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USING HYPERSPECTRAL IMAGING IN NUCLEAR RADIATION AERIAL RECONNAISSANCE? A PRELIMINARY STUDY[4][5]

This article aims at exploring the potential of hyperspectral imaging in order to develop further the Hungarian aerial nuclear reconnaissance system. First a description about the theoretical basis of ionizing radiations is provided. The different types of radiations, their characteristics, penetration range and effect on matter are presented. Then a critical analysis is done on the Hungarian nuclear reconnaissance system based on the detection capacities and operational implementation criteria. The last part explores the potential of hyperspectral imaging technology, its added values and the different possibilities envisaged for its application.

HIPERSPEKTRÁLIS KÉPALKOTÁS ALKALMAZÁSA A NUKLEÁRIS SUGÁRZÁS LÉGI FELDERÍTÉSÉBEN? ELŐZETES TANULMÁNY

A cikk célja a hiperspektrális képfelvételezés potenciáljának felmérése a magyar légi nukleáris felderítő rendszer továbbfejlesztése érdekében. Elsőként az ionizáló sugárzás elméleti alapjairól adunk leírást. Bemutatjuk a sugárzás különböző típusait, azok jellemzőit, behatolási tartományaikat, és az anyagra gyakorolt hatásaikat. Ezután egy kritikai elemzést végzünk a magyar nukleáris felderítő rendszerről, a felderítési kapacitásokra alapozva. Az utolsó rész a hiperspektrális képalkotási technológia lehetőségeit deríti fel, annak hozzáadott értékeit és megvizsgálandó alkalmazási lehetőségeit.

1. INTRODUCTION

Aerial nuclear reconnaissance is a survey technique used to detect, measure, identify and map radioactivity in the environment. The main field of application is the estimation of the contamination extent after a nuclear catastrophe or nuclear attack. Another possible application is the localization of lost punctual radioactive sources. All the aerial nuclear reconnaissance techniques are based on gamma radiation detection because it is the most penetrating radiation type. In average, in order to detect moderately intense radiations, the reconnaissance is done at an altitude of 200m above the ground. This is because of the quick attenuation of the gamma radiation by the air. In this study we would like to explore the opportunity offered by an optical remote sensing technique called hyperspectral imaging. Our assumption is that with optical remote sensing technique it could be possible to detect a larger range of radiations from a higher flight altitude.

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2. CHARACTERIZATION OF IONIZING RADIATIONS

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.

$$X \rightarrow X+ + e- \text{ (generic formula for single ionization)}$$

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. [1]

2.1. 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]

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

Tab. 1. Main ionizing radiations and their characteristics

2.2. Penetration ranges and consequences for airborne detection

The aerial detection of ionizing radiations is governed by two main principles which are the interaction of the ionizing radiations with matter (both with the sensor and the air) and the penetration of the ionizing radiation. [1]

Charged particles such as electrons, positrons, protons, alpha particles and beta particles strongly interact with electrons of an atom or molecule. Consequently they have a very low penetration range in matter. For example Alpha particles are absorbed by about 10-2 m of air and the penetration range of Beta particles is about 8 m in air. [1] Those radiations stopped far before the sensor cannot “activate” crystals or induce ions pair production in the chamber of scintillation or semi-conductor sensor used in classical airborne applications. With the present technology and practices those radiations are lost for the detection process.

Neutral particles like gamma and neutron interact less with matter, are indirectly ionizing and have the higher penetration range. The penetration range of gamma radiation is several hundreds of meters in the air. The penetration of neutron radiation depends on the content of water of the air, as water shields neutron radiation. Neutron radiation can induce gamma radiation after atomic activation. [1]

2.3. Effect on matter and detection strategies

Let's first confront the two different detection strategies considered in this study: Airborne Gamma Spectroscopy (AGS) and remote sensing optical methods.

