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COMBMORC - Combined analysis of primary and scattered components in mobile gamma spectrometric data for detection of materials out of regulatory control, NKS-B COMBMORC Report 2021

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Abstract

Radioactive material that has come out of authorities control (MORC) poses a danger. If such a threat is suspected, authorities must localise and secure the radioactive source. One method of searching for gamma-emitting radionuclides is mobile gamma spectrometry, where the primary gamma energy identifies the source. The primary gamma fluence becomes reduced if a shielding material is located between the source and the detector, leading to the distance at which gamma detectors can detect a source becoming shorter. At the same time, the scattered radiation increases, having lower energy than the primary radiation due to the Compton interaction in the radiation shield. A gamma spectrometer also registers the scattered radiation. The ratio of scattered to primary radiation provides information about the thickness of a radiation shield. The Nordic countries' radiation safety authorities have experimented with mobile gamma spectrometry to explore a combined analysis of primary and scattered radiation components. Mobile gamma spectrometry teams made measurements in eighteen setups with shielded and unshielded Cs-137 sources at varying distances from a road. Teams used one-second acquisition time intervals, passing the sources at 50 km/h. The experiments show that combined analysis of primary and scattered components could identify the shielding of sources, provided that the detector revealed a signal from primary photons. The results indicate that combined analysis may slightly increase the detection distance for shielded sources. The detection distance does not increase with combined analysis for unshielded radiation sources, but such an analysis can provide information that the source is unshielded.

Key words

Mobile gamma spectrometry, orphan sources, shielding

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About the COMBMORC 2021 report

The aim of COMBMORC 2021 is to carry out field experiments to investigate how ROI-based methods using combined analysis of primary and scattered radiation in mobile gamma spectrometry can improve the detectability of orphan gamma-ray sources. COMBMORC is scheduled for two years, and this is the report from the first year.

In October 2021, Medical Radiation Physics at Lund University (Malmö) constructed a joint Nordic field experiment in the area around Barsebäck for mobile detection of Cs-137 gamma-ray sources. Teams who participated in the NKS/COMBMORC Barsebäck experiments were: Denmark (DEMA), Finland (STUK), Iceland (GR/IRSA), Norway (DSA and NGU), and Sweden (SSM and Lund University).

This report describes the NKS/COMBMORC experiments with mobile gamma spectrometry in measuring shielded and unshielded Cs-137 point sources and provides examples of results from the experiments. The report also indicates whether the ROI method for primary and scattered radiation registration can contribute to increased ability to detect orphan point sources.

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Abstract

Radioactive material that has come out of authorities control (MORC) poses a danger. If such a threat is suspected, authorities must localise and secure the radioactive source. One method of searching for gamma-emitting radionuclides is mobile gamma spectrometry, where the primary gamma energy identifies the source. The primary gamma fluence becomes reduced if a shielding material is located between the source and the detector, leading to the distance at which gamma detectors can detect a source becoming shorter. At the same time, the scattered radiation increases, having lower energy than the primary radiation due to the Compton interaction in the radiation shield. A gamma spectrometer also registers the scattered radiation. The ratio of scattered to primary radiation provides information about the thickness of a radiation shield. The Nordic countries' radiation safety authorities have experimented with mobile gamma spectrometry to explore a combined analysis of primary and scattered radiation components. Mobile gamma spectrometry teams made measurements in eighteen setups with shielded and unshielded Cs-137 sources at varying distances from a road. Teams used one-second acquisition time intervals, passing the sources at 50 km/h. The experiments show that combined analysis of primary and scattered components could identify the shielding of sources, provided that the detector revealed a signal from primary photons. The results indicate that combined analysis may slightly increase the detection distance for shielded sources. The detection distance does not increase with combined analysis for unshielded radiation sources, but such an analysis can provide information that the source is unshielded.

Summary

The NKS activity COMBMORC addresses the problems of mobile detection of shielded gamma-ray sources, which is a likely scenario when searching for radioactive material out of regulatory control (MORC). The project is planned for two years, 2021-2022, with participants from all Nordic radiation safety authorities. This report describes activities during 2021 and provides some preliminary results.

The COMBMORC activity was preceded by the NKS financed SHIELDMORC activity in 2019 - 2020, which investigated the possibility to use registrations of Compton-scattered photons in a gamma spectrometer to assess the thickness of a shield between a gamma-ray source and a detector. SHIELDMORC was directed towards stationary (non-moving) detection, while COMBMORC attempts to do likewise but with moving detection.

The previous SHIELDMORC activity demonstrated that gamma spectrometers of the types used in the Nordic mobile units could be applied to determine the thickness of a radiation shield present between a gamma-ray source the measuring instrument. Teams in the Nordic countries tested the method for use with Cs-137, and Lund University made some preliminary tests also with Co-60. The technique uses the measured pulse height distribution divided into six regions of interest (ROI). Three represent recordings from Compton scattered radiation, and three represent primary radiation from the source. Lund University developed a mathematical relationship for the ratio of registrations from scattered and primary radiation as a function of the mass thickness of a radiation shield. It applied to a 4-litre NaI(Tl) spectrometer and could be used approximately for the same instrument type in Nordic countries. However, individually calibrated instruments for known shield mass thicknesses would provide more precise relationships. The method works for shields of typical building material with atomic numbers lower than 25.

Teams in the SHIELDMORC 2020 project tested the ROI method of determining the thickness of a radiation shield in stationary measurements for relatively long measurement times (tens of minutes). An important question is whether the technique is also applicable to moving gamma spectrometers with short acquisition times (seconds) when the mobile instrument passes a radiation source during a search mission. Therefore, the COMBMORC 2021 project designed a field experiment using a shielded and an unshielded Cs-137 source placed at varying and successively increasing distances from the road where the measuring vehicles passed. This choice led to the placement of the sources at 18 different distances from the road, called setups. At the beginning of the experiment, the distances were so short that the sources produced clear full energy peaks from the primary radiation in the gamma spectrometers. Towards the end of the experiment, the distances were so long that no signs of the sources' primary radiation were registered. The nearest source (shielded 1100 MBq) was 20 m from the roadside, and the farthest (unshielded 740 MBq) was placed at 160 m. The Nordic measurement teams carried out the measurements for three days in October 2021 near Barsebäck's nuclear power plant in southern Sweden. Each measurement team passed about ten times in each direction past the sources at a speed of 50 km/h using the acquisition time of one second. Together, the teams made about 2,000 passages past the Cs-137 sources and acquired a total of about one million measured ROI values. The COMBMORC project plans to analyse the

measurement data in detail in 2022. This report presents some examples of measurement results from the field experiment in 2021.

The preliminary analyses of the COMBMORC 2021 experiment show that it is possible with mobile gamma spectrometry to determine whether a radiation source passed at 50 km/h is shielded or not, provided that the primary radiation from the source gives a clear signal in the detector. The mobile method's accuracy of determining the shielding material's mass thickness remains to be investigated. The accuracy will depend, among other things, on the speed of the measuring vehicle, the acquisition time intervals and the number of passages past the source. Knowledge of the natural radiation background is also essential. Whether the method can be applied in any form without knowing the radiation background remains to investigate.

The combined analysis of scattered and primary radiation can only marginally improve the detection distances of shielded radiation sources. For unshielded radiation sources, there is no improvement in the detection distance. In that case, the contribution from scattered radiation is so small that identification of the radiation source only can be based on registrations from the primary radiation.

During the experiment, participating teams were allowed to use the Markov chain Monte Carlo (MCMC) method developed at Lund University to determine the distance and activity of identified Cs-137 sources. The MCMC method involves heavy post-processing of measurement data. This report shows the possibility of using a more straightforward approach based on "intensity curves" to obtain approximate information about the distance and activity of the radiation source. The method needs further testing and development to be practically helpful, as suggested by the proposed COMBMORC 2022 project.

1. Introduction

1.1 Background

Accidents with lost radioactive sources have occurred occasionally. On average, one accident with orphan sources has happened every two years since 1945, which has led to people unknowingly being exposed to ionising radiation and suffering radiation injuries or death (UNSCEAR, 2011). Radioactive sources could also be stolen, smuggled and used to harm people intentionally (IAEA, 2007). If a threat is suspected, authorities must localise and secure the radioactive source (material out of regulatory control, MORC). One method of searching for gamma-emitting radionuclides is mobile gamma spectrometry, where the primary gamma energy identifies the source. Mobile gamma spectrometry can be performed with instruments in aeroplanes, helicopters, and cars and carried out on foot with portable instrumentation. (Hjerpe et al, 2001; Finck and Ulvsand, 2003; Kock et al, 2010, Nilsson et al, 2014, 2015).

The reduction in gamma radiation fluence from point sources due to the "inverse distance square law" and air attenuation limits the detection of sources at distances. In NKS funded projects, mobile gamma spectrometry teams from the Nordic radiation safety authorities have participated in field experiments to determine detection distances for unshielded gamma-ray sources. (Finck et al., 2019). Lund University developed an algorithm to calculate maximum detection distances for point sources in mobile search in connection with the investigations. (Rääf et al., 2019). The maximum detection distance at which mobile gamma spectrometric search could detect an unshielded point-shaped gamma-ray source with a certain probability depends on several parameters. These are radionuclide, source activity, instrument efficiency, vehicle speed, acquisition time intervals, the selected alarm level indicating the presence of a source, and the acceptable frequency of false-positive indications.

Gamma-ray sources out of control may be more or less shielded, making them more challenging to detect. The shield reduces the primary radiation from the source, thereby shortening its detection distance, but increases the Compton scattered part of the photons. Hence, the ratio between scattered fluence and primary fluence increases with increasing shield thickness. Search teams can use this effect to determine the thickness of the shield, provided that registrations from the primary fluence are still visible in the spectrometers pulse height distribution. In 2020, the Nordic teams tested this method, using the output of count rates in regions of interest (ROI) from the spectrometers pulse height distribution. They found a mathematical relation between the shield's mass thickness and the source's count rate ratio of scattered to primary photons, making it possible to determine shield thickness at a distance from a located source. (Rääf et al., 2021). The gamma spectrometers stood still for relatively long measurement times (tens of minutes) when using this technique. An important question is whether the method is also applicable to moving gamma spectrometers with short acquisition times (seconds) when the mobile instrument passes a radiation source during a search mission. The aim of the COMBMORC 2021 - 2022 project is to investigate this.

1.2 Aim of the project

COMBMORC 2021 - 2022 aims to conduct field experiments to investigate ROI-based methods using combined registrations of scattered and primary radiation in mobile gamma spectrometers. The project should analyse measurement data to estimate shielding thicknesses, distances to radiation sources, activities of the sources and estimation of maximum detection distances. Lund University is the project coordinator, creates the field experiments conducted near the Barsebäck nuclear power station, collects all measurement data and makes the analysis in cooperation with the participating Nordic teams. The Nordic teams participate in practical experiments with their mobile gamma spectrometric search equipment.

2. Theory and method

The method of determining the thickness of radiation shielding material that may be present in connection with a gamma-ray point source uses the ratio between the fluence of Compton scattered radiation from the shield and the fluence from primary radiation penetrating the shield. This ratio increases with increasing shield thickness. The theory and a mathematical model giving the relation between shield mass thickness and scattered to primary count rate ratio is described in the NKS SHIELDMORC report (Rääf et al., 2021).

2.1 Regions of interest (ROI)

The analysis of mobile gamma spectrometric measurement data from both primary and scattered radiation uses the relatively simple method of defining a few regions of interest (ROI) over large energy areas instead of using the entire spectrum (in the form of all individual channels in the pulse height distribution). It is relatively easy to implement because all software for gamma spectrometry can output sums of count rates for selectable energy intervals.

For COMBMORC, six ROIs have been used, which represents Compton scattered and primary radiation from a Cs-137 point source. Table 1 gives the selected ROI subdivisions into energy intervals and which photon interaction they generally represent. For a NaI(Tl) spectrometer, there is always a substantial overlap of photon energies into adjacent ROIs because of the spectrometers' low energy resolution. More information for individual teams selection of ROI channels is provided in Appendix A.

Fig 1 shows how the six ROIs are defined for a pulse height distribution from a Cs-137 source measured by a NaI(Tl) spectrometer.

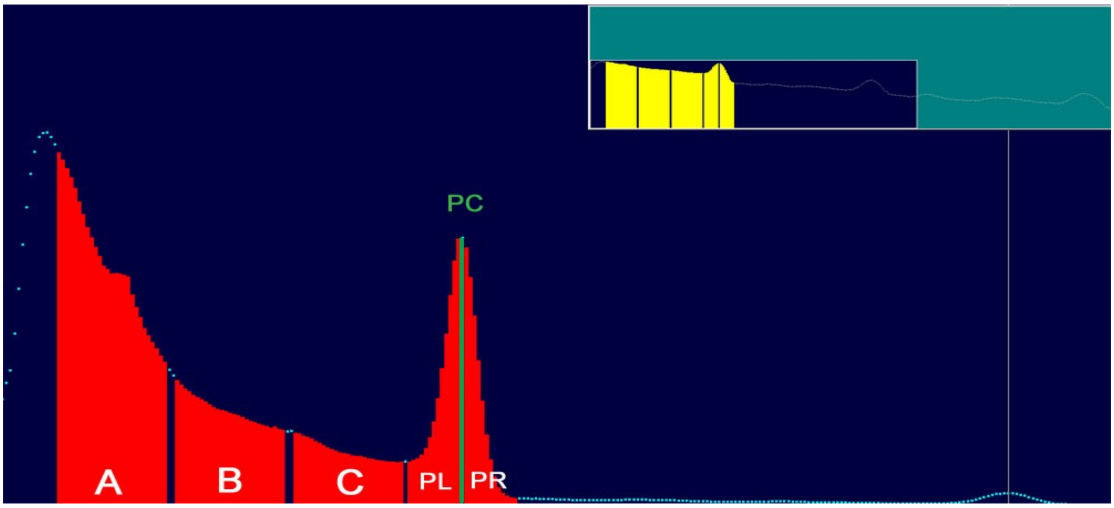


Figure 1. Net (background subtracted) pulse height distribution showing the ROIs defined in Table 1 for a Cs-137 source used in a function for calculating the mass thickness of a shield (kg/m^2) between the source and the detector from a pulse height distribution recorded by a NaI(Tl) spectrometer. The full energy peak is divided into three ROIs (PL, PC and PR). Compton scattered photons from the source, and photon interaction effects in the detector are registered in the three ROIs (A, B and C). The ROI P contains the counts PL+PC+PR.

Table 1. Energy regions for NaI(Tl) spectrometers in the COMBMORC experiment, assuming a channel width of 3 keV. For other channel widths the energy regions are adjusted to fit the channel division.

Region designation	Energy interval (keV)	Detected photons from the source are mainly…
ROI A	77 – 239	Compton scattered 110 - 180 degrees and multiple scattered
ROI B	245 – 407	Compton scattered 27 - 58 degrees
ROI C	413 – 575	Compton scattered 0 - 27 degrees
ROI PL	581 – 659	Primary and small angle Compton scattered
ROI PR	665 – 743	Primary
ROI P	581 – 743	Primary and small angle Compton scattered

2.2 Detection of Cs-137 point sources by the ROI method using primary and scattered radiation

The idea of the COMBMORC project is to investigate whether there is enough information in the registrations of scattered photons in the pulse height distribution of a mobile gamma spectrometer that would make it possible to increase the maximum detection distance. A simplified theoretical calculation has been made to test this. In addition, a first experimental evaluation has been performed with measurement data from the COMBMORC 2021 experiment.

2.2.1 Theoretical calculation

Making a complete theoretical calculation of the scattered component in a pulse height distribution from radiation sources at different distances is a complicated procedure. However, with simpler statistical calculations, any possible gain in detection distance can be estimated, assuming that the number of registered pulses increases. For an unshielded 250 MBq Cs-137 point source at 90 m distance measured with a 4 litre NaI(Tl) spectrometer, the total count rate in the low energy region from air scattered radiation becomes approximately the same as the count rate from primary photons. That means that the count rate is doubled from the source if also scattered radiation is included. Assuming double count rate and (falsely assume) double background count rate would correspond to change detector from a 4 litre NaI(Tl) to an 8 litre. Theoretical calculation using the MDD algorithm (Rääf et al., 2019) shows that this produces a marginal increase in detection distance (Fig 2). The distance increase (at 95% detection probability, 1 s acquisition time interval, 50 km/h) is 19% for a 100 MBq Cs-137 source, 14% for 1000 MBq, and 10% for 10000 MBq.

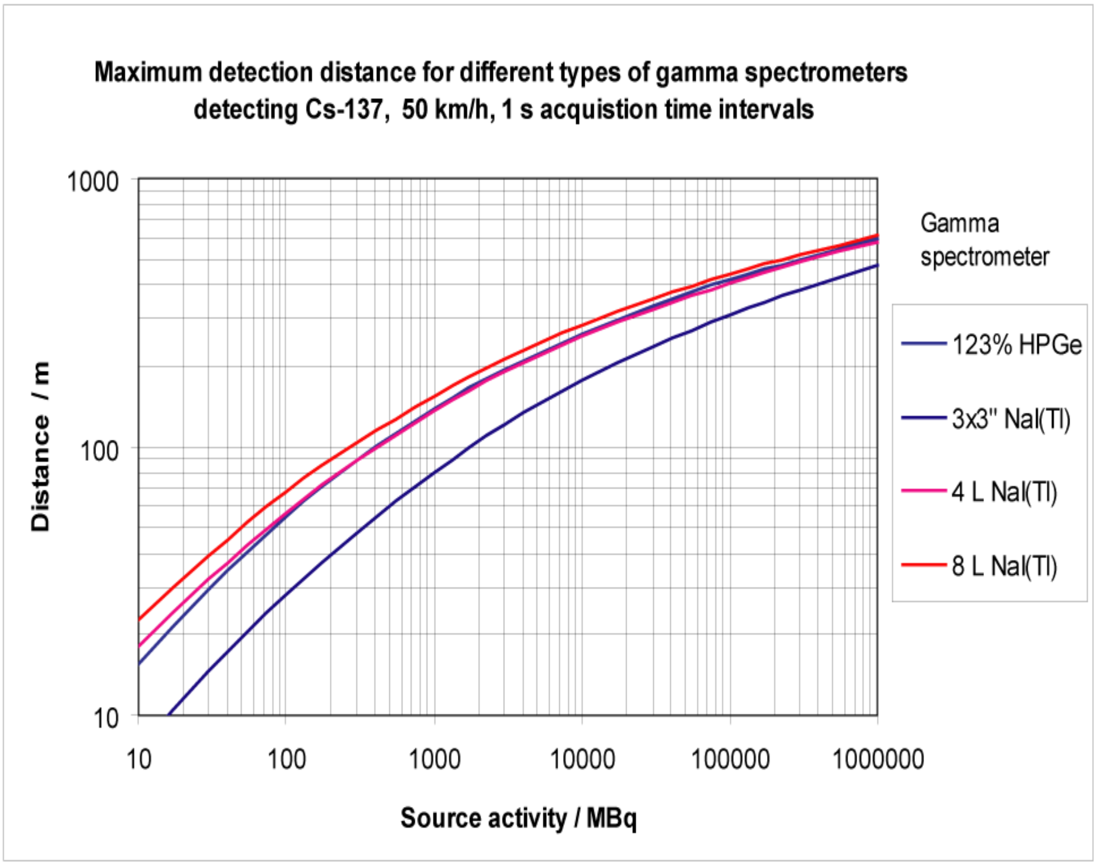


Figure 2. Maximum detection distances (95% detection probability, vehicle speed 50 km/h, 1 s acquisition time intervals) for unshielded Cs-137 point sources when using four different detector types (123% HPGe, 3"x3" NaI(Tl), 4 litre NaI(Tl), and 8 litre NaI(Tl). Theoretically calculated using the MDD program developed for NKS/AUTOMORC project (Rääf et al. 2019). The count rate of an 8 litre NaI(Tl) detector is about twice the count rate of a 4 litre NaI(Tl) detector, but producing only from 20% down to 10% increase of the detection distance for sources in the activity range from 100 to 10000 MBq.

