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Nordic Exercise for Unmanned Systems

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Abstract

The NORDUM exercise was the first joint Nordic exercise for unmanned systems. The NEXUS exercise further expanded the challenges to urban environments, contaminated fields and scenarios for fixed wing systems. A seminar was held at the end of the field activities such that teams had a chance to present their results, discuss challenges and successes, and present future plans.

The Nordic countries have a growing competence in radiation measurements utilizing unmanned aircraft systems. This NKS activity have strongly benefited the Nordic exchange and growth of knowledge and experiences in the topic.

The use of fixed wing platforms was tested and demonstrated briefly. The use of fixed wing UAV platforms could fill a gap between rotary wing UAS and full scale fixed wing systems in surveying larger areas.

The use of unmanned measurements in urban environments was tested and demonstrated in two scenarios, the oriental market and the 2-storey building. In particular the scenario around the 2-storey building demonstrated the 3D survey advantages with rotary wing systems.

Survey of contaminated areas in contrast to separate point sources was tested and demonstrated in the scenario with the contaminated area with dispersed activity in a pattern.

The aim to have team's report to reach back failed, presumably due to lack of time and preparations. This is something to develop since the end result should be decision support.

The capacities in the Nordic countries is still in development, but the exercise demonstrated that it is an ongoing development. This form of arrangement with an exercise in an area where the teams can see each other's approach and solutions is most inspiring for the exchange and growth of knowledge.

Key words

Drone, exercise, radiation measurement, UAS, mapping

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Final Report from the NKS-B NEXUS activity (Contract: AFT/B(17)6)

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1. Introduction

There are several measurement and sampling scenarios that may cause very high risks for humans to carry out, e.g. reactor accidents, such as Chernobyl and Fukushima, RDDs (radiological dispersal devices) before and after explosion, search of MORC (material out of regulatory control), or search inside buildings that are under the threat of collapsing. For these scenarios, remotely controlled radiation measurements and sampling using unmanned aircraft systems are developed.

The Nordic countries have a growing competence in radiation measurements utilizing unmanned aircraft systems. The NKS activities SemUnARS in 2014 and NORDUM in 2016 have benefited the Nordic exchange and growth of knowledge and experiences in the topic.

The NKS-B activity SemUnaRS – Seminar on Unmanned Radiometric Systems, was held on the 2-3rd of October 2014 in Linköping, Sweden. The seminar was the start-up and an inventory of the capacities for unmanned measurements in the Nordic countries. The seminar hosted many interesting discussions on different approaches to utilizing unmanned platforms, aircraft regulations and the collaborations between universities and the authorities (Gårdestig et al. 2015).

The NKS-B activity NORDUM - Intercomparison of Nordic unmanned aerial monitoring platforms, was held on the 5-7th of September 2016 in Norway. The exercise gave five teams the opportunity to test their rotary wing UAS in three scenarios including a total of ten radioactive sources. NORDUM had eager participation of measurement teams from Denmark, Finland, Sweden and Norway (Tazmini et al 2016).

The NORDUM exercise was the first joint Nordic exercise for unmanned systems. The NEXUS exercise further expanded the challenges to urban environments, contaminated fields and scenarios for fixed wing systems. The exercise was held at an open, joint exercise area where the teams could observe each other’s systems and techniques directly. The scenarios included small areas for rotary wing UAVs searching for point sources, larger areas for assessment of contaminated areas, and surveys in urban environment.

The teams were to report their result to a reach-back function. The reports were to be evaluated according to value as decision support to the scenario.

A seminar was held at the end of the field activities such that teams had a chance to present their results, discuss challenges and successes, and present future plans.

2. Pre-exercise work

The Swedish Transport Agency issues temporary licenses valid for three months to UAS holding a domestic license in a compatible category. The Swedish categories are regulated according to weight, kinetic energy and operation within or Beyond Visual Line of Sight

- 1A: <1,5 kg, <150 J, VLOS
- 1B: <7 kg, 1000J, VLOS
- 2: >7 kg, VLOS
- 3: BVLOS

Each team holding a domestic UAV license applied for a temporary (3 month) license in a compatible category to the Swedish Transport Agency. Some team had to supply some additional documentation due to the differences between the Nordic countries' regulations. The categorisation above was according to the current regulations at the time of the exercise. Since February 2018, the Swedish regulations are revised and there are now no licence requirement for UAS weighing less than 7 kg TOV.

The department of Radiation Physics at Lund University contributed with radioactive point sources and ground dispersion mimicking a fresh fall-out.
The coordinator and Lund University designed, constructed and supervised the test site, providing facilities such as e.g. electrical power.
The participants were responsible for travelling to the test site with their equipment and making measurements over a period of two days. They were also responsible for presenting results, analysing data and participating in a technical seminar. The coordinator was responsible for organizational aspects such that all participants were offered equal flight time over the site.
Positioning of sources and the characteristics of the sources were to vary during the NEXUS exercise such that the challenges posed to the teams would range from the elementary to situations that are more complex. It was intended that NEXUS would function less as a competition and more as a collaborative effort with a cooperative atmosphere.

3. Exercise area

The exercise area was Björka exercise field in the south of Sweden. The enclosed area houses a runway, an artificial urban environment, forest and grass fields. The field is well outside the Sturup Airport controlled zone. The exercise had access to the entire exercise field, marked in blue in Figure 1. In the middle of the runway there is an artificial town.

Figure 1 Satellite photo of the exercise area(left) www.forsvarsmakten.se/siteassets/3-organisation-forband/p7/sodra-skanska-regementet/bjorka-ovningsfalt.pdf and the urban environment in the middle of the runway (right) Photo: Marie Carlsson

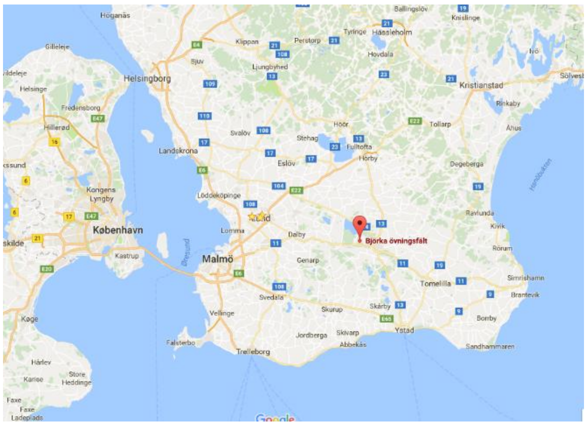


Figure 2 Location of the Björka exercise field in the south of Sweden. Google Maps

Exercise scenarios were arranged in

- Small field for rotary wing UAVs searching for point sources. Localization, identification and assessment of activities.
- Larger field for fixed wing UAVs searching for point sources and contaminated areas. Localization, identification and assessment of activities and activity concentrations (Bq/m^2).
- Urban environment for rotary wing UAVs searching for point sources. Localization, identification, assessment of activities and recommendations of rescue routes.

5. Exercise aims

The objective of the exercise was to test unmanned aerial platforms in use in the Nordic countries with respect to locating, identifying and estimating the activities of radioactive sources under field conditions. Thereby acquire competence within the RN emergency preparedness and response organizations in the Nordic countries.

NEXUS will extend the scenarios from the NORDUM exercise to also cover:

- The use of fixed wing platforms that are beneficial in covering larger areas. They are intended to solve survey missions with assessments of ground activity concentrations or search for sources over larger areas. Fixed wing vehicles have generally longer flight times than rotary wing, but greater cruise speed which challenges the detector systems and data processing.
- The use of unmanned measurements in urban environments. Several scenarios are plausible e.g. fall-out, spill, MORC or RED/RDD, where unmanned measurements between buildings or even indoors would be demanded.
- Scenarios with contaminated areas in contrast to separate point sources.
- The team’s reports to reach back are to be evaluated according to value as decision support in the scenario.

5. Implementation and results

The NEXUS exercise was held late October which is not an ideal season for small aircraft activities. However, that was the week we all could agree upon. We also experienced some disturbing rain, but since we had allocated enough time, there was enough flyable time.

5.1 Exercise setup

Day 1 - Test and verification of UAS

Björka exercise field open from 12:00.

The intention of the first day was to test and verify each team's drones, verification of "Go home" function and "Geo fence" function. Geo fence were to be set at 200-500 meters from take-off point. Geo fence could be set narrower if the team decided to limit their area to only cover each scenario area.

There was an opportunity to participate in an **open scenario** (known and marked sources) for testing and calibration. This open scenario was on an open small grass field.

There was no schedule and since each team operated under their own license there was no dedicated supervision, merely an opportunity for testing the systems.

Day 2

Four scenarios were offered the second day. The teams solved the scenarios in parallel or taking turns depending on weather conditions and readiness.

Figure 3 The east part of the urban environment. The grey 2-storey building in the center, oriental market to the right. Photo: Magnus Gårdestig, RadiaWing

The artificial oriental market
In the middle of the runway there is a built urban environment of several houses and sheds. A fenced area about 50x25 meters offers the setting of a street market with groupings of market stands and sheds. The teams were to assess the area from outside the market.

4 sources were placed on different heights according to Figure 4.
1 ^{133}Ba, 2 ^{60}Co, 1 ^{137}Cs.

Figure 4 Overview of the mock oriental market with marked positions of the sources. Google Earth

The building
The urban environment is also populated by a 2-storey building. 5 sources were placed on different floors and collimated by their container and by the building's window frames according to Figure 5.
1 ^{133}Ba, 4 ^{137}Cs.

Figure 5 Overview of the 2 storey building with marked positions of the sources. Google Earth

The strong source

In the end of the runway a 1 GBq ^{137}Cs source was placed on the ground for MDA testing. The source was unshielded upwards.

Figure 6 The strong source marked with a red cone in the end of the runway. Photo: Magnus Gårdestig, RadiaWing

The contaminated area
A part of the runway was contaminated with the total activity of 1150 MBq ^{99m}Tc (reference time 08:10).
The contamination was sprayed in the pattern of the letters S, W and E, with different activity concentrations, the letter ”S” was 2 times ”W” and ”E” was weak.

Figure 7 A schematic overview of the dispersed activity in the pattern of the letters “S, W, E”. Google Earth


Figure 8 The contaminated area started beyond the last container. Photo: Magnus Gårdestig, RadiaWing

5.2 Team Norway

Introduction

NRPA chosen to start with a UAV-multicopter carrying the measuring system.
We decided to go for a model from DJI, DJI S1000 +, because it was easily accessible, affordable and had the carrying capacity we wanted, see table below for technical data.
The measuring system consists of a sensor that can measure gamma radiation connected to an on-board computer.
For the measurement system, it was chosen to use 2" and 3" NaI detectors connected to an Osprey multi-channel analyzer (MCA from Canberra). This equipment is connected to a Raspberry Pi (on-board computer), along with an external GPS, and WiFi connection. Our in-house software on the Raspberry Pi stores data on the disk and transfers it to the real-time analysis on the ground. The data is also stored on a local database.
The ground station is composed of a rugged PC with radio / WiFi connection to on-board measurement system. For the ground station, NRPA team has developed in-house software (Gamma Analyzer) for the collection of measurement data and for analyzing spectra. This software gives us the ability to display data such as a waterfall rendering, collection of spectrum, list of ROIs, dose rate calculation, plotting on map, energy calibration and more features.
Furthermore, we also have a 3D software viewer that we can import our measurement data and have a 3D view.

Improvements since NKS NORDUM 2016:

1. Some adjustments and validations of our dose rate calculations.
2. Added Wi-Fi communication between the onboard computer and the ground unit.
3. Replaced the TCP protocol with UDP for data transmission.
4. Added ability to synchronize lost data during flight.
5. Several improvements to the user interface and data charts.
6. Added two FPV camera modules with flight data from the iOSD Mark II.
7. Added and tested LaBr to our collection of detectors.

