SECTION 93

SOIL MOISTURE MAPPING BY GROUND AND AIRBORNE MICROWAVE RADIOMETRY

by

G. Poe and A. T. Edgerton
Microwave Division
Aerojet-General Corporation
El Monte, California

ABSTRACT

This paper summarizes research performed by Aerojet-General Corporation concerning remote sensing techniques for soil moisture mapping. This work, sponsored by the National Environmental Satellite Service of NOAA, is concerned with the feasibility of mapping the horizontal and vertical distribution of soil moisture with microwave radiometry. Extensive ground-based and airborne investigations were undertaken in conjunction with laboratory dielectric measurements of soils and analytical modeling. Radiometric measurements were taken in the vicinity of Phoenix, Arizona at observational wavelengths ranging from 0.81 to 21 cm. Ground experiments were conducted with the Aerojet microwave field laboratory and airborne measurements were obtained from a CV-990 aircraft operated for the Goddard Space Flight Center. Research activities have been focused on establishing basic relationships between microwave emission and the distribution of moisture. This work, including theoretical studies, laboratory and field measurements, demonstrates a basic relationship between microwave emission and soil moisture content. Although the extensive ground control data (vertical soil moisture and temperature profiles) needed to quantitatively demonstrate airborne mapping of soil moisture content were not available during the initial flights, the early results have been very encouraging.

INTRODUCTION

The moisture content of the uppermost few feet of soil directly influences (1) the productivity of large tracts of rangeland, (2) the yield of all agricultural areas, (3) the amount and rate of runoff from large portions of the Continental U. S., and (4) the engineering properties of terrain surfaces. At present, the <u>only</u> source of accurate soil moisture data is from laborious ground surveys which rely on detailed coring and/or point measurements with radiation or electrical techniques which require direct contact with the soil. More qualitative estimates of soil moisture are often based on rainfall data.

Significant improvements in soil moisture survey accuracies can be achieved by monitoring soil moisture content throughout its areal extent rather than relying on limited point data. Synoptic remote sensing techniques offer this potential. Sensor requirements for this task are: (1) a direct response to soil moisture content, (2) ability to map or image soil moisture distribution with acceptable spatial resolution, (3) adverse weather capability for operation in the presence of clouds, and (4) ability to resolve the vertical distribution of moisture in upper few feet of soil. Since conventional and infrared sensors do not meet these requirements, the investigators have focused attention on the development of passive microwave soil moisture survey techniques. Natural microwave radiation from terrain surface materials penetrates clouds and can be mapped with imaging radiometers. Moreover, field investigations have demonstrated a direct and pronounced relationship between microwave emission from soils and the soil moisture content.

The following portions of this document summarize ground-based, laboratory and aircraft investigations of soil moisture determination with microwave radiometry. This work including theoretical studies, laboratory and field measurements, demonstrates a basic relationship between microwave emission and soil moisture content. These basic investigations have recently been augmented with aircraft measurements. Although the extensive ground control data (vertical soil moisture and temperature profiles) needed to quantitatively demonstrate airborne mapping of soil moisture content were not available during the initial flights, the early results have been very encouraging.

GROUND-BASED AND LABORATORY STUDIES

In the first phase of this program, a series of ground-based passive microwave measurements (1.42, 4.99, 13.4 and 37 GHz) were performed of a laboratory soil (United States Water Conservation Laboratory, Phoenix, Arizona) over a variety of moisture conditions under the auspices of the National Oceanic and Atmospheric Administration (NOAA). The experiments were designed to avoid, as much as possible, complicating features due to surface roughness (arising for example, from vegetal cover) and lateral structural variations. Extensive measurements of the near-surface (0 to 32 cm) vertical distribution of moisture and temperature accompanied the microwave measurements. Also, dielectric constant measurements of the soil as a function of the moisture concentration at ambient temperature (295°K) were performed at 37 GHz subsequent to the passive microwave measurements. Thus, the microwave emission properties of a relatively simple physical situation consisting of an isotropic, non-magnetic semi-infinitely extended specular soil having variations of moisture and temperature only in the vertical direction was investigated. Further details which are not presented here may be found in a separate document[1].

DESCRIPTION OF EXPERIMENT

The radiometric and physical measurements taken in July 1970 of the sandy clay soil at the USWCL, Phoenix, Arizona, may conveniently be divided into twelve experiments corresponding to twelve different soil moisture conditions. Each experiment consisted essentially of obtaining dual-polarized (horizontal and vertical) multifrequency (1.42, 4.99, 13.4 and 37 GHz) brightness temperatures at 30, 40 and 50 degree antenna viewing angles (measured from nadir) together with extensive moisture profiles (total moisture content in steps of 2, 4, 8, 16 and 32 cm) over the area of observation (10 x 16 foot ellipse for a 20-foot antenna height above ground at a 50-degree angle). Temperature profile data at the surface and 2, 4, 8, 16 and 32-cm depths were taken at several locations around the area of observation during the microwave measurements. On the average 20 to 30 one-inch-diameter core moisture samples spaced 1 to 2 feet apart were taken in each experiment immediately following the microwave measurements. Variations in the moisture data at a given depth were usually less than 0.5 percent (dry weight basis) while variation in the temperature data at a given depth were less than 1 or 2°K.

The effects of lateral variations of moisture and temperature in the USWCL soil plot were minimized by positioning the radiometers so that the same area of soil was observed at each view angle. The selection of the above number of view angles and moisture measurements was made so that changes in the moisture condition due, for example, to natural evaporative processes could be minimized. Both the microwave and moisture measurements in each experiment were usually completed in less than an hour. The choice of view angles was made to exhibit polarization differences in the measurements and to keep the beam spot size within reasonable limits.

Since the method of moisture sampling involved the destruction of the soil site, each experiment was conducted on slightly different portions of the larger soil plot. However, significant lateral changes in soil properties (density or grain size) during the series of experiments were found to be negligible.

The method used to alter the soil moisture concentration consisted of inundating a relatively large soil plot and allowing natural evaporative and drainage processes to occur. Approximately two and one-half weeks were spent obtaining the microwave and moisture data as the soil conditions varied from completely saturated to relatively dry.

Model of Microwave Soil Emissions

Of the models applicable to specular substances, the recent model due to Stogryn[2] appears to be the most appropriate for analyzing the previously described experiment. In the model, variations of the dielectric constant (and hence physical properties) and temperature are allowed in the direction normal to the substance's surface and are assumed negligible in directions parallel to the substance's surface. A practical numerical scheme for computing the brightness temperature of energy propagating away from the substance is discussed elsewhere[2]. Suffice it to say, the brightness temperature of a material may be computed from a knowledge of (1) the radiation incident on the substance's surface and (2) the functional dependence of the dielectric constant and temperature with distance below the surface (only differentiable functions having a finite number of discontinuities are allowed). In general, the computed brightness temperature depends on the choice of frequency, polarization and view angle. Atmospheric attenuation can be neglected in the present situation since the radiometers in the experiment were at most 20 feet above the soil. In reality the model is a generalization of the theory of emissions by homogeneous, istropic and non-magnetic specular substances described by the well-known Fresnel reflection coefficients[3].

