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GAMMAJET—FIXED-WING GAMMA SURVEY FOR THE DETECTION OF RADIOACTIVE MATERIALS

Finnish support to IAEA

Markku Kettunen (Defence Forces Technical Research Centre),
Mika Nikkinen (STUK)

STUK • SÄTEILYTURVAKESKUS
STRÅLSÄKERHETSCENTRALEN
RADIATION AND NUCLEAR SAFETY AUTHORITY

Osoite/Address • Laippatie 4, 00880 Helsinki
Postiosoite / Postal address • PL / P.O.Box 14, FIN-00881 Helsinki, FINLAND
Puh./Tel. (09) 759 881, +358 9 759 881 • Fax (09) 759 88 500, +358 9 759 88 500 • www.stuk.fi

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Abstract

Finland has the operational capability to make airborne gamma ray measurements in emergency situations. The original purpose of airborne radiation mapping was to determine hazardous areas containing radioactive fallout after nuclear accidents or the use of nuclear weapons. Regular exercises are held annually to keep operational functionality at high level for this purpose.

The knowledge and achieved practice can easily be extended to use in international radiation monitoring campaigns. The presented guidelines are based on Finnish know-how, but it is not limited to use with Finnish equipment.

The report describes the method and its usability in detecting the chain of nuclear material production using aerial gamma ray measurements. Technical details are given on how to manage measurement tasks, and information is also given on what is detectable from an aeroplane and how it is detected.

The ability to use the airborne detection system has been tested to reveal the use of undeclared nuclear material. Various scenarios were considered with which to reveal clandestine nuclear material production, enrichment, and nuclear waste trails. The exercises arranged during this programme show that it is possible to reveal such clandestine activities.

The fixed-wing gamma measurement technique developed under this contract is ready for detecting significant amounts of nuclear material efficiently and cost effectively. Large areas can be screened to find suspicious sub-areas for more accurate inspection. The approximate cost of screening is USD 17.4 per square kilometre.

Contents

1 Introduction

After the accident that occurred at the Chernobyl nuclear power plant and the subsequent fallout received in Finland, the Finnish national emergency preparedness officials made the decision to develop high-level tools further for the measuring and mapping of large-scale fallout situations. The primary officials responsible for this work were the Finnish Radiation Safety Authority (STUK) and the Defence Forces (DF). Several improvements were made in the nation-wide radiation-monitoring network to guarantee quick response in any fallout situation. The decision was also made to develop an operational system for measuring airborne gamma rays. The main goal of the airborne system was to guarantee its functionality and fulfil the needs to map large fallout areas rapidly. The development of the airborne measurement system was put in the hands of the Defence Forces.

Airborne gamma ray spectrometry is a powerful technique for rapidly and sensitively mapping the wide range of artificial radionuclides resulting from nuclear accidents. The measurement efficiency of the airborne system to scan large contaminated areas is unique. The complex mixture of radionuclides can be analysed with a sensitive detector. Maps of the fallout pattern are essential for planning emergency responses and for restricting the sale of agricultural produce. The capability for quick response to extraordinary situations is the key factor to minimizing the associated commercial loss and human suffering. All these facts together provide airborne radiation measurements with the support needed to maintain and develop the measurement system in Finland [1–7].

Airborne gamma measurement can also be used to find lost point sources. When the task is to locate lost point sources, the strategy for the measurement differs from that for fallout mapping. Shorter integration times and few statistics play a major role. Because of the short integration time, one important detector property is radiation detection efficiency, another is the long-term stability of the measurement system, and a third is the energy resolution of the detector. The importance of these three properties is of course dependent on the physical properties of the nuclide in the lost point source. Because the background radiation level is low for low-flying aircraft and it differs essentially from artificial radiation at point sources, the possibility to differentiate anomalies from natural terrestrial background is extremely good.

One important goal for a task locate a point source is to reveal undeclared nuclear activities. For example, the essential task for producing a nuclear bomb is to obtain enough nuclear material for the enrichment or reprocessing process. To get enough uranium for the bomb, mining-related processes must be carried out. These kinds of activities leave a trail in the environment, and airborne measurements can trace it.

Airborne radiation measurements can be used for other purposes as well. One scenario would be a terrorist action in which radioactive substances are distributed over populated areas. Such a scenario can be accomplished through the following means:

- Attack on a nuclear power plant, research reactor, or other facility containing large quantities of radioactive substances. For example, a hijacked aeroplane can be used as a penetrator.
- Traditional explosions surrounded by radioactive substances, for example, stolen radioactive sources can be exploded or burned in the neighbourhood of a strategic site as so-called “dirty bombs”.
- Radioactive waste can be spilled on an area producing food or other substances needed for daily living, for example, on fields, the sea, a

community water supply, the paper production chain or other similar sites.
- A hijacked aeroplane can be loaded with radioactive substances and dropped in the middle of a populated area.

All of these scenarios call for rapid aerial survey and the capability to report close to real time for further action plans. It must be noted that the threat itself can be used as a weapon, and in some cases we need to be able to prove that the claimed release of radioactive substances is not true. For example, such a rumour can have a severe psychological impact on a population. The economic impact can be large if the correct information is not released in a timely manner. Hardly anyone is willing to eat fish if a radiation terrorism attack has been assumed to occur on an unknown area at sea, for example. In extreme cases, a terrorist group could manufacture a nuclear weapon of their own or steal one and explode it in a city. No matter how successful this kind of explosion is, rapid survey is needed to determine the hazardous area.

The focus of these fixed-wing measurement tests in 1999 and 2000 was on providing guidelines for carrying out practical field measurements over large areas under hard conditions. In the autumn of 2001, the nuclear emergency exercise “Barents Rescue 2001 LIVEX” provided a valuable possibility to compare the properties of large and medium-size sodium iodine detectors. Particularly the "Gamma Search Cell" part of this exercise concentrated on revealing lost point sources. The results of the participating teams will be published by Nordiska Sällskapet för Strålskydd (NKS) [8].

2 Description of airborne measurement systems

The airborne gamma measurement system consists principally of the following four parts: gamma ray detector, analyser, computer and software. The platform of measurement is very challenging when compared with that for laboratory measurements or even with that of car-borne measurements. The reliability of all four components must be much higher. Especially the detector specifications must fulfil the requirements of the special measurement environment. Due to the high speed of the aircraft, the amount of collected data is huge. The computer systems must be capable of handling the data so that important spectra are saved on disk for post-processing. The programs must be efficient enough to process the data in real time, and reprocessing must be carried out easily.

The measurement data are usually presented in some form of a digital map. For fallout mapping, online triangle modelling is usually accurate enough. Post-processing and ground level modelling are needed when point sources are located.

3 Flight measurement system for Finnish emergency preparedness purposes "GammaJet"

Finland has a highly rated operational capability to execute fixed-wing gamma measurements for national security reasons; this preparedness was primarily built for fallout mapping purpose. For this security reason, the preparedness level is kept high through regular exercise. Changes in the security environment have emphasized the need to develop tools for use in emergency preparedness situations other than pure fallout mapping. The option to locate a point source must put more weight on development because it can offer many benefits in the foreseeable future.

The Defence Forces' airborne gamma spectrometry equipment consists of an Hyper Pure Germanium (HPGe) detector (relative efficiency 70% at 1332 keV) to measure nuclide-specific ground contamination. A 6×4 inch sodium iodine detector (NaI) was also installed on the rack to help find lost radioactive point sources. The spectroscopy system can be installed in both a helicopter and a jet plane. It has also been installed in commercial aircraft. The measurement results are analysed immediately, and the system produces fallout patterns in real time for one chosen nuclide on either a vector or a raster map. The positioning is based on world-wide reachable Global Positioning System (GPS) service, but Russian GLObal NAvigation Satellite System (GLONASS) position satellites can be also used. For navigation in Finland, it is possible take advantage of the DGPS service provided by the Finnish Broadcasting Company, which utilizes the Radio Data System (RDS) channel to obtain position accuracy within 2 metres. The correction signal can be picked up nationwide on the FM transmitter network.

__Figure 1.__ The Finnish Air Force Learjet 35A/S used for radiation monitoring. Photo by FDF /Jyrki Laukkanen.

The fallout maps for each important nuclide are produced using the MicroStation program with TerraModeler application. This application software can produce the map in real time for one nuclide, and for other important nuclides these fallout maps can be produced quickly after the end of the measurement. The measured spectra and the fallout maps must be sent as quickly as possible to the civil defence authorities. After the aeroplane lands, the cellular telephone data connection can also be used to send data to the national emergency database. The map system allows the use of vector and raster maps.

Detection limits for the airborne monitoring system in case of fallout

The flight parameter influences the required detection limit with the following decreasing order: altitude, speed, and acquisition time. The detection limits (15 seconds integration time, uniform distribution and 70% germanium (HPGe) detector) for a helicopter flying at an altitude of 60 metres are:

Gamma source	^{241}Am	^{57}Co	^{137}Cs	^{60}Co
Energy [keV]	59.5	122.4	661.6	1332.5
[kBq/m^2]	25.3	3.30	1.81	0.65

These values have been calculated using MDA calculation formulas by Currie [9].

With minor preparation, the equipment can be used all over the world in cold winter conditions, as well as in oppressive summer environments.

In several exercises, for example, in International Nuclear Exercise (INEX); INEX-2-FIN [10] and Barents Rescue 2001 [8] international exercises, the described system has proved its capability to produce radiation maps reliably and rapidly.

At the end of the exercise, the Defence Forces made fallout mapping of the area northeast of Nuclear Power Plant (NPP) and produced a fallout map of the area (Fig. 2). This measurement was done from a helicopter, and 370 square kilometres were measured in 1 hour and 17 minutes. The final fallout map was sent 41 minutes after the plane landed via a GSM data connection to a SVO+ server at 1746 local time.

The procedure for making aerial measurements in emergency situations is, in general, the following: The Radiation Safety Authority (STUK) requests the headquarters of the Armed Forces to execute a radiation reconnaissance flight above a certain area. The headquarters gives the order to carry out the task to the air forces or land forces. The aeroplane or the helicopter is supplied on its home base. At the same time, the Defence Forces Technical Research Centre prepares the measurement system, and the measurement platform and system are combined at the Pirkkala air base. During workhours this procedure takes 2 hours. At the air base, the installation takes no longer than 2 hours (usually 1 hour). After the survey the results are sent to the headquarters of the Defence Forces and also to STUK.

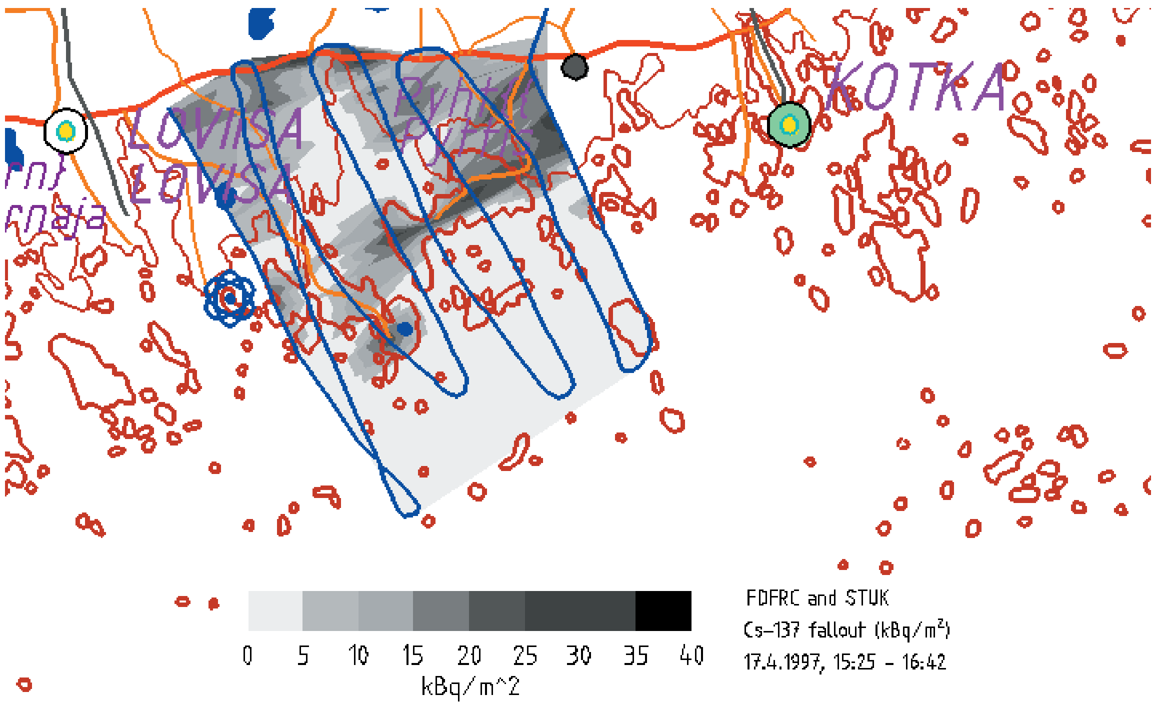

Figure 2. *Aerial ^{137}Cs mapping of an INEX-2-FIN exercise done from a helicopter between at 1525 and 1642 local time. The average line spacing was about 2.5 kilometres. The base map is a digital vector map to allow for easy scaling.*

4 Detection capability case studies

The project includes three case studies; two were carried out in Otaniemi and one at the time of the Barents Rescue exercise in Sweden. The aim was to compare the capability of the detectors to find point sources when advanced post-processing and ground level modelling are combined with gamma measurements.

