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REMOTE SENSING OF SOIL MOISTURE

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1. Introduction

The unique thermal and dielectric properties of water afford two possibilities for remotely sensing the moisture content of soils. The large heat capacity and thermal conductivity of water enable moist soils to have a large thermal inertia. This thermal inertia can be remotely sensed by observing the diurnal range of surface temperature.

The dielectric constant for water is an order of magnitude larger than that of dry soils at microwave wavelengths ($30 > \lambda > 1$ cm). As a result the surface emissivity and reflectivity for the soil are strong functions of its moisture content. The changes in emissivity can be observed by passive microwave techniques (radiometry) and the changes in reflectivity can be observed by active microwave techniques (radar).

Both of these approaches, thermal and microwave, have been demonstrated in extensive field measurements, and to a certain extent in measurements made from aircraft and spacecraft platforms. The measurements have indicated that these methods are responding to the moisture in the 0 to 5 cm surface layer. It is, however, the moisture content of this layer that determines the evaporation of moisture from bare ground.

In this paper we will discuss these results and indicate the relative advantage of each method.

2.1 Thermal Methods

The amplitude of the diurnal range of surface temperature for the soil is a function of both internal and external factors. The internal factors are thermal conductivity (K), and heat capacity (C), where $P = (KC)^{1/2}$ defines what is known as "thermal inertia." The external factors are primarily meteorological; solar radiation, air temperature, relative humidity, cloudiness, wind, etc. The combined effect of these external factors is that of the driving function for the diurnal variation of surface temperature. Thermal inertia then is an indication of the soil's resistance to this driving force. Since both the heat capacity and thermal conductivity of a soil increase with an increase of soil moisture, the resulting diurnal range of surface temperature will decrease.

The basic phenomena are illustrated in figure 1, which presents surface temperatures as measured with a thermocouple for a field versus time, before and after irrigation. These data were obtained by Dr. Ray Jackson and his colleagues at the U.S. Water Conservation Laboratory in Phoenix and have been published in a recent paper [1].

The solid line in figure 1 is the plot of surface temperature before irrigation, and the filled circles reflect the data on the day following irrigation. There is a dramatic difference in the maximum temperature achieved on these two days. On succeeding days the maximum temperature increases as the field dries out.

The summary of results from many such experiments is shown in figure 2 where the amplitude of the diurnal range is plotted as a function of the soil moisture as measured at the surface and at 0- to 1-cm, 0- to 2-cm, and 0- to 4 cm layers. There is a good correlation with the soil moisture in the 0- to 2-cm and 0- to 4-cm layers of the soil, and this response is related to the thermal inertia of the soil. Initially, when the surface is moist, the temperatures are more or less controlled by evaporation. Once the surface layer dries below a certain level, the temperature will be determined by the thermal inertia of the soil. These results indicate that for this particular soil, the diurnal range of surface temperature is a good measure of its moisture content.

When these measurements are repeated for different soils, there are differences which depend on the soil type. However, there are certain characteristics that are independent of the soil type, and these relate to the evaporation of the water from the soil. Soil physicists have characterized the drying of a soil in three stages. They are:

- The wet stage, where the evaporation is solely determined by the meteorological conditions;
- An intermediate or drying stage where it starts out being in the wet stage early in the day, but because there is not a sufficient amount of water in the soil to meet the evaporative demand, the evaporation rate falls off; and
- The dry stage, where evaporation is solely determined by the molecular transfer properties of water within the soil

There is a striking change in both the albedo and the evaporation rate as the soil dries during the transition from the wet stage to drying stage.

Temperature measurements were repeated for different soil types, and the results indicate that the transitions from the wet stage to the drying stage occur at about the same values of ΔT for the different soils. Figure 3 summarizes these results for three different soil types. The soils ranged from sandy or light soils to heavy clay soils, and it is clear that for a given diurnal temperature difference, there can be a wide range of moisture content for these soils.

However, it has been observed that, as these soils dry out, the ΔT is approximately the same for these soil types during transition from the wet stage to the intermediate stage. Similarly, at the transition from the intermediate stage to the final stage, or the dry stage, again the ΔT is approximately the same for these soil types. Thus, this technique can be used, while not to give an absolute value of soil moisture, at least to determine the qualitative state of the moisture in the soil independent of soil type.

I would like to emphasize that these experiments were all made in a field, using thermal-couples, and were not remotely sensed. In March, 1975, an experiment was performed in which remotely sensed thermal infrared temperatures were compared with the in situ thermocouple measurements over a 5 day period. There was good agreement between the thermocouple measurements and the remotely sensed radiation measurements made from the aircraft [2] indicating that the conclusions based on the thermocouple measurements would also be valid for radiation temperature observation.

This approach will be studied further by additional high altitude aircraft flights and by the Heat Capacity Mapping Radiometer to be on the first Applications Explorer Satellite which will be launched in 1978.