Technical description

NRPA M1		
Aircraft/RC Helicopter		
Platform	Spreading Wings S1000 plus	Quadcopter, center body with 6 arms
Flight Controller	DJI A2	
Radio Transmitter	Futaba T14SG	
iOSD Controller	DJI iOSD Mark II	
Engine	Electric	4114 Pro
Max speed	15-20 m/s	
Camera	Two FPV CMOS Camera	connect to IOSD Mark II
Ground control	DJI IPad Ground Station	with 2G Bluetooth Datalink
Video Link	Fat Shark 5G8	5.8 GHz analog transmission
Measurement system		
On Board Computer	Raspberry Pi 3	1.2GHz 64-bit quad-core ARMv8 CPU
GPS	G-STAR IV	
Data Transport	5.8 GHz WiFi	
Detectors	Osprey MCA with 2” NaI detector Osprey MCA with 3” NaI detector Osprey MCA with 1” LaBr detector	
OS	ARCH Linux ARM	
Software	Gamma collector	NRPA in-house product (Python)
Ground Unit		
GU Computer	Dell E5540	
OS	Windows 10	
Software	Gamma Analyzer	NRPA in-house product (C#)
3D Software	Gamma Viewer 3D	NRPA in-house product (C++, Qt)

Figure 9: NRPA DJI S1000+ with the measurement system

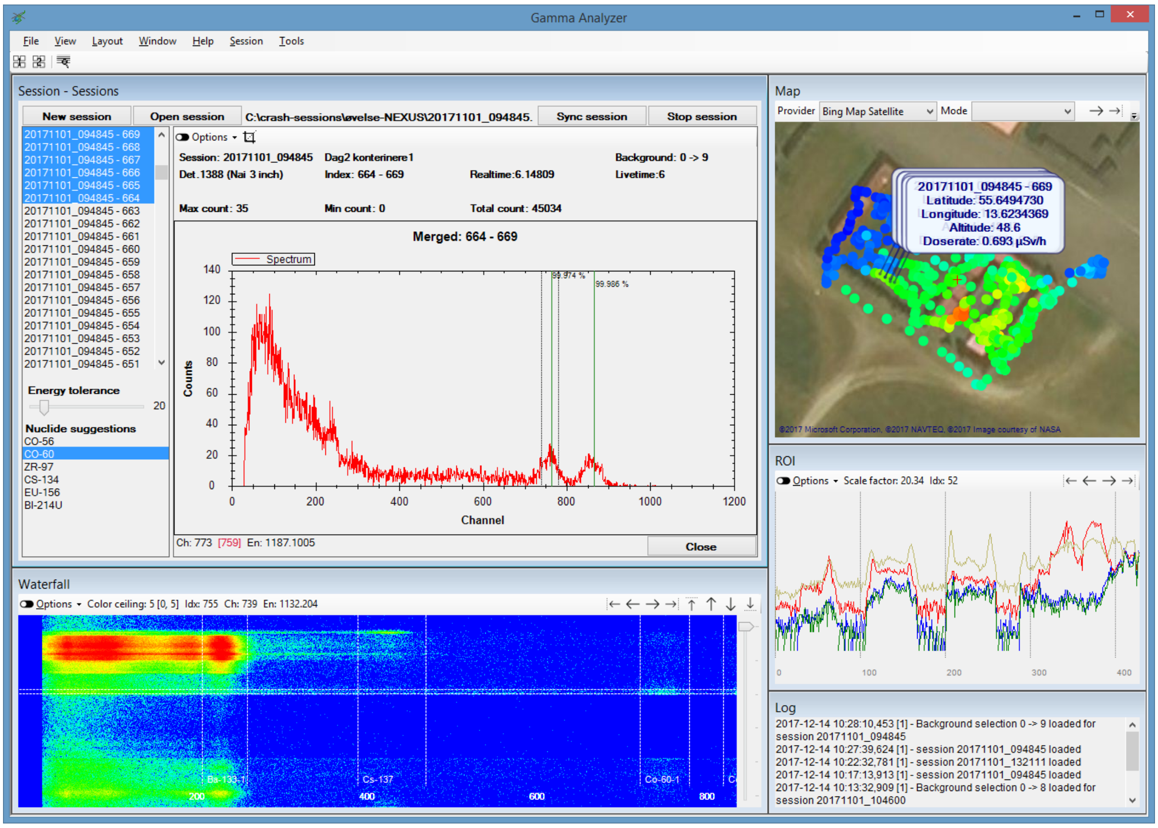


Figure 10: Gamma Analyzer Software (In-House software for search and identification of radiation sources.)

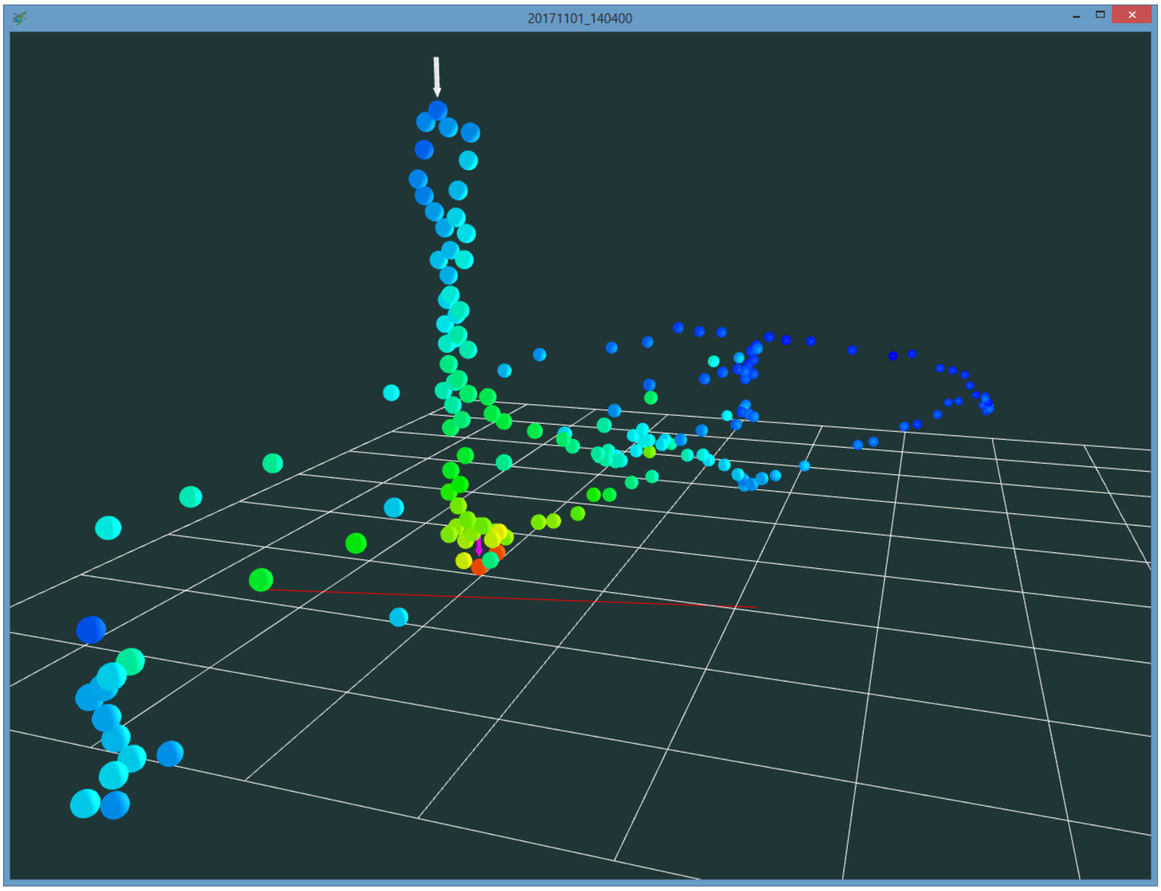


Figure 11: NRPA 3D viewer (In-House software for manufacturing flight data in 3D with color scaling adjusted according to dosage value.)

Results

Site 1, Oriental Market (45m x 25m):

This site was a closed area with a maze of concrete walls, simulating a small urban market. Our ground unit was located approximately 6 meter east of the market. We chose to use the DJI ground station to predefine a grid of waypoints to automate the flight. After finishing the waypoints we switched to manual mode to examine the most interesting spots. We found the first three sources during the flight and identified the last source after a more thorough analysis of the data.

Our activity calculations are based on a distance of 3 meters from unshielded source

Table 1: ***Detected sources at site 1, Oriental Market. Flight time 15 min.***

Source	Detector	Source	Activity
1	NaI 3 inch	Ba-133	~500 MBq
2	NaI 3 inch	Cs-137	~160 MBq
3	NaI 3 inch	Co-60	~45 MBq
4	NaI 3 inch	Co-60	~20 MBq

Figure 12: Map overview, detected sources at site 1, Oriental Market

Site 2: House, 45m x 15m

This site consisted of a large two floor building with windows covered with shutters. There were several sources placed inside the building. Since our drone is not designed to fly inside we decided to swipe the building from the outside covering all the windows.

Our ground unit was located west of the building. We flew two rounds around the building, one at the ground floor level and another at the first floor level. We wanted to estimate activities using the inverse square law formula, unfortunately it started to rain after our first swipe of the building so we didn't get the opportunity.
Despite this we managed to locate and identify all five sources during flight but only reported three as unique.

Table 2: Detected sources at site 2, the House.

Source	Flight time	Detector	Source
1	~9 min.	NaI 3 inch	Cs-137
2	~9 min.	NaI 3 inch	Cs-137
3	~9 min.	NaI 3 inch	Ba-133

