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AIRBORNE SOIL MOISTURE MEASUREMENT USING NATURAL TERRESTRIAL GAMMA RADIATION

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ABSTRACT

Measurements of the natural terrestrial gamma radiation flux near the soil surface are used to infer areal soil moisture. Airborne gamma radiation data are collected over a network of 240 flight lines (each approximately 6 square kilometers) in the upper Midwest and used to calculate real-time, areal soil moisture values. Ground-based soil moisture data collected along calibration flight lines indicate that airborne soil moisture values can be calculated with an RMS error of 3.2 percent soil moisture, which is 40 percent less than the mean standard deviation of the ground-based soil samples. The airborne soil moisture values calculated using data from three primary background surveys tend to be 1.5 percent less than the ground-sampled soil moisture values.

INTRODUCTION

Research has been conducted since 1969 by the National Weather Service (Peck et al. 1971; Peck and Bissell 1973; Bissell and Peck 1973; Bissell 1974; Larson 1975; Carroll 1979) and by EG&G, Inc. (Anderson et al. 1969; Jones et al., 1973; Fritzsche and Feimster 1975; Fritzsche 1977, 1979), to develop a technique using natural terrestrial gamma radiation attenuation to measure snow water equivalent and soil moisture from a low-flying aircraft. Gamma radiation soil moisture survey experiments have been conducted by EG&G, Inc., at Phoenix, Arizona (Feimster et al. 1975), and Luverne, Minnesota (Feimster and Fritzsche 1975). Both experiments indicate that terrestrial gamma radiation attenuation can be used to measure the change in soil moisture near the surface. Recent work in Canada by Loijens (1980) indicates that terrestrial gamma radiation measurements can be used to measure soil moisture in the upper 10 cm with an error of 3.3% soil moisture and in the upper 25 cm with an error of 2.5% soil moisture.

The National Weather Service has recently developed and currently maintains an operational Airborne Gamma Radiation Snow Survey Program in North Dakota, South Dakota, western Minnesota, and a portion of Saskatchewan (Peck et al. 1979). The snow survey program is intended primarily to provide real-time snow water equivalent data to the National Weather Service Forecast Offices in the region and River Forecast Centers in Kansas City and Minneapolis for use in the spring flood outlooks and flood forecasts made for the upper Midwest. Additionally, it is possible to utilize the resources of the Airborne Snow Survey Program to calculate reliable, real-time, mean, areal soil moisture values for large areas of the upper Midwest at critical times during the hydrologic and agricultural cycles.

A network of 240 flight lines, each 15 to 20 km long, has been established in the region. A twin-engine Aero Commander flies at an altitude of 150 m and measures natural terrestrial gamma radiation over a path 300 m wide. Consequently, radiation data collected over each flight line are mean areal measurements over approximately 4.5 to 6 km^2. The ability to measure *mean areal* soil moisture or snow water equivalent is attractive in light of the extensive ground sampling procedure required to estimate mean areal values with reasonable accuracy. The airborne mean areal values represent "large" point measurements over a watershed. Consequently, it is desirable to have several flight lines in one basin or sub-basin to calculate a reliable mean, areal soil moisture value for the total basin, which is typically many times the area of the flight lines within the basin. (The current detection system has the capability of collecting and analyzing data as frequently as every 5 sec (250 m) as the aircraft flies along a flight line. Radiation data collected at 5-sec intervals have been used by Carroll and Vadnais (1980) to analyze the snow water equivalent distribution along a 21-km flight line in North Dakota.) From the network of 240 flight lines, a special set of 40 calibration flight lines was selected, and approximately 25 ground-based soil samples are routinely collected on each calibration line during the day of the airborne radiation data collection.

