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Orphan source detection at REFOX with a 16-litre NaI car-mounted gamma ray spectrometer

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Title:
Orphan source detection at REFOX with a 16-litre NaI car-mounted gamma ray spectrometer

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Summary:

The Geological Survey of Norway (NGU) has been involved in measurements of anthropogenic radiation from the time of the Chernobyl accident of 1986, and since then has cooperated with the Norwegian Radiation Protection Authority (Statens strålevern) and Norway's nuclear preparedness organisation to provide mobile gamma ray measurement platforms for use in nuclear emergencies (Rønning 2008). NGU operates a mobile radiometric system which can be mounted on fixed-wing aircraft, helicopter, or car platforms, according to the needs of the particular emergency scenario. In autumn 2012 NGU participated in REFOX - an emergency exercise organised by Swedish authorities - with a 16-litre NaI car-mounted gamma ray spectrometer. This report summarises the experiences of the NGU team in locating and identifying a range of anthropogenic orphan sources.

The 16-litre system was able to detect most sources in a variety of exercise settings, although some sources were only detectable with post-processing. Lower energy sources such as I-131 and Ba-133 were difficult to identify. Directionality of source was difficult to determine due to the detector configuration used here, and the system would have benefited from the addition of shielding. A more detailed analysis of the data presented here could help to improve instrument settings and operator methodology for future car-borne measurements.

Keywords:		
Gamma Spectrometry	Radiometrics	Nuclear Emergency Preparedness
		Scientific Report

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1. INTRODUCTION

The Nordic emergency preparedness organisations have a history of close cooperation, and regularly organise joint exercises to enhance the capabilities of Nordic emergency response teams in handling radiological emergency scenarios. REFOX 2012 was such an exercise, organised by the Swedish authorities, and which took place in Skåne, Sweden, in September 2012. A variety of radiological response exercises were carried out, and included orphan source search and fallout exercises for hand-held, car-borne and airborne measurement systems.

The Geological Survey of Norway (NGU) has been involved in measurements of anthropogenic radiation from the time of the Chernobyl accident of 1986, and since then has cooperated with the Norwegian Radiation Protection Authority (NRPA) and Norway's nuclear preparedness organisations to provide mobile gamma ray measurement platforms for use in nuclear emergencies (Rønning 2008). NGU operates a mobile radiometric system which can be mounted on fixed-wing aircraft, helicopter, or car platforms, according to the needs of the particular emergency scenario. NGU has participated in several earlier Nordic exercises with both airborne and car-borne measurement systems (Rønning and Smethurst 1997, Smethurst et al. 2000, Smethurst et al. 2001), and has developed in-house acquisition and analysis software (Smethurst et al. 2005, Watson and Smethurst 2011) for use in orphan-source or fallout scenarios.

During summer and autumn 2012, NGU's radiometric system was occupied on geological mapping projects and was therefore unavailable for use in REFOX. NGU participated instead with a GR-820 system (Exploranium, Ontario, Canada) belonging to NRPA. Although the GR-820 is designed as an airborne detector, the system can also be mounted in a car; due to time constraints in the run-up to the exercise, NGU participated only with a car-borne system. NGU took part mainly in orphan source detection exercises at REFOX. The team also took part in a fallout calibration exercise, but as the data collected were not used in any subsequent activities, the exercise is not reported here. NGU participated in REFOX with team code NGC.

2. ORPHAN SOURCES

Orphan sources are hazardous radioactive sources which have fallen outside normal regulatory control, and may include high-activity medical or industrial isotopes which have been abandoned, lost or stolen. Because of their potential hazard, search operations may be instigated to locate and recover such sources, and these operations may take the form of airborne, car-borne, or back-pack searches, depending on the size of the desired search area and on the spatial resolution required.

3. REFOX

REFOX took place between 22nd and 28th September 2012 in the Skåne region of Sweden, with exercise headquarters at the MSB Revinge training facilities. REFOX focussed primarily on testing the response of Swedish emergency organisations to terrorist threats involving radioactive material, but also aimed to test the ability of Swedish authorities to accept assistance from other Nordic countries. A variety of emergency scenarios were organised, and included several orphan-source exercises aimed at car-borne gamma-spectrometer teams. The data presented in this report were collected from four car-borne exercises - G1, S6, S9 and R2 - which are described below.

3.1 G1 exercise

The G1 exercise was a *pre-exercise* intended to give car-borne teams the opportunity to familiarise themselves with their systems, and to establish the sensitivity of their systems to various types of orphan sources. The exercise took place on the taxiway of the disused airstrip at Björka övningsfält (Björka training area), alongside which anthropogenic sources were placed.

The exercise was divided into four runs, each run using a different configuration of sources. The taxiway was divided into eight zones, Z1 to Z8 (Figure 1), and in each configuration an anthropogenic source was placed in 6 of the 8 zones. Sources were placed some distance from the taxiway, and on both the north and south sides of the taxiway. In each run, car-borne teams drove along the taxiway at a steady velocity in two directions - once along the north side of the taxiway, and returning along the south side - and attempted to detect and identify any orphan sources. At the end of each run, teams were given a short period of time - around 15 minutes - to prepare a brief report which was submitted to REFOX organisers. This report comprised: the zone (Z1 to Z8) in which any sources were found; the radionuclide type of each source; and the side of the taxiway (north or south) in which the source was located.

The NGU team participated in two runs of the G1 exercise, and the source configurations for these runs are show in Table 1 and Table 2.

Figure 1: *Björka airstrip showing approximate delineation of zones for exercise G1.*

Table 1: *Source configurations for G1, run 1.*

Zone	Nuclide	Activity (MBq)	Distance (m)	North(N)/South (S)
Z1	Ba-133	24.6	28.6	N
Z3	Cs-137	40.0	28.6	S
Z5	Co-60	81.9	54	S
Z6	Co-60	16.5	44	N
Z7	Ba-133	246.3	45	N
Z8	Cs-137	32.1	33	N

Table 2: *Source configurations for G1, run 2.*

Zone	Nuclide	Activity (MBq)	Distance (m)	North (N)/South(S)
Z1	Cs-137	32.1	21.6	N
Z2	Cs-137	32.1	33	S
Z4	Cs-137	160.3	54	S
Z6	Ba-133	24.6	22	S
Z7	Ba-133	246.3	54	S
Z8	Co-60	16.5	23.4	N

3.2 S6 and S9 exercises

A series of *S* exercises were set up which required car-borne teams to locate orphan sources in various areas of Skåne. These regions were outside the Revinge training area, and involved the placement of sources in public areas, with the aim of providing teams with a more realistic search scenario. Teams were provided with a map of a region of Skåne - covering areas of the order of 4km by 4km - on which a search area was demarcated. A starting latitude/longitude coordinate was also provided. Teams were required to survey the search area and report the location and radionuclide type of any orphan sources found. Teams were instructed not to stop, or get out of the vehicle in the vicinity of any orphan sources, and were required to report any sources by mobile phone shortly after each one was located. NGU participated in two such exercises, S6 and S9. Details of source placements are provided in the RESULTS section.

3.3 R2 exercise

The *R* exercises were designed for both airborne and car-borne teams, and involved the detection of orphan sources placed around the training area at Revinge. Teams were provided with a demarcated map of the Revinge area, indicating search areas where sources might be located. Source configurations were changed from day to day. NGU participated in the R2 exercise. Details of source placement are provided in the RESULTS section.

4. NGU'S SYSTEM

4.1 System hardward: Exploranium GR 820

The Exploranium GR-820 comprises a detector unit with 4 x 4 litre NaI crystals, giving a total volume of 16 litres, and a 256 channel spectrometer. The detector system was mounted in the rear of an NGU van (Figure 2) with a controlling laptop situated in the front cabin. Data acquisition from the spectrometer was controlled by GammaLog software (Smethurst et al. 2005), which also controlled acquisition from a GPS receiver mounted on the roof of the vehicle. GPS and spectral data were recorded each second. GammaLog Playback (Watson and Smethurst 2011) was used to review recently captured datasets and assist in the location and identification of sources. The detector pack was mounted slightly to right side of the vehicle, and angled with the detector face pointing down at an approximately 45 degree angle; the rationale for the angular placement was to maximise the sensitivity of the instrument to sources lying close to the vehicle, although - as is discussed later - this, together with the lack of shielding or upward-looking detector on the back of the detector pack, led to difficulties in distinguishing between signals from the left and right sides of the vehicle.

Figure 2: *The GR-820 detector (red and black object in background) and spectrometer (foreground) mounted in the NGU van*.

4.2 System Software: GammaLog

The main windows of both GammaLog and GammaLog Playback (Figure 3) display an energy spectrum window, a waterfall chart window, and a strip chart window with 2 configurable strip charts. Some aspects of GammaLog functionality are described in more detail in the following sections.

