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AERIAL MEASUREMENT OF SNOW WATER EQUIVALENT BY TERRESTRIAL GAMMA RADIATION SURVEY

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ABSTRACT

Research studies measuring terrestrial gamma radiation from aircraft to determine snowpack water equivalent are reported. Both spectral and total count data were collected using 10·16 cm by 10·16 cm (4 in.) NaI (Tl) scintillation crystals. Extensive ground truth data were used in conjunction with count rates obtained to develop empirical procedures relating count attenuation with snow water equivalent. Soil moisture, altitude, and air density corrections were made in the course of development of the method. Spectral relations are compared with theoretical. Significant limitations on data collection and interpretation imposed by the presence of radon gas are discussed. Because of radon gas interference in the total count, the spectral method gives the best measurement of water equivalent in the snow-flood sensitive North-Central United States.

RÉSUMÉ

On rend compte des études faites en vue d'évaluer, à partir d'un avion, la radiation gamma terrestre et pour déterminer la hauteur d'eau équivalente des couches de neige. Les données spectrales ainsi que les données de calcul total ont été recueillies au moyen de cristaux de scintillation de 10·16 cm sur 10·16 cm (4 in.) NaI(Tl). Des données étendues sur la vérité terrestre furent utilisées de concert avec les taux de calculs obtenus pour développer les processus empiriques qui ont un rapport entre l'atténuation et la hauteur équivalente d'eau de neige. Des corrections sur l'humidité du sol, l'altitude et la densité de l'air ont été faites au cours du développement de la méthode et les rapports spectraux ont été comparés aux rapports théoriques. On discuta des limitations significatives sur la collection et l'interprétation des données imposées par la présence du gaz radon. A cause de l'intervention du gaz radon dans le calcul total, la méthode spectrale fournit la meilleure évaluation de la hauteur d'eau équivalente dans le Nord et le Centre des États-Unis qui sont sujets aux crues des neiges.

INTRODUCTION

Gamma rays measured by a detector near the earth's surface originate primarily from radioactive isotopes in the soil, principally ^{40}K and decay products in the Uranium and Thorium series. Attenuation of soil-originating gamma radiation by a snowpack is an indication of the mass of the water in the snowpack, providing the basis of a snow water equivalent measurement method.

The use of natural terrain radiation for measurement of snow cover has been reported by a number of investigators. These include Kogan *et al.* (1965); Zotimov (1965, 1968); Fritzsche and Burson (1970); Dahl and Odegaard (1970); Peck *et al.* (1971). It is reported that the technique is used on an operational basis in the Soviet Union (Kogan *et al.*, 1971).

The United States National Weather Service, which has the responsibility for providing river forecasts, is currently conducting a cooperative research study to evaluate the feasibility of using aerial gamma measurements operationally in portions of the country subject to frequent snowmelt flooding. The initial phases of the study were considerably restricted in scope in order to identify the various sources and magnitudes of error in such measurements. Flight lines selected for study were over non-forested and relatively level terrain.

Data Collection

Site Selection

The principal site selected for the study is a line 13·6 km long near Luverne, Minnesota at an elevation of 442 m located in the north central plains area of the United States. A second study site is a 6·7 km line in a high level valley (2130 m)in the Rocky Mountains near Steamboat Springs, Colorado, in the western United States. Both flight lines are parallel to all-year highways to allow positive location from the air and to facilitate the collection of ground truth data. Maximum water equivalent of the Luverne location is generally about 3 cm during the winter months. The peak accumulation at Steamboat Springs is generally about 25 cm.

Ground Truth

The flight lines are in agricultural areas and are divided into sections separated by roads crossing the flight path at intervals of 1·6 km (1 mile). Ground truth measurements for the earliest flights at the Luverne, Minnesota, site include 40 snow depth measurements, eight water equivalent (density) measurements, and two or three soil moisture measurements for each section along the flight line. For later flights at Luverne, more extensive measurements (depth measurements at 10 m intervals, water equivalent every 100 m and soil moisture every 200 m) were taken for three sections (4·8 km) while retaining original sampling density for the remainder of the line. The more extensive sampling density was employed for all flights for the entire 6·7 km line at Steamboat Springs, Colorado. Snow sampling conditions were generally very favourable on flight days.

Water equivalent measurements were collected by means of an Adirondack sampling tube at Luverne, Minnesota, and a Mount Rose snow sampler at Steamboat Springs, Colorado. Soil moisture was determined by the gravimetric method on 20 cm depth soil samples.

Instrumentation

The Aerial Radiological Measuring System (ARMS) was used in the study. The ARMS equipment is installed in a twin engine aircraft equipped with an accurate positioning system that measures the radar altitude of the aircraft above the ground, speed over the ground, drift angle and heading.

The gamma detector system in the aircraft consists of fourteen 10·16 cm by 10·16 cm NaI (Tl) scintillation crystals. The detector package is thermally insulated and mounted to prevent shock. The large volume of detectors provides a sensitivity for gamma radiation several thousand times greater than that of a common Geiger Counter. An on-board computer produces a paper tape record of all flight and radiation information. The system is explained in detail by Anderson *et al.* (1969).

Airborne Data Collected

The radiation data collected on board the aircraft are of two types. The 'total count', or 'gross count,' is the total number of photons detected having energies greater than 50 keV. 'Spectral' data consist of count values in each of 200 channels having a 15 keV energy interval for the range from 15 keV to 3·0 MeV. Well defined peaks on the spectrum defined by the 200 channels reveal the presence of isotopes emitting specific energy gamma rays. The spectrum shown in Fig. 1 has four peaks identified by their associated source isotopes.

Airborne missions include pre-flight calibration, a slow spiral down to 300 m from about 4500 m, and a series of flights over the selected flight line at five different altitudes ranging from 61 m to 305 m. Missions were concluded with a spiral back up to 4500 m altitude and a final calibration check. Altitude profiles of total count rate (counts per second) and ambient temperature are obtained by measuring during the spirals. Both spectral and total count data are collected during fixed altitude runs over the flight lines. Total count, radar altitude and location information are recorded at 1-sec intervals. Spectral data are accumulated over specified portions of the flight line.

