Evaluation of Snow Water Equivalent by Airborne Measurement of Passive Terrestrial Gamma Radiation

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Abstract. Recent research studies have investigated an airborne gamma radiation detection system to determine the water equivalent of snowpacks in nonmountainous areas. Snow attenuates natural gamma emissions from the soil, and the magnitude of attenuation is related to the mass of the water blanket between the soil and the detector. Gamma spectral and total counting rates are collected and recorded by an airborne system using 14 4- by 4-inch sodium iodide (NaI (Tl)) crystals. These data are corrected for soil moisture, background radiation, and effects of air density. Extensive snow depth and density measurements were taken to determine 'ground truth' water equivalent under the flight path. Results of the first year of research indicate that gamma spectral data may be expected to give areal measurement of snow water equivalent within at least 0.2–0.5 inch over favorable terrain. The use of total count data is even more promising but requires methodology still under development for eliminating background interference.

The accuracy of any forecast depends on the information available to the forecaster. For snowmelt streamflow forecasting the first requirement is knowledge of the basin snowpack water equivalent. In general practice, the snowpack water equivalent is obtained from a regular network of point measurements. When major flood potential exists, supplemental point measurements are made by mobile field teams. For any practicable sampling density, however, certain problems will always be inherent in a point sample method: (1) the set of points selected for sampling is not necessarily representative of the snow condition over the area; and (2) even after the sampling sites have been selected, there are often large errors in the water equivalents measured at the points. Among the snowpack conditions giving rise to large measurement errors are (1) very dry snow, which may fall out of the sampling tube as it is withdrawn from the snowpack, (2) very wet snow, from which water in the slush layer may drain as the core is withdrawn, and (3) ice lenses, which may not be penetrated by the snow tube or which may deform the underlying core as the lens is penetrated. Faced with these uncertainties, the forecaster would find invaluable a measurement method that would be independent of snowpack conditions and that would also give areal data rather than a series of point measurements.

A number of methods for remote measurement of areal snowpack conditions have recently been investigated by the National Weather Service. One such method, the measurement of the areal extent of snow cover by satellite sensing [*Barnes and Bowley*, 1968], has given good results in nonmountainous areas. No methods previously investigated, however, provide reliable measurement of snow water equivalent. The research program reported in this paper is being conducted by the National experience snowmelt floods and has a relatively high expected spring snow cover.

A second area was selected south of Steamboat Springs, Colorado. This site has most of the advantages available at Luverne, Minnesota, plus greater expected water equivalent.

Flight paths were selected parallel to all-year highways at both field sites to insure accurate identification from the air and to facilitate collection of ground truth data. On each survey day count rates were obtained several times over each flight path at each of five altitudes up to 1000 feet above ground level. Both total count and spectral data were collected during the surveys.

Collection of adequate ground truth data was considered of utmost importance. Fortunately conditions for snow tube sampling were generally very good. Over the 4.15-mile flight line at Steamboat Springs, Colorado, snow depth was measured about every 25 feet, snow density was measured every 250 feet, and soil samples were taken every 500 feet. Less dense sampling was employed over most of the 8.45-mile principal flight line at Luverne, Minnesota. For all but the first two flights, however, a sampling density similar to that employed at Steamboat Springs, Colorado, was used over a 3-mile subsection of the principal flight line. Detailed data on crop types, land slopes, and soil types along the flight lines were used in computing weighted averages by mile of water equivalent and soil moisture and were especially useful when the high density sampling was not employed.

DATA ANALYSIS

The object of the analysis is to relate ground truth data to that portion of the count rate coming through the snow surface from the soil. To do so, any contribution to the count rate from other sources must be evaluated.

Figure 2 shows the variation with altitude of the total count rate collected by altitude spirals prior to and subsequent to surveys conducted at Steamboat Springs, Colorado, on September 3, 1970. Cosmic and high altitude effects decrease with decreasing altitude to a point below which ground emission becomes the major contributing factor. The cosmic total count rate was extrapolated and subtracted from the total count rates obtained at the various survey levels near the ground. This correction also allows for background from any trace radioactive materials on the aircraft itself. No data for extrapolation of spectral peak backgrounds were collected during the 1969–1970 contract period.

