

Exercise. Response of environmental spectrometric monitors. Detection forcing and reciprocal variance reduction techniques

Arturo Vargas

Universitat Politècnica de Catalunya

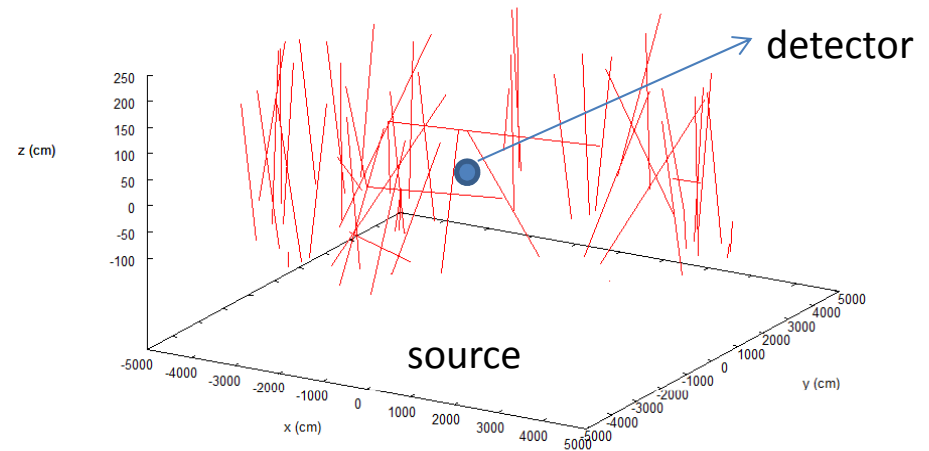


Aim

- Use of reciprocal and detection forcing variance reduction methods to calculate the energy fluence distribution from point, surface and volumetric contaminations. In the exercise a surface contamination will be used.
- Calculate a “real” spectrum considering energy resolution and uncertainty due to number of counts in every energy.
- Example: Calculate the distribution $p(E)$ of energy deposition events produced by a surface ^{137}Cs contamination in a spectrometric monitor (SpectroTRACER from SAPHYMO company).

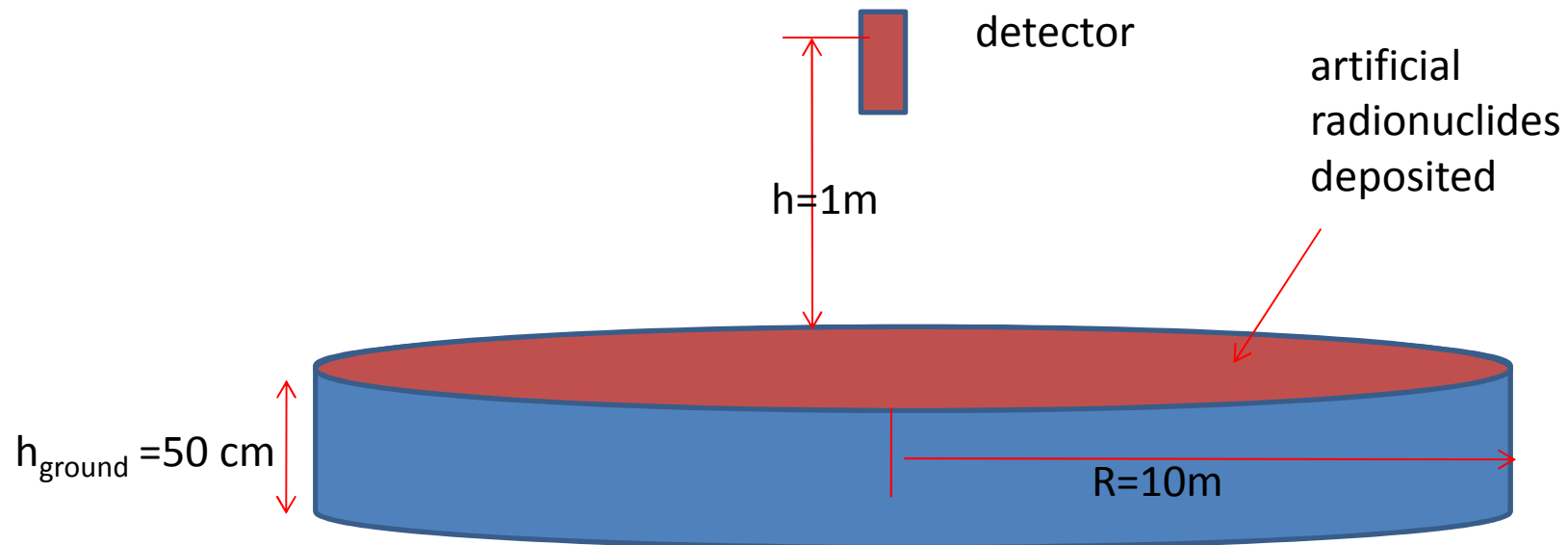
Introduction

Campus Sud station (Barcelona)



- Variance reduction techniques are needed in MC simulations when there is a large source and small source → simulation is inefficient
- These techniques are applied in the environmental geometries such as ground deposited contamination