4.1 Otaniemi 1999 and 2000

The source term, natural uranium, was placed in the geometry described in Appendix 1. The background radiation level of the Otaniemi cape is very diverse because of the topography, uranitic rocks, and large buildings placed on the cape. A Finnish Air Forces Learjet 35 was used. The speed of the aircraft over the test area was 450 km/h. The flight height was 100 metres, and the flight line spacing was 50 metres—first two 35 metres. Two medium-size NaI (1.83 litres) detectors and any other equipment needed for the measurements were installed in the cabin. The results showed that the source could be determined using these detectors. An accurate description of the test is presented in Appendix 1.

In the year 2000 the arrangements were similar. The speed and altitude were the same, and the line spacing was 25 metres. The source term was the same natural uranium placed with somewhat more open geometry. HPGe and NaI (6.83 litres) detectors were used. The results showed that the large NaI detector was not stable during the measurement, and the increased statistics did not offer the benefit of locating the source. The very few high-quality HPGe counts were more useable in pinpointing the source. An accurate description of the test is presented in Appendix 1.

4.2 Barents Rescue 2001

The goal of the Barents Rescue 2001 exercise was to find and characterize as many lost point sources as possible in a limited amount of time. Five different measurement areas (each 10 km^2) were used during the exercise, as were 50 minutes of flight time over every area. Medium-size NaI (1.83 litres) and HPGe detectors were installed on a commercial Swedish helicopter. An accurate description of the test exercise is presented in Appendix 1. The exercise involved 12 airborne search teams from 7 countries. The good spectral quality of the rather small detectors allowed most of the hidden sources to be found using the advanced post-processing technique. Altogether 13 of the 23 hidden sources were revealed. This is a top-quality result for the Barents Rescue exercise. Only the Danish team succeeded to find the same number of sources. The complete list of sources used in the exercise is also given in Appendix 1.

5 Equipment and procedures

5.1 Detectors

5.1.1 Detector properties

Sodium iodine detectors are based on the use of scintillation material and a photomultiplier tube. The light production in active material of the detector changes as the temperature changes. The photomultiplier gain is sensitive to temperature. These two characteristics combined cause the detector energy response to be unstable at fluctuating environmental temperatures. HPGe detectors are cooled by liquid nitrogen at a very low operating temperature, and environmental temperature changes do not affect the energy response. Mechanical vibration and acceleration can also affect the detector energy response. The vibration can be dampened, but long-lasting acceleration cannot be avoided. The HPGe detector is not sensitive to acceleration, but photomultiplier tubes are. The acceleration can shift the dynodes inside the photomultiplier tube and therefore change the gain. Large NaI detectors with a large photomultiplier tube are more vulnerable to this kind of environmental stress.

5.1.2 Detectors used at Otaniemi and the Barents Rescue exercise

In the experiments, one large and two medium-size NaI detectors and also one hyper pure HPGe detector were tested. The basic properties of these detectors are listed in Table I.

The 6×4 inch medium-size NaI detector is used for purposes of preparedness in Finland, as also is the 70% HPGe detector. The large NaI detector is property of the Geological Survey of Finland, and it was borrowed for the exercise.

5.1.3 Comparison of the large and medium-size detectors (NaI)

The outer cover of the large detector was king-size due to the good heat insulation structure, and the installation of this detector was complicated because the space in the jet plane was very limited. For medium-size detectors the installation was more convenient.

5.1.4 Conclusions regarding detectors

From a practical point of view the medium-size detector is much easier to handle and install. The large sodium iodine detector was not robust enough to produce undistorted high-quality spectral data during real missions in demanding circumstances.

5.2 Real mission requirements for detectors

5.2.1 Operating environment

The real mission environment is very challenging. Acceleration, vibration, and temperature gradients can affect detector stability. A long mission duration also makes special demands on detector usability and reliability factors.

Table I. *Technical data of the detectors. The shape of the detectors was cylindrical.*

Detector	Size (diameter × height)	Relative efficiency @1.17 MeV compared 3×3 inch NaI detector
1,83 litres NaI	6×4 inch 152×102 mm	540% Teledyne Brown Engineering Model S-2146 u/s and Scionix Holland BV 152 AS 102/5E-XQ
6.83 litres NaI	11.5×6 inch 292×102 mm	1000%
70% HPGe	69.7×76.9 mm	70% EG&G OrtecGEM-60200-P

With the large detector the bigger and heavier parts inside the photomultiplier may make it more vulnerable for the disturbances (acceleration, vibration) generated by aerial environments. The decrease of FWHM during the measurement and the changes of the used large NaI detector during energy response makes it impossible to benefit from the increased statistics offered by large detector.

5.2.2 Minimum requirements

The detectors must be stable against environmental temperature changes, acceleration and vibration; it is essential keep the spectral quality acceptable for post-processing to get good ground level model.

5.2.3 Conclusions

Medium-size NaI detectors are the most usable under field circumstances; their detection efficiency is better than that of HPGe detectors, and there is no need to cool them. The use of medium-size NaI detectors makes a long campaign more practicable to carry out with success.

5.3 Global positioning devices

GPS navigators were used to determine the position on earth. For this purpose, a dual-channel (GPS and GLONASS) positioning device was used. This device outputs data in NMEA 0183 format, which is commonly used for many applications on naval and airborne fields. GPS is owned by the United States, whereas GLONASS uses a Russian satellite network. Both of these systems are non-scrambled and freely usable for contemporary purposes.

The positioning system is rather accurate, the average accuracy ranging from 5 to 10 metres, which is rather good for airborne measurements. If more accurate positioning is needed, a differential system can be used to remove uncertainties in the positioning. In some countries radio bandwidth receivers are used on a commercial basis to transform corrected positioning; a new feature is available to make the correction directly via satellites. This correction is not yet available globally.

One adjustment was made for the GPS data handling. The dynamic correction factor was checked more carefully for the Barents rescue exercise. Earlier a static correction was made to

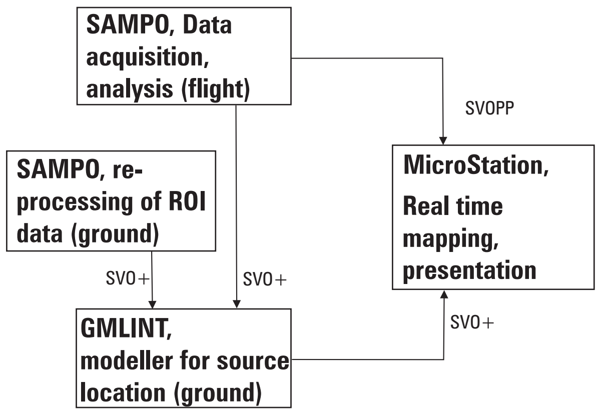

Figure. 3. *Computer data-processing dependencies and data exchange format.*

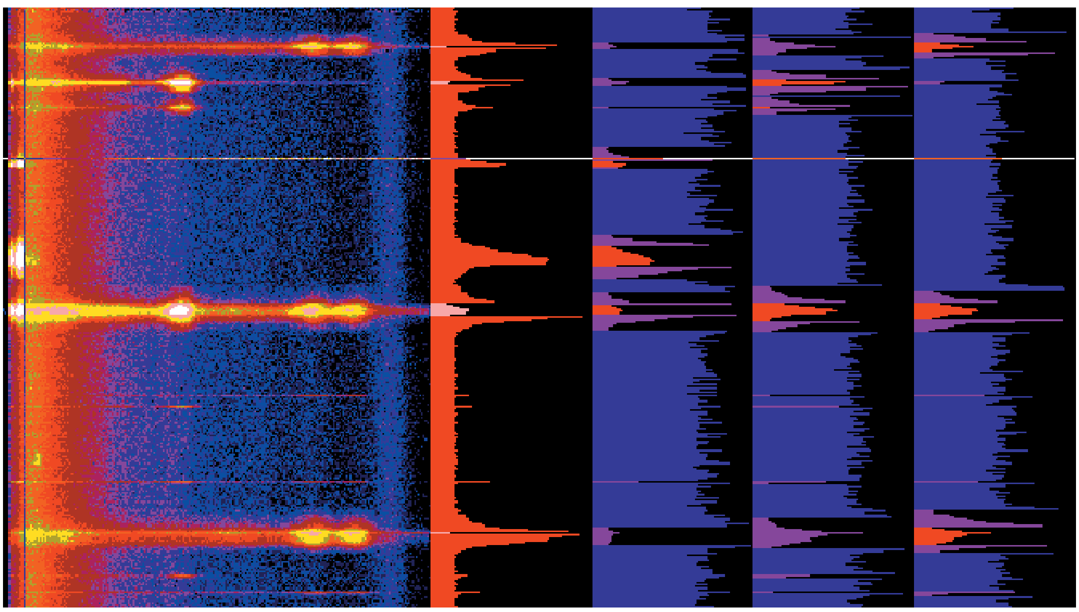

Figure. 4. *SAMPO measurement window during the data acquisition. This was a test in the laboratory using large sources. A whole spectrum and four regions of interest are shown in graphic form. Large sources can be detected, identified and located directly using this feature.*

the positioning, which was based on old information from previous exercises. Now the dynamic factor was set with an accuracy of 0.1 seconds instead of 1 second, which improved the positioning accuracy by more than 60 metres. This change resulted in more accurate mapping in the post-processing phase.

5.4 Computer infrastructure

In GammaJet application, the tasks of different computers were dedicated in advance, each detector having one computer. One computer was handling NaI data only, and one dealt with HPGe data. Navigation and flight lining was a separate application carried out by another NT computer. During real jet-plane application all the computers are interconnected via the Ethernet network. One additional computer can be set up to draw 3D information in a mapping system based on MicroStation CAD software.

Post-processing computers do re-analyses of data on NT computers supplied with SAMPO software. The result (energy window and position information) is transferred to a Linux computer, where data is modelled for ground level mapping. Output is a bitmap that can again be included in a mapping system based on vector maps.

5.5 Data processing

The data acquisition system was based on SAMPO software [11,12, 13]. SAMPO 4 takes the data from MCA and GPS receivers and couples them together. During the data acquisition, some analyses are already done for the data; four predefined regions of interest on the spectrum are investigated and visualized on what is called a rainbow or waterfall display. (See Figure 4.) Analyses can also contain peak detection and single peak quantification based on energy information. In a wide-range fallout analysis in which 1-minute data collection can be used, a full spectrum analysis, including peak location, peak area fitting and radionuclide identification, can be added.

Post-processing may contain analyses of the original raw data that resemble those during the acquisition. In the post-processing phase the user can change the regions of interest or use different kinds of graphic filters to enhance the visibility of anomalies detected in the gamma flux by the detector.

GMLINT software is used to model the data to produce a smooth output of the map. The idea of GMLINT is to determine the most probable data between the sparse grids developed by the measurement points. Different smoothing filters can be used for the fallout and source location to enhance the visibility of the sources or to make a more average map of the wide fallout area. Sample figures of the GMLINT results are shown in Appendix 1.

5.6 Mapping systems

Our mapping system is based on the MicroStation platform. We have the following two applications working with that platform: Tlink for a realtime connection to the measurement results of the measurement computer and Tmodel for modelling and presenting the results on the base map. The Tmodel uses a triangle for modelling the results, and, if it is combined with Tlink, the measurement data can be updated in real time on the map. Other surface models can also be used; for example, the model post-processed by GMLINT [14] can be presented on our map system. Vector or raster maps can be used for base maps. Different map projections can be converted to those supported by our system.

5.7 Recommended airborne measurement system

According our knowledge, the use of 2–4 medium-size NaI detector units installed in the aeroplane is recommended. Multiple units increase the total reliability of the system and offer more flexibility of choice between different scanning methods.

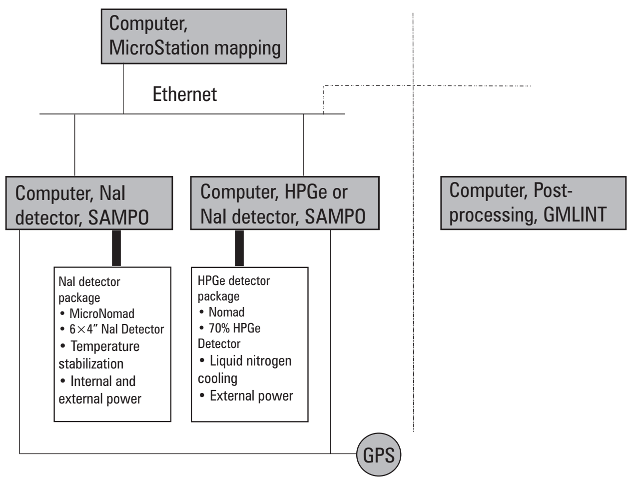

Figure 5. Schematic view of the recommended instruments needed for measurement campaigns. The detector block can easily be multiplied.

6 Conclusions

The field trials showed that it is possible detect a significant amount of radioactive material using a medium-size NaI detector and post-processing of the recorded data.

To increase the probability of carrying out a long-lasting campaign successfully, it is recommended that 2–4 medium-size NaI units be used.

Ground level modelling (GMLINT) was found to be important for the detection of anomalies.

