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GAMMA RAY SPECTROMETER
SURVEYING
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FOREWORD

Airborne gamma ray spectrometry has become, over the years, a mainstay in the armoury of the uranium explorationist. The technique has reached a high degree of maturity and sophistication since its was first used in the 1960s. The applications of the method have expanded considerably, particularly in the 1980s, which saw the development of new interest in the natural radiation of the environment and in the impact of radon in houses. Members of the mineral exploration community have developed an awareness of the relationship between the radioelements potassium, uranium and thorium (and their radioactive decay products), and other mineral commodities such as gold, tungsten, molybdenum, copper etc. Most recently, the nuclear reactor accident at Chernobyl in the USSR led to the employment of airborne gamma ray spectrometry in mapping the fallout, and to the demonstration of the power of the technique to map rapidly and sensitively the wide range of nuclides resulting from man's nuclear activities.

The International Atomic Energy Agency (IAEA) in its role as collector and disseminator of information on nuclear techniques has long had an interest in gamma ray spectrometer methods and has published a number of Technical Reports on various aspects of the subject. At an Advisory Group Meeting held in Vienna in November 1986 to review appropriate activities the IAEA could take following the Chernobyl accident, it was recommended that preparation begin on a new Technical Report on airborne gamma ray spectrometer surveying, taking into account the use of the technique for environmental monitoring as well as for nuclear emergency response requirements. Shortly thereafter the IAEA became the lead organization in the Radioelement Geochemical Mapping section of the International Geological Correlation Programme/United Nations Educational, Scientific and Cultural Organization (UNESCO) Project on International Geochemical Mapping. These two factors led to the preparation of the present Technical Report.

The preparation of the manual was the work of three consultants well known in the field: R.L. Grasty of the Geological Survey of Canada, H. Mellander, formerly of the Swedish Geological Company, now with the Swedish National Institute of Radiation Protection, and M. Parker, formerly with Hunting Geology and Geophysics Limited, now with the Eastern and Southern Africa Mineral Resources Development Centre.

The IAEA wishes to express its sincere thanks to these three individuals for their excellent work in the preparation of the manual and would also like to thank the Geological Survey of Canada for the preparation of the figures. The IAEA staff member responsible for the project was A.Y. Smith, formerly of the Division of Nuclear Fuel Cycle and Waste Management.
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1. INTRODUCTION

Modern uranium exploration techniques advanced significantly with the development of modern electronic instruments to measure the natural radioactivity of the surface of the Earth. The first such instrument, the Geiger-Müller counter, was relatively insensitive and could be used only in a qualitative way. Early surveys were carried out initially with one tube, but later multiple tubes were employed. In the 1950s, with the development of the scintillator based on the sodium iodide crystal gamma ray detector, measurement sensitivity increased considerably. This increase in sensitivity encouraged workers to attempt not only to measure radioactivity, but to relate it to the concentration and distribution of the naturally occurring radioelements, particularly uranium. The introduction of the gamma ray spectrometer in the mid-1960s made it possible to conduct direct, in situ analyses of radioelement concentrations of potassium, uranium and thorium in bedrock in the field.

1.1. MEASURING RADIOACTIVITY FROM THE AIR

Gamma ray surveys have come to be used for purposes other than uranium exploration. For the geologist, maps of the concentration of potassium, uranium and thorium in the rocks and soils can improve geological mapping and help to locate mineral deposits of gold, tin and tungsten where the mineralizing process is often accompanied by potassium metasomatism. For an environmental physicist, maps of background radiation provide a means to measure the risk to health and a baseline against which man-made contamination can be measured. After a nuclear accident, maps of the fallout pattern are essential for planning emergency responses and for restricting the sale of agricultural produce.

For all these purposes, the effectiveness of radioactivity measurements conducted from aircraft are unequalled. These measurements rely on the detection of the gamma rays produced by radioactive decay and are possible because the energy of gamma radiation produced by the decay of a particular nuclide is characteristic. If we measure the energies of the gamma rays reaching detectors in an aircraft, we can determine the activity of radioactive sources in the soil and rocks, as well as that lying on the surface or taken up by the vegetation. Airborne gamma ray spectrometry (AGRS) is the technique used to measure the energy spectrum and intensity of the radiation.

Regional gamma ray spectrometer surveys have been made in a number of countries. All of the continental United States of America was surveyed during the National Uranium Resource Evaluation (NURE) programme. Since the early 1970s the Geological Survey of Canada (GSC) has flown over extensive areas of the country using a high sensitivity gamma ray spectrometer instrument. This equipment was
used with great success to locate the fallout from the Soviet satellite Cosmos-954, which fell in northern Canada in 1978. Wide regional airborne radiometric coverage has been obtained in a number of other countries as well, including Finland, Germany, Sweden and many of the Eastern European nations. Under United Nations Development Programme sponsorship, many developing countries have also been surveyed. An outstanding example of the utility of AGRS measurements was given by the Swedish Geological Company (SGAB) in 1986, when the extent of the contamination and distribution of individual radioelements coming from the Chernobyl nuclear reactor accident was mapped rapidly and efficiently with SGAB airborne gamma ray spectrometer equipment.

1.2. PURPOSE AND SCOPE OF THE REPORT

The purpose of this report is to provide those interested in AGRS with an up-to-date review of AGRS instrumentation and practice conducted by government geological surveys, exploration and mining organizations, environmental organizations and those concerned with radiation protection field measurements.

Section 2 of this report provides a very brief outline of the physics of gamma rays and the principles of instrumentation used to detect them. The emphasis is on those aspects relevant to the practicalities of AGRS. Section 3 deals with the main airborne survey parameters such as flight line direction and spacing, detector volume and also with operational procedures during fieldwork. Auxiliary instrumentation used on spectrometric surveys is discussed as well.

Section 4 considers all aspects of calibration that are required to convert the airborne measurements to ground concentrations of potassium, uranium and thorium. The various topics covered include: calibration of radar altimeter and barometric pressure transducer, determination of equipment dead time and of cosmic, aircraft and radon backgrounds, evaluation of stripping ratios and height attenuation coefficients, and finally determination of system sensitivities.

The quality control goals and procedures are described in Section 5 as they apply mainly to spectrometric mapping of the distribution of natural radioelements or of fallout. Three types of variables requiring monitoring to ensure high quality radiometric data are discussed: instrumental, operational and environmental. Section 6 discusses processing requirements and procedures for natural radioelement mapping. Many of the calibrations and determinations are described in Sections 4 and 5. These include the daily quality control tests and checks which should be compiled in the field, together with any calibrations and determinations which are carried out during fieldwork. The products of natural radioelement mapping by AGRS are discussed in Section 7. These include profiles and profile maps, gridded contour maps, the digital data archive and reports.
Section 8 is devoted to the use of AGRS for environmental monitoring. The mapping of the Chernobyl fallout in Sweden is briefly described, followed by a discussion of the instrumental, calibration, processing and output requirements for environmental and emergency response monitoring. Section 9 describes briefly the use of AGRS surveying methods to locate lost radioactive objects and sources. Several cases are described, including the location of a lost $^{60}$Co source in the USA and the search for the fallout from the Soviet satellite Cosmos-954 in Canada. A discussion of system sensitivities and search strategy ends the section.

The Appendix provides a model of detailed specifications for contracting an AGRS survey, both for data acquisition and data processing. Specifications for an airborne magnetometer survey are included as well since the two methods are most frequently combined in one survey. Finally, a selected Bibliography is given, listing the most important literature on the various aspects of AGRS covered in the report.
2. PRINCIPLES OF AIRBORNE GAMMA RAY SPECTROMETRY

This section outlines briefly the physics of gamma rays and the principles of instrumentation used to detect them. The emphasis is on aspects relevant to the practical details of AGRS. For detailed accounts of these topics the reader should consult the texts noted in the Bibliography.

2.1. GAMMA RADIATION

2.1.1. Radioactive decay

There are many naturally occurring radioactive elements. However, only three have isotopes that emit gamma radiation of sufficient intensity to be measured by AGRS. These three major sources of gamma radiation are:

(a) Potassium-40 which is 0.0118% of total potassium,
(b) Daughter products in the $^{238}\text{U}$ decay series,
(c) Daughter products in the $^{232}\text{Th}$ series.

Many man-made radioactive isotopes also emit gamma radiation which can be measured by AGRS. These man-made isotopes are produced by nuclear reactors or are the result of atomic weapons testing programmes.

High energy cosmic rays produced outside the Earth's atmosphere can also be detected by AGRS. This cosmic radiation interacts with the molecules of the atmosphere, the aircraft structure and the detector itself to produce a variety of high energy radiation. This cosmic ray component increases exponentially with the height above sea level.

2.1.2. Gamma ray spectra

The energies of gamma rays produced by radioactive decay are characteristic of the decaying nuclide. For example $^{40}\text{K}$ decays to $^{40}\text{Ar}$ with the emission of gamma rays at 1460 keV. Gamma ray spectrometers are designed to measure the intensity and energies of gamma rays and hence the abundance of particular radioactive nuclides.

Figures 1, 2 and 3 show the gamma ray spectra for potassium, the uranium series and the thorium series. The spectra were obtained with a typical airborne spectrometer system on large concrete calibration pads at Walker Field, Grand Junction, Colorado in the USA. The concrete pads were doped with known concentrations of
FIG. 1. Gamma ray spectrum of potassium. The positions of the three radioelement energy windows are shown.
FIG. 2. Gamma ray spectrum of uranium. The positions of the three radioelement energy windows are shown.
FIG. 3. Gamma ray spectrum of thorium. The positions of the three radioelement energy windows are shown.
FIG. 4. Typical airborne gamma ray spectrum showing the gamma ray peaks of all three radioelements, along with the energy window used to detect the three radioelements.
potassium, uranium and thorium. Figure 4 is a typical airborne spectrum showing gamma ray peaks from all three radioelements.

The energy windows used to detect the gamma rays from potassium and the uranium and thorium decay series are shown in Figs 1–4 and it can be seen that each window contains some contribution from all three radioelements. Owing to gamma ray scattering in the ground, the aircraft structure and the detector, some counts from 2614 keV $^{208}$Tl photons from a pure thorium source are recorded in the lower energy potassium and uranium windows. Counts in these lower energy windows can also arise from low energy gamma ray photons in the thorium decay series. Similarly, counts will be recorded in the lower energy potassium window from a pure uranium source and can also appear in the high energy thorium window owing to high energy gamma ray photons of $^{214}$Bi in the uranium decay series. As a result of the poor resolution of sodium iodide detectors, counts can also be recorded in the uranium window from a pure potassium source. A correction procedure, known as stripping, must be made to gamma ray spectrometer data to compensate for this spectral overlapping.

2.1.3. Interaction of gamma rays with matter

It is clear from Fig. 1 that the monoenergetic spectral lines emitted during decay have been smeared and broadened by the time they are recorded by an airborne spectrometer. These broadened lines are generally called photopeaks and are the result of the limited resolution of the spectrometer. The gamma rays also interact with material in the ground and in the intervening air before reaching the detector. These interactions, as well as those within the detector itself, have a significant effect on the measured gamma ray spectrum.

Gamma rays interact with matter by several mechanisms including the photoelectric effect and Compton scattering. In the photoelectric effect the whole energy of a low energy gamma photon is given up to an atomic electron. In Compton scattering, gamma rays lose part of their energy to electrons and are scattered at an angle to their original direction. Because both these effects involve electrons, the attenuation of gamma rays in a particular material is proportional to its electron density. A third effect is pair production, in which the whole energy of a gamma ray is lost in the production of an electron–positron pair. This process predominates at high energies, particularly in materials with high atomic numbers, and is a significant process in the absorption of high energy gamma rays in sodium iodide detectors.

Because most materials (rocks, soils, air and water) encountered in airborne radioactivity measurements have a low atomic number and because most natural gamma rays have moderate to low energies (less than 2614 keV), Compton scattering and the photoelectric effect are the predominant absorption processes occurring in the ground and in the air. Since both these processes involve interactions with electrons, the attenuation of gamma rays in most materials is proportional to the electron density.
density of the material. In airborne spectrometry, the absorption of gamma rays from the ground by the mass of the air beneath the aircraft must be taken into account.

2.2. SPECTROMETER INSTRUMENTATION

2.2.1. Detectors

Gamma ray detectors rely on various types of interactions of gamma radiation with matter. For the measurement of low intensity gamma radiation, as required for airborne surveying, scintillation detectors are used almost exclusively. These scintillation detectors measure the fluorescence resulting from the excitation of atomic electrons in the detector material by gamma ray interactions. This type of detector is made of sodium iodide treated with thallium, in the form of single crystals of up to 4 L in volume. The sides of the crystals are coated with light reflecting magnesium oxide. The fluorescent photons (scintillations) produced in the detector by gamma ray interactions are reflected onto a photomultiplier tube (PMT) cemented onto one end of the detector. The charge produced by these photons at the photocathode of the tube is amplified by a factor of about $10^6$ across the tube. The amplitude of each pulse is proportional to the energy deposited by the gamma ray in the detector.

Detector packages for airborne spectrometry are made up of clusters of NaI crystals, each with its own PMT. Typically airborne surveys use total crystal volumes of from 16 to 50 L. The packages are usually thermally insulated and temperature controlled to minimize drift. Electronics to control and adjust the gain of each PMT are needed to ensure that the energy calibration of each detector is accurate. The stability of temperature controlled detectors is good, so that daily manual checking and adjustment of PMT gain are usually adequate. Some instruments have automatic gain control using the photopeak of a small artificial gamma ray source embedded in the detector or mimic scintillations produced by a precision light emitting diode. The most recent instruments use a software program to monitor the photopeak of a gamma emitter, usually potassium, present in the environment, and adjust the gains of the detectors accordingly.

2.2.2. Energy discrimination and counting

Figure 5 is a block diagram of a spectrometer. The pulse output from the photomultipliers of the detector is shaped and fed to a pulse height analyser which classifies the pulses according to energy and feeds them to the appropriate integrator for that energy. Each second, the contents of all the integrators are examined and output as digital values of counts/s. Other counting periods can be selected if required.

Two aspects of this process are of practical importance in gamma ray surveying. The instrument takes a finite time, typically around 10 $\mu$s, to process each pulse.
FIG. 5. Block diagram showing the components of a typical airborne gamma ray spectrometer.
During this time, known as the 'dead time', any new incoming pulse will be lost. If the total gamma ray flux is high, the dead time will result in significant errors and a correction must be made.

If two pulses arrive at the pulse height analyser at exactly the same instant, they will appear as a single pulse with the sum of the component energies. This is known as 'pulse pile-up' and causes distortion of the measured spectrum at high gamma ray fluxes. Spectrometer signal processing electronics can be designed to minimize this effect, but it is not possible to correct for pulse pile-up once it has occurred. Fortunately it is rarely large enough to cause problems. However, when determining the stripping ratios of a large volume airborne spectrometer by using concrete calibration pads, one must take care to avoid high count rates and the associated pulse pile-up effects. This is normally achieved by calibrating the detector packages separately.

2.2.3. Resolution

The precision with which a spectrometer can measure gamma ray energies is known as the system resolution. It can be found by plotting a spectrum which includes a photopeak from a source placed close to the detectors. The 662 keV photopeak of $^{137}$Cs is most commonly used. The full width of the peak at half the maximum amplitude (FWHM), expressed as a percentage of the photopeak energy, is used as the measure of resolution. Most airborne spectrometer systems have a resolution of around 8.5 to 9%. The procedure for determining resolution is described in Section 5.

2.2.4. Energy channels and windows

The natural gamma ray spectrum over the range of 0 to about 3000 keV is resolved by most modern airborne spectrometers into 255 channels, each one ranging from 10 to 12.5 keV in width. A separate channel records all high energy radiation above 3000 keV, caused by cosmic radiation. In order to minimize the number of pulses to be processed by the spectrometer, an energy threshold can be set, beneath which all pulses are ignored. This threshold is usually around 200 keV. The counts registered in each channel during the spectrometer sampling period (normally 1 s) are digitally recorded. This spectral information on the energy distribution of the gamma ray flux can then be processed to give the concentrations and distributions of the various nuclides in the ground.

For most surveys, particularly for natural radioelement mapping, the counts are summed over groups of channels to produce the windows shown in Fig. 4. Each window is particularly sensitive to energies associated with potassium, or the uranium or thorium decay series. The standard spectral windows are shown in Table I.
TABLE I. STANDARD WINDOWS FOR NATURAL RADIOELEMENT MAPPING

<table>
<thead>
<tr>
<th>Window name</th>
<th>Minimum energy (keV)</th>
<th>Maximum energy (keV)</th>
<th>Major peak (keV)</th>
<th>Radio-nuclide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potassium</td>
<td>1370</td>
<td>1570</td>
<td>1460</td>
<td>K-40</td>
</tr>
<tr>
<td>Uranium</td>
<td>1660</td>
<td>1860</td>
<td>1765</td>
<td>Bi-214</td>
</tr>
<tr>
<td>Thorium</td>
<td>2410</td>
<td>2810</td>
<td>2614</td>
<td>Tl-208</td>
</tr>
<tr>
<td>Total count</td>
<td>410</td>
<td>2810</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cosmic</td>
<td>3000</td>
<td>∞</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In some instruments the cosmic channel has an upper limit of about 6000 keV, but this reduces the measured cosmic count rate unnecessarily. Experimental use has been made of a composite uranium window in which the counts in a low energy window around the uranium peak at 1120 keV are summed with those from the standard uranium window from 1660 to 1860 keV. However the use of this composite window is not recommended, since it results in increased errors in estimating the uranium concentration of ground of normal radioelement composition.

