W O R L D   M E T E O R O L O G I C A L   O R G A N I Z A T I O N

WORKSHOP ON REMOTE SENSING OF SNOW AND SOIL MOISTURE BY NUCLEAR TECHNIQUES

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SOIL MOISTURE MEASUREMENTS DISCUSSION PAPER

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SUMMARY

This paper is to provide background information for the discussion of the Workshop on soil moisture measurements. The material is presented in four parts: (1) surface measurements, (2) remote measurements, (3) requirements for support of snow cover measurements, and (4) usefulness of aerial gamma radiation surveys. A list of items for discussion is presented for each of the four topics to be discussed.

INTRODUCTION

Soil moisture plays an important role in the land phase of the hydrological cycle. The amount of water stored as soil moisture is one of the major components in water balance studies. The amount of water in the upper layer of the soil often may be a determining factor for the rate of infiltration that can occur during periods of precipitation and/or snowmelt and on the evapotranspiration processes.

While the importance of soil moisture is clearly understood our ability to assess soil moisture conditions over a basin for hydrological analyses is severely limited.

The development of remote sensing techniques to provide a representative value for the average soil moisture conditions over a river basin would be of considerable value. The use of aerial gamma radiation surveys for obtaining such areal averages has shown definite promise [1, 2].

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The use of gamma radiation surveys to obtain remote measurement of the water equivalent of the snow cover is the subject of other sessions of this workshop. The purpose of this session is to provide a forum for discussion of the technical aspects and the probable usefulness of the gamma radiation method to obtain average areal measurements of soil moisture and to discuss the need of such measurements as an adjunct to the snow cover surveying program.

Considerable data on soil moisture have been collected in conjunction with the research on aerial gamma radiation survey techniques in the United States [3]. Research studies on other remote sensing methods were occasionally conducted simultaneously with the gamma radiation field surveys. Most of these surveys were made over a 13.6 km (8.45 mile) survey line near Luverne, Minnesota. Information on the research area and on the data collection techniques are available in the literature [4]. For convenience and to provide continuity, research results based primarily on data collected from this area will be used for examples in this paper.

The purpose of this paper is to provide background information for the discussions on problems and factors relating to measurement of soil moisture and on the value of using gamma radiation surveys for this purpose.

The discussions for the session on soil moisture measurements (and the information in this paper) are divided into four areas of interest:

1. surface measurements,

2. remote measurement,

3. requirements for support of snow cover measurements, and

4. usefulness of aerial gamma radiation surveys.

SURFACE MEASUREMENTS

General

Historically point measurements of soil moisture have been used as a basis for evaluating areal soil moisture conditions [5]. These data are used to determine the amount of water in the soil for water balance or agricultural purposes and as an index to soil characteristics (infiltration rate, etc.). Soil moisture is usually expressed as a percentage by weight, SM_w, with respect to the weight of dry soil or as a percentage by volume, SM_v, with respect to the soil volume. The bulk density, ρ_b, of the soil (dry mass of a known volume of soil expressed as weight per unit volume in grams per cubic centimeter) can be used to relate the percentage of soil moisture by weight, SM_w, to the percentage of volume, SM_v, by the equation:

$$SM_v = \frac{\rho_b}{\rho_w} SM_w , \qquad (1)$$

where ρ_w is the density of water and is considered to be equal to unity. The equivalent depth soil moisture for a specific depth, h, of soil may be calculated by the equation:

$$\text{Soil Moisture (cm)} = \frac{\rho_b}{\rho_w} (h)(SM_w) \qquad (2)$$

For the same soil (constant dry bulk density) percentage changes in SM_w may be directly converted to equivalent depth of water for a given depth, h, of soil. All further references to percentage of soil moisture in this paper (and in the discussion of the session) will be moisture percentage by weight, SM_w.

Measuring Techniques

The basic method for soil moisture determination is the gravimetric method [6]. Samples of the soil are weighed and then oven dried at 105°C until a constant weight is attained. The decrease in weight as a percentage of the dry weight is the soil moisture by weight, SM_w.

Other methods use measurements of the electric resistance capacitance or thermal conductivity of the soil, gamma ray attenuation or neutron scattering. Most of these methods require a permanent installation or are difficult to use under a snow cover, with or without ice layers. Because of these problems and since the Luverne, Minnesota research area is private property that is used for normal dry-land farming, the gravimetric method has been employed for obtaining all ground measurements of soil moisture for calibration and evaluation of the aerial gamma radiation survey program in the United States.

Areal Averages

Soil moisture conditions over a basin are probably one of the most heterogenous of all hydrometeorological parameters. The variability is due to the heterogenity of the soil and to many factors which influence the soil moisture at a point. These factors include variability in surface cover, drainage, microclimate, and chemical and physiological activity.

It is often stated that the variability of soil moisture is so large and the number of samples required to define the average conditions for an area so great that it is extremely difficult, if not impossible, to define accurately the actual distribution or even the average soil moisture for any area having a large range of soil conditions [7]. It is not the purpose of this discussion to try and solve the problems associated with obtaining a representative average for an area but to discuss how this difficulty can be handled.

Most areal average values for river basins or other areas have used random or grid point samplings techniques to arrive at areal values. Such sampling techniques have created a larger problem than necessary. There are certain drainage pathways (thalwegs) that persistently maintain near saturated conditions near the surface of the ground and become waterways during periods of heavy rainfall. In agricultural lands of north-central United States such areas may be seen as dark areas on infrared imagery [8]. In computing areal averages the inclusion of data from thalwegs areas (often representing a very small fraction of the total area) generally leads to values which are not representative. During periods of extreme drought most of these areas have low levels of soil moisture and for such periods the inclusion of data from these areas would not materially affect areal averages.

