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AUTOMORC – Improvement of automatic methods for identification of radioactive material out of regulatory control (MORC) by mobile gamma spectrometric search experiments. Report 2017

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Abstract

A model for calculating maximum detection distances in mobile search for lost gamma radiation sources was developed in a previous NKS supported project MOMORC 2016. A first validation of the model's correctness was done in a field experiment in September 2016 with participants from all Nordic countries. The model showed that maximum detection distances could be predicted within ± 30 m, which also was the limitation of the experiment. The model also showed that using combined analysis of sets of measurements along a vehicle path could be used to detect a possible source. The count rate from primary photons in the detector when driving past a point source at constant speed is depending on the source activity and the distance between the road and the source. The count rate versus time (the “intensity” curve) depends only on the distance to the source when the speed is fixed and the vehicle path is straight. This fact can be used to determine the distance to a source from a set of measurements. The problem can be solved with Bayesian statistical methods.

A Bayesian based Markov chain Monte Carlo method was used to determine the location and activity of some of the point sources in the MOMORC 2016 experiment. The method seems to produce reasonably correct values of distances to sources, provided that the count rate statistics in the detector is high enough for the computational algorithm to identify the “signal” (as an “intensity curve). The statistical uncertainty in the distance determination using measurement data from a 128 % HPGe-spectrometer was in the order of ±20%. The uncertainty in the activity determination was larger, especially for NaI(Tl)-spectrometers. This could be due to a systematic deviation in the efficiency calibration of the detectors, because when testing the method with synthetic data the activity calculations gave reasonably correct results.

The position of a source can be shown on a map as likelihood for a source present at a certain location together with its activity coupled to that location. Five examples of calculated likelihood locations based on Bayesian analysis of mobile measurements are given in the report.

Key words

Mobile gamma spectrometry, orphan source search, detection distance, Bayesian analysis, Markov chain Monte Carlo

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Summary

Searching for lost nuclear or radioactive sources (Material Out of Regulatory Control, MORC) is a necessary capability for radiation protection response organizations. Searching along roads with mobile gamma spectrometers is a common method. In order for the search effort to be effective within a limited time, instruments and methods should be selected so that maximum possible detection distances are achieved in relation to the area that has to be searched and the available amount of time for the mission. In the NKS supported project MOMORC 2016, a theoretical model was developed to calculate maximum detection distances. A first validation of the model's correctness was done in a field experiment in September 2016 with participants from all Nordic countries using their mobile search units. The model showed that the maximum distance could be predicted within ± 30 m, which also was the limitation of the experiment. Maximum detection distances were strongly depending on the efficiency of the spectrometer, which was expected. The model also showed that detection distances depend on the choice of acquisition time intervals and the speed of the vehicle. The optimum combinations are depending on the presumed activity of the source that is searched for.

If the activity of the source is unknown or the source is shielded, the optimum combination of vehicle speed and acquisitions time is undetermined. This led to an idea to investigate if using combined analysis of a whole set of measurements along a vehicle path could be used to detect a possible source. The MOMORC 2016 model showed that the count rate from primary photons in the detector when driving past a point source at constant speed is depending on the source activity and the distance between the road and the source, where there is direct proportionality between count rate and activity for all measurement points. The count rate versus time (the “intensity” curve) has a shape depending only on the distance to the source when the speed is fixed and the vehicle path is straight. This fact can be used to determine the distance to a source from the whole set of measurements.

Thus, from the physics of a radiation field from a point source, we have some prior knowledge of how the pattern of the count rate variation in the detector should look like when passing a source at a specific distance. To this should be added the statistical variations in count rate from the natural background and from the source. We have a situation where the counting statistics have to be analysed against the possible presence of an “intensity” curve, where we know that the curve should follow the shape of an equation, but we don’t know all the parameters in the equation (the distance is unknown). This problem can be solved with Bayesian statistical methods.

Lund University has tested a Bayesian statistical method using Markov chain Monte Carlo calculations to determine the location and activity of some of the point sources used in the MOMORC 2016 experiment. The theory is briefly described in this report and examples of results are given. The method seems to produce reasonably correct values of distances to sources, provided that the count rate statistics in the detector is high enough for the computational algorithm to identify the “signal” (as an “intensity curve). The statistical uncertainty in the distance determination using measurement data from a 128 % HPGe-spectrometer was in the order of ±20%. Calculated activities showed a larger statistical uncertainty, especially for NaI(Tl)-spectrometers. This could be due to a systematic deviation in the efficiency calibration of the detectors, because when testing the method with synthetic data the activity calculations gave reasonably correct results.

The position of a source can be shown on a map as likelihood for a source present at a certain location together with its activity coupled to that location. Five examples of calculated likelihood locations based on Bayesian analysis of mobile measurements are given in the report.

The AUTOMORC project has been scheduled for two years 2017 - 2018. For 2018 a field experiment has been planned to more systematically test automatic methods to detect gamma radiation sources.

1. Introduction

1.1 The problem

Searching for lost or stolen nuclear or radioactive material out of regulatory control (MORC) over large areas can be a difficult and resource-intensive task. The usual way to search is to use mobile instruments to detect the ionizing radiation emitted from the material. Because the distance that radiation travels in matter is limited, the radiation source cannot be detected at very long ranges. The distance within which it is possible to detect the source by mobile measurements depends on the type of radiation, the source activity, shielding, instrumentation, traveling speed, acquisition time and the method of analyzing collected data. In the NKS funded MOMORC 2016 project, detection distances for mobile search of single gamma radiation sources were calculated and presented in tables and diagrams. A field experiment with participants from all Nordic countries, carried out in September 2016 in the Barsebäck area in Sweden with mobile detection equipment, verified that experimentally obtained values of detection distances were in reasonably good agreement with the results obtained by the theoretical model (Finck et al. 2017).