An integral part of the Airborne Snow Survey Program is the collection of background (i.e., no snow cover) airborne radiation and ground soil moisture data on the calibration line network. Background surveys were conducted during June and October 1979 and February, March, and April 1980. (The low snow cover conditions during the winter of 1980 made it possible to collect limited background data when operational snow survey missions were normally flown.) The accumulation of a significant background data base has made it possible to examine further the ability of the gamma radiation attenuation technique to remotely measure mean areal soil moisture near the surface. The technique, however, has the limitation of requiring a one-time background radiation calibration, which involves ground soil sample collection. Consequently, the approach is most suitable to an operational program where repeated airborne soil moisture measurements are required for a region.

GAMMA RADIATION ATTENUATION TECHNIQUE

The determination of soil moisture is based on the difference between the natural terrestrial gamma radiation flux measured for comparatively wet and dry soils. The presence of moisture in the soil causes an effective increase in soil density, resulting in an increased attenuation of the gamma flux for relatively wet soil and a correspondingly lower flux at the ground surface. The gamma flux near the ground originates primarily from the ^{40}K, ^{238}U, and ^{208}Tl radioisotopes in the soil. In a typical soil, 91% of the gamma radiation is emitted from the top 10 cm of the soil, 96% from the top 20 cm, and 99% from the top 30 cm (Zotimov 1968). Other sources of radiation that contribute to the measured gamma flux include the daughter products of radon gas in the atmosphere (^{214}Bi), high energy cosmic particles (i.e., greater than 3.0 MeV), and trace sources of radioactivity within the aircraft and the detection system itself (Bissell and Peck 1973). During the calibration procedure, stripping equations are derived for isolating these extraneous sources of radiation (Fritzsche 1979). Calibration is accomplished by collecting radiation data at different altitudes and using the changing airmass as an attenuation medium. A reliable calibration can be generated in one area and used in another with a different radioisotope concentration. The radiosotope concentration in the soil does not significantly change with time; consequently, there is no need for additional background data collection once a radiation spectrum has been collected for a particular flight line.

Reliable, real-time, mean, areal soil moisture measurements can be made for the upper 20 cm of soil, if both background and current uncollided terrestrial gamma count rates and background soil moisture data are available. Three independent soil moisture values are calculated by measuring the attenuation of the gamma flux as a consequence of increased soil density due to the presence of moisture. Soil moisture values are calculated using data from the ^{40}K window (1.36 to 1.56 MeV), the ^{208}Tl window (2.41 to 2.81 MeV), and the gross count (GC) energy spectrum (0.41 to 3.0 MeV) (Fig. 1) by the following equations

$$M(^{40}\mathrm{K}) = \frac{\frac{K_0}{K}(100 + 1.11\ M_0) - 100}{1.11} \tag{1}$$

$$M(^{208}Tl) = \frac{\frac{T_0}{T}(100 + 1.11\ M_0) - 100}{1.11} \tag{2}$$

$$M(\mathrm{GC}) = \frac{\frac{GC_0}{GC}(100 + 1.11\ M_0) - 100}{1.11} \tag{3}$$

where

K, T, and GC = current uncollided terrestrial gamma count rates in windows K_w, T_w, and GC_w

K_0, T_0, and GC_0 = background uncollided terrestrial gamma count rates in windows K_w, T_w, and GC_w and

M and M_0 = current and background soil moisture for the upper 20 cm. Soil moisture is defined as sample moisture weight divided by dry sample weight

Incorporated in the soil moisture equations are two coefficients: 1.11 represents the ratio of gamma radiation attenuation in water to air; and