Geometry

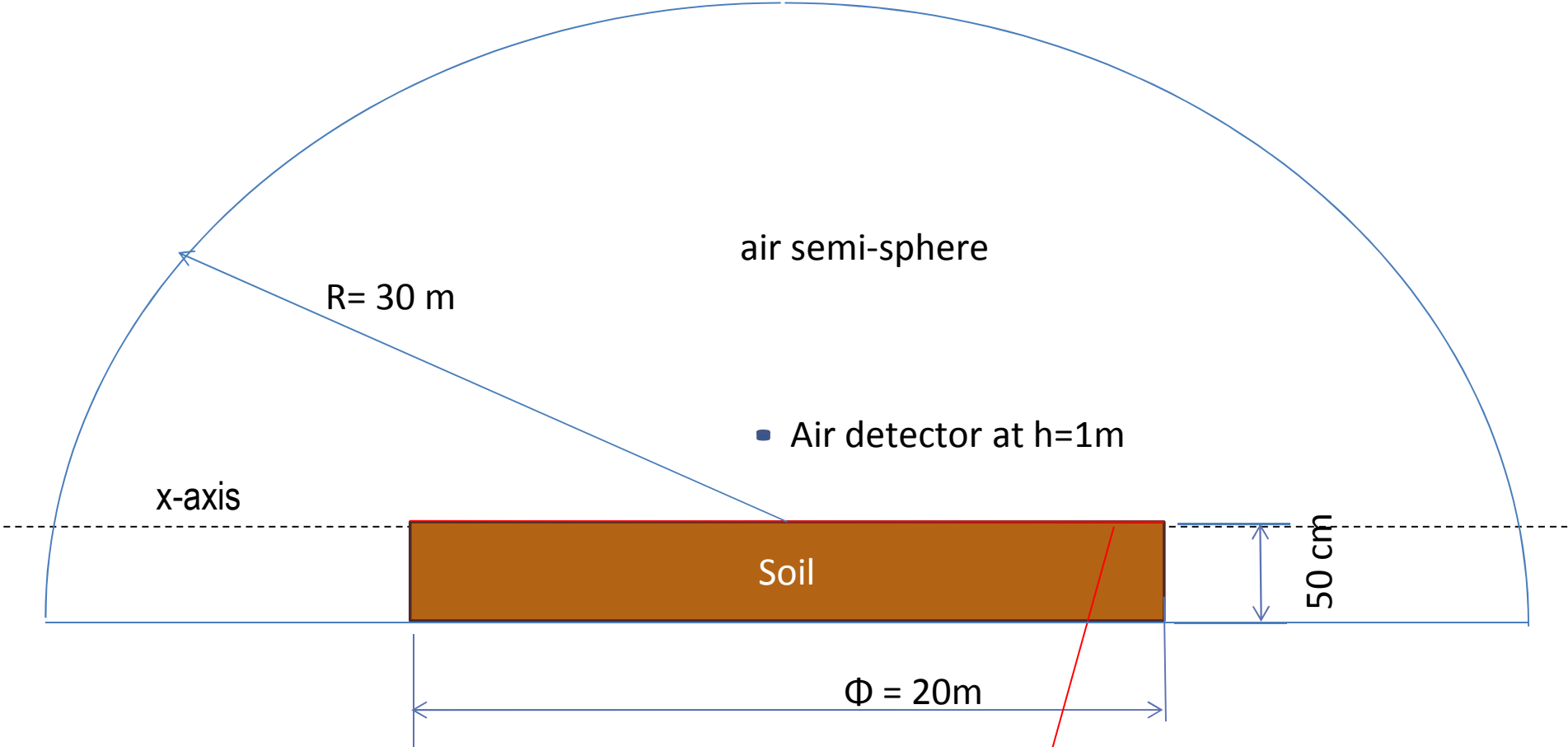


Guide

1. Fluence for 662 keV emitted gammas is calculated in the detector position by Monte Carlo simulations using variance reduction techniques.
2. Calculated fluence is convoluted according to the monitor response matrix. This matrix is previously calculated by Monte Carlo simulation → ideal spectrum
3. The ideal spectrum is modified according to energy resolution of the monitor and the detected number of counts in each energy bin according to the deposited activity.
4. In the example a Cs-137 surface contamination of 10 kBq m⁻² in a radius of 10m for LaBr₃ 1.5"x1,5" SpectroTRACER is simulated.

Detection forcing method

Geometry for detection forcing



BODY (1) Ground $R=10\text{m}$ $-50\text{cm} < z < 0$

BODY (2) Source air cylinder $R=10\text{m}$ $0 < z < 1 \text{ mm}$

BODY (3) Air semisphere $R=30\text{m}$

→ Source: surface deposited of **1 mm** thick (**air**)

Material definition

Air

- Build air material using the material list number 104

Soil

- Build soil material using the following characteristics
- Density: 1,27 g/cm³
- Enter chemical (stoichiometric) formula:
 - Number of elements in the molecule = 5
 - atomic number = 1 (H), atoms/molecule = 6.07340000E-01
 - atomic number = 8 (O), atoms/molecule = 1.00000000E+00
 - atomic number = 13 (Al), atoms/molecule = 1.09310000E-01
 - atomic number = 14 (Si), atoms/molecule = 2.95600000E-01
 - atomic number = 26 (Fe), atoms/molecule = 1.39503000E-02

Input file detection forcing

Source

- ^{137}Cs , i.e. 661.6 keV.
- Box, position: center (0,0,0.05) cm, sides (2000, 2000, 0.1), Material: air_source
- Direction: (0,0,1). Angular aperture complete (0,180), (0.360)

Tallies

- TALLY FLUENCE POINT DETECTOR [0 , 3.0] MeV with $N_{\text{bin}} = 3000$
- Position (0,0,100) cm. Radius of exclusion (3 cm)

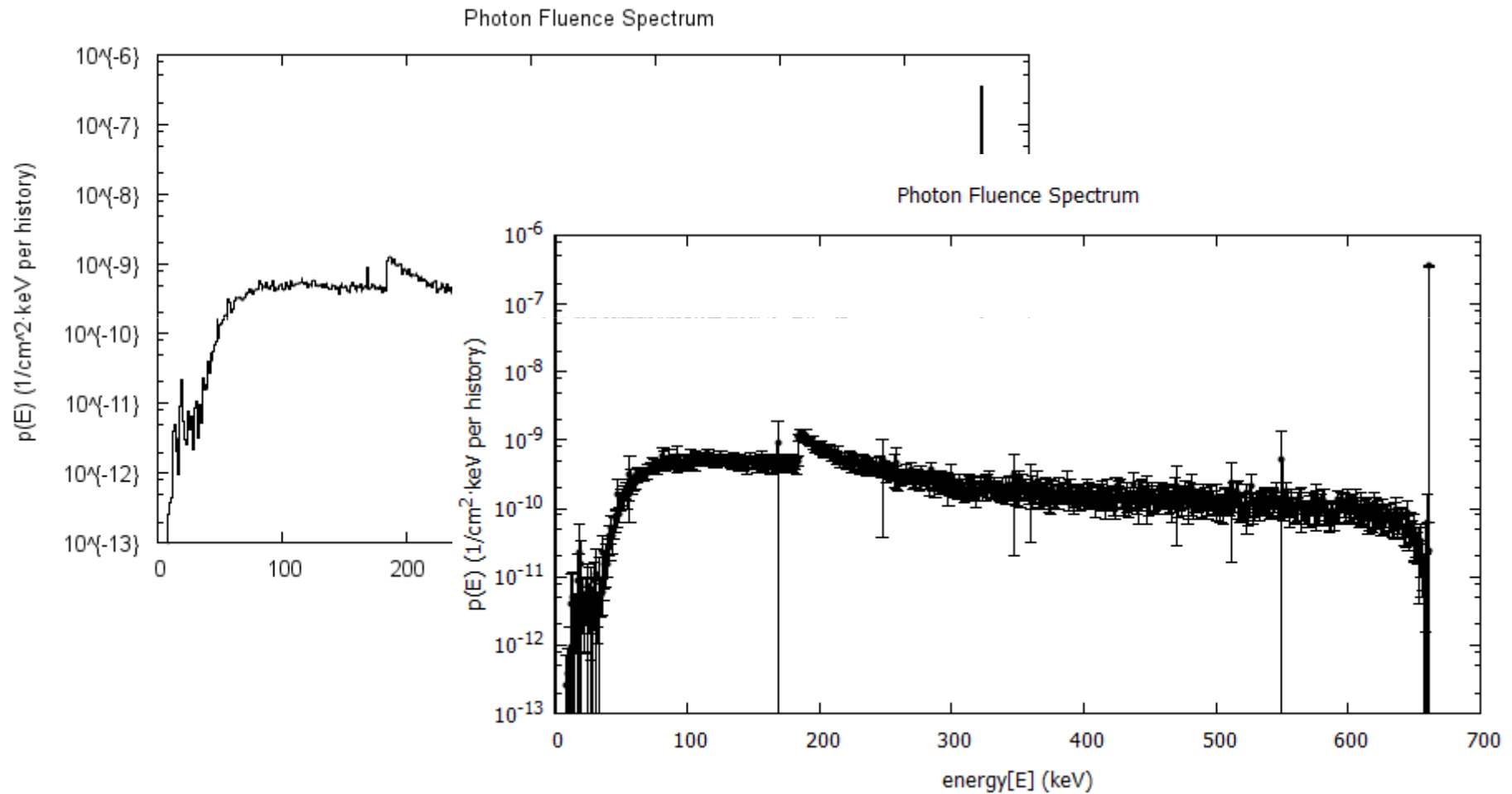
Configuration

- Simulation time = 600 s. → or better 300 s
- If no electron transport.
 - EABS(e^- , γ , e^+) = (+ ∞ , 1, + ∞)
 - C1, C2, WCC, WCR, DSMAX are all irrelevant.

> ~\penEasy.x < penEasy_forcing.in > forcing.out

Simulation time = 600 s in a Windows XP M370 @ 2.40 GHz

Number of simulated histories: 385011



Absorbed dose and H*(10) calculation

Use: TallyFluencePointDetector_dosecalculation_1keV H(10)_det_forcing.xls

Calculus:

i) Point source

$$D_p \left(\frac{PGy}{h} \right) = 1.602 \cdot 10^{-4} \left[\frac{pGy}{eV/g} \right] \cdot E[eV] \cdot \phi_{Tally_Point\ Detector} \left[\frac{1}{cm^2 \cdot eV} \right] \cdot \Delta E_{tally} [eV] \cdot \left(\frac{\mu}{\rho} \right) \left[\frac{cm^2}{g} \right] \cdot 3600 \left[\frac{s}{h} \right]$$

ii) Surface source

$$D_s \left(\frac{PGy}{h} \right) = D_p \left(\frac{PGy}{h} \right) \cdot S [m^2]$$

ii) Volumetric source

$$D_v \left(\frac{PGy}{h} \right) = D_p \left(\frac{PGy}{h} \right) \cdot M [kg]$$