AGS has been recognized as a very powerful tool for the detection of ground contamination and to locate lost radioactive sources. It is presently the method recommended by the IAEA for the detection of ionizing radiations. [2] Optical detection of radioactivity by remote sensing is still under experiment and has not proved yet efficiency in ionization detection. [6][7]

The two methods lay on totally different measurement principles. AGS detection principle is based on the "capture" of energetic photons by the detector, which means all the photons from gamma radiation stopped in the air prior the sensor are lost for the detection process and the low penetration range radiations (alpha and beta) are lost too. 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. Total count measurements register gamma rays of all energies. These are used to monitor the gross level of the gamma radiation field and to detect the presence of anomalous sources. Spectrometers, on the other hand, measure both the intensity and energy of radiation (Fig. 1), and this enables the source of the radiation to be diagnosed. Gamma ray spectrometry is thus a powerful tool for monitoring the radiation environment. [2]

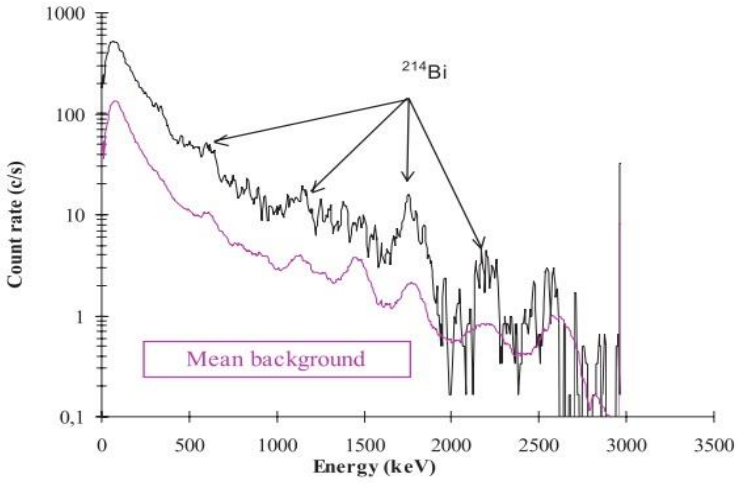

Fig. 1. Example of spectrogram generated by gamma spectrometry

Optical remote sensing methods can in theory detect what happens in the air and in the vicinity of the radioactive source (which encompass the effect of alpha and beta radiations on matter) as the detection medium (the electromagnetic radiations) is traveling almost freely in the air. The detection principles should allow detecting electronic excitation generated by the ionizing radiations (emission) and the molecular species generated by the ionization of the air (through the

radiations absorbed, reflected or transmitted and the associated spectral signature).

In conclusion the two detection methods are complementary and could be used in combination to improve the detection range and the accuracy of the detection.

3. CRITICAL DESCRIPTION OF THE HUNGARIAN NUCLEAR RECONNAISSANCE SYSTEM

The gamma spectrometry airborne nuclear reconnaissance system was designed for the primary survey of area contaminated by radiological materials. The system can be used to reach three major goals:

- to measure the extended contamination on a territory and to map it. This is made with total count measure of radiation rate.
- the localization of radioactive point sources.
- the identification of radioactive isotopes. [3][4][5]

3.1. System built up

The container of the system includes two nuclear detectors, a GPS-receiver, a barometric altitude-meter and data logger which can send the recorded data to the on-board notebook or to the PC of the operation center. One of the two detectors is a Geiger Müller tube (BNS-98) dose rate meter while the other one is a specially designed, highly sensitive NDI-65/SK type intelligent scintillation detector, built in a lead collimator which ensures the capability of finding and localizing discrete radiation sources on the ground. The system calculates the radiation level of the contaminated area (referred to 1 m altitude) or the dose rate of a discrete radiation source from the dose rate measured at the flying altitude considering the atmospheric and ground conditions.

