



Radiation surveillance using an unmanned aerial vehicle

Roy Pöllänen^{a,*}, Harri Toivonen^a, Kari Peräjärvi^a, Tero Karhunen^a, Tarja Ilander^a, Jukka Lehtinen^b, Kimmo Rintala^c, Tuure Katajainen^c, Jarkko Niemelä^c, Marko Juusela^c

^a STUK-Radiation and Nuclear Safety Authority, P.O. Box 14, FI-00881, Finland

^b Senya Ltd. Rekitie 7A, 00950 Helsinki, Finland

^c Patria Systems Oy, Naulakatu 3, FI-33100, Finland

ARTICLE INFO

Article history:

Received 9 June 2008

Received in revised form

10 October 2008

Accepted 16 October 2008

Keywords:

Unmanned aerial vehicle

Radiation surveillance

Air sampling

Dose rate

Alpha spectrometry

Gamma-ray spectrometry

¹³⁷Cs

¹⁹²Ir

ABSTRACT

Radiation surveillance equipment was mounted in a small unmanned aerial vehicle. The equipment consists of a commercial CsI detector for count rate measurement and a specially designed sampling unit for airborne radioactive particles. Field and flight tests were performed for the CsI detector in the area where ¹³⁷Cs fallout from the Chernobyl accident is 23–45 kBq m⁻². A 3-GBq ¹³⁷Cs point source could be detected at the altitude of 50 m using a flight speed of 70 km h⁻¹ and data acquisition interval of 1 s. Respective response for ¹⁹²Ir point source is 1 GBq. During the flight, the detector reacts fast to ambient external dose rate rise of 0.1 μSv h⁻¹, which gives for the activity concentration of ¹³¹I less than 1 kBq m⁻³. Operation of the sampler equipped with different type of filters was investigated using wind-tunnel experiments and field tests with the aid of radon progeny. Air flow rate through the sampler is 0.2–0.7 m³ h⁻¹ at a flight speed of 70 km h⁻¹ depending on the filter type in question. The tests showed that the sampler is able to collect airborne radioactive particles. Minimum detectable concentration for transuranium nuclides, such as ²³⁹Pu, is of the order of 0.2 Bq m⁻³ or less when alpha spectrometry with no radiochemical sample processing is used for activity determination immediately after the flight. When a gamma-ray spectrometer is used, minimum detectable concentrations for several fission products such as ¹³⁷Cs and ¹³¹I are of the order of 1 Bq m⁻³.

© 2008 Elsevier Ltd. All rights reserved.

1. Introduction

In a nuclear accident or in the aftermath of criminal actions radioactive materials may pose a severe health threat to individuals near the site of the incident. In these cases, rapid and extensive environmental radiation surveillance using mobile equipment is crucial to facilitate effective and timely countermeasures.

Several organisations responsible for radiation detection and protection have developed different types of mobile radiation surveillance equipment. These are typically mounted in a car or other ground-based platform, a helicopter, an aeroplane etc. Well-trained crew is usually necessary to operate the system. However, the crew may be exposed to ionising radiation which in the worst case may even prohibit the measurements (Kurvinen et al., 2005). In addition, possible contamination of the equipment may hinder their future use.

Small-size unmanned aerial vehicles (UAVs) may serve an appropriate platform for wide-area measurements in a nuclear or radiation incident. Costs of their procurement, maintenance and operation are small compared with those of manned aircraft.

Since the operator may remain in uncontaminated areas the risk of exposure to ionising radiation is minimal. This also means that a UAV should be able to stay in the contaminated area longer than a manned vehicle, and thus more detailed analyses of the plume can be performed.

Recent development in radiation detection and data management as well as modern solutions in aviation technology makes the exploitation of UAVs in different environmental applications possible. Unfortunately, the availability of low-cost commercial instrumentation to detect ionising radiation, and which may be used in a UAV, is limited. In the present paper we introduce a concept to detect radiation in the environment and to take samples from air using a small-size UAV as a platform. We show that the equipment is capable to locate high-active sources on the ground and to sample airborne radioactive particles.

