Exercise (May, 2014) .	4
1.4	Directional System for Truck-borne Survey during Unified Response Exercise (May, 2014)	6
1.5	Directional Spectrometer	7
2.1	RDD Test Site	12
2.2	Decay Scheme	14
2.3	Setup of Detector Arrays	16
2.4	Helicopter Detection System	18
2.5	Reconstructed Distribution of Surface Activity Concentration based on Airborne Dataset	20
2.6	RSX-1 Detector	22
2.7	Experimental Spectrum of ^{140}La	26
2.8	Background in the Experimental ^{140}La Spectrum	27
2.9	Determination of 4σ Energy Window for the 1.6 MeV Photopeak . .	29
2.10	Background Survey of June 5th	30
2.11	Distribution of Count Rate inside the 4σ Energy Window of the 1.6 MeV Photopeak of ^{140}La	31
2.12	Lag Correction	33
2.13	Spatial Averaging	34
2.14	Response Map for June 6th Dataset	36
2.15	Response Map for June 7th Dataset	37
3.1	Schematic of RSX-1 Log	40
3.2	Schematic of PMT	41
3.3	Directional Spectrometer in EGSnrc	42
3.4	Setup for the DRDC Calibration Experiment	46

3.5	Experimental Plan for Trials in the DRDC Calibration Experiment	47
3.6	Decay Curve for the Source Activity during the DRDC Calibration Experiment	49
3.7	Background Spectra of the DRDC Experiment	50
3.8	Best Estimate of the Truck Design	51
3.9	Comparison of Experimental and Simulated Spectra for DRDC Cali- bration Experiment, for the Best Simulated Estimate of Truck Design	52
3.10	Comparison of Experimental and Simulated Spectra for DRDC Cali- bration Experiment, for a Simulated Truck Design with Spread Mass Distribution	53
4.1	Profile of the Number of Primary Histories in the Disc Simulations	61
4.2	Sensitivity Curve for the Best Estimate of the Truck Design	62
4.3	Footprint of the Directional Spectrometer	63
4.4	Fits of the Sensitivity Equation to the Sensitivity Profile with Different Fitting Ranges	65
4.5	Sensitivity Curve for the Truck Design with a Spread Mass Distribution	66
4.6	One-Sigma Confidence Interval for Sensitivity Asymptote	67
4.7	Spatial Distribution of ^{140}La Surface Activity Concentration for the June 6th Suffield Dataset	69
4.8	Error Map for Reconstruction of the June 6th Dataset	70
4.9	Spatial Distribution of ^{140}La Surface Activity Concentration for the June 7th Suffield Dataset	71
4.10	Error Map for Reconstruction of the June 7th Dataset	72
5.1	Surface Activity Concentration along Sample Truck Path, based on the Infinite Plane Approximation	74
5.2	Visualization of a Linear System, as Applied to the Spatial Deconvo- lution Method	77
5.3	Experimental Array Response of the Sample Path for the Suffield Dataset	79
5.4	Array Responses for the Pixel-Source Simulations	82
5.5	Reconstruction of a Proximate Pixel Source using the Spatial Decon- volution Method	85
5.6	Reconstruction of a Remote Pixel Source using the Spatial Deconvo- lution Method	86

5.7	Reconstruction of a Rectangular Source using the Spatial Deconvolution Method	88
5.8	Negative Statistical Errors on the Rectangular Source Reconstruction	89
5.9	Positive Statistical Errors on the Rectangular Source Reconstruction	90
5.10	Reconstruction of an Extended Rectangular Source using the Spatial Deconvolution Method	92
5.11	Negative Statistical Errors on the Extended, Rectangular Source Reconstruction	94
5.12	Positive Statistical Errors on the Extended, Rectangular Source Reconstruction	95
5.13	Reconstruction of a Sample Path of the Suffield Dataset using the Spatial Deconvolution Method	97
5.14	Negative Statistical Errors on the Plume Reconstruction	99
5.15	Positive Statistical Errors on the Plume Reconstruction	100
5.16	Reconstruction of the Spatial Distribution of Surface Activity Concentration for the Suffield Dataset using a Spread Truck Mass Distribution	102
5.17	Reconstruction of the Spatial Distribution of Surface Activity Concentration for the Suffield Dataset with no Lag Correction	104
5.18	Reconstruction of the Spatial Distribution of Surface Activity Concentration for the Suffield Dataset using Higher Background	105
5.19	Map of Systematic Errors on the Reconstructed Plume Distribution of Surface Activity Concentration	107
6.1	Overlay of Reconstructed Spatial Distributions of Surface Activity Concentration	112
A.1	Composition of Poron	122
A.2	Composition of Felt	123
B.1	Best Estimate of the Truck Design	125
B.2	EGSnrc Truck Design with a Spread Distribution of Mass	126
D.1	Limiting Cases of the Sensitivity Profile based on the Exposure of the Directional Spectrometer to the Source	132

Nomenclature

Acronyms:

BC: Bound Compton

BH: Bethe-Heitler

CPU: Computer Processor Time

DND: Department of National Defence Canadian Forces

DRDC: Defence Research and Development Canada

EGSnrc: Electron Gamma Shower code of the National Research Council

FOI: Field of Interest

FNEP: Federal Nuclear Emergency Plan

GEANT 4: Geometry and Tracking, Version 4

GPS: Global Positioning System

HC: Health Canada

ISR: International Safety Research

LIDAR: Light Detection and Ranging

MCNP: Monte Carlo N-Particle code

MDT: Mountain Daylight Time

MIGRAD: Gradient Minimization processor of MINUIT

MINOS: Minimization Operations

MINUIT: Function Minimization tool of ROOT

NERT: Nuclear Emergency Response Team

NORM: Naturally-Occurring Radioactive Materials

NRCan: Natural Resources Canada

PCS: Photon Cross Sections

PEGS4: Data Preprocessor for EGS4

PMT: Photomultiplier Tube

RDD: Radiological Dispersal Device

ROOT: “OO” for Object-Oriented
RSI: Radiation Solutions, Inc.
SAC: Surface Activity Concentration
SAM: Sample Acquisition Manager
SI: Storm and Israel
SLOWPOKE: Safe Low-Power Kritical Experiment
SWORD: Software for Optimization of Radiation Detectors
UT1: Universal Transit Time, Type 1
UT: Universal Transit Time
UTC: Coordinated Universal Time
UTM: Universal Transverse Mercator

Chapter 1

Introduction

1.1 Context of the Radiological Dispersal Device

Since 9/11, the climate of defence research has been particularly sensitive to the various mechanisms used in terrorist activities. In a recent revision of Canada's Federal Nuclear Emergency Plan (FNEP), one of the goals was to conduct comprehensive research in the field of radiological dispersal devices (RDDs) [5]. An RDD requires high-tech sophistication in the packaging of a radioactive, dispersive material. The parameters involved in the manufacture of this device are difficult to control, so it is only in recent times that the device has become a feasible weapon design [6].

RDD events are a serious threat in light of the Goiânia accident, where some 400 individuals were contaminated after the mishandling of a teletherapy unit of 50 TBq ^{137}Cs powder [6]. This exposed the dangers of orphaned sources, in the same manner that the Litvinenko incident raised public awareness about the potential of the malicious use of radiological hazards [6]. Four of the Goiânia victims died from contamination, and many more were injured. The cause of this accident was the spread of the source via chance happenings, such as scavengers transporting the powder into areas where the source was accidentally collected in rubbish and brought to waste disposal sites [6].

With few state-owned reactors and large requirements of user-specific isotope products, a large chain of production has been set in place for the life cycle of a radionuclide. A number of parties separately transport the sources. The various levels of security, and the numerous permutations that could cause isotope loss, increase with each passing step in the production line. Therefore, it is of no great surprise that as many as 0.4 % of the total, unused 0.5 M sources are orphaned, per annum [6].

With light, dispersible material, a terrorist may easily shield the source and detonate it with a few explosives, thereby producing a high-dose area in an urban or recreational environment [7]. For example, the Hotspot code has been used to show that, via the inhalation pathway, 45 kg of TNT-equivalent (low-grade) explosives using ^{241}Am could be used to produce a 220 mSv dose after a few minutes' submersion in the warm zone [7]. When such an event occurs, it is important to understand the extent of the spatial distribution of surface activity concentration in order to help coordinate the activities of response groups. Furthermore, a longer, comprehensive analysis is required to describe the local dispersion of this activity, so that re-entry and permanent relocation are fulfilled in prompt time.

1.2 The Federal Nuclear Emergency Plan and The Nuclear Emergency Response Team

In 1984, the FNEP was established to outline an organized response plan for nuclear fall out events [5]. It explains the roles and responsibilities of the various federal organizations that deal with emergency situations, and details the collaboration procedures between the different teams. The Nuclear Emergency Response Team (NERT) is part of the Geological Survey of Canada, and is a constituent of the FNEP in partnership with Health Canada. The FNEP is updated in accordance with new incidents. For example, it was developed in 1984, in part because of the accident at Three Mile Island. There, a series of malfunctions occurred in the failsafe coolant devices, which led to overheating of the core and some levels of contamination. While the situation was contained and no one was struck ill, the event was a problematic one because of the lack of a developed strategy for public awareness. Furthermore, there was too little cohesion in the detailed analysis of the severity and extent of the contamination.

In the FNEP, it is the role of the NERT to provide the provinces with cartographic information of ground and air concentrations of the active materials [8]. The mobile systems are set up to provide rapid response to locations that do not have these services. For example, in the revised FNEP (fifth edition, endorsed in October, 2012), the ValidEx series was initiated to test the preparedness exercises set in the document [5]. The series led to a full-scale Unified Response exercise in May, 2014, where all the main FNEP members participated in the characterization of a simulated

Figure 1.1: Location of the FNEP operations base, for the full-scale Unified Response exercise. Location of Health Canada crew (tents and right trailers) and decontamination crew of AECL (leftmost truck). The site was Orono in Peterborough, Ontario (May, 2014) (Photograph taken by the author, a participant of the exercise).

fallout at Darlington nuclear power plant in Peterborough, Ontario. There, the NERT employed both airborne and groundborne surveys to determine the extent of the radioactive plume. Such capabilities are not immediately available around Toronto, so the limited information of the plume dispersion was complemented with the mobile survey maps in order to make decisions about quarantine perimeters and the spatial extremities of the contamination. Figure 1.1 shows the ground control base for the different participants in the exercise, while Figure 1.2 shows the helicopter returning from its survey mission. Figure 1.3 shows the Sprinter truck that was used for the truck-borne survey.

Figure 1.2: Helicopter that was used to conduct the airborne survey of a simulated contamination. Here, it is returning to base upon completion of a serpentine-pattern survey of the area of Peterborough, Ontario, for the full-scale Unified Response exercise (May, 2014) (Photograph taken by the author, a participant of the exercise).

Figure 1.3: Sprinter truck that was used for the truck-borne survey of the regions near Orono in Peterborough, Ontario, for the full-scale Unified Response exercise (May, 2014) (Photograph taken on August, 2013 at the Geomagnetic Laboratory by the author, on a day where airborne experiments were performed at the Geomagnetic Laboratory for the Comprehensive Test Ban Treaty).

1.3 Mobile Surveys

1.3.1 Motivation

Natural Resources Canada (NRCan) uses standard, thallium-activated sodium iodide (NaI(Tl)) detectors to measure the spectral response of gamma-ray emissions. A quantity of interest is the full-energy deposition photopeak, which is integrated to obtain the total number of full-energy depositions. The instruments are manufactured by Radiation Solutions, Inc. (RSI), and there are several designs, including the four-pack for airborne reconstruction and the ensemble used for truck-borne directional analyses.

While an airborne survey can point to the location of ground zero and describe its spread, the altitude of the NaI(Tl) spectrometers is such that the integrated peak count rates are prone to larger statistical uncertainty in reconstructing the localized distribution. Furthermore, the spatial averaging of the reconstructed surface activity concentration is over a larger area for the airborne survey than it is for a truck-borne survey. This leads to a loss of information about the localized regions of surface activity concentration, which cannot be ignored in the case of providing the accurate information required for the purposes of emergency response teams and the public itself.

1.3.2 Directional Systems

Directional systems are useful because of their versatility in the domain of mobile surveys. They may be used to characterize the spatial distribution of surface activity concentration for either localized or distributed sources. The application is powerful because real-time and post-survey analyses can be conducted to characterize the spatial extent for a variety of source configurations. This is useful for emergency response because by sampling the spatial distribution of the source, reconstruction can be performed with limited information about the initial conditions.

Figure 1.4 shows the setup of the directional system used for the truck-borne survey of the full-scale Unified Response exercise. Here, two RSI NaI(Tl) detectors (or logs) were mounted inside the Sprinter of Figure 1.3, and they were used to provide quick, detailed information of emission levels on either side of the path. It is important for defining the boundary zones on a source distribution because the survey

Figure 1.4: Directional system used in the full-scale Unified Response exercise in May, 2014 at Peterborough, Ontario. Two, strapped RSX-1 NaI(Tl) blocks are located on the far left and far right. Between these is an RSI neutron detector, were mounted at the rear of a Sprinter truck (Photograph taken by the author, a participant of the exercise).

stops along the turn-back region, or the contour of a warm zone. The other extreme occurs when the spectrometer begins to detect levels of radiation more comparable with natural background.

Recently, the NERT has been experimenting with a directional spectrometer for research with both point-like and distributed source-term morphologies. This detector is designed by Radiation Solutions, Inc., and consists of four standing logs of NaI(Tl) detectors (see Figure 1.5). Usually, the system is mounted by a forklift onto the Sprinter truck of Figure 1.3. In the Sprinter, a base is set for other detectors, such as Global Positioning System (GPS), and laptops and portal connections for WiFi. A dosimeter is normally included to provide live-time dose-rate information for control of crew safety.

Figure 1.5: Directional spectrometer used in the NERT mobile surveys. Four NaI(Tl) logs are tightly-packed in an ensemble (Photograph was taken by the author at the NRCan storage room).

The potential of a directional spectrometer is that it may describe the full, 2-D space of a sheet source based on local and azimuthal variations. In particular, the directional spectrometer is self-shielding, which means that the individual logs attenuate the signal from each other, depending on the orientation of the detection system with respect to the centre of mass of the source distribution in the sensitive Only one-dimensional approximations are possible for single-detector systems like the RadEye systems of Health Canada [9]. The potential of the directional system has been explored in recent times, particularly for the cases of point- and distributed-source reconstructions [10, 11].

1.4 Thesis Structure

In June 2012, some experiments were performed at the experimental proving ground of Defence Research and Development (DRDC) Suffield. They were the first outdoor tests involving the detonation of an active source; therefore, several of the FNEP organizations were present to take advantage of the opportunity to experiment and model the dynamics and effects of such a device in the exposed environment.

In Chapter 2, the properties of the directional, truck-borne system will be explored, such as its physical mechanisms for detection. The source in question is an RDD test source, lanthanum-140 (^{140}La), which is a gamma-beta emitter. In addition, there will be a description of the setup for the trials that took place in Suffield.

Chapter 3 will describe how the directional system is represented in the Monte Carlo code of EGSnrc. Using multiple permutations of source arrangements, spatial distributions may be inferred based on the experimental output. Thus, the simulated truck-borne spectrometer must be understood in terms of its 2π response to a radioactive source.

Chapter 4 commences a description of reconstruction of the survey datasets. The infinite plane model is a standard technique of in situ spectroscopy that defines an average surface activity concentration. This robust technique makes use of Monte Carlo calculations and the fluence-rate equation.

While the infinite plane calculation is important for fast computation of the average activity densities, the method does not provide significant information about some of the local anisotropies of surface activity concentration which occur in the vicinity of the truck. The onboard device is a directional spectrometer, and in an array of such instruments, the information from the spectral responses can be used to spatially unfold the path response profiles. This topic is covered in Chapter 5. Spatial information about the source distribution is provided in terms of a local spread of radiation about the truck path. Thus, where the infinite plane approximation could only provide a representation of the activity distribution as a series of averaged concentrations for the positions of the survey path, the truck-borne dataset offers the capability of reconstructing more intrinsic fluctuations of the activity density in the sensitive regions of the directional spectrometers.

Chapter 6 will present a summary, some conclusions, and an outlook.

Chapter 2

Experimental Setup

2.1 Full-Scale Experiments for a Radiological Dispersal Device

For RDDs, there is little experimental knowledge of the blast dynamics in the uncontrolled environment. More importantly, however, there is scarce information about the ability of mobile surveys to characterize these kinds of low-statistics plume distributions.

This lack of prior knowledge was motivation for the planning of a large-scale experiment, which came to fruition in the months of June and September of 2012, and saw a collaboration between several government research organizations. Several teams conducted independent research activities to characterize the important properties of the explosion and the deposition, including spatial activity levels and plume development.

To prepare for the full-scale trials, indoor experiments were performed using a ^{140}La source to understand its post-blast distribution in terms of the particle morphology [12]. The analyses of these data led to conclusions about the proposed setup of the detection instruments in the outdoor environment. The RDD project involved experimentation and modeling of an RDD. The trials of June 2012 were the first outdoor experiments involving the detonation of a radioactive material [9]. The plan was to attempt three shots, or detonations, of the RDD. Dates for these shots were set for June 6th, June 12th, and September 26th. With the difficulties of setup in an isolated environment, it was convenient to perform two shots in June, but the September trials were partly useful because of the differing weather conditions in the

fall. This document will present only data that was collected after the first shot.

2.2 Field Setup

For best control of the outdoor parameters, this experiment was performed in an isolated location. DRDC Suffield has a field site for experimental testing. This was an ideal location for testing the RDD because of the flat topography and the lack of spatial restrictions. Such considerations were important for retrieving the full range of dynamical properties of the explosion, but it also meant that there was unlimited potential for the mobile surveys to sample the distribution, which allowed for the subsequent reconstruction of surface activity concentration.

The other advantage of the landscape was the lack of obstruction to impede atmospheric transport. This allowed for modeling of a well-defined plume profile, with the discontinuities and dispersion almost solely dictated by the climate and weather.

The survey region was divided into two zones. A 500 m $\times$ 500 m perimeter was defined for the high-dose region around ground zero (also known as the warm zone). The second zone constituted the regions exterior to the perimeter. The truck-borne survey was conducted exclusively outside the warm zone.

Figure 2.1 shows the site of the RDD experiments. The inner circular area encloses ground zero. This circular area was inscribed inside the warm-zone boundary. In order to prevent an uncontrolled fire, it had been subjected to a controlled burn prior to the detonation experiments. The base camp was situated at a safe distance away (at top left in Figure 2.1) [9]. During the experiments, all participants wore personal protective equipment.