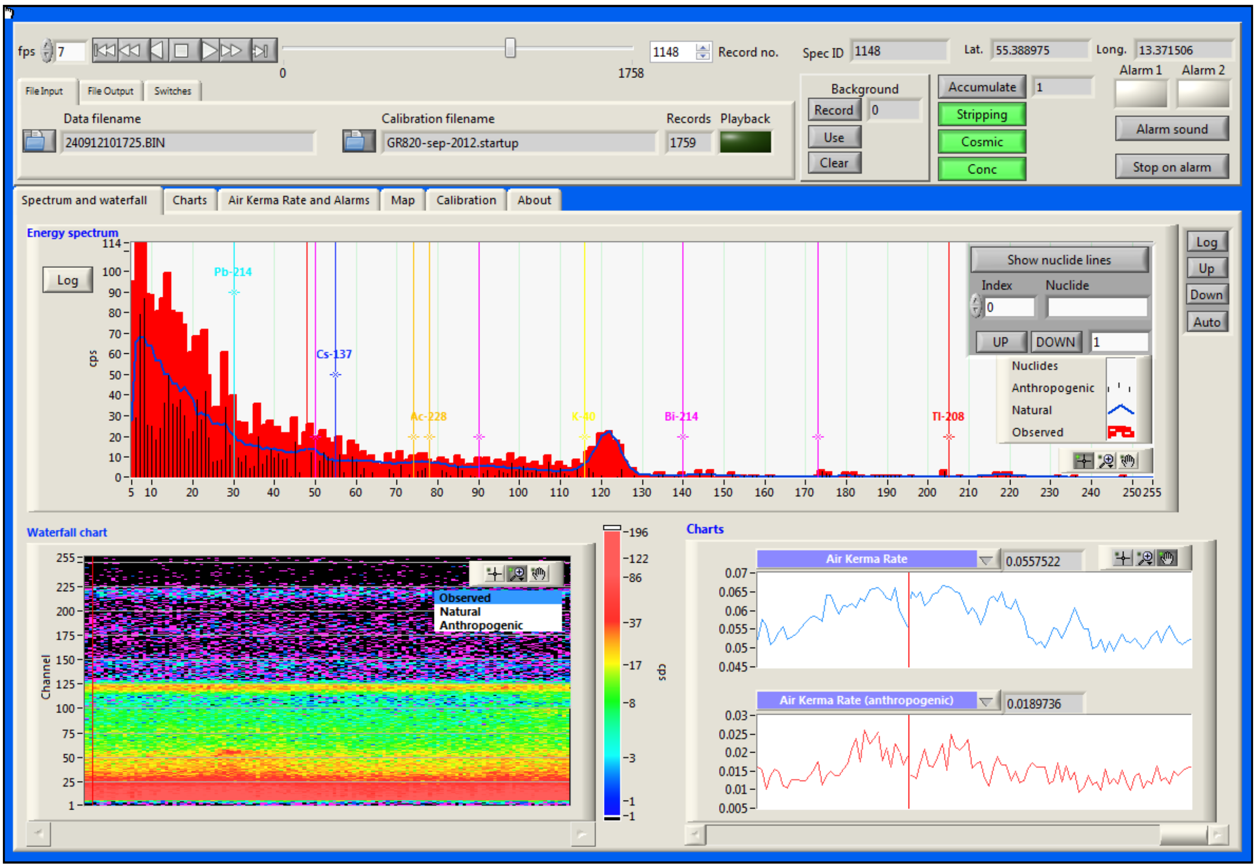

Figure 3: *The user interface of GammaLog Playback.*

4.2.1 Background subtraction and geological modelling

GammaLog has two methods of removing unwanted background signal:

1) background subtraction and
2) geological modelling.

In (1) the user records a background signal which can then be subtracted from any subsequent signals. The user can control the application of this background signal, and can re-set the background, or record a new background, at any time. In (2) GammaLog attempts to model the geological component of the observed signal by using the stripped counts in each of the Th-232, U-238 and K-40 windows, combined with unit spectra for each of these radioisotopes, to build up an estimate of the natural geological background signal; the difference between the observed signal and the natural background is interpreted as anthropogenic signal.

4.2.2 Display modes

The energy spectrum window displays 3 forms of signal (observed, natural model, and anthropogenic model) simultaneously, while the waterfall chart window allows the user to select (at any time) any one of the 3 forms. Strip charts can be configured to display one of a variety of raw or derived quantities including total counts, counts in user-specified ROIs (regions-of-interest), concentrations of radioisotopes (where concentration calibration values are known), or air kerma rates (where air kerma rate calibration factors are known). Air kerma rates can be separated into geological and anthropogenic components.

4.2.3 Other GammaLog features

Other GammaLog features which were used in these exercises included:

1) accumulated spectrum – the user can switch at any time between a second-by-second display and an averaged accumulated display. Accumulating several adjacent signals from a radionuclide can improve the signal-to-noise ratio and assist with source identification.

2) radionuclide tool – a small library of radionuclide lines and their relative abundances is loaded into GammaLog on startup. The user can switch on a radionuclide display which superimposes a spectrum representing a selected radionuclide's peaks, together with an estimate of the FWHM of each peak, on the main spectrum window (Figure 4). The relative amplitudes of the radionuclide spectrum and main spectrum can be adjusted, and the user can cycle through the range of radionuclides stored in the library.

3) alarms - the user can set dose-rate based alarms which result in an audible signal together with flashing indicators on the front panel.

4) export of data to text files – GammaLog exports a text version of its recorded data which can include, for each record: the record number; GPS coordinates; the state of the GammaLog controls; and derived quantities such as ROI counts and dose rates. This text file can be imported into GIS packages to produce map products.

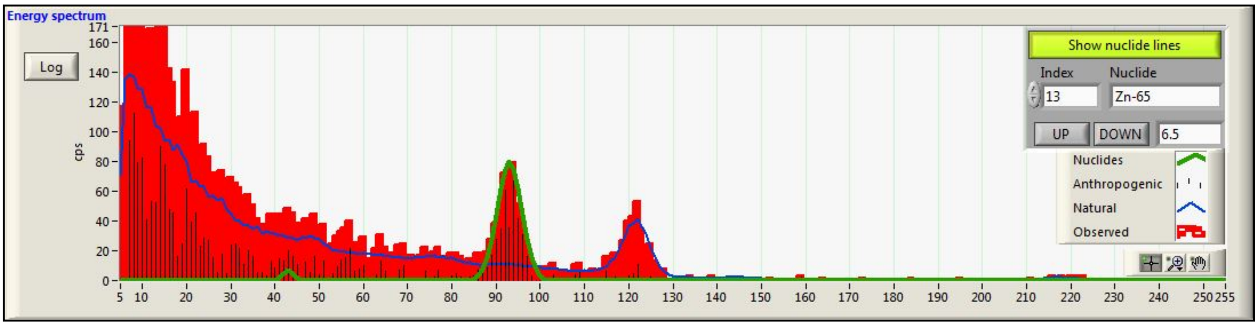

Figure 4: *GammaLog's radionuclide tool. Red bars: the observed spectrum; blue line: the geological model; black bars: estimated anthropogenic spectrum. The green line represents photopeaks from the selected library isotope (here Zn-65).*

4.3 Calibrations

NGU maintains a set of concrete calibration pads designed for use with mobile gamma spectrometers (Grasty et al. 1991). The set consists of 4 pads measuring 1 x 1 x 0.3 m; 3 of the pads are doped with known concentrations of Th-232, U-238 and K-40, while a fourth pad contains background levels of these radioisotopes. Background-corrected spectra obtained with the detector placed centrally on each doped pad provide unit spectra for Th-232, U-238 and K-40, and allow stripping factors (a measure of the contribution of compton scattering from each of the 3 natural radioisotopes to each other) to be calculated. The photopeaks for Th-232, U-238 and K-40 together with that obtained from a point Cs-137 source allow the relationship between channel number and energy to be determined. An opportunity to calibrate the system against known dose rates was provided by REFOX organisers; however the team's large volume system displayed distortion under the high count rates experienced during these measurements, and so no reliable dose rate data were obtained. Previously obtained dose rate calibration factors, collected with a similar system in a near-identical geometry, were used to give a rough indication of dose rates.

5. METHODS

5.1 General method

NGU's approach during orphan source exercises was to monitor GammaLog's front panel, often focussing on the anthropogenic mode waterfall chart, to locate sources. Where possible repeat passes of a suspected source location were performed; a short time later GammaLog Playback was used to examine in more detail the data recorded around the source location. In many of the exercises the sources were tightly collimated and visible in only several adjacent records; in such cases the accumulation tool was used to build up a spectrum with better signal-to-noise ratio. Source nuclide identification was then attempted using this accumulated spectrum in conjunction with the radionuclide tool. Where possible, more precise descriptions of source locations were provided, and in some cases (S6 and S9) source activities were estimated.