2.2.5. Upward looking detectors

One of the problems of AGRS is a result of the presence of radon and its decay products in the atmosphere. Radon is a decay product in the uranium decay series, and being a gas can diffuse out of the ground. Under certain climatic conditions, and in some geographic areas, the effect of radon and its gamma ray emitting decay products can be significant and cause serious errors in the measurement of ground concentrations of uranium.

The most reliable method of correcting for atmospheric radon is through the use of small secondary detectors placed on top of the main detectors and thus partly shielded from the radiation from the ground. The effective shielding is increased by incorporating an anticoincidence circuit into the secondary detector’s counting electronics to ignore pulses arriving simultaneously with pulses from the main detectors. In some installations a one half in $^1$ lead sheet is placed under the secondary detectors to increase the shielding still further. In fact this extra shielding is not strictly

$^1$ One in $= 2.54 \times 10^1$ mm.
necessary, particularly if the secondary detectors are located inside the main detector package immediately above the main crystals. The extra weight of the lead can be a severe penalty, particularly in helicopter operations. These secondary detectors are usually known as $2\pi$ or upward looking detectors as they respond principally to radiation from the half space above the aircraft.

2.2.6. Instrumental parameters

When describing or specifying airborne spectrometric instrumentation the following details should always be given:

- Detector volume in L or in$^3$
- Spectral energy window limits
- System resolution, typical values and tolerances
- Dead time, $\mu$s per pulse
- Details of upward looking detectors, volume, shielding, etc.
3. SURVEY METHODOLOGY

This section deals with choice of survey parameters such as line spacing and crystal volume, as well as with operational procedures during fieldwork. It also covers auxiliary instrumentation used on spectrometric surveys.

3.1. SURVEY PARAMETERS

3.1.1. Flight line direction

For natural radioelement mapping the flight line direction should be at right angles to the geological structures of interest, usually the geological strike, if this is known. For large scale reconnaissance surveys covering areas of variable strike, an arbitrary direction is chosen, often North–South or East–West. If aeromagnetic data are being recorded in addition to the radiometric measurements and the survey area is very close to the geomagnetic equator, then lines should be approximately North–South. In severe mountain terrain where regular grid flying is dangerous or impossible, flying is sometimes carried out by following the contours of the ground.

In searching for radioactive objects, the flight lines will generally be parallel to the long axis of the search zone, for example along the calculated track of a falling satellite. In fallout monitoring, the flight line direction should be approximately at right angles to the winds which were blowing at the time the fallout was deposited.

3.1.2. Flight line spacing

Flight line spacing is generally determined by the budget available, the need to provide coverage of a wide area and the acceptability of missing a small anomaly.

For reconnaissance scale geological surveys 1 km line spacing is typical, although for large areas if funds are limited, 2 km spacing is sometimes used. In detailed surveys for uranium exploration, line spacing may be as little as 100 m if the flying height is 100 m or less. The fall-off of a point source anomaly with distance should be considered.

In fallout mapping, wide line spacing can be used for the first look at the broad pattern, then followed up in contaminated areas by closer line spacing, as necessary. In radioactive search procedures, the activity of the target and its gamma ray energies should be considered since these factors will control the distance from which the source can be detected. This topic is discussed in detail in Section 9.
3.1.3. Flying height

Spectrometer surveys are flown at an approximately constant height above ground level (AGL). Gamma rays are attenuated by air in an exponential fashion. For an infinite slab source, the amplitude decreases by approximately one half for every 100 m of height.

The amplitude at 120 m is therefore only about 35% of the ground level amplitude. For a point source the fall-off is much greater. There has been a good deal of discussion on the merits of particular flying heights. A lower flying height provides a much stronger signal and can reduce signal to noise problems such as those associated with atmospheric radon. However, the area of ground sampled is obviously less at lower altitudes, so there is a greater chance of missing an anomaly from a localized source unless the line spacing is reduced. It should be noted that in rugged terrain, even the best pilot will have to deviate from the nominal height for safety reasons.

For natural radioelement mapping using fixed wing aircraft, flying height above ground level has been more or less standardized at 120 m. In flat terrain such as in Finland, heights as low as 30-50 m are used, mainly to benefit other geophysical methods such as electromagnetics (EM) and magnetics. Helicopter surveys are often flown low, particularly if a smaller detector volume is used.

Experience has shown that a flying height of 90-120 m is suitable for mapping fallout. For search procedures when the sources are strong it will often be possible to fly higher than is normal for mapping surveys. Some preliminary calculations based on the expected activity of the source will be necessary to determine the optimum trade-off between flying height, line spacing, detector volume and risk of missing the source (see Section 9).

3.1.4. Detector volume

The choice of detector volume will be most often determined by the capacity of the survey aircraft as detector packs are heavy. The general rule is to use the largest practical volume: 17 or 33 L for helicopter surveys and 33 or 50 L for fixed wing work. For lower altitude surveys the detector volume can be reduced. For fallout mapping, a smaller detector volume may be desirable if contamination is high, in order to avoid overloading the counting circuits.

3.1.5. Accumulation time and sampling rate

Data acquisition should be arranged so that the accumulation of the spectral data is a continuous process. While the data from one sample are being processed, new data are being acquired in the next sample interval. Sample intervals are there-
fore contiguous, with no 'dead time' while data are being processed. Normally, data are sampled once per second.

Because the aircraft moves forward during the accumulation time, the area of ground sampled is elongated. A rule of thumb gives 60–70% of the counts originating in an oval of width twice the flying height, and length twice the flying height plus the distance travelled during accumulation. For a typical fixed wing survey, at height 120 m, speed 140 km/h (40 m/s) and accumulation time 1 s, the area represented by each sample is about 240 m × 280 m.

3.2. AUXILIARY INSTRUMENTS

3.2.1. Navigation systems

In most surveys, navigation is carried out by a combination of visual methods, using maps or photomosaics marked with the intended flight line positions, and an electronic method such as Doppler radar, inertial position fixing, GPS satellite fixing or radio triangulation. The electronic fixes are digitally recorded with the spectrometric data for use in plotting the true flight track. A tracking video or film is also made during flying to cross-check the electronic system. This is particularly useful for correcting the instrumental drift of Doppler or inertial systems.

3.2.2. Other instruments

A precision radar altimeter, accurate to about 2 m, is needed for measuring the aircraft altitude above the ground, since attenuation corrections must be applied to the data. Temperature and pressure sensors are needed to convert the radar altitude to an effective height at standard temperature and pressure (STP). The pressure sensor may be a barometric transducer or a barometric altimeter.

On natural radioelement mapping surveys, other geophysical instruments such as magnetometers and EM instruments are often carried, and their data are recorded along with the spectrometric data.

The data from the spectrometer, navigation system and other instruments are formatted by an on-board computer or data acquisition system and digitally recorded on tape or some other medium. The computer also controls the sampling sequence of the instruments and supplies a sequence of numbers (fiducials) on the tracking video which corresponds to numbers on the data tape. In the past, chart records were made during flight to permit the operator to check the equipment and for use in quality control on the ground. Now these functions are normally performed using plots on the visual display units of the airborne and ground based computers. Hardcopy plots of the screen display can be produced if needed.
4. CALIBRATIONS FOR
NATURAL RADIOELEMENT MAPPING

This section deals with all aspects of calibration that are required to convert the airborne measurements to ground concentrations of K, U and Th. The various topics discussed are:

— Radar altimeter calibration
— Calibration of barometric pressure transducer
— Determination of equipment dead time
— Determination of cosmic and aircraft backgrounds
— Determination of radon background
— Determination of stripping ratios
— Determination of height attenuation coefficients
— Determination of system sensitivities.

4.1. RADAR ALTIMETER CALIBRATION

Many radar altimeters provide a digital output of the aircraft height which can be recorded directly. Some older instruments output a voltage which must be converted to height using the manufacturer’s calibration curve. This conversion may be done either by the data acquisitions software in real time or as part of the data processing procedure.

4.2. CALIBRATION OF BAROMETRIC PRESSURE TRANSDUCER

The gamma ray window count rates depend on temperature and pressure. Consequently, a knowledge of the barometric pressure (in mbar or kPa)\(^2\) is required at each measurement point.

The barometric pressure transducer may provide output in either pressure or height units. If the output is a voltage that is proportional to pressure, the manufacturer’s calibration must be used, since there is no practical way of calibrating the instrument in the field.

If the instrument outputs a voltage proportional to barometric height, the manufacturer’s calibration must be used to obtain the aircraft’s height. The pressure

\[ \text{One bar} = 1.00 \times 10^5 \text{ Pa} \]
can then be found using the equation relating height and pressure for a standard atmosphere. This is a logarithmic expression of the form:

\[ h = H + \frac{RT}{Mg} \ln \frac{P}{p} \]  (4.1)

where

- \( h \) is the height (metres),
- \( H \) is the datum height (sea level = 0),
- \( R \) is the universal gas constant (8314.32 J·K\(^{-1}\)·kmol\(^{-1}\)),
- \( T \) is the absolute temperature (293.15 K = 20°C),
- \( M \) is the molecular weight of air (28.964 42 kg·kmol\(^{-1}\)),
- \( g \) is the acceleration due to gravity (9.806 65 m·s\(^{-2}\)),
- \( P \) is the datum pressure at height \( H \) (1013.25 mbar at sea level),

and

- \( p \) is the observed pressure (in mbar)

The values in brackets are those for a standard atmosphere for which commercial altimeters are calibrated. When these values are used the equation becomes:

\[ h = 8580.87 \ln \left( \frac{1013.25}{p} \right) \]  (4.2)

The pressure can then be found by rearranging this expression to give:

\[ p = 1013.25 \exp \left( \frac{-h}{8580.87} \right) \]  (4.3)

4.3. DETERMINATION OF EQUIPMENT DEAD TIME

The technique of multichannel analysis employed in gamma ray spectrometry requires a finite time to process each pulse from the detectors. While one pulse is being processed, any other pulse that arrives will be rejected. Consequently, the ‘live’ time of a spectrometer is reduced by the time taken to process all pulses reaching the analyser. With modern electronics, the processing time for each pulse is typically around 6 μs, but for older equipment can be as high as 20 μs. For large volume airborne gamma ray spectrometers with their associated high count rates, the dead time can be significant and corrections must be made, particularly when measuring on calibration pads.

For some equipment, dead time is measured electronically and is recorded digitally together with the spectral data. For instruments without automatic dead time measurement, the dead time per pulse must be determined experimentally. A method
of dead time determination has been described in IAEA Technical Reports Series No. 309, Construction and Use of Calibration Facilities for Radiometric Field Equipment, published in 1989. For this technique, the spectrometer should be connected to two identical detector packages, and recordings of total count rate should be made first with one package, then with the other and finally with both packages together. To ensure uniform count rates, this test should be carried out over uniformly radioactive ground, such as an aircraft hangar or parking area. Because of the system dead time, the count rate from the combined detector system will be less than the sum of the individual count rates.

Let \( N_T \) be the total count rate recorded with both detector boxes operating and \( t \) the average time taken to process every pulse recorded in the total count window. The system will therefore take a time \( N_T t \) to process these \( N_T \) pulses and for this length of time cannot process any other pulses. Consequently, the true count rate \( T_T \) is given by:

\[
T_T = \frac{N_T}{1 - N_T t}
\]  
(4.4)

The true count rates \( T_1 \) and \( T_2 \) for the first and second boxes are given by similar formulas. However, we know that:

\[
T_1 + T_2 = T_T
\]

and consequently:

\[
\frac{N_1}{1 - N_1 t} + \frac{N_2}{1 - N_2 t} = \frac{N_T}{1 - N_T t}
\]  
(4.5)

where \( N_1 \) and \( N_2 \) are the measured count rates for the first and second boxes. The above equation is a quadratic which can readily be solved to determine \( t \), the dead time per pulse. It reduces to a particular simple form when \( N_1 \) and \( N_2 \) have the same value. In this case:

\[
t = \frac{2N - N_T}{NN_T}
\]  
(4.6)

where \( N \) is the average count rate of both detector packages.

In performing the series of measurements, it is important that the counts be accumulated for a sufficiently long time so that the statistical error in the calculated
value of \( t \) is reduced to acceptable levels. Over ground of normal radioactivity, a
counting time of 300 s for a standard 16.8 L system is normally adequate.

If only one detector package is available, the equipment dead time can be mea-
sured using two individual detectors. These detectors should be in similar positions
within the detector package. Two end detectors would be suitable. A similar proce-
dure can then be used to calculate the system dead time as described previously for
the two detector packages. However, in this case, owing to the much smaller
volume, the count rates will be much lower. Therefore, a small source should be
used to increase the count rate. This source should be placed in such a position to
give the same count rate in each detector.

4.4. DETERMINATION OF COSMIC AND AIRCRAFT BACKGROUNDS

The count rates due to cosmic radiation increase exponentially with height
above mean sea level in all spectral windows. Figure 6 shows the variation of the
Th window with height above mean sea level for a 33.6 L system. This exponential
function can be determined and used to correct the data for cosmic ray changes with
height above sea level. However, a better method is to use a cosmic window that
records all incident particles above 3 MeV. These particles can be high energy
gamma rays or other high energy cosmic ray particles. No terrestrial gamma rays
have energies above 3 MeV.

The count rates in the cosmic ray window are then related to counts due to cos-
mic radiation in various spectral windows by the linear function:

\[
N = a + bC
\]  \hspace{1cm} (4.7)

where

- \( N \) is the count rate in the given window,
- \( a \) is the aircraft background count rate for that particular window,
- \( b \) 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.

When the cosmic ray window count rate is zero, there can be no cosmic ray
contribution in any of the other windows. The value of \( a \) is therefore the background
in that particular window, arising from the radioactivity of the aircraft and its
equipment.

The values of \( a \) and \( b \) can be determined experimentally by means of a series
of flights at given altitudes. If possible, these flights should be carried out over the
sea when there is an on-shore breeze so that the radon contribution to all channels
is negligible. A suitable series of flights would be from 1500 to 3000 m or 3500 m at 300 m intervals with a 10 min measurement time.

The mean count rates in the cosmic and other channels can be obtained at each height from the digital data. Linear regression of the counts in each channel against the cosmic channel provides the values of a and b. If an upward looking detector is used, the values of a and b for the upward looking U window should also be determined.

Usually, it is not possible to carry out the cosmic calibration flights over the sea and they must therefore be carried out over land. To escape the effects of terrestrial radiation and the presence of radon decay products in the atmosphere, these flights should be carried out at least 1500 m above the local ground level. The principal effect of radon in the atmosphere is to increase the count rates of the total count window and the upward and downward looking U windows. When radon is present, the calculated aircraft backgrounds will be too high. The problem of radon contamination can frequently be recognized because the linear relationship between the cosmic and U windows breaks down at the lower elevations. Periodic cosmic calibration

![Graph](image)
FIG. 7. Typical cosmic calibration curves for the three radioelement windows: K, Th and upward U.
flights are therefore recommended to be sure that the calibration coefficients have been determined reliably.

Figure 7 shows a typical cosmic calibration for the three radioelement windows. Typical values of the aircraft background, $a$, and cosmic stripping ratios, $b$, for each of the windows are as follows:

<table>
<thead>
<tr>
<th>Aircraft background</th>
<th>Cosmic stripping ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Counts per second)</td>
<td>(Counts per cosmic count)</td>
</tr>
<tr>
<td>Total count</td>
<td>170</td>
</tr>
<tr>
<td>K</td>
<td>21</td>
</tr>
<tr>
<td>U</td>
<td>6.5</td>
</tr>
<tr>
<td>Th</td>
<td>3.4</td>
</tr>
<tr>
<td>Upward U</td>
<td>0.50</td>
</tr>
</tbody>
</table>

These values were obtained by using a cosmic ray window which records all events above 3 MeV as well as three detector boxes each containing four prismatic detectors 10 cm × 10 cm × 40 cm, a total volume of 50 L. Similar cosmic stripping ratios would be expected for one or two detector boxes. Aircraft backgrounds will be approximately in proportion to the detector volume, but will vary to some extent from installation to installation.

If the cosmic channel is not available, the cosmic and aircraft background can be determined using the relationship of the cosmic count rate with the height above sea level, or barometric pressure. Again, a series of flights should be made preferably over water or at a sufficient height above ground that the radon concentration in the atmosphere is negligible. The mean count rates in each window at each height are plotted against barometric altitude or pressure, and a suitable function fitted to the data.

Experimentally, it is found that the count rate in any of the windows is related exponentially to height above sea level:

$$N = A \exp(\mu h) + B$$

(4.8)

where $N$ is the window count rate being considered and $A$, $B$ and $\mu$ are constants. If the aircraft barometric altitude is not recorded, the altitude can be determined from the barometric pressure, $p$, (in mbar) using the relationship for a standard atmosphere (see Eq. (4.2)). Figure 6 shows a typical curve for the Th window of a 33.6 L system. At sea level, the aircraft plus cosmic component has a value of $6.81 - 1.01 = 5.80$ counts/s.
4.5. CALIBRATION OF UPWARD DETECTORS

One of the daughter radionuclides in the U decay series is the radioactive gas, radon (\(^{222}\text{Rn}\)), which has a relatively long half-life (3.8 d), and can diffuse from the ground into the atmosphere. The rate of diffusion depends on such factors as air pressure, soil moisture, ground cover, wind and temperature. The decay products, being charged particles, attach themselves to airborne aerosols. Under still air conditions, there is little mixing and measurable differences can be seen in atmospheric radioactivity at sites only a few km apart. Winds and air turbulence mix the air and reduce the atmospheric background close to the ground. In general, radon concentrations near the ground are higher in the still conditions in the early morning than in the afternoon, after mixing has occurred. Large seasonal variations are also observed in some countries and are probably due to the trapping of radon in frozen and snow covered ground in the winter.

