HADMÉRNÖK

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PRELIMINARY STUDY ON THE DETECTION OF RADIOACTIVITY WITH AIRBORNE REMOTE SENSING SYSTEMS

Abstract

This article presents the preliminary study done on the detection of radioactivity with remote sensing systems. It aims at identifying R&D possibilities for the development of the Hungarian nuclear reconnaissance system. First a description about the theoretical basis of ionizing radiations and their detection with sensors is provided. Then a review and analysis of the existing systems is done, leading to conclusions regarding the possible ways for re-use, technology transfers and improvements. A last part explores how alternative technologies (hyperspectral imaging in NVIR, thermal IR and LiDAR) could be integrated to nuclear reconnaissance systems and what would be the added values.

Ez a cikk előzetes tanulmány a radioaktivitás mérésének módszereiről légi távérzékelési rendszerek alkalmazásával. Célja, hogy K+F lehetőségeket határozzunk meg a hazai nukleáris felderítő rendszerről. Elsőször leírást adunk a ionizáló sugárzás elméleti alapjairól és szenzorokkal történő érzékeléséről. Ezután ismertetjük és elemezzük a már létező rendszereket, hogy ezáltal következtetni tudjunk a lehetséges újrahasznosítás, technológia transzfer és továbbfejlesztés módjairól. Az utolsó részben megvizsgáljuk, alternatív technológiákat (hiperspekrális, termális, LiDAR) hogyan tudnánk integrálni a nukleáris felismerő rendszerekbe, és melyek lennének a hozzáadott értékek.

Keywords: *ionizing radiation, radiological material, radioactivity, airborne nuclear reconnaissance, airborne radiation detection, aerial gamma spectrometry, hyperspectral imaging ~ ionizáló sugárzás, radioaktív anyagok, radioaktivitás, légi nukleáris felderítés, légi sugárzás észlelése, légi gamma spektrometria, hiperspektrális képalkotás*

INTRODUCTION

The tragic Fukushima Daiichi nuclear disaster remembered us that even if our society has reached a high technology development risks and vulnerability still exist. In the last decade the number of extreme phenomenon and environmental catastrophes increased in the world with the risk to impact nuclear sites. The nuclear installations are also getting older, requiring maintenance and expenses in a tighter economical context. In civil industry, the increase of nuclear source uses for medical, engineering and food industry associated with a permissive regulation has led to an increase of source losses and an associated danger of contamination. The risk of terrorist attack also exists. Even if regulations are adapted to minimize the risks, risk zero does not exist and preparedness is a must. A military detection system was already developed in Hungary but it does not offer all the flexibility expected for catastrophe management. First, the acquisition of information is only oriented towards the measurement of radioactivity whereas information about the status of infrastructure and environment are necessary for a catastrophe management. Secondly the reconnaissance system must be operated a low altitude (the optimal altitude above ground is 100 m) which requires numerous flight lines and consequently increase the time to operate and the costs. Another trend in airborne data acquisition is the use of UAV technologies and platforms in order to reduce the operational costs. The technological transfer of radiation detection system into UAV platform is another important R&D objective of this study. Further R&D will help to make this reconnaissance system less costly and increase our capacity to cope with nuclear disaster management.

OBJECTIVES OF THE PRELIMINARY STUDY, SCIENTIFIC QUESTIONS AND EXPECTED RESULTS.

The present study aims at answering to several scientific questions in relation with the detection of ionizing radiations and the further development of the existing Hungarian airborne nuclear reconnaissance system.

The first objective is to provide a comprehensive view on ionizing radiations, to characterize them and their interactions with matter. This part answers to the questions: *what are the different types of ionizing radiations, what are their physical characteristics and how do they interact with matter?*

A second objective aims at providing a comprehensive view on the detection of radiations with the review of the existing sensors. This part deals with the fundamental questions which follow: w*hat are the different types of sensors? What is their working principle? How are ionizing radiations detected or measured?* Once these fundamental questions are answered, we are able to understand how the reconnaissance systems work and to enter the next part of the study.

Next objective is to review some existing reconnaissance systems and provide the reader with relevant and critical information. Additionally to the question that *what exists*, we aim at discovering *what can be re-use, potentially transferred or improved? and what should be developed?* Our final objective (and results) is to formulate general research and development objectives.

Taking into consideration the development possibilities and lacks identified with detection systems, alternative sensors are finally presented and analyzed. It aims at identifying if some remote sensing technologies could fill the gap identified in the previous part and concluding about their potential and future use in the R&D process.

Characterization of ionizing radiations

We are interested to describe ionizing radiations first with their origin, secondly their physical characteristics and last their interaction with matter.

General definition: Ionizing radiation is radiation composed of particles that individually carry enough energy to liberate an electron from an atom or molecule. This involves the ejection of an orbital electron, resulting in the creation of an ion pair.

$X \rightarrow X^+ + e^-$ (generic formula for single ionization)

Ionizing radiation includes cosmic rays, alpha, beta and gamma rays, X-rays, and in general any charged particle moving at relativistic speeds. In the present study we consider ionizing radiations generated through nuclear reactions, either artificial or natural.

The different types of ionizing radiations: Radiations can be grouped into directly ionizing radiations and indirectly ionizing radiations (Tab.1). Directly ionizing radiations include all charged particles such as alpha particles, beta particles and heavier ions. All charged particle radiations lose energy interaction with the orbital electrons or nuclei of atoms in the materials they traverse. Indirectly ionizing radiations include some types of electromagnetic radiations and neutrons. These radiations interact with matter by giving rise to secondary radiation which is ionizing. Indirectly ionizing radiations lose energy by collisions with electrons, or atomic nuclei, and the charged particles thus set in motion interact in turn with the orbital electrons or nuclei [1].

Tab. 1. Main ionizing radiations and their characteristics

Type of radiation		**Ionizing radiation**	**Elementary charge**	**Mass (MeV/c^2)**
Electromagnetic radiation	Indirectly ionizing	ultraviolet	0	0
		X ray		
		Gamma Ray		
Particles		Neutron	0	940
	Directly ionizing	Electron / particle β-	-1	0.511
		Positon / particle β+	+1	0.511
		Muon	-1	106
		Proton	+1	938
		Ion 4He / particle α	+2	3730
		Ion 12C	+6	11193
		Other ions	Variable	Variable

Photons

Photons interact electromagnetically with charged particles. Photons of sufficiently high energy are ionizing. The only difference is the frequency and hence the energy of those photons. The energy at which photons can generate ionization begins to happen in the high-frequency end of the ultraviolet (UV) region of the electromagnetic spectrum, consequently most UV is not ionizing.

Gamma radiation is part of the electromagnetic spectrum. Gamma rays travel at the speed of light (c), and have a discreet energy (E), frequency (f), and wave length (λ). These are related by: $E = hf = hc/\lambda$. Gamma rays are generally the most energetic of radiation of high frequency, with frequencies above 10 exahertz (or >1019 Hz), and therefore have energies above 100 KeV. They are classically produced by the decay from high energy states of atomic nuclei (gamma decay).