The computation of the radiation incident on the soil's surface was made using a standard model atmosphere for the air temperature and pressure with reasonable estimates of the cosmic noise. A typical water vapor profile of the Phoenix Valley was also used in the calculation.

DIELECTRIC CONSTANT AND MIXING FORMULAS

Dielectric constant measurements were performed on the USWCL soil using a free-space measuring system known as an ellipsometer, operating at 13.4 and 37 GHz. Details of the technique of measurement can be found elsewhere[4]. Density, temperature and moisture measurements were taken on each sample. Great care was exercised during the dielectric measurement to insure that the soil samples resembled, as closely as possible, in situ soil in both density and moisture content. Table 1 presents the results together with measurement errors. K' and K'' are the real and imaginary parts of the dielectric constant, respectively.

Uncertainty in the temperature, density and moisture content were respectively less than 1°K, 0.1 g/cm^3, and 0.5 to 2 percent. Due to the small values of K'' associated with the low loss samples, only an upper bound could be determined for small moisture contents with the ellipsometer.

Several commonly used dielectric mixing formulas were selected to compare with measured data. The formulas of Rayleigh[5], Wiener[6], Bottcher[7], and Pierce[8] were investigated. To aid in the comparisons, the dielectric constant data of von Hippel[9] at 3 and 10 GHz were used. Since the dielectric constant of solid particles is known to be relatively independent of temperature while the dielectric constant of water may be calculated accurately as a function of temperature using equations of the Debye form[10], the dielectric constant of soil is known as a function of temperature and moisture content when computed from the mixing formulas. In the computations that follow the dielectric constant of dry soil was taken to 2.55+i.001.

The formula of Wiener typically provided best agreement although the form number (appearing in the formula), F , which gave the best fit was found to vary with frequency. Thus, Wiener's mixing formula together with an appropriate range of form numbers (32-64 for 1.42 and 4.99 GHz, 16-64 for 13.4 and 16-32 for 37 GHz) was selected to relate the dielectric constant of soil with the percentage of soil moisture and temperature. The effect of density on the dielectric constant other than that occurring due to the presence of water were not pursued.

COMPARISON OF THEORY AND EXPERIMENT

A comparison of 1.42, 4.99, 13.4 and 37 GHz brightness temperatures (measured in the previously described experiment) with those computed from the theory of vertically structured media[2] using Wiener's dielectric mixing formula[6] with measured moisture-temperature profiles is presented in Figures 1 and 2. The antenna view angle is 50 degrees. Similar results were obtained at the other view angles. The range of form numbers used in Wiener's formula are indicated in the figures. The numbers in the figures refer to the twelve experiments mentioned previously. The numerous soil moisture and temperature profiles are presented elsewhere[1].

A solid line has been drawn through the measured brightness temperatures in Figures 1 and 2. As can be seen, the agreement between theory and measurements is good except for the existence of systematic differences. The lack of accurate dielectric constant information at 1.42 GHz allows an explanation of the systematic differences in Figure 1 while the lack of a completely satisfactory mixing formula fits to measured 37 GHz dielectric constant data allows an explanation of the differences in Figure 2. In any case, the differences in vertically and horizontally polarized temperatures increase substantially with increasing moisture content and the differences are largest at lower frequencies. Also, decreases in the horizontally polarized temperatures are usually larger than the corresponding decreases in the vertically polarized temperature. This is due primarily to the Brewster angle effect associated with smooth surfaces.

MODEL FOR COMPUTING SOIL MOISTURE

Several theories of the radiometric emission characteristics of specular soils exist which may be used to compute the microwave brightness temperature of energy propagating away from soils provided information is available regarding the moisture and temperature distribution within the soil and the radiation incident on the soil surface. However, there are presently no models available which allow a computation of the moisture or temperature profiles from measured brightness temperatures. Until further theoretical and/or experimental information is available regarding the relationships between soil moisture content, dielectric constant and microwave emission (and others) empirically derived models appear appropriate.

The model described below permits a calculation of the vertical profile of the total volume of water per unit area using measured horizontally polarized brightness temperatures which have been normalized by the surface soil temperature. The model originates from the hypothesis that it is the total mass of water per unit area lying between the surface and one electromagnetic skin depth which determines the brightness temperature rather than the specific details of the distribution of moisture. The model consists of the following series of steps.

a. The measured horizontal brightness temperature (°K) is divided by the surface temperature (°K) of the soil. The units of the resulting numbers are defined as effective emissivities rather than emissivities since the single term emissivity can be misguiding when substantial temperature gradients occur within the soil.

b. From established curves relating effective emissivity with volume percent of water, the volume percent of water (g/cm^3) corresponding to the effective emissivity of a. is determined.

c. From established curves relating the skin depth with the volume percent of water, the skin depth (cm) corresponding to the volume percent of water of b. is determined.

d. Multiplying the skin depth (cm) of c. with the volume percent of water (g/cm^3) of b. yields the total volume of water per unit area (g/cm^2) lying beneath the soil surface and above the skin depth of c.

Thus utilizing a suitable combination of measured multifrequency horizontally polarized brightness temperatures (obtained at a particular view angle) together with the surface soil temperature, a computation of the vertical distribution of the volume of water per unit area can be made.

Several comments appear appropriate regarding the above-mentioned established curves. First, the curves in c. were obtained using Equation (1) and Wiener's mixing formula. It should be noted that the skin depth δ calculated from (1) applies to the nadir position, however, since the dielectric constant of soils having moisture contents greater than a few percent is much larger than $\sin^2\theta$ (θ is the angle from nadir) little error arises when using (1).

$$\frac{\delta}{\lambda} = \frac{1}{2\pi \mathrm{Im}(\sqrt{K})} \qquad (1)$$

λ is the free-space wavelength and K is the dielectric constant calculated from Wiener's formula. Im denotes taking the imaginary part. Figures 3a, b, c, and d present skin depths for 1.42, 4.99, 13.4 and 37 GHz as functions of the volume percent of water. The skin depths were then computed from Wiener's formula with two form numbers mentioned previously (32 and 64 for 1.42 GHz, 16 and 64 for 13.4 and 16 and 32 for 37 GHz). As can be seen, modest amounts of water greatly affect the skin depths of dry soils. An average thermal temperature of 300°K was used in computing K.