Unfortunately, one of the decay products of radon is \(^{214}\text{Bi}\), which is the nuclide used to measure the U content of the ground. It is therefore essential to quantify and correct for the effects of atmospheric radon.

Several methods have been used to monitor atmospheric background:

1. Flying at high altitude above the ground, to reduce the effects of ground radiation (generally around 700 m AGL);
2. Flying at survey altitude over water, before and after each day's flying or during the survey flights;
3. Flying a repeat test line at survey altitude, near the aircraft base of operations; this line is called a survey altitude test line;
4. Using upward looking detectors.

High altitude flights are not recommended since they require corrections for cosmic ray increase with altitude as well as for scattered Th gamma radiation from the ground. Even with these corrections, high altitude flights can give erroneous backgrounds because of non-uniform distributions of airborne radioactivity.

Flights over water and survey altitude test lines can be used to monitor atmospheric background, provided there are no local or short term time variations. The best survey altitude test lines are homogeneous and low in radioactivity. The procedures to use results from flights over water or survey altitude test lines to estimate radon background are described in the section on data processing.

In areas with few lakes, if local and time variations of atmospheric background occur, the only satisfactory procedure for monitoring these background variations is by using upward looking detectors. A description follows of procedures for calibrating the upward looking detectors so that the background radon component in the various windows can be determined.

The background contribution in each of the various windows originates from cosmic radiation, radon decay products in the air and radiation from the aircraft and
The total background is the count rate that would be measured over water, where radiation from the ground is negligible.

The objective is to use data from the upward looking detectors to predict the component of the count rates in the downward looking detectors that originates solely from radon decay products in the air. If the upward looking detectors could be perfectly shielded from the ground radiation, this prediction would be relatively easy. However, owing to scattering in the air, in the detectors, in the aircraft and in any shielding used, some contribution from the ground will always be detected in the upward looking U window.

The first step of the calibration process for upward looking detectors is to determine the relationship between the upward and downward detector count rates for radon in the air. This requires a series of flights over water, where there is no contribution from the ground. The count rates in each window over water include the aircraft background and the cosmic ray component in addition to any radon contribution. The aircraft background and cosmic component can be largely removed using the cosmic calibration of Eq. (4.7).

After removal of the aircraft and cosmic components from the data collected over water, only the radon component remains in the various windows. Changes in all windows from time to time or place to place will be due solely to variations in the concentration of $^{214}$Bi in the air; therefore, the total count, K, Th and upward and downward looking U windows vary linearly with one another. The count rate for Th over water will be close to zero after cosmic and aircraft corrections, irrespective of changes in the U window, because only a small percentage of $^{214}$Bi gamma rays has sufficiently high energy to be detected in the Th window.

The relationships between counts in the downward U window and in the other four windows, owing to atmospheric radon, can now be determined through linear regression. This should be carried out using data showing a wide range of radon concentrations. The equations are:

\[ u_r = a_u U_r + b_u \]  
\[ K_r = a_K U_r + b_K \]  
\[ T_r = a_T U_r + b_T \]  
\[ I_r = a_I U_r + b_I \]

where

$u_r$ is the radon component in the upward U window, $K_r$, $U_r$, $T_r$ and $I_r$ are the radon components in the various windows of the downward detectors, and the various $a$ and $b$ coefficients are the calibration constants required.
If the cosmic and aircraft components have been perfectly removed, the constant, b in Eqs (4.9) – (4.12) should be zero. However, in practice, the b's can have small residual non-zero values. An example of calibration over water for all four windows is shown in Fig. 8. Typical values for the calibration constants are:

<table>
<thead>
<tr>
<th>Constant</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_u$</td>
<td>0.209</td>
</tr>
<tr>
<td>$a_K$</td>
<td>0.867</td>
</tr>
<tr>
<td>$a_T$</td>
<td>0.119</td>
</tr>
<tr>
<td>$a_l$</td>
<td>16.0</td>
</tr>
</tbody>
</table>
These coefficients are quite similar to stripping ratios determined over calibration pads. For example, $a_K$ is equivalent to the U into K stripping ratio, $\gamma$, and $a_T$ to the U into Th stripping ratio, $a$. However, the calibration constant, $a_T$ is almost always found to be higher than the stripping ratio, a, because of the presence in the air of $^{220}\text{Rn}$ from the Th series. Also, $^{220}\text{Rn}$ decays to $^{208}\text{Tl}$ which produces the gamma ray peak at 2614 keV. The presence of $^{220}\text{Rn}$ is surprising since it has a half-life of only 55 s. However, this seems to be sufficient time for at least some $^{220}\text{Rn}$ to escape from the ground into the air.

The next stage in the calibration procedure is to determine the relationship between count rates in the upward looking detector and count rates in the downward detector, for radiation originating from U in the ground. It is not necessary to carry out any special calibration flights for this, since the factors can be obtained by analysis of the survey data.

The component of the upward detector count rate originating from the ground, $u_g$, will depend on the concentration of U and Th in the ground, as will the components of the U and Th downward window count rates, $U_g$ and $T_g$, that originate from the ground. Consequently the upward detector ground component is related to the downward detector ground components by the linear equation:

$$u_g = a_1 U_g + a_2 T_g \tag{4.13}$$

where $u_g$, $U_g$ and $T_g$ are the contributions in the windows that originate from the ground. The coefficients $a_1$ and $a_2$ are the calibration factors which must be determined.

Some equipment manufacturers have recommended using calibration pads to derive the two calibration factors of Eq. (4.13). However, the distribution of gamma radiation at ground level is quite different from that at survey altitude. In addition, calibration pads of finite dimensions cannot be considered as an infinite source of gamma radiation. Consequently, the calibration factors derived from calibration pads may be significantly different from their actual value at survey altitude.

In order to evaluate the calibration factors using Eq. (4.13), the aircraft background, cosmic and radon components must be subtracted from both the upward and downward detector data, leaving only the component of gamma radiation from the ground. Several alternative methods can be used. One fairly straightforward method uses data from sections of flight lines which are adjacent to a lake. The average overwater background in both the up and down detectors is subtracted from the average values over the adjacent land. This procedure assumes only that the background over land is the same as that over the water. If sections of flight lines close to the lake are used, this assumption is reasonable.

In areas without lakes an alternative method can be used. This procedure removes the cosmic, aircraft and radon components from a section of survey data by subtracting the average count rates from adjacent sections of the same line. The
differences in the count rates between the adjoining sections will then give values of \( u_g \), \( U_g \) and \( T_g \) for use with Eq. (4.13).

To obtain reliable estimates of \( a_1 \) and \( a_2 \), it is best to select sections of lines with a large range of U to Th ratios. These sections should also have a high average count rate and should be adjacent to a low count rate area. Errors in the mean count rates \( u_g \), \( U_g \) and \( T_g \), required to solve Eq. (4.13), will then be minimized.

From a series of calculated values of \( u_g \), \( U_g \) and \( T_g \), the calibration factors, \( a_1 \) and \( a_2 \), can be determined by a least squares method. This can be done by solving the two simultaneous equations:

\[
a_1 \sum (U_g)^2 + a_2 \sum U_g T_g = \sum u_g U_g
\]

\[
a_1 \sum U_g T_g + a_2 \sum (T_g)^2 = \sum u_g T_g
\] (4.14) (4.15)

This entire process can be carried out automatically on the whole data set for a survey, thereby ensuring that all ranges of U to Th ratios in the survey area are used. The flight lines are first divided into sections. Adjoining sections are then subtracted to remove the background component. This could be done for every data point, but to reduce the number of calculations, it is better to use successive averages over 10 adjacent measurements. Adjacent pairs of average values can then be subtracted as before.

Using this automatic technique, the statistical errors associated with individual pairs are quite large, particularly for the upward U window. Consequently, it is best to use a weighted least squares solution to solve Eq. (4.13). In this case, it is assumed that all the errors are associated with the upward U window count rates.

Suppose the average upward U window count rates of two adjacent line segments are \( u_1 \) and \( u_2 \) and these averages have been obtained from \( n \) measurements. Then the error due to counting statistics, \( \sigma \), on the difference between the two section averages is given by:

\[
\sigma^2 = (u_1 + u_2)/n
\] (4.16)

Equations (4.14) and (4.15) must then be modified to give a weighted least squares solution. They become:

\[
a_1 \sum U_g^2/\sigma^2 + a_2 \sum (U_g T_g)/\sigma^2 = \sum (u_g U_g)/\sigma^2
\] (4.17)

\[
a_1 \sum (U_g T_g)/\sigma^2 + a_2 \sum T_g^2/\sigma^2 = \sum (u_g T_g)/\sigma^2
\] (4.18)

where the weighting function \( \sigma^2 \) is given by Eq. (4.16).
In practice the values of a, and a^2 can be quite variable when they are calculated for individual flight lines. However, by using data from an entire survey area, they can be determined reliably. The values for one survey area were 0.033 9 ± 0.002 5 for a, and 0.016 2 ± 0.002 7 for a^2.

Once the calibration constants a, a_2, a_u a_T, b_U and b_T have been determined, the radon contribution in the downward U window can be calculated. After the cosmic and aircraft components are removed, the count rate in any window is made up of a component from the ground plus a component due to radon in the air. Consequently,

\[ u = u_g + u_r \]  \hspace{1cm} (4.19)

\[ U = U_g + U_r \]  \hspace{1cm} (4.20)

\[ T = T_g + T_r \]  \hspace{1cm} (4.21)

where

- u, U and T are the observed count rates after removal of the cosmic and aircraft backgrounds,
- u_g, U_g and T_g are the components of ground radiation,
- u_r, U_r and T_r are the radon components.

In Eq. (4.19) u_g and u_r are then replaced using Eqs (4.9) and (4.13) to give:

\[ u = a_1 U_g + a_2 T_g + a_u U_r + b_u \]  \hspace{1cm} (4.22)

In this equation U_g and T_g are then replaced using Eqs (4.20), (4.21) and (4.11) to give:

\[ U_r = \frac{u - a_1 U - a_2 T + a_2 b_T - b_u}{a_u - a_1 - a_2 a_T} \]  \hspace{1cm} (4.23)

The radon contributions to the K and total count windows are found using Eqs (4.10) and (4.12).

4.6. DETERMINATION OF STRIPPING RATIOS

The spectra of K, the U series and the Th series overlap. Because of this, each spectral window, chosen to detect one radioelement, will also contain some effect from the other two radioelements. Correcting for this spectral overlap is called 'stripping'.

The stripping procedure makes use of spectral ratios called stripping ratios. They are determined experimentally using concrete calibration pads containing
known concentrations of K, U and Th. These are normally square with dimensions about 8 m on each side and 0.5 m thick. A minimum of four is required to determine K, U and Th spectra and to remove the background. Figures 1, 2 and 3 show the three spectra obtained with an airborne spectrometer on calibration pads at Grand Junction, Colorado. Recently, it has been established that the stripping ratios can be reliably determined using much smaller calibration pads, 1 m × 1 m × 30 cm. These are cheaper to build and it is much easier to make them uniformly radioactive. Details of the construction and use of airborne calibration facilities are given in IAEA Technical Reports Series No. 309 as mentioned above.

There are several reasons for the spectral overlap shown in Figs 1, 2 and 3. Owing to Compton scattering in the ground, some counts from a pure Th source will be detected in the lower energy K and U windows. Counts in the lower energy windows can also arise from the incomplete absorption of 2.62 MeV photons in the detector or from lower energy gamma ray photons in the Th decay series. Similarly, counts will be recorded in the lower energy K window from a pure U source. High energy gamma ray photons of $^{214}$Bi in the U decay series can also be detected in the Th window.

The stripping ratios are the ratios of the counts detected in one window to those in another window for pure sources of K, U and Th. A notation has been adopted in which $\alpha$, $\beta$ and $\gamma$ are ratios of counts in a lower energy window to those in a higher energy window, and a, b and g are ratios of counts detected in a high energy window to those detected in a low energy window.

The Th into U stripping ratio, $\alpha$, is equal to the ratio of counts detected in the U window to those detected in the Th window from a pure Th source.

The reversed stripping ratio, a, is U into Th, equal to the ratio of counts detected in the Th window to those detected in the U window from a pure source of U.

Similarly, $\beta$ is the Th into K stripping ratio for a pure Th source, b is the reverse stripping ratio, K into Th for a pure K source, $\gamma$ is the U into K stripping ratio for a pure U source and g is the reverse stripping ratio, K into U for a pure K source.

From measurements on a calibration pad, the K, U and Th window count rates $n_K$, $n_U$ and $n_{Th}$ are linearly related to the K, U and Th concentrations of the pad, $c_K$, $c_U$ and $c_{Th}$. The equations are:

$$n_K = s_{K,K}c_K + s_{K,U}c_U + s_{K,th}c_{th} + b_K$$ (4.24)

$$n_U = s_{U,K}c_K + s_{U,U}c_U + s_{U,th}c_{th} + b_U$$ (4.25)

$$n_{Th} = s_{Th,K}c_K + s_{Th,U}c_U + s_{Th,th}c_{th} + b_{Th}$$ (4.26)

where $b_K$, $b_U$ and $b_{Th}$ are the background count rates originating from the radioactivity of the ground surrounding the pad, the radioactivity of the aircraft and its...
equipment, plus the contributions from cosmic radiation and the radioactivity of the air.

The nine 's' factors in these equations give the count rate in the three windows for each of the three radioelements. The six stripping ratios are given by:

\[ \alpha = s_{U,\text{Th}} s_{\text{Th},\text{Th}} \]  \hspace{1cm} (4.27)

\[ \beta = s_{\text{K,\text{Th}}} / s_{\text{Th},\text{Th}} \]  \hspace{1cm} (4.28)

\[ \gamma = s_{\text{K,U}} / s_{\text{U,U}} \]  \hspace{1cm} (4.29)

\[ a = s_{\text{Th,U}} / s_{\text{U,U}} \]  \hspace{1cm} (4.30)

\[ b = s_{\text{Th,K}} / s_{\text{K,K}} \]  \hspace{1cm} (4.31)

\[ g = s_{\text{U,K}} / s_{\text{K,K}} \]  \hspace{1cm} (4.32)

Each of Eqs (4.24), (4.25) and (4.26) has four unknowns, the window sensitivities for K, U and Th plus the background. Consequently from measurements on four or more calibration pads, these unknowns can be uniquely determined.

In practice, the four sets of equations in four unknowns can be reduced to a set of three equations with three unknowns, by subtracting the count rates and concentrations of the blank pad from those of the K, U and Th pad. The unknown backgrounds, \( b_{K} \), \( b_{U} \) and \( b_{\text{Th}} \), are then removed from the computation. In matrix notation, the 3 \( \times \) 3 count rate matrix \( N \) is then related to the concentration matrix \( C \) and the unknown 3 \( \times \) 3 sensitivity matrix \( S \) by the matrix equation:

\[
\begin{bmatrix}
  n_{K,K} & n_{K,U} & n_{K,\text{Th}} \\
  n_{U,K} & n_{U,U} & n_{U,\text{Th}} \\
  n_{\text{Th},K} & n_{\text{Th},U} & n_{\text{Th},\text{Th}}
\end{bmatrix}
\times
\begin{bmatrix}
  S_{K,K} & S_{K,U} & S_{K,\text{Th}} \\
  S_{U,K} & S_{U,U} & S_{U,\text{Th}} \\
  S_{\text{Th},K} & S_{\text{Th},U} & S_{\text{Th},\text{Th}}
\end{bmatrix}
\times
\begin{bmatrix}
  c_{K,K} & c_{K,U} & c_{K,\text{Th}} \\
  c_{U,K} & c_{U,U} & c_{U,\text{Th}} \\
  c_{\text{Th},K} & c_{\text{Th},U} & c_{\text{Th},\text{Th}}
\end{bmatrix}
\]  \hspace{1cm} (4.33)

where the \( N \)'s are the count rates and the \( C \)'s are the concentrations after removal of the blank pad values. In matrix notation:

\[
N = SC
\]  \hspace{1cm} (4.34)

from which the sensitivity matrix containing the nine 's' values in Eqs (4.24), (4.25) and (4.26) may be evaluated using:

\[
S = NC^{-1}
\]  \hspace{1cm} (4.35)
The six stripping ratios for two different spectrometer systems are shown in the following list. One system has good signal processing electronics (detector pulse shaping etc.) whereas the other system has poor signal processing. The system with poor signal processing has significantly higher stripping ratios. This situation arises because the pulse shaping of the detector signal results in overlapping pulses which cannot be separated by the multichannel analyser. The stripping ratios are therefore a good measure of the quality of a spectrometer system.

<table>
<thead>
<tr>
<th>Stripping ratio</th>
<th>Good system</th>
<th>Poor system</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>0.25</td>
<td>0.38</td>
</tr>
<tr>
<td>$\beta$</td>
<td>0.40</td>
<td>0.43</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>0.81</td>
<td>0.92</td>
</tr>
<tr>
<td>$\alpha'$</td>
<td>0.06</td>
<td>0.09</td>
</tr>
<tr>
<td>$b$</td>
<td>0</td>
<td>0.01</td>
</tr>
<tr>
<td>$g$</td>
<td>0.003</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Owing to the scattering of gamma rays in the air, the three stripping ratios $\alpha$, $\beta$ and $\gamma$ increase with altitude above the ground. In airborne surveys, it has become standard practice to measure the three stripping ratios at ground level and then calculate the increase in stripping ratio at the measured aircraft altitude. The increases in the three stripping ratios with altitude above the ground shown in the following list are based both on theory and experiment. No corrections are applied to the reverse stripping ratios $a$, $b$ and $g$ because these are small and generally have little effect on the stripped count rates in each window.