During the second year of data collection, the 1970–1971 winter period, vertical soundings of total count and air temperature were extended during some missions to include both morning and afternoon surveys.

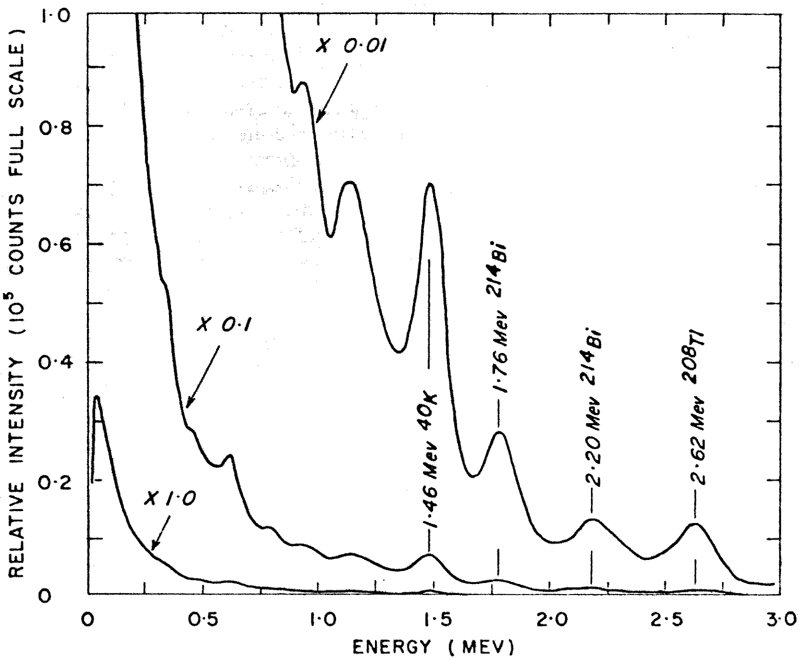

Fig. 1 — Spectrum at 229 m, Luverne, Minnesota, 20 August 1970.

COMPUTATION OF ATTENUATING MASS

Initial phases of the project were essentially approached as a point measurement study over the flight line. Before any meaning can be ascribed to a relation of gamma count rate and water equivalent of the snow, some knowledge of the variability of the ground measurements must be known.

By virtue of the large sample size for the ground truth data along the lines where extensive measurements were obtained, confidence intervals on the sample mean may be established. Ground truth snow water equivalent measurements (M_W) and their corresponding confidence intervals are given in Table 1.

The air mass between the ground and aircraft also attenuates radiation from the soil and therefore must be measured. The mass of the air blanket for each traverse of the flight line is computed from the air temperature, surface pressure and the average radar altitude along the line. Total count values obtained at the various flight levels are interpolated or extrapolated to standard air masses selected for each site. The selected air masses are those corresponding to 61,

TABLE 1

Ground truth confidence data—Luverne, Minnesota

Mission date	Elevation (m)	M_w (g/cm²)	0·68 confidence interval for M_w	M_a (g/cm²)	0·68 confidence interval for M_a	Me_w (g/cm²)	0·68 confidence interval for Me_w
11/20/69	61	0·84	±0·038	7·70	±0·039	7·77	±0·052
	91			11·53	0·044	11·22	0·055
	152			19·17	0·059	18·09	0·065
	229			28·64	0·083	26·62	0·084
	305			38·06	0·136	35·09	0·128
1/6/70	61	3·84	±0·104	7·98	±0·058	11·02	±0·116
	91			9·00	0·061	11·94	0·118
	152			20·00	0·078	21·84	0·125
	229			28·91	0·101	29·86	0·138
	305			39·73	0·195	39·60	0·204
2/17/70	61	6·30	±0·196	7·07	±0·061	12·66	±0·204
	91			10·70	missing	15·93	—
	152			17·93	missing	22·44	—
	229			26·83	missing	30·45	—
	305			34·56	missing	37·40	—
5/16/70	61	0·0	0·0	7·19	±0·026	6·47	±0·023
	91			10·80	0·033	9·72	0·030
	152			18·01	0·116	16·21	0·104
	229			26·97	0·108	24·27	0·097
	305			35·79	0·143	32·21	0·129
8/20/70	61	0·0	0·0	6·97	±0·066	6·27	±0·059
	91			10·43	0·045	9·39	0·041
	152			17·38	0·060	15·64	0·054
	229			25·91	0·088	23·32	0·079
	305			34·63	0·121	31·17	0·109

91, 152, 229, and 305 m of isothermal air at 0°C with a surface pressure equal to the US Standard Atmosphere for the elevation of the site.

In treating spectral data, a method reported by Fritzsche and Burson (1970) is used to determine peak area counts attributed to ^{40}K (1·46 MeV) and ^{208}Tl (2·62 MeV) in the soil. The method is designed to remove cosmic and aircraft background effects and significantly reduce 'spill over' from adjacent peaks into the peak of interest.

To facilitate comparison with spectral peak theoretical relations, the total 'effective mass' of the attenuating blanket (both air and water) is calculated for each spectrum. For gamma rays in the energy range considered, 1 g of water has the same attenuating effect as 1·11 g of air. The mass of the effective attenuating water blanket for each flight is therefore calculated as :

$$M_{ew} = M_w + 0{\cdot}90\,M_a \qquad (1)$$

where M_w is the mean measured water equivalent along the flight line as given in Table 1. The mean mass of the air blanket M_a is computed from the average of a large number of radar altimeter readings for each flight. Computed values and confidence intervals for the total effective attenuating mass blanket are also given in Table 1.