2.2 Passive Microwave Response to Soil Moisture

The basis for the use of microwave techniques for soil moisture sensing is the dramatic change in the dielectric properties of a soil as its moisture content increases. This is demonstrated in figure 4 where the dielectric constants of a clay loam soil at wavelengths of 21 cm [3] and 1.55 cm [4] are plotted versus soil moisture. This range of dielectric constant produces a change in emissivity from 0.9 for a dry soil to less than 0.6 for a wet soil, assuming an isotropic soil with a smooth surface. This change in emissivity for a soil has been observed by truck mounted radiometers in field experiments [5], [6], and by radiometers in aircraft [4] and satellites. [7] In no case were emissivities as low as 0.6 observed for real surfaces; we believe that this is primarily due to the effects of surface roughness which generally has the effect of increasing the surface emissivity.

At microwave wavelengths the intensity of the observed emission is essentially proportioned to the product of the temperature and emissivity of the surface (Rayleigh-Jeans approximation), this product is commonly referred to as brightness temperature. All our results will be expressed as brightness temperatures.

In this report we will primarily discuss the data acquired during various aircraft experiments. The microwave radiometers were in the wavelength range of 0.8 to 21 cm (37 GHz to 1.4 GHz). They were flown over agricultural test sites around Phoenix, Arizona and in The Imperial Valley of Southern California on the same day ground measurements of soil moisture were also made.

An example of the results from these flights is presented in figure 5. This is a plot of the 21 cm and thermal IR brightness temperatures for an East-West track over the Imperial Valley, starting over the Salton Sea and ending over the desert east of the agricultural area. Brightness temperatures for the sea, desert, and several agricultural fields with a range of moisture contents are indicated. These results indicate the range of brightness temperatures that can be expected.

Brightness temperatures for the individual fields were compared with ground measurements of soil moisture. Figure 6 gives the results for the 1.55 cm scanning radiometer and the average soil moisture in the top cm from the three flights in 1972 for light soils (sandy loam and loam) and heavy soil (clay loam). The range of brightness temperature is the same for both soil types and there is clearly a linear decrease of brightness temperature with soil moisture. The depression of the brightness temperature for a given moisture content is less for the heavy soils (greater field capacity) than for the light soils. The slope is less for the heavier soils because of the greater range of soil moisture that is possible for these soils. If the soil moisture is expressed as the percent of field capacity for the soil, this difference can be accounted for as shown in figure 7. Visually the scatter in the data is reduced and the correlation coefficient for these data is greater than for the light and heavy soils separately.

Similar behavior is observed for the brightness temperatures obtained with the 21 cm radiometer, i.e., a linear response when plotted as a function of the soil moisture expressed as percent of field capacity in the top centimeter (figure 8). When plotted versus the same quantity for the 2.5 cm layer there appears to be flat region out to about 50% of field capacity where the linear decrease begins. When the brightness temperatures are compared with the moisture in the 5 cm layer the flat region extends to higher moisture values. The behavior of the 21 cm results is qualitatively similar to those observed at 1.55 cm except that there was a greater range of brightness temperatures observed at 21 cm (about 100°K) than at 1.55 cm which is consistent with the larger dielectric constant for water at the longer wavelength. Thus the 21 cm radiometers appear to be responding to the moisture in a layer 1 to 2 centimeters thick at the surface.

Another advantage of the longer wavelength system is its ability to observe moisture variations through moderate amounts of vegetation. This is demonstrated in figure 9 which presents the results for fields with covers of small grains or alfalfa up to about 15 or 20 cm high. The results at 1.55 cm were essentially independent of soil moisture, because the shorter wavelength radiometer was responding to the emission from the vegetation only.

2.3 Active Microwave Response to Soil Moisture

The backscattering from an extended target, such as a soil medium, is characterized in terms of the target's scattering coefficient $\sigma°$. Thus, $\sigma°$ represents the link between the target properties and the scatterometer responses. For a given set of sensor parameters (wavelength, polarization and incidence angle relative to nadir), $\sigma°$ of bare soil is a function of the soil surface roughness and dielectric properties which depends on the moisture content. The variations of $\sigma°$ with soil moisture, surface roughness, incidence angle, and observation frequency have been studied extensively in ground based experiments conducted by Dr. F. T. Ulaby at the University of Kansas [8].

To understand the effects of look angle and surface roughness consider the plots of $\sigma°$ versus angle presented in figure 10 for three fields with essentially the same moisture content but with considerably different surface roughness. At the longest wavelength (2.75 GHz, figure 10a), $\sigma°$ for the smooth field is very sensitive to incidence angle near nadir, while for the rough field $\sigma°$ is almost independent of angle. At an angle of 5° the effects of roughness are minimized. As the wavelength decreases, figure 10b, all the fields appear rougher, especially the smooth field, and as a result the intersection point of the three curves moves out to larger angles. At 4.75 GHz the intersection occurs at 10°, and it was at this combination of angle and frequency that yielded the best sensitivity to soil moisture independent of roughness. The results are presented in figure 11 and considering the range of surface roughness included in the analysis the correlation of 0.69 is rather good.