<table>
<thead>
<tr>
<th>Stripping ratio</th>
<th>Increase per metre</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>0.000 49</td>
</tr>
<tr>
<td>$\beta$</td>
<td>0.000 65</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>0.000 69</td>
</tr>
</tbody>
</table>

4.7. DETERMINATION OF HEIGHT ATTENUATION COEFFICIENTS

Gamma rays from the ground must pass through the air to reach the detector in the aircraft. Because gamma rays interact with matter, they will be attenuated. This attenuation can be closely approximated by an exponential of the form:

$$N_h = N_0 e^{-\mu h}$$ (4.36)
where

\( N_h \) is the background corrected and stripped count rate,
\( N_0 \) is the count rate at ground level,
\( \mu \) is the attenuation coefficient,
and \( h \) is the height above ground level, corrected to equivalent height at STP.

The values of the attenuation coefficients for each window can be determined by making a series of flights at different heights over an airborne calibration range. A typical series of heights would be from 60 m to 240 m at 30 m intervals. This range of altitudes covers those normally found in survey operation. Flights are also required at the same heights over a nearby body of water for the measurement of background.

An airborne calibration range should have the following features, i.e. it should:

(a) Be relatively flat;
(b) Have uniform concentrations of K, U and Th;
(c) Be close to a body of water for measurement of background;
(d) Be free of flight restrictions;
(e) Be readily accessible for surface measurements;
(f) Be easy to navigate (a suitable calibration range would be a dirt road or a power line);
(g) Be about 8 km long, equivalent to about 150 s flying time at 50 m/s;
(h) Have no hills within about 1 km of the flight line.

The mean count rates of the total count, K, U and Th windows must first be calculated for each pass over the water and the calibration line. The measurements over the water should be subtracted from the measurements over the calibration line. This removes cosmic radiation, atmospheric radioactivity and the radioactivity of the aircraft.

The average air temperature and pressure and the aircraft altitude must also be determined for each pass. The equivalent height of the aircraft at STP can then be determined from the expression:

\[
H_e = H \frac{273.15}{T + 273.15} \frac{P}{1013.25} \tag{4.37}
\]

where

\( H \) is the observed height,
\( H_e \) is the equivalent height at STP,
\( T \) is the air temperature in degrees Celsius,
and \( P \) is the barometric pressure in mbar.
The next step is to calculate the stripping ratios at the STP equivalent height using the stripping ratio increase with aircraft altitude as listed above, and use them to strip the observed count rates in the three windows.

The three background corrected window count rates, $n_K$, $n_U$ and $n_{Th}$, are sums of the individual count rates from K, U and Th in the ground. Consequently,

$$n_K = n_{K,K} + n_{K,U} + n_{K,Th}$$  \hspace{1cm} (4.38)

$$n_U = n_{U,K} + n_{U,U} + n_{U,Th}$$  \hspace{1cm} (4.39)

$$n_{Th} = n_{Th,K} + n_{Th,U} + n_{Th,Th}$$  \hspace{1cm} (4.40)

where $n_{U,K}$ is the count rate in the U window that originates from K, etc.

Using the six stripping ratios, these equations become:

$$n_K = n_{K,K} + \gamma n_{U,U} + \beta n_{Th,Th}$$  \hspace{1cm} (4.41)

$$n_U = g n_{K,K} + n_{U,U} + \alpha n_{Th,Th}$$  \hspace{1cm} (4.42)

$$n_{Th} = b n_{K,K} + a n_{U,U} + n_{Th,Th}$$  \hspace{1cm} (4.43)

Solving these equations for $n_{K,K}$, $n_{U,U}$ and $n_{Th,Th}$ we get:

$$n_{K,K} = \frac{n_{Th}(\alpha \gamma - \beta) + n_{U}(\alpha \beta - \gamma) + n_{K}(1 - a \alpha)}{A}$$  \hspace{1cm} (4.44)

$$n_{U,U} = \frac{n_{Th}(g \beta - \alpha) + n_{U}(1 - b \beta) + n_{K}(b \alpha - g)}{A}$$  \hspace{1cm} (4.45)

$$n_{Th,Th} = \frac{n_{Th}(1 - g \gamma) + n_{U}(b \gamma - a) + n_{K}(a g - b)}{A}$$  \hspace{1cm} (4.46)

where $A$ has the value:

$$A = 1 - g \gamma - a(\gamma - gb) - b(\beta - a \gamma)$$  \hspace{1cm} (4.47)

These give the stripped count rates at each altitude, which can then be fitted to the exponential function (Eq. (4.36)) to give the height attenuation coefficient for each window. Figure 9 shows the exponential curves for all four windows, determined from a test strip.
Typical attenuation coefficients are:

<table>
<thead>
<tr>
<th>Window</th>
<th>Height attenuation coefficients (per metre at STP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total count</td>
<td>-0.006 7</td>
</tr>
<tr>
<td>K</td>
<td>-0.008 2</td>
</tr>
<tr>
<td>U</td>
<td>-0.008 4</td>
</tr>
<tr>
<td>Th</td>
<td>-0.006 6</td>
</tr>
</tbody>
</table>

4.8. DETERMINATION OF SYSTEM SENSITIVITIES

In order to compare the results from different airborne gamma ray systems, the count rates in each window should be converted to ground concentrations of K, U and Th. The calibration constants required for this conversion can be determined from the flights at different altitudes over the airborne calibration range. From the
measured ground concentrations of the range, the system sensitivities (counts per unit concentration of K, U and Th) may be determined at the nominal survey altitude. The ground concentrations can then be evaluated from measured count rates, if the areas represented by each sample are assumed to be approximately uniform.

The ground concentrations of an airborne calibration range should be measured with a calibrated portable spectrometer. Laboratory analyses of soil samples are not recommended because of radon changes in the soil between sample collection and analysis.

One of the main problems of measuring the ground concentration of an airborne calibration range is soil moisture change. The radioelement concentration of the strip varies with soil moisture content. In order to calibrate an airborne gamma ray spectrometer, the radioelement concentration of the test strip must be measured at the same time or within a very few days of the airborne flights. If the soil moisture content changes between the airborne and ground measurements, the calculated window sensitivities will be incorrect.

In measuring the ground concentrations of the test range, some consideration has to be given to the sampling pattern. Over uniform ground most of the gamma radiation from a uniform source comes from a strip directly beneath the aircraft. The sampling pattern must therefore be designed to give more weight to the ground directly under the flight path.

The number of ground spectrometer measurements is another consideration. The more measurements that are made, the more accurate will be the calculated ground concentration. In most situations, owing to counting statistics, measurements of the equivalent U concentration have the greatest uncertainties. Based on the sensitivity of a 76 mm × 76 mm detector, approximately fifty 2 min measurements will reduce the statistical error in the U window to an acceptable level.

The background may change while the test strip is being surveyed. It is therefore good practice to monitor the overwater background over the nearby body of water for a few days with the portable spectrometer. The significance of any background changes while the test strip is being surveyed can then be assessed.

Once the ground concentration of the test strip has been determined, the system sensitivities can easily be calculated. From the flights at different altitudes over the test strip, the stripped count rates in the three windows can be determined at the nominal survey altitude using Eq. (4.36). The sensitivity (S) for each window is then given by:

\[ S = \frac{N}{C} \]  

where \( N \) is the stripped count rate in the window at the survey altitude and \( C \) is the respective radioelement concentration of the test strip.

Typical sensitivities at 120 m for a standard detector package of 16.8 L containing 4 detectors 10 cm × 10 cm × 40 cm are:
<table>
<thead>
<tr>
<th>Window</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>30 counts·s⁻¹·(K)⁻¹</td>
</tr>
<tr>
<td>U</td>
<td>2.9 counts·s⁻¹·(ppm U)⁻¹</td>
</tr>
<tr>
<td>Th</td>
<td>2.0 counts·s⁻¹·(ppm Th)⁻¹</td>
</tr>
</tbody>
</table>

It is also useful to determine a factor to convert the total count to ground level exposure rate (μR/h) using the following conversions:

\[
1\% \text{ K} = 1.505 \ \mu\text{R/h} \\
1 \ \text{ppm} \ \text{eU} = 0.653 \ \mu\text{R/h} \\
1 \ \text{ppm} \ \text{eTh} = 0.287 \ \mu\text{R/h}
\]

Hence the total exposure rate (E) on the test range is:

\[
E = 1.505 \ K + 0.653 \ eU + 0.287 \ eTh
\] (4.49)

where K, eU and eTh are the K, eU and eTh concentrations of the test range.

It should be noted that the calculated exposure rate using Eq. (4.49) only includes the gamma ray exposure rate from radioactive sources in the ground and does not include the cosmic ray component or any caesium fallout on the ground.
5. QUALITY CONTROL

Three types of variables must be monitored or checked periodically to ensure high quality radiometric data. Instrumental variables include detector gain settings, spectral stability and the fidelity of digital records. Operational variables, which include flight path position and flying height, are similar to the operational variables of any airborne geophysical survey. The main environmental variables which affect spectrometer surveys are weather conditions.

The quality control goals and procedures described in this section apply mainly to spectrometric mapping of the distribution of natural radioelements or of fallout. Search procedures are not likely to require the same rigorous quality checking.

Sample specifications for a typical radioelement mapping survey are given in the Appendix.

5.1. INSTRUMENTAL VARIABLES

5.1.1. Spectrometer resolution

Resolution is a measure of the precision with which the energies of gamma rays can be measured by the spectrometer. The resolution will be poor if the gain setting of any of the detectors is faulty or if one of the detectors is damaged.

Resolution is measured using the 662 keV gamma rays from a $^{137}$Cs source. A spectrum is plotted, as shown in Fig. 10. The amplitude of the peak due to $^{137}$Cs is found and the width of the peak (as a number of channels) at half maximum amplitude is measured. This is defined as the 'full width at half maximum', or FWHM. The resolution is then calculated as:

$$R\% = \frac{100 \text{ (keV per channel) FWHM}}{662 \text{ keV}} \quad (5.1)$$

For quality control purposes during survey operations, the resolution should be found each morning immediately after any detector gain adjustments have been made. The resolution should also be determined after work each day, without making any further gain adjustment. The second value will show if there is excessive drift in any detector, owing to instrument problems such as poor temperature stability, or an electronic fault. Resolution should be 8.5–9.5% and must never exceed 12%. The results of tests should be recorded in a table or on a graph as the survey progresses and should be included in the operations report.
5.1.2. Spectral stability

Airborne spectrometers are very stable and it is unusual for sufficient drift to occur which would affect the results significantly. However, drift can occur if the temperature of the crystals changes or if electronic faults occur in the instrument. For this reason it is important to monitor spectral stability to ensure data quality.

If full spectral, 256 channel data, are recorded, the best way to check spectral stability is to plot spectra summed over segments of the survey data. Typically, spectra summed over 1000 s are used. During this period the flight line will cover a range of geology, so peaks of all three main radioelements should occur. The spectral plots should be made on a field computer if possible, to provide the check as soon as possible. Each plot should be checked to see that the K and Th peaks lie in the correct channels (±2 channels) and that the peaks are not unusually wide. If any one of the criteria is not met, the instrument should be thoroughly checked as a fault has probably occurred. Any flight lines affected should be reflown.

FIG. 10. Spectrum showing the $^{137}$Cs peak used for determining the resolution of a system (FWHM — full width at half maximum).
A second check of stability is provided by daily source checks made on the ground before survey work each day. These also provide a check of the spectrometer sensitivity. Source checks are mandatory if only four window data are being recorded and are normal procedures for all natural radioelement mapping surveys. The sources must always be placed at exactly the same point relative to the detectors in the aircraft, using a rigid locating frame if possible. The radioactive homogeneity of the airfield apron where the source checks are to be carried out should be investigated and, if necessary, a particular location occupied for every source check. A set of dead time determinations should be made at this location, for the background and for each source. Dead time is found in the manner described in Section 4 for calibration pads.

A standard daily source check procedure is composed of: a 60 s background recording, with sources placed at least 30 m from the aircraft, Th source recording, U source recording and 60 s background recording (repeated).

The U and Th recordings should be carried out over sufficient time to accumulate at least 10 000 counts in the U window for the U source and in the Th window for the Th source. The digital average of each recording should be determined, on a field computer if possible, and dead time corrected. The average of the two background recordings must be subtracted from each source reading, and the results plotted against time over the survey period for inclusion in the operations report. If a source check gives results which differ by more than 5% from the mean of checks to date, the cause of the change should be investigated.

5.1.3. Digital data fidelity

The digital data should be checked as soon as possible to ensure that all instruments are functioning and the data system and recording system are working correctly.

If possible, profiles should be plotted from the digital data and examined to identify any spikes, gaps or other problems in the data. If a field computer is available, it should be used for this checking so that any faults can be identified as early as possible.

5.1.4. Test line

If upward detectors are not used, regular flights should be made at survey altitude over water or over a repeatable test line over land, in order to monitor atmospheric radon variations. An overland test line also provides a daily dynamic check of instrument performance and some indication of the effects of environmental variables such as rainfall.
If a body of water at least 2 km long and 0.5 km wide is available, then flights over water can be used to provide a direct estimate of radon background. If upward detectors are used, then flights over are required to determine the coefficients for the calculation of radon background. Separate overwater flights are not necessary if many lakes are crossed during the survey as, for example, in northern Canada.

If no suitable body of water is available, a test line should be chosen to be logistically convenient, easily repeatable and as far as possible typical of the survey area. These requirements are usually fulfilled by using a straight road or railway close to the aircraft base. The line should be about 5 to 8 km long, equivalent to a flying time of about 100 s. The start and end of the line should be marked by features which can be clearly identified on the tracking film or video. If possible the radio-element concentrations should be more or less uniform along the length of the line. It is worth taking a little trouble to get the best line possible.

When flying the test line at survey altitude, one should take care to maintain constant flying height and the correct flight path. When the data are returned to the field base, the fiducials of the start and end points of the line should be determined and the averages of the various radiometric and altimeter data determined over the interval using the field computer. The data should be corrected for dead time, as well as cosmic and aircraft background. The results should be plotted against time over the survey period and the plots included in the operations report. Use of test line results to estimate radon background is described in the section on data processing.

High level test lines, flown at 800 m above ground level, have been used to estimate radon background, but this procedure cannot be recommended. The radon measured at this level may not be representative of the value at survey height and there may also be a significant contribution from the ground if the area contains granites or other radioactive rocks.

5.2. OPERATIONAL VARIABLES

5.2.1. Flying height

Flying height at AGL is an important operational variable, because gamma rays are attenuated by air, and corrections must be made for variations in flying height.

The normal acceptable variation in flying height is ±20% of the nominal height, that is from 110 to 135 m for a nominal survey height of 120 m. In hilly or mountainous terrain, it may not be safe to remain within these limits, and pilots must use skill and judgement to provide the best results without endangering the aircraft. As a general rule, spectrometric data obtained at a height greater than 250 m over a distance greater than 1–2 km will be of little value.
To monitor flying height, one should examine the profiles of radar altitude and any areas where the flying height is out of specification should be discussed with the pilot. Provided aircraft safety permits, these lines should be reflo wn or infill lines introduced. In some cases, deviation of the flight line may be preferable to a large deviation from nominal flying height.

5.2.2. Flight path spacing

Each survey flight should be plotted onto the navigation maps as soon as possible. Any out of tolerance flying should be identified quickly so that infill or repeat flights can be specified.

The tolerance normally permitted for flight path spacing for natural radioelement mapping is 150% of the nominal spacing over a maximum distance of 5 km, or 200% of nominal spacing at any point. For 1 km spacing, this means that any gap greater than 1.5 km × 5 km between two adjacent lines must be infilled, and that any flight lines more than 2 km apart are out of tolerance. Safety considerations override the specifications for flight line spacing.

Flight path spacing is of importance in a search for radioelements as poor navigation can result in a target being missed. The same tolerances as those used for mapping surveys can be set and must be taken into account when deciding the optimum search pattern.

5.2.3. Flying speed

The aircraft speed is rarely the cause of problems in spectrometric surveying. The area of ground sampled by the detector during each second will be greater as the speed increases and a point source anomaly will be reduced in amplitude. For highly detailed mapping surveys, a maximum acceptable speed may be set.

5.3. ENVIRONMENTAL VARIABLES

5.3.1. Precipitation

Rain affects the results of a natural radioelement mapping survey because waterlogged soil attenuates radiation from the ground. Areas of recent heavy rain should therefore be avoided during surveying.

Rain during a fallout mapping survey will bring down more radioactive dust onto the ground. Contamination of the survey aircraft by fallout in rain, either while the plane is in flight or on the ground, should be avoided.
Snow forms a radiation attenuating blanket over the ground: 10 cm of fresh snow is equivalent to about 10 m of air. Mapping surveys should be discontinued if there are more than 1 or 2 cm of snow on the ground.

5.3.2. Atmospheric radon

As discussed in the section on calibration, there are ways to estimate and remove the effects of atmospheric radon. However, the problems caused by radon are greatest when temperature inversion conditions occur, as the radon becomes trapped beneath the inversion. If possible, these conditions should be avoided, particularly if no upward detectors are used.
6. PROCESSING DATA FOR NATURAL RADIOELEMENT MAPPING

6.1. FIELD PROCESSING

Any calibrations and determinations described in Sections 4 and 5 that are carried out during fieldwork should be compiled in the field together with the daily quality control tests and checks. A flight path map will normally be produced in the field to check flying tolerances, particularly if visual or mixed visual/Doppler or visual/inertial flight path recovery is used.

If quick results are needed, for example, to follow up U anomalies on the ground or to take action in the event of high levels of fallout, then a hand calculator or a field computer can be used to carry out data reduction on the spot to permit anomaly maps to be produced by hand. For U exploration these maps should show the locations of anomaly maxima and half-amplitude widths annotated with their maximum amplitude and U/Th ratios.

6.2. PROCESSING SEQUENCE

Figure 11 shows a flow chart of the processing sequence for AGRS surveys.

