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Mobile Measurement: Field Exercise in Fallout Mapping in the Belarusian Exclusion Zone (MOBELRAD)

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Abstract

Car borne measurement systems are and are likely to remain a mainstay in the emergency response arsenal of many countries to incidents involving widespread radioactive contamination as evidenced recently by the events in Fukushima. Such systems constitute a useful means of support provision in situations where another country may be handling a contamination incident. As for any analytical technique, competence must be maintained via exercising of personnel and testing of equipment. For car borne measurement this is intrinsically more difficult than for other activities in emergency response as reproducing the conditions in which such measurements are often required to be made in actuality is impracticable. The MOBELRAD activity, aimed at the provision of an exercise opportunity in making mobile measurements under complex conditions, involved the conducting of such measurements by a number or teams from the Nordic countries within the territory of the Belarusian Exclusion Zone. The exercise involved the making of measurements along a comprehensively precharacterised route through the zone, extending from the borders of the zone to within 10 km of the Chernobyl power plant. The route covered various types of road surface, differing levels of contamination, different terrain types and the teams utilised equipment ranging from small sized LaBr detectors to large volume NaI. The experiences of the teams highlighted the difficulties of making such measurements in landscapes where redistribution processes have had an effect on the distribution of contaminant nuclides and the importance of ensuring appropriate detector-geometry configurations. The exercise demonstrated the suitability of the countries chosen equipment suites in provision of measurement capabilities in third party countries in the event of a serious contamination event and the robustness of such equipment under field conditions.

Key words

Mobile gamma spectrometry, Chernobyl, Exclusion Zone

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Mobile Measurement: Field Exercise in Fallout Mapping in the Belarusian Exclusion Zone (MOBELRAD).

Final Report from the NKS-B Project MOBELRAD (Contract: AFT/B(14)4).

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1.0 Introduction

Car borne measurement systems are and are likely to remain a mainstay in the emergency response arsenal of many countries to incidents involving widespread radioactive contamination as evidenced recently by the events in Fukushima. As car borne systems are a powerful tool for mapping and monitoring contamination that have the advantage of being operable by small teams, they constitute a useful means of support provision in situations where another country may be handling a contamination incident. As for any analytical technique, competence must be maintained via exercising of personnel and testing of equipment. For car borne measurement this is intrinsically more difficult than for other activities in emergency response as reproducing the conditions in which such measurements are often required to be made in actuality is impracticable. Related to this is the fact that it is also relatively difficult to exercise in the provision of support to another country or conversely, practice in addressing the challenges posed in a situation where support is being received.

Exercise opportunities in mobile measurement have been provided in recent years by national activities, regional activities such as those within Barents Rescue etc., NKS activities and larger international efforts. A recent example of an exercise involving an international assistance dimension has been the RANET field exercise in Fukushima in May 2013. In relation to the Nordic context, it is fair to say that mobile measurement activities, aside from one or two examples, have been conducted in relation to radioactive contamination levels as are to be found in the Nordic countries and have not dealt with the "international support" aspect in that participants tended to use their own vehicles, in environments similar to those of their own countries with a level of organisation on the ground arguably atypical of the conditions that would exist in the aftermath of a large scale accident.

Considering the above, the MOBELRAD activity was intended to address some of these aspects. The activity involved measurement of radioactive contamination in an area exhibiting significant contamination and which was far removed from the Scandinavian/Nordic environment in which NKS countries are most used to honing their skills. The activity was intended, to an extent, to test the abilities of the participating teams in the field, removed from their usual support structures, in a complex and challenging environment. The following can be considered as being representative of the challenges the participating teams had to address:

- A highly heterogenous contamination situation featuring some of the highest contamination levels in Europe.

- A contamination environment in which signals not only arise from the ground but also from the trees and vegetation which exhibit significant levels of contaminants in their tissues.

- Rugged terrain, rural setting.

- A previously well-mapped and characterised area of contamination with good knowledge as to the “true” situation.

- Isolation from the support facilities of the organisations head offices.

- Liaising with both the other teams on the ground and the host country.

The activity was intended to provide an opportunity for the participating teams to test their performance in a radiation environment of a complexity not typically found in Scandinavia. The teams were required to perform as they would if they had been providing support after an actual accident. The activity was intended to provide a useful opportunity for the participants to train new scientists or exercise older ones in addition to testing the teams’ self reliance in the field. The activity provided a reasonably unique opportunity to test, if so desired, communications/reach back with home base in an area where mobile communications coverage is uneven at best. Perhaps most importantly, the activity provided a chance for teams to assess their performance in relation to the actual situation on the ground (which has been extensively mapped in detail in past years) as well as providing a chance to compare results with the othr teams participating.

2.0 The Belarusian Exclusion Zone

The most contaminated regions in Belarus occur in the southern reaches of the Gomel Region along the border with the Ukraine, the Belarusian exclusion zone beginning just south of the town of Khoiniki. The most contaminated areas are sealed off from public access and now function as a scientific nature reserve. All entry to and activities within these areas are strictly controlled by the relevant authorities. An approximate indication of the controlled zone is provided in Figure 1 including the main settlements in the area.

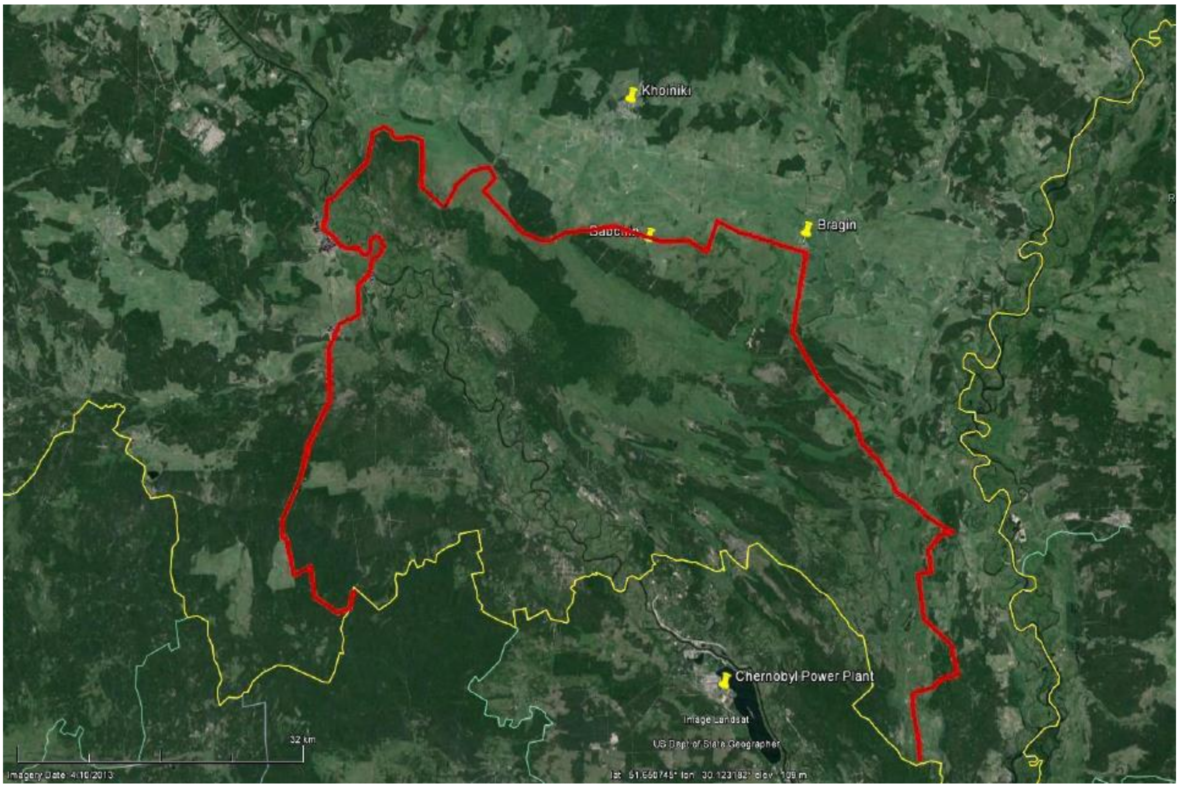

Figure 1. *The extent of the PSRER, delineated in red, and major settlements. The location of the Ukrainian- Belarus border is also indicated as well as the location of the Chernobyl power plant.*

Heaviest contamination, in excess of 1.4 MBq/m^2 of ^{137}Cs is found in the southernmost parts of the zone nearest the reactor (the reactor is, at its closest, some kilometers from the southernmost extent of the Belarusian zone and is visible over the trees in places) although patches of high contamination can be found in many places throughout the zone. Significant amounts of ^{90}Sr are also present (up to 3 MBq/m^2) with some ^{241}Am (which has approximately doubled in concentration of the past twenty years, currently of the order of up to 100 kBq/m^2), actinides (^{238}Pu up to 37 kBq/m^2; ^{239,240}Pu up to 74 kBq/m^2) and in places ^{154}Eu. Estimates indicate that approximately 1/3 of the radiocesium and 70% of the strontium released from Chernobyl ended up on the territories of the the PSRER. The broad picture of the contamination pattern in relation to ^{137}Cs is given in Figure 2. On a local scale, the contamination is highly heterogenous (over scales of 10’s of meters or less). Significant contamination is also present in the tree canopy and above ground vegetation, in water bodies and courses and in sediments therof.

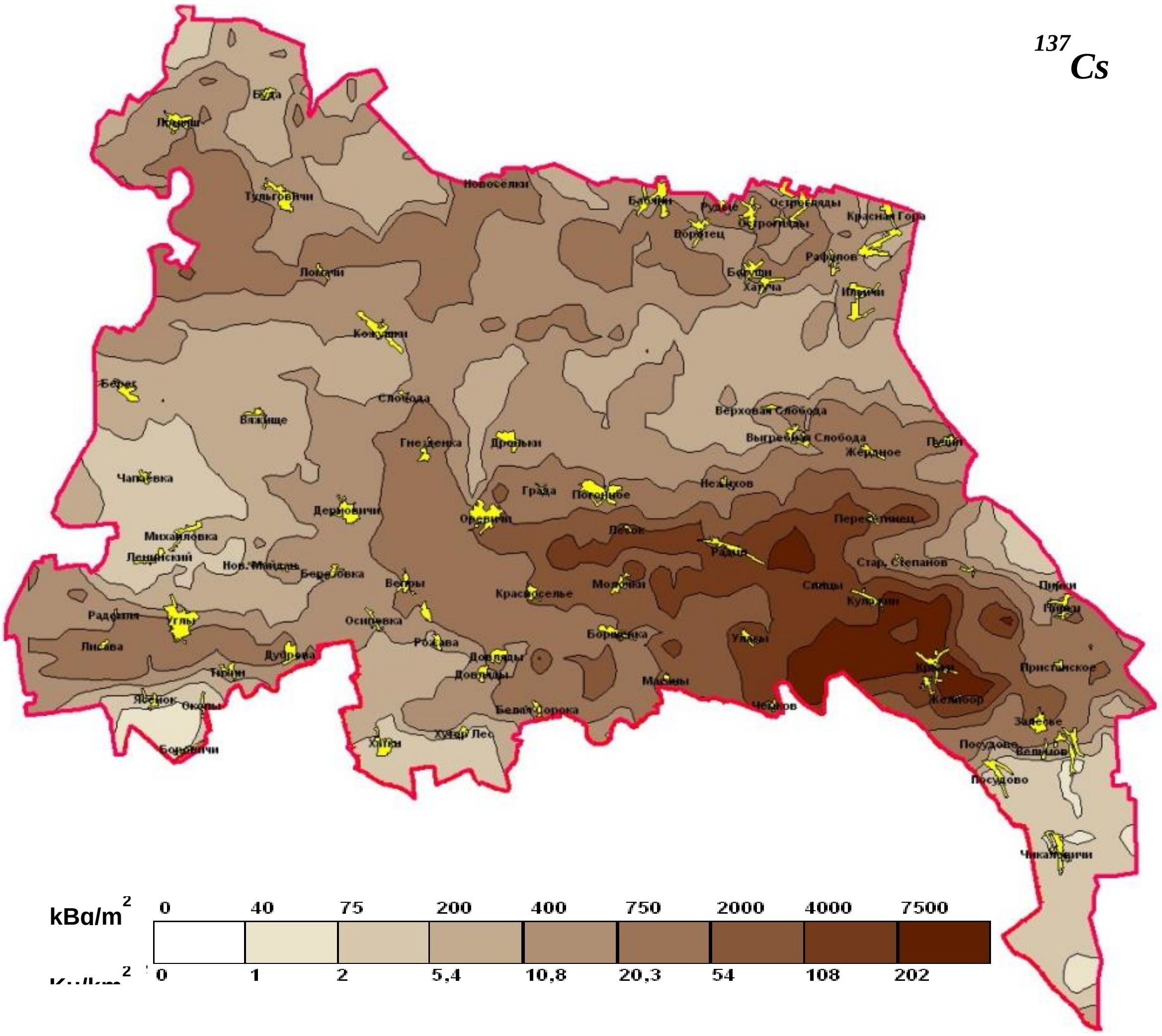

Figure 2. *Current contamination densities of ^{137}Cs over the territory of the PSRER.*

The regulations of the Central Committee CPB and Council of Ministers of BSSR № 59-5 from February, 24th, 1988 established a nature reserve on the land of the Belarusian sector within a 30-km zone of the Chernobyl NPP. The reserve commenced operations in September, 1988 after the order № 354-p from August, 23rd, 1988 by Gomel District Executive Committee "*About the formation of temporal administration of the Polessian state ecological nature reserve*". It initially consisted of 131.3 thousand hectares and was managed by the State Committee on Ecology of the Republic of Belarus. The regulation of the Council of Ministers of Belarus № 122 from February, 10th, 1989 renamed it to the Polessian State Radiation-Ecological Reserve (PSRER) which at the present is managed by the Department for Liquidation of the Consequences of the Accident at the Chernobyl NPP of the Ministry of Emergency Measures of Belarus. In 1993 the PSRER was expanded to include 84.8 thousand more hectares of land and its area then made up a total of 216.2 thousand hectares.

Administratively it occupies part of the Hoyniksky, Braginsky and Narovlyansky areas of the Gomel district which earlier had 92 settlements, now all abandoned. It is structurally divided into three distinct sites located on the territories of the corresponding areas and 16 forest areas.