2.3 The RDD Source

The RDD source was the β and γ emitter ^{140}La , with 1.7 day half life [14] and activity of 1.5 Ci [9]. It was produced at the SLOWPOKE reactor of University of Alberta by irradiating a ceramic powder of La_2O_3 for 24 h to induce neutron activation reactions in the ^{139}La of the sample [12, 15]. The source was transported from Edmonton a day before the first shot [12]. The decay time of $t_{1/2} = 1.7$ days meant that it was reasonable to return to the test site a week after the experimentation that was

Figure 2.1: Aerial view of the RDD test site. ^{140}La source is located at the centre of the large circular area. The fixed-point detector array is inside the circular domain. The detectors are scattered around ground zero, ranging over the circular area. Top left, a road extends away from the circle. It crosses first a dividing line of the warm and cool zones, which is marked by the first set of vehicles and equipment to the left, away from ground zero. At the end of this track, the workstations and storage areas are installed [13](used under permissions of NRCan to copy or modify and distribute).

conducted for the plume deposition of the first shot and repeat the experiment with another shot. The excess background of the lanthanum-140 was removed from the overall background spectrum.

^{140}La is a source of gamma rays. A partial decay scheme of that shown in [15] ^{140}La is displayed in Figure 2.2. The parent spontaneously undergoes β^- decay to one of a multitude of ^{140}Ce excited states [14]. For simplicity, Figure 2.2 shows these states folded into one state, which itself is labeled as $^{140}\text{Ce}^*$. On average, the de-excitation of $^{140}\text{Ce}^*$ leads to about two gamma emissions per decay. In the full decay scheme of [15], only five emission energies are important. The probabilities of these emission energies add up to 193.7 %. Of particular interest is the 1.6 MeV emission, which was used as a marker for the number of decays of ^{140}La in unit time. Therefore, only this $^{140}\text{Ce}^*$ decay mode is illustrated in Figure 2.2.

^{140}La behaves like a good RDD source. It constitutes a lightweight, dispersible material when it is in an unstable, powder state of La_2O_3 [9]. It has a large airborne release fraction of 50 %, which is associated with a dangerous respirable fraction [7,9]. As mentioned in Section 1.1, it is the aerial pathway that is susceptible to greatest exposure in the immediate aftermath of an RDD event.

2.4 Field-Trial Measurement Systems

The RDD was detonated on June 6th, 2014, at time 09:28 Mountain Daylight Time (MDT), at a height of a few feet above ground (it was mounted on a stool top). The initial blast was followed by atmospheric transport of the plume, in which the ^{140}La was distributed over a range of ≥ 6 km. Its direction of motion was in line with the wind direction, which was blowing northeast. In the immediate aftermath, a series of detectors tracked the development of the plume. In addition, a suite of instruments measured plume deposition levels, while some detectors monitored the atmospheric conditions. The mobile systems of the NERT were only deployed once the plume had settled. Other post-blast systems measured dose rates for beta and gamma emissions, and these fixed-point detectors partially served as sampling instruments for the ground truth of the mobile surveys. The following list provides a summary of select detection systems.

Figure 2.2: Partial decay scheme of ^{140}La . The parent source spontaneously decays by β^- emission, thereby making a transition to one of the excited states of its daughter nuclide, $^{140}\text{Ce}^*$. $^{140}\text{Ce}^*$ de-excites to the ground state by emitting about two photons per decay, of which 1.6 MeV emissions occur approximately 95 times out of 200, on average. Decay and normalization schemes inspired by [15].

Instruments used in the Field Trials to Describe and Characterize the Effects of the RDD

LIDAR (DRDC Valcartier) Measured the time evolution of the cloud volume by reflecting laser light off its particulate constituents [12]. The relative backscatter was related to the cloud density, which allowed for definition of the cloud mass distribution [12].

Data-logger array (DRDC Ottawa, ISR) Connected to data-loggers, and mounted on metre-high stands, these RadEye detectors were distributed around ground zero in order to determine the azimuthal extent of the plume profile [9]. Fifty of these dataloggers were set to transmit live streaming of the events record for animation of the plume, while nine of these were shielded on the sides to monitor only the overpass of the plume with respect to the array [9].

RS 250 array (HC) Assembled outside the perimeter, these NaI(Tl) spectrometers are more sensitive than RadEyes, and they recorded the spatial extent of the plume development [9]. They measured air kerma, which is the energy imparted directly to electrons from incident gammas.

Deposition filters (HC) 0.25 m² polypropylene filters, read using an autoradiographer [12]. These sample plume deposition as a function of distance from ground zero. The density and size of the spots are used to reconstruct the particle mass and speed.

SAM 940 array (NRCan) $\varnothing$ 3" $\times$ 3" NaI(Tl), hand-held detectors for ground truth of mobile surveys.

Weather stations (DND and DRDC) Sensors and sonic anemometers were set up in the survey area to record the 2-D wind speed and direction [9].

Figure 2.3 shows the setup of the detector arrays for data that were collected near to real-time. Included are: the RadEye data-logger array; the RS-250 array; the air sampling filters, and the LIDAR system. The RS-250 array extends the polar reach of the data-logger array. The air samplers recorded plume deposition levels.

From measurements of the wind speed it was found that, during the first shot, the wind speed was (7 ± 1) m/s [12]. From the LIDAR measurements, the relative concentration of the plume was sampled to give a still-frame animation of the plume

Figure 2.3: Setup of the arrays used for detection of the plume passage, used in the immediate aftermath of the RDD explosion. The vertical axis points north, while the horizontal axis points east. The warm-zone perimeter is defined by four, filled-circle vertices. Solid diamonds show positions of the dataloggers, which extend to around 500 m radius in the two eastern quadrants, and to 100 m radial distance in the other two. Those with overlapping crosses are detectors that are shielded on all sides but the top. Radiographic air samplers (unfilled outer diamonds) were also contained within the enclosure, and were accompanied by air sampler towers (two, unfilled diamonds, with crosses). RS 250s (solid circles) extended the polar arrays outside the warm zone. The LIDAR system, which was in a truck, is labeled on the lower left. Coordinates are in easting and northing, and correspond to metric UTM units (Source: Deb Quayle, Health Canada. Used under permissions to copy or modify and distribute).

passage. The data-logger array provided accompanying animations of the expansion, with a description of the polar-development rate [12]. From these measurements, and the air kerma measurements of the RS 250s, it was found that the entirety of the cloud passed through the perimeter of the survey area within 2 s [16].

2.5 Airborne, Mobile Surveys

The NERT was responsible for the mobile surveys, which were performed after the plume had been deposited over the field. A background survey was performed over the field site on June 5th, one day ahead of the first shot. Mechanical difficulties prevented the deployment of the airborne system on the day of the first shot; however, data were collected the day after, on June 7th. Data were collected again after the second and third shots, but they will not be discussed in this dissertation.

The airborne system used a Dart Heli-Utility basket containing two NaI(Tl) logs. For optimal exposure, the crystals were laid on their sides (see Figure 2.4) [13]. A Novatel DL-V3 GPS receiver was kept onboard for centimetre-accuracy position measurements of the airborne detection system [13]. A back-up inertial navigation system (Oxford Solutions Inertial +) was used as cover for periods of weaker GPS reception or black-outs. With weaker position accuracy in the GPS altitude measurement, a laser altimeter (Riegl LD90-3800VHS-FLP) was used. GPS measures height above ellipsoid, but corrections are regularly required for topographic deviations in the altitude.

A field of interest (FOI) was filled with flight lines spaced some 20 m apart [13]. Over these paths, the helicopter flew a serpentine pattern at a constant altitude of 15 m, and the spectrometers recorded the count rate, in counts per second. The result was a plume measurement, which took the form of a raster pattern. The measurement showed the summed, 1.6 MeV peak count rates of the two logs, at all locations traversed by the helicopter. Using the summed count rates, the spatial distribution of surface activity concentration was reconstructed in a way that is analogous to the method which will be presented in Chapter 4. Figure 2.5 shows results for the detailed survey of June 7th. Using a software called Oasis Montaj, grid interpolation was performed to fill in the gaps between the reconstructed values of surface activity concentration along the survey path lines, using an interpolation technique called the minimum curvature algorithm [17]. The distribution of surface activity concentration

Figure 2.4: Airborne system, with two RSX-1 logs in the interior of the basket. Black logs are the RSX-1 detectors. The central box contains the inertial navigation system, while the box to its left holds the laser altimeter. The GPS receiver is right of the altimeter and navigation system [13](used under permissions to copy or modify and distribute).

consists of a nucleus at ground zero and a far-reaching tail extending 2 km downwind. In the warm zone, the surface activity concentration ranges from 50-100 kBq/m². In the warm zone, the spherical symmetry of deposition is indicative of the shock front of the explosion, which expanded spherically. The remaining deposition is due to wind transport. With the wind blowing steadily 40° [W of N] (measurement from the environment recording instruments), the plume was guided fairly constantly over the northwest direction [12]. As can be seen in Figure 2.5, the plume was deposited over a large distance toward the northeast, and the gradient is relatively smooth.

2.6 Truck-borne, Mobile Surveys

Scintillators have been used for particle detection since the times of Rutherford's investigations of scattering alpha particles in a ZnS crystal [18]. One of the most important moments in the field of gamma-ray spectroscopy occurred in 1948 when Hofstadter discovered that NaI(Tl) was a remarkably effective scintillation medium [19]. Since then, the material has been invaluable in a large variety of medical and environmental physics applications, including in situ surveys of contaminated areas.

2.6.1 The Truck-borne Mobile Survey System

The Truck-borne Directional Spectrometer

A directional spectrometer is defined as four standing, NaI(Tl) spectrometers, which are packed closely together. Refer back to Figure 1.5 for the image of the arrangement. The full system weighs $\mathcal{O}(100)$ kg, so it is mounted onto the truck using a forklift. For the RDD trials, a pick-up truck was used ¹.

Table 2.1 provides a summary of the important parameters of an RSX-1 detector [20]. The RSX-1 system is designed by RSI, as are several of the major platforms that the NERT uses to conduct mobile spectroscopy. For example, the airborne system is an RS700 model.

Figure 2.6 shows the interior components of an RSX-1 log. The crystal is encased in Al shielding, which is itself wrapped in the white felt padding. The outer, black

¹A 4 × 4 pickup truck was required to traverse over the terrain, but in most emergency response procedures, the Sprinter truck (see Figure 1.3) would be used because it is weather-proof.

Figure 2.5: Results of the aerial survey for the spatial distribution of surface activity concentration, in kBq/m². The data were acquired on June 7th, but these are decay-corrected to show the activity concentration map for the time of the blast (June 6th, at 09:28 MDT). Map units in easting and northing coordinates, which are displayed in units of metres [17](used under permissions to copy or modify and distribute).

Design Parameter	Specifications
Deadtime	Effectively none for $\mathcal{O}(100) - \mathcal{O}(1000)$ cps
Gain stabilization	Automatic Multipeak
Sampling rate	(0.1 - 10) s
Energy resolution	$\leq 8.5\%$ (FWHM at 662 keV)
Weight	22.7 kg
Size	$10.16 \times 10.16 \times 40.64 \text{ cm}^3$
Operating temperature	-30 - 45° C
Intrinsic efficiency	$\sim 50\%$ for 1.6 MeV gammas.

Table 2.1: RSX-1 specifications.

casing is carbon fibre, and every material has a low cross section for 1.6 MeV gammas, except for the standard Al casing. Al casing is required because NaI(Tl) is soluble. NaI(Tl) exceeds the capacity of other common scintillator materials, including CsI(Tl) (less prone to pulse pile-up from ~ 900 ns decay time) and bismuth germanate oxide (better light output, cheaper in large batches) [18].

Detection Mechanism

Primary interactions inside the active medium lead to secondary events, in which the de-exciting lattice undergoes the process of emitting visible, or scintillation, light [21]. The production of an electron-hole pair leaves the lattice structure in an excited state [18]. Diffusing electrons are captured in the conduction bands of ionic cores [18]. In pure NaI, the electron would de-excite and traverse the entire band gap to reach the ground state of the molecule and recombine with its hole; however, the transition results in a UV emission, which does not yield significant light output [21]. Tl is introduced to optimize the light yield [21]. It introduces an acceptor site for the de-exciting electron, which forces the electron to make a transition to the impurity centre [18]. To continue its de-excitation to the valence band, the electron makes a second transition, and scintillation light is emitted.

The light output of a material is the number of visible photons produced per unit of incident photon energy, via the scintillation mechanism [18]. Relative light output is defined with respect to the light output of anthracene [18]. The relative

Figure 2.6: RSX-1 detector materials. The NaI(Tl) crystal is enclosed in Al casing and felt padding. It is connected to a photomultiplier tube with steel housing, which is itself attached to a steel-enclosed analyzer, which contains the preamp and ADC. The crystal-PMT-analyzer module has been removed from its black, carbon-fibre casing, which is shown behind.

light output for NaI(Tl) is 230, which means that the crystal has high scintillation sensitivity to incoming gammas [18]. The result of the interaction of a 1.6 MeV photon with NaI(Tl) is a flash of orange light, with a spectral response peaking at 415 nm wavelength. The peak is contained in a window from 340-490 nm.

The next step in the detection mechanism is transportation of the scintillation light to the photomultiplier tube (PMT). Scintillation light is emitted isotropically, so as the scintillation radiation collides with the detector walls, it will undergo total internal reflection if it is incident on the wall at $\geq \theta_c$, where θ_c is the critical angle [18]. The crystal is hermetically encased in Al for hygroscopic protection, but the material also acts as a specular reflector [18]. Here, attenuation is neglected because crystals are transparent to their own scintillation.

Scintillation photons that make it through the glass exit window interact with the low-workfunction photocathode [21]. With Hamamatsu PMTs, typical values of photocathode quantum efficiency tend to be around 30 % [18]. The amount of photoelectric interaction in the photocathode is optimal when the wavelength of the scintillation photons is in the same range as that holding the spectral response peak of NaI(Tl) [21]. That is, its spectral sensitivity curve overlaps with the spectral response curve of the NaI(Tl) crystal, peaking around the wavelength of maximum emission (415 nm).

The dynode series is an array of dynodes connected to a circuit that consists of a chain of resistors [21]. With each passing dynode, the number of electrons is amplified, and the net amplification over the whole array is the gain of the PMT. The gain is $\mathcal{O}(10^8)$, but this value tends to fluctuate in response to high temperature gradients. A temperature fluctuation may lead to thermionic emission of electrons from the photocathode [21]. RSX-1 detectors are designed with gain stabilization capability, in the form of an algorithm called “Automatic Multipeak”. It searches for reference peaks, and relocates stray peaks by moving them over to those expected ones. However, artificial radiation can interfere in the process when the signal peak overlaps with a background peak. Then, the algorithm incorrectly moves pulses of the source peak to the location of the adjacent background peak. During experiments conducted by the NERT, gain stabilization is turned off because of this issue. This means that there is still a component to the intrinsic resolution of the energy deposition spectrum that is due to temperature variation in the PMT.

Finally, the current at the end of the PMT is a pulsed output, and it is transformed

into a digital signal by the RSI electronics.

Geographical Measurement Systems

Installed on the truck-borne setup was a NOVATel GPS user receiver, which provided standard readings of the truck position. The measurement is based on height above ellipsoid, where the Earth ellipsoid model is from the 1984 World Geodetic System (WGS84) [22]. The position is provided on the WGS84 world map. From these coordinates, the position is defined on a spherical coordinate system. For mapping purposes, it is convenient to migrate to a flat, 2-D, Cartesian system, and so the geographic data is converted to the Universal Transverse Mercator (UTM) system using the Geographiclib software package [11]. The UTM system divides the Earth into sixty numbered zones between the International Date Line and the Prime Meridian [11]. Within 1° instalments of longitude, the Earth's curvature is relatively smooth, and the projected coordinates do not deviate substantially from those of the curved space [11].

The GPS receiver also keeps track of Coordinated Universal Time (UTC) ². The UTC time of the shot of June 6th was $t = 1,338,997,110$ unix seconds.

2.6.2 Interactions of Gamma Rays in NaI

Interaction Mechanisms

Table 2.2 shows the cross sections of NaI(Tl) for 1.6 MeV gamma rays [23]. Incoherent scatter is the dominant interaction mechanism, occurring well over an order of magnitude more often than other mechanisms combined.

The RSX-1 crystals are some 36 g/cm^2 thick, which exceeds the 1.6-MeV photon interaction depth of $\frac{1}{(\frac{\mu}{\rho})_{\text{NaI(Tl)}}} = 22 \text{ g/cm}^2$ ($\mu_{\text{NaI(Tl)}}$ is the attenuation coefficient for NaI(Tl) and $\rho_{\text{NaI(Tl)}}$ is its mass density). Therefore, there is a high likelihood of interaction in the crystal [21]. Because incoherent scattering is the dominant mode of interaction inside the medium, the process of full-energy deposition inside the 1.6 MeV photopeak is caused by the multiple scattering of photons. In cases of incomplete transfer, the photons may escape to the exit window and be registered as

²UTC is measured with a particular type of second called the unix second, which corresponds to the amount of time passed since 1970.

Interaction	Cross Section (10^{-2} cm ² /g)
Coherent Scattering	0.05
Incoherent Scattering	4.28
Photoelectric Effect	0.15
Pair Production	0.11

Table 2.2: Cross sections of the primary interaction mechanisms for 1.6 MeV photons incident on NaI.

part of the Compton continuum.

¹⁴⁰La Energy Deposition Spectrum and Background

Figure 2.7 shows the averaged ¹⁴⁰La and background spectra of the crystal responses, summed over the four crystals (this is called the gross count) for a truck-borne directional spectrometer. It was acquired over a sample of truck path in the vicinity of ground zero after the first shot in the Suffield trials. This is from a location that borders the warm-zone perimeter of the survey site, so a path line extracted from this area was liable to give good statistics in the pulse height distribution.

The most prominent ¹⁴⁰La peaks are noticeable in the pulse height distribution. The known spectrum is normalized so that the 1.6 MeV peak is the same height as the corresponding experimental peak. The low-energy continuum is primarily the result of downscatter of natural radioactivity in the ground. There is also a lesser contribution from downscatter in the truck. The energy window is displayed for the 1.6 MeV peak. Its derivation is described in the following section.

Figure 2.8 depicts the same ¹⁴⁰La spectrum, but now the background contributions are highlighted. Three peaks of naturally-occurring radioactive materials (NORM) stand out. Table 2.3 lists the energies for these nuclides [17].

NORM occurs in the environment. ⁴⁰K is the most important in the calculations of this document because its gamma emissions are strong in the domain of the 4σ energy window of the 1.6 MeV ¹⁴⁰La gammas. This reduces specificity in the photopeak counts, and introduces uncertainty in the number of photopeak counts contained in the window.