3. Discussion

At the present time none of the three methods presented here has the clear advantage for being the preferred method of remote sensing of soil moisture. The thermal IR approach has the advantage of providing useful thermal data that may be an indicator of crop status and is capable of providing soil moisture data at high spatial resolutions. However the usefulness of this approach is lost in the presence of cloud cover. The ability of the microwave sensors to penetrate non-raining clouds makes them very attractive for use as soil moisture sensors. The passive microwave technique has been demonstrated by both aircraft and spacecraft instruments, but the spatial resolution is limited by the size of the antenna which can be flown. For example at a wavelength of 21 cm, a 10 x 10 m antenna is required to yield 10 km resolution from a satellite altitude of 500 km. It is possible to make use of the coherent nature of the signal in active microwave systems (Synthetic Aperture Radar, SAR) to obtain better spatial resolutions [9]. However, the capabilities of such systems for soil moisture sensing remain to be demonstrated from either aircraft or spacecraft platforms. Also the strong effects of incidence angle and surface roughness make the unambiguous determination of soil moisture difficult with this type of sensor.

While no one system will provide the answer alone, I expect that some combination of a low and high resolution system will be able to provide useful soil moisture information in the near future.

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FIGURE CAPTIONS

1. Diurnal surface temperature variation

2. Summary of results for the diurnal temperature variation versus soil moisture

3. Effect of soil type on the temperature difference versus soil moisture relationship

4. Soil dielectric constant versus soil moisture

5. Infrared (10-12 μm) and 21 cm brightness temperature over Imperial Valley, California

6. Plots of 1.55 cm brightness temperature versus soil moisture for light soil (sandy loam and loam) and heavy soil (clay loam) for bare fields

7. Plot of 1.55 cm brightness temperature versus soil moisture expressed as a percent of field capacity for bare fields

8. Plot of 21 cm brightness temperatures versus soil moisture expressed as a percent of field capacity for bare fields

9. Plot of 21 cm brightness temperatures for vegetated fields

10a. Angular response of σ° for three bare fields with similar moisture conditions but different surface roughnesses (2.75 GHz)

10b. Angular response of σ° for three bare fields with similar moisture conditions but different surface roughnesses (7.25 GHz)

