



AIRBORNE AND TRUCK-BORNE "RADIATION FOOTPRINTS" OF AREAS PRODUCING, STORING, USING OR BEING EXPOSED TO NUCLEAR MATERIALS

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Abstract

The paper discusses the use of advanced Airborne Gamma Ray Spectrometer for environmental assessment of nuclear radiation in areas exposed to radioactive materials. The use of high capacity real time processors operating in parallel mode packaged into one mechanical enclosure together with navigation, allows implementation of highly sophisticated proprietary algorithms to produce results in absolute physical units. Airborne footprinting provides rapid, well defined spatial images of natural and manmade radioactive contamination. Integrated GPS guidance systems provides instant position information related to the internal geographical data base. Short time span of data acquisition provides consistent data. Airborne acquisition of data guarantees good spatial resolution. Airborne measurements are calculated via special algorithms in absolute units and related to the individual radioactive nuclei on the ground in real time. Full raw and calculated data recording is provided including the position coordinates. More precise results may be achieved via post flight processing. Principles of ground contamination estimates measured from the air and the sensitivities for different radioactive nuclei are also discussed. Results from an Ontario Hydro (Canada) test over a nuclear power plant, an Atom bomb blast measurements in Maralinga (Australia), after 40 years, and a Nuclear power plant in Slovakia and Uranium mining area in Germany are presented and discussed.

1. GAMMA RADIATION SURVEY — A NECESSITY

The general lack of natural sensors to detect and monitor radioactive hazards, particularly in this technologically advanced society has necessitated the development of new instrumentation and processing techniques that can rapidly produce visual images of areas exposed to radiation. Protecting the health of the population in case of a nuclear accident is essential and a social priority.

Monitoring of existing levels of natural and manmade radioactive sources, in and around nuclear installations and nuclear materials handling facilities becomes a valuable reference data source "footprint" that quickly determines the current levels of contamination and can assist in directing future emergency planning.

Fast deployment of airborne radiation monitoring systems in the case of nuclear accidents is essential. The portability of the new range of instrumentation with accurate navigation, data acquisition and real time processing can provide fast and low cost surveys that produce almost instant maps indicating the radiation distribution over the surveyed area.

Repeated surveys, once or twice per year, over nuclear facilities, including active and non-active uranium mines provide a history of the radioactive background and contamination of these areas. This information will become a part of the ISO14000 environmental documentation. At the same time it provides important information for public education and information that can address early remedies and avoid potentially serious problems. Also the proper documentation of the long term radiation levels may reduce liability risks to companies handling nuclear materials.

2. TYPES OF RADIATION SURVEYS — GROUND AND AIRBORNE

There are two techniques on how to produce radiation images over nuclear handling facilities and surrounding areas.

Ground survey

Data can be collected on foot or by a survey vehicle.

Advantages:

- Very detailed image depending only on the selected grid size or speed of the vehicle.
- Different measurements such as Alpha, Beta and Gamma can be obtained.

Disadvantages:

- Limited or restricted access (buildings, terrain).
- Time consuming, takes long time to cover suitable area.
- Geographically non consistent data.
- Dangerous in case of high radiation levels.

Airborne survey

Advantages:

- Fast, with no access limitation.
- Almost instant classification of the area.
- Efficient and large coverage per time unit.
- Integral view of the area, with resolution of the measurements related to the altitude and speed of the aircraft.
- Low cost per surveyed line km.
- Geographically consistent data.
- With proper safety procedures, limited potential to dangerous exposure.

Disadvantages:

- Initial cost of renting/using aircraft or helicopter.
- Somewhat limited spatial resolution.
- Only Gamma measurements can be recorded.

When comparing the total cost and time required to collect and process the data to obtain a global image and assessment of the surveyed area, it is apparent that an airborne survey is the practical answer. With the new technology, particularly with the advanced navigation system, it is possible to collect adequate information flying at the altitude of 50 to 80 metres with the flight line separation as close as 50 metres or less. To survey an area of 10 by 10 kilometres at an altitude of 70 metres with a line separation of 70 m, the total line kilometres flown is approximately 1 400 km. While taking into consideration the necessary turns and the average speed of the airplane (helicopter) at about 120 km/hr, the required time to fly this area is about 16 flight hours or approximately 3 working days. Preliminary maps can be processed within hours after the flight and final images of the area can be ready in a couple of days. To acquire similar volume of data on the ground would take a considerably longer time at a much greater cost.