Experience from the NKS funded MOMORC 2016 project showed that the detection sensitivity in terms of the longest possible detection distance was depending on the type of advanced processing of the data, when using mobile NaI(Tl)-spectrometry systems. Simpler methods using only an alarm for increased count rate in a single energy window gave shorter detection distances and often difficulties to identify the radionuclide in cases where more than one radionuclide could be considered. More advanced processing methods made retrospectively, could generally identify the radionuclide at somewhat larger distances. Manual after-analysis requires specialist knowledge and takes time to perform. More advanced numerical methods for automatic instant analysis of measurement data would probably improve the prompt identification of radionuclides and extend the detection distances. Such methods could be based on analysis of variance using the method described by Kock et al. (2010), statistical processing according to Hjerpe et al. (2001), peak hypotheseis testing (S. Kuukankorpi et al, 2007), or noise reduction methods (Hovgaard and Grasty, 1997). Simultaneous analysis of varying time intervals would also improve detection capability (Nilsson, 2016; Finck et al., 2017).

1.2 The AUTOMORC project

In January 2017 NKS-B gave funding for the project AUTOMORC to improve automatic methods to identify radioactive materials (MORC) by mobile gamma spectrometry. The project is directed towards mobile NaI(Tl)-spectrometry with the aims to:

1. select and program at least one improved automatic method for instant source detection on a standalone computer (2017),
2. test the method on measurement data collected from the project MOMORC 2016 (2017),
3. provide Nordic participants with the description and access to the method for use with their own detectors and measuring systems (2017), and
4. carry out a joint field experiment with mobile measuring equipment where the method is tested against combinations of radiation fields using medical radionuclides and shielded or partially shielded strong sources where the scattered radiation is an essential component, (2018).

The project was scheduled for a two-year period with points 1 - 3 to be carried out in 2017 and point 4, the field experiment to be realized in spring 2018 with evaluation of the experiment during the summer and autumn and a follow-up meeting in October 2018.

1.3 Update for the AUTOMORC 2017 project

When the AUTOMORC project started in the beginning of 2017, the initial idea was to test if simultaneous analysis of measured data in region of interests (ROI) for varying time intervals could increase detection distances. From the theoretical model for calculating detection distances it is seen that selecting an optimal acquisition time depending on the assumed source activity is important. At the speed of 50 km/h, the increase in detection distance for a 1 GBq source is in the order of 10 - 80 meters (for Tc-99m and Co-60 respectively) if the best acquisition time interval is chosen instead of (the short) 1 s time intervals. One way of using both short acquisition times and obtaining the longest possible detection distance would be to simultaneously test a set of rolling added 1 s intervals corresponding to say 5, 10, 30 and 60 s integrated time intervals. For ground-based vehicles with driving speed lower than 90 km/h, acquisition time intervals shorter than 1 s is not needed (Finck et al., 2017).

Although theory shows that detection distances should increase in the order of 10 – 80 m when selecting an optimal acquisition time interval for an unshielded 1 GBq source, the way to experimentally prove it using the MOMORC data is somewhat limited. This is because sources used in the MOMORC experiment generally had activities below 1 GBq and were placed in distance steps of 30 m, which in most MOMORC cases will be to large a step to experimentally prove an increased detection distance. To experimentally prove the feasibility of simultaneous analysis with different acquisition time intervals using sources in the range of some hundreds of MBq, an experiment with shorter and more flexible distance steps would be needed. Such an experiment is scheduled for the AUTOMORC 2018 project in an application to NKS.

During the theoretical work with AUTOMORC in 2017, an idea rose to test a method to simultaneously determine the distance and activity using combined 1 s measurements. The teams in the MOMORC experiment usually used this time interval. The method was Bayesian based statistical analysis, which is described in this report together with first results from some MOMORC measurements. The method seems to reproduce the distance to the source reasonably well. The activities, however, seem to show a larger variation, especially for NaI(Tl)-spectrometers. The reason for this is being investigated. One reason could be that the efficiency calibration of the detectors could be somewhat wrong. An experiment with higher accuracy in the efficiency calibration and shorter distance steps would be feasible to determine the capability of the Bayesian method. This will be accomplished in the AUTOMORC 2018 experiment.

1.4 Participants in the NKS/AUTOMORC project 2017

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2 Theory

2.1 Why using Bayesian statistical analysis in mobile search for MORC?

When using mobile gamma spectrometry along roads to search for a radiation source, an increased signal may indicate a source nearby. The source may not necessarily be on the road but could probably be somewhere in the area at a certain distance from the road. If there are no more roads nearby and if the vehicle cannot enter into the terrain, the only possible measurement is the gradient of the detector signal along the road. This one-dimensional measurement does not provide immediate information about the location of the source on the surface of the two-dimensional plane or in the three-dimensional space around the road. When the variation in the measurement signal along the road is plotted, it appears in the one-dimensional space along the road path as if the source would be on the road where the maximum signal is obtained. However, there is more information that can be used to locate the radiation source in two dimensions. The propagation of primary radiation around a point source follows the geometric law of the fluence being inversely proportional to the square of the distance as well as the physical law of attenuation of the radiation in the air. This relationship can be used in a Bayesian statistical analysis as prior knowledge of how the detector signal should vary along the road for varying distances to a gamma-emitting source. It provides a method to calculate the most likely location of the radiation source in the two-dimensional plane. When the source position is known, the activity of the source can be calculated from the measured photon fluence rate because there is a direct proportion between the primary fluence rate and the activity of the source. This is independent of the activity of the source. Bayesian statistical analysis on one-dimensional measurement data using the physical properties of radiation as prior knowledge thus seems to allow the determination of the most likely location and activity of a radiation source in a two-dimensional area.

