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## Soil Moisture

**March 1983**

**Semi-annual Report**

# A MICROWAVE SYSTEMS APPROACH TO MEASURING ROOT ZONE SOIL MOISTURE


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**B. V. Clark**

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16. Abstract

The current availability of water for agricultural purposes has become a severe problem in Texas and Oklahoma. This document describes an approach to developing a technique of monitoring soil water conditions over large areas, utilizing an orbiting passive microwave remote sensing system to estimate near surface moisture and a deterministic soil water model to predict the moisture at root zone depth based on the near surface soil moisture estimate. The problem was divided into two issues: (1) the evaluation of the ability to make a large area surface soil moisture estimate using an orbiting passive microwave system (Newton et al., 1979) and (2) the development and evaluation of the model that is capable of utilizing the near surface soil moisture estimate as an input, with soil characteristics to predict the moisture within the root zone depth. Computer microwave satellite simulation models were developed to evaluate the approach and to validate the results with actual field experimentation, and the program was used to test the ability of a coarse resolution passive microwave sensor to measure soil moisture over large areas, and to evaluate the effect of heterogenous ground covers within the resolution cell on the accuracy of the soil moisture estimate. Utilization of realistic scenes containing only 10 to 15% bare soil and significant vegetation made it to possible observe a 60°K decrease in brightness temperature from a 5% soil moisture to a 35% soil moisture at a 21 cm microwave wavelength, providing a 1.5° to 2° K per percent soil moisture sensitivity to soil moisture. It was shown that resolution does not affect the basic ability to measure soil moisture with a microwave radiometer system.

Experimental microwave and ground field data were acquired for developing and testing a root zone soil moisture prediction algorithm. The experimental measurements demonstrated that the depth of penetration at a 21 cm microwave wavelength is not greater than 5 cm. The report presents simulations of brightness temperature over bare soil conditions that can be utilized to test the lower profile prediction scheme of Jackson [1980]. In addition, field experimental measurements exist to validate this work.

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SEMI-ANNUAL REPORT

# A MICROWAVE SYSTEMS APPROACH TO MEASURING ROOT ZONE SOIL MOISTURE

By

R. W. Newton
J. F. Paris
B. V. Clark

This report describes activity carried out in support of the Soil Moisture Research activities of the Project.

TEXAS A&M UNIVERSITY
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MAY 1983

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TO MEASURING ROOT ZONE SOIL MOISTURE

## SUMMARY

The current availability of water for agricultural purposes has become a severe problem in the last few years especially in Texas and Oklahoma. Development of efficient and effective methods of regulating, monitoring and utilizing the remaining water resources is crucial to taking action to minimize the problem. This document describes an approach to developing a technique of monitoring soil water conditions over large areas for potential use to agricultural managers. This approach utilizes an orbiting passive microwave remote sensing system to estimate near surface moisture and a deterministic soil water model to predict the moisture at root zone depth based on the near surface soil moisture estimate.

This microwave systems approach to remotely measuring large area soil water information is currently in the development and evaluation stage. This issue has been addressed thus far by dividing the problem into two issues. One is the evaluation of the ability to make a large area surface soil moisture estimate using an orbiting passive microwave system (Newton _et al_., 1979). The second is the development and evaluation of the model that is capable of utilizing the near surface soil moisture estimate as an input along with soil characteristics to predict the moisture within the root zone depth. The problem has been approached by developing computer simulation models to evaluate the approach and to validate these results where possible with actual field experimentation.

A microwave satellite simulation program was developed (Newton, *et al.*, 1979) to test the ability of using a coarse resolution passive microwave sensor to measure soil moisture over large areas. The effect of heterogenous ground covers within the resolution cell on the accuracy of the soil moisture estimate was evaluated. It was determined, that utilizing realistic scenes containing only 10 to 15% bare soil and significant vegetation that it was possible to observe a 60°K decrease in brightness temperature from a 5% soil moisture to a 35% soil moisture at a 21 cm microwave wavelength. This provides a 1.5° to 2° K per percent soil moisture sensitivity to soil moisture. It was also shown that resolution which has been of primary concern to many investigators, does not affect the basic ability to measure soil moisture with a microwave radiometer system. This work did not, however, address the effect of spatial distributions of moisture caused by weather patterns, but rather only spatial distributions of brightness temperature due to ground cover.

Experimental microwave and ground field data have been acquired for developing and testing a root zone soil moisture prediction algorithm. The experimental measurements have demonstrated that the depth of penetration at a 21 cm microwave wavelength is not greater than 5 cm. Previous work by Jackson [1980] indicates that the moisture in the lower profile (below 5 cm) can be estimated with a 0.06 standard error by using surface soil moisture for the top 5 cm. This document presents simulations of brightness temperature over bare soil conditions that can be utilized to test the lower profile prediction scheme of Jackson [1980]. In addition, field experimental measurements exist to validate this work.

# INTRODUCTION

The availability of water has attracted much attention within the last two years and has the potential of becoming a severe problem in the near future. The potential magnitude of the problem in agriculture is illustrated by the rapid depletion of the Ogallala aquifer that currently supplies the Great Plains States with irrigation water. The number of irrigation rigs supplied by the Ogallala aquifer is steadily increasing, while the depletion rates of the aquifer vary from one to two feet per year to ten feet per year in areas of Texas and Oklahoma. In order to improve water and energy utilization efficiency it could well become a necessity to develop a capability to monitor water conditions over large areas and provide water availability information to agricultural managers. In order to assure its utilization, however, this information must be provided in a timely fashion and in a form that is usable for assessing water related impacts on crop and rangeland condition and production.

One technique that offers several of the ingredients needed for the implementation of such a program is microwave remote sensing. Serious programmatic efforts aimed at evaluating microwave remote sensing for measuring agriculturally related soil water information have been ongoing for over a decade. This program has developed in a rigorous scientific manner. A basic understanding of the underlying phenomenon that causes a microwave remote sensor to respond to soil water has been developed by numerous scientists through an in-depth understanding of the effect of water on the electrical properties of soil and through a theoretical understanding of the electromagnetic energy interaction with the soil volume. In addition, a number of organizations have aquired a large collection of ground-based and aircraft experimental measurements that verify the theoretical understanding.

Microwave remote sensor systems are not the ultimate tool for the measurement of soil water information in that they cannot measure root zone soil moisture directly. There are advantages and disadvantages associated with the use of microwave sensor systems. However, these advantages and disadvantages are well known. By utilizing the existing underlying theoretical and experimental background, a large area soil moisture measurement system can be devised that maximizes the advantages of microwave remote sensing while minimizing its disadvantages. This paper identifies such a technique and describes current efforts toward testing the procedure by utilizing computer simulation.

## BACKGROUND

Sensors that operate in the microwave portion of the electromagnetic spectrum can be implemented as active or passive devices. Active devices are termed radars and passive devices are radiometers. Radars transmit energy and measure the energy that is backscattered from the scene and returned to the receiving antenna. Radiometers measure only the naturally emitted microwave radiation coming from the scene. Although there are basic differences in the relationship between the two types of measurements and the ability to infer soil water information from them, either active or passive microwave sensors can be used as the devices for measuring near surface soil moisture. However, the individual techniques developed would differ considerably due to resolution, surface roughness and vegetation effects. This research effort deals with passive microwave sensors as the primary measurement tool in a technique for large area soil moisture remote sensing. There is a large amount of literature describing the results of previous research and the current status of utilizing radar systems for measuring soil moisture. However, only literature primarily dealing with passive microwave remote sensing will be presented below.

An understanding of the relationships between microwave emission and the moisture and temperature profile in the soil volume have been developed primarily through numerical solutions to the radiative transfer equations that describe the emission phenomenon. Njoku and Kong [1977], Wilheit [1978], and Burke et al. [1979] show results of computation of microwave brightness temperature for smooth soil surfaces containing nonuniform soil moisture and soil temperature profiles. Other researchers such as Choudhury et al. [1979], Tsang and Newton [1982] and Fung [1982] have produced models that describe the effect of surface roughness. These models have been utilized extensively to understand and enhance the results of experimental measurements that have been obtained with both truck-mounted radiometers and aircraft-mounted radiometers.

Field experiments using truck-mounted radiometers have been executed by Poe et al., [1971], Blinn et al., [1972], Shanda et al. [1978], Newton [1977], Newton and Rouse [1980], Wang et al. [1980], Wang et al., [1982a], and Wang et al., [1982b]. Measurements by radiometers mounted in aircraft have been reported by Schmugge et al. [1974], Burke et al. [1979], Choudhury et al. [1979], and Jackson [1982]. These measurements have demonstrated the relationship between microwave brightness temperature and soil moisture as well as the effects of surface roughness, soil texture and vegetation cover, as will be demonstrated below. In general, the longer the microwave wavelength utilized, the less severe the impact of these parameters. Longer wavelengths have better penetration capability of the atmosphere, vegetation and soil, all of which are desirable features of a soil moisture estimation technique. Examples that demonstrate the basic results of experimental research are briefly presented below.

Figures 1 and 2 demonstrate the dependence of microwave brightness temperature to soil moisture and surface roughness utilizing experimentally obtained measurements (Newton, 1977; Newton and Rouse, 1980). Figure 1 is a plot of microwave brightness temperature measured as a function of incident angle, from nadir to 50°, for two polarizational states, vertical and horizontal, at a microwave frequency of 1.4 GHz which corresponds to a wavelength of 21 cm. These measurements were made over smooth bare soil for four different soil moisture contents ranging from approximately 6% to approximately 25% soil moisture by weight. It can clearly be seen that there is a large change in measured brightness temperature as the soil moisture changes. Figure 2 is also a plot of measured microwave brightness temperature as a function of incident angle at 1.4 GHz, for both vertical and horizontal polarization for three bare fields each

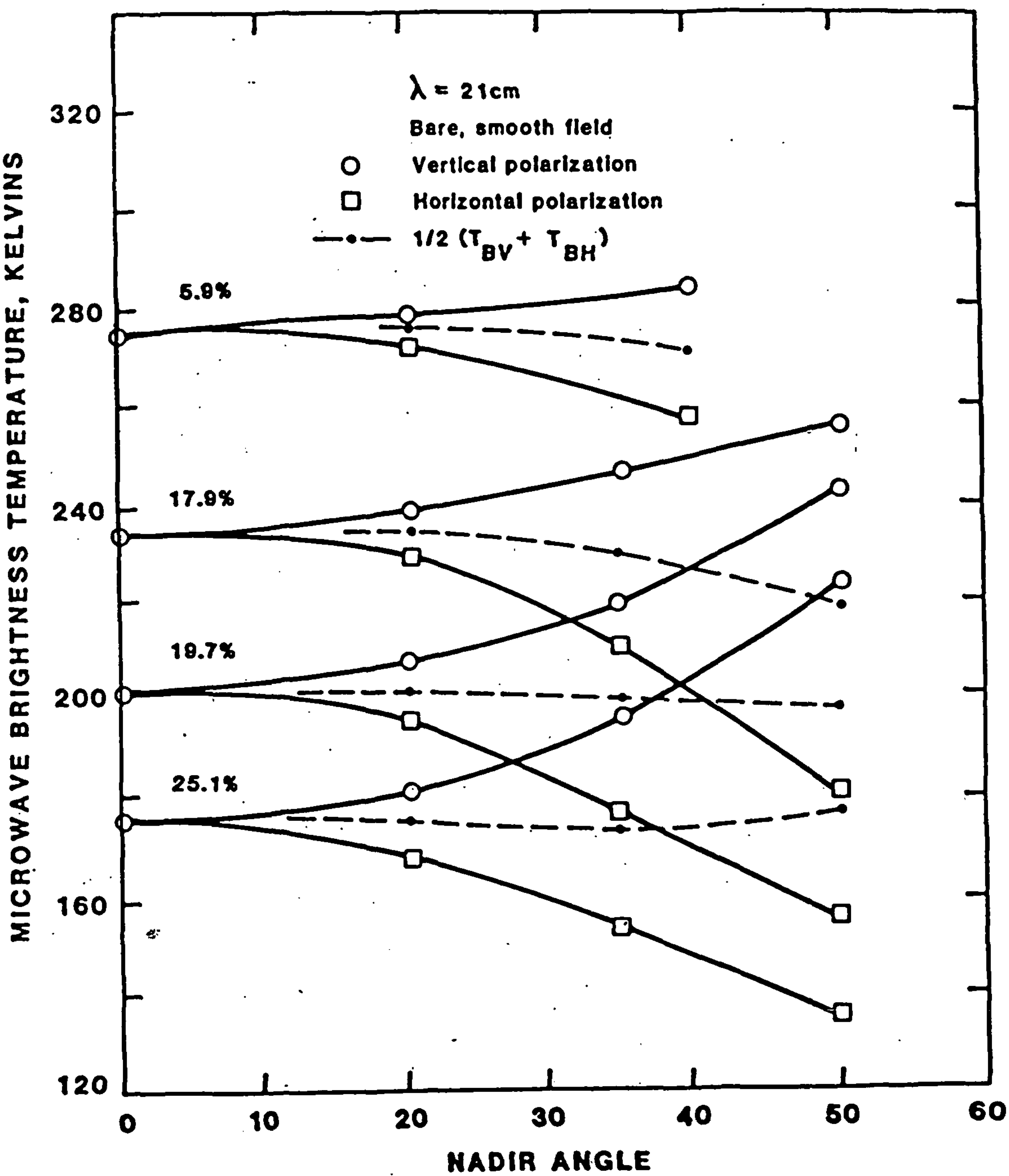


Figure 1. Microwave brightness temperatures (21 cm wavelength) as a function of incident angle and gravimetric soil moisture content. Measurements were made for a smooth bare soil. $T_{BV}$ and $T_{BH}$ are brightness temperature at vertical and horizontal polarizations, respectively.

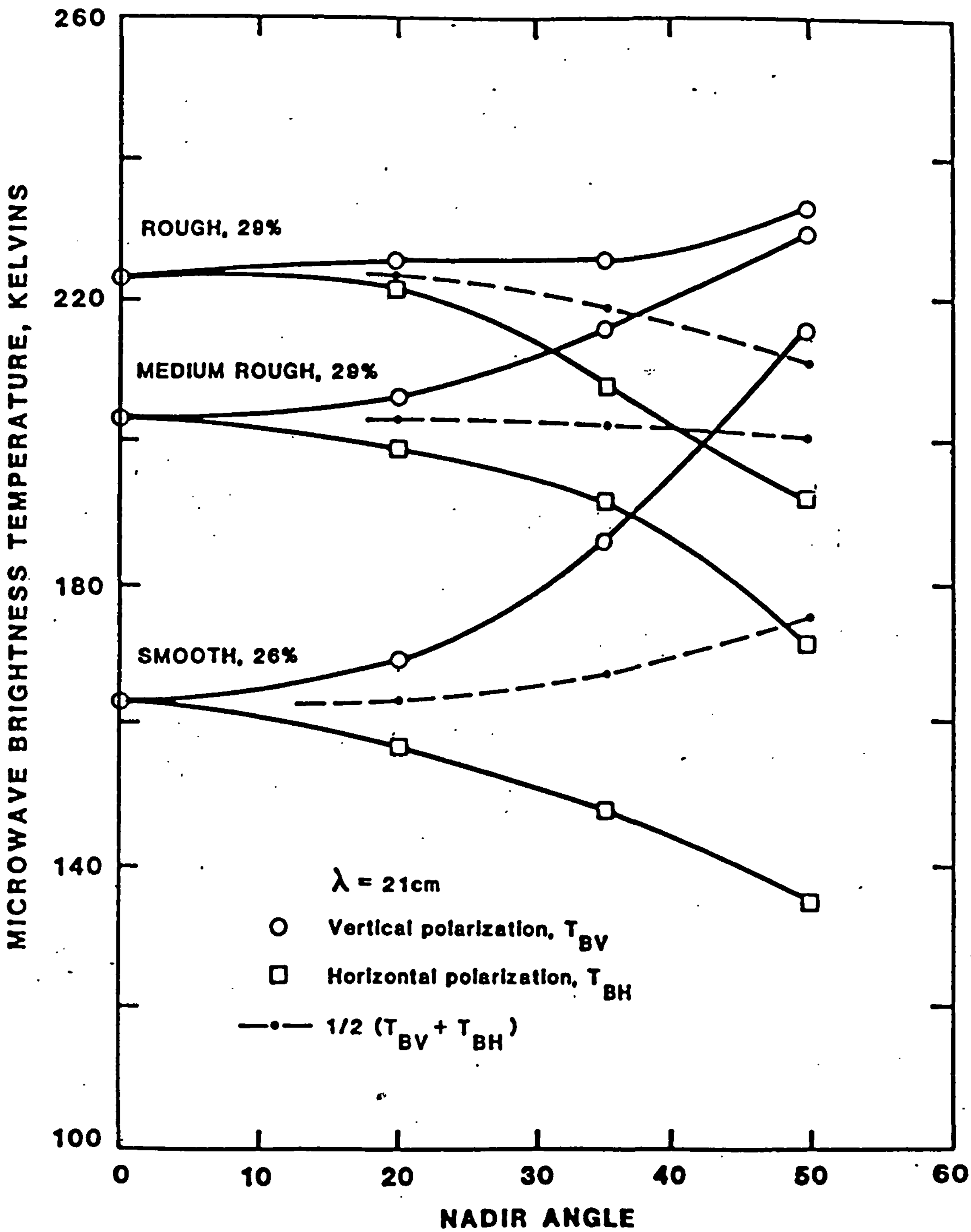


Figure 2. Microwave brightness temperatures (21 cm wavelength) as a function of incident angle for three bare fields of the same soil moisture content but different surface roughness. $T_{BV}$ and $T_{BH}$ are brightness temperatures at vertical and horizontal polarizations, respectively.

with a different surface roughness, but all at approximately the same moisture content. It can be seen that surface roughness also affects the microwave brightness temperature. The microwave brightness temperature increases as surface roughness increases.