Gamma rays interact with atoms of matter by three principal processes: the photoelectric effect, Compton scattering, and pair production [1].

Photoelectric effect. This describes the case in which a gamma photon interacts with and transfers all its energy to an atomic electron, causing the ejection of that electron from the atom. The kinetic energy of the resulting photoelectron is equal to the energy of the incident gamma photon minus the energy that originally bound the electron to the atom (binding energy). The

photoelectric effect is the dominant energy transfer mechanism for X-ray and gamma ray photons with energies below 50 KeV, but it is much less important at higher energies.

Compton scattering. This is an interaction in which an incident gamma photon loses enough energy to an atomic electron to cause its ejection, with the remainder of the original photon's energy emitted as a new, lower energy gamma photon whose emission direction is different from that of the incident gamma photon, hence the term "scattering". The probability of Compton scattering decreases with increasing photon energy. Compton scattering is thought to be the principal absorption mechanism for gamma rays in the intermediate energy range 100 KeV to 10 MeV. Compton scattering is relatively independent of the atomic number of the absorbing material, which is why very dense materials like lead are only modestly better shields, on a per weight basis, than are less dense materials.

Pair production. This becomes possible with gamma energies exceeding 1.02 MeV, and becomes important as an absorption mechanism at energies over 5 MeV. By interaction with the electric field of a nucleus, the energy of the incident photon is converted into the mass of an electron-positron pair. Any gamma energy in excess of the equivalent rest mass of the two particles (totaling at least 1.02 MeV) appears as the kinetic energy of the pair and in the recoil of the emitting nucleus. At the end of the positron's range, it combines with a free electron, and the two annihilate, and the entire mass of these two is then converted into two gamma photons of at least 0.51 MeV energy each (or higher according to the kinetic energy of the annihilated particles).

The secondary electrons (and/or positrons) produced in any of these three processes frequently have enough energy to produce much ionization themselves.

The probability that a photon will interact with matter, expressed by the cross-section σ (m2), depends on the photon energy, E, and the composition of the matter. Fig. 1 illustrates the relationship between the scattering and absorption processes, the energy of the incident photon, and the atomic number of the absorbing medium.

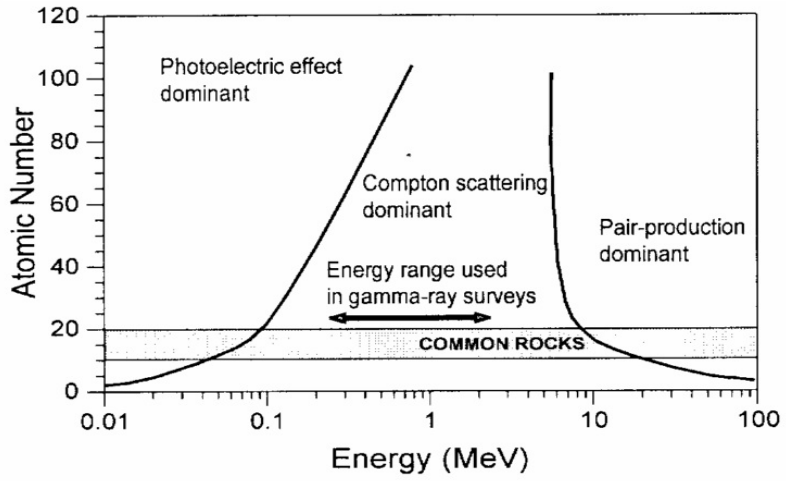


Fig.1. Dominant effect depending on the atomic number of absorbing medium and incident photon energy (source IAEA)

For gamma rays of natural terrestrial origin (energy up to 2.615 MeV) and for matter comprising rock, water and air, Compton scattering is the dominant interaction process. Typically, gamma ray photons lose energy through successive Compton scattering events, until eventually the resulting low-energy photons are absorbed through the photoelectric effect. As a result of the interaction of gamma rays with matter, the intensity of radiation decreases with distance from the source. The absorption of gamma rays of a specific energy in matter is described by either a linear attenuation coefficients μ (m^{-1}) or a mass attenuation coefficient μ/ρ (m^2/kg). For a narrow beam of gamma rays, the attenuation of the gamma rays can be modeled

by an exponential function. The range of gamma rays of natural radionuclide is about 700 m in air, up to 0.5 m in rocks and a few cm in lead. Gamma rays have a discrete energy that is specific for a particular radionuclide. Since gamma rays are the most penetrating component of natural and man-made radiation, they are widely used in the study of the radiation environment, in AGS (Airborne Gamma Spectrometry) for example.

Charged particles

Charged particles such as electrons, positrons, protons, alpha particles and beta particles also interact electromagnetically with electrons of an atom or molecule, and all may cause ionization.

Alpha decay is accompanied by the release of an alpha particle consisting of 2 protons and 2 neutrons [1]. Alpha radiation is a flux of positively charged alpha particles.

$^{A}X \rightarrow ^{A-4}Y + \alpha$ (alpha emission), $ZY = ZX - 2$

Alpha particles have an initial energy of several MeV, and an initial velocity of the order 107 m/s. They exhibit high ionization, and their penetration range in matter is low. Alpha particles are absorbed by about 10^{-2} m of air, and 10^{-5} m of rock. Alpha particles have a discrete energy that is specific for a particular radionuclide [2].

Beta- decay is realized by the emission of a beta particle identical to a negatively charged electron.

$AX \rightarrow AY + \beta$ (beta- emission), $ZY = ZX + 1$

Beta radiation is a flux of electrons with a continuous energy spectrum up to a maximum energy, which depends on the particular radionuclide. The initial velocity of beta particles can approach the velocity of light. The penetration range for beta particles depends on the initial energy of the particle. For E=2 MeV, the penetration range is about 8 m in air and 1 cm in water. Beta radiation passing through matter loses its energy by ionization and generates electromagnetic radiation called bremsstrahlung. Positrons passing through matter combine with electrons, and generate two annihilation gamma quanta of energy 511 KeV each [2].

Beta+ decay, which is less frequent, is accompanied by the emission of a positively charged positron. Electron capture occurs through the absorption of an orbital electron of an atom by the atomic nucleus. The replacement of the vacant electron position is followed by the emission of characteristic radiation (electromagnetic radiation of low energy).

$^{A}X \rightarrow ^{A}Y$ + photon (electron capture), $ZY = ZX - 1$

Spontaneous fission occurs through the splitting of heavy atoms into two fragments and the subsequent release of neutrons and energy. The decay of a radionuclide usually leaves the newly formed nucleus in an energy excited state, and the surplus energy is radiated as gamma rays [2].