Evaluating the total count contribution of air-carried decay products of radon gas may be critical under certain conditions. The methodology for evaluating this effect is under de-

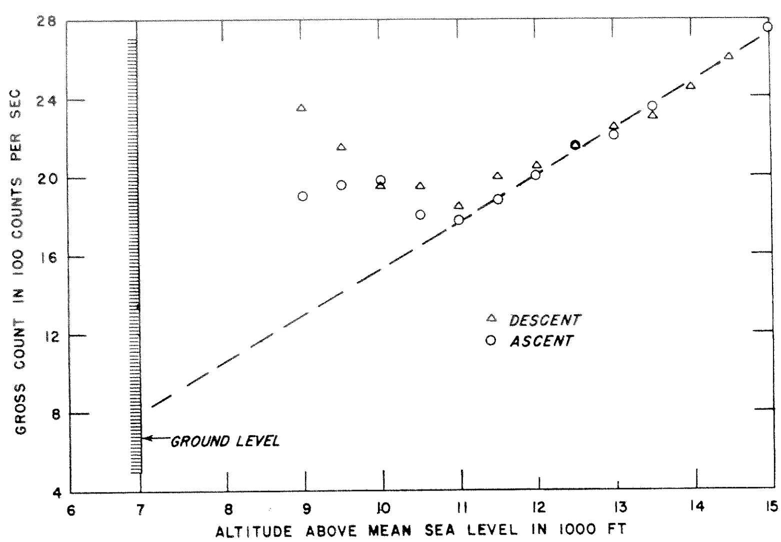

Fig. 2. Gross count variation with altitude, Steamboat Springs, Colorado, September 3, 1970.

velopment. The significance of the effect is presently judged by comparing the relative size versus the altitude of the ^{214}Bi (a decay product of radon gas) spectral peaks to that of the ^{40}K and ^{208}Tl peaks.

Variation in the soil moisture must also be considered. An increase in soil moisture causes a decrease in the gamma flux from the soil surface. Knowledge of the depth distribution in the soil of both moisture and radioactive emitters is necessary for accurate treatment of this effect. In the present analysis Soviet data [*Zotimov*, 1968] giving a typical distribution of radioactive potassium with soil depth were used to estimate the percentage change in the gamma flux at the soil surface resulting from soil moisture changes. For the range of soil moisture (treated as constant in the top several inches) expected under field conditions, it was calculated that a 10% increase in soil moisture would give a 5% reduction of counts in the ^{40}K spectral peak. To obtain the effect of soil moisture on the ^{208}Tl spectral peak, the ^{208}Tl distribution in the soil was assumed to be proportional to the ^{40}K distribution. Then comparing the mass attenuation coefficients for ^{40}K and ^{208}Tl in water indicated a 3.5% reduction of ^{208}Tl peak counts for each 10% increase in soil moisture. The total gamma ray count was estimated to decrease 3.0% for each 10% increase in soil moisture. In application, soil moisture corrections to count rates were calculated for each flight date relative to an arbitrarily selected base soil moisture.

The air mass between the aircraft and the ground attenuates gamma rays just as the snow does. The radar altimeter readings, recorded every second, are averaged along the flight line to obtain the flight altitude. The air mass is then calculated for the flight altitude by using the air pressure and temperature profiles. For spectral data this air mass is converted to an 'equivalent' water mass, that is, one that would have the same attenuating effect. For total count data count rates are interpolated to one of five selected air masses. The selected air blankets are those between the ground and 200, 300, 500, 750, or 1000 feet consisting of an isothermal layer of 0°C and a surface pressure equal to the U.S. standard atmosphere for the elevation of the site.

Spectral peak areas were determined for ^{40}K (1.46 Mev) and ^{208}Tl (2.62 Mev) by a method reported by *Fritzsche and Burson* [1970], which is designed to remove cosmic and aircraft background effects and which significantly reduces spillover into the peak of interest from adjacent peaks.