2. Equipment for radiation surveillance

2.1. Mini-UAV

Patria mini-UAV (MASS, modular airborne sensor system; Fig. 1) is a modular multi-mission airborne sensor system capable of performing operations from reconnaissance to CBRN

* Corresponding author. Tel.: +358 9 75988425; fax: +358 9 75988433.

E-mail address: roy.pollanen@stuk.fi (R. Pöllänen).

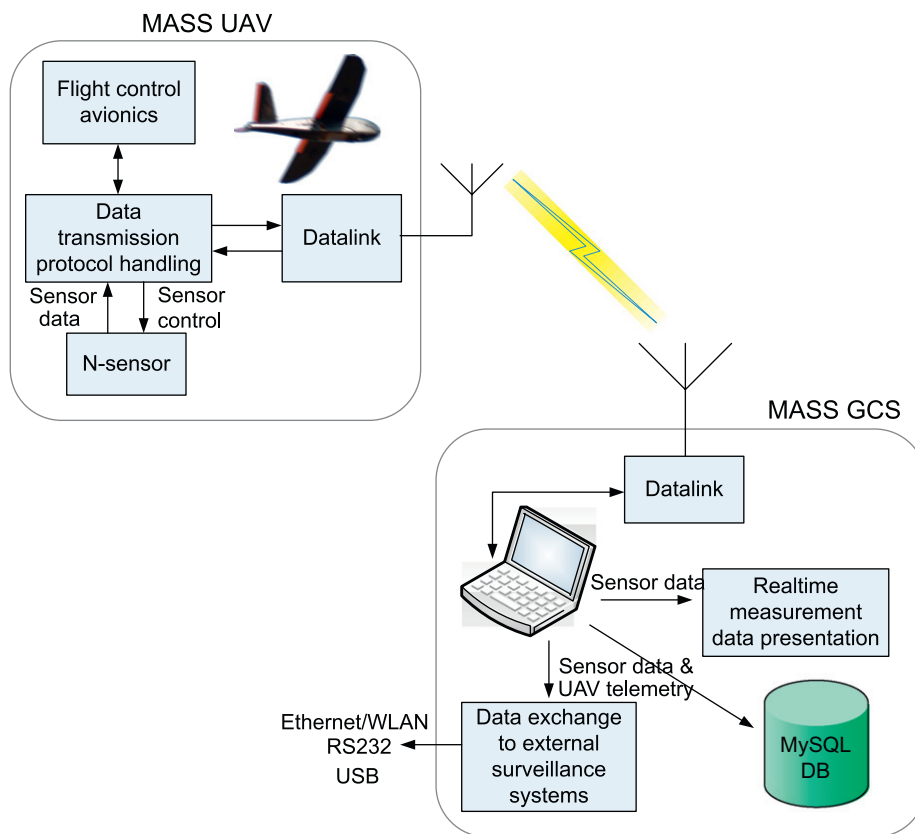


Fig. 1. Data flow in the mini-UAV and the ground control station (GCS).

(chemical, biological, radiological, nuclear) surveillance. The system consists of 1–3 UAV's with multiple payload options. The system also includes communications suite, a ground control station with ruggedized laptop-PC, a telescopic antenna mast and launching equipment. The UAV functions fully autonomously and the system can be operated by one person with no aircraft piloting skills needed. Operating time of the UAV is over 1 h with operating range of 10–20 km. Optimal cruise speed is 60 km h⁻¹ and flight altitude 50–150 m. The UAV can carry payloads for up to 0.5 kg.

The communications suite allows the operator to supervise and control the flying vehicle during the mission. The payload's data can be monitored in real time during the flight. In the case of radiation detector payload, the measured data is first framed with data transmission protocol and then transmitted via the UAV's datalink to the ground control station where it is checked for data transmission errors and presented in real time to the UAV operator. The data with appropriate UAV telemetry information is saved to a MySQL database for later exploitation.