Neutrons

As a result of nuclear fission or nuclear fusion, it consists of the release of free neutrons from atoms, and these free neutrons react with nuclei of other atoms to form new isotopes, which, in turn, may produce radiation. Neutrons -having zero electrical charge- do not interact electromagnetically with electrons, and so they cannot directly cause ionization by this mechanism. However, fast neutrons will interact with the protons in hydrogen, and this mechanism produces proton radiation (fast protons). These protons are ionizing because they are of high energy, are charged, and interact with the electrons in matter. A neutron can also interact with other atomic nuclei, depending on the nucleus and the neutron's velocity; these reactions happen with fast neutrons and slow neutrons, depending on the situation. Neutron interactions with most types of matter in this manner usually produce radioactive nuclei, which produce ionizing radiation when they decay (called neutron activation).

Neutron radiation is the only type of radiation that can make matter radioactive.

RADIATION DETECTORS USED IN AERIAL GAMMA SPECTROMETRY

This chapter describes the sensors commonly used in airborne remote sensing of radioactivity.

Ionizing radiation cannot be detected by any of the human senses. Consequently special instruments have to be used. Ionizing radiation can be measured through the physical and chemical effects of its interaction with matter. Field and laboratory methods are based mainly on the ionizing properties of radiation and the use of instruments that convert the radiation to electrical signals [1,2]. The aerial remote sensing of environmental radioactivity is achieved only through the detection of gamma radiation because gamma rays can penetrate the air and be absorbed by an airborne sensor.

Individual radionuclide emits gamma rays of specific energies that are characteristic for an element and isotope. Gamma ray measurements can be conducted in two modes [1].

Total count measurements register gamma rays of all energies and can be used to estimate the overall radiation level. These are used to monitor the gross level of the gamma radiation field and to detect the presence of anomalous sources. Total count instruments have an energy discrimination threshold above which all gamma rays are recorded. Any change in the energy discrimination threshold will affect the response of the instrument [3]. Total count measurements are performed by Geiger-Muller counter for example.

Spectrometers, on the other hand, measure both the intensity and energy of radiation, and this enables the source of the radiation to be diagnosed. Gamma ray spectrometry is thus a powerful tool for monitoring the radiation environment [1]. NaI(Tl) scintillator counters are the sensors the most commonly use for this application.

Describing the detectors, some significant parameters have to be considered. According to Solymosi, they are:

- sensitivity: counting rate per unit dose rate,
- linearity: counting rate as a function of dose rate,
- energy resolution: sensitivity as a function of energy of gamma-radiation,
- temperature dependence: sensitivity as a function of temperature,
- dead time: time interval, while the detector can not detect any interaction (this is related to linearity) [3].

The efficiency of a detector is a measure of the probability that an incident photon will be absorbed in the detector. It is usually quoted as the ratio of recorded counts to incident photons. The energy resolution of a detector is a measure of its ability to distinguish between two gamma rays of only slightly different energies. This is usually defined as the full width of a photo peak at half the maximum amplitude (FWHM) divided by its energy. Instruments used in in-situ gamma ray spectrometry are usually specified by the energy resolution of the 137Cs photo peak at 662 KeV. Dead time refers to the finite time required for a detector to process an individual particle of radiation. During this time all incoming pulses are ignored. Dead time should be as small as possible [2].

A Geiger-Muller counter (GM counter) consists of a gas-filled tube equipped with a metal cylinder (the cathode) and a thin conductive wire (the anode) mounted along the tube axis (Fig. 2.). GM counters are 2 to 30 cm long and 1 to 4 cm in diameter, and they operate with applied voltage of several hundred volts. GM counters make use of the progressive growth of ionization in a strong electric field between the anode and the cathode. An incident photon interacts with the cathode and releases an electron that may be directed into the GM tube. The growth of ionization between the anode and the cathode amplifies the signal and generates an electric current between the electrodes. This results in a voltage pulse at the anode output of the GM counter. The multiplication coefficient of the gas ionizing chain reaction is of the order of 106, and the output pulse is not proportional to the absorbed gamma ray energy. The detection

efficiency of GM counters is very low (less than 2%) and the dead time is of the order 10-4 s [2].

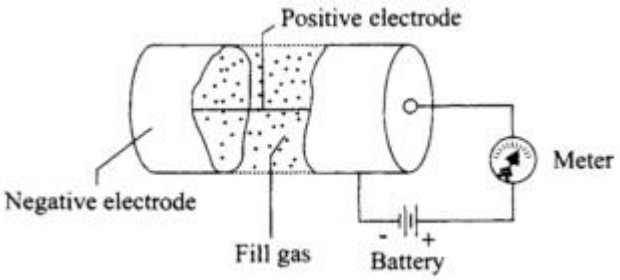


Fig. 2. Basic elements of gas-filled detector (from Valković)

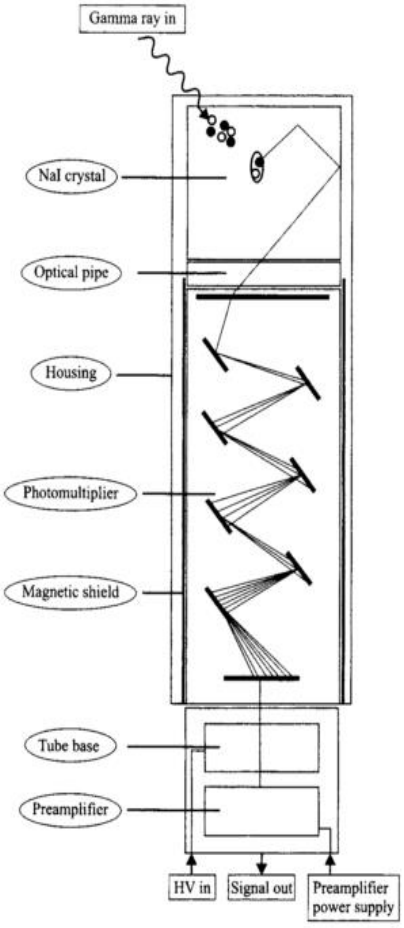


Fig. 3. Basic components and operating principle of a scintillator detector (from Valković).