ANALYSIS OF RESULTS

Gross count method. After all corrections have been made, the proof of the method is whether the corrected count rates give a good measurement of snow water equivalent. First, consider the relation between net count (total count corrected for background and other effects) and ground truth water equivalent. The Luverne, Minnesota, net count rates at each flight altitude are plotted against snow water equivalent in Figure 3. For flight altitudes over 500 feet, the net count actually appears to increase rather than decrease with increasing water equivalent. This effect illustrates the necessity of carefully delineating all background contributions. The effect results primarily from the influence of radon gas decay products (notably ^{214}Bi and ^{214}Pb) in the air, as is indicated by two considerations: (1) air temperature profiles for the two days of maximum snow cover show inversions near the ground; thus the existence of a layer of entrapped radon gas is quite probable; (2) spectral peak attenuations indicate that much of the source ^{214}Bi is in the air. Figure 4 plots the ratios of specific energy levels of the measured spectral

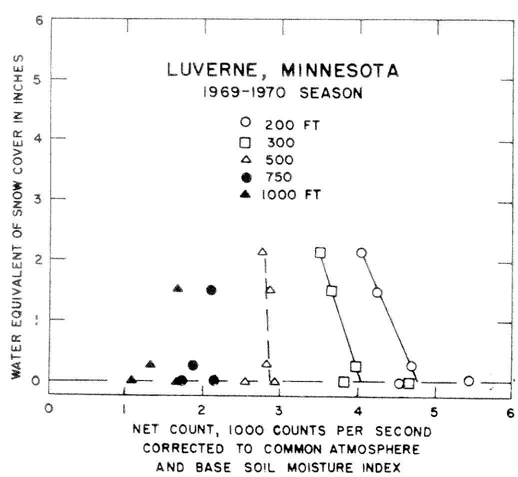

Fig. 3. Relation between net count and snow water equivalent, Luverne, Minnesota.

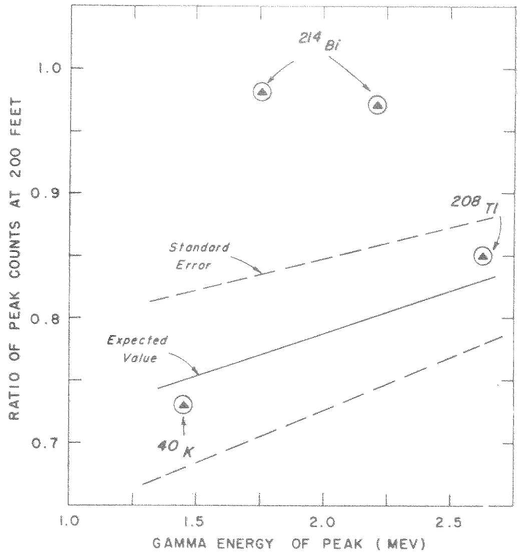

Fig. 4. Attenuation of spectral peaks, Luverne, Minnesota, November 20, 1969–January 6, 1970.

peak counts for a day with 1.5 inches of water equivalent (January 6, 1970) and that for a day with much less snow (0.3 inch; November 20, 1969). The attenuations of the spectral peaks associated with ^{40}K and ^{208}Tl (expected to be principally in the soil) fall within the ranges expected from the change in snow water equivalent. The spectral peak ratios associated with ^{214}Bi, however, fall far outside the standard error range of the expected attenuation. Thus a much greater influence from radon gas on January 6, 1970, than on November 20, 1969, is indicated. Note that the occurrence of the ^{214}Bi peak ratios near the expected value is a necessary but not a sufficient indication of the absence of radon interference for both days.

A plot of the net count against the snow water equivalent for Steamboat Springs, Colorado, is shown in Figure 5. The relations appear reasonable for altitudes up to 1000 feet. The data are not sufficient, however, to evaluate the technique adequately. Furthermore, inspection of the spectral peak ratios of the Steamboat Springs data also reveals effects due to radon gas. Comparison of Figures 3 and 5 indicates that either the Steamboat Springs data had less radon gas effect or the site's large changes of water equivalent tended to obscure the radon gas effect.

