2013/846

ISSN 1797-3457 (verkkojulkaisu)
ISBN (PDF) 978-951-25-2536-2

SUMMARY REPORT

Radioactive source localization with spectrometric data

Radioaktiivisen lähteen paikantaminen spektrometrisistä havainnoista

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Abstract

Due to criminal or other activities, radioactive materials may be out of regulatory control. For the authorities it is of utmost importance to detect, identify and localize these materials. There are many measurement systems available for detection and identification but none for source localization. Therefore, the present study focuses on development and testing of mathematical models aimed to support in-field search operations in different environments. The models include a grid-based algorithm and a recursive Bayesian particle filter algorithm. Both methods performed well in a controlled or simulated environment. The algorithms were tested with realistic measurement data. The source localization worked well in controlled situations, when three or more observations are available. The tests revealed problems related to the uncertainties of mobile measurements. However, the problems have been identified and the methods will be further developed towards operational usage for nuclear security and other in-field applications. The Finnish in-field measurement system with reachback is an excellent platform to run localization algorithms because all relevant input data are available in real time in one central server.

1. Introduction

Radioactivity can be used maliciously against the society or individuals. A release of radioactive materials can cause large economical and political consequences even in cases where the impact on public health is small. The importance of radiation detection is emphasized at the EU level (CBRN Action Plan 2009) and at the national level (Yhteiskunnan turvallisuusstrategia 2010). Finland has a good operational ability to detect and identify dangerous radioactive sources. Localizing the source is, however, an extremely difficult task requiring spectrometric data and advanced data analysis.

In the present project mathematical models for automatic source localization were developed and tested. Localizing a source can be divided into six different cases presented in the Table 1. Tests were conducted covering all cases except moving sources with a single or multiple moving detectors.

The tests and development focused on two localization methods: a grid-based solution and a particle filter solution. The grid-based solution analyzes the whole area of interest and is straightforward to implement but has the disadvantage of being computationally intractable as the number of measurements increase. The particle filter solution has the advantage of being computationally independent of the number of measurements and therefore it suits well for situations were the source or the detectors are moving.

Table 1. Categorization of the source localization problem.

	Stationary source	***Moving source***
Multiple stationary detectors	• At least 3 detectors • Long measurement times possible • Asymmetric shielding complicates localization	• At least 3 detectors • Short measurement times or event-based data processing
Single moving detector	• At least 3 measurements • Short measurement times or event-based data processing	• Event-based data processing or very short measurement times
Multiple moving detectors	• Expert system	• Expert system

2. Research objectives

The research objectives were to develop and test a realistic localization model that takes into account asymmetrical shielding effects that are always present in the field conditions. A further objective was to study the advantage of list-mode data. In this data acquisition mode, every detected event is stored separately with a time stamp, resulting in much better timing than is possible with traditional integrated spectra.

3. Materials and methods

The signal strength of a detector depends on the nuclide involved, its activity, detector properties, source-detector distance and material between the source and the detector. In the ideal case, where the detector positions, radiation absorbing materials and the signal strength are exactly known, the position of the source can be calculated analytically from measurements in three different positions. Geometrically, the solution can be seen as calculating the crossings of circles, each of which is created by combining two measurement positions.

The grid-based solution [7] uses the analytical solution but takes into account the uncertainties of the signal strength and detection efficiency and calculates a gridded probability distribution. Every combination of the measurement position pairs is gone through to provide the final probability distribution. The location of the maximum of the probability distribution then ideally corresponds to the actual source location.

The particle filter solution takes a Monte Carlo-style recursive Bayesian approach [1, 3, 5]. A large number of weighted particles, each representing a state consisting of the position and source activity, are first given random states. For each new measurement result, the weights of the particles are updated corresponding to the probability that the particle state would have caused the measurement result. By re-sampling the particles the particles converge to the same solution, ideally corresponding to the actual source location.

The Finnish Radiation and Nuclear Safety Authority (STUK) has developed radiation detection backpacks (Vasikka). The system acquires spectra continuously, analyzes them, and sends the measurement raw data and analysis results to a database (Linssi) on a remote server. The data flow contains also current GPS coordinates of the backpack. Thus the operational information needed for source localization can be easily obtained by the reachback centre of STUK.