Absorbed dose and H*(10) calculation

Copy the colum #3 (fluence) from the tallyFluencePointDetector.dat into the column #3 (dFluence(1/cm2.eV)) in the excel file

Check the Hground(m), R(m) and soil density values (if is the case)

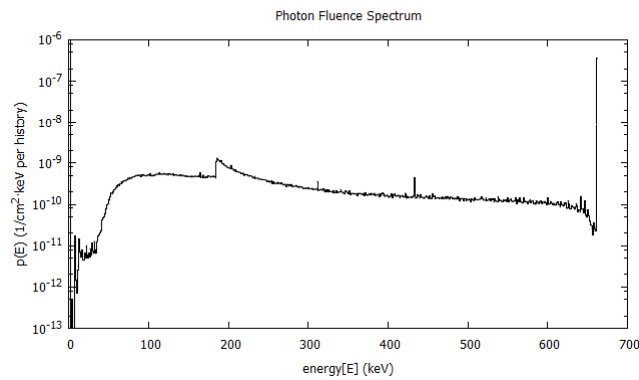
Results:

1.468 in Zähringer and Sempau

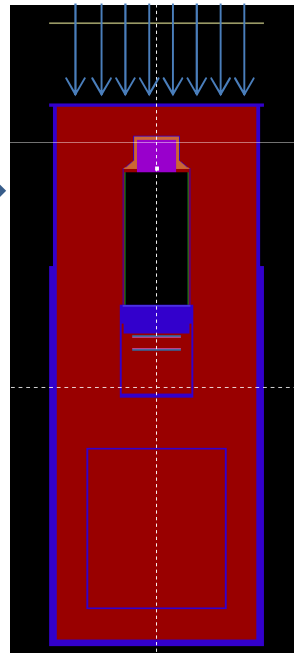
Surface contamination	total	Photopeak	Scat/total (%)
Dose (pGy h-1) per (gamma s-1 m-2)	1.464	1.246	14.85
H*(10) (pSv h-1) per (gamma s-1 m-2)	1.780	1.492	16.17
Average dose to H*(10)	1.216		

Fluence \rightarrow ideal spectrum

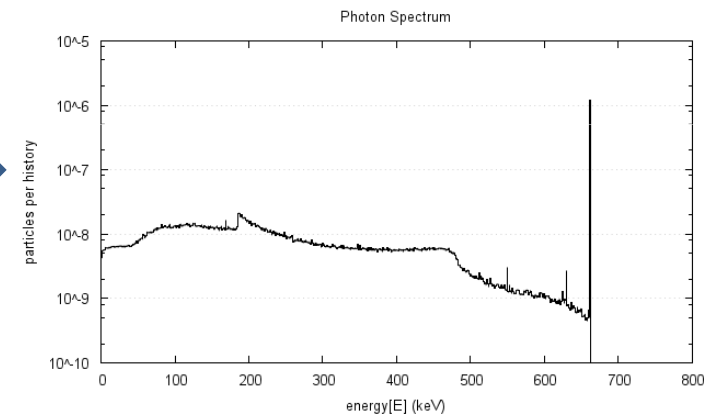
Simulated fluence



Response of the monitor obtained by simulations of parallel gamma-rays



Ideal spectrum



Detector response matrix

> ~ \gfortran matrix_1keV.f -o matrix_1keV.x -O

Inputs: tallyPulseHeightSpectrum_XXXXkeV.dat, where XXXX is the energy in keV in steps of 10 keV from 10 keV to 3000 keV. The quantity reported is the number of events per simulated history in each bin, divided by the bin width.

Input file: input_matrix.dat

Calculus:

$$p(i, j) = \frac{\sum_{k=1}^n P_{tallyE=j}(i, k)}{n} S_{flux} \left[\frac{cm^2}{eV} \right]$$

Where $p(i, j)$ is the probability that a parallel photon fluence of $1/cm^2$ of energy j is detected in the i energy bin per eV. Note that $p(j, j)$ is the photopeak efficiency per unit fluence

> ~ \matrix_1keV.x > log.out

Output: matrix_1keV.dat

detector response matrix per unit fluence
(I = J)

$$\begin{bmatrix} p(1,1), 0, \dots, 0 \\ p(1,2), p(2,2), 0, \dots, 0 \\ \cdot \\ p(1, j), p(2, j), \dots, p(i, j), 0, \dots, 0 \\ \cdot \\ p(1, J-1), p(2, J-1), \dots, p(I-1, J-1), 0 \\ p(1, J), p(2, J), \dots, p(I, J) \end{bmatrix}$$

Fluence → ideal spectrum

Program: Fluence2spec.f

> ~\gfortran fluence2spec.f -o fluence2spec.x -O

Inputs: tallyFluencePointDetector.dat. The fluence spectrum is calculated in a point with an exclusion sphere. The fluence is reported per unit simulated history. Its units are particles/(eV*cm²).

Matrix_SPT.dat → response matrix of the selected monitor.

Input file: input.dat → input the response matrix file of the monitor to be studied and other needed information to run the program.

Calculation:

$$n(i) = \phi_{Tally_Point\ Detector} \cdot \Delta E_{tally} \cdot p(i, j) \cdot \Delta E_{p(i, j)} \quad [particles]$$

Where n(i) is the detected number of particles per unit simulated history. Its units are (particles/cm² · eV) (eV) (cm²/eV) (eV) = particles per history

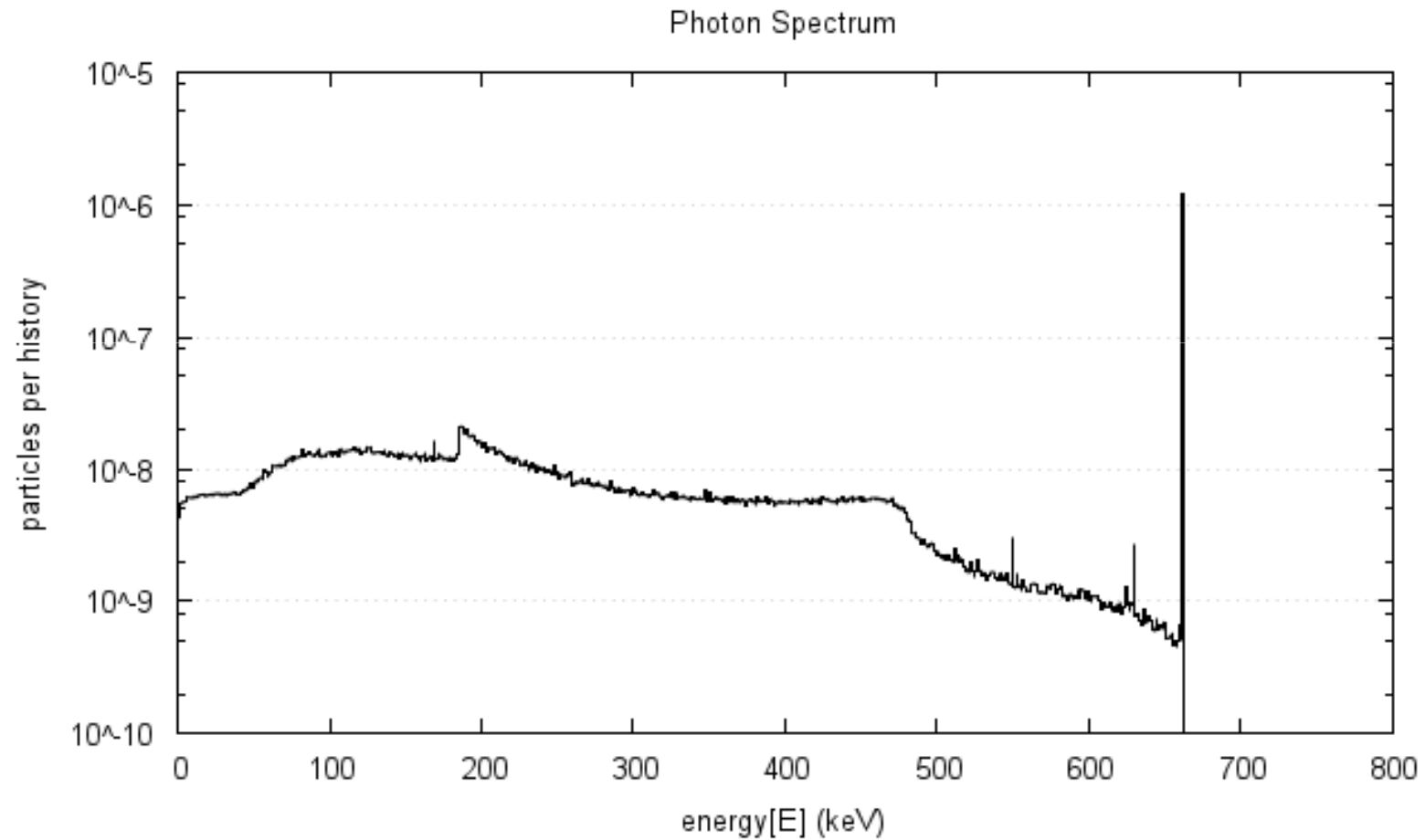
> ~\fluence2spec.x > log.out

Output: detector: Spectrum_0661keV.dat Ideal spectrum file.