If radon interference can successfully be removed from the data, the total count approach has great operational potential. The high total count values obtained (up to 1 million per 8-mile flight) minimize errors due to natural fluctuation in the gross count. Since the number of counts n received in any time interval is a random variable with Poisson distribution, the standard deviation of the count is estimated by $n^{1/2}$. Thus for 1 million counts the standard deviation is 0.1%. Attenuation of the count rate by a heavy snowpack to one-tenth of the bare ground rate still gives a standard deviation due to natural gamma count fluctuation of less than 1%. The research presently being conducted to develop methods of removing radon obfuscation should allow more constructive discussion of the total count method in the future.

Spectral method. Corrected for soil moisture variations, the Luverne, Minnesota, spectral peak areas are plotted against the effective attenuating water mass for ^{40}K in Figure 6 and for ^{208}Tl in Figure 7. A fixed mass of water is 1.11 times as effective in attenuating gamma rays in the energy range considered as the

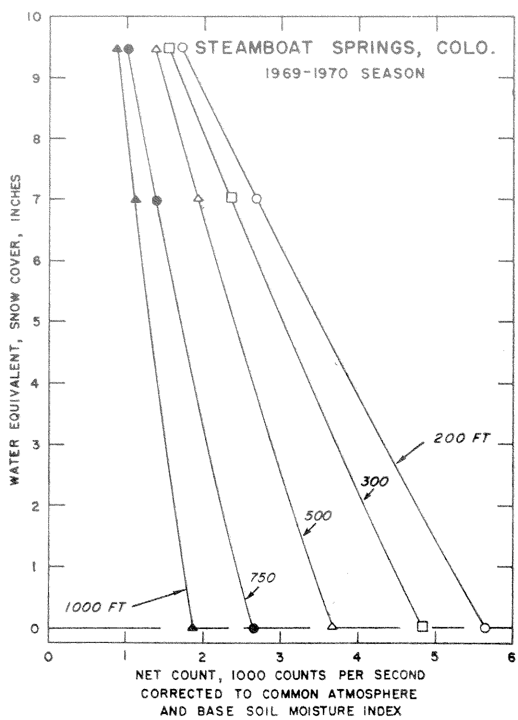

Fig. 5. Relation between net count and snow water equivalent, Steamboat Springs, Colorado.

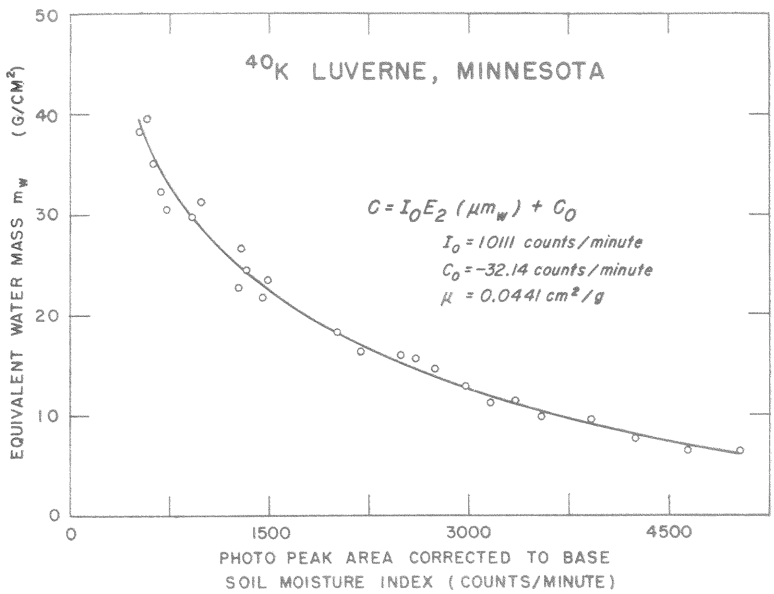

Fig. 6. Relation between ^{40}K photo peak area and equivalent water mass separating aircraft and ground. Solid line indicates relations given by equation 4.