5.2 Method - G1

Exercise G1 is described in more detail in section 3.1. In G1 it was anticipated that the background signal would be relatively stable and so it was decided to use a constant background subtraction throughout. A background signal was recorded for around one minute during the vehicle's approach to the start of the first zone (Z1). On crossing into Z1, the background recording was stopped, and subtracted from subsequent signals. During the drive, the record numbers corresponding to locations of candidate orphan sources were noted, as were the record numbers at the boundaries between the zones Z1 to Z8. On finishing the run, GammaLog Playback was used to investigate the signals from candidate orphan sources in more detail. Typically each orphan source was highly collimated and was visible in only a few adjacent records; these records were accumulated in an attempt to ease identification. As each source was passed in both a northward and southward direction, comparison of the signal strength on each pass was used to determine the North/South location. Radionuclides were identified either by the team's familiarity with typical signals from given radionuclides (in the case of the radionuclides Cs-137 and Co-60) or with the help of the radionuclide tool.

5.3 Method - S6 and S9

Exercises S6 and S9 are described in more detail in section 3.2. As this exercise involved driving around a range of natural and urban settings, the natural background varied considerably. GammaLog was therefore operated in “geological modelling” mode. After a suspected orphan source was discovered, the record number was noted, and at least one other pass of the source was made. A short time later the vehicle was stopped, and GammaLog Playback was used to investigate the signals in more detail. As with exercise G1 above, the signals tended to be highly collimated, visible for only several adjacent records. Signals were accumulated, and identification was attempted using the radionuclide tool. The orphan source was then reported to the control centre by mobile phone. After the exercise, attempts were made to identify any nuclides which could not be identified during the exercise; if possible the distance of the source from the vehicle was also estimated by using the signal strength in conjunction with positional data from several passes, and assuming a $1/r^2$ dependence of signal amplitude with distance r. This distance could then be used to derive a source activity using the dose rate calibration values discussed in section 4.3.

5.4 Method - R2

Exercise R2 is described in more detail in section 3.3. Here, as with the S6 and S9 exercises, GammaLog was operated in “geological modelling” mode. On finding a candidate source, several passes were typically made to help determine the source location, and accumulated spectra were used to assist source identification as necessary.

6. RESULTS

6.1 Results - G1

NGU participated in two runs in the G1 exercise. In the first run the team's system for note-taking in the vehicle was poor, resulting in difficulties identifying the source zones. Nevertheless reported sources are shown in Table 3.

Table 3: *Results of exercise G1, run 1.*

Zone	Actual source				Reported source	
	Nuclide	Side	Activity (MBq)	Distance (m)	Nuclide	Side
Z1	Ba-133	N	24.6	28.6		
Z2					Co-60	S
Z3	Cs-137	S	40.0	28.6	Cs-137	S
Z4						
Z5	Co-60	S	81.9	54	Co-60	N
Z6	Co-60	N	16.5	44		
Z7	Ba-133	N	246.3	45	I-131	N
Z8	Cs-137	N	32.1	33		

In the second run an improved note-taking system was used; the results are shown in Table 4.

Table 4: *Results of exercise G1, run 2.*

Zone	Actual source				Reported source	
	Nuclide	Side	Activity (MBq)	Distance (m)	Nuclide	Side
Z1	Cs-137	N	32.1	21.6	Cs-137	Not reported
Z2	Cs-137	S	32.1	33	Cs-137	N
Z3						
Z4	Cs-137	S	160.3	54	Cs-137	S
Z5						
Z6	Ba-133	S	24.6	22		
Z7	Ba-133	S	246.3	54	I-131	N
Z8	Co-60	N	16.5	23.4	Co-60	S

In run 1, 4 out of 6 sources were reported. Due to note-taking issues Co-60 sources were reported in Z2 and Z5 instead of Z5 and Z6. Ba-133 was misidentified as I-131. The correct side was reported only for the sources in Z3 and Z7, and sources in zones Z1 and Z8 were not reported.

In run 2, 5 out of 6 sources were reported; Ba-133 was again misidentified as I-131, and the source in Z6 was not reported. The identification of side (N/S) was poor, with only 1 correct (Z4).

The tables above indicate sources which were identifiable in the car, either at the time of data recording with GammaLog, or a short time afterwards with GammaLog Playback. As the identification of sources is sensitive to the settings of the software system and the methodology of the operators, it is of interest to investigate if alternative system settings might have aided with source location and identification.

6.1.1 Source zone location

Figure 5 shows waterfall charts for run 1. These have been produced using GammaLog Playback and show essentially that which was visible in the car during data collection, except that the width of the waterfall chart has been extended so that roughly the entire length of the taxiway is visible in a single image. North and south passes are shown together in each figure; the south image was obtained by running GammaLog Playback in "reverse" mode. Approximate zone positions, along with the actual source in each zone, are marked in the figure. At the time of the exercise it was only possible to see the 128 most recent records (corresponding to roughly three zones here), and it was not possible to see both north and south passes simultaneously.

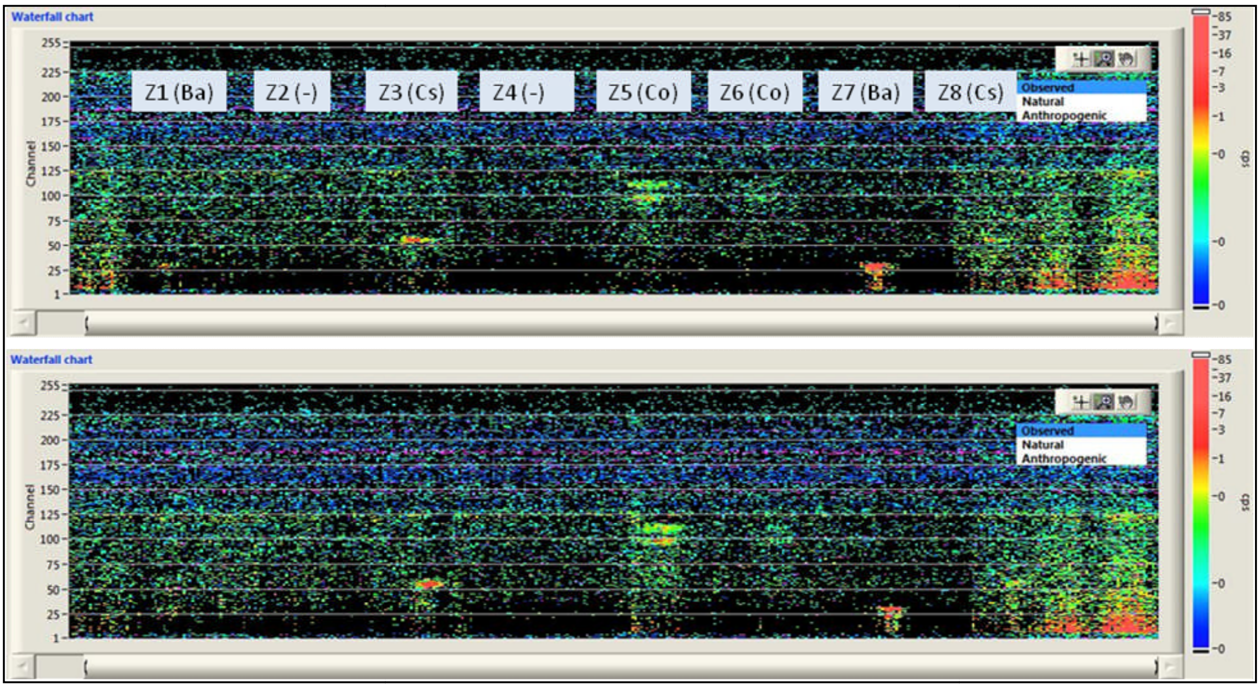

Figure 5: *Waterfall chart for exercise G1, run 1. Upper image: north pass; lower image: south pass (reversed). Approximate zone locations, and sources in each zone, are indicated in the upper image.*

Sources in Z3, Z5, Z6 and Z7 can be seen, but those in Z1 and Z8 are not clearly visible. The variation in background signal throughout the run can be seen, with stronger background in Z8 and part of Z1. The geological modelling mode could help to minimise this background; however at the time of the exercise, the geological modelling mode produced generally noisier waterfall charts than those obtained in background-subtraction mode, and so background-subtraction was used throughout. The ability to discern point sources above the background signal in a waterfall chart is sensitive to the colour scale used. In Figure 5 the waterfall charts used GammaLog's default "autoscale" mode (i.e. that which was used during the exercise); with appropriate choice of fixed z-scales however, it is arguable that the sources in Z1 and Z8 become visible, as shown in Figure 6.