Emidd (keV) Efficiency Fluence (1/cm² eV)

Fluence \rightarrow ideal spectrum

Spectrum_0661keV.dat



ideal spectrum → real spectrum

Program: Build_real.f

> ~\gfortran Build_real.f -o Build_real.x -O

Inputs: - Spectrum_0661keV.dat → Spectrum_XXXXkeV.dat where XXXX is the INT of
- Table_Cs137.dat the radionuclide gamma energies
- input.dat

Source types: point, surface and volumetric

Source characteristics: Radius, Height, soil density (use only if needed)

Detector type: scintillator or semiconductor (due to energy resolution equation)

Background file name: N42 format/ASCII, could be set to zeroes for ASCII

e1, e2, e3: $\text{FWHM} = e1 + e2 \cdot \text{ch} + e3 \cdot \text{ch}^2$ (only for non-N42 format)

r1, r2, r3: Scintillator → $\text{FWHM} = r1 \cdot E r^2$

Semiconductor → $\text{FWHM} = (r1 + r2 \cdot E + r3 \cdot E^2)^{0.5}$

nbin: number of bins in the simulated spectrum (Spectrum_0661keV.dat)

nbinexp: number of bins in the background spectrum.

NR: number of radionuclides in the radioactive source

Radio(1) Radio(NR): radionuclide identification (see end of input.dat)

A(1) A(NR): activity for each radionuclide Bq, Bq/m², Bq/kg

Ltime: Measuring time period in seconds. Only for non-N42 format

Define the variance reduction methodology

Reciprocal detector: height (only read in case of reciprocal method is used)

ideal spectrum → real spectrum

Calculus:

$$NC(i) = p(i) \left[\frac{part}{\gamma} \right] \cdot A \left[Bq, \frac{Bq}{m^2}, \frac{Bq}{kg} \right] \cdot yield \left[\frac{\gamma}{Bq} \right] \cdot t[s] \cdot Surface[m^2] \cdot Mass[kg] \quad [particles]$$

For point source: The program sets Surface = 1 and Mass = 1

For surface source: The program sets Mass = 1

For volumetric source: The program sets Surface = 1

Spread counts due to detector energy resolution: For every particle detected in i bin the probability to be detected in an adjacent bin $i+k$ is calculated

$$DE(i) = \sigma(i) \cdot (-2 \cdot \sqrt{\log(rand1)}) \cdot \cos(2 \cdot \pi \cdot rand2) \quad \sigma(i) = \frac{FWHM(i)}{2.35}$$

$$NC(i+k) = NC(i+k) + DE(i)$$

Spread counts due to detected counts:

$$DE(i) = \sigma(i) \cdot (-2 \cdot \sqrt{\log(rand1)}) \cdot \cos(2 \cdot \pi \cdot rand2) \quad \sigma(i) = \sqrt{NC(i)}$$

$$NC(i) = NC(i) + DE(i)$$

ideal spectrum → real spectrum

Add the simulated spread counts to the background spectrum

i is the energy bin in the simulated spectrum and defined in 1 keV

j is the energy bin in the experimental spectrum is variable and > 1 keV

$$NC(j) = \sum NC(i)$$

These sums take into account when the i bin is shared by two bins in the experimental (background spectrum)

$$NC_{real}(j) = NC(j) + N_{measured}(j)$$

`> ~\build_real.x > log.out`

With a surface contamination $A = 10$ kBq/m²

BG Spectrum: 20150616_085000_121_STLB0165_1.n42

Outputs:

Simulated_spectrum.dat

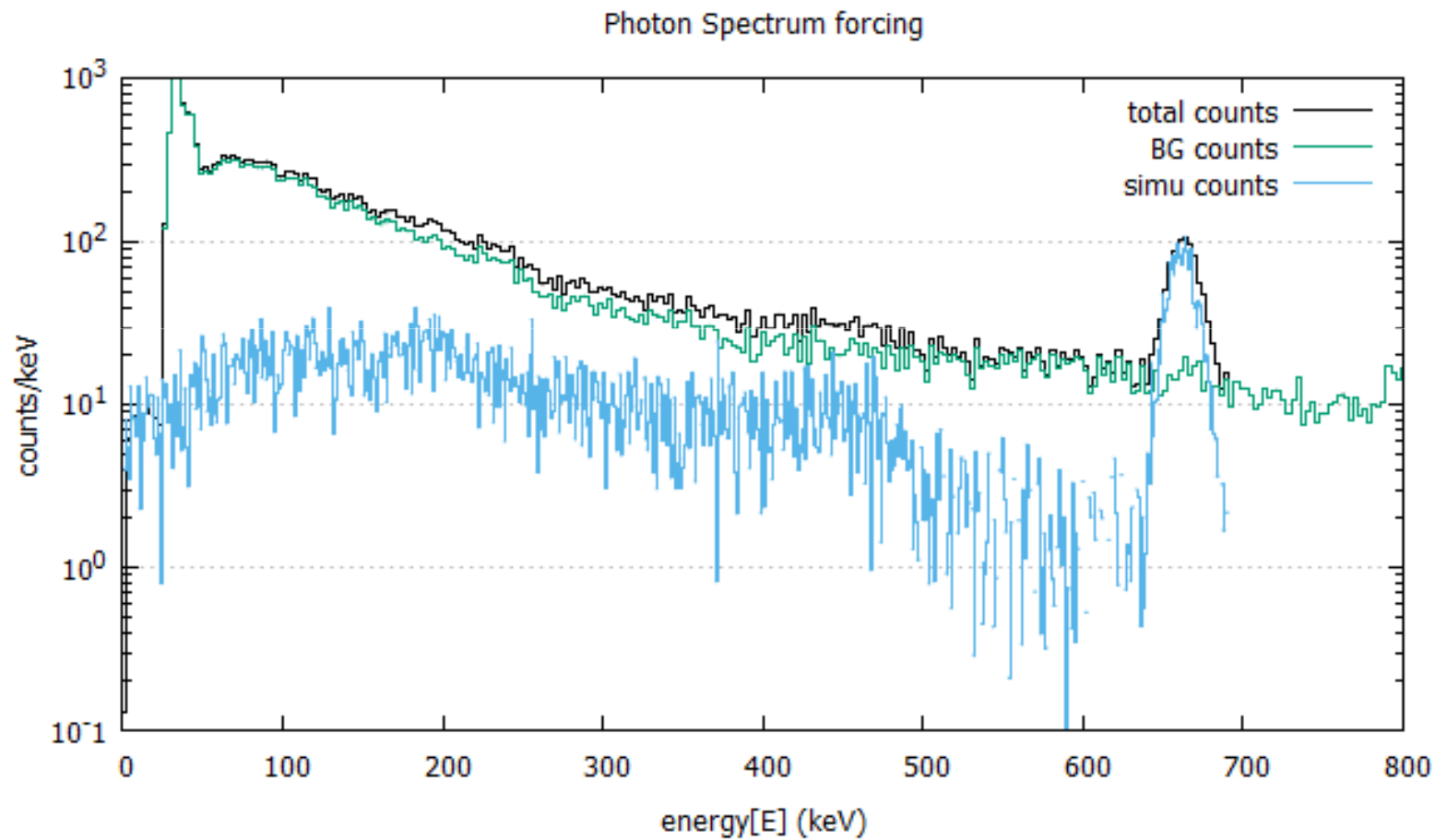
<u>E (keV)</u>	<u>sim_counts/keV</u>	<u>sim_counts(only resolution)/keV</u>	<u>sim_counts(ideal)/keV</u>
----------------	-----------------------	--	------------------------------