Scintillation counters consist of a scintillator and a photomultiplier (Fig. 3.). Scintillation means the production of small flashes of light. Some crystals, e.g. sodium iodide (NaI) convert the ionization and excitation produced by radiation into a light pulse or scintillation. An incident gamma ray photon interacts with the material of the scintillation crystal to produce scintillations. These photons of visible light induce the ejection of electrons from the photocathode of the attached photomultiplier. Their number multiplies progressively at dynodes of the photomultiplier, and an electron cloud strikes the anode. This induces a negative voltage pulse as output, with amplitude proportional to the energy of the incident photon. Scintillation counters are widely used in gamma ray spectrometry. Thallium-activated sodium iodide NaI(Tl) crystals are mainly used as detectors in field gamma ray surveys. They have a detection efficiency of up to 100% for low-energy gamma rays but somewhat less for high-energy gamma rays. The dead time is of the order 10^{-7} s and the energy resolution for ^{137}Cs at 662 KeV is in

the range ranges 7-10%, depending on the volume and quality of the detector. NaI(Tl) detectors are hygroscopic, they age, they are fragile, and the photomultiplier tube function is dependent on temperature. Their large crystal volumes are an advantage in applications such as airborne surveying where measurement times are necessarily short. Thallium-activated cesium-iodide CsI(Tl) crystals are neither hygroscopic nor particularly fragile. They have a density of 4.51 g/cm^3, and a dead time of the order 10^{-9} s. But they are too expensive for widespread use. Bismuth-germanium-oxygen $Bi_4Ge_3O_{12}$ scintillation crystals have been applied to field gamma ray spectrometry in boreholes. Due to their high density (7.13 g/cm^3) they are efficient at high gamma ray energies [1,2].

EXISTING RECONNAISSANCE SYSTEMS AND LATEST ATTEMPTS IN RADIOACTIVITY DETECTION

This chapter reviews the reconnaissance systems existing worldwide and analyzes their capacities. The last discoveries which are not yet applied are also relevant to this study. In this respect the bibliographic research was enlarged to the last developments and attempts ongoing with ionizing radiation detection.

A summary of the reconnaissance system reviewed is provided in the table below.

Tab. 2. Summary of the review of reconnaissance systems worldwide.

Name	**Count.**	**Sensors in the system**	**Operating mode**	**Detection capacities**
LABV airborne nucelar reconnaissance system, by Gamma Zrt. [4,5] (hu1)	Hu	-BNS-98 (2s) remote dose-rate meter (GM tube); - NaI(Tl) (0.5s) crystal NDI-65/SK intelligent scintillator in plumb collimator	Helicopter (MI-24D) - uniform contamination: Speed: 150-180 km/h Altitude: 80-100 m. Coverage: 300 km2/h - Point source: Speed: 100-120 km/h Altitude: 50-60 m. Coverage: 18-20 km2/h	- Point sources: 1.5-2 times the natural ground value 2-3 times the natural ground value for radiation level - uniform activities: over 2-5 mGy/h of dose rate over 10-20 μGy/h count rate
Helinuc, By CEA [6]	Fr	-NaI crystals pack (16 L, 2s) + Exploranium GR-820 spectrometer. - 2 Ge detectors	Helicopter Speed: 70 km/h Altitude: 40m. Line spacing: 50-500 meters. Coverage: 5-10 km2/h	Detection of uniform activities and point sources. High sensitivity for detection of small quantities of radioactive materials (detection limit 10 to 120 kBq for uniform activity and 60 Mbq to 550 Gbq for point sources). Energy range: 40 KeV to 2800 KeV
[7]	Ge	- NaI(Tl)-detector array (1s) - high purity germanium-semi-conductor (HPGe) detector (60s)	Helicopter (Alouette II, EC 135) uniform activity: Altitude: 100 m. Line spacing: 500 meters.	NaI(Tl) detector → gamma dose rate. HPGe) → individual radionuclides identification Lower limit of detection for HPGe-detector for 137Cs at a flight altitude of 100 m above ground and measurement times of 60s is in the range of 2 kBq/m2.

Airborne Radiation Reconnaissance System (ARRS), by Canberra Dover (us1)	USA	- NaI Detector + AN/PDR-77 Multi-function Radiac Meter.	Helicopter	Detect, identify and locate gamma radiation from nuclear accident or attack in contaminated terrain and clouds. Detect radiation levels from natural background to maximum values from various altitudes. Measure both dose and dose rate levels of detected contamination on the ground and in clouds Identify radiation source isotopes.
[8]	Fi	CsI probe 5cm3 (1s) air sampling unit	Patria MASS mini-UAV. carry load: 0,5 kg operating time: 1h operating range: 10-20 km. altitude: 50m. Speed: 60-70 km/h	Count rate measurement. Take sample from air. Detection of high-active source. Tested in area where Cs: 23–45 kBqm-2 - 192Ir 1GBq point source detected - 137Cs 3GBq point source detected Minimum detectable concentrations for some important radionuclides (i.e. severe nuclear accident) were estimated on the basis of external dose rate rise of 0.1mSvh-1. For example, activity concentration of 131I may be detected in real time at the level of 1kBqm-3 or less. Info in real time. Acquisition of count per second converted into external dose rates.
[9]	Fi	GM, NaI(Tl) and CZT air sampling unit	Ranger UAV	Sample taking Real time transmission

The review highlight one important fact: all the existing airborne reconnaissance systems use gamma spectrometry. No system was found using any other technology or method (optical remote sensing for example).

The technical characteristics of the systems described above are congruent with the technical recommendations gathered in the IAEA guidelines for aerial gamma spectrometry [2] and show that no significant development or discovery found some application since that time. In overall the built-up, characteristics, capacities, operation mode and limitations are quite similar from one system to another. The systems can detect point source or extensive contamination, map the contamination level and identify isotopes. They are operated on helicopters at an average altitude of 100m above the ground for the detection of moderately intense radiation sources.

The main limitation identified is the low flying altitude required to measure gamma radiation, in average from 100 to 200m above ground. Another main limitation is that low penetration radiations cannot be detected and are lost for the detection process. Alpha, beta and scattered gamma are stopped by the air in the vicinity of the radioactive materials.

The main difference we could identify lies in the algorithm for the data processing and information extraction and in the real time communication of the survey result by radio system. The algorithms perform height correction using elevation data from GPS but the systems actually do not carry LiDAR sensors on board for precise altitude measurements. Several references mentioned a successful transfer of gamma spectrometry measurement technique to UAV platform (Finland, Hungary).

After the review of the existing systems, a bibliographic research was pursued on the experiments done with measurement of radioactivity with alternative methods. Only few references could be found. In 1999, Moss et al. made an interesting attempt with remote sensing

optical measurement of radioactivity [10]. The main idea of the study was to detect new molecular species generated by ionization in the surrounding of radioactive materials. Moss explored the detection possibilities of differential absorption LiDAR (DIAL) and concluded that for moderately intense sources of gamma rays and neutrons, currently available optical techniques, while sensitive, were not sensitive enough for this application. Puckrin & Theriault demonstrated that FTIR imaging can be used to identify radioactive materials but the method was not applied yet in airborne conditions [11]. According to Holma, AisaOWL (fi2) is capable to record LWIR data with high spatial and spectral resolution as well as excellent signal-to-noise characteristics [12]. According to Tuominem the development of airborne LWIR hyperspectral imagers will probably be the most significant advancement in hyperspectral technology. The use of the LWIR range (8-14 μm) enables remote identification of chemicals, radioactive materials and gases in many cases where current full-range (400-2500 nm) hyperspectral imagery fails. The use of LWIR has two benefits: atmospheric attenuation is low and many materials have distinct spectral features in the LWIR range (i.e. absorption points and reflectance peaks). But, unfortunately, hyperspectral imaging in the LWIR region is still in an early stage of development. This is true especially in airborne remote sensing, but also in industrial processes or quality control and laboratory studies [13].

