676-80

A CALIBRATION PROCEDURE FOR AIRBORNE GAMMA RAY SNOW SURVEYS [1]

By

J.E. Glynn [2] and R.L. Grasty [3]

Introduction

Gamma rays emitted by natural radioactive decay in the ground are attenuated by snow cover. This principle led researchers at the Soviet Hydrological Institute to test the feasibility of determining snow water equivalent using airborne gamma ray detectors. During the period 1963-68 the method was tested extensively and after successful results were obtained, the Soviet Union initiated operational gamma ray snow surveys (Vershinina and Dimaksyan, 1971). Other countries, including the United States (Peck et al, 1979) have now begun operational field programs using airborne systems. The Geological Survey of Canada (GSC) has been using gamma ray spectrometry for determining snow water equivalent since 1972 (Loijens and Grasty, 1973). This winter (1979-80) the GSC together with the National Hydrology Research Institute of Environment Canada has undertaken to perform a snow survey of Southern Ontario for Parks Canada and the Ontario Ministry of Natural Resources.

The GSC is flying the survey using a Short's Skyvan aircraft and a gamma ray spectrometer of their own design based on a Nova mini-computer (Bristow, 1979). The system utilizes twelve 102 x 102 x 406 mm sodium iodide detectors and records spectral data in 256 channels once every second on magnetic tape. Analysis of the data is performed off-line on a CDC 6600 computer.

This paper describes the calibration procedure which is being used in this winter's program to determine snow water equivalent. The calibration procedure is based on experimental results over large radioactive concrete pads and incorporates height dependent spectral responses for potassium, uranium and thorium. The effect of counting statistics on the repeatability of the airborne method was studied by a Monte-Carlo technique from the results of a series of flights over a test area near Ottawa. Other factors such as flight line duplication, background variation and soil moisture sampling problems were not included in this study.

Basic Concepts

The three natural radioactive elements in the ground are potassium, uranium and thorium. Gamma-rays emitted by these radioelements are accumulated into four commonly used windows (Table 2). An Integral window monitors overall levels of radioactivity. Since the system is airborne, photons emitted from the ground must travel through air as well as snow to reach the detector, and both these media will scatter as well as absorb the gamma radiation. This implies, for example, that some of the counts detected in the potassium window in the airborne spectrometer will have originated from decays in the uranium decay series in the ground. Hence the shape of the gamma-ray spectrum is altered by both the aircraft flying height and the water equivalent of snow on the ground. The first step in the calibration procedure is to determine the ratio of the counts detected in one window to those in another window from a pure uranium, potassium, or thorium source at ground level. This ratio is commonly called a stripping ratio.

The calibration procedure used to determine these stripping ratios utilizes large radioactive concrete pads and has been described by Grasty (1977). For a measurement on the calibration pads a series of equations can be formulated to relate the observed count rate N_T, N_U, and N_K in the three radioelement windows to the radioelement concentration, T_{ppm}, U_{ppm} and K_{pct} of each pad.

---

[1] Presented at Western Snow Conference, Laramie, Wyoming, 15-17 April, 1980.

[2] National Hydrology Research Institute, Environment Canada, Ottawa, Ontario, KIA OE7, Canada.

[3] Geological Survey of Canada, Department of Energy, Mines and Resources, Ottawa, Ontario, KIA OE8, Canada.

$$N_T = \varepsilon_{TK} K_{pct} + \varepsilon_{TU} U_{ppm} + \varepsilon_{TT} T_{ppm} + B_T \quad (1)$$

$$N_U = \varepsilon_{UK} K_{pct} + \varepsilon_{UU} U_{ppm} + \varepsilon_{UT} T_{ppm} + B_U \quad (2)$$

$$N_K = \varepsilon_{KK} K_{pct} + \varepsilon_{KU} U_{ppm} + \varepsilon_{KT} T_{ppm} + B_K \quad (3)$$

B_T, B_U and B_K are background count rates arising from the radioactivity of the aircraft and its equipment, the radioactivity of the ground surrounding the pads plus cosmic radiation and the radioactivity in the air. The ε_{IJ}'s are constants to be determined and give the count rate in window I per unit concentration of element J.