Output_file:

<u>E (keV)</u>	<u>counts</u>	<u>counts/keV</u>	<u>INT(counts)</u>	<u>counts_BG</u>	<u>counts_BG/keV</u>
----------------	---------------	-------------------	--------------------	------------------	----------------------

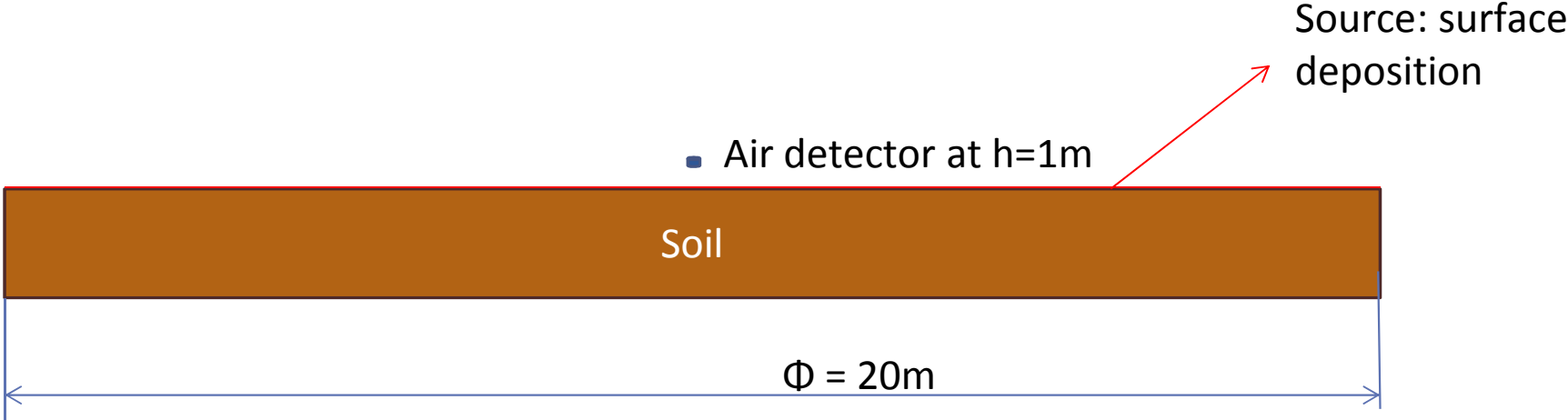
ideal spectrum → real spectrum

Simulated_spectrum.dat and outputfile

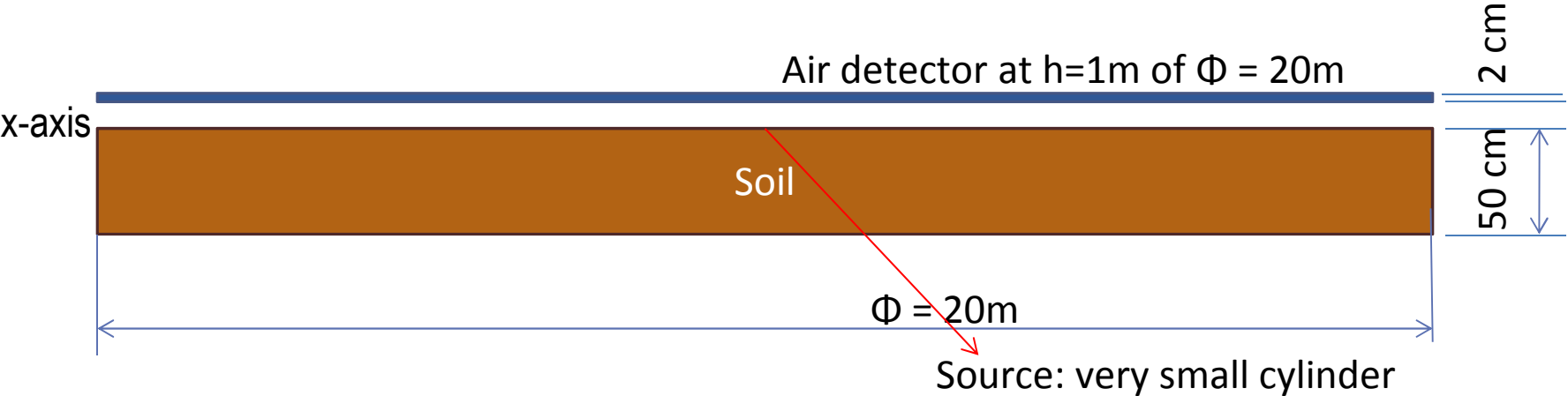


Reciprocal method

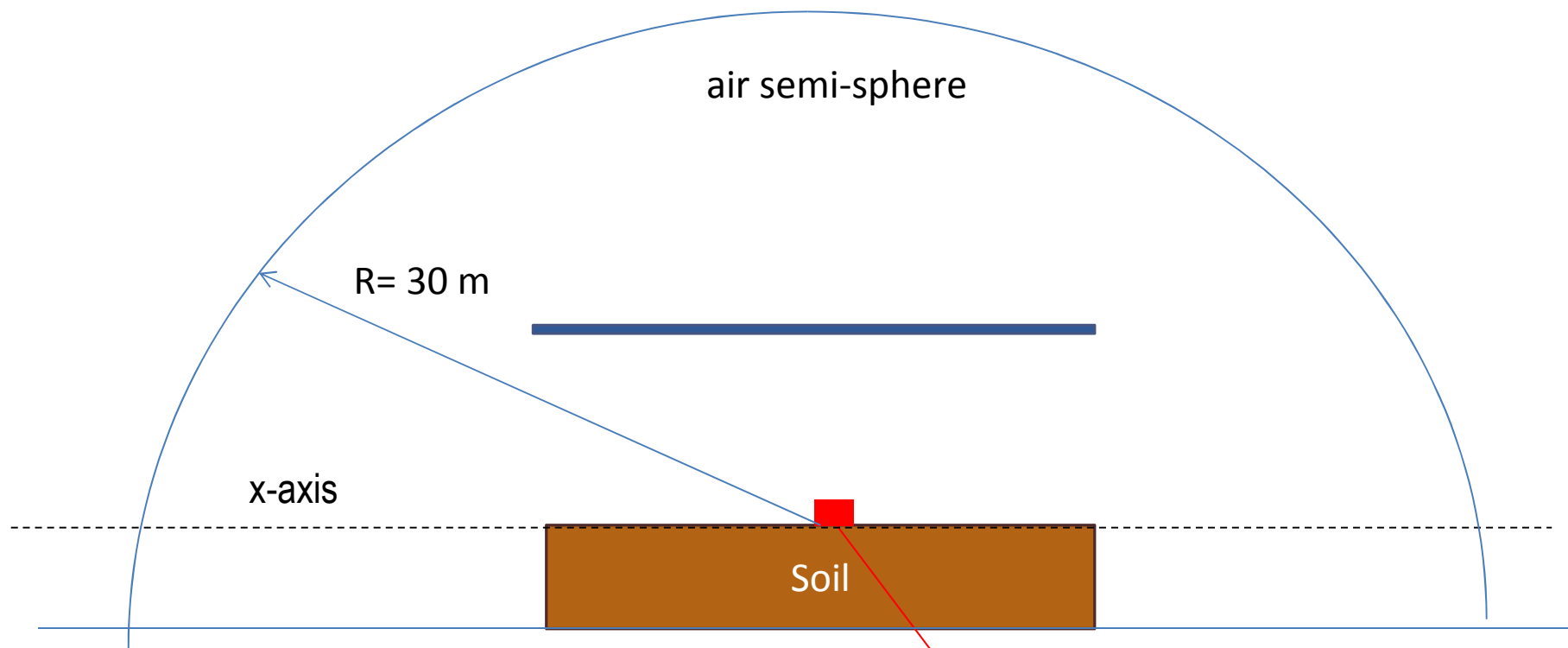
Geometry for reciprocal method



The detector is substituted by an air volume with the dimensions of soil source and the source is transform to almost a point source.