Figure 2.7: Spectrum of ^{140}La for a distributed source near ground zero of an RDD explosion site. The experimental spectrum (solid curve) is compared with the normalized, known spectrum (solid, vertical lines). The 4σ energy window is depicted for the 1.6 MeV emissions of interest (dashed, vertical lines).

Figure 2.8: Spectrum of ^{140}La for a distributed source near ground zero of an RDD explosion site. The experimental spectrum (solid curve) shows both ^{140}La peaks and background peaks. The background peaks are displayed using the known energy emissions of these isotopes (vertical lines).

Nuclide	E (MeV)
^{40}K	1.46
^{238}U	1.765
^{232}Th	2.614

Table 2.3: NORM peaks in the background spectrum.

2.6.3 Energy Resolution and Selection of Bounds on Photopeak Integration

Figure 2.9 shows a background-subtracted ^{140}La spectrum that was acquired at the Shirley’s Bay branch of DRDC Ottawa. A source was positioned directly below the truck-borne spectrometer, at a position marked “E” (see Chapter 3 for a full explanation of the DRDC experiments). The fit panel of ROOT was used to make a least-squares approximation for a Gaussian fit to the photopeak, over the range of $1.54 \text{ MeV} < E < 1.65 \text{ MeV}$. The best estimate for the standard deviation was $\sigma = (3.8 \pm 0.1) \times 10^{-2} \text{ MeV}$.

In mobile surveys, the count rate response of the detector for 1.6 MeV emissions is defined as the integrated sum over all the full-energy deposition events within a 4σ energy window of the incident photon energy. Therefore, peak count rates were obtained by summing all the bin entries within the 4σ confidence interval, 1.52 to 1.67 MeV.

2.6.4 Background Subtraction

The background survey was performed on June 5th. The truck traversed over the dirt paths and tracks that surrounded the survey area. It was shown in Figure 2.8 how some of the ^{40}K peak was contained inside the 4σ energy window of the ^{140}La photopeak. Figure 2.10 shows a map of the background count rate inside this window. The background signal is stronger along the dirt paths than in the fields. Inside the 4σ energy window, the combined gross count rates of ^{40}K , ^{238}U and ^{232}Th average around 65 cps along the road, whereas in the field areas, they fall to some 55 cps. Thus, background variation under the photopeak may be attributed almost entirely to the positional variation of the truck.

Figure 2.9: Photopeak of background-subtracted ^{140}La for an experiment conducted at DRDC Ottawa. Points come from the experimental results. Solid curve is a fit by ROOT of a Gaussian to the data within the interval, $1.54 \text{ MeV} < E < 1.65 \text{ MeV}$.

Figure 2.10: Background survey of June 5th, 2012, using the summed count rate in the 4σ energy window of ^{140}La window for each survey position of the directional spectrometer. Colour scale has been selected to span the 95 % confidence interval of the average background, assuming Poisson statistics. The majority of these paths are nearly linear because the truck traversed over dirt paths. The warm-zone perimeter (square region, in the southwest) is in the field area, as is the central path.

Figure 2.11: Histogram of the summed, background count rates in the 4σ energy window of the 1.6 MeV photopeak of the ^{140}La spectrum of RSX-1 crystals over the entire background survey of June 5th, 2012.

Figure 2.11 shows a histogram of the background count rates in the ^{140}La photopeak energy window. The spread in background count rate was roughly modeled by a Poisson distribution. The estimate for the background count rate was (58 ± 8) cps, and it was used for the background subtraction of the integrated photopeak rates ³.

2.6.5 Decay Correction

In the reconstruction methods that will be described in Chapters 4 and 5, it is crucial that the results of the mobile survey be used to represent the moving truck over different times as a static array of individual directional spectrometers. This is only

³It is possible that changing the energy window to exclude the major ^{40}K contributions in the photopeak could improve the uncertainty of the measurement. While a loss of data in the photopeak would raise the statistical uncertainty of the measurement, it would lower the systematic uncertainty associated with the background subtraction amount. This possible improvement in uncertainty has yet to be tested.

accomplished if it is assumed that the array of directional spectrometers recorded the surface activity concentration at the same time.

Of interest is the distribution of surface activity concentration immediately after the blast, which occurred at 09:28 on June 6th, 2012. Thus, a decay correction was required to normalize the spectra to their states in the immediate aftermath of the plume deposition (i.e., approximately within two seconds of the shot).

The decay correction was applied to each directional spectrometer count rate by using the decay expression,

$$N_0 = N(t)e^{\frac{\ln(2)}{t_{1/2}}(t-t_0)}, \quad (2.1)$$

where: t is the UTC time of the current spectrum acquisition (i.e., the averaged time of the data acquisition between commencement and completion); t_0 is the UTC time at the start of the blast; and $t_{1/2}$ is the half life of ^{140}La .

2.6.6 Lag Correction

During the truck-borne surveys of the Suffield experiments, the spectra of logs in a directional spectrometer were each acquired over a one-second interval. A GPS measurement recorded the position of the directional spectrometer at the start of the acquisition interval. As a result, the position of the directional spectrometer, on average, was always half a second behind the average location at which the spectrum was acquired. For a single spectrum acquisition, the detector traversed over some 5 m of land (i.e., the truck was moving at ~ 20 km/h). This introduced an ambiguity of $\sim 2 - 3$ m either side of the halfway point between two recorded GPS locations. This positional uncertainty is entirely caused by the time dependence of the directional spectrometer on the movement of the truck, and the phenomenon is called lag.

From maps of the truck-borne survey, it can be seen that, for most of the survey, the truck travelled in straight-line motion; thus, linear interpolation was used to determine an average position of the directional spectrometer to represent the most likely position at which it acquired the spectrum.

During the survey, only basic GPS positional information was used. Normally, the positional uncertainty of the coordinates of the directional spectrometer would be accounted for by a differencing method that removes correlated errors between the receiver system and a reference station; however, the positional uncertainty of the moving truck is usually much greater than the GPS deviations themselves.

Figure 2.12: Lag correction, with D1 to D3 representing the locations of directional spectrometer centroids, and D1' and D2' representing the lag-corrected coordinates for the first three positions, respectively. D3' was obtained using the directional spectrometers labeled by D3 and D4, in the same way as D1 to D3 were used for D1' and D2'.

Figure 2.12 illustrates the concept of lag correction. A survey result is considered for a single spectrometer at positions 1, 2, 3, and 4, in order to represent a measurement from multiple spectrometers, D1, D2, D3, and D4, respectively. For two adjacent directional spectrometer units, D1 and D2, at the UTM locations $\mathbf{x}_{D1} = (e_{D1}, n_{D1})$ and $\mathbf{x}_{D2} = (e_{D2}, n_{D2})$, respectively, the lag-corrected detector for D1, D1', is halfway between the first and the second ensembles, at $\mathbf{x}_{D1'} = \frac{\mathbf{x}_{D1} + \mathbf{x}_{D2}}{2}$. This operation is repeated for detector D2, which is lag-corrected by averaging its initial position with the location of D3, $\mathbf{x}_{D3}$, to give the new position of D2, $\mathbf{x}_{D2'}$.

2.6.7 Spatial Averaging

A second approximation is required in the case of simulating a sample array. Over a one-second data acquisition interval, the truck was sampling at a spatial interval less than its full dimension. This will be a problem in Chapter 5 when the moving truck is simulated as a stationary array of trucks because the truck geometries will overlap.

Figure 2.13: Averaging correction, with $D1'$ to $D3'$ representing the lag-corrected locations of the directional spectrometer centroids, and $D1''$ to $D2''$ representing the average-corrected positions for the first three positions, respectively.

The solution to this problem is to average the positions of two adjacent trucks, and then replace them with a single truck at the intermediate location (see Figure 2.13). The peak counts of the two sets of crystals are summed and then divided by their combined spectrum acquisition interval (~ 2 s).

Spatial averaging is accomplished by taking the average between $\mathbf{x}_{D1'}$ and $\mathbf{x}_{D2'}$. Then, the averaged detector, $D1''$, is situated at $\mathbf{x}_{D1''} = \frac{\mathbf{x}_{D1'} + \mathbf{x}_{D2'}}{2}$. The average displacement of the detector between two lag-corrected points follows a straight-line path between $D1'$ and $D2'$ ⁴. The heading of the averaged detector is then $H = \arctan\left(\frac{y_{D1''} - y_{D1'}}{x_{D1''} - x_{D1'}}\right)$.

The drawback of averaging the detectors together is that the directional information from each four-crystal assembly is weaker. Moreover, the large amount of directional information from multiple positions is expected to compensate for the smearing imposed by the averaging techniques.

⁴Note that the path is close to a linear one, so the positions of $D1''$ and $D2''$ should be approximately equal to the positions of $D2$ and $D3$, respectively (this is particularly evident for $D2''$ in Figure 2.13)

2.6.8 Response Maps

The maps in Figures 2.14 and 2.15 show data that were collected on the day of the blast and on the day after, respectively. These show background- and decay-corrected, gross count rates of the directional spectrometers, which occur inside a 4σ energy window of the 1.6 MeV photopeak. The spectrometer locations are all lag-corrected. The maps show that the truck took a serpentine path to collect line samples that cut across the plume at different locations over distance. Notice that, in the two surveys, the truck path traces out the warm-zone perimeter outline in the southwest corner. The warm-zone area entirely encloses the most intense part of the source distribution, which corresponds to the red, orange and yellow regions of Figure 2.5. Also note how the intensity gradient rises significantly as the truck approaches ground zero. Partly, this is because the more massive powder particles were distributed locally around ground zero. The strong wind transported large portions of the plume in the northeastern direction, as is seen in Figure 2.15 because the surface activity concentration only begins to tail off to zero over a kilometer away from ground zero.

Between the surveys of the 6th and the 7th, decay of the source led to a drop of around 20-25 % in the count-rate magnitudes, so a greater decay correction was performed for the map of Figure 2.15. As a result, the June 7th data are expected to lead to a larger statistical uncertainty on the reconstructed response rate than the June 6th map.

The benefit of the June 7th dataset is that it consists of a better sample of the spatial distribution of the plume. More extensive sampling was performed, and where the June 6th sample gave a starting point to represent the gradient of the surface activity concentration away from ground zero, the second survey was planned so that the truck would traverse over a larger fraction of the plume, and even over and along the plume direction itself. This shows a major benefit of a mobile survey: a second one can be performed soon after the preliminary survey, in order to better characterize the source distribution.

A final note is that the sampling was suitable to adequately represent the plume distribution. The plume extends some 100-200 m in width, which is far wider than the sampling interval of the directional spectrometer. Therefore, the major fluctuations are not missed in this dataset.

Figure 2.14: ^{140}La count rates in the 4σ energy window of the 1.6 MeV photopeak, for the time of blast, as reconstructed from the June 6th survey. Truck positions are lag-corrected. The incomplete square region toward the southwest encloses the perimeter of the warm zone.

Figure 2.15: ^{140}La count rates in the 4σ energy window of the 1.6 MeV photopeak, for the time of blast, as reconstructed from the June 7th survey. Truck positions are lag-corrected. The incomplete square region toward the southwest encloses the perimeter of the warm zone.

By removing the effects of time on the response map, the data is now set for reconstruction of the spatial distribution of the surface activity concentration at the time immediately after the plume deposition. Therefore, the data has been corrected so that the set of data from the single, moving directional spectrometer can be treated as a static array of multiple directional spectrometers.

Chapter 3

Reconstructing the Truck-borne, Directional Spectrometer in Simulation

One of the greatest problems associated with an RDD event is the series of long-term effects caused by its deposition of dispersed radioactive material. The RDD models are not well constrained. In order that the measurements of the mobile survey be used to constrain these models, they must be presented in absolute units of surface activity concentration. To convert the measurements (in cps) to absolute units of activity concentration (in kBq/m²), and to quantify the systematic uncertainties on this reconstructed contamination, Monte Carlo simulation was used. This chapter describes the setup for the truck-borne, directional spectrometer, as modelled in simulation. The approach is based on the calibration of the response of the truck-borne, directional spectrometer to point sources at different positions.

3.1 Modelling the Directional Spectrometer in EGSnrc

Chapters 4 and 5 will describe the Monte Carlo techniques for characterization of a spatial distribution of radioactivity. In each of these calculations, photons are transported through air and a variety of attenuating materials. The Electron Gamma Shower code from the National Research Council (EGSnrc) is the gold standard for such calculations, so it was used as the basis of physical simulations. For sampling, it makes use of precise cross-section distributions, and it is highly efficient compared with the general-particle codes of GEANT4. The C++ class library of EGSnrc was used for the simulations because of the simplicity of the input file structure. For

Figure 3.1: Cross-sectional schematic of a single RSX-1 NaI(Tl) detector used in EGSnrc. All lengths are in centimetres, diagram not to scale. Materials are those used in simulation, although Poron was used instead of carbon fibre. Inside the upper casing, the PMT and analyzer components are missing.

more details of the advantages of using this interface, see Appendix A. In modelling the truck design, it was necessary to account for the anisotropy of the 2π response of the directional spectrometer that was caused by the asymmetry of the truck mass distribution.

Figure 3.1 shows the schematic of a single RSX-1 log. Figure 3.2 shows another schematic for the PMT-analyzer geometry. All dimensions were obtained by rule measurement, except for the interior dimensions of the PMT-analyzer system, which themselves were based on the required room space for a glass PMT tube and for cable installation. The entire steel casing was assigned a uniform width of 3.6 mm. The mass of the simulated PMT-analyzer system was 1.44 kg, which exceeds the true mass of 1.07 kg by 44 %. In reality, the mass of the analyzer is 70 g, that of the PMT is ~ 200 g (7 oz), and the housing mass is 800 g. With photons coming from below the spectrometer, the main effect of the steel component is to produce backscatter. In the photopeak window, backscatter is not important, so this representation of reality is adequate.

Table 3.1 lists the densities and linear attenuation coefficients for the respective media. The main attenuating component was the Al casing, as it has a significant cross section for incoherent scatter. Poron foam was used instead of carbon fibre because it already existed in the PEGS4 database, and had a similar density to

Figure 3.2: Cross-sectional schematic of the PMT-Analyzer geometry used in EGSnrc. The interior is vacuum, while the housing is made of 3.6 mm-thick steel. All lengths are in centimetres.

PEGS4 Medium	Density (g/cm ³)	μ/ρ (10 ⁻² cm ² /g)
NaI(Tl)	3.67	4.64
Al	2.70	5.00
Felt	0.16	5.20
Poron	0.24	5.65
Steel	8.06	4.87

Table 3.1: Material properties of a simulated RSX-1 log.

carbon fibre.

Figure 3.3 displays the simulated geometry of the directional spectrometer. The orientations of the detector and the materials surrounding it are constructed with high precision, and the spatial representation is close to reality.

World geometries were made of air, and they were designed as tall structures, 228.28 cm in height (20 $\times$ the elevation of the centroid of the detector ensemble). This was an overly conservative usage of space because most of the 1.6 MeV gammas are scattered in air in the forward direction; this means that the only gammas that would have been backscattered in air to reach the directional spectrometer would have been remote and on the ground; the gammas must reach the detection system from an oblique angle. Due to larger attenuation of the signal at these distances, only

Figure 3.3: EGSnrc design of the directional spectrometer. Green NaI logs are tainted royal blue with Al casing. Boxes represent the steel analyzer geometries, while below each of them are steel PMT holders. The holders contain vacuum interiors (dark holes). Red housing is made of Poron. Felt padding is not included in the image.

a small fraction of the backscatter should affect the 1.6 MeV photopeak. No soil was simulated, although like air, it is not expected to have a major contribution in the 1.6 MeV photopeak.

3.2 Particle Sources

All source objects used in simulations were based on the `EGS.IsotropicSource` abstract class, which generates an isotropic gamma emitters. In the `EGSnrc` reconstruction of the DRDC calibration experiment, a single point source was used, and its solid angle of emission was restricted to 2π in the upper hemisphere. The source vial was assumed to be sufficiently isotropic that it was represented as containing a point source. Furthermore, no container was simulated because, in reality, it did not have a major attenuating effect on the signal. There is low probability for the event of a gamma emitted in the downward direction to scatter into the crystal, and deposit high enough energy in the crystal to generate a pulse inside the 4σ energy window of the photopeak. This probability was treated as negligible. For all simulations in Chapters 4 and 5, ^{140}La was used. In the `EGSnrc` input file, the polyenergetic emissions were defined in a tabulated spectrum, which included the most important emissions of the known spectrum. The spectrum definition was

```
energies = 0.3228 0.4870 0.8158 0.9252 1.5962 2.5213
probabilities = 20.0 45.0 23.3 6.9 95.0 3.5
```

where energies are in MeV and probabilities are percentages.

This input has unnormalized probabilities, in that they add up to 193.7 as opposed to 100. For a net probability of 100 and a number N_H , of primary histories, the generation of N_H events would be equivalent to N_H decays of ^{140}La . However, in this case, N_H events correspond to $\sim \frac{N_H}{2}$ decays of ^{140}La , since the probability of emission per decay is 193.7 % (i.e., two photons are created per decay of ^{140}La).

Parameter	Default	Photon Simulation
Rayleigh scattering (“Rayleigh”)	Off	On
Bound Compton scattering (“BC”)	Off	On
Electron Impact Ionization	Off	On
Pair Cross Sections	Bethe-Heitler (“BH”)	NRC
Photon Cross Sections (“PCS”)	Storm and Israel (“SI”)	XCOM
Compton Cross Sections	Default	Default

Table 3.2: Parameter selection for photon transport.

3.3 Photon Transport, Particle Scoring, and Generated Output

EGSnrc has default parameters to describe particle transport. A set of parameters was used to optimize the efficiency of photon transport, in accordance with the recommendations of [24]. Table 3.2 shows a comparison of the default parameter set and that used for photon transport.

The threshold energy for delta-ray production was $AE = 0.521$ MeV, and the threshold energy for production of secondary photons was $AP = 0.01$ MeV. The NERT has a cluster at its disposal, which contains some 200 CPUs. Therefore, time requirements were not exceedingly long for the case of the photon simulations (for example, about one day was required to run a set of 36 involved simulations with 10^8 primary histories in each of them).

For the main simulations of Chapters 4 and 5, the “tutor7pp.cpp” application was used. The output of this program is in the form of a binned spectrum, and this information was re-binned to match the output bins of the RSX-1 spectrometer. From Section 2.6.3, the energy resolution of a RSX-1 detector was found to be about 6 %. Accordingly, a Gaussian smearing technique was implemented to obtain a spectrum that better approaches the form of the experimental spectrum. At each energy bin, the deposited energy was centred on a value E , and contained a number of counts, N_E . A Gaussian distribution was defined, which was centred on E . Sampling of this distribution was repeated N_E times. Bins corresponding to each new energy window were filled accordingly. The smearing code is available in Appendix C.