2.2.2 Conclusions from the theoretical calculation

When increasing the detected count rate to double, the simplified calculation assumed that the background count rate was also only doubled. However, this is not the case when including registrations from low energy photons. The background in the low energy region is about tenfold the background in the region of the primary photon registrations for a Cs-137 source. This fact leads to a deteriorated statistical accuracy for registering scattered photons in the low energy area. The effect is that the detection distance for unshielded radiation sources is not improved by including scattered radiation in the analysis.

For shielded sources, using registrations of scattered photons can somewhat increase detection distances, which is shown by preliminary results from the COMBMORC experiment.

2.3 Measuring equipment

Participants used the same type of mobile measuring equipment reported in the NKS project AUTOMORC (Rääf et al., 2019).

Output of measurement data from ROIs followed the format given in Appendix A

2.4 Radiation source setups and measurement route

Four Cs-137 point sources were used in the NKS/COMBMORC field experiment with mobile detection. (Table 2).

Table 2. Gamma point sources used in the COMBMORC 2021 experiment. Source activities are valid for 13 October 2021 and preliminary. Activities are corrected for primary photons attenuated in the iron encapsulation by a factor 0.81.

Mark	Activity	Purpose
RI-196	912 MBq	Cs-137 used in the experiment with the shielded source placed 0.5 m above ground in location B at distances 20 - 105 m in steps of 5 m. 130 mm thick concrete blocks shielded the source.
RI-405	602 MBq	Cs-137 used in the experiment with the unshielded source placed 2.5 m above ground in location A at distances 40 - 120 m in steps of 10 m.
RI-403	196 MBq	Cs-137 used in the experiment with the unshielded source placed 2.5 m above ground in location A at distances 80 - 160 m in steps of 10 m.
RI-600	49.8 MBq	Cs-137 used for efficiency calibration of detectors.

The sources were placed with gradually increasing distances in 18 setups. Positions and distances are given in Tables 3a and 3b. In the first setups, the distances from the road were chosen so that all teams' measuring equipment could detect the source. In the last setups, the far distances from the road made detecting the source very unlikely.

The shielded radiation source in location B was placed in a trailer to be easily moved to successively longer distances from the road. The source was shielded with 130 mm concrete blocks in the direction of the road. In other directions, it was shielded with 50 mm brick. Fig. 3 shows the position of the source behind the concrete shield. Fig. 4 shows the shield in the upward direction and the direction of the road.

The unshielded source in location A was placed on top of 2.5 m wooden poles and successively moved 10 m further away from the road for each new setup. Fig 5 shows the location.

Teams made mobile measurements along Kraftverksvägen outside the restricted area of Barsebäck's nuclear power plant. The road length was 1724 m, but the teams usually turned around a little earlier, making the measurement stretch about 1600 m. Fig 6 shows the road map and the locations of sources A and B.

Figure 3. The 130 cm shielding of the source B built by concrete blocks in a trailer to be easily moved. The position of the source is marked with a red circle.

Figure 4. After placing the source, the shielding was completed with burnt clay bricks. The bricks shielded the source downwards, sideward and upwards. The concrete blocks shielded the source in the direction of the road where the measurement vehicles passed.

Figure 5. The location A for unshielded sources placed on poles (not shown) along the cattle fence at distances 40 - 160 m from the roadside.

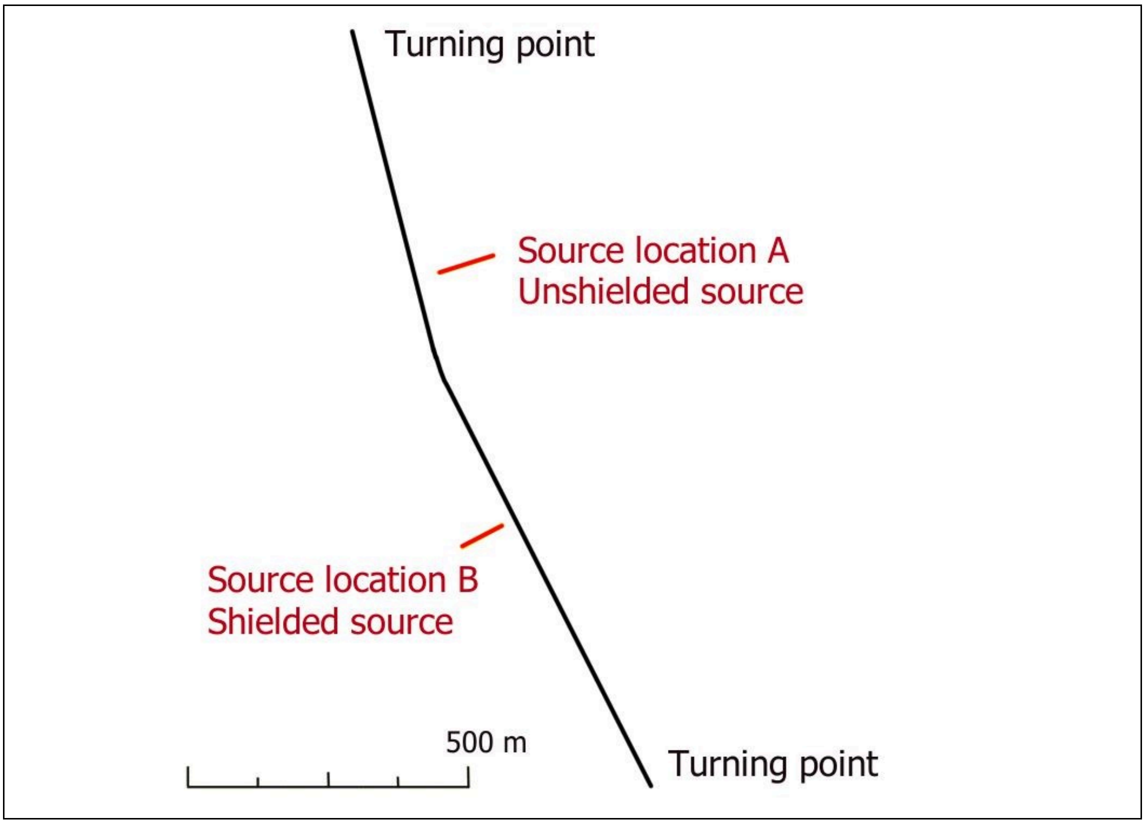


Figure 6. The measurement route along the road *Kraftverksvägen* outside of the Barsebäck nuclear power station in southern Sweden. At location A, unshielded sources were placed in steps of 10 m successively from 40 to 160 m distance from the road. At location B, a shielded source was placed in steps of 5 m successively from 20 to 105 m from the road.

Table 3a. Locations for unshielded Cs-137 sources at position A. Coordinates at the roadside are WGS 84: 55.752817; 12.917603 or SWEREF RT-90 2.5 gon V: 6184189 1318710

Setup #	Shielding	Activity/MBq	Distance/m	File name
1	No	196	40	*_S_01
2	No	196	50	*_S_02
3	No	196	60	*_S_03
4	No	196	70	*_S_04
5	No	196	80	*_S_05
6	No	196	90	*_S_06
7	No	196	100	*_S_07
8	No	196	110	*_S_08
9	No	196	120	*_S_09
10	No	602	80	*_S_10
11	No	602	90	*_S_11
12	No	602	100	*_S_12
13	No	602	110	*_S_13
14	No	602	120	*_S_14
15	No	602	130	*_S_15
16	No	602	140	*_S_16
17	No	602	150	*_S_17
18	No	602	160	*_S_18

Table 3b. Locations for the shielded Cs-137 source at position B. Coordinates at the roadside are WGS 84: 55.748523; 12.921496 or SWEREF RT-90 2.5 gon V: 6183701 1318934

Setup #	Shielding	Activity/MBq	Distance/m	File name
1	13 cm concrete	912	20	*_S_01
2	13 cm concrete	912	25	*_S_02
3	13 cm concrete	912	30	*_S_03
4	13 cm concrete	912	35	*_S_04
5	13 cm concrete	912	40	*_S_05
6	13 cm concrete	912	45	*_S_06
7	13 cm concrete	912	50	*_S_07
8	13 cm concrete	912	55	*_S_08
9	13 cm concrete	912	60	*_S_09
10	13 cm concrete	912	65	*_S_10
11	13 cm concrete	912	70	*_S_11
12	13 cm concrete	912	75	*_S_12
13	13 cm concrete	912	80	*_S_13
14	13 cm concrete	912	85	*_S_14
15	13 cm concrete	912	90	*_S_15
16	13 cm concrete	912	95	*_S_16
17	13 cm concrete	912	100	*_S_17
18	13 cm concrete	912	105	*_S_18

2.5 Computer program for determining the distance and activity of a source by Bayesian inference

The teams were offered the opportunity to use their measurement data to calculate distances and activities for the radiation sources applying Bayesian inference according to the method developed at Lund University (Bukartas et al., 2019; 2021). The program was made available to the teams as a web application for a limited time during and after the COMBMORC experiment.

Instructions for the program are given in Appendix B. The program is available for download from GitHub (Bukartas, 2021).

Results of the Bayesian inference calculations are not reported here. Examples will be given in the 2022 final report.

3. Results and discussion examples

In the following, examples of measurement results from the extensive measurement data material collected during the COMBMORC 2021 experiments in Barsebäck. The seven mobile measuring groups from the Nordic countries collected together over a million region of interest (ROI) measurement data during the three days that the measurements were going on.

3.1 Examples of background measurement data

In mobile gamma-ray spectrometry, when trying to detect weak radiation sources or distant sources that gives little contribution above the background counts in the spectrometers' pulse height distribution, it is important to know how the natural background varies. All teams made background measurements along the measurement route, Kraftverksvägen. When analyzing measurement data, the background for each team and measuring instruments was subtracted to get the net contribution from the deployed Cs-137 sources.

Fig 7a shows the background count rate data for the six ROI used for output in the experiment. The example is from the Danish team using a 4 litre NaI(Tl) detector mounted on the vehicles' rooftop. The count rate in the low-energy ROI A (77 - 239 keV) varies significantly along the measurement route. This energy region is affected by all radionuclides in the natural background and their spatial variation.

Fig 7b shows the background count rate data collected by the Norwegian NGU team using a 4x4 litre NaI(Tl) spectrometer. The count rate is about four times higher compared to a single 4 litre NaI(Tl) spectrometer due to the larger detector volume.

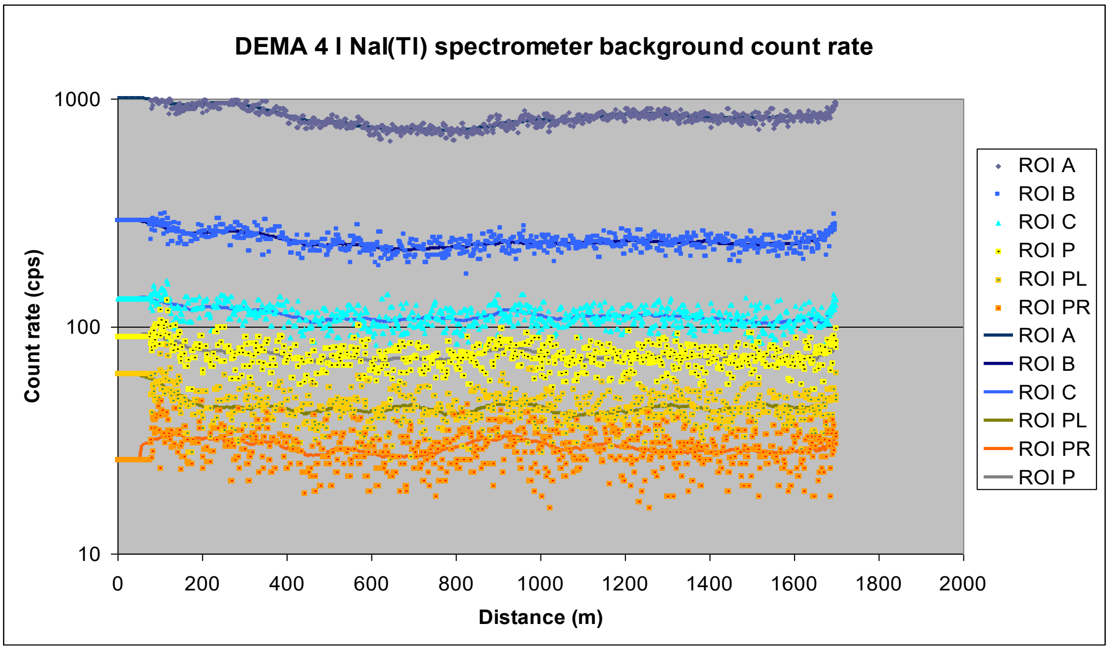


Figure 7a. Background count rate variation along the measurement route Kraftverksvägen, collected by the Danish DEMA team, using a 4 litre NaI(Tl) detector on the rooftop of the car. The different ROI are defined in Table 1.

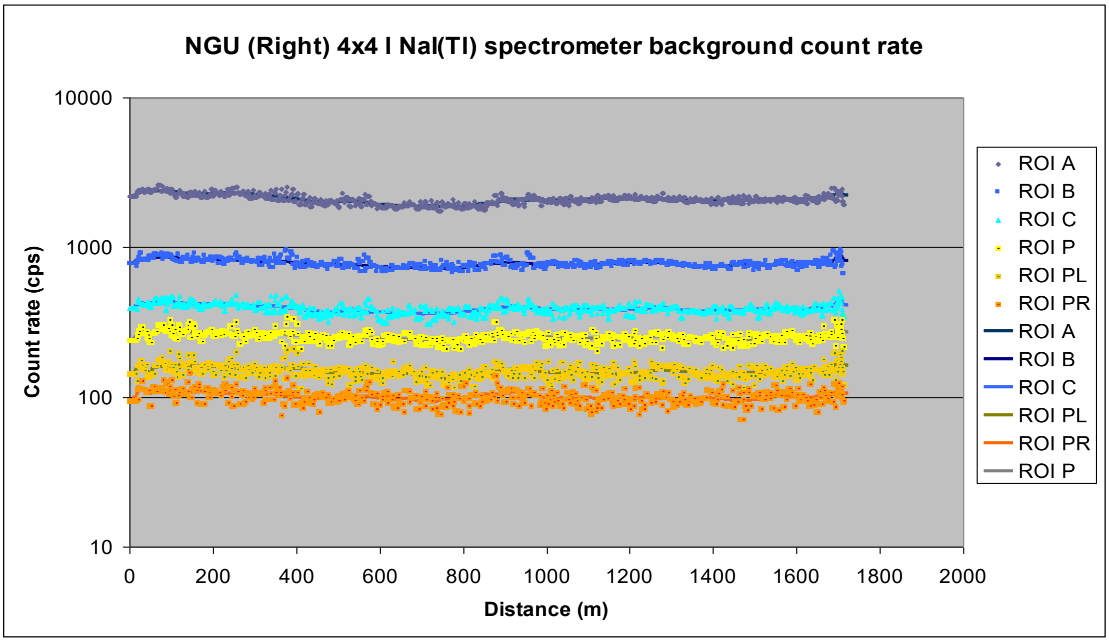


Figure 7b. Background count rate variation along the measurement route Kraftverksvägen, collected by the Norwegian NGU team, using a 4x4 litre NaI(Tl) detector inside a car. The different ROIs are defined in Table 1.

3.2 Examples of net (background subtracted) measurement data

Fig 8a - 8c shows examples of net (background subtracted) count rates for scattered radiation from Cs-137 sources in ROI A (77 - 239 keV), ROI B (245 -407 keV), and ROI C (413 - 575 keV). The distances to the shielded source B (912 MBq) is 45 m and to the unshielded source A (196 MBq) is 90 m. The shielded source B produces much scattered radiation, but the scattered component from the unshielded source A is low. Fig 8d shows registrations from the primary radiation in ROI P (581 - 743 keV) for source A and B.

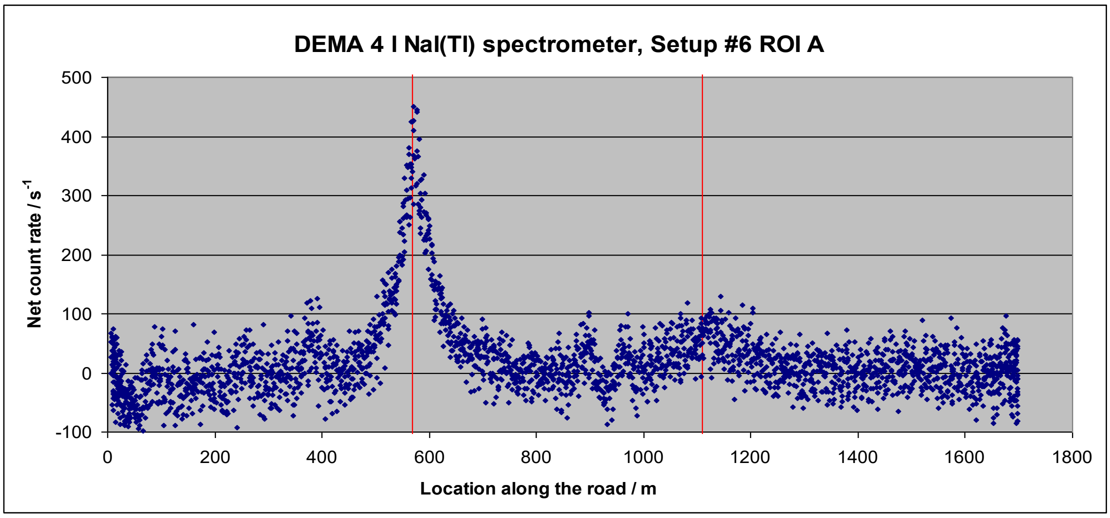


Figure 8a. Net (background subtracted) count rate data for ROI A (77 - 239 keV) when passing the shielded source B at 570 m and the unshielded source A at 1109 m along the measurement route. The scattered radiation from the shielded Cs-137 source 45 m from the roadside is clearly seen, but there is only little scattered radiation registered from the unshielded source A at 90 m from the roadside.

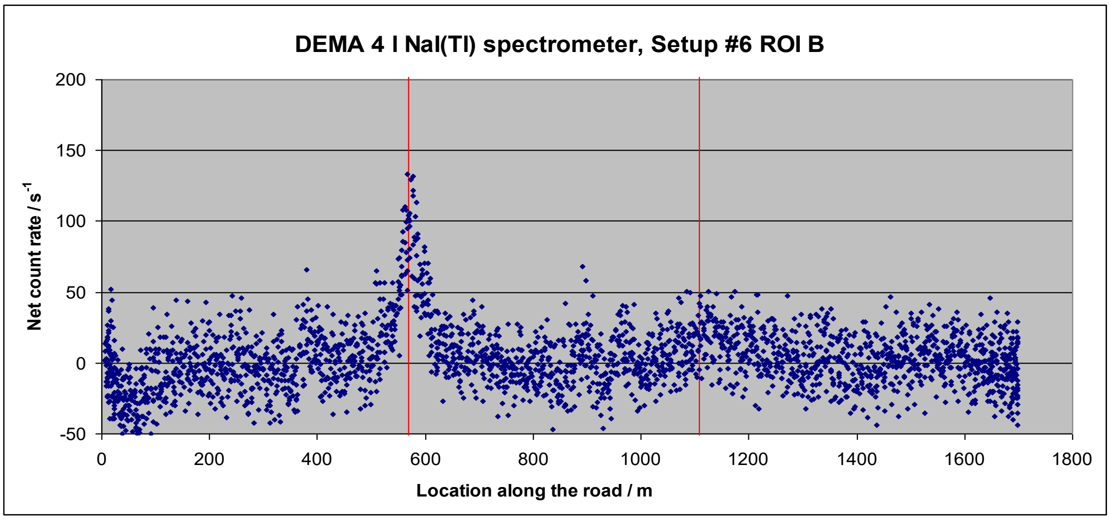


Figure 8b. Net (background subtracted) count rate data for ROI B (245 - 407 keV) when passing the shielded source B at 570 m and the unshielded source A at 1109 m.