For most of the areas surveyed in the United States by the gamma radiation method the near surface water table conditions represent only a small portion of the survey area. Average values using data from freely draining areas (with slopes of 2% to 3%) appear to yield representative values. In addition differences in the computer average values from one survey to another have been found to correlate well with the measured gamma radiation estimates of soil moisture.

A study by Filippova [9] proposed the same general idea for excluding data from thalwegs in computing the averaged soil moisture on experimental catchments.

Field Observations

Ground soil moisture measurements from the Luverne, Minnesota research line are shown in figures 1, 2 and 3 to illustrate the consistency of data from selected locations. The land in the Luverne area is is divided into one square mile sections by a series of roads. Since the Luverne survey line begins at a road there are eight even sections in the flight line plus a small portion on the northern end of the line. For all surveys, with or without snow cover, soil moisture data are collected at a minimum of two established points in each mile segment. When surveys are made with snow cover, additional soil moisture data are generally collected. Each point in figures 1, 2 and 3 represents a weighted average of the individual samples within each segment for surveys conducted during the 1969-1972 seasons. The consistency of the data for each survey appears to be good even though only one sample was collected at each of the established points. In addition the change in the average soil moisture value from one survey to another is fairly well reflected by individual point changes.

Frozen Ground

Frozen soil conditions introduce many additional problems in obtaining accurate soil moisture measurements. Not the least of these is obtaining a sample. The effect of changes in the bulk density of the soil because of freezing of the water also introduces errors in the calculation of the soil moisture [10].

Items for Discussion

1. What ground measurement techniques have been used to collect point soil moisture data for use with gamma radiation survey?

   a. With non-frozen soil?

   b. With frozen soil?

   c. With varying vegetation cover?

2. What methods are used to compute areal averages from point or other data? How are sample points chosen?

3. What are considered to be the accuracies of soil moisture estimates?

-- A research program should investigate sampling depth sensitivity, soil moisture profile dynamics, and effects of soil type, surface roughness, and vegetation.

-- Use of present meteorological satellites should be more fully explored, particularly for thermal and reflective applications.

-- Major attention should be given to assessing moisture profiles using modelling techniques that use meteorological data and can be fine tuned frequently with remote-sensing inputs.

-- More multispectral (visible and near infrared, thermal, microwave) modeling research is required.

-- Optimum angles of incidence and frequencies for identifying and reducing effects of surface roughness and vegetation should be determined.

-- Theoretical models appropriate for soil moisture measurement problems should be developed. Modeling research should be multispectral (visible, IR, active and passive microwave).

-- Effects of soil characteristics on the microwave response to soil moisture should be evaluated.

-- The potential of passive and active microwave sensors should be demonstrated for estimating soil moisture on an operational basis with aircraft and spacecraft sensors that integrate large areas of natural, non-idealized terrain.

-- Gamma radiation technology should be utilized for calibration and ground truth purposes.

At the present time remote sensing of soil moisture conditions from space vehicles cannot produce measurements of direct practical value. However, as indicated by the above statements, additional research does hold promise for development of techniques to provide useful measurements. A major problem in evaluating the accuracy of remote measurements is the lack of representative ground truth for comparison. Aerial gamma radiation measurement is considered by some to be an accurate method of providing areal measurements that can be used for this purpose.

Example of Dual Measurements

In June of 1972, simultaneous flights of microwave and gamma radiation sensors were conducted over the Luverne, Minnesota flight line [13]. The microwave measurement recorded vertically and horizontally

REMOTE MEASUREMENTS

General

For most hydrological purposes there is a need to know the variation of the soil moisture with depth (vertical profile) as well as to have a knowledge of the spatial distribution. No single remote sensing method can provide all of the required information even under the most ideal of conditions. Blanchard's [11] paper in this section has introduced a new concept that considers the dynamic depth in the remote measurement. This paper does not propose to discuss the many remote techniques used to measure soil moisture.

State of the Art

Many remote measuring methods that have been used are based on measurements of the reflected solar, emitted thermal infrared or microwave radiation.

The following statements from a recent soil moisture workshop held in the United States give some indication of the current state of the art in remote sensing of soil moisture [12]:

-- Very few present and potential users of soil moisture information can define their data needs in terms of accuracy, resolution, and frequency of coverage.

-- Current reflected-solar and thermal-infrared techniques are most successful for bare soil and for complete canopy cover, and are least successful for intermediate canopy cover.

-- A relationship exists between near-surface soil moisture and reflected-solar and emitted-thermal infrared radiation.

-- Agrometeorological models supplemented by remote sensing inputs presently have the greatest potential for predicting soil moisture and soil moisture profile on a daily basis.

-- Theoretical and experimental work should be conducted to determine the dependence of the sensing depth on frequency and moisture profile characteristics.

-- Visible, reflective IR, thermal IR, active and passive microwave techniques should be fully considered in a research and development program. At the present time, no single technique appears advantageous over others for the total range of applications. For specific applications one or more of the techniques may be preferred.

polarized radiation at 4.99 and 13.4 GHz (6 and 2.2 cm). Gamma radiation was measured with NaI scintillation crystals connected to a multichannel analyzer in the energy range from 0.05 to 3.0 Mev. Measurements of soil moisture were also obtained by the gravimetric method along the flight line.