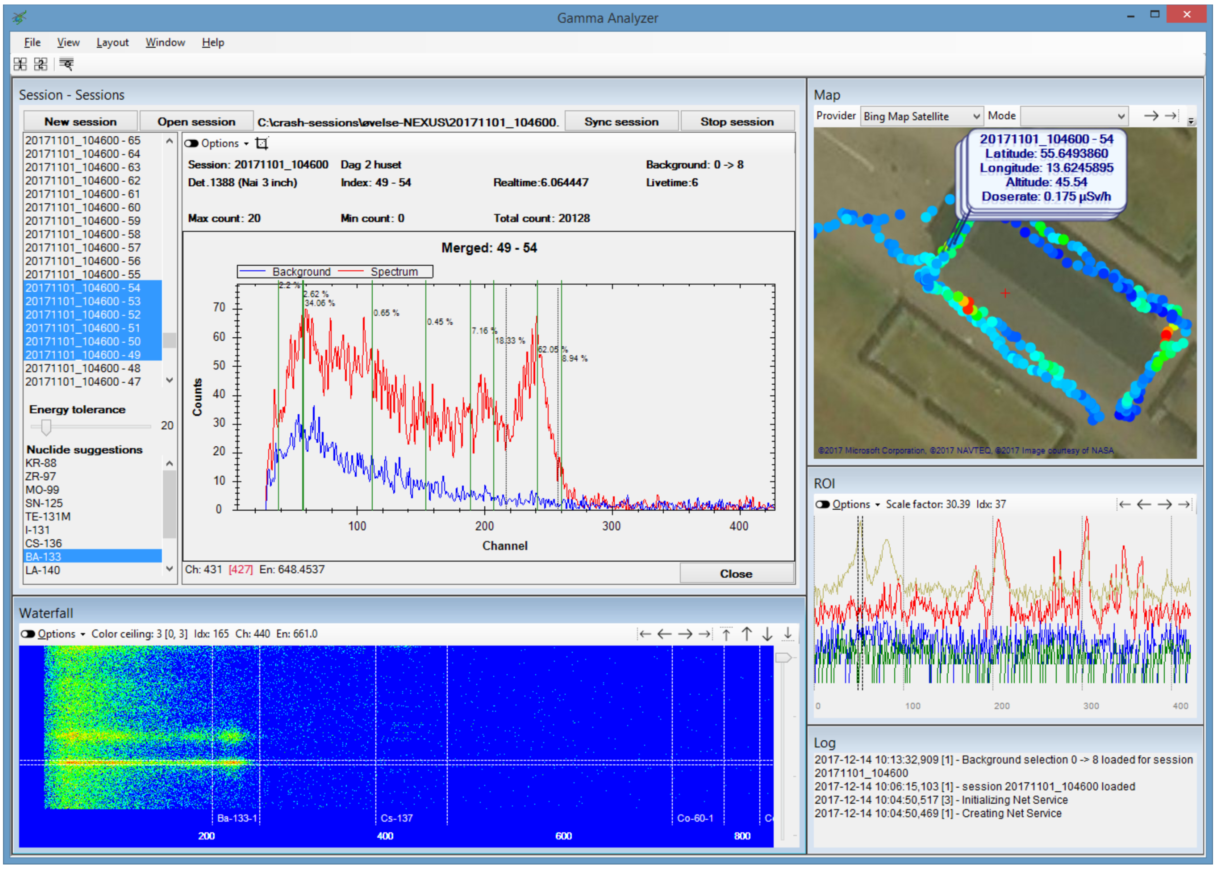


Figure 13: Site2, The House, View from Gamma Analyzer

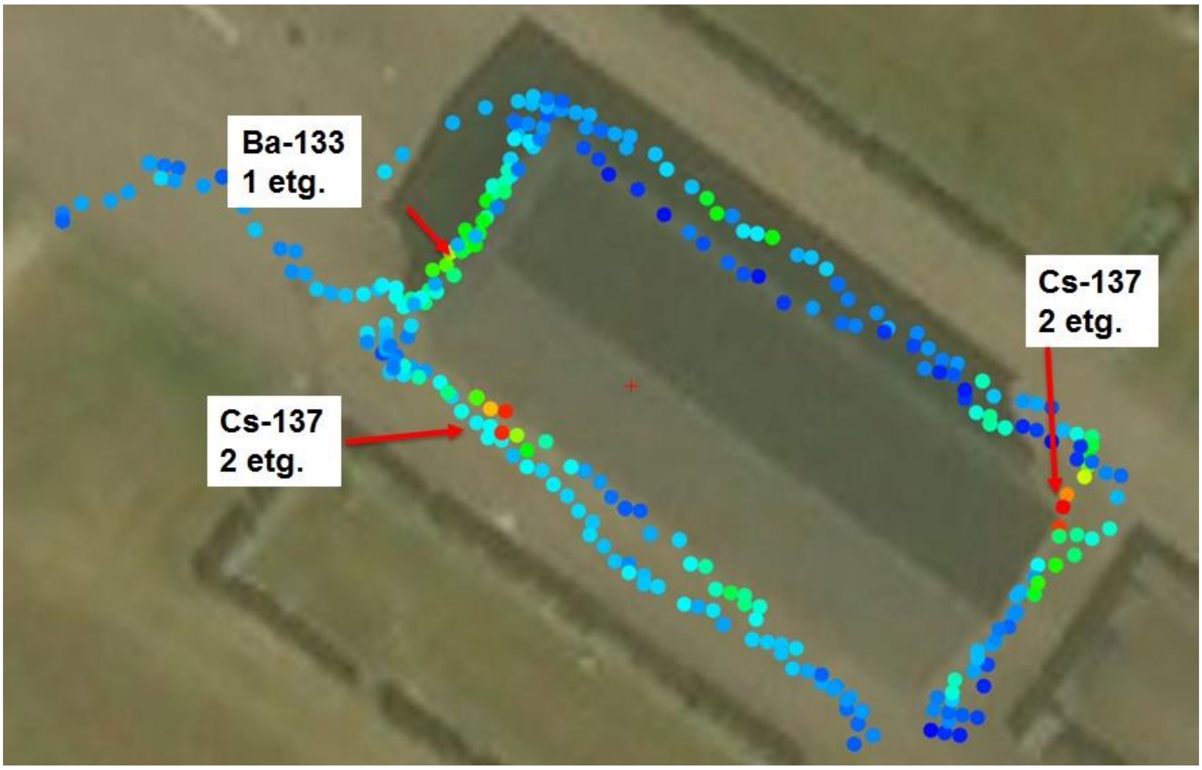


Figure 14: Map Overview, Detected sources at site 2, the House

Site 3: Runway 1

This site consisted of a liquid pattern of radioactive substance spread over a limited area on a runway. The task was to identify the source and look for any patterns.
On the first flight our ground unit was located east of the area and we flew manually about two meters above the runway in an east to west pattern.
On the second flight the ground unit was located west of the area and the DJI ground station was configured to follow a predefined grid of waypoints going from north to south.

We immediately recognized the source to be Tc-99m, but we were unable to recognize any obvious pattern.

Table 3: Overview for flight at Runway 1

Source	Flight time	Detector	Source
1	~12 min.	NaI 3 inch	Tc-99m
1	~13 min.	NaI 3 inch	Tc-99m

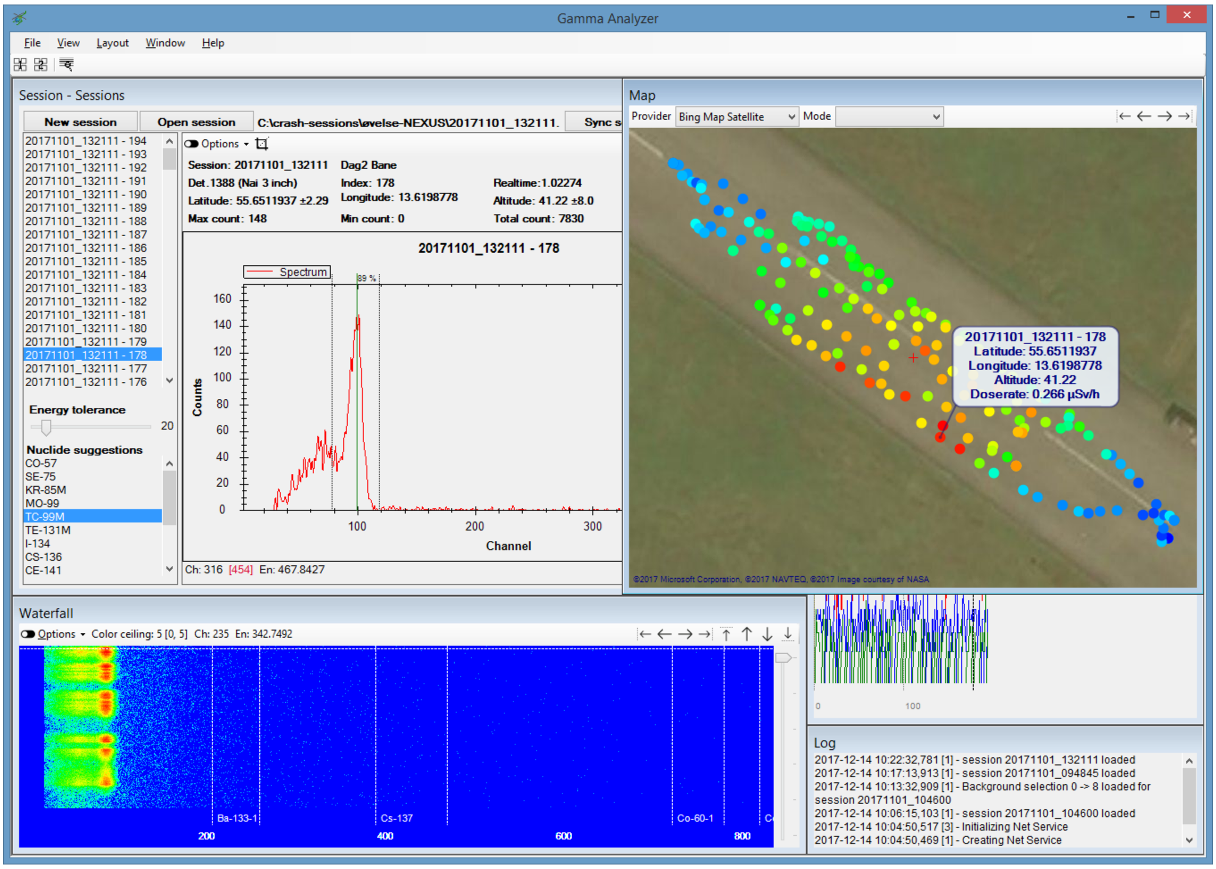


Figure 15: Map Overview, our flight over Runway 1.

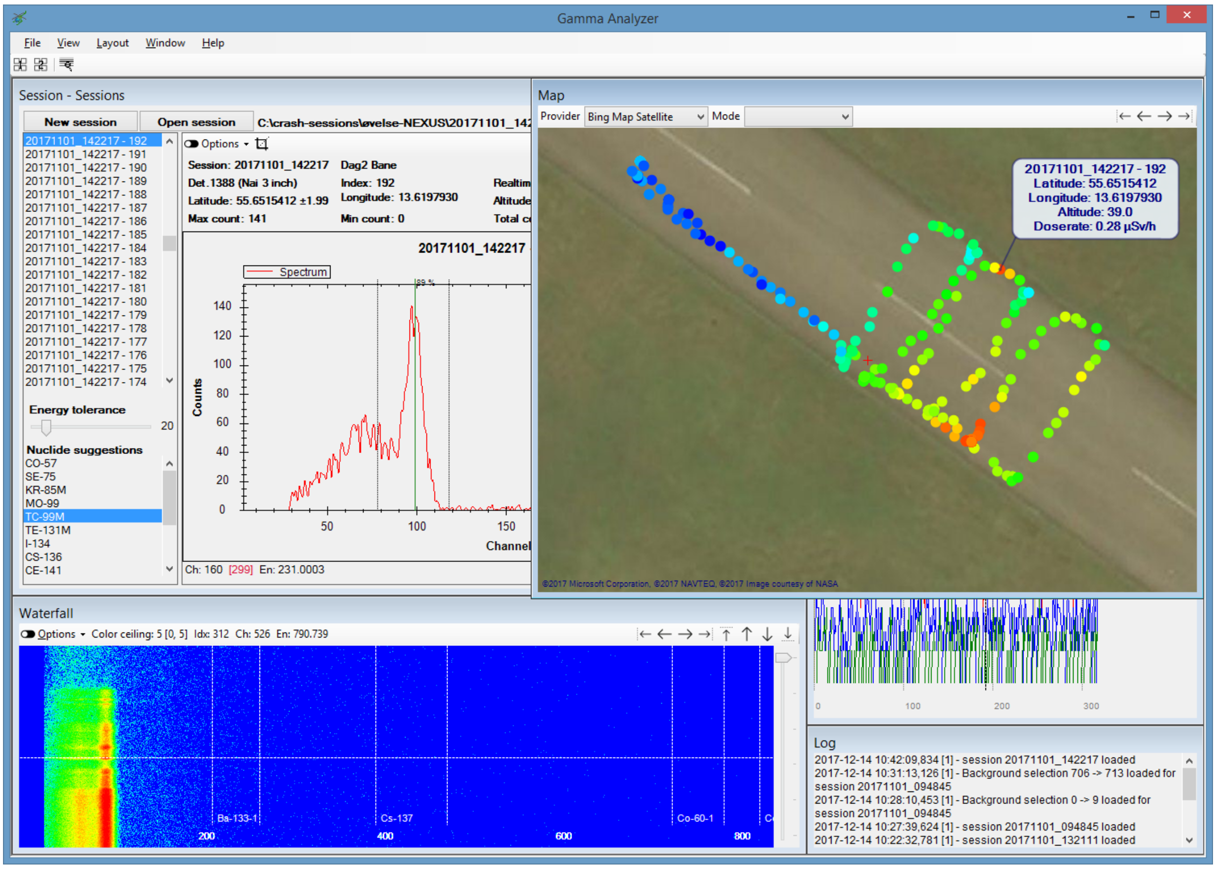


Figure 16: *Map Overview, our flight over Runway 1, from different start point.*

Site 4: Runway 2

On this site a 1 GBq Cs-137 was placed on the ground for MDA testing. We started by flying over the source at about 6 meters height and then increased the altitude. At about 30 meters, the source started to fade completely from the spectrum. We also tested high speed flyby in different heights with a maximum of about 15 meters. The source was clearly visible as can be seen in the waterfall chart.