Measurements were performed with the Vasikka backpacks in both controlled and realistic environments. Controlled measurements were performed indoors with exactly known detector and source positions. The tests included the use of asymmetrical source shields. The source was stationary or moved in a controlled manner using an automated track. Realistic measurements were performed outdoors using Vasikka GPS coordinates. No differential correction was performed to improve the precision of the GPS positioning. The source localization methods were also tested using simulated measurement results.

4. Results and discussion

Source localization in a controlled environment

The localization methods perform well in the controlled measurements. Figure 1 presents the probability distribution of the grid-based method with and without asymmetrical shielding [2]. The algorithm localizes the source correctly in the unshielded case and behaves as expected in the asymmetrical case. It was found that using the total count rate for the localization can reduce the effect of asymmetrical shielding compared to using the peak count rate corresponding to the source nuclide. This is expected, since a) part of the radiation will only loose energy in the shield, but not be absorbed completely and b) the shield doesn’t reduce the amount of radiation that reaches the detector by scattering around the shield.

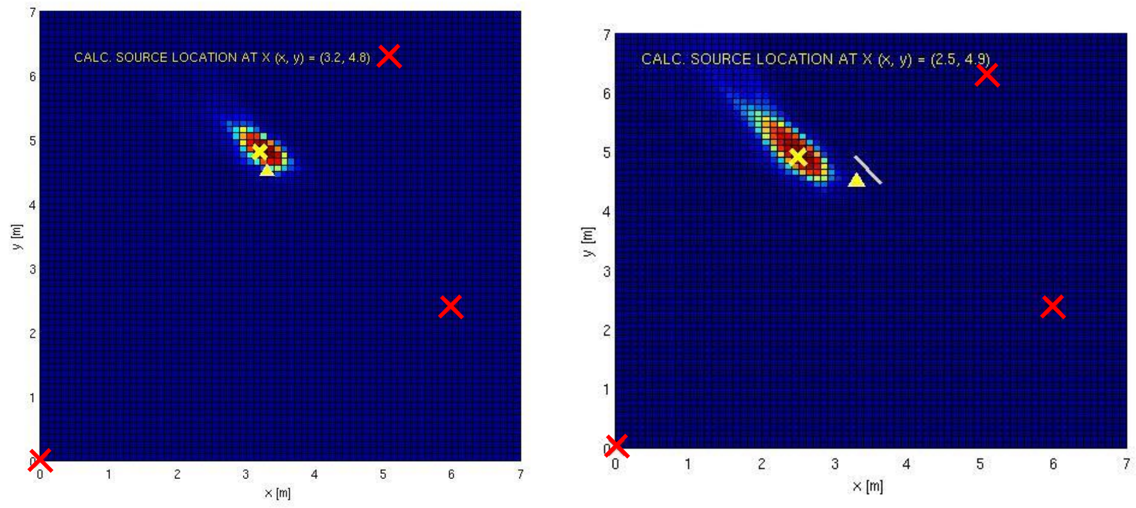


Figure 1. Grid-based source localization [2]. The red crosses mark detector positions and the yellow triangle marks the actual ^{137}Cs source position. The yellow cross indicates the maximum of the probability distribution, which corresponds to the source location estimate. On the right side, a 1 cm thick iron shield was placed between the source and the uppermost detector position. The total count rate was used in the calculations. Note that although the source location is not quite correct, each field team would have received a good direction estimate (azimuth) towards which they would have started to

In Figure 2, the source was moved using the automated test system of STUK (16 m track) [2]. Since only the relative movement matters, the case is equal to the detector being moved and the source being stationary. The results were analysed in this symmetrical setting, using the known track positions as detector positions. Note that since the movement was on a straight line, it is not possible to know on which side of the line the source is. The localization method correctly gives two symmetrical solutions, one of which corresponds to the actual source position.