It should also be pointed out that the microwave brightness temperature is also a function of the physical soil temperature. However, the effect of soil temperature can be minimized by normalizing the microwave brightness temperature by the physical soil temperature. Figure 3 is a plot of microwave brightness temperature normalized in this fashion as a function of 0-5 cm average volumetric soil moisture. Figure 3 contains plots of the best fit straight lines to the normalized brightness temperature measured at a 20° incident angle for horizontal polarization for the three bare fields, smooth, medium rough, and very rough. The slope of the straight line for the smooth field in Figure 3 represents a brightness temperature change of approximately 4°K/percent soil moisture. However, it can be seen in Figures 2 and 3 that surface roughness reduces the magnitude of the change in brightness temperature for the same change in soil moisture. It should be noted that the surface roughness represented in these figures ranges from a bare field that was very smooth having been rolled with a heavy roller, to a field that had been deep plowed and was extremely rough. These surface conditions span the range that could reasonably be expected within an agricultural situation. The medium rough field with a brightness temperature range of approximately 80°K from dry to wet soil is probably most representative of an average surface roughness condition that would be encountered in an actual agricultural environment.

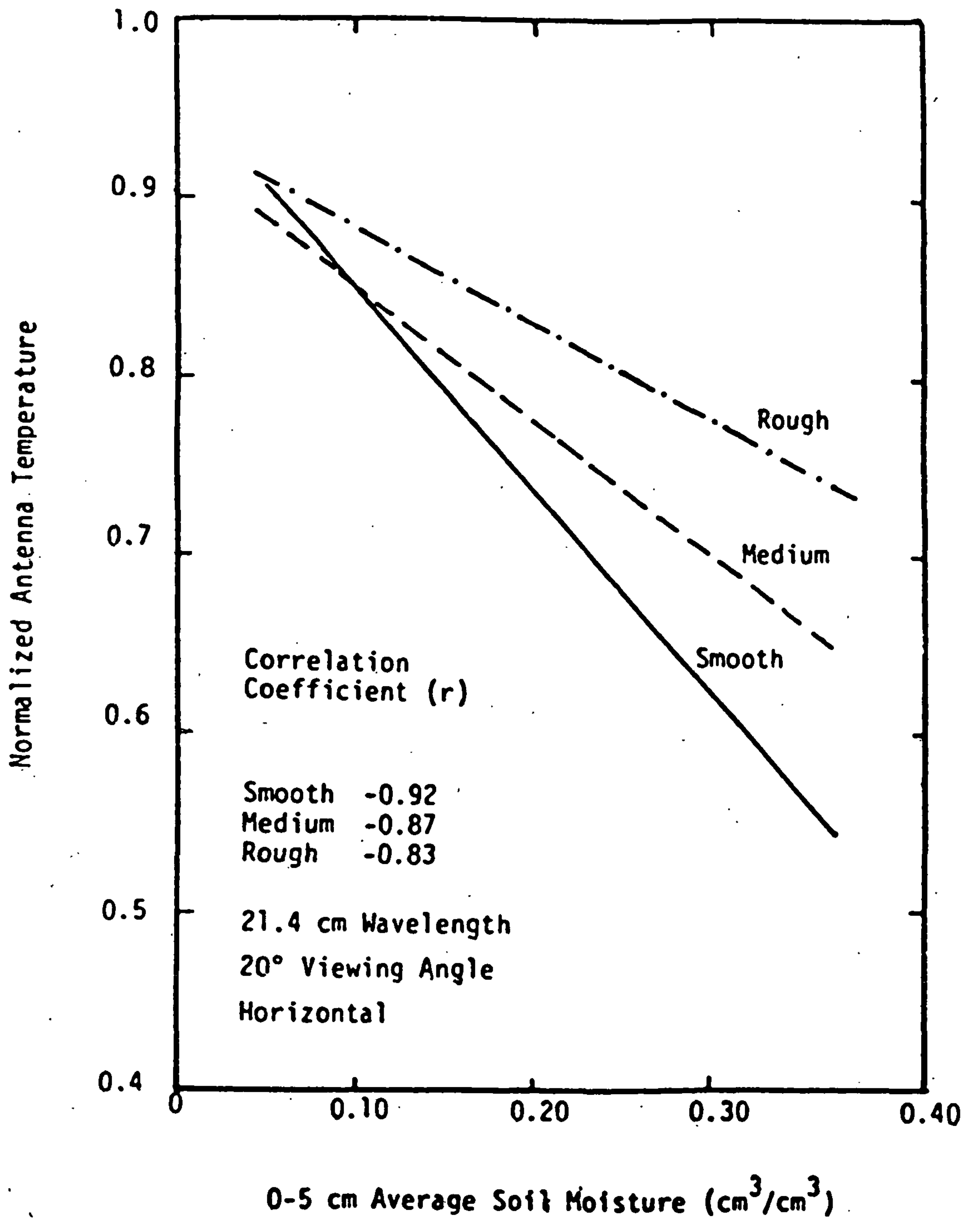


Figure 3. Brightness temperatures normalized by the physical soil temperature as a function of the 0-5 cm average volumetric soil moisture content for three surface roughness.

An interesting feature of brightness temperature measurements is shown in Figures 1 and 2. Although there is a change in brightness temperature as a function of angle of viewing, the average of the vertical and horizontal brightness temperatures is essentially independent of viewing angle out to approximately 40°. This result might be useful for eliminating the angular dependence in an image produced by a radiometer constructed to scan over viewing angle as a means of producing the image.

Similar results have been obtained from aircraft experiments performed over actual agricultural terrain. Schmugge [1980] showed results from aircraft experiments over irrigated agricultural fields in Phoenix, Arizona that had a range of soil textures from sandy loam to heavy clay. This experiment illustrated the fact that the brightness temperature response to soil moisture depended on the soil texture. However, it was also shown that the texture dependence could be removed by normalizing the soil moisture within a field to the field capacity for the particular soil in the field. This result has important implications. Although field capacity is somewhat ambiguous, Newton [1977] has suggested that microwave brightness temperature is related to soil water matric potential independently of soil texture.

In devising a technique for measuring soil moisture in agricultural situations, it is obvious that vegetation must be taken into account. A vegetation layer over a soil surface will affect the brightness temperature measured by a radiometer. The effect is dependent upon the density of the vegetation within the canopy. This is illustrated in Figure 4 which summarizes the results of Basharinov and

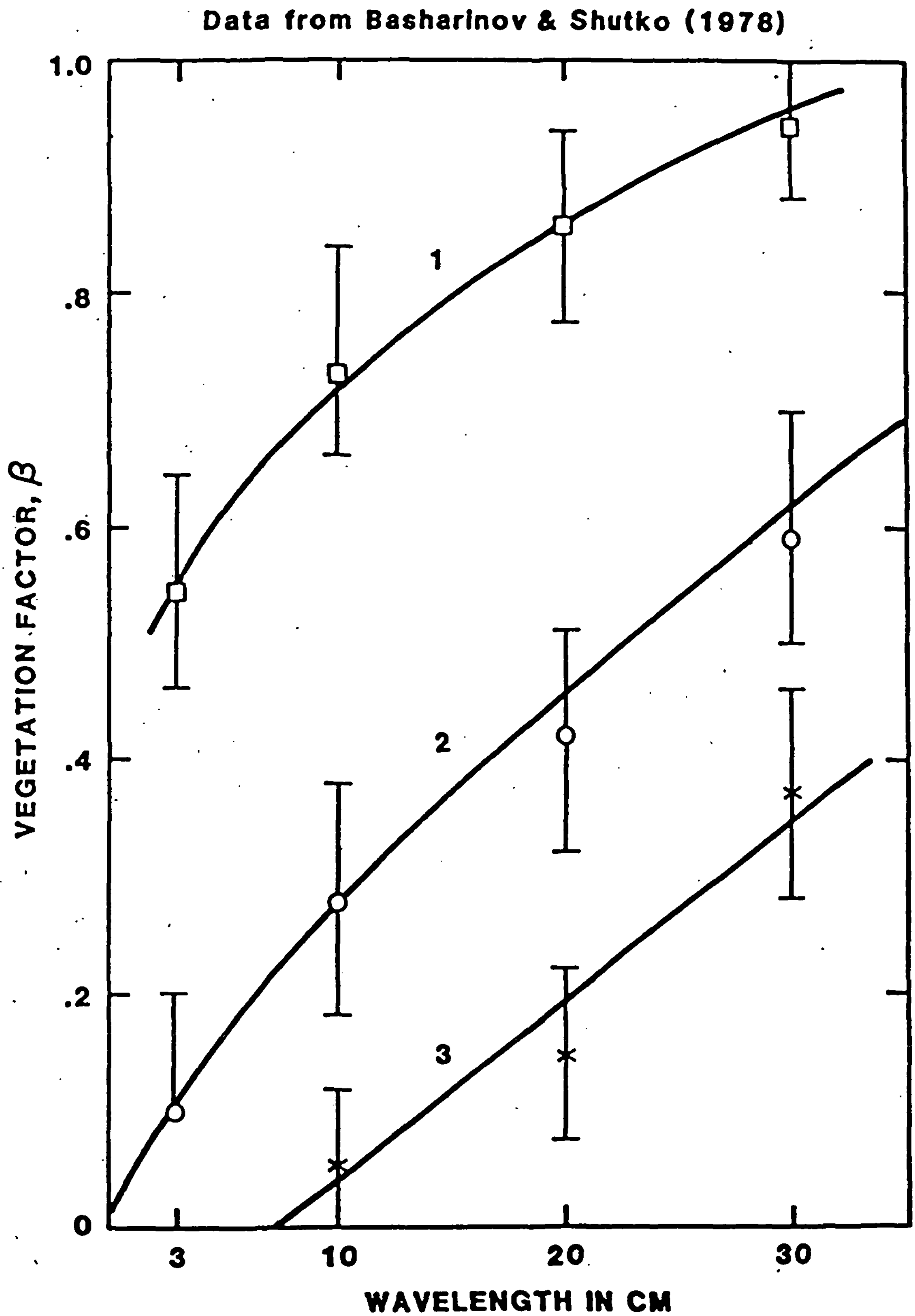


Figure 4. Dependence of the vegetation factor, defined as one minus the effective transmissivity of the vegetation, upon wavelength for three types of vegetation: 1) small grains; 2) broad leaf cultures; and 3) mixed forest (after Schmugge et al., 1980).

Shutko [1978] and Kirdiashev _et al_. [1979]. These observations were made in the USSR with a wavelength range of 3 to 30 centimeters for a variety of crops. The figure shows a vegetation factor which is the effective transmissivity of the vegetation. Thus, one minus the vegetation factor becomes the percent reduction in sensitivity of microwave brightness temperature to soil moisture below the vegetation canopy. Newton and Rouse [1980] and Wang _et al_. [1982a] have documented the effects of vegetation cover with similar results.

Research described above documents the potential of using microwave remote sensing systems for estimating a soil water parameter. However, strong evidence exists in both active and passive microwave measurements that indicate the measurements are only directly dependent upon the complex dielectric constant and thus soil moisture in the upper few centimeters of the soil. This is consistent with theoretical estimates by Black and Newton [1981], and Wilheit [1978]. The theoretical investigations show that the microwave emissivity of a soil will be determined by the dielectric contrast at the air soil interface. The magnitude of this contrast is determined by the soil moisture in a depth of only a few tenths of the microwave wavelength. At 21 cm this depth is on the order of 2-5 cm and is termed the reflectivity sampling depth. Although emissivity is primarily controlled by the shallow depth, the total microwave energy generated within the soil volume is also influenced by the thermal soil temperature extending to depths on the order of a wavelength. This depth is termed the thermal sampling depth. These results have been verified experimentally by Newton _et al_. [1982].

In summary, it has been well established that passive microwave sensor systems have a significant response to soil moisture. However, the soil moisture that has the primary effect is contained within a shallow surface layer only a few tenths of a wavelength thick. Additionally, all agriculturally related factors such as roughness, soil texture and vegetation response have been investigated. Although the effects of the parameters are to reduce the sensitivity of the microwave response to soil moisture, these factors are not so detrimental as to preclude the potential utility of passive microwave sensor systems for measuring soil moisture information.

## PROBLEM STATEMENT

There are two basic problems to consider in addressing the development of a remote sensing system for estimating soil moisture information of use in agricultural management over large areas. One is the development and verification of an approach to measuring soil moisture information over large areas. Secondly, since remote sensing techniques, including microwave sensors, can provide only direct information on soil moisture in a very shallow surface layer, the overall system must involve a technique of utilizing this near surface measurement to predict the moisture in root zone depths. Results of a completed research project addressing the first problem are summarized in the next section, while preliminary results and the general procedure currently being followed for addressing the second are described in more detail.

## Large Area Moisture Estimate

Although the basic theoretical work to understand the interaction phenomena of microwave emission and soil water as well as the associated ground and aircraft experimental studies are natural first phase efforts, eventual application of using microwave remote sensing techniques for estimating soil water information will most likely be implemented from space platforms in order to achieve rapid large scale coverage. The ground resolution cells associated with spaceborne passive sensors operating at low microwave frequencies are quite large because of limitations on the antenna size. Acquisition of data from homogeneous, uniform areas as done with low altitude passive microwave sensors will not be possible with spaceborne systems. At low orbit altitudes, resolutions of spaceborne passive microwave systems on the order of 5 kilometers to 20 kilometers could be achieved with current technology.

Although there are currently no passive microwave sensors in space that were designed to optimize a soil moisture estimate, studies have been reported that strongly support the potential of spaceborne microwave radiometers. McFarland and Blanchard [1977] and Schmugge _et al_. [1977] report results based on the Nimbus-5 satellite electrically scanning microwave radiometer (ESMR) that operated at 1.5 cm wavelength. These studies show that the ESMR brightness temperature has a significant correlation with soil moisture over agricultural areas during preplanting and early stages of crop growth. Subsequently, Blanchard _et al_., [1981a] and Theis [1982] showed similar results. The limitation at this short microwave wavelength is primarily caused by the vegetation cover which tends to mask the emission from the soil and large scale features such as mountainous terrain.

The only long wavelength, 21 cm (1.4 GHz), passive microwave system that has flown in space was aboard Skylab as part of the earth resources experiment package (EREP). The sensor was nonscanning and it had a 115-kilometer field of view. Even with this extremely coarse resolution, encouraging implications were found by McFarland [1976] and Eagleman and Lin [1976]. McFarland [1976] showed a strong relationship between antecedent precipitation index (API) for data obtained over the Texas and Oklahoma. Blanchard et al., [1981b] has since shown a relationship between API and soil moisture. Eagleman and Lin [1976] compared brightness temperature with estimates of soil moisture over the radiometer footprints. They obtained a correlation of 0.96 with data obtained during the five different Skylab passes over Texas, Oklahoma and Kansas.

**Root Zone Moisture Prediction**

Since microwave remote sensing techniques can provide soil moisture only in the very shallow surface zone, it will be necessary to develop techniques that utilize this measurement as an input to a model that can predict the soil moisture to the root zone depth. A variety of simulation models exist that utilize soil properties as well as meteorological inputs for simulating soil moisture and soil temperature profiles (Hillel et al., 1975; van Bavel and Hillel, 1975).

Jackson [1980] describes a study in which a soil moisture profile model described by Hillel [1977] was used to test a procedure for using surface layer estimates of soil moisture to predict the average soil-column moisture to a depth of one meter. This study was predicated on the fact that such a procedure will be needed to fully utilize remote sensing techniques for large area estimates of agriculturally useful soil moisture information. Jackson's method is based on soil physics relationships and the assumption of hydraulic potential equilibrium throughout the soil profile at the time of the surface layer moisture measurement. Jackson's approach was to utilize the simulation model to generate typical detailed soil moisture profiles for bare soils under a variety of conditions, then to utilize these profiles as a standard against which to evaluate the proposed surface layer prediction model.

The surface layer prediction model consisted of utilizing the surface soil moisture to compute the matric potential of the surface layer, then compute the matric potential at the midpoint of a second layer (immediately below the surface layer) of an arbitrary thickness. Jackson utilized approximately one meter as the bottom of this second layer. The computed matric potential of the second layer was then used to solve for the average moisture content of the second layer.

To evaluate this prediction model, Jackson compared the average moisture content in the second layer as computed using the prediction model to the average moisture content of the second layer as computed from the detailed soil moisture profiles previously simulated. Jackson computed the standard error of estimate for the average moisture in the second layer as a function of potential evaporation, initial matric potential, rainfall and no rainfall, soil type and surface layer thickness. He found that the standard error of estimate was dependent upon the surface layer thickness with the standard error of estimate improving as the surface layer thickness increased. However, he found that the standard error of estimate improvement was minimal for surface layer thicknesses greater than approximately 10 cm. At the 10 cm surface layer thickness the average standard error estimate for all simulations was approximately 0.05 for the rainfall situations and approximately 0.03 for the no rainfall situations. At surface layer thicknesses of 5 cm, the standard error of estimates increased to approximately 0.04 for no rainfall situations and approximately 0.06 for rainfall situations. Jackson also found that the standard error of estimates was worse for clay soils, and that the errors were minimum if the surface soil moisture measurements were assumed to be made during pre-dawn. This latter result was expected since the basic assumption of hydraulic potential equilibrium is normally less severe during the pre-dawn time period.