6.2.1. Energy calibration

If full spectral data have been recorded, the count rate in the various windows must first be determined to reduce the volume of data to be transferred from the field records to the processing database.

The simplest method of carrying out this windowing procedure is to plot spectra summed over whole lines or groups of lines and to use the plots to identify the channels at which the K 1460 keV and the Th 2614 keV photopeaks occur. The K and Th windows are then centered on these channels and the U window defined in proportion to them. This procedure can be automated fairly easily.

Spectral fitting using calibrated K, U and Th spectra of known keV per channel for small sections of line can also be used, but it is considerably more complicated and the improvement in determining the window positions is minimal as spectral drift occurs only slowly.

6.2.2. Data selection and editing

In order to extract the on-line data from the field records, the starts and ends of each flight line are determined and the on-line data read into the database. Prelimi-
FLOWCHART FOR SPECTROMETER DATA PROCESSING

Read survey data and extract flight lines
Rewindow spectrum if necessary

Database
Quick look profiles for data checking
Edit data
Dead time correction
Filtering (radar altimeter, cosmic channel etc)
Calculate STP altitude
Subtract cosmic and aircraft background
Subtract radon background

Cosmic stripping ratios and aircraft backgrounds
Stripping ratios from calibration pads
Sensitivities from dynamic test range

Convert to radioelement
Corrected radioelement data

Multiparameter profiles
Gridding
Archive tapes

Contour maps
Colour maps

FIG. 11. Flow chart for spectrometer data processing.
nary profiles are then plotted from the digital data to check for any gaps, spikes, radio noise or other problems. If necessary the data can be edited to remove these effects.

6.2.3. Merging navigation

The flight track maps, plotted at the field base, are digitized and checked before merging with the spectrometric data. If visual or mixed navigation were used, the digitizing can be checked by carrying out ‘speed checks’, i.e.: calculating the apparent speed between adjacent fixes and flagging any segments in which this speed is unrealistic. Visual fixes may be used to control drift on electronic navigation systems automatically. Any serious mismatch in this case will probably be caused by a digitizing error. Finally the flight path maps can be plotted and checked for errors.

When fully checked and edited, the navigation can be merged with the spectrometric data, interpolating the location of samples between fixes if necessary.

6.2.4. Dead time correction

The first step in the reduction sequence for radiometric data is dead time correction. If possible this should be carried out using electronically measured dead time data. Dead time correction is made to each window using the expression:

\[ N = \frac{n}{1 - t} \quad (6.1) \]

where

\( N \) is the corrected count in each second,
\( n \) is the raw count recorded in each second,
and \( t \) is the recorded dead time, i.e. the time taken to process all pulses reaching the detector in one second.

If the dead time is not recorded, the total count window can be used as described in Section 4.3. The dead time, \( t \), in Eq. (6.1) is then calculated from the total count windows using the expression:

\[ t = \frac{n}{n_T} \quad (6.2) \]

where \( n_T \) is the total count rate, and \( t \) is the calculated time to process each pulse in the total count window as given by Eq. (4.6).
Dead time correction should be applied to each window in the downward looking detector (including the cosmic and total count windows), but not to the upward looking data as these are processed by different circuits.

6.2.5. Filtering

Digital filters should be applied to some parameters to reduce statistical noise or certain instrumental effects. For example, radar altimeter data should be lightly filtered to smooth sudden jumps that can arise when flying over steep terrain and which cause problems when height correcting the data. A 5 point filter would be suitable. The spectrometer cosmic channel should also be filtered to reduce statistical noise. In this case, a 10 to 20 point filter could be used. To calculate radon background from the upward looking detector data, heavily filtered U upward, U downward and Th downward data are needed as described below. Original data should also be preserved, however.

6.2.6. Calculation of effective height AGL

The radar altimeter data are lightly filtered for use in adjusting the stripping ratios for altitude and for carrying out attenuation corrections. They are then converted to effective height \( h_e \) at STP by the expression:

\[
h_e = h \frac{273.15}{T + 273.15} \frac{P}{1013.25}
\]  

(6.3)

where

- \( h \) is the observed radar altitude,
- \( T \) is the measured air temperature in °C,
- \( P \) is the barometric pressure in mbar.

If necessary, the pressure can be estimated from the barometric altitude using the expression:

\[
P = 1013 \exp \left(-\frac{H}{8581}\right)
\]

(6.4)

where \( H \) is the barometric altitude in metres.
6.2.7. Cosmic and aircraft background

The determination of the cosmic and aircraft background expressions for each spectral window has been described in Section 4. These expressions are of the form:

\[ N = a + bC \]  \hspace{2cm} (6.5)

where

- \( N \) is the combined cosmic and aircraft background in each spectral window,
- \( a \) is the aircraft background in the window,
- \( C \) is the cosmic channel count,
- \( b \) is the cosmic stripping factor for the window.

The expressions are evaluated for each window at each data point, using the filtered cosmic channel data and the results subtracted from the data.

6.2.8. Radon background

Several methods for estimating the atmospheric radon background are available. These methods are:

(a) Using upward looking detectors,
(b) Flying at survey altitude over water,
(c) Flying a survey altitude test line.

If upward looking detectors are used, the expression for the radon component in the downward \( U \) window is given by the equation:

\[ U_r = \frac{u - a_1 U - a_2 T + a_2 b_T - b_u}{a_u - a_1 - a_2 a_T} \]  \hspace{2cm} (6.6)

where

- \( U_r \) is the radon background measured in the downward \( U \) window,
- \( u \) is the measured count in the upward \( U \) window,
- \( U \) is the measured count in the downward \( U \) window,
- \( T \) is the measured count in the downward \( Th \) window,
- \( a_1, a_2, a_u \) and \( a_T \) are proportionality factors,
- \( b_u \) and \( b_T \) are constants determined experimentally.

The measured count rates \( u, U \) and \( T \) used in Eq. (6.6) must first be corrected for cosmic and aircraft background. The radon counts in the total count, \( K \) and \( Th \) windows can be calculated from \( U_r \) using Eqs (4.10)-(4.12).
Because of the low count rate in the upward U window, this window must be filtered considerably to reduce statistical noise. For a 50 L system with two upward looking detectors of volume 8.4 L, a 200 point running average has been found suitable. In areas of unusually high radioactivity, pulse pile-up can occur and errors will arise in the calculated value of \( U \). In these areas the radon background component should not be calculated but interpolated from adjacent sections of line.

Flights over water and survey altitude test line data can also be used to monitor atmospheric background if the background stays relatively constant on a particular day and does not vary much from place to place.

Flights over water are relatively easy to use. If only one background measurement is made for each survey flight, this value must be subtracted from the U window data for all measurements. With more than one background measurement, the background can be estimated for each data point by linear interpolation based on the time the backgrounds were measured.

The repeated use of a survey altitude test line is somewhat more complicated. Variations in the U window can be due partly to radon but also to soil moisture variations or small changes in the flying height or flight path. Variations due to soil moisture and flight path errors can largely be overcome by a simple normalization procedure based on the count in the Th window. The procedure assumes that a given percentage change in Th count from the ground will correspond to the same percentage change in the U counts from the ground. First, the average Th count rate for the test line over the whole survey period is found. Then, for each flight, the U count rate is multiplied by the average Th count, divided by the Th count for that flight. Changes from flight to flight in the resulting normalized U count are then due to variations in radon and corrections can be determined for each flight.

### 6.2.9. Stripping

The stripping ratios \( \alpha, \beta, \gamma, a, b \) and \( g \) are determined over calibration pads as described in Section 4. The principal ratios \( \alpha, \beta \) and \( \gamma \) vary with STP altitude above the ground and should be adjusted according to Fig. 6 before stripping is carried out. Using the six stripping ratios, the background corrected count rates in the three windows can be stripped to give the counts in the K, U and Th windows that originate solely from K, U and Th. These stripped count rates are given in Eqs (4.44)–(4.47).

The following simplified stripping equations, which assume that \( b \) and \( g \) are negligible, are often used in the field to give approximate values for the stripped count rates:

\[
n_{\text{Th,Th}} = \frac{n_{\text{Th}} - a n_{\text{U}}}{1 - a \alpha}
\]

(6.7)
\[ n_{U,U} = \frac{n_U - \alpha n_{Th}}{1 - a\alpha} \]  \hspace{1cm} (6.8)

then

\[ n_{K,K} = n_K - \beta n_{Th,Th} - \gamma n_{U,U} \]  \hspace{1cm} (6.9)

where the notation is the same as that used in Eqs (4.44)-(4.47).

6.2.10. Attenuation correction

The stripped count rates vary exponentially with aircraft altitude according to Eq. (4.36). Consequently, the measured count rate is related to the count rate at the nominal survey altitude by the equation:

\[ N_s = N_m \exp \left[ \mu (h_0 - h) \right] \]  \hspace{1cm} (6.10)

where

\( N_s \) is the count rate normalized to the nominal survey altitude, \( h_0 \).
\( N_m \) is the background corrected, stripped count rate at STP equivalent height \( h \),
and \( \mu \) is the attenuation coefficient for that window.

In severe terrain, problems may be encountered if the height exceeds about 250 m because the statistical noise as well as any errors in background determination are greatly amplified. It is common practice in these conditions to limit the exponential term to the equivalent of 250 m.

6.2.11. Conversion to apparent radioelement concentrations

The fully corrected count rate data can be used to estimate the concentrations in the ground of each of the three radioelements, K, U and Th. This has the advantage that, for properly calibrated equipment, the results are independent of survey variables such as crystal volume and survey height.

The procedure determines the concentrations which would give the observed count rates, if uniformly distributed in an infinite horizontal slab source. Because the U and Th windows actually measure \(^{214}\)Bi and \(^{208}\)Tl respectively, the calculation implicitly assumes radioactive equilibrium in the U and Th decay series. The U and Th concentrations are therefore expressed as equivalent concentrations, \( eU \) and \( eTh \).

The calculated K, U and Th concentrations are determined using the expression:

\[ C = \frac{N}{S} \]  \hspace{1cm} (6.11)
where

\[ C \text{ is the concentration of element (K\%, eU ppm or eTh ppm)}, \]
\[ S \text{ is the broad source sensitivity for the window}, \]
\[ N \text{ is the count rate for each window after dead time, background, stripping and attenuation correction.} \]

Determination of the broad source sensitivities, which are used to convert count rates to concentrations, is carried out over a dynamic test range as described in Section 5.

An estimate of the ground level exposure rate from geological sources can be made from the total count rate using the expression:

\[ E = sN \] (6.12)

where

\[ E \text{ is the exposure rate}, \]
\[ s \text{ is the conversion factor determined experimentally}, \]
\[ N \text{ is the fully corrected total count rate.} \]

The ground level exposure rate can also be calculated from the apparent concentrations, K\%, eU ppm and eTh ppm, using the expression:

\[ E = 1.505K + 0.653eU + 0.287eTh \] (6.13)

6.2.12. Calculation of radioelement ratios

The ratios of the three radioelements (U/Th, U/K and Th/K) are frequently plotted as profiles. Owing to statistical uncertainties in the individual radioelement measurements, some care should be taken in the calculation of these ratios. A common method of determining ratios is as follows:

(1) Neglect any data points where the K concentration is less than 0.25\%, as these measurements are likely to be over water.
(2) Select the element with the lowest corrected count rate. This is usually U.
(3) Progressively sum the element concentrations of adjacent points on either side of the data point until the total accumulated U concentration exceeds a certain threshold value. This threshold is normally set to be equivalent to 100 counts. For example, using a 2000 in³ system with a U sensitivity of 5.8 counts/s per ppm, a minimum of 17 ppm must be accumulated for U.
(4) Calculate the ratios using the accumulated sums.

With this method, the errors associated with the calculated ratios will be similar for all data points. For contouring, the ratios can be produced directly from the gridded concentration data as the algorithms used in gridding provide sufficient smoothing.
7. PRODUCTS IN NATURAL
RADIOELEMENT MAPPING

7.1. PROFILES

Profiles of the geophysical results along each flight line are usually produced as multiparameter plots on paper. The plots are drawn to a true linear scale, e.g. 1:50 000 or 1:100 000, with the horizontal axis annotated with the fiducial numbers. Plots are typically 0.5-1 m wide and show K%, eU, eTh and exposure rate with effective ground clearance, barometric height, magnetometer and other geophysical data if available. These plots are sometimes called ‘stacked profiles’, but this name is ambiguous as it is sometimes used to denote profile maps of the type described below. Figure 12 shows an example of this type of profile.

7.2. PROFILE MAPS

Maps on which the data are plotted as profiles along horizontal axes formed by each flight line provide a quick and useful means of viewing the results of a survey. They can be produced fairly easily on a field computer. Sometimes on these maps features can be seen which do not survive the subsampling and smoothing implicit in gridding and contouring operations. A sample profile map is shown in Fig. 13. Other map presentations on which the data are plotted sample by sample along the flight line, for example, as bars with length proportional to amplitude, have also been tried with some success.

7.3. GRIDDING

Most map products require the data to be interpolated onto a regular grid. There are many ways for this to be done. Several of the standard gridding algorithms are unsuited to radiometric data, because of inherent statistical variations. A suitable gridding algorithm is one which takes the average of all data points lying within a circular area, weighted for distance from the grid point.

7.4. CONTOUR MAPS

Contour maps in one form or another are still the most widely used product of most airborne spectrometer surveys. The choice of gridding algorithm, contour interval and style will normally be made after some experimentation, in consultation
FIG. 12. Typical profiles showing altitude, $e\text{Th}/K$, $eU/K$, $eU/e\text{Th}$, $e\text{Th}$, $eU$, $K(\%)$, exposure rate, magnetic and other geophysical data from an airborne geophysical survey line.
with the end user of the data. However this choice will generally involve a minimum of smoothing to respect the raw data as closely as possible.

Use of computer produced colour contour maps is now widespread. Again, the gridding algorithm, colour palette and other variables are usually determined after some tests and experiments. These maps are a very effective means of displaying the data, but they are difficult to reproduce unless expensive colour printing is used. The conventional contour line map therefore retains its traditional place as the main large scale map product for many surveys.

Another effective map presentation is the colour ternary map on which each radioelement is represented by one of the three primary colours, with intensity varying according to the radioelement concentration. There are several different ways to produce these maps, which give pleasing and more or less quantitative results.

Ternary maps are produced most easily by using image processing software. In this case the additive primary colours, red, green and blue are used. The intensity of each colour depends on the concentration of the radioelement: black represents low concentrations of all three. The appearance of the image is optimized using interactive contrast stretching. This method gives visually satisfying images quickly and easily, but they are essentially qualitative as the quantitative information is largely lost in the optimization process. The final product is a photographic image which can be enlarged to the map scale required.
Electrostatic or ink jet plotters can also be used to produce ternary maps. In this case the subtractive primary colours, yellow, magenta and cyan are used to represent the three radioelements; the lowest concentrations of all three are shown as white. With care and some experimentation, colour intensity scales can be chosen which produce a map that is both visually satisfying and quantitative, so that a particular colour denotes a known combination of concentration values. Choice of colour scales can often be made more easily by making use of a cumulative probability plot of the data for each radioelement.

In a simpler form of map, the colours are distributed on a triangular diagram according to the relative proportions of the elements, with respect to their sum. Pure magenta signifies very high K with negligible U and Th; yellow signifies high Th with negligible U and K; cyan represents high U with no K or Th. This type of map is essentially a ratio map, since the colours depict the relative concentrations of the radioelements.

7.5. DIGITAL ARCHIVE

In addition to the field tapes which carry the raw data, the digital archive contains processed records of both flight line data and gridded data. The flight line data should have, for each sample, the fiducial number, the line number, map coordinates, the apparent radioelement concentrations, exposure rate, effective height AGL, the corrected values of magnetic field and any other geophysical data. The raw values of the K, U and Th, total count, cosmic and upward U windows, temperature, pressure and radar altitude can also be included. Each tape should have a header text file with descriptions of the format and contents. Grid data tapes need header information specifying the grid origin and orientation, X and Y spacing and numbers of X and Y points. One half in, 1600 bpi (bits per in) tapes coded in ASCII or EBCIDIC are still the normal and the preferred medium for digital archives.

7.6. REPORTS

Complete technical reports covering survey operations, calibrations and processing are a necessary part of every airborne gamma ray survey, but are often overlooked. A list of the main topics to be covered is given in the sample specifications in the Appendix.
8. ENVIRONMENTAL MONITORING

Airborne gamma ray spectrometer systems designed for mapping natural radioelements can also be used for environmental surveys. This section describes the use of such systems for environmental monitoring and gives a case history based on Swedish experience following the Chernobyl accident.

8.1. MAPPING OF CHERNOBYL Fallout IN SWEDEN

The nuclear reactor accident at Chernobyl occurred during the night of 25–26 April 1986. On the morning of 28 April, the nuclear power plant at Forsmark, Sweden, north of Stockholm, reported elevated radioactivity. On the basis of meteorological conditions and the composition of the fallout, it was evident that the source lay outside Sweden and was most likely a nuclear power plant accident.

Elevated radioactivity which was reported from numerous places in eastern Sweden was caused by fine radioactive dust and some larger ‘hot’ particles. The exposure rate increase was of the same magnitude as the natural background. The following morning, after rainfall during the night, numerous reports reached the National Institute of Radiation Protection (SSI) of higher levels of radioactivity, primarily from an area north of Stockholm. Radioactivity values reaching 5 mR/h were reported.

At this point SGAB was requested by SSI to carry out an airborne gamma ray survey to map the fallout. The survey began on 1 May and continued for approximately seven weeks.