Second, the curves in b. were obtained as follows: horizontally polarized brightness temperature T were computed for a homogeneous, isotropic, isothermal, semi-infinitely extended, non-magnetic soil having a smooth planar surface using Equations (2) and (3). Conservation of energy and local thermodynamic equilibrium has been assumed. R is the horizontally polarized power reflection coefficient determined by the Fresnel reflection coefficients[3], T_g is the soil temperature; K is the dielectric constant; θ is the view angle from nadir; and T_s is the brightness temperature of the energy incident on the soil surface.

$$T(\theta) = (1 - R(\theta))\, T_g + R(\theta)\, T_s(\theta) \qquad (2)$$

$$R(\theta) = \left| \frac{\cos\theta - \sqrt{K - \sin^2\theta}}{\cos\theta + \sqrt{K - \sin^2\theta}} \right|^2 \qquad (3)$$

T_s was assumed due to atmospheric absorption of cosmic noise. As noted earlier atmospheric attenuation of T can be neglected. T depends on the frequency through the frequency dependence of K and T_s . T_g was taken to be 297°K since the 13.4 and 37 GHz dielectric constant measurements were performed near this temperature. K was computed from Wiener's mixing formula.

Figures 4a, b, c and d present effective emissivities at 1.42, 4.99, 13.4 and 37 GHz as functions of volume percent of water for a 50-degree view angle. Similar curves were obtained for other view angles. The form numbers used in Wiener's formula are indicated in the figure. It should be noted that effects on the curves in b. and c. due to changes in the soil temperature have been neglected in the computations that follow. However, it is judged that for most soil temperatures that are encountered in situ, the effects are less than the uncertainties introduced when using Wiener's mixing formula.

COMPARISON OF CALCULATED AND MEASURED MOISTURE PROFILES

Utilizing the above model, effective emissivities were computed from the multifrequency horizontally polarized brightness temperatures and surface soil temperatures measured during the previously described experiment. The skin depths and total volumes of water per unit area corresponding to these effective emissivities were also computed. Computations were made for 30, 40, and 50 degree view angles. Figures 5 and 6 present a typical comparison of measured and computed results. A solid line has been drawn through the measured data which was linearly extrapolated beyond 32 cm. The vertical bars indicate ranges of variations associated with the moisture measurements. Wavelengths are given near the computed results. Form numbers used in Wiener's formula are indicated in the figures.

As can be seen, good agreement between measured and computed moisture contents for moderately moist to saturated soil conditions occurs at all wavelengths (Figure 5). However, there is at times relatively poor agreement for "dry" soil conditions (Figure 6). The lack of agreement for dry soils is believed due to uncertainties in the measured values of the imaginary part of the dielectric constant which in turn introduces uncertainties in the computed skin depths. It is anticipated that additional information regarding the dependence of the imaginary part of K on the moisture content of dry soils will allow better agreement between measured and computed moisture profiles for dry soils.

AIRCRAFT MEASUREMENTS AND ANALYSIS

In the second phase of this program, multifrequency aircraft measurements of a portion of the Phoenix Valley, Arizona, were analyzed in terms of soil moisture content and compared with brightness temperature values computed with a uniform media emission model. Aircraft data were obtained by the Goddard Space Flight Center. The sensor frequencies considered in these analyses are 1.42, 4.99, 19.35, 37 and 94 GHz. Ground-control soil moisture and temperature measurements were performed by Biospheric Incorporated[11] and AGC. Results from the dielectric studies of soils as a function of moisture content are also used in the analysis.

EXPERIMENTAL DATA

The Biospherics moisture measurements were obtained from soil samples taken in the 0 to 15 cm depth interval. The temperature measurements were performed at 7.5 cm below the soil's surface. Approximately 200 soil plots (each approximately 1/4 section) were investigated by Biospherics. Soil plot locations are available in a separate report[11]. Four moisture samples were taken from each soil plot. AGC performed detailed soil moisture and temperature measurements at four locations along the north-south flight lines. Typical depth intervals at which soil moisture and temperature measurements were performed by AGC include surface to 1, 2, 4, 8, 16, and 32 cm. AGC also performed 13.4 GHz radiometric measurements on each of the sites.

The AGC soil temperature measurements showed relatively good agreement with the aircraft infrared temperatures. Fortunately, the infrared measurements did not vary significantly during the overflights, hence an average $20^{\circ}C$ ($\pm 2^{\circ}C$) was used.

The correlation of the position of the aircraft (and hence radiometers) flight lines with the locations of the soil moisture measurements was made using information supplied by Goddard Space Flight Center. Although moisture measurements performed by Biospherics were taken in several hundred soil plots (each approximately 0.4 km square) along the flight lines, the number of cases in which one could state with reasonable certainty that a particular soil plot was being viewed by a particular radiometer was not large. Moreover, the set of soil plots was different for each altitude. To minimize the effect of finite beamwidth of the antenna, only those cases in which a soil plot encompassed most of the 3-dB antenna beam spot size were considered. Although this restriction limits the number of comparisons of measured results with those computed from the model of uniform media, it did allow, for the most part, statistically meaningful analyses at 1.42, 4.99, 37 and 94 GHz.

Since only bulk moisture data were available for large portions of the Phoenix Valley, it was necessary to employ the model of uniform media to compute brightness temperatures. Computations were made of predicted airborne brightness temperatures at 1.42, 4.99, 37 and 94 GHz. Atmospheric attenuation effects were also incorporated in the calculations.

Figure 7 provides a comparison of measured and computed temperatures for 1.42 and 4.99 GHz corresponding to data taken on February 25. Average moisture contents and plot numbers (defined by Biospherics) are also shown in the figures. Descriptions of vegetal cover and general conditions of the soil are also given in the figure. Several general comments are appropriate.

First, although the vertical and horizontal polarizations of the 1.42 GHz radiometer were pointed in the nadir position, a systematic difference of the order of 10 to 15 degrees occurs between the two polarizations with the vertical component greater. A somewhat similar situation holds for measurements at 4.99 GHz for the February flight. It is reasonable to assume that the primary agent responsible for the systematic errors occurring between the two polarizations are calibration errors (due, for example, to lack of precise calibration of antenna and waveguide losses) rather than a consistent anisotropic emission of the soil. However, this explanation is not entirely satisfactory (provided antenna and waveguide losses have not changed) since airborne measurements of the Salton Sea in Southern Calibornia (February 25) show the vertically polarized temperature at 1.42 and 4.99 GHz to be less than the horizontally polarized temperature[12].

Second, somewhat systematic differences occur between measured and computed temperatures at both 1.42 and 4.99 GHz. The systematic errors may be ascribed to radiometer calibration errors, roughness effects, and/or inadequacy of Wiener's dielectric mixing formula.