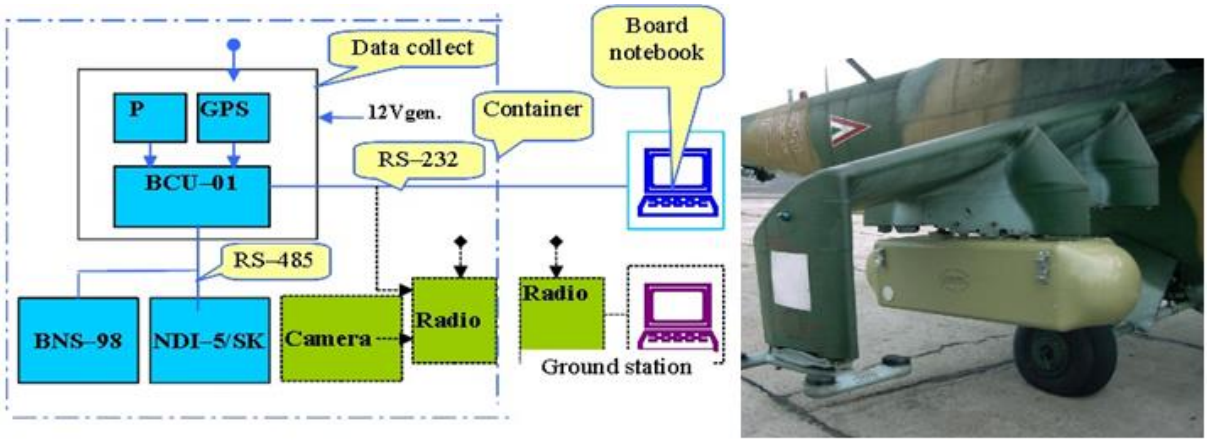

Fig. 2. Details about the composition of the nuclear reconnaissance system

3.2. Characteristics of the system

Name	Sensors in the system	Operating mode	Detection capacities
LABV airborne	-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 km^2/h **Point source:** Speed: 100-120 km/h Altitude: 50-60 m. Coverage: 18-20 km^2/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

Tab. 2. Main characteristics of the Hungarian reconnaissance system.

The main limitations identified is the low flying altitude required to measure gamma radiation, from 50m to 200m above ground. Another limitation is the fact that low penetration radiations (which are stopped by the air in the vicinity of the radioactive materials) cannot be detected and are lost for the detection process. It should also be noticed that the reconnaissance system is not performing geo-referenced imaging of the impacted area during the flight, which in case of catastrophe management could be a source of relevant information for evaluating the impacts on environment and population.

4. 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. [11]

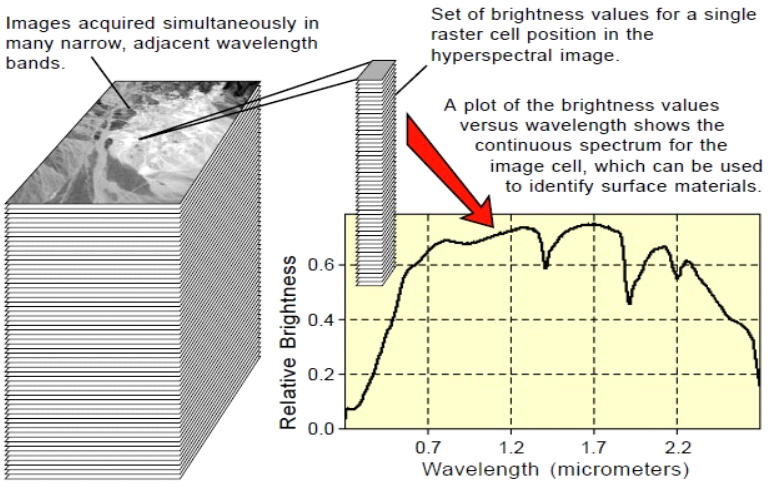

Fig. 3. General principle of hyperspectral imaging - ©MicroImages, Inc., 1999-2012

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. [11]

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 airborne sensors owned by Karoly Robert College.

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

Tab. 3. Available sensors and their detection ranges

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 consist 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. The detailed specifications are provided in Tab. 4.

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	

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

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 some results were published on successful LWIR identification of hazardous gasses. [16] LWIR hyperspectral imaging is also capable in identifying chemicals used in chemical warfare (Farley et al, 2006). [17] FTIR imaging has been successfully used to identify radioactive materials. [8] Some preliminary works has been done with hyperspectral remote sensing for the identification of uranium mine tailings.

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. [13]

Last but not least, hyperspectral technology is evolving very quickly. The sensors developed recently have a made a significant progress with signal-to-noise ratio and spectral resolution. This open new possibilities for the detection of traces of gas and molecules. [9][14]

5. 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 interaction with matter we are trying in this chapter to set some basis for the indirect detection of ionizing radiations with hyperspectral imaging technology.