Following the notation adopted by Grasty (1977), the stripping ratios α,β,γ,a, b, and g are then related to the ε_{IJ} constants by the equations:-

$\alpha = \varepsilon_{UT}/\varepsilon_{TT}$ (the thorium into uranium stripping ratio)

$\beta = \varepsilon_{KT}/\varepsilon_{TT}$ (the thorium into potassium stripping ratio)

$\gamma = \varepsilon_{KU}/\varepsilon_{UU}$ (the uranium into potassium stripping ratio)

$a = \varepsilon_{TU}/\varepsilon_{UU}$ (the reversed stripping ratio, uranium into thorium)

$b = \varepsilon_{TK}/\varepsilon_{KK}$ (the reversed stripping ratio, potassium into thorium)

$g = \varepsilon_{UK}/\varepsilon_{KK}$ (the reversed stripping ratio, potassium into uranium)

The three equations (1), (2), and (3) can readily be solved by a least squares technique to derive the various ε_{IJ}'s from which the stripping ratios α,β,γ,a,b, and g may be calculated.

For an airborne measurement, the background-corrected count rates, N_T, N_U and N_K are related to the stripped or corrected count rates T_c, U_c and K_c from pure thorium, uranium and potassium by the equations:-

$$N_T = T_c + aU_c + bK_c \quad (4)$$

$$N_U = \alpha T_c + U_c + gK_c \quad (5)$$

$$N_K = \beta T_c + \gamma U_c + K_c \quad (6)$$

These equations may then be inverted to obtain the stripped count rates for each of the pure radioelements as described by Grasty (1977).

In reality, the stripping ratios are dependent on the aircraft altitude and on the snow water equivalent. To study the variation of the stripping ratios with absorber thickness, an experiment was performed on the calibration pads at Grand Junction, Colorado, (Carson et al, 1979).

A detector system consisting of four, prismatic 102 x 102 x 406 mm sodium iodide detectors was placed on plywood sheets on a baggage trolley and positioned over the centre of each pad. The experiment was repeated with varying thicknesses of plywood sheet under this calibration detector package. Thicknesses of plywood up to an equivalent of 150 mm of water were used. This water equivalent was calculated from the number of electrons per unit area of the plywood sheets (Kogan et al, 1969). Analysis of the results indicated a linear increase of α,β and γ with equivalent water depth but no systematic variation in a, b or g. (Figures 1, 2 and 3). The slope, or increase in the stripping ratios with water depth was assumed to be the same for both the aircraft and calibration spectrometer used in the experiment. However, the aircraft spectrometer was used to determine the value of each stripping ratio at ground level when no absorber was present, to give the operational curves. (Figures 1, 2 and 3). These results are also presented in Table 1.

Experimentally it is found that the background corrected stripped count rates in any window, N_c, are related to the water equivalent of the aircraft altitude, h, by a simple exponential of the following form:

$$N_c = N_o \exp(-\mu h) \tag{7}$$

where N_o is a constant and μ is the linear attenuation coefficient for water. A similar expression is also found for the background-corrected count rates in the Integral window.

In order to determine the attenuation coefficients for the four windows the spectrometer was flown over a test strip near Breckenridge, Quebec (Grasty and Charbonneau, 1974) at twelve different altitudes. The recorded count rates were first corrected for background from flights over the Ottawa River and then stripped and plotted against the aircraft altitude. The results for potassium are shown in Figure (4) and the calculated attenuation coefficients for all four windows presented in Table 2. In practice, the uranium window is not used to calculate snow water equivalent because of its low count rate and problems of background variation.

Operational Procedure

In order to perform an operational gamma ray snow survey, two flights must be flown, one in the fall before any snow has fallen, and the other at the time the survey is required. The data collected must be corrected for background radiation and for any soil moisture changes between the two surveys.

Background radiation results from cosmic radiation, the radioactivity of the aircraft and its equipment, and the presence, in the air, of daughter products of radon gas. Corrections for variations in the background are achieved by flying the aircraft over a large body of water close to the flight line which is sufficiently deep to absorb the terrestrial gamma ray emissions. The average count rate obtained from the background flight can then be subtracted from the average count rate along each flight line.

The presence of soil moisture affects the base level of radiation emitted from the ground. As soil moisture increases, the water in the soil absorbs more of the gamma radiation and hence leads to an apparent lowering of the ground level count rate, N_o, given in Equation (7). Hence, soil moisture samples must be collected at the time of each survey.

As given by Kogan et al (1969), the count rate, N_o, at the surface of the ground is related to the soil moisture content by the equation:-

$$N_o = \frac{100\ N_d}{100 + 1.11\ W} \tag{8}$$

where W is the soil moisture content expressed in percentage of dry weight and N_d is the count rate at the surface for dry rock.

Combining the results of the pre-snow and snow survey we obtain the following formula for the water equivalent, d:-

$$d = \frac{1}{\mu} \ln \left\{ \frac{N_p(100 + 1.11W_p)}{N_s(100 + 1.11W_s)} \right\} + h_s - h_p \tag{9}$$

where N_p, N_s and W_p and W_s are the corrected count rates and soil moisture contents for the pre-snow and snow surveys respectively. h_p and h_s are the average water equivalent aircraft altitudes for the pre-snow and snow surveys.