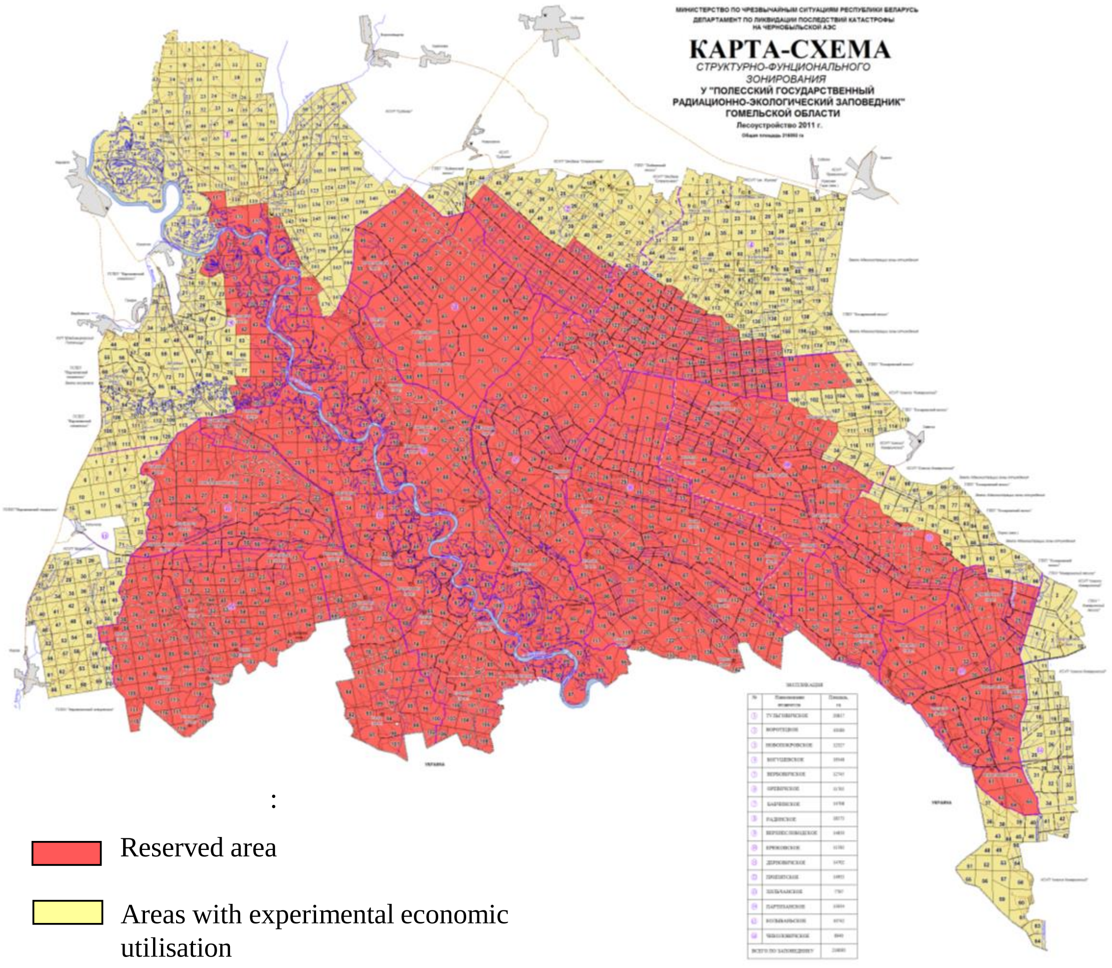

Figure 3. *Division of the PSRER into areas of total access restriction and areas where trial schemes in relation to economic activity take place*.

The Belarusian zone is managed by the staff of the reserve. This entity is responsible for managing the zone, controlling entry, conducting scientific research etc. It has a workforce that is probably approaches 700 and answers to the Ministry of Emergency Measures. They have their main base within the zone at a facility called Babchin as well as operating two other similar facilities and a number of research and fire stations much farther into the zone itself. The reserve also operates some experimental farms and other sites which function to serve the authorities initiatives in trying to investigate possible uses for the zone. The Babchin facility includes laboratories, workshops and administrative facilities for the staff as well as basic overnighting facilities for the staff and a canteen. There is also a museum and other things.

The primary goals of the PSRER in their management of the zone are:

- Protection of the territory from unauthorized entry and fire prevention;
- Measures to prevent the spread of radionuclides to adjoining areas,
- Radioecological monitoring of land, air, water, flora and fauna;
- Research on the influence of radioactive pollution on flora and fauna,
- Afforestation of the land, primarily those subject to wind and water erosion.

Twelve control posts exist within the zone, manned on a 24 hour basis for the purpose of protection of the territory from unauthorized entries. All perimeters and access points are manned and patrolled. Warning notices and barriers are visible on the perimeter of the reserve and on roads approaching too and within the zone. Warning signs as to areas of heavy contamination can be found within the zone although the accuracy of some of them, given their age, is unclear. Extensive fire prevention measures have been constructed and fire protection consists of fire breaks and observation posts. Approximately 155 km of fire breaks with a width of 40 m, 200 km with a width width of 15 m and 1440 km of deforested mineralized zones have been created to hinder fire spreading. Some 99 artificial water reservoirs have been created to assist fire fighting and 37 observation towers have been established in order to monitor for fire outbreaks.

Staff of the PSRER are subject to special regulation in relation to restriction of the time they may spend in the zone, the useage of personal radiation monitoring devices, individual control regimes for exzternal and internal exposure, decontamination procedures for personnel and vehicles and health checks.

The PSRER is located in a subzone of foliar and pine woods, forested areas making up 109.7 thousand hectares (51.1 % of the territory) of which pine woods constitute 43.9 % of the afforested areas, birch woods 30.7 %, black alder 12.4 %, oak 6.3 % and other species 6.7 %. The territories not covered by woods (basically abandoned agricultural lands) constitute 82.2 thousand hectares (38.0 %) and non-agricultural unforested lands occupy 20.1 thousand hectares (9.3 %).

Figure 4. *Representation of some of the various landscape types found within the territory of the PSRER.*

Some 884 species of vascular plants are found in the territory including a high number of rare and protected species. Over 60 species of mammal are found in Belarus, 46 species being found in the PSRER. These species include 6 of the 7 red listed species found in Belarus and include brown bear, lynx, wolf and European bison. Przewalski horses have been regularly observed since 2007.The three scientific departments of the PSRER cover radioecological monitoring, the ecology of vegetation, the ecology of fauna and a laboratory for spectrometry and radiochemistry. The laboratory of spectrometry and radiochemistry is accredited according to the requirements STB ISO/MEK 17025 since 2005. The PSRER also conducts studies into possible methods for the rehabilitation of the contaminated zone. These investigations include the construction of an experimental bee apiary and gardens and a horse breeding programme initiated in 1996.

In relation to the conducting of mobile measurement within the territory of the PSRER a number of challenges are apparent. Road surfaces within the reserve bear witness to the area having been abandoned for over 30 years and vary from asphalt surfaces in various states of repair to tracks established on virgin ground by the repeated passage of vehicles (see Fig. 5). In places there is significant overhang of the road by vegetation and trees. As there has been significant uptake of radionuclides by trees and vegetation in the reserve, the presence of such overhang and the radionuclide content of trees and bushes pose challenges for mobile measurement of deposition levels of radionuclides.

Figure 5. *Depiction of the range of road surface types within the PSRER*.

The topography of the area is reasonably flat and even, small elevations and depressions being encountered locally. Small villages and buildings are encountered along the road but are in the main largely dominated by surrounding vegetation and trees. Numerous water features are present both beside and under the roads in places. These consist largely of small streams, rivers, drainage and irrigation channels, flooded areas and small lakes and swamps. Forested areas are present throughout the reserve – comprised of managed plantations on the peripherery of the reserve (see Fig. 3) and more natural stands of trees in the interior. In all areas extensive and wide firebreaks have been constructed, the exposed overburden along these breaks being mostly vegetation free and consisting of exposed or deposited sand. There are essentially no visible outcrops of the underlying geology and few buildings constructed of natural stone in the vicinity of the roads. Some parts of the reserve, in particular near research stations in the interior have been modified by having the upper layers of soil removed to reduce ambient dose rates but these modifications are primarily confined to the immediate surroundings of these facilities.

3.0 The MOBELRAD Activity

The primary focus of the MOBELRAD activity was the provision of an opportunity for participants to conduct vehicular based mobile measurements in a complex environment providing challenges over and above those faced by the participants in normal operations in their own countries.

3.1 The Participating Teams

Five teams were present for the MOBELRAD activity being drawn from Norway, Sweden, Denmark and Iceland.

Team 1. Iceland

The following equipment was deployed by the Iceland team during MOBELRAD. Radiation Pager-S (Sensor Technology Engineering Inc.), two units. This is a small, self contained gamma-ray radiation detector, which is specifically designed to be easily used by trained security forces and emergency responders. It is one of the most sensitive radiation detectors for its size commercially available. The detector is a 1.3 x 3.8 cm Caesium Iodide Scintillator with a typical sensitivity of 1.8 cps per microR/hr (^{137}Cs gamma). The unit‘s response is extremely fast. It has a function that updates the radiation background value to the average of the past 6 seconds when selected. The team‘s tests under controlled conditions (using a 7.4 GBq ^{137}Cs calibration source at a distance of 30 m) have shown that the unit starts alarming at around 0.3 µSv/h and saturates at around 110 µSv/h. These radiation pagers are well worth bringing to field work as they require little attention, and are useful in indicating rapidly rising radiation levels.

Rad-Eye G-10 (Thermo Scientific), two units. This is a portable dose- and dose rate meter for measurement of ambient equivalent dose rates (Sv/h) of gamma and X-ray radiation. The detector is a GM tube. The sensitivity range of the unit was quite suitable for the task and the two units showed acceptably uniform results but it was noted that the response time is rather slow, expecially compared to the Radiation Pagers-S. Rados RDS-110 Multi-purpose Survey Meter with external GMP-11 probe for Beta detection (Rados Technology Oy), one unit. This meter worked well and is easy to use although it does not store data, which is a drawback, and the response time could be faster. With the external probe it can be suitable as a contamination meter.

Exploranium GR-135 Plus (SAIC). One unit with two detectors, NaI, GM for gamma and He^3 for neutron detection. The main modes of use were SEARCH, DOSE and IDENTIFY. Spectra can be collected and saved. This instrument worked well during the field operation. The response time is fast. The dominating nuclide was identified as ^{137}Cs throughout the area, but in the strongest radiation fields the instrument was not able to make an identification.

INFIELD Backpack system (D.O.E. Remote Sensing Lab), one unit. This is a search unit that detects gamma and neutron radiation using a NaI detector and an array of pressurized Helium-3 neutron detector tubes. It is very useful for searching for missing sources but with the software currently installed it is essentially useless in an environment that has generally high radiation, since there is no calibration or other interpretation of counts to dose. With updated software it will be excellent as it is relatively compact and lightweight, and the sensitivity is quite enough for the area.

SPARCS - SPectral Advanced Radiological Computer System (D.O.E. Remote Sensing Lab). This is a sensitive survey system that is portable and can be mounted in vehicles, boats or aircraft for a variety of applications, such as radiation searches, portal monitoring, baseline surveys and emergency response missions. The detectors are two NaI 5 cm x 10 cm x 40 cm (4 l total). The system is designed to find, identify and warn of radioactive materials. It performs real time identification for 7 isotopes – ^{235}U, ^{238}U, ^{239}Pu, ^{232}Th, ^{241}Am, ^{137}Cs and ^{60}Co and allows for collection of spectra. The sampling rate is 1s by default but can be changed. The system‘s response is fast. The default product is a map with a GPS track that includes all measurement data. Unfortunately, the system turned out to be inoperable because of an internal electronic failure that could not be fixed on site. However, similarly to the backpack system, the software does not seem to be well suited for this particular application since it lacks any direct link to dose, and only a proportional approach is practicable.

Unfortunately, it could not be tested whether the size of the detectors would be excessive for this particular environment.

Figure 6. *The SPARCS mobile measurement system*.

The system requires one power outlet and uses a power cord of 3 m length which is included in the system. The system can be run off a cigarette lighter type connection or can also be accommodated using a bare wire connection to a standard car battery. The SPARCS detector box containes two NaI detectors of dimensions 5 cm x 10 cm x 40 cm and includes the HV power supplies, preamplifiers and multi-channel analyzers. The SPARCS system is flexible in how it can be mounted but is most conveniently contained within the vehicle and therefore requires no special mounting system.

Team 2 and 3. Swedish Radiation Safety Authority (SSM) and Lund University

Both Swedish Teams (Teams 2 and 3) employed the same equipment type. This equipment was comprised of:

- A backpack
- A 1,5” x 1,5” LaBr-detector with a Ortec Digibase mounted in a robust and moisture proof plastic tube.
- A GPS and a GPS antenna
- A tablet PC connected to detector and GPS for data collection
- A tablet PC wi-fi connected to the main computer for viewing the collected data.

Figure 7. *The backpack system of the Swedish teams*.

Under normal circumstances the equipment does not require power to be drawn from the vehicle. The systems can run for approximately 6 hours on their own batteries. The detector in its tube was removed from the backpack during measurements in the car. The weight of the tube was 1-2 kg. It could be mounted with tape or simple straps wherever it was possible, either on the roof or on the inside of a window. The cable between the tube and the computer in the backpack is 5 meters. No special requirements were necessary for mounting on the vehicle. The Swedish teams also brought a few hand held detectors for dose rate measurements and search for hot spots.

Team 4: Norwegian Radiation Protection Authority (NRPA)

Team 4 employed a Radiation Solutions RS700 4 l NaI detector with a RS701 console and laptop. The system required power inputs of 12 V DC and drew approximately 27 W total. A standard cigarette type connection was employed throughout with no problems. The detectors were fully robust and could be mounted on the floor of the vehicle.

Figure 8. *Team 4's detectors mounted in a vehicle with associated electronics. Only one of the shown detectors was brought to MOBELRAD.*

Team 5. Danish Emergency Management Agency (DEMA)

Team 5 employed a Radiation Solutions RS-725/21, 0.39 l (3” x 3”) NaI detector of weight 6.8 kg, and dimensions 381 mm x 101 mm x 101 mm. The associated electronics were a Radiation Solution RS-701 Console of 6.8 kg weight and dimensions 233 mm x 112 mm x 198 mm. A laptop computer was also used.

Figure 9. *Team 5 equipment*.

A Radiation Solutions RS-220 hand-held gamma-ray spectrometer was employed. It was intended that all equipment would be mounted in the vehicle – no roof mounting was necessary. The equipment ran on 12 V DC supply and draws a total of about 22 W. The equipment can use normal “cigarette lighter” type connections and has a cable length of approx. 3-5 m. The equipment is built for carborne measurements and should be able to withstand normal use in a moving vehicle. The dose rate calibration for the Danish DEMA equipment was done with a 7 GBq ^{137}Cs source in a Sentinel Instrument Calibrator Model 773. The source was placed outside of the car (not that employed in MOBELRAD) and the detector was irradiated with various dose rates both with the car doors opened and closed. The measured dose rates were compared to measurements with an RDS-200 dose rate monitor placed close to the detector during irradiation. The results of the measurements lead to a dose correction factor of 6.37 which was applied to the dose rates measured in the field with the 3” x 3” NaI crystal (Fig. 10).

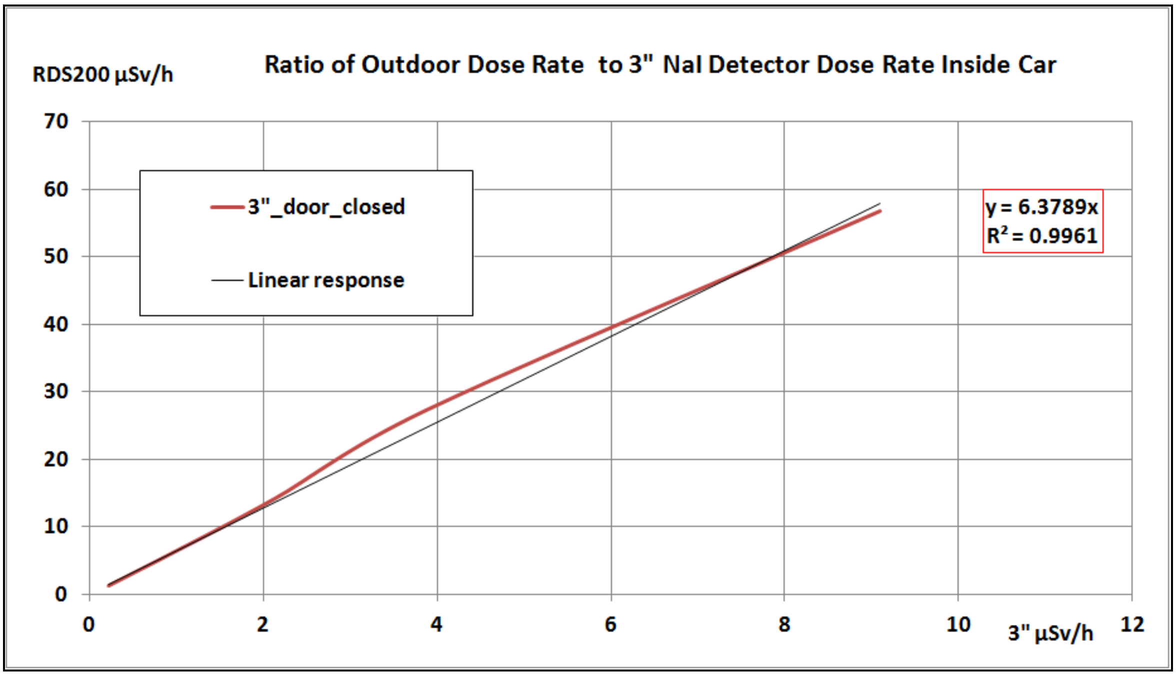

Figure 10. *The ratio of dose rates measured with RDS 200 (open door and outdoor dose rate) and with 3" x 3" NaI crystal with the door closed.*

Later, on September 15 when dose rates were measured at the calibration site in Belarus, the DEMA team measured 0.32 µSv/h with the RDS200 dose rate monitor and 0.29 µ Sv/h with the 3" x 3" NaI crystal. This should be compared to the dose rates obtained by the scientists at PSRE which was between 0.25 and 0.37 at 1 m above ground.