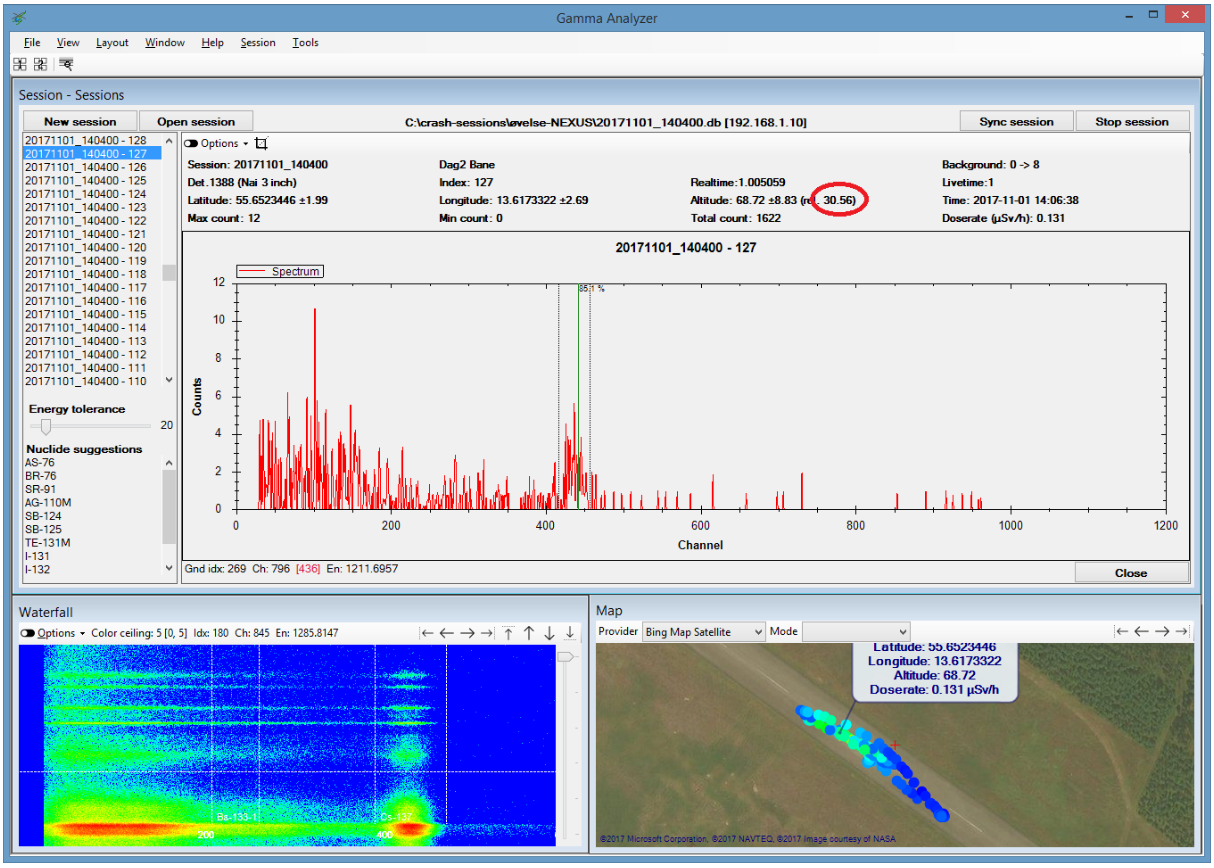


Figure 17: Map overview, Our flight over the Cs-137 source

Conclusions

Our system and software work well under most of these circumstances with the exception of indoors measurements.

With a lighter detector we could possibly collimate the detector that might help us locate the pattern at site 3.

Our equipment is not water resistant, so the rain causes problems with our current system.

5.3 Team Finland

The University of Oulu participated with a two member team, Prof. Juha Röning and Phd. student Marko Kauppinen. Marko operated as the pilot and Prof. Juha Röning as the remote monitoring PC operator and guided the pilot according to real-time monitored values. The UI of the remote PC software, created using Python, is shown in Figure 18.

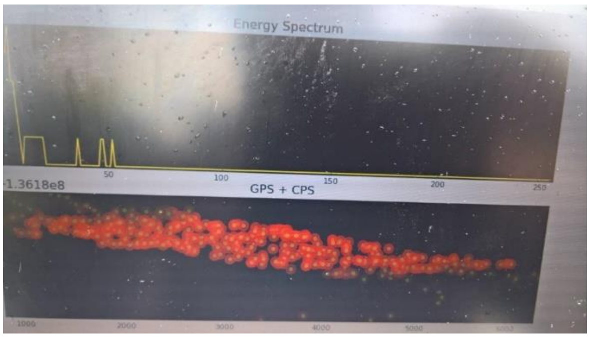


Figure 18. The UI visible to the remote PC. For saving bandwidth, the energy spectrum was not sampled at full channel resolution of the sensor. Below is the visualized intensity of measured radiation at different GPS points. The plots are updated in real time.

Platform details

	Name	**DJI Inspire 1**
Drone specifications	**Picture**	**Error! Reference source not found.**
	Type	Quadcopter, center body, lifting arms w. landing gear
	Configuration	4 rotor, H
	Temperature range	0–40 C
	Engines	DJI 3510H, 350 KV
	Battery	6S LiPo, 4.8 Ah, 99.9Wh
	Propellers	DJI 1345T
	Frame	DJI T600
	Controller	DJI proprietary
	GPS	Yes
	Range Finder	dual Sonar, DJI proprietary
	Optical Flow	Yes, DJI proprietary
	RC	DJI proprietary 2.4 GHz
	Telemetry	Piggy bagged via 2.4 GHz DJI C1 remote controller
	Data link	No
	Ground control	DJI Ground Control Station Software
	Automatic flight	GPS Waypoints
	Fail-safe system	Yes, return home
Imaging	**Camera**	DJI X3, 4k resolution @ 24 FPS
	Gimbal	ZENMUSE X3
Dimensions	**Length**	0.5 m
	Width	0.5 m
	Height	~30 cm

	Name	DJI Inspire 1
Weight & payload	**Aircraft Weight (1 battery)**	2.845 kg
	Aircraft Weight (1 battery, gimbal, camera)	3.060 kg
	Extra battery, ea	570 g
	Max payload Weight (excluding battery, camera and gimbal)	~0.5 kg
	Max Gross Take-off Weight	3.5 kg
Speed	**Max speed**	22 m/s
	Cruise speed	5 m/s
Other information		
	Maximum altitude	120 m
	Endurance	~18 min
	Max. kinetic energy	1000 J
	Wind	<6 m/s

Stand-alone sensor Package (Figure x)	**weight**	~0.3 – 0.4 kg
	Gamma Detector	Kromek GR1
	Other sensors	PixFalcon (micro-PX4 clone) as GPS and IMU
	Computer	Raspberry Pi Zero
	Data link	3DR 433 MHz
	Sampling rate	Software adjustable, 1 Hz was used

Gamma-ray spectrometer specifications	
Manufacturer	Kromek
Model name	GR1
Sensor type	1 cm^3 co-planar grid CZT detector
Energy resolution	2 % FWHM @ 662 keV
Electronic noise	< 10 keV FWHM
Maximum Throughput	30 000 counts/s
Channels	4096 (12 bits)
Differential non-linearity	< ±1%
Power consumption	250 mW
Dimensions	25 x 25 x 63 mm
Weight	60 grams
Temperature	0 – 40 °C

Figure 19. The DJI Inspire 1 carrying a sensor package 1.5 meters below it.

Figure 20. Sensor package containing the Kromek GR1 gamma-ray spectrometer, GPS + IMU via PixFalcon (micro PX4), Raspberry Pi ZeroW and a 1300 mAh USB-power bank.

Sensor calibration

The estimated sensor calibration curve, for taking in to account the detection efficiency of the sensor, is shown in Figure 21. The efficiency curve marks how much of the gamma-radiation hitting the sensor at specific energy levels is registered by the sensor. The curve is based on the tests performed by STUK in Finland with Kromek GR1-A sensor. It is apparent that the sensor is less sensitive the higher the gamma ray energy level is. Note there is a maximum of 7% error in the source data used for obtaining this calibration curve. When considering the resolution error of Kromek GR1, at least 10% of error should be assumed for this calibration and manufacturer has informed that the minimum energy level detectable by the device is 25 keV. We will not disclose the elements used in obtaining this curve as the source data has not been made publicly available. However, five different sources were used for obtaining this curve.

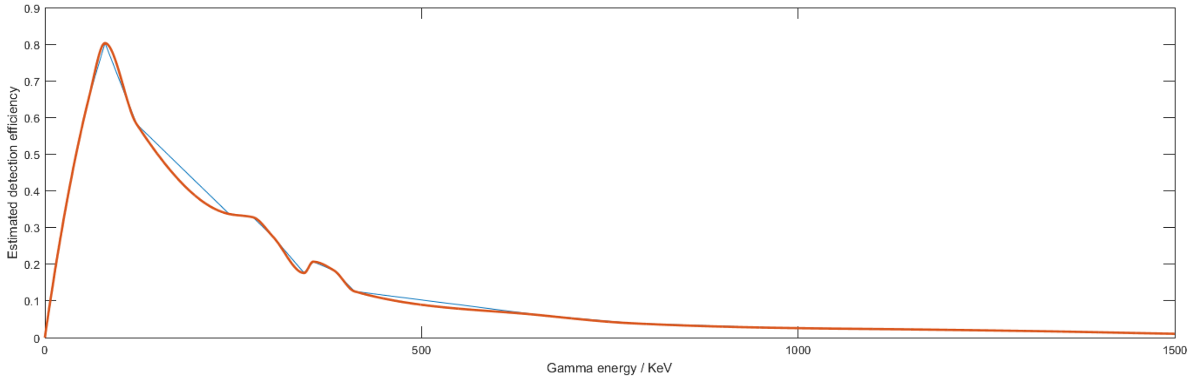


Figure 21. The estimated detection efficiency of the Kromek GR1 in the sub 1.5 MeV range based on tests performed with five different radiation sources. The red line is piecewise interpolated by using Matlab 2016b's Piecewise Cubic Hermite Interpolation offered by the pchip function.

Results

Here we have the compilation of results we obtained using our measurement setup. For visualizing the measured points, we also reconstructed 3D models of the measured sites from separately recorded short flight videos. The reconstruction was made by using the Agisoft Photoscan software [1] from 1080p screen captures of the recorded aerial video. The 3D models were aligned by hand, due to geotagged images not being available, and imported to the Google Earth as KMZ files. Due to Google Earth limitations, the models had to be strongly decimated so the quality is significantly lower in Google Earth (less than 16 000 vertices, while the original generated models had over 1 million vertices). The gamma ray measurement data points are visualized in Google Earth as well. For each data point, the sampling time for the measurement was one second, i.e. the sampling frequency was 1 Hz.

The measurements conditions were challenging for our equipment, as the air humidity was high and there were constant drizzling with some intermittent rain. Also, because we could only bring a few batteries with us with limited capacity, due to public air travel regulations, we had to keep our test flights short. We did not use automatic waypoint flying in the scenarios as the heavily clouded and rainy weather seemed to affect the GPS signal quality. In addition, the building obstructed the GPS signal at some points when flying very near the walls. The sonar altitude sensor of the DJI Inspire 1 seemed to be affected as well and the barometer in the sensor package was strongly affected by high air humidity and quick changes in the weather. Therefore, the altitude estimations had quite a lot of error as well. In addition, especially in Scenario 2 (building), assigning 3D GPS points with the DJI GO application would have been difficult to do on-site.