Third, the correlation of measured and computed brightness temperatures was best at 1.42 and 4.99 GHz. Note that directions of changes in the computed temperatures agree, in most cases, with the directions of changes in measured temperature at 1.42 and 4.99 GHz although the changes in magnitude of measured data are usually less than changes in computed results. Of special note are cases in which changes in measured temperatures agree with computed changes even in the presence of vegetal cover (alfalfa and wheat), see Plots 120 and 97 in Figure 7. The measurements in Plot 159 in Figure 7, however do not show the same agreement. The agreement in Plots 120 and 97 is probably related to the relatively high moisture contents (14.5 to 21 percent) while the disagreement in Plot 159 is probably related to the low moisture content (8 percent). This agrees with intuition since the contrast in emissivities between vegetal cover and dry soil is significantly less than the contrast between vegetal cover and wet soil. Carrying this conjecture slightly further, one can infer that detection of soil moisture through vegetal cover occurs when substantial amounts of water are contained in the underlying soil. Although penetration through certain forms of vegetal cover in reasonably moist soils appears possible at 1.42 and 4.99 GHz, a consistent response of 37 or 94 GHz data to soil moisture beneath vegetal cover was not apparent.

Finally, it appears that outside of systematic differences at 1.42 and 4.99 GHz, consistently better agreement occurs between measured and computed temperatures at lower frequencies (1.42 and 4.99 GHz) than at higher frequencies (37 and 94 GHz). Attributing the mechanism(s) that are responsible for this observation to small or large scale roughness effects of the soil is consistent with the intuitive feeling that what is slightly "rough" at lower frequencies is "rougher" at higher frequencies. However, a qualitative deduction of this sort really cannot be based on the above data since an equally plausible alternative can be made using the fact that the higher frequencies penetrate less in moist soils than lower frequencies. Thus, it is the near-surface moisture conditions which determine the high frequency radiometric emissions. Reasonable estimates of the depth of penetration or power skin depth δ presented earlier (Figures 3a, b, c, and d) indicate that for moisture contents greater than ten percent (by volume) the depth of penetration at 37 GHz is less than a free-space wavelength. Since relatively large changes in moisture concentration can occur between the 1 cm and 15 cm deep soil samples, it is not difficult to see that the poor agreement between measured and computed results at 37 and 94 GHz could be due to near-surface moisture variations which were not measured by the 15-cm-deep soil samples available for this study.

CORRELATION OF AIRBORNE MICROWAVE MEASUREMENTS AND SOIL MOISTURE CONTENT

As mentioned above, comparisons of presently available theory and measured airborne data reveal that a statistically meaningful dependence of measured brightness temperature on the measured soil moisture content occurs more conspicuously at the lower frequencies (1.42 and 4.99 GHz) than at the higher ones (37 and 94 GHz). In an attempt to provide quantitative information of the correlation of a set of measured brightness temperatures $\{T_i\}$ and a corresponding set of measured soil moisture values $\{M_i\}$ a correlation $\kappa(\{T_i\},\{M_i\}$ is defined

$$\kappa\left[\{T_i\},\{M_i\}\right] = \frac{\sum_{i=1}^{N}\left(T_i-\bar{T}\right)\left(M_i-\bar{M}\right)}{\sqrt{\sum_{i=1}^{N}\left(T_i-\bar{T}\right)^2}\sqrt{\sum_{i=1}^{N}\left(M_i-\bar{M}\right)^2}} \qquad i = 1, \ldots N \qquad (4)$$

N is the number of temperature or moisture measurements and $\bar{T}$ and $\bar{M}$ are averages defined by

$$\bar{T} = \frac{1}{N}\sum_{i=1}^{N} T_i \qquad (5)$$

$$\bar{M} = \frac{1}{N}\sum_{i=1}^{N} M_i \qquad (6)$$

Computations of κ were performed for the Phoenix Valley temperature data. A qualitative illustration of the dependence of the correlation coefficient κ with frequency is shown on Figure 8. Both polarizations were averaged for each frequency. The bars in the figure indicate the range of values of κ at each frequency. The 19.35 GHz data were not used. As can be seen, a substantial decrease in κ occurs with increasing frequency for the 15-cm moisture data. It is believed that larger negative values of κ (better correlation) would have occurred at the higher frequencies had ground-based moisture measurements been taken over shallower depth intervals.

CONCLUSIONS

The ultimate goal of research reported herein is the development of a practical remote sensing technique for synoptic aerial and/or satellite mapping of the horizontal and vertical distribution of soil moisture. The initial step toward this goal has been an integrated research program consisting of numerical modeling, laboratory and field measurements and airborne data studies to establish the basic relationships between microwave emission and the hydrological properties of soil. Ground-based experiments were designed so that vegetal cover or terrain irregularities may be neglected.

Comparisons of ground-based measured brightness temperatures of a sandy soil at 21.4, 6.0, 2.2 and 0.81 cm for 30, 40 and 50 degree view angles (from nadir) with those computed from the recent theory of vertically structured media using measured vertical profiles of moisture and temperature reveal that a semi-quantitative understanding of the microwave emission properties of the soil has been achieved. Generally speaking, the agreement between measured and computed temperatures was good over a large range of moisture conditions. The major sources of uncertainties arising in the comparisons were attributed to (1) measurement errors, (2) lack of dielectric constant measurements at 21.4 and 6.0 cm and (3) lack of dielectric mixing formula to fit measured data completely satisfactorily.

A model was hypothesized to allow a computation of the vertical distribution of soil moisture (per unit area) using the ground-based measured horizontally polarized brightness temperatures and the soil surface temperature. A comparison of measured moisture profiles with those computed from 21.4, 6.0, 2.2 and 0.81 cm data for 30, 40 and 50 degree view angles shows that excellent agreement occurs for cases of reasonably damp to saturated soil conditions (8 to 30 percent moisture, dry weight basis). The agreement for "dry" soils was found to be poor. This lack of agreement is attributed to present uncertainties in the loss tangent measurements of low-loss soils since the greatest sensitivity of the soil skin depth occurs at low moisture concentrations. An interesting feature in the comparison of measured and computed moisture profiles was the fact that best agreement occurred at high moisture concentrations where uncertainties in measured brightness temperatures were apparently largest. Thus, it appears that the proposed empirical model depends more heavily on an accurate knowledge of the skin depth than on present microwave measurement uncertainties. This limitation can be removed by obtaining more precise dielectric constant data for soil and by developing improved mixing formulas.

A comparison of measured airborne brightness temperatures of the Phoenix agricultural farmlands with those computed from presently available theoretical models (uniform media and vertically structured media models) reveals that statistically meaningful agreement occurred at 1.42 and 4.99 GHz except for systematic differences listed below. Less agreement occurred between the measured and computed 37 and 94 GHz data.

The systematic differences observed in the comparisons at lower frequencies can arise from the following sources: (1) aircraft radiometer calibration errors, (2) roughness effects and (3) inadequacy of Wiener's dielectric mixing formula which is used in the computation of brightness temperatures. A check on the absolute calibration of the radiometers reveals that (1) can account for a portion but not all of the differences. Results of an earlier study indicate that (3) can account for about half of the difference. No estimates of (2) can be made at present due to the lack of theory of the emission of diffuse substances and the lack of properly controlled experimental data.

