HONG KONG OBSERVATORY

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AERIAL RADIOLOGICAL MONITORING IN HONG KONG

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ABSTRACT

This report describes the Aerial Monitoring System operated by the Hong Kong Observatory since 1997, including its technical details and the flying strategies adopted during emergency operations. The system was re-calibrated following the use of a new helicopter by the Government Flying Service in 2003. Using the new calibration parameters, results of activity concentrations measured on board the new helicopter were presented.

摘要

本報告描述香港天文台自 1997 年開始運作的空中監測系統，包括系統的技術詳情及應急時的巡測策略。在 2003 年，系統須重新刻度以應用於政府飛行服務隊的新直升機機種。本報告記載使用新刻度參數後的測量結果。

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1. INTRODUCTION

In connection with the operation of the Guangdong Nuclear Power Station (and the operation in 2002 of Lingao Nuclear Power Station about 1 km away from the former) located some 50 km to the northeast of Hong Kong, an emergency monitoring programme has been in operation in Hong Kong since 1990. As an integral component of the emergency monitoring programme, the Hong Kong Observatory implemented in October 1997 an Aerial Monitoring System (AMS) for rapid surveillance of local radiation levels in the event of an accident occurring at the stations. Although Hong Kong is outside the commonly-accepted Plume Emergency Planning Zone for a nuclear power station, the AMS serves the purpose of dispelling rumours and reassuring the public that Hong Kong is not adversely affected by any aerial release of radioactive materials arising from such accidents.

In this report, the configuration of the AMS is described in Section 2, followed by an elaboration of the survey methodology, namely the plume tracking mode and ground contamination measurement mode, in Section 3. The system was re-calibrated following the use of a new helicopter by the Government Flying Service in 2003. Section 4 describes details of the calibration process. Finally, some survey results are presented in Section 5.

2. SYSTEM CONFIGURATIONS

The AMS consists of a central control, a data display unit and two detector boxes. The detector boxes are configured with two different sets of sodium-iodide (NaI) type gamma-ray detectors to suit different survey modes: one detector box is designed for plume tracking while the other is used for ground contamination measurement. Only one of these detector boxes is used at any one aerial survey. Positioning data on the helicopter's latitude, longitude and flying altitude above ground surface are acquired from the ARINC system of the helicopter. All radiation data and positioning data are updated once every second and displayed graphically in real-time. A schematic diagram of the AMS is shown in Figure 1.

The detector box used for plume tracking consists of two identical 4-litre thallium-doped NaI crystal detectors. These detectors are aligned vertically and separated from each other by a lead plate 0.4 cm thick. This special configuration is designed for locating the horizontal axis of a radioactive plume by comparing the count rates between the upper and lower detectors.

The detector box used for ground contamination measurement consists of five identical 1.6-litre thallium-doped Na-I crystal detectors aligned side by side in the horizontal direction. During operation, a spectrum is accumulated for each of the detectors. Before being combined, the spectra are gain-corrected individually.

Each time it was deployed for aerial survey since 1997, the system was installed on board the Government Flying Service's (GFS) Sikorsky S76A+ helicopter. Since January 2003, the AMS had been deployed on the new Super Puma L2 helicopter which replaced the Sikorsky model.

The fuel tanks of the Super Puma L2 are located beneath the floor of the cabin. To avoid blockage by these tanks, the detector box has to be mounted at a spot in front of the rear seats in the passenger compartment, where there is no fuel tank underneath. Both the central station and the detector are fixed to standard attachment points on the floor. Installation can be completed within one hour. Figure 2 shows the positions of the system's central station and detector box on board the Super Puma L2 helicopter.

3. SURVEY METHODOLOGY

The AMS has two modes of operations, namely plume tracking and ground contamination measurement. The plume tracking mode will be used in the initial phase of a nuclear accident to detect whether there is any radioactive plume over Hong Kong. The system has the capability of delineating the extent of the plume. The ground contamination measurement mode will be used after the passage of the plume to identify contaminated ground surfaces and locate hot spots if any.

3.1 Emergency operations

3.1.1 Plume tracking mode

A flying strategy has been developed to detect the existence and extent of the radioactive materials in the atmosphere in emergency operations, without the need to fly into the plume (Wong *et al.*, 2000). Both the radiation level (in total count rate) within the energy range from 410 to 3000 keV and the radionuclide-specific count rate (in counts per second) are analyzed and displayed in real time.

The initial flight level is fixed at an altitude immediately above the inversion, or by default at 500 metres if the height of the inversion is not known. The choice of 500 metres is based on the study of Koo *et al*. (1984) that the monthly mixing height at Junk Bay ranges from 211 metres to 440 metres. Starting from a point close to Ping Chau, the helicopter cruises along northwest-southeast orientated flight lines towards the expected plume area. The orientation of these flight lines is based on a prevailing wind from a general northeast direction. If there is no noticeable rise in the count rate after completing a flight line, the process will be repeated with the next flight line downwind. The separation between flight lines is about 5 km. A typical flight pattern for searching a radioactive plume is shown in Figure 3. If only background radiation levels are measured, it will be concluded that a radioactive plume does not exist in the area surveyed.

When the total count rate exceeds 10 times the background level, the AMS is considered to have detected the existence of a plume. The flight path will immediately change to one which turns away from the plume and follows downwind until the count rate falls back to the background level. The latter point will serve as the starting point of the next approach. The process will be repeated until no further increase in the count rate is observed, thus resulting in a zig-zag flight pattern. A typical flight pattern is shown in Figure 4. The turning points thus determined will define the approximate boundary of the radioactive plume on one side of the axis of the prevailing wind direction. The process will be repeated with the helicopter flying on the other side of the plume, thereby defining a complete plume coverage.

Apart from the total count rate, count rates for the regions-of-interest corresponding to the radionuclides K-40, Ru-103, Xe-133, I-131 and Cs-137 can also be analyzed and displayed in real time.

In emergency operations, the raw count rates of the upper and lower detectors are monitored and directly compared with the background levels determined during routine surveys. Therefore, during an emergency there is no need for a re-determination of the background radiation levels of the helicopter and the detectors' sensitivities and efficiency calibration under the plume tracking mode of operation.

3.1.2 Ground contamination measurement mode

When the AMS operates in the ground contamination measurement mode, the helicopter will fly at an altitude of about 100 m above ground level. In emergency operations, a fast scanning strategy will initially be used to detect hot spots, if any, on the ground before zeroing in on more detailed measurements. For fast scanning, NW-SE orientated flight lines at a 5-km separation will be used. The flight line closest to the power station will be flown first. A typical flight pattern for fast scanning is shown in Figure 5. In case a hot spot(s) is detected, a detailed aerial survey around the hot spot will be conducted at a flight line separation of about 200 m. The detailed survey will establish the isotopic content of the contaminants and their activity concentrations, while detailed analyses of spectra using system calibration parameters will be conducted post-flight.

3.2 Routine operations

The objectives of routine aerial surveys are:

(1) to gather background information as a reference level for use during emergency; and

(2) to monitor the radiation level in the territory as part of the Environmental Radiation Monitoring Programme.

3.2.1 Plume tracking mode

Under the plume tracking mode, background measurements are conducted to determine the radiation levels at different altitudes, namely at 500 m and 600 m above mean sea level. The helicopter flies at a speed of about 100 km h^{-1}. The design of the flight plan is based on 5-km square grid boxes which are carefully positioned such that the helicopter following the flight paths will not fly close to the ground at the flying heights. Figure 6 shows a typical flight plan for making background measurements at 500 m under the plume tracking mode.

3.2.2 Ground contamination measurement mode

Under the ground contamination measurement mode, the helicopter flies at 100 m above ground following the terrain at a cruising speed of about 150 km h^{-1}. A rectangular flight box over an area of interest will be defined. Neighboring flight paths are separated by 200 m within the flight box. An interlacing technique is employed in order to ensure smooth turning from one line to the other. Figure 7 shows the interlacing pattern.

4 CALIBRATION

4.1 Gamma spectrometer

When operating the NaI detectors, the gamma-ray spectrum over the energy range of 0 to about 3000 keV was resolved by the spectrometer into 255 channels. An additional channel, channel number 256, was used for registering high-energy gamma rays above 3000 keV caused by cosmic radiation. Measurements were taken every second and all data registered in each channel were digitally recorded.

Within the spectrometer, the channels were grouped into different 'windows'. Some of the windows were designated for natural radionuclides while others were for artificial radionuclides. The 'total count' window covers the range from 410 keV up to 3000 keV inclusive while the 'cosmic' window includes all high energy gamma rays above 3000 keV. Table 1 lists the energy windows used on the AMS.

4.2 Cosmic and helicopter background

The count rates due to cosmic radiation increase exponentially with height above the mean sea level in all spectral windows (IAEA, 1991). To calculate the contribution of cosmic radiation to the gamma-ray spectrum, the calibration was conducted above sea areas, so that the influence of terrestrial radiation is minimized, for instance through absorption by the water body. Calibration flights on board the Super Puma helicopter for the cosmic contribution were carried out over sea areas in the eastern part of Hong Kong. Such flights were also carried out when the prevailing flow was a maritime airstream so that the contribution of radon (which arises largely from terrestrial radiation) to all channels is negligible. The flights were conducted at altitudes from 606 m to 2730 m above sea level at 300 m intervals horizontally, with a 10-minute measurement time at each height interval.

The counts due to cosmic radiation in various spectral windows are related to the count rates in the cosmic window by a linear function (IAEA, 1991):

$$N = A + kC \qquad \text{Eqn. [1]}$$

where

- N is the count rate in the given window;
- A is the helicopter background count rate for that particular window;
- k is the cosmic stripping ratio - the counts in the given window per count in the cosmic window; and
- C is the cosmic window count rate

A plot of the counts in each window against those in the cosmic window allows A and k for each window to be determined. Figure 8 shows the calibration results for the total count, potassium, uranium and thorium windows. The values of the helicopter background and cosmic stripping ratios for each of the windows determined from the plots are listed in Table 2.

4.3 Spectral stripping and system sensitivities

The gamma-ray spectra obtained during field measurements were composed of contributions from several radionuclides. This is further complicated by scattering, which can occur in the ground, in air and in the detector itself. The spectral stripping correction removes the contributions from scattered photons and from other radionuclides, so that the readings in respect of any window only reflects counts directly arising from the radionuclide corresponding to that window. The correction only applies to windows representing a photo peak, and is not required for the total count window.