Theoretical calculations can be used to determine the magnitude of unscattered photon flux for the detector produced by combined homogeneous radiation sources.

The aircraft platform must be suitable for measuring the installation, and the attenuation factor of the body structure must be as small as possible.

A professional aeroplane operator is essential for successful installation.

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APPENDIX 1 CASE RESULTS

Three case studies were carried out during this project, two at Otaniemi in Finland in 1999–2000 and one in Sweden at the Barents Rescue 2001 exercise. The aim was to compare the capability of detectors to find natural uranium point sources when advanced post-processing was added to the search. The detectors studied were 70% HPGe, 6.83 and 1.83 litres NaI.

1 Source description

These two source geometries did not differ much with respect to flight measures. The 2000 geometry was somewhat less shadowed.

2 Field trials in Otaniemi, Finland

The source term, natural uranium, was used in the aforementioned geometries. The background radiation level of the Otaniemi cape is very diverse because of the topography, uranitic rocks, and large buildings placed on the cape. A Finnish Air Force Learjet 35 was used. All the detectors and other equipment needed for the measurements were installed in the cabin. The installations were inspected and accepted by the Finnish Air Force Depot, which is the aviation authority for military aeroplane installations.

Figure A1-1. *Source term used in the December 1999 test. The elements are in two beds.*

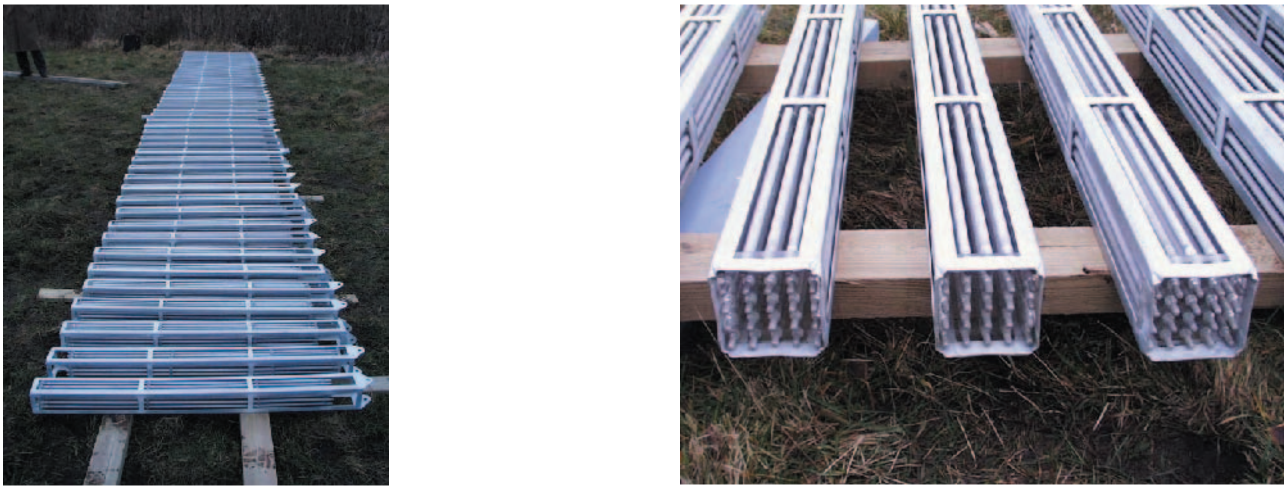

Figure A1-2. *Source term used in the December 2000 test. The elements were placed in a row to decrease attenuation. The row was 15 metres long.*

The aeroplane body was strengthened using arched and longitudinal structures. Detector placement had to be optimized to decrease the attenuation of the aeroplane body.

2.1 Otaniemi exercise in 1999

The test was made using two medium NaI detectors. The volume of the medium-size detector was 1.83 litres [diameter 152 mm, height 102 mm]. These two spectrometers worked independently. The WGS coordinates in the form of the NMEA-0183 norm were obtained from the internal combined GPS-inertial navigation system of the Learjet.

The flight altitude of the jet plane was 100 metres, and the speed varied between 400 and

Figure A1-3. *An example of typical equipment installation accepted for continuous use in Finland. In this case two HPGe-detectors were being installed. The first HPGe detector was not completely in place.*

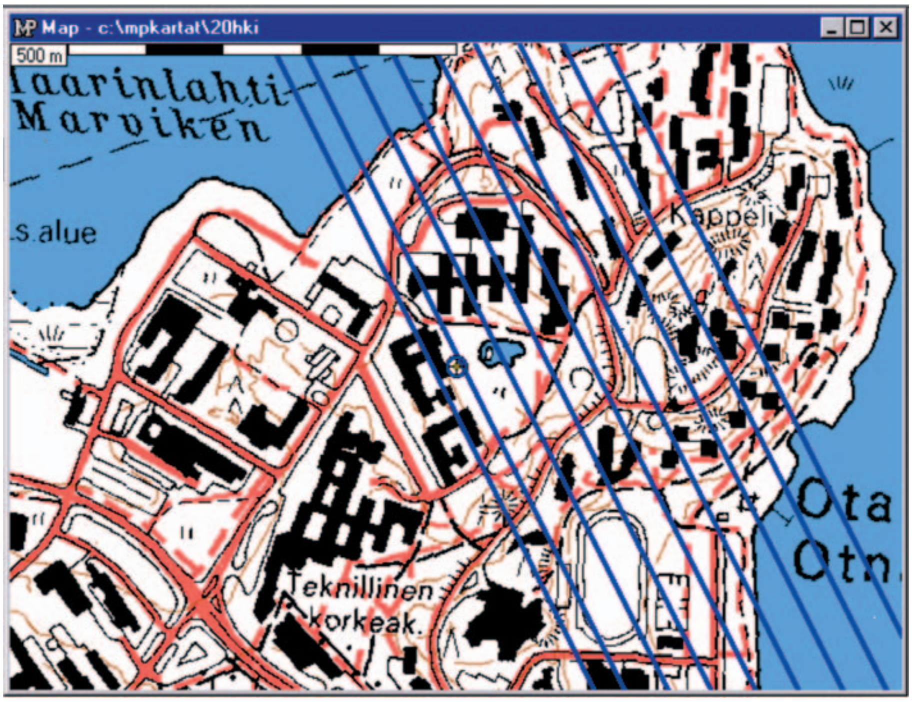

Figure A1-4. *Planned flight lines used for the Otaniemi exercise in 1999.*

APPENDIX 1 — CASE RESULTS

500 km/h, 460 km/h mainly being used. The first two line spacings were 35 metres and the rest were 50 metres. There was water on both sides of the cape. The background is very difficult over the cape. The source term is indicated in the figure near the pond.

On the 1999 measurement, we found a signal (1001 keV) from a uranium source during the flight. Some signals were also detected from the uranitic rocks. A signal (1461 keV) from naturally occurring K-40 nuclide was also detected.

2.2 Otaniemi exercise in 2000

The measurement was conducted using one large NaI detector and one 70% relative efficiency HPGe detector. The large detector was a 6.83 litre [diameter 292 mm, height 102 mm] NaI crystal used in geological surveys of natural radiation. It had not been used for some 20 years. These two spectrometers worked independently. The WGS coordinates were obtained in the form of the NMEA-0183 norm from the internal combined GPS-inertial navigation system of the Learjet.

The placement of the equipment and operators (in the test there were three operators on the plane) were demanding for the test flight task because of the very limited space in the cabin. We finally found a functional arrangement that was also acceptable to the aviation authority.

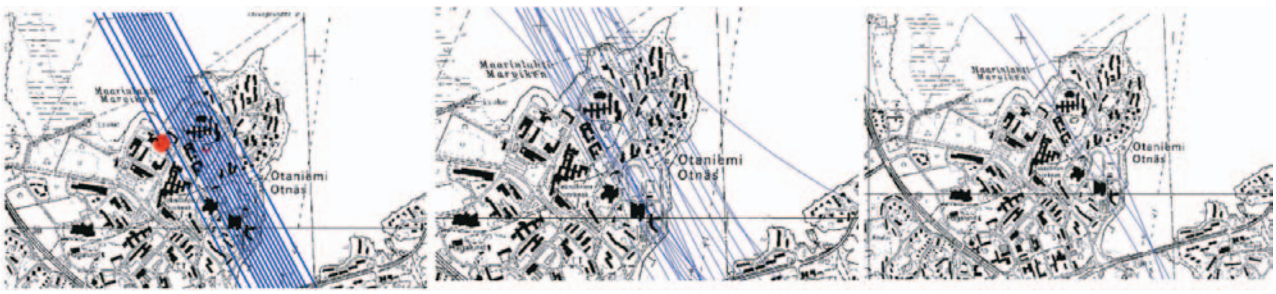

__Figure A1-5.__ The planned and actual flight lines used in the Otaniemi 2000 exercise. The bigger red spot on the left is a big chimney. The source term is the smaller red line on that same picture. The three lines at the right were flown in opposite directions.

__Figure A1-6.__ The Learjet 35 flying above the target and the installations in the cabin. The large "barrel" at the front is the 6.83 litre (11.5 × 4 inch) NaI detector, the second detector, installed inside the cube, is a 70% HPGe detector and ahead of the operators are spectrometers and a computer.

2.3 Detailed data analysis

The final results were evaluated from recorded spectra. The SAMPO program was used for the post-processing. Baseline reductions were carried out using high-energy gamma flux correction when recorded data quality made it possible to use this advanced analysis method. The final results were produced using the GMLINT program. The GMLINT program uses point source characteristics (including properties of material between the source and detector) to locate the possible point source.

2.3.1 Analysis of the Otaniemi 1999 spectra

The data from the two small NaI (6×4 inch) detectors were similar. The data quality (inter alia peak resolution) was the same as that measured under fixed laboratory conditions. See the sum spectra in Figure A1-7.

The quality of the recorded data allowed the use of a small window in the regions of interest, as well as advanced data post-processing with baseline reduction using high-energy gamma flux correction.

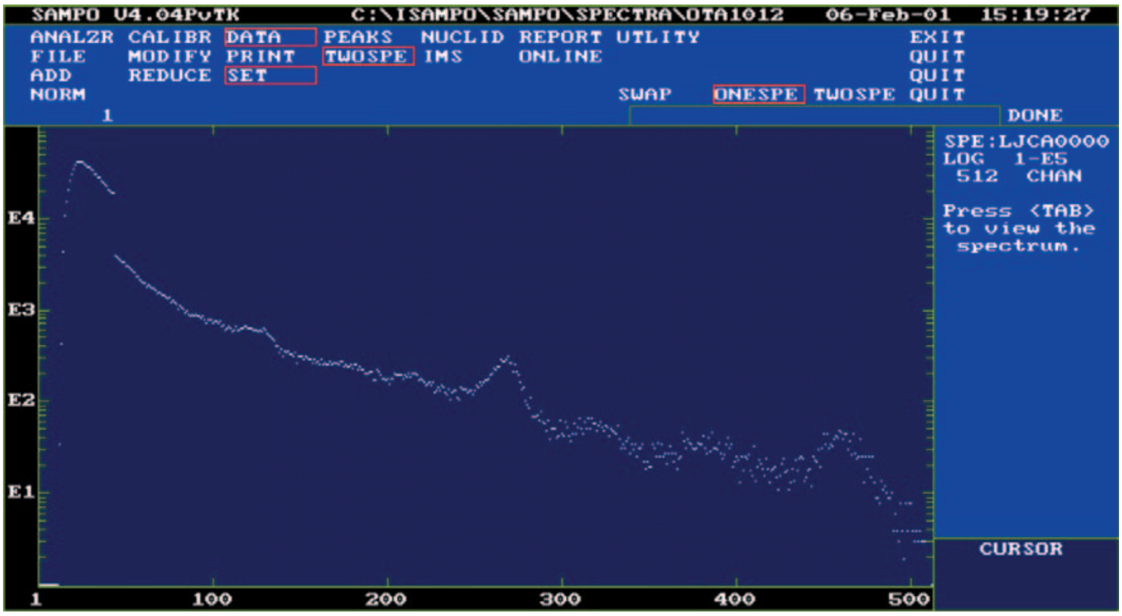

Figure A1-7. *Sum spectra of all the spectra recorded with one medium-size NaI (6×4 inch, 1.83 litres) detector in the 1999 exercise. No broadening of the spectra can be detected. The discontinuation at the beginning of the spectra is due to some error in the summing.*

APPENDIX 1 CASE RESULTS

Table A1-I. Detector properties.

Detector size	FWHM in the laboratory (%) @661 keV	FWHM on the field (%) @661 keV	Relative efficiency @1.17 MeV compared 3×3 NaI
0.35 litres	6		100%
1.83 litres	4.7	5	540%
6.83 litres	11.7	22	1000%

2.3.2 Analysis of the Otaniemi 2000 spectra

Table A1-I shows the properties of the medium 6×4 inch NaI and large 11.5×4 inch NaI detector.

2.4 Remarks on the Otaniemi exercises

Since the measurement signal was assumed to be at the top of a natural signal in this case, the signal-to-noise ratio caused the 1.83 litre detector to be better than the 6.83 litre detector. The signal-to-noise ratio is proportional to the square root of FWHM, and the higher efficiency of the large detector also causes extra impairment, especially when the FWHM is poor. K-40 1461 keV gammas give pulses in the background under the 1001 keV peak, and the detection limit decreases.