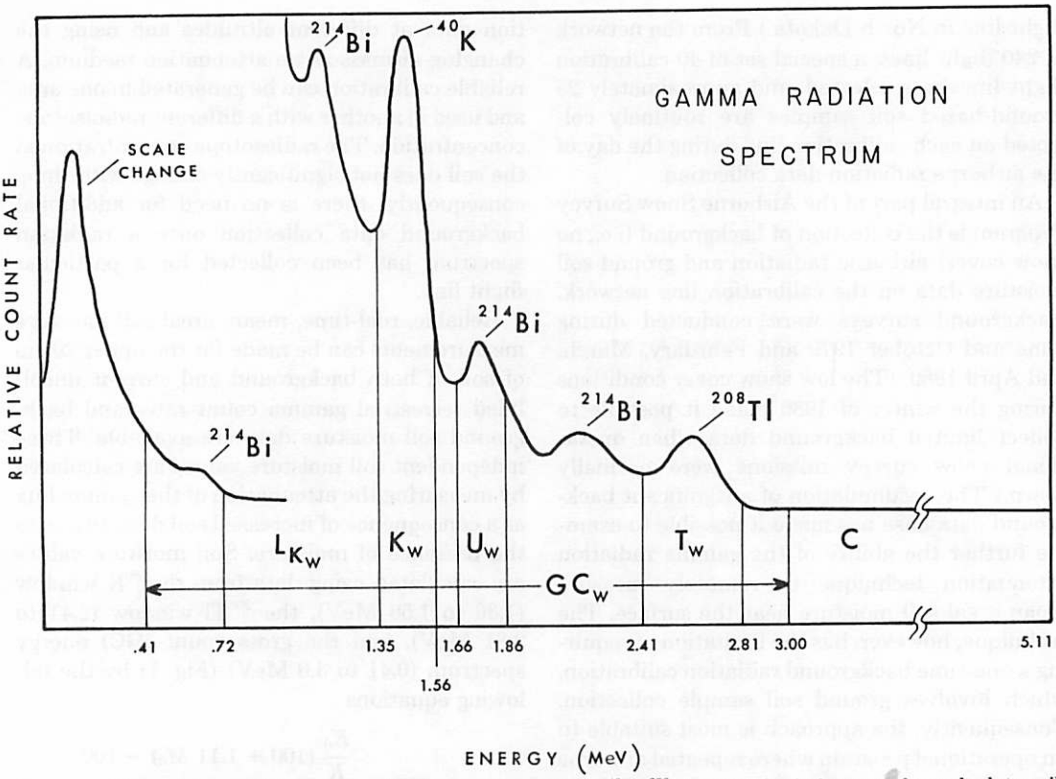

FIG. 1. Natural terrestrial gamma radiation spectrum giving ^{40}K, ^{208}Tl, and GC windows used to calculate soil moisture.

100 is used because soil moisture is reported in percentages.

The single best theoretical value to be derived from the three soil moisture values can be obtained by weighting each of the photopeak results and the gross count result with their respective inverse variances in the following manner

$$\bar{M} = \frac{\Sigma \frac{M_i}{\sigma_i^2}}{\Sigma \frac{1}{\sigma_i^2}} \tag{4}$$

where

$\bar{M}$ = weighted mean soil moisture
M_i = soil moisture result for method i and
σ_i^2 = variance for method i

AIRBORNE DETECTION SYSTEM

The airborne detector package represented in Fig. 2 and described by Carroll and Vadnais (1979) consists of five downward-looking 10.2 × 10.2 × 40.6-cm NaI(Tl) scintillation detectors; two 10.2 × 10.2 × 20.3-cm, upward-looking detectors (used to isolate the effects of the random gas contribution); a pulse height analyzer (PHA); a Hewlett-Packard 9825 minicomputer used to reduce and record the output data onto magnetic tape; temperature, pressure, and radar altitude sensors; and a remote control unit used by the system operator or navigator to control and monitor the data collection. Two microprocessors contained in the PHA time, amplify, analyze, and accumulate the pulse output from the crystals. One microprocessor initializes and controls the system and formats the output, while the second is used in the analog to digital conversion of the temperature, pressure, and radar altitude data. All the data, including the two gamma radiation spectra (i.e., from the up and down detectors), are accumulated in 1024 discrete channels, each of which is a 24-bit binary number at a given address.