For each simulation, the EGSnrc user code produced a thousand-bin pulse height distribution. The problem with this scoring technique is that the output pulse height distributions of “tutor7pp.cpp” are already binned. In practice, it would have been more accurate to have written each energy deposition event in the startNewShower() method to a text file. It would have been most appropriate if, only after all of the energy depositions were stored, they were then smeared before the energy distributions were binned.

3.4 Obtaining an Accurate Model of the Simulated Truck Design using a Calibration Experiment

A calibration experiment was carried out on March 19th, 2014 to provide insight on the mass distribution of the truck. The experiment was carried out at the Shirley’s Bay branch of DRDC Ottawa. At 9:00 a.m. that morning, a ^{140}La source was prepared with initial activity of 20 MBq, according to the members of Shirley’s Bay. Figure 3.4 shows the setup of the experiment, with the truck-borne spectrometer system at the centre, the source directly underneath the truck, and lead shielding blocks for the source vial on the counter to the left.

That morning, temperatures rose from -7°C to 0°C , over the course of about 4-5 hours. However, this variation did not greatly affect the measurements of the RSX-1 ensemble.

Figure 3.5 is a schematic of the experimental setup. On March 18th, the setup was prepared by placing pieces of tape at the source positions A - H, using tape measure and a laser level (Johnson Level 40-6662, accuracy $\pm 2\text{ m} / 10\text{ m}$ [25]). A safety line was also determined. The line was 3 m from the source position closest to the operators, where the dose of this source was predicted to be $\sim 0.6\ \mu\text{Sv/h}$. In Figure 3.4, the striped tape marks the safety line. Long tongs were used to carry the source to the different positions.

Table 3.3 describes the proceedings of the experiment, with the source activity curve shown in Figure 3.6. The source activity was determined with the standard decay equation for ^{140}La , knowing the initial activity of 20 MBq at 9:00 a.m. The RSI system provided output of counts per second, and the gain stabilization algorithm

Figure 3.4: Setup of DRDC experiment on March 19th, 2014. The ^{140}La source is contained inside a white vial which is situated directly underneath the truck. The counter to the left holds the lead shielding for this vial, which is used for background measurements. The safety line is 3 m behind the truck, and is marked by the striped tape.

Figure 3.5: Experimental plan for the DRDC trials. A ^{140}La source was positioned at points A through H. The green, central square represents the directional spectrometer. For scale, point D is 2 m from point E [13](used under permissions to copy or modify and distribute).

Time (EST)	Source Position Label	Source Position (m)
10:22:57	H	(0, 4.02)
10:26:15	G	(0, -2.02)
10:30:43	E	(0, 0)
10:35:52	C	(0, 2.00)
10:40:24	B	(0, 2.61)
10:46:40	A	(0, 6.60)
10:50:43	D	(-2.00, 0)
11:13:10	F	(2.01, 0)

Table 3.3: Order of events for the DRDC trials. The x-value of the position is the displacement of the source along the minor axis of the truck, where $x = 0$ m is directly underneath the directional spectrometer. The y-value of the position is the displacement of the source along the length of the truck, where $y = 0$ m is directly under the directional spectrometer.

was turned off. Data were recorded over one-minute intervals.

Figure 3.7 shows the background spectrum of two measurements, conducted before and after the experimental procedures defined in Table 3.3. In each of these measurements, the ^{140}La source was placed behind the lead blocks. The peaks from NORM are all present (see Section 2.6.2). The average spectrum was used in the subtraction of the trial spectra in order to extract the respective ^{140}La responses.

The pickup truck for the RDD trials was a Ford F-250 model, although the truck used for the DRDC experiments was a Chevrolet design. In this document, it will be assumed that the effects of the truck asymmetry are relatively similar for these designs. As will be seen in this chapter, the systematic uncertainties for Monte Carlo models will be large enough to enclose the uncertainty associated with this inconsistency.

The total mass of a F-250 (or equivalent Chevrolet) is ~ 2300 kg (5000 lbs). In EGSnrc, the distribution of this mass was determined interactively by comparing the generated spectra in EGSnrc with the DRDC spectra. From such experimentation, two designs were selected from several trial geometries, which yielded the closest fits

Figure 3.6: Decay curve of the activity of the ^{140}La source during the experiment. Times correspond to the source being positioned at the respective locations defined in Table 3.3.

Figure 3.7: Background spectrum for the calibration experiment. The solid curve shows the background spectrum obtained over a one-minute spectrum acquisition interval before the experiment was performed. The dashed curve shows the background spectrum that was obtained after the trials outlined in Table 3.3. The dot-dash curve shows the average of the two spectra.

Figure 3.8: Best estimate of the truck design. It has a mixed mass distribution, with a front plate of shielding, a concentrated trunk, and a spread cab and base.

to the experimental spectra. For reference, they are exhibited in Appendix B, as are their mass distributions. One was chosen as the best-estimate design, while the other was chosen to quantify the systematic uncertainty associated with the truck mass distribution. The best-estimate design is shown in Figure 3.8.

In simulation, the ^{140}La was represented as a point source. The simulated spectra are normalized so that they represent the number of expected counts for the experimental source, as of the time of the measurement.

In Figures 3.8 - 3.10, the measured spectra are shown overlaid on the EGSnrc results for the two truck designs. The plots are in relative positions that correspond with the same locations in Figure 3.5. Note that there was no Monte Carlo simulation for the case that the spectrum was placed at position B, although the experimental spectrum is displayed.

Figure 3.9 shows the energy spectra for the best-estimate truck design. At position E, there is a 50 % discrepancy in the experimental and simulated photopeak amplitudes. Either the structure or the material composition of the underside shielding is still not exactly consistent with reality because the EGSnrc photopeak has an amplitude two-thirds that of the experimental data. The discrepancy also occurs for

Figure 3.9: Comparisons between experimental and EGSnrc energy spectra, for a truck design that has a mixed mass distribution, with a front plate of Al shielding, a concentrated Al trunk, and a spread, steel cab and base. Solid curves are for the experimental spectra, while the dashed curves are for the EGSnrc spectra. The relative location of each plot corresponds to the positions A through H.

Figure 3.10: Comparisons between experimental and EGSnrc energy spectra, for a truck design that has a spread mass distribution. Solid curves are for the experimental spectra, while the dashed curves are for the EGSnrc spectra. The relative location of each plot corresponds to the positions A through H.

source positions D and F. For source positions G and H, the discrepancy is similar and opposite; there is too little shielding in the corresponding components of the simulated truck design. For source position C, the Monte Carlo photopeak shows clear agreement with the experimental photopeak. The front of the truck is particularly massive, as evinced by the striking deficit in the experimental count rates in the case that the source was situated at positions A and B. The overapproximation of the spectrometer response shows that the simulated truck does not have adequate front shielding.

Figure 3.10 shows spectra from simulations that incorporated the spread-truck design. This truck has a moderately-attenuating Al cab component, some 2 cm thick. It consists of a compact rectangular prism at the front. Some of the trunk mass was re-distributed to the rear components by making the base longer.

For the case that the source is at position C, this truck design preserves the good agreement with the experimental spectrum. For the source at positions D, F, and G there is a slight improvement in the agreement between the Monte Carlo and the experimental data. Because it has more mass in the front, this truck design reduces the predicted count rate for source position A, and there is greater agreement between the corresponding spectra. For source position H, this model contrasts with the best-estimate design, in that the signal is overly attenuated.

The designs lack detailed descriptions of the front-end materials, such as compressed air (air bags), motor oil, etc. However, the total truck mass is accounted for because, together with the truck body and the engine, these materials are treated as an averaged composite.

For the purpose of measuring 1.6 MeV emissions, these spectra were sufficient, but in general, the truck geometry was far from the finished article. With more trials of simulated truck design, this iterative procedure will produce a better representation of the truck mass distribution, and for published results, this was achieved [10]. Within the scope of this dissertation, however, the systematic uncertainty on the mass distribution will dominate the uncertainty on the reconstructions of Chapters 4 and 5.

Experimental spectra may now be explained in part by the Monte Carlo results. Significant attenuation occurs at the rear of the truck due to the steel base. The incoherent scatter of the metal leads to great amounts of low-energy emissions in all of the spectra. For photons incident from the side of the box, the truck attenuation

is less important, and absolute efficiency is dictated by the inverse square law and air attenuation. When the source is at position C, a similar deficit in shielding manifests itself in the high peak count rate. Most of the truck mass was in the engine area, leading to severe attenuation of the source when it was in positions A and B.

The background subtraction of spectrum B resulted in non-physical, negative probabilities. It is likely that this is a consequence of leakage from the lead shielding of the ^{140}La during background measurements. Indeed, the front of the truck appears to have better shielded the spectrometer from the ^{140}La emitter than the lead blocks. The background spectrum, which contained these low-energy emissions of lead downscatter, was subtracted from the measured spectrum, to obtain the response spectrum. Therefore, there may be a slight underestimation of the photopeak counts in the experimental spectra. The effect of this leakage on the uncertainties may be considered negligible, as there are much grosser deviations of the compared spectrum sets that are caused by the imperfect truck design in EGSnrc.

Chapter 4

Reconstruction by Spatial Averaging: The Infinite Plane Approximation

The basis of the infinite plane approximation is to treat the response of each directional spectrometer as having been caused by a finite disc source, uniformly populated with isotropic point emitters of ^{140}La . This source representation makes no claims about the fine variations of the underlying spatial distribution, but allows for the determination of an averaged surface activity concentration inside the sensitive region of each directional spectrometer in the array. The crucial concept in this approximation is that the cumulative sensitivity of the directional spectrometer is expected to plateau within $O(100)$ m. That is, the radial profile of sensitivity for a homogeneous disc source is expected to closely approach an asymptote within a finite disc radius.

The result of the reconstruction is a scaled version of the response maps in Figures 2.14 and 2.14. The values of surface activity concentration correspond to discs of dimension comparable with an approximate radial limit on the sensitivity of the directional spectrometer. With a large radius attributed to each disc, nearby directional spectrometer will contain overlapping regions of the plume contamination, so the averaged spatial regions of surface activity concentration between adjacent directional spectrometers will not greatly differ. Therefore, the use of the infinite plane method is to define the spatial variation of a plume activity density over a slowly-varying contamination.

For cases of widespread contaminations like the RDD distribution, the reconstruction method is useful because it defines an absolute measure of the activity concentration for the entire sample without requiring involved calculations. In particular, the reduced requirements of CPU time make the computation feasible in the

case that information is required for rapid characterization of the plume deposition, for instances in which the emergency response teams require prompt information before entering the contaminated area. Furthermore, the method is useful because it improves on airborne surveys, with better statistics acquired in the one-second spectra of the detection system. In addition, the area of sensitivity is smaller, so there is an improvement on defining the spatial extent of the plume deposition and the more rapid spatial fluctuations in the surface activity concentration.

Initially, the infinite plane approximation did not make use of Monte Carlo; it was a purely analytical method, which made use of the fluence-rate equation. Success of this type of model extends back to the 1970s, where the fluence-rate equation was used to determine the volume concentration of ^{133}Xe in the air during the aftermath of the Three Mile Island incident [26]. In that case, the ^{133}Xe contributions were isolated from the measured spectra, and the detector response was converted to volume activity concentration for an infinite sphere. Predictions of the concentrations were in good agreement with the grab sampling release measurements [26]. This was a breakthrough for characterizing spread sources using a simplified physical model, and the infinite plane model has been invaluable up until as recently as the Fukushima fallout: U.S. teams collected count rates over the survey areas, and converted them to surface activity concentrations using the infinite plane model. During the same incident, a similar model was used to determine the concentration of radioactive xenon along the west coast of Vancouver [1].

4.1 The Infinite Plane Method

In the fluence-rate equation the directional spectrometer is treated as a gross count detector, rather than an ensemble of individual crystals. That is, in the directional spectrometer, the responses of the four logs are summed, and the directional spectrometer is now considered a monolithic detection system.

For a disc of radius R that is uniformly populated with isotropic emitters, the fluence rate, $\phi(R)$ may be determined at an observation point at a height h above ground. For simplification in the derivation, it is convenient to treat the point as a spherical detector geometry; then the detector response is isotropic. That is, regardless of the direction from which the gammas are incident on the sphere, the photons encounter the same cross section. If S_0 is the surface activity concentration of the

uniform source, then the fluence-rate equation is

$$\phi(R) = \frac{S_0}{2} \int_0^R \frac{e^{-\mu_a \sqrt{\rho^2 + h^2}}}{\rho^2 + h^2} \rho d\rho. \quad (4.1)$$

where μ_a is the linear attenuation coefficient for air, and ρ is the radial variable of integration. This equation is equivalent to

$$\phi(R) = \frac{S_0}{2} \left(\int_0^\infty \frac{e^{-\mu_a \sqrt{\rho^2 + h^2}}}{\rho^2 + h^2} \rho d\rho - \int_R^\infty \frac{e^{-\mu_a \sqrt{\rho^2 + h^2}}}{\rho^2 + h^2} \rho d\rho \right).$$

A change of variables, $t = \mu_a \sqrt{\rho^2 + h^2}$, is applied. Equation 4.1 becomes

$$\phi(R) = \frac{S_0}{2} \left(\int_{\mu_a h}^\infty \frac{e^{-t}}{t} dt - \int_{\mu_a \sqrt{R^2 + h^2}}^\infty \frac{e^{-t}}{t} dt \right).$$

The equation must be solved numerically. ROOT has a function for the exponential integral, which is mentioned in [27], and is given by

$$E_i(x) = - \int_{-x}^\infty \frac{e^{-t}}{t} dt.$$

Therefore,

$$\phi(R) = \frac{S_0}{2} \left[E_i(-\mu_a \sqrt{R^2 + h^2}) - E_i(-\mu_a h) \right]. \quad (4.2)$$

This is the fluence-rate equation for a finite disc source. It is asymptotic with R. That is,

$$\phi_\infty = \lim_{R \rightarrow \infty} \phi(R) = -\frac{S_0}{2} E_i(-\mu_a h). \quad (4.3)$$

Because it is assumed that the detection system is isotropic, the number of counts per second that the detector records only differs from the fluence rate by a constant factor, A_{eff} , which also accounts for the intrinsic efficiency, and is called the effective area. Thus, the count rate, $r(R)$ of the detector is given by

$$r(R) = A_{\text{eff}} \phi(R) \quad (4.4)$$

The expression may be scaled to obtain the sensitivity, $\kappa(R)$, which is

$$\kappa(R) = \frac{r(R)}{S_0}. \quad (4.5)$$

Then, the sensitivity equation can be expressed as

$$\kappa(R) = \kappa_0 \left(E_i(-\mu_a \sqrt{R^2 + h^2}) - E_i(-\mu_a h) \right), \quad (4.6)$$

where $\kappa_0 = \frac{A_{\text{eff}}}{2}$ is a constant [27]. The maximum sensitivity is

$$\kappa_\infty = -\kappa_0 E_i(-\mu_a h). \quad (4.7)$$

The reciprocal of this function gives a conversion factor, which can be used to convert the count rate (in counts per second) to the surface activity concentration for an infinite sheet source (in kBq/m²). The conversion factor (ξ) has units (kBq/m²)/cps, and is given by

$$\xi = \frac{1}{\kappa_\infty}. \quad (4.8)$$

This conversion factor can be rapidly applied to a full experimental dataset, so the entire survey region can be defined in terms of an averaged surface activity concentration.

4.2 Determination of a Conversion Factor for Surface Activity Concentration

Monte Carlo simulations were carried out to sample the radius of a disc source and determine the dependence of the output response on the disc size. The advantage of Monte Carlo is that it can simulate all the variables that are included in the system function.

Twenty finite discs were sampled at 10 m radial increments, with a further two disc sizes selected at 29 m and 30 m. Each source maintained a constant density of primary histories, and contained uniformly distributed, 2π -isotropic emitters of gamma photons. Table 4.1 lists the details of the simulations, while Figure 4.1 shows the profile for the number of histories used in successive simulations. The number of histories rises quadratically with radius in order to maintain constant primary-history

Simulation parameter	Description
Source	Infinite, uniform disc of isotropic emitters
Angular Coverage	Upper hemisphere
History Density	10.4 k per square metre
EGSnrc Output	Pulse height distributions, per crystal
Spectrum Energies (MeV)	0.3228, 0.4870, 0.8158, 0.9252, 1.5962, 2.5213
Spectrum Probabilities	20.0, 45.0, 23.3, 6.9, 95.0, 3.5
Energy Window	1.52 MeV to 1.67 MeV (4σ)
CPU Time for Spectrum	~ 3 h
World Geometry	Air; Cube geometry, ~ 400 m on side

Table 4.1: Details of parameters used in the finite disc simulations in EGSnrc.

density.

The EGSnrc user code, “tutor7pp.cpp”, was modified for the simulations. The output of this user code comes in the form of normalized pulse height spectra. For each spectrum, the number of 1.6 MeV emissions in the 4σ photopeak was computed and normalized by the density of primary histories. The result was a radial profile of the cumulative sensitivity of the spectrometer, in $\frac{\text{cps}}{\text{kBq/m}^2}$.

For the central estimate of the cumulative sensitivity profile, the simulated detector was carried by the best estimate of the truck design, based on the results of Section 3.4. The results are shown in Figure 4.2. The simulation results show that the cumulative sensitivity rises with R toward an asymptote.

The flux expression for a spherically symmetric detector may be compared with the Monte Carlo result for the sensitivity curve. Equation 4.6 is plotted in Figure 4.2, with $h = 1.1 \text{ m}^1$ and $\mu_a = 6.2 \times 10^{-3} \text{ m}^{-1}$ for 1.6 MeV photons [23]. The sensitivity, κ_0 , has been determined by a fit to Equation 4.6. Using the ROOT analysis software, Equation 4.6 was fitted to the Monte Carlo data points, for $R \geq 200 \text{ m}$. The fit gave an estimate for the amplitude parameter, κ_0 , of Equation 4.6. Then, the sensitivity asymptote was found to be $\kappa_\infty = (10.8 \pm 0.3) \frac{\text{cps}}{\text{kBq/m}^2}$. The profile

¹The height is important for in-situ, gamma-ray spectroscopy because it is optimal for the detection system to acquire photons over a large field of view, without significantly losing information due to signal attenuation [28].

Figure 4.1: Radial profile of the number of primary histories. Points and the curve were determined with the same analytical expression, based on the density of primary histories.