11. Soil moisture response of σ° for the three surface roughnesses

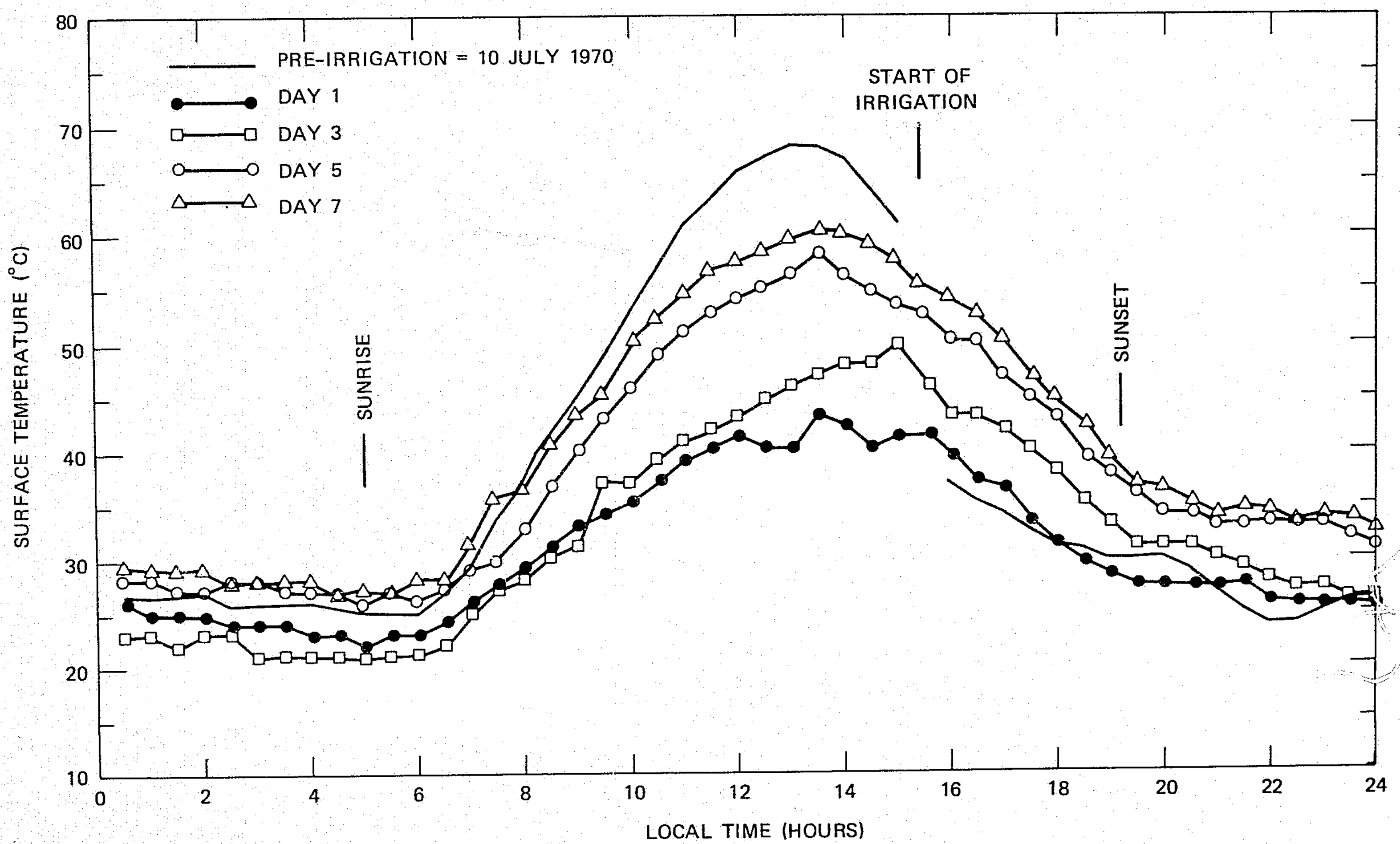


Figure 1. Diurnal surface temperature variation

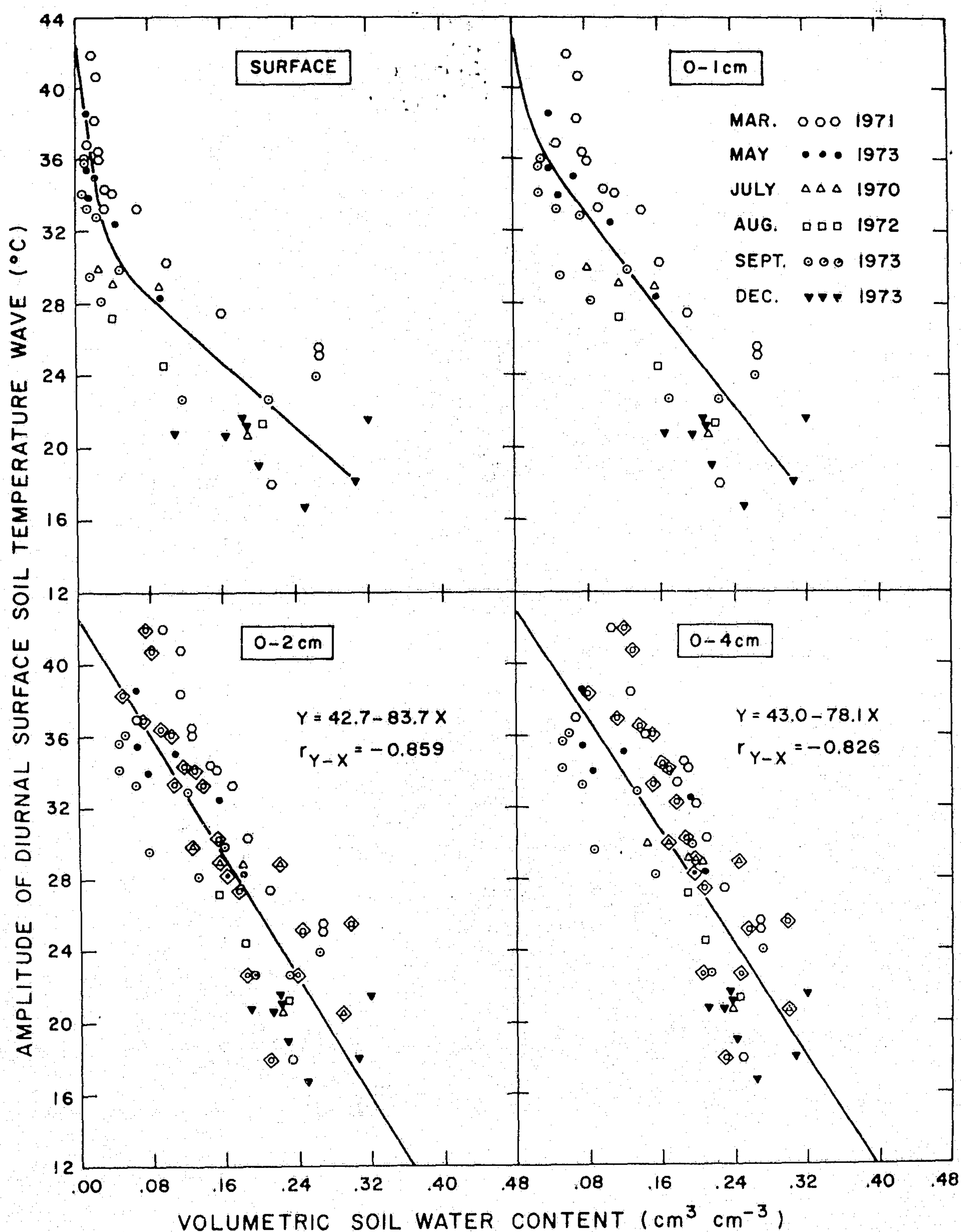


Figure 2. Summary of results for the diurnal temperature variation versus soil moisture