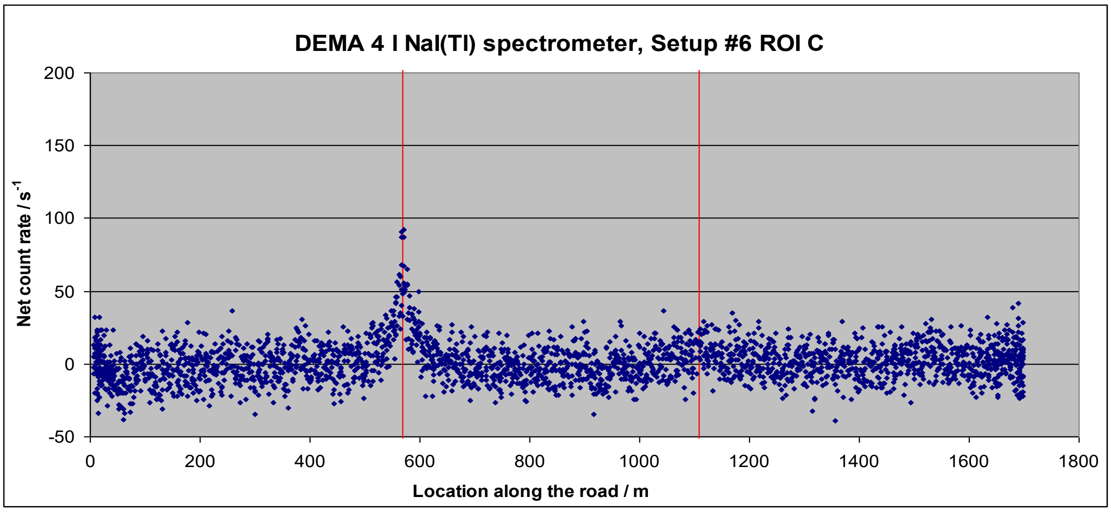


Figure 8c. Net (background subtracted) count rate data for ROI C (413 - 575 keV) when passing the shielded source B at 570 m and the unshielded source A at 1109 m.

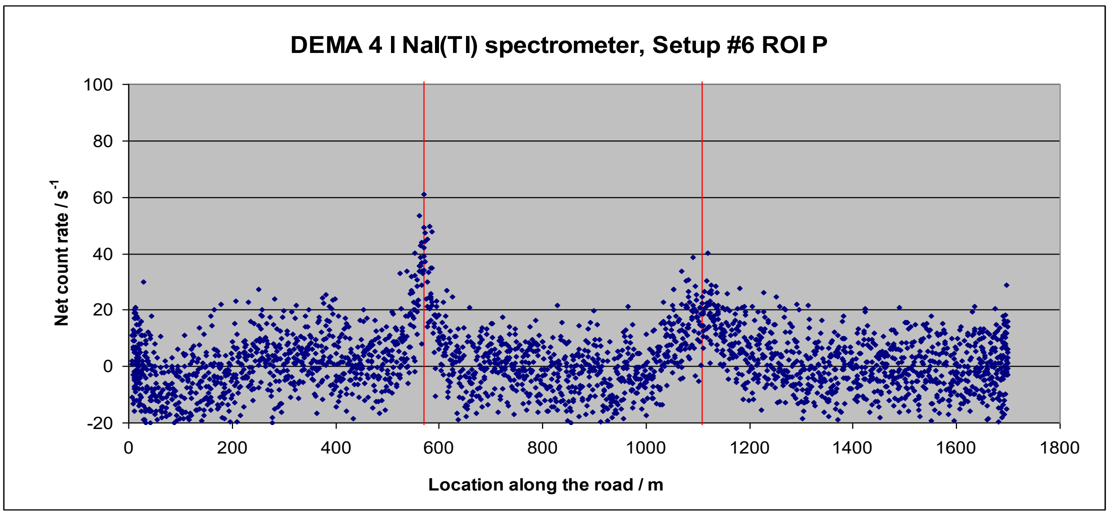


Figure 8d. Net (background subtracted) count rate data for primary radiation in ROI P (581 - 743 keV) when passing the shielded source B at 570 m and the unshielded source A at 1109 m. The primary component is distinguishable for both sources.

Fig 9a - 9c shows examples of net (background subtracted) count rates for scattered radiation from Cs-137 sources in ROI A, ROI B and ROI C. The distances to the shielded source B (912 MBq) is 65 m and to the unshielded source A (602 MBq) 80 m. Both sources show registrations from scattered radiation, but the primary radiation from the shielded source B is hardly visible, while there is a large signal of primary radiation from the unshielded source A (Fig 9d).

The higher activity source B that is closer to the road than source A shows very little primary radiation at the roadside because of its 130 mm concrete shielding. However, there are still registrations from scattered radiation from source B. This may contribute to detection of the shielded source at somewhat longer distance than predicted by its primary component., although special analysis software would be needed to identify this situation.

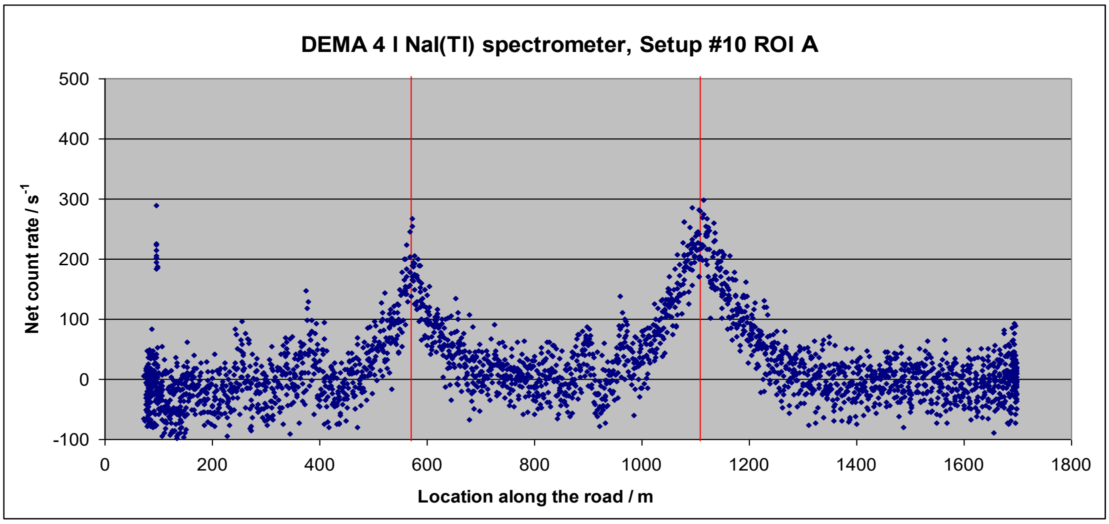


Figure 9a. Net (background subtracted) count rate data for ROI A (77 - 239 keV) when passing the shielded source B at 570 m and the unshielded source A at 1109 m along the measurement route. Scattered radiation from the shielded Cs-137 source 65 m from the roadside and the unshielded source 80 m from the roadside is seen.

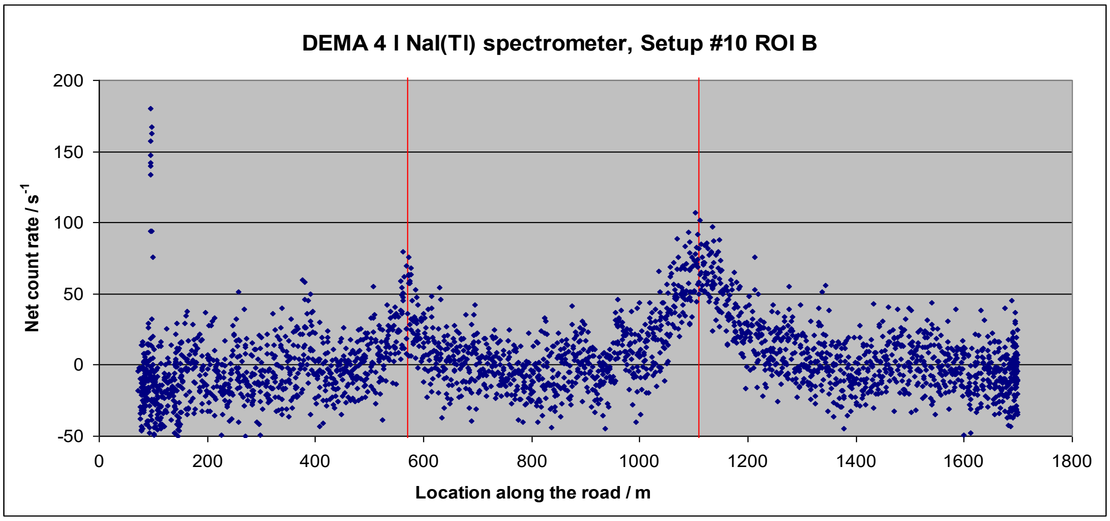


Figure 9b. Net (background subtracted) count rate data for ROI B (245 - 407 keV) when passing the shielded source B at 570 m and the unshielded source A at 1109 m.

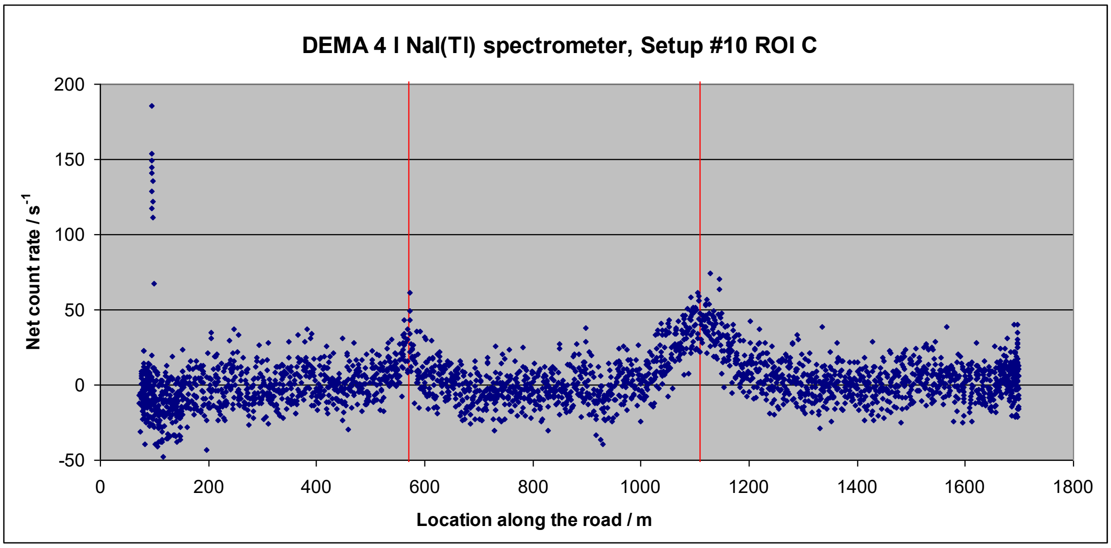


Figure 9c. Net (background subtracted) count rate data for ROI C (413 - 575 keV) when passing the shielded source B at 570 m and the unshielded source A at 1109 m.

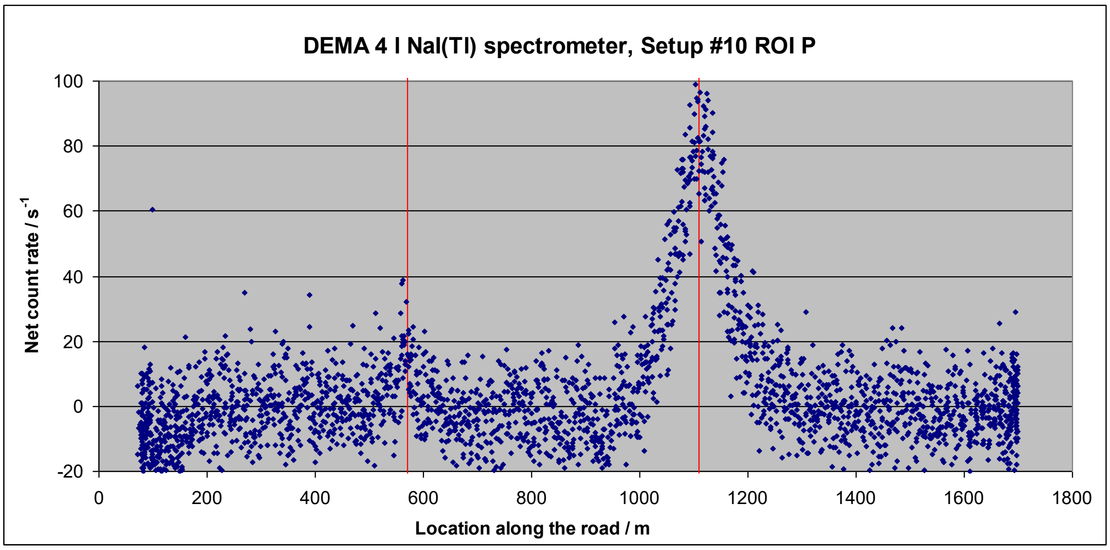


Figure 9d. Net (background subtracted) count rate data for primary radiation in ROI P (581 - 743 keV) when passing the shielded source B at 570 m and the unshielded source A at 1109 m. The primary component is only seen for source A.

3.2 Detecting a shielded source - Examples of scattered to primary count rate ratios

The SHIELDMORC project (Rääf et al., 2021) showed that there is a mathematical relationship in the ratio of scattered to primary radiation for shielded sources as a function of the mass thickness of the shield, if it consists of conventional building materials with atomic numbers lower than 25. The relationship was shown by stationary measurements with acquisition times of several minutes. Here COMB-MORC shows that it should be possible to utilize this relationship also for the short acquisition times (seconds) used in mobile measurements.

Fig 10a and 10b shows the ratio of scattered radiation registration in ROI A, ROI B, ROI C and the primary radiation in ROI P measured by DEMA with a mobile 4 liter

NaI(Tl) spectrometer at 50 km/h and one second acquisition time. The vehicle has passed the radiation sources ten times. The figures show the mean of the ten passages.

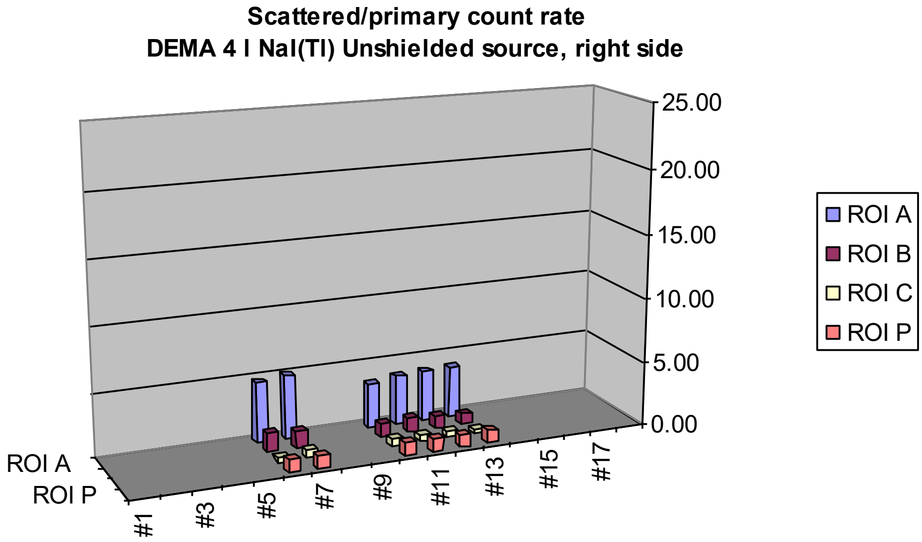


Figure 10a. Scattered to primary count rate ratios for an unshielded Cs-137 source at different distances and two different activities (#6 90 m, 196 MBq; #7 100 m, 196 MBq; #10 80 m, 602 MBq; #11 90 m, 602 MBq; #12 100 m, 602 MBq; #13 110 m, 602 MBq). Average values measured by DEMA mobile 4 litre NaI(Tl) spectrometer at 50 km/h and one second acquisition time. Average values for ten passes past the source. Measurements are only shown where a setup was measured and the primary component in ROI P was detected.

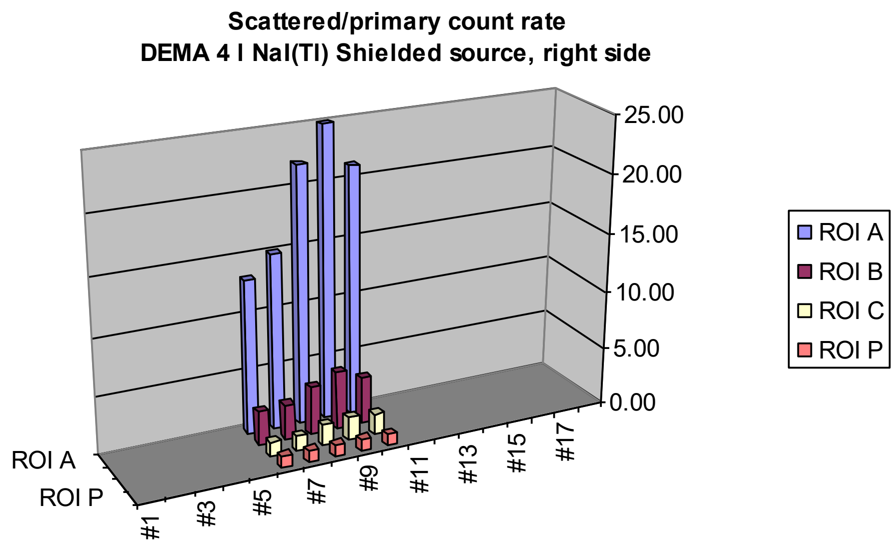


Figure 10b. Scattered to primary count rate ratios for a shielded Cs-137 source at different distances and one activity (912 MBq) (#6 45 m, #7 50 m; #8 55 m; #9 60 m, #10 65 m) Average values measured by DEMA mobile 4 litre NaI(Tl) spectrometer at 50 km/h and one second acquisition time. Average values for ten passes past the source. Measurements are only shown where a setup was measured and the primary component in ROI P was detected.

Fig 10a shows a nearly constant relation in the scattered to primary radiation independent of the distance and activity of the source for the unshielded source. The count rate ratio ROI A/ROI P is about 4.

Fig 10b shows the relation in the scattered to primary radiation for the shielded source at different distances. The count rate ratio ROI A/ROI P is about 15 - 25, indicating that the source is shielded.

All mobile teams obtained corresponding measurement results. Examples of results from teams are displayed in Figs 11 - 14.

Fig 11a shows the registered count rate ratio of scattered to primary radiation for the unshielded source measured by DSA mobile 2x4 litre NaI(Tl) spectrometer. Fig 11b shows the corresponding values for the shielded source.

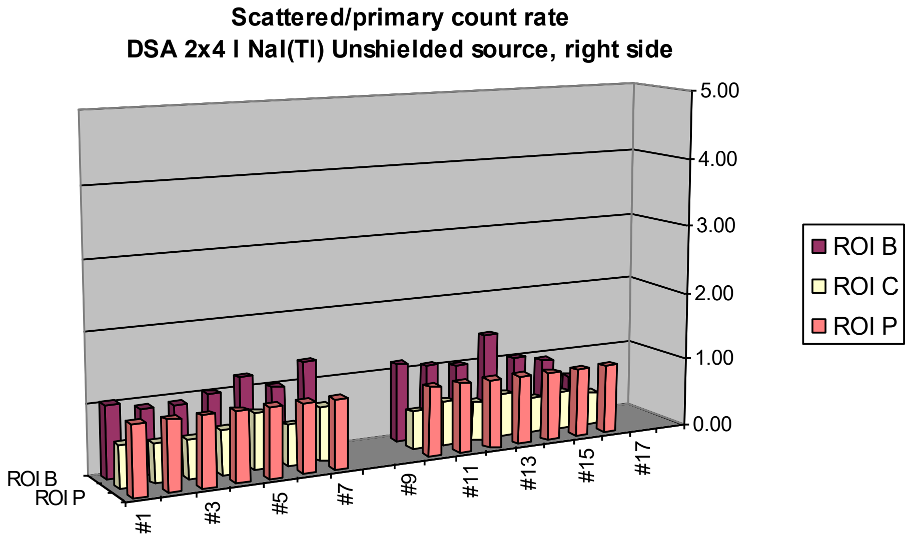


Figure 11a. Scattered to primary count rate ratios for an unshielded Cs-137 source at different distances and two different activities (See Table 3a). Values measured by DSA mobile 2x4 litre NaI(Tl) spectrometer at 50 km/h and one second acquisition time. Average values for ten passes past the source. Measurements are only shown where the primary component in ROI P was detected. ROI A was not registered.