Corrections Applied to Raw Data

Figure 2 shows gross count profiles collected during descent and ascent spirals prior to and subsequent to surveys conducted at Steamboat Springs, Colorado, on 3 September, 1970. It is seen that cosmic and atmospheric effects decrease with decreasing altitude until a point is reached below which ground emission is the dominant contributing factor. The high altitude count rate is extrapolated and subtracted from the total count rates obtained at the various survey flight altitudes. The corrected total count is hereafter referred to as 'net count'. No altitude profiles of spectral count have been collected to date.

The effect of soil moisture variation is treated by adjusting all count rates obtained to a base soil moisture. For the soil moisture range encountered assumed radioactivity profiles gave 5 and 3·5 per cent reduction in ^{40}K and ^{208}Tl peak area counts respectively for 10 per cent soil moisture increase. A 3·0 per cent reduction in total count was assumed for a 10 per cent increase in soil moisture.

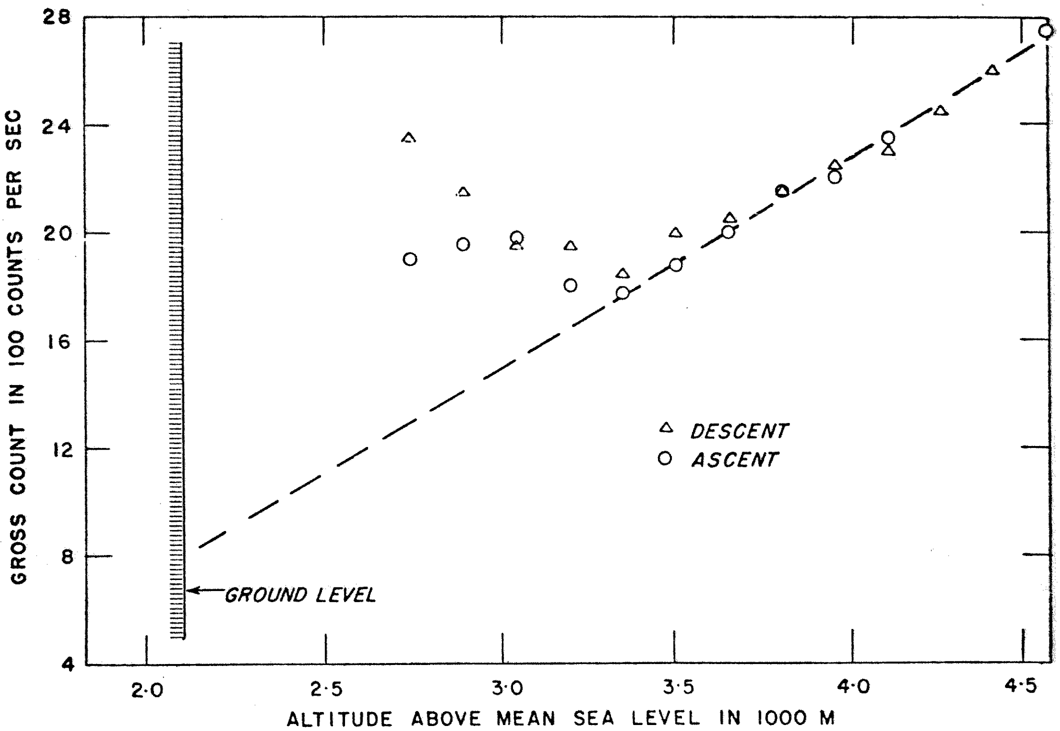

Fig. 2 — Gross count variation with altitude, Steamboat Springs, Colorado, 3 September 1970.

Net Count as an Indicator of Water Equivalent

The use of total count data would be preferred over the use of spectral peak areas in making snow measurements for the following reasons :

(a) Total count rates are greater, requiring shorter collection times.
(b) Total count instrumentation is less expensive.
(c) Less computation is required to produce water equivalent measurement.

The total count rates obtained during the first research season are graphed against ground truth snow water equivalent in Figs. 3 and 4. Relations for the five standard air masses are shown. For flight altitude above the 152 m level at Luverne, Minnesota, the net count appears to increase rather than decrease with increasing water equivalent. Presumably the effect results

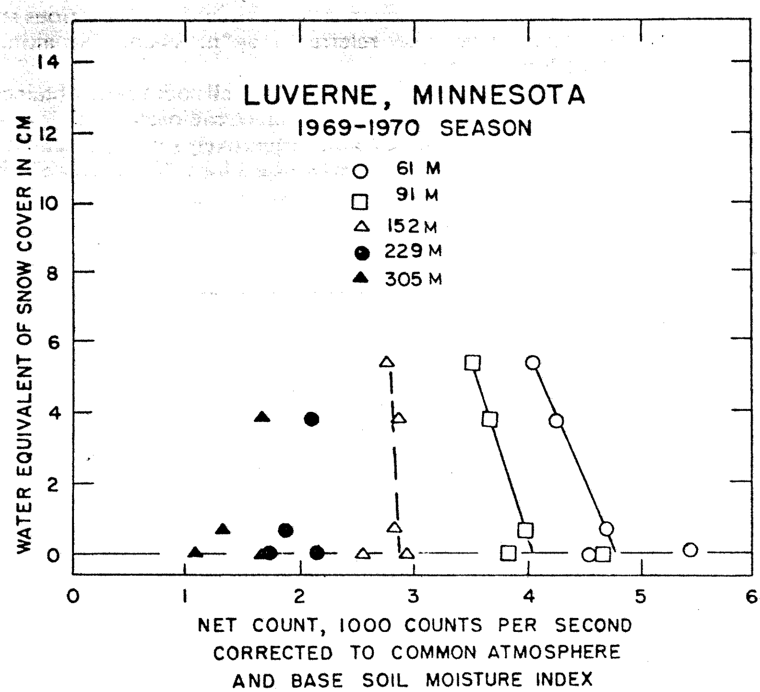

Fig. 3 — Relation between net count and snow water equivalent, Luverne, Minnesota, 1969–1970 research period.