2.2. The detector

A commercial handheld radiation detector with a cylindrical CsI probe of volume 5 cm³, diameter 13 mm, length 38 mm and equipped with a photodiode was mounted to the UAV. All measurements were done in 1-s intervals (0.6 s dead-time between the intervals) and the readings (i.e., counts per second, cps) were later converted to the external dose rate. Flight tests in addition to the ground tests were performed for the detector.

Measurements in the ground were made to determine the response (cps per GBq) of the detector as a function of source-to-detector distance. In addition, the detector response at varying temperature and electric/magnetic field was studied. Short-term variation in the count rate was detected when the temperature of

the detector is changing rapidly. Weak electromagnetic fields had no effect on the observed count rates.

External dose rate calculation is done in the ground control station using the equation

$$\dot{D}(\text{cps}) = a(\text{cps} - b) + c,$$

where cps is the measured count rate, $a = 0.00589$, $b = 2.48$ and $c = 0.043$. This equation was obtained from the calibrations. When the count rate is less than 2.48, the dose rate is set to 0.043 $\mu\text{Sv h}^{-1}$ which is the ambient dose rate on the sea level in Finland caused by cosmic radiation. This equation gives good dose rate estimation in a radiation field dominated by ¹³⁷Cs. For other nuclides the discrepancy may be up to 50%.

2.3. The sampling unit

The low-weight sampling unit located above the UAV (Fig. 2) is designed to minimise the drag force caused by the sampler and to maximise the flow rate through the unit (Peräjärvi et al., 2008). No external pump is needed to collect a sample. The filter cannot be changed during a radiation surveillance mission. After the mission the sample is readily available for *in-situ* analyses such as gamma-ray spectrometry or alpha spectrometry.

Dimensioning of the sampler was performed using the computational fluid dynamics code FLUENT 6.3 (Fig. 3). The sampler was developed for a filter of 47 mm in diameter and for the flight speed of 70–120 km h⁻¹. Petrianov, Fluoropore and Camfil A500G were the filters used in the simulations and tests (see Peräjärvi et al., 2008). Wind tunnel was used to verify the flow rates through the filters. For example, in the case of Fluoropore filter the flow rate through the filter at the optimum flight speed is 0.2 m³ h⁻¹. This number is by a factor of 3 higher for Petrianov. The effect of the angle of incidence of the flow was also

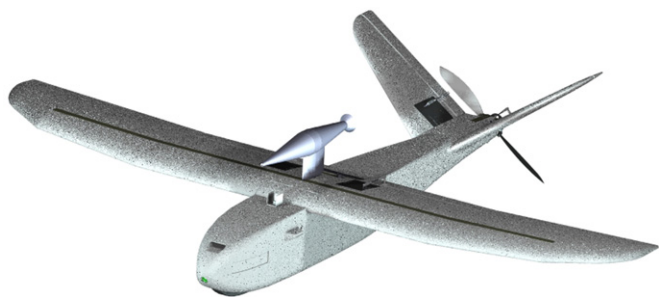


Fig. 2. Mini-UAV equipped with a sampling unit.

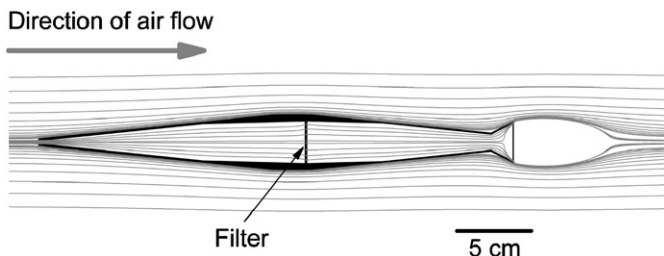


Fig. 3. Simulated streamlines around the sampler at the air flow velocity of 70 km h^{-1} .

investigated. The simulations, the wind tunnel tests and the tests performed in the field showed that when the angle is less than 20° the flow rate is reduced 15% at the flight speed of 70 km h^{-1} .