Jackson's [1980] study is a first step in the eventual application of remote sensing technique to soil moisture monitoring. However, it is limited by the assumption of bare soil, hydraulic potential equilibrium at the time of surface soil moisture measurement, and neglecting the utilization of ancillary data that might be useful, such as antecedent soil moisture and meteorological data that might be generally available anywhere in the world. In addition, the additional error in the root zone soil moisture due to utilizing a microwave estimate of the near surface soil moisture must be evaluated as well as a determination of how many near surface moisture observations will be needed temporally to produce an adequate root zone moisture estimate.

## GENERAL METHOD

### Summary of Resolution Study

Before the federal government will fund an orbiting passive microwave sensor system designed to measure near surface soil moisture, certain critical questions relating to its design parameters and expected performance must be answered. Under a separate study (Newton et al., 1979), a sensor/scene simulation program was developed in order to evaluate design parameters and predict sensor performance for potential sensor configurations. The simulation program was used to specifically evaluate scene heterogeniety, resolution, microwave frequency, look angle, and surface moisture and temperature relations on the performance of a spaceborne passive microwave system designed to estimate soil water information. A computer program was implemented that could simulate a passive microwave sensor operating at 21 cm, 6 cm, and 3 cm wavelengths for arbitrary antenna and orbit parameters. In order to ensure that the simulation results are not biased by artificial scene surface covers and geometries, the model utilizes a realistic scene generated from eight full frame Landsat images of central and east Texas. Thus, the scene contains actual distributions of vegetation, water, and urban areas as well as actual geometric configurations of these surface covers. In addition, the scene can be overlaid with arbitrary soil moisture and temperature spatial variations. These studies were specifically aimed at determining the overall brightness temperature response to soil moisture as a function of sensor resolution, microwave frequency and scene makeup.

## Root Zone Moisture Prediction

The evaluation of a technique for coupling a microwave estimate of near surface soil moisture to a model that will predict root zone soil moisture was handled as a separate problem from evaluating the capability of making large scale near surface soil moisture estimates with a satellite passive microwave system. In this manner, the technique for predicting root zone soil moisture could be evaluated both theoretically and experimentally utilizing small scale controlled experiments. The basic approach was first to execute a controlled field experiment to acquire actual microwave brightness temperature and soil moisture and temperature profile measurements that could be used as a standard against which theoretical simulations could be compared. Second, simulate the soil moisture and soil temperature profiles for the experimental situation utilizing the soil moisture profile simulation model described by van Bavel et al. [1975]. Third, utilize these simulated profiles to compute the theoretical microwave brightness temperatures from the soil surfaces by using the radiative transfer model described by Burke et al., [1979]. Fourth, use the simulated brightness temperatures to estimate the near surface soil moisture using brightness temperature/soil moisture relationships identified from the experimental measurements. And finally, use the near surface soil moisture estimated from the brightness temperature computation to predict a root zone moisture in a fashion similar to Jackson [1980] and to evaluate its accuracy by comparing it to the actual ground truth and the simulations using the van Bavel et al. [1975] model. This simulation system could also used to identify and test more sophisticated techniques than the one identified by Jackson [1980].

This method has not been completely executed as of this writing. The experimental measurement program has been executed and completed, the soil moisture profile model has been developed and validated (Lascano and van Bavel, 1982), and the microwave brightness temperatures for the simulated profiles have been computed for the same conditions under which the experimental measurements were acquired. The results of these efforts and corresponding conclusions are presented below.

## RESULTS

### Satellite Simulation

To ensure that the ground scene used in the radiometer simulation was as realistic as possible, eight full frame Landsat images of central and east Texas were used to build the scene. The Landsat images were classified by the Texas Parks and Wildlife Department to various vegetation classes. These classes were then aggregated into six classifications meaningful to microwave emission phenomena. Table 1 identifies these classes. Figure 5 denotes the locations of the six Landsat images to build the scene. These particular images were chosen because they contain a wide variety of surface cover characteristics ranging from the semi-arid region of central west Texas to the humid forest region of east Texas. Even in the semi-arid region of central and west Texas there is significant vegetation contained within the scene. This is illustrated in Figures 6 through 9 showing the individual distributions and densities of selected classes within the scene as utilized within the simulation model. Figure 6 which includes the class map of the urban areas also shows two flight paths that were simulated to provide the results presented below.

Table 1. Class Definitions

| Class | Description |
|---|---|
| 2 | bare soil |
| 3 | urban |
| 4 | mixed soil and vegetation |
| 5 | fully vegetated |
| 6 | forest |

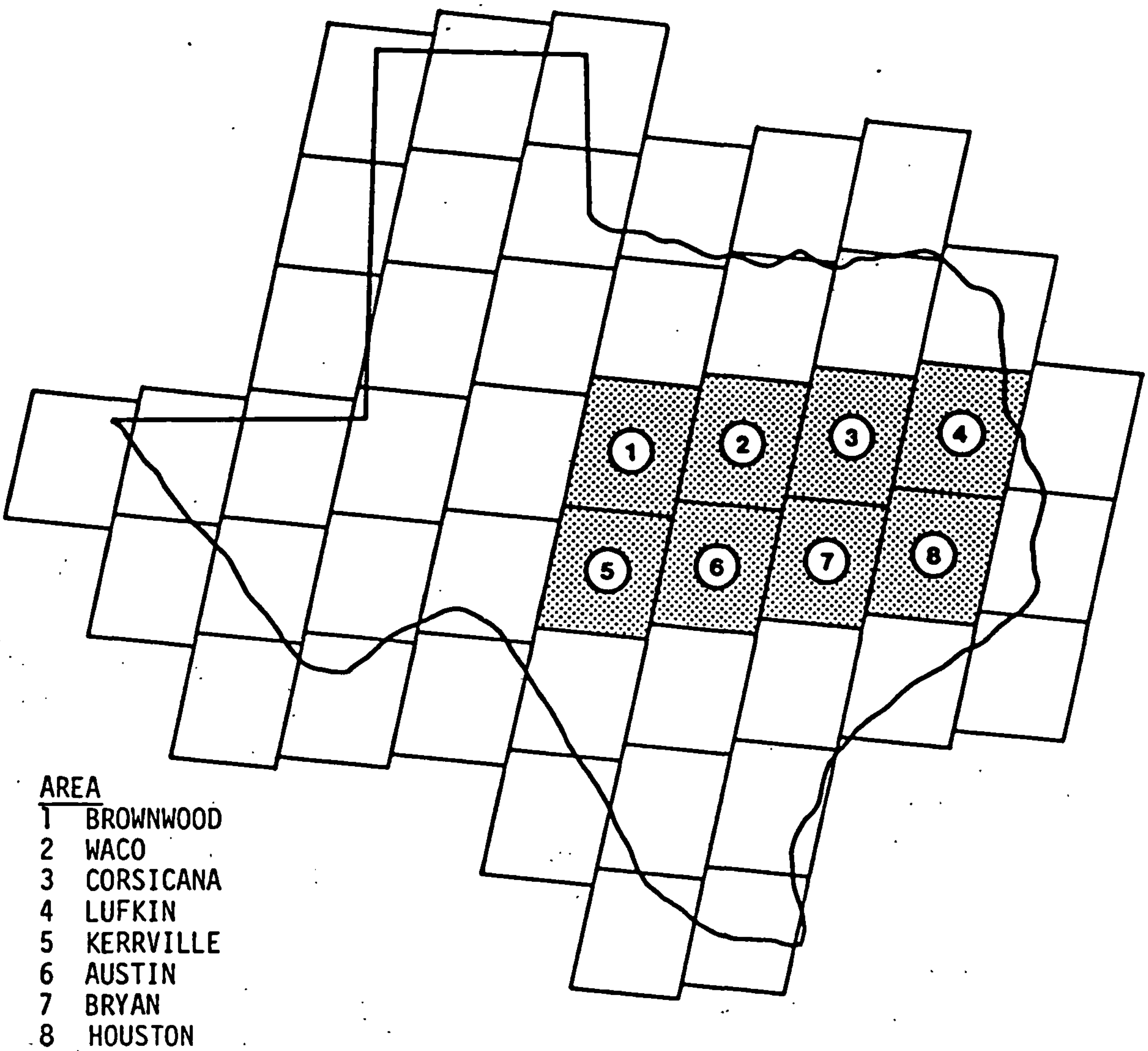


FIGURE 5. Areas covered by the eight Landsat scenes used to generate the simulated scene.

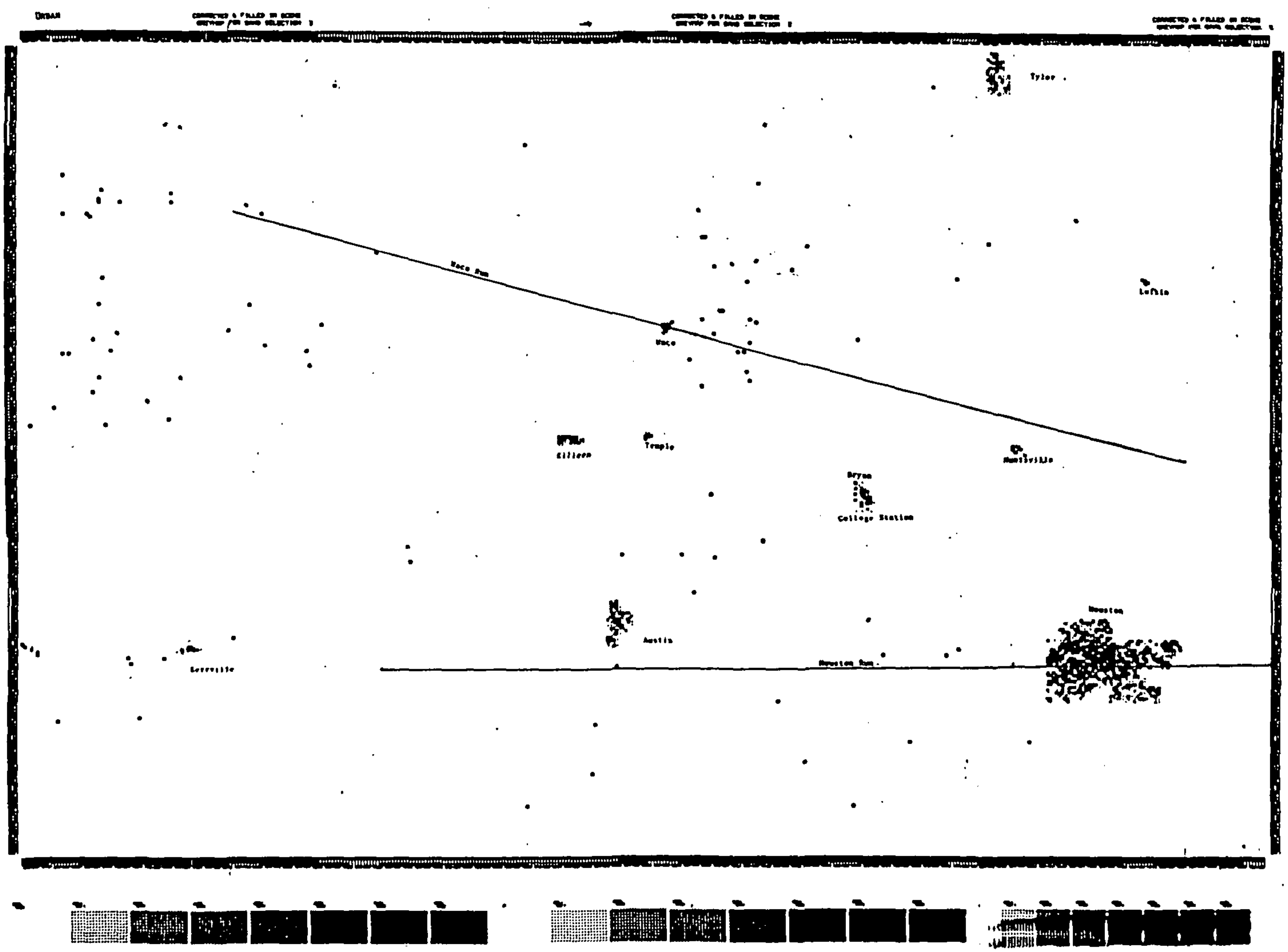


FIGURE 6. Full scene pixels classified as "urban" areas; e.g., cities and towns.

**Note: The two run lines are the ground-track of the satellite pass for the "run" indicated.


FIGURE 7. Ground scene image showing pixels classified as "bare soil".

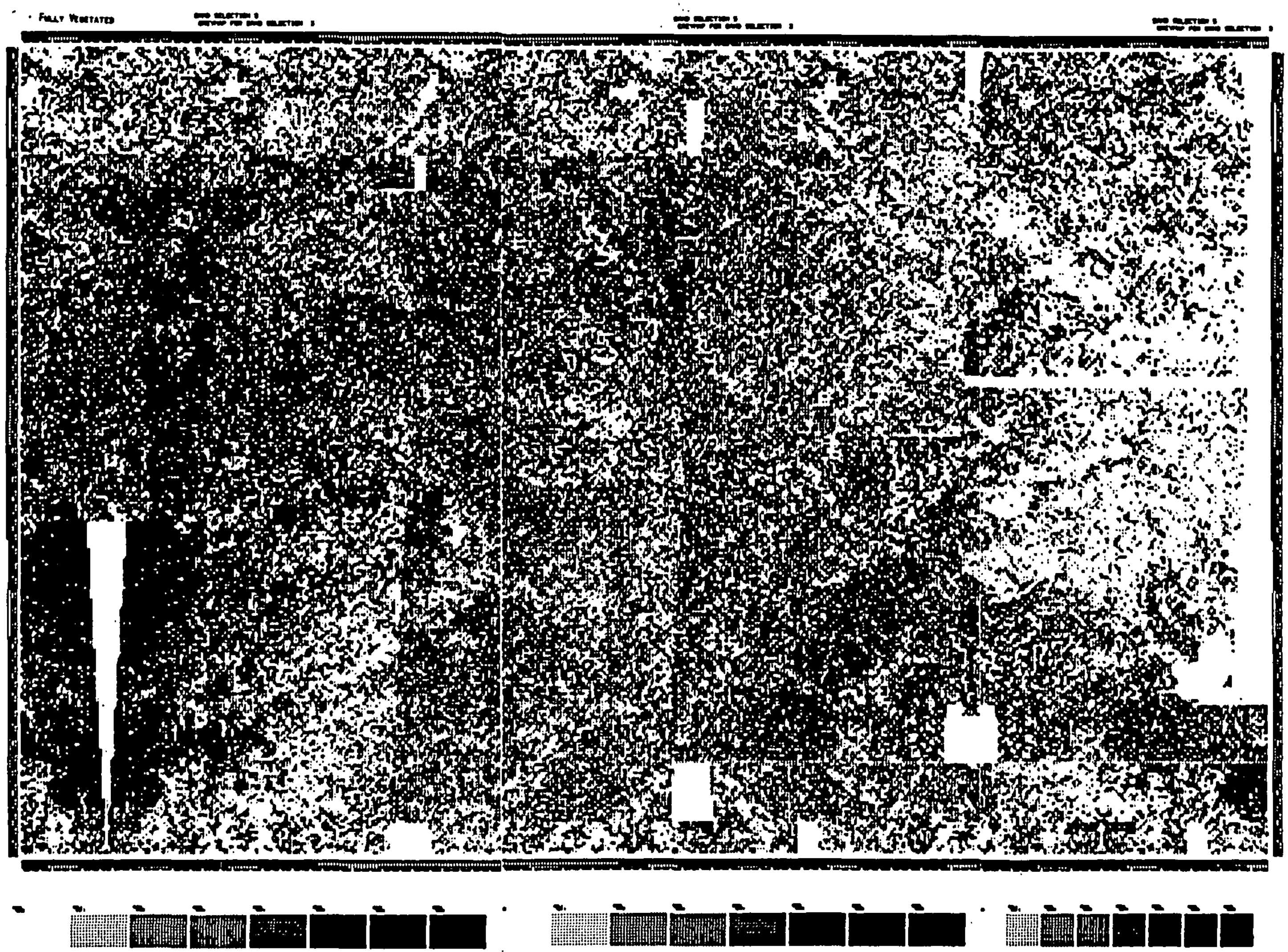


FIGURE 8. Grey-scale map of pixels classified as "fully vegetated".