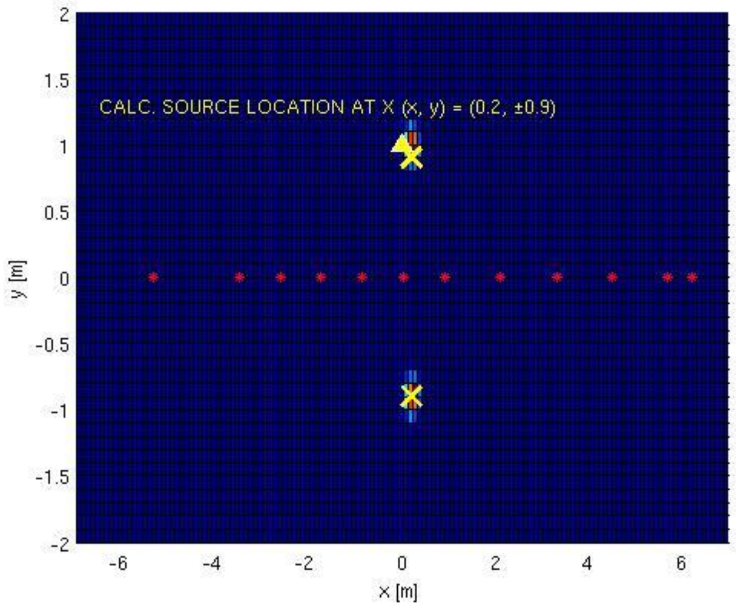
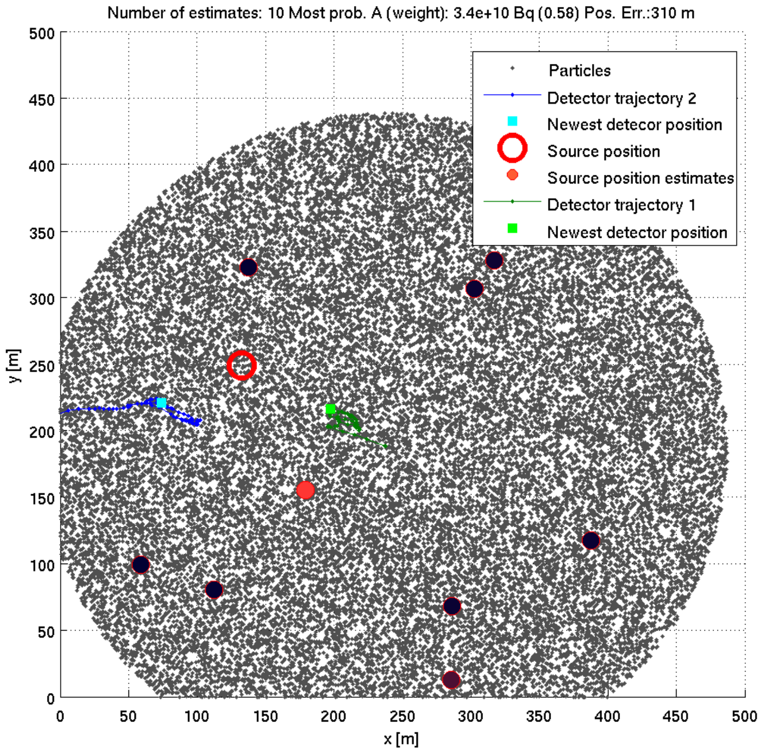


Figure 2. Cs-137 at (0 m, 1 m), movement speed *v*=1.2 m/s [2]. Measurement time 1 s. The red crosses mark the detector position. The yellow triangle marks the actual source position, while the yellow crosses mark the calculated source positions.

Source localization in a realistic environment

Measurements were performed outdoors with two Vasikka backpacks. Early measurements indicated that relying on only few measurements can cause problems because of the large uncertainties regarding the measurement environment and the position of the detector (human being is also a shield) [4]. For instance, an attempt to localize the source using 3-4 measurements taken at different positions failed because of GPS measurement failure. This was one of the problems leading to the development of the particle filter solution. Because of the computational tractability of the particle filter, it can use every measurement provided by the backpacks and thus minimize to errors produced by uncertainties in single measurements.

Figure 3 illustrates a case where the particle filter successfully localizes the source combining the data of two moving detectors [3]. In the upper picture, the measurements have not yet provided enough data for the particles to converge to a single position. The lower picture shows the situation 2 minutes later, when enough data has been gathered for a successful localization. The measurements were done with a 2.7 GBq ^{137}Cs source and the peak count rate (analysed in real-time by the Vasikka software) was used in the calculations. The backpacks were used as in operative use, providing 4 seconds long measurements and GPS coordinates with 1 second intervals.