When compared with data from the 1999 exercise, the sum spectra had a very smooth peak shape. In September 1998 we sent an interim report, "Fixed Wing Survey, Gamma Detector Comparison", which describes the dependency of the minimum detectable activity on the square root of the ratio of the resolution of the compared detectors. The big difference between the behaviour of the large and middle-size detectors in the actual measurement situation was the key factor leading to the recommendation of the medium size detector in execution of the wide area measurement campaign.

In geological surveys the detector can be stabilized using naturally occurring radionuclides like K-40 or Pa-234m. The aeroplane used for geological surveys in Finland is a small plane equipped with a twin propeller motor; the flight speed is about 200 km/h. Therefore the measurement environment differs completely from that of jet-based measurements. The speed of a jet plane is about 500 km/h; at this speed the stress caused by acceleration forces is significantly larger.

Since the measurements must be done with short intervals to reach adequate local accuracy, the information per measured square metre is much lower with the jet-plane measurement system.

If the target country has low background in respect to naturally occurring radionuclides, automated stabilization cannot be used.

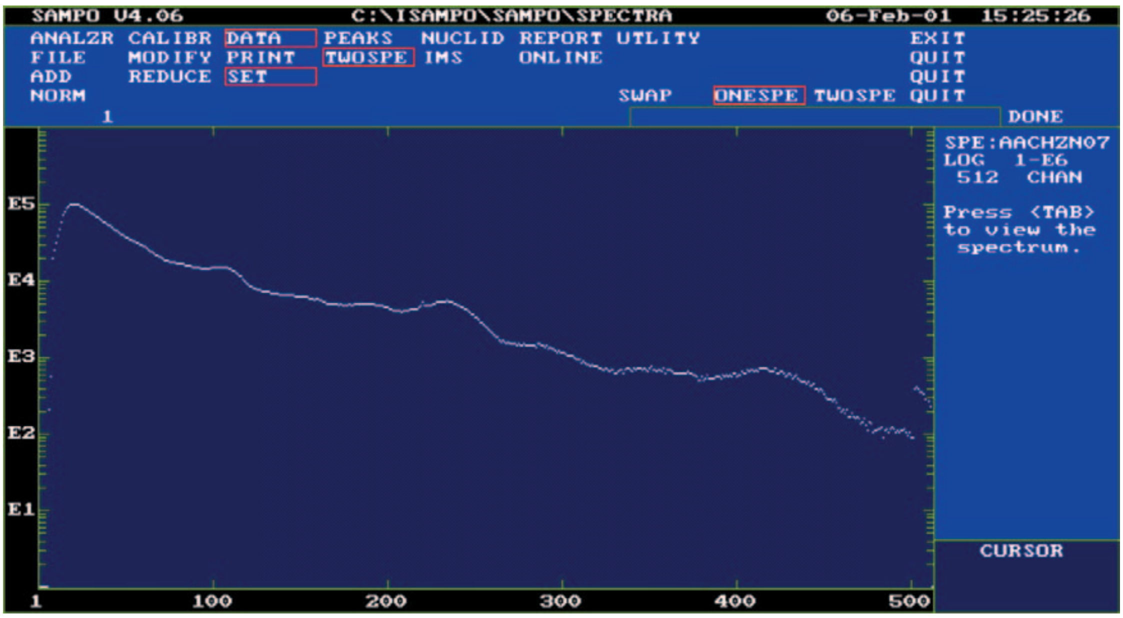

Figure A1-8. Sum spectra of all the spectra recorded with the large NaI (11.5 × 4 inch, 6.83 litres) detector in the 2000 exercise. Clear broadening of the spectra can be detected.

2.5 Post-processing of the Otaniemi spectra

The Otaniemi spectra were post-processed by the GMLINT program.

2.6 Data interpretation

2.6.1 Interpretation of the 1999 results

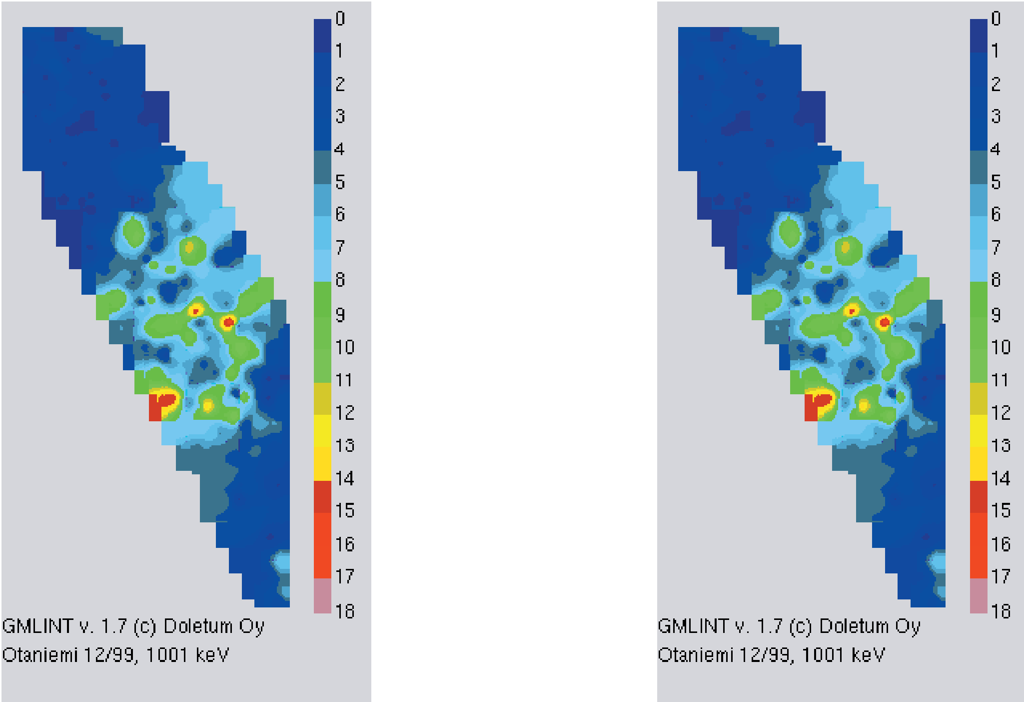

Figure A1-9. *Processed results from the 1999 measurements presented by the GMLINT program. The data were obtained with the small NaI detector (A4). The data quality allowed advanced data processing.*

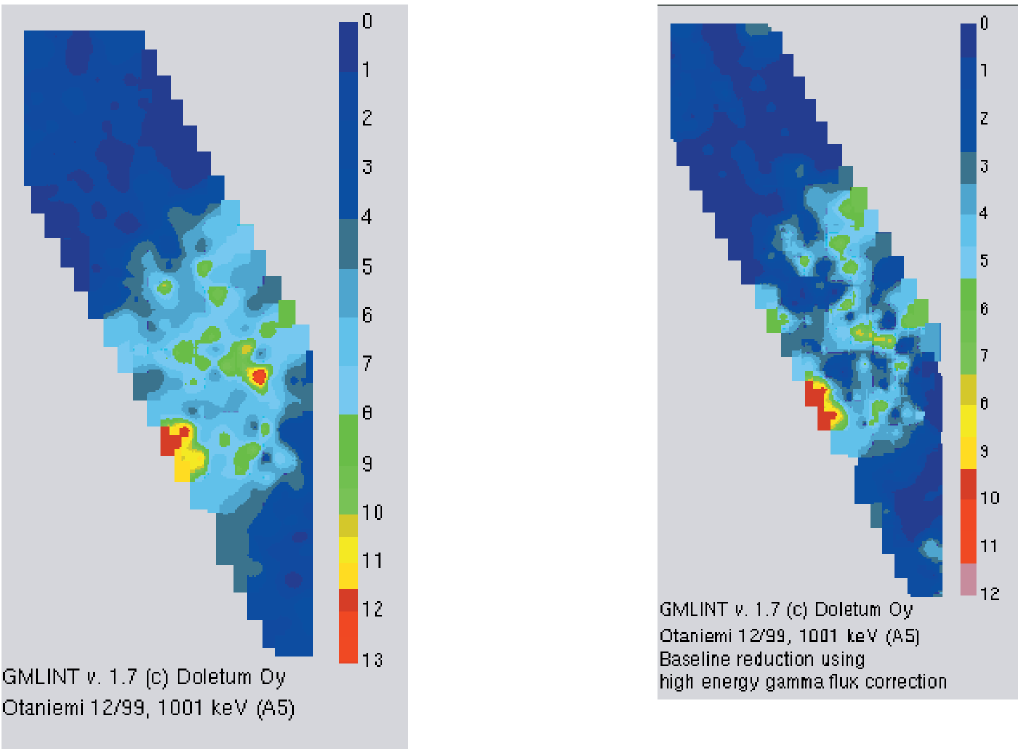

Figure A1-10. *Processed results from the 1999 measurements presented by the GMLINT program. The data were obtained from the small NaI detector (A5). The data quality allowed advanced data processing.*

2.6.2 Interpretation of the 2000 results

It was noted that, during the 2000 measurements, the detector gain was living ≥40 keV within the energy range of Pa-234m. The accelerator forces caused this variation. It caused the FWHM of the peak at 1001 keV to be more than 100% higher than in the laboratory environment. The measured FWHM value of the large detector in the laboratory environment was 11.7% at 661 KeV and during the flight test it was 22%. As a result, the signal-to-noise ratio was much worse than with the medium-size detectors used in the previous test measurements, and the source was less visible than in the measurements performed in 1999.

See also Appendix 2: Calculated and detected counts

The usefulness of the quality of the measured data was also demonstrated using a "wide" window on the HPGe detector spectra in the caesium window. In addition to the low statistics of the data, the source can also be found in the HPGe data; see Figure A1-12.

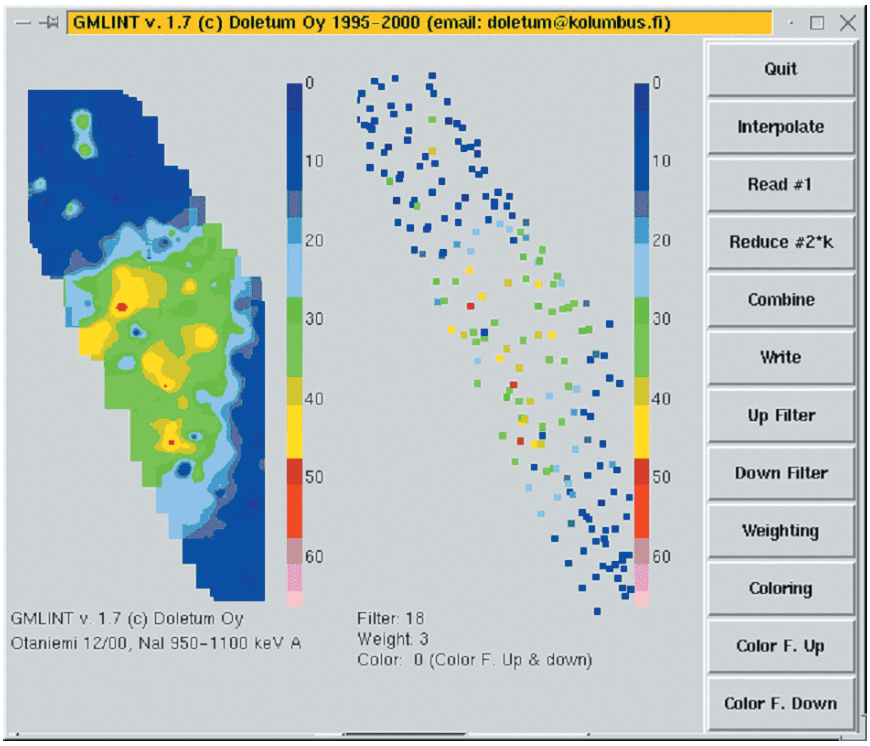

Figure A1-11. *Processed results from the 2000 measurements presented by the GMLINT program. The data were obtained from the large NaI detector. The data quality did* ***not*** *allow for advanced data processing.*

The 1999 results were more valuable for finding a natural uranium source. The low background of the flying jet plane enabled source detection from a few “high quality” counts. The benefit of advanced data post-processing then becomes available.

In 2000 we obtained more statistics but less advantageous data. The large NaI detector was more vulnerable to disturbance than the medium-size detectors were. The few high-quality HPGe counts were more useful for pinpointing the source.

The comparison showed that the source is possible to detect using a medium-size NaI detector at high speed at an altitude of 100 metres in a jet plane. Flight lines must be followed accurately, and some signals from the source can be detected during the flight. The measurement data must be post-processed after the flight to obtain the final result.