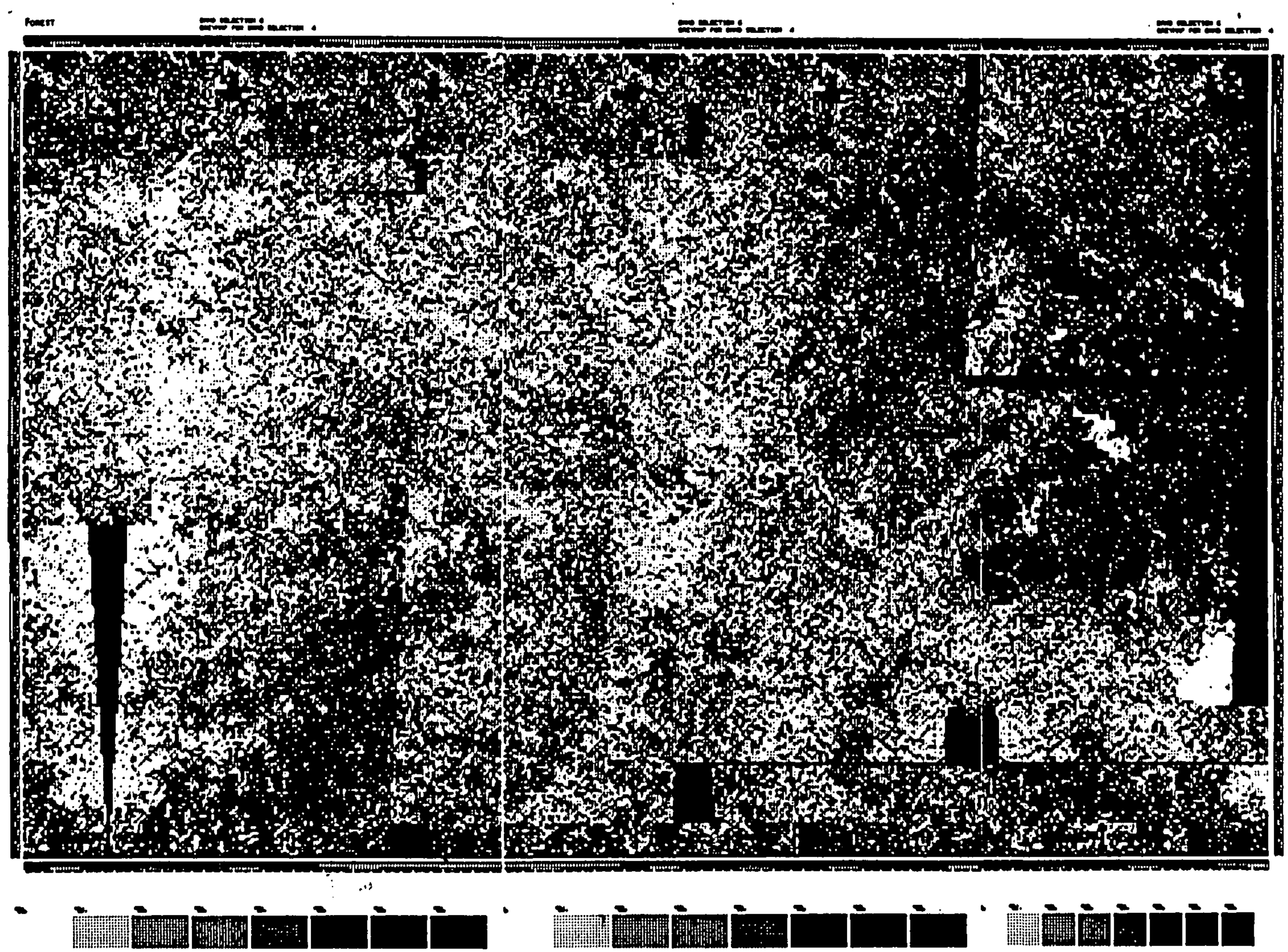

FIGURE 9. Ground scene image of pixels classified as "forested" areas.

The brightness temperature that would be measured by an orbiting microwave radiometer flying over the scene is computed based on mathematical models that predict the microwave emission of land or water surfaces for each of the six basic land cover types for each pixel within the antenna footprint. These mathematical models are based on experimental measurements with truck mounted or airborne microwave radiometers where possible. In those cases where measurements did not exist, theoretical models were used. The mathematical models was structured so that the soil temperature of bare soil areas were dependent upon the soil moisture. In addition, the temperature of vegetation or open water was computed based on a soil temperature that was input to the simulation model. Also, a roughness parameter could be entered into the model to account for the effects of surface roughness. Figure 10 illustrates the relationship between brightness temperature and soil moisture for the six surface cover classes at the 21 cm microwave wavelength, horizontal polarization, 50° viewing angle and smooth surfaces. Figure 11 illustrates the relationships for the 3 cm microwave wavelength. This simulation program is fully documented in Newton et al., [1980].

There are several scene and system parameters that can affect the ability to use a microwave radiometer for estimating soil moisture over extended scenes. This study was concerned only with the problems associated with the estimation of soil moisture assuming a spatially uniform soil moisture distribution over the scene of consideration. No consideration was given to the effects of soil moisture profile on the emission at the various microwave frequencies. This problem is

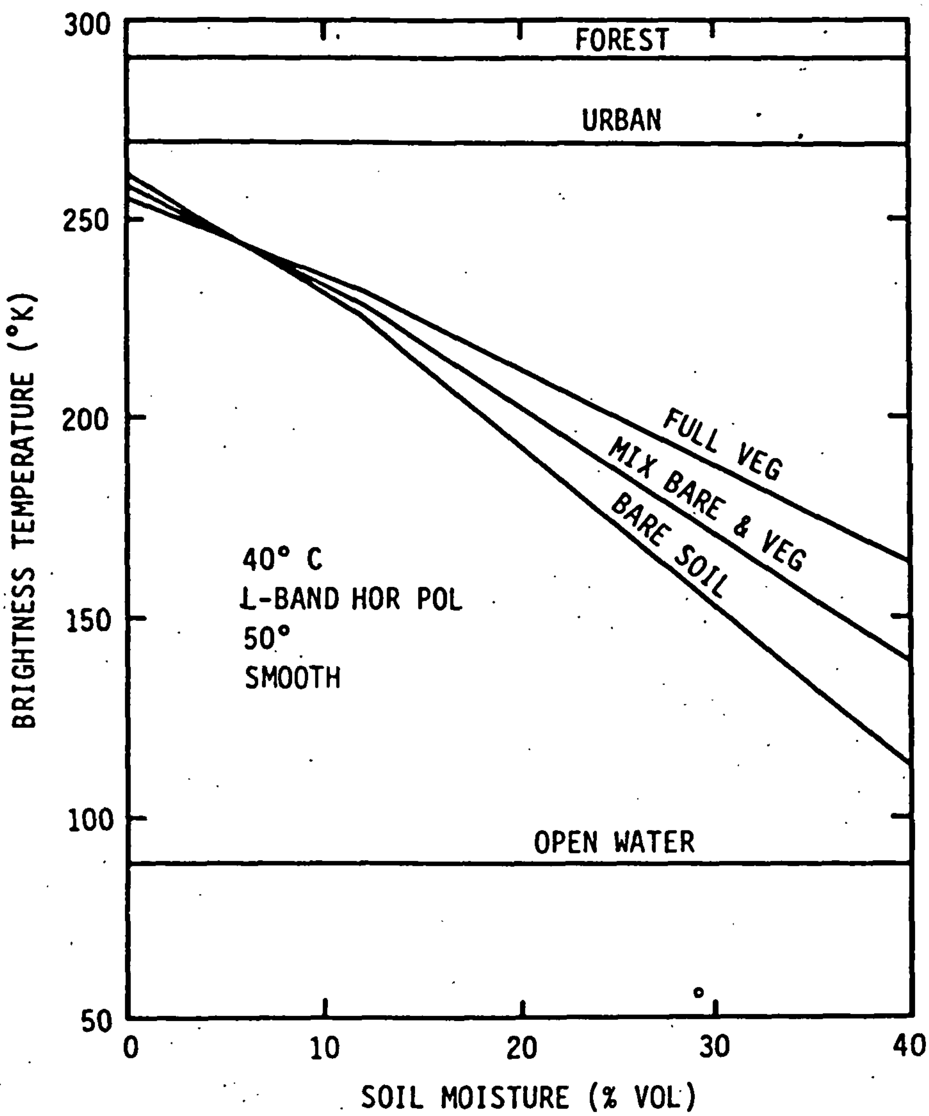


FIGURE 10. Example of the dependence of brightness temperature on soil moisture for all classes at L-band horizonal polarization.

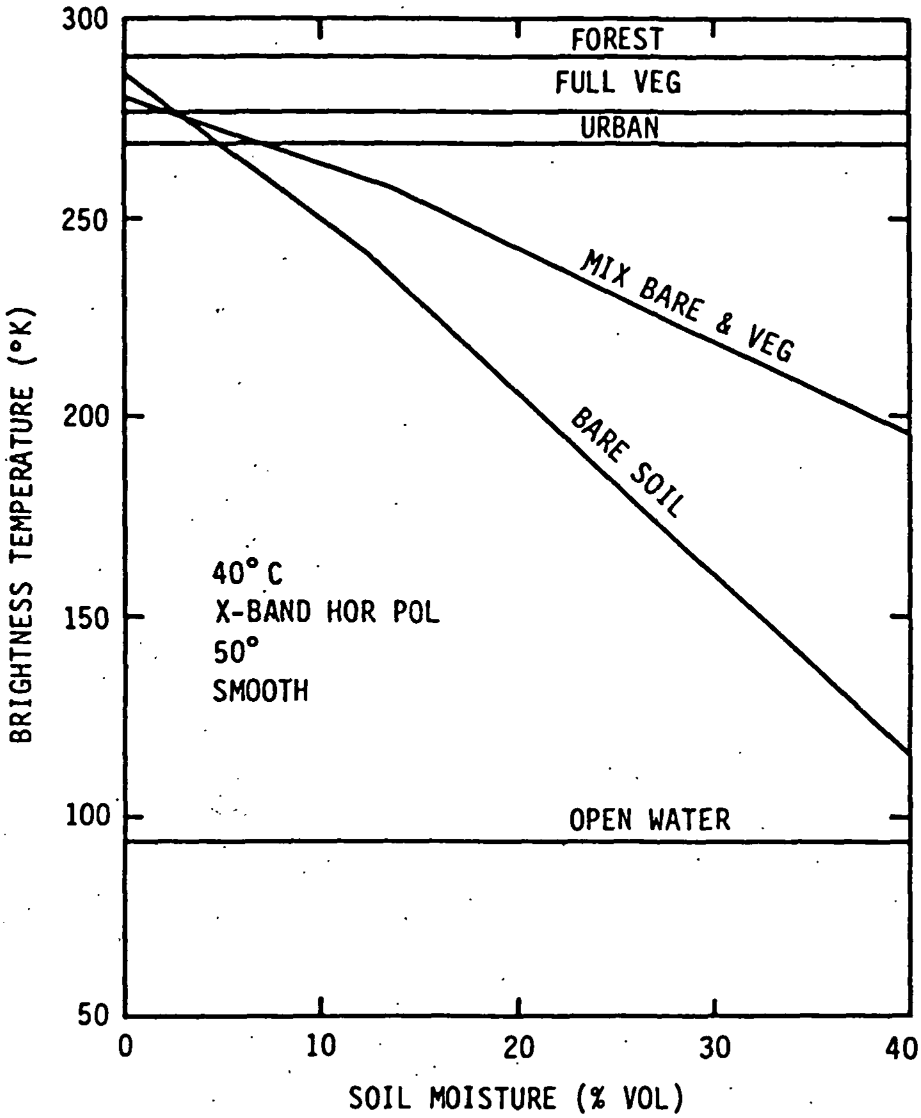


FIGURE 11. Example of the dependence of brightness temperature on soil moisture for all classes at X-band horizonal polarization.

handled in the section below. The scene and sensor parameters that were concerned in this study were heterogeneity and its relationship to sensor resolution, surface roughness, soil temperature and sensor incident angle. Specific simulation computations along the ground tracks identified in Figure 6 were made to provide data to address these factors. However, the most emphasis in this study centered around the effect of scene heterogeneity and resolution since these are the most critical parameters about which the least is currently known.

In utilizing the scene to simulate microwave radiometer measurements for analyses of the effects of scene heterogeneity, it was necessary to be careful in choosing the ground tract of the radiometer flight path. Analysis of simulated radiometer measurements to determine the ability to estimate soil moisture from space can be severely biased by the amount of vegetation contained in the radiometer resolution elements. As a result, the ground tracts were chosen based on two general criteria. The first criterion was that the ground tract pass over areas of heavy forest vegetation as well as areas of sparser vegetation, and that the ground tracts pass over features that would be recognizable from the simulated radiometer measurement. One ground tract ran from just north of Waco, Texas southeastward to Lake Livingston, Texas. The other ground tract ran east and west from approximately Kerrville, Texas eastward to Houston, Texas and out into the Trinity Bay area. Numerous radiometer measurement simulations were computed for the two ground tracts described. The simulations were run using the parameters documented in Table 2. The simulation

Table 2. Simulation Parameters used in Test Runs

| Parameter | Value |
|---|---|
| frequency | L-, C-, X-band |
| soil moisture | 0%, 35% |
| temperature | 10°C, 60°C |
| roughness | 0.3 |
| antenna footprint | 5 km, 20 km, 60 km |

model computed both vertical and horizontal brightness temperature for nadar angles from 0° to 50° in 10° increments.

In order to quantify the effect of scene makeup on the microwave radiometer brightness temperature computation, the model was constructed to compute and keep track of the percentage of each class contained in each radiometer footprint. In this manner, the response of the microwave brightness temperature can be analyzed with regard to the effect of each specific scene component. Figures 12 through 15 demonstrate the performance of the simulation model as a function of microwave frequency, antenna footprint size and soil moisture. Figures 12, 13 and 14 are plots of horizontal brightness temperature computed at 35° incidence for an antenna footprint of 5 km for 21 cm, 6 cm, and 3 cm microwave wavelengths, respectively, as a function of range along the Waco to Livingston ground tract for two values of soil moisture, 5% and 35%. These computations were made using a roughness factor of 0.3 which corresponds to a medium scale roughness that would be typical of agricultural fields. The brightness temperature computed for each microwave wavelength responds to soil moisture although the magnitude of the response decreases as the microwave wavelength decreases. It can also be seen that the effect of the increasing density of forest from a range of approximately 350 km to 600 km is obvious. The large difference between the horizontal brightness temperature at 5% soil moisture and 35% soil moisture decreases as the forest cover density increases. Beyond the range of 550 km, where the percent of forest cover is in the 90% range, the sensitivity to soil moisture is practically eliminated at all microwave wavelengths. The

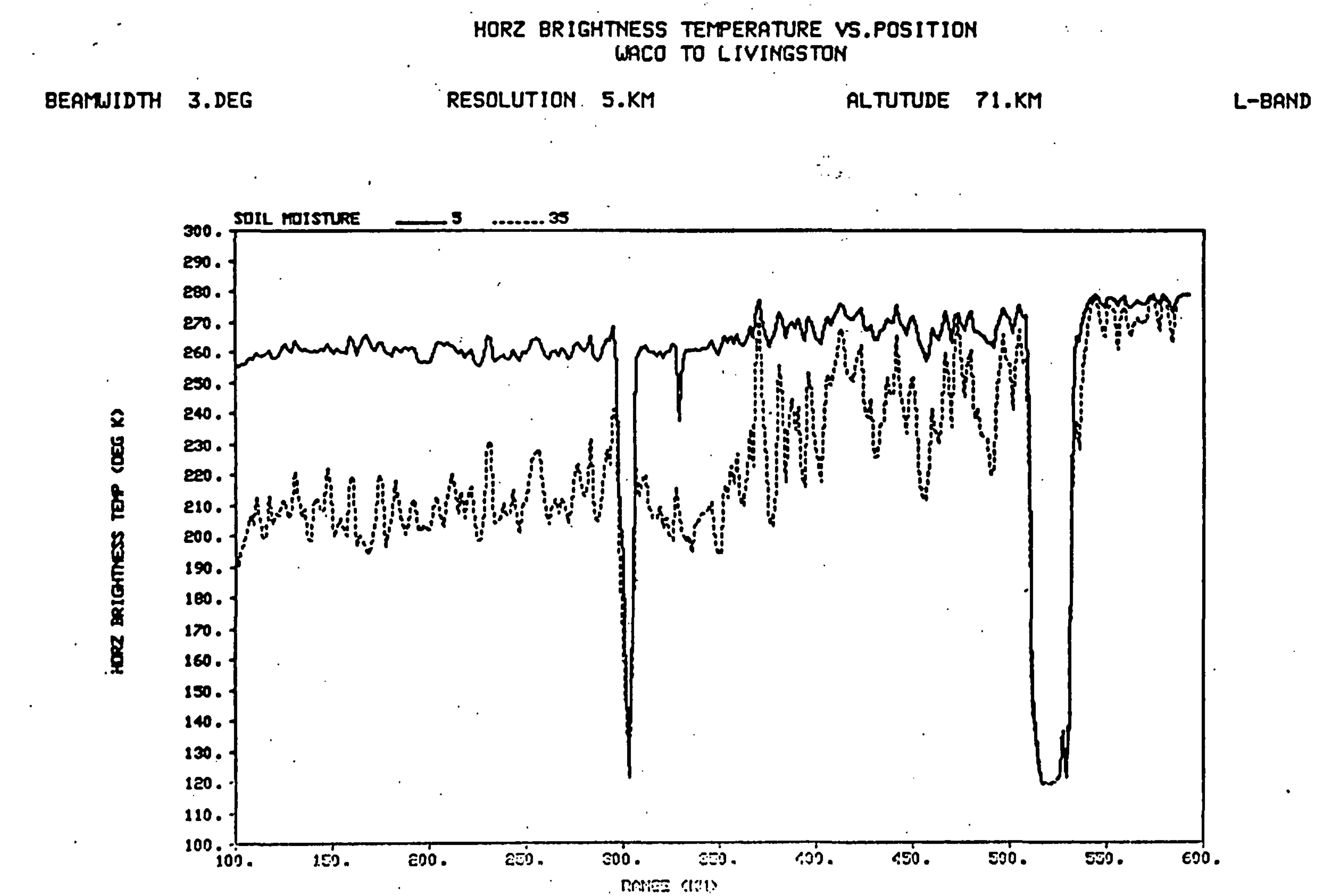


FIGURE 12. Horizontal brightness temperature computed at L-band and a 5 kilometer resolution for the Waco to Livingston ground track at two soil moistures, 5% and 35%.