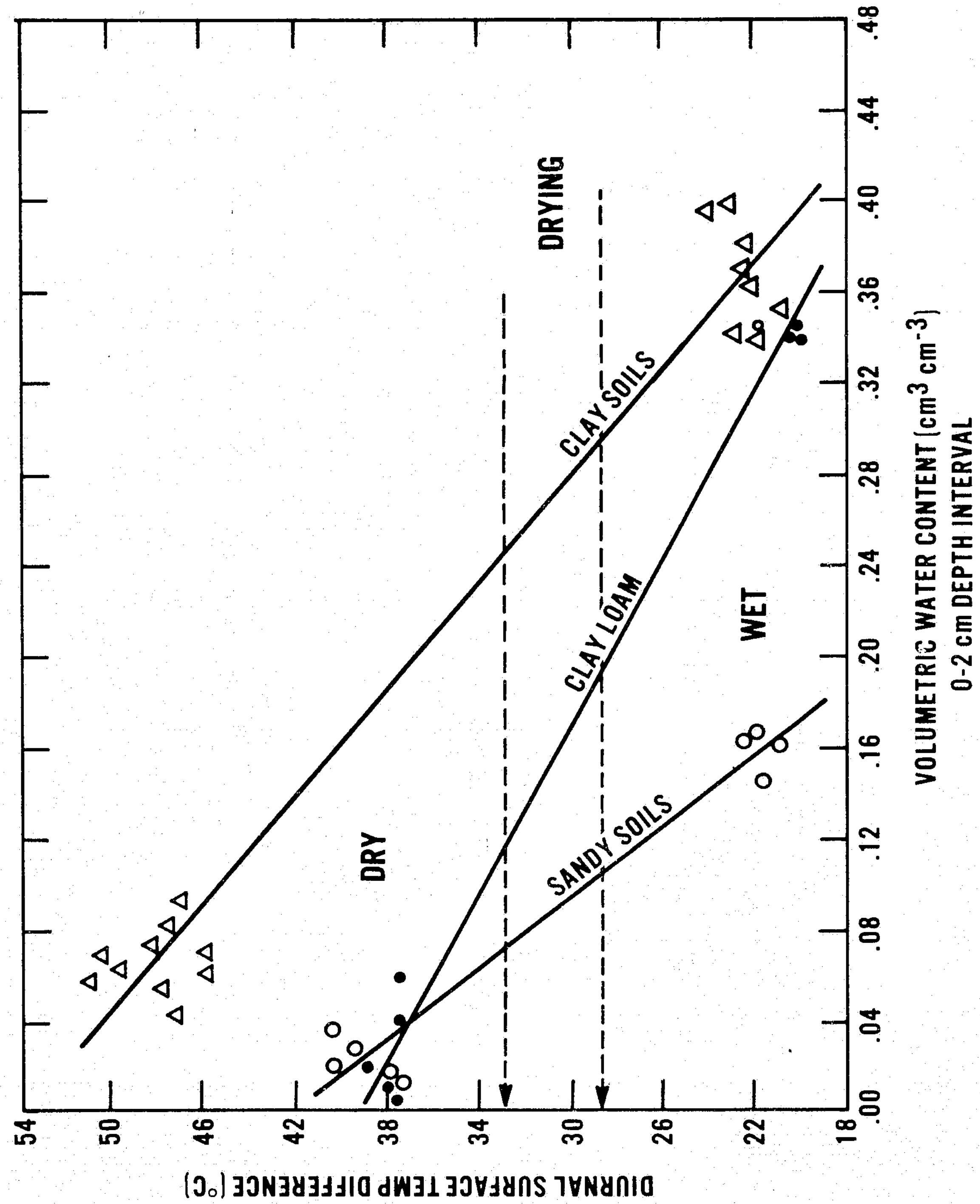


Figure 3. Effect of soil type on the temperature difference versus soil moisture relationship