3. AIRBORNE TO GROUND DATA CONVERSION

In order to be able to interpret airborne survey data properly, the data must be recalculated into absolute (physical) units. This can be achieved in two ways. In real time and in postflight processing. In case of emergency response the real time processing is a must. Health authorities need processed information as soon as possible (in real time) in order to activate emergency procedures. Picodas Group Inc. together with the Technical University of Prague, Faculty of Nuclear Engineering, developed modeling techniques to provide the required results.

A complex mathematical model of air to ground data conversion was developed. There are two models, both based on an infinite ground plane of radioactive contamination. A surface model

for deposits of manmade radioactive materials and a spatial, homogenous, model for natural elements. Both models are theoretical and in most cases depending upon time, the distribution of manmade contamination is somewhere in between. The time factor in determining a homogenous environment is weather dependent. Longer in dry areas, shorter under wet conditions.

Surface contamination produces a hemisphere distribution of the Gamma flux above the ground and is measured in activity per area (square metre). The homogenous (isotropic) contamination produces the Lambertian (cosine) distribution and is measured in activity per volume (kg, cubic metre etc.). Activity of radiation is measured in Bq. One Bq is a unit for one disintegration.

Airborne equipment flown at altitudes over 10 metres can only measure the Gamma content of disintegrations. Any disintegration of a radioactive element is characterized in relation to the Gamma radiation by the "Peak Energy Intensity" expressed in percent of Gamma particles emitted by one disintegration.

Altitude of the aircraft is the next variable in the process relating airborne data to the ground level (see Fig. 1). The attenuation of the Gamma particles going through the air layer is dependent upon the energy of the particle and thickness of the air layer.

Detector size and shape are other factors of the model. A Gamma particle on its way from its origin to the detector faces many obstacles and only a small number of the particles are detected with its original energy by the airborne detector. The number of these particles is further reduced by the inadequate stopping efficiency of the detector.

To properly detect the lower energy emitting elements, the deconvolution of the higher energy elements from collected spectra, called stripping, must be applied. To be able to classify the elements, the "Net peaks" (e.g. peaks stripped of the attenuated content from higher energies and not properly detected particles) in the collected spectrum must be properly determined.

Speed of the aircraft only defines the spatial resolution of the detection.

The air to ground model can be expressed as a function:

Model = Function(Distribution of contamination, Detector shape and size, Detector efficiency, Altitude of the aircraft, Energy of the radioactive element, Peak energy intensity, Stripping).

4. INSTRUMENTATION SENSITIVITIES

To define the system sensitivity for individual radioactive elements we have to consider the Spectral Energy Resolution of the system and statistical character of the Gamma detection process. Since the sensitivity of the detector is directly proportional to the detection area of the detector, for non emergency airborne footprinting, a larger size of detectors is desirable. The NaI(Tl) crystal (10 × 10 × 40 cm) is a generally accepted detector size. An array of these detectors (usually 4) are mounted in a single detector package forming a detection surface area of 40 × 40 cm.

Statistical character of the measurement limits the sensitivity related to the unit of time (usually 1 second). Resolution of the detector limits the detectability of the neighboring energy peaks. Even though the model of air to ground is quite complex and the statistical nature of the detection process further complicates the issue, a relatively simple sensitivity formula for each element can be drawn.

For instance for **K-40** (1.4612 MeV) with a detector size of 40 × 40 × 10 cm the estimated number of detected Gamma particles for one Bq of homogeneously saturated layer with the density of 1.66 g/cm³ in relation to the altitude of the detector are:

Altitude	Distribution (model)	Gamma/Bq	Bq/Gamma
30 m	lambertian	0.4121	2.430
60 m	lambertian	0.3221	3.104
90 m	lambertian	0.2333	4.286
120 m	lambertian	0.1621	6.169
150 m	lambertian	0.0965	10.36

Statistically the results vary within ± 3 standard deviations. In other words **ten** detected Gamma particles in the **K-40 Net peak** energy window in a time unit will give $\pm 90\%$ reliability of the measurement.