Of special note is the apparent penetration through alfalfa and wheat (25 cm and 15 cm tall, respectively) in several cases at 1.42 and 4.99 GHz. The penetration was noted only in cases where the underlying soil had substantial amounts of moisture in excess of 14 to 21 percent (dry weight basis). Lack of detectable penetration of vegetal cover over relatively dry soil is probably due to the lack of significant contrast in the emissivities of vegetal cover and dry soil. Vegetal penetration at the higher frequencies (19.35, 37 and 94 GHz) was not observed with any discernible consistency.

The decrease in agreement of theory and measured data at 37 and 94 GHz compared with the agreement obtained at 1.42 and 4.99 GHz may be attributed to: (1) roughness effects and (2) lack of penetration into moist soils. As before, estimate of (1) cannot be made at present due to lack of experimental controlled data. Estimates of the depth of penetration indicate the emission at 37 and 94 GHz is controlled by the moisture contained in the near-surface regions of soils. (Approximately one free-space wavelength for moisture contents greater than 6.5 percent on dry weight basis.) Thus, the lack of correlation in the measured and computed 37 and 94 GHz temperatures can be due to near-surface moisture changes which were not detected in the 15-cm-deep soil samples.

An analysis of a correlation coefficient using measured and computed brightness temperatures with measured soil moisture data at all frequencies shows substantial agreement with the results mentioned above. That is, values of the correlation coefficients were consistently larger in magnitude at 1.42 and 4.99 GHz than at 37 and 94 GHz.

REFERENCES

1. Poe, G., A. Stogryn and A. T. Edgerton, "Determination of Soil Moisture Content Using Microwave Radiometry," Final Tech. Report, 1684R-1, Aerojet-General Corp., El Monte, Calif., Contract No. 0-35239, June, 1971.

2. Stogryn, A., "The Brightness Temperature of a Vertically Structured Medium," Radio Science, Vol. 5, No. 12, Dec., 1970.

3. Stratton, J., *Electromagnetic Theory*, McGraw-Hill Co., N. Y., 1941.

4. Poe, G., "Determination of Dielectric Properties of Natural Materials," Tech. Report No. 5, SD9016-5, Aerojet-General Corp., El Monte, Calif., Contract NOnr 4767(00)NR387-033, Feb., 1970.

5. Rayleigh, Lord (J. W. Strutt), "On the Influence of Obstacles A Arranged in Rectangular Order on the Properties of a Medium," Phil. Mag., 34, 1892.

6. Wiener, O., "leipziger Berichte," 62, 1910.

7. Bottcher, C., *Theory of Electric Polarization*, Elsevier, Amsterdam, 1952.

8. Pierce, C., "The Permittivity of Two Phase Mixtures," Brit. J. A. Phys., Vol. 6, Oct., 1955.

9. von Hippel, A., *Dielectric Materials and Applications*, MIT Press, Cambridge, Mass., 1954.

10. Stogryn, A., "Equations for Calculating the Dielectric Constant of Saline Water at GHz Frequencies," IEEE Trans. on MTT, Aug., 1971.

11. Biospherics Incorporated, "Soil Moisture Ground Truth Data for Correlation with Microwave Radiation Data," Contract No. NAS 5-21610, April 1971, Rockville, Maryland.

12. Poe, G. and A. T. Edgerton, "Determination of Soil Moisture Content with Airborne Microwave Radiometry," Final Tech. Report (to be published), 4006R-1, Aerojet-General Corp., El Monte, Calif., Contract No. 1-35378.

Table I

DIELECTRIC CONSTANT MEASUREMENTS AT 37 and 13.4 GHZ

Freq (GHz)	Temp (^oK)	% Moisture (Dry Wt)	Density (g/cm^3)	K'	K''
37	300	2.4	1.51	2.2 ± 0.15	<0.06
37	296	12.0	1.6	3.5 ± 0.2	1.0 ± 0.1
37	296	22.0	1.70	7.6 ± 0.4	3.5 ± 0.3
37	295	25.0	1.75	9.0 ± 0.4	5.0 ± 0.5
37	293	40.0	1.81	13.0 ± 0.5	9.0 ± 0.9
13.4	296	2.0	1.50	2.35 ± 0.15	< 0.06
13.4	294	18.0	1.75	5.8 ± 0.5	1.4 ± 0.1
13.4	293	28.0	1.80	23.0 ± 3.0	8.5 ± 1.5

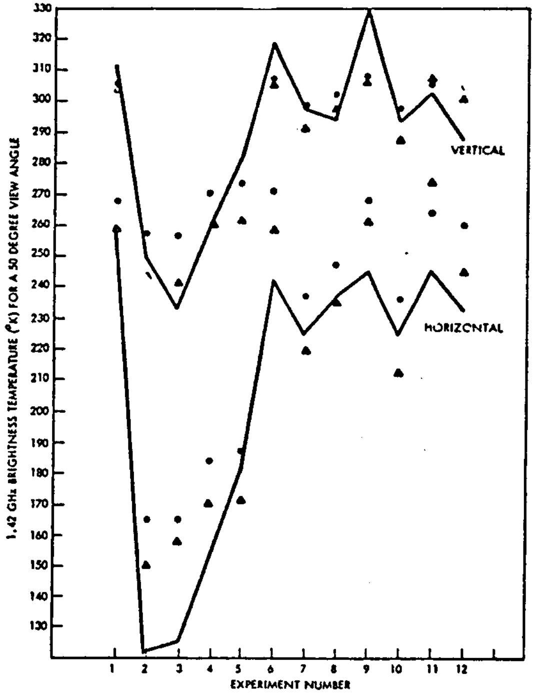

Figure 1. Comparison of measured and computed 1.42 GHz brightness temperatures. —— indicates measured temperatures while ● and ▲ indicate computed temperatures with form numbers = 32 and 64, respectively.

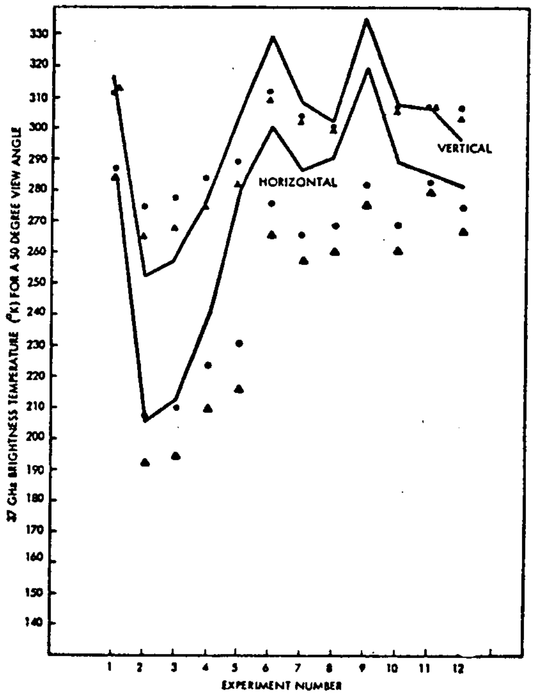

Figure 2. Comparison of measured and computed 37 GHz brightness temperatures. —— indicates measured temperatures while ● and ▲ indicate computed temperatures with form numbers = 16 and 32, respectively.