Both ground and aerial measurements were made along this flight line on June 12, 1972, and again on June 19, 1972. A comparison of the significant factors influencing radiation on the two flights is shown in table 1.

TABLE I. MEASUREMENT CONDITIONS ON JUNE 12 AND JUNE 19, 1972

Variable	June 12		June 19	
	Microwave	Gamma	Microwave	Gamma
Flight time, LST	1450-1612	1441	1045-1155	1241
Altitude	762 m	91 m	762 m	91 m
Sky condition	Low thick overcast		Low thick cumulus	
Mean surface temperature measured by thermal scanner	28°C		24°C	
Rain history, Steen, Minn.	No rain previous 5 days.		0.8 mm on 16th; 27.2 mm 2 hours a.m. of 17th; trace 18th.	

The gamma flux flights were flown at a nominal altitude of 91 m; and, at this height, the sensor instantaneously sampled a circle on the ground approximately 610 m in diameter. As the plane moved over the ground, the readings were integrated for 2 seconds and then recorded. The number of recordings varied from 6 to 8 per kilometer depending on the aircraft speed and the position of the timer when a given segment was entered.

The microwave flights were flown at altitudes of 152 and 762 m with a 37° forward look angle. The microwave footprints were 21 x 17 and 106 x 82 m, respectively. Both of the microwave flights tended to resolve variations on the ground much more than the gamma flight. The higher altitude microwave flight sampling area was larger and therefore more compatible in sampling size with the gamma flight.

There were 34 ground sampling sites along the 13.6 km (8.45 mile) flight line. Samples were taken for 5, 10, and 20 cm depths. Variation of soil moisture between depths was generally no more than 4 percent.

The microwave data from these flights were published in a report for NOAA [14]. They reported that a good correlation was obtained between the vertical and horizontal polarizations and between the radiation measured at the two different frequencies. In addition, certain decreases in radiation were collocatable with stream locations. There was, however, little correlation between the microwave measurements and the soil moisture measurements made on the ground.

Comparison of the microwave (measured at 762 m) with the gamma radiation for the full flight line resulted in poor correlation. Measurements were then compared on a field-by-field basis for the following reasons:

1. By taking a relatively large area, the difference resulting from instantaneous sampling size differences could be smoothed and uncertainty as to sensor location along the flight lines could be reduced. Field sizes varied from 0.4 to 0.8 km (¼ to ½ mile) in their dimension along the flight line.

2. This allowed crops of a single type to be compared, thus, avoiding variations in measurements that might be due to the type of vegetative cover.

Uncertainty in the microwave sensor location was corrected by adjusting distinct valleys on the microwave trace to stream locations on the map. Field averages were taken by graphically integrating the microwave trace.

Correlations of the differences measured by the two methods between June 12 and 19 are show in table 2. Figure 4 shows plots of the measurements for corn fields. Plots and correlations were best for comparisons using only corn fields and microwave flights at 762 m. There were not sufficient data on other crop types to warrant comparison. Correlation of gamma flux with microwave measurements at an altitude of 150 m was significantly lower. Over wet areas there were large variations in the passive microwave radiation measurements compared to those from dry land agricultural areas. This occurred even over areas which had only minor variation in the gamma radiation.

TABLE 2. CORRELATION OF DIFFERENCES IN MEASURED RADIATION BETWEEN JUNE 12 AND JUNE 19, 1972

Crop	Microwave		Gamma	
	Altitude	Polarization	Altitude	R
Corn only	762 m	Vertical	91 m	0.82
Corn only	762 m	Horizontal	91 m	.84
All crops	762 m	Vertical	91 m	.66
All crops	762 m	Horizontal	91 m	.68
Oats only	762 m	Vertical	91 m	.69
Oats only	762 m	Horizontal	91 m	.72

This particular set of measurements is unusual in that field and sky conditions were very similar a week apart. Simultaneous areal measurements by both airborne techniques, as well as ground measurements, indicated an increase in soil moisture from June 12 to June 19.

If we assume gamma radiation surveys provide an accurate measurement of soil moisture for all conditions experienced on the Luverne, Minnesota flight line, the following can be inferred from the results of the comparison measurement study:

1. For a single crop cover microwave techniques can provide an accurate measurement of soil moisture.

2. For mixed crop areas there is not a linear relation between measurement data for microwave and gamma radiation.

3. For small drainage areas it was evident the microwave was reflecting soil moisture variations not observed by the gamma radiation method.

Items for Discussion

1. Experience of participants in simultaneous measurements of snow and soil moisture by gamma radiation and other remote sensing methods.

2. Experience of participants in relating remote measurements to simulated soil moisture from hydrological or agrometeorological models.

3. Limitations imposed by vegetation, recent weather, time of day, factors of soil depth related to various sensing methods.

4. Advantages and disadvantages of the various techniques for estimating areal soil moisture and snow cover for various space and time scales.

5. Suitability of gamma radiation measurements as "ground truth" in evaluating and calibrating other remote sensing methods.

REQUIREMENTS FOR SUPPORT OF SNOW COVER MEASUREMENTS

General

Most researches have found it necessary to adjust for soil moisture in using an aerial gamma radiation survey to measure the water equivalent of the snow cover [2, 4]. Unless some knowledge of the soil moisture conditions for both the non-snow background and snow survey are known the potential errors are of such magnitude to render the measurements useless for operational purposes [15].