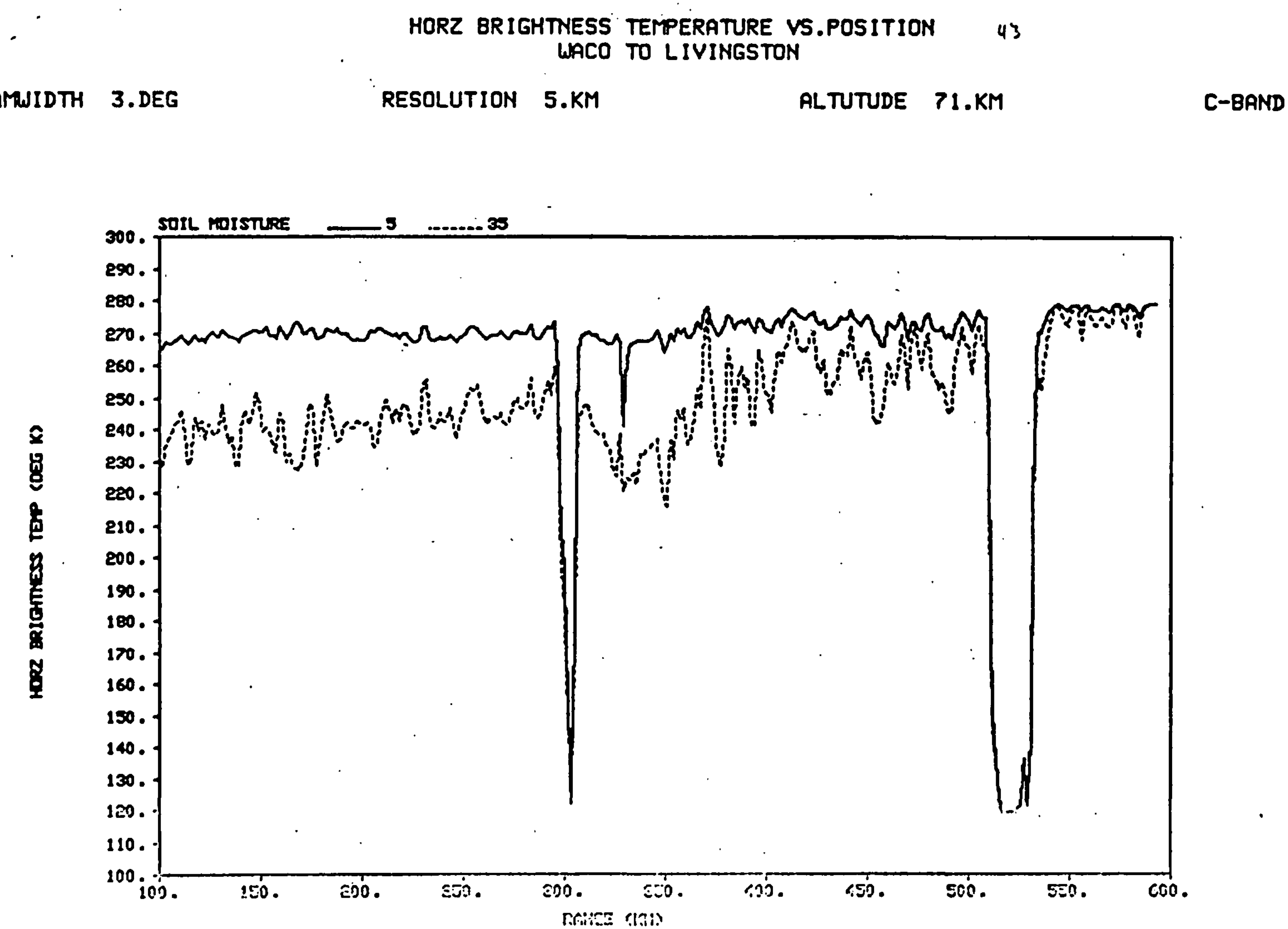


FIGURE 13. Horizontal brightness temperature computed at C-band and a 5 kilometer resolution for the Waco to Livingston ground track at two soil moistures, 5% and 35%.

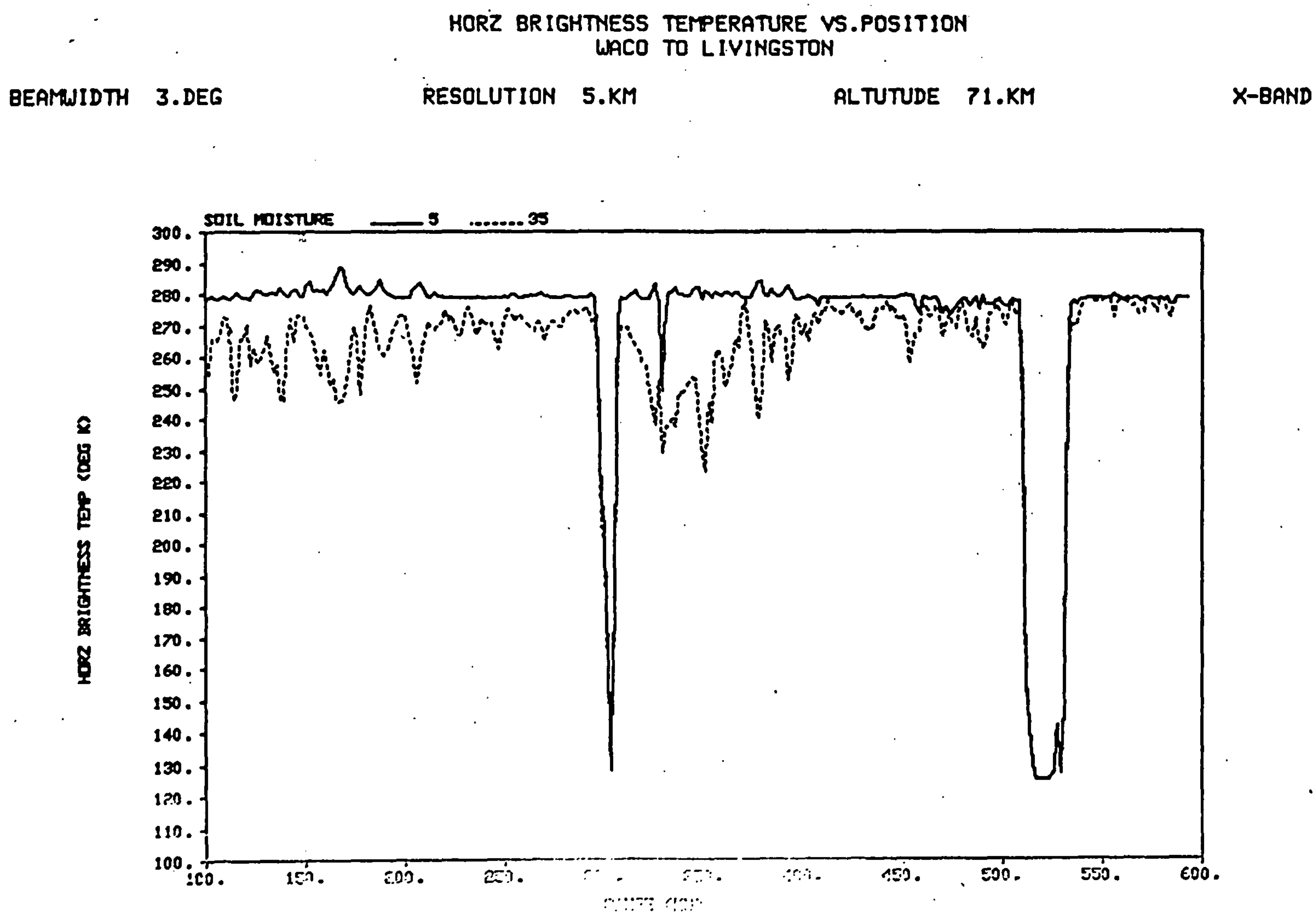


FIGURE 14. Horizontal brightness temperature computed at X-band and a 5 kilometer resolution for the Waco to Livingston ground track at two soil moistures, 5% and 35%.

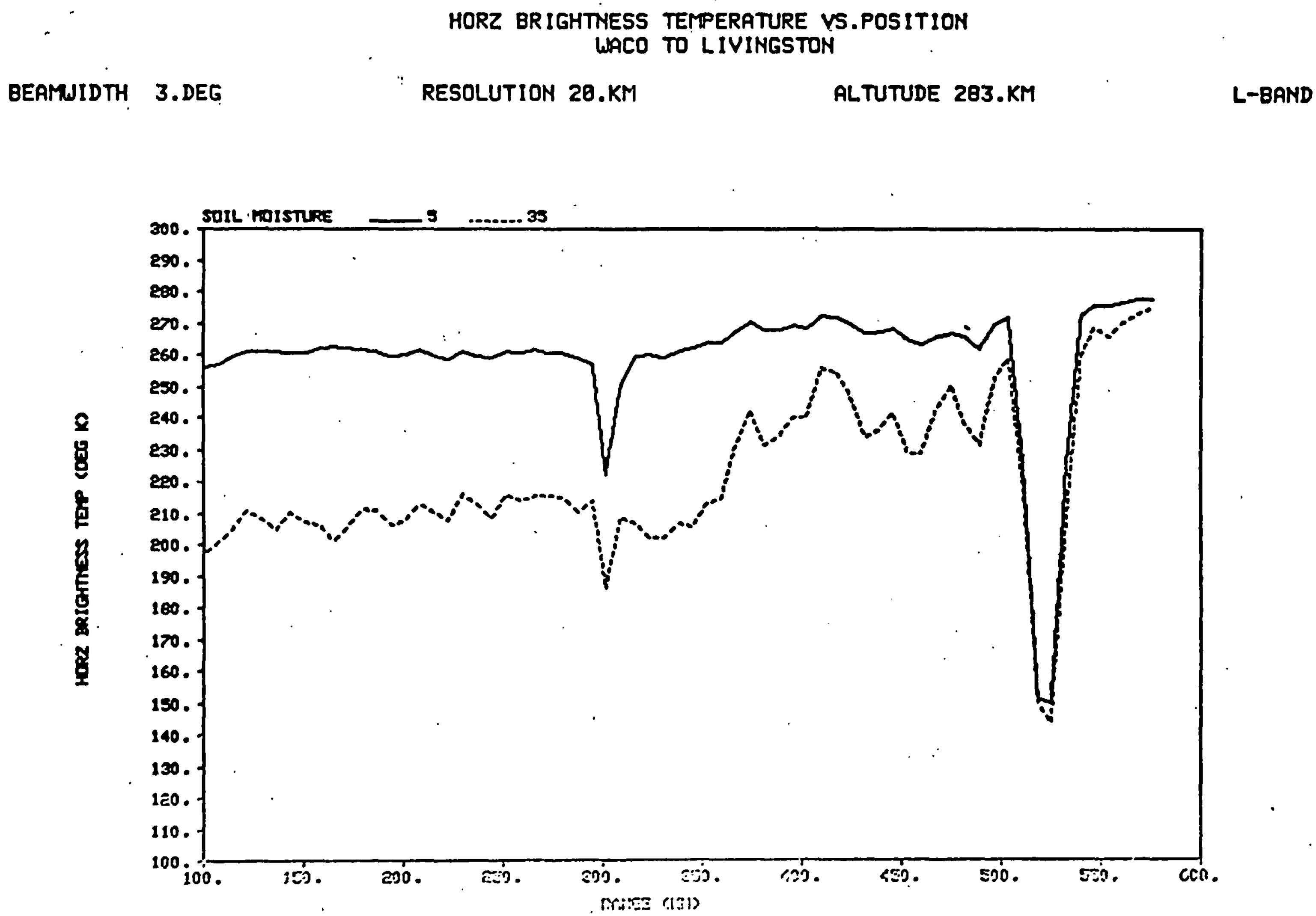


FIGURE 15. Horizontal brightness temperature computed at L-band and a 20 kilometer resolution for the Waco to Livingston ground track at two soil moistures, 5% and 35%.

effects of open water such as Lake Conroe at approximately 300 dm and Lake Livingston at approximately 525 km of range are obvious. In addition, the maximum percentage of bare soil occurs in the range of 350 km where the maximum difference between the brightness temperature at 5% moisture and 35% moisture occurs.

The effect of increasing antenna footprint size to 20 km can be seen by comparing Figures 12 and 15. The effect of the larger antenna footprint size is simply a smoothing effect of the brightness temperature computation as a function of range. Although the ability to resolve physcial features such as Lake Conroe and Lake Livingston is diminished, these two features are still observable. The same effect occurs for an antenna footprint the size of 60 km.

In order to better identify the effect of each ground cover class on the response of the brightness temperature to soil moisture, brightness temperatures computed at 5% soil moisture and 35% soil moisture are plotted as a function of percent class for each individual ground cover class. Figure 16 is an example of such a plot for the mixed bare and vegetated class. Above approximately 10% of the mixed bare and vegetation ground cover class within each antenna footprint, there is approximately a 55°K difference in the brightness temperature between the 5% soil moisture and 35% soil moisture conditions. Note that there is considerable scatter in the computation below approximately 20% of the class. This is due to the fact that the antenna footprints in that range contained much higher percentages of other class constituents on a random basis.

In order to quantify the sensitivity of the brightness temperature to soil moisture, the slope of the best-fit straight line between

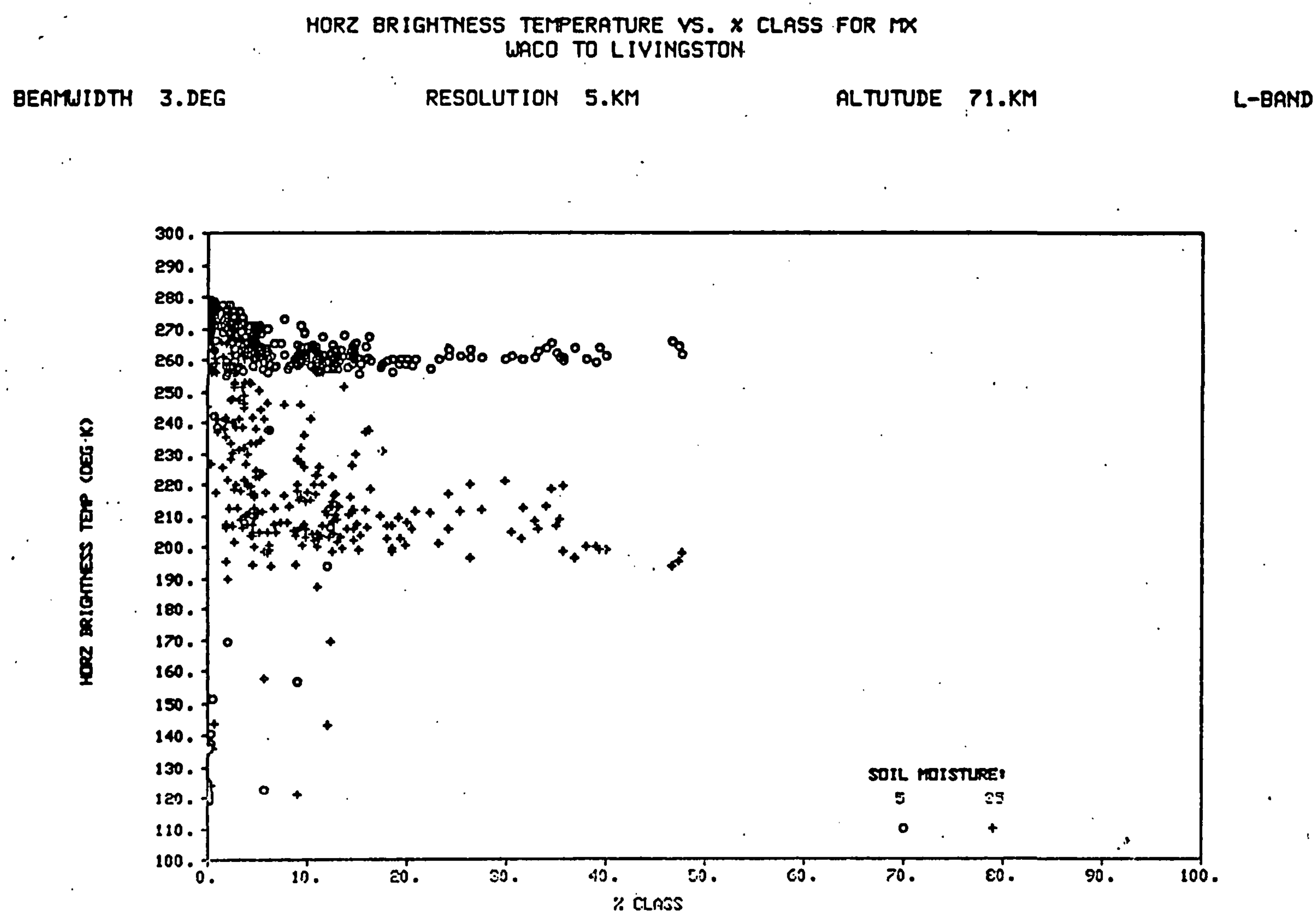


FIGURE 16. Horizontal brightness temperature computed at L-band for the Waco to Livingston ground track at a 5 kilometer resolution plotted as a function of percent class of mixed bare and vegetation at two soil moistures, 5% and 35%.