At the altitude of 90 metres the described detector can theoretically detect 1 647 Bq for isotropic and 1 250 Bq for lambertian distribution with the reliability of $\pm 30\%$. The reality is not as good since the stripping is introducing additional statistical noise. For Potassium we should consider the lambertian model only. The Gamma events detected in the Net K-40 window are related to the emanation from one metre square. Should we assume that the K-40 is dispersed homogeneously in a saturated layer (density of 1.6 g/cm³) then the detectable contamination of K-40 is 16.5 Bq/kg. This level is well below the normal natural radiation level (approx 250 Bq) and therefore this method provides reliable measuring results.

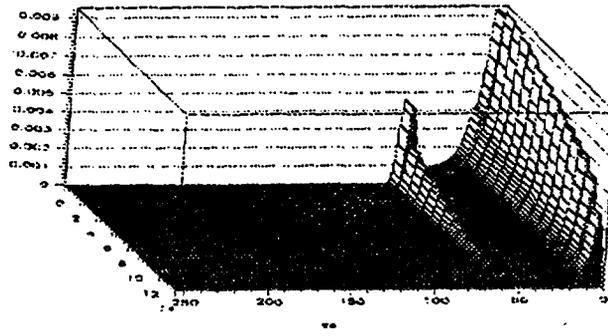
Element	Cs-137 Bq/m ²	Co-60 Bq/m ²	K-40 Bq/kg	Bi-214 Bq/kg	Tl-208 Bq/kg
Normal (area related) Background	7000	1000	250	30	40
Detection $\pm 50\%$ @90 m	6200	3320	214	112	50

We conclude that the above discussed detector package can, with the exception of Co-60, and Bi-214 quite reliably measure levels of the background radiation and anomalies exceeding twice the background levels. Since a secondary peak of Bi-214 may be measured, the reliability of Bi-214 increases to the level of the other elements. It is to be noted that the higher measured radiation levels provide better statistics and therefore better reliability of the measurements.

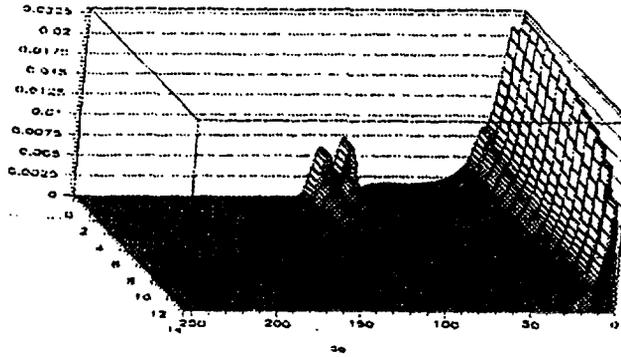
5. PROCESSING TECHNIQUES AND INSTRUMENTATION

Picodas Group Inc., Picodas Prague s.r.o., both part of the World Geoscience Corporation Limited, together with the Faculty of Nuclear Engineering of the Technical University of Prague developed the above mentioned models for use in practical applications. Picodas Group Inc. has developed the portable, fully integrated instrumentation ENMOS 2001 for this application comprising of a fully digital Gamma Spectrometer, Data Acquisition, Differential GPS Navigation, Pilot Guidance system and Geographical Data Base with flight and ground support software, as well as having developed a processing model to be used on board of the aircraft in real time. A complete data set (raw and processed) are recorded in the aircraft and may be reprocessed on the ground to higher resolutions. An integrated data processing package, including modelling and map making software has been developed to provide preliminary and final dosage and contamination maps soon after survey flights.