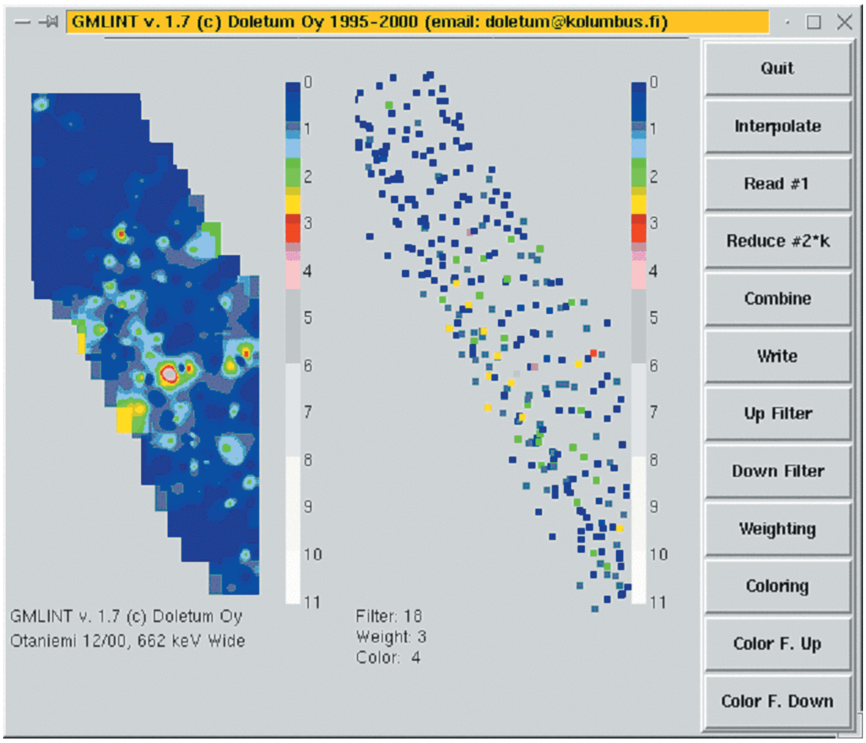

Figure A1-12. *High quality HPGe data presented by the GMLINT program. The low statistics did not prevent the source from being found.*

APPENDIX 1

2.7 Barents Rescue 2001

The Barents Rescue 2001 LIVEX exercise was held in the spirit of the Partnership for Peace to conduct exercises aimed at the search for and identification of orphan radioactive sources over large areas.

2.7.1 Equipment used in the exercise

- 6×4 inch NaI detector + MicroNomad analyser
- 70% HPGe detector + DART analyser
- GPS GLONASS satellite navigator
- Three IBM ThinkPad laptop computers
- DC/AC inverter

The listed instruments were installed in a Swedish civilian helicopter (Eurocopter 350), which was furnished by the organizer of the “Barents Rescue 2001” event, Appendix 5.

2.7.2 Methods of search

The helicopter flew continuously over the measurement area at a height of 60 metres. Its speed varied between 150 and 230 km/h. The lines were spaced 100 meters apart. The spectrometers had an integration time of about 1 second. Navigation was primarily based on the GPS and MapPerfect navigation programs. The aim was to provide coverage that was as uniform as possible for the whole measurement area within the limited flight time.

A back seat was removed from the helicopter, and the detectors were positioned in its place. The detectors were protected against shock and vibration. Their location was chosen to minimize attenuation from incoming radiation. The attenuation factor of the helicopter body was modelled using point-source measurement.

2.7.3 Data analysis

The online detection of the source was based on the online display of the SAMPO program. Sources were recognized using predefined regions of interest (ROI) by checking for the sum spectra after the measurement and then processing the data. Data obtained with the HPGe and NaI detectors were used to determine both the nuclide and the activity of the orphan source. The SAMPO and GMLINT programs were used for the post-processing. The activity estimate was based on the approximation done by the GMLINT program. All possible shielding was evaluated.

2.7.4 Results

The locations of hidden sources are presented at the end of this appendix. During the exercise, all five of the measurement areas were scanned. The results were delivered to the organizer 1 hour after the helicopter landed. The co-ordinates were in WGS-84.

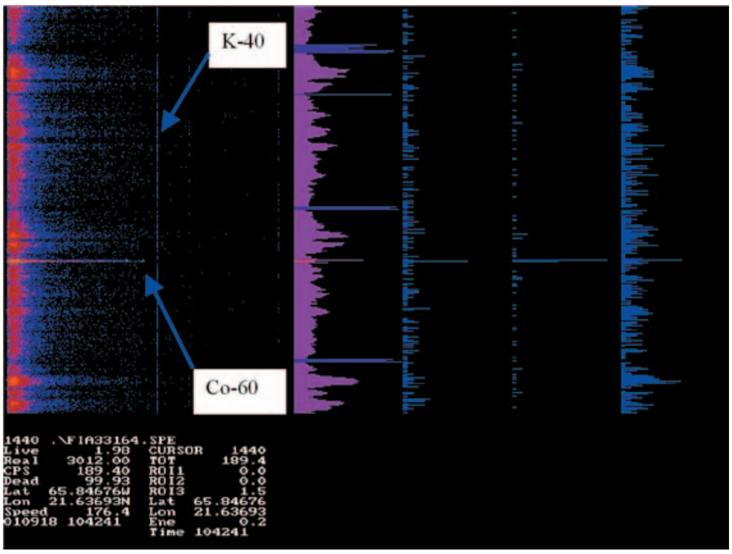

Figure A1-13. *An example of a SAMPO window. The last 360 spectra of the measurement are shown. K-40 can be easily identified, and two peaks of Co-60 point sources are visible.*

Table A1-II. Sources found in area A1.

Nuclide	Coordinate (E)	Coordinate (N)	Activity	Remarks
I-131	21°22'52.68"	65°41'29.60"	3 GBq	Open source
Co-60	21°22'48.97"	65°41'45.86"	1 GBq	Open source
Co-60	21°23'54.90"	65°42'08.50"	1.2 GBq	Open source
Co-60	21°22'41.99"	65°40'53.75"	0.6 GBq	Prop collimated
Cs-137	21°23'54.90"	65°42'09.00"	0.25 GBq	Uncertain

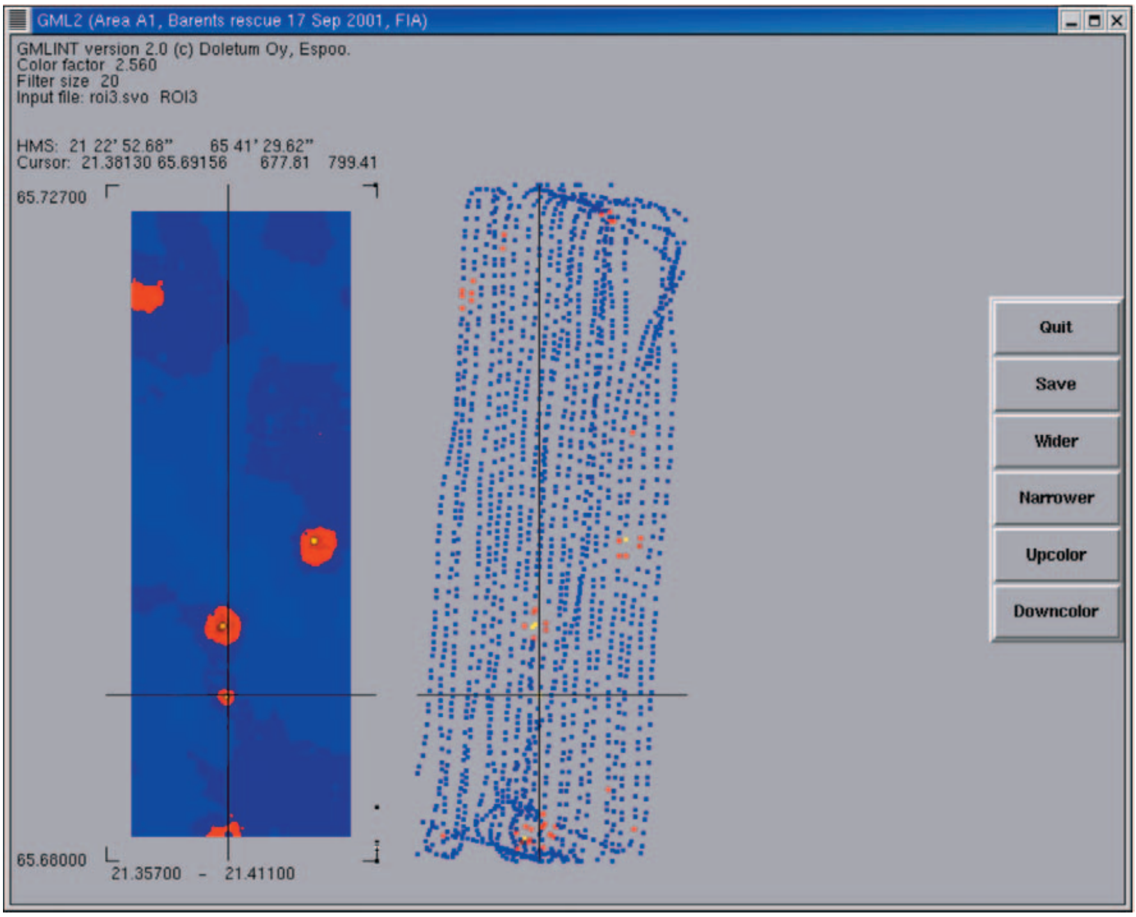

Figure A1-14. *A low-energy window showing both Co-60 and I-131 detections. The red point in the upper left corner is an open top of a hill. All the A1 sources were found and identified correctly, with one extra Cs-137 source being reported as "not absolutely certain".*

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Table A1-III. *Sources found in area A2.*

Nuclide	Coordinate (E)	Coordinate (N)	Activity	Remarks
Cs-137	21°36'33.00"	65°46'22.80"	1 GBq	
Cs-137	21°35'45.51"	65°44'26.39"	0.5 GBq	

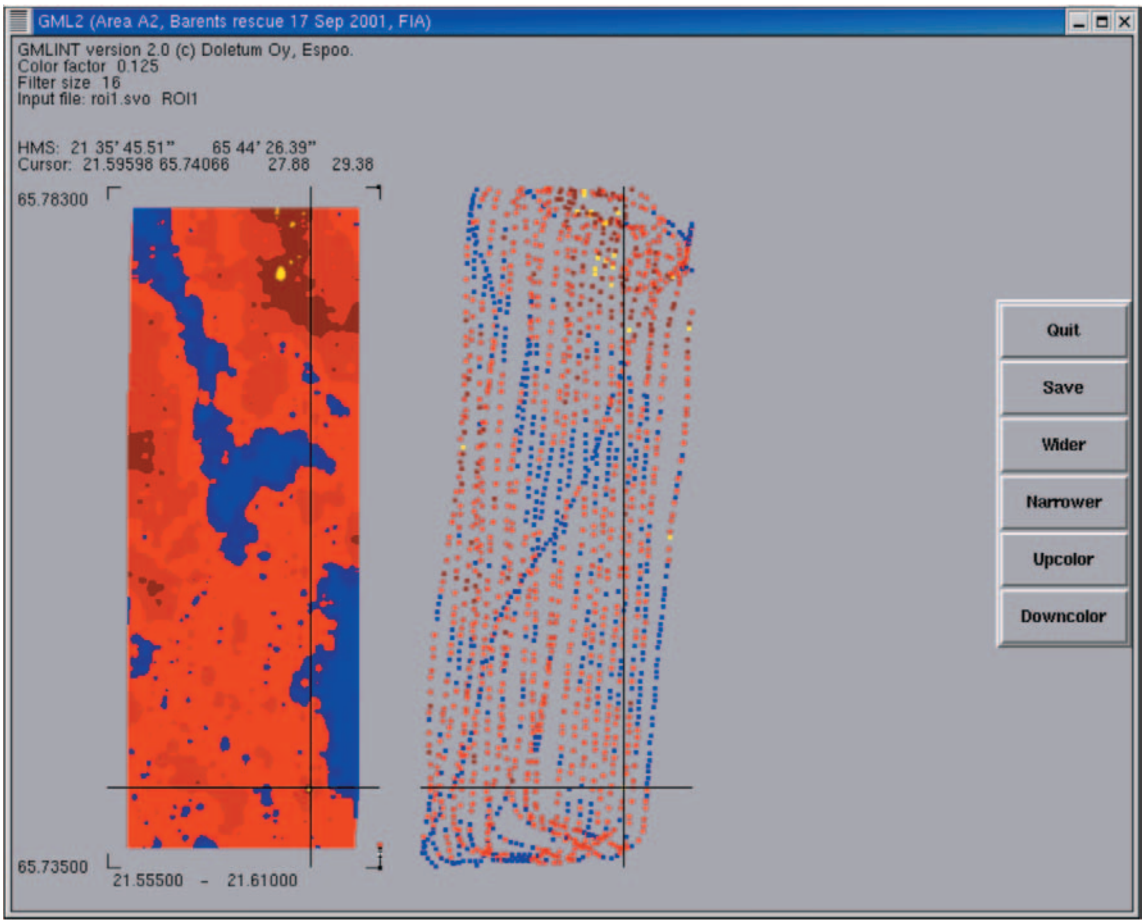

Figure A1-15. *Somewhat uncertain sources within the area. The upper source was found outside the area. It could also have been scattered radiation due to the hill that was being approached. The lower identified point was close to the detection limit. Five A2 sources were missed, one Mo-99 source being found and reported as Cs-137.*

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Table A1-IV. Sources found in area A3.