In the case of the Integral window, this formula can be applied directly. However, in the case of the potassium and thorium windows, the stripped count rate, N_s, will be dependent on the snow water equivalent. A simple iterative procedure was adopted for the water equivalent calculation for these windows by initially calculating N_s, assuming d to be zero. A new value of d could then be calculated from equation (9), N_s correspondingly updated, and the process repeated. It was found that this procedure converged to within 0.1 mm water equivalent of the correct value in two or three iterations.

Due to the physical nature of radioactive decay, the recorded counts are subject to Poisson distributed random noise. The Poisson distribution representing accumulated counts in a given time interval may be quite well approximated by a normal distribution when the average number of counts in the interval is greater than 10 (Cinlar, 1975). This makes it possible to derive an estimate of the variance in the calculated snow water equivalent by means of a Monte-Carlo simulation. This simulation incorporates uncertainties in the measurement of background as well as uncertainties in the counts accumulated along each line. 100 replications of the calculation were generally found to provide a standard deviation within 1 mm of the true value.

Another technique for computing the variance in the snow water equivalent has been described by Loijens and Grasty (1973). In this technique, the flight line is subdivided into 5 or more sections and the snow water equivalent computed along each section. These values can then be used to compute the variance of the snow water equivalent for the entire line. Both methods were found to give similar values.

Given the means, S_K, S_T and S_I and variances σ^2_K, σ^2_T and σ^2_I for the snow water equivalent computed using the potassium, thorium and Integral windows respectively, one may weight these values in the standard way to derive an expression for the snow water equivalent having minimum variance. The mean S and variance σ^2 of this weighted average may be approximated by the following formulae:-

$$S = \frac{\dfrac{S_K}{\sigma^2_K} + \dfrac{S_T}{\sigma^2_T} + \dfrac{S_I}{\sigma^2_I}}{\dfrac{1}{\sigma^2_K} + \dfrac{1}{\sigma^2_T} + \dfrac{1}{\sigma^2_I}}$$

$$\sigma^2 = \frac{1}{\dfrac{1}{\sigma^2_K} + \dfrac{1}{\sigma^2_T} + \dfrac{1}{\sigma^2_I}}$$

These formulae are approximations because the actual computed snow water equivalents are not statistically independent. However, using a Monte-Carlo technique to compute the covariance matrix, it was found that the approximation was adequate.

Airborne Tests

On February 28th 1979, and again on June 19th, 1979, a series of nine flights were carried out along a 10 km line, near the community of Finch, about 40 km south-east of Ottawa. These flights were used to test the calibration procedure and the repeatability of the method. On each occasion 3 flights were flown at each of three different altitudes from approximately 90 to 210 m. The line selected ran along a power line for ease of navigation and covered flat farmland with little radiometric relief. Backgrounds at several different altitudes were recorded over the Ottawa River. Sixteen soil moisture measurements were taken at the time of each survey and nine snow water equivalent ground measurements carried out at the time of the February survey.

The snow water equivalent measurements on the ground had a sample average of 142 mm and a large standard deviation of 32 mm. However, when the number of samples is taken into consideration, the standard deviation of the average snow water equivalent is reduced to a much smaller value of 11 mm. The soil moisture measurements for February had an average moisture content of 64 ± 6% and the June results an average of 31 ± 7%.

Nine independent airborne measurements of snow water equivalent were determined by pairing data from each flight of the snow survey with unique data from the pre-snow survey flown at the same altitude. The results of the airborne measurements together with their standard deviations calculated by the Monte-Carlo method are presented in Table (3). The results show that there is no significant difference between the ground and airborne results. The results also show that the Integral window gives the most consistent snow water equivalent values and the thorium the least consistent. This is also indicated by the Monte-Carlo simulation for the variance of each water equivalent calculation. These simulations appear to provide a good estimate of the repeatability of the airborne measurements for this particular series of flights.

REFERENCES

Bristow, Q., (1979). A Gamma Ray Spectrometry System for Airborne Geological Research. Current Research, Part C, Geological Survey of Canada, Paper 79-1C, p. 55-61.

Carson, J.M., Holman, P.B. and Grasty, R.L., (1979). Airborne γ-Ray Spectrometer Experiments - Intercalibration and Variation of Calibration Constants with Altitude. Transactions of the American Nuclear Society, Vol. 32, p. 138-139.