The stripping ratios are determined experimentally using three transportable concrete calibration pads containing known concentrations of K, U and Th and a background pad (Grasty *et al*, 1991). They are square in shape with dimension 1 m x 1 m x 30 cm and individual weight of approximately 675 kg. The concentrations of radioelement in the transportable concrete pads are listed in Table 3.

The calibration measurements were carried out at the apron of the Government Flying Service at Chek Lap Kok in early 2003. With the detector mounted on board the Super Puma L2 helicopter, the calibration concrete pads were positioned at a distance 1 m from the detector. The measuring time was 10 minutes. The computer program PADWIN (Grasty *et al*, 1991) is used to determine the stripping ratios of the detector and the system sensitivities for infinite sources.

The stripping ratios of the detector assembly as determined for the ground contamination mode of operation are listed in Table 4. IAEA (1991) suggested stripping ratios for a ‘good’ and a ‘poor’ system which were included in Table 4 for easy reference. It is observed that the stripping ratios of the AMS are acceptable except for the value of α which is worse than the ‘poor’ system. It can be explained by the relatively small volume of the crystal (with thickness of 4 cm only) which inherently is unable to fully stop high-energy gamma rays.

The system sensitivities for infinite sources were calculated by the computer program

PADWIN which makes use of the Monte Carlo Method to transform measurements from the concrete pads, which are finite sources, into infinite sources since the extent of any ground contamination is assumed to be infinite.

The calculated parameters are listed below:

Window	Sensitivity
K	30.5 cps per %K
U	3.7 cps per ppm eU
Th	1.74 cps per ppm eTh

For data processing purpose, they are expressed as sensitivities in radioactivity concentration as follows:

Window	Sensitivity (cps per Bqkg^{-1})
K	0.10
U	0.30
Th	0.43

4.4 Height attenuation coefficients

The values of the attenuation coefficients for each window can be determined by making a series of flights at different heights over a flat area with uniform concentrations of potassium, uranium and thorium. The 2-km long runway at Shek Kong in the northwestern part of the New Territories was chosen to be the calibration range. The flying heights ranged from 60 m to 240 m and measurements were made at 30 m intervals. This range of altitudes covered those adopted in normal survey operation. Flights at the same heights over water were also flown, and measurements taken so that contributions from atmospheric radon and from the helicopter itself could be subtracted.

The mean count rates of the total count, K, U and Th windows were first calculated for each flying height over water. The same calculations were repeated for those obtained over the runway. The values over water were then subtracted from those over the runway. This removed contributions from cosmic radiation, atmospheric radioactivity and the aircraft's own background radioactivity.

The average air temperature and pressure as well as the aircraft altitude were determined simultaneously during each flight line. The equivalent height of the aircraft at standard temperature and pressure (STP) was then determined from the expression:

$$H_e = H\,[273.15/(T+273.150)]\,[P/1013.25] \qquad \text{Eqn. [2]}$$

where

- H is the observed height,
- H_e is the equivalent height at STP,
- T is the air temperature in °C, and
- P is the barometric pressure in mbar.

The stripped count rates at each altitude were then fitted to the exponential function

$$N_h = N_0\, e^{-\mu h} \qquad \text{Eqn. [3]}$$

to give the height attenuation coefficient for each window. Figure 9 shows the exponential curves for all four windows. The height attenuation coefficients for the system were determined to be:

Window	Height attenuation coefficient (per metre at STP)
Total count	-0.0065
K	-0.0073
U	-0.0052
Th	-0.0071

5 SURVEY RESULTS AND CONCLUDING REMARK

5.1 Background flight for plume tracking

Measurement of the background radiation level at 500 m was completed in 2003. After removing fictitious data such as spikes or gaps, a contour map of the background count rates at 500 m above sea level was produced (Figure 10).

5.2 Background flight for ground contamination check

Using the calibration parameters in Section 4, the raw data obtained in ground contamination check were processed according to the steps in the flowchart in Figure 11. Thorium concentrations at the two remote islands, namely Kat O and Po Toi, were calculated and mapped as shown in Figure 12 and 13, respectively. The thorium concentration at Po Toi is found to be higher than that at Kat O. The measurement results show a good correlation with the geochemical map for thorium (Figure 14, from Sewell, 1999). Similar results were obtained for uranium. They are presented in Figure 15 – 17 respectively.

A map of activity concentration of K-40 at Kat O is presented in Figure 18. The concentration was found to range from 300 to 700 Bq kg^{-1} over land with a majority of readings at around 400 Bq kg^{-1}. This agreed very well with the value of 411 ± 23 Bq kg^{-1} obtained by laboratory measurements of sampled land soil at Kat O (Hong Kong Observatory, 1994).

The activity concentrations of the natural radionuclides (K-40, U-238 and Th-232) were used to evaluate the environmental gamma absorbed dose rate in air at the average gonadal height of 1 m above the ground, using the formula by Beck *et al.* (1972):

$$D = 0.429\ A_U + 0.666\ A_{Th} + 0.042\ A_K \qquad \text{Eqn. [4]}$$

where 0.429, 0.666 and 0.042 are the dose rate factors for U-238, Th-232 and K-40 respectively.

Maps of the environmental gamma absorbed dose rate in air at Kat O and Po Toi are presented in Figure 19 and 20 respectively.

5.3 Concluding remark

The AMS was operated onboard a new helicopter since 2003. The system was re-calibrated and the data processing procedures have been updated. Using the new calibration parameters, results of activity concentrations measured on board the new helicopter agreed very well with those obtained by sampling and laboratory measurements. This corroborates the system's capability in rapid surveillance of local radiation levels.

ACKNOWLEDGEMENTS

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* The Hong Kong Observatory was listed as ‘Royal Observatory Hong Kong’ in publications released before 1 July 1997.

Window name		Start channel	End channel	Major peak (keV)	Radionuclide
Total count		34	255		
NATURAL	Potassium	111	137	1460	K-40
	Thorium	202	242	2615	Tl-208
	Uranium	135	165	1765	Bi-214
ARTIFICIAL	Cesium	48	64	662	Cs-137
	Cobalt	88	110	1173	Co-60
	Iodine	25	36	364	I-131
	Ruthenium	37	48	497	Ru-103
Cosmic		256	256		

Table 1 Energy windows used on the gamma spectrometer for the Aerial Monitoring System

Energy window	Helicopter background (counts per second)	Cosmic stripping factor (counts per cosmic count)
Total count	13	3.5
Potassium	2.7	0.25
Uranium	0.47	0.11
Thorium	0.07	0.23
Upward uranium	5.5	0.26

Table 2 Helicopter background and cosmic stripping factors

Pad	K (pct)	eU (ppm)	eTh (ppm)
Blank	1.41 ± 0.01	0.97 ± 0.03	2.26 ± 0.10
K-pad	8.71 ± 0.09	0.32 ± 0.02	0.74 ± 0.10
U-pad	1.34 ± 0.02	52.9 ± 1.0	3.40 ± 0.14
Th-pad	1.34 ± 0.02	2.96 ± 0.06	136.0 ± 2.1

Table 3 Concentrations of radioelements in the transportable concrete pads

Stripping ratio	AMS on board Super Puma L2 helicopter	Good system (IAEA, 1991)	Poor system (IAEA, 1991)
α (Th into U)	0.47	0.25	0.38
β (Th into K)	0.40	0.4	0.43
γ (U into K)	0.51	0.81	0.92
a (U into Th)	0.07	0.06	0.09
b (K into Th)	0.007	0	0.01
g (K into U)	0.023	0.003	0.06

Table 4 Tripping ratios of the AMS and values for ‘good’ and ‘poor’ systems

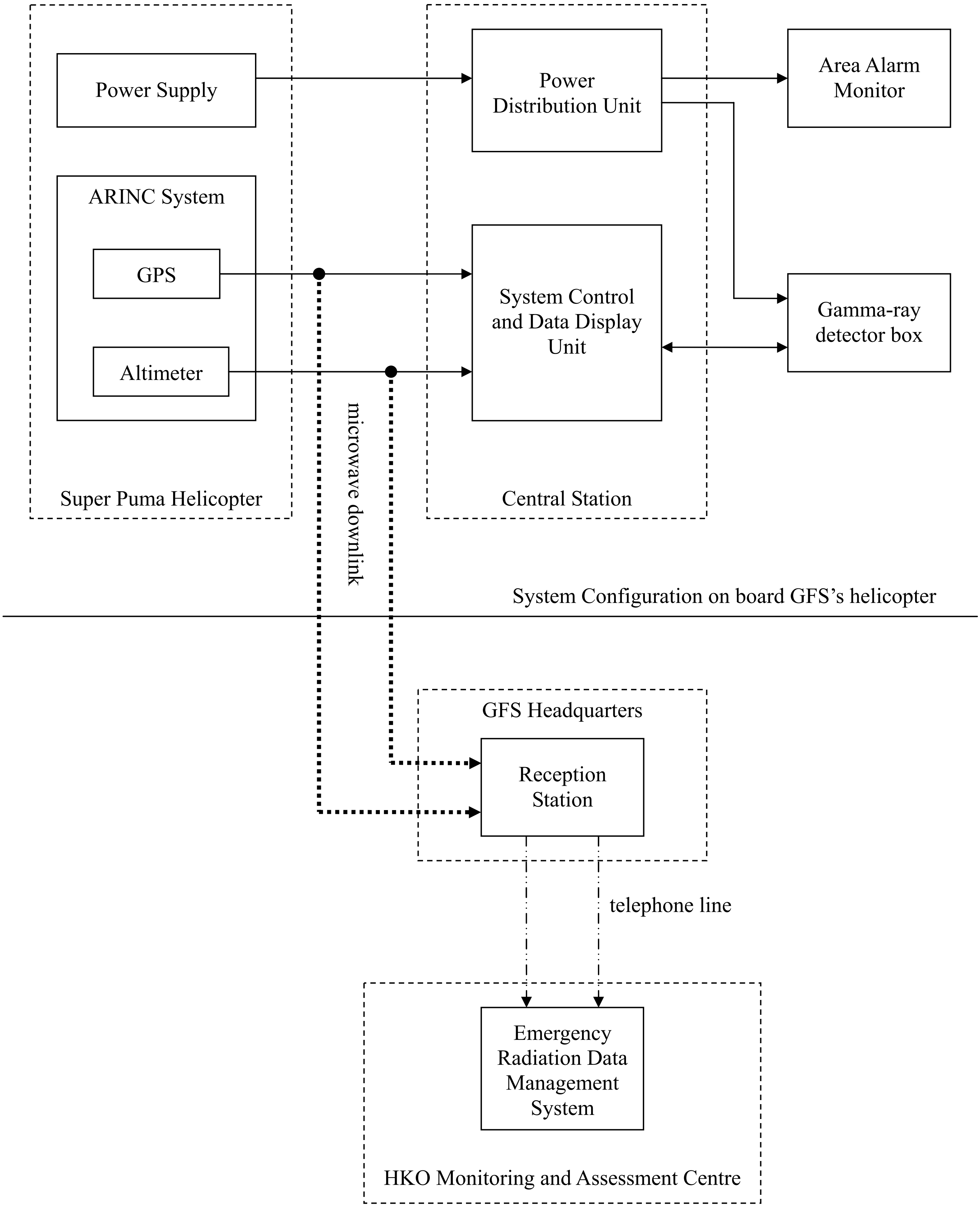

Figure 1 Schematic diagram of the Aerial Monitoring System

Figure 2 Arrangement of the Aerial Monitoring System on board the Super Puma L2 helicopter