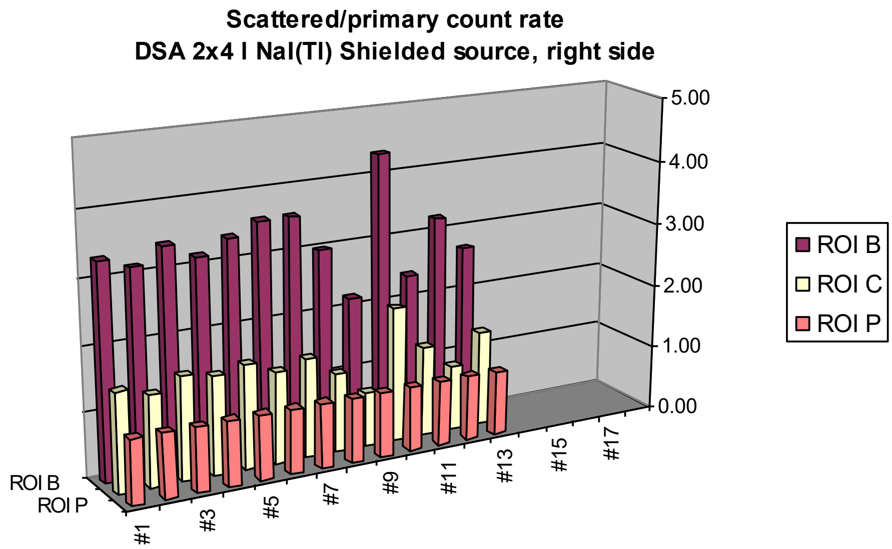


Figure 11b. Scattered to primary count rate ratios for a shielded Cs-137 source at different distances and one activity (912 MBq) (see Table 3b). Values measured by DSA mobile 2x4 litre NaI(Tl) spectrometer at 50 km/h and one second acquisition time. Average values for ten passes past the source. Measurements are only shown where the primary component in ROI P was detected. ROI A was not registered.

Fig 12a shows the registered count rate ratio of scattered to primary radiation for the unshielded source measured by GR/IRSA mobile 2x2 litre NaI(Tl) spectrometer. Fig 12b shows the corresponding values for the shielded source.

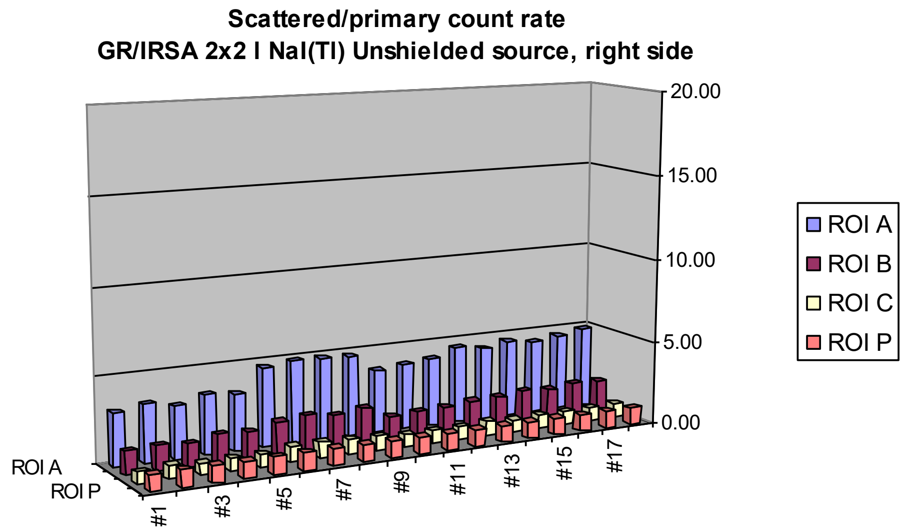


Figure 12a. Scattered to primary count rate ratios for an unshielded Cs-137 source at different distances and two different activities (See Table 3a). Values measured by GR/IRSA mobile 2x2 litre NaI(Tl) spectrometer at 50 km/h and one second acquisition time. Average values for ten passes past the source. Measurements are only shown where the primary component in ROI P was detected.

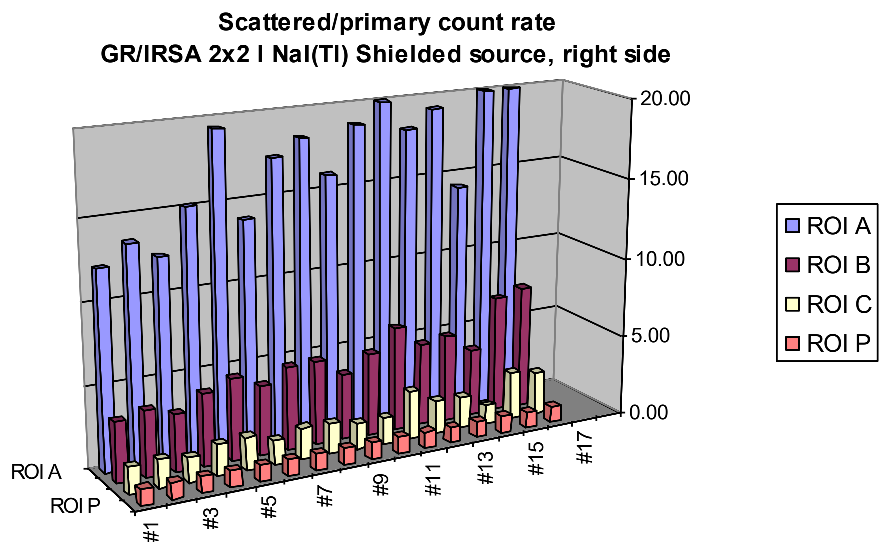


Figure 12b. Scattered to primary count rate ratios for a shielded Cs-137 source at different distances and one activity (912 MBq) (see Table 3b). Values measured by GR/IRSA mobile 2x2 litre NaI(Tl) spectrometer at 50 km/h and one second acquisition time. Average values for ten passes past the source. Measurements are only shown where the primary component in ROI P was detected.

Fig 13a shows the registered count rate ratio of scattered to primary radiation for the unshielded source measured by NGU mobile 4x4 litre NaI(Tl) spectrometer. Fig 13b shows the corresponding values for the shielded source.

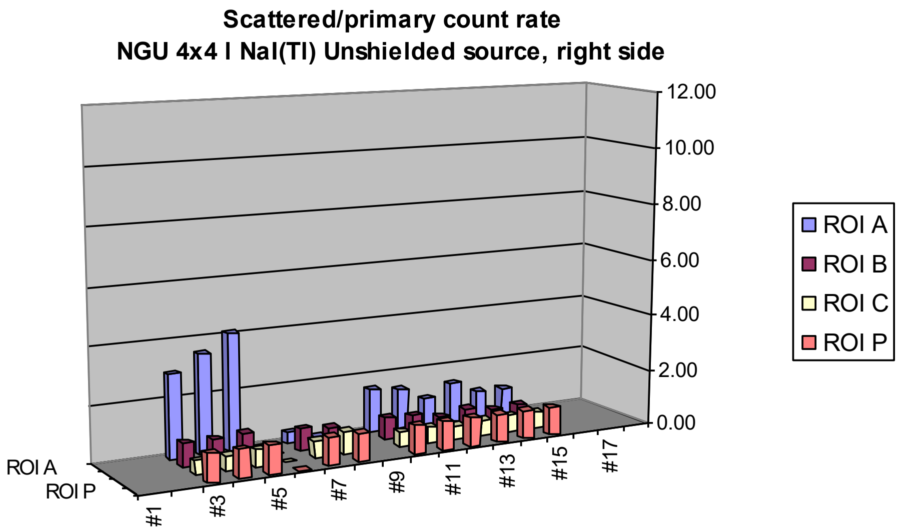


Figure 13a. Scattered to primary count rate ratios for an unshielded Cs-137 source at different distances and two different activities (See Table 3a). Values measured by NGU mobile 4x4 litre NaI(Tl) spectrometer at 50 km/h and one second acquisition time. Average values for ten passes past the source. Measurements are only shown where the primary component in ROI P was detected.

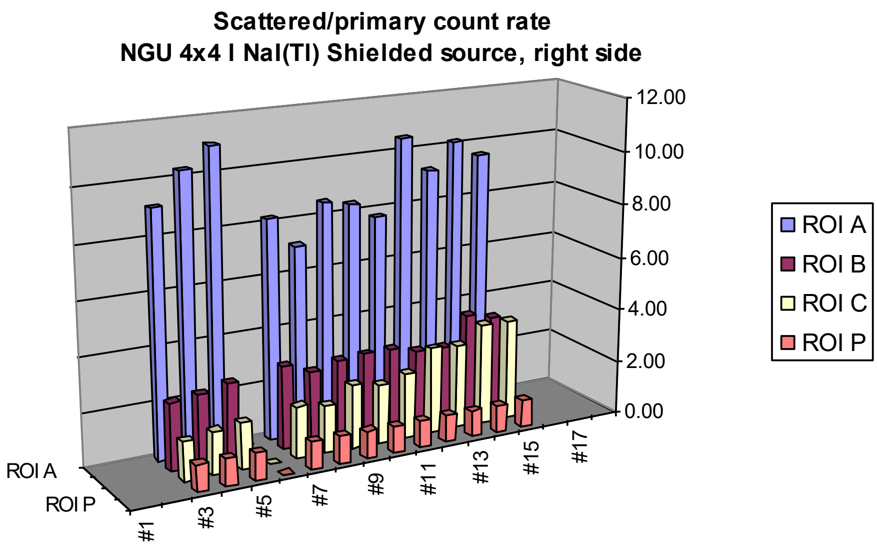


Figure 13b. Scattered to primary count rate ratios for a shielded Cs-137 source at different distances and one activity (912 MBq) (see Table 3b). Values measured by NGU mobile 4x4 litre NaI(Tl) spectrometer at 50 km/h and one second acquisition time. Average values for ten passes past the source. Measurements are only shown where the primary component in ROI P was detected.

Fig 14a shows the registered count rate ratio of scattered to primary radiation for the unshielded source measured by SSM mobile 2x4 litre NaI(Tl) spectrometer. Fig 14b shows the corresponding values for the shielded source.

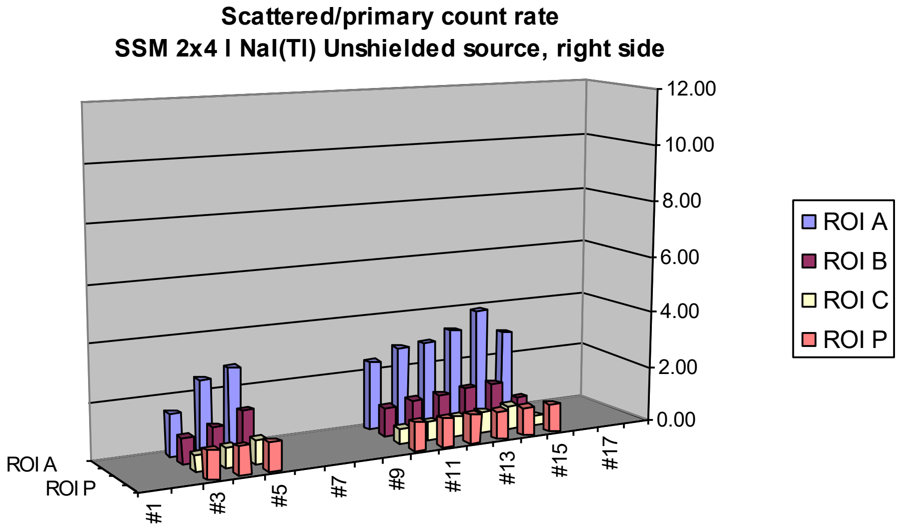


Figure 14a. Scattered to primary count rate ratios for an unshielded Cs-137 source at different distances and two different activities (See Table 3a). Values measured by SSM mobile 2x4 litre NaI(Tl) spectrometer at 50 km/h and one second acquisition time. Average values for ten passes past the source. Measurements are only shown where the primary component in ROI P was detected.

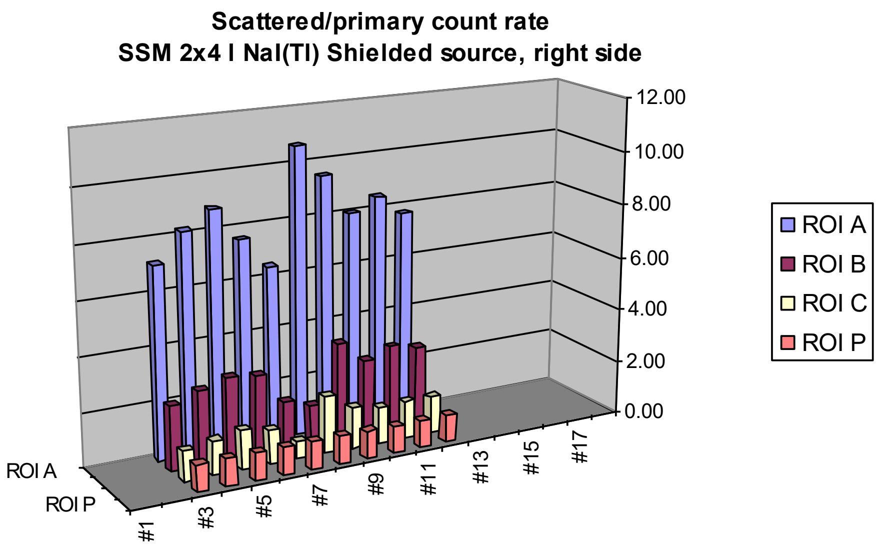


Figure 14b. Scattered to primary count rate ratios for a shielded Cs-137 source at different distances and one activity (912 MBq) (see Table 3b). Values measured by SSM mobile 2x4 litre NaI(Tl) spectrometer at 50 km/h and one second acquisition time. Average values for ten passes past the source. Measurements are only shown where the primary component in ROI P was detected.

3.3 Obtaining the distance and activity of a source by the "intensity curve" method - some examples

The primary photon fluence rate $\dot{\phi}$ in the air at a distance, *r,* from a point source, with activity *A*, can be written:

$$\dot{\phi} = \frac{A b \, e^{-(\mu/\rho)_a \, \rho_a \, r}}{4\pi \, r^2} \tag{1}$$

where *b* is the branching ratio for the photon energy, $(\mu/\rho)_a$ is the mass attenuation coefficient for photon interactions in air, and ρ_a is the air density, ρ_a. (Finck et al., 2019). When the measuring vehicle passes the source, the distance *r* varies and so does the primary fluence rate $\dot{\phi}$, forming an "intensity curve" with maximum value just opposite the source where *r* is at minimum. The width of the "intensity curve" along the vehicle path depends on the path-source distance at its shortest location, generally called "the distance to the source from the road". If a monitoring team can measure the shape of the "intensity curve" when passing the source, the road-source distance can be determined. If the primary count rate (ROI P) is high enough it follows the shape of the "intensity curve", provided that the angular efficiency of the detector is approximately uniform. If not so, an angular correction to the detector efficiency must be applied.

By fitting the primary count rate from ROI P to the "intensity curve" as a function of *r*, the shortest road-source distance *x*, can be obtained. Then the activity of the source can be determined from the equation:

$$A = \frac{4\pi \, x^2 \, \dot{N}}{\varepsilon \, b \, e^{-(\mu/\rho)_a \, \rho_a \, x}} \tag{2}$$

where ε is the detector efficiency expressed as the virtual detector area (m^2), which corresponds to total absorption of all primary photons incident on the area ε. $\dot{N}$ is the full energy peak count rate obtained in ROI P.

Four examples of using the "intensity curve" method are given in the following. All examples are taken from NGU measurements with a 4x4 litre NaI(Tl) spectrometer while passing the sources on the right side of the vehicle.

3.3.1 Unshielded Cs-137 source 60 m from the road

Fig 15a shows count rates in the three ROI A, ROI B and ROI C, representing scattered radiation from the unshielded Cs-137 source placed at 60 m from the road.

Fig 15b shows count rates in ROI P, representing primary radiation. Three “intensity curves” are shown together with the measured values. The black curve representing a road-source distance of 60 m seems to provide a reasonable fit.

Table 15 gives values of the source activity for road-source distances 40, 60 and 80 m, ranging from 70 to 460 MBq. Using Eqn 2, supposing the road-source distance is 60 m, the calculated activity of the source is 215 MBq. The true value is 196 MBq.

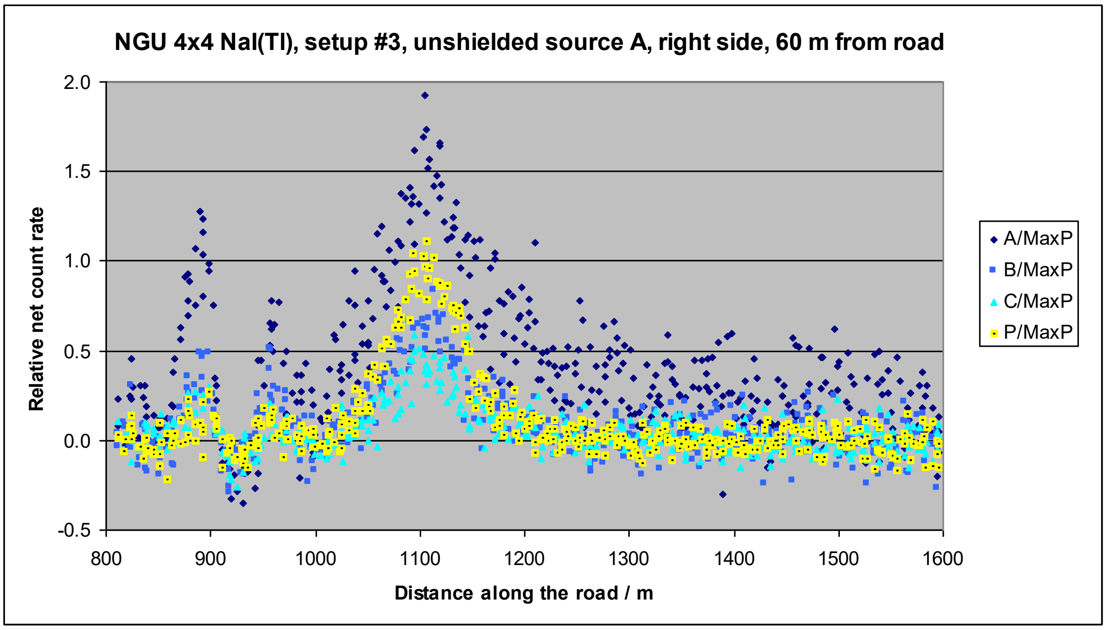


Figure 15a. Count rates in ROI A, ROI B and ROI C representing scattered radiation from an unshielded 196 MBq Cs-137 source 60 m from the road, measured by NGU 4x4 litre NaI(Tl) spectrometer during 10 passes past the source. The count rate in ROI P represents primary radiation from the source.