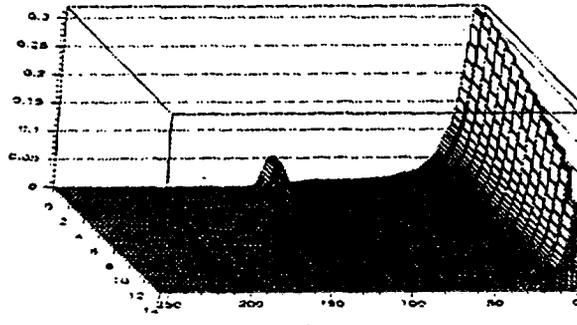
Cs-137



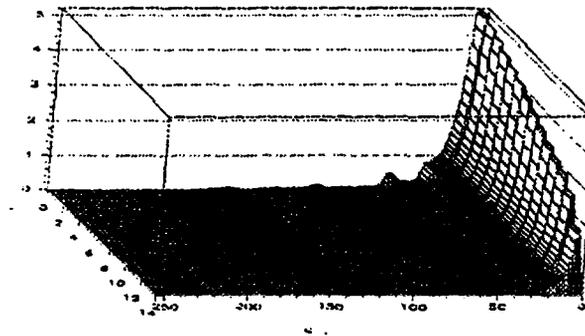
Co-60



K-40



Bi-214



Tl-208

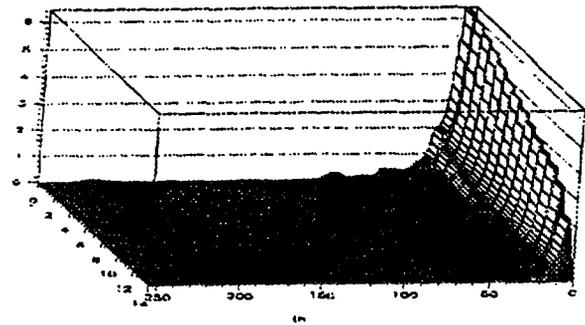


FIG. 1. Altitude attenuation and energy distribution for Cs-137, Co-60, K-40, Bi-214, TL-208.

6. CASE HISTORY

6.1. Ontario Hydro BRUCE Nuclear Power Plant

The Bruce NPP is a large complex with eight nuclear reactors, each in the range of 900 MW capacity. The site is located on the shore of Lake Huron, 150 km northeast of Toronto. In October 1995 Ontario Hydro and Picodas Group Inc. conducted a joint test to overfly and document the Bruce NPP and surrounding area.

Equipment:	ENMOS 2001 (256 channel spectrometer) GPS real time differential navigation system Radar Altimeter TRA 3000
Measured Energy range:	200 keV to 3 MeV in 256 channels above 3 MeV one channel
Altitude:	80 m above ground
Ground speed:	35 m/second
Aircraft:	Hydro Bell 206 Jet Ranger Helicopter
Line spacing:	inside NPP perimeter 75 m outside perimeter 150 m

Survey Procedures and Methodology

Due to bad weather conditions the survey was carried out in two time periods requiring two separate equipment installations. Each installation took approximately 1 to 2 hours and 30 minutes to remove the equipment.

The total survey time was about three working days with 16 hours of helicopter flight time to cover an area approximately 10×20 km or 200 km² with 1800 km of survey lines.

The survey area may be divided into three main parts.

- a) Inside perimeter of the NPP.
- b) Swampy belt approximately 1 to 2 km wide close to the lake shore.
- c) Agricultural inland area outside of the perimeter of the NPP.

Observations

- a) The inside perimeter of the Bruce NPP shows relatively low natural radiation. However there are small localities showing distinctive anomalies of man made radionuclides such as Cs-137 and Co-60. Some of those localities are exhibiting anomalies of natural radionuclides of U-238 (Ra-226) and Th-232.
- b) Because of the water content, the swampy belt shows substantially suppressed radiation levels and no anomalies are detected in this area.
- c) The agricultural (inland) area does not indicate any radiation generated from man made products. Natural radiation is affected mostly by the surface of the ground (plowed), vegetation and humidity. The highest "natural contamination" seen is the K-40. Observed variations of the K-40 contamination are caused by changes of ground moisture, vegetation and by fertilization of the fields.

Low energy (up to 3 MeV) radiation exposure (dosage rate) reaches maximum of 250 nSv/hr in the locality of the strongest anomaly inside the perimeter of the NPP. Most of the inside perimeter and all of the outside perimeter indicate the low levels of radiation reaching only approximately 40 nSv/hr.

The highest anomalies within the inside perimeter are composed approximately of:

Cs-137	29%
Co-60	26%
K-40	4%
U-238	30%
Th-232	11%

Collected data sets indicate that there is an increase of the high energy radiation (above 3 MeV) over the active nuclear reactors. This is caused by the N16 in the energy range of 4 and 6 MeV. It is estimated that the dosage rate related to the normal cosmic radiation is approximately 30–40 nSv/hr. Estimation of the additional dosage due to the high energy radiation above the reactors is the ratio of measured "cosmic rays" over normal terrain and the reactors. Additional dosage produced by the high energy radiation is in the order of 250 nSv/hr.