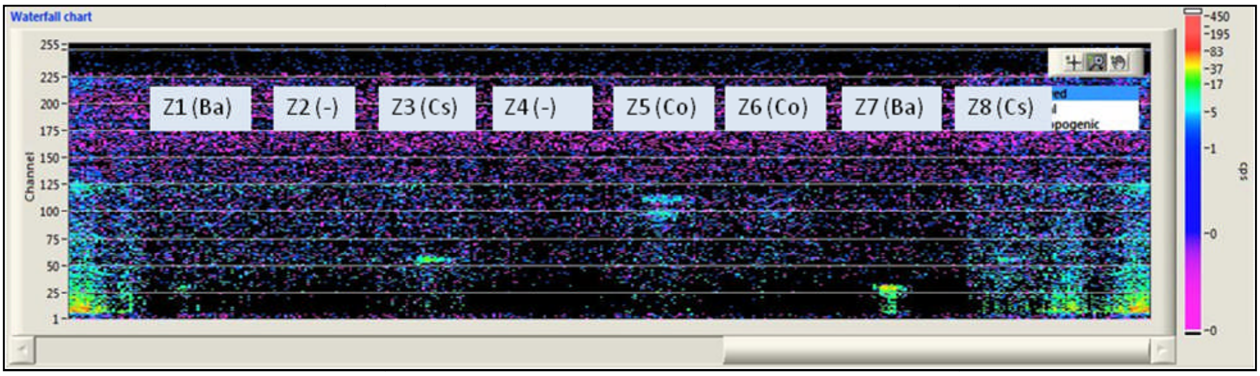

Figure 6: *Waterfall chart for north pass of exercise G1, run 1, with fixed z-scale. Approximate zone locations, and sources in each zone, are indicated.*

In run 2, while 5 of the 6 sources were located in the original run using the default auto-scaled waterfall chart, the weaker Ba-133 source in Z6 was not reported. Figure 7 shows the waterfall charts for run 2 with a fixed z-scale; here the Z6 Ba-133 source is visible, at least with the benefit of viewing both north and south passes simultaneously.

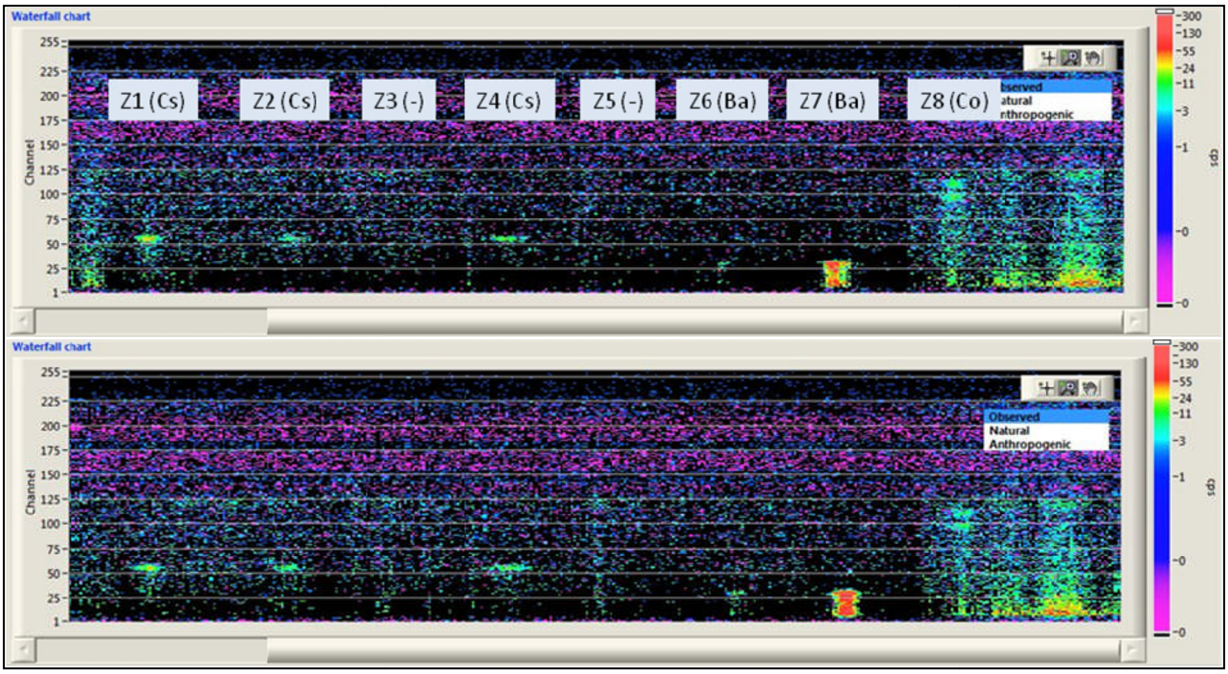

Figure 7: *Waterfall chart for exercise G1, run 2, with fixed z-scale. Upper image: north pass; lower image: south pass. Approximate zone locations, and sources in each zone, are indicated.*

6.1.2 Source direction

The detector system has no shielding on its upper surface, and determining directionality (in this case North/South position) of sources proved difficult. In the short post-processing period possible after the exercise, estimates of North/South position were poor; however with more processing time it is likely that better North/South estimates could have been provided. Figure 7 above suggests that slightly stronger signals are visible in the south image for the sources in zones Z2, Z4, Z6 and Z7, and in the north image for Z8, in agreement with the run 2 solutions in Table 2. However the differences are small, and would have been difficult to determine at the time of the exercise.

6.1.3 Source radionuclide type

Three radionuclide types were used here; Co-60, Ba-133 and Cs-137. Co-60 and Cs-137 were easily identifiable, either directly from the waterfall chart or with the aid of an accumulated energy spectrum. Ba-133 was reported as I-131, the 364 keV I-131 peak and the 356 keV peak of Ba-133 being difficult to distinguish. Figure 8 shows a detail from an accumulated energy spectrum after background subtraction. Accumulation was performed on 10 records around the peak signal from a Ba-133 source, in this case that from zone Z7 in run 2. Two photopeaks from Ba-133 - at 356 keV (channel 29) and 303 keV (channel 24) - are visible, and arguably Ba-133 could have been identified with better knowledge of the isotope's energy spectrum.

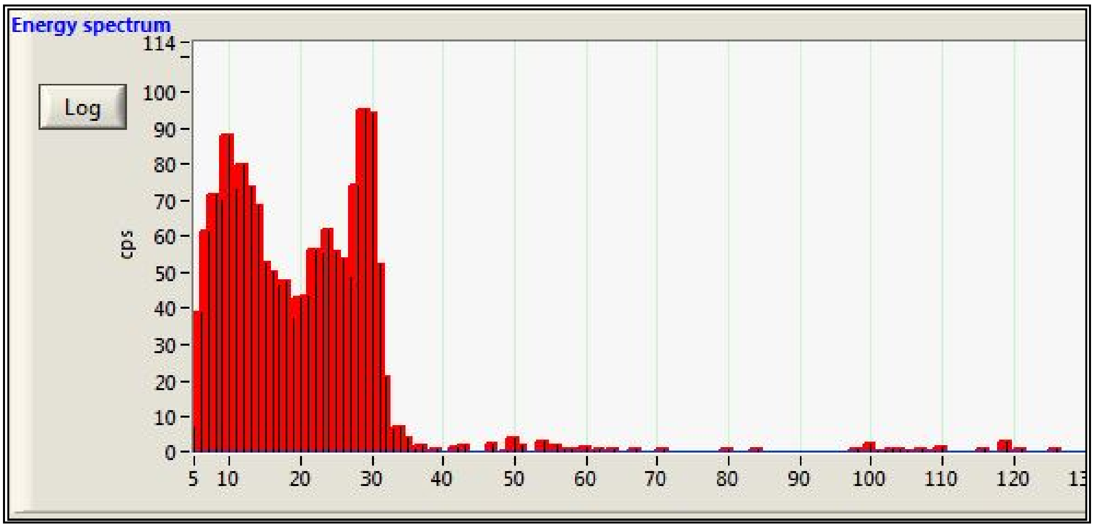

Figure 8: *Accumulated and background subtracted energy spectrum from the Ba-133 source in zone Z7 from exercise G1, run 2.*

6.2 Results - S6

Three sources were placed in the S6 search region as indicated in the exercise solution shown in Figure 9.