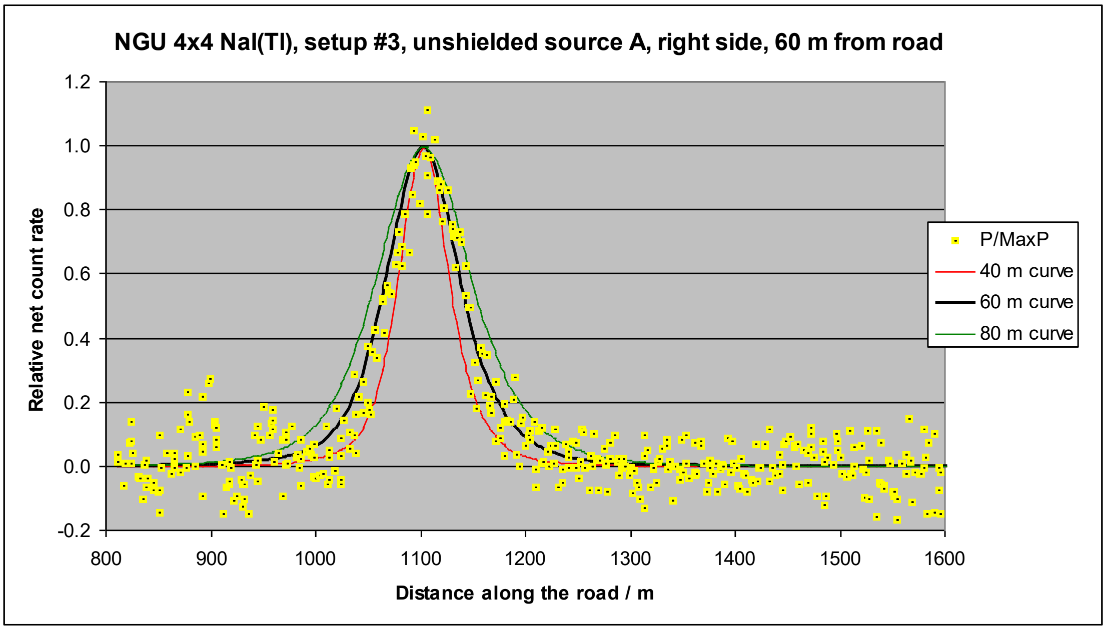


Figure 15b. The count rates in ROI A, representing primary radiation from the unshielded 196 MBq Cs-137 source. Three "intensity curves" are shown for road-source distances 40 m (red), 60 m (black) and 80 m (green) distance.

Table 15. Calculated activity for an unshielded Cs-137 point source at presumed distances. The measurement was made with NGU 4x4 litre NaI(Tl) spectrometer giving a full energy peak area, ROI P, average maximum of 472 cps when passing the source ten times with 50 km/h and one second acquisition time. Setup #3 source A on the right side. The true distance to the source was 60 m. The true activity was 196 MBq.

Selected intensity curve	Presumed distance m	Calculated activity MBq	True activity MBq
Red	40	79	
Black	60	214	196
Green	80	460	

3.3.2 Unshielded Cs-137 source 80 m from the road

Fig 16a shows count rates in the three ROI A, ROI B and ROI C, representing scattered radiation from the unshielded Cs-137 source placed at 80 m from the road.

Fig 16b shows count rates in ROI P, representing primary radiation. Three “intensity curves” are shown together with the measured values. The black curve representing a road-source distance of 80 m seems to provide a reasonable fit.

Table 16 gives values of the source activity for road-source distances 60, 80 and 100 m, ranging from 307 to 1245 MBq. Using Eqn 2, supposing the road-source distance is 60 m, the calculated activity of the source is 659 MBq. The true value is 602 MBq.

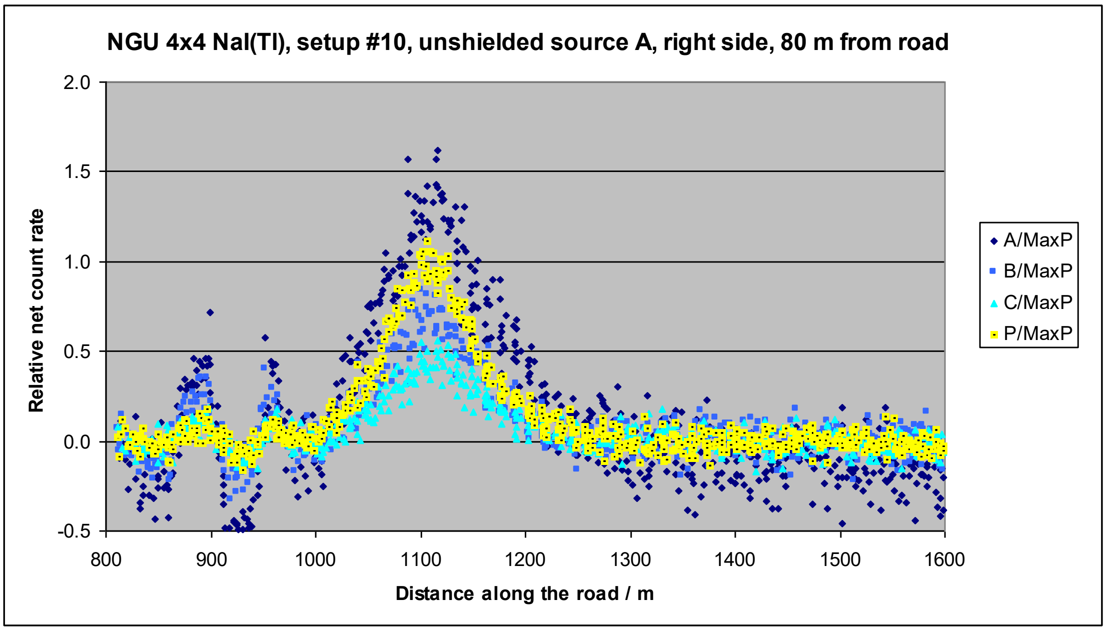


Figure 16a. Count rates in ROI A, ROI B and ROI C representing scattered radiation from an unshielded 602 MBq Cs-137 source 80 m from the road, measured by NGU 4x4 litre NaI(Tl) spectrometer during 10 passes past the source. The count rate in ROI P represents primary radiation from the source.

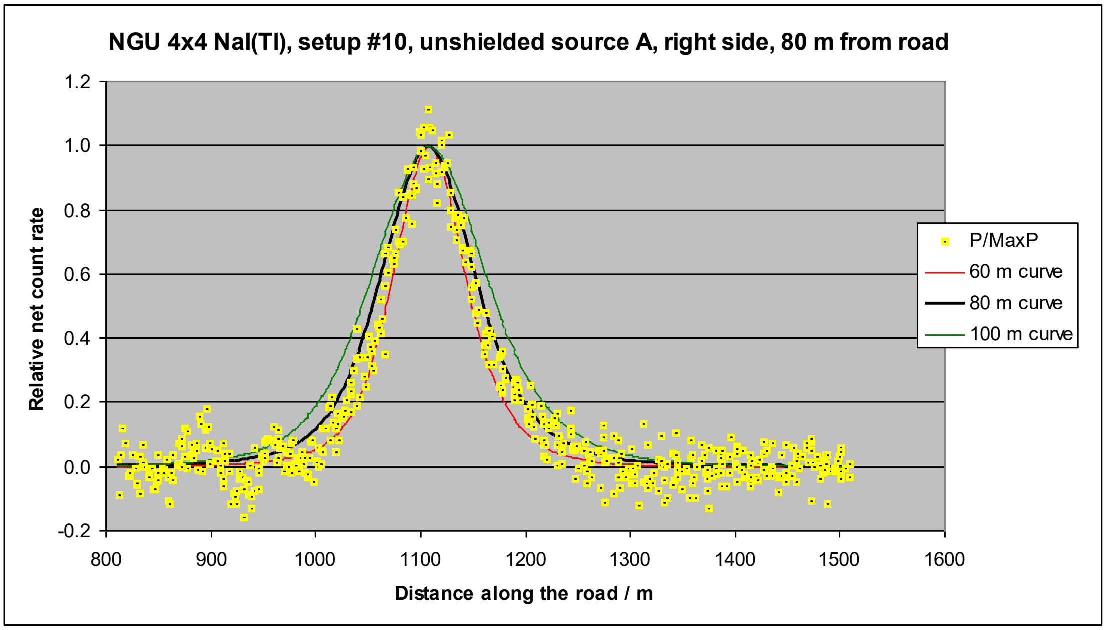


Figure 16b. The count rates in ROI A, representing primary radiation from the unshielded 602 MBq Cs-137 source. Three “intensity curves” are shown for road-source distances 60 m (red), 80 m (black) and 100 m (green) distance.

Table 16. Calculated activity for an unshielded Cs-137 point source at presumed distances. The measurement was made with NGU 4x4 litre NaI(Tl) spectrometer giving a full energy peak area, ROI P, average maximum of 341 cps when passing the source ten times with 50 km/h and one second acquisition time. Setup #10 source A on the right side. The true distance to the source was 80 m. The true activity was 602 MBq.

Selected intensity curve	Presumed distance M	Calculated activity MBq	True activity MBq
Red	60	307	
Black	80	659	602
Green	100	1245	

3.3.3 Unshielded Cs-137 source 130 m from the road

Fig 17a shows count rates in the three ROI A, ROI B and ROI C, representing scattered radiation from the unshielded Cs-137 source placed at 130 m from the road.

Fig 17b shows count rates in ROI P, representing primary radiation. Three "intensity curves" are shown together with the measured values. Both the red and the black curve representing a road-source distances of 100 and 130 m may represent the data, while the green curve for 160 m distance is to wide.

Table 17 gives values of the source activity for road-source distances 100, 130 and 160 m, ranging from 273 to 1235 MBq. Using Eqn 2, supposing the road-source distance is 130 m, the calculated activity of the source is 614 MBq. The true value is 602 MBq.

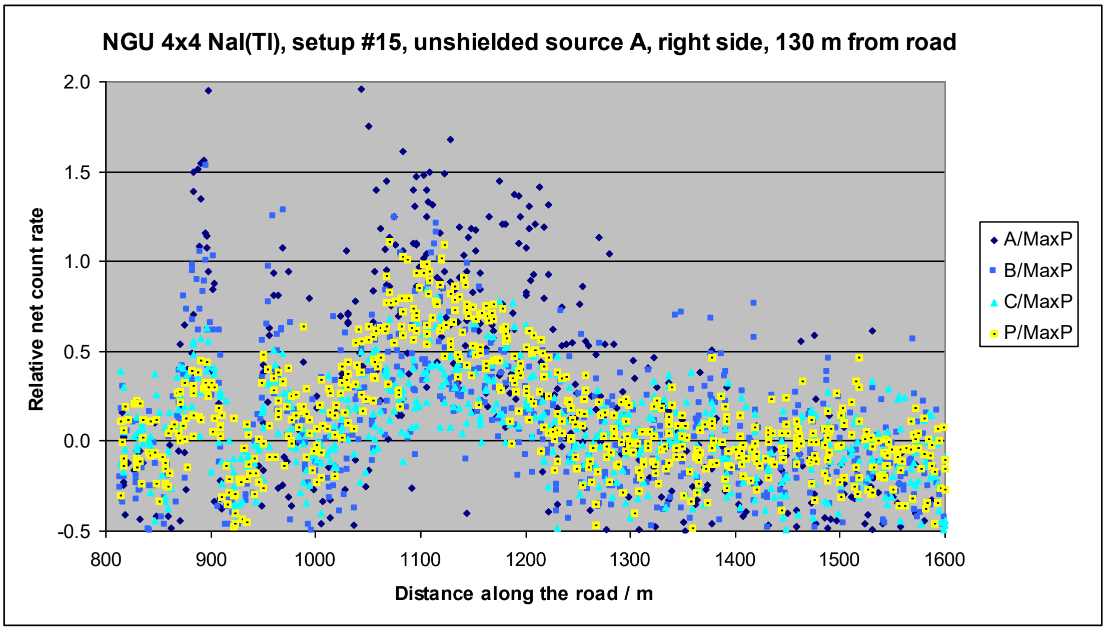


Figure 17a. Count rates in ROI A, ROI B and ROI C representing scattered radiation from an unshielded 602 MBq Cs-137 source 130 m from the road, measured by NGU 4x4 litre NaI(Tl) spectrometer during 10 passes past the source. The count rate in ROI P represents primary radiation from the source.

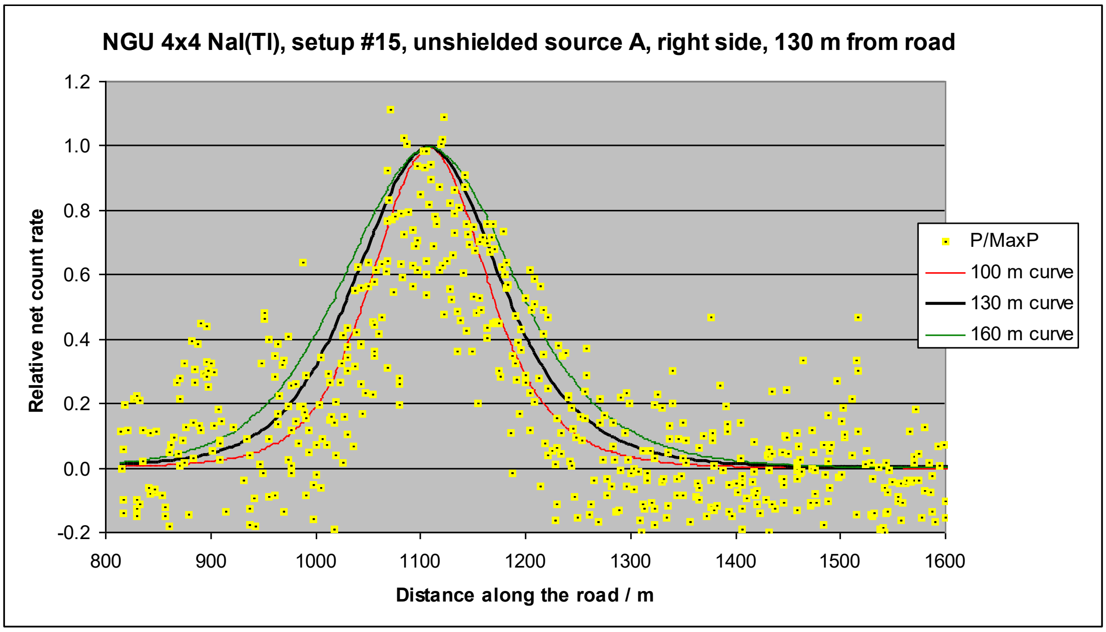


Figure 17b. The count rates in ROI A, representing primary radiation from the unshielded 602 MBq Cs-137 source. Three "intensity curves" are shown for road-source distances 100 m (red), 130 m (black) and 160 m (green) distance.

Table 17. Calculated activity for an unshielded Cs-137 point source at presumed distances. The measurement was made with NGU 4x4 litre NaI(Tl) spectrometer giving a full energy peak area, ROI P, average maximum of 75 cps when passing the source ten times with 50 km/h and one second acquisition time. Setup #15 source A on the right side. The true distance to the source was 80 m. The true activity was 602 MBq.

Selected intensity curve	Presumed distance M	Calculated activity MBq	True activity MBq
Red	100	273	
Black	130	614	602
Green	160	1235	

3.3.4 Shielded Cs-137 source 30 m from the road

Fig 18a shows count rates in the three ROI A, ROI B and ROI C, representing scattered radiation from the shielded Cs-137 source placed 30 m from the road.

Fig 18b shows count rates in ROI P, representing primary radiation. Three “intensity curves” are shown together with the measured values. The black curve seems to best represent the data for a road-source distances of 20 m..

Table 18 gives values of the source activity for road-source distances 10, 20, 30 and 40 m, ranging from 7.4 to 156 MBq. Using Eqn 2, supposing the road-source distance is 20 m, the calculated activity of the source is 32 MBq. However, the source is shielded, which can be seen from the ratio of ROA A to ROI P being about 6, while unshielded source have ratios about 2 when measured by the 4x4 litre NaI(Tl) spectrometer.

The shield thickness can be approximately determined from the count rate ratio ROI A to ROI P as described in the SHIELDMORC report (Rääf et al., 2020). It has not been done here because the 4x4 NaI(Tl) spectrometer has not been fully calibrated for assessing shield thickness. Assuming the distance 20 m and the true value of 130 mm concrete, the “unshielded” activity would be 288 MBq. Using the correct distance 30 m, the “unshielded” activity would be 720 MBq. The true activity value is 912 MBq.

The “intensity curve” method seems to underestimate the true activity somewhat for the shielded source. However, this is only one example and further analysis using measurement data from the whole COMBMORC experiment is needed to draw more definite conclusions.

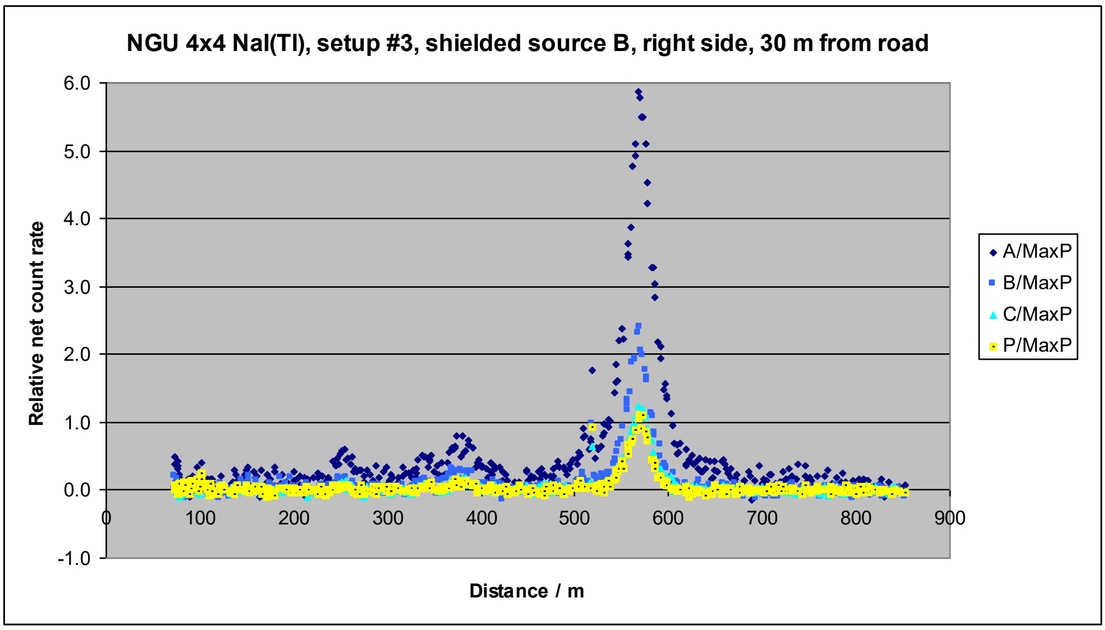


Figure 18a. Count rates in ROI A, ROI B and ROI C representing scattered radiation from the shielded 912 MBq Cs-137 source 30 m from the road, measured by NGU 4x4 litre NaI(Tl) spectrometer during 10 passes past the source. The count rate in ROI P represents primary radiation from the source.