Figure 4.2: Radial profile of the ratio of peak count rate to density of generated events, for the best-estimate truck. Data points represent the ratio of the detector response (in cps) to the surface activity concentration (in kBq/m²) for a disc source of radius R . The points are results from individual EGSnrc simulations of finite discs that are uniformly populated with isotropic emitters. The solid line is a fitted curve based on the analytical formulation of this radial relationship in Equation 4.6, with $h = 1.1$ m and $\mu_a = 6.2 \times 10^{-3} \text{ m}^{-1}$. The fit was performed for Monte Carlo data points in the range, $200 \text{ m} \leq R \leq 300 \text{ m}$.

satisfies theoretical constraints of the sensitivity equation. Appendix D includes a more detailed discussion of this validation.

An important description of the asymptotic behaviour of the Monte Carlo results is the footprint of the directional spectrometer, or the percentage sensitivity of the asymptote as a function of the disc radius. This was derived using the fit for Equation 4.6, and scaling it by $\frac{1}{\kappa_\infty}$. Figure 4.3 shows the footprint, where it can be seen that the detector response exceeds 80 % of the infinite-plane sensitivity before $R = 50$ m. Furthermore, 95 % of the maximum sensitivity is reached by $R = 150$ m. For an infinite plane source of ^{140}La emitters, those emitters that are located beyond

Figure 4.3: Radial profile for the ratio of sensitivity to asymptote value. Dashed lines show percentiles of the asymptote sensitivity.

$R = 200$ m contribute a negligible amount to the total sensitivity. Therefore, the net sensitivity of the directional spectrometer for an infinite disc may be used to approximate the amount of surface activity concentration for a uniform disc source of some 200 m. Associated with this representation of the averaged surface activity concentration is a 5 % error, but it will be shown in Section 4.3 that the systematic uncertainties are much larger. For the intents of this reconstruction method, it is reasonable to assume that the net sensitivity of the directional spectrometer of an infinite plane is the same as for the case that the source is a finite disc of $R = 200$ m.

Truck Design	κ_0 (cps/(kBq/m ²))	κ_∞ (cps/(kBq/m ²))
Best Estimate	10.8 ± 0.3	49 ± 1
Spread Truck	13.6 ± 0.3	62 ± 1

Table 4.2: Amplitudes and asymptotes of the sensitivity equation for different simulations of the truck design. The fits were both performed for Monte Carlo data points in the range, $200 \text{ m} \leq R \leq 300 \text{ m}$.

4.3 Systematic Uncertainties Affecting the Conversion Factor

Equation 4.6 was fit to the dataset for different radial domains. The results of these fits are shown in Figure 4.4. One fit took into account all of the data points over the full range of sampled radii (central sensitivity curve), and the other two were performed over radii below and above $R = 200 \text{ m}$ (sensitivity curves below and above the central curve, respectively). The asymptotes of these curves show that differing fitting ranges can yield a 5 % variation in the approximation of κ_∞ . This is a conservative estimate for the systematic error, because the fit to $R < 200 \text{ m}$ points considers disc sizes where the sensitivity of the directional spectrometer varies significantly with radial dimension.

For comparison with Figure 4.2, Figure 4.5 shows the sensitivity as predicted by EGSnrc for the spread truck. It is again found that the sensitivity exhibits asymptotic behaviour with R .

For both of the truck designs, EGSnrc results deviate from the fluence-rate expression. When constrained to fit the Monte Carlo data for large R , the flux expression for an isotropic detector overestimates the the Monte Carlo data for small R . In the far field, the fluence-rate expression provides a good description for the Monte Carlo data, which suggests that it is a valid approach to extract the asymptote using this fit. However, this argument would be strengthened with more large- R data points in the plot, which requires further simulation.

Table 4.2 shows the fit parameters that ROOT determined for the amplitudes of the respective curves. It also lists the asymptotes of the sensitivity profiles.

The central value of the sensitivity curve was obtained with simulations in which

Figure 4.4: Curves of cumulative peak count rate to surface activity concentration, for finite discs of uniformly distributed, isotropic emitters, and for the best estimate of the truck design. Data points are from EGSnrc simulations of the disc sources. Curves are based on fits according to small (dashed lines) and large (dashed-dotted lines) discs, respectively, as well as on predictions according to discs of all sizes (solid lines).

Figure 4.5: Radial profile of the ratio of peak count rate to density of generated events, for the spread truck. Data points represent the ratio of the detector response (in cps) to the surface activity concentration (in kBq/m^2) for a disc source of radius R . The points are results from individual EGSnrc simulations of discs uniformly populated with isotropic emitters and finite radii. The solid line is a fitted curve based on the analytical formulation of this radial relationship in Equation 4.6, with $h = 1.1$ m and $\mu_a = 6.2 \times 10^{-3} \text{ m}^{-1}$. The fit was performed for Monte Carlo data points in the range, $200 \text{ m} \leq R \leq 300 \text{ m}$.

Figure 4.6: Best estimation for the sensitivity curve of the truck-borne directional spectrometer. Data points represent the ratio of the peak count rate (in cps) to the surface activity concentration (in kBq/m²), for finite disc sources of uniformly distributed, isotropic emitters. These are from individual EGSnrc simulations. The solid line is a fit curve for Monte Carlo data points in the range, $200 \text{ m} \leq R \leq 300 \text{ m}$. The hashed area shows the 1σ confidence interval. The fit asymptote is represented by the dash/dot line.

the best estimation of the simulated truck design was used. Because it is the asymptotic behaviour which is used for the infinite plane sensitivity, only sensitivity points for $R \geq 200 \text{ m}$ were used in the fit (this corresponds to cumulative sensitivities over 98 % of the asymptote value). A systematic uncertainty was assigned to the measurement for the truck mass uncertainty. From the calculations, the best estimation of the sensitivity asymptote was found to be

$$\kappa_{\infty} = (49 \pm 1 \text{ (statistical)} \pm 7 \text{ (systematic)}) \frac{\text{cps}}{\text{kBq/m}^2}$$

The 1-sigma confidence interval is displayed in Figure 4.6. Knowing the sensitivity

of the detector for an infinite disc allows for the determination of a conversion factor for the detector response, which is

$$\xi = (2.04 \pm 0.04 \text{ (statistical)} \pm 0.29 \text{ (systematic)}) \times 10^{-2} \frac{\text{kBq/m}^2}{\text{cps}}.$$

4.4 Application to the RDD Datasets

The conversion factor was used to scale the measured count rate of the truck-borne surveys of June 6th and June 7th. The corrected maps of Section 2.6.8 were used, so that the contamination was shown as it was immediately after the plume deposition. Figures 4.7 and 4.8 show maps of the surface activity concentration, as reconstructed from the surveys that took place on June 6th. Figures 4.9 and 4.10 show maps of the surface activity concentration, as reconstructed from a survey that was performed on June 7th. Each shows an increase of surface activity concentration toward ground zero.

The maps of surface activity concentrations show spatial distributions that strongly agree. As was mentioned in Section 2.6.8, it was reasoned that the statistics of the June 7th spectra are less precise than those of the June 6th dataset because of the radioactive decay of the source over the course of a day. The differences in the reconstructed maps of surface activity concentration show that the discrepancies between approximated values are much smaller than the systematic uncertainties shown in Figures 4.8 and 4.10.

The results of this exercise show how an averaged spatial distribution can be determined along the survey path, based on the data of a truck-borne survey, and using a Monte Carlo calculation. CPU times of the simulations are not particularly long, and the analysis is not complicated.

The method described in this chapter is an improvement on the purely analytical methods that have previously been used to calculate the surface activity concentration. Now, the fluence-rate equation is only used to extract an asymptote from the Monte Carlo profile of the sensitivity of the directional spectrometer. In other words, it is the EGSnrc data that dictates the usage of the analytic expression, whose role has been restricted to modeling the cumulative sensitivity for large discs.

Figure 4.7: Spatial distribution of ^{140}La surface activity concentration (SAC) for the June 6th Suffield dataset. Each position of the mobile spectrometer is associated with a surface activity concentration of a 200 m disc source, uniformly populated with isotropic emitters.

Figure 4.8: Map of systematic error on the surface activity concentration (SAC) for the June 6th Suffield dataset.

Figure 4.9: Spatial distribution of ^{140}La surface activity concentration (SAC) for the June 7th Suffield dataset. Each position of the mobile spectrometer is associated with a surface activity concentration of a 200 m disc source, uniformly populated with isotropic emitters.

Figure 4.10: Map of the systematic error on the surface activity concentration (SAC) for the June 7th Suffield dataset.

Chapter 5

The Spatial Deconvolution Method: Reconstructing the Local Distribution of Surface Activity Concentration

In Chapter 4, a conversion factor was determined for the absolute surface activity concentration of an infinite and uniform radiating plane under the directional spectrometer. The conversion factor yielded activity concentrations averaged over an area characterized by a sensitivity curve, which plateaued at a radius of some 200 m. Thus, it was possible to reconstruct a spatially-averaged activity concentration within the sensitive region of each directional spectrometer along the line of motion. While the infinite plane approximation is beneficial for rapid characterization of the activity levels, it lacks the level of detail required for the purposes of understanding fluctuations within the sensitive regions of the survey.

From the directional information of the directional spectrometer, it is possible to improve on the infinite plane approximation by reconstructing more localized regions of space within the most sensitive area of the static array. To accomplish this task, it is no longer possible to consider each directional spectrometer independently, so the Monte Carlo computation is much more involved than for the infinite plane approximation. All the individual responses of the NaI(Tl) logs are now used simultaneously, and this far increases the level of precision in the reconstruction. Note that, due to the greater complexity of the problem, it has been possible to process only a very small portion of the data represented in Chapter 4 with the spatial deconvolution method. This is the subject of the following chapter.

Figure 5.1: Profile of the surface activity concentration over the course of a sampled path line of directional spectrometers. The reconstructed magnitudes were obtained from the sensitivity asymptote of the directional spectrometer for uniformly-distributed isotropic emitters of ^{140}La , but are attributed to a finite disc source of 200 m radius.

5.1 Theory: The Spatial Deconvolution Method

5.1.1 Setup of the Problem

The purpose of the spatial deconvolution method is to reconstruct the spatial distribution of surface activity concentration in a pixelized area based on an array of truck-borne, directional spectrometers. Figure 5.1 shows the infinite plane approximation for a profile of the surface activity concentration over a path sample of the June 6th Suffield dataset. In Figure 4.7, it corresponds to a single traverse across the plume with easting-northing coordinate pairs from $\sim (0, 250)$ m to $\sim (250, 0)$ m. Each point quantifies the averaged activity concentration within 200 m of the directional spectrometer.

The results of the local survey region may be used as if the single moving detector were equivalent to multiple stationary detectors, and a calculation may be performed to reconstruct the underlying spatial distribution of surface activity concentration

that generated the array response. In imaging applications, the detector response is the result of a system function acting on the continuous signal input, and in many cases the system is approximately linear [2].

5.1.2 Linear Systems

The distribution of surface activity concentration represents a continuous signal function. The signal is said to pass through a system function, which converts it into a discrete output, called the array response. which includes the parameters of air and truck attenuation, and accounts for the inverse square law. The system function accounts for all the parameters involved in modeling the path sample as a static array of truck-borne, directional spectrometers. These parameters include the effects of averaging the count rates and positions of adjacent directional spectrometers (see Sections 2.6.6 and 2.6.7). Furthermore, the system function includes all the effects caused by the intrinsic properties of the directional spectrometer, such as self-shielding of the logs.

A linear problem has the potential of providing accurate results for complicated problems. If the continuous signal of the activity distribution is represented as a linear combination of constituent signal functions, then the system is linear if it acts on the signal to output an array response, which itself is a linear combination of the array responses induced by those respective signal functions. In particular, the individual array responses are given the same respective weights as the corresponding signal functions that constitute the nodes of the signal combination. Without knowing the true form of the system function, it is necessary to use Monte Carlo in order to both model it and approximate its dependencies on the details of the experimental design.

5.1.3 The Spatial Deconvolution Method

A square FOI was chosen to enclose the plume peak, with dimension of 120 m on a side. Based on the number of crystals in the sample array, and in accordance with the footprint of Figure 4.3, the FOI was segmented into six pixels by six pixels, each being 20 m on a side. From this setup, and using the assumption of a linear system, it is plausible that an arbitrary source distribution could be represented as a weighted sum of discrete, uniform, pixels, each of which contains the same, uniform contamination.

Figure 5.2 shows the concept of a linear system, as used in the spatial deconvolution method (inspired by [2]).

In the FOI, the true distribution of surface activity concentration is a continuous signal function, $f(x, y)$ (notation inspired by [2]). Here, x and y are defined as the offset easting and northing coordinates that were defined for the entire survey area in Figure 4.7.

The array response function, $\mathbf{g}^{\text{MEAS}}$, is a vector of individual crystal responses, and:

$$\mathbf{g}^{\text{MEAS}} = \mathcal{S}\{f(x, y)\},$$

where $\mathcal{S}$ is the system function. Let $f_k(x, y)$ represent the signal function of the k 'th pixel (in kBq/m^2), when the pixel area is uniformly populated with a set number of isotropic emitters of ^{140}La (this corresponds to what will be denoted as a pixel source). The discrete array response, $\mathbf{g}_k$, is defined as the output after the system has acted on $f_k(x, y)$:

$$\mathbf{g}_k = \mathcal{S}\{f_k(x, y)\}.$$

In the experimental dataset, the array response may be represented as a linear combination of the array responses for respective pixel sources. The sum may be expressed by the fit function, $\mathbf{g}^{\text{FIT}}$, where

$$\mathbf{g}^{\text{FIT}} = \sum_{k=1}^{N_{\text{pixels}}} w_k \mathbf{g}_k. \quad (5.1)$$

The parameters of this expression are the weights, w_k , and they are found by making a least-squares fit of $\mathbf{g}^{\text{FIT}}$ to $\mathbf{g}^{\text{MEAS}}$ to obtain the w_k .

Finally, the linearity of the problem means that the inverse equation is easily retrieved for the system. Knowing the w_k parameters, the reconstructed activity concentration is

$$f^{\text{REC}}(x, y) = \sum_{k=1}^{N_{\text{pixels}}} w_k f_k(x, y), \quad (5.2)$$

where f^{REC} is the reconstructed image function of the underlying surface activity concentration, $f(x, y)$. Therefore, the k 'th pixel of the reconstructed FOI image will have a reconstructed value of the averaged surface activity concentration inside the pixel that is given by $w_k f_k(x, y)$.

Figure 5.2: The system, $\mathcal{S}$, transforms a continuous input signal, $f(x, y)$, (the surface activity concentration of the ^{140}La distribution) into a discrete output, called the array response. $\mathcal{S}$ is a linear system because it transforms a linear combination of k signals, f_k , into a linear combination of the k respective array responses, $\mathbf{g}_k$. By definition, the weights, w_k , are equal for both of these linear combinations. By fitting the linear combination of the $\mathbf{g}_k$ to the experimental array response, the reconstructed array response, $\mathbf{g}^{\text{FIT}}$, is determined. Then, the w_k weigh the f_k in the linear combination for the image function, f^{REC} . Each $w_k f_k(x, y)$ is a reconstructed surface activity concentration for the k 'th pixel.

5.2 The Experimental Dataset

Figure 5.3 shows an alternative representation of the profile of Figure 5.1, but per directional-spectrometer location, it shows the count rate per crystal rather than the surface activity concentration. Each directional spectrometer is assigned an index number (x-axis in the figure). Responses were background-subtracted and decay-corrected, as per Sections 2.6.4 and 2.6.5, respectively. In addition to situating the peak of the deposition, the profile now provides directional information that begins to reveal the spatial distribution of the surface activity concentration. The direction of the truck is from directional spectrometer index 10 to 35, and corresponds to a motion toward the northwest. Consider the orientation of the directional spectrometer as it crosses the plume. The truck motion was in the direction SE-NW. Starting from the forward-right crystal in the direction of the truck, and then proceeding clockwise, crystals are labeled $\{1,2,3,4\}$. Crystals 1 and 4 (orange and grey, respectively) receive a greater signal when the truck is approaching the plume region because they shield crystals 2 and 3. On the other hand, crystals 2 and 3 (brown and violet, respectively) receive the majority of the response once the spectrometer has passed the plume region. This is because they are exposed to the source, which is now behind the truck.

The other major features in this figure are due to the presence of the truck in the detection system. Given the anisotropic responses that were seen in the DRDC experiments of Section 3.4, it is of no surprise that crystals 2 and 3 (brown and violet, respectively) receive the greatest responses for the most part of the path. Around spectrometer index 20, all four crystals receive ≥ 300 cps. However, on the other side of the peak (around index 25), there is a clear surfeit of counts for the near crystals, 2 and 3 (orange and grey, respectively). This is because of signal attenuation from the front components of the truck. For spectrometer indices ≤ 18 , the response curve is more symmetric, with crystals 1 and 4 being slightly more important. For indices ≥ 27 , the crystal responses of respective directional spectrometers are more symmetric, even with increased significance for crystals 2 and 3 (brown and violet). These results help to define the region of the plume, where the spatial variation in the surface activity concentration is much greater than the random noise.

The array response of Figure 5.3 is the vector of individual crystal responses for the experimental data, $\mathbf{g}^{\text{MEAS}}$, which will be used in the method of Section 5.4.

Figure 5.3: Count rate versus directional spectrometer index for the detector array. Each directional spectrometer is assigned an integer label. Individual crystals are grouped together in batches of four, per index of directional spectrometer. Starting from the forward-right crystal in the direction of the truck, and proceeding clockwise, crystals are labeled $\{1,2,3,4\}$. The colour scheme is as follows: $\{\text{orange, brown, violet, grey}\} = \{1,2,3,4\}$.

Simulation parameter	Description
Source	Pixel source of uniformly distributed, isotropic emitters
Source Dimensions	20 m $\times$ 20 m
Angular Coverage	Upper hemisphere
History Density	40 M per pixel
EGSnrc Output	Pulse height distributions, per crystal
Spectrum Energies (MeV)	0.323, 0.49, 0.82, 0.93, 1.60, 2.52
Spectrum Probabilities (%)	20.0, 45.0, 23.3, 6.9, 95.0, 3.5
Energy Window	1.52 MeV to 1.67 MeV (4σ)
CPU Time	10 h (simulations of all 36 basis-pixel sources)
World Geometry	Air block; 421 m $\times$ 362 m $\times$ 228 m
Truck Design	Best estimation of mass distribution for DRDC dataset
Number of CPUs	36

Table 5.1: Setup parameters for simulations of the pixel sources.

5.3 Monte Carlo Simulations of Template Sources

EGSnrc was used to model the detector array, and simulations were carried out in order to determine the array responses for each of the pixel sources in the FOI. Table 5.1 lists the parameters of the simulations performed for the detector array. The detectors had the same positions and orientations as the truck-borne detectors in the recorded data.