same mass of air. The effective attenuating water mass is then calculated as:

$$M_{ew} = M_w + 0.9M_a \qquad (3)$$

where M_w is the mass of the snow blanket in grams per square centimeter and M_a is the mass of the air blanket between the detector and the ground. Thus as previously mentioned, the spectral count rate is theoretically related to the effective water blanket by equation 1, which in practice is modified to:

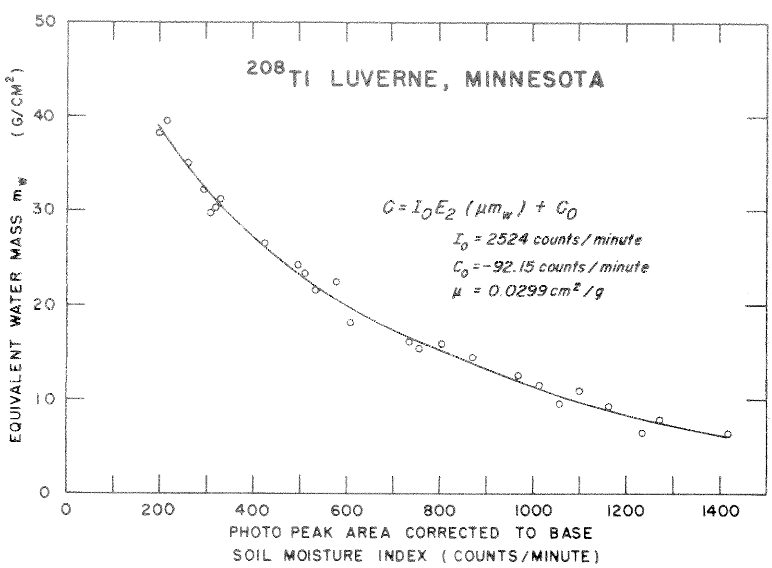

Fig. 7. Relation between ^{208}Tl photo peak area and equivalent water mass separating aircraft and ground. Solid line indicates relations given by equation 4.

TABLE 1. Reduction Coefficients for ^{40}K and ^{208}Tl Spectral Peaks in Water, in cm^2/g

	Mass Attenuation Coefficient in Water, μ_w	Optimum μ in Water	Theoretical Approximation of μ
^{40}K at 1.46 Mev	0.0590	0.0441	0.0545
^{208}Tl at 2.62 Mev	0.0424	0.0299	0.0408

$$C(M_{ew}) = I_0 E_2(\mu M_{ew}) + C_0 \qquad (4)$$

where $C(M_{ew})$ are the spectral peak counts for equivalent attenuating water mass M_{ew}; C_o is some residual background after application of the peak area determination method; I_o is the count rate at the soil surface, excluding background C_o; and μ is the gamma water mass reduction coefficient, expected to have a value near the mass attenuation coefficient.

The gamma water mass reduction coefficient μ would nearly equal the mass attenuation coefficient if the spectral peak were narrow and sharp. Gamma rays, however, can undergo Compton scattering (one of several gamma ray interactions with mass) to slightly lesser energies and still have an energy falling within the measured spectral peak. Thus the reduction coefficient μ should be somewhat below the mass attenuation coefficient for the particular energy of the peak. The values I_o and C_o were determined by linear regression by using various values of μ for both ^{40}K and ^{208}Tl. The optimum values for μ (i.e., values for which the standard error in water measurement is minimized) are shown in Table 1. Theoretical approximations of the peak reduction coefficients are also shown in Table 1. A certain percentage of once-scattered gamma rays still fall within the lower energy boundary of each spectral peak. The theoretical approximations of the reduction coefficients were obtained by reducing the mass attenuation coefficients by these percentages. The considerable difference between the theoretical approximations and the optimum reduction coefficients may be characteristic of the method of peak area determination. Any optimum reduction coefficients obtained are peculiar to the particular method of peak area determination employed.