The brightness temperatures computed for 5% soil moisture and 35% soil moisture was computed for each antenna footprint. Since it is known from other investigations that the microwave brightness temperature is linearly related to soil moisture, the slope can be termed the sensitivity of the brightness temperature to soil moisture in °K per percent soil moisture. Figures 17 through 19 are plots of sensitivity computed in this manner for the 21 cm microwave wavelength and three surface cover classes, mixed bare and vegetated, fully vegetated and forest. It can be seen that the maximum sensitivity for any of these classes is on the order of 2°K/percent soil moisture. The sensitivity for the mixed bare and vegetated class approaches 2°K/percent soil moisture above the 20% of class point primarily because the percentage of bare soil within the antenna footprints that contain greater than 20% of mixed bare and vegetated is low, somewhere between 20% and 25%. Similar comments can be made concerning the fully vegetated class as shown in Figure 18. The forest class behaves as would be expected whereby the sensivitity decreases as the percent of class increases.

Although it is instructive to compare the sensitivity of brightness temperature to soil moisture as a function of the percentage of each scene constituent within the antenna footprint, the ultimate test is to compare the sensitivity of the brightness temperature to soil moisture for all ground resolution elements without regard to the constituency of the scene within each antenna footprint. Figure 23 is such a plot. This result definitely demonstrates the effect of microwave frequency on the sensitivity to soil moisture. This effect is

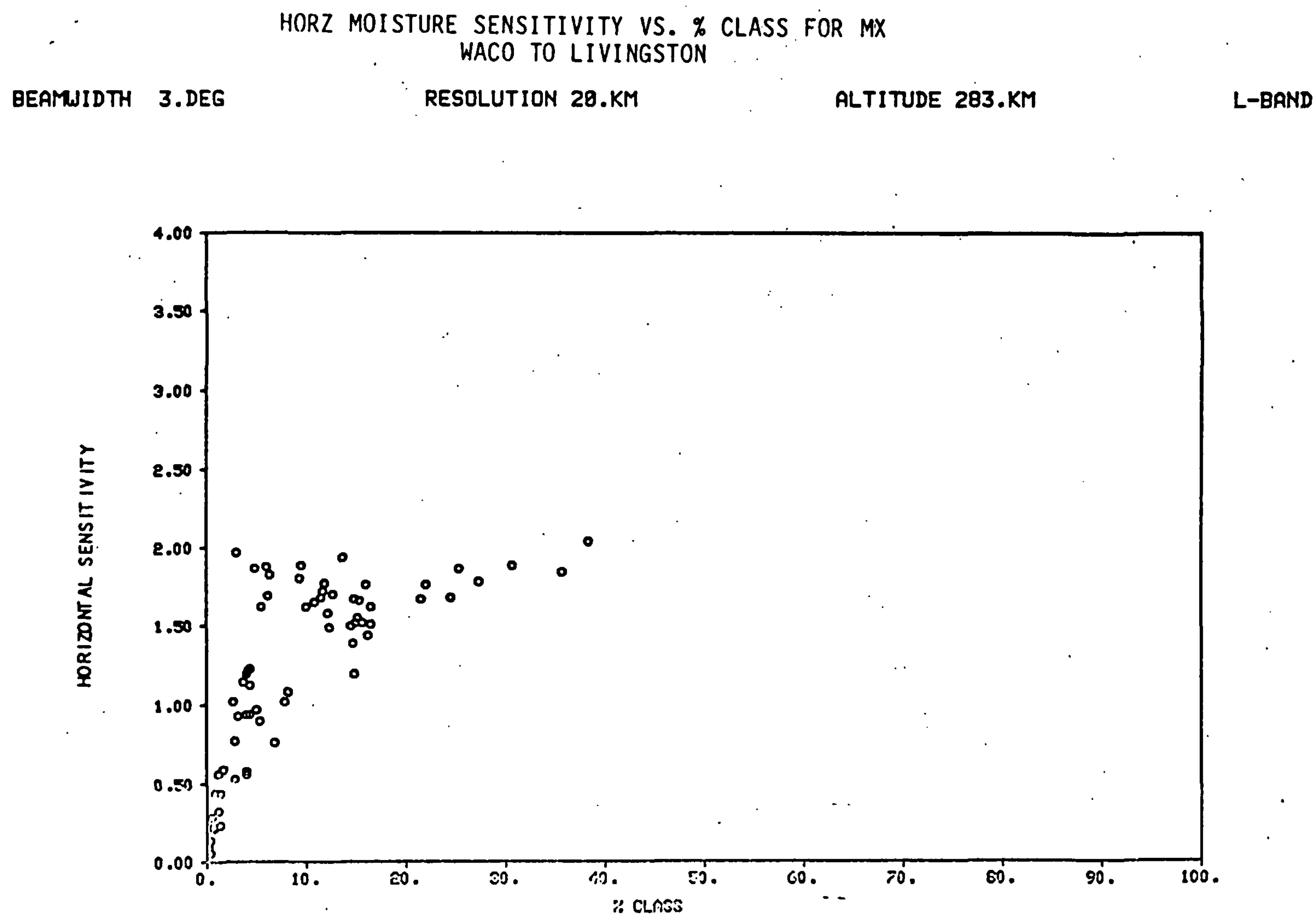


FIGURE 17. Soil moisture sensitivity of the L-band horizontally polarized brightness temperature for the Waco to Livingston ground track at a 20 kilometer resolution plotted as a function of percent mixed bare and vegetated class.

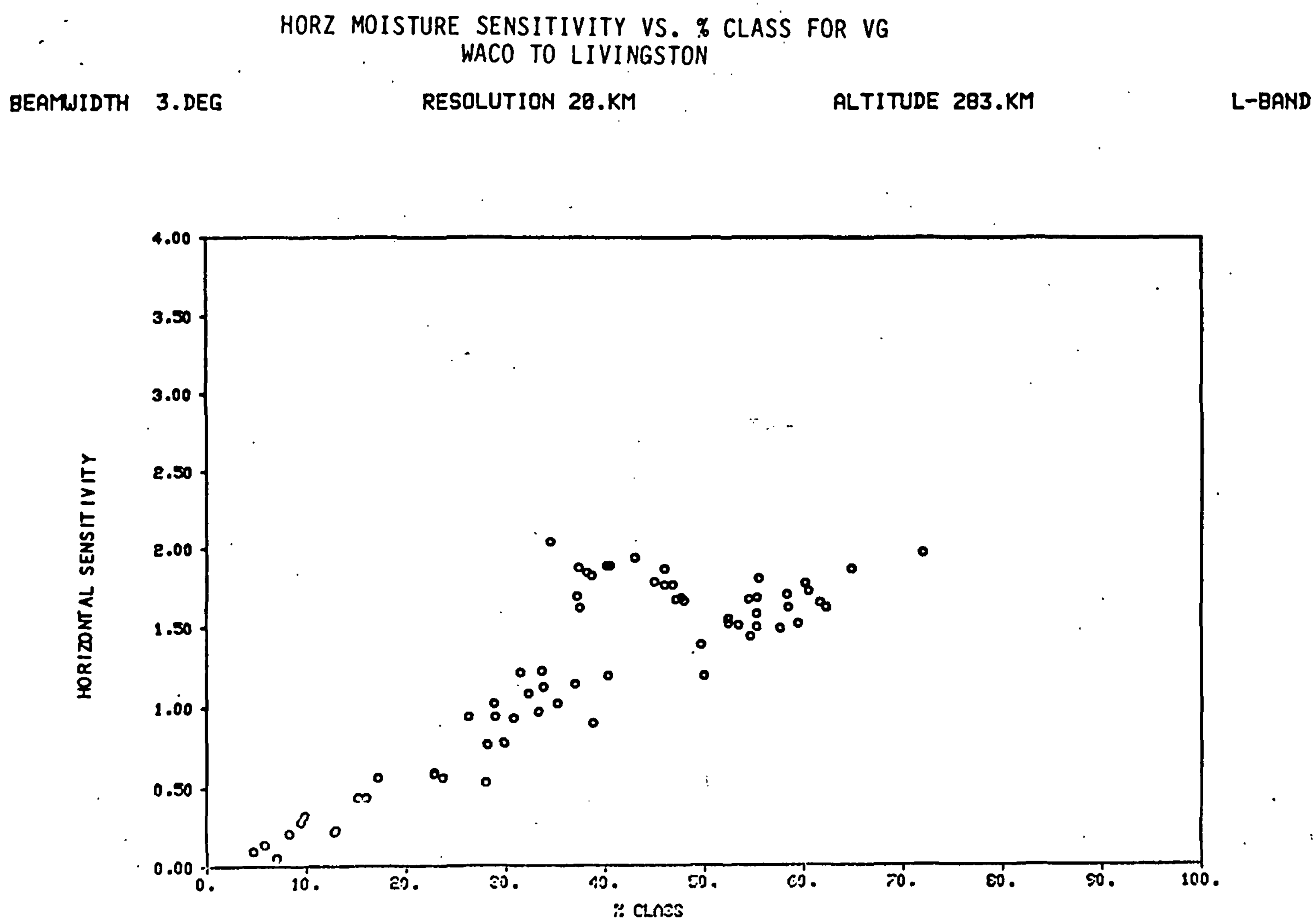


FIGURE 18. Soil moisture sensitivity of the L-band horizontally polarized brightness temperature for the Waco to Livingston ground track at a 20 kilometer resolution plotted as a function of percent fully vegetated class.

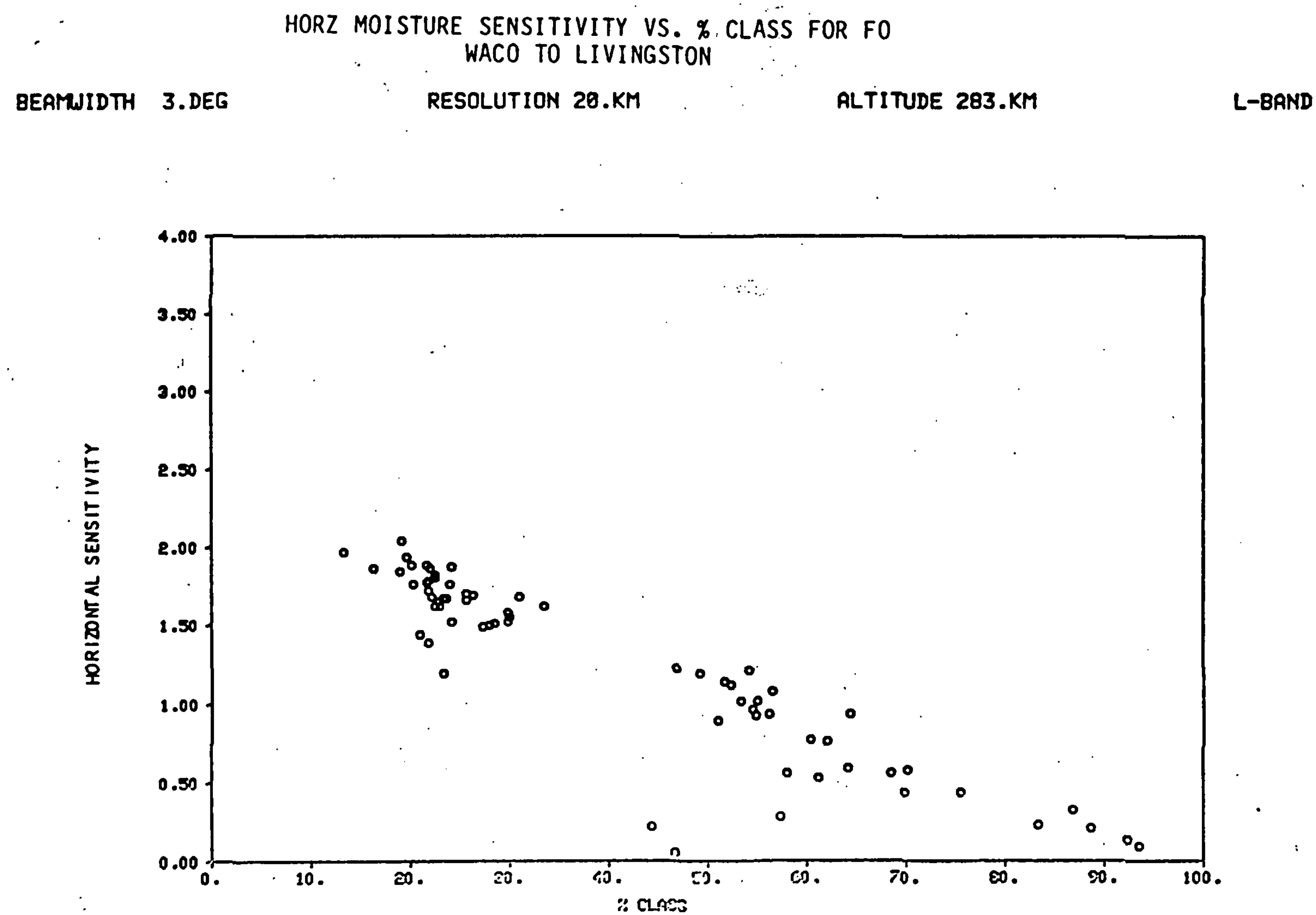


FIGURE 19. Soil moisture sensitivity of the L-band horizontally polarized brightness temperature for the Waco to Livingston ground track at a 20 kilometer resolution plotted as a function of percent forest class.

primarily due to the vegetation conditions within the scene. In addition, it is clearly seen that increasing the antenna footprint size does not significantly affect the sensitivity of the brightness temperature measurement to soil moisture. This fact is supported by the work of McFarland [1976] and Eagleman and Lin [1976] in which good correlations were obtained between antecedent precipitation and soil moisture, respectively using the 21 cm radiometer flown aboard Skylab that had a 115 km antenna footprint size. It is obvious that the effect of forest class is significant on reducing the sensitivity of brightness temperature to soil moisture. If the position of the antenna footprint is known with some reasonable degree of accuracy, brightness temperatures measured over forested areas can be avoided and the overall sensitivity to soil moisture can be improved. Figure 21 demonstrates this by showing the sensitivity and 95% confidence intervals associated with those sensitivity computations for all antenna footprints containing less than 40% of the forest class. Note that at the 21 cm wavelength, the sensitivity to soil moisture is on the order of 1.5°K/percent soil moisture.

**Current Results: Root Zone Soil Moisture Prediction**

Work is currently ongoing toward the development of a technique of predicting the soil moisture in the root zone utilizing a microwave estimate of the near surface soil moisture. However, several significant results have been demonstrated to date and will be presented. During the summer of 1980 a field experiment was executed at Texas A&M University utilizing four bare fields ranging in surface roughness from smooth to very rough (Makanvand and Newton, 1982; Makanvand and Newton, 1982; Newton et al., 1982). During the experiment, microwave

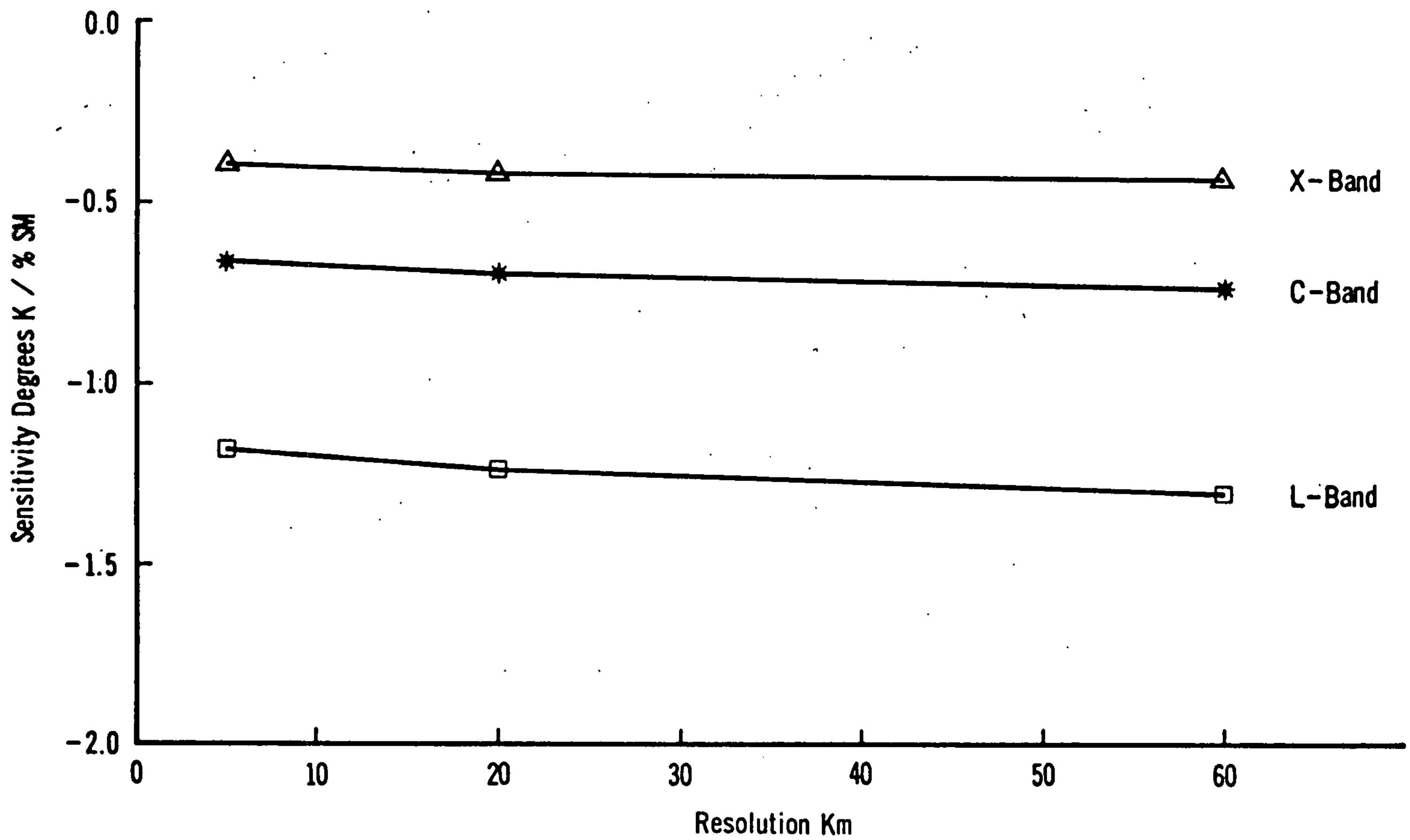


FIGURE 20. Average soil moisture sensitivity plotted as a function of frequency and resolution without regard to class constituency within the antenna footprints.