2.2 Bayesian detection method

Common methods to analyze measured data from mobile gamma spectrometry involve various statistical methods (Hjerpe, 2004; Kuukankorpi et al., 2007; Kock, 2012; Nilsson, 2016). These methods are strictly statistical and applied without input of physical laws of radiation transport. By incorporating prior knowledge in the form of physical laws in Bayesian-based statistical analysis, more information about a possible source location and source activity can be obtained. Bayesian based methods have successfully been applied to search and rescue operation of lost vessels at sea (Breivik et al., 2013). The Bayesian method approach to locate lost radiation sources is a rather unexplored area. Some publications exist (Miller et al., 1993; Hykes, 2012; Tandon et al., 2015), but there is still a promising potential for development of Bayesian statistics for car-borne search of orphan sources.

Input to the Bayesian calculation is a set of mobile measurements (count rates) recorded in the region of interest (ROI) of a specific radionuclide independently of the setting of an alarm level. The method is currently tested on measurement data from the MOMORC field experiment (Finck et al., 2017).

2.3 Physical model

The primary photon fluence rate $\dot{\phi}$ in air at distance, *r*, from a photon source, which emits $\dot{S}$ photons per second, can be written:

$$\dot{\phi} = \frac{\dot{S}\, e^{-(\mu/\rho)\rho r}}{4\pi r^2} \qquad (1)$$

where μ is the linear attenuation coefficient, and μ/ρ is the mass attenuation coefficient of air, where ρ is the density of air.

Assuming that the primary fluence rate $\dot{\phi}$ at photon energy E will produce the net count rate $\dot{N}(E,r)$ in the detector with a detection efficiency $\varepsilon(E)$, (unit: area^2) and that $b_\gamma(E)$ is the branching ratio (photons per decay) for the primary photons emitted from a source with activity A, then the count rate in the detector is given by:

$$\dot{N}(E,r) = \frac{A\, b_\gamma(E)\, \varepsilon(E)\; e^{-(\mu/\rho)\rho r}}{4\pi r^2} \qquad (2)$$

When the measuring vehicle passes the source the distance r changes and therefore also the count rate $\dot{N}(E,r)$ in the detector. The function $\dot{N}(E,r)$ is often called the "intensity curve". An example of an "intensity curve" is shown in Fig 1.

Eqn 2 is used as the prior knowledge in the Bayesian statistical analysis method described in the next section.

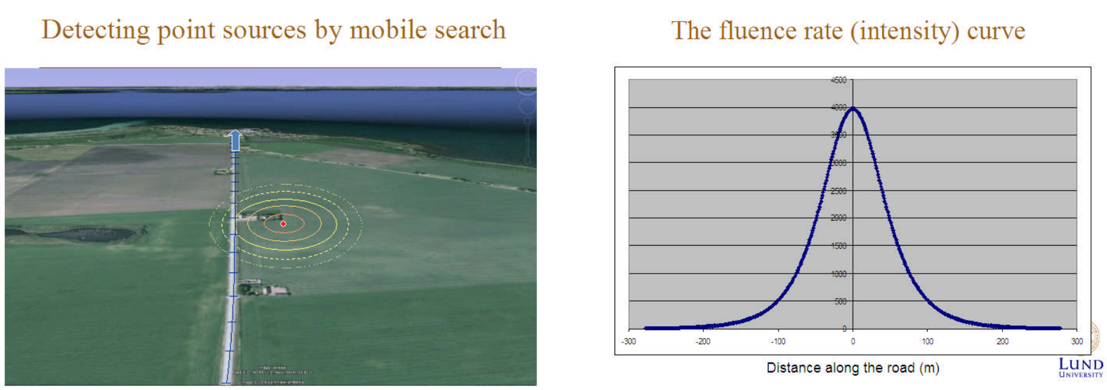


Fig 1. When making mobile measurements along a straight road with constant speed (left picture), the primary photon fluence along the road from a point source located somewhere off the road follows an "intensity curve" given by Eqn 1 (right picture). The shape of the curve is depending on the shortest distance between the road and the source, but not depending on the activity of the source. If a detector has uniform efficiency for all angles of incidence, the count rate for primary photons follows the same shape and can be described by Eqn 2. This fact can be used to determine the distance from a road to a point source from mobile measurements. For the method described in this report, it is not necessary for the road to be straight.

2.4 Bayesian model

The Bayesian approach consists of formulating a prior distribution for the parameters of interest, representing the prior knowledge about the parameters. Then, as new information (data) is available it is incorporated in the model by updating the prior to a posterior distribution, through the likelihood function using Bayes theorem. In this section, a Bayesian model is described for a single unknown source in a specific area, S, with a constant level of background radiation, C, where the parameters of interest are the position of the source, $P \in \mathbb{R}^2$ and activity of the source, $A \in \mathbb{R}^+$. A number, n, of consecutive experimentally measured count rates $Y = (y_1, y_2, \ldots y_n)$ in a specific region of interest (ROI) in the pulse height distribution from the spectrometer, measured at locations $X = (x_1, x_2, \ldots x_n)$ are used as the data in the Bayesian model.

Let $\pi(P,A)$ be the prior distribution for the parameters, and let $\pi(Y|X,P,A)$ be the distribution of the data given the parameters. Then the posterior distribution (the distribution of the parameters given the data) can be derived using Bayes theorem:

$$\pi(P,A\,|\,Y,X) = \frac{\pi(Y\,|\,X,P,A)\,\pi(P,A)}{\pi(Y\,|\,X)} \propto \pi(Y\,|\,X,P,A)\,\pi(P,A) \tag{3}$$

This distribution will represent information about the source location and activity given the information in the observations.