2.4. Data formats and data processing

The data from a radiation surveillance mission is transferred in real-time to the ground control station equipped with MySQL database. Data formats are designed to be generic (XML) and they do not depend on the detector type used in the UAV. In addition, the structure of the database supports online mapping and fast analysis of the data. The measurement data can be transferred to other systems for further analyses using the XML-format but copying the database (MySQL dump file) is also possible.

Two types of data are in the database. The static data are updated only in the beginning of each mission whereas the data from the measurements with geographic information are continuously updated. Static data describe the mission in question, the devices (i.e., detectors, samplers, etc.) used in the mission and the alarm limits in a specified region-of-interest (ROI) of the spectrum. The varying real time data consist of the measurement data and geographic information attached to it, ROI data and sampling data. For the future use, additional tables were defined for hypothesis testing (i.e., calculation of the peak significance) from spectral data.

Measurement data and geographic information are connected with unique primary keys. Calculation of the dose rate, as well as the sampled air volume, is performed in the ground control station where the time series data (cps and moving average of the measurements) with preselected alarm limits can be plotted on screen.

3. Results of the flight and field tests

3.1. Flight tests of the CsI detector

Flight tests of the CsI radiation detector mounted in the mini-UAV were performed in Jämijärvi airfield, Finland, using ^{137}Cs

Table 1

Background count rate as a function of altitude measured by the CsI detector.

Altitude (m)	$\langle \text{cps} \rangle$	σ_{cps}
0.3	29	5.5
45–55	18	4.2
85–95	15	4.0
95–105	15	4.0
105–115	14	3.8
145–155	11	3.0
155–165	10	2.9
195–205	8	2.8

Second column represents the mean count rate and third column its standard deviation, σ_{cps} . The ambient dose rate at the ground level is $0.2 \mu\text{Sv h}^{-1}$.

(activity 3 GBq) and ^{192}Ir (0.64 GBq) point sources. In the test area the ^{137}Cs fallout from the Chernobyl accident was $23\text{--}45 \text{ kBq m}^{-2}$ (Arvela et al., 1990). Background radiation levels were registered as a function of altitude (Table 1) before the point source tests.

The detection limits of different radionuclides in air can be estimated assuming that the rise of the count rate is due to the presence of gamma-emitting artificial radionuclides. As reported in Table 1, the background count rate at the altitudes of $150\text{--}200 \text{ m}$ is $11\text{--}8 \text{ s}^{-1}$ with standard deviation $\sigma_{\text{cps}} < 3 \text{ s}^{-1}$. At these altitudes neither the local variation of the ^{137}Cs fallout nor the variations of naturally occurring radionuclides in the soil cause significant contribution to the detected count rates. If the count rate rises for example $5 \times \sigma_{\text{cps}} = 15 \text{ s}^{-1}$ or more, i.e., total count rate is $> 23 \text{ cps}$, this rise is caused by the presence of gamma-ray emitting radionuclides in air (false positive risk $< 10^{-6}$). The count rate rise of 15 s^{-1} corresponds to the external dose rate rise of $0.1 \mu\text{Sv h}^{-1}$. Assuming that the radionuclides are homogeneously distributed in air, we can use dose rate conversion factors to estimate the activity concentration of different radionuclides that would cause this dose rate. The conversion factors, i.e., dose rates per unit activity (Kocher, 1985), are appropriate for radionuclide immersion in semi-infinite air (air-ground interface), but for the sake of simplicity they are applied here. Table 2 presents minimum detectable concentrations for some important radionuclides that may be released into the atmosphere in a severe nuclear incident. The detection limits are for individual nuclides present in the air, not for their mixture.