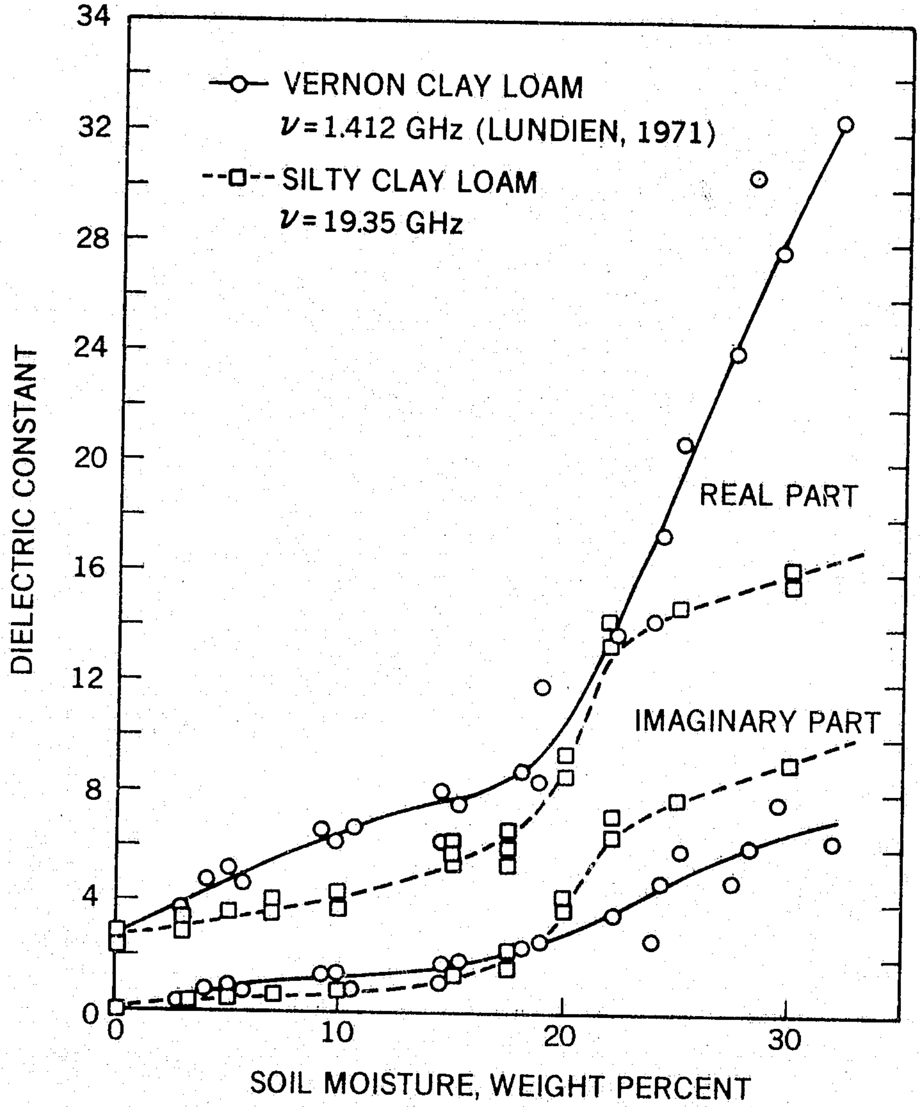


Figure 4. Soil dielectric constant versus soil moisture

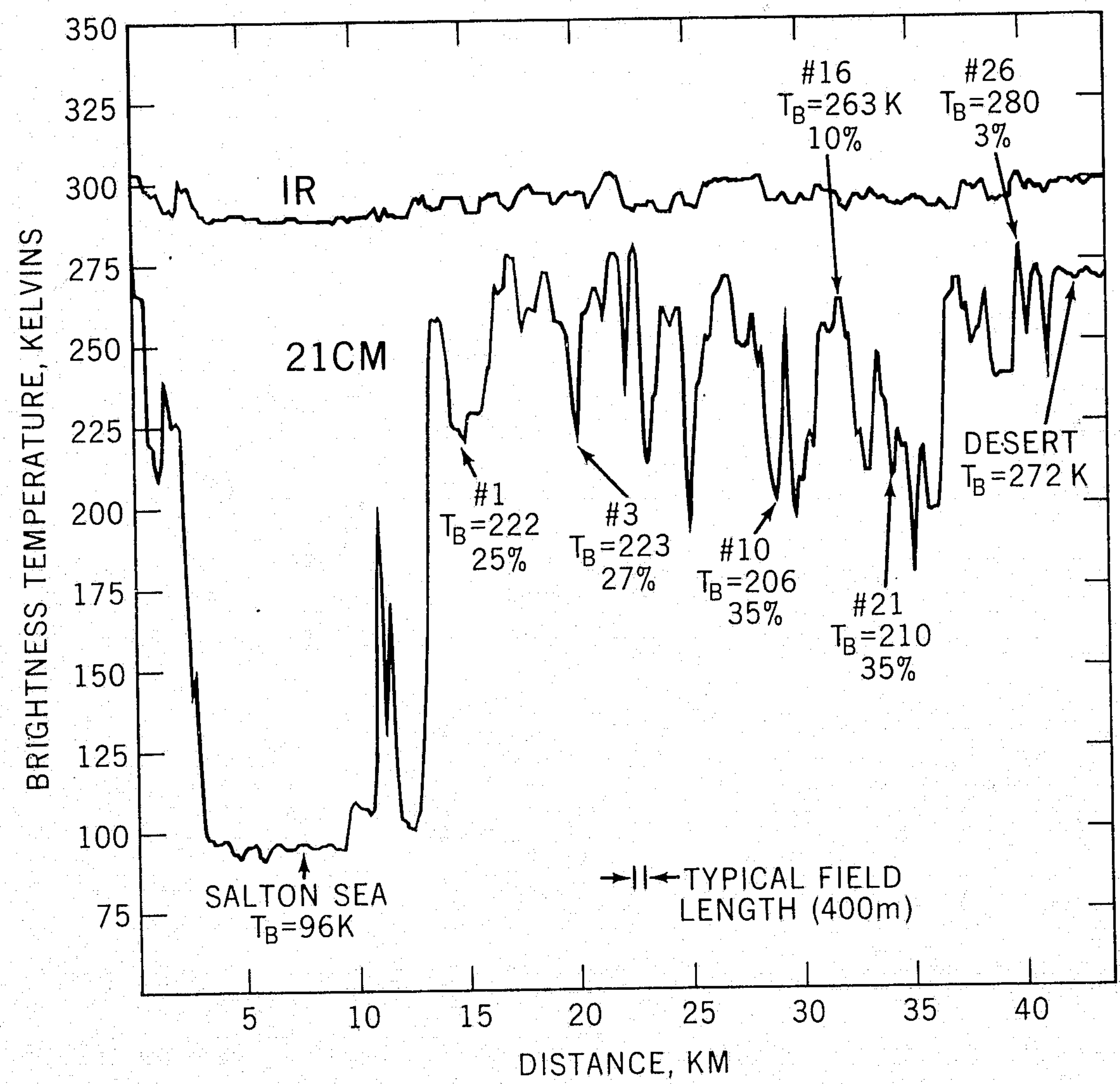


Figure 5. Infrared (10-12 μm) and 21 cm brightness temperature over Imperial Valley, California