The 3" x 3" NaI crystal was also calibrated for Equivalent Surface Concentration (ESC) using a 1.24 m x 1.36 m sheet with a surface concentration of 31.2 kBq/m^2 ^{137}Cs at the date of measurements. Again, the NaI detector was placed on the floor of the car in horizontal position. The Equivalent Surface Concentration (ESC) represents the amount of true, homogeneous surface contamination pr. unit area that gives the same primary fluence rate at a certain energy at a certain height as does the actual depth distributed source. In practice the detector count rate and not the fluence rate was used. ESC represents the situation shortly after a fallout where is lying on the surface.

Twenty-three measurements were made, 13 of which only represented the one side of the car and therefore were doubled to represent the entire car. The counting efficiency just a few meters from the car was very low and approaching normal background fluctuations. This probably means that the calculated ESC sensitivity of 0.748 cps/(kBq/m^2) is underestimated. The positions of the sheet and three examples of measured spectra (T, C and G) are shown in

Fig. 11. The spectrum for G and further away from the car approaches the background zero level. A corresponding sensitivity for a 4 l detector on rooftop (composite case) is 20.3 cps/(kBq/m^2). For a 3" (aluminum case) on rooftop one might expect a sensitivity of 1.5 cps/(kBq/m^2).

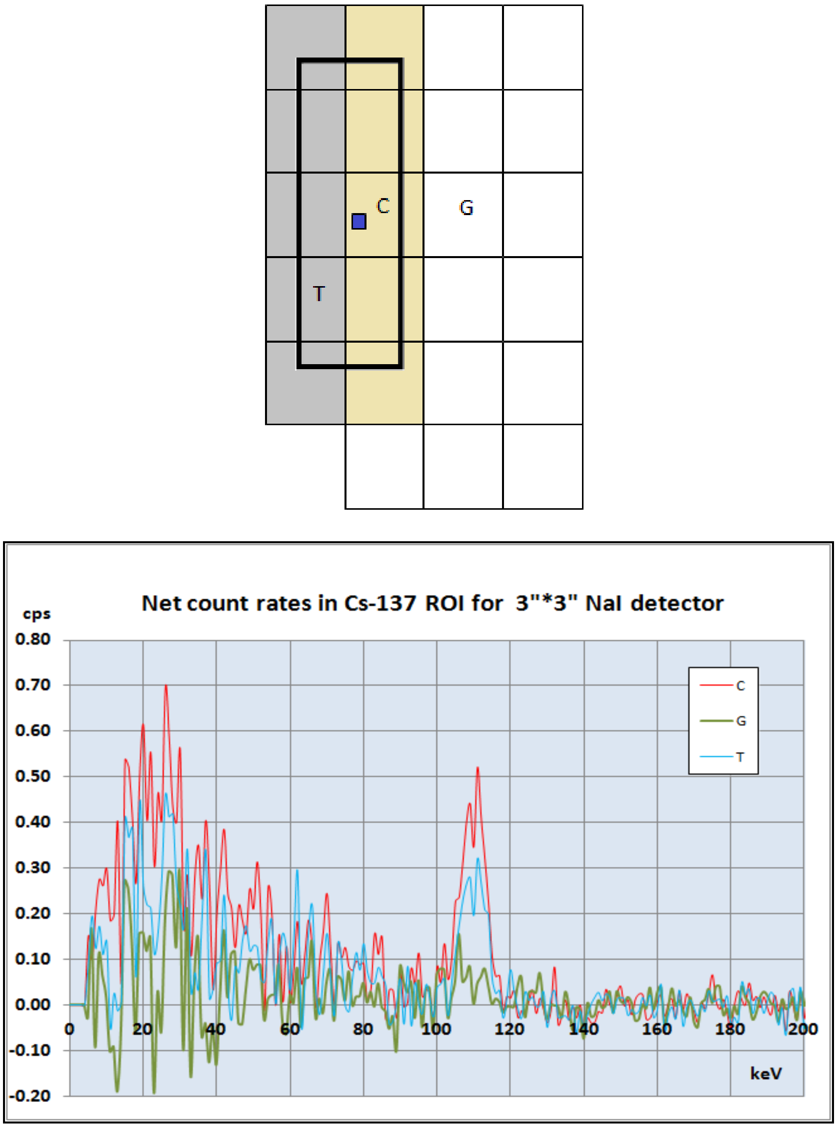

Figure 11. *Position of the* ^{137}*Cs calibration sheet (top), and measured spectra at position T, C and G (bottom).*

When the calculated sensitivity for the 3” x 3” NaI detector was applied to the data obtained at the calibration site in Belarus they translate to a ESC value of 273 kBq/m^2 and 218 kBq/m^2 respectively for the two visits to the calibration site on September 15 and 17. The average ^{137}Cs concentrations obtained by PSRE and measured on soil samples is 691 kBq/m^2. This value is more comparable with an IC (Inventory Concentration) integrated to a specific depth and is therefore not comparable to the ESC value estimate by DEMA. Experience shows that the loss of contribution to the ^{137}Cs signal from “buried” ^{137}Cs can result in a difference of more than a factor two for a mass depth of approximately 1 g/cm^2 for a detector placed at 1 m height.

3.2 The Test Route

Prior to the actual MOBELRAD activity taking place, preparation of a defined test route through the exclusion was conducted by staff of the PSRER in consultation with the MOBELRAD organizer. The objective of the work for which the test route was prepared was to evaluate the radiation situation along the route in terms of dose rates and radioactive contamination levels by ^{137}Cs using dosimetric and spectrometric equipment installed on vehicles, comparison and analysis of the results generated with help of the maps and databases on radioactive contamination of the territory of exclusion zone and identification of the reasons of data disagreement.

In preparing the test route, the main tasks included:

- choosing the route through the exclusion zone to include sections differing with respect to road surface (asphalt, gravel, country road) and landscape (grassland, field, forest),
- determination of equivalent dose rate and contamination density of ^{137}Cs along the route,
- evaluation of the radiation situation along the route,
- preparation of a site with known density of contamination of the soil by ^{137}Cs and equivalent dose rate for calibration/checking of dosimetric and spectrometric equipment,
- collection and systematization of the data on the density of contamination of territories adjacent to the route by ^{137}Cs;
- selection of stopping points for more careful measurement of the above parameters in situ.

The preparation of the test route for the vehicles involved:

- selection of sections of the route where the adjacent area was covered by forest or over open land;
- the determination of the approximate lengths of individual sections;
- classification of the sections depending on kind of plant association;
- determination of the dominating composition of vegetation on elementary sections.

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The final test route for the teams participating in the exercise is presented in Figures 12 and 13.

To evaluate the radiation situation along the route, measurements of equivalent dose rate at 147 points along the 80 km route were made. The route passed through the territories of 3 regions of the Khoiniki part of reserve – Vorotetskoe, Babchinskoe and Radinskoe and included 48 forest compartments of which 10 belonged to Vorotetskoe, 26 to Babchinskoe and 12 of the Radinskoe forestry area. Four kinds of landscape dominated the route – mixed leaf forest, pine forest, fallow grassland and old gardens. Practically all features of the landscape, hydrology and key forest conditions of the reserve were represented along the route. Analysis of the route from that standpoint permited division of the route into 26 elementary sections.

A substantial fraction (about 70 %) of length of the route occured through territories covered by forest. Of these, mixed leaf wood with a domination of alder and birch comprised about 50% of the route, fallow grasslands comprised 24 % and pine forests comprised 21 % characterized by different age compositions, structures and various degrees of humification. A lesser extent (about 7 %) was comprised of old and feral gardens with typical vegetation assemblages for the locality (apples, berries, plum trees).

The road surface along the route varied in both its properties and age having therefore an expected influence on measured values of equivalent dose rate. The length of the route with old asphalt was equal to 41.5 km, new asphalt covered aprroximately 3.5 km, gravel surface was featured on 25 km and country road/track was found on 10 km. The route was arranged in such a way that a substantial part was passed both in the outbound and return directions which allowed for comparison of the data generated on both legs of the journey.

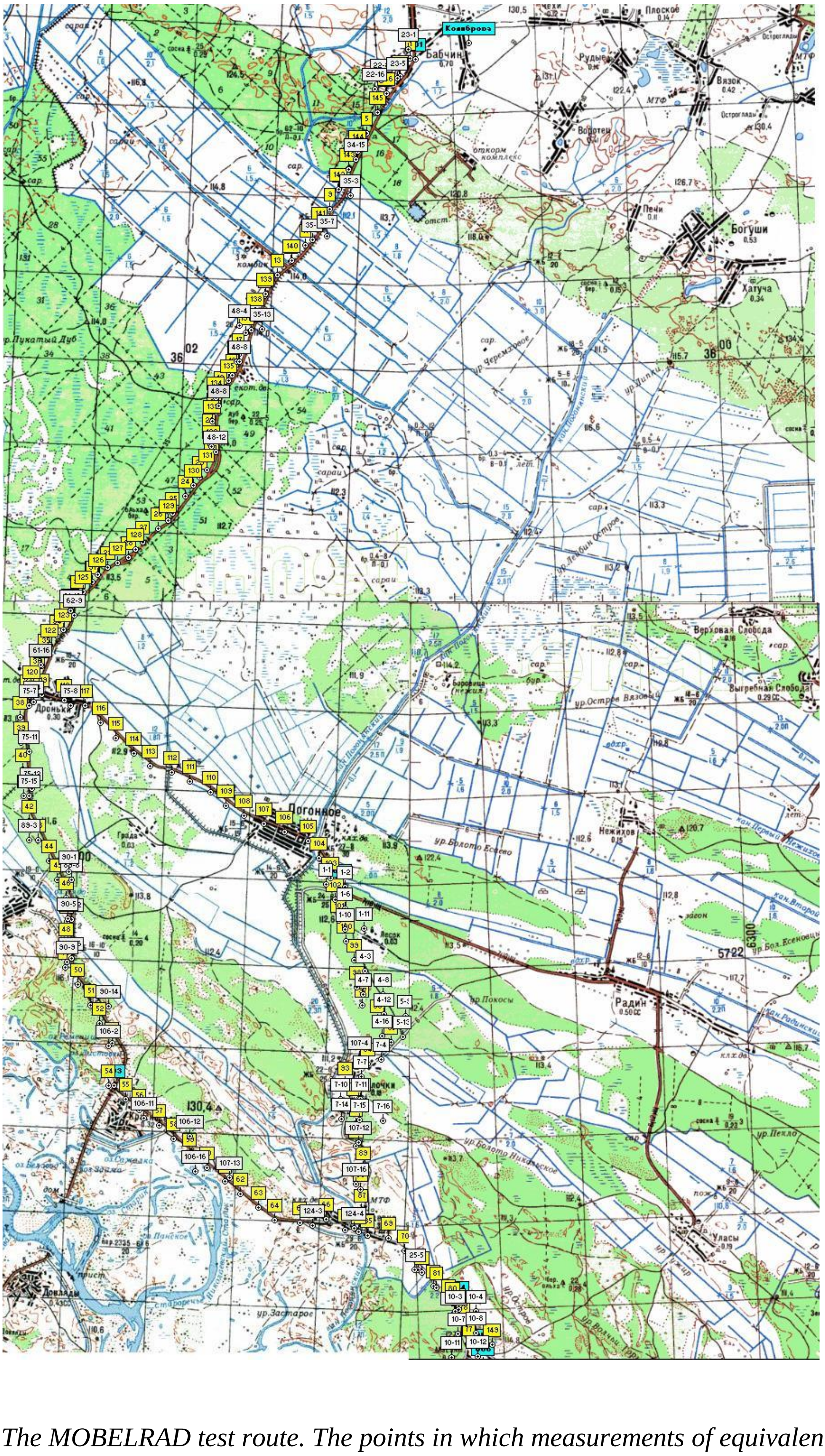

Figure 12. *The MOBELRAD test route. The points in which measurements of equivalent dose rate were fulfilled by workers of PSRER are marked by yellow color. The blue points indicate the stop points and calibration site. Sampling and analysis of soil for* ^{137}*Cs was conducted at the white points, equivalent dose rate measurements were conducted at the yellow points.*

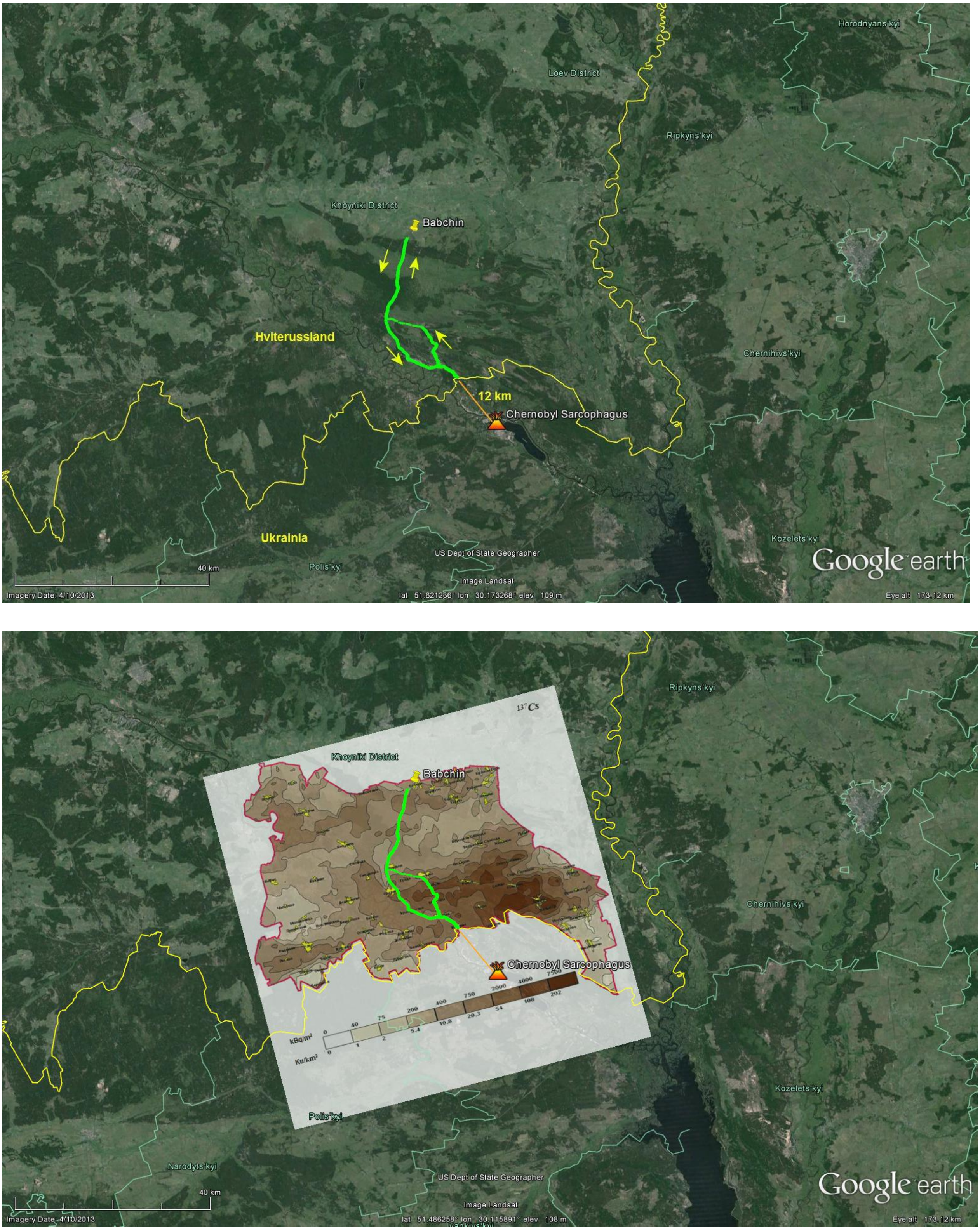

Figure 13. *The MOBELRAD test route in relation to the Belarusian exclusion zone and the Chernobyl power plant (top), and the overall* ^{137}*Cs contamination status as of 2010 (bottom).*

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The levels of ^{137}Cs contamination along the route are as depicted in Figure 14. Values of equivalent dose rate were measured along the route and change some 35 times over a range from 0.16 to 5.5 μSv/h. The soil contamination density of ^{137}Cs is varied from 74 to 4000 kBq/m^2. Available information on the radioactive contamination of the territory of the PSRER was used in the work. The first source of information were the results of the mapping of the territory of the PSRER in 2007-2008 during a joint programme between Russia and Belarus on the liquidation of the consequences of the Chernobyl accident [1]. The second source of data was the NATO project 983057 during 2009-2011 [2]. The points at which soil samples were taken for spectrometric analysis to determine the contamination density of ^{137}Cs are designated in white in Figure 12. The availability of that information allowed comparison between the equivalent dose rate measured along the route with the density of contamination of nearby areas by ^{137}Cs (Fig. 14).