5.1. The strategical 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. [8] The demonstration was made using MODTRAN4 modeling. [8]

Fig. 4. and Tab. 5. 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.

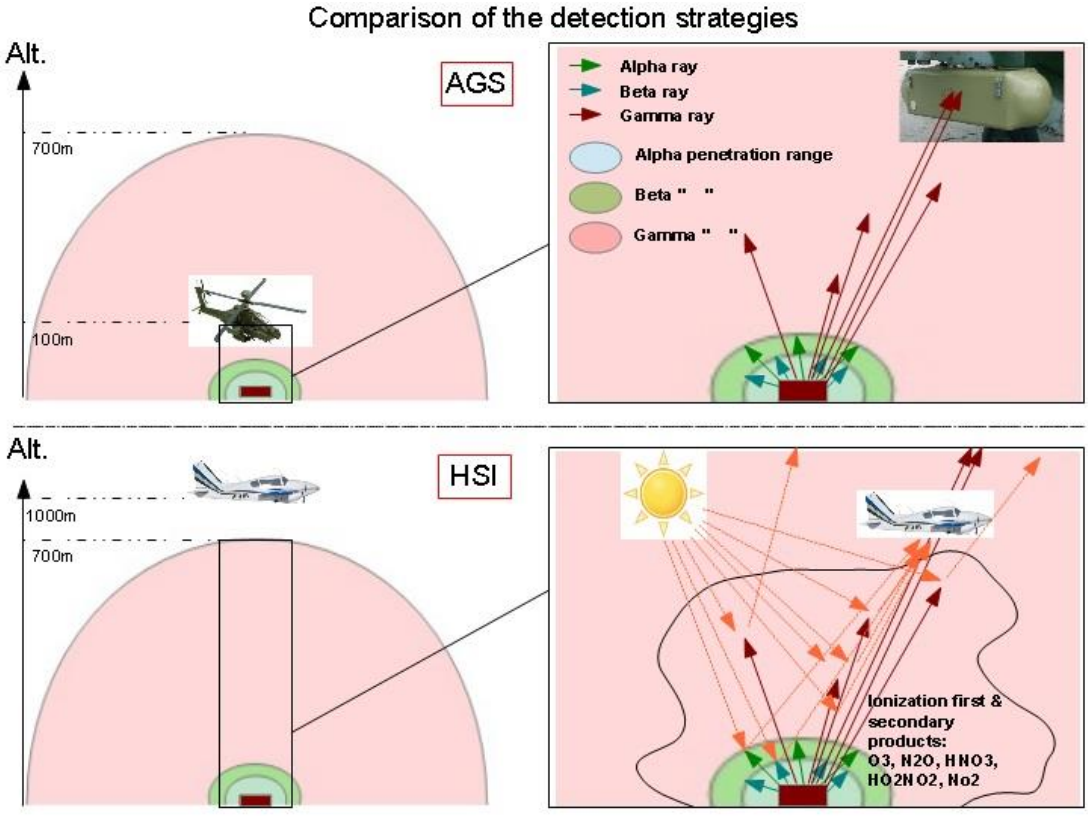

Fig. 4. Comparison of Airborne Gamma Spectrometry and hyperpectral imaging for the detection of ionizing radiations.

	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 (O_3))	-
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).	

Tab. 5. 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).

5.2. 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. [6] 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 result is the value of the molar fraction 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 indicator species are theoretically known, we should explore the detection possibilities. In this article we decided to concentrate on O_3 and N_2.

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.

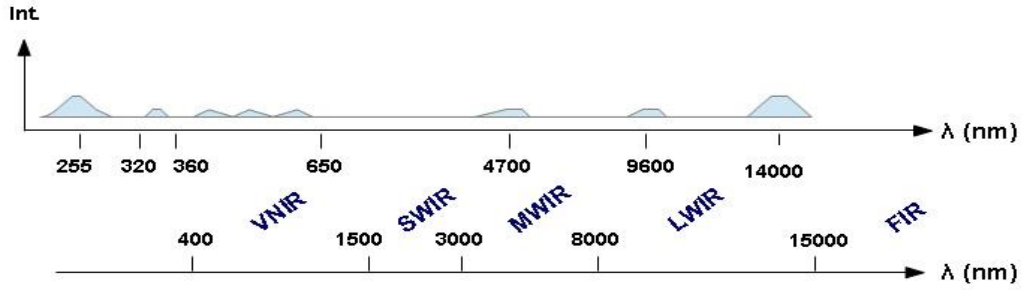

Fig. 5. Match between the absorption of ozone and the light spectrum sub-regions.