The point sources were placed at a selected spot on the ground. Instead of the autopilot, the UAV was controlled manually. This is because of low flight altitudes (even less than 50 m) used in these tests. The measurements were started just before the take off (see Fig. 4). During the tests the UAV was first launched to the altitude of 150 m and then gradually to lower altitudes. The sources were clearly identified especially at low altitudes. Minimum detectable point source activities depend on the data acquisition time, the nuclide in question, the background radiation, the flight altitude and the horizontal distance, Δx (distance in the x -direction when the UAV is above the source, y -direction refers to the direction of flight and z -direction is the altitude), from the source (Table 3). The data acquisition time in the present study is 1 s ; no data summation is done although the database supports such mode of analysis.

3.2. Field tests of the sampler

The flow rates through the sampler for different type of filters and different flight velocities were determined from wind tunnel tests. Field tests are necessary to verify the operation of the sampler. For obvious reasons it is not possible to disperse artificial

Table 2
Activity concentration, MDC, of some radionuclides in air that would cause a dose rate rise of $0.1 \mu\text{Sv h}^{-1}$.

Nuclide	MDC (Bq m^{-3})
^{131}I	830
^{132}I	130
^{133}I	500
^{135}I	190
^{133}Xe	9000
^{135}Xe	1300
^{88}Kr	140
^{134}Cs	200
^{137}Cs	520
^{132}Te	1500

For ^{137}Cs the contribution of $^{137\text{m}}\text{Ba}$ is taken into account.

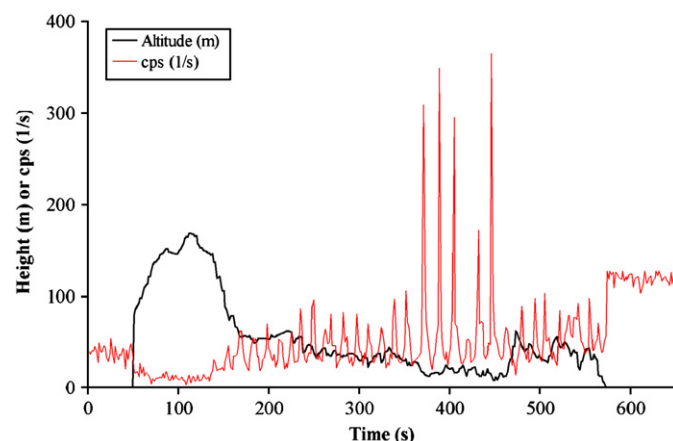


Fig. 4. Altitude of the UAV with respective cps data when detecting the ^{137}Cs point source on the ground. The peaks in the cps data arise from passing the source repeatedly. At the end of the mission, the UAV landed close to the unshielded source which led to the higher count rate (120 cps).

Table 3
Estimated minimum detectable activities for ^{137}Cs and ^{192}Ir point sources as a function of flight altitude.

Altitude (m)	Minimum detectable activity (GBq)	
	^{137}Cs	^{192}Ir
50	6.1	1.1
100	15	2.3
150	32	3.9
200	60	5.7

In this conservative estimation the low type 1 error risk is assumed (false positive risk $< 10^{-6}$, see Kuukankorpi et al., 2007) to avoid false positive signals.

radioactive materials into the air to test the sampler. In addition, if naturally occurring radon progeny is used as a marker, flight tests are not a perfect option. This is because of low radon concentrations at higher altitudes. However, radon progeny can be used for the tests performed in ground-level air.

Tested samplers were attached to a specially designed holder which is strapped in a car rack (Peräjärvi et al., 2008). The samplers were placed in free air in front of the car. A set of tests were performed in the early morning hours when the radon concentrations are highest. Alpha spectrometry with no radiochemical sample processing is used for the filters. The most important nuclide with respect to the tests is ^{214}Po although ^{218}Po , ^{212}Po and ^{212}Bi may also be detected in the alpha spectra.