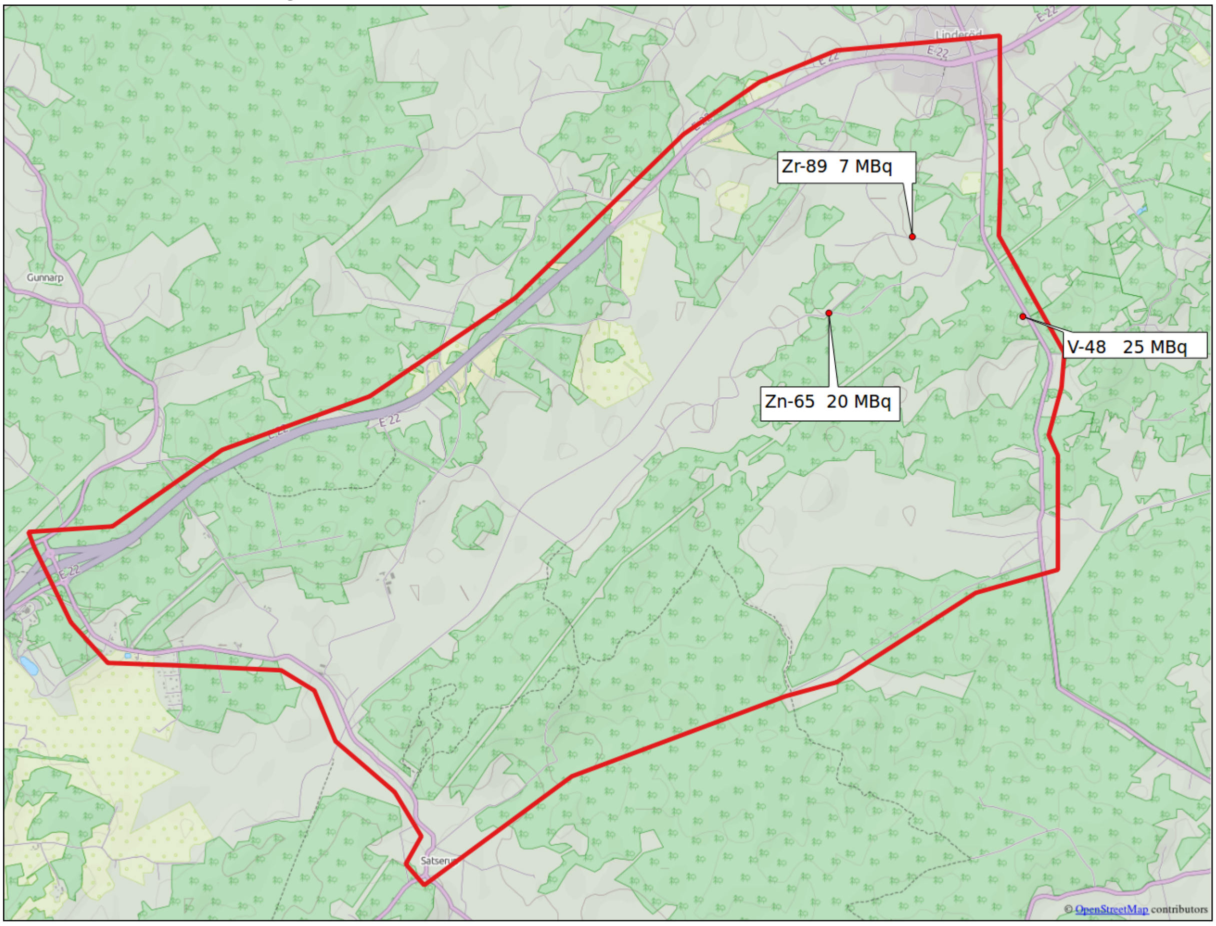

Figure 9: *Placement of sources in exercise S6. The search area is outlined in red.*

Table 5: *Results from exercise S6.*

Actual source		Reported source		
Nuclide	Activity (MBq)	Correctly located	Nuclide	Activity (MBq)
Zr-89	7	Yes	No nuclide identified	10
V-48	25	Yes	V-48 or Cd-115	8
Zn-65	20	Yes	Zn-65	0.7

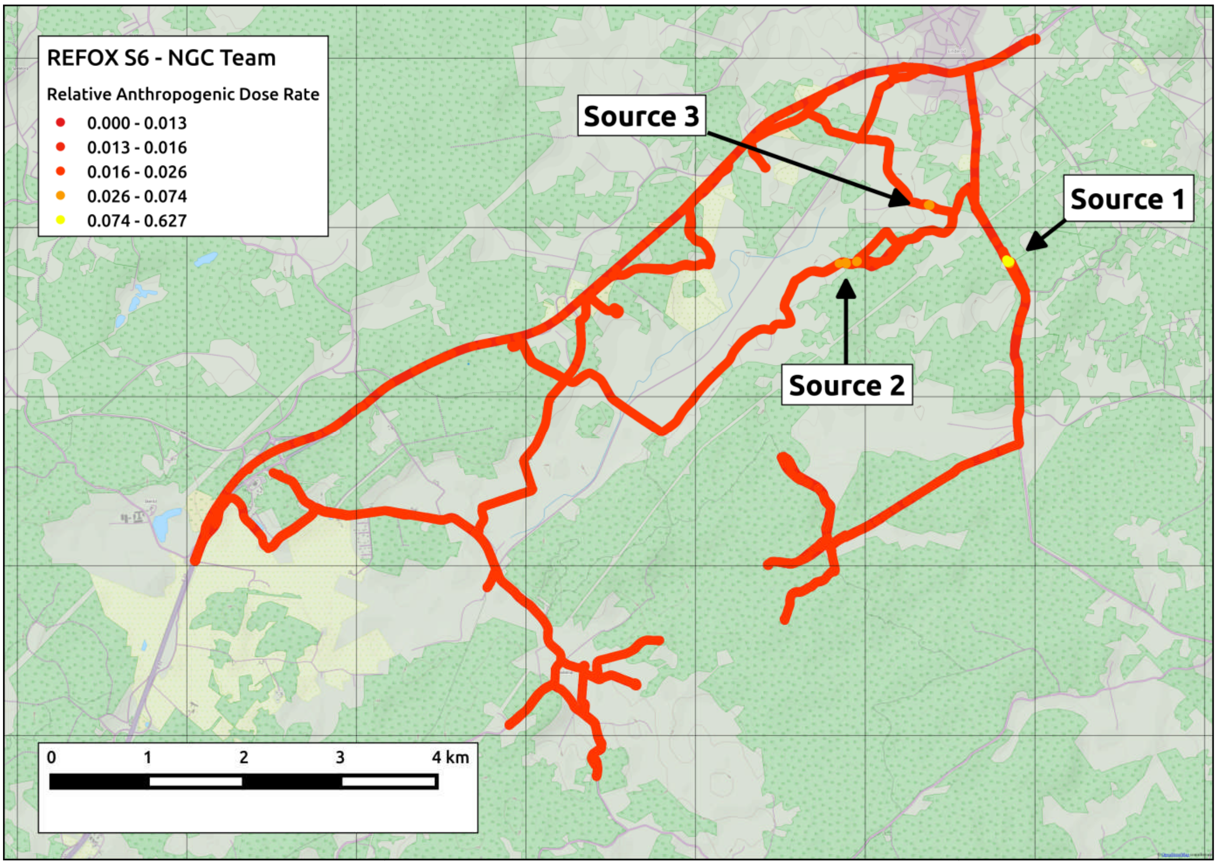

Figure 10: *Vehicle track, estimated dose rates (relative units), and detected sources from exercise S6.*

The results are shown in Figure 10 and Table 5. Three sources were found at the correct locations; Zn-65 was correctly identified, and V-48 was reported as a possible nuclide type for the V-48 source. Zr-89 was not identified. Source distances were difficult to determine due to the collimated nature of the sources, and the limited possibilities to collect data at multiple source distances; nevertheless source distance estimates were used to determine source activities using the dose rate calibration data described in section 4.3. No false positives were reported.

6.3 Results - S9

Two sources were positioned in the S9 search area, as indicated in Figure 11, and results are shown in Figure 12 and Table 6.