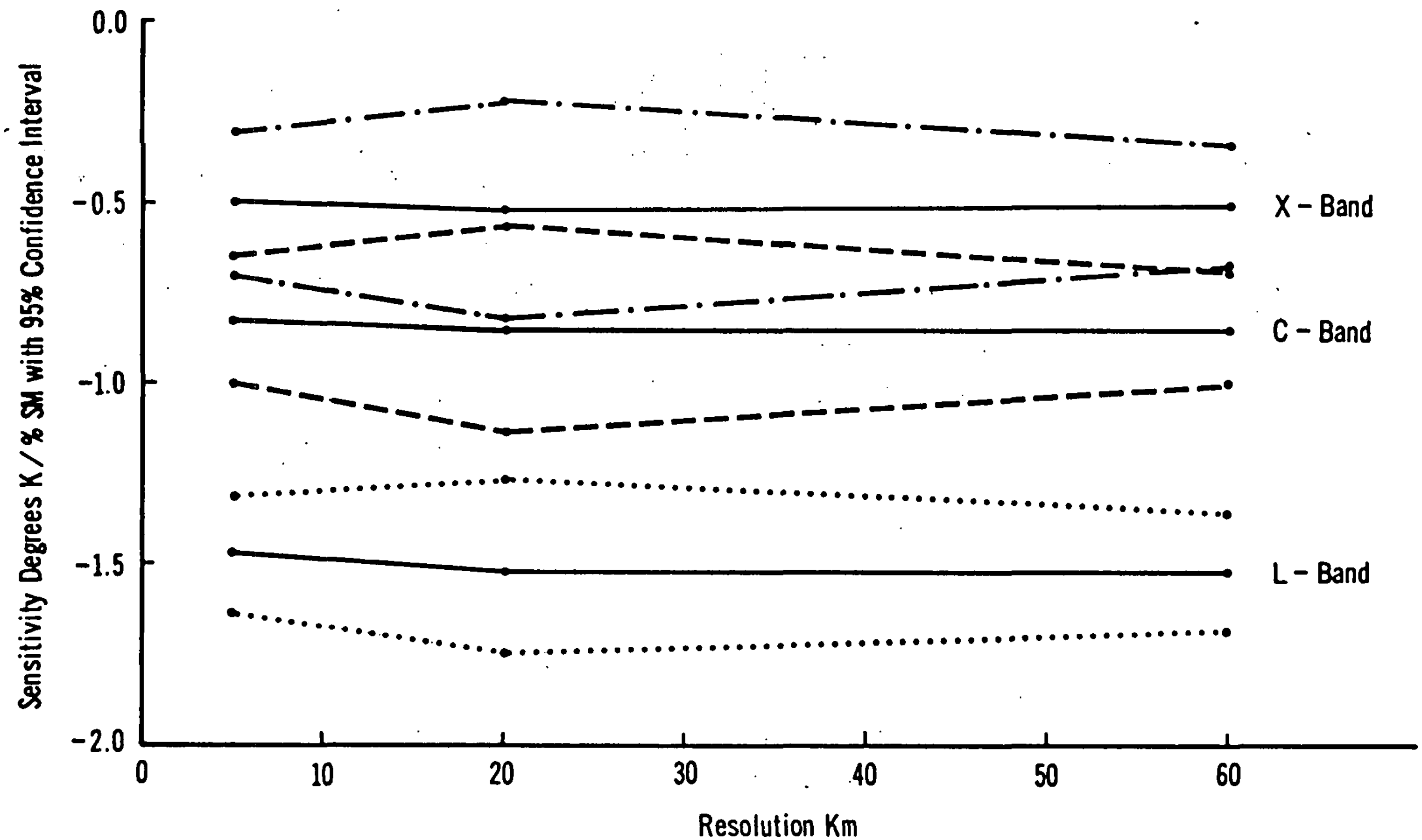


FIGURE 21. Soil moisture sensitivity plotted as a function of resolution and frequency for antenna footprints containing less than 40% forest class with the 95% confidence intervals indicated.

brightness temperatures were measured at 21 cm, 6 cm, and 2.8 cm. Ground truth measurements were made in each field simultaneously with the microwave measurements. Three techniques were used to measure the soil moisture profile. Soil moisture was measured gravimetrically at ten locations within each field, with a gamma ray attenuation technique at four locations within each field, and with a neutron probe at six locations within each field. Soil temperature profiles were measured with thermal couples at two locations within each field and surface soil temperature was measured using a thermal radiometer boresighted with the microwave antennas. Surface roughness was measured several times during the experiment at two locations within each field.

It should be pointed out that during this experiment Texas was in a severe drought condition and no rainfall occurred during the entire time interval. As a result, the test site was irrigated for 18 hours using a sprinkler system that produced 3/4 inch of water per hour. A complete set of measurements was acquired twice prior to irrigation and then at irregular intervals depending on the dry down rate until the soil profile had dried significantly.

In addition to these data, meteorological measurements required to support the model described by van Bavel et al. [1979] were also acquired at 30 minute intervals throughout the experiment. Lascano and van Bavel [1982] executed a continuous simulation of the soil moisture and soil temperature profile using the meteorological data acquired during the experiment. This simulation produced soil moisture and soil temperature profiles every hour for a time period of 18 days.

As described in the general method, simulated soil moisture and soil temperature profiles were used to compute simulated microwave brightness temperatures for the smooth field. The next step is to apply a soil moisture estimation algorithm to the simulated brightness temperatures to estimate the near surface soil moisture. This near surface soil moisture estimate will then be used to predict the lower profile average soil moisture using a derivative of the van Bavel soil temperature and soil moisture profile model. In addition, for experimental verification purposes, the actual brightness temperature measurements will also be used to predict the lower profile soil moisture. These two results will then be compared to one another and compared to the actual gravimetrically measured soil moisture to evaluate the procedure.

Significant results that have been obtained to date include the acquisition of both microwave brightness temperature and ground truth experimental measurements from which: 1) brightness temperature simulations have been computed to evaluate the effects of diurnal variations in both soil temperature and soil moisture; 2) from which experimental verification of the depth of penetration of a microwave measurement can be made; and 3) from which the worse case dry down rate can be determined.

Figures 22 and 23 are plots of the 0-2 cm average soil temperature and 0-2 average volumetric soil moisture measurements in the smooth bare field. The diurnal effects are evident in both of these figures. In Figure 22 it can be seen that there are excursions of soil temperature between night and day on the order of 10°C under very

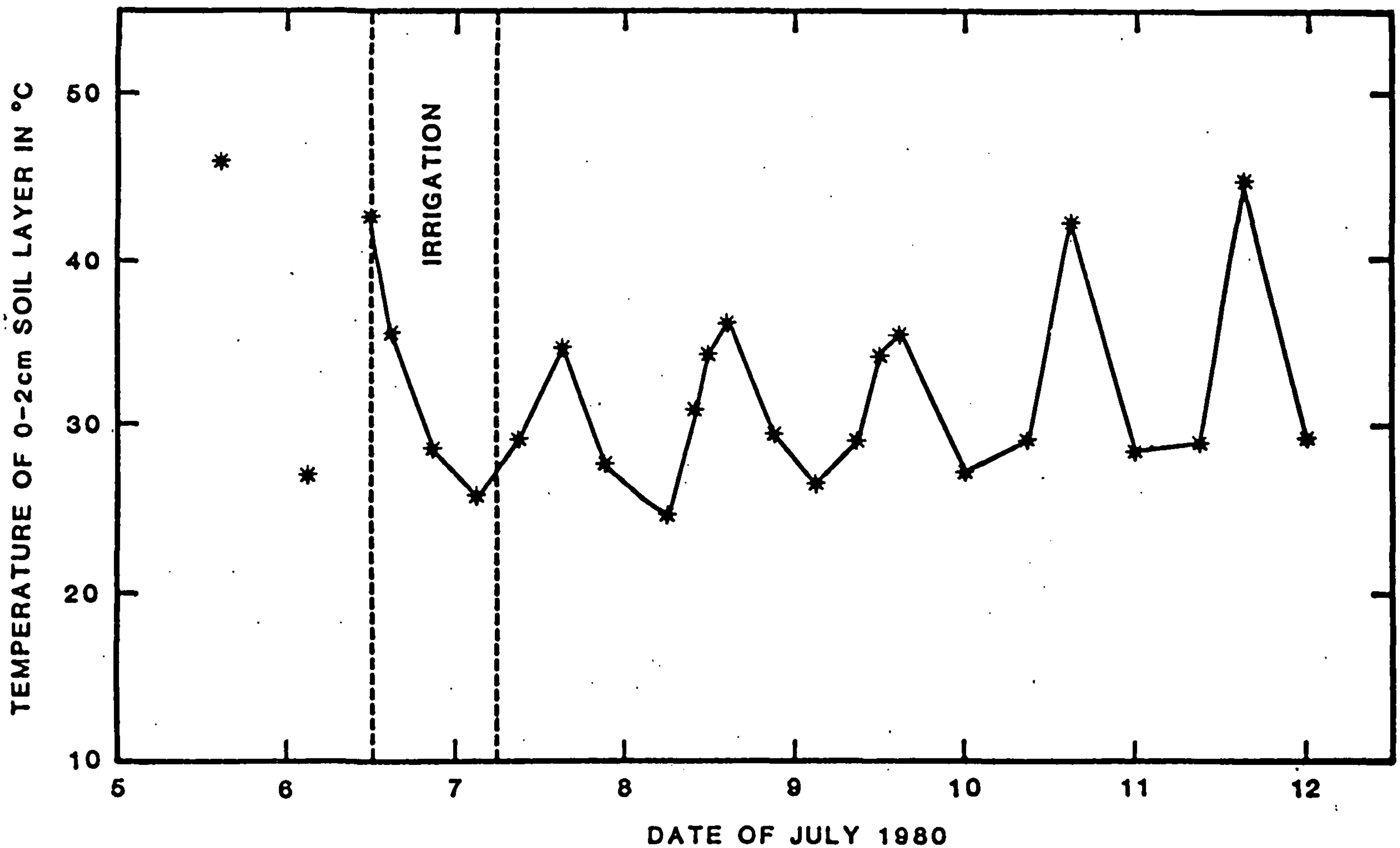


Figure 22. Simulated soil temperature for the upper 2 cm of a smooth bare soil.

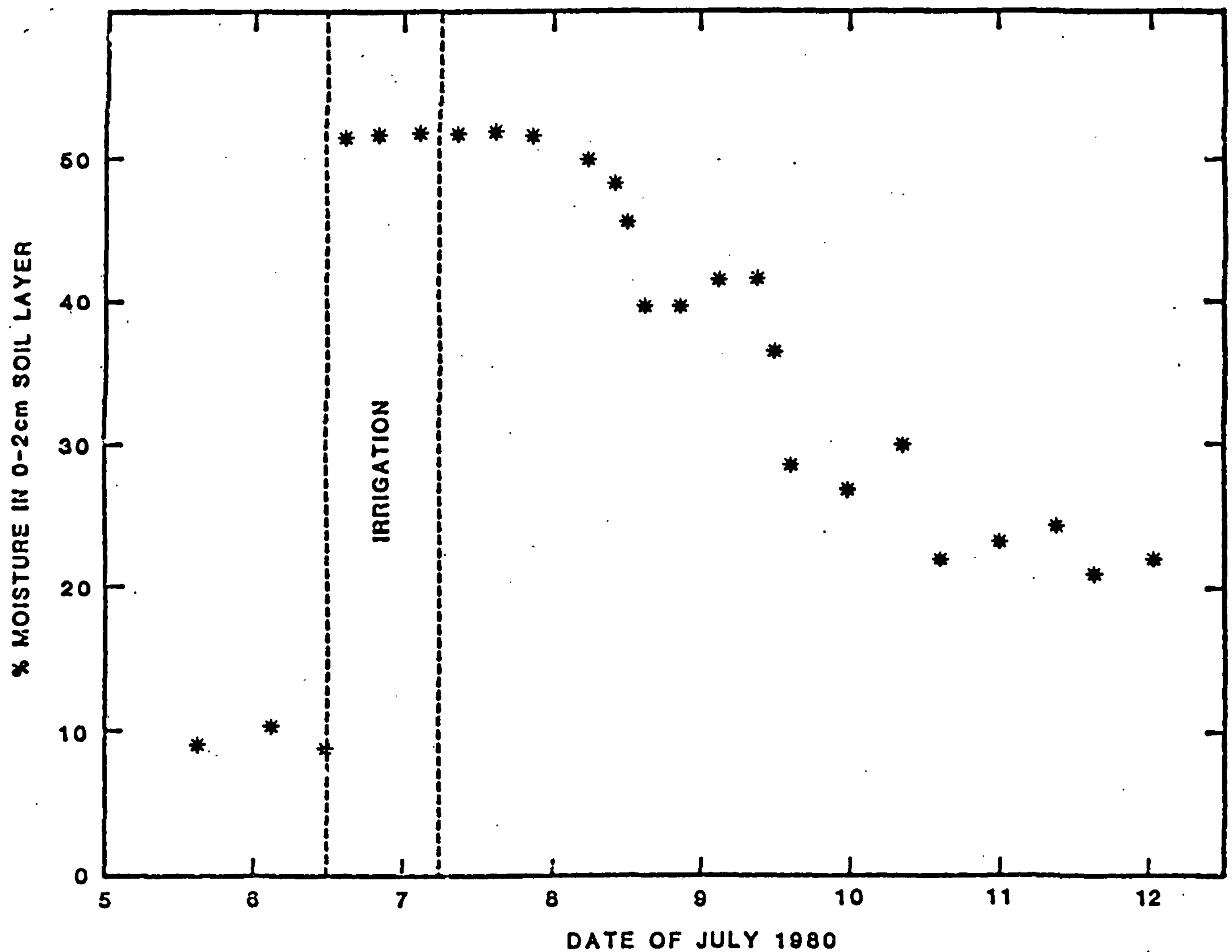


Figure 23. Simulated soil moisture content for the upper 2 cm of a smooth, bare soil.

wet conditions, increasing to approximately 15°C under dry conditions. In Figure 23 there are also diurnal variations in the 0-2 soil moisture, but they appear less symmetric due to the fact that the average moisture is changing rapidly over the period of times presented. The effects of these diurnal variations can be seen in the simulations of brightness temperature shown in Figure 24. Note that the diurnal variations evident in Figure 24 show the same periodicity as the diurnal variations in Figure 22 of the 0-2 cm soil temperature. However, the magnitude of the simulated brightness temperature diurnal variations is moderated by the effect of changing soil moisture. An important point of consideration is that the brightness temperature measurements demonstrate both effects of soil temperature as well as soil moisture. Converting the brightness temperature to an effective emissivity by normalizing the brightness temperature computations to the 0-2 cm soil temperature, the effect of the soil moisture diurnal variations is minimized. This effective emissivity is shown in Figure 25. Note that the effective emissivity shows only the characteristics that are evident in the 0-2 cm average soil moisture plot of Figure 23. This can readily be seen by noting that the emissivity plot is very nearly an exact mirror image of the 0-2 cm average soil moisture data.