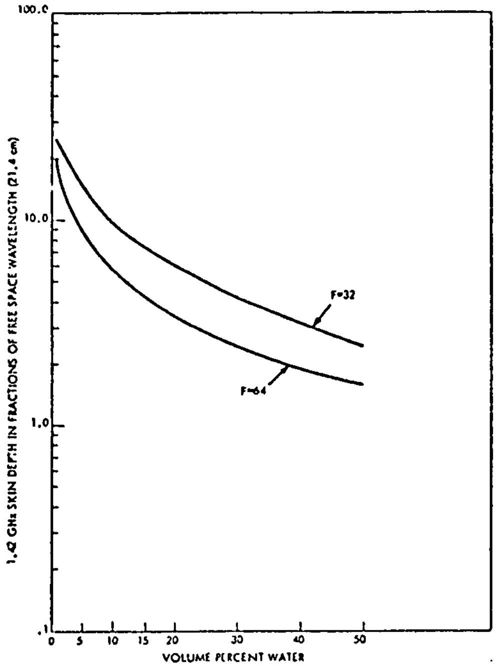

Figure 3a. Skin depth at 1.42 GHz as a function of the volume percentage of water computed from Wiener's mixing formula with form numbers 32 and 64.

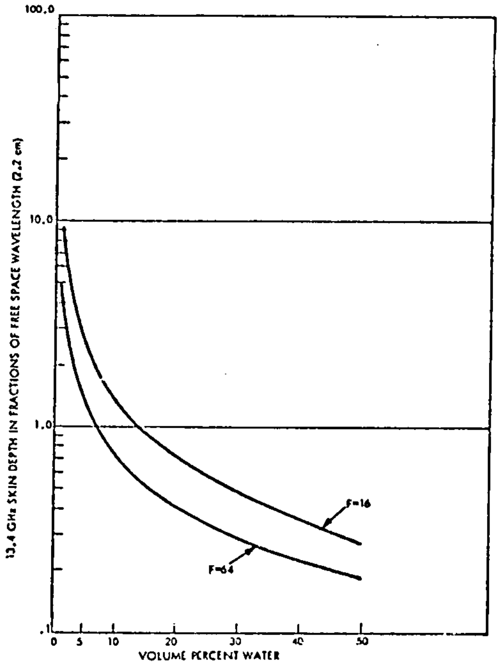

Figure 3b. Skin depth at 13.4 GHz as a function of the volume percentage of water computed from Wiener's mixing formula with form numbers 16 and 64.

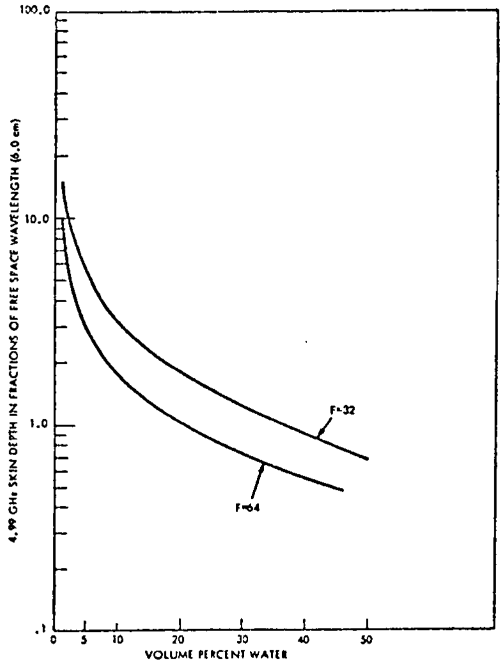

Figure 3c. Skin depth at 4.99 GHz as a function of the volume percentage of water computed from Wiener's mixing formula with form numbers 32 and 64.

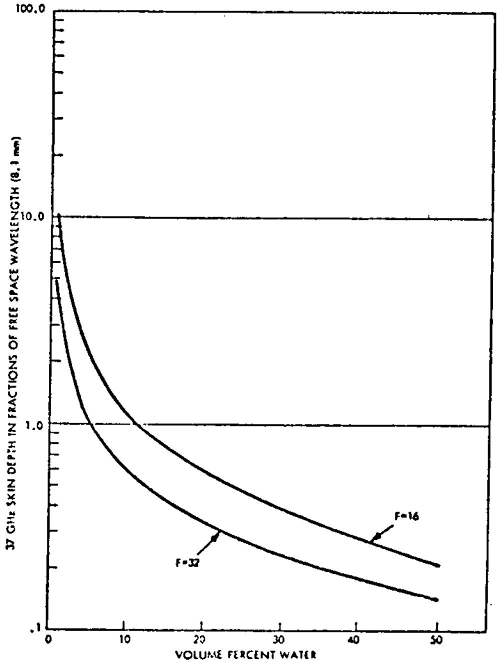

Figure 3d. Skin depth at 37 GHz as a function of the volume percentage of water computed from Wiener's mixing formula with form numbers 16 and 32.

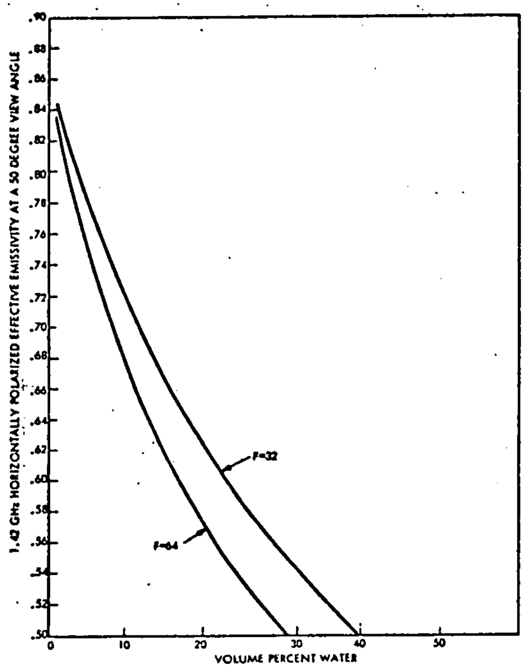

Figure 4a. Horizontally polarized 50° view angle effective emissivity at 1.42 GHz as function of the volume percentage of water computed from Wiener's mixing formula with form numbers 32 and 64.