Cinlar, E.I., (1975). Introduction to Stochastic Processes. Prentice-Hall, Englewood Cliffs, N.J., p. 79.

Grasty, R.L., (1977). A General Calibration Procedure for Airborne Gamma Ray Spectrometers. Report of Activities, Part C, Geological Survey of Canada, Paper 77-1C.

Grasty, R.L. and Charbonneau, B.W., (1974). Gamma-Ray Spectrometer Calibration Facilities. *In* Report of Activities, Part B, Geol. Surv. of Can., Paper 74-1B, p. 69-71.

Kogan, R.M., Nazarov, I.M. and Fridman, Sh.D., (1969). Gamma Spectrometry of Natural Environments and Formations Israel Program for Scientific Translations, Jerusalem, 1971.

Loijens, H.S. and Grasty, R.L., (1973). Airborne Measurement of Snow-Water Equivalent Using Natural Gamma Radiation over Southern Ontario, 1972-73. Scientific Series No. 34, Inland Waters Directorate, Water Resources Branch, Ottawa, Canada.

Peck, E.L., Carroll, T.R. and Van Demark, S.C., (1979). Operational Aerial Snow Surveying in the United States. W.M.O. Workshop on Remote Sensing of Snow and Soil Moisture by Nuclear Techniques, Norwegian National Committee for Hydrology.

Vershinina, L.K. and Dimaksyan, A.M., (1969). Determination of the Water Equivalent of Snow Cover. Israel Program for Scientific Translation, Jerusalem, 1971.

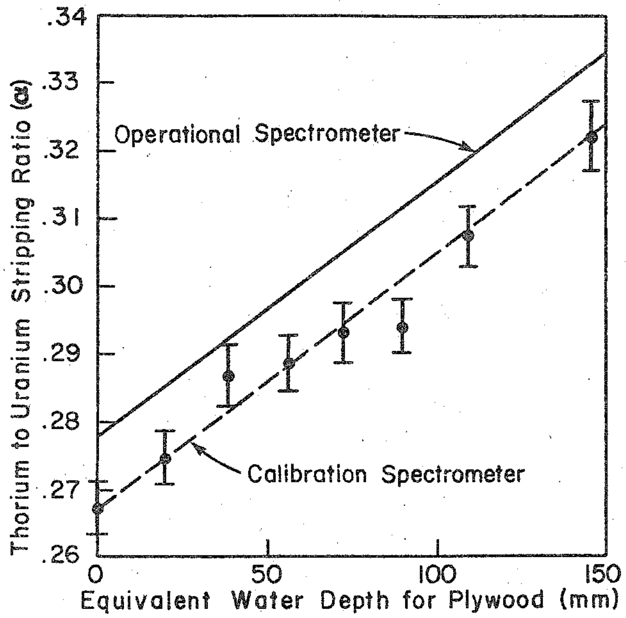

Figure 1 - Height Dependency of the Thorium to Uranium Stripping Ratio (α)

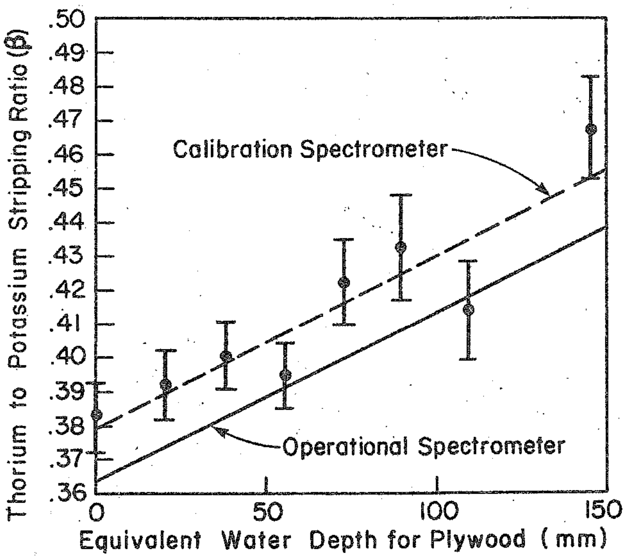

Figure 2 - Height Dependency of the Thorium to Potassium Stripping Ratio (β)