The data acquisition procedure is designed to accumulate and store window data in multiple cycles of 5 sec or longer. This provides the capability of analyzing the snow cover or soil moisture distribution along a flight line in approximately 250-m segments. At the end of each

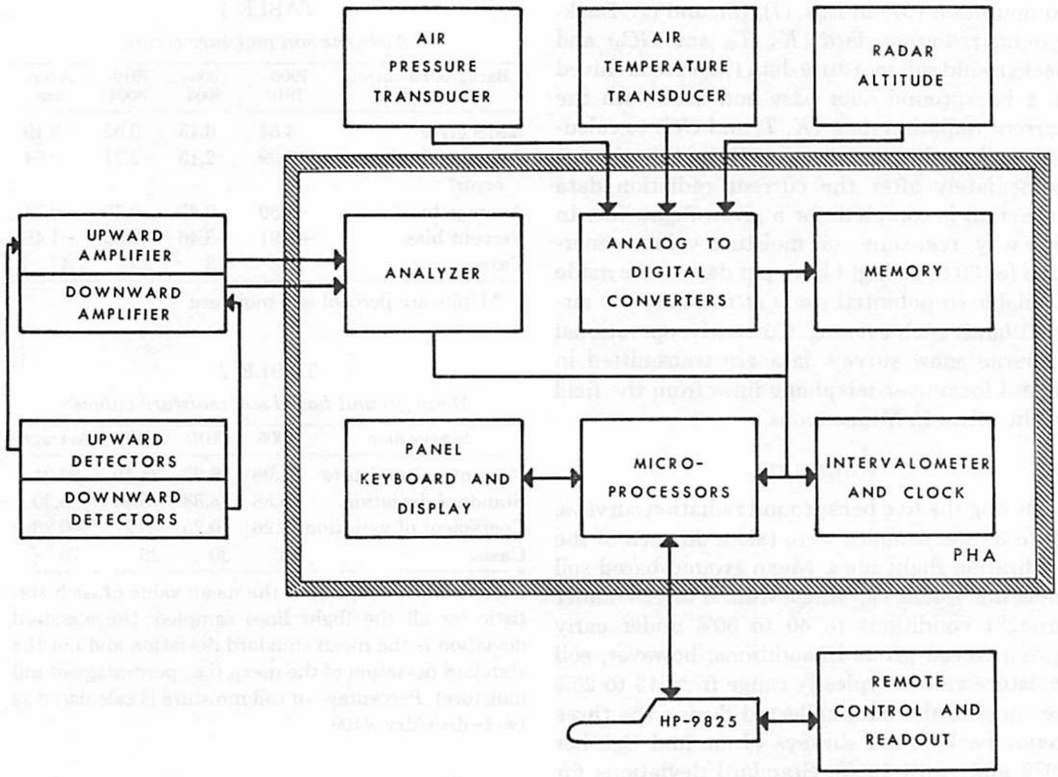

FIG. 2. Block diagram of the National Weather Service airborne gamma radiation detection system.

flight line, the total radiation spectra (.05 to 5.1 MeV) accumulated over the length of the flight line for both the up and down detectors are stored on magnetic tape. These data are archived on disk for additional analysis.

Techniques have been developed to calibrate airborne gamma radiation detection systems (Fritzsche 1979; Glynn and Grasty 1980). Experiments must be performed to determine values for 20 parameters that describe the physical nature of the radiation attenuation process. Multiple high altitude and lake flights are used to obtain background components. Data collected from simulation pads, loaded with various concentrations of ^{40}K, ^{232}Th, and ^{238}U, give photopeak stripping coefficients and basic system sensitivity. Multiple altitude flights over land lines provide data necessary to calculate air attenuation coefficients, which are subsequently converted to water attenuation coefficients.