The count rates were from averaged, truck-borne detectors. As mentioned in Section 2.6.7, adjacent, truck-borne detectors were merged into a single, fictitious, truck-borne detector, whose crystal responses were defined to be the sum of the corresponding crystal responses of the two truck-borne detectors. In the representation where the detector was moving (as was the case in reality), this corresponds to summing the crystal responses over a 2 s spectrum acquisition interval. Then, the counts for the average-detector crystals were divided by 2 s to give the count rates for the averaged crystals. The truck design was the best-estimate design from the DRDC experiments, as described in Section 3.4. The world dimensions in the x-y plane were determined by the full extent of the array. A 100 cm border was used to ensure

backscatter was contained from the remote locations.

The spatial averaging requirement was important because, without it, the truck geometries in the static array would have been separated by less than 2 m in EGSnc; the long side of the truck is greater than 2 m, so adjacent truck geometries would have overlapped. This would have ruined the simulation in modeling reality.

Figure 5.4 shows the array responses for simulations of the template square sources, which were positioned at the respective pixel locations. In each histogram, the crystal responses are collected in batches of four, per directional spectrometer. The abscissa displays the directional spectrometer index, while the ordinate is the detector response, in counts per second.

In these plots, the breadth of the response peak is indicative of the distance of the source from the array. The relative crystal responses of directional spectrometers are sensitive to the orientation of the ensemble with respect to the plume direction. In each of the histograms of Figure 5.4, checks of this dependence were made for the individual spectrometers. For the intents of saving space, the array-response histograms were altogether displayed in this figure, where only the broad features are straightforward to discern. For example, when the source pixel is close to the array, the spectrometers in that part of the array register more energy depositions.

The array responses of Figure 5.4 are the thirty six $\mathbf{g}_k$ to be used in the unfolding described in Section 5.4.

5.4 Implementation of the Method

With all $\mathbf{g}_k$ known, these responses can be used as constants in a fit to $\mathbf{g}^{\text{MEAS}}$, of the experimental dataset. This is accomplished by performing a least-squares fit. The function to be minimized is called the objective function [29]. It is

$$M = \sum_{i=1}^{N_{\text{Spectrometers}}} \sum_{j=1}^4 \frac{\left(g_{i,j}^{\text{MEAS}} - \sum_{k=1}^{N_{\text{pixels}}} w_k g_{i,j,k} \right)^2}{\sigma_{i,j}^2}, \quad (5.3)$$

where the response, $g_{i,j}^{\text{MEAS}}$, of the j'th crystal of the i'th directional spectrometer is compared with the the linear combination of the w_k parameters. i is the directional spectrometer index of Figure 5.3, while j is the crystal index for that directional spectrometer (these are the coloured bars in Figure 5.3). Each $g_{i,j,k}$ represents the

Figure 5.4: Plots of count rate (in cps) vs. directional spectrometer index for pixel-source experiments in which squares of isotropic emitters were located at the relative positions of the exhibited plots. Crystal responses of each directional spectrometer are grouped together in batches of four, per index of directional spectrometer. Starting from the front-right direction, crystals in a directional spectrometer are labeled $\{1, 2, 3, 4\}$ in the clockwise direction. The colour scheme is as follows: $\{\text{orange, brown, violet, grey}\} = \{1, 2, 3, 4\}$.

response of the crystal response with directional spectrometer index i and crystal index j in the array of directional spectrometers, as obtained in simulation for the k 'th pixel source. The error term, $\sigma_{i,j}$, includes only random deviations in the experimental array response. Note that only those crystal responses have been included, where $g_{i,j,k} \geq 10$ cps. These rates satisfy the criterion of the number of events required for the bin distribution to follow Gaussian behaviour.

Refer to Figure 5.4. For pixels proximate to the array axis, the shapes of their array response distributions play the greatest role in the least-squares fitting algorithm, and they provide the majority of statistical information about the experimental response that was shown in Figure 5.3. It is noticeable that the rapid fall-off of statistical quality over the distance from the array is not dissimilar to the predictions of the sensitivity distribution which were inferred from the detector footprint of a uniform, infinite plane distribution. For pixel sources ≥ 60 m from the array (equivalent to two pixels on either side of the diagonal of Figure 5.4), the pixel sources begin to induce low count rates in the directional-spectrometer array. Compare this spatial variation of the array sensitivity to remote sources with the prediction of the detector footprint (Figure 4.3), which shows that the cumulative sensitivity is at 80 % that of a homogeneous, infinite plane beyond the disc radius, $R = 60$ m.

MIGRAD, a processor of the MINUIT function minimization tool of ROOT, was used to minimize Equation 5.3 [29]. Table 5.2 details the minimization parameters that were set to perform the optimization. Constraints were imposed on the range of permissible parameter values to ensure that only physical values of the surface activity concentration were permissible for the reconstructed image. The problem with MIGRAD is that it continuously updates the error matrix during the parameter search, with the assumption of an adiabatic error matrix [30]. The approach breaks down once limits are imposed on the range of values assigned to every parameter; MIGRAD uses a nonlinear transformation for the constrained, user-defined external parameter to create an internal, freely-varying parameter in 36-space [31]. Several parameters should approach zero to match the fall-off of the surface activity concentration profile in reality; thus, the symmetric errors are undefined when the parameters in question are too close to nil [30].

In order to account for these difficulties, the MINOS processor was used to determine the errors. The algorithm is versatile, and it defines asymmetric confidence regions [30]. A standard procedure is used, in which the objective function is traced

Simulation Parameter	Description
Initial Estimates	$[1, 1, \dots, 1]$ (36-vector)
Step Size	0.01
Parameter Lower Limit	0
Parameter Upper Limit	3
Maximum Number of Calls	10^6
Tolerance	0.1 (default)

Table 5.2: Setup of MIGRAD for parameter optimization

out from the minimum, and values are sampled about individual contours until the $1\text{-}\sigma$ contour is reached [29].

5.5 Reconstruction of Artificial Source Distributions

5.5.1 Pixel Source Distributions

The minimization of Equation 5.3 was performed for a variety of artificial sources in order to test the quality of the reconstruction using the spatial deconvolution method. To begin, a single pixel source was used as the artificial source. The simulations made use of the truck design from Section 3.4, which had a spread mass distribution. A threshold of 10 counts was used for the reconstructions. The photopeaks of the pixel-source EGSnrc energy spectra were not smeared before fitting because the individual source that was to be reconstructed was also generated in EGSnrc.

Results are shown in Figure 5.5 for the reconstruction of a 100 kBq/m^2 pixel source that is close to the array. The source is centred on $(x, y) = (150, 90) \text{ m}$, where coordinates x and y respectively represent offset easting and northing coordinates for the coordinate system of a Suffield dataset (see Section 2.6.8). In all the figures presented in this section, an arbitrary easting and northing offset has been applied. The direction of motion of the truck is indicated with sky-blue vectors, whose tails originate from the locations of their associated directional spectrometers. Directional vectors are included at the location of each truck-borne, directional spectrometer. The directional vector of a single directional spectrometer has components with magnitudes

Figure 5.5: Pixelized image reconstruction of the surface activity concentration (SAC), for a proximate, square pixel source, 20 m on a side and centred on $(x, y) = (150, 90)$ m. True concentration is 100 kBq/m^2 . Reconstructed vectors, in pink, overlap the yellow vectors of the experimental array response, and indicate the relative responses in the respective crystals. Blue vectors indicate the direction of motion of the truck.

equal to the count differences of the two pairs of diagonally-aligned crystals [11]. The vectors help to show discrepancies between the experimental counts and the reconstructed counts, but such was the perfect nature of the fit that the experimental vectors (yellow) are almost completely hidden by the overlapping, reconstructed vectors (pink). The spatial extent and magnitude of the reconstructed distribution are also in nearly perfect agreement with the true distribution.

Figure 5.6 shows the reconstructed distribution for another pixel source, which is more distant with respect to the array axis. Reconstruction of the remote pixel leads to a quality of array-response fit that is similar to the fit obtained for reconstruction of the proximate pixel. The length of a directional vector is proportional to the significance of the differences in counts among the crystals of that detector. Here, the diminished vector magnitudes imply that there are poorer statistics associated with the experimental array response. The directions are more randomly-distributed than those associated with the array response of the proximate pixel source. However,

Figure 5.6: Pixelized image reconstruction of the surface activity concentration (SAC), for a remote, square pixel source, 20 m on a side and centred on $(x, y) = (110, 50)$ m. True concentration is 100 kBq/m^2 . Reconstructed vectors, in pink, overlap the yellow vectors of the experimental array response, and indicate the relative responses in the respective crystals. Blue vectors indicate the direction of motion of the truck.

perfect agreement of the reconstructed surface activity concentration with the known value is consistent with the expectation that the minimization algorithm of MIGRAD is able to correctly identify the dominance of these pixels in generating the respective experimental array responses, $\mathbf{g}^{\text{MEAS}}$.

For the simulated results of several pixel sources, Table 5.3 shows the reconstructed surface activity concentrations and their statistical errors. From these results, it is evident that, even in the case of a nearly perfect reconstruction, pixel concentrations nearer the array are better reconstructed by the spatial deconvolution method than concentrations of the remote pixels. This is because a remote source induces lower count rates in the crystals of the array, and so the relative errors in the array response are greater in the denominators of the corresponding terms of the objective function. It is evident that the proximate pixel concentration has a more precisely reconstructed surface activity concentration because it agrees with the truth, but with significantly

(x, y)	Surface Activity Concentration (kBq/m ²)	(σ^+, σ^-) (kBq/m ²)
(150, 90)	99.8	(6.5, -72)
(110, 50)	100.0	(1.1, -1.4)
(190,130)	99.9	(4.2, -10.1)

Table 5.3: Reconstructed surface activity concentrations and associated errors for individual pixel synthetic source distributions. Reconstruction of the pixel at (190, 130) m, which is presented in the third row, is not graphically shown in the text.

lower errors.

5.5.2 Rectangular Source Distribution

The quality of the reconstruction was then examined for synthetic datasets. One was a rectangular distribution which covered exactly three collinear pixels in $120 \text{ m} < x < 140 \text{ m}$ and $60 \text{ m} < y < 120 \text{ m}$. Here, the EGSnrc simulations were set up to generate a 100 kBq/m^2 density of primary histories per pixel source. Again, the truck design was the one from Section 3.4 that had a spread mass distribution. The threshold for a binned crystal response to be included in the summation of Equation 5.3 was ≥ 20 counts. Figure 5.7 shows the reconstructed surface activity concentration. Figure 5.8 shows the negative statistical error map, while Figure 5.9 shows the positive error map; both of these were obtained using MINOS, which determined a 1σ confidence hypercontour, given the parameter constraints. The reconstruction is reasonable because the surface activity concentration is mostly inside the perimeter of the true geometry (outlined with a black contour). The errors of Figures 5.8 and 5.9 lead to agreement between the reconstructed magnitudes and the truth. Outside the rectangle, for example, the activity concentration at $(x, y) = (110, 90) \text{ m}$ is associated with a large, negative error; thus, the 2σ contour should overlap zero, and which makes the concentration magnitude consistent with zero. The same is true for the pixel at $(x, y) = (130, 70) \text{ m}$, which is consistent with 100 kBq/m^2 , but only at the cost of having a larger positive error.

In some cases, there are small deviations from the expected result. For example,

Figure 5.7: Reconstruction for a simulated rectangle, enclosed within three of the pixels (black contour). The true surface activity concentration is 100 kBq/m^2 . Yellow directional vectors are for the simulated response, while the pink vectors are reconstructed. Rectangle region is defined to be bounded by $100 \text{ m} < x < 120 \text{ m}$ and $60 \text{ m} < y < 120 \text{ m}$.

Figure 5.8: Negative errors on the reconstructed synthetic rectangle source of Figure 5.7. The rectangular source is defined to be enclosed by $100 \text{ m} < x < 120 \text{ m}$ and $60 \text{ m} < y < 120 \text{ m}$. Surface activity concentration had been set to 100 kBq/m^2 for the synthetic source. The error is associated with a 1σ confidence hypercontour for the 36 weighting parameters.

Figure 5.9: Positive errors on the reconstructed synthetic rectangle source of Figure 5.7. The rectangular source is defined to be enclosed by $100 \text{ m} < x < 120 \text{ m}$ and $60 \text{ m} < y < 120 \text{ m}$. Surface activity concentration had been set to 100 kBq/m^2 for the synthetic source. The error is associated with a 1σ confidence hypercontour for the 36 weighting parameters.

consider the pixel at (190, 130) m, where the negative error is insufficient to lead to agreement with zero surface activity concentration. This points to a limitation of the model. Equation 5.3 includes only the statistical error of the experimental data in the denominator. Thus, the method is designed for use where the statistical uncertainty of the data dominates over the statistical uncertainty of the template sources. This may be the reason for the minor failings of the method, as applied here, where the density of the generated histories was as high for the synthetic data as for the template histograms.

5.5.3 Extended Rectangular Source Distribution

Another synthetic dataset was an extended rectangular source distribution. Results for this dataset were obtained from an independent analysis [10]. The truck design that was used in the analysis was a variation on the same design as the trucks used in the other analyses of this dissertation. Three paths were selected from the Suffield dataset of June 6th (compare with Figure 2.14). For each of these paths, a 120×120 m² FOI was constructed, and each of these contained 6×6 pixels. Figure 5.10 shows the reconstructed FOIs (tiles). In addition, the rectangular source is indicated with a black contour. The extended source spans 400 m in the vertical and only 20 m in width. It covers a greater vertical dimension than the three FOIs combined. The surface activity concentration is uniform over the rectangle, at 61 kBq/m². Figure 5.11 shows the negative error maps for each of the three reconstructed tiles of the distribution, while Figure 5.12 shows the corresponding positive error maps.

The goal of this exercise was to determine how successfully reconstruction of a $120 \text{ m} \times 120 \text{ m}$ FOI could represent an extended rectangular dataset, as is to be done with the plume deposition of the Suffield dataset. Each tile was reconstructed separately.

In Figure 5.10, the lower left tile does not have any activity, and indeed there is almost none after the reconstruction. When the fit is made for the upper tiles, both clearly demonstrate the capability of the spatial deconvolution technique. For example, the regions that best reconstruct the source distribution are associated with pixels that overlap the rectangle region, and which occur nearest the spectrometer

Figure 5.10: Reconstruction for a simulated rectangle, covering three independent FOIs. Black dots represent the positions of directional spectrometers, whose crystal responses were used to reconstruct each of the three tiles, respectively. The true surface activity concentration is 61 kBq/m². Rectangle region is defined to be bounded by 320 m < x < 340 m and 40 m < y < 460 m. It is enclosed by a black contour [10](used under permissions to copy or modify and distribute).

arrays. In each tile, the effects of statistical losses for remote pixel sources become important around the regions furthest from the respective truck paths. In these regions of lower confidence, there exist non-zero values for the surface activity concentration where in reality there should be none. These deviations are largely accounted for by the statistical errors shown in Figures 5.11 and 5.12. The remaining discrepancy may be due to the neglected statistical uncertainty of the template histograms themselves, as discussed in the previous section.

For the most part, the method is successful in discriminating vacant pixels from those with source. Near the source, and close to the tile corners of the northernmost tile, the pixels have large errors, such as $+70 \text{ kBq/m}^2$ and -40 kBq/m^2 for the green outlier pixel; its surface activity concentration of $\text{SAC} = 85 \text{ kBq/m}^2$ is consistent with zero at 2σ . In both of the northernmost tiles, the 180 kBq/m^2 reconstruction does not agree within 2σ of zero because the negative error is only -25 kBq/m^2 . This reinforces the problems that are associated with the method, in that the outer pixels of the FOI can fail to reconstruct the surface activity concentration, in spite of their large errors. In addition, the southernmost tile shows a single pixel with some surface activity concentration, at the very northeast corner. The overestimated concentration of 30 kBq/m^2 is still in agreement with zero because its negative error is 15 kBq/m^2 . However, its agreement is weaker than those of proximate pixels.

Figure 5.11: Negative errors on the reconstructed synthetic rectangle source of Figure 5.10. The source is contained in a rectangular area enclosed by $320 \text{ m} < x < 340 \text{ m}$ and $40 \text{ m} < y < 460 \text{ m}$. This perimeter is defined by a black contour. Surface activity concentration had been set to 61 kBq/m^2 for the synthetic source [10](used under permissions to copy or modify and distribute).

Figure 5.12: Positive errors on the reconstructed synthetic rectangle source of Figure 5.10. The source is contained in a rectangular area enclosed by $320 \text{ m} < x < 340 \text{ m}$ and $40 \text{ m} < y < 460 \text{ m}$. This perimeter is defined by a black contour. Surface activity concentration had been set to 61 kBq/m^2 for the synthetic source [10](used under permissions to copy or modify and distribute).

5.6 Application of the Spatial Deconvolution Method to the Suffield Dataset of June 6th

5.6.1 Reconstruction for the Map of the Central Values

Having determined the limitations and strengths of the spatial deconvolution method with artificial sources, the method was now applied to the path sample of Figure 5.1. Using the array responses from the template pixel simulations of Section 5.4 a least-squares fit was made to reconstruct the spatial distribution of the surface activity concentration of the June 6th dataset. For inclusion of a crystal count rate in Equation 5.3, the threshold was 10 cps. Figure 5.13 shows the reconstructed map of surface activity concentration for the pixelized FOI.

The figure clearly shows that the reconstruction has successfully captured the plume region. There is a steep peak in activity along the axis of the detector array, which is held inside $(x, y) = (120, 120)$ m and $(x, y) = (160, 80)$ m. All the high-concentration pixels indicate that the plume propagates along the direction SW-NE. This is consistent with the known deposition distribution from other instruments. For example, the results from the airborne survey shown in Figure 2.5 showed that the surface activity concentration declines in this direction away from ground zero.

Because of the 20 m spatial resolution, it is expected that the plume reconstruction does not appear as a smooth, continuous image. As was the case for the infinite plane calculation, the representation of the concentration distribution is based on an averaging of the activity density over substantial regions of space. Some pixels underestimate the true surface activity concentration because they contain only an edge of the plume distribution. For example, the pixels at $(x, y) = (130, 110)$ m and $(x, y) = (150, 90)$ m clearly contain the plume edges. This makes sense because Figure 5.1 shows the peak to be spread over 30 m, comparable to the diagonal of a single pixel. Of the four central pixels, the ones along the plume direction (SW-NE) have much greater surface activity concentrations, which indicates that they hold most of the plume. Some of the plume would continue through the other two side pixels, and in each of these pixels, the local feature would be smoothed out over the area of the pixel. As expected, finite pixelization fails to represent the local details within 10 m fluctuations.

Figure 5.13: Map of the best approximation for distribution of surface activity concentration. Blue arrows point along the direction of motion, while yellow and pink arrows represent the directional vectors of the experimental counts and the reconstructed counts in the crystals, respectively.