Since prior information of the parameters of interest is not known, vague priors are chosen, which consist of parameter settings that have a minor influence on the posterior distribution. This is common in Bayesian modeling. It is assumed that P is uniformly distributed over S, i.e., each point in S is equally likely to be the position of the source. Likewise, for the activity, A, a Gamma distribution, Γ, is chosen with shape α and rate β parameters that will have little effect on the posterior distribution $\Gamma(\alpha=1.2, \beta=0.0001)$ for activities in MBq.

To derive the distribution of the data given the parameters, a well known fact is used that radioactive decay is a Poisson process resulting in Poisson distributed count rate measurements (Kirkpatrick and Young, 2009). Therefore, the number of counts in a background-free environment in the selected ROI can be obtained by sampling a Poisson distribution with mean given by Eqn 2. However in mobile gamma spectrometry applications an environment without background radiation is not realistic. It is assumed instead that the observations are perturbed by independent Poisson noise with a mean value C. This information defines a distribution of the data given the parameters, i.e. the likelihood:

$$\pi(\mathrm{Y}\,|\,\mathrm{A,C,X}) = \prod_{i=1}^{n} \mathrm{Pois}\left(y_i \,|\, \lambda_i = \frac{A\,b_\gamma(E)\,\varepsilon(E)\;e^{-(\mu/\rho)\rho\|p-x_i\|}}{4\pi\|\,p-x_i\,\|^2} + C\right) \tag{4}$$

Eqn 4 then provides the information needed to derive the posterior dirstribution $\pi(P,A\,|\,Y,X)$. This distribution is not an explicit distribution, and it is thus not possible to make inferences from it. However, it is possible to make inferences through Monte Carlo methods, since it ius possible to evaluate the density (up to a normalizing constant) which allows the use of Markov Chain Monte Carlo (MCMC) algorithms to generate random samples from the distribution (Robert and Casella, 2004). An adaptive MCMC algorithm was used to maximize the sampling efficiency by aiming for a fixed ratio of accepted to rejected proposals. (Andrieu and Thoms, 2008).

Examples of Bayesian inference, using MOMORC 2016 measurement data (Finck et al, 2017) with an adaptive MCMC-algorithm, are given in the following sections.

2.5 Computer program

The equations for inference of the probability distribution of locations and activities of a gamma emitting point source as described in the previous section has been programmed in the free library programming language R, supported by the R Foundation for Statistical Computing, (Hornik, 2015).

The program is still in a test version using a limited set of measurement data. It will be made available to participants in the AUTOMORC project after it has been validated against further experimental data.

2.6 Bayesian calculations

The count rate in the ROI for the radionuclide of interest was considered as the data in the likelihood formulated in Eqn 4. The background level, C, was estimated as a mean of selected count rates obtained in a particular run during the experiment, with the intention of imitating on-line usage of the method. To minimize the influence of the radiation from the sources, only count rates obtained at distances greater than 200 m from all of the sources were considered. Priors were set as described in section 2.4. The algorithm was running for 50,000 adaptive MCMC iterations.

3 Results and discussion

The Bayesian analysis method has been tested by Lund University partly with synthetic data and partly with experimentally measured data from the MOMORC 2016 experiment.

Results from testing with synthetic data show good agreement between “true” values of locations and activities and calculated values if the counting statistics have signal to background noise ratios > 5. Examples of results from these tests have been given in AUTOMORC progress report 2 (Rääf et al., 2017).

Testing with measurement data from the MOMORC 2016 experiment have been done for five situations where measurements were made with a 123% HPGe-spectrometer (from Lund University), a 16 litre NaI(Tl)-spectrometry (from NGU), and a 4 litre NaI(Tl)-spectrometer (from DEMA). The measurement equipment and experimental setup is described in the final MOMORC report (Finck et al., 2017).

Fig 2 shows the calculated location and activity for mobile detection of a 468 MBq I-131 point source placed 60 m from the roadside (which is about 61 m from the path of the detector on the road). Bayesian analysis on measurements made by Lund University using a 123% HPGe-spectrometer mounted inside the car returns a calculated location 58.6 m from the detector path on the road and a calculated activity of 413 MBq (12% below the true value).

Fig 3 shows the calculated location and activity for mobile detection of a 183 MBq Ba-133 point source placed about 31 m from the path of the detector on the road. Bayesian analysis on measurements made by Lund University using the 123% HPGe-spectrometer returns a calculated location 37.7 m from the detector path on the road and a calculated activity of 220 MBq (20% above the true value).

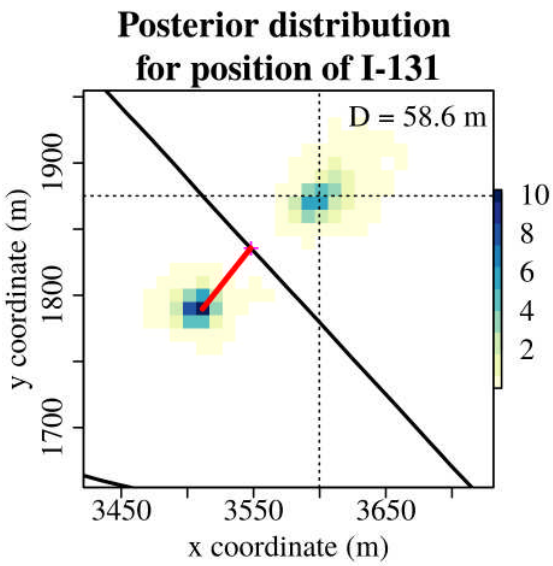
Fig 4 shows the calculated location and activity for mobile detection of a 298 MBq Cs-137 point source placed about 31 m from the path of the detector on the road. Bayesian analysis on measurements made by Lund University using the 123% HPGe-spectrometer returns a calculated location 27.2 m from the detector path on the road and a calculated activity of 126 MBq (58% below the true value).