Nuclide	Coordinate (E)	Coordinate (N)	Activity	Remarks
Co-60	21°38'26.16"	65°50'28.61"	2.5 GBq	
–	21°39'19.08"	65°51'33.12"		Fortress, added for further checking

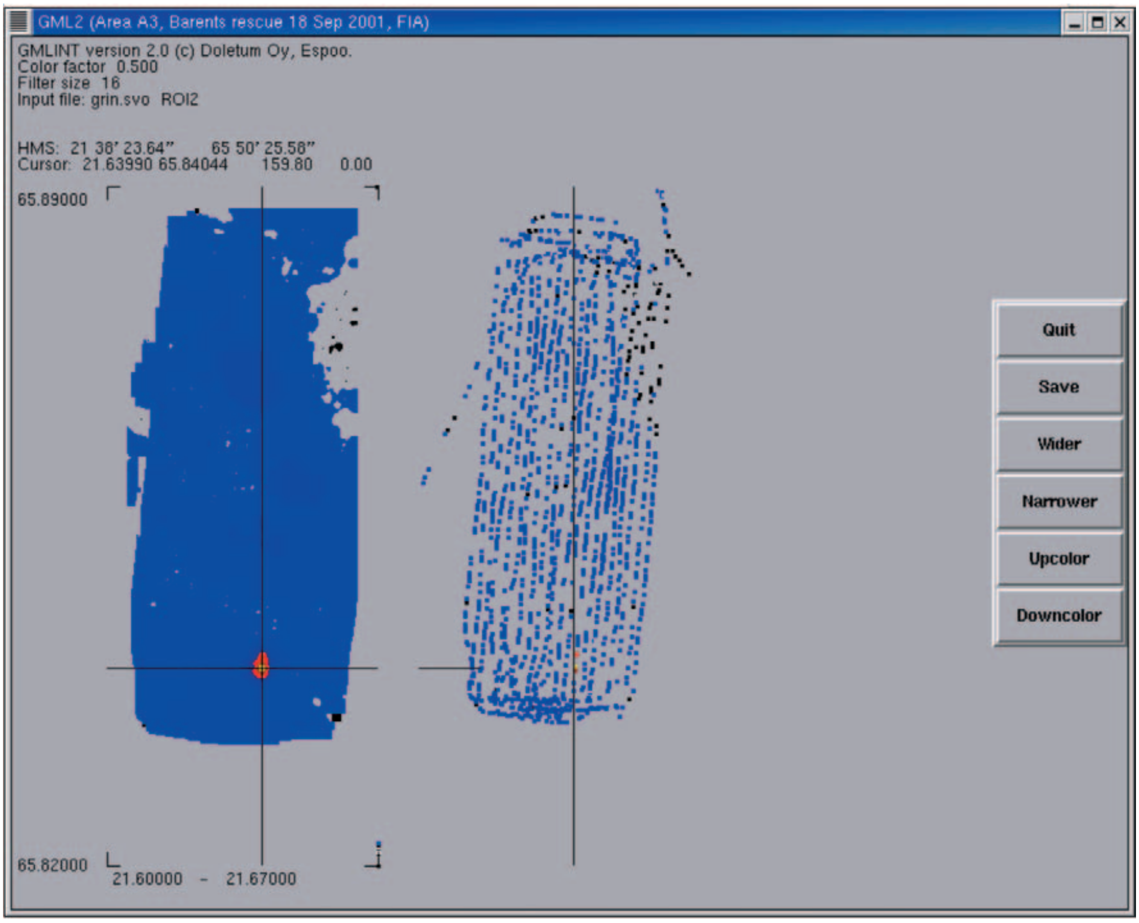

Figure A1-16. *Co-60 map of the area, with one clear source visible. The fortress on the top of the hill produced a higher count rate. There may have been a source inside the building or the count rate may have been higher due to the K-40 found in the concrete. An A3 Co-60 source was correctly found, and a bunker was checked as a possible hidden source.*

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Table A1-V. *Sources found in area A4.*

Nuclide	Coordinate (E)	Coordinate (N)	Activity	Remarks
Ir-192	21°31'23.16"	65°54'30.39"	2.7 GBq	
Co-60	21°32'26.16"	65°54'21.31"	0.3 GBq	
Cs-137	21°33'01.44"	65°54'30.39"	0.8 GBq	
Cs-137	21°31'54.40"	65°53'10.75"	0.5 GBq	Apparent activity, probably collimated

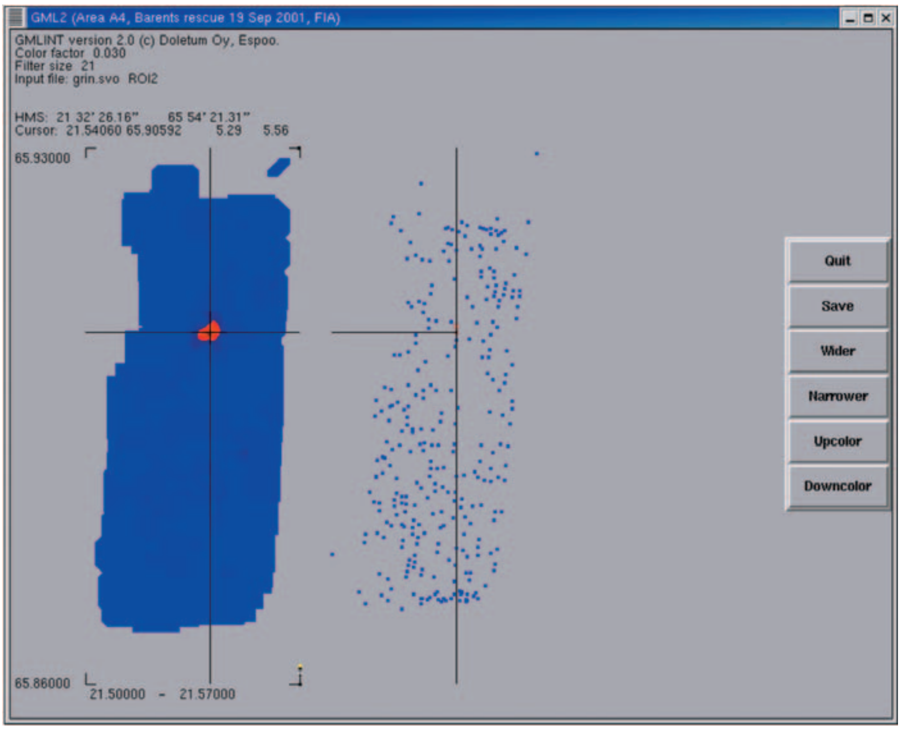

Figure A1-17. *A Co-60 map of the area, with one clear source visible.*

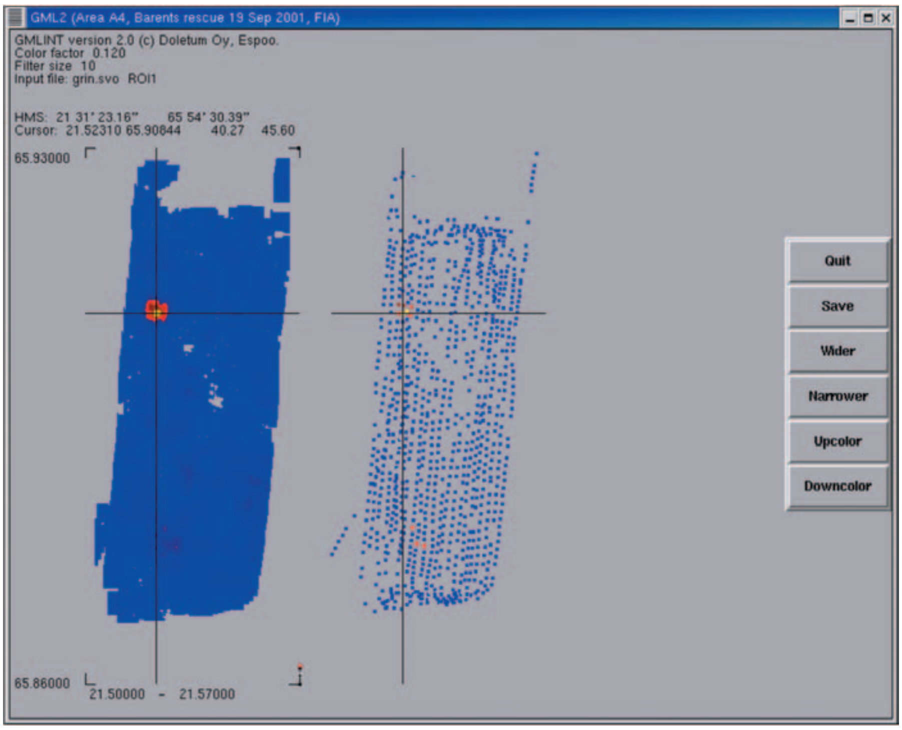

Figure A1-18. *Total counts for area 4. One Ir-192 source is clearly visible. Four A4 sources were found and identified correctly.*

Table A1-VI. *Sources found in area A5.*

Nuclide	Coordinate (E)	Coordinate (N)	Activity	Remarks
Co-60	21°25'11.10"	65°53'34.79"	2 GBq	
Ir-192	21°26'26.70"	65°54'55.94"	2.9 GBq	
–	21°26'39.30"	65°53'42.86"	–	Uncertain, added for further checking

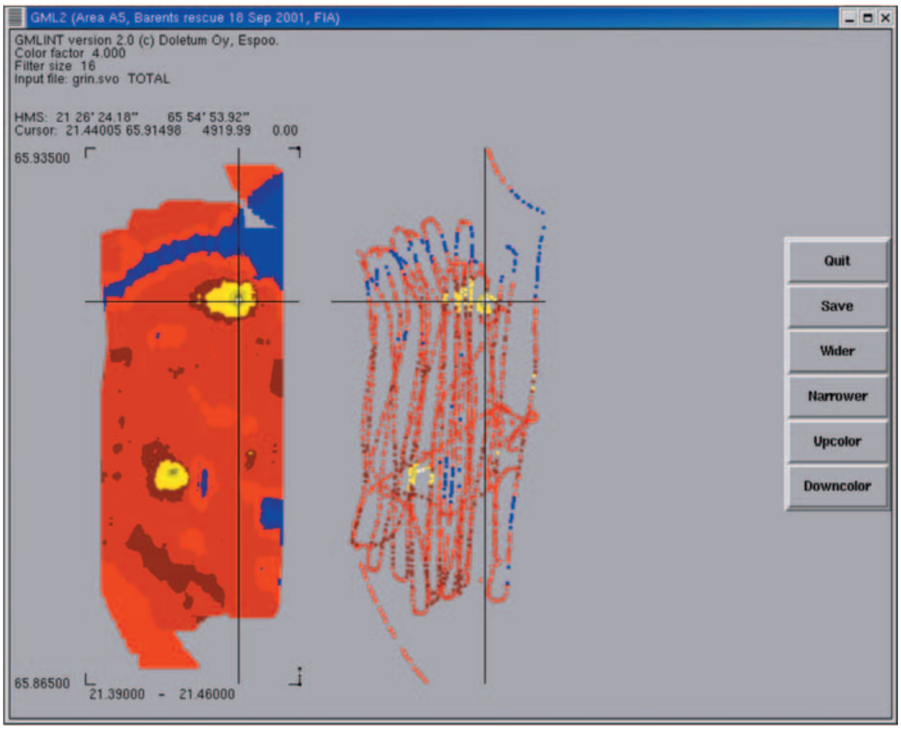

Figure A1-19. *Total counts found in area 5. Two strong sources were clearly visible. One additional high count, a "hot spot", was added for further inspection by the car teams. The flight lines were selected according to visual navigation. Three A5 sources were found, and two were correctly identified.*

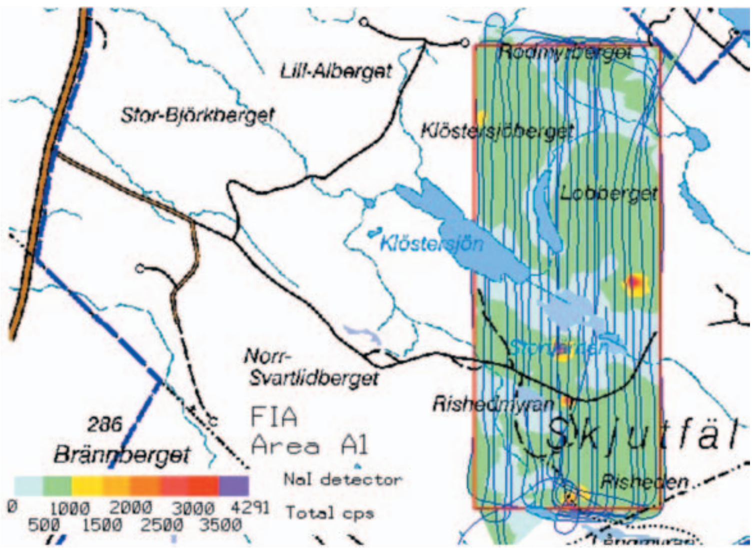

Figure A1-20. *Results of the measurements and the flight path plotted on the map in real time when the PC network connected the computers. This map was produced after the measurements had been made.*

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Table A1-VII. *Point sources hidden in the exercise areas. For the airborne measurements, there was a total of 23 hidden sources. Data are given for the Barents Rescue Gamma Search Cell. The aerial measurement areas were A1…A5. The coordinates were in RT-90.*