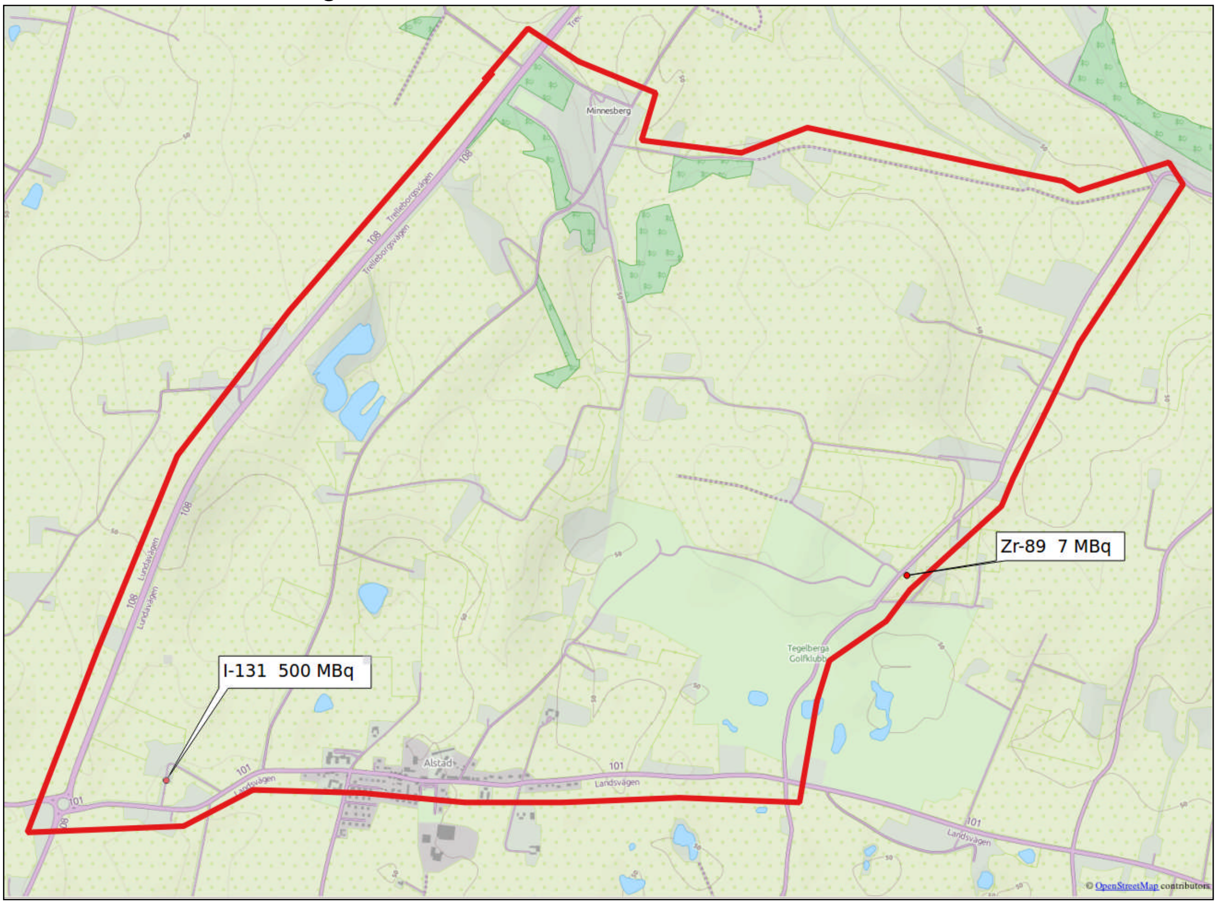

Figure 11: *Placement of sources in exercise S9. The search area is outlined in red.*

Table 6: *Results from exercise S9.*

Actual source		Reported source		
Nuclide	Activity (MBq)	Correctly located	Nuclide	Activity (MBq)
Zr-89	7	Yes	Zr-89	15
I-131	500	*Not reported*	-	-

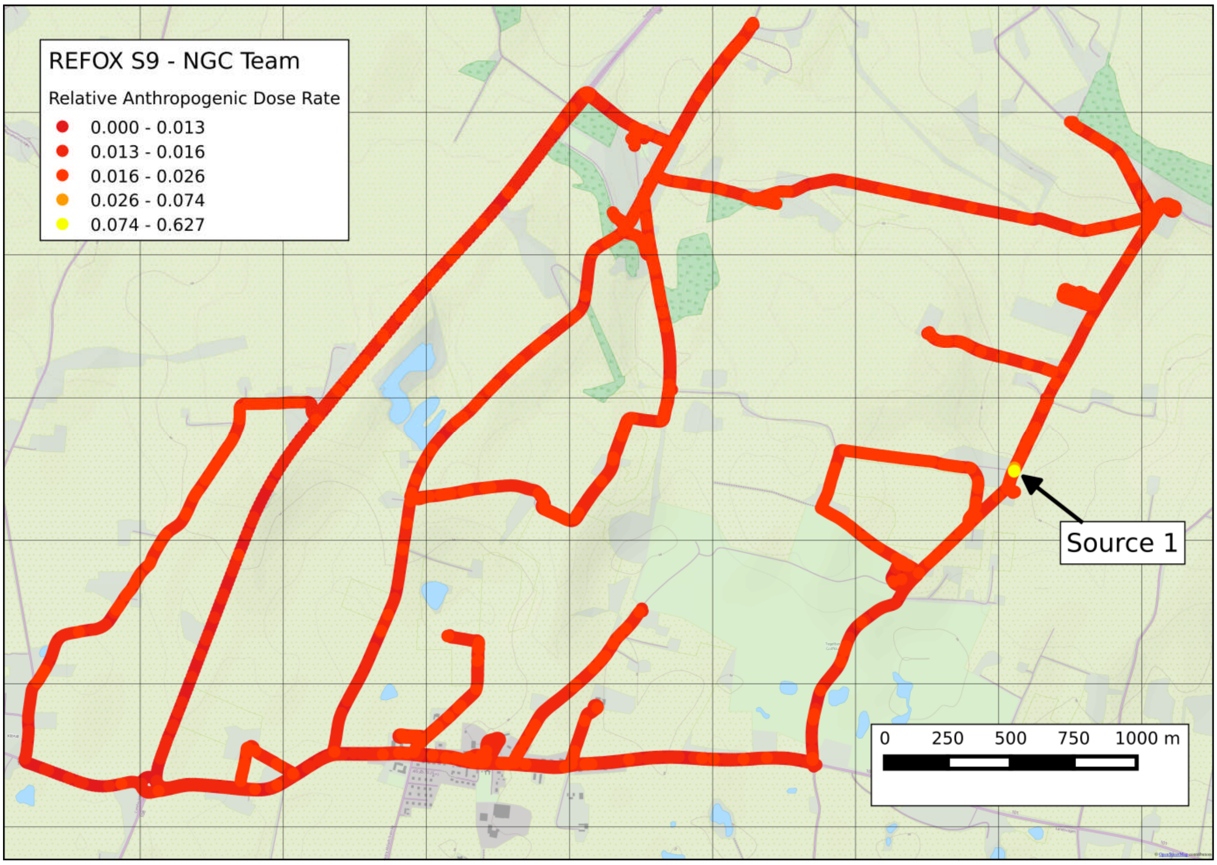

Figure 12: *Vehicle track, estimated dose rate (relative units), and detected source for exercise S9.*

Note that the marked source position in Figure 11 is slightly different from that observed in Figure 12 ; however given the strength of observed signal from multiple passes, and the extent to which the GPS track matches road features in the area, there can be little doubt that the reported location in Figure 12 reflects the real source location at the time of the exercise. The I-131 source was not detected. A source activity was estimated, but the estimate suffers from the same problems described in 6.2. No false positives were reported.

A more detailed view of the area around the I-131 location is shown in Figure 13. The breadcrumb trail here indicates the estimated anthropogenic component of dose rate, and shows considerable variation, with no obvious source location. The waterfall chart, with adjusted z-axis colour scales, suggests a possible source location, indicated by arrows. No more detailed information about the actual source placement was available.

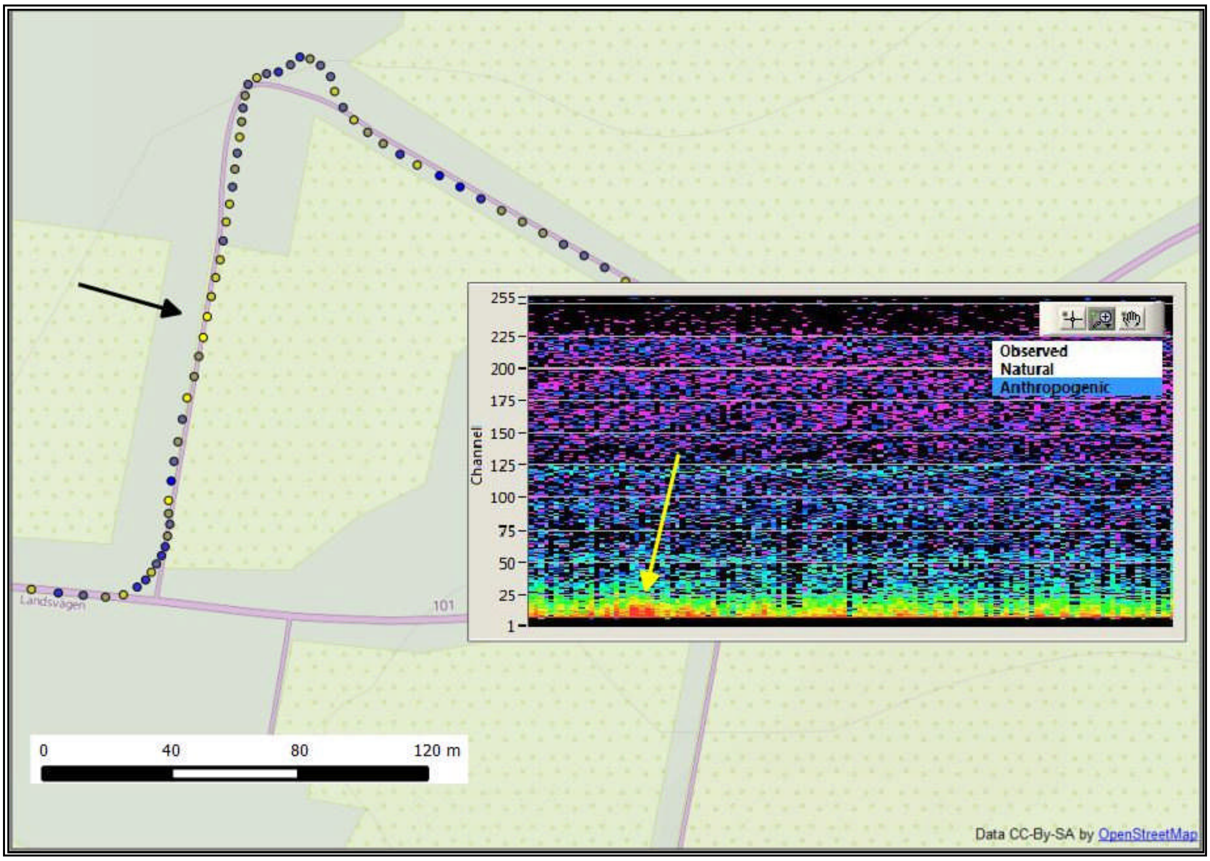

Figure 13: *Detail from S9 dataset showing vehicle track and estimated anthropogenic dose rate (blue: lower dose rates; yellow: higher dose rates). Inset: waterfall chart from same part of dataset. Arrows indicate possible source location.*

6.4 Results - R2

The R2 exercise consisted of 5 sources placed as indicated in Figure 14. Reported sources are shown in Table 7, and a map indicating the vehicle track, estimated dose rates, and interpretations of high dose rate areas, is shown in Figure 15.