Relation of units

Absorbed dose 1 Gy = 1 Sv (dose equivalent) for quality factor Q = 1
 Quality factor Q characterizes specific radiation. Further we assume the Q = 1.

Dose equivalent

- 1 Sv = 100 rem
- 1 uR/hr = 2.4139 pG/s
- 1 pG/s = 31.536 uG/year
- 1 pG/s = 3.6 nG/hr
- 1 uR/hr = 8.7 nG/hr = 0.0087 uG/hr

Natural exposure measured in dose equivalent is 3 to 10 μR/hr (25 to 87 nSv/hr or 2.5 to 8.7 urem/hr), therefore all of the areas except for the anomalous locations are well within the normal natural radiation levels of less than 5 μR/hr (45 nSv/hr or 4.5 urem/hr).

Normal limitation of absorbed dosage for humans is about 273 nSv/hr (2.4 mSv/year or 240 mrem/year).

List of anomalous locations

There are six detected locations with noticeable elevated Dose Rates:

three small locations (A-south, B, C-north) on south west shore of the N.P.D., one larger one (D) on the north shore of the N.P.D., one in the middle of the N.P.D. (E) and one in the south central location (F).

Notes: L.E.D. low energy dosage — up to 3 MeV
 H.E.D. high energy dosage — above 3 MeV
 backg = background

Location	L.E.D. nS/hr	H.E.D. nS/hr	Cs-137 Bq/m ²	Co-60 Bq/m ²	K-40 Bq/kg	U214 Bq/kg	Tl-208 Bq/kg
approximate (area specific) background	35	35	7000	1000	300	30	40
A	< 40	> 200	backg	< 2000	backg	backg	backg
B	45	> 200	backg	> 2300	backg	backg	> 30
C	54	backg	< 6000	> 1000	backg	> 40	backg
D	72	> 200	> 10000	> 4500	backg	> 50	> 30
E	250	backg	> 22000	> 8000	backg	> 150	> 80
F	105	backg	> 31000	> 2400	backg	backg	backg

Relatively large contributions of H.E.D. to the total dosage *may not* be noticed at the ground level since the immediate dosage levels depend upon the heavy shielding of the reactor. Upwards shielding above the reactors is considerably less. The contribution to the ground dosage from the H.E.D. would be mostly through radiation scattering.

The Co-60 map exhibits substantial level of noise in the area of the outside perimeter. This corresponds to the model sensitivities calculated for Co-60. This could be considered an indirect verification of the air to ground model assumptions. All images of the data were overlaid on the aerial WGS84 calibrated photography.

6.2. Atom bomb blast measurements in Maralinga - Australia

World Geoscience Corporation Limited has recently flown the nuclear bomb test site last used in the 1950s. From images collected over this area it is obvious that the levels of radioactive contamination are still very high. It indicates that after forty years the isotropic model is becoming lambertian with a relaxation depth to about 15 cm. All data was overlaid on Spot satellite imagery.

6.3. Nuclear power plant in Slovakia

In 1992 a series of tests flights over a Slovakian Nuclear Power Plant were carried out. One area of the power plant shows substantial increased levels of radiation. To better delineate areas of interest the data was overlaid on Spot satellite imagery.

6.4. Uranium mining area in Germany

In 1994 a pilot project was conducted over an old uranium mining area near Gera in Germany. Increased Uranium contamination was detected and it is directly related to previously known mining activities.

7. CONCLUSIONS

- Detection sensitivities of the demonstrated system are adequate for the altitudes of operation under 90 m. Portability allows for rapid engagement and disengagement of the system. It is possible that the system may be used not only for new measurements, but also for calibration of older, regionally collected data by other airborne multichannel instruments to recalculate the pulses per second or ppms to absolute physical units.
- As is evident from the observed results, a reliable dosage based map (footprint) over any nuclear facility can now be produced rapidly and at a reasonable cost.
- There is a considerable value in having a comprehensive regional background radiation footprint, which provides the basis for environmental assessment and can assist in directing future emergency planning.

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