Data Requirements

The primary requirement is to have a reasonable knowledge of the change in the areal soil-moisture conditions over the survey line between the time of the background survey without snow cover and the snow cover survey. Thus, it is not necessary to know the absolute values of the average soil moisture but only of the difference in soil moisture between the two surveys. For the northern plains of the United States where operational surveys are required, it has been observed that the soil moisture is generally quite high during the late winter. Thus it is the standard practice to obtain background surveys during the spring and fall when soil moisture is near as possible to field capacity. This minimizes the correction required for the soil moisture condition normally experienced during the primary operational snow cover surveys. For the clay-loam soils found over much of the northern plains the field capacity of the soil has been established by soil scientists as 30% to 32% soil moisture.

Upward Movement of Soil Moisture

It has been observed in the northern areas of the United States that the soil moisture under the snow cover generally increases during the winter months if the snow cover or below freezing weather persists for a long period of time [16]. This increase often results in soil moisture as much as 10% to 20% greater than normal field capacity. As shown by equation 2 even a 10% increase in soil moisture for 20 cm of soil with a bulk density of 1.3 represents an addition of 2.5 cm of water.

Many investigators have reported on the upward movement of moisture in the vapor phase when the surface layer of the soil is frozen due to the difference in vapor pressure which exists over ice and water particles [17, 18]. Willis et al. have reported on the depth of frost in the northern plains area of the United States and the associated decrease in the free-water table indicating a decided upward movement of water during the winter period [19].

In addition to the frozen ground effects, two other factors have been found to be of importance; first, the field capacity of the soil is a function of temperature (decrease with increase in temperature) [20] and second, the layer of the soil near the surface can retain additional moisture above field capacity when subject to the temperature gradients that are observed under the winter snow cover [21]. Studies by Taylor and Carry [21] and by Kapotov [10] have indicated that considerably more moisture moves upward than would be indicated only by consideration of the vapor movement resulting from frozen conditions. Their conclusion is that a large part of the movement of moisture is in the liquid phase rather than as vapor. Taylor [22] also has stated that the force acting to move liquid water in the soil resulting from temperature gradients sometimes may be many times greater than that due to gravity.

Examples of Field Data

Figures 1, 2 and 3 show the variations in soil moisture conditions observed during the 1969-70, 1970-71, and 1971-72 seasons for the Luverne, Minnesota flight line. In each of these three diagrams the top set of data represents the soil moisture conditions found under the late-season snow cover. The lower two sets of data are for relatively "wet" periods earlier in the winter or following disappearance of snow in the spring. In all three of these cases, frost was observed under the snow cover in the late season.

An aerial reconnaissance snow survey program was conducted over the Lake Ontario Basin in New York state during 1972-73 in conjunction with the International Field Year for the Great Lakes (IFYGL).

Figure 5 shows the soil moisture differences, observed by the gravimetric method, in this area between very wet non-snow periods and February 28, 1973, just prior to loss of the snow cover. During the previous month of January, three unseasonal thaws occurred which had removed the entire snow cover. Frost was observed on February 28 in the ground beneath the snow cover that accumulated during February. The soil survey on June 15, 1972 was made only 12 hours after a very heavy rainstorm (64 mm) had occurred over the area. A survey on March 9, 1973 was taken shortly after the snow cover had completely melted.

The high soil moisture values on February 28, 1973 could have resulted from several processes such as earlier melt water and by vapor and/or liquid transport from lower subsurface layers. Regardless of the origin of the excess moisture, the additional moisture was retained in the upper layer of the soil by virtue of the temperature gradients that existed.

It is interesting to note that the buildup of soil moisture generally has not been observed to occur during the winter months under deeper snow cover in the western mountains of the United States. Upward movement has been observed under snow covers in Chena River Basin in Alaska [23]. In this case the processes operating to move the soil moisture upward apparently continues for a sufficiently long period with the result that the tundra under the soil becomes extremely dry. The moisture moves upwards into the snow pack and forms hoarfrost. The overall effect is to increase the water equivalent of the snow cover with an offsetting decrease in the soil moisture of unfrozen ground above the lower frozen permafrost zone.

Items for Discussion

1. The experience of the participants as to the magnitude of error in aerial gamma radiation snow surveys resulting from lack of proper correction for change in soil moisture.

2. Experience of participants in observing soil moisture changes under the snow cover.

3. What soil moisture data are required to support the snow survey program.

4. Physical processes governing the movement of soil moisture in cold regions.

USEFULNESS OF AERIAL GAMMA RADIATION SURVEYS

General

The gamma radiation technique has many advantages over other remote sensing techniques for measuring soil moisture since variations in the emission rate of gamma radiation from the ground varies only with variation in mass of the soil. It does not vary with the physical state of water, the roughness of the ground or many of the other causes for variation in other radiation measurements.

There are problems, however. Most of the problems associated with using the method to measure the snow cover also exists for measuring soil moisture. Of these the most difficult to handle adequately is that resulting from variations in radon gas in the air.

When the upper layer of the soil has an even distribution of soil moisture in the vertical, the measurement can be very accurate. Problems arise when the soil is drying and the top portion of the ground becomes dryer than below; also, when light rains wet the upper portion of the soil and the lower portion is still very dry. In these two situations one can postulate two states of the system to have exactly the same average soil moisture in the top 20 cm of soil. In this hypothetical case, the measurement with the dryer upper portion of the soil would indicate much less soil moisture than would a measurement of the soil with the upper portion wetter than the lower. However, these problems would be further magnified for a remote measuring system that reacted only to a thin surface layer of the soil.