DATA COLLECTION

Ambient radiation data are collected by the detection system and immediately reduced using algorithms developed to describe the presence of atmospheric radon, high-energy cosmic radiation, Compton scattering effects within the radiation spectra, and extraneous background radiation contributed by the aircraft and detection system. Pressure, temperature, and radar altitude data are also recorded and used to calculate the attenuation of terrestrial radiation due to the air mass between the source and sensor (approximately 17 g cm^{-2} at an altitude of 150 m). Uncollided terrestrial radiation count rates normalized to time and air mass are used in the aircraft to calculate snow water equivalent or soil moisture values immediately following data collection for a flight line.

Ground soil samples are collected along calibration flight lines during the day airborne radiation data are collected. From a typical flight line 20 km long, approximately 25 soil samples are collected from the upper 20 cm at representative sample sites along the flight line, and standard gravimetric techniques are used to determine the soil moisture content. Ground-sampled soil moisture data are used to determine background soil moisture conditions (M_0) and as an independent check on the airborne soil moisture computation (M) in Eqs. (*1*), (*2*), and (*3*). Background radiation data (K_0, T_0, and GC_0) and background soil moisture data (M_0) are archived in a background data base and used with the current radiation data (K, T, and GC) to calculate soil moisture values (M) in the aircraft immediately after the current radiation data collection is complete for a given flight line. In this way, real-time soil moisture values generated for 30 to 50 flight lines per day can be made available to potential users at the time the aircraft lands each evening. Currently, operational airborne snow survey data are transmitted in digital form over telephone lines from the field to the office in Minneapolis.

RESULTS

During the five background radiation surveys, 20 to 30 soil samples were taken on each of the calibration flight lines. Mean ground-based soil moisture values can range from 8 to 12% under drought conditions to 40 to 50% under early spring frozen ground conditions; however, soil moisture values typically range from 15 to 25% for most of the data collected during the three major background surveys (June and October 1979 and April 1980). Standard deviations for ground-based soil moisture observations consistently range from 3 to 7% soil moisture, with a mean coefficient of variation of 0.3. (Because soil moisture is measured in percentages, terminology can be confusing: a change from 22% soil moisture to 25% soil moisture represents both an increase of *3% soil moisture* and an increase of *13.6%*.)

Table 1 gives the errors associated with the airborne soil moisture computation when compared with the ground-based soil moisture values for the three primary background surveys. Table 2 gives a summary of the ground-based soil moisture measurements for the three primary background surveys. Figure 3 represents the relationship of the airborne soil moisture values to the ground-based soil moisture data. The average RMS error of 3.19% soil moisture indicates that the gamma radiation attenuation technique can be used with some confidence to measure mean areal soil moisture in the upper 20 cm of the soil surface. In fact, the RMS error associated with airborne measurements is 40% less than the average standard deviation of the ground samples collected along the flight lines. To reduce the RMS error, a greater number of ground samples would be required to define more precisely the background soil moisture (M_0) used in Eqs. (*1*), (*2*), and (*3*). The average biases of −0.34% soil moisture and −1.46% for the three surveys probably reflect random errors rather than systematic errors associated with the technique.

TABLE 1

Airborne soil moisture errors

Background-current survey date	7906–7910	7906–8004	7910–8004	Average
RMS error[a]	3.54	3.15	3.02	3.19
Average absolute error[a]	2.69	2.13	2.71	2.54
Average bias[a]	−1.89	−0.87	0.70	−0.34
Percent bias	−9.91	−3.46	2.85	−1.46
Cases	11	13	23	47

[a] Units are percent soil moisture.

TABLE 2

Mean ground-based soil moisture values[a]

Survey date	7906	7910	8004	Average
Percent soil moisture	21.08	19.20	21.19	20.31
Standard deviation	5.58	4.88	5.66	5.30
Coefficient of variation	0.26	0.25	0.27	0.26
Cases	14	30	26	70

[a] The values represent the mean value of each statistic for all the flight lines sampled: the standard deviation is the mean standard deviation and not the standard deviation of the mean (i.e., percentage of soil moisture). Percentage of soil moisture is calculated as (wet−dry)/dry ×100.