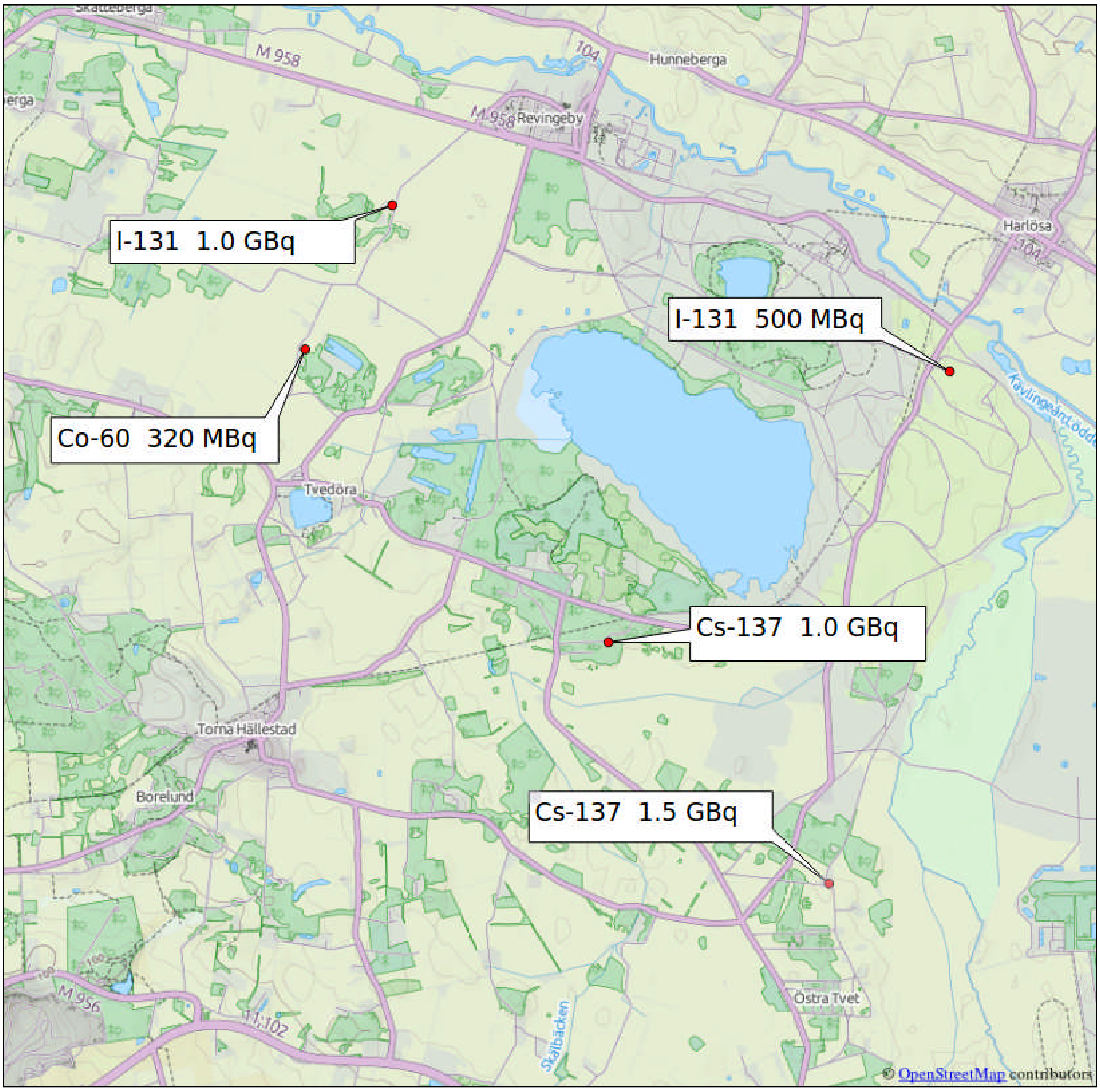

Figure 14: *Placement of orphan sources in exercise R2.*

Table 7: *Results from exercise R2.*

Actual source		Reported source	
Nuclide	Activity	Correctly located	Nuclide
I-131	1 GBq	Yes	I-131
Co-60	320 MBq	Yes	Co-60
Cs-137	1 GBq	*Not reported*	
Cs-137	1.5 GBq	Yes	Cs-137
I-131	0.5 GBq	*Not reported*	

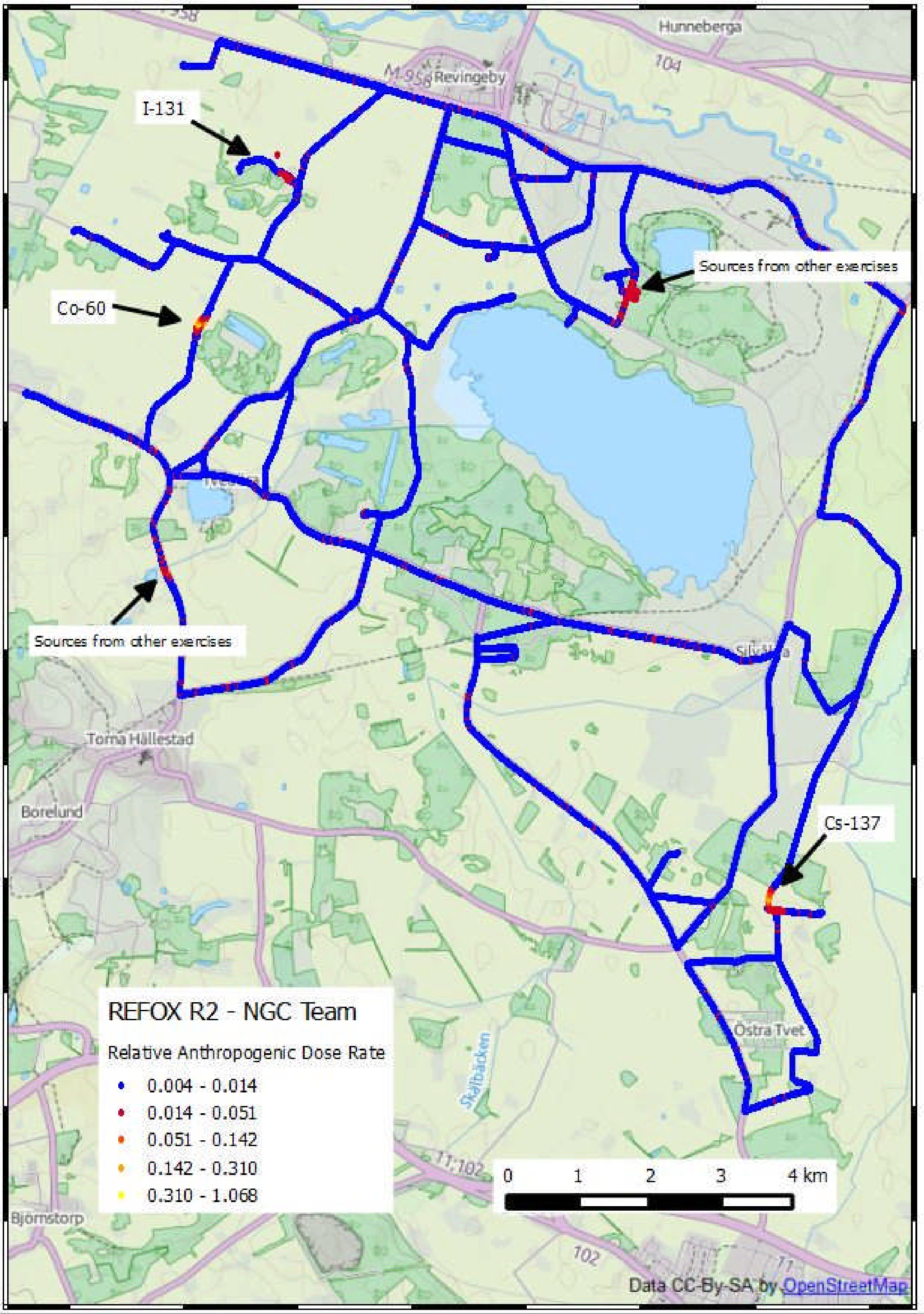

Figure 15: *Vehicle track for exercise R2. Colours indicate anthropogenic component of dose rate (arbitrary units), and reported sources are marked.*

Several REFOX exercises ran simultaneously in the Revinge area. During the R2 exercise, activity from several sources lying outside the recommended search area, and associated with other exercises, were recorded and reported; these are also indicated in Figure 15. Source activities were not estimated. Two of the exercise sources were not reported: the Cs-137 source situated roughly centrally in Figure 14, and the I-131 source situated to the north-east of Figure 14. Due to pressure of time it was not possible to investigate the north-eastern regions of the map (where the unreported I-131 source was located) in detail. The exact location of these sources is not known beyond the information available in Figure 14; it can be estimated that the team drove within around 200 m of the Cs-137 source and within around 150 m of the I-131 source. A Cs-137 signal was detected at the vehicle's closest points to the marked location of the Cs-137 source, but it was not possible to determine a clear point source origin (in contrast to the other located sources), and it was not reported as an orphan source. There were no indications of an I-131 source, either at the time of the exercise or with the aid of post-processing.