Number of estimates: 10 Most prob. A (weight): 3.4e+10 Bq (0.58) Pos. Err.:310 m
Particles
Detector trajectory 2
Newest detecor position
Source position
Source position estimates
Detector trajectory 1
Newest detector position
y [m]
x [m]

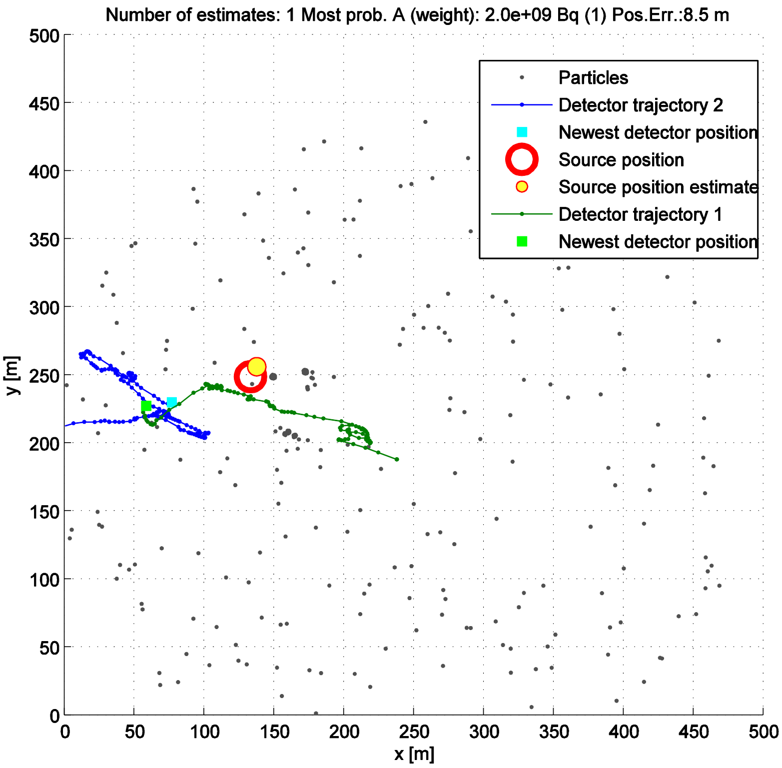

Number of estimates: 1 Most prob. A (weight): 2.0e+09 Bq (1) Pos.Err.:8.5 m
Particles
Detector trajectory 2
Newest detector position
Source position
Source position estimate
Detector trajectory 1
Newest detector position
y [m]
x [m]

Figure 3. Particle filter converges to approximately the right source position. In the upper picture, several source location estimates are given with weights represented by the brightness of the circles. In the lower picture, the filter has converged to one location estimate which is 8.5 m from the actual source location. Most of the particles (represented by black dots) lie under the yellow circle representing the source location estimate. The time difference between the pictures is two minutes.

Problems in source localization

The particle filter was tested with several realistic measurements. In certain cases, such as the one presented in Figure 3, the source localization was accurate, but in many cases, the source location estimate was not near the actual source position. Figure 4 shows a histogram of the localization error of 600 solutions of the particle filter. Six different detector path combinations are included in the histogram, with 100 particle filter runs per case. The errors are large compared to the closest distance between the source and detectors.