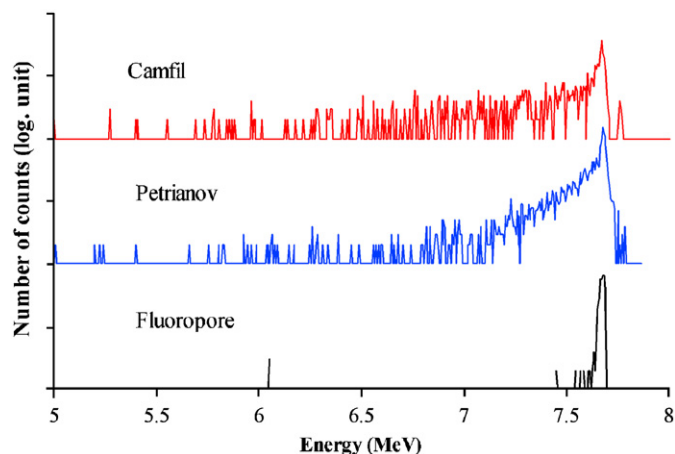


Fig. 5. Alpha spectra (5–8 MeV) measured from outdoor air samples (logarithmic y-axis scale) taken using Camfil, Petrianov and Fluoropore filters. The peak present in the spectra refers to ^{214}Po .

Table 4
Estimated minimum detectable activity concentrations for some radionuclides that may be present in outdoor air in a nuclear incident.

Nuclide	Minimum detectable activity concentration (Bq m^{-3})	
	α Spectrometry	γ -Ray spectrometry
^{239}Pu	0.13	–
^{241}Am	0.15	1.8
^{134}Cs	–	0.39
^{137}Cs	–	0.51
^{131}I	–	0.39

The filtration efficiency of the nuclides was assumed to be 100%.

The tests revealed that the designed sampler is able to collect airborne radioactive particles. Measured results coincide well with those obtained from the simulations and wind tunnel measurements (Peräjärvi et al., 2008). The use of Fluoropore (or similar type of) filter is recommended for the sampling especially when direct alpha spectrometry is used for the analysis. This is because radioactive particles do not penetrate deep into the filter and, consequently, narrow peaks are produced in the alpha spectrum (Fig. 5).

Identification of the radionuclides and determination of their activities in the sample are necessary to evaluate internal radiation doses. Minimum detectable activity concentrations (MDCs) were estimated for some important radionuclides that may be released into the atmosphere in a nuclear incident (Table 4). Alpha spectrometry and gamma-ray spectrometry were the detection methods assumed for the Fluoropore filter. The flow rate through the filter is assumed to be $0.2 \text{ m}^3 \text{ h}^{-1}$ and the activity concentrations were assumed to be constant during the sampling. Sampling time was assumed to be 1 h, decay time between the end of the sampling and beginning of the data acquisition was assumed to be 5 min and the measurement time 1 h. Short decay time of 5 min implies that the spectrometers are readily available, e.g., in a vehicle (Smolander et al., 2005), after the landing of the UAV. To avoid too optimistic figures the amount of naturally occurring nuclides in outdoor air was assumed to be same as that prevailing in typical ground level air.

For alpha-particle emitting radionuclides the MDCs were estimated using the method presented by Pöllänen and Siiskonen (2006). A high-resolution PIPS alpha detector of diameter 450 mm^2 , a filter of diameter 37 mm and a filter-to-detector distance of 5 mm were assumed in the calculation (Table 4). For

gamma-ray emitting radionuclides the MDCs were estimated assuming an HPGe detector of relative efficiency 38% and background typical in a laboratory. However, detection limits depend strongly on the nuclide and detector type in question, background shielding, measurement geometry, etc. In the present case the background is dominated by the nuclides present in the sample. Nevertheless, ^{238}U series radionuclides, ^{214}Pb and ^{214}Bi were detected in the gamma-ray spectra.