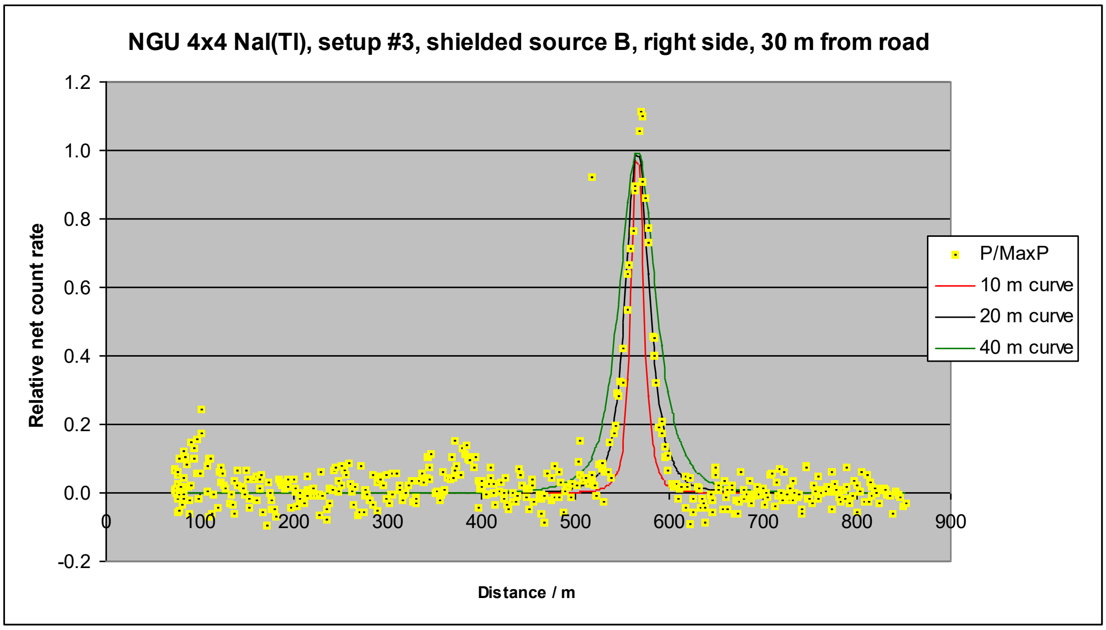


Figure 18b. The count rates in ROI A, representing primary radiation from the shielded 912 MBq Cs-137 source. Three "intensity curves" are shown for road-source distances 10 m (red), 20 m (black) and 40 m (green) distance.

Table 18. Calculated activity for an unshielded and a shielded Cs-137 point source at presumed distances. The measurement was made with NGU 4x4 litre NaI(Tl) spectrometer giving a full energy peak area, ROI P, average maximum of 238 cps when passing the source ten times with 50 km/h and one second acquisition time. Setup #3 source B on the right side. The true distance to the source was 30 m. The true activity was 912 MBq. The true shielding was 130 cm concrete

Selected intensity curve	Presumed distance m	Calculated activity for an unshielded source MBq	Calculated activity for a source shielded with 130 cm concrete MBq	True activity MBq
Red	10	7.4	67	
Black	20	32	288	
	30	80	720	912
Green	40	156	1405	

4. Conclusions

In mobile gamma spectrometry, combined analysis of registrations from primary and scattered photons may ease the detection of shielded sources compared to using only registrations of primary photons. From the ratio of registrations of scattered to primary photons, the shield thickness may be assessed, provided that the counting statistics is sufficient. Special software has to be developed to do this in practice.

When searching for unshielded sources at distances shorter than 100 m, detecting primary radiation is the preferred method. Air scattered radiation does not contribute to the potential of detecting the source. The effect of including scattered radiation in the detection method has not been investigated for sources at more considerable distances. Still, there is reason to believe that detecting the primary radiation for unshielded sources will always be the superior method.

This report shows the possibility of using an approach based on "intensity curves" to obtain approximate information about the distance and activity of a radiation source. The method needs further testing and development to be practically helpful, as suggested by the proposed COMBMORC 2022 project.

References

Antanas Bukartas, Robert Finck, Jonas Wallin, Christopher L. Rääf. A Bayesian method to localize lost gamma sources. Applied Radiation and Isotopes, 145 pp 142-147. March 2019. https://doi.org/10.1016/j.apradiso.2018.11.008

Bukartas A, Wallin J, Finck R, Rääf C, Bayesian algorithm to estimate position and activity of an orphan gamma source utilizing multiple detectors in a mobile gamma spectrometry system. PloS ONE 16(1):e0245440. 2021. https://doi.org/10.1371/journal.pone.0245440

Antanas Bukartas, Computer program for determining the distance and activity of a gamma-ray point source by Bayesian inference, 2021: https://github.com/SpontaneousFusion/BCP_COMBORC_2021

R.R. Finck, T.Ulvsand. Search for orphan gamma radiation sources, Experiences from the Barents Rescue 2001 exercise. Proceedings, Security of Radioactive Sources held at IAEA, Vienna, Austria, 10-13 March 2003. IAEA, Vienna, pp 123 – 137, 2003.

R. Finck, T. Geber-Bergstrand, J. Jarneborn, G. Jónsson, M. Jönsson, S. Juul Krogh, S. Karlsson, J. Nilsson, M. Persson, P. Reppenhagen Grim, C.L. Rääf, M. Sickel, P. Smolander, R. Watson, K. Östlund, Mobile search of material out of regulatory control (MORC) –Detection limits assessed by field experiments, Nordic Nuclear Safety Research Report NKS-421, ISBN 978-87-7893-510-6, March 2019. http://dx.doi.org/doi:10.13140/RG.2.2.20782.33605

Thomas Hjerpe, Robert R. Finck, and Christer Samuelsson. 2001. Statistical Data Evaluation in Mobile Gamma Spectrometry: An Optimization of On-Line Search Strategies in the Scenario of Lost Point Sources. Health Physics Vol 80 No 6, pp 563 – 570, 2001. http://dx.doi.org/doi:10.1097/00004032-200106000-00006

IAEA, Combating Illicit Trafficking in Nuclear and Other Radioactive Material, IAEA Nuclear Security Series No. 6, Technical Guidance, Vienna, 2007.

Peder Karl-Johan Kock; Robert R Finck; Jonas M Nilsson; Karl Östlund; Christer Samuelsson. A Deviation Display Method for Visualising Data in Mobile Gamma-ray Spectrometry. Applied Radiation and Isotopes, Volume 68, Issue 9, pp 1832-1838, 2010. http://dx.doi.org/10.1016/j.apradiso.2010.04.004

Jonas Nilsson, Karl Östlund, Joakim Söderberg, Sören Mattsson, Christopher Rääf. Tests of HPGe- and scintillation-based backpack γ-radiation survey systems. Journal of Environmental Radioactivity 135:54–62, 2014. http://dx.doi.org/10.1016/j.jenvrad.2014.03.013

Jonas M.C. Nilsson, Robert R. Finck, Christopher Rääf, Investigation and optimisation of mobile NaI(Tl) and 3He-based neutron detectors for finding point sources. Nuclear Instruments and Methods in Physics Research A, 786, pp 127 – 134, 2015. http://dx.doi.org/10.1016/j.nima.2015.03.013

Christopher L. Rääf (chair), Robert R. Finck (co-chair) Antanas Bukartas, Gísli Jónsson, Sune Juul Krogh, Simon Karlsson, Morten Sickel, Petri Smolander, Jonas

Wallin, Robin Watson, AUTOMORC – Improvement of automatic methods for identification of radioactive material out of regulatory control (MORC) by mobile gamma spectrometric search experiments. Report 2017. Nordic Nuclear Safety Research Report NKS 422, March 2019.

Christopher L. Rääf (chair), Robert R. Finck (co-chair), Vikas C. Baranwal, Antanas Bukartas, Marie-Andrée Dumais, Kjartan Guðnason, Yvonne Hinrichsen, Gísli Jónsson, Mattias Jönsson, Peder Kock, Sune Juul Krogh, Simon Karlsson, Frode Ofstad, Jan Steinar Rønning, Petri Smolander, Kasra Tazmani, Mikael Westin, SHIELDMORC – Detection distances and methods to locate orphan gamma radiation sources in shielded building geometries by mobile gamma spectrometry, Nordic Nuclear Safety Research, Report NKS-433, March 2020.

Christopher L. Rääf, Robert R. Finck, Vikas C. Baranwal, Jonas Boson, Antanas Bukartas, Marie-Andrée Dumais, Kjartan Guðnason, Marjan Ilkov, Gísli Jónsson, Mattias Jönsson, Simon Karlsson, Marie Lundgaard Davidsdóttir, Frode Ofstad, Jan Steinar Rønning, Petri Smolander, Mikael Westin, Detection of orphan gamma radiation sources in shielded building geometries by mobile gamma spectrometry. A method of using Compton scattered radiation to estimate the shielding mass thickness of common building material, Nordic Nuclear Safety Research Report NKS-448, June 2021.

UNSCEAR. Sources and Effects of Ionizing Radiation: United nations Scientific Committee on the Effects of Atomic Radiation 2008 Report, Volume II, Scientific Annex C, Radiation Exposures in Accidents, United Nation Publication, April 2011.

Appendix A
Instructions for the COMBMORC 2021 experiment in Barsebäck, 12-14 October 2021

Appendix A contains instructions and input data for the NKS/COMBMORC experiment in Barsebäck in October 2021.

A1. Region of interest (ROI) for the 2021 NKS/COMBMORC experiment

In order to use a standard format shared by all teams for the COMBMORC 2021 experiment, the same ROIs should be used for the SHIELDMORC experiments. This enables postprocessing of primary and scattered radiation combinations to achieve somewhat increased detection distances and identify shielded sources.

For Cs-137 measured by a NaI(Tl) spectrometer, six ROIs are proposed. Three represent photon energies of Compton scattered photons, and three represent combinations of primary and scattered photons. Due to a NaI(Tl) spectrometer's low energy resolution, it is impossible to obtain an ROI containing only registrations from primary photons. However, by dividing the full energy peak into sub-components, it is possible to approach the ideal case of recording primary and scattered photons separately. For a gamma spectrometer with an energy width of 3 keV per channel, the ROI energy limits have been set to ROI A (77-239 keV), ROI B (245-407 keV), ROI C (413-575 keV), ROI PL (581-659 keV), ROI PR (665-743 keV). In the SHIELDMORC experiment, an ROI PC for the centre channel of the 662 keV peak was used. Here, instead, the whole region of the peak should be included in an ROI P (581 -743 keV).

The six ROIs represent the following photon energy regions (with limits rounded to whole numbers):

ROI A, 77 - 239 keV, contains Compton scattered photons 110 - 180 degrees in the material behind the source and on its sides, multiple scattered photons and interaction effects in the detector and its surroundings.

ROI B, 245 - 407 keV, contains Compton scattered photons 58 - 110 degrees in the shielding material between the source and detector and in the material surrounding the source, multiple scattered photons and interaction effects in the detector and its surroundings.

ROI C, 413 - 575 keV, contains Compton scattered photons 27 - 58 degrees in the shielding material between the source and detector, multiple scattered photons and interaction effects in the detector and its surroundings.

ROI PL, 581 - 659 keV, contains Compton scattered photons 0 - 27 degrees in the shielding material between the source and detector, primary photons from the source that have penetrated through the shield, some small-angle multiple scattered photons and interaction effects in the detector and its surroundings.

ROI PC, 662 keV, contains primary photons from the source, some small-angle scattered photons and interaction effects in the detector and its surroundings. The counts in ROI PC is not written to the csv-file.

ROI PR, 665 - 743 keV, contains primary photons from the source, a minor contribution of small-angle scattered photons and interaction effects in the detector and its surroundings.

ROI P, 581 - 743 keV, contains primary photons from the source, some small-angle scattered photons and interaction effects in the detector and its surroundings. The counts in ROI P is equal to PL + PC + PR.

Depending on the number of channels and the gain setting in a gamma spectrometer, the conversion between photon energy and channel number can be set differently for different measuring systems. This makes the translation of energy interval to channel interval more or less rough from system to system. In order to be able to compare the response of multi-channel analyzers with different numbers of channels and gains, the translation from energy interval to channel interval needs to be made as similar as possible for different systems..

Table A1 provides examples of ROIs for different conversion gains and energy widths per channel.

Table A1. Suggested ROIs with energy interval limits given in keV for detecting primary and scattered photons measured by a gamma spectrometer having 1024, 512 or 256 channels corresponding to channel widths of 3, 6 or 12 keV/channel. The peak area ROI is suitable for a NaI(Tl) spectrometer and is divided into three sub-components: left peak area (PL), centre channel (PC) and right peak area (PR), which together constitutes the full energy peak area (P).

ROI	Energy node (keV)	Compton scattered degree	3 keV/ch (keV)	ROI width chs	6 keV/ch (keV)	ROI width chs	12 keV/ch (keV)	ROI width ch
	74							
A			77-239	55	80-236	27	86-230	13
	242	110						
B			245-407	55	248-404	27	254-398	13
	410	58						
C			413-575	55	416-572	27	422-566	13
	578	27						
PL			581-659	27	584-656	13	590-650	6
PC			662	1	662	1	662	1
PR			665-743	27	668-740	13	674-734	6
P*			581-743	55	584-740	27	590-734	13

* The ROI P should for the COMBMORC experiment 2021 contain the whole area P = PL + PC + PR. Since PC = P - PL - PR, it is not necessary to write out ROI PC.

A2. Format for providing data to the COMBMORC 2021 activity

Data should be given as comma separated values (csv), row by row, where a "," separates each value and a "." represents the decimal dot. Each file should contain measurements from one setup. Setups should be numbered at the end of the file name.

The contents of a csv-file should follow this format:

Value number	Contains	Example:
1	Date (dd-mmm-yy)	13-oct-21
2	Time (hh:mm:ss)	11:35:23
3	Acquisition time interval in seconds	1
4	North coordinate in WGS84 decimal value	55.761982
5	East coordinate in WGS84 decimal value	12.931692
6	Counts in the ROI A	152
7	Counts in the ROI B	148
8	Counts in the ROI C	121
9	Counts in the ROI PL	135
10	Counts in the ROI PR	83
11	Counts in the ROI P	228

The counts given as value numbers 6 - 11 should be the gross number of counts in the ROI (not the count rate) for the specific radionuclide without any background subtraction or other type of compensation.

The csv-file naming principle should be the following:
AAAA_DDDDDD_2021_10_M_N.csv

Where	is one of these
AAAA	DEMA, DSA, GR, LU, NGU, SSM, STUK
DDDDDD	HPGE, NAI3I, NAI4L, NAI8L, NAI16L
M	S if the file contains measurements when sources are placed B if the file contains background measurements
N	1, 2, 3, etc source setup number or background measurement number

A3. Full energy peak efficiency for Nordic mobile gamma spectrometers

Table A3. Full energy peak efficiencies (effective detector area) for 662 keV photons using Nordic mobile gamma spectrometers. Data[1] from calibrations made during the NKS AUTOMORC field experiment (Rääf et al, 2019). Data[2] from calibrations made during this NKS COMBMORC field experiment.

Mobile gamma spectrometer in car geometry	Left side Effective detector area / m^2	Right side Effective detector area / m^2
DEMA 4 litre NaI(Tl) detector on roof-top geometry[1]	0.0256	0.0258
DSA 4 litre NaI(Tl) detector, left detector[2]	0.0255	0.00164
DSA 4 litre NaI(Tl) detector, right detector[2]	0.00232	0.0252
DSA 3x3 inch NaI(Tl) detector[2]	0.00259	0.00125
GR/IRSA 2x2 litre NaI(Tl) detector[1]	0.0261	0.0299
NGU 4x4 litre NaI(Tl) detector(1)[2]	0.0766	0.104
NGU 1x4 litre NaI(Tl) detector(2)[2]	0.0232	0.00242
STUK 4 litre NaI(Tl) detector (1) right side[1]	-	0.0229
STUK 4 litre NaI(Tl) detector (2) right side[1]	0.0229	-
SSM 2x4 litre NaI(Tl) detector[1]	0.0557	0.0559
SSM 120% HPGe detector[1]	0.00269	0.00272
LU 4 litre NaI(Tl) detector rear[1]	0.0236	0.0261
LU 4 litre NaI(Tl) detector front[1]	0.0255	0.0254
LU 2x4 litre NaI(Tl) detector[1]	0.0514	0.0514
LU 3”x3” NaI(Tl) detector[1]	0.00151	0.00236
LU 123% HPGe detector[1]	0.00230	0.00229

A4. Report form for detector calibration in the NKS/COMBMORC 2021 experiment

COMBMORC Detector Reference Report

Team		
Date		
Start (hh:mm)		
Stop (hh:mm)		
Detector # (type left, right)		
Distance to car side	left m	right m

Cs-137 reference	RI-600		61 MBq
ROI P	keV		keV
Backgr Reference pos	cps		
Backgr Kraftverksvägn	cps		
	*Distance m	Gross cps	Net cps
Right side of the car*			
Left side of the car*			

* Distance between the reference source and the detector center

A5. Report form for the NKS/COMBMORC 2021 experiment

COMBMORC Mobile Detection Report

Team		
Detector # (type, left, right)		
Setup #		
Date		
Start (hh:mm)		
Stop (hh:mm)		
Speed (km/h)		
Acquisition time (s)		
ROI P Backgr (cps)		
ROI P Alarm level (cps)		
Source detection		
Source location	Each round Yes=1, No=0	Sum detected
B on left side		
A on right side		
A on left side		
B on right side		
Number of rounds		

A6. Report form for ROI setup in the NKS/COMBMORC 2021 experiment

ROI setup for the COMBMORC 2021 experiment

Team: ?				
Detector # (type, left right): ?				
Software system: ?				
ROI	Energy node (keV)	Energy interval (keV)	Channel interval	Number of channels
Node	(75) ?			
ROI A		? - ?	? - ?	?
Node	(241) ?			
ROI B		? - ?	? - ?	?
Node	(411) ?			
ROI C		? - ?	? - ?	?
Node	(579) ?			
ROI PL		? - ?	? - ?	?
ROI PC	(662) ?	?	?	1
ROI PR		? - ?	? - ?	?
Node	(744) ?			
ROI P (PL+PC+PR)				

Please fill in data where there are question marks. The energy values within parenthesis are recommended nodes delimiting ROIs. Depending on the number of channels in the gamma spectrometer, the nodes may be differ a few keV from the values given. The setup is defined so that ROI A, ROI B, ROI C and ROI P should have equal number of channels (the same energy width).

A7. Participants in the NKS/COMBMORC 2021 experiment

Fig A7. Participants in the NKS/COMBMORC 2021 experiment 12-14 October 2021

DSA, Norway
Bredo Møller,
Per Otto Hetland,
Jon.Drefvelin

NGU Norway
Vikas.Baranwal
Tom Kristiansen

STUK, Finland
Petri Smolander,

DEMA, Denmark
Marie Lundgaard Davidsdóttir
Jan Gert Olsen
Charlotte Alfast Espensen

IRSA, Iceland
Gísli Jónsson
Kjartan Gudnason

SSM, Sweden
Peder Kock,
Mikael Westin
Johannes Eriksson

Lund University, Sweden
Antanas Bukartas,
Mattias Jönsson

Lund University organisation
Christopher Rääf
Kerstin Lundmark
Robert Finck

Appendix B
Bayesian inference of source activity and distance in the 2021 NKS/COMBMORC experiment

Bayesian inference will be used to determine the activities and distances to the point sources to resolve how well that method can reconstruct actual values and extend detection distances.

B1. Retrospective calculations using data from ROIs

All calculations from experimental measurements are done in retrospect using predetermined ROI from the pulse height distributions. The ROIs should be defined following the recommendations in Appendix A

The COMBMORC format for providing ROI data in files is defined in Appendix A. "Format for providing data to the COMBMORC 2021 activity".

B2. Collecting measurement data

Several setups with varying source activities and distances will be used. There may be one or two sources along the road for each setup, and the measuring vehicle will pass the sources on both sides. Teams should make at least 10 rounds past the sources in each setup. Acquisition time intervals should be 1 s. Vehicle speeds should be 50 m/h.

Teams should provide measured data in the COMBMORC format in one file for each detector and setup containing several (at least 10) rounds. Different setups and vehicle speeds should be reported in different files.

B3. R-software

The Bayesian inference is programmed in R. The intention was that each team should be able to do calculations in the evening after each measurement day. During the experiment, the program was available via a web interface for a limited time.

B4. Github Repository for the COMBMORC 2021 Bayesian calculation program.