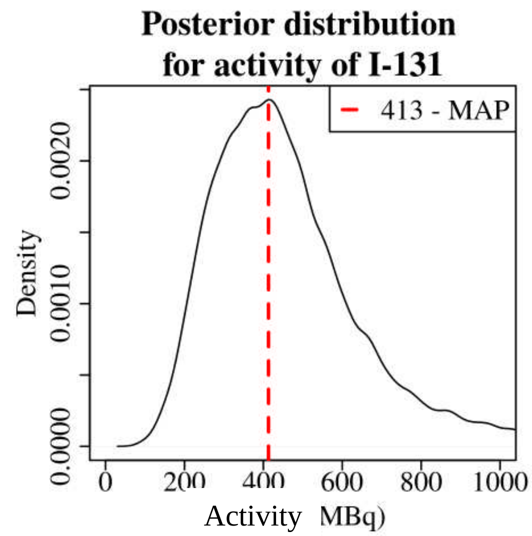
Fig 5 shows the calculated location and activity for mobile detection of a 468 MBq I-131 point source placed about 61 m from the path of the detector on the road. Bayesian analysis on measurements made by Geological Survey of Norway (NGU) using a 16 litre NaI(Tl)-spectrometer returns a calculated location 45.9 m from the detector path on the road and a calculated activity of 117 MBq (75% below the true value).

Fig 6 shows the calculated location and activity for mobile detection of a 468 MBq I-131 point source placed about 61 m from the path of the detector on the road. Bayesian analysis on measurements made by Danish Emergency Management Agency (DEMA) using a 4 litre NaI(Tl)-spectrometer returns a calculated location 49.5 m from the detector path on the road and a calculated activity of 183 MBq (61% below the true value).

Bayesian calculated locations and activities in the five cases are summarized in Table 1.

Calculated location distances were generally within 5 – 25%. The reason for the deviation of calculated locations from the true values is that the number of counts per time interval in the pulse height distribution around the full energy peak is low. The statistical fluctuations do not allow a more exact determination of the location. This implies that the effect of counting statistics on the calculated result should be further investigated.





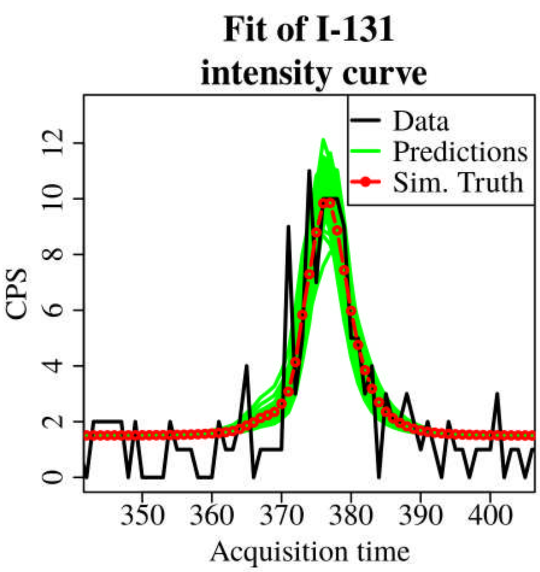
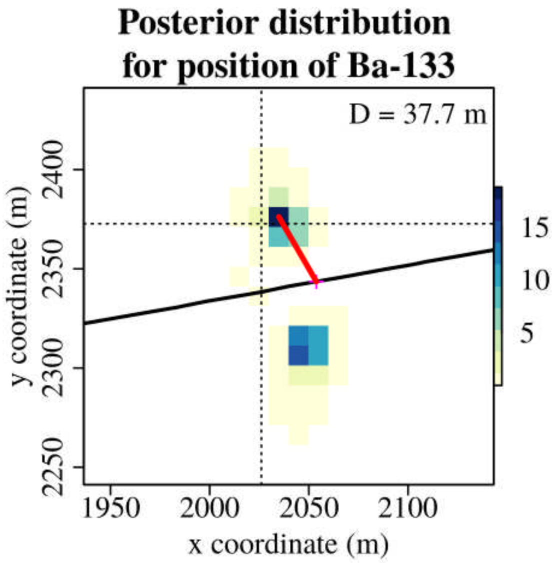
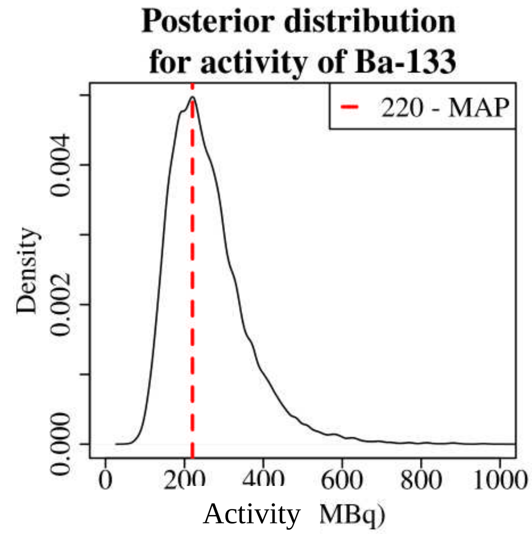


Fig 2. Calculated location (upper left map) and activity (upper right diagram) for mobile detection of a I-131 point source with activity 468 MBq placed in position G, 60 m from the roadside in the MOMORC 2016 experiment 2016-09-20 11:00-14:30. (Finck et al., 2017). Measurements made by Lund University using a 123% HPGe-spectrometer mounted inside the car. The true position of the source is shown at the cross hair (upper left map). The green line (left diagram) fit the data shown by the black line. The red line displays the count rate from Eqn 2 along the road assuming a given detector efficiency and the source placed in the calculated location.