7. DISCUSSION

Determining source direction was challenging with the detector configuration used here. Future use of similar car-borne systems could benefit from shielding on one side of the vehicle, or from arranging the detector geometry such that signals from individual crystals provide directional information. Data from individual crystals were not available from the GR-820 system, but newer systems such as the RSX-5 provide this capability. NGU's own system is an RSX-5, and the GR-820 detector used during this exercise has, since REFOX, been upgraded to an RSX-5 system. These systems also have an additional 4-litre upward looking crystal (a common feature on airborne spectrometers), providing another option for directionality.

The source direction issue was particularly confusing in the R2 exercise where sources were located atop flagpoles. Figure 16 shows the vehicle track while passing a Cs-137 source. The arrows indicate the direction of travel; blue circles indicate lower dose rates and yellow circles indicate higher dose rates. The higher signals during the southward passage of the vehicle and the location of the detector on the right-hand side of the vehicle would suggest the source location to be west of the road; in fact the flagpole source was to the east. This is likely explicable by the difference in solid angle extended at the detector by the source in each direction of travel. Figure 17 is a schematic of the southward travel direction (out of the page) where, although being slightly further from the source, a larger solid angle is realised than when driving northward, as in Figure 18.

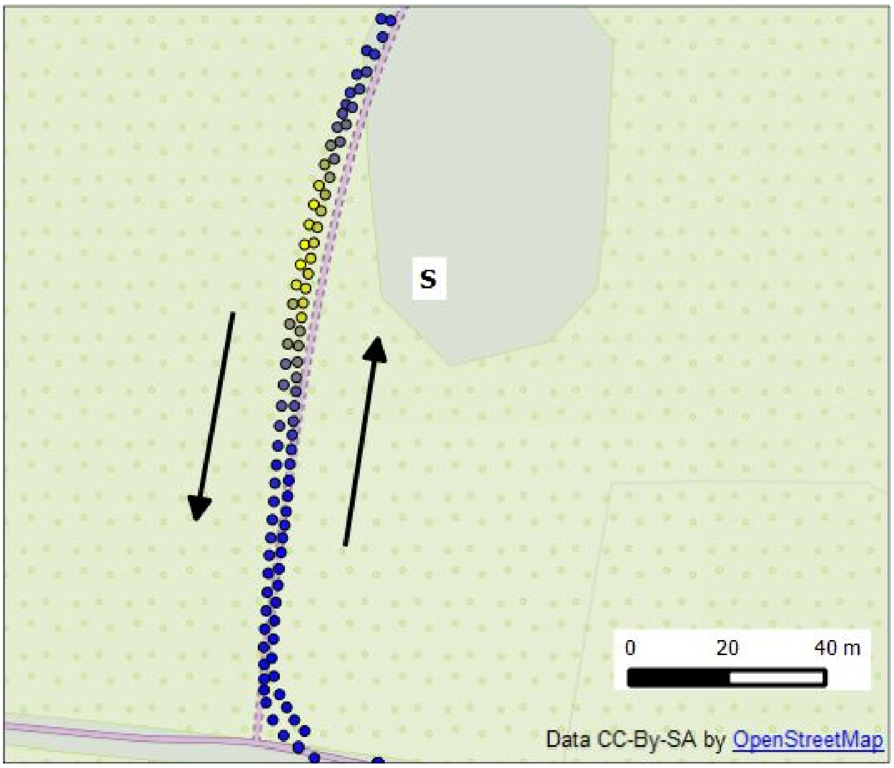

Figure 16: *Vehicle track and dose rate (blue: lower dose rates; yellow: higher dose rates) around the Cs-137 source in exercise R2. S marks the approximate source location. Arrows indicate direction of travel.*

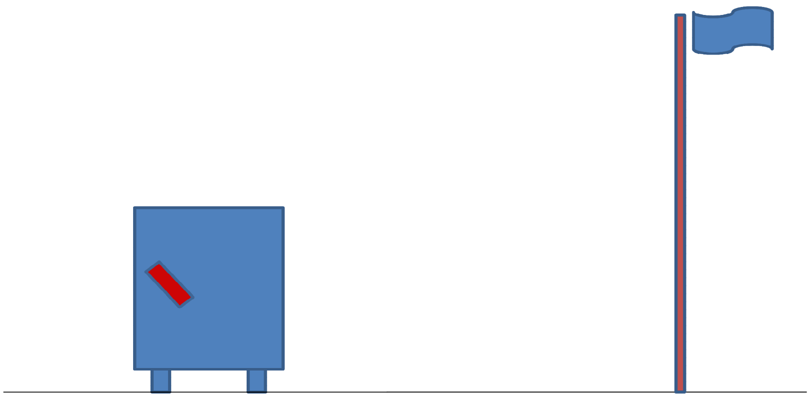

Figure 17: *Schematic indicating relative geometry of source and detector when vehicle is coming "out of the page", corresponding to the left-hand (southward) track in* Figure 16*.*

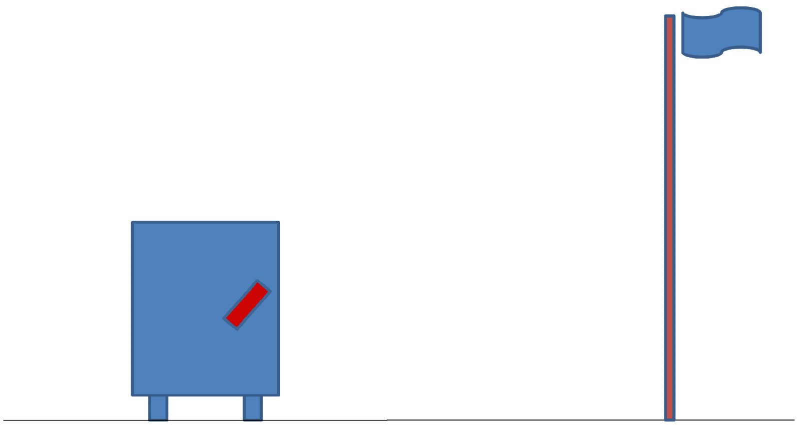

Figure 18: *Schematic indicating relative geometry of source and detector when vehicle is going "into the page", and corresponding to the right-hand (northward) track in* Figure 16*.*

8. CONCLUSIONS

The 16 litre NaI system operated by NGU at REFOX appears to have been **capable of detecting** all the sources in the G1 pre-exercise. Software settings and operator methods however, were not always appropriate for making full use of this sensitivity, some sources being visible only with post-processing. Most sources in the S6, S9 and R2 exercise were located.

Source identification was straightforward in the case of Cs-137 and Co-60, but more challenging for less commonly encountered sources, or lower energy sources, with I-131 being mis-identified as Ba-133 in the G1 exercise. On two separate occasions (S9 and R2) a 500 MBq I-131 source was not detected, although post-processing in the S9 exercise revealed a possible source.

Determination of **source direction** in real-time was challenging due to the detector configuration; future car-borne exercises with similar hardware may benefit from shielding on one side of the detector.

Although **source activities** in S6 and S9 were reported, determination of activity requires a knowledge of source distance together with a dose-rate calibration. Both of these were problematic due to the difficulty in collecting data from a range of vehicle-to-source distances, and the dose-rate calibration issues discussed in 4.3.

In post-processing of the G1 dataset, only a brief analysis concentrating on waterfall display settings has been performed here; the REFOX orphan source exercises, and the G1 exercise in particular, provide useful datasets for studies of processing approaches, and for comparisons of the sensitivity of different detector systems, although no such comparisons have so far been undertaken. Such studies may help to optimise instrument settings and improve operator methodology for future car-borne measurements.

9. ACKNOWLEDGEMENTS

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