primarily from the influence of radon gas decay products (notably ^{214}Bi and ^{214}Pb) in the air, as is indicated by several considerations. First early morning air temperature profiles for the two days of maximum snow cover show inversions near the ground. Such temperature inversions are usually accompanied by the accumulation of aerosols (among which would be radon decay products) below the inversion layer. A second indication of the presence of airborne radon and its decay products is the attenuation of particular spectral peaks from one day to another. The reduction of four particular spectral peak areas between a day with 0·84 cm water and a day with 3·84 cm water is shown in Fig. 5. The peak ratios associated with ^{214}Bi, a decay product of radon gas, fall far outside the expected range. The attenuations of the peaks associated with ^{40}K and ^{208}Tl (expected to be primarily in the soil) fall near the values expected from the water equivalent difference between the two days. This phenomenon indicates a much greater influence from radon gas on 6 January 1970, than on 20 November 1969.

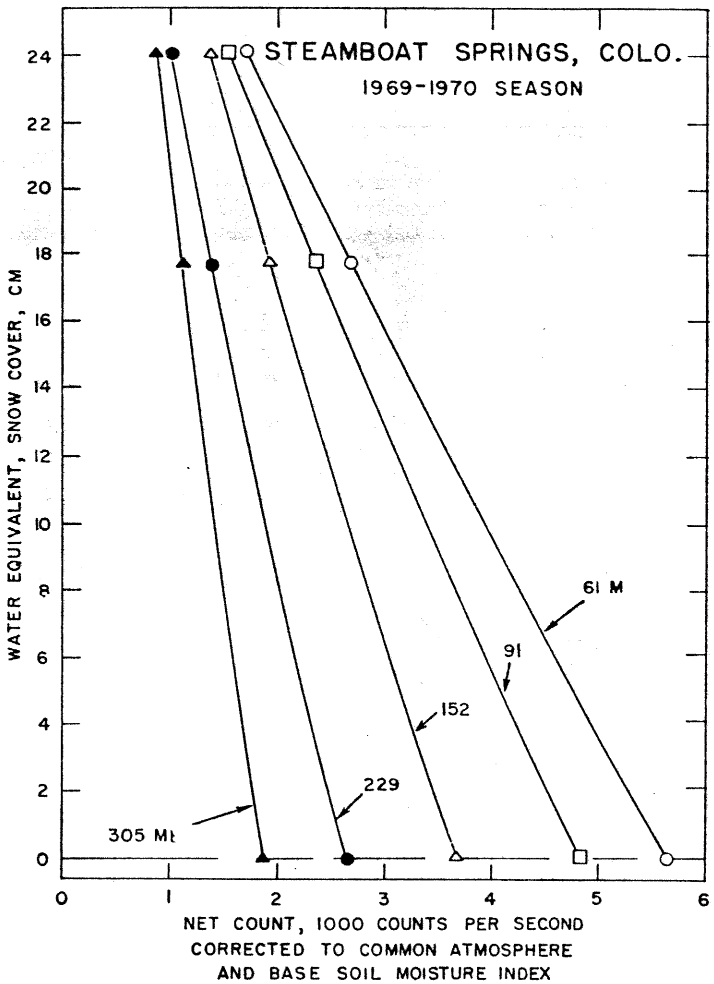

Fig. 4 — Relation between net count and snow water equivalent, Steamboat Springs, Colorado, 1969–1970 research period.

Following the determination that radon gas is indeed a factor influencing measured radiation data, flight procedures were revised. Missions were made to include both pre-flight and post-flight air temperature and gross count profiles with altitude. In this way it is hoped to monitor variations in radon interference over the span of a few hours and relate any such variations to meteorological variables.

The profiles of air temperature and gross count with altitude clearly demonstrate that significant changes in gross count do occur even during the few hours of a survey period. The

6 January 1971, temperature profiles at Luverne, Minnesota, shown in Fig. 6, are typical of a morning temperature inversion near the ground gradually rising to higher altitude as the day progresses. The solid lines represent the temperature measured during spirals previous to the mid-day mission and following the late afternoon missions. Little change occurred above 1100 meters during the four hours. The dashed lines represent temperature measurements at the various flight altitudes for the gamma surveys. The upward progression of the inversion to near 300 m by 1600 hours is evident.

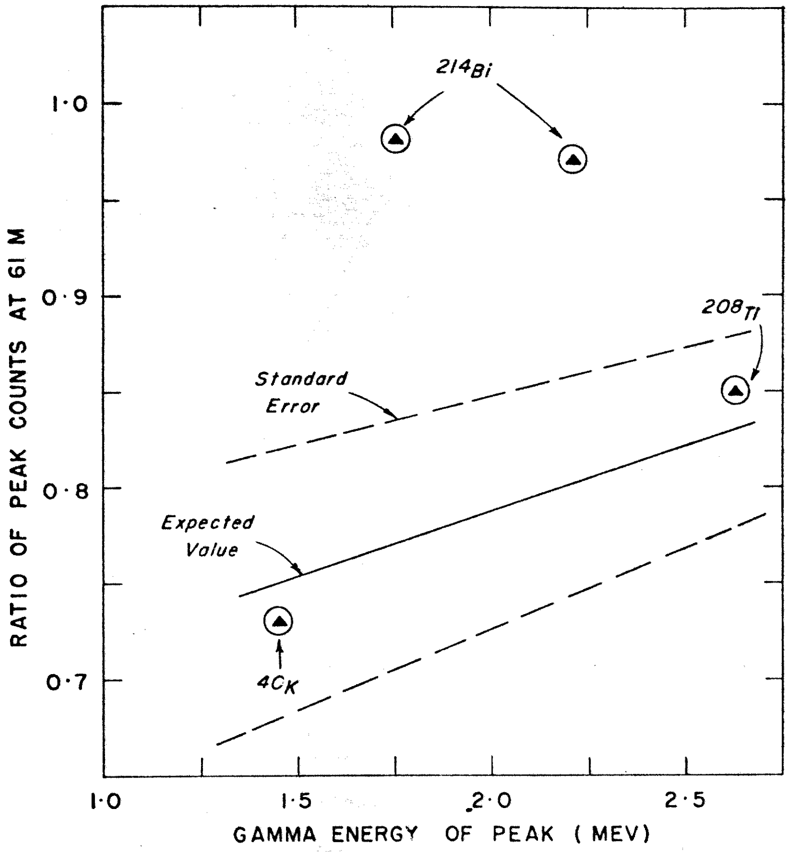

Fig. 5 — Attenuation of spectral peaks, Luverne, Minnesota, between 20 November 1969, and 6 January 1970.