Calculated activities were generally within ±10 – 20% for cases measured with the HPGe-spectrometer, and underestimated 60 – 75% for the two cases with NaI(Tl)-spectrometers. The reason for large underestimation with the NaI(Tl)-detectors is not clear. It could be due to a systematic error in the determination of the net count rate or in the detector efficiency determination made during the MOMORC experiment. This should be further investigated by rechecking the efficiency calibrations of the detectors, best done in connection with the AUTOMORC 2018 field experiment.

A wrong efficiency calibration does not influence the calculation of the distance to the source, because the shape of the “intensity curve” (Fig 1) is not affected by the activity of the source and it is the shape that determines the location of the source. However, poor counting statistics, will increase the uncertainty in fitting the “intensity curve” to the data as can be seen (green lines) in Fig 2 – 6. Generally an underestimation of the distance to the source will lead to an underestimation of the source activity and vice versa. This is because sources further away must have higher activity to produce the same count rate as a source closer to the detector.





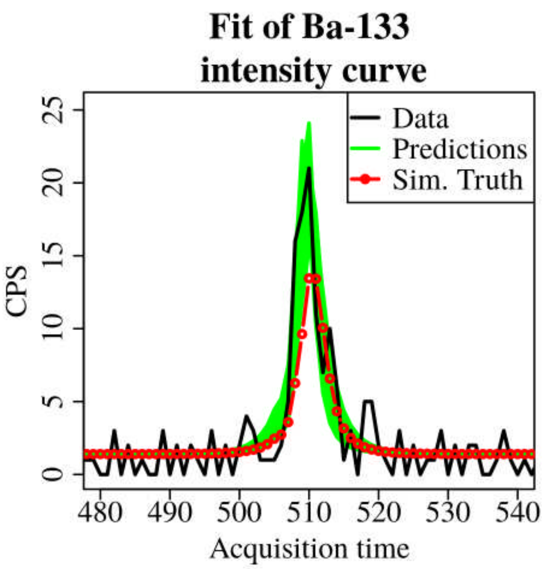
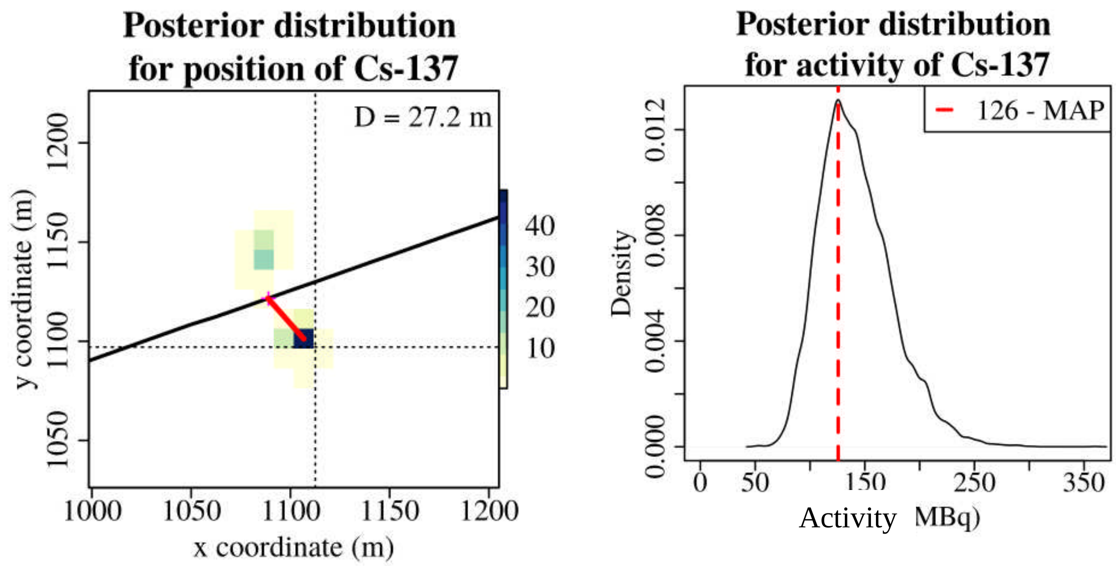


Fig 3. Calculated location (upper left map) and activity (upper right diagram) for mobile detection of a Ba-133 point source with activity 183 MBq placed in position H, 30 m from the roadside in the MOMORC 2016 experiment 2016-09-20 11:00-14:30. (Finck et al., 2017). Measurements made by Lund University using a 123% HPGe-spectrometer mounted inside the car. The true position of the source is shown at the cross hair (upper left map). The green line (left diagram) fit the data shown by the black line. The red line displays the count rate from Eqn 2 along the road assuming a given detector efficiency and the source placed in the calculated location.