Accuracy

Gamma radiation measuring techniques in the field of hydrology have been developed and used primarily for measurement of the water equivalent of the snow cover. Measurement of soil moisture occurs primarily when background radiation surveys are made in support of the snow surveying program. Consequently there has been limited testing of the accuracy of the gamma radiation method for measuring soil moisture.

The largest sources of error for measuring soil moisture are those resulting from the deficient counting statistics and the error induced because of variations in radon gas. It can be assumed these errors are similar to those determined for measuring snow. The accuracy of the gamma measurement technique will be a major subject for discussion during the session of this conference on snow surveying. Therefore no attempt to summarize this information will be made in this paper.

Usefulness

The use of soil moisture estimates from ground samples as "ground truth" to evaluate the accuracy of the gamma radiation technique has distinct limitations. From experience in the United States, soil moisture measurements from aerial gamma radiation surveys over a well-calibrated flight line are considered to be as reliable, or more reliable, than estimates based on ground measurements alone. Analysis of all errors involved in the ground measurement and in the aerial measurement technique can be used to develop a rational method to arrive at a best estimate of the true "areal average" for the soil moisture. Such an approach could be used only for lines where considerable data are available.

The paper by Mullins and Rowse [24] indicates the gamma monitoring technique has been found useful in the United Kingdom.

Items for discussion

Subjects for discussion pertaining to use of aerial gamma radiation method for measuring soil moisture are:

1. Experiences in measuring soil moisture.

2. Methods to improve accuracy of soil moisture measurements.

   a. Techniques used in evaluating accuracy.

   b. Recommended techniques for evaluating accuracy.

3. Sharing problems encountered in measuring soil moisture.

4. Problems in measuring during or after precipitation.

5. Operational plans for measuring soil moisture by aerial gamma radiation method.

6. Future research or problems still requiring resolution.

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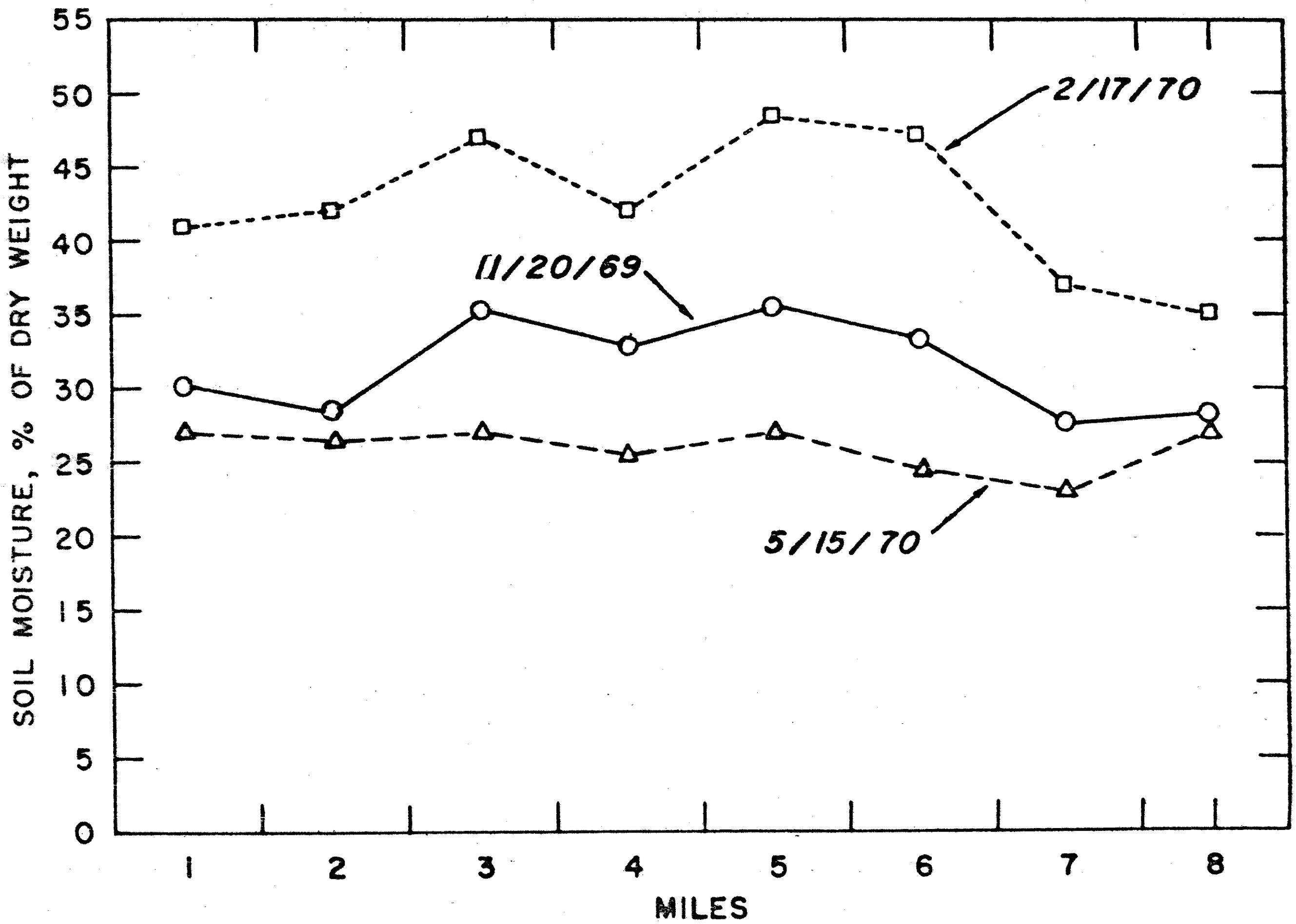