The program is available for download from GitHub. The source code can be found here:

https://github.com/SpontaneousFusion/BCP_COMBORC_2021

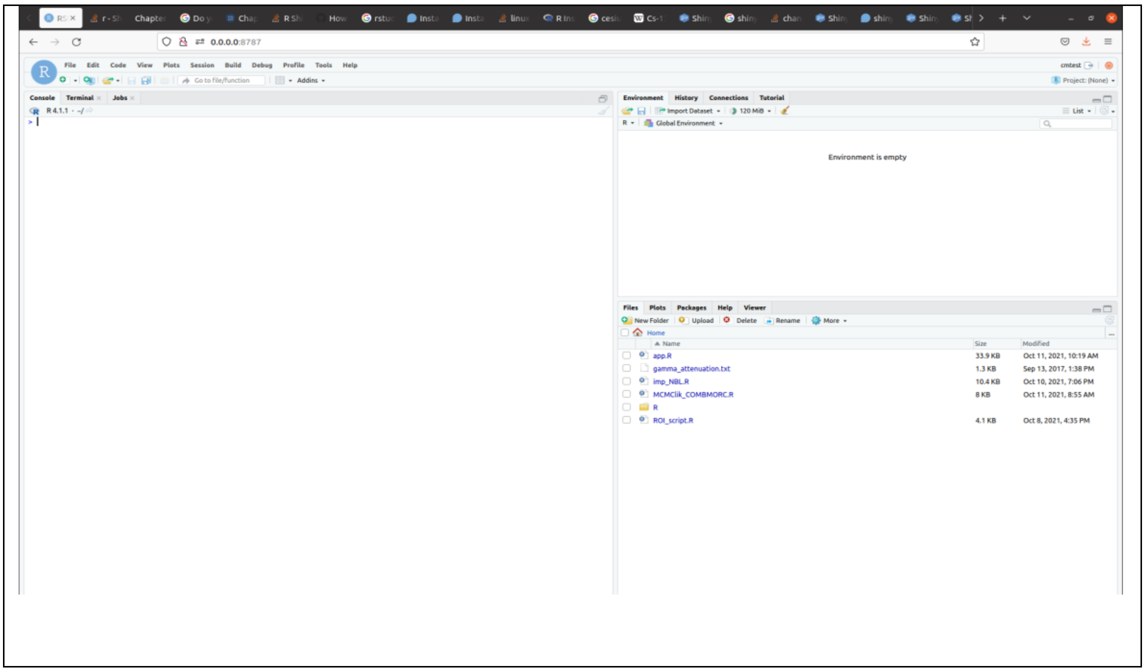
Feel free to contact if assistance is needed in setting up and using the software locally.

It is recommend using Linux for this, as it is a lot easier to fix things if something goes bad.

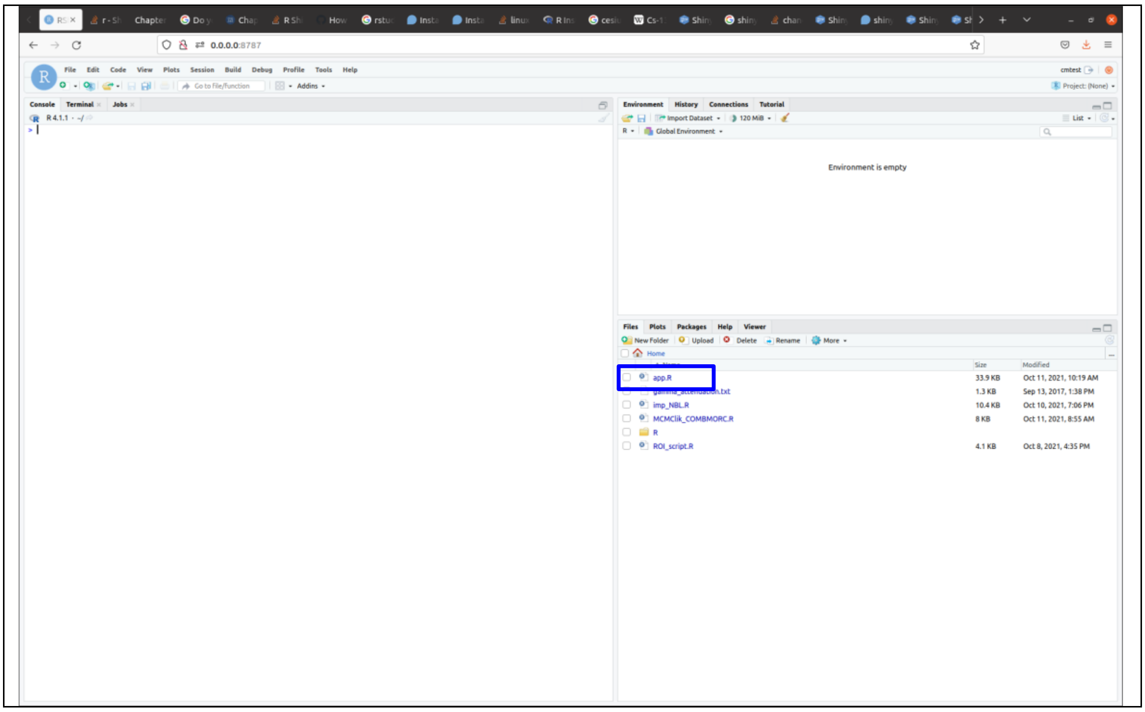
B5. Bayesian Calculation Program Guide

B5 I. Running the software:

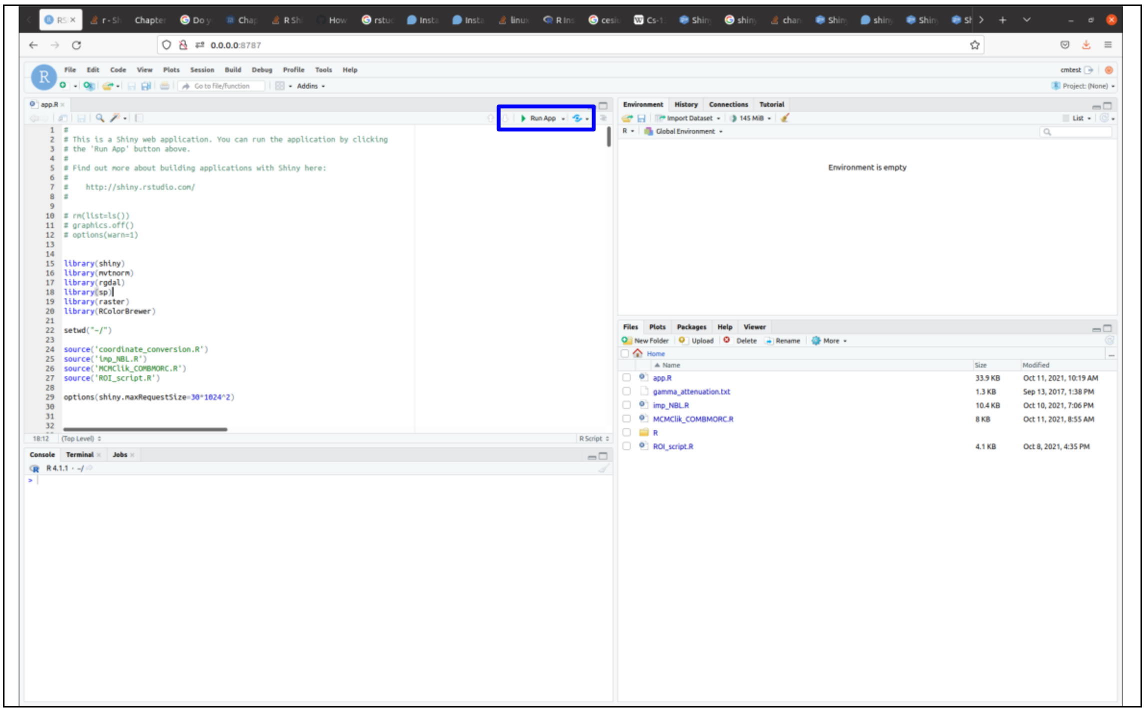
After starting the Rstudio, you will see such a screen:



You will need to open the app.R file:

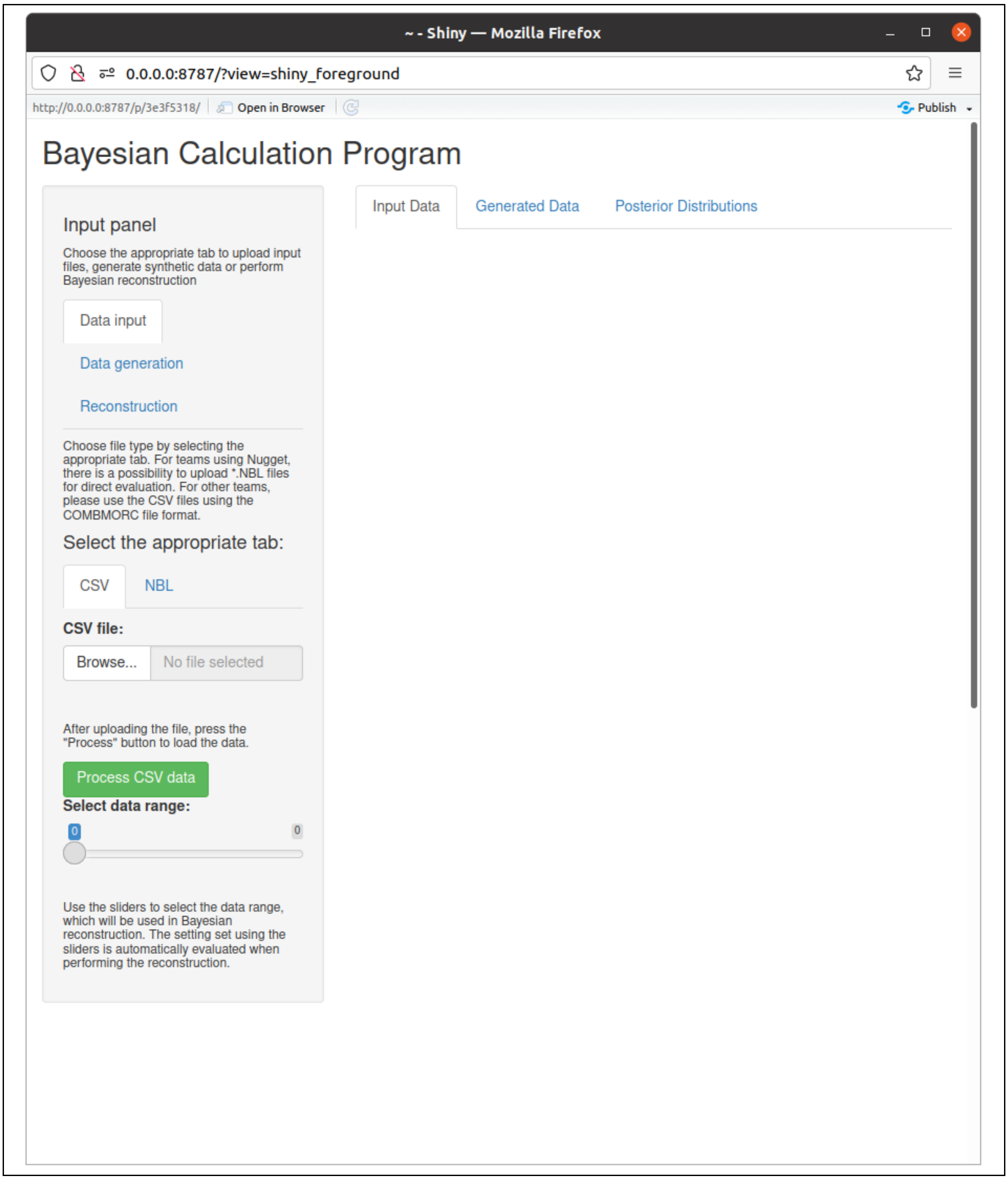


The app.R file will open in the document viewer of the Rstudio. To run the app you need to press the “Run App” button:



A new window should pop up:

This is the main window of the calculation program. You will use the window to upload the files, change the parameters and run the Bayesian calculations. The program is divided in to three separate sections: (i) Data input, (ii) Data generation and (iii) Reconstruction. Each section has representative input tabs on the gray portion of the screen on the left, and output tabs, on the white portion of the screen on the right.



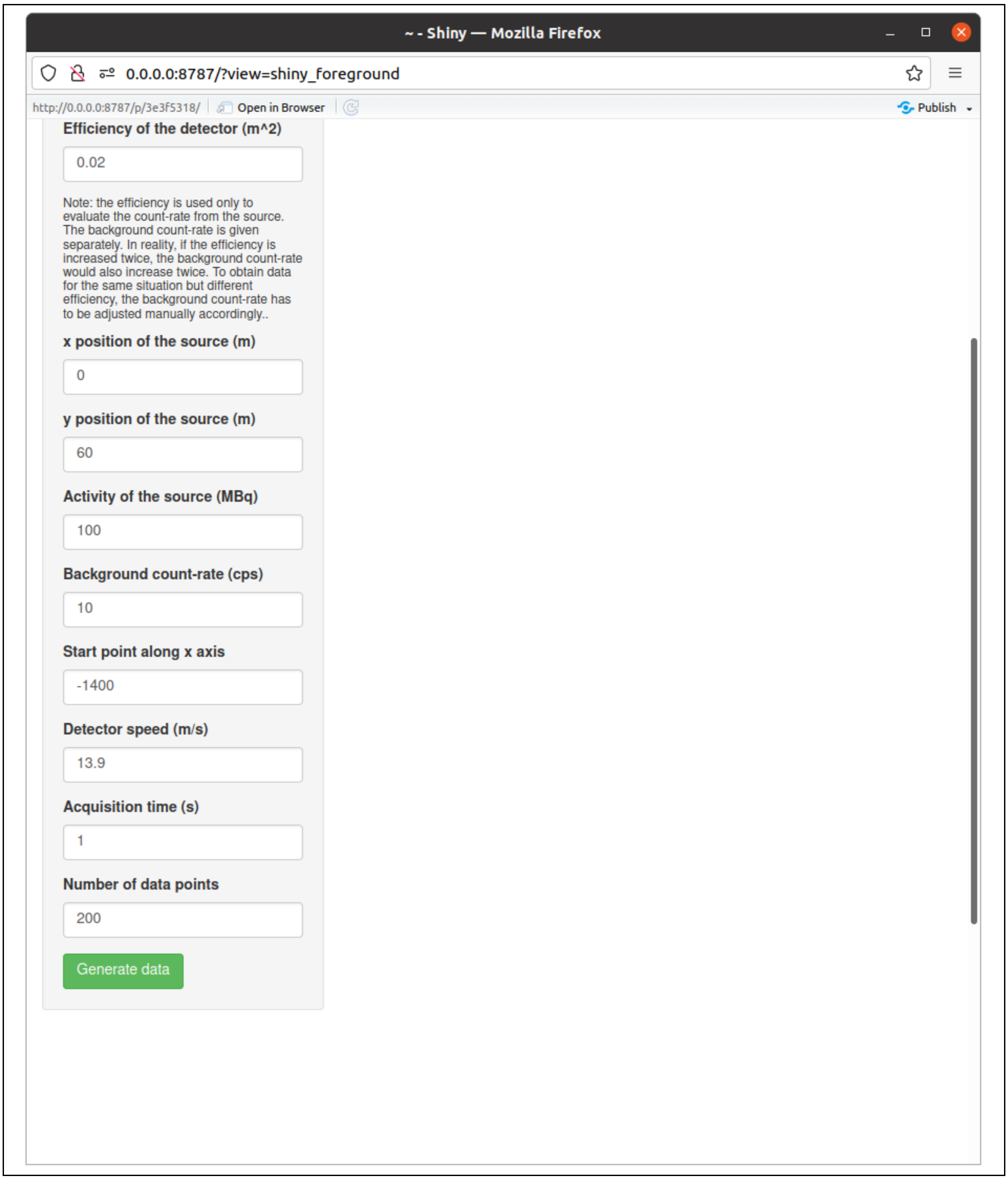
B5 II. Uploading data

To upload the data, choose the file type you will use, either CSV or NBL. Then, upload files accordingly. After the required files are uploaded, press the big “Process” button to store the data in the memory.

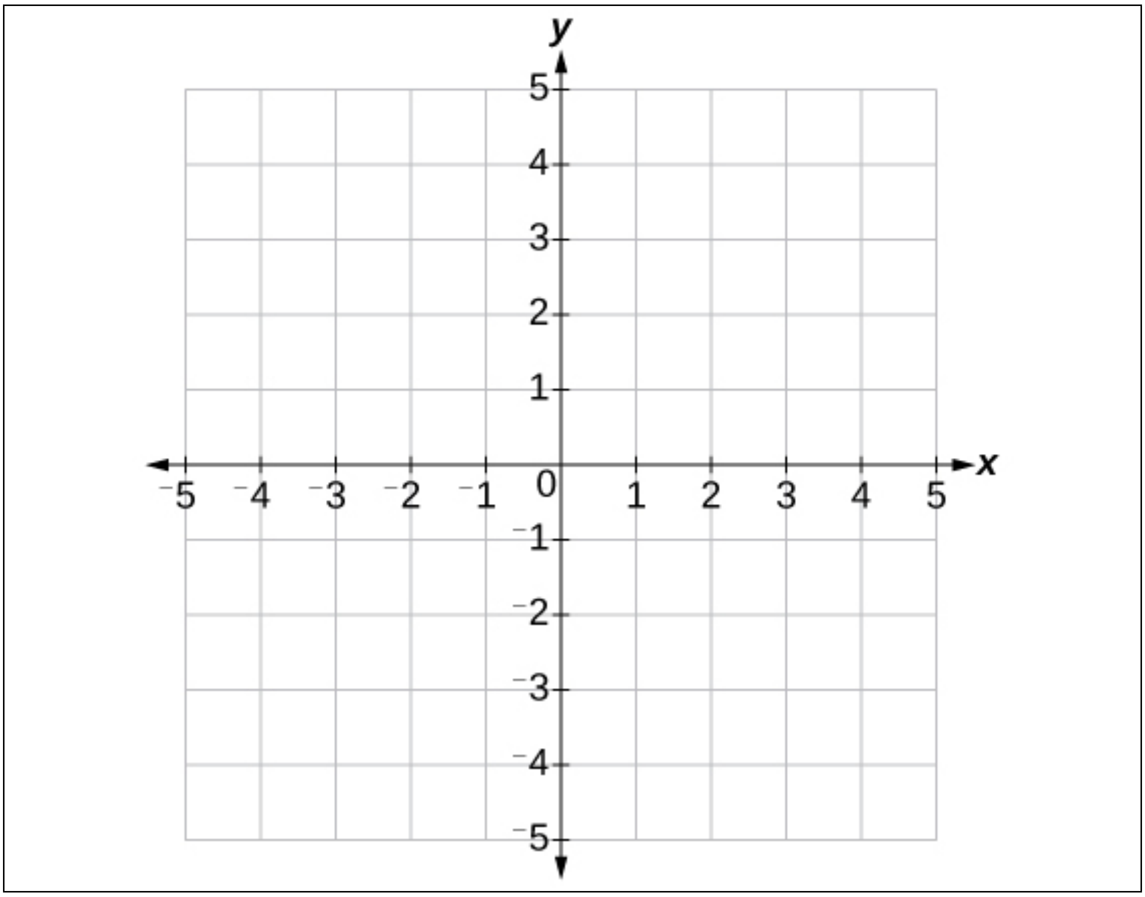
You can use the data selection slider to select the data range, which will be used in Bayesian calculations. The selected range will automatically be used. There are no buttons to confirm the selected range (you can leave the setting and go to different tab).

B5 III. Data generation

There is a possibility to generate mobile gamma spectrometry data using the Generate tab. You need to input the position of the source, activity, background count rate, starting position of the survey, speed, acquisition time, and number of measurement points.



The direction of the virtual detector is along the x-axis. Here is an image representing the coordinate system used:



The efficiency of the detector set here is used only for data generation. Also, not that the efficiency is used only to evaluate the count-rate from the source. The background count-rate is given separately. In reality, if the efficiency is increased twice, the background count-rate would also increase twice. To obtain data for the same situation but different efficiency, the background count-rate has to be adjusted manually accordingly.