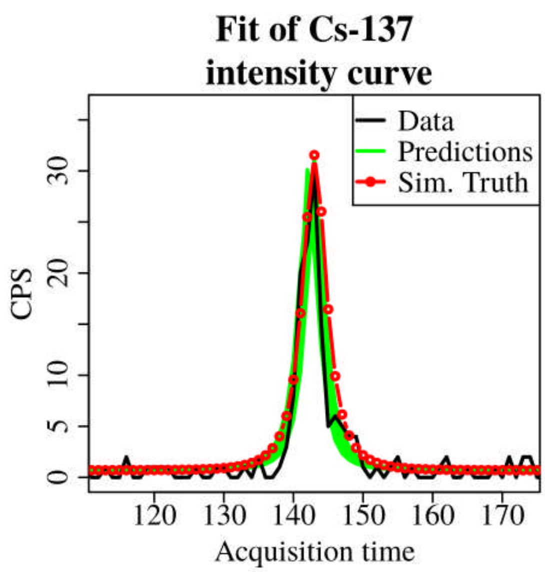
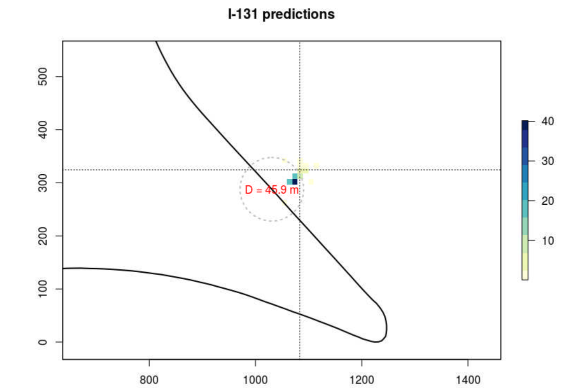
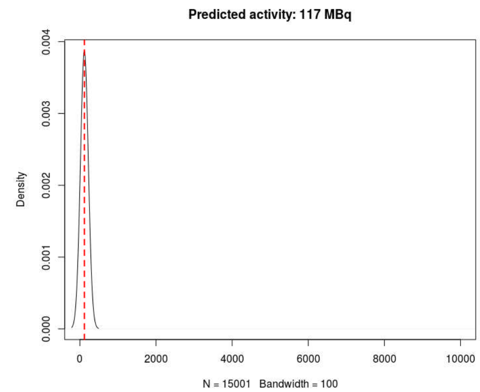


Fig 4. Calculated location (upper left map) and activity (upper right diagram) for mobile detection of a Cs-137 point source with activity 298 MBq placed in position B, 30 m from the roadside in the MOMORC 2016 experiment 2016-09-20 11:00-14:30. (Finck et al., 2017). Measurements made by Lund University using a 123% HPGe-spectrometer mounted inside the car. The true position of the source is shown at the cross hair (upper left map). The green line (left diagram) fit the data shown by the black line. The red line displays the count rate from Eqn 2 along the road assuming a given detector efficiency and the source placed in the calculated location.





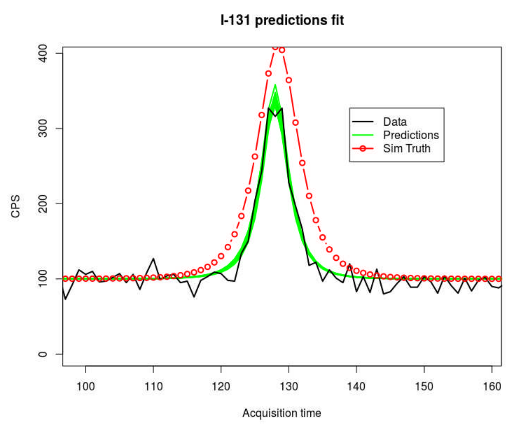
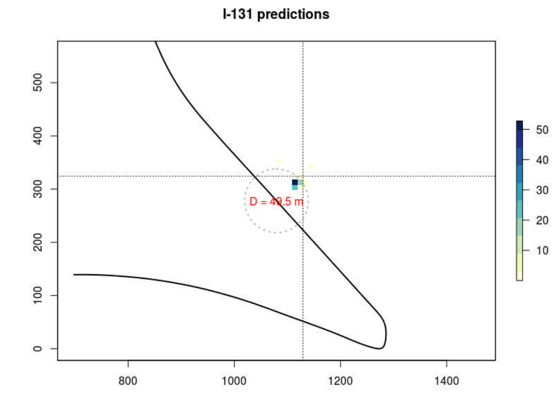
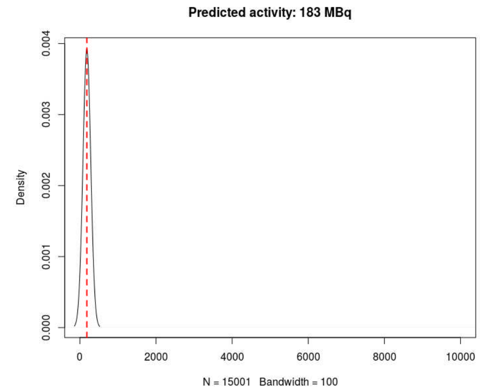


Fig 5. Calculated location (upper left map) and activity (upper right diagram) for mobile detection of a I-131 point source with activity 468 MBq placed in position G, 60 m from the roadside in the MOMORC 2016 experiment 2016-09-20 11:00-14:30. (Finck et al., 2017). Measurements made by the Geological Survey of Norway using a 16 litre NaI(Tl)-spectrometer mounted inside the car. The true position of the source is shown at the cross hair (upper left map). The green line (left diagram) fit the data shown by the black line. The red line displays the count rate from Eqn 2 along the road assuming a given detector efficiency and the source placed in the calculated location.