FIGURE 1. AVERAGE SOIL MOISTURE FOR RESEARCH FLIGHT LINE NEAR LUVERNE, MINNESOTA, 1969-1970 SEASON

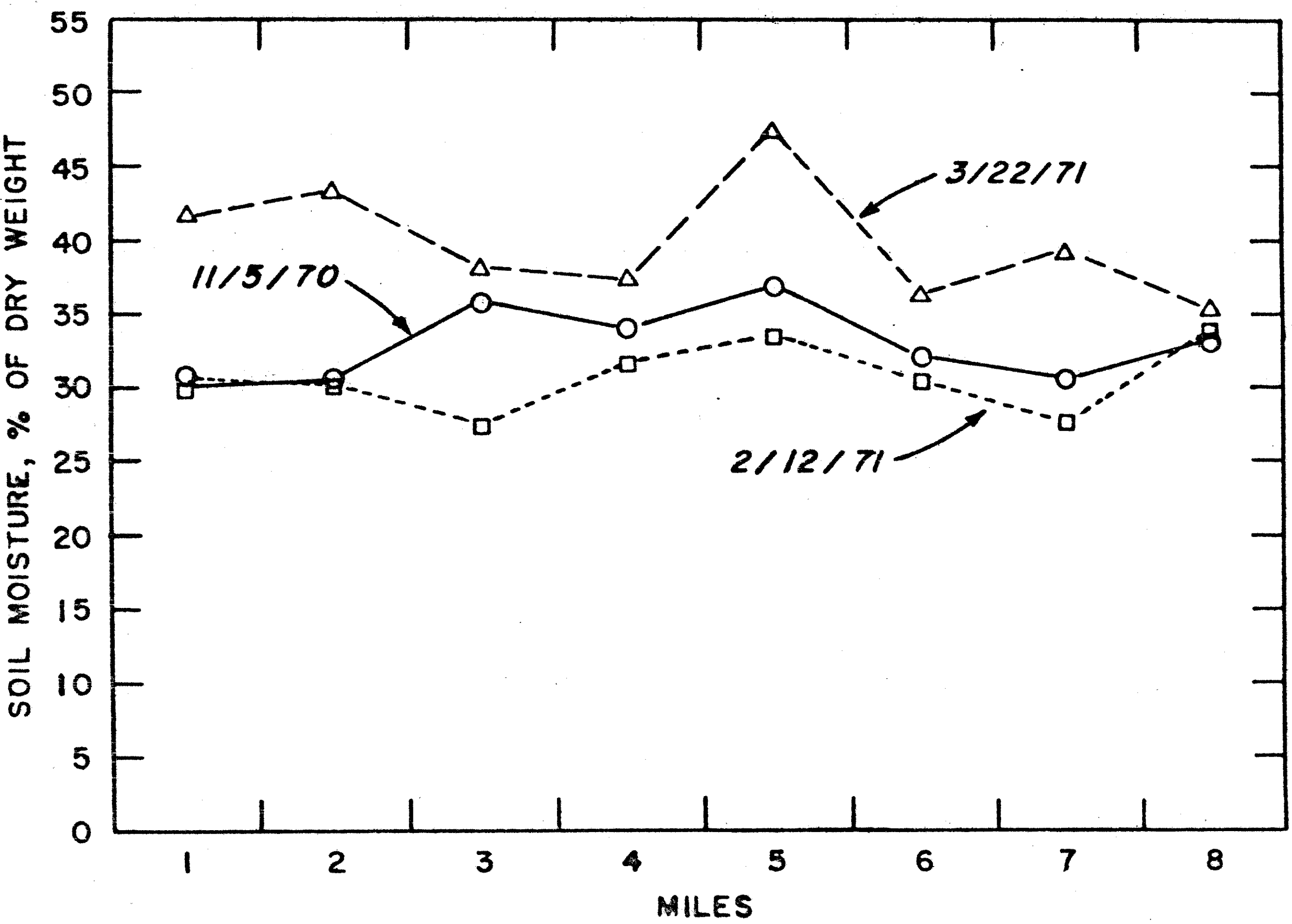

FIGURE 2. AVERAGE SOIL MOISTURE FOR RESEARCH FLIGHT LINE NEAR LUVERNE, MINNESOTA, 1970-1971 SEASON

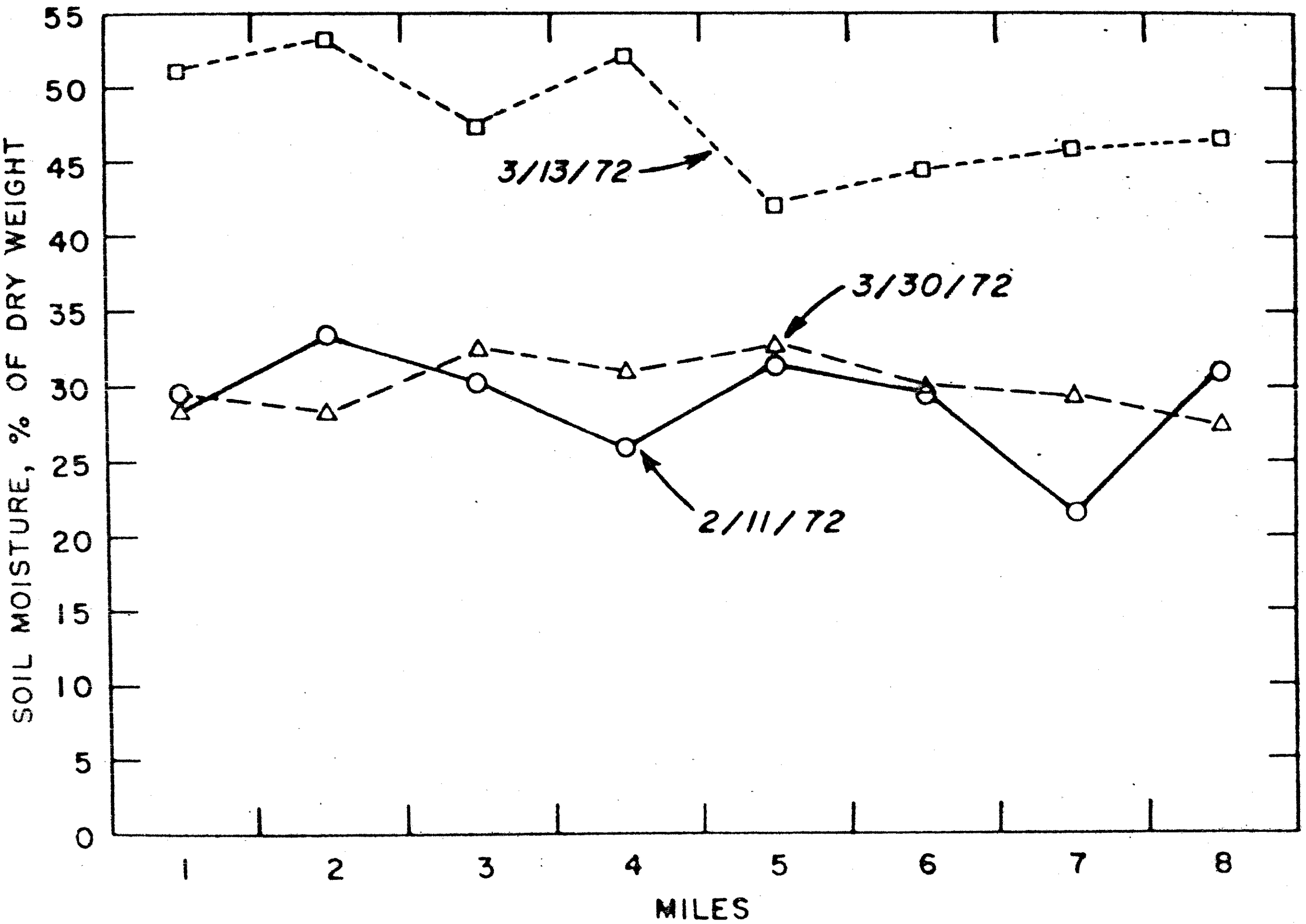