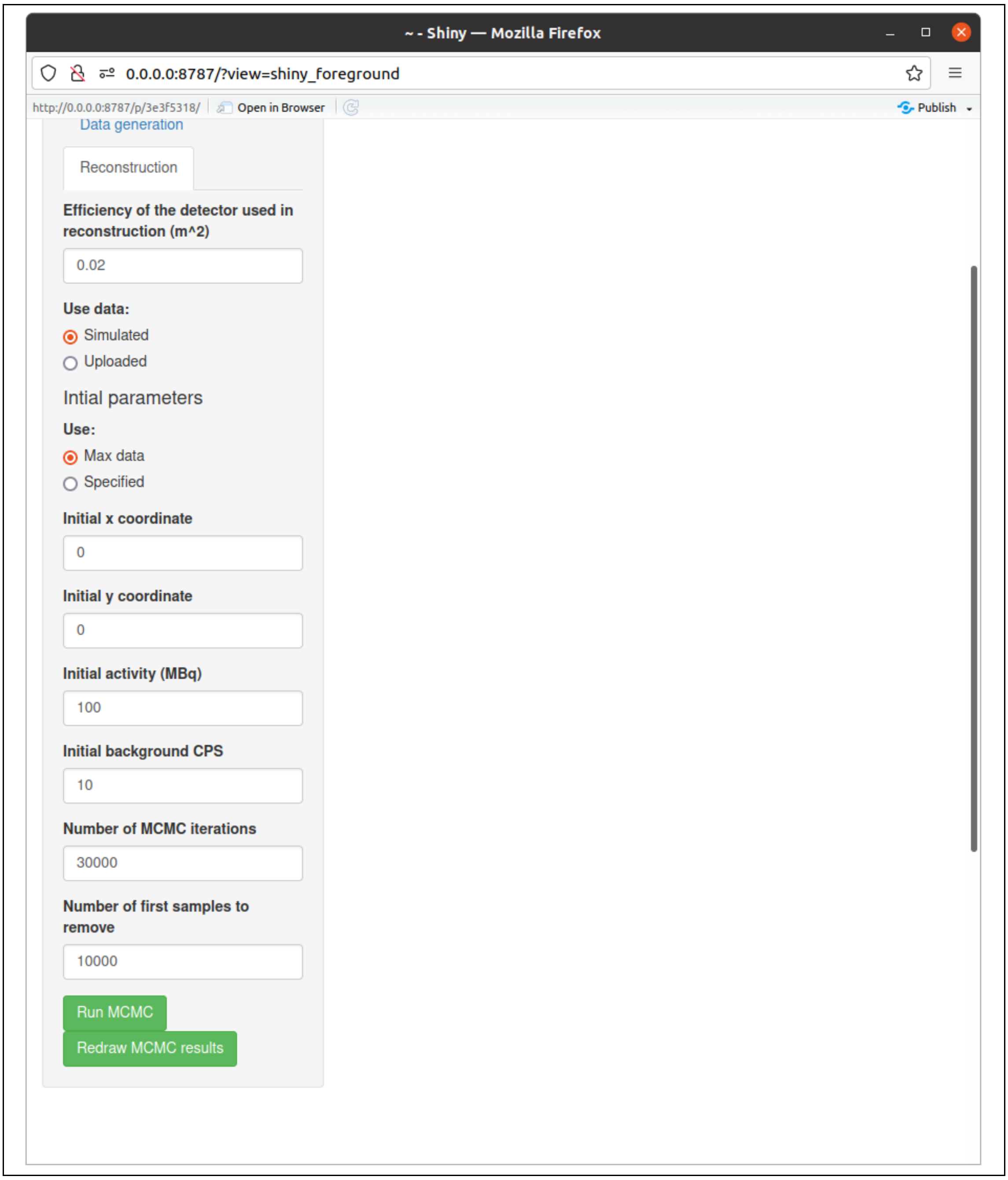
B5 IV. Bayesian calculations

The reconstruction tab allows to run the Bayesian reconstruction using MCMC algorithm. The settings regarding the efficiency is in the Reconstruction tab:

The efficiency value used here will be used in the Bayesian estimation only. Input the efficiency value of your detectors here.

IMPORTANT: BEFORE RUNNING THE RECONSTRUCTION MAKE SURE THAT THE USE DATA RADIO BUTTON IS IN THE CORRECT SETTING.

If it is set to uploaded data, and there is no data uploaded, the program will crash. Likewise for the generated data. Make sure that there is data before running the calculations

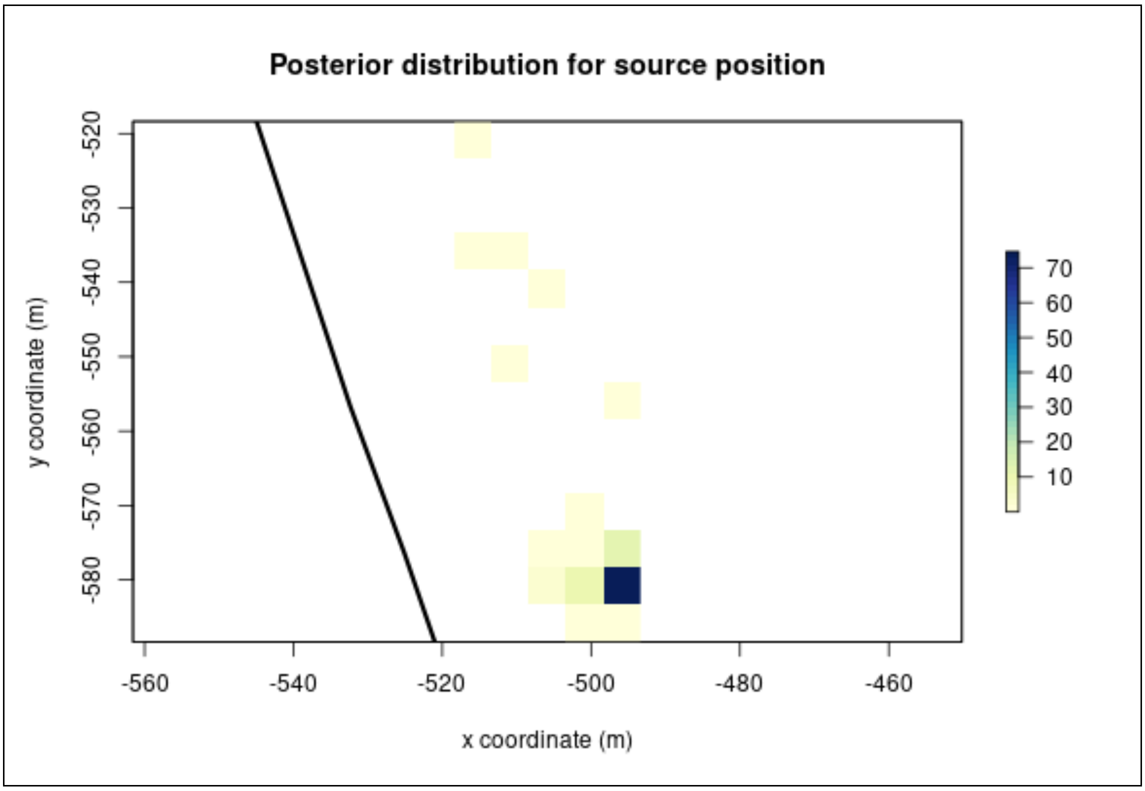


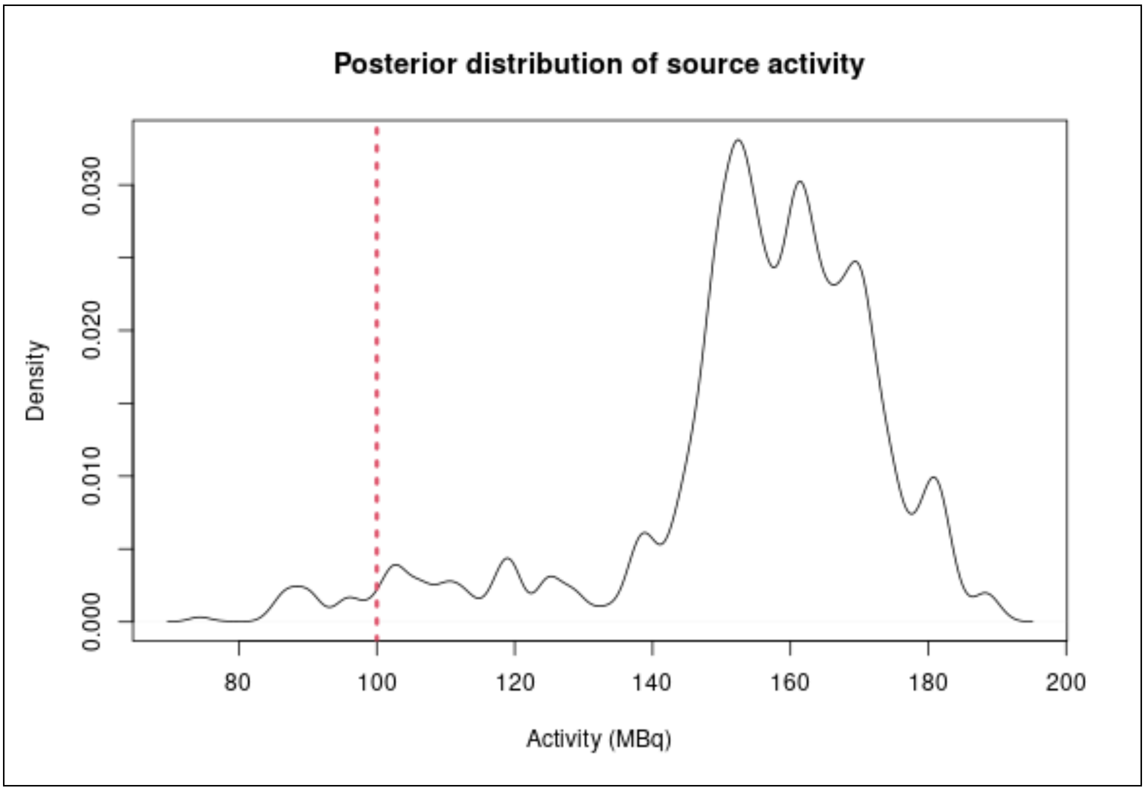
You also have the possibility to change the initial value of the MCMC chain. To do that, change the initial parameter radio button to “specified” and change the parameters.

Change the number of MCMC iterations used by altering the value of the appropriate field.

You can change the burn-in value yourself. Burn-in denotes the number of discarded first samples, which are not representative of the target posterior distribution. After changing the parameter, you need to press the redraw button.

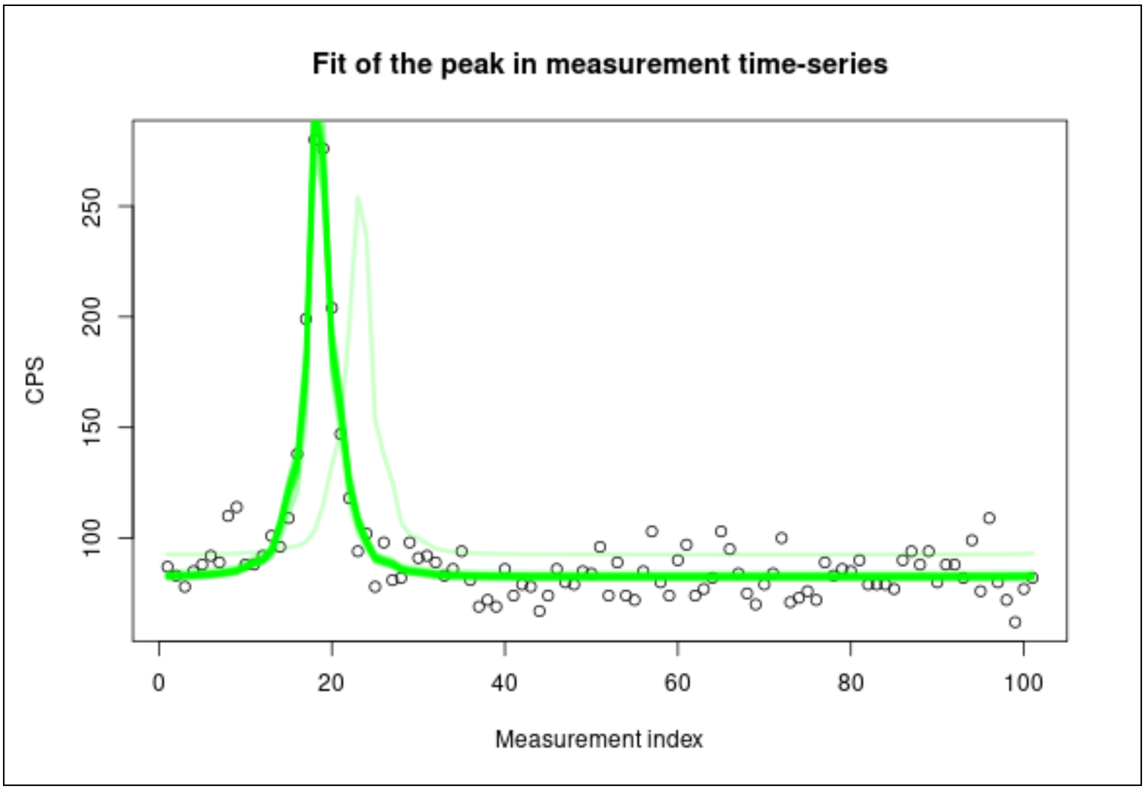
Below are examples of posterior distribution plots that you will get after a successful run:





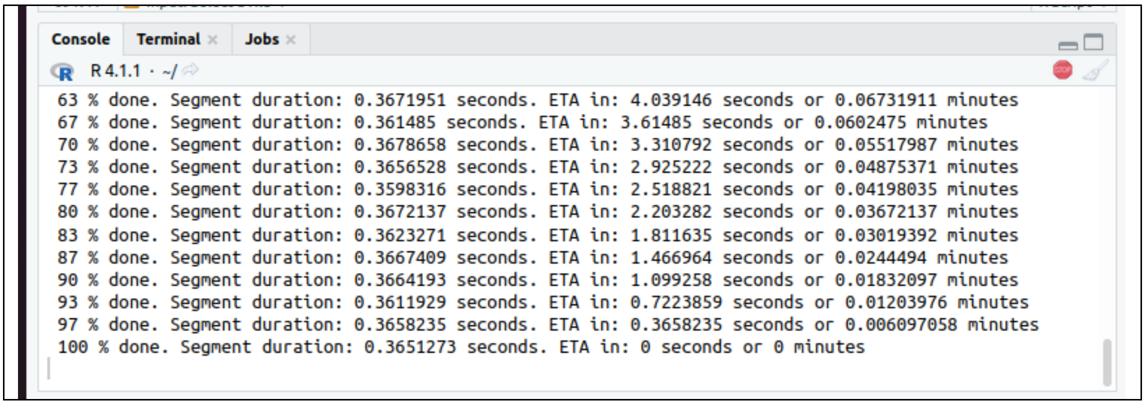
The graphs are probability distributions. In the graph **Posterior distribution of source position**, the darker the shade of the color, the higher the probability for the source being there. For the **Posterior distribution of source activity**, the higher the probability density of a given activity value, the higher the probability that the source is of that activity.

As a checkup, the fit of the data is displayed below the posterior distributions. It displays the projected mean count-rate given the estimated parameters of the source position, activity and background.



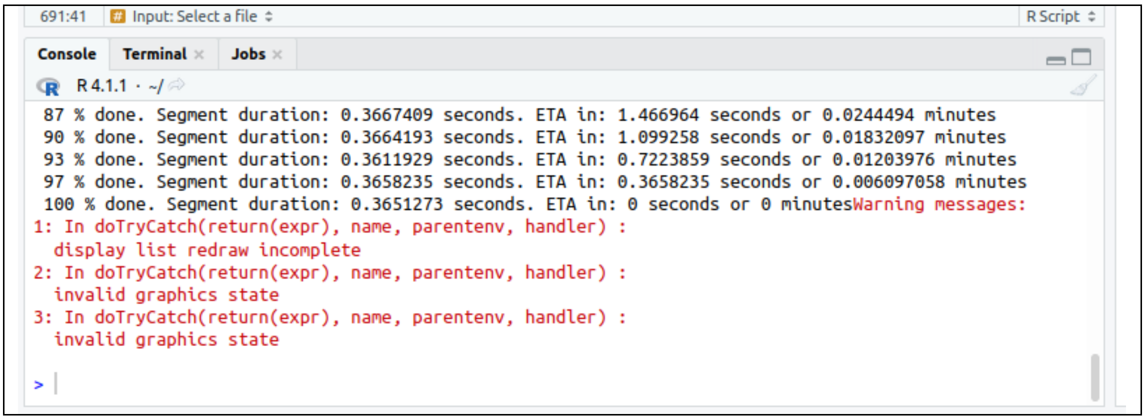
B5 V. In case of a crash

If for some reason the program crashes, make sure that the R session is ready first, before running the app again.



This image above corresponds to a busy R session, which is not actively listening for new commands, with the red stop sign available on the top-right part of the console window in the R studio screen. It is possible to terminate the R session in case it is stuck for example by pressing the red stop sign.

Then, when you see the “>” symbol available in the console, the R session is ready and listening for new inputs.



Then, the app can be safely restarted using the “Run App” button.

Bibliographic Data Sheet **NKS-474**

Title	COMBMORC - Combined analysis of primary and scattered components in mobile gamma spectrometric data for detection of materials out of regulatory control, NKS-B COMBMORC Report 2021
Author(s)	Christopher L. Rääf[1] (chair), Robert R. Finck[1] (co-chair), Einar Ameen[6], Vikas C. Baranwal[5], Marco Brønner[5], Antanas Bukartas[1], Jon Drefvelin[6], Johannes Eriksson[7], Kjartan Guðnason[4], Gísli Jónsson[4], Mattias Jönsson[1], Simon Karlsson[7], Peder Kock[7], Marie Lundgaard Davidsdóttir[2], Bredo Møller[6], Petri Smolander[3], Mikael Westin[7]
Affiliation(s)	[1]Medical Radiation Physics, ITM, Lund University, Sweden [2]Danish Emergency Management Agency, Denmark [3]Radiation and Nuclear Safety Authority, Finland [4]Icelandic Radiation Safety Authority, Iceland [5]Geological Survey of Norway, Norway [6]Norwegian Radiation and Nuclear Safety Authority, Norway [7]Swedish Radiation Safety Authority, Sweden
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No. of pages	62
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Abstract max. 2000 characters	Radioactive material that has come out of authorities control (MORC) poses a danger. If such a threat is suspected, authorities must localise and secure the radioactive source. One method of searching for gamma-emitting radionuclides is mobile gamma spectrometry, where the primary gamma energy identifies the source. The primary gamma fluence becomes reduced if a shielding material is located between the source and the detector, leading to the distance at which gamma detectors can detect a source becoming shorter. At the same time, the scattered radiation increases, having lower energy than the primary radiation due to the Compton interaction in the radiation shield. A gamma spectrometer also registers the scattered radiation. The ratio of scattered to primary radiation provides information about the thickness of a radiation shield. The Nordic countries' radiation safety authorities have experimented with mobile gamma spectrometry to explore a

combined analysis of primary and scattered radiation components. Mobile gamma spectrometry teams made measurements in eighteen setups with shielded and unshielded Cs-137 sources at varying distances from a road. Teams used one-second acquisition time intervals, passing the sources at 50 km/h. The experiments show that combined analysis of primary and scattered components could identify the shielding of sources, provided that the detector revealed a signal from primary photons. The results indicate that combined analysis may slightly increase the detection distance for shielded sources. The detection distance does not increase with combined analysis for unshielded radiation sources, but such an analysis can provide information that the source is unshielded.

Key words Mobile gamma spectrometry, orphan sources, shielding