Geometry for reciprocal method



- BODY (1) Reciprocal detector air
- BODY (2) Ground $R=10\text{m}$ $-50\text{cm}<z<0$
- BODY (3) Reciprocal source air
- BODY (4) air control volume

Source: air cylinder
 $R= 1 \text{ mm}$
 $h = 1\text{mm}$

Input file

Source

- ^{137}Cs , i.e. 661.6 keV.
- Box, position: center (0,0,0.05) cm, sides (0.2, 0.2, 0.1), Material: air_source
- Direction: (0,0,1). Angular aperture complete (0,180), (0.360)

Tallies

- Fluence track length in the air detector in [0 , 3.0] MeV with $N_{\text{bin}} = 3000$.

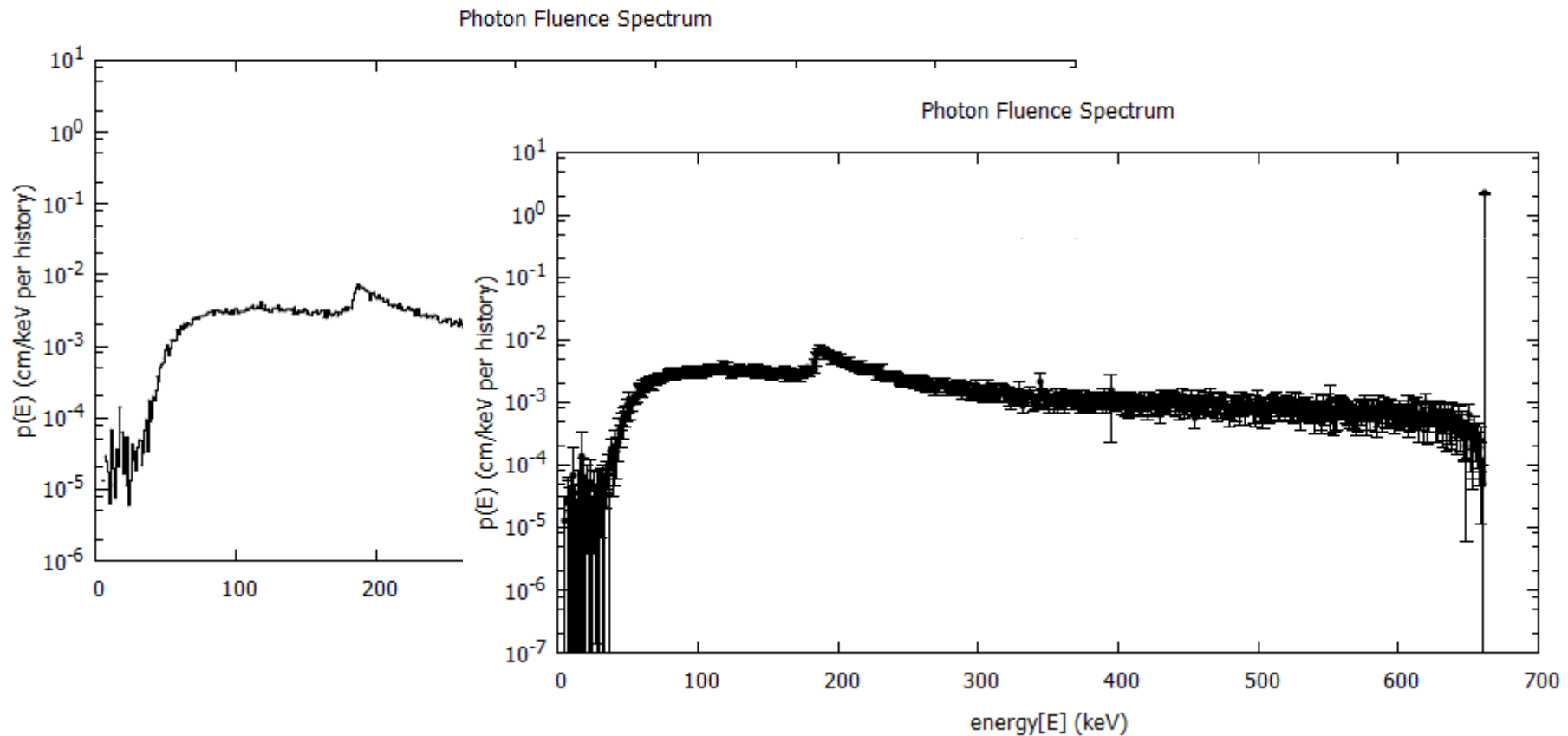
Configuration

- Simulation time = 600 s.
- If no electron transport.
 - $\text{EABS}(e^-, \gamma, e^+) = (+\infty, 1, +\infty)$
 - C1, C2, WCC, WCR, DSMAX are all irrelevant.

Simulation time = 600 s

Simulated histories = 389913

tallyFluenceTrackLength-photon.dat, The fluence spectrum integrated over the volume of the declared DETECTION MATERIAL is calculated. The fluence is reported per unit simulated history. Its units are $\text{cm}^3 \cdot \text{particles} / (\text{eV} \cdot \text{cm}^2) = \text{particles} \cdot \text{cm} / \text{eV}$. To obtain it, the track length estimator is used, that is, the distance travelled by each particle type in the detector is tallied as a function of the energy.



Absorbed dose and H*(10) calculation

Use: TallyFluenceTrackLength_dosecalculation_1keV H(10)_reciprocal.xls

Calculus:

i) Surface source

$$D_s \left(\frac{PGy/h}{\gamma/s m^2} \right) = 1.602 \cdot 10^{-4} \left[\frac{pGy}{eV/g} \right] \cdot E [eV] \cdot \phi_{Tally_TrackLength} \left[\frac{cm}{eV} \right] \cdot \Delta E_{tally} [eV] \cdot \frac{S_{real_source}}{S_{recip_detector} \cdot h_{recip_det.}} \left[\frac{1}{cm} \right] \left(\frac{\mu}{\rho} \right) \left[\frac{cm^2}{g} \right] \cdot 10^{-4} \left[\frac{m^2}{cm^2} \right] \cdot 3600 \left[\frac{s}{h} \right]$$

ii) Volumetric source

$$D_v \left(\frac{PGy/h}{\gamma/s kg} \right) = 1.602 \cdot 10^{-4} \left[\frac{pGy}{eV/g} \right] \cdot E [eV] \cdot \phi_{Tally_TrackLength} \left[\frac{cm}{eV} \right] \cdot \Delta E_{tally} [eV] \cdot \frac{S_{real_source} \cdot h_{real_source}}{S_{recip_detector} \cdot h_{recip_det.}} \rho \left[\frac{g}{cm^3} \right] \cdot 10^{-3} \left[\frac{kg}{g} \right] \cdot \left(\frac{\mu}{\rho} \right) \left[\frac{cm^2}{g} \right] \cdot 3600 \left[\frac{s}{h} \right]$$

Absorbed dose and H*(10) calculation

Copy the column #3 (fluence) from the tallyFluenceTrackLength_600s.dat into the column #3 (dFluence(cm/eV)) in the excel file

Check h_{ground} (cm), $h_{\text{recip_detector}}$ (m) and soil density values (if is the case)

Results:

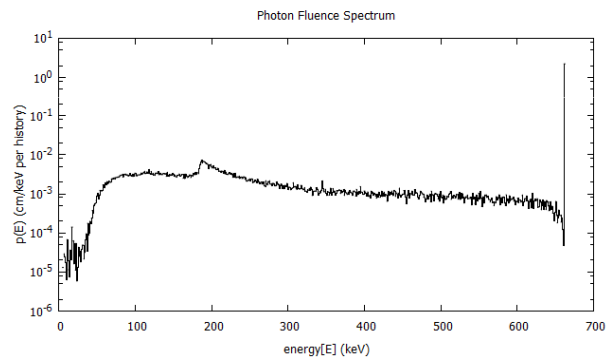
TOTAL DOSE (pGy/h per gamma*s-1*m-2)	Scattering	Peak	Ratio(Scater/total)
1.467	0.222	1.244	0.152
TOTAL H*(10) (pGy/h per gamma*s-1*m-2)	Scattering	Peak	Ratio(Scater/total)
1.783	0.293	1.489	0.165
MEAN ratio dosetoH*(10)			
1.215			

1.468 in Zähringer and Sempau

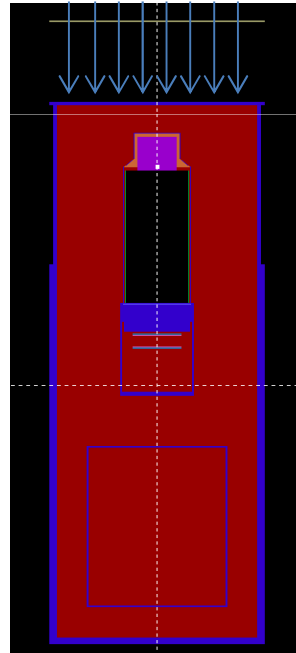
Fluence \rightarrow ideal spectrum

tallyFluenceTrackLength-photon.dat

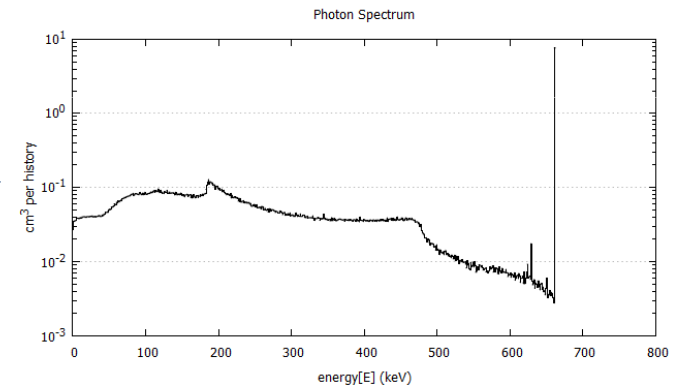
Simulated fluence



Response of the monitor obtained by simulations of parallel gamma-rays



Simulated spectrum



Fluence → ideal spectrum

Program: fluence2spec.f

> ~\gfortran fluence2spec.f -o fluence2spec.x -O

Inputs: tallyFluenceTrackLength-photon.dat

Input file: input.dat → input the response matrix file of the monitor to be studied and other needed information to run the program.

Calculus:
$$n(i) = \phi_{tally_track} \cdot \Delta E_{tally} \cdot p(i, j) \cdot \Delta E_{p(i, j)} \quad [cm^3]$$

Where $n(i)$ is the detected number of particles integrated over the declared DETECTION MATERIAL per unit simulated history. Its units are (particles*cm/eV) (eV) (cm²/eV) (eV) = particles * cm³

> ~\fluence2spec.x > log.out

Output: detector: Spectrum_0661keV.dat Ideal spectrum file.

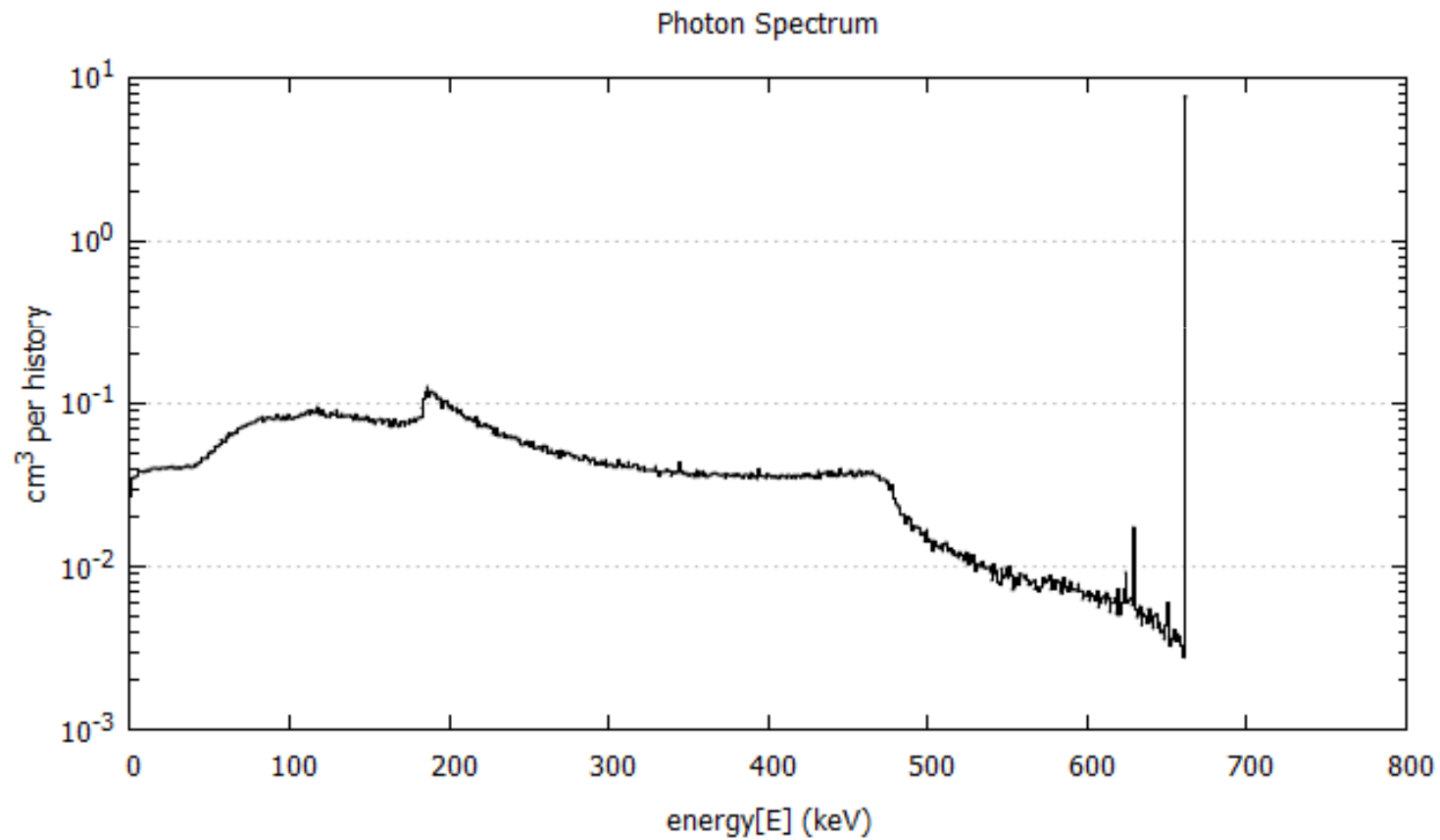
Emidd (keV)

Efficiency(cm³)

Fluence (1/cm² eV)

Fluence \rightarrow ideal spectrum

Spectrum_0661keV.dat



ideal spectrum → real spectrum

Program: Build_real.f (the same used for detection forcing, but modified input.dat)

Inputs: Spectrum_0661keV.dat
Input.dat (see detection forcing slide)

Calculation:

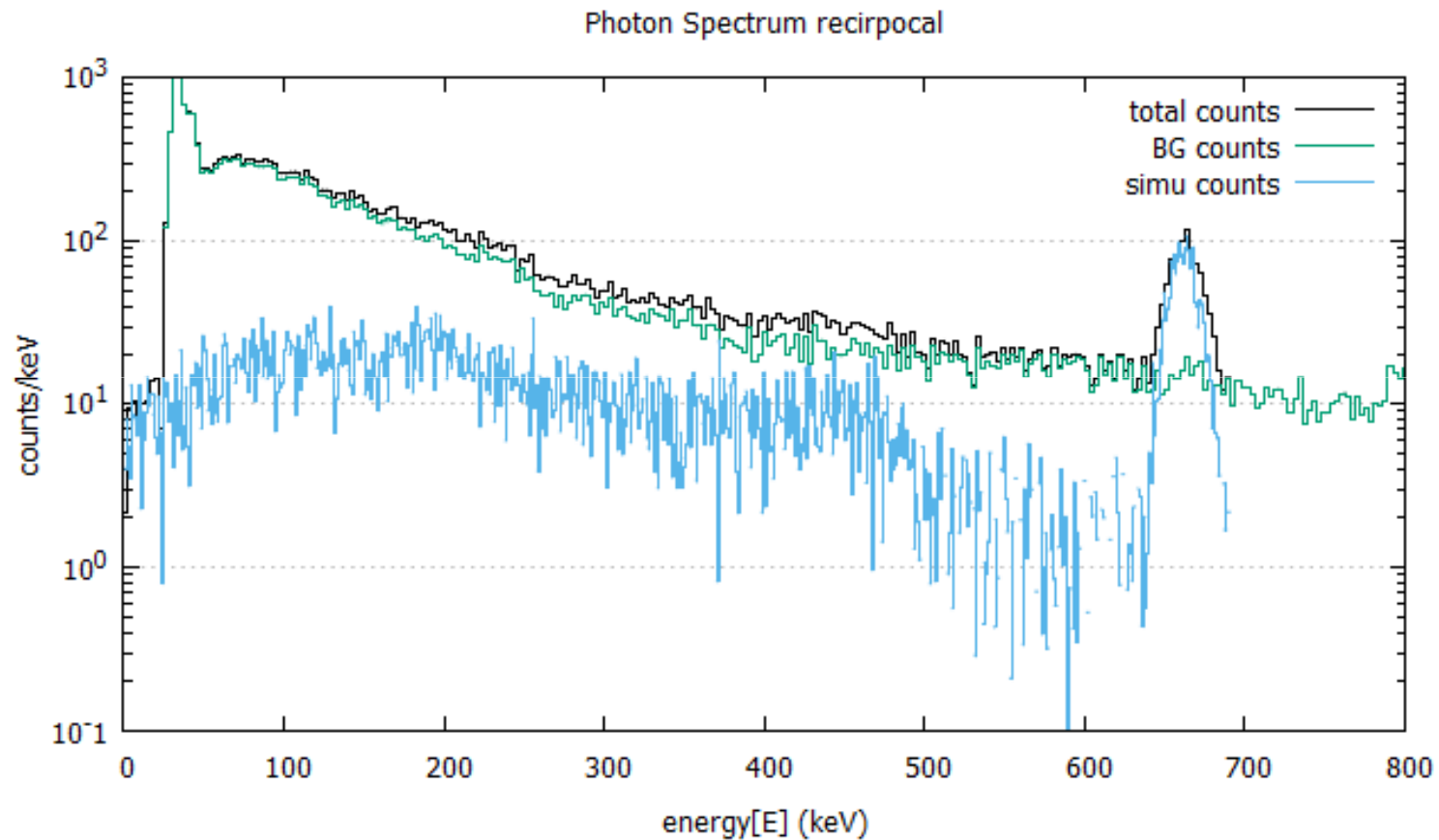
i) For surface contamination:

$$NC(i) = p(i)[cm^3] \cdot A \left[\frac{Bq}{cm^2} \right] \cdot yield \left[\frac{\gamma/s}{Bq} \right] \cdot t[s] \cdot \frac{S_{real_source}[cm^2]}{S_{reciprocal_det}[cm^2] \cdot h_{reciprocal}[cm]} \quad [particles]$$

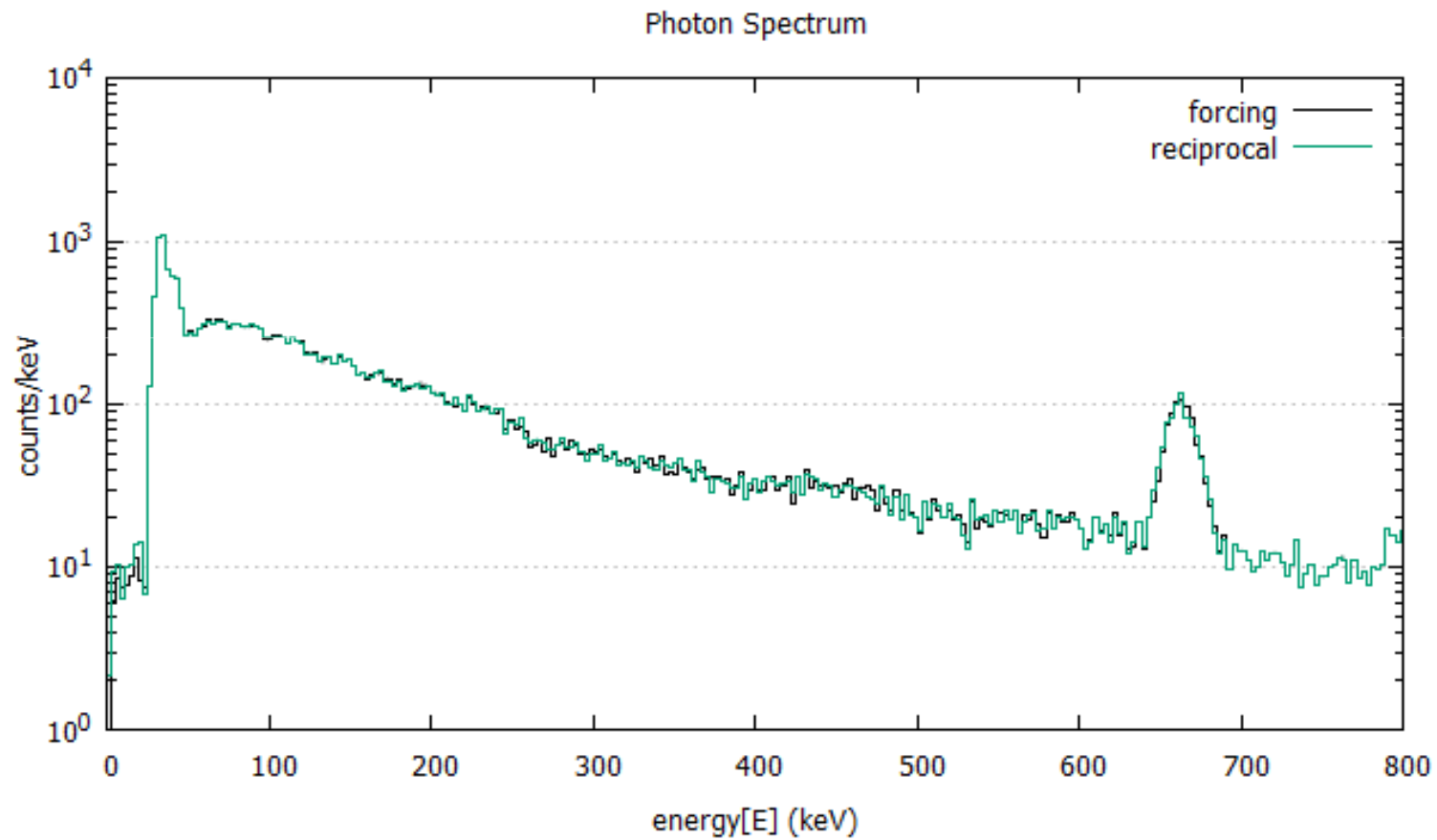
ii) For soil (volume) contamination:

$$NC(i) = p(i)[cm^3] \cdot A \left[\frac{Bq/g}{g} \right] \cdot yield \left[\frac{\gamma/s}{Bq} \right] \cdot \rho \left[\frac{g}{cm^3} \right] \cdot t[s] \cdot \frac{S_{real_source}[cm^2] \cdot h_{real_source}[cm]}{S_{reciprocal_det}[cm^2] \cdot h_{reciprocal}[cm]} \quad [particles]$$

ideal spectrum \rightarrow real spectrum



Comparison forcing/reciprocal



Thank you.