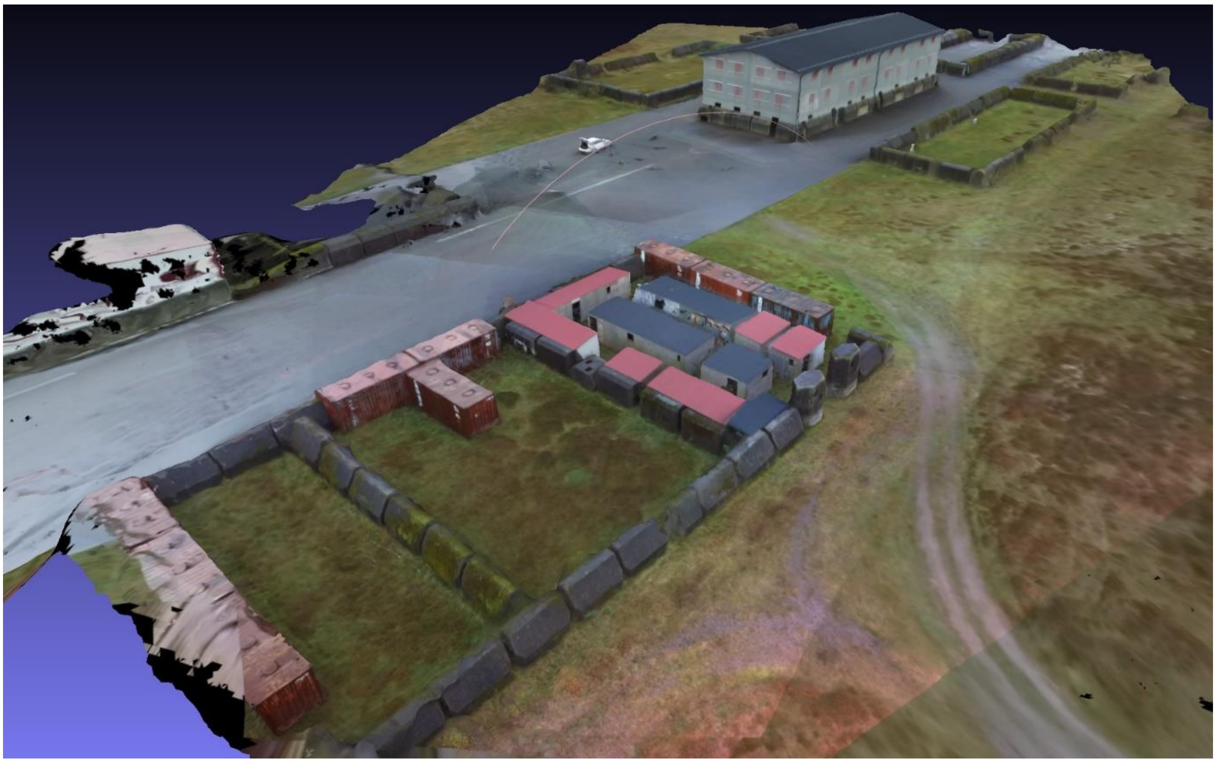


Figure 22. MeshLab view of the 3D reconstructed model of sites 1 and 2.

Figure 23. Low-quality 3D reconstruction of the Site 2, manually aligned and imported to Google Earth.

Site 1: Oriental market

The oriental market scenario consisted of small huts in an occluded area, with a height of approximately 2 meters. During the flight, the sensor package hovered 0.5 – 1.5 meters above the roofline of the huts. The huts appeared to have a metal roofs and plywood walls. The scenario area was the area contained within the concrete element walls. Note that because it started to train, we had to stop early during this scenario, and to conserve batteries for the remaining two scenario sites 3 and 4. For this reason, our measurements only covered the hutted area.

The observed spectrum of the energies accumulated over the entire flight above the area is shown in Figure 25. In the above graph, the raw data obtained with Kromek GR1 is shown. On

the lower graph, the data has been compensated dividing the raw spectrum values with the corresponding estimated internal efficiency of the sensor, which is shown earlier in Figure 21. To have cleaner visualization of the data, the spectrum was re-binned from 4096 channel bins to 256 bins. This reduces the accuracy a bit, but the given sensor error margin for detecting energy levels is 2% and re-binning does not shift the results to outside of this error margin.
From the spectrum over the entire flight, two sources are clearly visible, Ba-133 (356 keV) and Cs-137 (661.64 keV). Strangely, a spike was formed also at 302 keV, which corresponds most closely to Tb-160 (299 keV) according to [2]. However, this spike correlated strongly with the area of the Ba-133 detection, so they might have been the same source or the 302 keV spike is an artefact and not an actual detection.
Estimating the activity and location of the sources proved to be difficult due to inaccuracies in the GPS position and the sensor height readings. Also, it is unknown how the observed radiation pattern is affected by the structures.
The detected hotspots and sources are visualized in Figure 25. Local histogram of hotspot 1 had too weak markers to identify the source material from the noise. Hotspot 2 had clear markers of Ba-133 and hotspot 3 had markers of Cs-137.

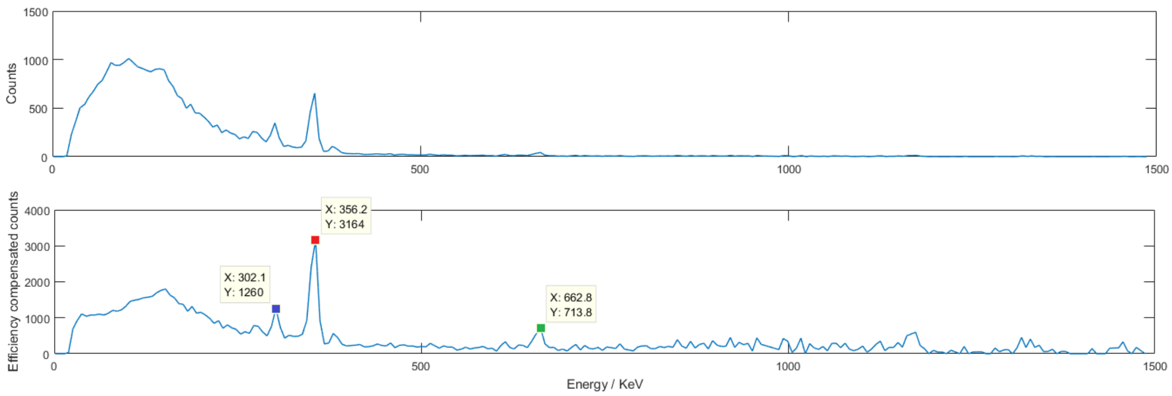


Figure 24. Top; the raw data over the entire recorded data from the scenario. Bottom; the sensor sensitivity compensated spectrum of the area. Note that all the data presented in later pictures are also sensitivity compensated.

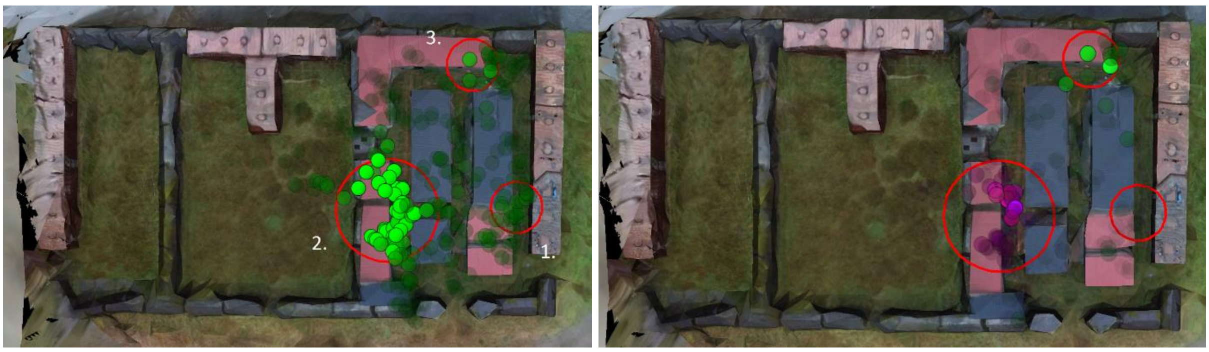


Figure 25. On the left, visualization of the radiation intensity observed from the CPS (counts per second) detected by the sensor package. On the right, radiation from different sources visualized by different colours assigned to each detected energy spike in Figure 24. Green corresponds to Cs-137, red to Ba-133 and blue to what seems to be detected at the 302 KeV spike.

Site 2: Two-storey concrete building

On this site, two flights were performed. In the first flight, the sensor package was flown on top of the roof and circulating around the edges of the roof. On the second flight, the package was flown around the house at roughly half the height of the building. The distance of the sensor varied between 0.5 to 2 meters from the surfaces of the building. Especially in this scenario, we can observe that the height measurements are not exact as the recorded data points seem to be at a higher altitude when visualized in Google Earth than what they were observed to be during the scenario. The high air humidity and its effects to the sensors probably affected the altitude measurements.

In the data recorded on the first flight, spectrum shown in Figure 26, we can clearly see the presence of Cs-137 (661.64 keV). On the second flight, where we flew around the walls of the building at middle height, we can additionally see signs of Ba-133 (356 keV). The accumulated spectrum of the second flight is shown in Figure 27.

The detected hotspots and sources are visualized in Figure 28. Local histogram of hotspot 1 had markers for Ba-133 and hotspot 3 had clear markers for Cs-137. Hotspots 2 and 4 had barely identifiable markers for Cs-137 in their local spectrums (spectrums accumulated of points contained within the red circles). The building from different orientations is shown in Figure 29.

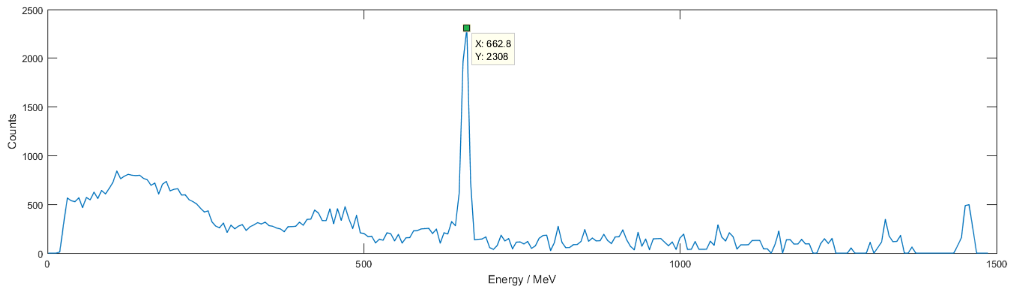


Figure 26. Accumulated spectrum of the first flight around the roof edges and on the top of the roof of the building.

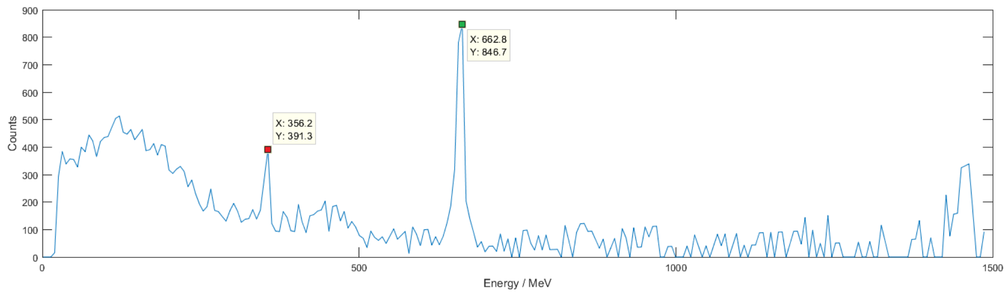


Figure 27. Accumulated spectrum of the second flight, where the sensor package travelled roughly along the middle height of the walls of the building. In addition, the roof was flown through once again along the centreline of the roof.

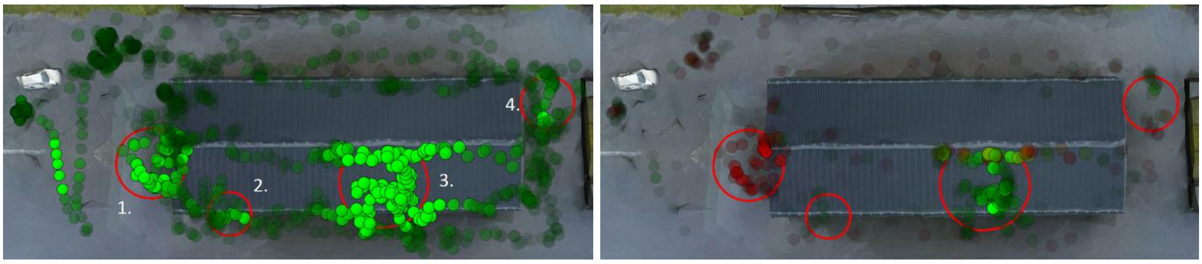


Figure 28. On the left, visualization of the radiation intensity observed from the CPS (counts per second) detected by the sensor package. On the right, radiation from different sources visualized by different colors assigned to each detected energy spike in Figure 26 and Figure 27. Red corresponds to Ba-133 and green to Cs-137.