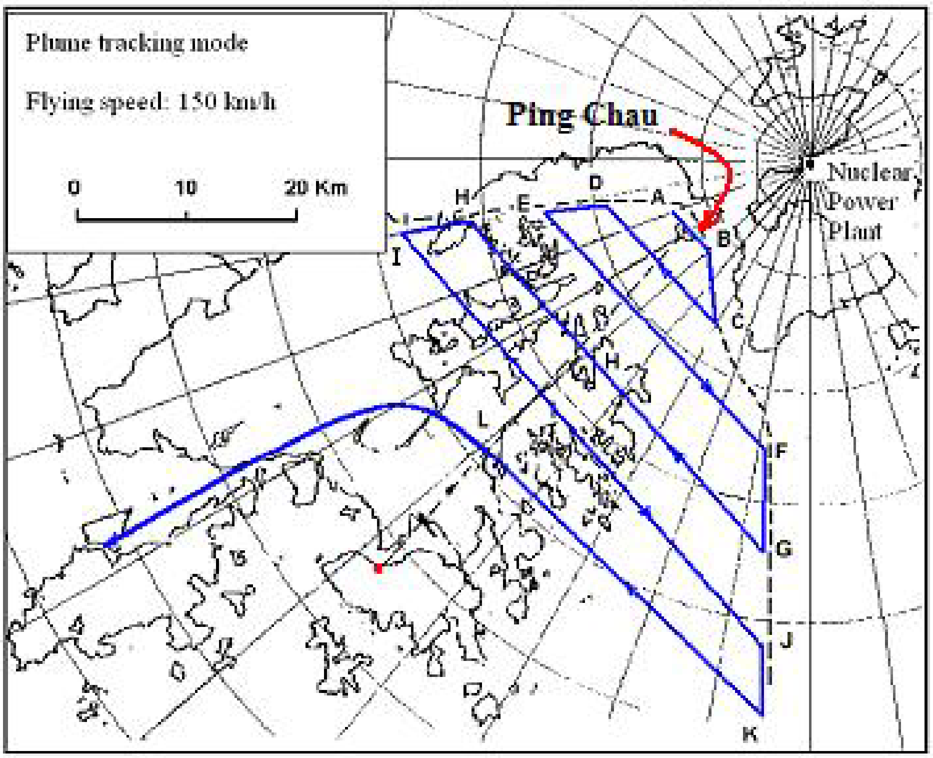

Figure 3 Flight pattern for searching radioactive plume

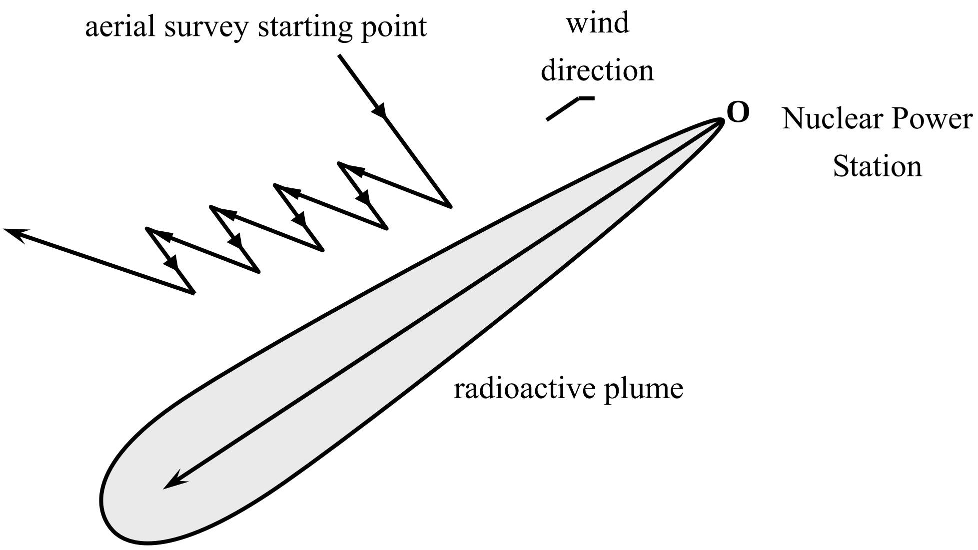

Figure 4 A typical flying pattern for tracking a radioactive plume

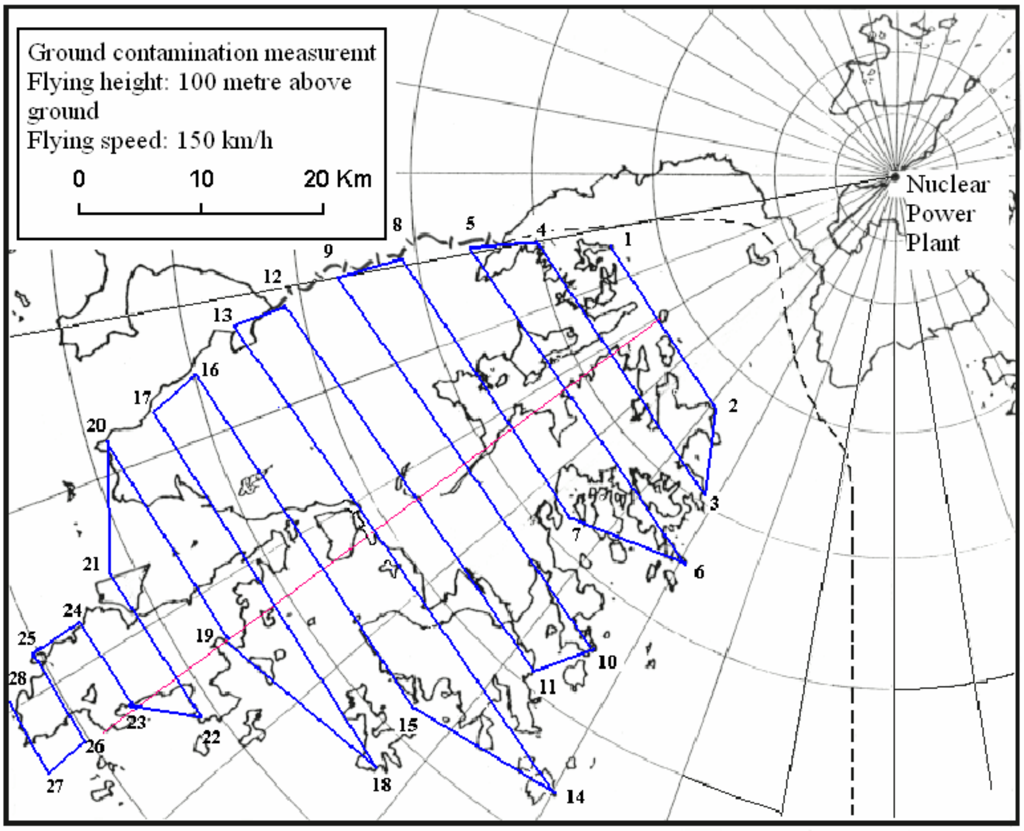

Figure 5 Fast scanning flying pattern for ground contamination measurement

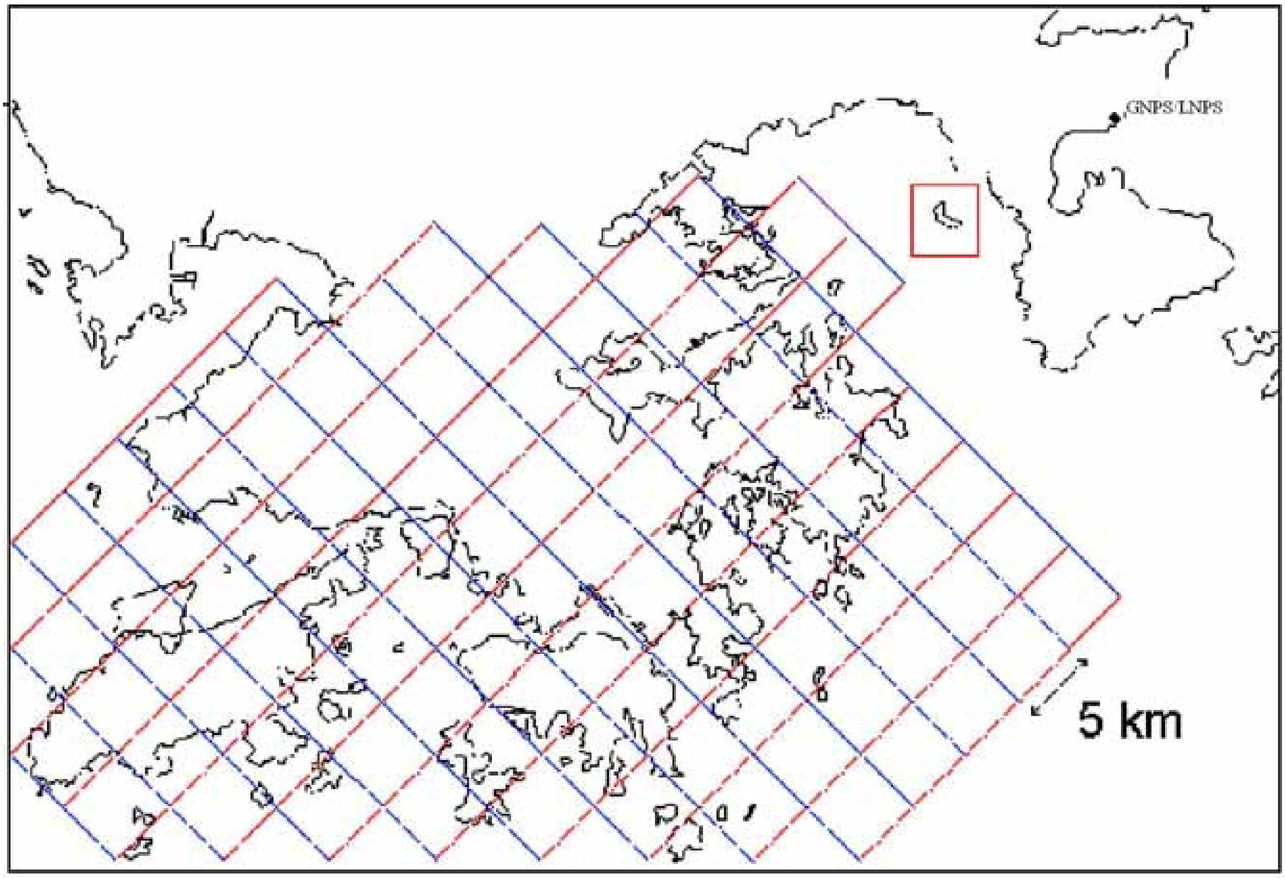

Figure 6 Flight pattern for background measurement under the plume tracking mode