5.6.2 Statistical Uncertainties

Figures 5.14 and 5.15 show the negative and positive statistical errors that were determined by MINOS, respectively. These maps show that the errors at the central pixels are consistently low, whereas the errors for remote pixels are consistently high. Figure 5.15, shows a symmetrical rise in the relative error on either side of the detector array. The discrepancy between the southwest and northeastern pixels arises from the fact that the plume concentration decreases with distance from ground zero. From Figure 5.13, for example, the surface activity concentration in the southwest is in the range of 30-50 kBq/m². For these pixels, the positive errors range from 15-60 kBq/m². Likewise, errors in the northeastern pixels range from 5-30 kBq/m². Thus, the data are consistent with a plume trending generally from SW to NE.

The negative error map agrees with expectation. Where there is negligible source, there is clearly low negative uncertainty, because negative surface activity concentrations are unphysical. This is one of the benefits of using the asymmetric confidence intervals of MINOS: it allows for a stringent bound to be placed on the parameters, without costing the algorithm the opportunity to search for larger positive errors.

An interesting property of the method is the effect of the 10 m pixel resolution on obscuring the finer details of the source. Ground zero is located southwest of this FOI. Thus, the surface activity concentration should be increasing toward the southwestern regions of the map. In Figure 5.13, the vertical streak of activity concentration which emanates from the central four pixels is likely a good representation of the general level of surface activity concentration because the relatively low, positive and negative errors of these pixels is nearly symmetric. In other words, there is no lower bound to restrict the value of the negative error, so this error is well-defined. In the rest of the southwestern pixels, the error is primarily positive by amounts that far exceed the reconstructed concentrations. Therefore, it is possible that the activity concentration was underestimated in these pixels. The northeastern pixels of Figure 5.15 show similar relative increases being more likely than lower values of the contamination. In itself, this is a sign of the asymmetry of the plume, whose activity density decreases with distance from ground zero.

Figure 5.14: Map of negative statistical errors for the best approximation of the distribution of surface activity concentration.

Figure 5.15: Map of positive statistical errors for the best approximation of the distribution of surface activity concentration.

Effect	Significance
Truck mass distribution	Most Important
Lag correction	Less Important
Background subtraction	Least important
Decay correction	Negligible

Table 5.4: Systematic effects.

5.6.3 Systematic Uncertainties

Systematic uncertainties are studied by observing the dependence of the result on a particular system parameter. Table 5.4 describes some permutations in the setup for the reconstruction. The first tests were performed for variations in the mass distribution of the truck. Then, a simulation was performed to determine the effects of the lag correction. Finally, two tests were performed to determine the variation of the image reconstruction in response to varying the amount of background in the 4σ photopeak window.

Figure 5.16 shows the image reconstruction for the truck design with a spread mass distribution (described in Section 3.4). There is good agreement between this reconstruction and that in Figure 5.13. The central four pixels show no striking discrepancies, while the plume direction is similar in both cases. For pixels ≤ 55 m (two pixel diagonals) off axis, the differences are not particularly pronounced, so that in these regions of greater array sensitivity, the two approximations are generally in agreement about the extent of the plume width, and the relative levels of surface activity concentration. There is indication of greater surface activity concentration coming from the southwest than from the northeast. This bias is due to two of the most southwestern pixels, which occur at $(x, y) = (110, 50)$ m and $(x, y) = (110, 70)$ m, respectively. The concentration of the first of these pixels is ~ 60 kBq/m², which contrasts markedly from the negligible amount in Figure 5.13. These are, however, in agreement with the corresponding pixels if the positive statistical uncertainties of Figure 5.15 are considered. The positive error of the first central-value pixel is ~ 40 kBq/m², while for the second pixel, it is only slightly lower.

A check was made about the assumption that most of the data was collected with

Figure 5.16: Image reconstruction of the surface activity concentration for the RDD dataset, and a truck design with a spread distribution of mass. Blue arrows point along the direction of motion, while yellow and pink arrows represent the directional vectors of the experimental counts and the reconstructed counts in the crystals, respectively.

the truck moving at constant speed. It is unlikely that the directional spectrometer would have traversed the full displacement over 1 s only after it acquired the full spectrum. In most of the simulations for the stationary detector array, the GPS positions of adjacent directional spectrometers were lag corrected. Figure 5.17 shows the reconstructed map for the case that no lag correction was performed, and spatial averaging was performed only for the purpose of avoiding truck overlap in simulation space (see Sections 2.6.6 and 2.6.7). In other words, the directional spectrometers were all shifted some 1.5-2 m toward the southeast. The concentrations in the central pixels are associated with regions where the statistical uncertainty is lowest, and for them, the reconstructed values are in agreement with the central values of Figure 5.13 within 15-20 %.

In the EGSnrc pixel-source simulations, a shift of the directional spectrometers to the southeast means that the detectors in the array see all the pixel sources in the FOI shift to the northwest. Therefore, MIGRAD is expected to overestimate the values of surface activity concentration for the eastern pixels. This check likely overestimates the positional uncertainty because, for a constant truck speed, the average truck position should be in the vicinity of the actual averaged coordinates for the spectrum acquisition. Therefore, the resulting systematic error may be considered overly conservative. For example, the effect of lag should not correspond to an uncertainty as high as ~ 160 kBq/m² in the pixel at (190, 130) m. However, it is also important to note that the low statistical errors of the outer pixels make the reconstructed values of surface activity concentration prone to greater variations in response to spatial uncertainties in the array than is the case for pixel reconstructions in the proximate pixels.

The background distribution of the June 5th dataset did not give a complete account of the background levels along this sample path. There could have been a significant variation of the ⁴⁰K peak compared to what was determined by taking a straight average background rate of the full distribution. Figure 5.18 shows the image reconstruction map for the case that the background levels were increased by $1\sigma = 8$ cps above the mean (see Section 2.6.4). This change does not induce significant variation from the reconstructed map of Figure 5.13. While the southern pixel at $(x, y) = (130, 50)$ m overestimates the surface activity concentration of the central value, this is a remote pixel, and its statistical error is large enough to account

Figure 5.17: Image reconstruction of the surface activity concentration for the RDD dataset, and a slight shift of the detector locations. Blue arrows point along the direction of motion, while yellow and pink arrows represent the directional vectors of the experimental counts and the reconstructed counts in the crystals, respectively.

Figure 5.18: Image reconstruction of the surface activity concentration for the RDD dataset, with a 1σ increment in the background subtraction. Used a truck design with a spread distribution of mass, with extra trunk shielding and a Al plate directly under the directional spectrometer. Blue arrows point along the direction of motion, while yellow and pink arrows represent the directional vectors of the experimental counts and the reconstructed counts in the crystals, respectively.

for the discrepancy.

The central pixels of the maps all agree on the direction of the plume across the FOI, and they tend to suggest an increasing gradient toward ground zero. However, there tend to be great differences in the reconstructed values in the outer, southwestern pixels of the FOI. This is accounted for by the large error that the reconstruction assigned to these pixels.

Figure 5.16 suggests that there is ambiguity in the choice of the best estimate of the truck design, because the spectra of the spread design do not agree as well with the experimental spectra of the DRDC experiment as do those of the best estimate, but for the Suffield dataset, it leads to similar agreement between the experimental array response and the reconstructed response.

5.6.4 Net Systematic Uncertainties

Using the three alternative approximations for the system setup, it was possible to determine the systematic uncertainty on the central estimate of Figure 5.13 by adding the deviations of these maps in quadrature [32]. The systematic error map is presented in Figure 5.19 based on the combined contributions of the systematic errors.

The system parameters most affect the outer regions of the array sensitivity, which leads to increasingly large fluctuations in the remote pixels.

In the band of highest sensitivity, the systematic error of the pixels does not exceed 15 kBq/m². Between the two truck designs, their respective front and back components do not significantly differ. The majority of the systematic uncertainty occurs in the remote pixels, as might be expected because only the near-field attenuation properties of the truck were accounted for in the DRDC calibration of truck design. More importantly, the large statistical uncertainty of the reconstructed values for these pixels lead to greater fluctuation in the reconstructed activity concentrations in response to variation of the system parameters. The other reason for the uncertainties is that, in reality, the outer pixels contained parts of the source distribution, which induced broader responses in the detector array; thus, their statistics are not sufficient for adequate reconstruction in these regions.

Errors are large in the eastern pixels. This is primarily caused by the spatial uncertainties of the detector position (lag-correction effects). However, recall that this is a conservative estimate. Most of the southwestern deviations are caused by

Figure 5.19: Map of systematic uncertainties on the best approximation for the distribution of surface activity concentration.

the effects of the truck mass distribution and the background subtraction. Were it not for the effects of lag uncertainty, Figure 5.19 would be similar to the positive error map of Figure 5.15; there would be a general increase in the uncertainty from the northeast to the southwest, which likely corresponds to the fact that more source could lie there to shine on the detector array.

Chapter 6

Conclusion

The truck-borne system of the NERT provides the necessary data for reconstructing the spatial distributions of varying types of radioactive sources, based on mobile, in-situ spectroscopy. In 2012, a series of experiments was conducted at the DRDC Suffield experimental proving ground at Medicine Hat in Suffield, Alberta. The purpose of the trials was to experiment with and model the blast dynamics of an outdoor radiological dispersal device (RDD), since no prior experimentation had been performed with detonation of active sources. The source was ^{140}La . The goal of the mobile surveys was to characterize the spatial distribution of the surface activity concentration, and the detection systems performed full surveys. The results of these surveys were sample lines of detector response, and at each truck position, these were used to determine an approximation of the surface activity concentration, as produced by a homogeneous, infinite plane. Furthermore, analyses were conducted to unfold the line responses and represent the distribution of surface activity concentration in the most sensitive regions of the sample array.

Note that the work presented in this thesis constitutes an entirely independent analysis of data, which has been publicly presented elsewhere [10, 33, 34]. There is generally good agreement between the two analyses. A full comparison and discussion of discrepancies is available [3].

6.1 The Infinite Plane Calculation

The infinite-plane model was based on the approximation that the sensitivity curve of the gross-count spectrometer could be used to extract an asymptote, whose reciprocal was used to determine the number of kBq/m^2 required from a large, uniform,

isotropic disc to generate a counts-per-second response in the directional spectrometer. EGSnrc was used to simulate uniform, isotropic, finite discs of increasing radii, and from the integrated photopeak counts, a sensitivity profile was obtained. The fluence-rate equation was fit to the profile, and this gave the sensitivity curve of the spectrometer. One of the terms in the fluence-rate equation is the asymptote of the sensitivity curve, so it was found from using the best estimate of the fit parameter. In the simulations, a model directional spectrometer was held by a steel-aluminium, composite truck. The truck design was based on interactive simulations of EGSnrc to reproduce the spectra for a series of point-source positions of a calibration experiment. The best estimate was a truck with substantial shielding at the front (i.e., a thick trunk-cab combination), and significant back shielding, in the form of a steel base. To impose bounds on the mass distribution of the truck, another design was tested, with all the mass spread out in the cab and base components. The asymptotes were used to define an estimate of the standard deviation for the systematic uncertainty of the central estimate. It was found that the sensitivity asymptote was $\kappa_{\infty} = (49 \pm 1 \text{ (statistical)} \pm 7 \text{ (systematic)}) \frac{\text{cps}}{\text{kBq/m}^2}$. The reciprocal is a conversion factor for count-rate measurements of the truck-borne survey. It was $\xi = (2.04 \pm 0.04 \text{ (statistical)} \pm 0.29 \text{ (systematic)}) \times 10^{-2} \frac{\text{kBq/m}^2}{\text{cps}}$.

The analysis of the infinite plane calculation was successful in producing a map of the averaged surface activity concentration along the truck path. It improved on the basic formalism of the fluence-rate equation by itself, which makes basic assumptions about the detector geometry; the truck design is still in doubt, but more interactive modeling should lead to a stronger representation of the truck-borne system in simulation space.

The plume concentrations were found to be $\sim 140 \text{ kBq/m}^2$ at the point in the survey nearest ground zero, or at $(x, y) = (-300, -400)$ in offset easting and northing coordinates. The surface activity concentration was found to decline rapidly with the wind direction, such that the concentrations of $\sim 40 \text{ kBq/m}^2$ were observed at 1 km from ground zero.

6.2 The Spatial Deconvolution Method

A sample truck path was used from the June 6th dataset to unfold the line response profile of the truck-borne spectrometer. This was accomplished by initially supposing

that a single, truck-borne detector could be represented as a stationary array of multiple, truck-borne detectors. A $120 \times 120 \text{ m}^2$ field of interest (FOI) was selected to enclose all the detectors in the profile, and spatial and averaging corrections were performed to account for lag uncertainty and to prevent truck overlap in simulation space. That is, the incentive was to reproduce the truck-borne system in EGSnrc as accurately as possible. With averaging, specific directional information was lost over 1 s sampling intervals, although the scale of the pixelization was such that the discrepancies over $\sim 5 \text{ m}$ ranges was not expected to be significant.

In a 6×6 grid, each FOI pixel was used to represent the averaged source distribution of ^{140}La in that area. To retrieve this spatial representation, EGSnrc was used to model independent pixel sources. Using the experimental array response from the RDD dataset, the FOI pixels were assigned weighting coefficients for surface activity concentration, which were exactly the same weights of the array response to respective pixel sources. In other words, it was assumed that the system function was linear.

It was demonstrated that the spatial deconvolution method accurately reconstructs a simulated rectangular source distribution that exactly coincides with three of the FOI pixels. It is also capable of reconstructing a simulated, extended, rectangular source distribution that covers over three FOIs in the vertical dimension.

Finally, the method was applied to a sample of the survey data collected following in the aftermath of the RDD shot at Suffield.

6.3 Comparison the Spatial Deconvolution Results with Results of the Infinite Plane Calculation

Figure 6.1 shows the image reconstruction of the spatial distribution of surface activity concentration for the line response between $(x, y) = (1.8, 2.1) \text{ km}$ and $(x, y) = (1.6, 2.3) \text{ km}$ (offset easting and northing coordinates). For comparison, results from the infinite-plane model are presented here as well.

The only concentrations that are statistically significant occur in the vicinity of the array. Using the spatial deconvolution method, concentrations reach around 100 kBq/m^2 near the array. The concentrations are greater than those which are observed using the uniform, infinite plane assumption. The spatial deconvolution

Figure 6.1: Maps of the reconstructed surface activity concentration (SAC) for implementation of the best-truck design, lag correction and averaging. The plot shows the results for the activity concentration based on the assumption that there is an underlying, infinite plane of uniformly distributed, isotropic emitters. These are denoted by the coloured circles, and their magnitudes of surface activity concentration are defined by the inner colour chart. Also on this plot is the pixelized representation of the unfolded plume distribution, using $20 \text{ m} \times 20 \text{ m}$ pixels. These values of the surface activity concentration are defined by the outer colour chart.

method leads to an image of the plume of 20-30 m width. The concentrations obtained with the spatial deconvolution method are greater than the concentrations obtained at the same location when using the infinite plane calculation because the spatial deconvolution method averages over $20\text{ m} \times 20\text{ m}$ pixels, while the uniform, infinite plane method averages over an area with radius of 200 m, as characterized by the sensitivity curves.

These measurements will be used to constrain models for RDD explosions and the subsequent particle dispersion. The methods are also useful in emergency response. For example, a quick spatial deconvolution would be possible for a fixed stationary array of detectors surrounding a nuclear power plant. Furthermore, the methods are of use in the consequence management phase of an emergency response. For example, the ability of the spatial deconvolution method to show that the concentrations are elevated over a narrow region of space could be important to responder safety or to determining the suitability of rehabilitation of a previously evacuated area.

6.4 Further Improvements

There is much uncertainty about the level of impact of each of the systematic effects. The variation in the truck design causes significant changes in the results of a spatial reconstruction. Furthermore, spatial corrections also make the influence of the truck design important because of the fact that the front components are highly anisotropic in the near field. Therefore, the truck mass distribution must be examined in more detail.

To begin, more EGSnrc models could be constructed in an iterative manner, using the relative agreement between the DRDC spectra and the simulated ones to improve the model. Another possibility is to conduct a more detailed version of the DRDC experiment, such as the one outlined in [35]. It involves using a point source, such as the ^{140}La one of the DRDC experiments, which is positioned in a grid of sample positions about the truck-borne spectrometer. This type of experiment was attempted in Denmark for a 16.8 MBq , ^{137}Cs source, with a carborne, NaI(Tl) spectrometer ($10 \times 10 \times 40\text{ cm}^3$) 2.2 m above ground (atop a car) [35]. From the results of 791 positions and 10 s collection intervals, a sensitivity map was created [35]. Not only is this useful for calibrating the simulated truck design, but it provides a strong basis for benchmarking the spectrometer footprint itself.

Experiments were only performed for a select few truck designs, which meant that there would likely have been inconsistency when comparing the results of certain truck designs with both the experimental datasets of the Suffield and DRDC experiments. In the case of the former experiment, the dominant contributions should be coming from much larger distances than were accounted for in the DRDC experiment. To some extent, the truck designs were decided based on their capacity to accurately reconstruct the far-field data of the RDD dataset, but there is no experimental verification that this implies a more accurate design.

To some extent, environmental effects should be considered in the simulations. For example, the levels of scatter from the soil could affect the ^{140}La spectrum acquired at the spectrometer. Berkeley Laboratory has a truck-borne system of a 10×10 NaI(Tl) array, called RadMAP [36]. It conducted experiments with a mobile, ^{137}Cs point source at a 20 m standoff distance [36]. The SWORD code (a GEANT 4 application) was used to simulate the detector array for the case of soil and no soil [36]. Inclusion of soil led to as high as a 20 % increase in the amplitude of the 661.6 keV photopeak. From [28], a typical soil composition contains mostly silicon dioxide and partly water, with trace amounts of aluminium oxide, iron oxide, and carbon dioxide. These media between them have the capacity to produce a significant level of incoherent scatter. On the other hand, only a forward scatter would lead to energy deposition in the photopeak, which would mean that the only contributing scatter would arise from large R, and would likely be negligible compared to the small-R, non-scattered contribution.

Finally, it might be useful to include water vapor in the PEGS4 definition of air in the world geometry. Having had a lightning storm within 48 hours of the first shot, humidity could have been important in the signal attenuation, which would have increased the uncertainty in the results. However, this systematic uncertainty is not expected to greatly contribute to the total.

6.5 Closing Comments

From the analysis of the spatial deconvolution method, it was found that the unfolding technique was capable of producing a reasonable spatial reconstruction of the surface activity concentration. Errors tend to be significant, especially at the edges of the FOI; however, further modeling of the truck design could be pivotal in obtaining a

more accurate model of reality. More work is also required to account for systematic uncertainties imposed by the background radiation.