It should also be noticed that if some of the reconnaissance systems are performing imaging with camera on board, none of the systems perform geo-referenced imaging, which in case of catastrophe management could be a source of relevant information for evaluating the impacts on environment, infrastructure and consequently for population.

The limitations mentioned above open research and development possibilities:

- the detection range of the aerial reconnaissance systems could be improved, with not only the measurement of gamma radiations but also the measurement of alpha and beta radiations.
- To realize the complete transfer of the detection technology to UAV platform.
- The flight altitude could be increased.
- Flight speed could be increased.
- With higher flying altitude and speed, aircraft platform could replace the helicopter.
- The automatic and real time transfer of the information to the ground.
- The acquisition of geo-referenced RGB-IR imagery.
- The acquisition and integration of accurate elevation data from LiDAR.

PRESENTATION OF HYPER SPECTRAL IMAGING TECHNOLOGY, WORKING PRINCIPLE AND AVAILABLE SENSOR:

Hyper spectral images are produced by instruments called imaging spectrometers. The spectrometers measure the energy received simultaneously in hundreds of narrow (several nm)), adjacent spectral bands. These measurements make it possible to derive a continuous spectrum for each image cell. Spectroscopy science analyzes how reflectance varies with wavelength in a spectrum. A spectrum is like a fingerprint where are appearing spectral domains of low and high reflectance as a consequence of the physico-chemical properties of the materials surveyed. By the identification of characteristic absorption or reflection patterns it is possible to determine which materials are imaged [14].

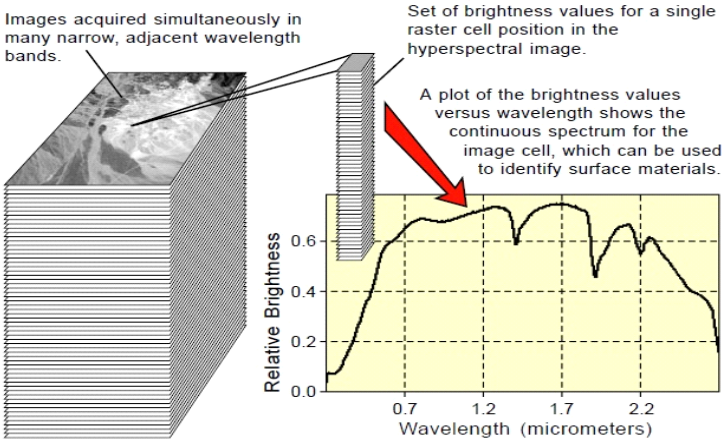


Fig. 4. General principle of hyperspectral imaging - ©MicroImages, Inc., 1999-2012

Image spectra can be compared with field or laboratory reflectance spectra in order to recognize and map surface materials such as particular types of vegetation or diagnostic minerals associated with ore deposits. Wavelength-specific absorption may also be caused by the presence of particular chemical elements or ions or the ionic charge of certain elements. Reflectance varies with wavelength for most materials because energy at certain wavelengths is scattered or absorbed to different degrees [14].

Once should distinguish the reflected light spectroscopy method where the spectral reflectance (ratio of reflected energy to incident energy as a function of wavelength) is measured and the emission spectroscopy where the electromagnetic emission from elements or chemical species are measured.

The most important characteristics of imaging spectrometers are:

- spectral range
- spectral resolution
- spatial resolution
- signal-to-noise ratio

The Tab. 3. shows a summary of the sensors owned by Karoly Robert College.

Tab. 3. Available sensors and their detection ranges

Sensor name	Sensor type	Spectral range
AISA Eagle	Hyperspectral sensor (VNIR)	400-970 nm
AISA Hawk	Hyperspectral sensor (SWIR)	970-2450 nm

The AISA Eagle and Hawk respectively cover the 400-970 nm and 970-2450 nm spectral range. Their technical characteristics differ regarding the spectral resolution: 2.9 nm for Eagle and 8.5 nm for Hawk. When used at the highest spectral resolution the dual sensor collects 498 bands in the 400-2450 nm region. Spectral binning which consists in regrouping spectral bands is possible with the two sensors and offer a stronger signal if there is a strong response in one part of the spectrum (fi1). The detailed specifications are provided in Tab. 4.

Tab.4. Technical specifications of the AISA dual hyperspectral sensor by SPECIM (fi1)

SENSOR HEAD				TYPICAL SPECIFICATIONS				
Spectral range	VNIR 400-970 nm				SWIR 970-2450 nm			
	Total 400-2450 nm							
Spectral resolution	VNIR 2.9 nm				SWIR 8.5 nm			
Spectral binning options	VNIR	none	2x	4x	SWIR	none	2x	4x
# spectral bands		244	122	60		254	127	63
Spectral sampling/band (nm)		2.3	4.6	9.2		5.8	11.6	23.2
FORE OPTICS								
Swath acquisition, option 1	See data acquisition option 1 on right							
# spatial pixels		VNIR	320		SWIR		320	
FOV			24 degrees				24 degrees	
IFOV			0.075 degrees				0.075 degrees	
Swath width			0.43 x altitude				0.43 x altitude	
Swath acquisition, option 2	See data acquisition option 2 on right							
# spatial pixels		VNIR	1024		SWIR		320	
FOV			37.7 degrees				35.5 degrees	
IFOV			0.037 degrees				0.111 degrees	
Swath width			0.68 x altitude				0.64 x altitude	

Natural color images and RGB-IR images (orthophotos) can be derived from hyper spectral imaging. This additional source of information is of high relevance for catastrophe management.

Hyperspectral imaging had demonstrated many applications in resource management, agriculture, mineral exploration, monitoring of vegetation and contamination detection. At present no application was attempted for the detection of ionizing radiations but some successful applications at the margin of our topic could be adapted to fit our specific objectives. For example Gittins & Marinelli (1998) published results on successful LWIR identification of hazardous gasses. LWIR hyperspectral imaging is also capable in identifying chemicals used in chemical warfare (Farley et al, 2006). FTIR imaging has been successfully used to identify radioactive materials [11]. Some preliminary works has been done with hyperspectral remote sensing for the identification of uranium mine tailings, Fig. 5 [15].