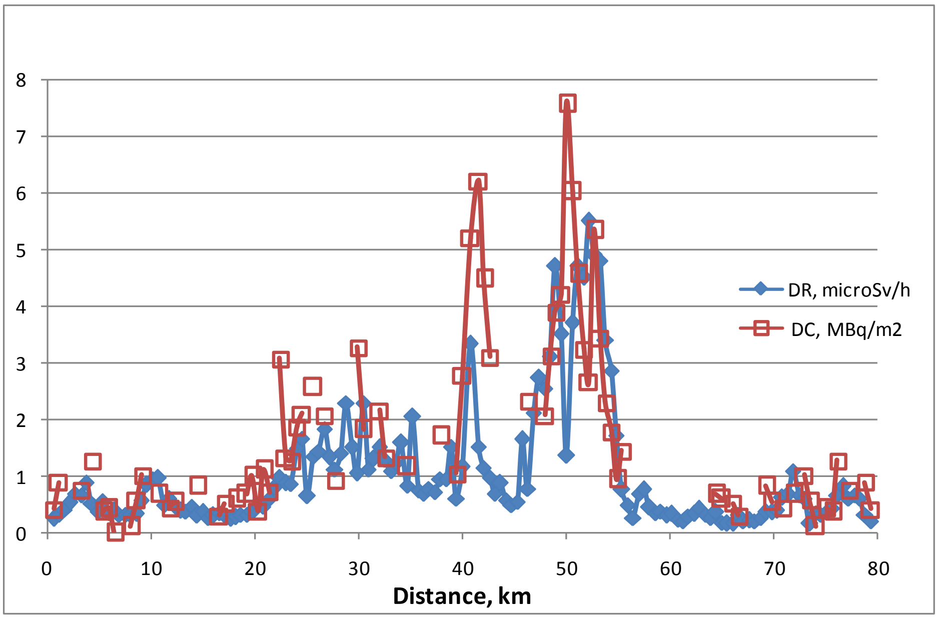
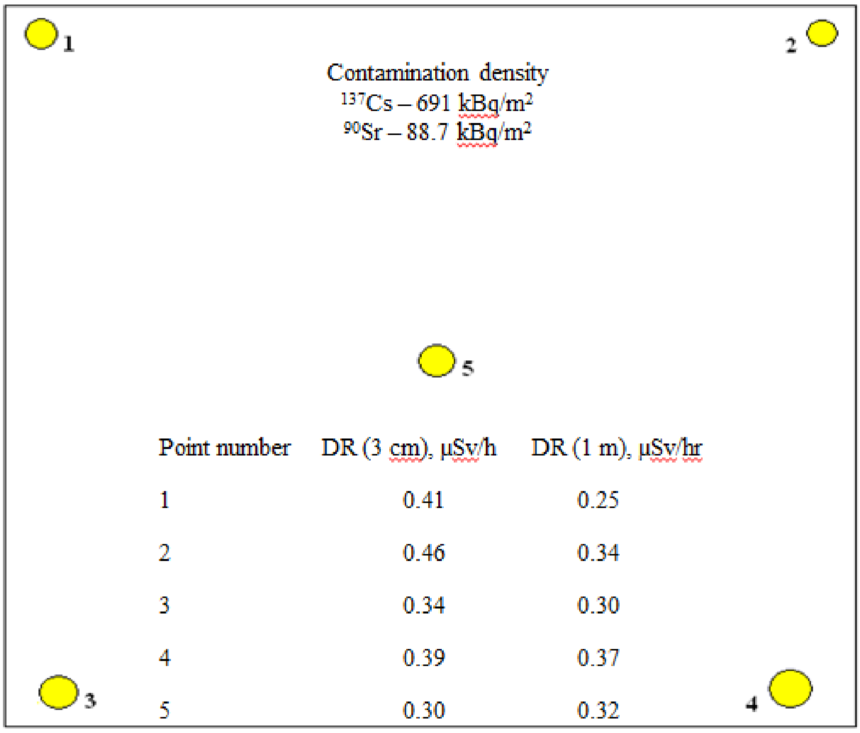


Figure 14. *Comparison of the equivalent dose rate (DR) measured along the route with contamination densities of ^{137}Cs.*

The content of gamma-emitting radionuclides in the environment determines the equivalent dose rate and according to the results of long-term studies in the area, a direct dependence exists between dose rate of gamma-emission and total density of contamination of soil by gamma-emitting radionuclides. At present, assuming the absence of short-lived isotopes, the main contribution to the dose rate is provided by ^{137}Cs over the entire length of the route.

An experimental site for the calibration and control of dosimetric and spectrometric equipment was situated 350 m from the scientific headquartes of the PSRER in the direction of the former settlement Vorotets. The geographical coordinates were: N 51° 47.046′, E 030° 01.122′. The values of the equivalent dose rate on the soil surface at the time of measurements (June 2014) varied between 0.31 and 0.38 microSv/h with an average of 0.36 microSv/h. At a height of 1 m the values of the equivalent dose rate varied from 0.29 to 0.41 microSv/h with an average of 0.35 microSv/h. The density of soil contamination by ^{137}Cs was 594 kBq/m^2 (16.1 Ci/km^2) and by ^{90}Sr 80.6 kBq/m^2 (2.18 Ci/km^2). The calibration site was chosen to be near the former settlement Babchin, close to the starting point of the route which means it was located within the "far" zone of the PSRER where limited economical activity permitted. Therefore the contribution of wild boars to redistribution of the deposited contamination within the upper soil layers could not be excluded and was confirmed through measurement. According to the results the calibration site was characterized by a deeper penetration of ^{137}Cs into the soil in comparison with that exhibited over undisturbed lands along the main part of the route.



Contamination density
^{137}Cs – 691 kBq/m^2
^{90}Sr – 88.7 kBq/m^2

Point number	DR (3 cm), μSv/h	DR (1 m), μSv/hr
1	0.41	0.25
2	0.46	0.34
3	0.34	0.30
4	0.39	0.37
5	0.30	0.32

Figure 15. *Calibration/control site. Approximate length of one side – 40 m. DR – equivalent dose rate.*

A series of stop points were established along the route, points 1-4 and 6 being indicated in Fig. 12. The fifth stopping point at the center of the route was of dimensions 100 m × 100 m and was characterized in more detail than the others. Information as to the stopping points is provided in Table 1. The fifth stop point (Fig. 9) was situated on fallow grassland near the research station of the PSRER known as "Masany" at a distance of some 10 km from the ChNPP. The site has vegetation typical for that of the general area of the PSRER and includes cereals, leguminous plants, buckwheat, compositae, buttercup and other families. The soil at the site is sod-podzol, the forest layer being absent. According to results of measurements, the maximal values for contamination density at the site is 8.08 MBq/m^2 (212.4 Ci/km^2) of ^{137}Cs. The mean value of the dose rate at a height of 1 m amounted to 3.69 µSv/h. The results of measurements of the dose rate which were made on the experimental site indictaed low variability – the value of the coefficient of variation (V) was equal to 8.5 % (table 1,).

Stop point No	Distance from the start, km	Road surface	Landscape	DR* 1 m high, µSv/h	DC adjacent territory, kBq/m^2 *
1. "Babchin"	0	Asphalt	Open land	0.23	420
2. "Maidan"	8	Asphalt	Open land	0.21	580
3."Krasnosel'e"	27	Gravel	Open land	1.52	940
4. Memorial	36.5	Gravel	Forest to south, field to the north from the road	1.19	1180
5. "Masany"	39	Unsurfaced road	Open land	3.70	2500-5500
6. "Pogonnoe"	51.5	Gravel	Forest	1.08	680

* - Data from PSRER

Table 1. *Characteristics of the stop points along the route.*

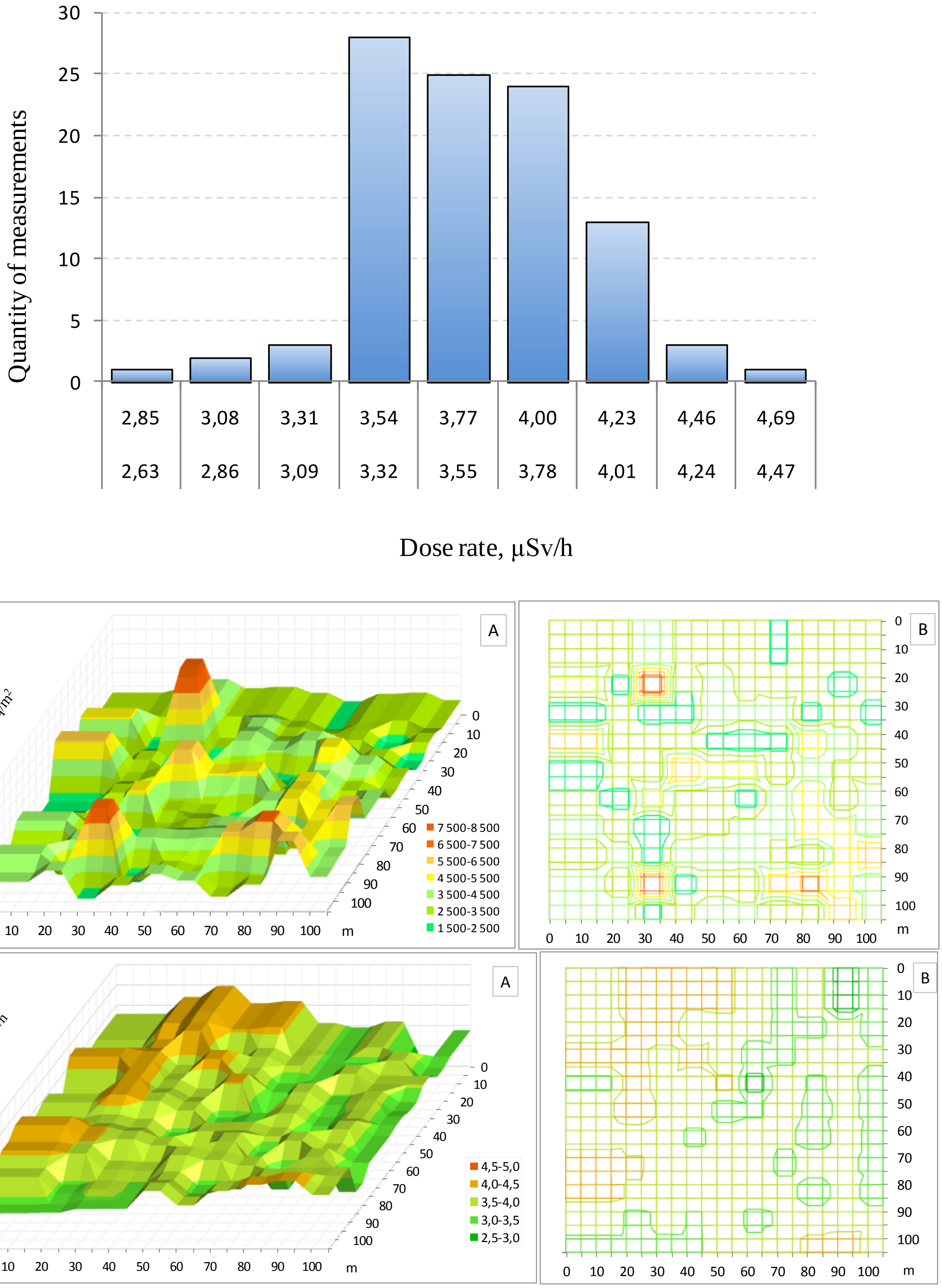


Figure 16. *Histogram of distribution of values of dose rate on soil surface of stopping point 5 (masany) (top), lateral distributions of gamma dose rate at height 1 m (μSv/h) and 137Cs contamination (kBq/m^2).*

The nature of the distribution of dose rate values at stopping point 5 was mainly due to the features of the initial deposition of aerosols on the soil surface with subsequent redistribution of the radionuclides under the influence of biota and climate. At the time of deposition, the site presented itself with typical agrocenosis, being a minimal assemblage of herbaceous vegetation up to a monocultural state. These circumstances allowed consideration of the fifth stopping point as demonstrative of the influence of natural seral processes on horizontal redistribution of the radionuclides since deposition in contrast to sites covered by forest. The heterogeneity of microrelief and the regime of humidification do not influence to any great extent the variation of the radiation situation because height differences are small and are smoothed out to an extent by the activity of burrowing animals. The indicators of asymmetry and excess, their uncertainties and significance criteria were evaluated by us in calculation of parameters of variational series. In our studies for N = 100 the uncertainties of asymmetry and excess correspond to Sas = 0.24 and Sex = 0.48. In calculation of confidence criteria of these evaluations (tAs, tEx) the conclusion could be made that values of dose rate are distributed according to the normal law (Fig. 16). Checking on biometrical tables approves this conclusion.

4.0 Results and Discussion

Figure 17 displays the average spectra obtained by the Danish team at the calibration site in Belarus during the two visits to the site (September 15 and 17). There is a difference of approximately 20% between the two measurement series. This suggests that the measurement system may not have been in the exact same position in the car – and/or the car could have been placed at a slightly different location within the calibration site. In any case, it indicates that the dose rate on the calibrations site was not very homogeneous.

The concentration of ^{137}Cs expressed as ESC along the route traveled in the Radiation Ecological Reserve by the DEMA team and measured on September 16 is shown on Fig.s 18 and 19.