Profiles of gross count for the same spirals are shown in Fig. 7. During the four hours the gross count decreased at the lower levels and increased at altitudes near the inversion layer. Total count at the 100 m level decreased by 7·8 per cent while that near the 600 m level increased by 16·7 per cent. Similar plottings for days with little or no snow with early morning inversions that raised during the day showed exceptionally large changes in gross count up to 3000 m in periods as short as 2 h.

To verify that the behaviour of the gross count profile was related to radon decay product concentrations in the air, the ^{214}Bi peak at 1·76 MeV was plotted in a similar fashion. The altitude profiles of counts in the 1·69–1·86 MeV range for 6 January 1971, and for another day with nearly identical snow cover are shown in Fig. 8. Two especially noteworthy observations are made. First, the count rates obtained on 6 January 1971, are roughly 50 to 100 per cent greater at the normal survey altitudes than the count rates obtained on 12 February 1971. Similar profiles of the ^{208}Tl peak at 2·62 MeV for the same two days are essentially indistinguishable. Second, at the two lowest survey levels mid-day count rates are about 15 per cent greater than the late afternoon count rates. A distinct reversal of this trend is seen above 200 m. The temperature profiles in Fig. 6 explain this well. At mid-day the inversion was around 150 m. As the afternoon progressed, the inversion lifted, allowing the mixing of the radioactive aerosols up to about 300 m by late afternoon.

The Steamboat Springs, Colorado, net count versus water equivalent relations shown in Fig. 4 appear to be more reasonable than the Luverne, Minnesota, relations. Inspection of spectral peak ratios and comparison of morning and afternoon altitude profiles of total count

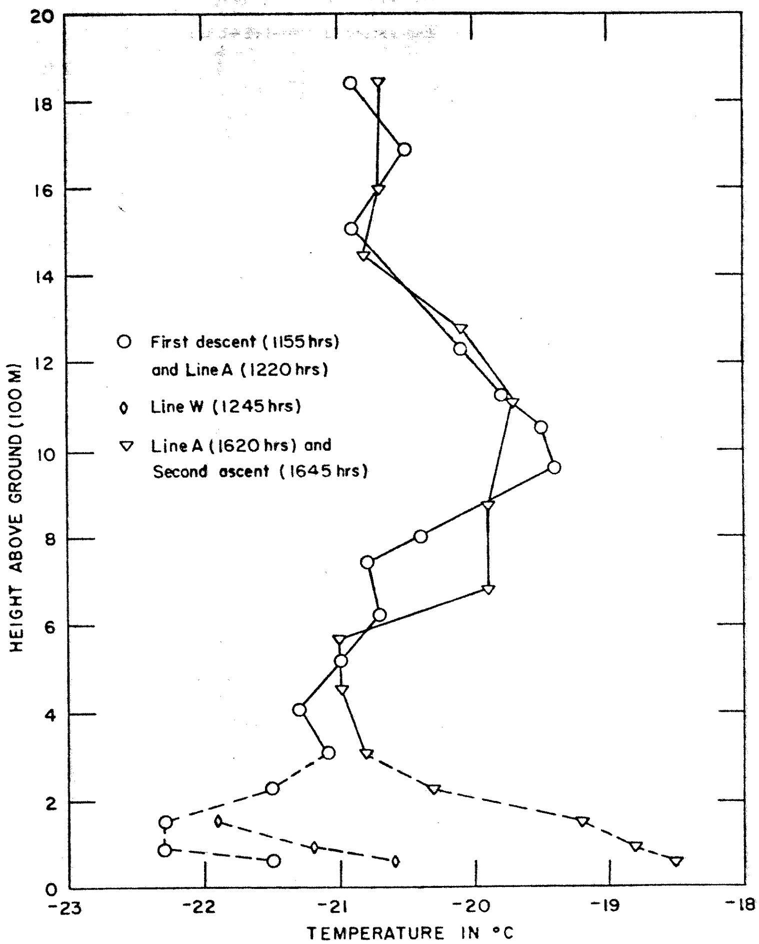

Fig. 6 — Altitude profiles of air temperature, Luverne, Minnesota, 6 January 1971.

at Steamboat Springs indicated radon complications were present at that site also, although to a lesser extent. Due to these results, current research in use of net count in snow measurement has been temporarily redirected toward development of radon interference delineation methods. Results of the current research in this area should allow more constructive discussion of the total count method in the future.