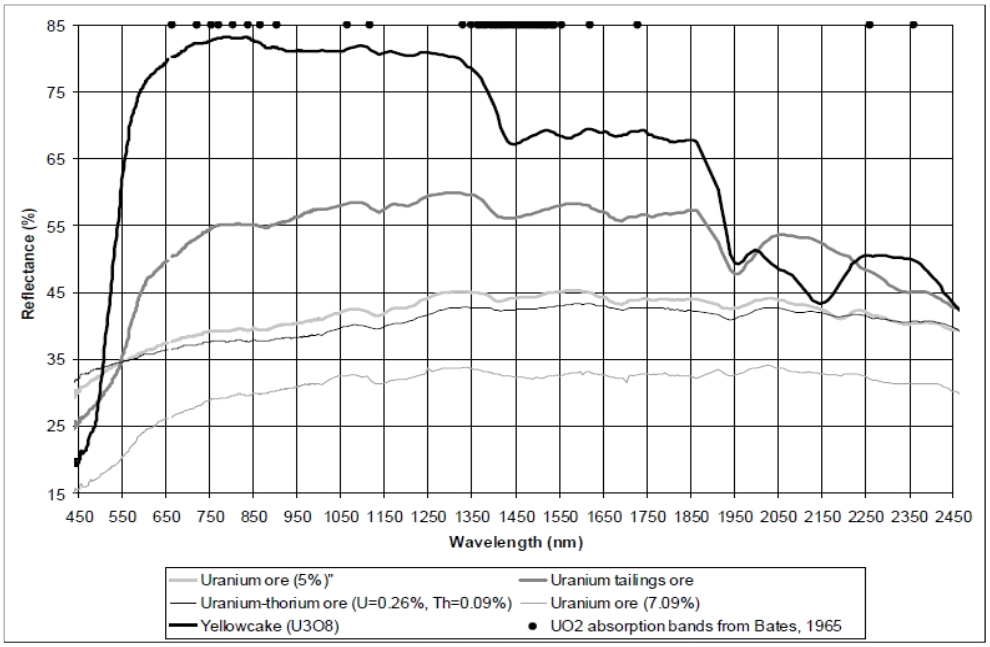


Fig. 5. Laboratory spectra of uranium compounds and the absorption bands of a UO2 crystal from Bates (1965)

The work recently done for the detection of soil contamination with the red mud catastrophe in Kolontar also shows some interesting potential with the detection of contaminant in low concentration in soil [16].

Last but not least, hyperspectral technology is evolving very quickly. The sensors developed recently have made a significant progress with signal-to-noise ratio and spectral resolution. This opens new possibilities for the detection of traces of gas and molecules [17].

STUDY ON THEORETICAL PHYSICAL BASIS

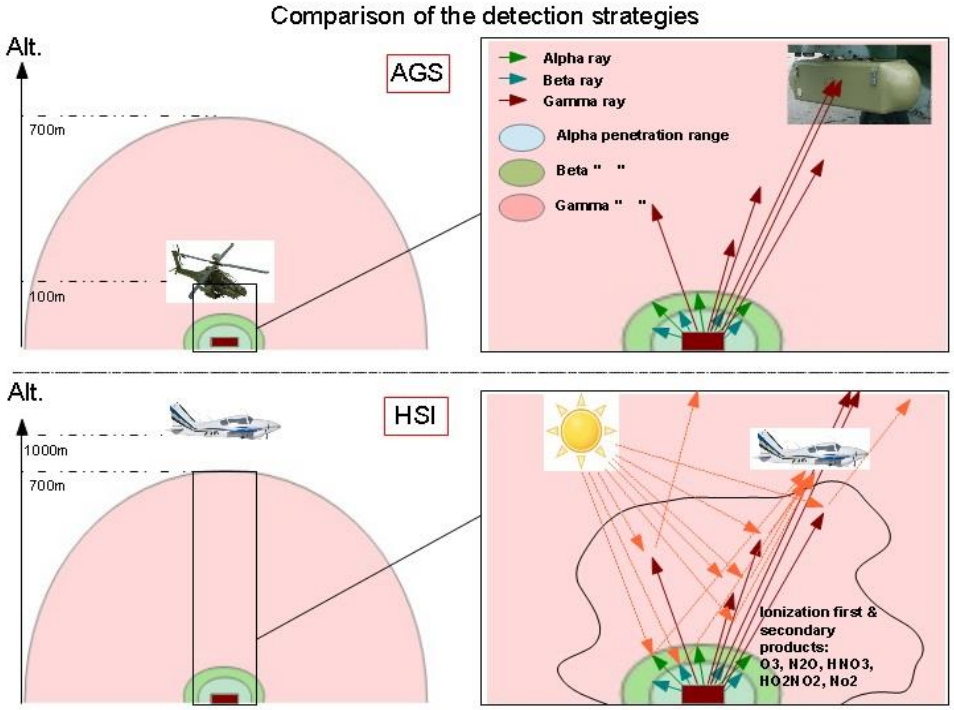
In the previous chapter we have described the general principles regarding hyperspectral technology and have introduced one sensor as an example. In the light of the additional explanations given about the ionizing radiations and their interactions with matter we are trying in this chapter to set some basis for the indirect detection of ionizing radiations with hyperspectral imaging technology.

The strategic basis

As we have seen previously, presently the aerial detection of ionizing radiation is only done with Aerial Gamma Spectrometry (AGS). This method specifically senses the high energy photons generated by the decay of radiological materials (only gamma unscattered radiation). Only photons have a sufficient penetration range to travel in the air and reach an airborne sensor. Alpha and Beta radiations which are respectively stopped by a few cm and 9 cm of air are lost for such detection process. Gamma radiation intensity decreases exponentially with altitude. Because of this reason, the sensor should be flown at an average altitude of 100-200m (with helicopter) for moderately intense radiation sources, which is a main disadvantage: it is costly and lack of flexibility as regards to the new challenges in nuclear reconnaissance.

We would like to develop a new detection method based on a different strategy. Instead of using gamma radiation detection, we would like to use an optical remote sensing approach and to detect the ions and molecules specifically generated in the air by the ionization radiations around radioactive materials. This approach would be done with reflected light spectrometry. This is an indirect measurement method, but it offers two advantages. First the effects of alpha, beta and scattered gamma radiations on matter would be sensed. The activity of radioactive materials could then be retrieved from appropriate calibration and computation. As a consequence hyperspectral imaging could be used as a complementary method. AGS and hyperspectral imaging would detect (indirectly for the sake of hyperspectral imaging) the full range of radiations in the vicinity of the radiological material and in the air from the radiological source to the sensor. Secondly, as light travel more freely in the air, the flying altitude could be increased. Puckrin have demonstrated that in the case of passive detection with FTIR, radiation can in theory be detected from an altitude of 1000m above the ground if the conditions are optimal [11]. The demonstration was made using MODTRAN4 modeling.

Fig. 6. emphasizes on the difference in the application of Airborne Gamma Spectrometry and the application of hyperspectral imaging as regard to the flight altitude, the platform used, the “objects” sensed, the medium used. It should be noticed that all the information related to the implementation of hyperspectral imaging are only hypothetical as this method was not put in practice yet.