A good test of the technique occurs when background and current soil moisture differ widely. Of the available data from the three survey missions, the most extreme case occurs when a background soil moisture (M_0) of 28.2% is used as background for a frozen ground condition with a mean value of 50.2% soil moisture. In this case, the airborne technique indicates 47.6% soil moisture and differs from the ground sample by 2.6% soil moisture and 5.2% (Fig. 3).

Technique errors

Errors associated with the airborne percentage of soil moisture calculation stem from two principle sources: (1) the uncertainty of M_0, and (2) the uncertainty of the pure uncollided gamma count rates (i.e., K, T, GC, K_0, T_0, GC_0).

Because only a finite number of ground-based soil samples are available over a flight line, a

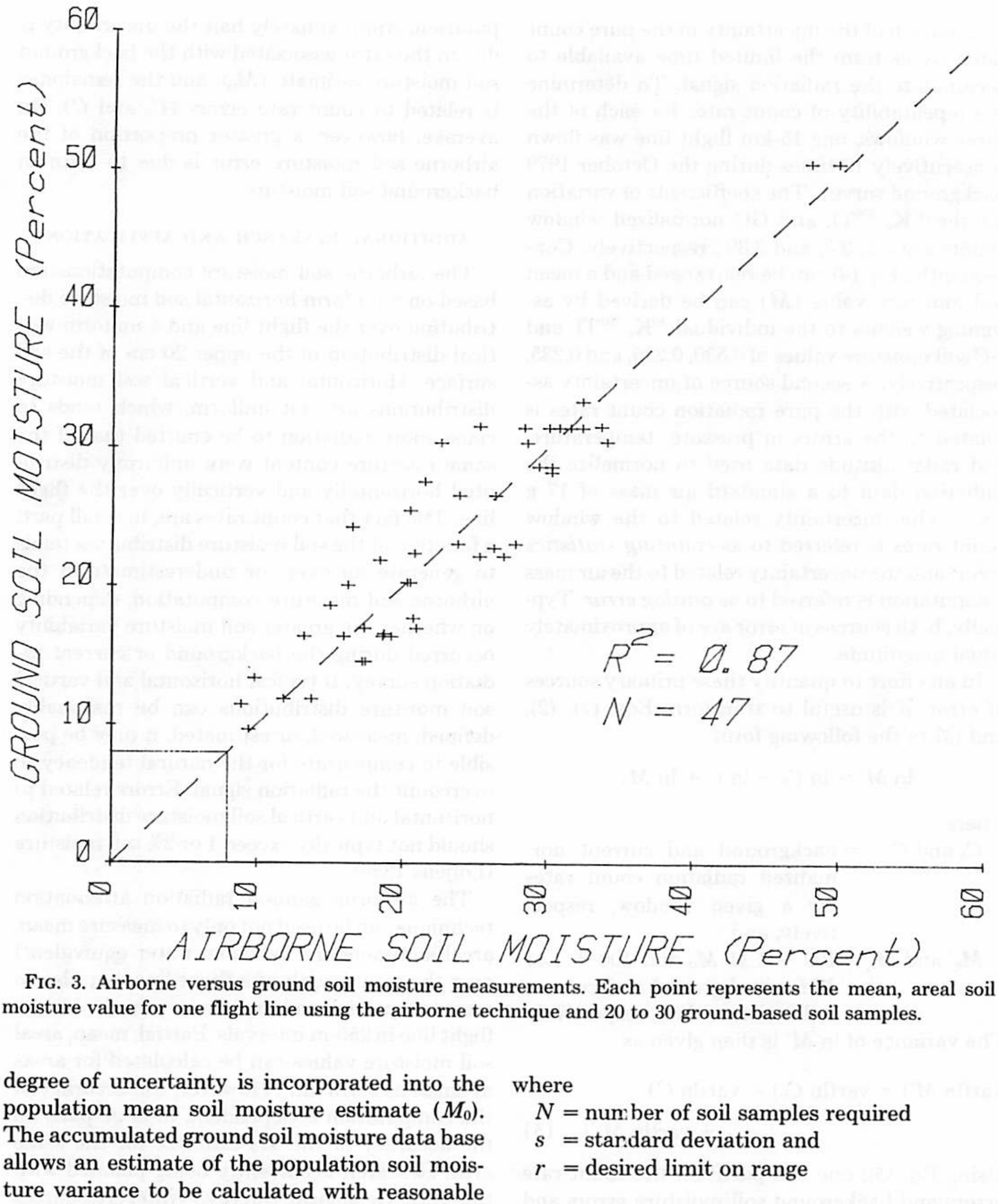

FIG. 3. Airborne versus ground soil moisture measurements. Each point represents the mean, areal soil moisture value for one flight line using the airborne technique and 20 to 30 ground-based soil samples.

degree of uncertainty is incorporated into the population mean soil moisture estimate (M_0). The accumulated ground soil moisture data base allows an estimate of the population soil moisture variance to be calculated with reasonable confidence. Using the estimate of the population variance, it is possible to calculate the number of ground soil samples required per flight line to estimate the population mean soil moisture for the flight line with a confidence interval of 95% by the following relationship

$$N = \left(\frac{1.96\, s}{r}\right)^2$$

where

N = number of soil samples required
s = standard deviation and
r = desired limit on range

The mean soil moisture standard deviation of 5.3% soil moisture makes it necessary to collect, on average, 27 soil samples per flight line if the population mean is to fall within ± 2% soil moisture of the sample mean at the 95% confidence level (Snedecor and Cochran 1967). Consequently, reasonable confidence can be placed in the background soil moisture value (M_0) used to calculate current soil moisture.