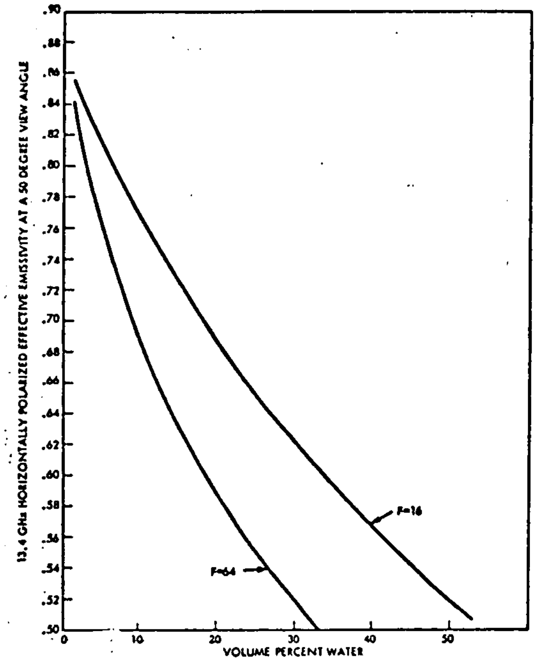

Figure 4b. Horizontally polarized 50° view angle effective emissivity at 13.4 GHz as function of the volume percentage of water computed from Wiener's mixing formula with form numbers 16 and 64.

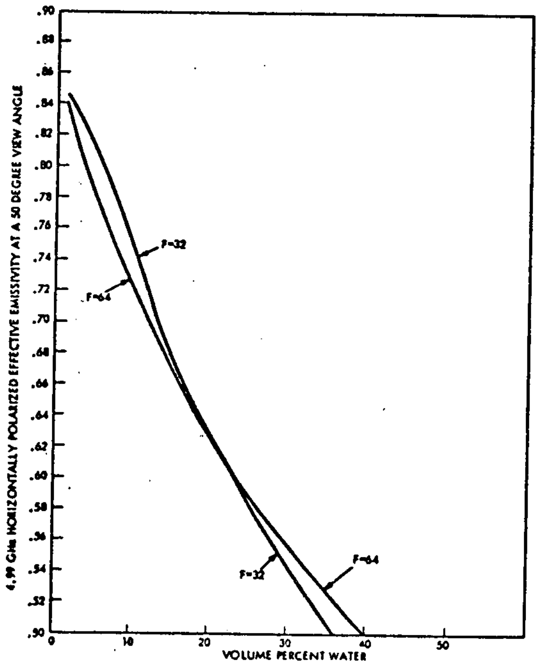

Figure 4c. Horizontally polarized 50° view angle effective emissivity at 4.99 GHz as function of the volume percentage of water computed from Wiener's mixing formula with form numbers 32 and 64.

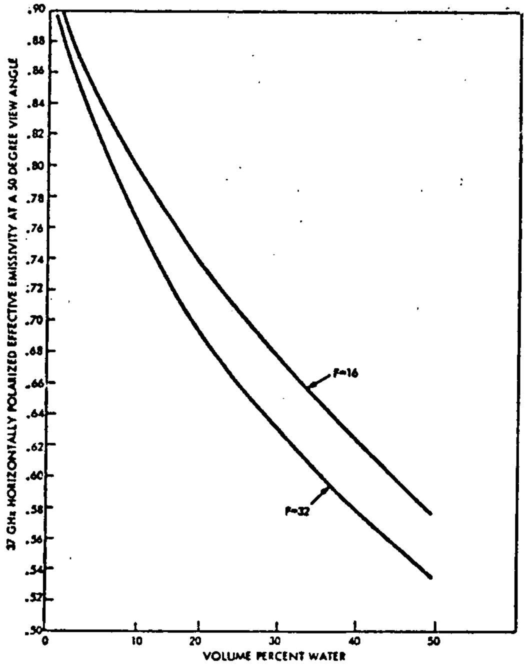

Figure 4d. Horizontally polarized 50° view angle effective emissivity at 37 GHz as function of the volume percentage of water computed from Wiener's mixing formula with form numbers 16 and 32.

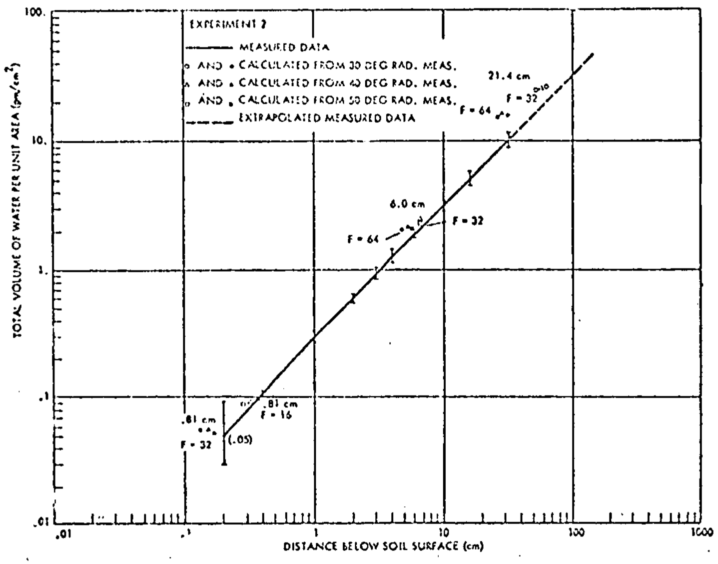

Figure 5. Comparison of measured and computed vertical moisture profiles for Experiment 2. Wavelengths are indicated near computed results with Form Numbers F.

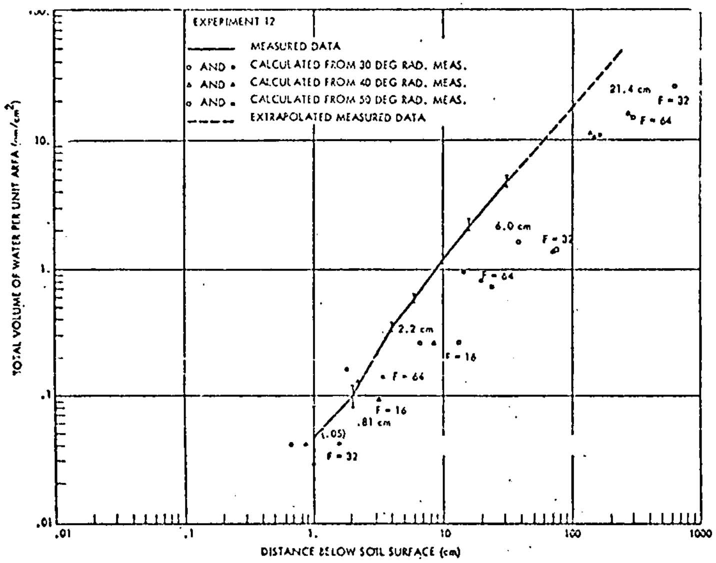

Figure 6. Comparison of measured and computed vertical moisture profiles for Experiment 12. Wavelengths are indicated near computed results with Form Numbers F.