	Airborne Gamma Spectrometry		Airborne hyper spectral imaging	
	Detected	Not detected and lost for detection process	Potentially detected	Not detected and lost for detection process
Vector	Photons (gamma)		Molecules and excited atoms	
Radiation	Gamma ray from: - unscattered gamma - neutron activation.	Alpha, beta, scattered gamma, neutron (partly) and charged particles.	Partly: alpha, beta, scattered gamma, neutron, charged particles.	Unscattered Gamma (photons of high energy not stopped by the air).
Effect on matter	X+,e-pairs creation on the crystal of the sensor.	X+,e-pairs created in the air before the sensor. Atomic excitation.	Atomic excitation. Specific species created by ionizing radiation (ions, secondary product (O3))	-
Detection range	On the crystals of the sensors. Only the photons intercepted by the sensors are counted.	On the surface of the radioactive material, in the vicinity of RA material, in the air between the ground and the sensor.	In the field of view of the sensor, i.e. in the vicinity of radioactive material in the air or on the ground.	Over the sensors (photons with high energy)
Physical effect used in the detection	Ionization and scintillation created by photons by: - photoelectric effect, - Compton scattering, - pair production.		Electromagnetic radiation emission (after de-excitation of atomic electrons), absorption and reflexion (by the product of ionization reactions).	

Fig. 6. Comparison of Airborne Gamma Spectrometry and hyperpectral imaging for the detection of ionizing radiations.

The strategy with the use of hyperspectral technology can be twofold:

- to detect the presence of products generated by ionization (molecules species) by reflected light spectrometry. The absorption and reflection patterns of the products specific to ionization reactions should then be known and identified.
- to exploit the excitation generated by the ionizing radiations, which means to measure the energy emitted by excited atoms when returning to ground state (O, N, H).

Detection of new molecular species by reflected light spectroscopy:

From the bibliographic research we know that Moss already attempted to detected ionizing radiations through the detection of new species generated by radiation with optical remote sensing method [10]. If the strategy is the same as the one we want to develop, the method differs as he used differential absorption LiDAR (DIAL) for the detection. Nevertheless Moss made an interesting exploration regarding the specific species present in the surrounding of radioactive materials. He has calculated the molar fraction as a function of time of the species formed in air by irradiation with a 60 Curie source of ^{113}Cd. The simulation was done with a gas-phase chemical kinetics code developed at the Los Alamos National Laboratory. The results of the simulation are very interesting. Instead of having ions as a product of the ionization of air (which is expected primarily from ionization), the model shows that rather secondary products are accumulated in the vicinity of the radiological materials. The model generated the following secondary products: O_3, N_2O, HNO_3, H_2NO_2, and NO_2. The second important results are the value of the molar fractions calculated by the model. They are very low, from the order of 10^{-5} to 10^{-7}. The absence of ions is probably explained by their high reactivity and very quick life time in the air. Once the specific species are theoretically known, we should explore the detection possibilities.

The classical absorption bands of ozone are the following:

- the Hartley bands between 200 and 300 nanometers in the ultraviolet, with a very intense maximum absorption at 255 nanometers. It is the strongest absorption band.
- the Huggins bands, weak absorption between 320 and 360 nanometers
- the Chappuis bands, a weak diffuse system between 375 and 650 nanometers in the visible spectrum
- the Wulf bands in the infrared beyond 700 nm, centered at 4,700, 9,600 and 14,100 nanometers, the latter being the most intense.

The figure bellow represents the absorption bands for ozone and the different domain of hyperspectral sensors.

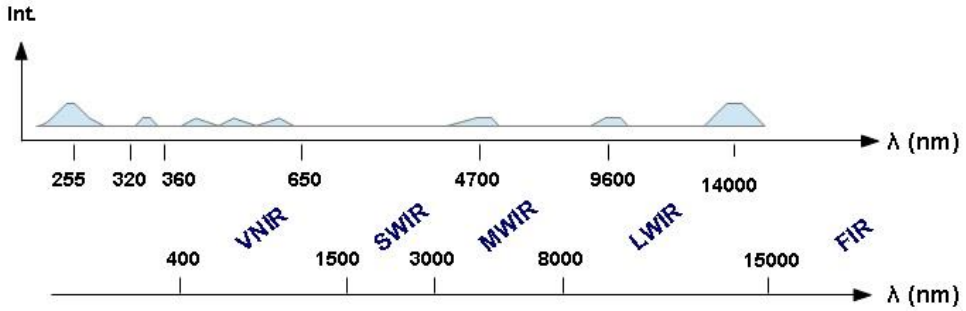


Fig. 7. Match between the absorption of ozone and the light spectrum sub-regions.

Absorption is located in the VNIR and MWIR regions. The highest potential is in the LWIR region comprising the 14100 nm band (Fig. 7.).

Regarding the other target species, additional research about their spectral signature should be done in order to know if it makes sense to try to detect them.

Electronic excitation

Regarding nitrogen, the following reactions happen:

$N_2 \rightarrow N_2^*$ $\qquad$ $N_2^* \rightarrow N_2 + hv$

References are available about the atomic emission line from spectroscopy analysis. Atomic emission spectroscopy is a method of chemical analysis used in laboratory for identifying the elements in a sample. The principle reposes on the emission of photons by excited atoms.

Fig. 8. and 9. represent the atomic emission spectrum of Nitrogen. They were elaborated from the atomic basic spectroscopic data provided by the National Institute of Standards and Technology (NIST) [18]. Only the observed strong emission lines are represented on the figure.

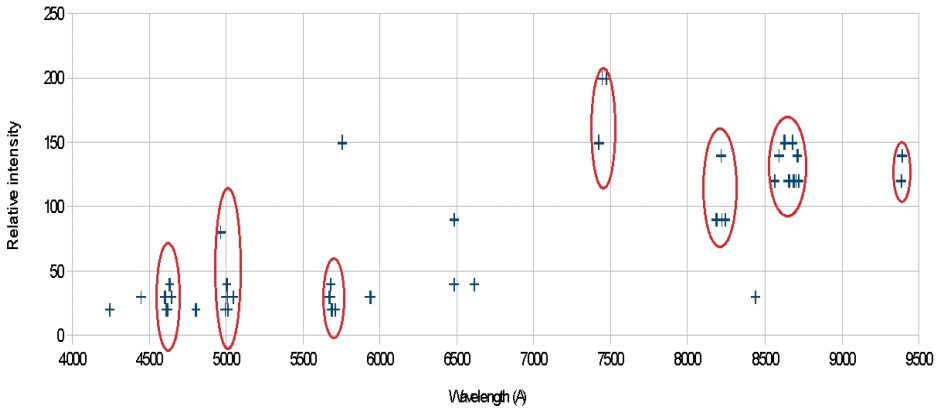


Fig. 8. Atomic emission spectrum for Nitrogen I-II in the spectral range of Eagle (4000-9500 Å).