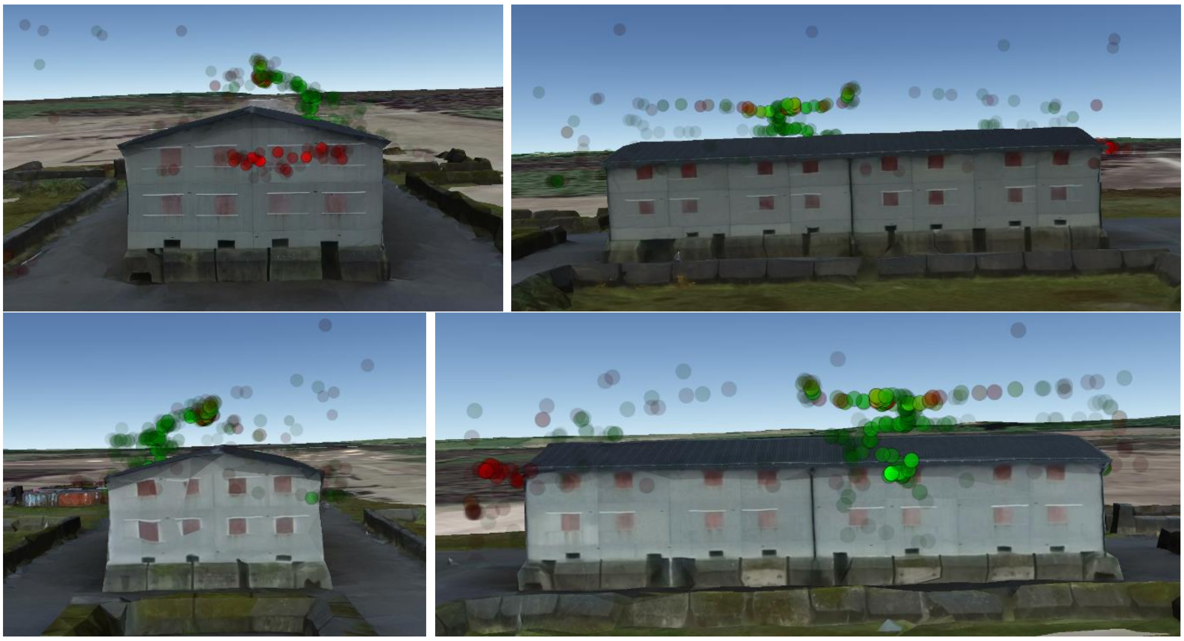


Figure 29. The measurements from each side of the building. Note that the measured points appear to be around 1 – 1.5 meters higher than what the measured points actually were during the flight. There was clearly an issue with the height measurements.

Site 3: Airfield with sources on the tarmac

In this scenario, a one type of source material was known to be on the field. The source in question is Tc-99m (140 keV) and is clearly visible in the spectrum recorded from the scenario in Figure 30. In this test, the radiation sensor is used to detect the shape of the field of radiation. However, due to GPS inaccuracies, this proved to be quite difficult even though we systematically flew through the samples in a grid. The sensor package travelled above the samples at 0.5 to 1.5 meter altitude during the flight.
In Figure 31, the CPS of the measured data points are shown. The sparse heat map can be seen in Figure 32. We can clearly see that the GPS accuracy is a huge factor in determining the radiation field shape effectively. Even though our sensor package uses Extended Kalman Filter (EKF) to support the GPS localization via IMU data fusion, the challenging wet conditions and cloudy atmosphere most likely significantly affected the tracking accuracy of the sensor package.

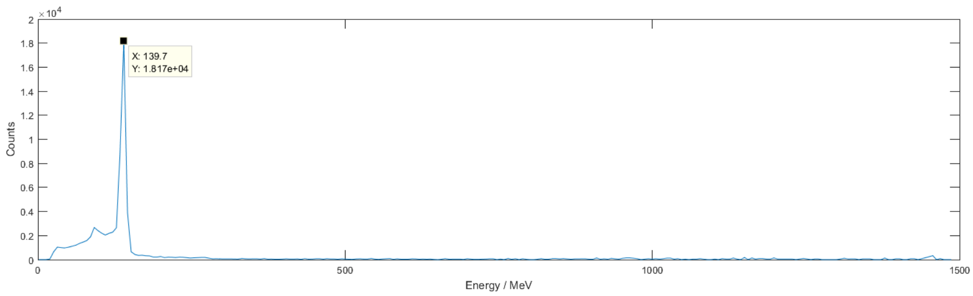


Figure 30. Accumulated spectrum of the flight over the test site 3.

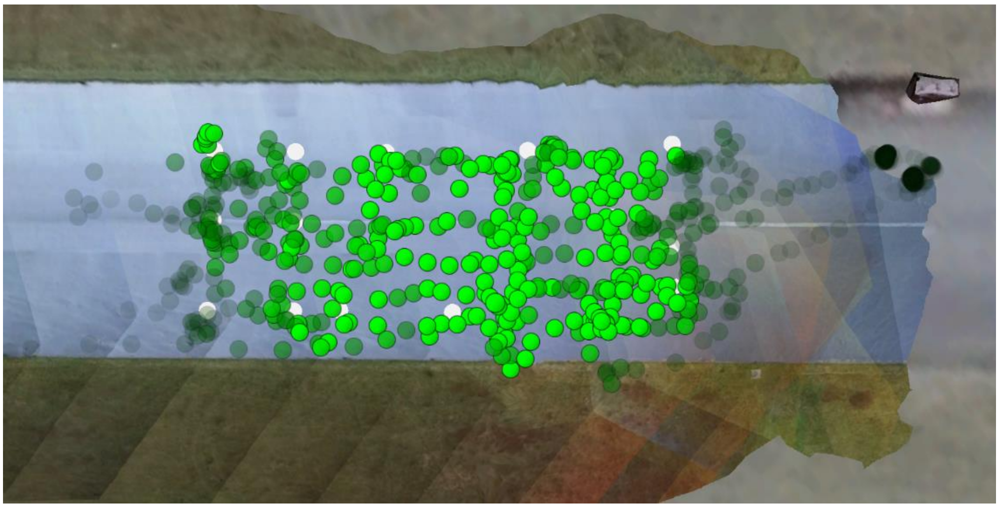


Figure 31. Visualization of the radiation intensity observed from the CPS (counts per second) detected by the sensor package over the airfield. The rough locations of the radiation sources based on the map constructed from the flight video are shown by the white dots.

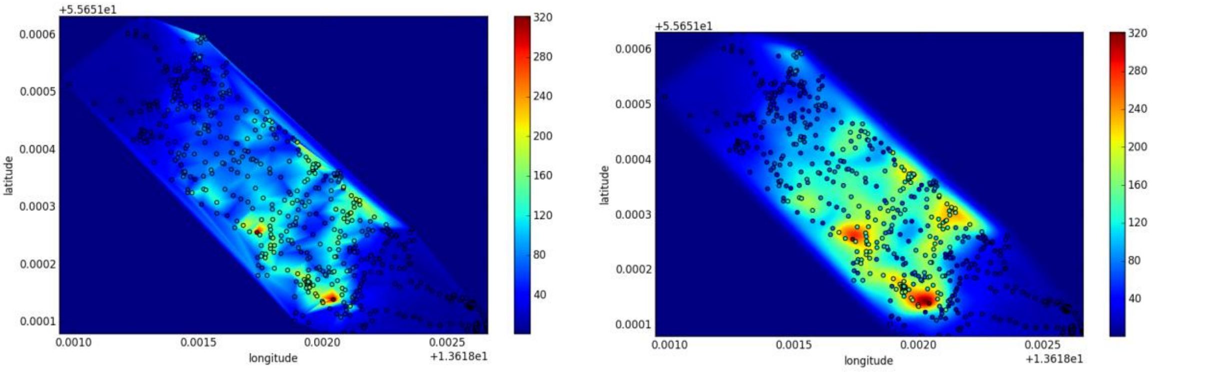


Figure 32. "Heat map" of the area based on CPS values from the sensor package measurements. Linear interpolation between points is utilized on the left. It can be seen straight away that the GPS accuracy and the statistical variance in the CPS measurements result in a poor quality heat map. Clearly more measurement samples would have been needed. On the right, the left side heat map is run through a Gaussian filter in normalized image coordinate space. This is just to make the map look nicer and should not be considered representative of the ground truth. A standard deviation value of 16 and a mean deviation of zero was used for the 2D Gaussian kernel.

Site 4, one Giga Becquerel Cs-137 sample

In this scenario, there was only a single strong known radiation source in the field. Unfortunately, we encountered a data logging failure near the sample, so we did not collect the full data of the scenario. Therefore, we also have to leave out the analysis for this report. The problem was that the sensor package and the DJI Inspire 1 both encountered a logging error near the source. It is clear that the radiation affected the electronics sufficiently to cause disturbances, which points to a need of further development in the shielding of the equipment.

However, it was seen that the automatic software reset on the sensor package worked correctly and the system recovered by itself when the package was moved away from the source. In the remote UI, the software reset was not noticed at all, so the UI should be added with a status display from the sensor package to clearly indicate if there is a problem.

Conclusions

Although the testing was done in challenging conditions, some results were obtained. The issues to be solved seems to be mostly related to visualization of recorded data in real-time at the measurement location. To solve these issues, the copter would need to have also some level of SLAM (Simultaneous Localization And Mapping) capabilities. This would also shift the system to be less reliant on GPS signal availability and the relative position of the sensor should be easier to visualize with respect to the measured locations. In addition, autonomous operation of the copter should be implemented to have better coverage of the measured sites.

A small separate sensor package that was used in our approach might be beneficial in situations where a radiation source is detected coarsely when being carried with the copter and then it could be easily detached and taken indoors to find the exact location of the source. Also, the small sensor package hanging from the copter is easier to get closer to the measured spots. A metal chain is probably the best option for hanging the package from the copter as there is no risk of having the chain being tangled in the propellers during take-off or landing.

As the biggest issues during the scenario related to sensor package localization accuracy, the next iteration of the sensor package will include a flow sensor and a LiDAR (Light Detection And Ranging) to have more robust tracking performance. Below, in Figure 33, is one of the test iterations of the sensor package with PX4Flow and LIDAR-Lite modules attached.

One other issue detected during the testing was that the sensor package needs some sort of shielding in high radiation environments. In the area with a one Giga Becquerel Cs-137 test source, the sensor package software did reset itself when very near to the source, at less than 2 meter distance. The sensor package software recovered automatically after moving away from the source as it was designed to do and continued measurements. Interestingly, when near the highly radiating source, even the DJI Inspire 1 quad copter’s internal log-file was corrupted. Clearly, the copter also needs some additional shielding in high radiation environments; luckily, the copter flight capabilities were not affected.

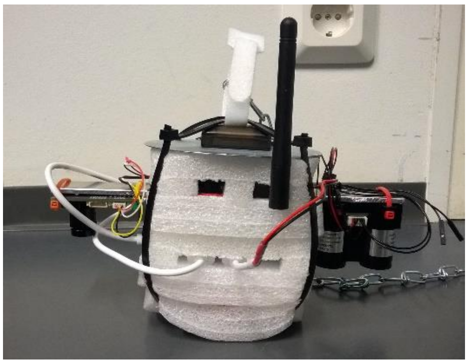


Figure 33. Test package with additional optical flow and LiDAR based altitude measurements for increasing the localization performance. The final version will have a 3D printed case.

References

[1] http://www.agisoft.com/

[2] https://www.cpp.edu/~pbsiegel/bio431/genergies.html

5.4 Team Sweden

Linköping University coordinated the exercise, but also participated with a team. The team was Magnus Gårdestig as team leader and analyst and Claes Meijer as the pilot. Håkan Pettersson and Marie Carlsson practically supported the entire exercise.

Our experiences from the last exercise, NORDUM, in Norway in 2016, were that the detection system should be more robust with dedicated power supply, which we now have. During the exercise last time, the detector broke and is now replaced.

Since NORDUM we have been focusing on our fixed wing system and have had less activity in the project.

During the exercise we did not have the time for the scenario with the 2-storey building.