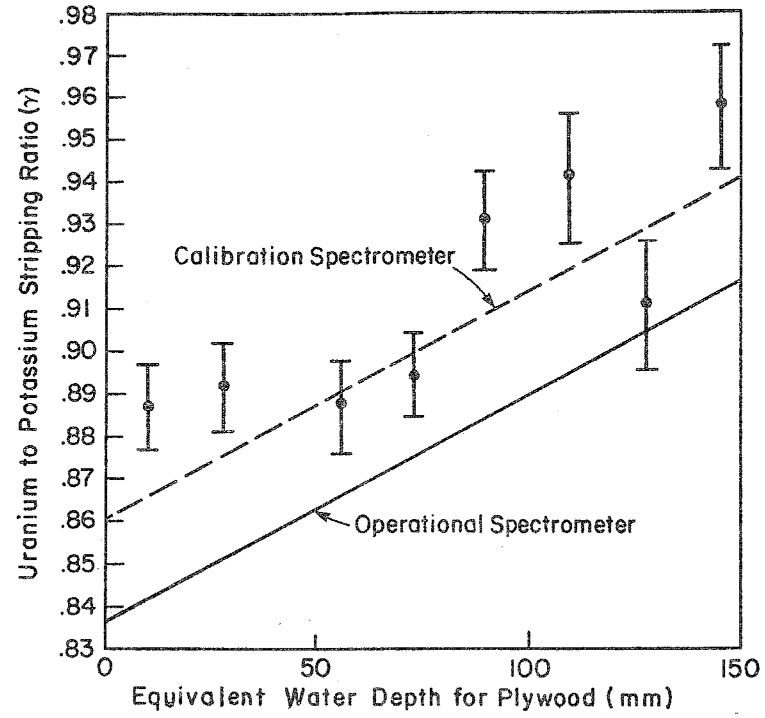

Figure 3 - Height Dependency of the Uranium to Potassium Stripping Ratio (γ)

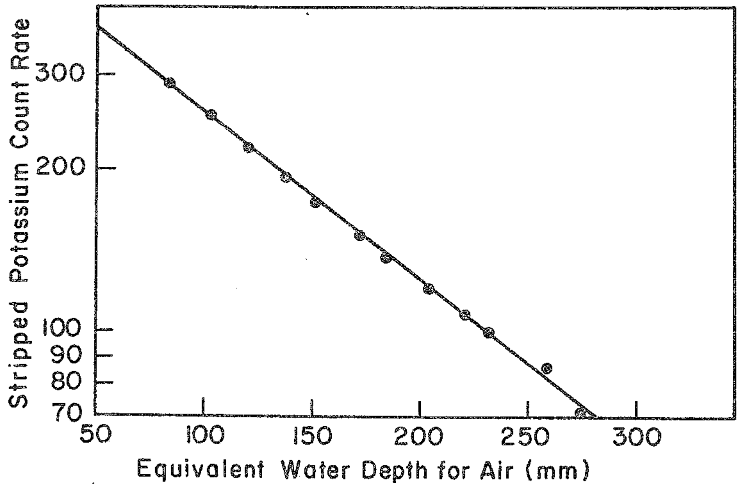

Figure 4 - Attenuation Coefficient for Potassium

Table 1 Formulae for Height Dependent Stripping Coefficients for Water

Stripping Coefficient	Intercept	Slope mm^{-1} Water
Thorium into uranium (α)	.278	.000381
Thorium into potassium (β)	.363	.000503
Uranium into potassium (γ)	.836	.000535
Uranium into thorium (a)	.0953	.0
Potassium into uranium (g)	.0216	.0
Potassium into thorium (b)	.0	.0

Table 2 Attenuation Coefficients and Window Ranges

Window	Window Range (MEV)	Attenuation Coefficient mm^{-1} Water
Potassium	1.37 - 1.57	.00722
Uranium	1.66 - 1.86	.00591
Thorium	2.41 - 2.81	.00591
Integral	.41 - 2.81	.00588

Table 3 Snow Water Equivalent (SWE) for Finch Flights Using Height Dependent Stripping Coefficients

Results are corrected for soil moisture

Aircraft Height	Integral		Potassium		Thorium		Weighted Average	
Metres	S.W.E. mm	σ mm	S.W.E.	σ mm	S.W.E.	σ mm	S.W.E.	σ mm
91	139.9	.8	153.0	3.0	152.3	7.3	140.9	.8
91	140.7	.8	156.0	2.9	153.1	7.2	141.8	.8
91	138.1	.8	149.2	2.8	144.7	7.0	139.0	.8
152	141.3	1.1	146.9	4.3	133.5	9.5	141.5	1.1
152	139.6	1.1	147.5	4.4	135.6	9.2	140.1	1.1
152	139.6	1.1	148.6	4.4	131.7	9.2	140.1	1.1
213	140.0	1.6	151.0	6.7	123.6	12.3	140.3	1.5
213	137.8	1.5	136.8	6.1	123.4	12.5	137.5	1.5
213	136.9	1.5	148.6	6.6	134.7	13.3	137.5	1.5