Nuclide	Area	Activity GBq	Coordinate (E)	Coordinate (N)	Remarks
Co-60	A1	5	1756005	7298134	In wooden cage in gravel pit, shielded upwards with concrete blocks
I-131	A1	9.25	1756005	7299224	In shed, collimated with lead bricks upwards and to the west
Co-60	A1	5	1755956	7299830	In wooden cage at the end of the road
Co-60	A1	5	1756747	7300334	In wooden cage on the south side of the closed road
Co-60	A2	5	1764029	7307246	Inside the round concrete bunker
Co-60	A2	5	1764048	7307266	Inside the concrete bunker, collimated obliquely upwards
Mo-99	A2	3.1	1764844	7307031	Inside tracked vehicle cart
Mo-99	A2	18	1765350	7305451	In the house on the attic
Cs-137	A2	3×0.5	1763466	7306095	Inside tracked vehicle cart, level guards, directed upwards
Co-60	A2	3×0.02	1763466	7306095	Inside tracked vehicle cart, level guards, directed southwest
Co-60	A3	4×5	1766304	7316848	In storehouse 36, side shielded with lots of concrete blocks
Cs-137	A4	0.4	1760923	7321390	In red shed, in lead container, side shielded
Cs-137	A4	2.5	1760488	7323895	In “birdhouse”, shielded with a lead brick upwards
Ir-192	A4	13	1760488	7323933	Radiographic source in a tree
Co-60	A4	5	1761137	7323702	In concrete fire trench, covered with a steel plate and sand
Co-60	A4	5	1761117	7323744	In concrete fire trench, covered with a steel plate and sand
Cs-137	A4	1.3	1761442	7323932	In tracked vehicle cart, shielded upwards with concrete blocks
Cs-137	A4	1.9	1761559	7323941	In tracked vehicle cart, side shielded with transport container
Co-60	A5	40	1756869	7322034	Radiographic source in drainage drum under the road
Cs-137	A	2.6	1755733	7321627	In red shed, no shielding
Co-60	A5	2×5	1755750	7321686	n wooden cage, no shielding
Cs-137	A5	1.9	Chancing	Chancing	In car cart moving along the roads, shielded to all sides
Ir-192	A5	46	1756402	7324293	Radiographic source below boulder

2.8 Remarks

The good spectral quality of the rather small detectors allowed most of the hidden sources to be found using the advanced post-processing technique. Altogether 13 of the 23 hidden sources were revealed. This was a top-quality result of the Barents Rescue exercise.

The source inventory given by the Barents Rescue 2001 Gamma Search Cell is listed in Table A1-VII. The airborne measurement areas are codes “A1…A5”.

APPENDIX 2 Calculated and detected counts

Markku Kettunen, Mika Nikkinen and Mika Juvela

1 The evaluated examination and calculations for the Otaniemi source

Flight measurements and a sub-part of a significant amount of metallic uranium (Otaniemi).

The purpose of the measurements was to test the ability to detect anomalies like excess uranium at the ground level. The measurement results have been analysed, and we found that there were substantial uncertainties in the quantitative results. The most important issue was to detect the anomalies. Therefore, a jet plane was used to *screen* the landscape, the data were recorded, and the greatest anomalies were prompted during the flight. The data were post-processed, and *relative* radiation levels were displayed to find true hot spots after every mission. The true absolute values did not give us too much additional information due to the large uncertainties.

The conclusions on the modelling, measurements, and source calculations follow:

- The results still contained very low statistics. The highest measured value was 13 counts (1-second measurement), and therefore one sigma error for this measurement was around 30%.

- The Otaniemi district represents the "worst case" for this type of measurements. There are large buildings and a high variation in the ground level of uranium due to a high uranium concentration in the bedrock (4–10 cps in the window continuously). Background measurements were not possible during the flight. We could not determine the accurate gamma flux from the sample empirically because we did not know the baseline U/Th concentration at the site without the source. We did assume a value of 1000 keV ROI to be 6 cps (average value of the district). This level can cause a 50% error in the measured net values. The situation in the target country was much easier due to the more homogeneous natural radiation concentration.

- The landscape varied due to 20-metre high hills, which caused a difference of up to 35% in the detected ground level of radiation flux since the flying altitude had a variation between 100 and 80 metres.

- The radiation source was not homogeneous due to inaccurate stacking; the unpredictable shadowing effect caused an error of some 10–20% in the quantitative results.

2 Sodium iodine detector efficiency

Due to the low resolution of the NaI detector, for single isotope identification, a wide region of interest had to be selected. Therefore, other isotopes could also be detected in the same region. Usually this occurrence detrimentally affects the measurement, but, if we are trying to detect any anomalies and uranium ore or old processing waste, it actually helps the situation, since the source transmits more gamma rays to the interesting energy window. This situation can be illustrated by uranium measurements. Before the flight measurement, 54 kilogrammes of depleted uranium were measured with a HPGe detector (Fig. A2-1a). The spectrum showed many peaks also above 1001 keV.

Since the real measurements are performed at distances of 100 metres, a large portion of these higher energy gamma-lines is scattered and actually affects the 1001 keV region that we measured. Therefore, the actual gamma flux in the 1001 keV region was larger than for Pa-234m alone. The spectra from the measurement of the natural uranium bundle in Fig. A2-1b have a similar structure.

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- The efficiency of the NaI detector was not easy to determine in this case. Normally, in gamma spectrometry, the net area of a peak is used to determine the efficiency of the detector. Therefore the baseline (i.e., counts below the peak that are not coming from the source) is removed. When measuring a multi-line source like ours at a distance of 100 metres, we did not have any accurate method for reducing the baseline. Therefore, we could use only the gross pulses in the ROI window. We made an empirical test in the laboratory using a large uranium source, and we found that the pure peak from Pa-234m stands above the compton continuum, which has the same number of pulses as the peak itself. (See Fig. A1-2.) Furthermore, there were nearly as many net pulses in the higher energy channels, which are likely to scatter to the 1001 keV ROI or more if the distance is 100 metres (the laboratory measurements were performed at a distance of 4 metres). At the same time part of the "real" 1001keV gammas were scattered to the lower energies. Because of these effects, we assumed that we could see

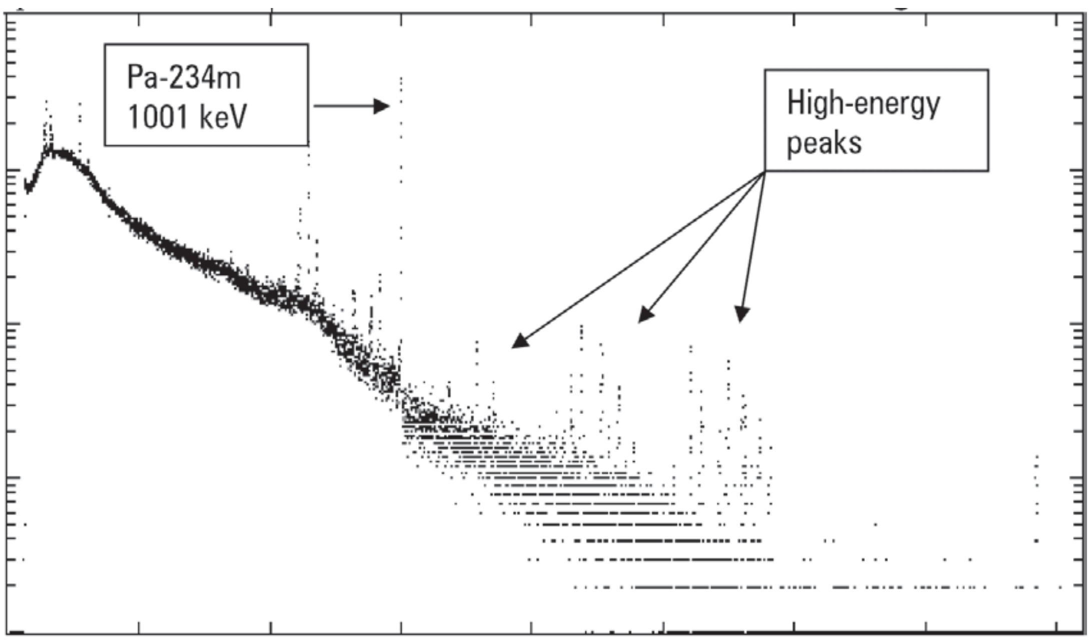

Figure A2-1a. *HPGe spectra from 54 kilogrammes of depleted uranium.*

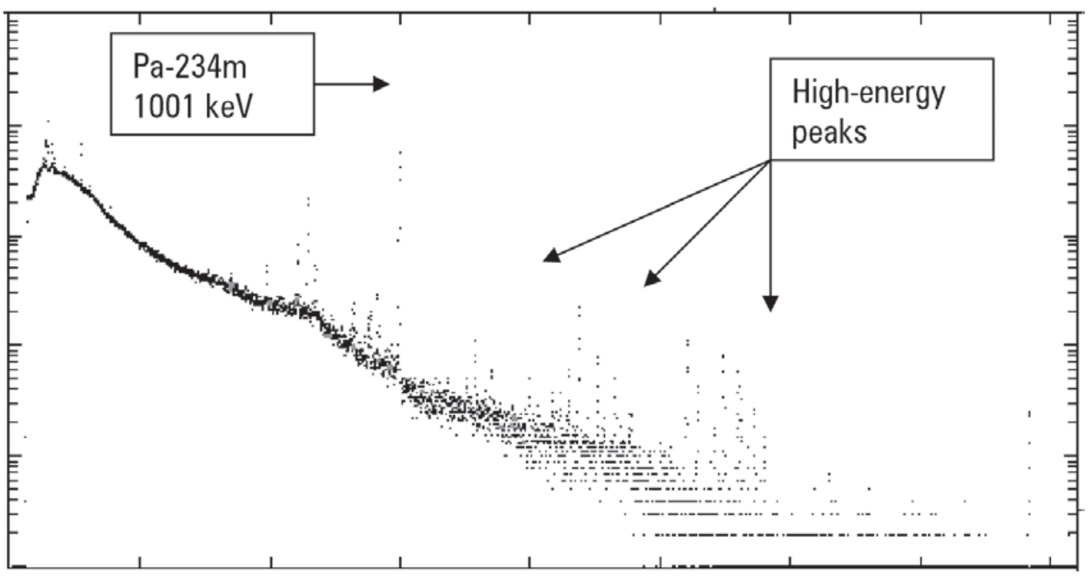

Figure A2-1b. *HPGe spectra from a uranium bundle of 30 kilogrammes.*

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2–3 times more gamma rays in the 1001 keV ROI window than what is assumed for pure peak efficiency.

- The efficiency is also dependent on the width of the ROI. The more accurate results were achieved by widening the window somewhat. This step also increased the efficiency, since we were actually detecting more scattered photons from the source. The efficiency can be about 1.5–2 times better this way.

- If we add all of these uncertainties together, no conclusion can be drawn about the quantitative results, since we can have up to 3–400% uncertainty in the absolute values.

- The method we used takes into account the nature of low statistics, and it improves the situation by averaging the radiation flux at ground level with the correct physical model. Using this method with the Otaniemi measurements, we were able to pinpoint some anomalies that would normally lead to onsite inspection of the region.

For detection capability, ground level source modelling is important. In this manner, the maximum amount of information can be used to display the real hot spots on the ground. The GMLINT method used in the Otaniemi exercise utilizes all the measurement points to re-build the lattice on ground level. This way the gap between the flight lines is filled, and more accurate results are achieved because of better statistics.

With the use of these evaluated values of the activity 1.24E+02 gammas (1001 keV) per second per gram of natural uranium and the broad efficiency concept, the calculations of the RADINT-predicted count rate show a maximum value of 4 cps over the Otaniemi natural uranium source.

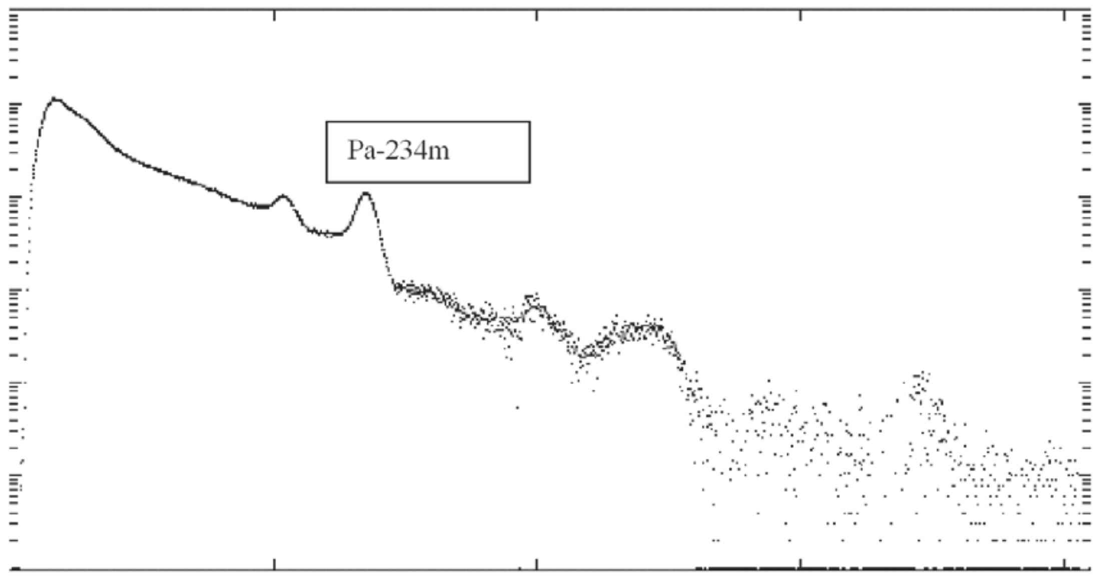

Figure A2-2. *Twelve-hour measurement with a uranium sample after the background reduction. Note that the Pa-234m peak is located above the high baseline continuum; the number of counts in the baseline below the peak is about equal to the number of counts in the real peak. The measurement was performed at a distance of 4 metres. At an altitude of 100 metres, the signal-to-baseline ratio is closer to 1:2 since all the gamma rays above the 1001 keV have a tendency to come to lower energy due to the interaction with air.*

APPENDIX 2

3 Conclusions

This exercise did prove that a sub-part of a significant amount of a natural uranium source in this type of lattice will emit enough gammas for detection by a 6×4 inch NaI detector. If we had eight times more natural uranium (eight similar "heaps" in the same place), we would detect 28 cps with the same detector. This number of cps would definitely trigger the automated alarm during the data acquisition. Therefore the position of the source and the identification of the results would be prompted for the measurement operator during the flight.