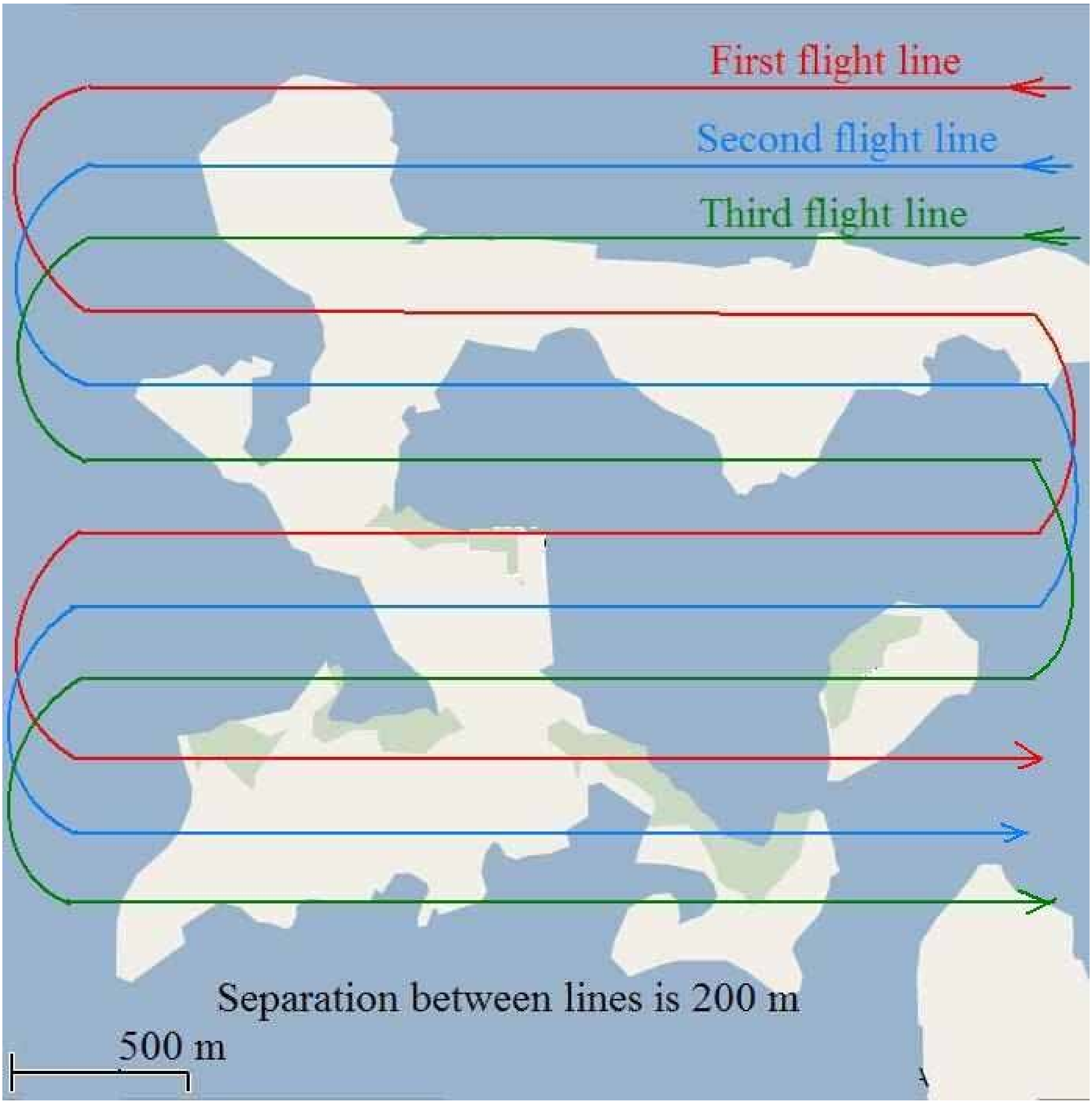

Figure 7 An example of flight lines for ground contamination measurement over the island of Kat O. An interlacing pattern is adopted in which the helicopter makes a 180-degree turn over a distance of 600 m. The separation between the flight lines is 200 m.

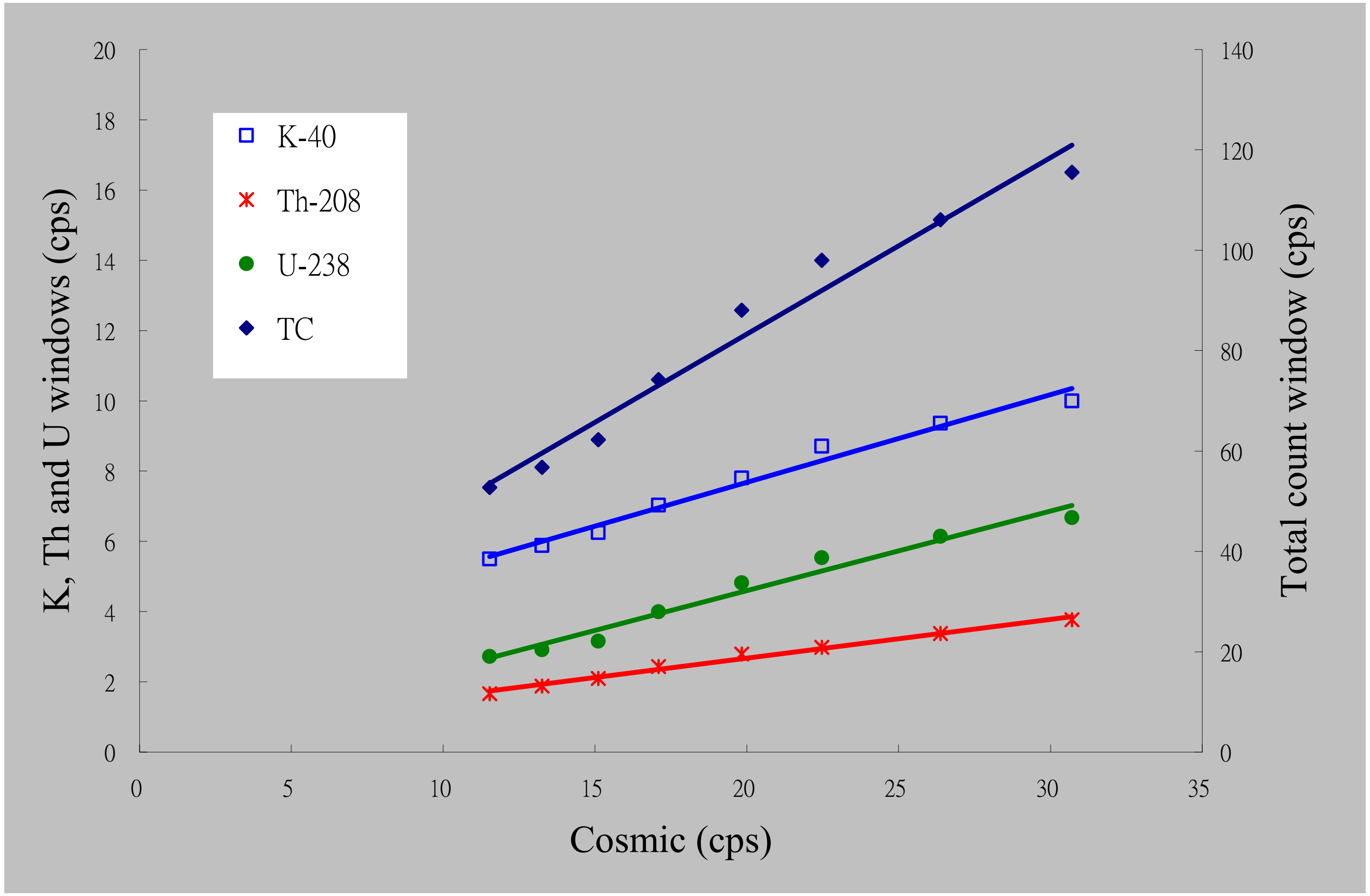

Figure 8 Cosmic calibrations for total count (TC), Potassium (K), Thorium (Th) and Uranium (U) windows