Because of the diurnal variations described, it is advantageous to obtain a microwave measurement for estimating near surface soil moisture at the same time for each date of measurement. In addition, as noted by Jackson [1980], pre-dawn is most likely the best time of day to make the near surface soil moisture estimate for several rea-

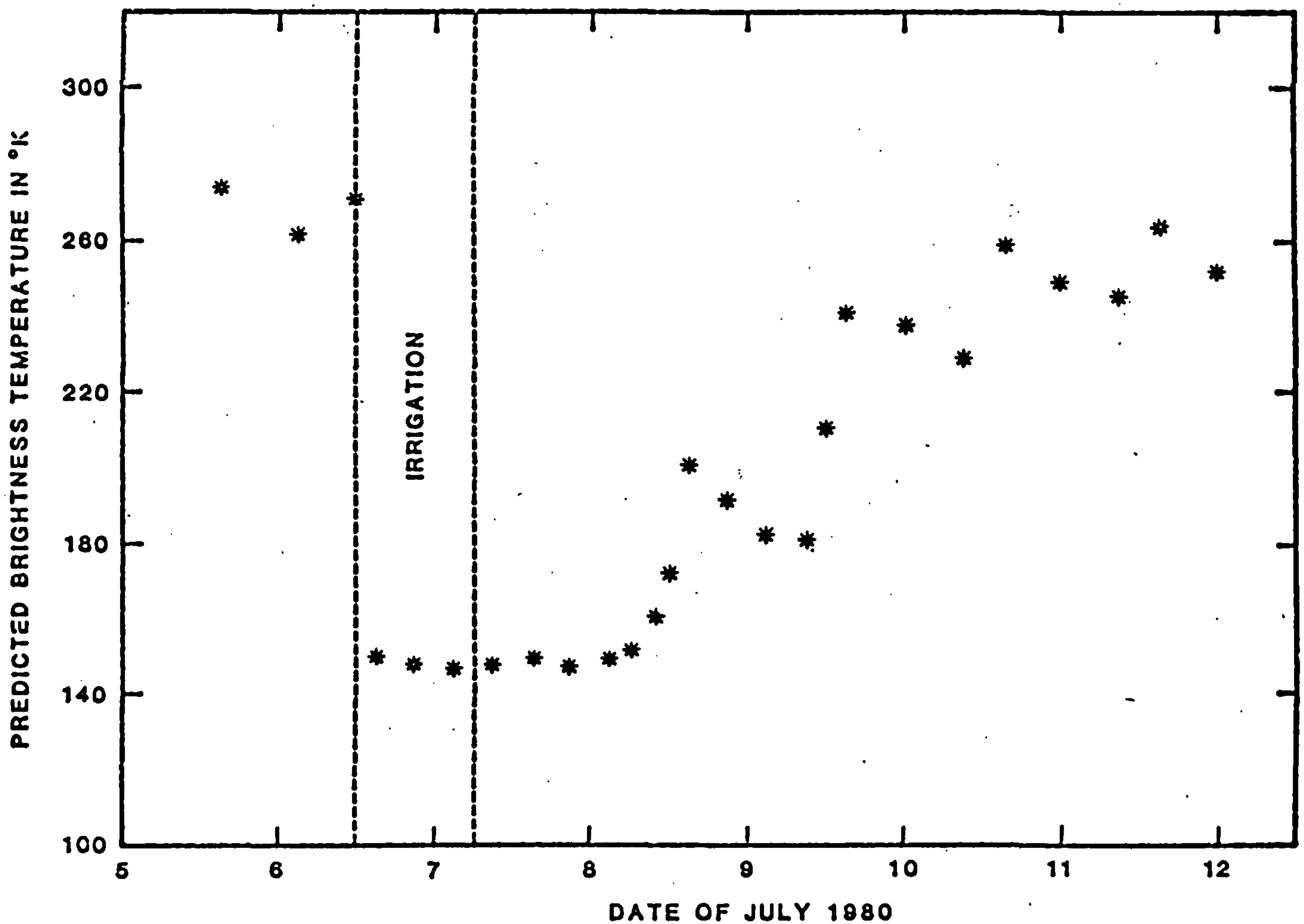


Figure 24. Simulated 21 cm brightness temperature for a smooth, bare soil.

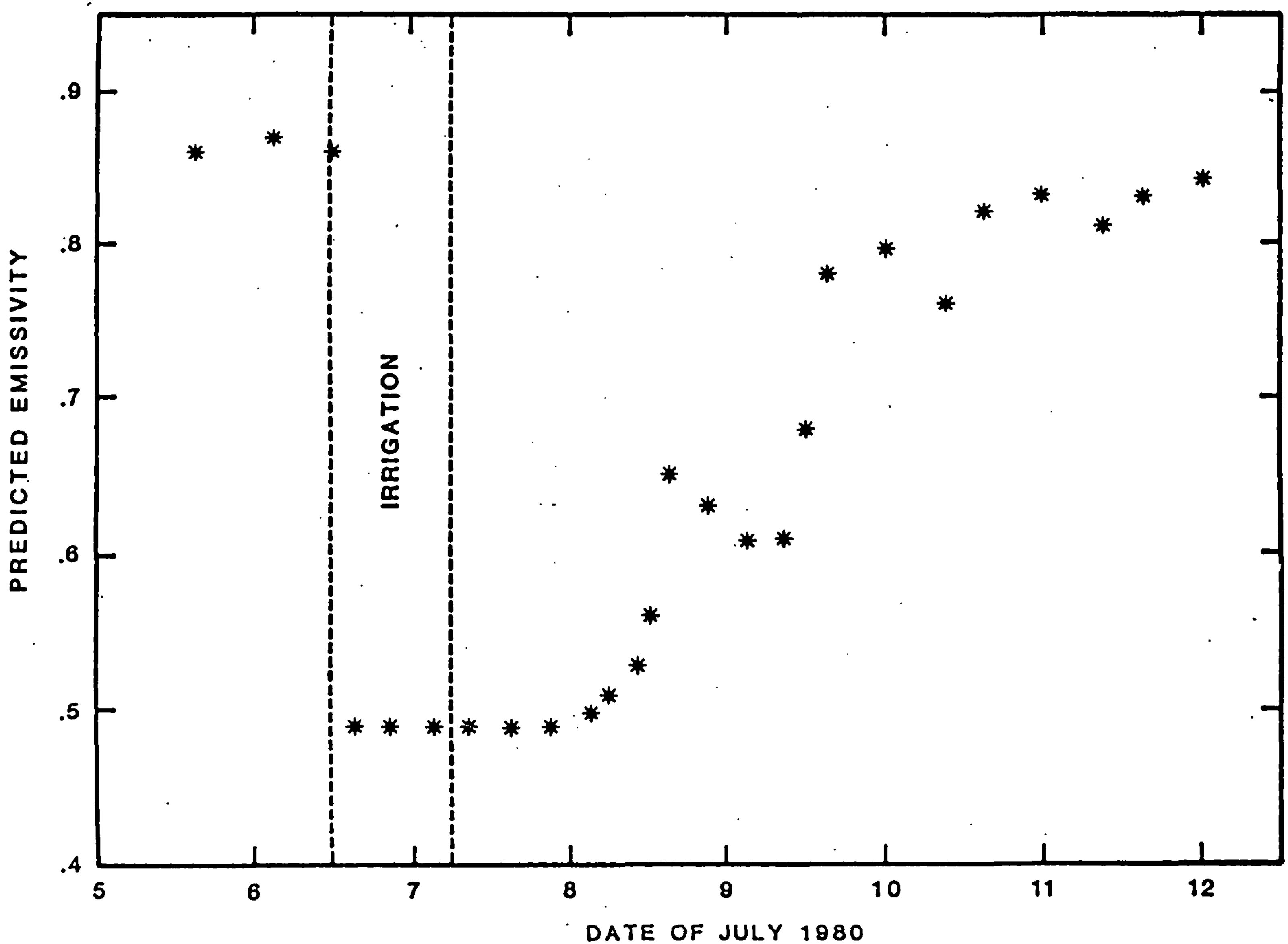


Figure 25. Simulated effective emissivity for a smooth, bare soil. Effective emissivity was computed by normalizing the simulated brightness temperature by the 0-2 soil temperature.

sons. The prediction equations for the lower profile moisture will most likely involve assumptions of equilibrium. During pre-dawn the temperature within the vegetation canopy will most likely be less than during the daytime, and the temperature within the soil volume and within the vegetation canopy will be closer to a state of equilibrium than during the day. These latter two factors have some significance on the microwave emission from the scene. One difficulty of acquiring pre-dawn microwave measurements lies in the possibility of having moisture on the vegetation canopy as a result of dew. This issue needs to be considered further.

Several investigators have addressed the issue of depth of penetration in using microwave sensors to measure near surface soil moisture. However, these investigations have been theoretical in nature. The experimental brightness temperature measurements made in the experiment described above provide a means of experimentally verifying the depth of measurement. Figure 26 shows a plot of gravimetrically measured soil moisture for the smooth field at three different surface layer thicknesses. It can be seen that if the surface layer thickness is increased, the dry down rate decreases. By comparing the rate at which the microwave brightness temperature changes as a function of time to the data in Figure 22, it can be experimentally demonstrated which surface layer most closely correlates to the brightness temperature measurement. Figure 27 shows estimates of near surface soil moisture made from the actual brightness temperature measurements at the three microwave wavelengths. Note that these measurements were made at approximately the same time of day to minimize the diurnal

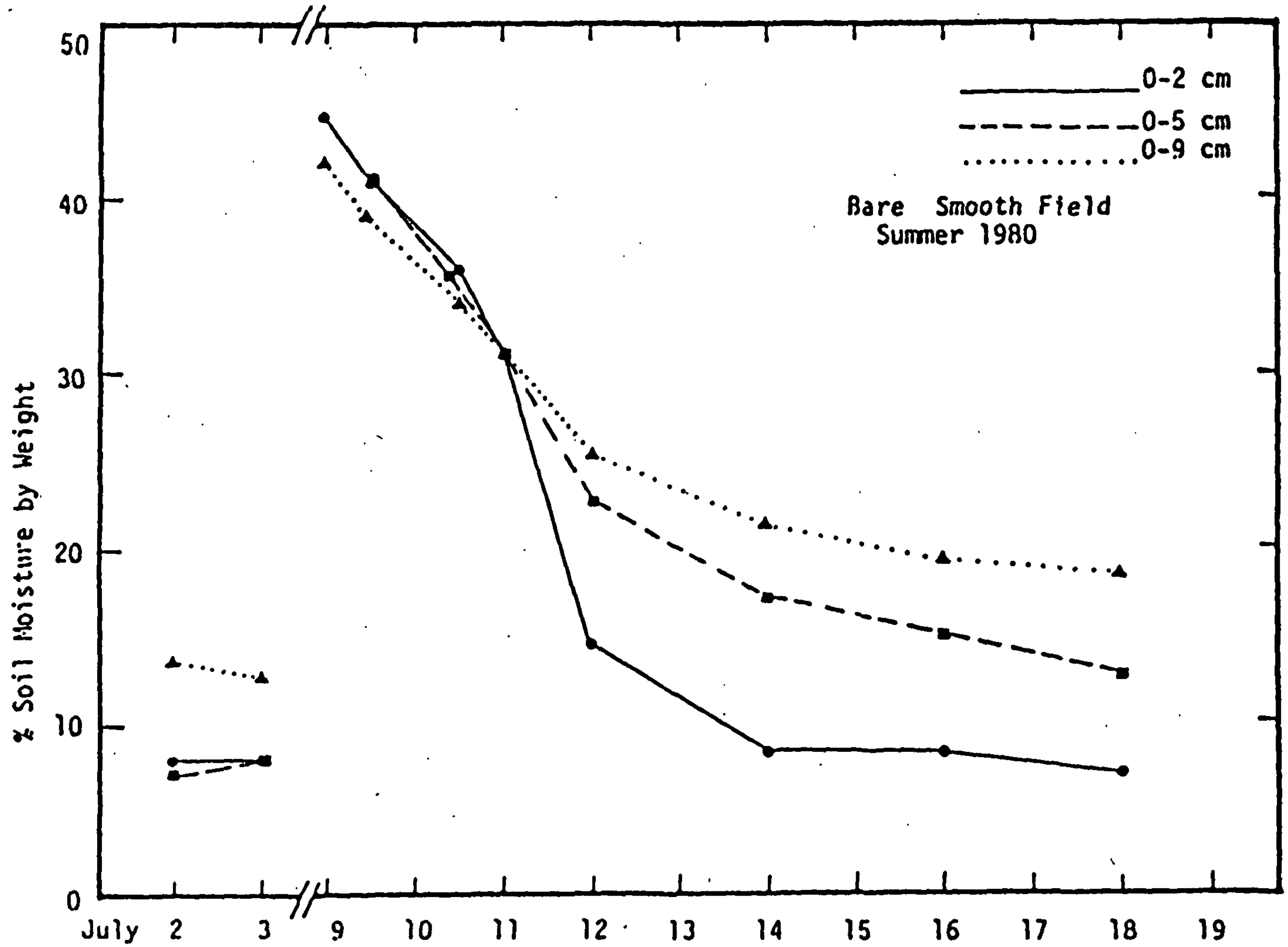


Figure 26. Gravimetrically-measured soil moisture content, for three surface layer thicknesses, as a function of date, for a smooth, bare soil.

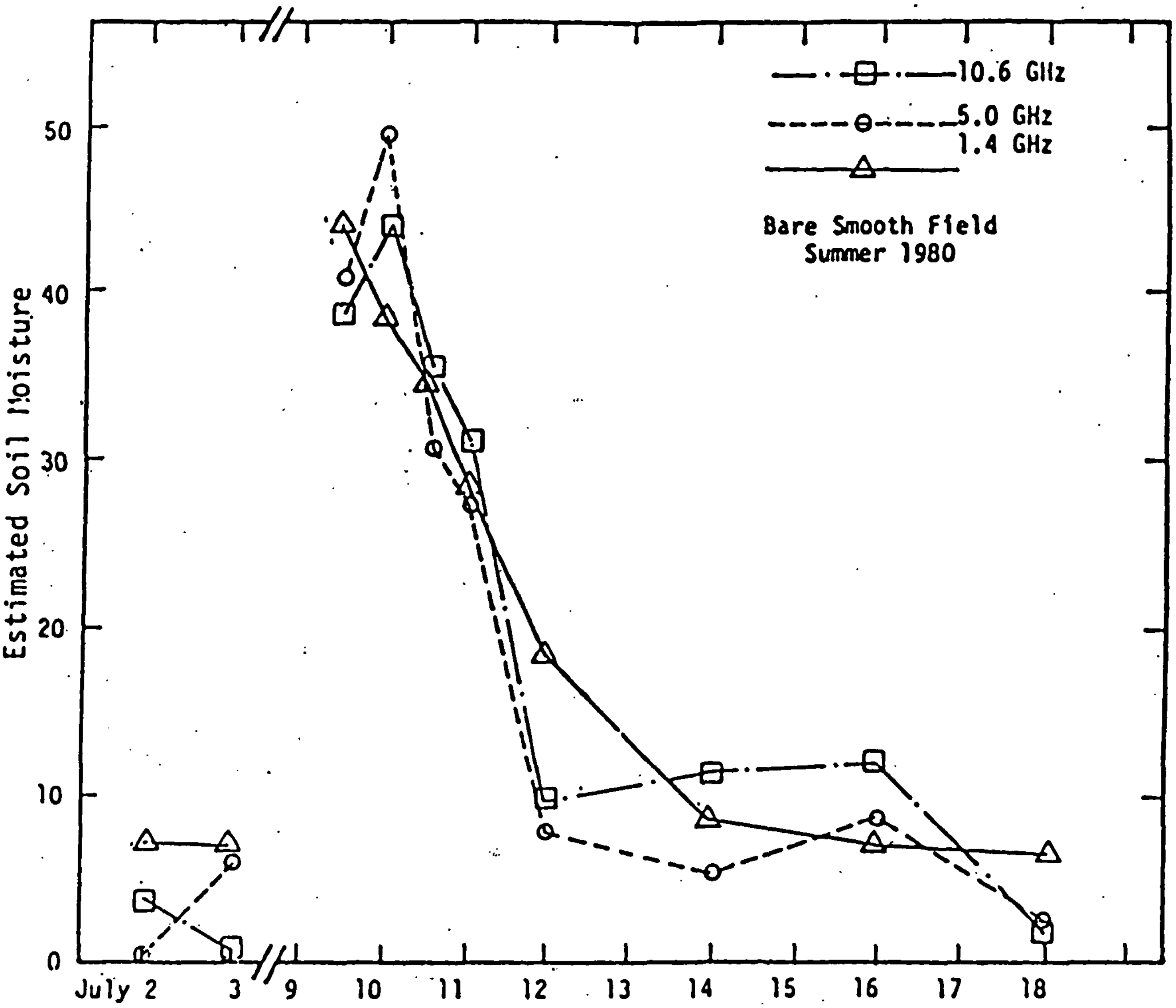


Figure 27. Near Surface soil moisture content estimated from brightness temperature measurements at three frequencies, as a function of date, for a smooth, bare soil.

effects in estimating near surface soil moisture. It can be seen that even the longest wavelength of 21 cm does not correspond to the depth greater than 5 cm. This is consistent with the theoretical results that were previously discussed by Wilheit [1978] and Black and Newton [1981]. In addition, these figures demonstrate that near surface soil moisture measurements must be made at least every two days in order to ensure that a rainfall event will not be missed.

## CONCLUSIONS

The results of the microwave satellite simulation program have shown that it is theoretically possible to measure soil moisture over large areas. From realistic scenes containing only 10 to 15% bare soil and significant vegetation, it was shown that a 60°K change in brightness temperature occurs from 5% soil moisture to 35% soil moisture at a 21 cm microwave wavelength. This provides a 1.5°K to 2°K per percent soil moisture sensitivity to soil moisture. The current state-of-the-art in sensitivity and absolute accuracy for microwave radiometers is much less than 1° for sensitivity and 3° to 5° for absolute accuracy. It was also shown that resolution which has been of primary concern to many investigators, does not affect the basic ability to measure soil moisture with a microwave radiometer system. This work did not, however, address the effect of spatial distributions of moisture caused by weather patterns. These distributions will be dependent upon geographical location. In the Texas and Oklahoma area the average size of thunderstorm systems is approximately five kilometers. However, it remains to be seen whether or not this is a resolution limitation.

The experimental data have been acquired for developing and testing a root zone moisture prediction algorithm. The experimental measurements have demonstrated that the depth of penetration at a 21 cm microwave wavelength is not greater than 5 cm. Jackson's [1980] work indicates that the moisture in the lower profile can be estimated with a 0.06 standard error by using surface soil moisture for the top 5 cm. This was done even with a simple lower profile moisture estimation scheme.

This work will be continued to complete the evaluation of a simple technique of utilizing microwave estimates of near surface moisture to predict lower surface moisture with both theoretical simulations and actual field measurements. In addition, the more sophisticated approach to the lower profile moisture prediction scheme will be addressed by utilizing antecedent moisture conditions or limited meteorological data.

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