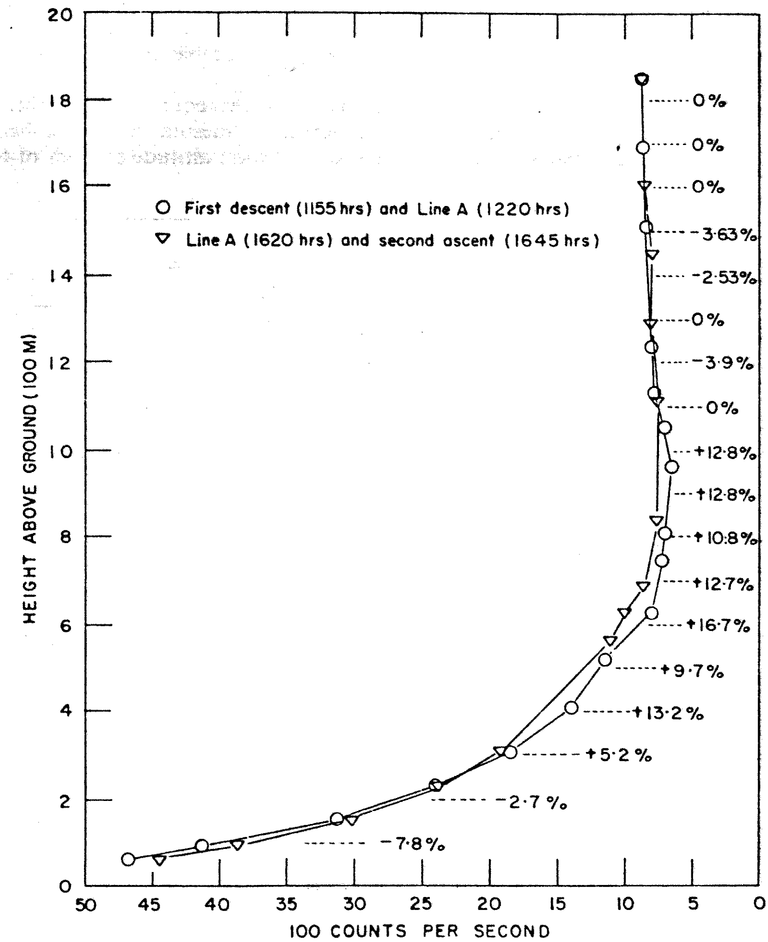

Fig. 7 — Mid-day and later afternoon altitude profiles and percent differences of net count, Luverne, Minnesota, 6 January 1971.

Spectral Peaks as Indicators of Snow Water Equivalent

Theory

The flux of gamma rays of energy E at some altitude above a flat snow covered soil containing only an isotope emitting gamma rays of energy E is given theoretically (Kogan *et al.*, 1965) by

$$\phi(E) = \frac{A}{2\mu_g(E)} \int_1^{\infty} \frac{e^{-x \sec\theta}}{(\sec\theta)^2} d(\sec\theta) \equiv \frac{A}{2\mu_g(E)} E_2(x) \quad (2)$$

where

θ = look angle from aircraft, measured from vertical;
A = isotope concentration, assumed homogeneous, in soil (number of gammas/g-sec);
$E_2(x)$ = exponential integral of the second kind, a tabulated function;
x = $\mu_w(E) M_w + \mu_a(E) M_a$;
M_w = water mass of snow blanket (g/cm^2);
M_a = mass of air blanket (g/cm^2);
$\mu_w(E)$ = mass attenuation coefficient in water for gamma rays of energy E (cm^2/g);
$\mu_a(E)$ = mass attenuation coefficient in air (cm^2/g);
$\mu_g(E)$ = mass attenuation coefficient in soil (cm^2/g).

Practical application of this equation requires that character stics of the detector which trans-

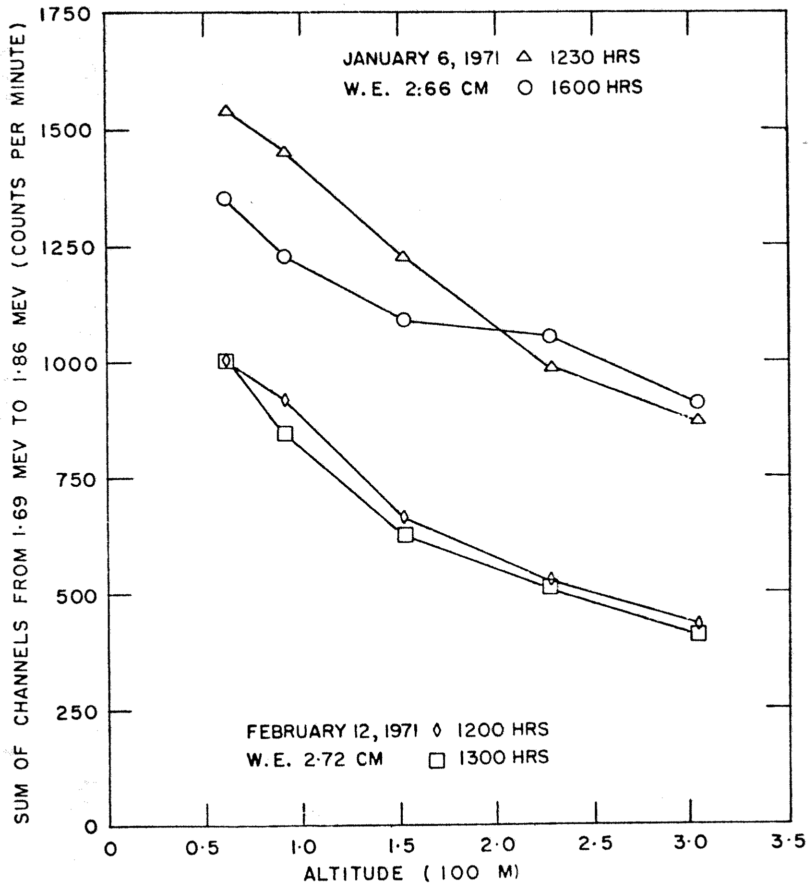

Fig. 8 — Altitude profiles of 1·76 MeV (^{214}Bi) peak counts, Luverne, Minnesota, 6 January 1971, and 12 February 1971.

lates gamma flux into counts be taken into account. The detector has a marked angular response. It is assumed that the effective area of the crystal array as a function of look angle is the major source of angular variation in detector efficiency. In practice the theoretical relation (2) is modified to express measured count rate C as a function of the effective water blanket mass M_{ew}:

$$C(M_{ew}) = I_0 E_{2m}(\mu M_{ew}) + C_0 \tag{3}$$

where

C_0 = some residual background after application of peak area determination method;
I_0 = count rate at soil surface, excluding background C_0;
μ = gamma water mass reduction coefficient, expected to have a value near the mass attenuation coefficient.