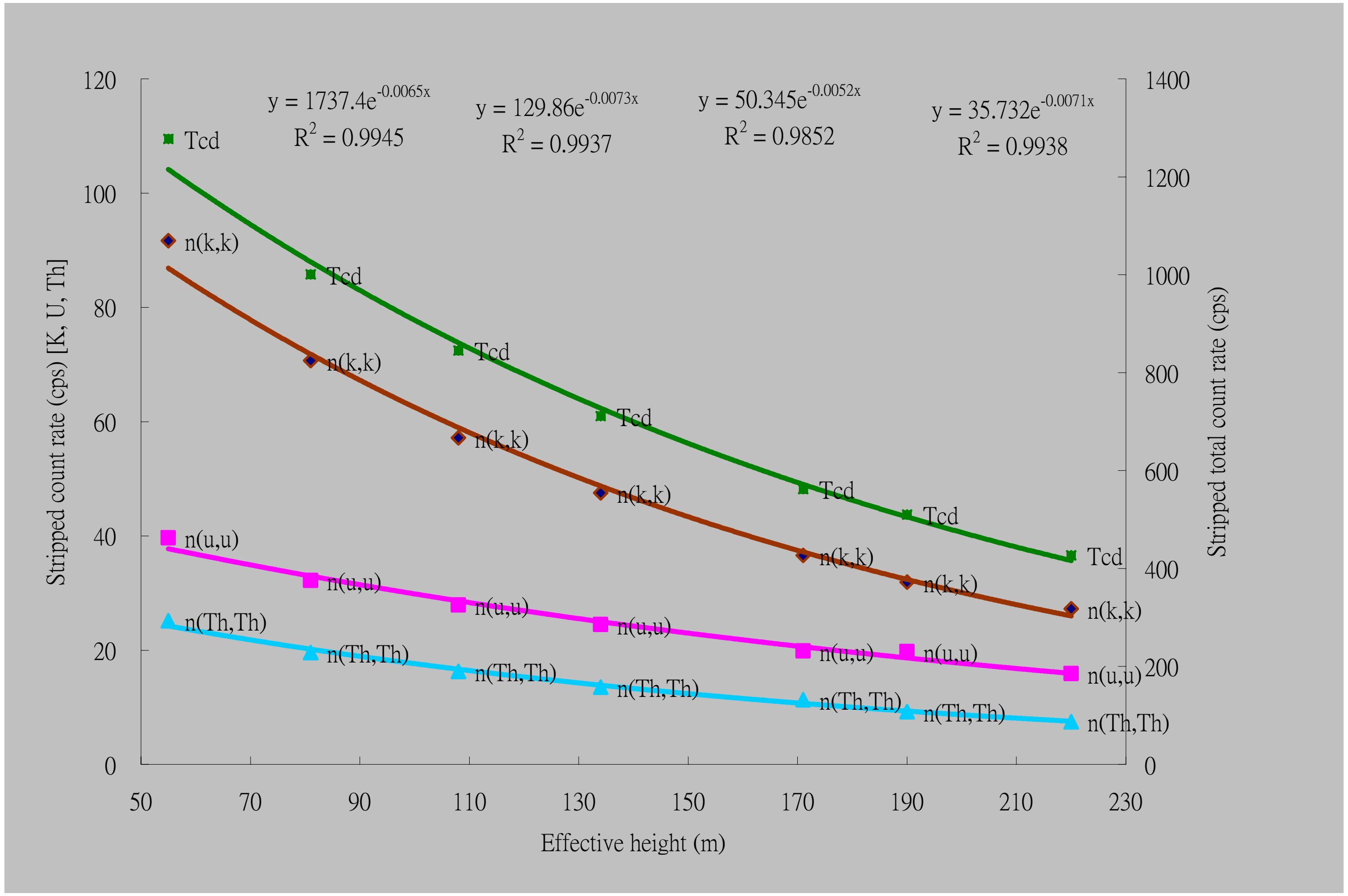

Figure 9 Exponential height attenuation for total count (TC), Potassium (K), Uranium (U) and Thorium (Th) windows

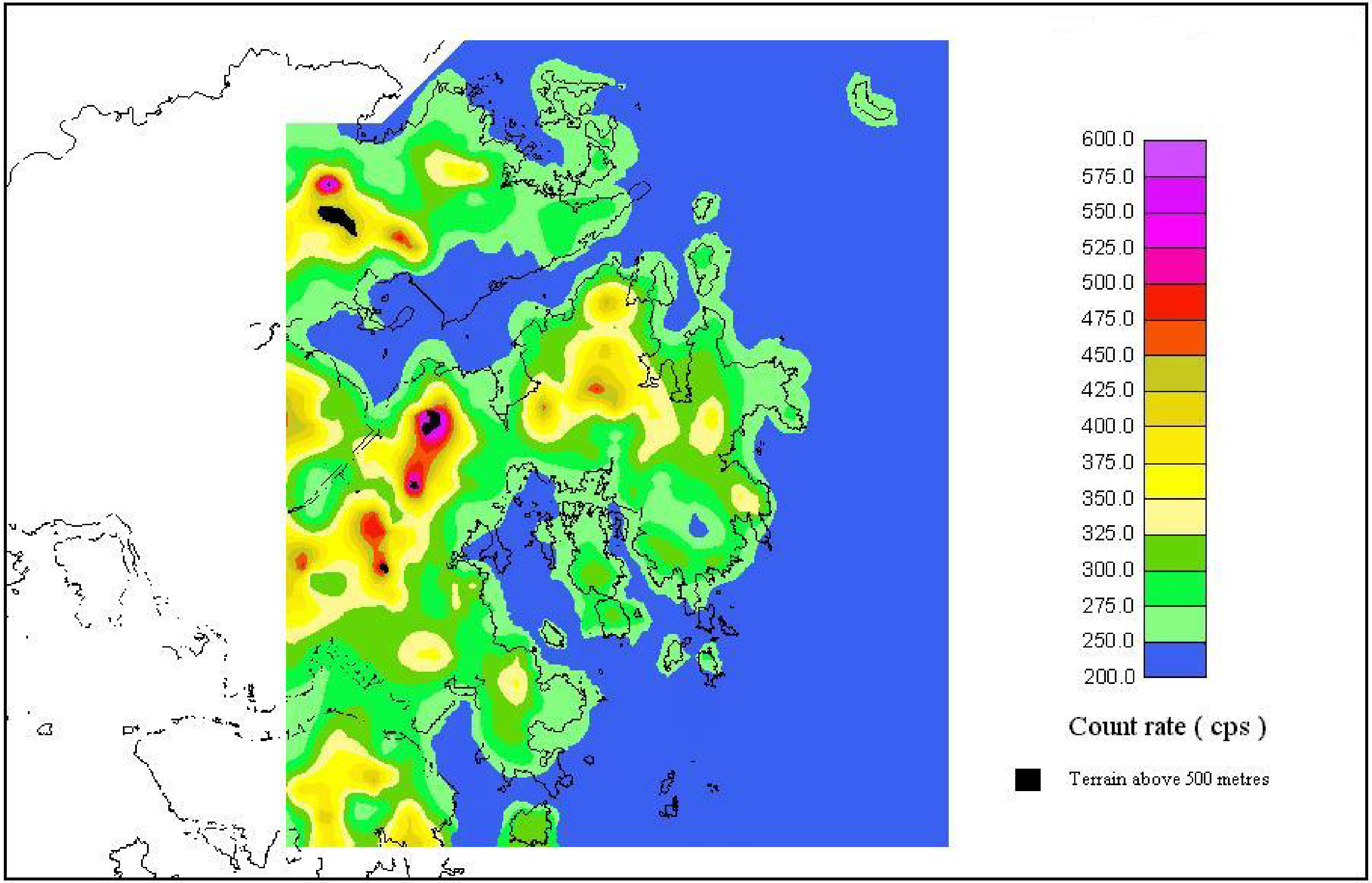

Figure 10 Contour map of the background count rates measured at 500 metres above sea level (survey conducted in 2003)