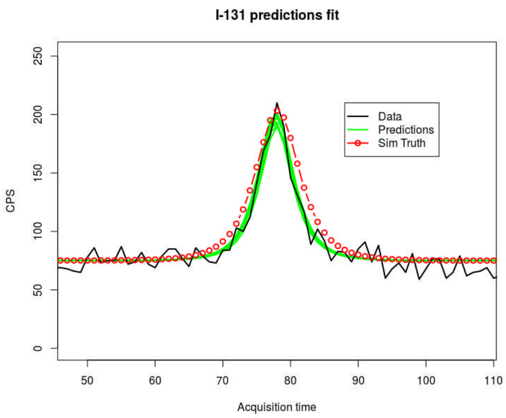


Fig 6. Calculated location (upper left map) and activity (upper right diagram) for mobile detection of a I-131 point source with activity 468 MBq placed in position G, 60 m from the roadside in the MOMORC 2016 experiment 2016-09-20 11:00-14:30. (Finck et al., 2017). Measurements made by the Danish Emergency Management Agency using a 4 litre NaI(Tl)-spectrometer mounted on top of the car. The true position of the source is shown at the cross hair (upper left map). The green line (left diagram) fit the data shown by the black line. The red line displays the count rate from Eqn 2 along the road assuming a given detector efficiency and the source placed in the calculated location.

Table 1. Calculated distance and activity in mobile detection of point sources in the MOMORC 2016 experiment, using Bayesian based statistical analysis on gamma spectrometric data and compared to actual values.

Team	Detector	Source	True distance m	Calculated distance m	Deviation from true distance	True activity MBq	Calculated activity MBq	Deviation from true activity
LU[1]	123% HPGe	I-131	61	58.6	-4%	468	413	-12%
LU[1]	123% HPGe	Ba-133	31	37.7	22%	183	220	20%
LU[1]	123% HPGe	Cs-137	31	27.2	-12%	298	126	-58%
NGU[2]	16 l NaI(Tl)	I-131	61	45.9	-25%	468	117	-75%
DEMA[3]	4 l NaI(Tl)	I-131	61	49.5	-19%	468	183	-61%

[1]Lund University, [2]Geological Survey of Norway, [3]Danish Emergency Management Agency.

4 Conclusions

The Bayesian statistical analysis method to determine locations and activities for gamma emitting point sources in mobile search seems to produce reasonably correct values of distances to sources when tested against synthetic measurement data. When testing the method against data from the MOMORC 2016 experiment, calculated distances were within ±20%. The position of a source can be shown on a map as likelihood for a source present at a certain location together with its activity coupled to that location.

The distance determination is based on the variation in count rate in the region of interest (ROI) selected for the radionuclide when passing the source, the “intensity curve”. Few counts per acquisition time interval will lead to large statistical uncertainties in the determination of distance and activity of the source. Further testing of the method is needed to draw conclusions on how the accuracy in distance calculation is affected by the signal to background ratio.

Calculated activities were generally underestimated when the calculated distance to the source was underestimated and vice versa. This is expected since a source at longer distances will need higher activity to produce the same count rate in the detector as a source at shorter distance.

Much testing remains in order to determine the possibilities and limitations of the method. The Bayesian statistical analysis method will be further tested in the NKS/AUTOMORC 2018 experiment.

5 Suggested continuation - field experiment

Participants in the AUTOMORC project submitted an application to NKS for a continuation a second year of the project in 2018. NKS approved the application in the beginning of 2018. The continuation is especially directed towards a field experiment with mobile gamma spectrometry in order to better verify the correctness of the model for calculation of detection distances and to test the Bayesian based method to infer both the position and activity of point sources.

The aim of the field experiment is to:

1. Validate the model calculations of maximum detection distances against experimentally determined distances with higher distance resolution than ± 30 m and in practice test the alarm analysis method of simultaneous combinations of contiguous varying time intervals using data processing on a stand alone computer.
2. Evaluate in practice the ability of the Bayesian statistical analysis method to simultaneously determine the distance and activity to single point sources in mobile detection using data processing on a stand-alone computer.
3. Identify disturbances in spectral distribution and analysis procedures due to scattered radiation from shielded sources when performing mobile search in order to gain experiences and try to find methods to overcome the difficulties.

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Abstract
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A model for calculating maximum detection distances in mobile search for lost gamma radiation sources was developed in a previous NKS supported project MOMORC 2016. A first validation of the model's correctness was done in a field experiment in September 2016 with participants from all Nordic countries. The model showed that maximum detection distances could be predicted within ± 30 m, which also was the limitation of the experiment. The model also showed that using combined analysis of sets of measurements along a vehicle path could be used to detect a possible source. The count rate from primary photons in the detector when driving past a point source at constant speed is depending on the source activity and the distance between the road and the source. The count rate versus time (the “intensity” curve) depends only on the distance to the source when the speed is fixed and the vehicle path is straight. This fact can be used to determine the distance to a source from a set of measurements. The problem can be solved with Bayesian statistical methods.

A Bayesian based Markov chain Monte Carlo method was used to determine the location and activity of some of the point sources in the MOMORC 2016 experiment. The method seems to produce reasonably correct values of distances to sources, provided that the count rate statistics in the detector is high enough for the computational algorithm to identify the “signal” (as an “intensity curve). The statistical uncertainty in the distance determination using measurement data from a 128 % HPGe-spectrometer was in the order of ±20%. The uncertainty in the activity determination was larger, especially for NaI(Tl)-spectrometers. This could be due to a systematic deviation in the efficiency calibration of the detectors, because when testing the method with synthetic data the activity calculations gave reasonably correct results.

The position of a source can be shown on a map as likelihood for a source present at a certain location together with its activity coupled to that location. Five examples of calculated likelihood locations based on Bayesian analysis of mobile measurements are given in the report.

Key words

Mobile gamma spectrometry, orphan source search, detection distance, Bayesian analysis, Markov chain Monte Carlo.