8.1.1. Equipment used

The following standard SGAB gamma ray spectrometer system, normally used for mapping natural nuclides, was employed for surveying the Chernobyl fallout:

- Aircraft: Aero Commander 680E (twin engine)
- Detector: One package of total volume 16.8 L NaI
- Gamma spectrometer: 256 channels
- Data: Digitally stored on magnetic tape
- Navigation: Visual

8.1.2. Survey procedure

The survey began in the area north of Stockholm where high values had been reported. Areas of high contamination were quickly discovered, particularly around
FIG. 14. Gamma ray radiation map of Sweden presented on 9 May 1986 after eight days of measurement, showing the contamination mainly in the east of the country. All flight lines are shown.
FIG. 15. Contamination map showing the distribution of radioactive fallout from the Chernobyl accident, on the basis of airborne measurements made between 9 May and 3 June 1986. The contribution from natural radioelements has been removed.
the town of Gävle, 170 km north of Stockholm. After 4 days, the whole southern half of the country had been covered with lines 20 to 50 km apart. The fallout was found to have affected mainly the eastern parts of the country (Fig. 14). The measurements were continued northwards with line spacings of 100 km. By the eighth day almost the entire country had been covered.

Owing to the passage of a second radioactive cloud and rainfall over the southern part of Sweden, further contamination was expected in the southwest of the country. A second survey was therefore begun in this area and once again extended to cover the whole country. After the second survey, the overall distribution of the fallout was clear (Fig. 15).

The main areas of contamination in Sweden were in the east, in the north and over the mountains along the Norwegian border. Detailed follow-up measurements were then made with line spacings between 2 and 10 km over the most contaminated areas. When the airborne surveys were finished at the beginning of October 1986, a total of approximately 35 000 line km had been flown.

8.1.3. Calibration

Initially it was considered almost impossible to perform any sophisticated spectral analysis because of the large number of gamma emitting nuclides and the rapid decay of some short lived species. Therefore estimates of ground level exposure rates were based on daily flights over a 1 km test line which was monitored on the ground with hand held scintillometers. This test line was used to level the results to a particular day.

Gradually, as the short lived nuclides decayed, the spectrum became dominated by gamma lines from $^{134}\text{Cs}$ and $^{137}\text{Cs}$. The surface concentrations of these nuclides were measured using a spectral analysis technique described in Section 8.6. The calibration was performed using ground measurements with a solid state Ge system operated by the National Defence Research Institute.

8.1.4. Products

The method of showing the results of the airborne survey changed over the course of the operation. In the beginning, simple profile plots and hand drawn contour maps were produced. These showed the total ground level exposure rate including the natural background. Later, the profiles and maps showed only the exposure rate from the fallout. By the end of May, contour maps showing the distribution of $^{134}\text{Cs}$ and $^{137}\text{Cs}$ in Bq/m$^2$ were being produced. These contour maps were hand drawn from the computer produced profiles. A map showing the distribution of $^{137}\text{Cs}$ in kBq/m$^2$ was distributed to every household in Sweden in the autumn of 1986.
8.2. PRINCIPLES OF FALLOUT MONITORING

Environmental contamination may take many forms. In this discussion it is supposed that the environment has been contaminated by gamma ray emitting man-made nuclides from nuclear fallout. The fallout has been spread to the environment by atmospheric processes and varies only slowly from place to place. However, the distribution can be affected locally by small scale mechanisms such as rain showers and the melting of snow.

If the contamination is of a different kind, for example a number of point sources lost or spread in the environment, the situation is quite different and therefore is dealt with separately in Section 9.

Use of AGRS for fallout mapping is possible because most man-made nuclides can be distinguished from those occurring naturally. The detection limit is dependent on the system used, the survey parameters and the ground concentration of natural gamma ray emitters. On the basis of Swedish experience after the Chernobyl accident, a 5% increase in mean gamma ray exposure rate can be detected at an altitude of 60 m, using detectors of 16.8 L NaI.

If the exposure rate is too high, there will be problems using the standard airborne geological system because of dead time effects due to the high count rates. Depending on the count rates, this problem can be overcome by switching off individual detectors or detector packages. If the fallout is too high for a large volume NaI system, solid state detectors could be used instead with the added benefit of a much better energy resolution.

8.3. FALLOUT NUCLIDES

Most of the man-made radioactive nuclides in the environment originate either from nuclear bomb tests, nuclear reactors or from nuclear power stations. The most important gamma ray emitting nuclides, man-made and natural, that can be expected are presented in Table II.

Most of the gamma energies of the man-made nuclides are well below the energy interval normally used for measuring the natural radioelements K, U and Th (Table II). However, the \(^{140}\)La gamma ray peak at 1596 keV interferes with both the K and the U windows.

8.4. SYSTEM REQUIREMENTS

To discriminate between man-made and natural gamma ray emitting nuclides, the minimum spectrometry requirements are: three windows for monitoring natural nuclides and one total count window with a low energy threshold of around 400 keV.
TABLE II. EXAMPLES OF MAN-MADE AND NATURAL GAMMA EMITTERS PRESENT IN THE ENVIRONMENT. NATURAL EMITTERS ARE PRESENTED WITHOUT NOTES ON THE HALF-LIFE OWING TO THE VERY LONG HALF-LIFE OF THEIR RESPECTIVE MOTHER NUCLIDE

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Most important gamma energies (keV)</th>
<th>Half-life (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Man-made:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{95}$Zr</td>
<td>724, 756</td>
<td>65</td>
</tr>
<tr>
<td>$^{95}$Nb</td>
<td>765</td>
<td>35</td>
</tr>
<tr>
<td>$^{99}$Mo</td>
<td>740</td>
<td>3</td>
</tr>
<tr>
<td>$^{103}$Ru</td>
<td>497</td>
<td>40</td>
</tr>
<tr>
<td>$^{106}$Ru</td>
<td>512</td>
<td>368</td>
</tr>
<tr>
<td>$^{131}$I</td>
<td>364</td>
<td>8</td>
</tr>
<tr>
<td>$^{132}$Te</td>
<td>230</td>
<td>3</td>
</tr>
<tr>
<td>$^{134}$Cs</td>
<td>605, 795</td>
<td>730</td>
</tr>
<tr>
<td>$^{137}$Cs</td>
<td>662</td>
<td>11 000</td>
</tr>
<tr>
<td>$^{140}$Ba/La</td>
<td>1596</td>
<td>13</td>
</tr>
<tr>
<td>Natural:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{40}$K</td>
<td></td>
<td>1460</td>
</tr>
<tr>
<td>Uranium series:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{214}$Pb</td>
<td></td>
<td>350</td>
</tr>
<tr>
<td>$^{214}$Bi</td>
<td></td>
<td>609, 1120, 1764</td>
</tr>
<tr>
<td>Thorium series:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{228}$Ac</td>
<td></td>
<td>910, 960</td>
</tr>
<tr>
<td>$^{208}$Tl</td>
<td></td>
<td>583, 2620</td>
</tr>
</tbody>
</table>

Such a system can be used to detect the presence of man-made gamma emitters, provided that the count rate contribution of the natural elements into the total channel is known. However it is generally not possible to quantify the concentrations of the man-made nuclides.

For quantitative fallout mapping, a 256 channel system should be used. Such systems are widely used for U prospecting and natural radioelement mapping. A suitable system should have a total detector volume of at least 17 L NaI with the capa-
bility to switch off individual detectors in areas of high contamination. The sampling
time would typically be 0.5–1.0 s at flying heights of 30–60 m, but could be longer
at higher altitudes.

8.5. EXPOSURE RATE CALIBRATION

In the early period after a nuclear reactor accident, a large number of nuclides
can be expected to be present, with varying half-lives from a few days to several
years. Over the first few days, the exposure rate decreases rapidly and the gamma
ray spectrum becomes less complex. In this period of rapid change, it is important
to define a time datum to which all measurements are referred.

The recommended procedure for converting the count rates to ground level
exposure rate is by means of a test strip. The calibration procedure is as follows:

1. A test strip should be selected in an area known to be contaminated. This test
   strip should be as close to the aircraft base as possible.
2. The ground level exposure rate over the strip should be measured, preferably
   with a calibrated ionization chamber. Initially this should be done every day.
3. The test strip should be flown at survey altitude at least once a day.
4. From the airborne measurements, establish the ground level exposure rate
   from natural radioelements as described in Section 4. Subtract this value from
   the ground level measurements to determine the exposure rate from fallout.
5. From the total count window subtract the contribution of natural gamma radia-
   tion. This requires a knowledge of the K, U and Th spectral shapes as
   described in Section 8.6.
6. Calculate the conversion factor from airborne counts due to fallout to ground
   level exposure rate due to fallout.
7. Use the daily ground level fallout exposure rates to normalize all airborne
   measurements to a single time datum.

This method can be used with a four window system, but better results will
be obtained with 256 channel recording. This is because of the gamma ray peak of
\(^{140}\text{La}\) at 1596 keV which interferes with the standard K and U windows. This
nuclide has a half-life of 13 d and soon ceases to be a problem.

If the relative proportions of the man-made nuclides change from place to
place, it may be necessary to use more than one test line. Spectra plotted from differ-
ent parts of the survey area will show if this is a problem.

8.6. CALIBRATION FOR SPECTRAL ANALYSES

To use a 256 channel gamma ray spectrometer for fallout mapping, the spectral
response at different flying heights should be known for unit concentrations of K,
U and Th. The spectral response of all gamma ray emitting nuclides with energies above the photopeak of the nuclide of interest must also be determined.

### 8.6.1. Natural nuclides

The aim of this calibration is to establish the unit spectra for each of the three radioelements at different flying heights. These are the detector responses for unit concentrations of each of the three radioelements in equilibrium with their respective daughter products.

Provided that gamma energies below about 500 keV are of little interest, these unit spectra can be established on large aircraft calibration pads. Below about 500 keV, the spectra measured over calibration pads are incorrect because of the lack of the skyshine component. The procedure to derive the unit spectra on calibration pads is, in principle, the same as that described in Section 4 for determining the three window sensitivities. In this case, instead of three windows, there are 256. This procedure yields unit spectra at ground level.

Two methods have been used to derive the unit spectra at different heights. One method uses material such as wood, placed underneath the detectors on the calibration pads to simulate the absorption of gamma rays in the air. By increasing the thickness of the material, one can determine the gamma ray spectra at different altitudes, provided the density of the wood is known.

The other method makes use of multiple test strips. A minimum of three test strips is required, each one anomalous in one of the elements K, U and Th. Flights are made at different altitudes over each of the strips whose concentrations have been established with a calibrated portable gamma ray spectrometer. The unit spectra at each altitude can then be determined as if they had been recorded on the pads.

The test strip measurements yield better results in the low energy part of the spectrum than do the pad experiments. However, the test strip method has the disadvantage that the spectra are less reliable owing to variations in aircraft altitude and uncertainties in the ground concentration of the test strips.

The spectral change with altitude can be determined using a set of absorption coefficients, one for each channel and element from which the unit spectra at any altitude can be calculated.

### 8.6.2. Other nuclides

It may be possible to ignore part of the gamma spectrum, depending on the nuclides of interest. For example, if $^{137}$Cs is the only man-made nuclide present, only four channels are needed to map it. These would be the standard three windows plus an additional window from 550 to 750 keV, covering the $^{137}$Cs gamma ray peak at 662 keV. From the unit spectra at the survey altitude, the natural component...
in the Cs window can be removed. The residual count rate in this window will be proportional to the ground concentration of $^{137}\text{Cs}$.

Because of the limited resolution of NaI detectors, there is a limit to the number of nuclides that can be distinguished. For example, in the Chernobyl accident, the following nuclides could in theory have been measured:

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Energy (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{131}\text{I}$</td>
<td>364</td>
</tr>
<tr>
<td>$^{103/106}\text{Ru}$</td>
<td>497, 512</td>
</tr>
<tr>
<td>$^{137}\text{Cs}$</td>
<td>662</td>
</tr>
<tr>
<td>$^{134}\text{Cs}$</td>
<td>605, 795</td>
</tr>
<tr>
<td>$^{140}\text{Ba/La}$</td>
<td>1596</td>
</tr>
</tbody>
</table>

In the initial stages of the Swedish mapping of the Chernobyl fallout, only $^{134}\text{Cs}$ and $^{140}\text{Ba/La}$ could be measured reliably. Later, it was possible to measure $^{137}\text{Cs}$ as well.

For the measurements of many nuclides, the unit spectrum of each nuclide must be known, which makes the calibration difficult in practice. In a nuclear emergency the priority would be to determine the pattern of fallout as quickly as possible. The nuclides of interest will not be known until after the accident has occurred. Calibration may have to wait until the situation is under control.

In the Swedish case the first calibration took place two weeks after the accident. The final calibration was performed several months later. The calibration technique was to use a grass airfield on which the concentration of $^{134}\text{Cs}$ and $^{137}\text{Cs}$ had been measured on the ground, using a Ge system. Flights were made over the airfield at four different altitudes between 30 and 150 m. At each altitude, the spectra from Th, U and K were removed by using an interactive method. The residual spectrum of $^{134}\text{Cs}$ and $^{137}\text{Cs}$ was split into its two components using a synthetic $^{137}\text{Cs}$ spectrum. By comparison with the ground measurements, the two unit spectra were calculated.

There are other methods which can be used for calibration such as flights at different heights and distances from point sources of known activity.

### 8.7. PROCESSING

Any spectrum measured with an airborne system can be considered a mix of spectra from separate sources. The most important sources are:

- (a) Cosmic background
- (b) Aircraft and instrument backgrounds
- (c) Airborne Rn gamma emitting daughters
FIG. 16. A 256 channel gamma spectrum measured in May 1986 with an 8.4 L detector, at an altitude of 150 m.

(d) $^{40}$K in the ground
(e) Gamma emitting daughters of $^{238}$U in the ground
(f) Gamma emitting daughters of $^{232}$Th in the ground
(g) $^{137}$Cs originating from nuclear bomb tests or nuclear power plant accidents
(h) Other man-made gamma emitting nuclides.

The calibration and processing procedures for the measurement of natural nuclides have been described in Sections 4 and 6. For mapping man-made nuclides, the processing techniques must be modified since more of the spectrum is used.

In natural radioelement surveys, the cosmic, aircraft and atmospheric radon components are considered as background. The basic methods to remove these backgrounds have been described; however, for fallout mapping, this background removal must be applied to all channels of the spectrum.

In a fallout survey the gamma rays from natural radioelements in the ground are often also considered as background. These components of the gamma spectrum are removed using the unit spectra described in Section 8.6.1.

The natural spectra could be removed using a process analogous to that method used for radioelement mapping, extended to cover all channels. However this becomes cumbersome when there are many fallout nuclides. An alternative tech-
nique which utilizes the unit spectra and a least squares spectral fitting technique will be described here. This technique assumes that:

1. Cosmic and aircraft background spectra have been determined.
2. Shapes of the unit spectra and their variation with altitude have been established for the natural elements K, U and Th.
3. Spectral response of unit concentrations of the fallout nuclides and their variation with altitude is known.
4. Full spectra have been recorded on a number of windows which cover at least the major peaks of all nuclides present. An example of such a configuration which covers the natural elements plus $^{134}$Cs and $^{137}$Cs is shown in Fig. 16.

If the number of unknown nuclides is equal to the number of windows, the general least squares spectral fitting method may be solved by normal matrix inversion.

### 8.7.1. Least squares spectral fitting method

**Definitions:**

- $j$: element (nuclide) index
- $n_e$: number of elements (nuclides)
- $i$: channel (window) index
- $n_c$: number of channels (windows)
- $M_i$: measured spectrum (measured counts in channel $i$)
- $Z_{i,j}$: unit spectrum (counts in channel $i$ per unit concentration of nuclide $j$)
- $C_i$: calculated spectrum (using unit spectra and a combination of concentrations)
- $Q_j$: concentration of element $j$
- $w_i$: weight for channel (window) $i$

First, a weight for each channel is obtained by:

$$w_i = 1/C_i$$ \hspace{1cm} (8.1)

The relation between the calculated spectrum, the unit spectra and concentration is:

$$C_i = \sum_{j=1}^{n_e} Z_{i,j}Q_j$$ \hspace{1cm} (8.2)
The least squares spectral fitting method means that the following expression should be minimized:

\[ \sum_{i=1}^{n_c} w_i (M_i - C_i)^2 \quad (8.3) \]

Equation (8.3) can be rewritten:

\[ \sum_{i=1}^{n_c} w_i (M_i - \sum_{j=1}^{n_c} Z_{i,j} Q_j)^2 \quad (8.4) \]

Minimizing Eq. (8.4) means that the derivative with respect to \( Q_j \) \((j = 1, 2, 3, \ldots, n_c)\) should be zero. This results in equations in number equal to the number of elements. The equation for the \( k \)th element is:

\[ \sum_{i=1}^{n_c} ((M_i - \sum_{j=1}^{n_c} Z_{i,j} Q_j) Z_{i,k} w_i) = 0 \quad (8.5) \]

This expression can be rewritten:

\[ \sum_{j=1}^{n_c} Q_j D_{j,k} = E_k \quad (8.6) \]

where

\[ D_{j,k} = \sum_{i=1}^{n_c} Z_{i,j} Z_{i,k} w_i \quad (8.7) \]

and

\[ E_k = \sum_{i=1}^{n_c} M_i Z_{i,k} w_i \quad (8.8) \]

Using matrix notation, Eq. (8.6) can be written:

\[ QD = E \quad (8.9) \]
or

\[ Q = D^{-1}E \]  \hspace{1cm} (8.10)

where \( D^{-1} \) (elements \( d_{jk} \)) is the inverse matrix of \( D \).

The concentration equation for element (nuclide) \( k \) is:

\[ Q_k = \sum_{j=1}^{n_e} \sum_{i=1}^{n_c} d_{jk} M_i Z_{i,k} w_i \]  \hspace{1cm} (8.11)

8.7.2. Linear coefficients

The concentration equation above can be solved for each measured spectrum. This, however, results in quite heavy calculations. Therefore more simple methods are used, one of which is described below.