Several spectral regions show a high density of emission lines. This is of interest for the detection with the hyperspectral sensors. In the spectral range of Eagle the 460, 500, 570, 750, 820, 870 and 940 nm regions seem promising.

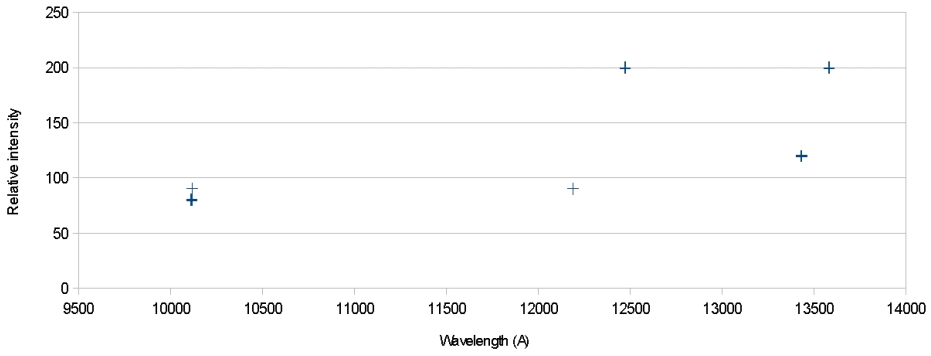


Fig. 9. Atomic emission spectrum for Nitrogen I-II in the 9500-14 000Å region.

The emission spectrum of nitrogen in the spectral range of Hawk seems quantitatively less important. Emission lines in the 1010 and 1350 nm region could offer some detection possibilities.

The excited state of oxygen is somewhat more stable than nitrogen. While de-excitation can occur by emission of photons, more probable mechanism at atmospheric pressure is a chemical reaction with other oxygen molecules, forming ozone.

$O_2 \rightarrow O_2^+ + e^-$

$O_2^+ + 2O_2 \rightarrow 2O_3$

The detection possibilities are then the same as the ones already exposed above. The creation of ozone molecule by both excitation and ionization is an interesting fact for the detection capacities as it can strengthen the absorption signal.

Limitations and problem expected with hyperspectral imaging

As mentioned, only traces of molecular species are expected in the air around the radiological materials. We wonder about the intensity of the spectral signature the sensor can detect from the specific species. The question of the relative intensity compared to the other spectral signatures (background) is a key point for the extraction of the spectrum of the specific species. If the reflectance is too weak, the atmosphere could also create too much disturbances and their spectrum could not be extractable. A last question is the spectral accuracy necessary to be sure to see the spectral signature. Is the scale of 3-4 nm sufficient or should the sensor have a sub-nanometer spectral resolution? Laboratory and field test with different sensors will try to answer these questions.

Indirect detection by measurement of anomalies and stress on vegetation.

For the sake of completeness a third strategy can be mentioned. Davids & Tyler presented results of laboratory experiments and in situ spectroradiometry measurements of silver birch (Bentula pendula) and Scots pine (Pinus sylvestris) across a range of contamination levels in the Chernobyl exclusion zone. The results were used to evaluate whether vegetation stress caused by radionuclide contamination can be detected using remote sensing techniques and whether this stress may be distinguished from vegetation stress related to variation in moisture conditions. Five different Vegetation Indices were tested. Results showed that Chlorophyll Red Edge and the Three Channel Vegetation Index (TCHVI) correlate well with activity concentrations of ^{90}Sr and ^{137}Cs in leaves, gamma dose rates and ^{137}Cs inventories in soil. Results also show that both indices are independent of soil moisture, which indicates that contamination-induced stress can be distinguished from soil-moisture related stress [19]. Such results could be use reversely to estimate the concentration of contaminant and gamma dose rate in contaminated areas covered by vegetation.

CONCLUSIONS AND PERSPECTIVES: R&D POSSIBILITIES AND INTEGRATION

The bibliographic research has demonstrated that the aerial nuclear reconnaissance systems are quite similar worldwide regarding their detection principle, construction, implementation and capacities. The detection principle always relies on gamma radiation measurement with a combination of sensors (usually a GM sensor and a scintillator). The systems can measure extended and point source contamination from an average altitude of 100-200m above ground for moderately intense radiation sources. The systems can also identify which radioisotopes are present.

Two main conclusions can be formulated. At present, alpha, beta and scattered gamma radiations are not "sensed" by aerial reconnaissance systems which can only detect unscattered gamma radiations. So developing the detection range is a first R&D possibility. Secondly as a main limitation is the low flight altitude required to perform the reconnaissance, R&D efforts should be oriented to increase the flight altitude.

Some other R&D objectives have also been identified; we can mention the following:

- - the transmission of the information in real time.
- - the transfer of aerial gamma spectrometry to UAV technology and the sample taking option developed for some of them.
- - the acquisition of geo-referenced images for evaluation of the effect of contamination on the impacted area.
- - the acquisition of precise elevation data with LiDAR to feed model.

The theoretical analysis conducted with hyperspectral imaging reveals an interesting potential for the detection of alpha, beta and scattered gamma radiations through the detection

of specific signal signatures from the generated ions and secondary products of ionization reactions. Consequently hyperspectral imaging potentially constitute a complementary detection method to aerial gamma spectrometry. The integration of the two detection methods on the same platform would allow an integrated approach in the detection of ionizing radiations. Furthermore this optical remote sensing technique can be applied at an altitude much higher than 100m. Nevertheless several difficulties have been identified. It seems the products of ionization are present in the air in infinitesimal quantities. Laboratory and field measurements work should confirm if optical detection is sensitive enough and applicable. The strength of the radiological source and the distance with the source are important parameters to consider in this work. A second question deals with the reflectance and spectral signature of ionized molecules and secondary products, in particular the intensity and profile of the signals. A weak or "flat" signal would offer limited applications as the spectral signature could not be extracted from a mixed spectrum comprising the general environmental effects (atmospheric and background). For example it would make no sense to try to exploit a signature where the intensity would be smaller than overall deviations.

Hyper spectral imaging offers two other added values. Orthorectified RGB-IR images can be produced and used for estimating the damage on the environment. The spectral signature of vegetation in the infrared red region can be used as an indicator of stress and help in the identification of radiological contamination.

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(fi2) SPECIM Ltd. Aisa owl hyperspectral sensor. http://www.spectralcameras.com/files/AISA/AisaOWL_ver1-2012.pdf

(us1) TRADESWAYS Ltd Airborne radiation reconnaissance system (ARRS). http://www.bmd.it/download/CBRNE/1.Rivelazione_ed_Identificazione/3.%20Nuclear%20Detection/06.%20Airborne%20Radiation%20Recon.%20System.pdf