4. Conclusions and discussion

Radiation surveillance instrumentation, i.e., a CsI detector and a sampling unit for airborne radioactive substances, were mounted in the mini-UAV. Field and flight tests showed that the equipment is functioning as designed.

Operation of the radiation detector was tested using different unshielded sources. The equipment can easily detect unshielded ^{137}Cs and ^{192}Ir point sources whose activities correspond to those mentioned in the HASS directive (2003). HASS-values for ^{137}Cs and ^{192}Ir are 20 and 10 GBq, respectively. The purpose of this directive is to prevent exposure of workers and the public to ionising radiation arising from inadequate control of high-activity sealed radioactive sources and orphan sources. The equipment can also be used to detect radioactive “hot spots” on the ground but manned aircraft are better for mapping fallout in wide areas.

Minimum detectable concentrations for some important radionuclides that may be released into the atmosphere in a severe nuclear accident were estimated on the basis of external dose rate rise of $0.1 \mu\text{Sv h}^{-1}$. For example, activity concentration of ^{131}I may be detected in real time at the level of 1 kBq m^{-3} or less. This concentration is below the value that would justify iodine prophylaxis in the case of a short-term release. For other isotopes of I the detection limits are smaller.

The sampling unit was shown to collect airborne radioactive particles. Non-destructive alpha spectrometry and gamma-ray

spectrometry are the *in-situ* detection methods that may be applied for the filter samples. Using alpha spectrometry the minimum detectable activity concentrations for transuranium elements in outdoor air are less than 0.2 Bq m^{-3} . Using gamma-ray spectrometry the corresponding values for fission products are generally of the order of 1 Bq m^{-3} depending on the nuclide in question. Provided that the samples can be analysed *in-situ* these values can be obtained within two hours from the beginning of the radiation surveillance mission.

The CsI detector mounted in the UAV was operating in the cps-mode and, thus, no energy spectra were available. Lower detection limits and nuclide identification capacity are possible using a spectrometer with good energy resolution. A CZT spectrometer might be ideal for UAV reconnaissance.

References

- Arvela, H., Markkanen, M., Lemmelä, H., 1990. Mobile survey of environmental gamma radiation and fall-out levels in Finland after the Chernobyl accident. *Radiat. Prot. Dosimetry* 32, 177–184.
- Kocher, D.C., 1985. Dose-rate conversion factors for external exposure to photons and electrons. *Health Phys.* 45, 665–686.
- Kurvinen, K., Smolander, P., Pöllänen, R., Kuukankorpi, S., Lyytinen, J., Kettunen, M., 2005. Design of a radiation surveillance unit for an unmanned aerial vehicle. *J. Environ. Radioact.* 81, 1–10.
- Kuukankorpi, S., Toivonen, H., Moring, M., Smolander, P., 2007. Mobile spectrometry for source finding and prompt reporting, STUK-A224, pp. 1–50.
- Peräjärvi, K., Lehtinen, J., Pöllänen, R., Toivonen, H., 2008. Design of a sampler for a small-size unmanned aerial vehicle, submitted for publication.
- Pöllänen, R., Siiskonen, T., 2006. High-resolution alpha spectrometry under field conditions—fast identification of alpha particle emitting radionuclides from air samples. *J. Environ. Radioact.* 87, 279–288.
- Smolander, P., Kuukankorpi, S., Moring, M., Toivonen, H., 2005. Real-time mobile measurement and analysis in a radiological emergency. In: Strand, P., Børretzen, P., Jølle, T. (Eds.), *Proceedings from the 2nd International Conference on Radioactivity in the Environment*, 2–6 October 2005, Nice, France, pp. 388–391.
- The Council of the European Union, HASS 2003. Council directive 2003/122/EURATOM of 22 December 2003 on the control of high-activity sealed radioactive sources and orphan sources, Official Journal of the European Union, 31 December 2003.