A portion of the uncertainty in the pure count rates stems from the limited time available to accumulate the radiation signal. To determine the repeatability of count rates for each of the three windows, one 15-km flight line was flown consecutively 10 times during the October 1979 background survey. The coefficients of variation for the ^{40}K, ^{208}Tl, and GC normalized window counts are 2.2, 3.3, and 3.3%, respectively. Consequently, Eq. (*4*) can be rearranged and a mean soil moisture value ($\bar{M}$) can be derived by assigning weights to the individual ^{40}K, ^{208}Tl, and GC soil moisture values of 0.530, 0.235, and 0.235, respectively. A second source of uncertainty associated with the pure radiation count rates is related to the errors in pressure, temperature, and radar altitude data used to normalize the radiation data to a standard air mass of 17 g cm^{-2}. The uncertainty related to the window count rates is referred to as *counting statistics error*, and the uncertainty related to the air mass computation is referred to as *analog error*. Typically, both sources of error are of approximately equal magnitude.

In an effort to quantify these primary sources of error, it is useful to transform Eqs. (*1*), (*2*), and (*3*) to the following form

$$\ln M' = \ln C_0 - \ln C + \ln M_0'$$

where

C_0 and C = background and current normalized radiation count rates for a given window, respectively, and

M_0' and M' = $100 + 1.11\ M_0$ and $100 + 1.11\ M$ for background and current soil moisture data, respectively

The variance of $\ln M'$ is then given as

$$\mathrm{var}(\ln M') = \mathrm{var}(\ln C_0) + \mathrm{var}(\ln C) + \mathrm{var}(\ln M_0') \qquad (5)$$

Using Eq. (*5*), one can partition the count rate errors and background soil moisture errors and assign an asymmetrical confidence interval to the airborne soil moisture computation. A typical example of the airborne ^{40}K soil moisture computation gives a value of 19.7% soil moisture, with an error of +4.7 to −4.5% soil moisture. These values correspond to a mean and standard deviation of 19.8 and 6.0% soil moisture, respectively, for the ground-sampled data. In this case, the ground sample demonstrates 30% *more* uncertainty than the airborne soil moisture computation. Approximately half the uncertainty is due to the error associated with the background soil moisture estimate (M_0), and the remainder is related to count rate errors (C_0 and C). On average, however, a greater proportion of the airborne soil moisture error is due to error in background soil moisture.