The relations given by equation 4 are plotted in Figures 6 and 7 by using the optimum reduction coefficients obtained. The standard errors in the corresponding water equivalents are 0.50 inch and 0.38 inch when the ^{40}K and ^{208}Tl peaks are used, respectively. Values of the standard errors for the different flight altitudes are given in Table 2. The ^{208}Tl errors may indicate slightly better measurement at lower levels. The ^{40}K peak clearly gives greater measurement error at higher altitudes. This behavior is expected owing to the larger errors in measuring the air blanket and the decreased peak area counts (hence relatively greater statistical fluctuations) at higher levels. For ^{40}K the greater error at higher altitudes is also attributed to radon decay products in the air. When the ^{40}K peak area at 1.46 Mev is determined, the spillover from other peaks (notably the ^{214}Bi peak at 1.76 Mev) will not be removed completely. This residual count will be more apparent at higher altitudes, where the gamma flux from the soil is less dominant. Reduction of this residual is an area of current research.

It appears that ^{40}K data obtained at lower levels should give the best snow measurement results. Since only five points are available at each flight level, however, more data is necessary to confirm this conclusion. If the ^{40}K and ^{208}Tl peaks were used simultaneously in measuring water equivalent, more information would be available and the associated error would certainly be no worse than that derived by using either peak individually. Specific methods for using the two peaks simultaneously, however, have not yet been evaluated.

TABLE 2. Standard Error in Snow Water Measurement by Spectral Method, in Inches

	200 Feet	300 Feet	500 Feet	750 Feet	1000 Feet	200 and 300 Feet	All Levels
^{40}K at 1.46 Mev	0.18	0.26	0.52	0.66	0.68	0.22	0.50
^{208}Tl at 2.62 Mev	0.37	0.26	0.45	0.42	0.37	0.32	0.38

The standard errors shown in Table 2 include error not only in the gamma measurement method but also from the treatment of ground truth water equivalent as without error. Also, the errors shown in Table 2 were determined for relatively short data collection times. No evaluation has been made of the contribution of random error during each given day (which could be reduced by increasing the number of data collection times during each day) as opposed to error due to factors that may change from day to day or from season to season.

The forgoing discussion was centered on spectral data collected at Luverne, Minnesota, where the snow water equivalent did not exceed 3 inches, and the conclusions apply to shallow snowpacks. Bare ground net count values of up to 1 million for a typical flight at an altitude of 200 feet were previously mentioned. For the same flight, typical spectral peak areas might be 15,000 counts for ^{40}K and 5000 counts for ^{208}Tl. Deep snowpacks would reduce these counts to a range in which natural fluctuations of the count rate could be significant. A 10-inch water equivalent snowpack would reduce the ^{40}K peak to about 2200 counts, an associated standard error of 0.16 inch of water being due to natural count fluctuations alone. A 10-inch water equivalent snowpack would reduce the ^{208}Tl peak to about 1000 counts, an associated standard error of 0.20 inch of water being due to natural count fluctuations. Furthermore, such a large reduction of peak areas would allow the residual background to have a relatively greater effect, the signal-noise ratio being decreased. Hence the spectral peak method would have diminished accuracy in deep snowpacks.

CONCLUSIONS

The remote measurement of snow water equivalent over an area is certainly an attractive prospect, especially when the pitfalls of using sparse point data as an alternative are considered. Furthermore, the fact that an aircraft can cover a wide area is an additional benefit. Results of the first year of research show that gamma spectral data may be expected to give areal measurement of snow water equivalent within at least 0.2–0.5 inch over the open, relatively flat terrain of the Midwest, where snow water equivalents rarely exceed 6 inches. Longer data collection times may substantially improve this accuracy.

The total count method has considerable potential by virtue of its high count rates. Methodology for eliminating interference from airborne decay products of radon gas must be developed, however, before the total count method can be considered for wide operational application.

The spectral method is good for water depths up to about 10 inches, whereas the total count method is good for greater depths when radon gas is not a complicating factor. Improvement of the technique in the second year of research should improve its accuracy.

Acknowledgment. This paper was presented at the national fall meeting of the American Geophysical Union, December 7–10, 1970, in San Francisco, California.

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(Manuscript received April 28, 1971.)