Some absorption is located in the VNIR and MWIR regions. The highest potential is in the LWIR region comprising the 14100 nm band (Fig. 5.).

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.

5.3. Electronic excitation

Regarding nitrogen, the following reactions happen:

$$N2 \rightarrow N2^* \qquad N2^* \rightarrow N2 + hv$$

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). [15] Only the observed strong emission lines are represented on the figure.

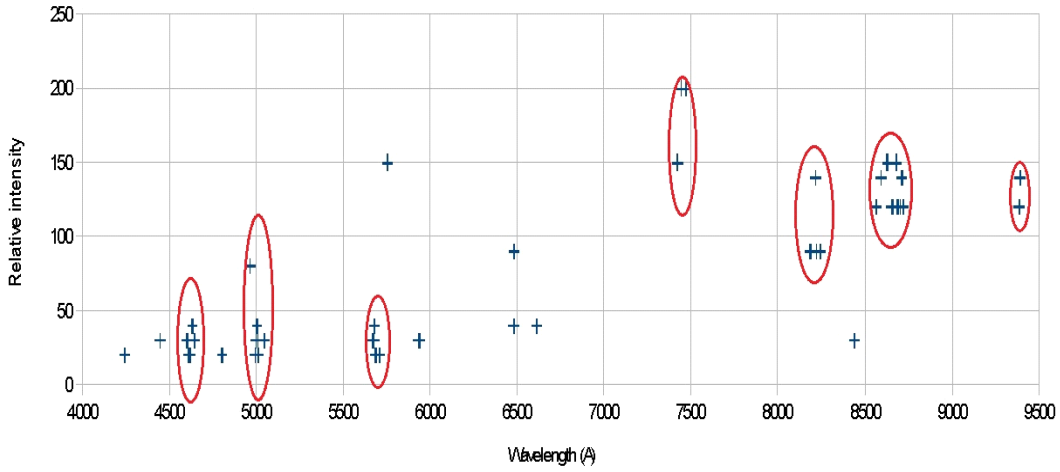

Fig. 6. Atomic emission spectrum for Nitrogen I-II in the spectral range of Eagle (4000-9500 Å).

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.

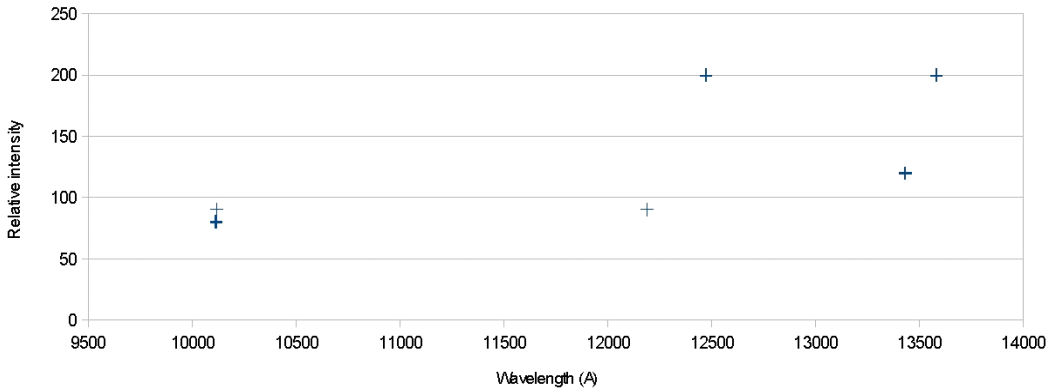

Fig. 7. Atomic emission spectrum for Nitrogen I-II in the 9500-14 000Å region.

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.

$$O2 \rightarrow O2+ + e-$$

$$O2+ + 2O2 \rightarrow 2O3$$

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.