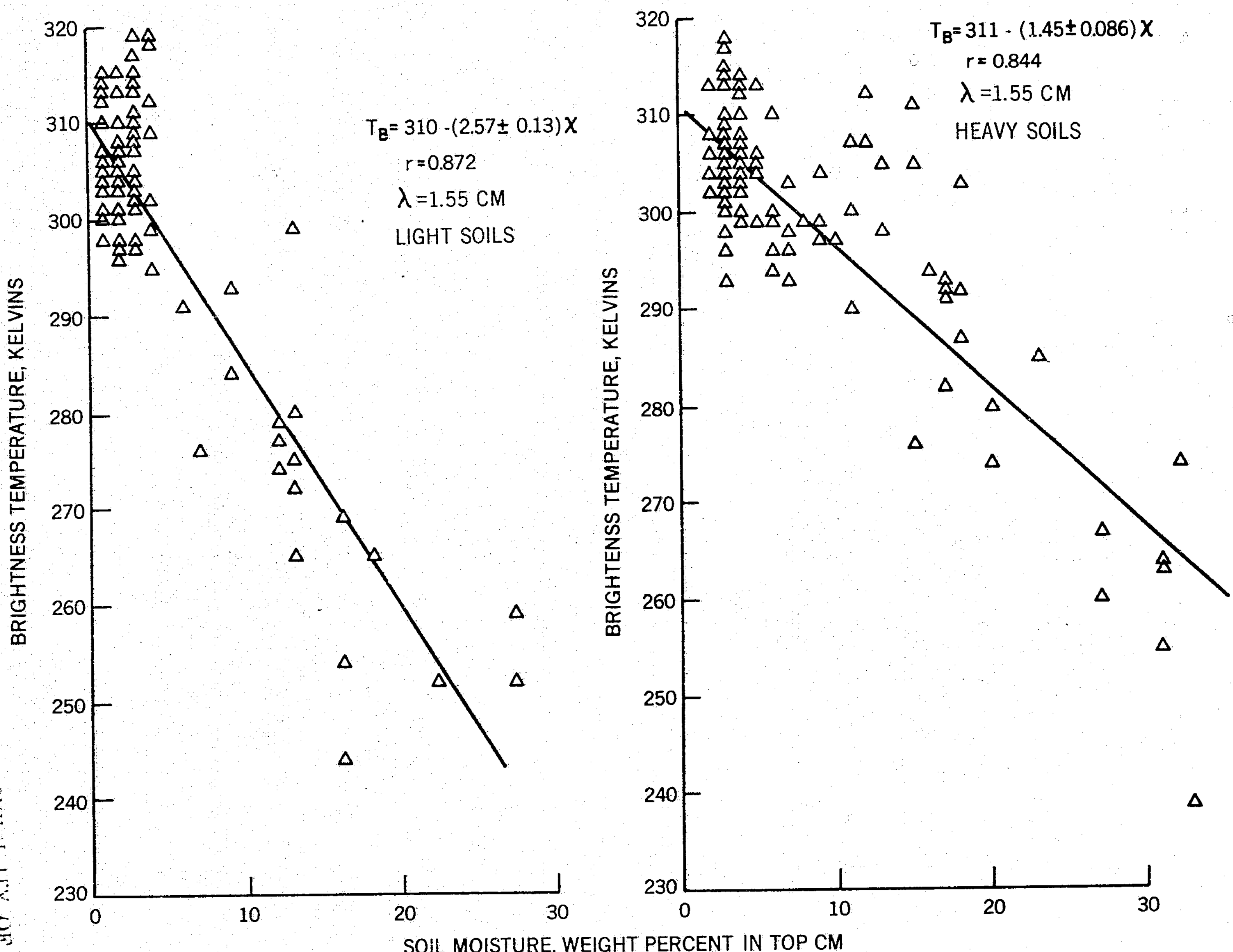


Figure 6. Plots of 1.55 cm brightness temperature versus soil moisture for light soil (sandy loam and loam) and heavy soil (clay loam) for bare fields