The techniques for the infinite-plane calculation and the spatial deconvolution method successfully expanded on the basic theoretical model of the fluence-rate equation to make use of the anisotropic considerations specific to the problem. Monte Carlo was used not only to improve the understanding of limitations imposed by a truck-borne spectrometer geometry on the asymptotic nature of the sensitivity, but allowed for the removal of the infinite plane assumption. In particular, the result of the spatial deconvolution method provided an estimation of the local spatial distribution of this quantity to an extent that it has the potential for use in both understanding the blast dynamics of a radiological dispersal device and defining an appropriate level of pixelization to characterize its spread along a significant field of interest.

List of References

- [1] L. E. Sinclair *et al.*, “Aerial Measurements of Radioxenon Concentration,” *Journal of Environmental Radioactivity* 102(11): 1018-1023, 2011.
- [2] J. L. Prince and J. M. Links, *Medical Imaging: Signals and Systems*. New Jersey: Pearson - Prentice Hall, 2006.
- [3] F. A. Marshall, “The June 6th Suffield Experiment: Results of the Background Survey, and Validation of Reconstruction Models for a Spatial Distribution of Surface Activity Concentration,” August 2014. NER 004-00023 (2014).
- [4] C. McGrew, “PHYS310: Lecture 11 - Using MINUIT (in ROOT).” superk.physics.sunysb.edu/~mcgrew/phys310/lectures/phys310-lecture-11-2007.pdf. State University of New York at Stony Brook, Date modified: February 2007, Access date: May 2012, Presentation.
- [5] “Health Concerns: Federal Nuclear Emergency Plan.” :www.hc-sc.gc.ca/hc-ps/ed-ud/fedplan/index-eng.php. Date modified: April 1st 2014, Access date: March 2014.
- [6] A. Sohier and F. Hardeman, “Radiological Dispersion Devices: are we prepared?,” *Journal of Environmental Radioactivity*, 2006. :www.sciencedirect.com.
- [7] J. L. Regens, J. T. Gunter, and C. E. Beebe, “Estimating Total Effective Dose Equivalents from Terrorist Use of Radiological Dispersion Devices,” *Human and Ecological Risk Assessment*, January 2007.
- [8] E. Briere, “Mapping Radioactivity to Improve Nuclear Emergency Response.” :chis.nrcan.gc.ca/ERM-CRU/index-eng.php. Date modified: December 2010, Access date: June 2012.
- [9] NRCan, “Full-Scale Radiation Dispersal Device: Experimental Plan for Fall 2012,” August 2012.
- [10] L. E. Sinclair, F. A. Marshall, R. Fortin, and A. A. MacCleod, “Reconstruction of the Spatial Distribution of Radioactive Contamination using an Array of Directional Spectrometers,” June 2014. Poster presented by F. Marshall at the Symposium on Radiation Measurements and Applications in Ann Arbor of USA.
- [11] S. Khan, “Source Localization using a Directional Gamma Ray Spectrometer,” Master’s thesis, Carleton University, Ottawa, January 2013.

- [12] L. Erhardt, "CRTI 07-0103RD: Full-Scale RDD Experiments and Models," June 2013. Presentation at the Radiological Analysis and Defence Group - Ottawa RCMP civilian research building.
- [13] R. Fortin *et al.*, "Full Scale RDD field trials: NRCan's Field Operations and Data Acquisition," Fall 2013. Presentation at Booth Street.
- [14] J. Lilley, *Nuclear Physics: Principles and Applications*. Great Britain: John Wiley Sons, Ltd., 2008.
- [15] R. Heath, "Scintillation Spectrometry: Gamma-Ray Spectrum Catalogue." Gamma-Ray Spectrometry Centre, <http://www.osti.gov/scitech/servlets/purl/4486001>, 1997.
- [16] L. Lebel, "Atmospheric Dispersion Modeling of Suffield Full-Scale RDD Tests," March 2014. Meeting at DRDC Shirley's Bay branch in Ottawa.
- [17] R. Fortin, "Full Scale RDD field trials: Airborne and Truckborne Data Processing," May 2014. Meeting at DRDC Shirley's Bay branch in Ottawa.
- [18] R. Fernow, *Introduction to experimental particle physics*. Melbourne, Australia: Cambridge University Press, 2001.
- [19] M. Moszynski, "Intrinsic energy resolution of NaI(Tl)," *Nuclear Instruments Methods in Physics Research A*, 2002.
- [20] "Technical Specifications." :www.radiationsolutions.ca/fileadmin/pdf/RS500TechData.pdf. Access date: Summer 2013.
- [21] V. Mualeedhara, *Nuclear Radiation Detection, Measurements and Analysis*. Oxford, U.K.: Alpha Science International Ltd., 2009.
- [22] J. Sillicker, "Intermediate GPS Training," Summer 2013. GPS training course.
- [23] "NIST XCOM: Element/Compound/Mixture." :physics.nist.gov/PhysRefData/Xcom/html/xcom1.html. Date Accessed: June, 2014.
- [24] D. Rogers, "Photon transport and COMIN/STACK in EGSnrc," March 2013. Photon transport lecture of PHYS 5291 A by D.W.O. Rogers.
- [25] "Laser Levels - Line Laser Levels: Self-Leveling Quad-Line Cross-Line Laser with Plum Beam." :[//johnsonlevel.com/P/70/QuadLineSelfLevelingCross](http://johnsonlevel.com/P/70/QuadLineSelfLevelingCross). Access date: August 2014.
- [26] "Gamma-Ray Spectroscopy in the Environment," 1994. ICRU Report 53.
- [27] H. Seywerd, "Simulations for Air to Ground Extrapolation," February 2013. Presentation at NRCan Booth Street, in Ottawa.
- [28] K. M. Miller and P. Shebell, "In Situ Gamma-Ray Spectrometry: A Tutorial for Environmental Radiation Scientists," *Environmental Measurements Laboratory U.S. Department of Energy*, October 1993.

- [29] F. James, “Interpretation of the errors on Minuit parameters,” in *MINUIT, Function Minimization and Error Analysis: Reference Manual*, vol. Version 94.1, CERN Geneva, Switzerland: Computing and Networks Division, 1998. Last modified: May 18th, 2000, Date Accessed: July, 2014, <http://wwwasdoc.web.cern.ch/wwwasdoc/minuit/node31.html>.
- [30] T. R. team, “Fitting Histograms: The Minimization Package,” in *ROOT: An Object-Oriented Data Analysis Framework: Users Guide 5.26* (O. C. Ilka Antcheva, ed.), CERN Geneva, Switzerland: CERN, December, 2009.
- [31] F. James and M. Winkler, “Minuit User’s Guide.” <http://seal.web.cern.ch/seal/documents/minuit/mnusersguide.pdf>, June 2004. Date Accessed: July, 2014.
- [32] V. Blobel, “Statistical and other errors.” http://www.desy.de/~blobel/blobel_errors.pdf, March 2005. Presentation.
- [33] L. Sinclair *et al.*, “Truckborne and Aerial Mobile Radiation Survey following Detonation of a Radiological Dispersal Device,” July 2014. Presentation at The 59th Annual Meeting of the Health Physics Society, Baltimore, Maryland, U.S.
- [34] L. E. Sinclair, R. Fortin, and F. A. Marshall, “Calculations of Sensitivities for the Airborne and Truckborne Systems by Monte Carlo Simulation,” May 2014. Meeting at DRDC Shirley’s Bay branch in Ottawa.
- [35] H. Aage *et al.*, “Carborne gamma-ray spectrometry. Calibration and applications,” *Applied Radiation and Isotopes* 64, 2006.
- [36] J. C. Curtis *et al.*, “Benchmarking the RadMAP Gamma-Ray Sensors,” June 2014. Poster Presentation for the SORMA conference in Michigan.
- [37] E. Manegra-Hing, “EGS++ Geometry Class,” March 2013. Special lecture in the course, PHYS 5291 A by D.W.O. Rogers.

Appendix A

EGSnrc Directional Spectrometer Geometry

The EGSnrc C++ class library was used for all simulations because of its efficient use of object-oriented programming. One of the main features of this interface is that it uses dynamic binding to implement the methods of abstract base classes in heirarchical structures. Abstract classes are defined for geometry modules, such as prisms and spheres. They are categorized as members of an EGS_BaseGeometry class [37].

Whereas Monte Carlo N-Particle (MCNP) is slow for complex geometries, the methodology of the C++ library promotes the concept of interface handling to high priority [37]. In particular, geometry definitions are set so that all the subclasses of the abstract class, EGS_BaseGeometry, must inherit the set of methods described in Table A.1 [37].

Method	Result
howfar()	Will particle enter a new region?
hownear()	What are the nearest regions?
isInside()	Basic information about current region.
isWhere()	Basic information about current region.
medium()	Basic information about current region.
regions()	Number of geometries in current region

Table A.1: Methods for efficient interface crossing.

In the setup of a simulation, regions are defined, which may contain numerous geometries. For example, the directional spectrometer consists of four composites of material in the constituent logs. A directional spectrometer object is then one that contains all of the various materials of those four logs, and it can be used as a single entity by defining an EGS_GENvelope to contain the RSX-1 logs. That is, the RSX-1 system is treated as a single geometric region. Because the region has several geometries, the transport code must be able to answer the basic questions, such as whether a photon has entered the ensemble before deciding whether to check the interior components of the RSX-1 logs. Thus, the whole detector ensemble inherits the isInside() method, which is checked for every step of particle transport. For transport in the air region, this means that only the directional spectrometer and the air regions are considered, and there is no need for examination of the multiple geometries within the RSX-1 ensemble, as is the case for MCNP. This is a primary example of the efficiency of the C++ interface.

Table A.2 shows the EGSnrc geometries used for the individual components of the detectors.

Component	Material	Geometry Module
Exterior crystal housing	Poron	EGS_Block
Exterior crystal housing (inscribed in Poron)	Felt	EGS_Block
Exterior crystal housing (inscribed in Felt)	Al	EGS_Block
Crystal (inscribed in Al)	NaI[Tl]	EGS_Block
PMT space (inscribed in Poron)	Vacuum	EGS_Block
PMT base	Steel	EGS_Block
PMT tube, casing	Steel	EGS_ConeStack
PMT tube, interior	Vacuum	EGS_ConeStack
Analyzer, interior	Vacuum	EGS_Block
Analyzer, casing	Steel	EGS_Block

Table A.2: Geometry modules for directional spectrometer.

Implementation of dynamic binding in the EGS++ geometry modules allows for straightforward definitions of the subcomponents in a RSX-1 log. In particular, the individual detectors were constructed as union objects of geometries, some of which were inscribed in others. A directional spectrometer geometry was built by replicating four log geometries, and applying transformations and rotations to them.

Figure A.1 and Figure A.2 show the compositions of Poron and felt, respectively. These media were defined using PEGS4.

Figure A.1: Composition of Poron in EGSnrc.

Figure A.2: Composition of felt in EGSnrc.

Appendix B

Truck Designs in EGSnrc for the DRDC Experiments

Two truck designs were used in this analysis. The first design was used as the central estimate because of its consistently reasonable agreement with the DRDC spectra for a ^{140}La point source located at different positions around the truck-borne spectrometer. The second design was more simplistic, with a spread mass distribution, and using more basic geometries in the composite design.

Figure B.1: Best estimate of the truck design. It has a mixed mass distribution, with a front plate of shielding, a concentrated trunk, and a spread cab and base.

Component	Length	Width	Height	Density	Mass
Units	cm	cm	cm	g/cm^3	t
Front Trunk	80.00	50.74	20.00	2.70	0.22
Trunk	25.00	50.74	25.00	2.70	0.09
Cab	2.00	202.95	110.0	2.70	0.12
Axel Block	200.00	40.00	4.19	7.79	0.26
Base	200.44	202.95	1.98	7.79	0.63

Table B.1: Design details for the best estimate of the truck design, as based on the DRDC calibration experiment. Front trunk and main trunk are composed of aluminium, as is the cab component. The Axel block and the base components consist of steel.

The best estimate for the truck design is displayed below in Figure B.1. Table B.1 lists the design layout for this design.

Figure B.2: Spread-truck design. It has a short, condensed trunk, a thin, Al cab and a spread base of steel.

Component	Length	Width	Height	Density	Mass
Units	cm	cm	cm	g/cm ³	t
Trunk	25.00	202.95	25.00	2.70	0.34
Cab	2.00	202.95	110.00	2.70	0.12
Base	250.44	202.95	1.98	7.79	0.78

Table B.2: Design details for the spread-truck estimate of the truck design, as based on the DRDC calibration experiment.

The spread-truck estimate of the truck design is displayed in Figure B.2. Table B.2 lists the design layout.

Appendix C

Smearing Code for EGSnrc Pulse Height Distribution

This code smears a pulse height distribution that was generated by EGSnrc. The spectrum information is contained inside the “stream_par” parameter for a crystal of the directional spectrometer whose index “index_par”. The number of primary histories, “num_histories”, is used to remove the normalization imposed by the user code on the output.

```
struct Spectrum{
    vector<double> energies, counts;
};

#define NUMCHAN_MC 1000

//Experimental parameters.
const double peak_energy = 1.5962; //MeV
const double energy_resolution = 38/sqrt(peak_energy*1e3)*2.354; //From fit.
const double peak_FWHM = energy_resolution*sqrt(peak_energy*1000.0);
const double peak_sigma = peak_FWHM/2.354;

//Monte Carlo parameters.
//Centre of first bin, [0,2.5213] keV.
const float channel_size = 0.00126065; //MeV
const float max_E_in_MC = 2.0*channel_size*NUMCHAN_MC;
```

```

//Windowing parameters.
const float E_LBi = peak_energy - 2.0*peak_sigma/1000.0;
const float E_UBi = peak_energy + 2.0*peak_sigma/1000.0;
const int CH_LB = NUMCHAN_MC/max_E_in_MC*E_LBi;
const int CH_UB = NUMCHAN_MC/max_E_in_MC*E_UBi;
const double E_LB = (CH_LB+0.5)*channel_size*2.0;
const double E_UB = (CH_UB+0.5)*channel_size*2.0;

//Windowing variables.
double FWHM = 0.0, sigma = 0.0;

//Function to read in the spectrum information from a file and smear it.

void read_PHD(fstream &stream_par, const int index_par, const int
num_histories){

    Spectrum spectrum;

    vector< vector<double> > counts_vectors;
    while(stream_par >> temp_index >> temp_energy >> temp_count >>
temp_count_error){
        vector<double> cv(2);
        cv[0] = temp_energy;
        cv[1] = temp_count*num_histories;
        counts_vectors.push_back(cv);
    }
    TH1F *smeared_spectrum;
    smeared_spectrum = (TH1F *)gROOT->FindObject("smeared_spectrum");
    if (smeared_spectrum) smeared_spectrum->Delete();
    smeared_spectrum = new TH1F("smeared_spectrum", "Smeared
Spectrum;E_{deposited} (MeV);Counts",NUMCHAN_MC,0,max_E_in_MC);
    for(int i = 0; i < counts_vectors.size(); i++){

```

```

        FWHM = energy_resolution*sqrt(1000.0*counts_vectors[i][0]); //Resolution
from stochastic deviations.
        sigma = FWHM/2.354;
        for(int j = 0; j < int(counts_vectors[i][1]); j++){
            temp_energy = gRandom->Gaus(counts_vectors[i][0]*1000.0,sigma);
            if(temp_energy >= (E_LB*1000.0) && temp_energy <= (E_UB*1000.0)){
total_counts.counts[index_par]++;
            }
        }
    }
}

```

Appendix D

Validation of the Method: Comparison with Theoretical Constraints

In Chapter 4, the sensitivity equation was used to extract an asymptote from the data of EGSnrc simulations of finite discs uniformly populated with isotropic emitters. A check can be performed to confirm that the Monte Carlo data are describable within the constraints of theory. This means ensuring that the constant term in the sensitivity equation is within reasonable bounds.

D.0.1 Limiting Bounds on the Sensitivity Profile: Efficiency Considerations

Equation 4.4 contained an effective area term, A_{eff} . The bounds on this parameter were determined by examining the intrinsic efficiency of the directional spectrometer for the extreme cases of photons incident either from directly below or incident exclusively from the sides.

Simulations were performed in which two broad, parallel, square beams were incident on the detector. The first was incident from the underside of the detector, while the second was directly incident on one of the side faces. Both beams entirely covered the faces, and for them, ten thousand primary histories were generated per area of smaller face (~ 9 primary histories per cm^2).

The results of the simulations are listed in Table D.1. Efficiencies were obtained by dividing the integrated photopeak counts (obtained within a 4σ photopeak window) by the number of gammas incident on the directional spectrometer (equivalent to the number of primary histories).

Direction of Incidence	$A_{\text{geometric}}$ (m ²)	Intrinsic Efficiency (%)
Underside	0.038	49.71
Side	0.086	46.08

Table D.1: Results for directional spectrometer of intrinsic efficiency.

For the disc sources, a monoenergetic spectrum was used, and photons were emitted over the full solid angle. Note that the simulations involved a greater density of primary histories than those for the truck-borne simulations ¹.

Figure D.1 shows the relative magnitude of the fit sensitivity curve with those predicted by the limiting cases of A_{eff} . The data points correspond to the photopeak counts obtained for simulations of uniformly distributed, isotropic disc sources of radius R . The lower-bound curve is for the case of photons incident from directly underneath the spectrometer. Here, $A_{\text{eff, min}} = A_{\text{geometric, underside}} \times \epsilon_{\text{underside}} = 0.02 \text{ m}^2$. The upper-bound curve is for the case of photons incident from two sides and underneath the spectrometer. Here, $A_{\text{eff, max}} = A_{\text{eff, min}} + 2 \times A_{\text{geometric, side}} \times \epsilon_{\text{side}} = 0.1 \text{ m}^2$. The fit sensitivity curve lies within the bounds of reason defined by the limiting cases of A_{eff} . Also, the curve is closer to the approximation of photons incident from the sides and the underside.

¹There is a significant reduction of CPU time when simulating an exposed directional spectrometer because, for 1.6 MeV emissions the cross sections of steel and aluminium are much greater than those of the casing materials, and because in the truck-borne simulations, they were simulated in bulk quantities compared to the crystal shielding. Therefore, it was possible to create a more precise dataset, using a large number of primary histories, with density 10^4 primaries per small crystal face (that is, $\sim 10^6$ primaries per squared metre). Only an overnight simulation of a hundred CPUs was required to obtain a precise solution for this more basic system.

Figure D.1: Peak count rate per surface activity concentration, based on the limiting cases of photon incidence. Central curve (black, solid line) is the best estimate of the sensitivity profile of an isolated directional spectrometer. The lower curve (pink, dashed) is the corresponding curve for the limiting case of photons incident from directly below the spectrometer, while the topmost curve (pink, dot/dash) is for the case of photons incident from all the sides.