A practical method to calculate concentrations is to use Eq. (8.11) to derive a set of linear coefficients for each element and each channel. The linear coefficient, \( l_{k,i} \), for element (nuclide) \( k \) in channel \( i \) is:

\[ l_{k,i} = \sum_{j=1}^{n_e} d_{jk} Z_{i,k} w_i \]  \hspace{1cm} (8.12)

This method depends on the use of a fixed weight spectrum, which implies the use of a set of assumed concentrations for all nuclides present. One effect of this technique is that if the actual concentrations differ significantly from the assumed, a slight increase in statistical noise can be expected. The practice in Sweden, when measuring natural nuclides, is to assume concentrations close to the expected mean of the survey area (2% K, 2 ppm eU and 7 ppm Th). When the measurements of \(^{137}\text{Cs}\) were performed in Sweden in 1986 (after the accident in Chernobyl), the ground concentration assumed for this nuclide was low due to the fact that the estimate was more uncertain then. Thus, when a single nuclide is monitored, the weights should be calculated for an expected measured spectrum in which all nuclides present are significant to the spectral shape. If, instead, several or all nuclides are of interest, a typical concentration situation is recommended as the basis for the weight calculations.

In practice the calculations are made by computer using:

- Number of elements (nuclides) \( n_e \)
- Number of channels \( n_c \)
- Unit spectra for each element (nuclide) \( Z_{i,k} \)
- Assumed normal ground concentrations to calculate \( w_i \).
The coefficients are calculated for each flying height at which the unit spectra have been obtained. A library of linear coefficients is then produced by splining the coefficients for each channel and each element to be determined. During processing, the computer chooses the coefficient file closest to the actual corrected flying height. It is not necessary to produce these coefficient files for the natural elements unless their concentrations are needed.

8.7.3. Processing sequence

In the processing procedure, the following steps are taken for each recorded spectrum:

(a) Subtract cosmic and aircraft background,
(b) Calculate the STP flying height,
(c) Select the linear coefficient file for this altitude, for each nuclide to be calculated,
(d) Multiply the background corrected spectrum by the coefficients to give the various nuclide concentrations.

This method, which is fast and well adapted to computers, can also be applied to natural radioelement mapping by using any number of windows.

8.8. PRODUCTS FOR ENVIRONMENTAL MONITORING

The products for fallout mapping will be more or less the same as for natural radioelement mapping. However, for reconnaissance surveys with wide line spacing, which would be carried out in the initial stages, hand drawn contour maps may prove more satisfactory than those produced by computer.
9. SEARCHING FOR RADIOACTIVE OBJECTS

The first part of this section describes three different airborne surveys that successfully located lost radioactive sources. The three incidents were quite different in nature and provide useful information should similar accidents occur in the future. Section 9 concludes with a discussion showing how to estimate the count rate which would be observed by AGRS from a radioactive source. These results can be used to plan searches for lost radioactive sources.

9.1. RECOVERY OF A LOST $^{60}$CO SOURCE

In the late 1950s, the United States Atomic Energy Commission developed an airborne nuclear radiation measuring system for a variety of nuclear accidents. The radiation detection system in the Aerial Radiological Measuring System (ARMS) aircraft consisted of fourteen 10.2 cm x 10.2 cm detectors, a single channel analyser, multichannel analysers, a chart recorder, radar altimeter and associated computer hardware.

On 21 June 1968, a 325 mCi $^{60}$Co source was lost in transit somewhere between Salt Lake City, Utah, and Kansas City, Missouri, a distance of 1800 km. On the basis of measurements over point sources, it was estimated that there was a good chance of locating the source along the highway, using the ARMS aircraft.

The route followed by the shipment truck was plotted on a map and the normal Doppler positioning system was removed from the aircraft to increase its range. A chart recorder was used to record both the radar altimeter and the total gamma ray count rate.

On 22 June, the aircraft flying at a nominal height of 123 m commenced the search along the truck route. The following day a strong radiation anomaly was detected on the total count chart record. Analysis of the spectral data showed that $^{60}$Co was the source of the anomaly. A subsequent search of the area with a ground vehicle and hand-held monitor successfully located the source.

9.2. LOCATING THE LOST ATHENA MISSILE

On 11 July 1970, a US Athena missile carrying two $^{57}$Co sources, each of approximately 470 mCi, crashed in northern Mexico. On the basis of the volume and surface area of the ARMS system and the activity of the sources, it was calculated that the chances of detecting the sources were good if the ARMS aircraft flew at an altitude of 75 m along flight lines 300 m apart.

\[1 \text{ Ci} = 3.7 \times 10^{10} \text{ Bq}.\]
On 1 August, using a small $^{57}\text{Co}$ source for calibration, the ARMS system was adjusted for a narrow 20 keV window centred on the $^{57}\text{Co}$ peak at 122 keV. Flight lines were then flown at 200 m intervals along the projected impact trajectory. The single channel count rate and the radar altitude were recorded on a strip chart. Single channel count rates, position information and radar altimeter data were listed on a printer. Visual navigation techniques were combined with a Doppler radar positioning system to give positions accurate to ±30 m.

On the eleventh flight line, the count rate in the $^{57}\text{Co}$ window increased to about two times background for 6 s. Several passes over the same point at various altitudes verified the existence of a point source which proved to be the impact site of the missile. A ground recovery team was directed to the site and found that the sources were not intact, but were distributed relatively uniformly over a large area.

9.3. COSMOS-954 INCIDENT

On 24 January 1978, COSMOS-954, a nuclear powered Soviet satellite, disintegrated on re-entering the Earth's atmosphere and scattered radioactive debris over a large area of northern Canada. The US Government offered the Canadian Government the assistance of the US Nuclear Emergency Search Team (NEST) with three gamma ray spectrometers. These three gamma ray spectrometers, together with one from the GSC, were all involved in the search operation.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Gamma ray energy (keV)</th>
<th>Half-life (d)</th>
<th>Origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{95}\text{Zr}$</td>
<td>724, 756</td>
<td>65</td>
<td>Fission product</td>
</tr>
<tr>
<td>$^{95}\text{Nb}$</td>
<td>765</td>
<td>35</td>
<td>Fission product (Daughter of $^{95}\text{Zr}$)</td>
</tr>
<tr>
<td>$^{103}\text{Ru}$</td>
<td>497</td>
<td>40</td>
<td>Fission product</td>
</tr>
<tr>
<td>$^{58}\text{Co}$</td>
<td>810</td>
<td>71</td>
<td>Neutron activation of $^{58}\text{Ni}$</td>
</tr>
<tr>
<td>$^{54}\text{Mn}$</td>
<td>835</td>
<td>300</td>
<td>Neutron activation of $^{54}\text{Fe}$</td>
</tr>
<tr>
<td>$^{140}\text{La}$</td>
<td>1590</td>
<td>1.5</td>
<td>Fission product</td>
</tr>
</tbody>
</table>
FIG. 17. Total count (a) and ratio of high to low energy (b) showing the detection of artificial radiation from Cosmos-954 debris in northern Canada.

On the basis of computer re-entry predictions, the probable impact zone covered an area 800 km long by 50 km wide. For logistical reasons, this initial search area was divided into 8 sectors. To cover this large area, four C-130 Hercules aircraft flew a reconnaissance survey along lines 1600 m apart at an altitude of 500 m. The first of the three US gamma ray spectrometers was airborne early on the morning of 25 January. The Canadian system was in the air 24 h later.

Fission products of a reactor emit gamma radiation with a higher proportion of low energy gamma rays than naturally occurring radioactive isotopes. Gamma rays from the neutron activation of steel are also predominantly of low energy.
FIG. 18. Total count trace (a) and gamma ray spectrum (b) showing the peaks of $^{103}\text{Ru}$, $^{95}\text{Zr}$, $^{95}\text{Nb}$ and $^{140}\text{La}$. 
Table III shows the major gamma rays emitted by fission and neutron activation products which are most likely to be observed soon after reactor shutdown. The half-lives of the various isotopes are also indicated. The more volatile elements such as Cs and I were not expected to have reached the ground because of the heat of re-entry.

Because of the high levels of radioactivity of rocks in the search area, a ratio technique was used to detect the artificial sources of radiation. This technique makes use of the fact that the radiation from the satellite debris is predominantly of low energy. The ratio of gamma rays in a 300–1400 keV window to those of 1400–2800 keV was found to remain constant for all natural sources of radioactivity. Radioactive satellite debris was indicated by an increase in this ratio as shown in Fig. 17.

On the night of 26–27 January, the Canadian spectrometer detected a radioactive source on the ice of Great Slave Lake. Subsequent computer analysis of the data recorded on magnetic tape confirmed the presence of gamma rays characteristic of the products of nuclear fission. The gamma ray spectrum of the source, obtained by subtracting the spectrum from neighbouring points, is shown in Fig. 18, together with the total count profile, showing the significant low energy component.

By 31 January the search had shown that all large radioactive fragments from the satellite had fallen within a strip 10 km wide along part of the predicted re-entry path. As much of the area was north of the tree line with few reference points, considerable difficulty was found in pinpointing the location of radioactive debris detected. In order to provide accurate and systematic coverage of the narrow zone where radioactive debris had been found, two microwave ranging systems were employed. Detailed coverage of this narrow search area was flown at a line spacing of 500 m at a nominal terrain clearance of 250 m.

On 10 February, by chance, a low flying helicopter discovered many radioactive sources some distance from the original search area. These sources were too weak to be detected at the altitude flown by the Hercules aircraft. Later analyses of these minute pieces showed them to be part of the missing reactor core. In the next few days, other low flying helicopters detected more radioactive particles even farther from the satellite track. The reactor core had apparently disintegrated on entering the Earth’s atmosphere and minute pieces of the core had been carried by the wind to dust many thousands of km² of northern Canada. These minute particles were not considered to be cause for concern.

9.4. CALCULATION OF SYSTEM SENSITIVITIES

In planning a search procedure for lost gamma ray sources, it is important to have a good estimate of the sensitivity of the system. This is best carried out by flying
over sources of known activity. However, reasonable estimates can be made from a knowledge of the activity of the source and the dimensions of the airborne system.

Airborne systems for U exploration and geological mapping have been designed specifically for detecting high energy gamma rays from the U and Th series. An optimum detector thickness for these high energy gamma rays is considered to be 10.2 cm. In almost all cases, man-made radioactive sources will be considerably lower in energy. It can be assumed that all gamma rays striking the detector will be completely absorbed. The area of the detector presented to the source will therefore be directly proportional to the number of gamma rays detected.

The number of gamma rays detected per second by an airborne system which is directly above a point source on the ground will be given by:

\[ N = \frac{B f A \exp(-\mu H)}{4H^2} \]  
(9.1)

where

- \( B \) is the activity of the source in Bq,
- \( N \) is the number of gamma rays detected per second,
- \( f \) is the fraction of disintegrations producing gamma rays,
- \( H \) is the altitude of the aircraft above the ground,
- \( \mu \) is the linear attenuation in air of the gamma ray energies being considered, and
- \( A \) is the cross-section area of the detector.

Table IV gives the linear attenuation coefficients of air at STP for gamma ray energies of different energies.

For example, a 10 mCi \(^{137}\)Cs source will emit \( 3 \times 10^8 \times 0.85 \) gamma rays per second at 662 keV. The factor 0.85 arises because only 85% of \(^{137}\)Cs disintegrations produce gamma rays. From Table IV it is seen that these gamma rays have a linear attenuation coefficient of approximately 0.01 per metre. From Eq. (9.1), one standard airborne detector package with a lower surface area of 40.64 cm \( \times \) 40.64 cm will detect approximately 120 gamma rays in the 662 keV photopeak at an altitude of 100 m. From previous data collected by the airborne system, about 70 counts/s from typical ground will be expected in a 100 keV window centred at 662 keV.

Equation (9.1) can be applied directly to situations such as the lost \(^{60}\)Co source previously described. In this case, where the source was lost along a road, there is only one dimension of uncertainty. However, in a case such as the lost Athena missile, it cannot be assumed that the aircraft will fly directly over the source and there are therefore two dimensions of uncertainty and the situation is more complicated. In order to determine the system count rate, consideration must be given to the solid angle subtended by the detector at the source. This will depend on the
TABLE IV. LINEAR ATTENUATION COEFFICIENTS FOR GAMMA RAYS OF DIFFERENT ENERGIES

<table>
<thead>
<tr>
<th>Photon energy (keV)</th>
<th>Linear attenuation coefficient (per metre)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.623</td>
</tr>
<tr>
<td>100</td>
<td>0.019 5</td>
</tr>
<tr>
<td>150</td>
<td>0.017 4</td>
</tr>
<tr>
<td>200</td>
<td>0.015 9</td>
</tr>
<tr>
<td>300</td>
<td>0.013 7</td>
</tr>
<tr>
<td>400</td>
<td>0.012 3</td>
</tr>
<tr>
<td>500</td>
<td>0.011 2</td>
</tr>
<tr>
<td>600</td>
<td>0.010 4</td>
</tr>
<tr>
<td>800</td>
<td>0.009 13</td>
</tr>
<tr>
<td>1000</td>
<td>0.008 21</td>
</tr>
<tr>
<td>1500</td>
<td>0.006 68</td>
</tr>
</tbody>
</table>

flight line spacing as well as on the aircraft flying height. Equation (9.1) will then be modified to give:

\[
N = \frac{BfAh \exp(-\mu(D^2 + H^2)^{1/2})}{4\pi(D^2 + H^2)^{3/2}}
\]  

(9.2)

where \(D\) is the horizontal distance from the source and all other notation is the same as in Eq. (9.1).

9.5. SEARCH STRATEGY

The following points should be considered when planning any search operation:

(1) Probable location of the source: this area should be flown first;
(2) Locations of populated areas: these should be given priority within the search area;
(3) Flight line spacing and flying height: these will be determined by the activity and number of sources and the sensitivity of the system;

(4) Navigational capabilities of the search aircraft;

(5) Communication between the ground teams and the search aircraft.
Appendix

AIRBORNE GAMMA RAY SPECTROMETRIC SURVEY
SAMPLE SPECIFICATIONS

A.1. INTRODUCTION

These specifications are for an airborne gamma ray spectrometer and sup-
plementary aeromagnetic survey to be carried out as part of a national geological
mapping programme. The data will be used to help identify mineral deposits and to
assist in geological mapping. The data will also be available to provide a map of
natural radiation dose at ground level. Specifications for the acquisition and process-
ing of aeromagnetic data along with the spectrometric data are included since the two
methods are often used together.

The work is divided into two separate contracts, one for data acquisition and
the other for data processing, but the two are often carried out by the same
contractor.

A.2. DATA ACQUISITION

The main responsibilities of the acquisition contractor will be as follows:

(a) Flying operations including all necessary permits, fuel and lubricants, logisti-
cal support, etc;

(b) Survey operations including operation and maintenance of geophysical equip-
ment, day to day programme and logistics;

(c) Reflying any out of tolerance data;

(d) Ensuring that the data are available for inspection at all times;

(e) Flight path recovery and production of navigation maps;

(f) Delivery at the end of the work of all digital data, test results and navigation
maps.

The main responsibilities of the client will be to:

(1) Assist the contractor to obtain any necessary permits or licences;

(2) Provide three sets of topographic maps of the area for navigation and flight
path recovery;

(3) Check data quality throughout survey operations and inform the contractor
immediately of any data out of tolerance.

In the following sections the specifications for each aspect of the survey are
given. The work will follow closely the standards and procedures recommended in
this present IAEA Technical Reports Series, Airborne Gamma Ray Spectromer Surveying.

A.2.1. Crew and equipment

The contractor will provide as a minimum the following crew:

— Geophysicist/project manager
— Electronics engineer to operate and maintain the instruments
— Data compiler to carry out flight path plotting
— Pilot
— Navigator
— Aircraft engineer.

The client will provide a representative to check the data quality and to provide guidance on any problems encountered.

The contractor will provide a twin engine aircraft suitable for the survey conditions, with the following instruments installed in it:

— Gamma ray spectrometer with a minimum 32 L detector
— Total field magnetometer
— Digital data acquisition and recording system
— Analogue chart recorder for field checking of data
— Tracking camera or video fully synchronized with the data acquisition system
— Doppler or other suitable navigation system interfaced to the data acquisition system
— Precision radar altimeter
— Barometric altimeter or pressure sensor
— Field computer for verifying digital records and other quality control purposes.

Detailed specifications of the instrumentation are given below.

A.2.2. Survey parameters

A.2.2.1. Area of survey

The boundaries of the survey area are shown on the figure that would be provided. The estimated line km total for flight lines, tie lines and peripheral lines will be specified.

A.2.2.2. Flight line direction and spacing

The flight lines will be flown at a true bearing of degrees which will be specified, with a spacing of 1 km. The tie lines or control lines will be flown 10 km apart
at 90 degrees to the flight lines. Peripheral lines will be flown if the distance between the edge of the survey area and the nearest tie line is greater than 5 km.

The distance between adjacent flight lines must not exceed 1.5 km over a distance of more than 5 km, and must not exceed 2 km at any point. Any parts of the survey outside these tolerances must be reflown or infilled with lines flown between tie lines, at the contractor's expense. This tolerance may be relaxed in specific cases for flight safety reasons. The pilot's decision on matters of safety will be final.

A.2.2.3. Flying height and speed

The survey will be flown at a constant ground clearance of 120 m above ground level at an aircraft speed of not more than 200 km/h. Any sections of line longer than 2.5 km flown at a height greater than 140 m or less than 100 m must be reflown at the contractor's expense. This tolerance may be relaxed in specific cases for flight safety reasons. The pilot's decision on safety will be final.