Figure 34 Ground control station with the quad in the air. Photo: Marie Carlsson

Technical specifications

Name	Quad	RadiaWing
Picture		
Type	Quadcopter, center body with 4 arms	Fixed wing
Engine	Electric, KV 620	Electric, KV 690
Battery	6S	6S
Propellers	12x4.5/305x114	14x8 foldable
Configuration	X	Tractor
Manufacturer	Tarot Iron Man 650	Claes Meijer
Controller	PixHawk	
GPS	Yes	
RC	Futuba S.Bus T10J 2.4 GHz	
Telemetry	3DR 433 MHz	
Data link	XBee Pro SS 868 MHz	
Ground control	MissionPlanner by 3DR telemetry	
Length		1,6 m
Width	0,8 m	3 m wingspan
Height	28 cm	62 cm
Aircraft Weight (1 battery)	2,5 kg	4 kg
Extra battery, ea	825 g	825 g
Max payload Weight, excl. battery	2 kg	3 kg
Max Gross Take-off Weight	5 kg	7 kg
Max speed	20 m/s	20 m/s
Cruise speed	5 m/s	15 m/s
Launch type (fixed wing)		Throw, skid landing
Maximum altitude (regulations)	120 m	120 m
Endurance (approx.)	25 min	40 min
Max kinectic energy	1000 J	2000 J
Wind	<6 m/s	<6 m/s
Gamma Detector, weight	60 g/1000 g	1000 g/2000 g
Automatic flight	GPS Waypoints	GPS Waypoints
Fail-safe system	Yes, return home	Yes, return home, Wing breaks off on impact

The detector system is either the CZT spectrometer Kromek GR1 or a NaI spectrometer with a MCA from Bridgeport Instruments, a 2” or a 3”. During the entire NEXUS exercise, we used our 2” NaI-spectrometer.

The detector data is sampled with a Raspberry Pi, stored and transmitted by a XBee 868 MHz radio link. The spectra are stored in XML format according to the ANSI N42.42.

The measurement ground station is an in-house developed Windows application UARS Monitor, Figure 35 that displays the map, energy spectrum, waterfall spectrum, dose rate and raw data. This software can replay a mission, giving the opportunity to reset parameters as ROIs, sums of spectra, new calibration coefficients etc. for better visualization and analysis of sampled data.

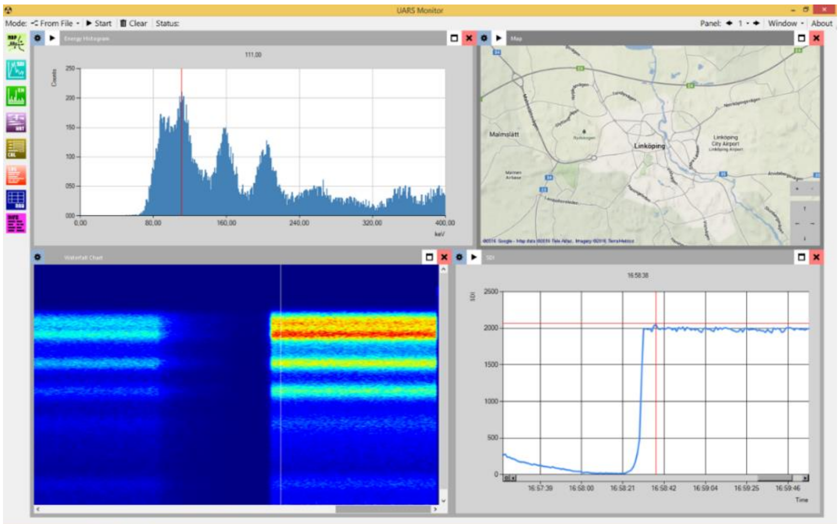


Figure 35 The display and analysis screen of the measurement ground station.

The drones are monitored, and route directed by the flight plan and telemetry data software Missionplanner, Figure 36. Both ground stations were run on the same computer, with an other laptop acting as an external screen using the Spacedesk software (https://www.spacedesk.net/).

Figure 36 The Missionplanner flight data screen of the ground control station

Post processing was made in Matlab.

The mock Oriental market

We flew manually over the sheds taking measurements from 3-10 meters altitude. We found three of the four sources as indicated in the figure below. We missed the fourth source because we didn't cover the market completely or we flew to high to detect it.

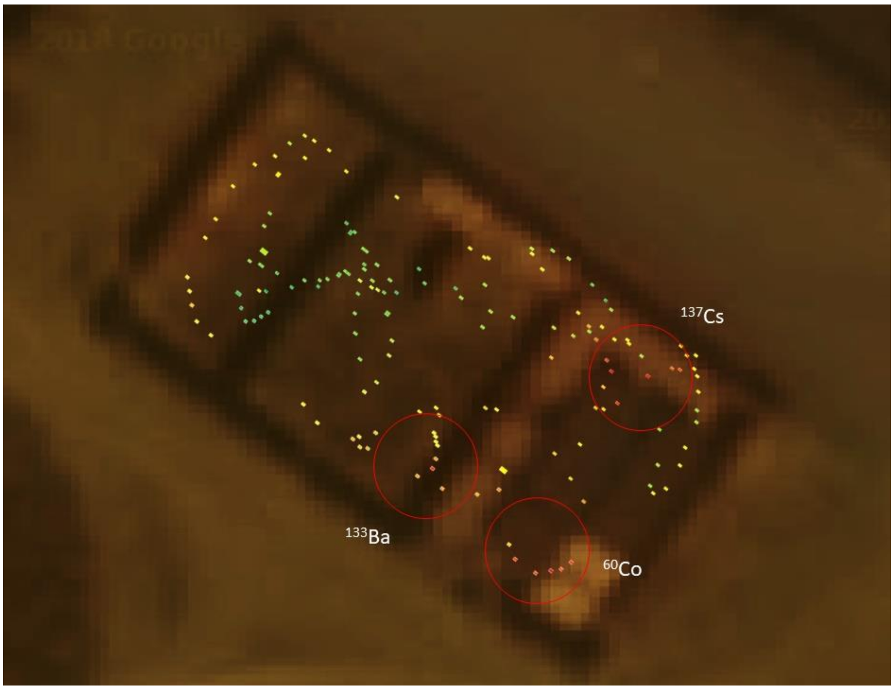


Figure 37 Dose rates indicated in colours over the market.

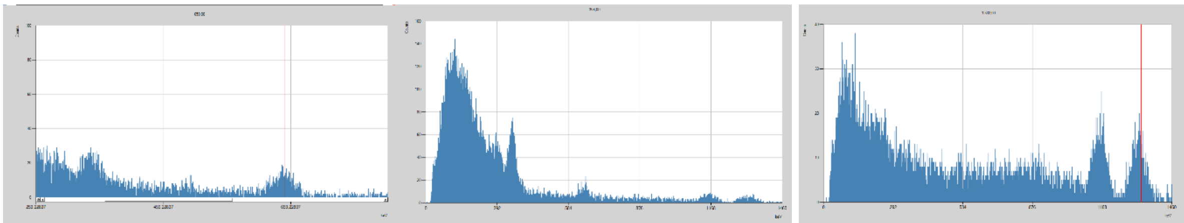


Figure 38 Energy spectra for the found sources. From left; ^{137}Cs, ^{133}Ba and ^{60}Co.

Point source

At the end of the runway, there was a strong point source facing the sky. We hovered over it and tried to find the maximum dose rate at separate altitudes. The dose rates recalculated to 1 m AGL agreed fairly good. At about 30 meters the source was no longer detectable.

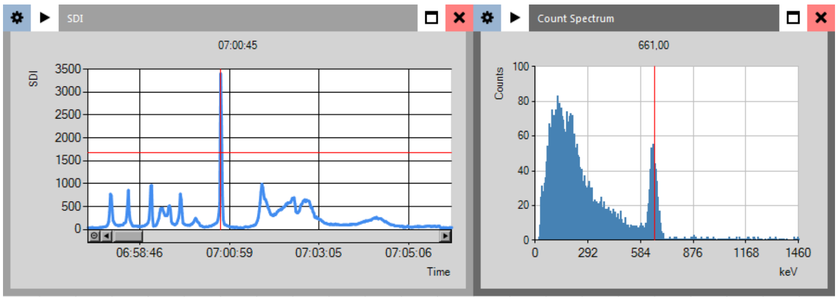


Figure 39 Point source at 3,5 meters altitude.

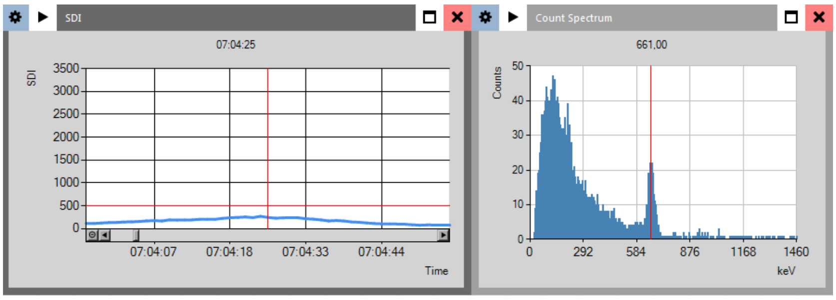


Figure 40 Point source at 18 meters altitude

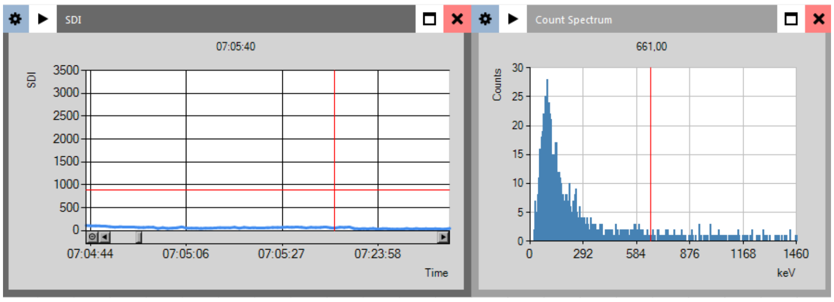


Figure 41 Point source at 30-35 meters altitude.

Table 4 Dose rates (SDI) recalculated to 1 m AGL.

Altitude [m]	SDI	SDI-bkg	1 m AGL
7	850	750	36750
3,5	3500	3400	41650
10	550	450	45000
18	250	150	48600
30	100		
35	100		

The contaminated runway

The contaminated area was clearly a contamination of ^{99m}Tc that seemed to fade in activity towards the end of the runway. Any pattern in the contamination was however hard to determine. The contamination could have been diluted by the rain.

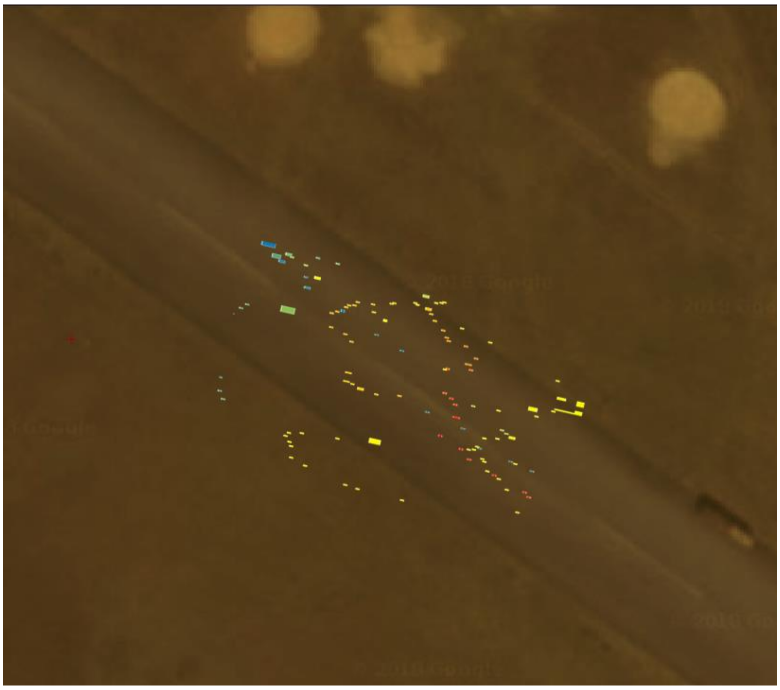


Figure 42 The contaminated area intensity from red to blue

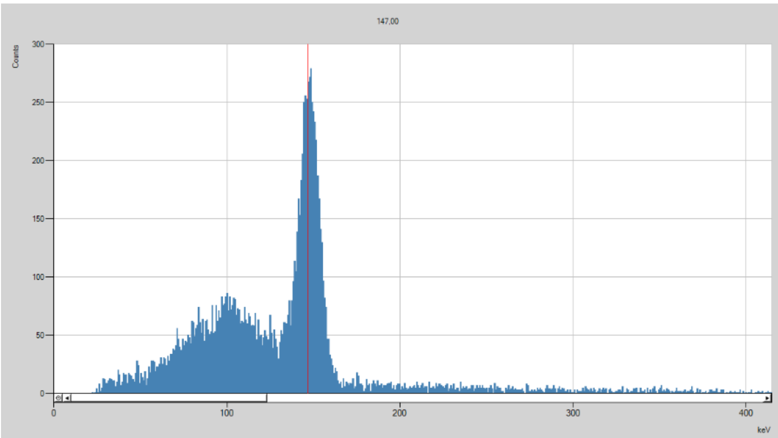


Figure 43 The contamination of ^{99m}Tc, determined by the dominating 141 keV peak.