FIGURE 3. AVERAGE SOIL MOISTURE FOR RESEARCH FLIGHT LINE NEAR LUVERNE, MINNESOTA, 1971-1972 SEASON

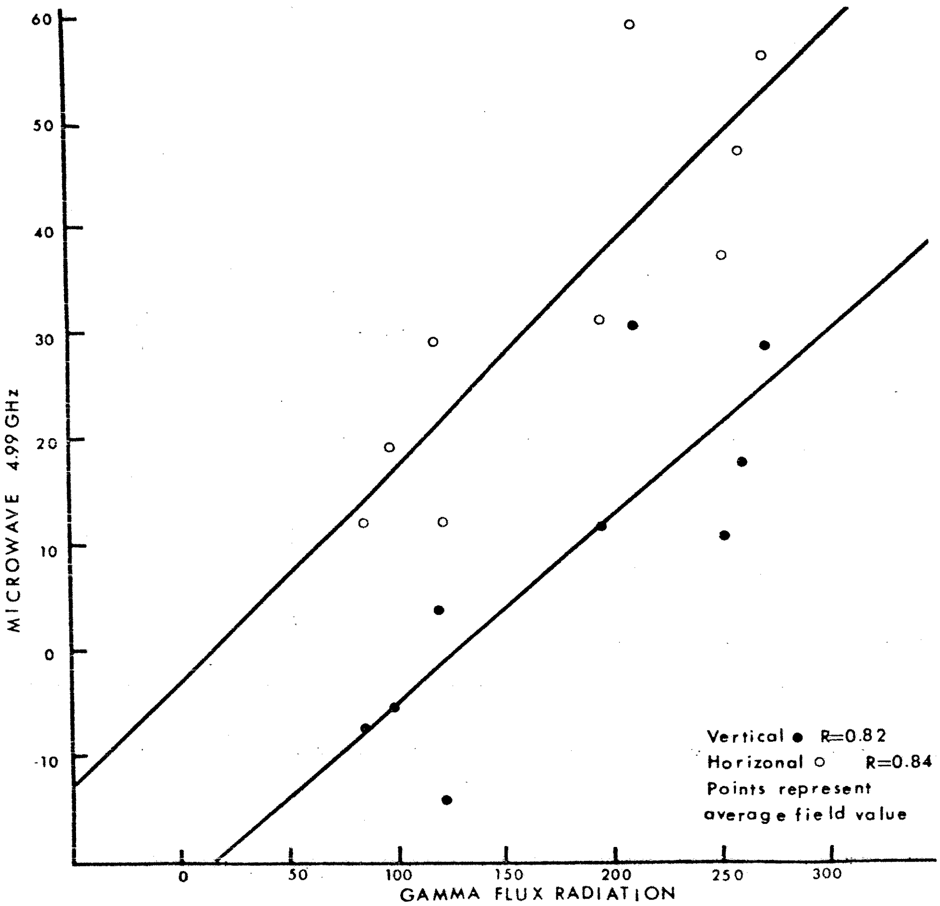

FIGURE 4. COMPARISON OF DIFFERENCES IN THE MEASURED MICROWAVE RADIATION FLOWN AT AN ALTITUDE OF 762 METERS AND THE GAMMA RADIATION