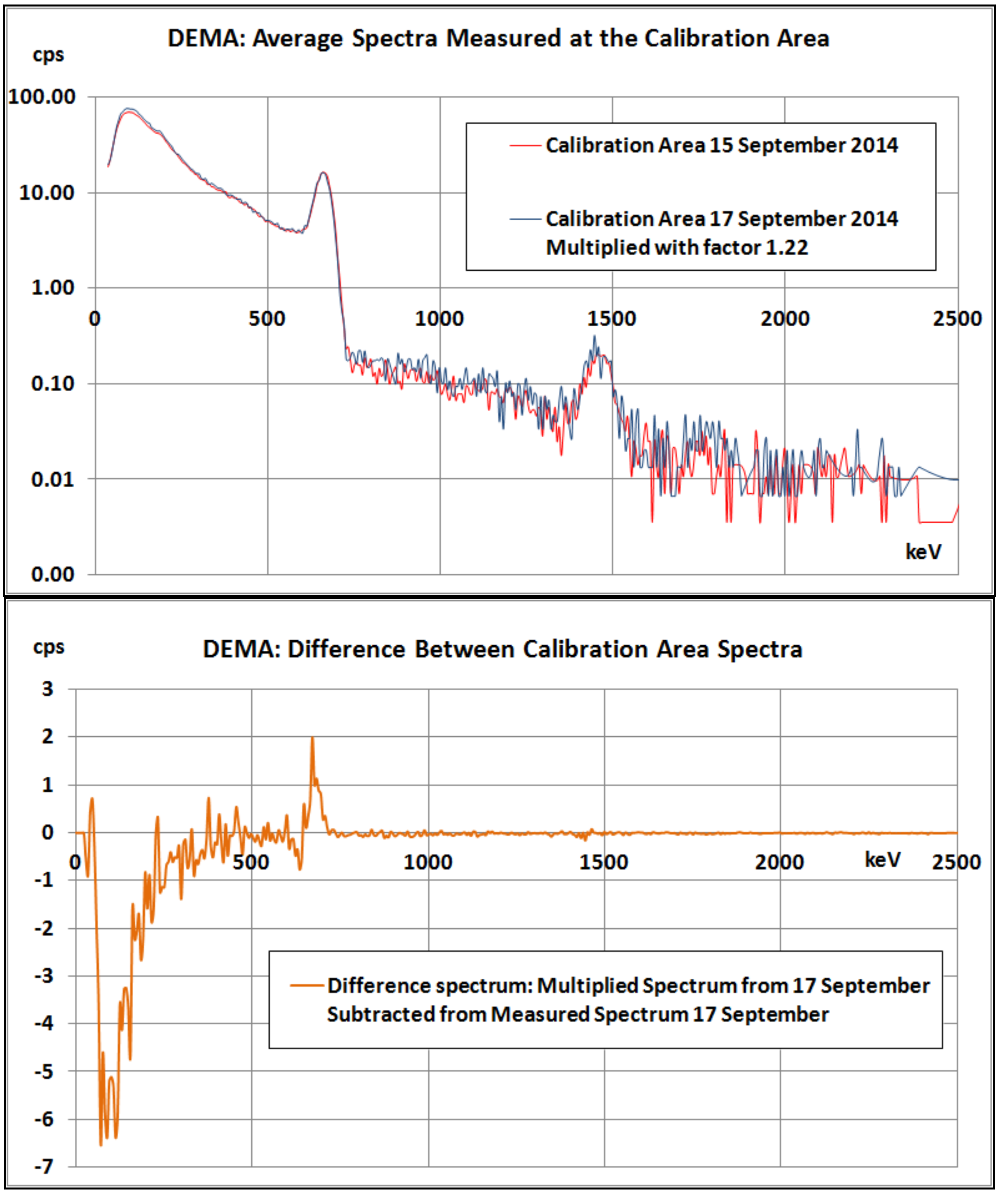


Figure 17. *Average spectra form the calibration site measured at two occasions (top) the resulting difference between the two spectra shown at bottom figure.*

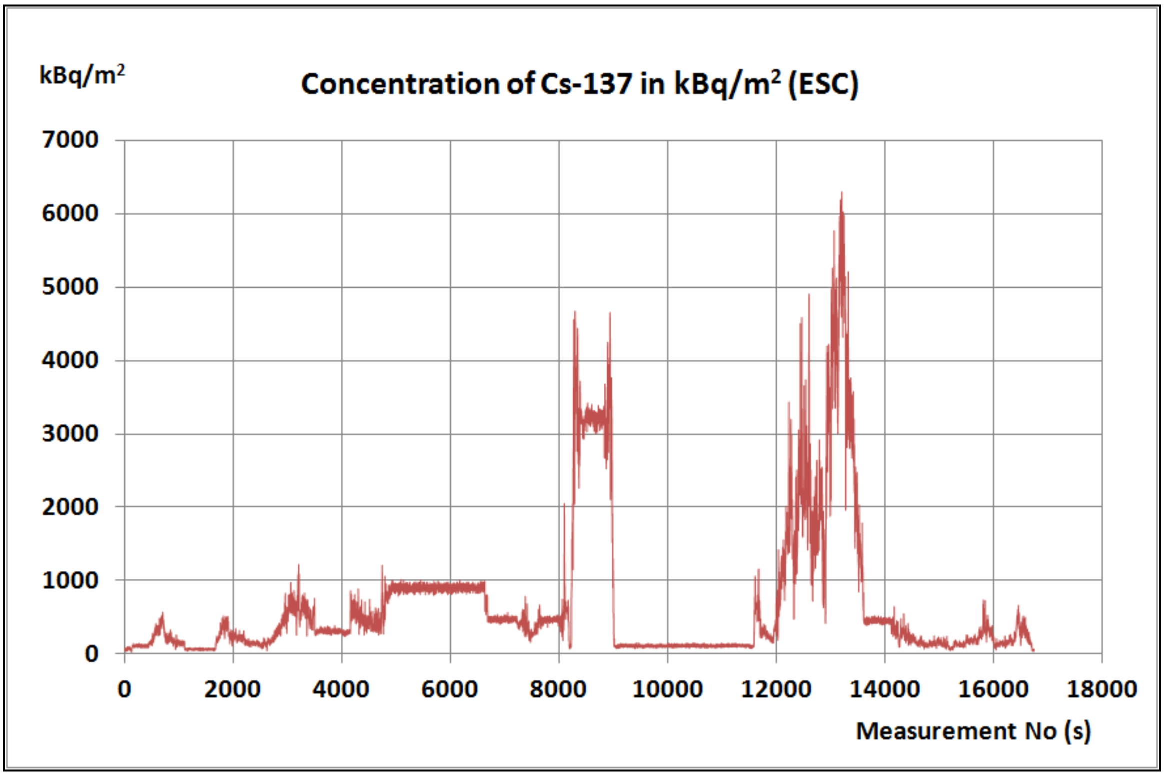


Figure 18. *Concentration of* ^{137}*Cs as a function of time along the route in the Polesye State Radiation Ecological Reserve. The data series include times where the car was not moving.*

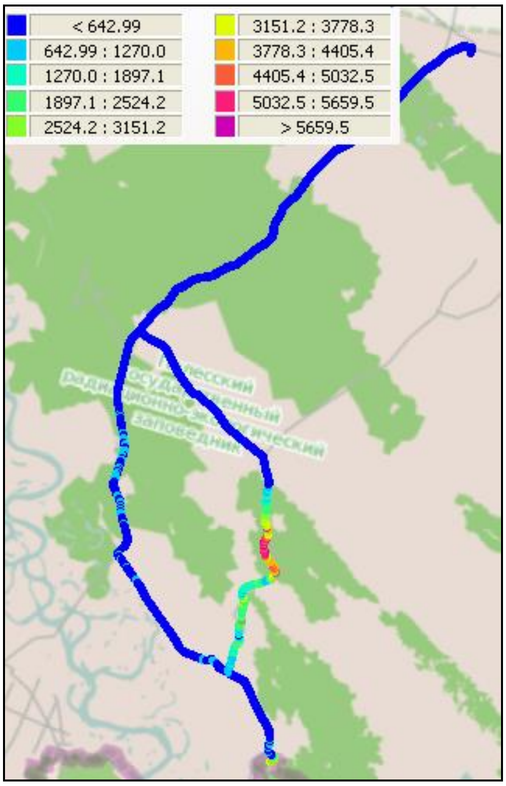


Figure 19. *A color plot representation of the same parameter as shown in Figure 18, ESC in kBq/m*^{2}*, along the route traveled by all the Scandinavian teams.*

Figure 20. *Colour plot of dose rates measures by DEMA in nSv/h along the route in the Polesye State Radiation Ecological Reserve traveled by all Scandinavian teams*.

The Swedish Radiation Safety Authority (SSM) had recently developed a new backpack system, based on a 1.5” LaBr(Ce) detector as described in Section 4 of this Report. The detector was mounted with tape on the back of the car seat (Fig. 21) for four reasons: (1) to increase its field of view; (2) to decrease the relative influence of contamination on the road or close to the road; (3) to avoid the shielding of the bottom plate of the car and; (4) since it was a suitable spot for the mounting.

By using a spectrometer with a small active volume (low efficiency) and high throughput no problems due to high dead time or paralysation of the detector were expected nor observed. Furthermore, the resolution of the LaBr(Ce) spectrometer (< 3 % at 662 keV) would make it easier to discern between different isotopes. At this time, however, only Cs-137 was identified in the area. A tripod was also brought which allowed us to conduct in-situ measurements with an identical LaBr(Ce) spectrometer, Figure X.2.

The GPS-antenna was mounted on the roof with a magnet and the analysis shows that only a few of the thousands of measurements collected lacked GPS fix, which is an acceptable proportion.

Figure 21. *Mounting positions of the SSM detector*.

The backpack system consists of two tablet computers, one for collecting data every second and one for viewing the data collected. During the surveys the tablet computer collecting the data was still in the backpack and the other tablet, here referred to as the screen, controlled the computer via a wireless connection (Wifi). Having a portable wireless screen allows for great mobility near or within the range of the car and reduced the risk of cables disconnecting from the computer.

Two different handheld dose rate meters were used: a SRV-2000 instrument with a GM-tube and fixed integration time (5 min) and an Identifinder containing a LaBr crystal which was used for shorter integration times (20 s) at the calibration points and at stops along the test route.

The SRV-2000 was used as a calibration measurements for all Nordic teams during the first day’s calibration exercise since it was calibrated at SSM to H*(10) at 662 keV. However, the discrepancy between the SRV-2000 and the Identifinder turned out to be negligible at the calibration exercise and hence the latter with its shorter integration time was used at all occasions except at the initial calibration exercise.

The team had no ability to charge the computers in the vehicle. Only 220 V chargers were brought to Belarus. At one time the computer collecting data got warm while collecting data, placed in the backpack under a pile of clothes. The heat reduced the operation time of the battery. At this occasion it was discovered in time to avoid depletion before the test route was finished, but a 12 V charger or an external battery would have added redundancy.

The background subtraction method used to derive counts from individual isotopes (see below) needs to be further investigated. For instance it is possible that in a case like this where only ^{137}Cs is present is would be better, i.e. give lower uncertainties, if the natural background was ignored. A number of additional improvements in the mobile gamma spectrometry software used by SSM and Lund University (Nugget) were also identified, but none were critical or had any effect on the ability to collect data in Belarus or in the subsequent analysis of collected data.

Dose rates were calculated from spectra according to the Spectral Dose Index (SDI) method [3] which uses a channel-weighted sum of the spectrum multiplied by an SDI-dose rate factor. During the calibration exercise the SDI-dose rate factor for the detector mounted inside the car was adjusted to match the dose rate as measured by the SRV-2000 outside of the car, 1 m above ground at the calibration point. The car was removed during the dose rate measurement to minimise the shielding effect from the vehicle.

SDI dose rates (uSv/h) along the test route as measured by the Swedish Team are given in Fig. 22. Two areas with higher contamination, i.e. > 2 uSv/h, are seen in Fig. 22: one area along the eastern track and one area in the southernmost part of the route. The area in the southernmost part near the PSRER “Masany” research station is further described in Section 4.1.

The distribution of activity in the ground and above the ground will affect the attenuation and thus the dose rate. A calibration factor was derived in the calibration exercise (large grass field) and used along the whole test route. The dose rate is always estimated from the whole spectrum, and it should therefore be less sensitive to such variations than the activity per unit area estimation.

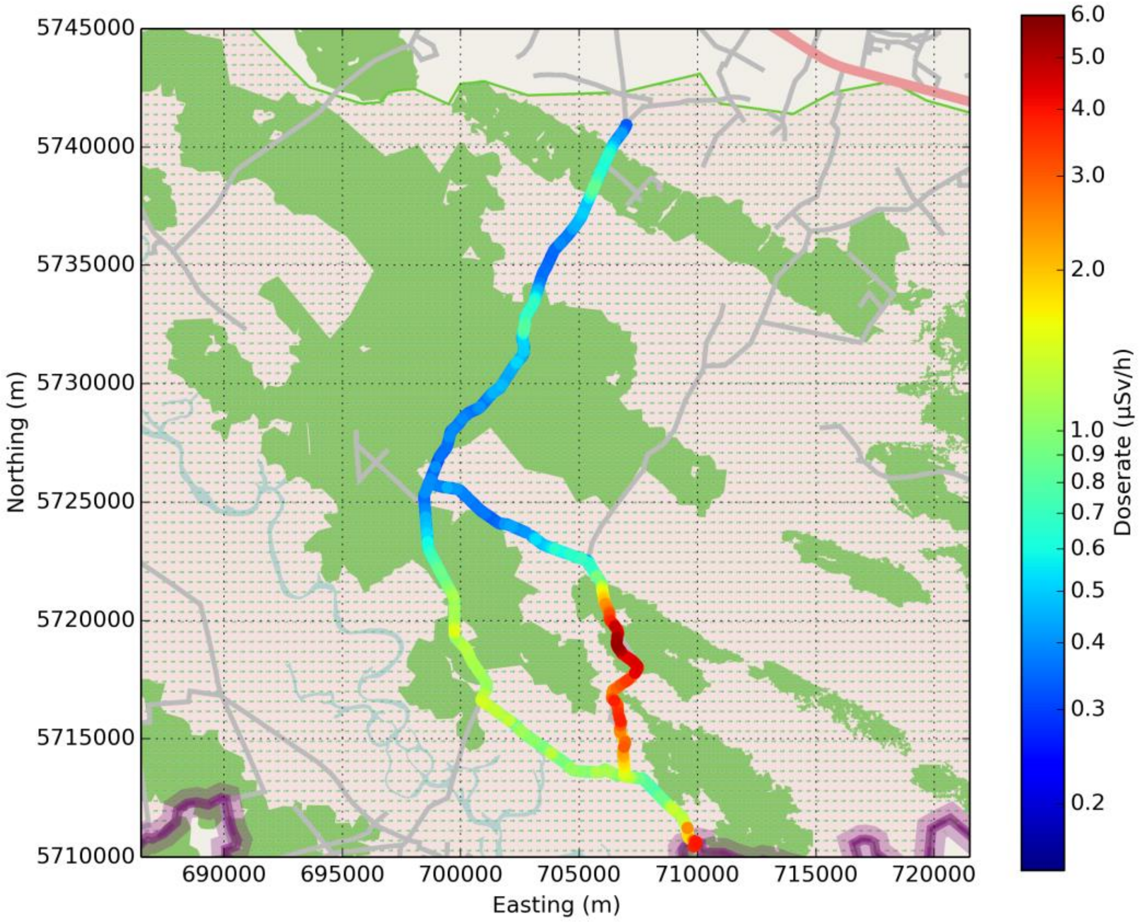


Figure 22. *SDI dose rates (uSv/h) along the test route as measured by the Swedish Team*.