Fixed wing
We had an ambitious, successful first flight, but unfortunately, during the next flight our prop broke with a following hard landing. The detector system survived, and we could have just replaced the motor and propeller with minor damage to the fuselage and carried on. However, we didn't try our luck any more and the sun set.

Figure 44 Happy crew after the first successful landing. Photo: Marie Carlsson

Figure 45 Photo from the fixed wing flying over the runway.

Figure 46 The first flight over the runway with the fixed wing.

Conclusions and experiences from NEXUS

Our systems are still in development stages and need a lot more development to be in a more ready-to-go state.
The NEXUS was a great inspiration and a good bench mark of our capacity and intentions.
We were able to sample a lot of data, which is a success, but we need to develop faster post processing and analysis software to provide better and faster decision support.

Our experience was that even if the weather was not in our favour with some rain and low temperatures, we were still able to make the flights and the measurements. Efforts to make the systems more resistant should however still be taken.

To exercise based on scenarios with unknown sources is most valuable.

7. Overall conclusions

The Nordic countries have a growing competence in radiation measurements utilizing unmanned aircraft systems. This NKS activity have strongly benefited the Nordic exchange and growth of knowledge and experiences in the topic.

The use of fixed wing platforms was tested and demonstrated briefly. The Swedish team had their fixed wing designed for carrying a detector system in the air. The use of fixed wing UAS platforms could fill a gap between rotary wing UAS and full scale fixed wing systems in surveying larger areas.

The use of unmanned measurements in urban environments was tested and demonstrated in two scenarios, the oriental market and the 2-storey building. In particular the scenario around the 2-storey building demonstrated the 3D survey advantages with rotary wing systems.

Survey of contaminated areas in contrast to separate point sources was tested and demonstrated in the scenario with the contaminated area with dispersed activity in a pattern.

The aim to have team's report to reach back failed, presumably due to lack of time and preparations. This is something to develop since the end result should be decision support.

The capacities in the Nordic countries are still in development, but the exercise demonstrated that it is an ongoing development. This form of arrangement with an exercise in an area where the teams can see each other's approach and solutions is most inspiring for the exchange and growth of knowledge.

8. References

Gårdestig, M., Pöllänen, R., Aleksandersen, T. B. (2015). SemUnaRS – Seminar on Unmanned Radiometric Systems. NKS. **331**.

Tazmini, K., D. Robøle, J. Drefvelin, Ø. G. Selnæs, J. V. Jensen, M. Gårdestig, M. Kettunen and J. Röning (2016). Intercomparison of Nordic Unmanned Aerial Monitoring Platforms, NKS. **378**.

Appendix A NEXUS Program

NKS-B NEXUS
Nordic EXercise for Unmanned Systems
SWEDEN
31/10-2/11 2017

The NEXUS activity is from Tuesday to Thursday (31/10- 2/11) in Björka and Revinge, Sweden.

Day 1 [31/10] - Verification of your drone "Go home function" and "Geo fence"
- Open exercise (Björka)

Day 1 [1/11] - Exercise day (Björka)

Day 2 [2/11] - Workshop day (MSB College Revinge)

Program

Day 1 - Test and verification of your UAS, Tuesday 31/10

If you wish to check in at MSB College Revinge before arriving at Björka it is ok.

We have Björka exercise field open from 12:00.

Lunch is served at site from 12:00

Test and verification of your drone, “Go home function” and “Geo fence” function. Geo fence 200-500 meters from take-off point. Geo fence could be set narrower if you decide to limit your area to only cover each scenario area.

There will also be an opportunity to participate in an **open scenario** (known and marked sources) for testing and calibration.

There is no schedule and since you operate under your own license there will be no supervision, merely an opportunity for you to test your systems. Note that the **sun sets at 17!**

Coffee, water and snacks will be available near the scenario sites (base camp) during the entire day.

Dinner 16:00-18:30 at MSB College Revinge

Important for the activities on Björka:

- Lund University (Karl and Thérese) is the exercise leader.
- Lund University is radiation supervisor (Radiation protection officer).
- Each team is responsible for their own personal dosimetry.
- It is very important that you have identification documents with you, otherwise you will not be able to enter the site. Passport is the best solution.

Day 2 - Wednesday 1/11 NKS NEXUS – Exercise -

07:00-08:15 Breakfast at MSB College Revinge

Transport to Björka

Maps and information about the scenarios will be distributed at site

09:00 Welcome and information - LiU: Magnus Gårdestig, LU: Karl Östlund

Preparations

Team activities with the scenarios:

Time	**Sweden**	**Finland**	**Norway**
10:00-12:00	S1	S3	S2
12:00-13:00	Lunch break in base camp		
13:00-15:00	S2	S1	S3
15:00-17:00	S3	S2	S1

Exercise debriefing if time, else on Thursday

16:00-18:30 Dinner MSB College Revinge

Coffee, water and snacks will be available near the scenario sites (base camp) during the entire day.

Day 3 – Thursday 02/11 NKS NEXUS – Workshop

MSB College Revinge

07:00-08:15 Breakfast at MSB College Revinge

NKS-B NEXUS – Workshop

08:15 – 08:30 Welcome LiU, introduction

08:30 – 09:00 Team 1 – presentation system and data
09:15 – 09:45 Team 2 – presentation system and data

10:00 – 10:15 Coffee Break

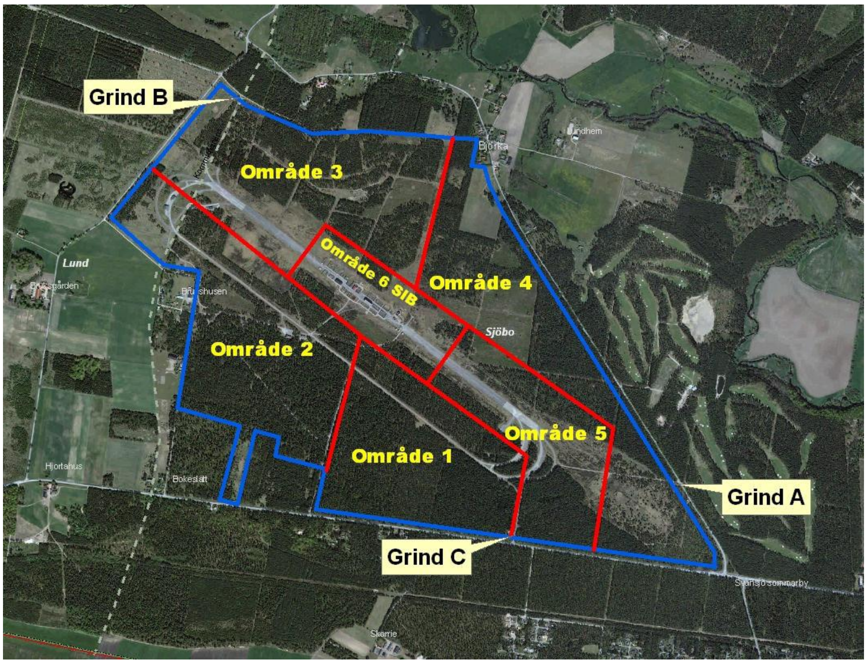
10:15 – 10:45 Team 3 – presentation system and data
11:00 – 11:30 Exercise Leader - Presentation of the scenarios
11:45 – 12:00 The road ahead

12:00 Lunch
Good bye

Maps and more information for the sites

Day 1 and 2 – Björka:
The exercise will be on the exercise field called Björka: https://goo.gl/maps/Nqidya54G3S2 about 30 km east of Lund.

At the Björka exercise field we enter through Gate A (Grind A). The marked areas in the map below is not related to our exercise.



https://www.forsvarsmakten.se/siteassets/3-organisation-forband/p7/sodra-skanska-regementet/bjorka-ovningsfalt.pdf

Accommodation

MSB College Revinge, Swedish Civil Contingencies agency’s school.
https://goo.gl/maps/Qjhdp8M6pE42
Hostel standard; individual rooms with shared shower. Bed linens available.
On Thursday our workshop will be in our lounge.

Practical

The participants will be responsible for travelling to the test site with their equipment and making measurements over a period of one or two days. They will also be responsible for presenting results and experiences on the workshop.

Reporting

After each scenario you are asked to report your findings to a **figurative expert reachback**. Simply upload any form of report and supporting data to answer the questions in the scenario.

There will be an 3G-router in the base camp for reporting from the scenarios. Please use the quota wisely, it should be enough, but there is a limit.

Find your folder and upload your report. Access will be denied after 2/11

Appendix B Participants

Name	Role	Affiliation
Team Sweden		
Magnus Gårdestig magnus.gardestig@liu.se	Coordinator, Team leader	Linköping University
Claes Meijer	Pilot	Scandinavisk UAV och Teknik Support
Håkan Pettersson		Linköping University
Marie Carlsson		Linköping University
Team Finland		
Juha Röning juha.roning@oulu.fi	Team leader	Department of Electrical and Information Engineering, Oulu University
Marko Kauppinen		Department of Electrical and Information Engineering, Oulu University
Team Norway		
Kasra Tazmini kasra.tazmini@nrpa.no	Team leader	NRPA
Dag Robøle		NRPA
Jon Drefvelin		NRPA
Christian Lexow Andersson		Consultant
Exercise organization		
Karl Östlund	Exercise leader, RPO	Lund University
Therése Geber-Bergstrand	Exercise leader	Lund University

Title	Nordic Exercise for Unmanned Systems
Author(s)	Magnus Gårdestig[1] Kasra Tazmini[2], Dag Robøle [2], Jon Drefvelin[2] Juha Röning[3], Marko Kauppinen[3] Karl Östlund[4]
Affiliation(s)	[1]Linköping University, Sweden. [2]NRPA, Norway [3]Oulu University, Finland [4]Lund University, Sweden
ISBN	978-87-7893-496-3
Date	April 2018
Project	NKS-B / NEXUS - Nordic Exercise for Unmanned Systems
No. of pages	45
No. of tables	9
No. of illustrations	48
No. of references	2
Abstract max. 2000 characters	The NORDUM exercise was the first joint Nordic exercise for unmanned systems. The NEXUS exercise further expanded the challenges to urban environments, contaminated fields and scenarios for fixed wing systems. A seminar was held at the end of the field activities such that teams had a chance to present their results, discuss challenges and successes, and present future plans. The Nordic countries have a growing competence in radiation measurements utilizing unmanned aircraft systems. This NKS activity have strongly benefited the Nordic exchange and growth of knowledge and experiences in the topic. The use of fixed wing platforms was tested and demonstrated briefly. The use of fixed wing UAV platforms could fill a gap between rotary wing UAS and full scale fixed wing systems in surveying larger areas. The use of unmanned measurements in urban environments was tested and demonstrated in two scenarios, the oriental market and the 2-storey building. In particular the scenario around the 2-storey building demonstrated the 3D survey advantages with rotary wing systems.

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The capacities in the Nordic countries is still in development, but the exercise demonstrated that it is an ongoing development. This form of arrangement with an exercise in an area where the teams can see each other's approach and solutions is most inspiring for the exchange and growth of knowledge.

Key words Drone, exercise, radiation measurement, UAS, mapping