FLOWN AT AN ALTITUDE OF 91 METERS BETWEEN 12 JUNE AND 19 JUNE OF 1972. VALUES ARE LIMITED TO THOSE MEASURED OVER CORN FIELDS.

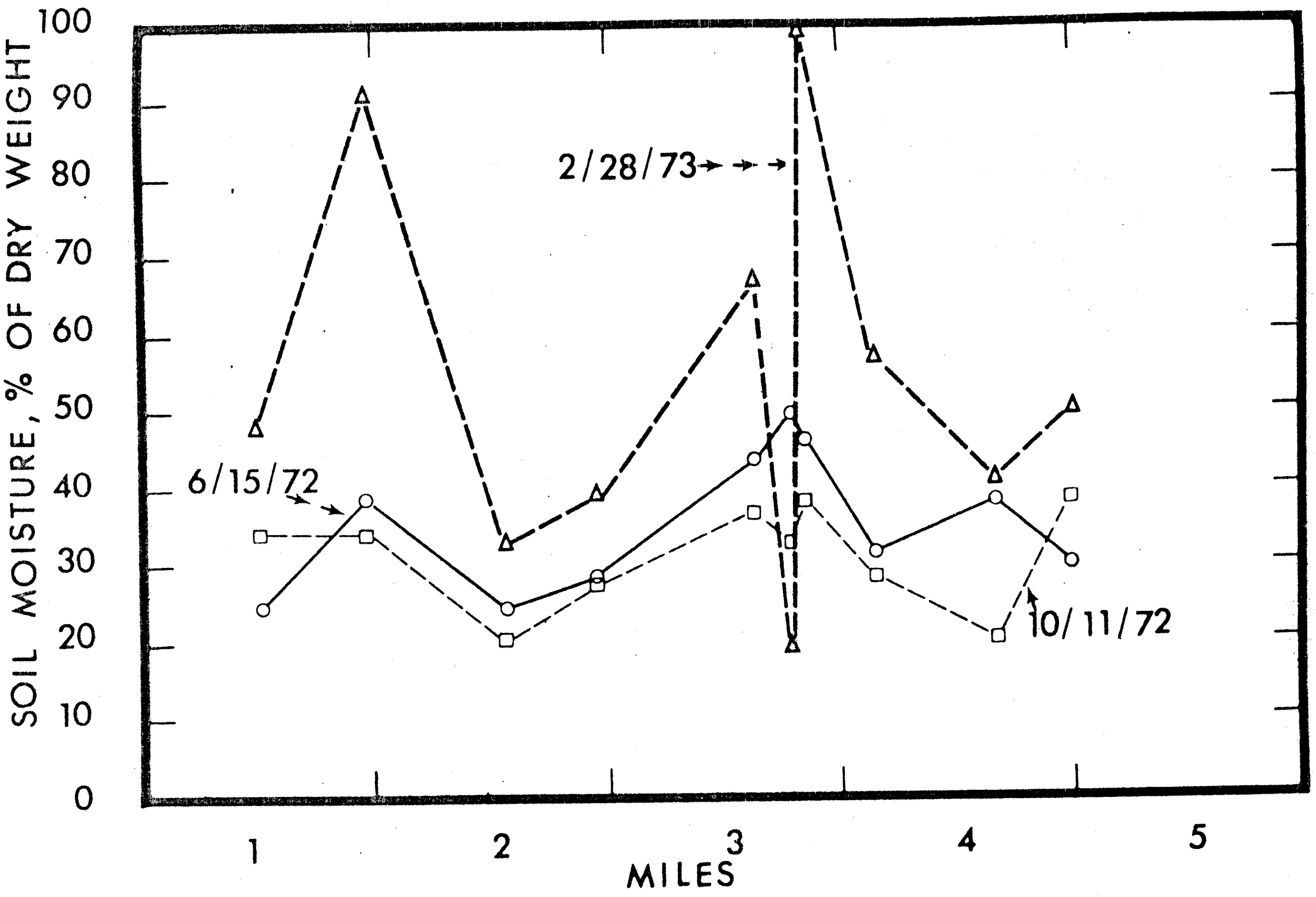

FIGURE 5. AVERAGE SOIL MOISTURE FOR SEASONAL FLIGHT LINE NEAR FLEMING-SCIPIO CENTER, NEW YORK, 1972-1973 SEASON