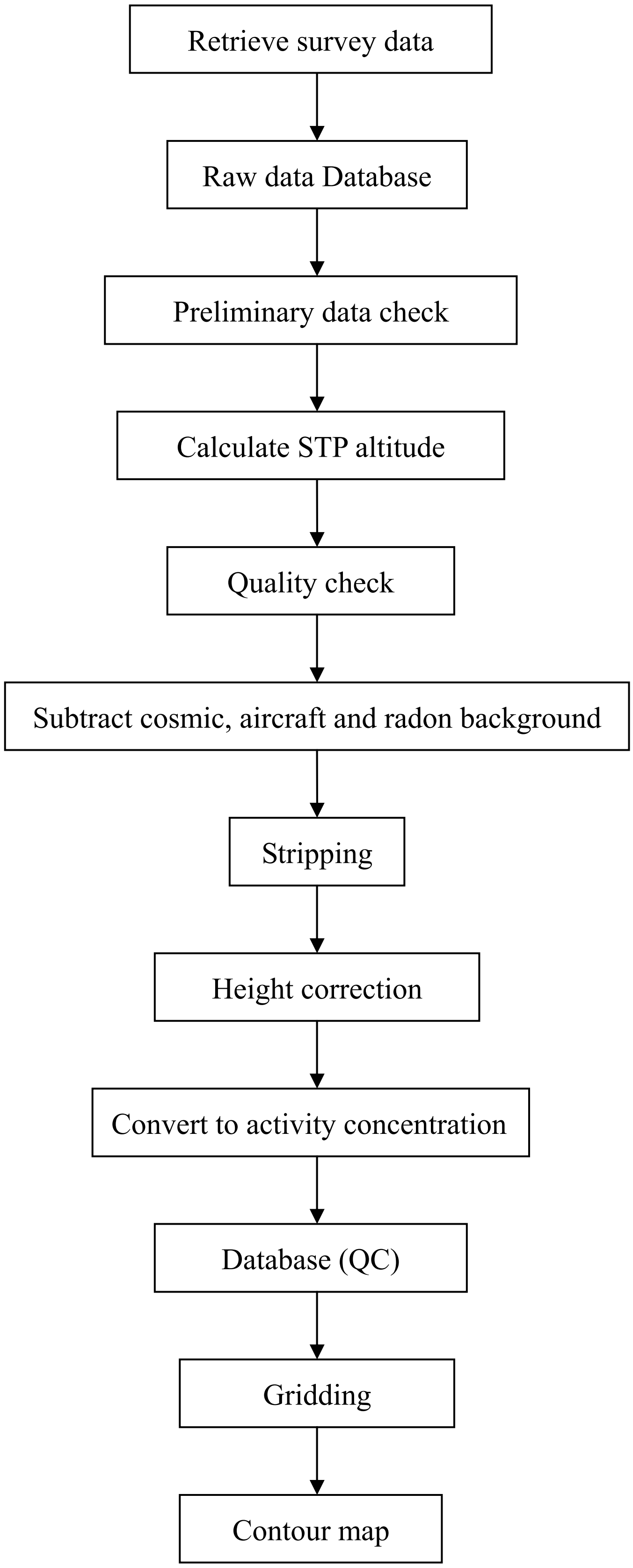

Figure 11 Flowchart for spectrometer data processing

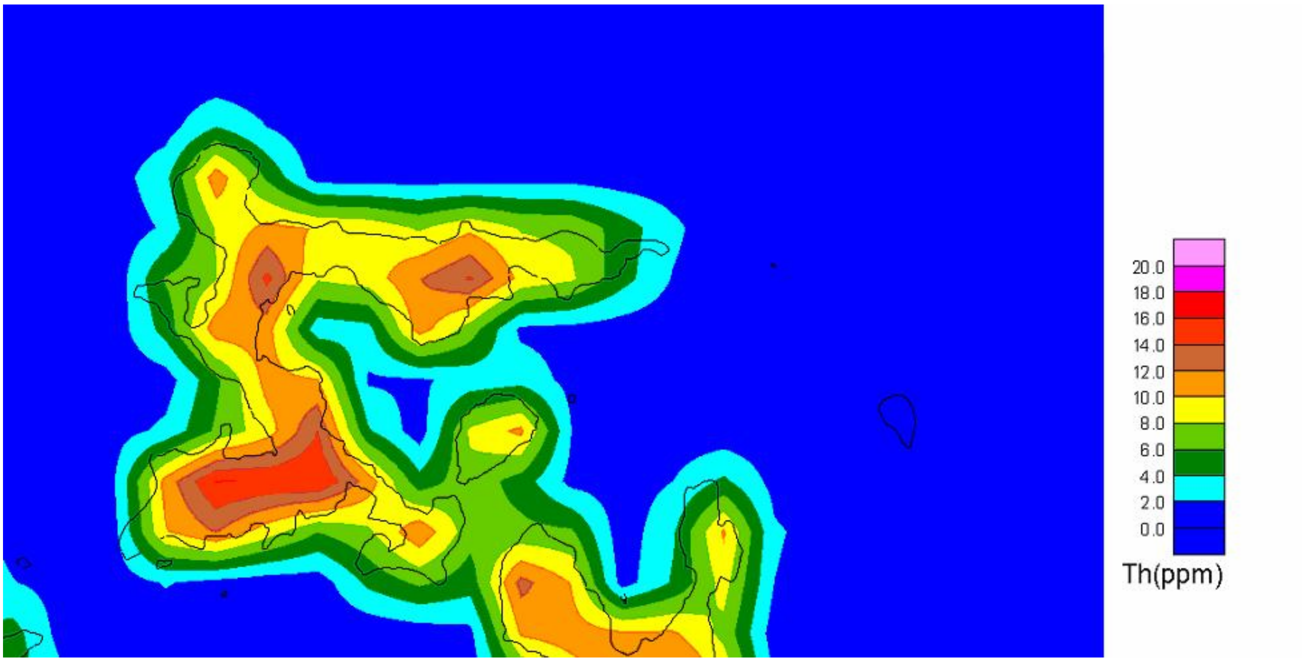

Figure 12 Contour map of the radioelement Thorium at Kat O
(survey conducted in 2004)

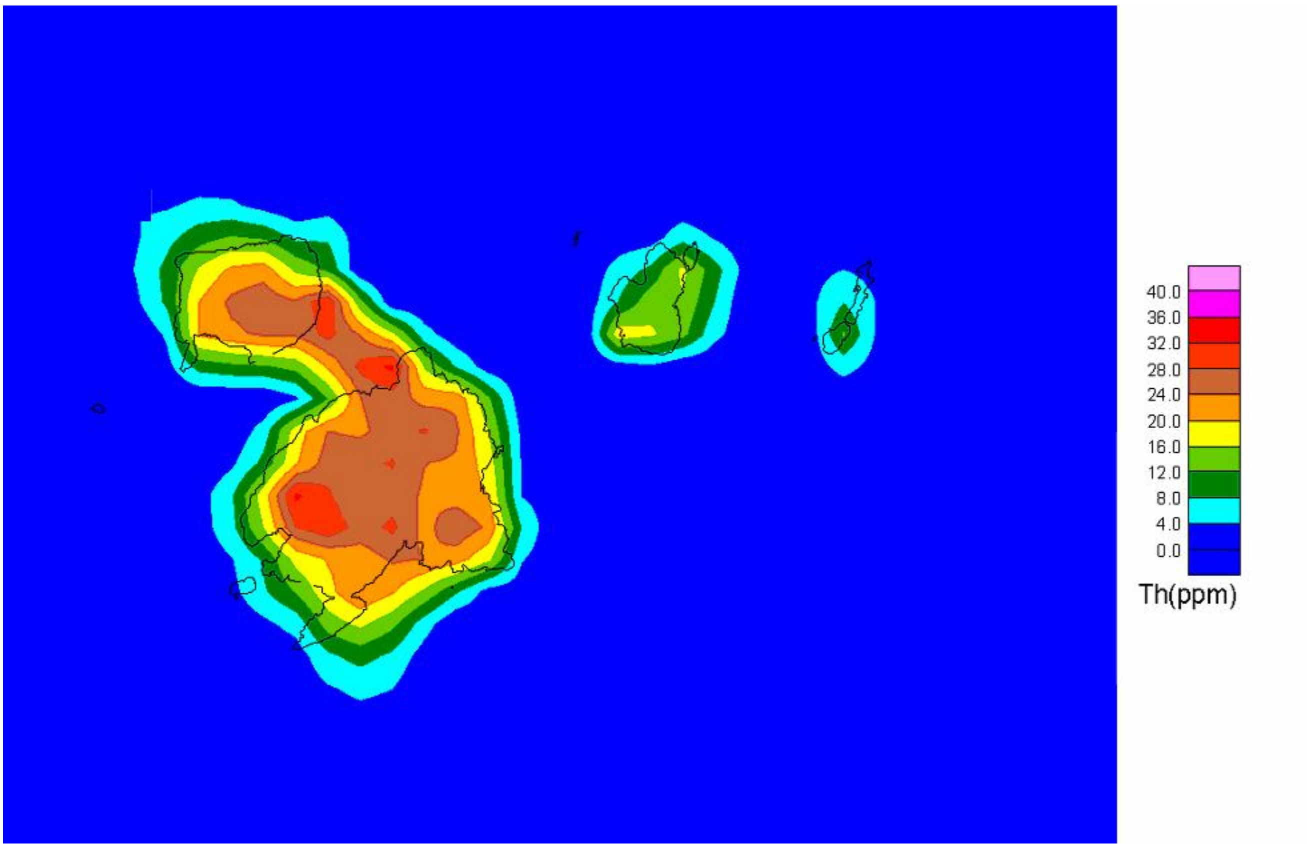

Figure 13 Contour map of the radioelement Thorium at Po Toi
(survey conducted in 2005)

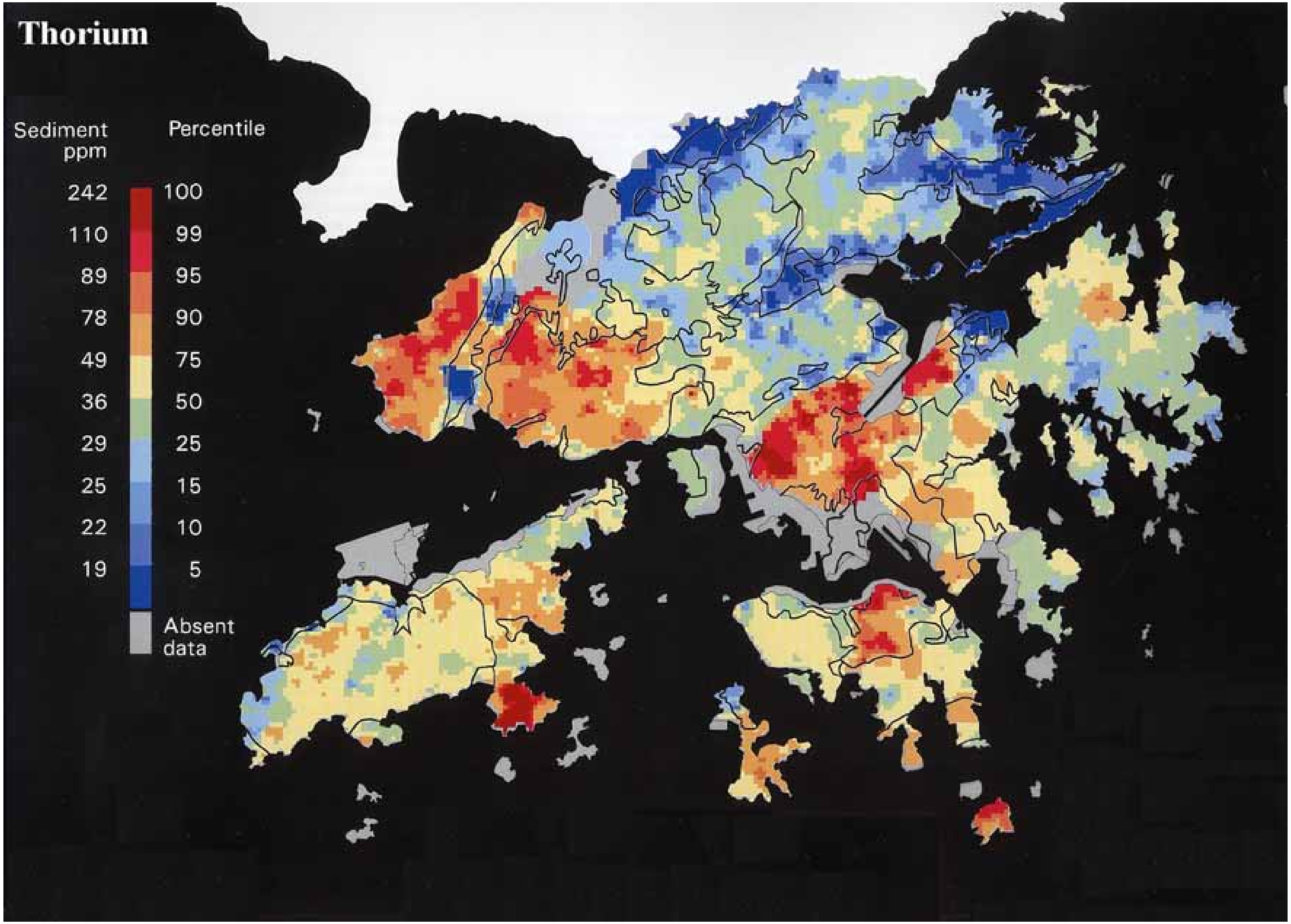

Figure 14 Geochemical map of Thorium (Sewell, 1999)