Ground level modelling (GMLINT) was found to be important for the detection of anomalies; this is the way to reveal even a subpart of the significant amount of uranium at ground level. To ensure detection capability, we need information on the natural radiation background of the target country. This information is required for the determination of the flight line distance. According to the preliminary information, the background is substantially lower than in Finland, which means that a similar source is much more visible.

We should also emphasize the attenuation measurements of the aeroplane body in relation to point source detection. This step is also essential with respect to the choice of the aeroplane.

APPENDIX 3 BACKGROUND ESTIMATION ABOVE DIFFERENT AREAS

Background of airborne measurements are primarily based on isotopes (natural and manmade) found in the aeroplane or helicopter. The ground-based background is usually based on natural isotopes on the ground (Th, U, Ac series). Ground-based backgrounds can have large variations, depending on the bedrock type and the amount of vegetation on the bedrock or other source of radiation. For example, the Chernobyl accident caused a ^{137}Cs background in part of Europe.

To determine the background in the aeroplane, one can do the measurement above the sea or a lake. One has to note that the background is typical of an aeroplane; natural radioactive substances are usually difficult to remove if the plane suffers from contamination by these substances. Usually, the background is an essential factor below 500 keV; above 1.2 MeV one can almost ignore the effect of old contamination in the aeroplane.

Measured background spectra above the sea or a lake

Background spectra measured from large and medium-size detectors while above the sea follow. The background spectra of the large detector are shown in Fig. A3-1, and that of the medium-size detector is presented in Fig. A3-2. The measurement time was about 40 seconds. For comparison, 15-minute HPGe spectra measured from an MI-8 helicopter is shown in Fig. A3-3. All the spectra were measured at a height of 100 metres.

In our case the larger NaI detector had an essentially higher background in the 1001 keV region of interest. This occurrence makes the determination of uranium isotopes more difficult with the larger detector.

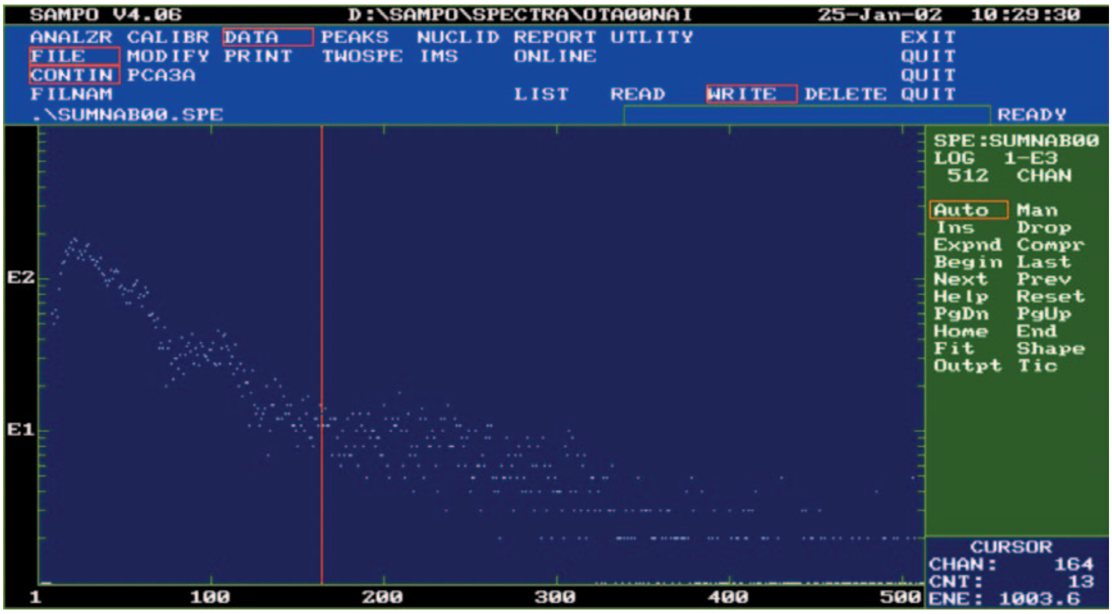

Figure A3-1. *Background spectra 100 metres above the sea. Large-size NaI detector. Integration time 38.2 seconds. The spectra were measured from a jet plane.*

APPENDIX 3

BACKGROUND ESTIMATION ABOVE DIFFERENT AREAS

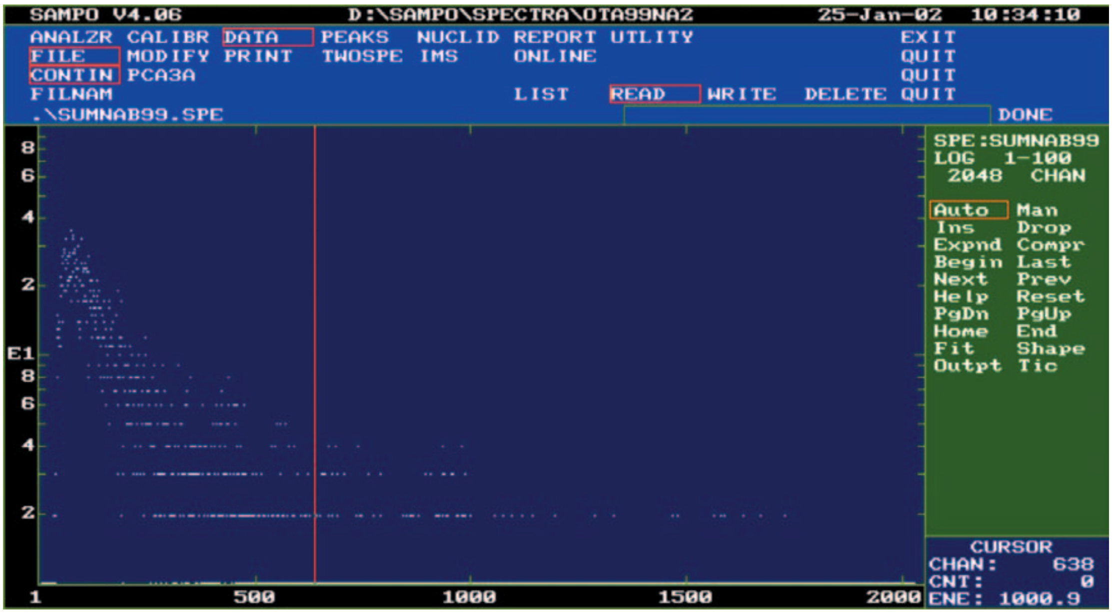

Figure A3-2. *Background spectra 100 metres above the sea. Medium-size NaI detector. Integration time 35.4 seconds. The spectra were measured from a jet plane.*

Figure A3-3. *Background spectra 100 metres above lake Näsijärvi. HPGe detector. The spectra were measured from a helicopter. Integration time 900 seconds. The large "peak" near 120 keV is a consequence of improper damping of helicopter vibration at the location of the detector.*

APPENDIX 4 Detection limits

In addition to the information on pulse rates, it is important to know how good the detection is in the statistical sense. For this purpose, the following two metrics are generally used: the error estimate of the signal and the detection limit (i.e., signal/noise relationship). For the error estimate in airborne measurements, classical Poisson statistics can be used, and the determination of the error estimate is equal to the square root of the pulses detected at one point. For detection limits, the Currie-defined decision limit is the most useful criterion. For these two variables, a separate map can be determined simply by calculating them from a modelled map, as seen in the following figure.

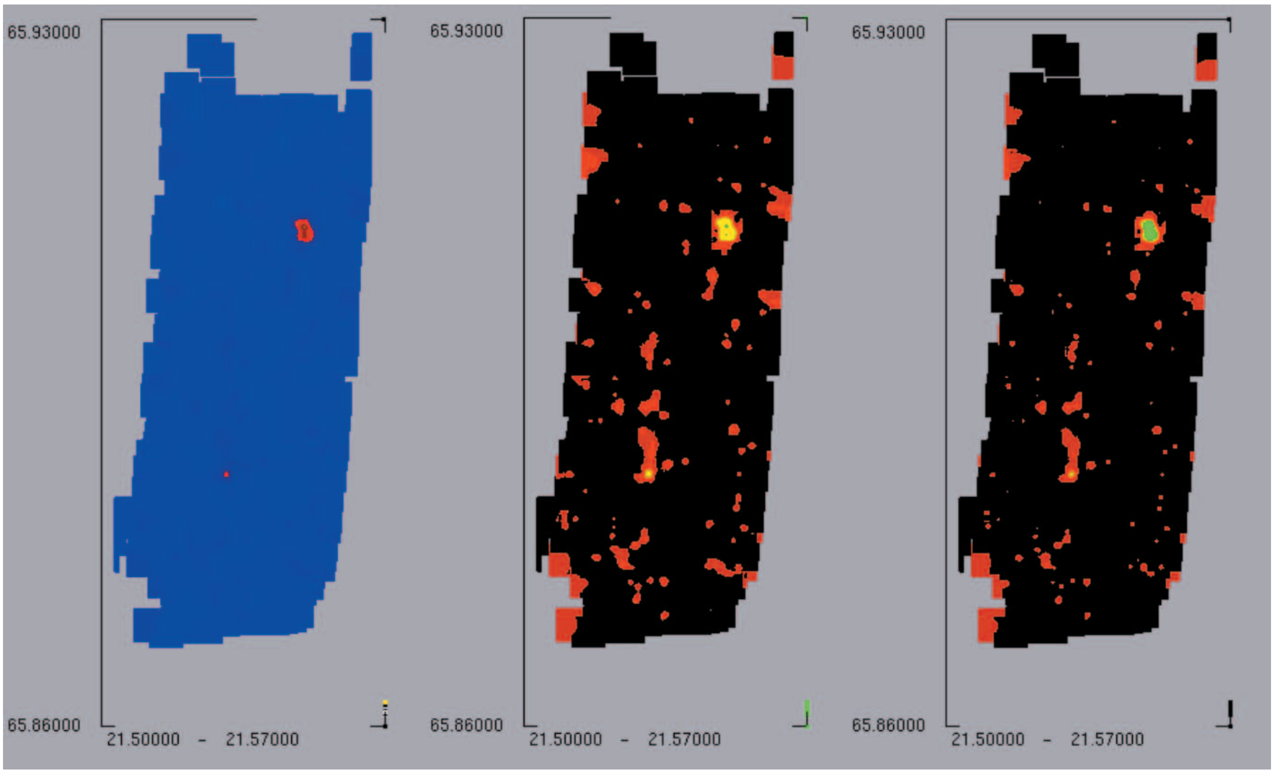

Figure A4-1. *In this figure, a map of a detected signal, the error for the signal and the detection limit is shown. In the middle figure the 1-sigma error estimates are color-coded: green = 0–30%, yellow = 30–60%, red = 60–90%, and black = more than 90%. In the rightmost figure the detection limit is color coded as well; this map gives the Currie Lc (decision limit) at the 95% probability level: green = signal well over the detection limit, yellow = signal 80–100% of the detection limit, red = signal 50–80% of detection limit, black = signal improbable. As a result, these maps show confidence for the source found in the upper corner of the flight area and good confidence for the small source found in the middle of the area. These measurement data are based on Barents Rescue exercise; this is a picture of the area containing two sources, for which only the Finnish team was able to find both sources.*

APPENDIX 5 Installation into commercial aircraft

The radiation detection system was installed in a Eurocopter 350 B 1 helicopter. The following units were included in the installation:

1. Medium-size NaI detector (1.83 litres)
2. HPGe detector (70%)
3. Analyser MicroNomad
4. Analyser DART
5. GPS receiver Ashtech
6. Three laptop computers IBM
7. Static inverter Avionic Instruments

The Air Forces Aviation Technology Institute accepts these instruments for use in aircraft. The electromagnetic disturbance of the devices was measured and found to be acceptable. The mechanical construction was made for the installation by PirMec Rakenne Oy, which has a licence to make plans for installation for aviation. The installation construction included vibration and shock dampening for the detectors. The helicopter operator Norrlandsflyg inspected the installation plans for use. Both the electrical and mechanical connections were checked.

The placement of the detectors was chosen to minimize the “shadow” from the body structure of the helicopter from the gamma radiation coming from land surfaces. The actual attenuation factor was measured to downward directions using suitable point sources with computer-aided calculations. The determined attenuation factor of the gamma radiation in the body structure of the helicopter was acceptable.

The installation procedure required three trips to Sweden to get the radiation measurement unit installed properly into the commercial aircraft.