To estimate the activity per unit area (Bq/m^2) of ^{137}Cs, the net counts present in the full absorption energy peak of ^{137}Cs was estimated in each collected spectrum. The spectrum background was estimated from the counts present in 2 channels on either side of the peak (trapezoidal method) and then subtracted from the gross peak counts. As for the dose rate a spectrum sampled at the calibration point was used as reference to correlate the counts to activity per unit area. This activity was adjusted to match the total activity per unit area as measured in soil samples by the PSRER.

The calibration factor, i.e. cps per Bq/m^2, was 21.5 ± 1.0 cps (1 σ, assuming a normal distribution) at the calibration site giving 21.5/0.69=31 ± 1.4 cps per MBq/m^2, neglecting the uncertainty in the soil sample. When applying this calibration factor on all measured ^{137}Cs count rates along the test route one arrives at the derived activity values presented in Figure 23. However, the activity depth profile measured by the PSRER at the calibration point is not valid for the whole test route. Activity in trees as well as other activity depth profiles will influence the calibration factorresults. Hence, the uncertainties of the activity values given in Figure X.4 will have a relatively large systematic component (in addition to the 5 % statistical uncertainty) which is difficult to estimate without further investigations against other well-characterized areas. The activity per unit area measurements made by the PSRER from soil samples should be lower than the mobile estimate, since the mobile systems are affected by all Cs-137 sources, including trees and vegetation.

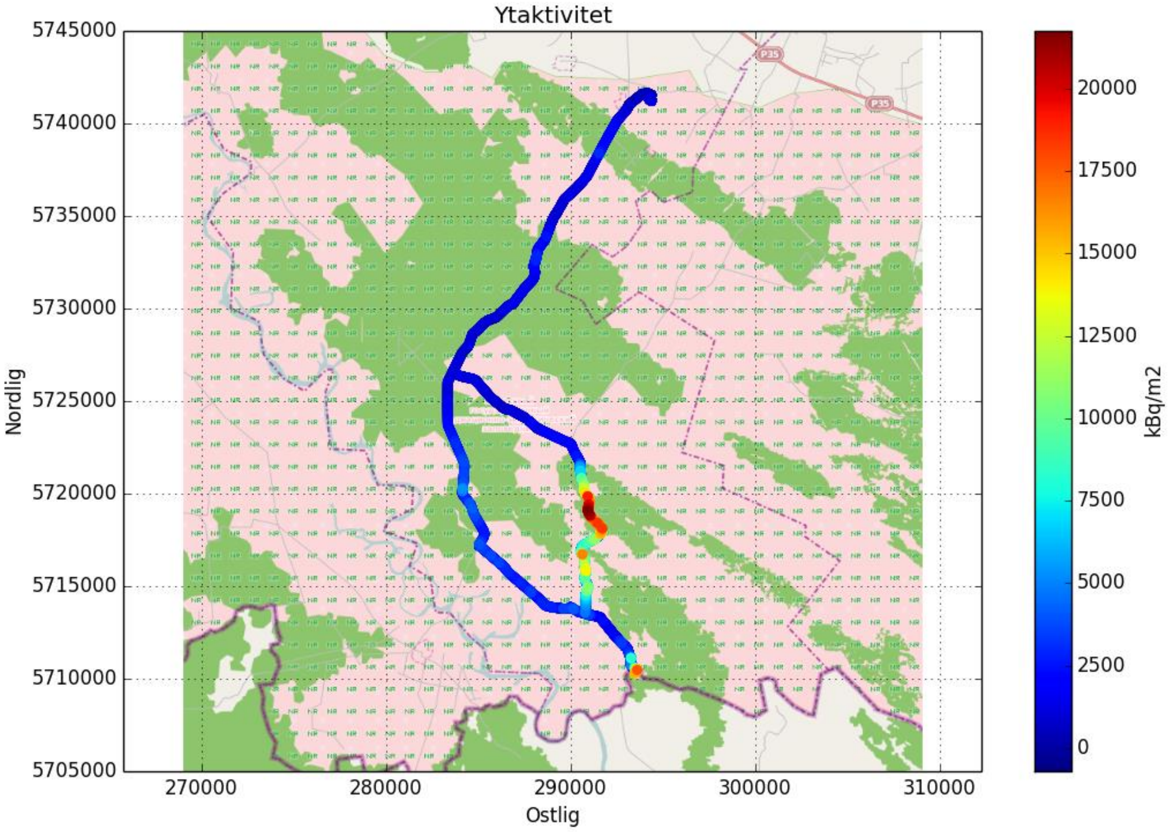


Figure 23. *Derived activity values for* ^{137}*Cs.*

As both Swedish teams deployed similar equipment types, maps of the dose rate as calculated from the pulse height distributions collected by the two Swedish backpack systems are shown in Figures 24 (backpack 1) and 25 (backpack 2) for comparative purposes. It was quite clear that the two backpack systems did not yield the same result. One of the reasons for this was that backpack 1 had an integration time of 1 second and backpack 2 had an integration time of 5 seconds which had the effect of evening out statistical and spatial variability in the measurements. Furthermore, the measurement points in the maps were rendered in a reverse order of intensity which means that measurements representing lower values were rendered first on the map and were thus largely covered by points with colors representing higher dose rates. This amplified the difference in integration time between the two backpack systems.

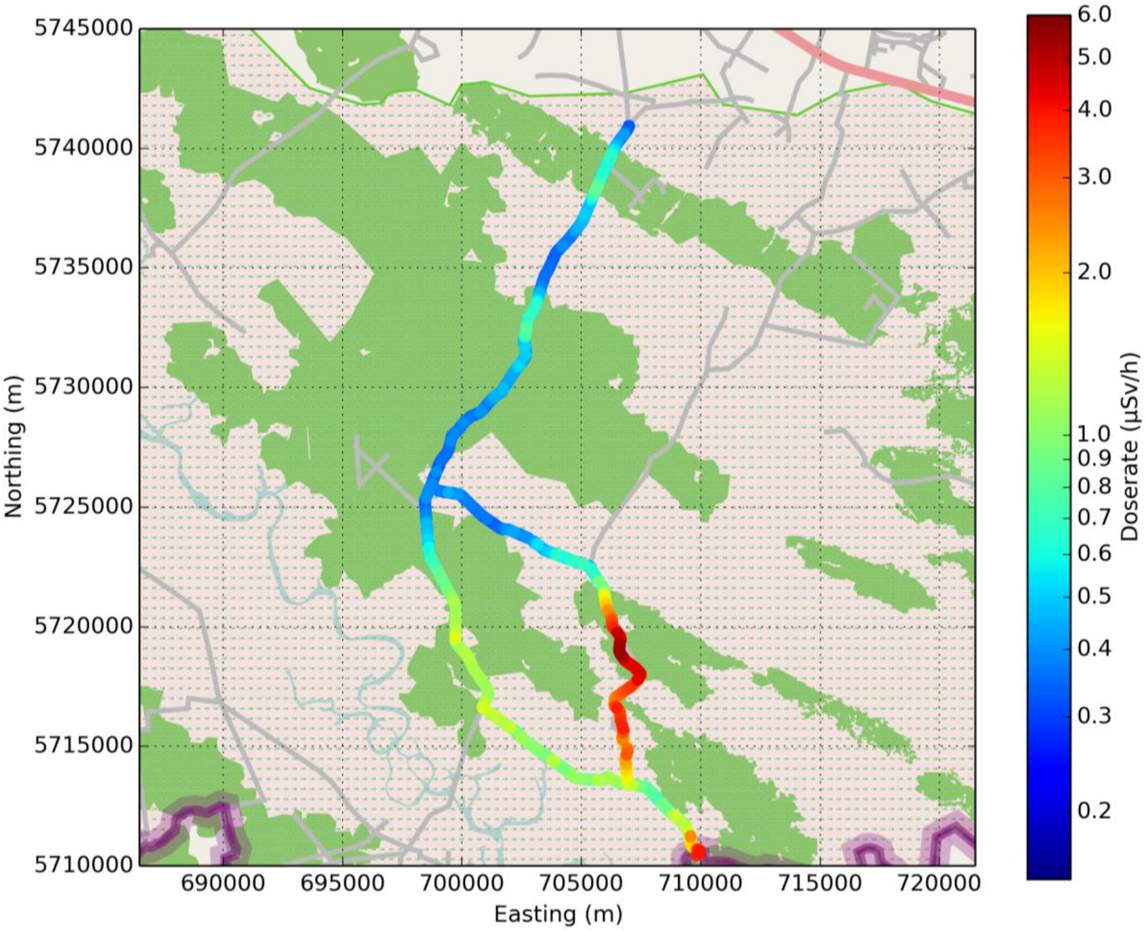


Figure 24. Map of the dose rate as calculated from the pulse height distributions collected by Backpack system 1 of the Swedish teams.

Also, the placement of the detectors had an effect on the field of view of the detectors. The detector of backpack 1 was placed at a higher height in the vehicle than backpack 2 which gave it a larger field of view.

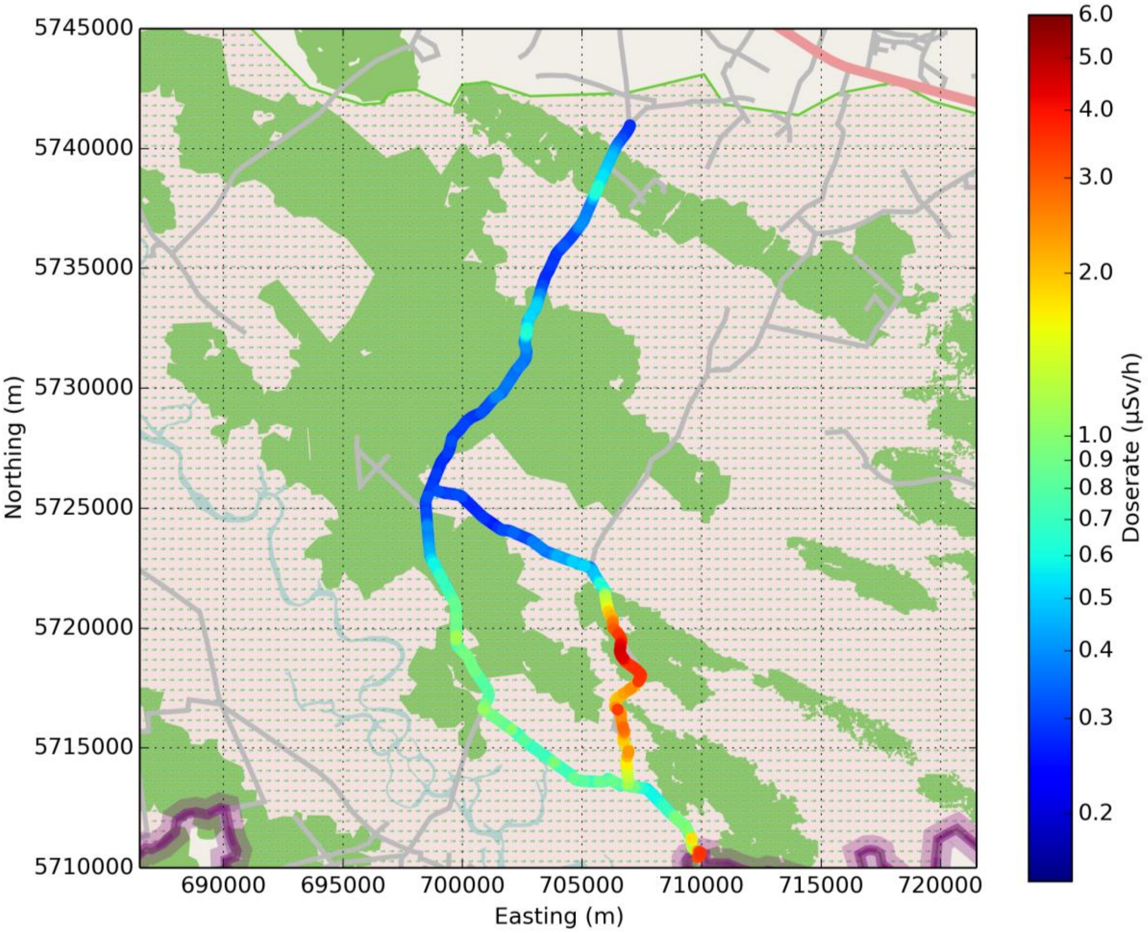


Figure 25. Map of the dose rate as calculated from the pulse height distributions collected by Backpack system 2 of the Swedish teams.

If it is assumed that the area surveyed only contained ^{137}Cs, the pulse height distributions collected in this area should primarily contain five components:

1. The full energy peak from ^{137}Cs (661.7 keV).
2. Compton scattered radiation from ^{137}Cs.
3. X-rays originating from ^{137}Cs or from surrounding materials hit by radiation from ^{137}Cs.
4. Cosmic background radiation.
5. Other.

If it is also assumed that components 3, 4 and 5 are very small in comparison to 1 and 2, the ratio between pulses in the full energy peak and the scattered pulses (from below the peak to 0 keV) should give an indication to the amount of material in the vicinity which scatters the radiation. Figures 26 and 27 show maps of the peak to scatter ratio for backpacks 1 and 2 of the Swedish teams.The peak to scatter ratio is also shown as a function of distance in Figure 27. Interesting to note is the peak at 40 km which is the southernmost measured point in the survey and which, according to the PSRER, had one of the shallowest distributions of 137Cs in the area.

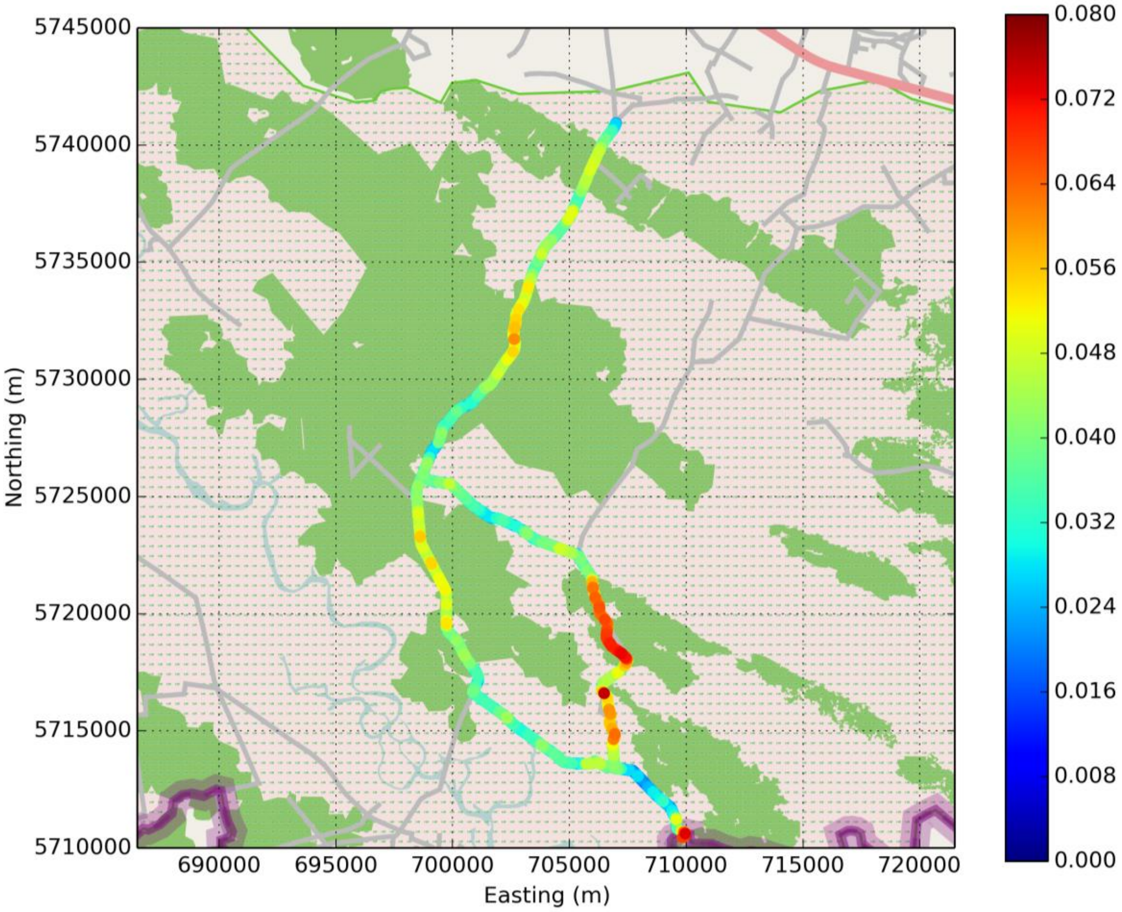


Figure 26. Graph of relationship between full energy peak (^{137}Cs) and scattered radiation (0 keV to full energy) – backpack 1.