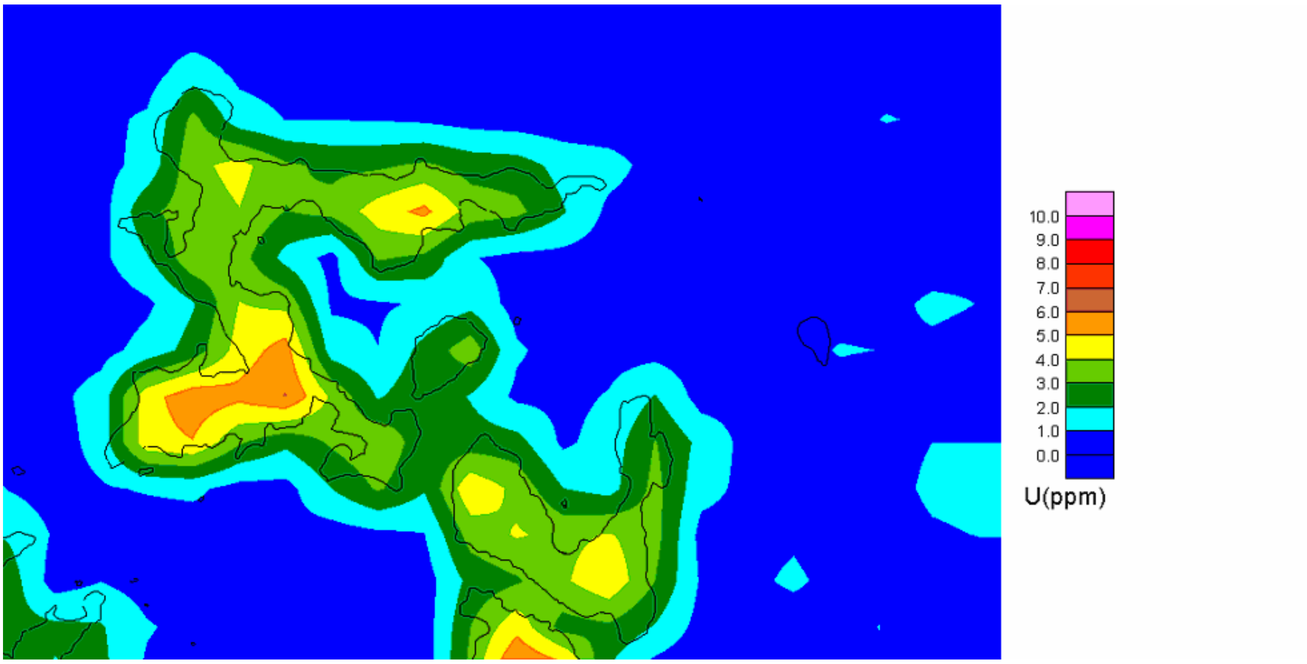

Figure 15 Contour map of the radioelement Uranium at Kat O
(survey conducted in 2004)

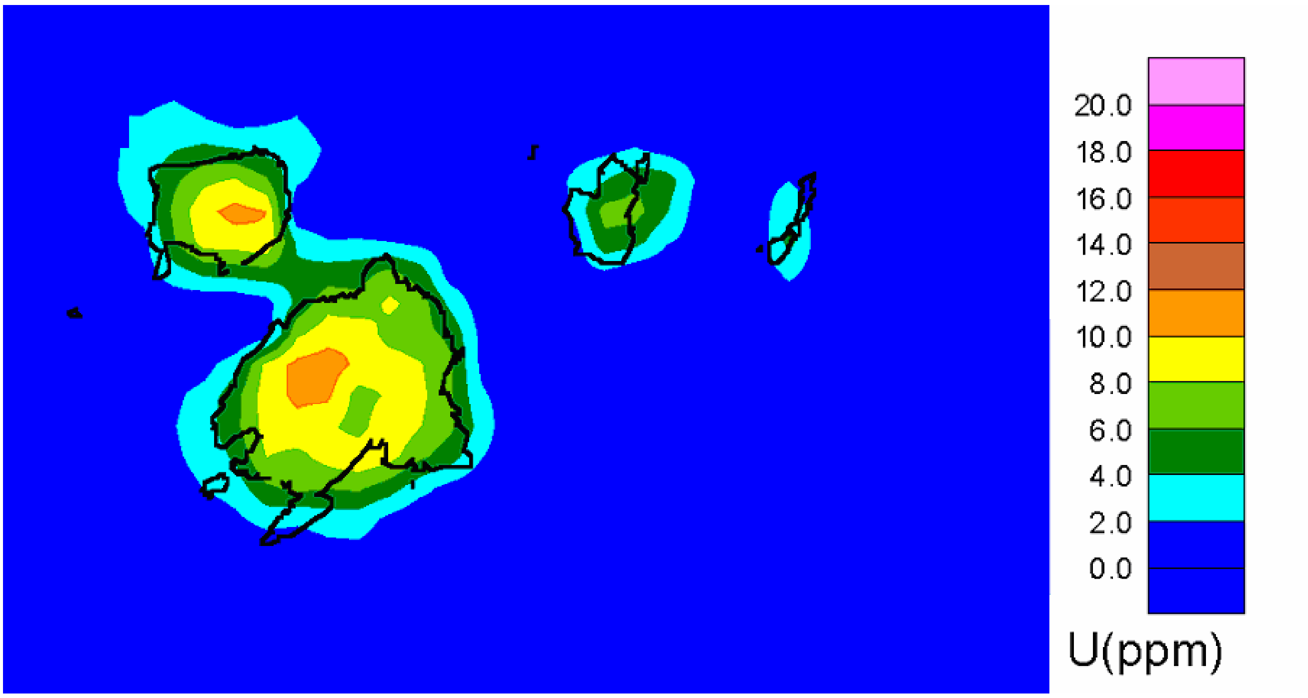

Figure 16 Contour map of the radioelement Uranium at Po Toi
(survey conducted in 2005)

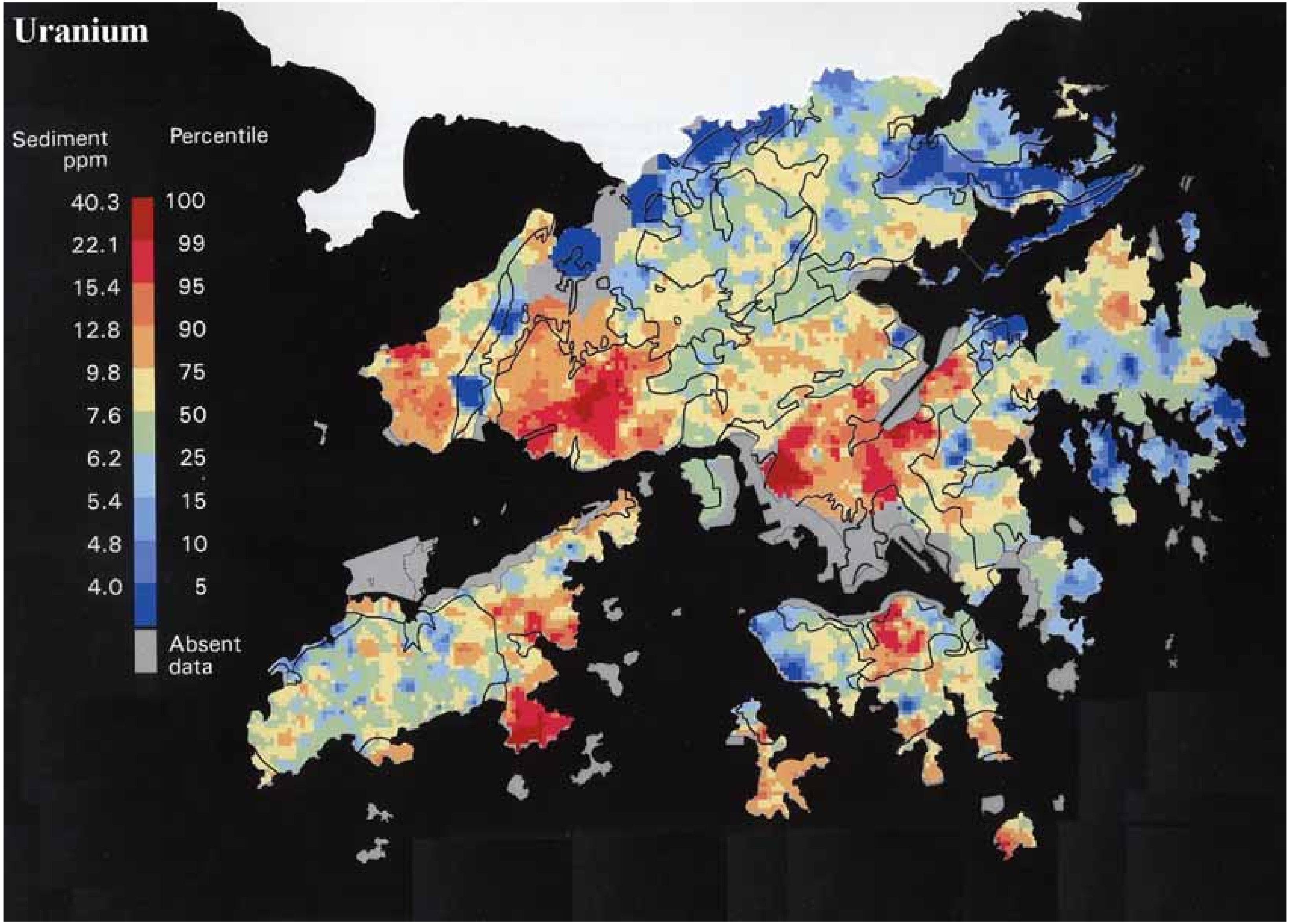

Figure 17 Geochemical map of Uranium (Sewell, 1999)