A.2.2.4. Sampling rate

The sampling rate for the spectrometer, magnetometer, barometer, altimeters and navigation system will be one per second.

A.2.3. Flight path recovery

A.2.3.1. Instrumentation

A tracking camera or video will be installed in the aircraft. If a film camera is used, it should be triggered and annotated by the data acquisition system. Each video frame will be annotated with fiducial numbers from the data acquisition system.

The aircraft will be fitted with a Doppler, inertial or other navigation system to assist the pilot. Output from the system will be recorded with the geophysical data. The navigation system must be specified in detail by the contractor and approved by the client.

A.2.3.2. Flight track plotting

At the operational base the tracking film or video will be used to plot visual fixes onto topographic base maps. A minimum of one visual fix should be plotted per 10–15 km of line, wherever possible. The data recorded from the navigation system will be used to determine the flight path between these plotted points. The method for combining the visual and navigation system fixes must be agreed between the contractor and the client before the contract is signed.
Backup copies of all flight path maps will be made and deposited with the client on demobilization from the field operations base.

A.2.4. Gamma ray spectrometry

A.2.4.1. Instrumentation

A spectrometer with full spectral recording and at least 33.6 L of detector volume will be used. The following standard windows measured in keV will be recorded:

- Potassium: 1370–1570
- Uranium: 1660–1860
- Thorium: 2410–2810
- Total count: 400–2810
- Cosmic: 3000–∞

A cosmic window of 3000–6000 keV will be acceptable.

The system will have an upward looking detector of minimum 4.2 L, for which only the U window data need be recorded.

The accumulation time and sampling time will be 1 s. The detectors of the spectrometer will be kept at operating temperature throughout the period of the survey, using an external power supply to the aircraft overnight.

A.2.4.2. Determination of stripping ratios

At the beginning and end of the survey, calibration of the spectrometer on an approved set of calibration pads is required. Full details and the values of the stripping ratios should be provided to the client.

A.2.4.3. Daily spectrometer checks

The detector gains should be checked daily before productive flying and adjusted if necessary. A check on spectral stability and system sensitivity should be kept by means of twice daily source checks and resolution checks.

Source checks will be carried out before and after productive work each day. These checks will take the following form:

- 60 s background record (sources at least 30 m from the aircraft)
- Uranium source, sufficient time to give minimum of 10 000 counts in the U window
- Thorium source, sufficient time to give minimum of 10 000 counts in the Th window
- 60 s background repeat record.
Care will be taken to ensure that the sources are always placed in exactly the same position relative to the detectors, preferably on the ground beneath the aircraft. The digital average of each check will be determined using the field computer and corrected for dead time. The average of the two background readings will be subtracted from each source reading and the results plotted against time over the survey period. If a source check gives results which differ by more than 5% from the mean of checks to date, the cause of the change should be investigated.

Spectral stability will also be checked by plotting the spectrum of a $^{137}$Cs source twice daily and checking the resolution immediately after checking the gains before flying and again after flying, but without further adjusting the gains.

The plots of source checks and resolution determinations should be kept up to date for inspection by the client's representative and for later inclusion in the operations report.

A.2.4.4. Radon background

Radon background will be determined using the upward looking detector. However, the contractor must demonstrate that the coefficients required for this calculation have been well determined for his equipment. If necessary, regular over-water flights at survey altitude must be made during the survey period to permit determination of these coefficients.

A.2.4.5. Attenuation coefficients and system sensitivities

To determine the attenuation coefficients and system sensitivities, a series of flights will be made over an approved dynamic test range. The flights will be at 60, 90, 120, 150, 180, 210 and 240 m both over land and over water. If necessary, a dynamic test range will be established close to the survey area.

A.2.4.6. Cosmic and aircraft background test flights

To determine the aircraft background and to find expressions for the cosmic background, a series of flights should be made over the sea or a large lake, at heights 1500 to 3000 m above mean sea level at 300 m intervals. The aircraft background should be checked each week by flying at least 1500 m above ground level. If the result varies by more than 5% from the expected value, the full series of flights must be repeated.

A.2.4.7. Rainfall

Records of rainfall at a meteorological station near the survey area must be obtained and a rainfall graph showing periods of data acquisition will be included by the contractor in his report.
A.2.5. Magnetometer

A.2.5.1. Instrumentation

A magnetometer will be carried in the aircraft to measure total magnetic intensity. The sensor may be in either a ‘stinger’ or a ‘bird’ installation. The resolution of the magnetometer will be 1 nT or better.

A.2.5.2. Magnetic storm monitoring

A recording magnetometer will be set up at a suitable site, away from strong magnetic gradients or cultural effects, in order to monitor the geomagnetic diurnal and other time varying fields. The digital data from this monitor will be used to correct the airborne data. (Note: This method of removing time varying effects is not suitable for use in surveys close to the sea-coast, at the geomagnetic equator or in the auroral zones near the poles. In these conditions, a maximum acceptable non-linear component (typically 5 nT over 5 min) must be defined and any data acquired during non-linear events larger than this will be deemed out of tolerance.)

Verified backup copies of the storm monitor digital records will be made using the field computer and will be deposited with the client on demobilization from the field operations base.

A.2.5.3. Heading Test

An eight point heading test will be carried out over a clearly identifiable point in a magnetically quiet area.

A.2.5.4. Lag test

The magnetometer lag will be determined by passes in opposite directions over a strongly magnetic body such as a railway bridge.

A.2.6. Altimeters

A.2.6.1. Instrumentation

The aircraft will be equipped with a precision radar altimeter, accurate to 3 m or better, and a barometric altimeter. Both instruments will be interfaced to the data acquisition system and their output sampled once per second. The barometric altimeter may be calibrated in units of height or pressure.
A.2.6.2. Calibration

The calibration of the radar altimeter (volts to metres) will be confirmed by flights at different heights (60–250 m) over water, using the pilot’s indicator.

A.2.6.3. Temperature

The outside air temperature will be measured by a sensor located so as to be out of direct sunlight; the results will be recorded with the other data to permit reduction of the flying height to standard temperature and pressure (STP).

A.2.7. Data acquisition and recording

A.2.7.1. Instrumentation

The aircraft will be fitted with a data acquisition system which will perform the following functions:

(a) Capture data from the geophysical instruments, altimeters and navigation system, at a 1 s sample rate;
(b) Format the digital data for recording on tape or other medium;
(c) Trigger the tracking camera and/or annotate the tracking film or video with fiducial numbers.

The data will be recorded on a digital recording device carried in the aircraft and the contractor must provide a means of producing analogue charts for checking the data quality.

A.2.7.2. Formats of field records

The format of the digital data will be agreed between the client and the contractor.

The following digital data will be recorded at 1 s intervals:

— Spectrometer K, U, Th and total count window count rates
— Spectrometer cosmic channel count rate
— Spectrometer full spectral data
— Total magnetic intensity temperature
— Radar and barometric altimeter
— Outside air temperature
— Co-ordinates from the navigation system. Doppler velocity components or other data from which co-ordinates can be calculated will be acceptable.
Analogue records will be produced to permit the data quality to be checked. These should display the K, U, Th and total count spectrometer windows, the magnetometer data, the radar and barometric altitudes and should also carry fiducial marks and numbers at regular intervals. The analogue records may be made in real time or plotted by the field computer from the digital records. The scales of the analogue records will be agreed between the contractor and the client.

Both digital and analogue records will be fully labelled. Reports will be produced describing fully the formats of digital data and listing the contents of each data tape.

A.2.7.3. Loss of digital data

The digital data must be verified before it will be accepted by the client. This verification will probably be carried out using a field computer. In the event of loss of more than 20 s of continuous digital data from any instrument, the loss will be made good at the contractor’s expense, either by reflying between tie lines or by digitizing analogue records. This requirement may be relaxed at the client’s discretion, in specific instances.

Verified backup copies of the digital data will be made using the field computer and deposited with the client on a weekly basis.

A.2.8. Field computer

The contractor will operate a computer at the field base with the hardware and software to carry out the following tasks:

- Verify the digital data from the survey
- Make backup copies of the field data
- Read and list sections of digital data
- Provide a means of combining the visual and digital navigation data
- Calculate mean values of the digital data over selected fiducial intervals
- Plot profiles of selected data over fiducial intervals
- Plot spectra from the digital records.

A.2.9. Final delivery

The following products will be delivered to the client on completion of the survey:

- All digital records, fully labelled and annotated
- All analogue records, fully labelled
- All flight path maps
- All results of calibrations, tests and checks
— All flight logs and data reports
— All ground magnetometer records, fully labelled
— Any other intermediate or working products.

An operations report will also be delivered containing the following information:

— Diary of operations
— List of the crew members and their job descriptions
— Description of the instruments used and their specifications
— Summary of the survey parameters and tolerances
— Details of the flight path recovery method
— Description of all calibrations, tests and checks, with results in graphical and tabular form
— Details of the method used to determine coefficients for radon background calculation
— Graph of rainfall at the nearest meteorological observatory
— Description of the formats of digital records and the scales of analogue records, with samples
— Lists of lines flown, start and end fiducials, length, date and flight number.

A.3. DATA PROCESSING

The main responsibilities of the processing contractor will be to:

— Read the digital survey data
— Check the data for gaps, spikes and other defects and edit where necessary
— Digitize the flight path maps
— Check the digitized navigation data
— Plot final flight path maps
— Merge navigation and geophysical data
— Filter raw data
— Carry out spectrometer data corrections and convert to apparent radioelement concentrations and ground level exposure rates
— Level aeromagnetic data and subtract the international geomagnetic reference field (IGRF)
— Plot multiple parameter profiles
— Grid the geophysical data
— Plot contour maps
— Produce archive tapes of line by line and gridded data.

Details of each of these processes are given below. The work will follow closely the standards and procedures recommended in this present IAEA Technical Reports Series, Airborne Gamma Ray Spectrometer Surveying.
The main responsibilities of the client will be to:

— Provide verified digital data to the contractor
— Provide navigation maps suitable for digitizing
— Provide values for all experimental quantities needed to carry out the radiometric processing
— Check and approve the processing stages, in particular filtering, smoothing and contouring operations.

A.3.1. Raw data

A.3.1.1. Digital data

The format of the digital data will be agreed beforehand between the client, the acquisition contractor and the processing contractor. A full format description will be provided.

The contractor will read the tapes, check the data for gaps, spikes or other defects and edit the data where necessary. It is expected that defects will not exceed twenty records in length.

Spectrometric data will be rewindowed if necessary from the 256-channel data, based on spectra summed over each flight line. Rewindowing need not be carried out if the radioelement peaks lie within ±2 channels of the correct positions.

The ground magnetometer data will be checked, edited where necessary and merged with the airborne data.

A.3.1.2. Navigation data

The flight path data will be in the form of maps showing visual fixes and intermediate points based on data from the navigation system. The processing contractor will digitize sufficient points from the maps to represent adequately the true flight paths and then use the navigation system data to interpolate the locations between them. The digitized data will be checked by calculating the apparent speeds between fixes.

A.3.1.3. Merging navigation and geophysical data

The navigation and geophysical data sets will be merged so that each fiducial is correctly located. Filters may be applied to the various geophysical data channels by agreement with the client to reduce high frequency noise. The results will be included on the archive tapes as the ‘raw’ data.
A.3.2. Spectrometer corrections

A.3.2.1. Reduction to STP

The radar altimeter data will be converted to effective height in metres at STP, using the pressure and temperature data.

A.3.2.2. Dead time correction

The downward looking data will be corrected for dead time.

A.3.2.3. Aircraft and cosmic background corrections

Corrections for cosmic and aircraft backgrounds will be made using expressions of the form:

\[ N_c = N - a - bC \]  \hspace{1cm} (A.1)

where

\( N_c \) is the corrected count rate in the window,
\( N \) is the raw count rate,
\( a \) is the constant aircraft background,
\( b \) is the cosmic stripping factor for the window,
\( C \) is the count rate in the cosmic window.

The values of \( a \) and \( b \) for each channel will be provided by the client from the information supplied by the acquisition contractor.

A.3.2.4. Radon background

The radon background will be determined from the upward looking detector data. To minimize statistical noise effects, the calculation will be carried out using 20 point running means of the \( U \) upward, \( U \) downward and \( Th \) downward data. In areas of unusually high radioactivity where pulse pile-up could occur, backgrounds will be interpolated between adjacent sections of lines. The radon background is determined by:

\[ U_r = \frac{u - a_1U - a_2T + a_2b_T - b_U}{a_U - a_1 - a_2a_T} \]  \hspace{1cm} (A.2)
where

- \( U_r \) is the radon background to be subtracted from the \( U \) window data,
- \( u \) is the running mean upward \( U \) count, cosmic and aircraft background corrected,
- \( U \) is the running mean downward \( U \) count, dead time, cosmic and aircraft background corrected,
- \( T \) is the running mean downward \( Th \) count, dead time, cosmic and aircraft background corrected,

and \( a_1, a_2, a_U \) and \( a_T \) are experimentally determined factors which will be provided to the contractor together with the constants \( b_T \) and \( b_U \).

The radon corrections to be applied to the \( K \) and total count data are found by applying proportionality factors to the radon correction for the \( U \) window which will be provided by the client from information supplied by the acquisition contractor.

### A.3.2.5. Stripping

Stripping will be carried out to remove the effects of spectral overlap. The expressions for stripping and the values of the stripping ratios will be provided by the client from information supplied by the acquisition contractor. The stripping ratios will be adjusted for effective height above ground level (AGL) on a sample by sample basis.

### A.3.2.6. Attenuation corrections

Attenuation corrections will be carried out using the radar altitude reduced to STP and attenuation coefficients provided by the client from information supplied by the acquisition contractor. The expression for the correction is:

\[
N_c = N \exp(\mu (H - H_0)) \tag{A.3}
\]

where

- \( N_c \) is the corrected count rate in each window,
- \( N \) is the background corrected, stripped count rate,
- \( \mu \) is the attenuation coefficient for the window,
- \( H \) is the radar altitude reduced to STP,
- \( H_0 \) is the nominal survey height AGL (120 m).

In consultation with the client, a maximum altitude will be determined above which no further correction will be applied. The initial value for this maximum will be 250 m AGL.
A.3.2.7. **Conversion to apparent radioelement concentrations**

The count rates in the K, U and Th windows will be converted to apparent radioelement concentrations, K%, eU ppm and eTh ppm. The total count rate will be converted to ground level exposure rate in \( \mu \text{R/h} \) using sensitivity factors provided by the client from information supplied by the acquisition contractor.

A.3.3. **Magnetometer data**

A.3.3.1. **Diurnal subtraction**

The digital diurnal data will be subtracted from the airborne magnetometer data. A quantity equal to the mean of the ground magnetometer data over the survey period will be added to the results.

A.3.3.2. **Levelling**

The flight line-tie line intersections will be determined and used to level the magnetometer data. The levelling process to be used must be fully described by the processing contractor and approved by the client.

A.3.3.3. **IGRF subtraction**

The IGRF for the period of the survey will be subtracted from the levelled data.

A.3.4. **Gridded data**

The K, U, Th, total count and aeromagnetic data will be gridded. The mesh size and gridding algorithms will be agreed upon with the client after examples have been produced. An initial square mesh of dimension 0.25 times the flight line spacing will be used.

A.3.5. **Final products**

A.3.5.1. **Flight line maps**

The flight tracks will be plotted on stable base film, on the same scale and sheet lines as the national topographic maps. The flight lines will be annotated with fiducial ticks every 20 fiducials and fiducial numbers every 100 fiducials, or as agreed upon with the client after tests. The line numbers (and line part numbers) will be shown
at each end of the line and at each edge of the map sheet. Two stable base copies suitable for making dye line copies will be delivered.

A.3.5.2. Multiprofile plots

Plots will be produced showing profiles of the following quantities at 1:50 000 horizontal scale: radar altitude, barometric altitude, K (%), U (ppm), Th (ppm), exposure rate (\(\mu\text{R/h}\)) and magnetic anomaly. The magnetic anomaly at a second vertical scale and the ratios U/Th and U/K may also be displayed if requested by the client. The vertical scales and the annotations of the profiles will be agreed upon with the client.

A.3.5.3. Contour maps

Contour maps of all the gridded quantities will be produced on stable base film on the same scale and sheet lines as the national topographic map series. The flight lines will be shown half screened on the contour maps and the contour intervals and map annotations will be agreed upon with the client. Two stable base copies suitable for making dye line copies and five paper copies of each map sheet will be delivered.

A.3.5.4. Colour maps

Colour aeromagnetic maps and ternary radioelement maps will be produced at 1:250 000 scale. The colour palettes will be agreed upon with the client after tests. Colour map sheets will be delivered in five paper copies.

A.3.5.5. Archive tapes

Data archives will be ASCII coded and produced on one half in, 1600 bpi (bits per inch) computer compatible tapes. One set of tapes will carry line by line data including the (edited and filtered) raw spectrometer, magnetometer, altimeter and ground magnetometer data, fiducial and line numbers, positional co-ordinates, apparent radioelement concentrations and exposure rates, U/Th, U/K and Th/K ratios, and magnetic anomalies.

A second set of tapes will carry the gridded data.

Each tape will be explicitly labelled and a full format description will be provided in a text header file on each tape. The grid tapes will contain header information on the grid origin and orientation, X and Y spacing and numbers of X and Y points.

A duplicate set of archive tapes may be kept by the contractor, provided strict and complete confidentiality is preserved and no use of any kind is made of the data without the written permission of the client.

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A.3.5.6. Processing report

A report describing in full all the stages of processing will be delivered in six copies. The report will also contain a list of the members of the processing team with their job descriptions, a diary of progress, examples of the effects of filters used, sample products and a full description of archive tape formats.
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