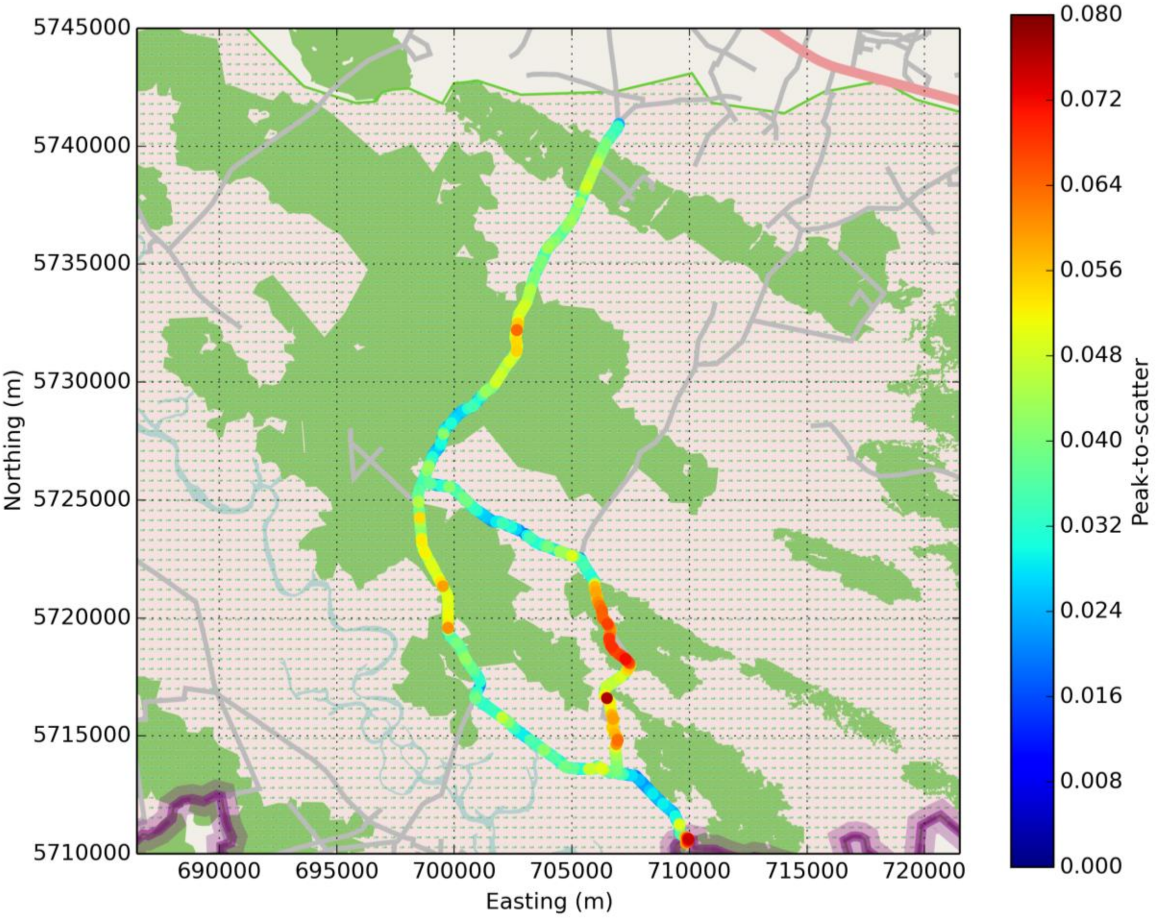


Figure 26. Map of relationship between full energy peak (^{137}Cs) and scattered radiation (0 keV to full energy) – backpack 2.

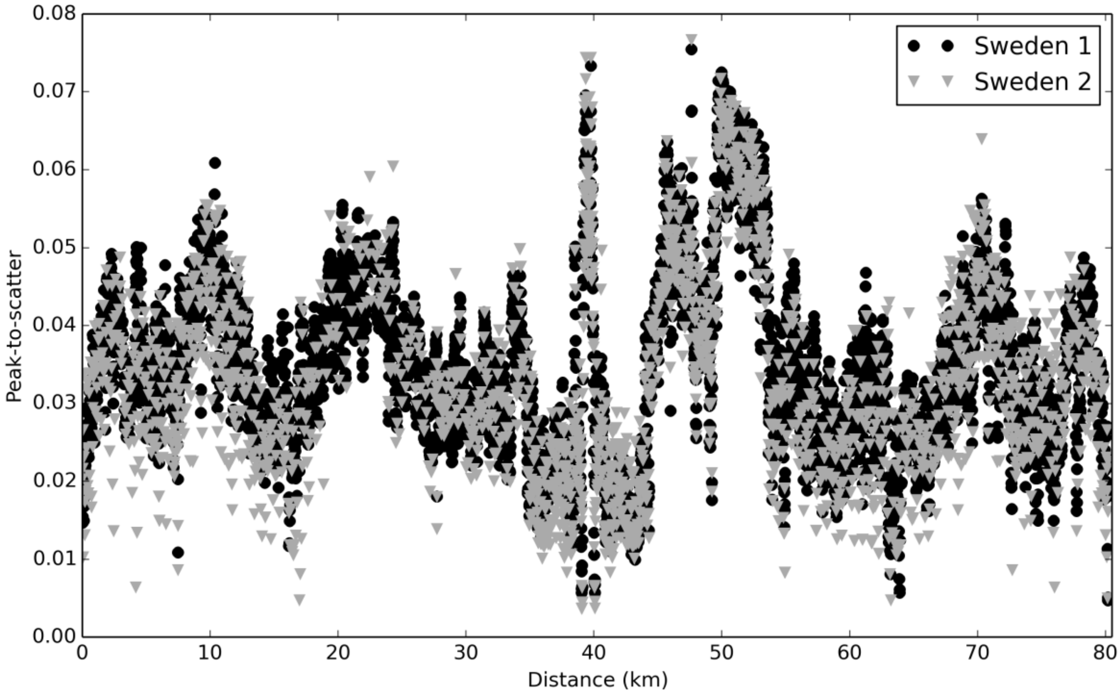


Figure 27. Graph of peak to scatter ratio as a function of distance for both Swedish backpacks.

Figure 28shows a comparison in measured dose rate, as a function of distance travelled, between the Danish, Norwegian and Swedish systems as measured on the individual surveys. The arrows indicate the measurement points used to compare the dose rate measured by the different systems. It is quite apparent that the Swedish system deviated significantly in measured dose rate from the Norwegian and Danish systems. The reason for this is not clear but could be caused by a difference in how SDI-dose rate is calculated, a difference in placement of the detector in the vehicle, a difference in properties of the scintillator or several other reasons.

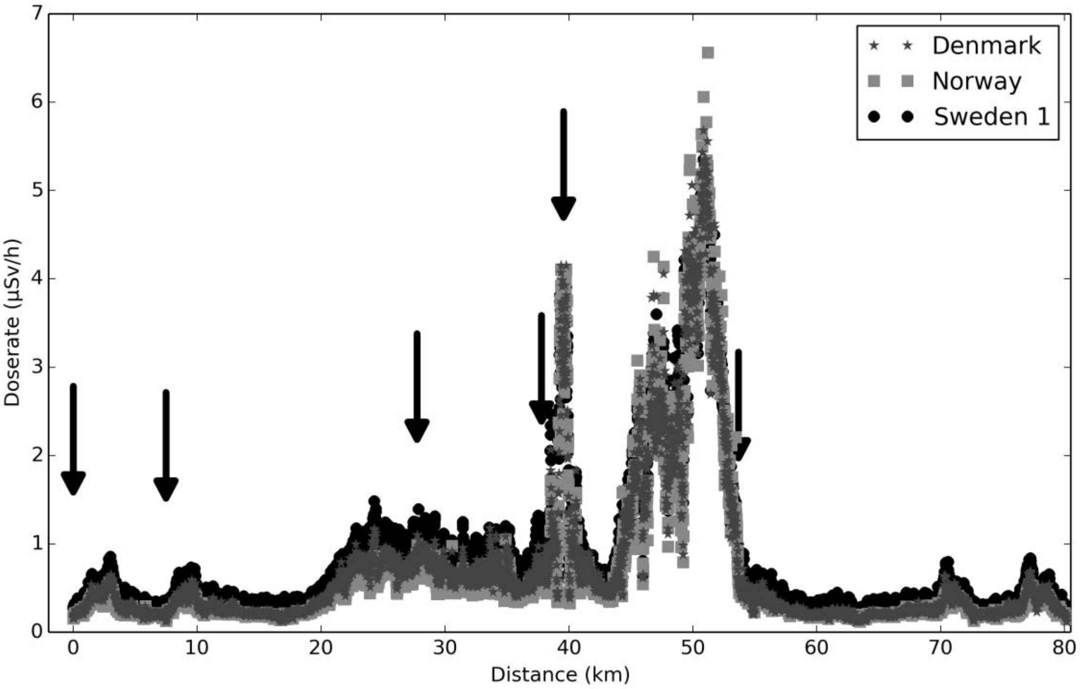


Figure 28. Comparison of measured dose rates with distance for Danish Swedish and Norwegian teams.

Due to the differences, the measurements were repeated on the last day in the area by placing the systems from the three nordic countries in the same vehicle and re-doing the survey. This repeat survey followed a slightly shorter route which is shown in Figure 29. The white dots once again represent points where the vehicle stopped to make stationary comparison measurements with the difference that, this time, measurements were also made with a hand held dose-rate instrument outside the vehicle at each of these locations. Figure 30 shows the dose rate as a function of distance for the three systems as measured on the last day. The arrows represent the locations where stationary measurements were done.

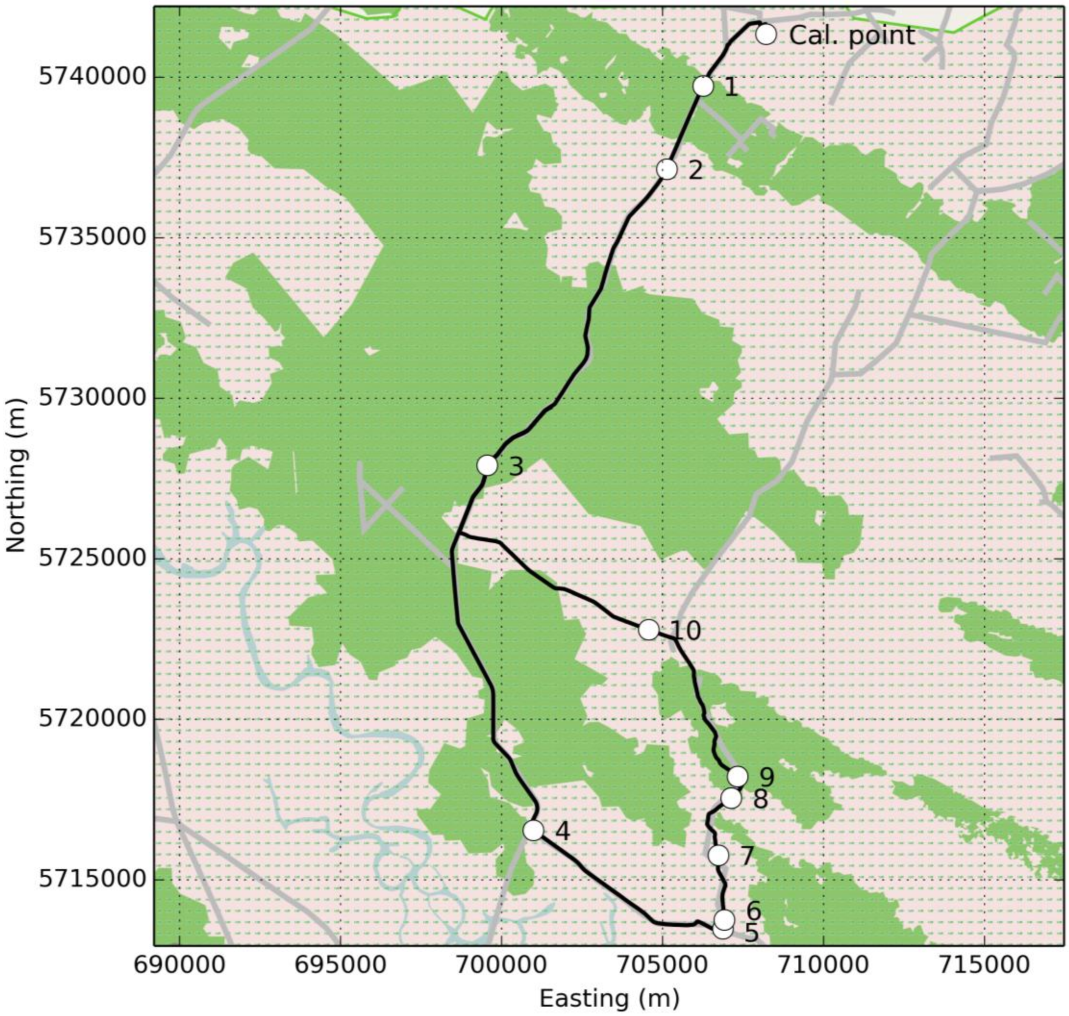


Figure 29. Shortened route of day 2 with intercomparison points.

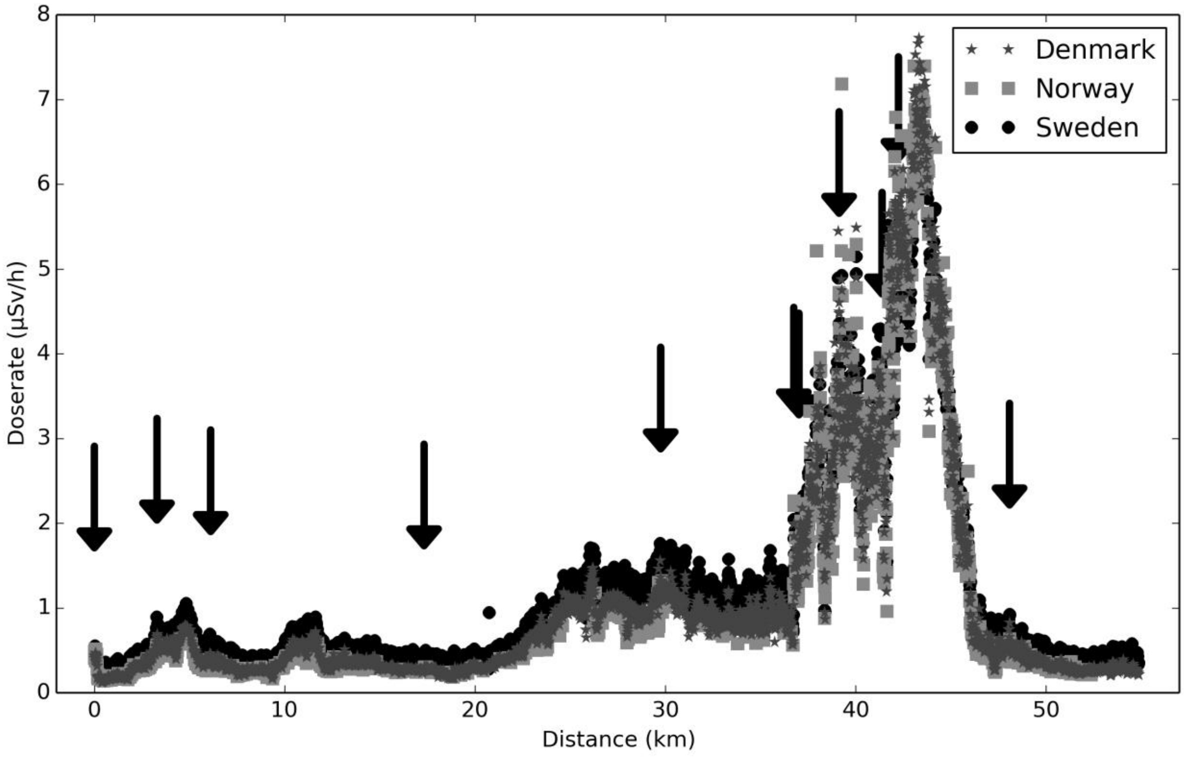


Figure 30. Comparison of measured dose rates with distance for Danish Swedish and Norwegian teams made during simulateneous measurements on day 2.