E_{2m} is the exponential integral of the second order, modified to allow for the angular response of the crystal array:

$$E_{2m}(x) = N \int_1^\infty \frac{e^{-xz}}{z^2} A_{eff}(\sec^{-1} z)\,dz \tag{4}$$

where N is a normalizing factor such that $E_{2m}(0)$ is unity, and $A_{eff}(\theta)$ is the effective area of the crystal array as a function of look angle from the vertical.

Analysis

The coefficient μ in equation (3) should be quite nearly the mass attenuation coefficient if the spectral peak were narrow and sharp. A gamma ray, however, can undergo Compton scattering to a reduced energy and still have an energy falling within the lower bound of the measured spectral peak. Adjusted values of μ were calculated by subtracting from the total scattering cross section the integral of the Compton differential cross section over the solid angle in which down-shifted energies would still fall above the lower threshold of the measured spectral peak. The adjusted values of μ are given in Table 2.

TABLE 2

Reduction coefficients for ^{40}K and ^{208}Tl spectral peaks in water

Energy	Mass attenuation coefficient in water μ_w (cm^2/g)	Optimum coefficient μ in water (cm^2/g)	Mass attenuation coefficient adjusted for peak width (cm^2/g)
1·46 MeV (^{40}K)	0·0590	0·0463	0·0545
2·62 MeV (^{208}Tl)	0·0424	0·0337	0·0408

Values of the surface count rate I_0 and residual background C_0 in equation (3) were determined by linear regression using several values of μ for both the ^{40}K and ^{208}Tl spectral peaks. Optimum values of μ (for which the standard error in water measurement was minimized on our data set) are also given in Table 2. There is a notable difference between the adjusted mass attenuation coefficient and the optimum reduction coefficient obtained for both the ^{40}K and ^{208}Tl peaks. Possible sources of this discrepancy include the method of peak area determination employed and detector response characteristics not yet accounted for.

The ^{40}K and ^{208}Tl relations given by equation (3) using the optimum attenuation coefficients are plotted as solid lines in Figs. 9 and 10 along with the data points from which the coefficients were derived. The standard error in water measurement is given in Table 3 for both peaks at the various measurement altitudes. The tendency for better measurement at lower altitudes is especially noted for the ^{40}K peak data. Increased errors are expected at higher altitudes due to larger errors in air blanket measurement and due to decreased count values (hence decreased signal-to-noise ratios).

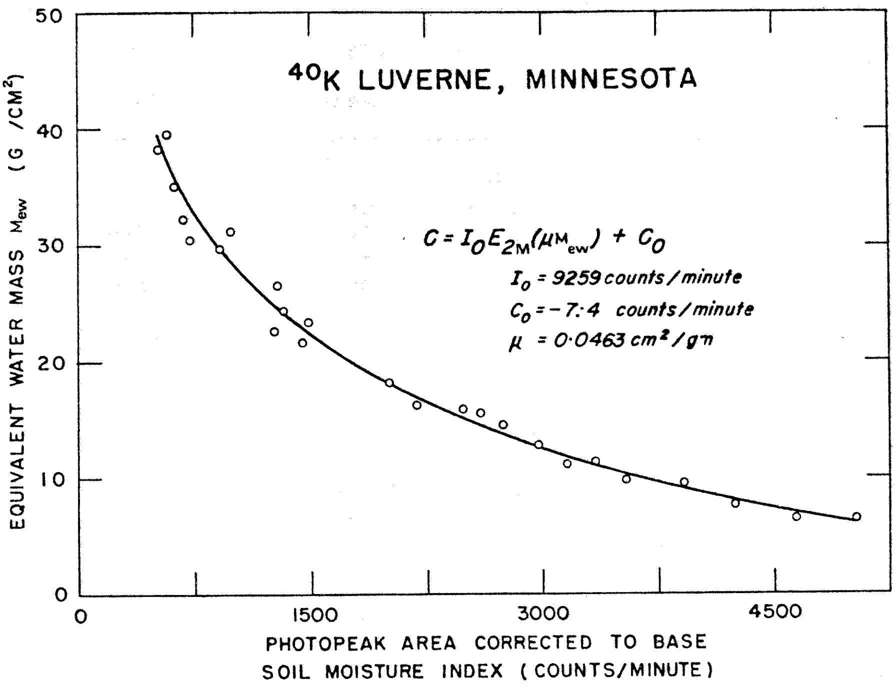

Fig. 9 — Relation between ^{40}K photo peak area and equivalent water mass separating aircraft and ground, Luverne, Minnesota, 1969–1970 research period.

The increased error in the ^{40}K peak measurement at higher altitudes is also attributed to radon gas in the air. Some interference exists in the ^{40}K peak from emissions of radon decay products (notably 1·76 MeV gammas from ^{214}Bi). A small residual of this interference is expected after calculation of the ^{40}K peak area. This residual count would be more troublesome at higher altitudes where gamma flux from the soil is less dominant.

Discussion of Results and Method Limitations

The conclusion, limited by the small number of data points upon which it is based, is that best measurement of snow water equivalent using a single spectral peak may be expected by monitoring ^{40}K peak counts at the lowest flight altitudes possible. As an alternative to using a single spectral peak, a weighted average of the water measurements infered from the ^{40}K and ^{208}Tl peaks can be used. Such a random variable would have variance smaller than the variance of either individual measurement, provided the covariance between the two individual measure-

TABLE 3

Standard error in snow water measurement (cm) by spectral method

	Flight altitude						
Spectral peak	61 m	91 m	152 m	229 m	305 m	61 and 91	all levels
1·46 MeV (^{40}K)	0·47	0·63	1·30	1·62	1·75	0·56	1·27
2·62 MeV (^{208}Tl)	0·94	0·65	1·15	1·03	0·96	0·81	0·96

ments is sufficiently small. Use of such a linear combination is currently being investigated.