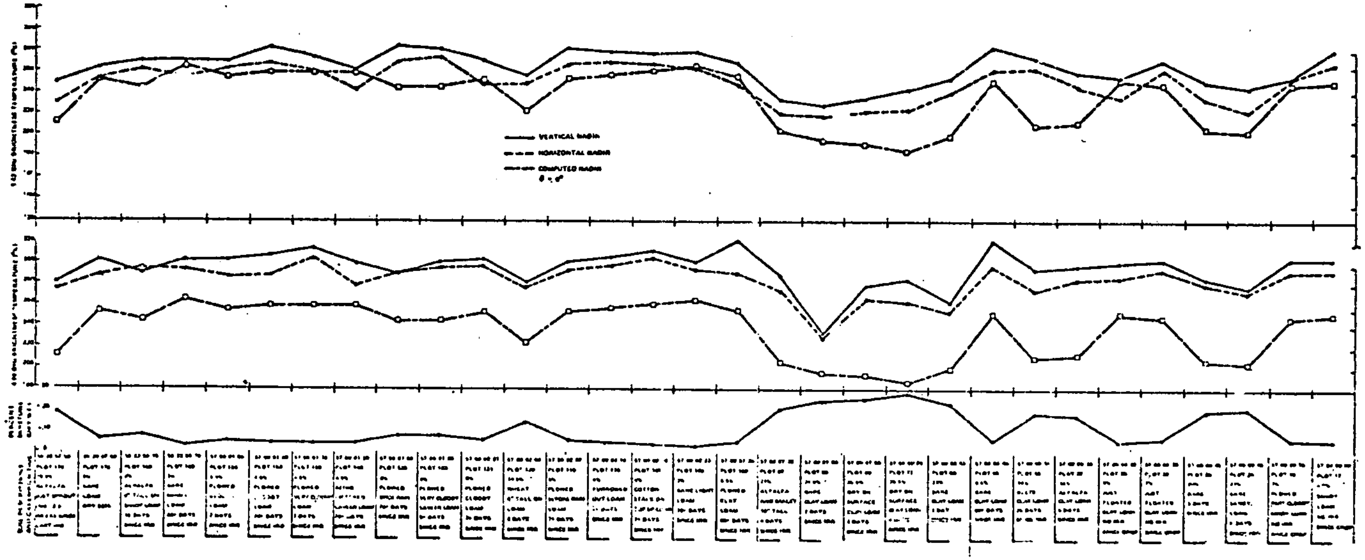

Figure 7. Comparison of airborne and computed 1.42 and 4.99 GHz brightness temperatures for the February soil moisture flight at 0.9 km altitude. Soil descriptions and integrated 15 cm deep soil moisture values are shown. Computations are based on the uniform model.

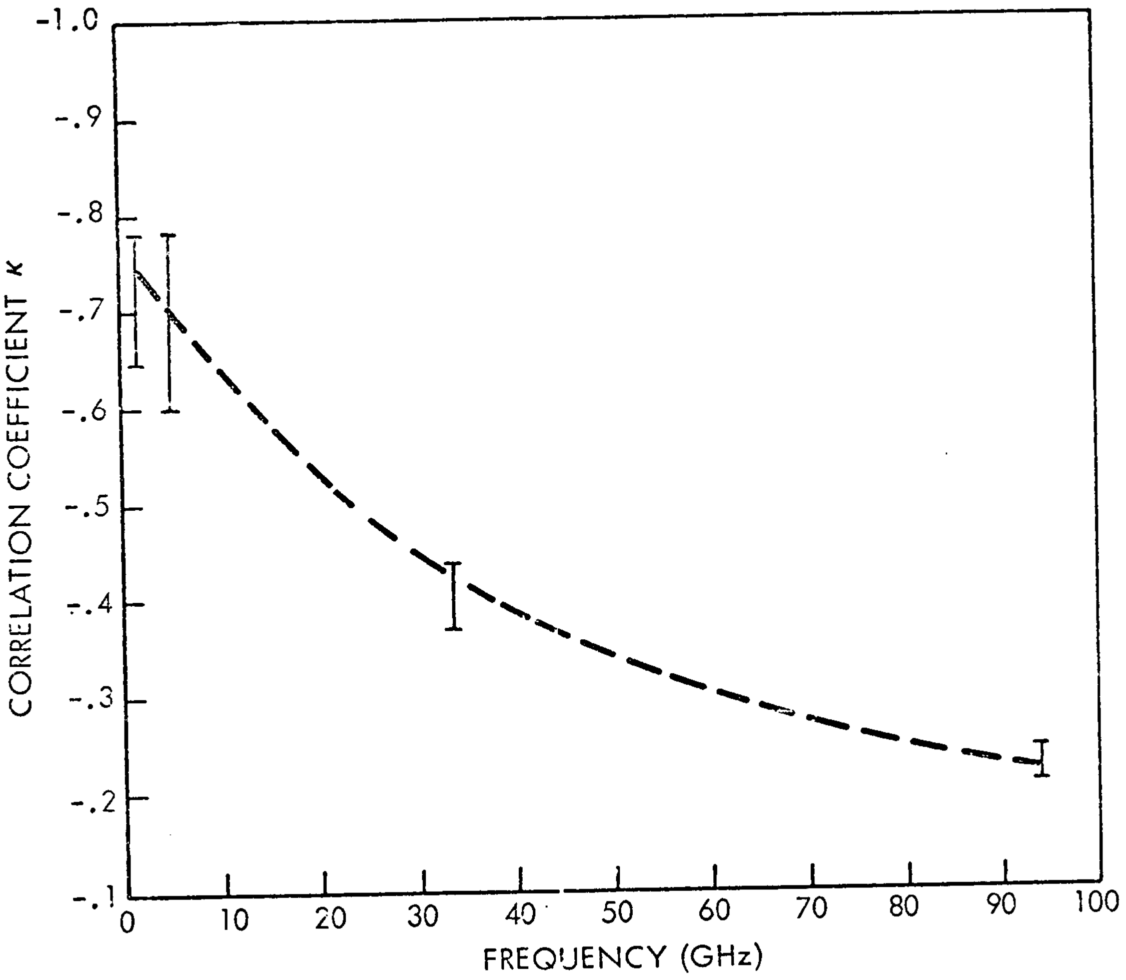

Figure 8. Correlation Coefficient versus Frequency