ADDITIONAL RESEARCH AND APPLICATION

The airborne soil moisture computations are based on a uniform horizontal soil moisture distribution over the flight line and a uniform vertical distribution in the upper 20 cm of the soil surface. Horizontal and vertical soil moisture distributions are not uniform, which tends to cause more radiation to be emitted than if the same moisture content were uniformly distributed horizontally and vertically over the flight line. The fact that count rates are, in small part, a function of the soil moisture distribution tends to generate an over- or underestimate in the airborne soil moisture computation, depending on whether the greater soil moisture variability occurred during the background or current radiation survey. If typical horizontal and vertical soil moisture distributions can be reasonably defined, measured, or estimated, it may be possible to compensate for the natural tendency to overcount the radiation signal. Errors related to horizontal and vertical soil moisture distribution should not typically exceed 1 or 2% soil moisture (Loijens 1980).

The airborne gamma radiation attenuation technique can be used not only to measure mean, areal soil moisture (or snow water equivalent) over the total length of a flight line, but also to measure partial soil moisture values along a flight line in 250-m intervals. Partial, mean, areal soil moisture values can be calculated for areas as small as 0.075 km^2. However, the accuracy of the computation is dependent, in large part, on the accuracy of the M_0 estimate for the same area. Research is currently being planned with the U.S. Geological Survey, Water Resources Division, to address problems related to horizontal soil moisture distribution and partial, mean, areal soil moisture calculations.

Real-time assessment of soil moisture conditions for large areas of the upper Midwest has extensive research, agricultural, and hydrologic applications. Airborne soil moisture values have recently been used by the National Environmental Satellite Service as a check on research data gathered by NASA high-altitude aircraft and satellites. Reliable, real-time, airborne soil moisture values were calculated for all the flight lines flown on the April 1980 background data collection mission in the upper Midwest and Canada. The data were disseminated to the Soil Conservation Service for use in making agricultural decisions during the extremely dry spring.

If a formal, operational, airborne soil moisture survey program were established in the upper Midwest, then reliable, real-time soil moisture data would be available to the National Weather Service River Forecast Centers in Minneapolis and Kansas City responsible for river and flood forecasting and to the Forecast Offices in the region responsible for communicating the forecasts to the public. Soil moisture data could be collected operationally in October and November, prior to winter snow accumulation, to assess antecedent soil moisture conditions for use in hydrologic models currently used for river and flood forecasting in the upper Midwest. Additionally, observed airborne soil moisture values could be used to update comparable soil moisture values generated by conceptual hydrologic models. The National Weather Service River Forecast System (Monro and Anderson 1974) is a collection of utility computer programs and conceptual models. Included in the system is a soil moisture accounting model (Burnash et al. 1973) that simulates upper zone tension water physically located near the soil surface. It may be possible to update the simulated soil moisture value based on the observed airborne value in an effort to reduce simulated stream discharge errors.

CONCLUSIONS

The gamma radiation attenuation technique is capable of measuring the soil moisture flux in the upper 20 cm of the soil surface with the accuracy necessary for operational applications. Ground-based soil moisture data collected from a network of 240 flight lines in the upper Midwest indicate that mean areal soil moisture values can be calculated with an RMS error of 3.2% soil moisture. The airborne soil moisture values tend to be 1.5% less than the ground-sampled values. The airborne gamma radiation technique is capable of measuring reliable, real-time, mean, areal soil moisture values over large areas with the accuracy required for operational hydrologic and agricultural applications. An operational soil moisture survey program could make real-time data available to users interested in soil moisture conditions in the fall prior to snow accumulation, in the spring to assess surface conditions prior to crop planting, or at any time to quantify extremely wet or dry soil moisture conditions over large areas of the upper Midwest.

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