The degree to which the standard errors in Table 3 reflect the variance of the measurement method must be considered. It is first noted that the curves in Figs. 9 and 10 were obtained by linear regression on the data points and by optimizing the mass attenuation coefficients to give smallest errors in water measurement. The standard errors obtained, therefore, are smaller than would be obtained using the 'true' values of C_0, I_0, and μ. The standard errors obtained using the 'true' coefficients, however, should not be significantly larger. The standard errors

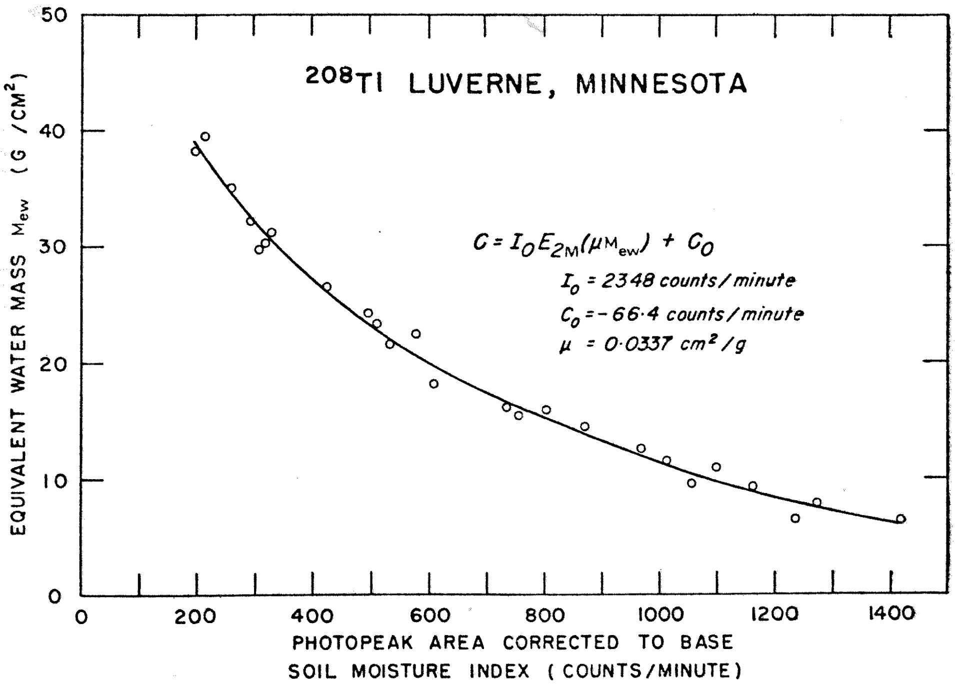

Fig. 10 — Relation between ^{208}Tl photo peak area and equivalent water mass separating aircraft and ground, Luverne, Minnesota, 1969–1970 research period.

given in Table 3 not only reflect error in the gamma measurement method, but also include error introduced by treating 'ground truth' water equivalent as having no error. Reference to Table 1, however, shows that at the 0·68 confidence level the difference between the true effective water blanket mass and the measured effective water is generally an order of magnitude smaller than the measurement standard errors shown in Table 3. Thus ground truth measurement errors are considered to be a minor factor contributing to the standard errors shown in Table 3.

An additional error source which was investigated was the effect of variations in snow depth along the course. The relation between count rate and effective attenuating water mass is not linear. The expected count rate through a uniform snowpack is therefore not the same as the expected count rate for a non-uniform snowpack having the same mean water equivalent. The systematic error in the gamma snow measurement arising from snow variability was estimated using Poisson distributions with unit size selected to give measured means and standard deviations. Snow covers on the experiment days were fairly uniform and the resultant systematic errors computed were generally an order of magnitude smaller than the standard errors given in Table 3.

Does increased airborne data collection time (within a given day) give significantly greater accuracy? The essence of this question is whether major sources of error come from factors which change within a given day, or from factors which change from day to day or month to month. If long-term variations dominate, then increased data collection times cannot assure significantly greater accuracy. No evaluation has yet been made of the error contribution due to random error within each given day as opposed to that due to factors changing on a longer time basis.

A final comment on method limitations should be made. Since high count rates were obtained over shallow packs, water measurement errors resulting from natural fluctuations in count rate were ignored. Deep snowpacks, however, would reduce the peak area counts significantly. For example, a no-snow spectrum obtained from a flight along the Luverne, Minnesota, line would typically give 15000 counts in the ^{40}K peak and 5000 counts in the ^{208}Tl peak. A 25 cm water equivalent snowpack would reduce the ^{40}K peak to about 2200 counts with an associated estimated standard deviation of 0·41 cm water due to natural count fluctuations alone. For the same snowpack the decreased ^{208}Tl peak areas would have an associated estimated standard deviation of 0·51 cm due only to natural count fluctuations. More important, however, is that large reductions in count rate decrease the signal-to-noise ratio, further diminishing measurement accuracy in deep snowpacks.

Conclusions

Initial results indicate that, under favourable measurement conditions, areal snowpack water equivalent over a previously calibrated flight line can be measured by the gamma spectral peak method to accuracies required for operational purposes.

Results indicate that the total gamma ray count method appears to be a less reliable indicator of water equivalent unless correction for radioactive aerosol contributions can be made. In particular, contributions from decay products of radon gas are highly variable from day to day. Changes in atmospheric stability can even cause marked count rate fluctuations over a few hours. When techniques are developed for removal of atmospheric interference, the total count method may be preferred because its high count rates allow shorter data collection times than would be required in the spectral peak method.

The accuracy of gamma measurement methods decreases for deeper snowpacks due to decreased signal-to-noise ratio. Also, the methods should be used with caution over highly variable snow covers because of the non-linear relationship between count rate and water equivalent.

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