5.4. 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.

6. CONCLUSIONS AND PERSPECTIVES

The theoretical analysis conducted on hyperspectral technology 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).

The laboratory work in the near future should help to determine which spectral region is the most promising and which indicator species have the best potential for ionizing radiation detection.

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.

REFERENCES

[1] V. VALKOVIĆ: Chapter 5 - Measurements of Radioactivity. *Radioactivity in the Environment.* Amsterdam, Elsevier Science: 117-258, 2000.

[2] IAEA: Guidelines for radioelement mapping using gamma ray spectrometry data, 2003

[3] J. SOLYMOSI, E. BAUMLER, A. SARKADI, Á. GUJGICZER, I. PINTÉR, Á. VINCZE: Wide range universal radiation measuring instrument. *AARMS,* Volume 1(1) (2002) 133–144.

[4] J. ZELENÁK, J. CSURGAI: Analysis of the applicability of the airborne radiological reconnaissance in case of searching lost or stolen radioactive sources. *Hadmérnök,* (2009) 46-62.

[5] J. SOLYMOSI, E. BAUMLER: *Eljárás és berendezés ismeretlen összetetélű és/vagy többkomponensű, főként hasadási termékekkel kontaminált terepszakaszok sugárszintjének légi felderitésére*, Hungarian Patent 201161 B, issued 1990-09-28.

[6] C. E., MOSS, R. M. GOELLER, D. F. MILLIGAN, J. E. VALENCIA, J. ZINN: Remote sensing of radiation. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 422(1-3) (1999) 832 – 836.

[7] S. IHANTOLA, J. SAND, K. PERAJARVI, J. TOIVONEN, H. TOIVONEN: Fluorescence-Assisted Gamma Spectrometry for Surface Contamination Analysis. *IEEE Transactions on Nuclear Science*,, Vol. 60 , Issue: 1 , Part: 2 (2013).

[8] E. PUCKRIN, J. THÉRIAULT: Passive standoff detection of radiological products by Fourier-transform infrared radiometry, *Opt. Lett.*, 29 (2004) 1375-1377.

[9] H. HOLMA, A. J. MATTILA, & T. HYVÄRINEN: New thermal infrared hyperspectral imagers. *NATO Technical report*, RTO-SET-151, 2009.

[10] J. TUOMINEN, T. LIPPING: Detection of Environmental Change Using Hyperspectral Remote Sensing at Olkiluoto Repository Site, 2011.

[11] R. B. SMITH: Introduction to hyperspectral imaging, 2012.

[12] J. LÉVESQUE, R. A. NEVILLE, K. STAENZ, Q.S. TRUONG: Preliminary results on the investigation of hyperspectral remote sensing for the identification of uranium mine tailings. In: *Proceedings of the ISSSR*: June 10-15, 2001, Quebec City, Canada

[13] Cs. LENART, P. BURAI, A. SMAILBEGOVIC, T. BIRO, Zs. KATONA, R. ANDRICEVIC: Multi-sensor integration and mapping strategies for the detection and remediation of the red mud spill in Kolontar, Hungary: Estimating the thickness of the spill layer using hyperspectral imaging and Lidar, Hyperspectral Image and Signal Processing. *Evolution in Remote Sensing (WHISPERS)*. 3rd Workshop, Lisbon, Portugal. (2011).

[14] R. RICHTER: Hyperspectral Sensors for Military Applications. Emerging EO Phenomenology, 2005.

[15] J. E. SANSONETTIA, W. C. MARTIN: Handbook of Basic Atomic Spectroscopic Data. *J. Phys. Chem,* Ref. Data Vol. 34(No. 4) (2005)1885-1890.

[16] G.M. GITTINS, W. J. MARINELLI: LWIR multispectral imaging chemical sensor. In *proc. SPIE 3533, Air Monitoring and Detection of Chemical and Biological Agents*, 93, Boston. (1999).

[17] V. Farley, A. Valleres, M. Chamberland, A. Villemaire: Performance of the FIRST, a longwave infrared hyperspectral imaging sensor. *Proceedings of SPIE optically based biological and chemical detection for defense,* Stockholm, Sweden. (2006).