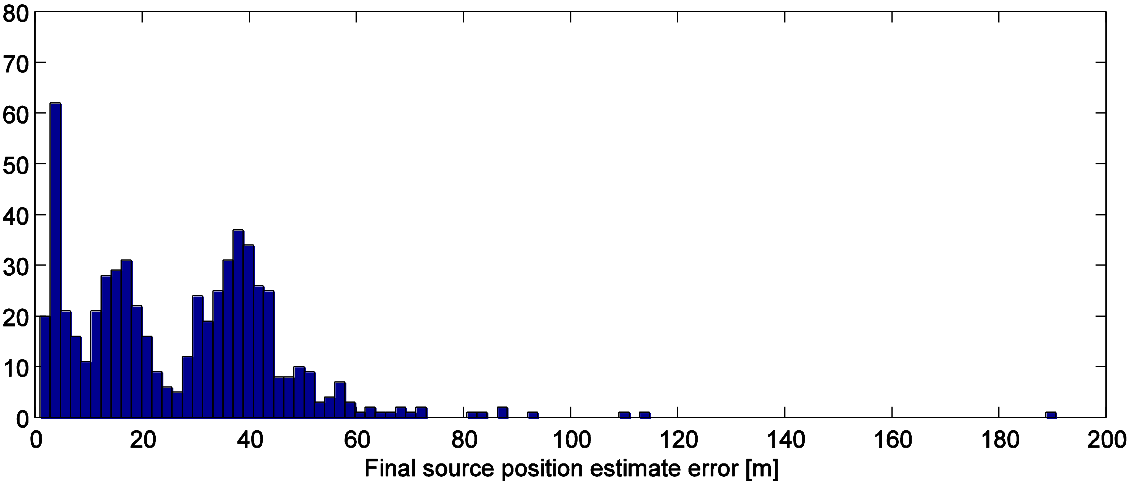


Figure 4. Particle filter localization error for 6 different cases with 100 filter runs each.

The errors are attributed to the large uncertainties caused by the unknown environment and measurement errors. It is also possible that certain types of detector paths produce better localization results. For instance in Figure 3, the source was localized correctly when one of the detectors passed the source.

5. Conclusions

Source localization methods were developed and tested. The localization methods work well in controlled environments. Therefore the first operational applications could be built for conditions where the detectors are in fixed positions and have a good view over the area of interest. Such situations are at the border control, for example. While cars and people approach a control point, the source could be pinpointed although there were a crowd of people or several vehicles around. Another application is a transit hall of goods through which legal shipments are carried. The exact track of the radioactive shipment could be quickly monitored and verified that they are handled according to the approved procedures.

The problems of the localization algorithms were attributed to the uncertainties of mobile measurements and environmental effects that are difficult to predict. The initial research objectives were slightly shifted to address these problems and consequently, statistical models were developed to handle these uncertainties. The project gave valuable expertise towards the development of an operational system for mobile in-field teams. The Finnish measurement system with reachback is an excellent platform to run localization algorithms because all relevant input data are available in real time in one central server.

The field tests were performed with a standard GPS equipment which may have a positioning error of 10 metres. Even with this large uncertainty some of the source localization efforts were successful, but not all. We know that the algorithms work well when the coordinates of the detector are known precisely. Therefore the use of differential GPS correction should improve the results drastically. The obvious next step to continue development towards operational usage is to carry out field test with much better positioning devices that were available in the present project.

6. Scientific publishing and other reports produced by the research project

Six technical reports (1-6) were written as part of the project. The grid-based localization method was developed already in 2011 (7).

1. Holm P., Peräjärvi K., Ilander T., Ihantola S., Toivonen H. Localization of a radioactive source with particle filter for mobile measurements. TTL-TECDOC-2013-016, STUK 2013. (Localization with the particle filter method is described).
2. Holm P., Peräjärvi K., Ilander T., Ihantola S., Toivonen H. Grid-based source localization method test. TTL-TECDOC-2013-017, STUK 2013. (The grid-based localization method is tested in a controlled environment).
3. Holm P., Peräjärvi K., Ilander T., Ihantola S., Toivonen H. Radioactive source localization with improved particle filter. TTL-TECDOC-2013-018, STUK 2013. (The particle filter is improved further and tested thoroughly).
4. Holm P., Peräjärvi K., Ilander T., Ihantola S., Toivonen H. Grid-based source localization method outdoor test. TTL-TECDOC-2013-019, STUK 2013. (The grid-based source localization method is tested with realistic outdoor measurement data).
5. Holm P., Peräjärvi K., Ilander T., Ihantola S., Toivonen H. Kalman filter for GPS coordinates. TTL-TECDOC-2013-020, STUK 2013. (A method for improving GPS measurement data is described).
6. Holm P., Peräjärvi K., Ilander T., Ihantola S., Toivonen H. Radiation detection event density. TTL-TECDOC-2013-021, STUK 2013. (The use of kernel density estimation as a tool for localizing sources with list mode data is presented).
7. Toivonen H. Source location using several measurements in different locations. TTL-TECDOC-2011-001, STUK 2011. (The grid-based source localization method is described).