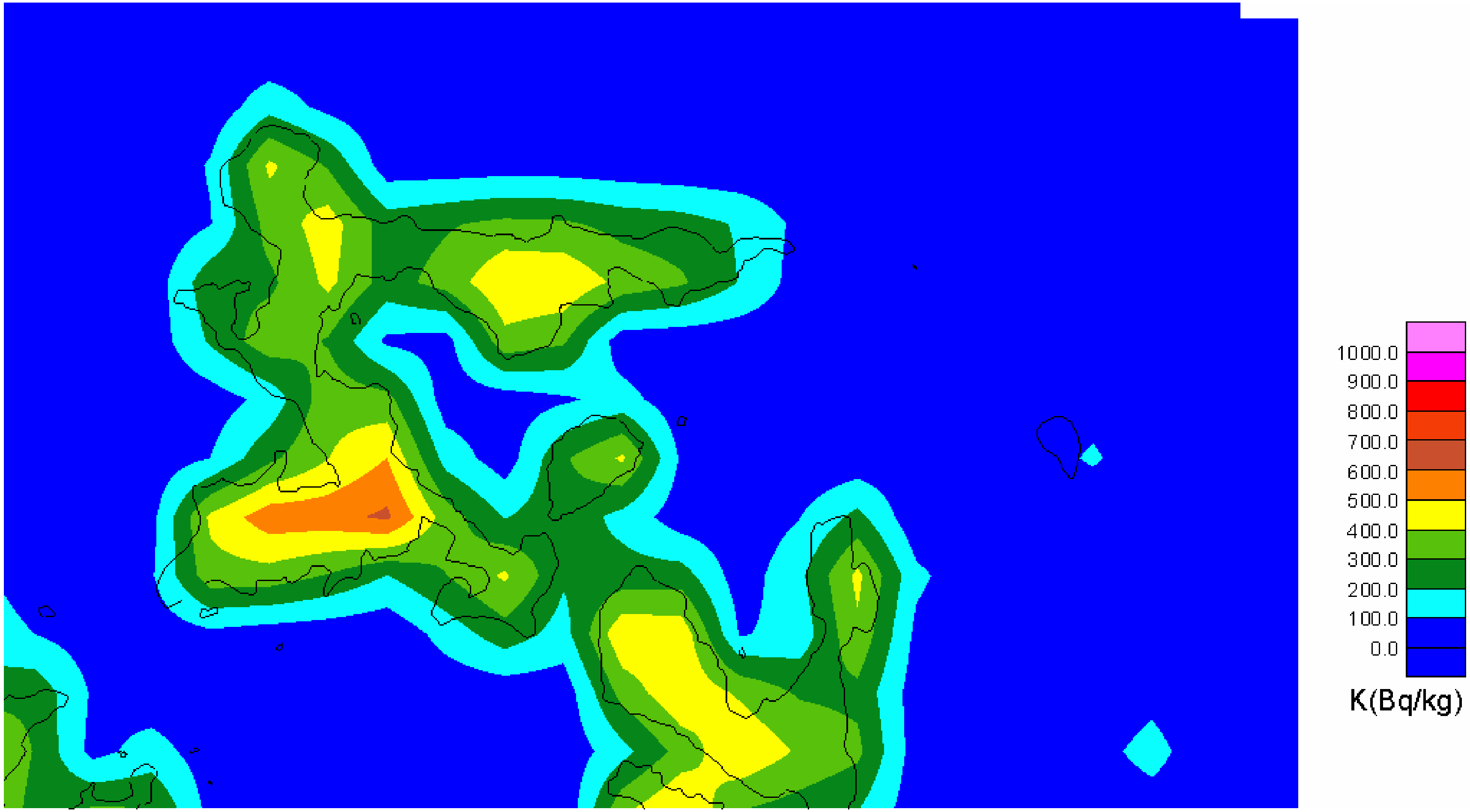

Figure 18 Contour map of the background activity concentration of K-40 at Kat O (survey conducted in 2004)

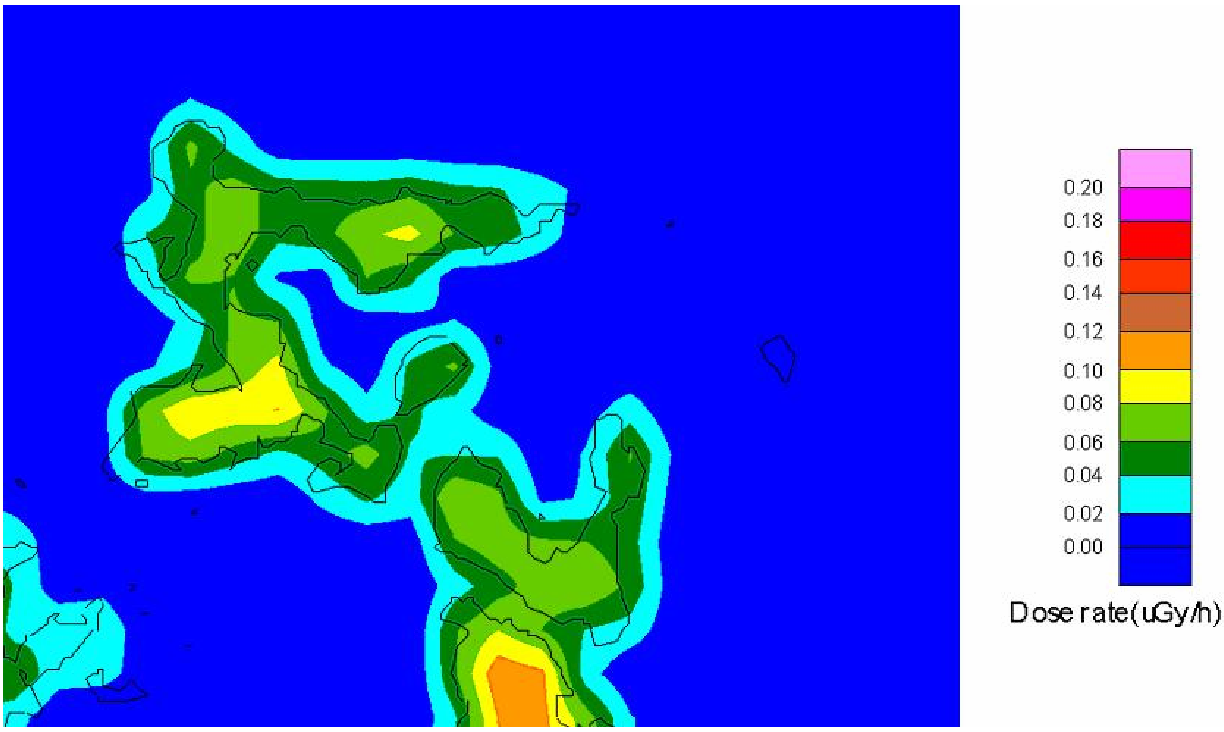

Figure 19 Contour map of environmental gamma absorbed dose rate in air at Kat O (survey conducted in 2004)

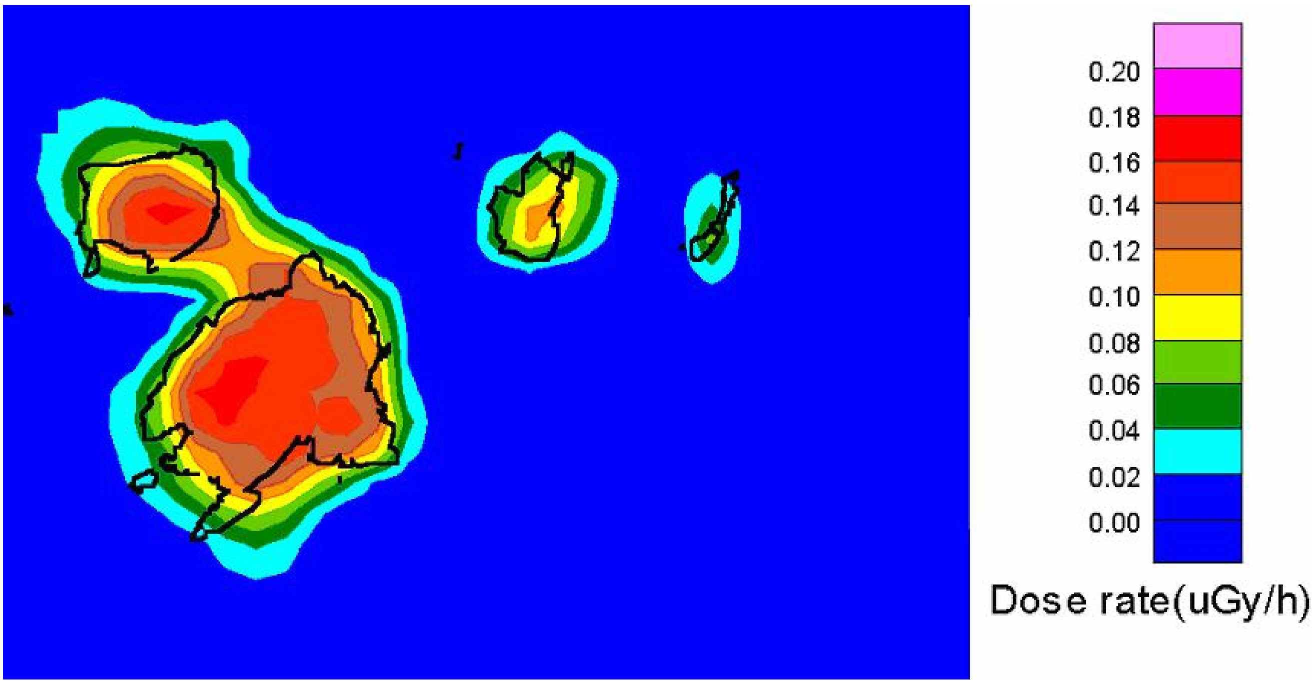

Figure 20 Contour map of environmental gamma absorbed dose rate in air at Po Toi (survey conducted in 2005)