The results from the stationary measurements as well as peak to scatter ratios for these locations are shown in Figure 31. There is some indication in Figure 31 that the difference in measured dose rates between the systems is related to a difference in peak to scatter ratio. However, further measurements under more controlled conditions would have to be performed to say if this is indeed the case.

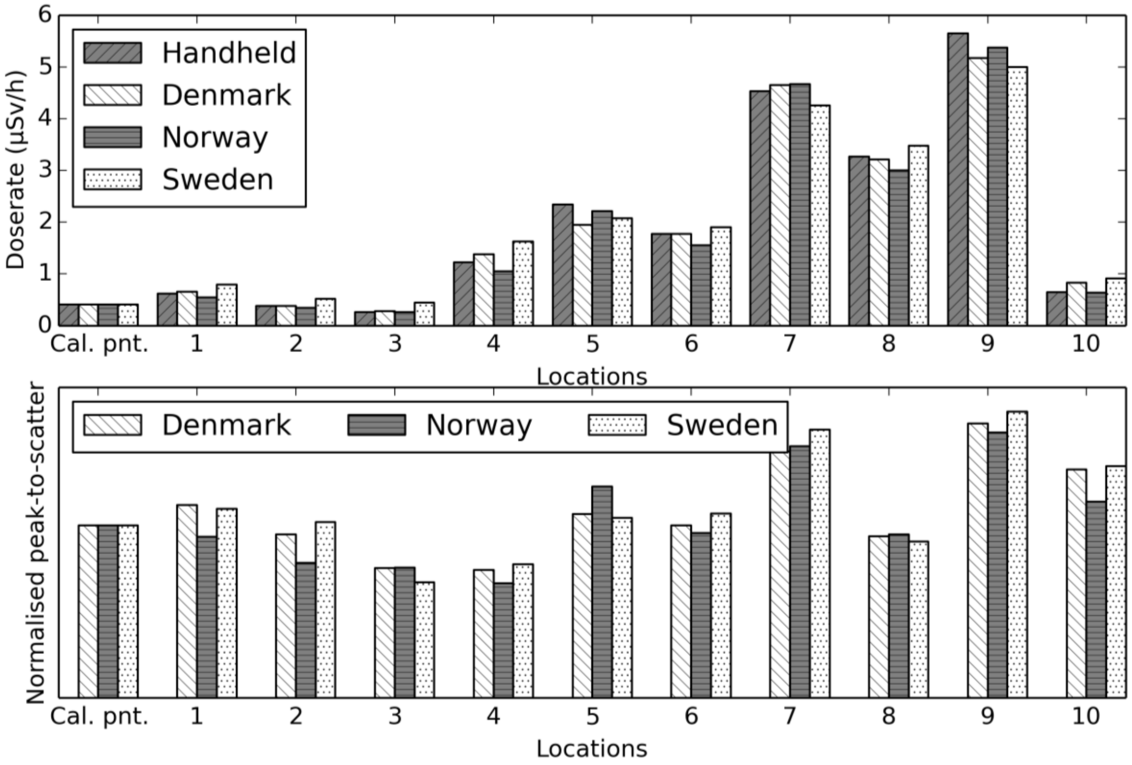


Figure 31. Comparison of doserate measurements and peak to scatter ratios for Swedish, Norwegian and Danish teams during the simulaneous measurement run.

Comparsion of results obtained by the teams during the individual runs indicated had indicated earlier that there were some disparities between dose rates being measured by the teams over some sections of the test routes. As an example, the situation at stopping point 2 of the test route is described in Figure 32, data having being generated by the teams during their individual runs. At this point it was obvious that the Danish team was reporting results that, while in reasonable agreement with the Norwegian teams data, were lower than either of the Sweidish teams data, which also exhibited some differences between themselves.

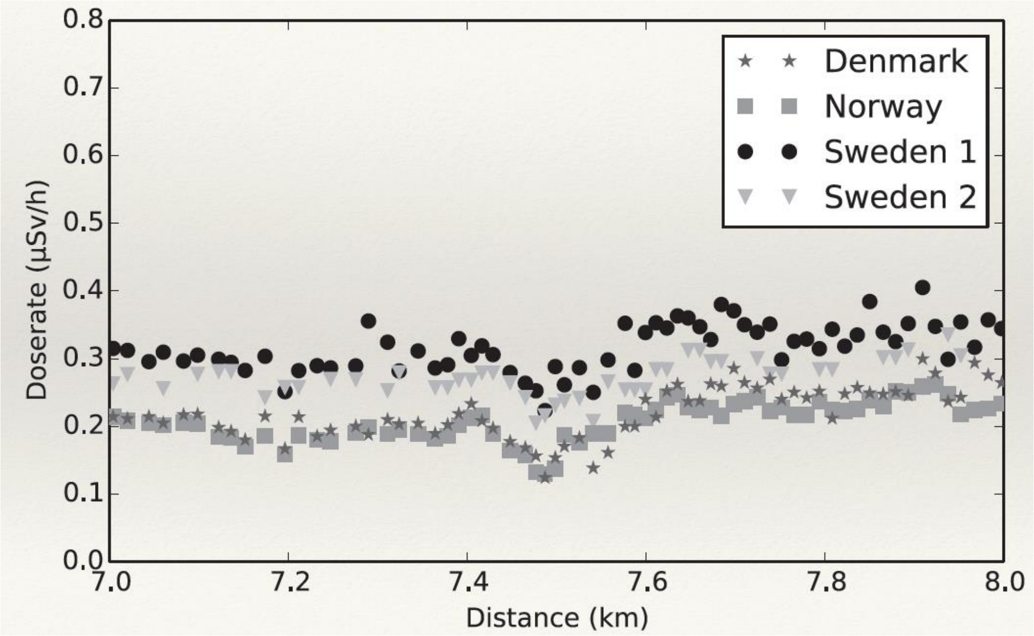


Figure 32. Comparison of doserate measurements made by teams during individual runs at the second stopping point.

This disparity did not appear to be exhibited over the entire route. A comparison conducted at the fifth stopping point, the research station at Masany, indicated a lower degree of difference between the teams. The data for the Masany stopping point is displayed in Fig. 33.

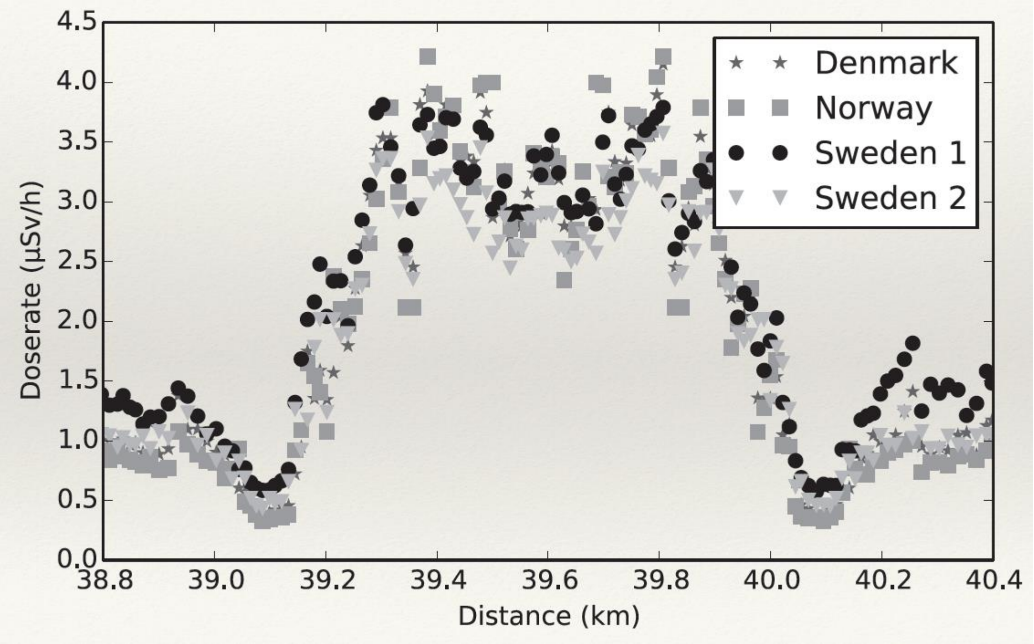


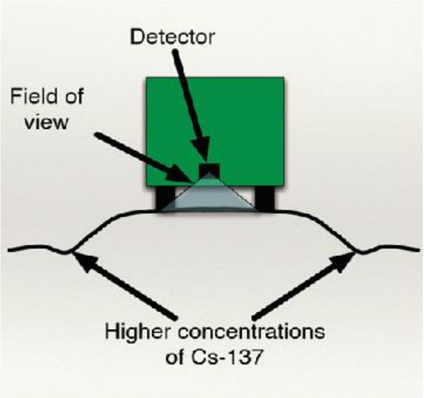
Figure 33. Comparison of doserate measurements made by teams during individual runs at the fifth stopping point.

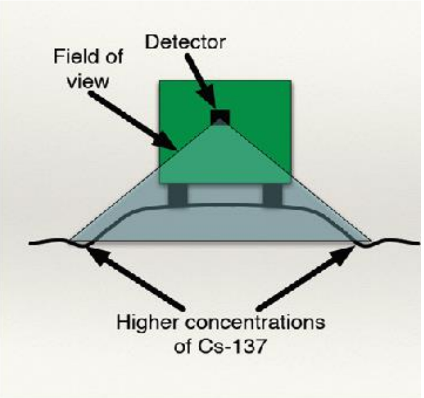
In attempting to adcertain the reasons behind the disparity, consideration was made of two factors – the nature of the surface being driven upon and positioning of the detectors within the vehicle relative to that surface. Stopping point two was an asphalt road with road side ditches (see Figure 34).

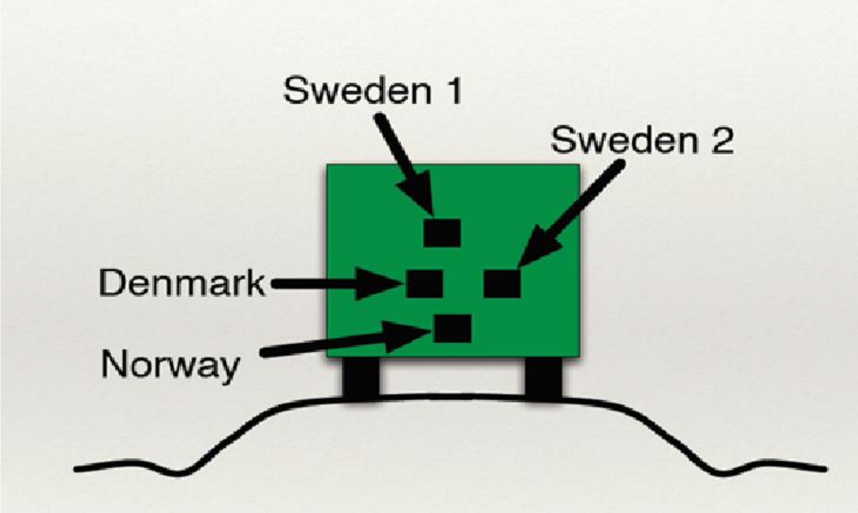
Figure 34. Comparison of road and surface conditions for stopping points 2 (top) and 5 (bottom).

The road side depressions at both sides of the road at stopping point 2 potentially contain higher levels of contamination than either the road or the immediate area as they are the lowest points in the immediate vicinity of the vehicle and accumulate runoff. In this context they are likely to exert some influence over the dose rate measurement observed depending upon the height of the detector placed in the vehicle.

Figure 35 provides a schematic of the relative positions of the detectors for the individual teams within the vehicle.







5.0 Conclusions

The MOBELRAD activity highlighted a number of aspects in relation to the conducting of mobile measurements in contaminated areas where the contamination event occurred at some time in the past long enough for redistribution processes to have played a significant role. It was apparent throughout the exercise that significant contamination was present in above ground vegetation, detector responses being greater within areas of extensive over growth of the route yet similar deposition levels. Local information indicated that significant transfer of contamination to trees had occurred in the years since the accident and this transfer presented a unique aspect in relation top mobile measuremets. Conversely, penetration of the deposited contamination to deeper soil layers and variable levels of penetration along the route presented challenges in relation to how the vertical distribution of nuclides differed from the location where calibrations had been established. The effect of this downward migration was observable over the route in general but was more visible at various points. In terms of technical observations, it was noted that little difference was observable between detectors with respect to dose rate mapping. The smallest detector performed equally well as the largest and in all cases measured doserates were comparable both between the mobile systems and in relation to hand held detectors. Good agreement was observed between the measurements of the teams and the advance measurements made by the staff of the reserve. The largest detector, 4 l NaI, had problems for count times longer than one second in areas where dose rates exceeded 2 µSv/hr due to saturation of the electronics. The problem was solvable by reducing the count time but the observation was made that large sized detectors may not be optimal in terms of dose rate mapping where higher levels of contamination are expected. The role of positioning of detectors within the vehicle was clear throughout the activity. While slight differences in positioning may be considered of little consequence at first consideration, it was clear from the activity that variations in contamination near the vehicle due to local conditions may cause disparities between measurements made by detectors at slightly different positions relative to the road surface.

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Abstract max. 2000 characters	Car borne measurement systems are and are likely to remain a mainstay in the emergency response arsenal of many countries to incidents involving widespread radioactive contamination as evidenced recently by the events in Fukushima. Such systems constitute a useful means of support provision in situations where another country may be handling a contamination incident. As for any analytical technique, competence must be maintained via exercising of personnel and testing of equipment. For car borne measurement this is intrinsically more difficult than for other activities in emergency response as reproducing the conditions in which such measurements are often required to be made in actuality is impracticable. The MOBELRAD activity, aimed at the provision of an exercise opportunity in making mobile measurements under complex conditions, involved the conducting of such measurements by a number or teams from the Nordic countries within the territory of the Belarusian Exclusion Zone. The exercise involved the making of measurements along a comprehensively precharacterised route

through the zone, extending from the borders of the zone to within 10 km of the Chernobyl power plant. The route covered various types of road surface, differing levels of contamination, different terrain types and the teams utilised equipment ranging from small sized LaBr detectors to large volume NaI. The experiences of the teams highlighted the difficulties of making such measurements in landscapes where redistribution processes have had an effect on the distribution of contaminant nuclides and the importance of ensuring appropriate detector-geometry configurations. The exercise demonstrated the suitability of the countries chosen equipment suites in provision of measurement capabilities in third party countries in the event of a serious contamination event and the robustness of such equipment under field conditions.

Key words Mobile gamma spectrometry, Chernobyl, Exclusion Zone

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