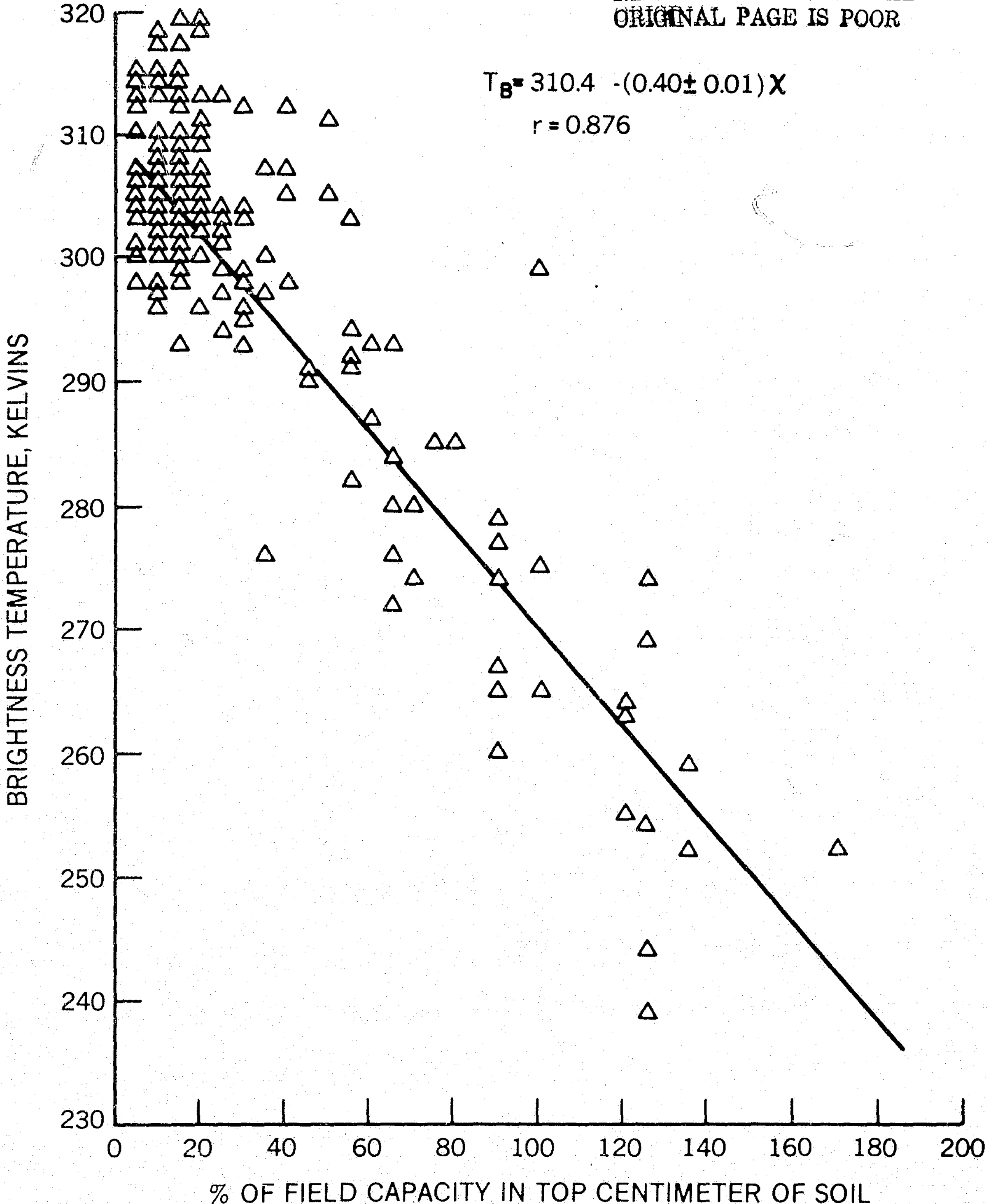


Figure 7. Plot of 1.55 cm brightness temperature versus soil moisture expressed as a percent of field capacity for bare fields

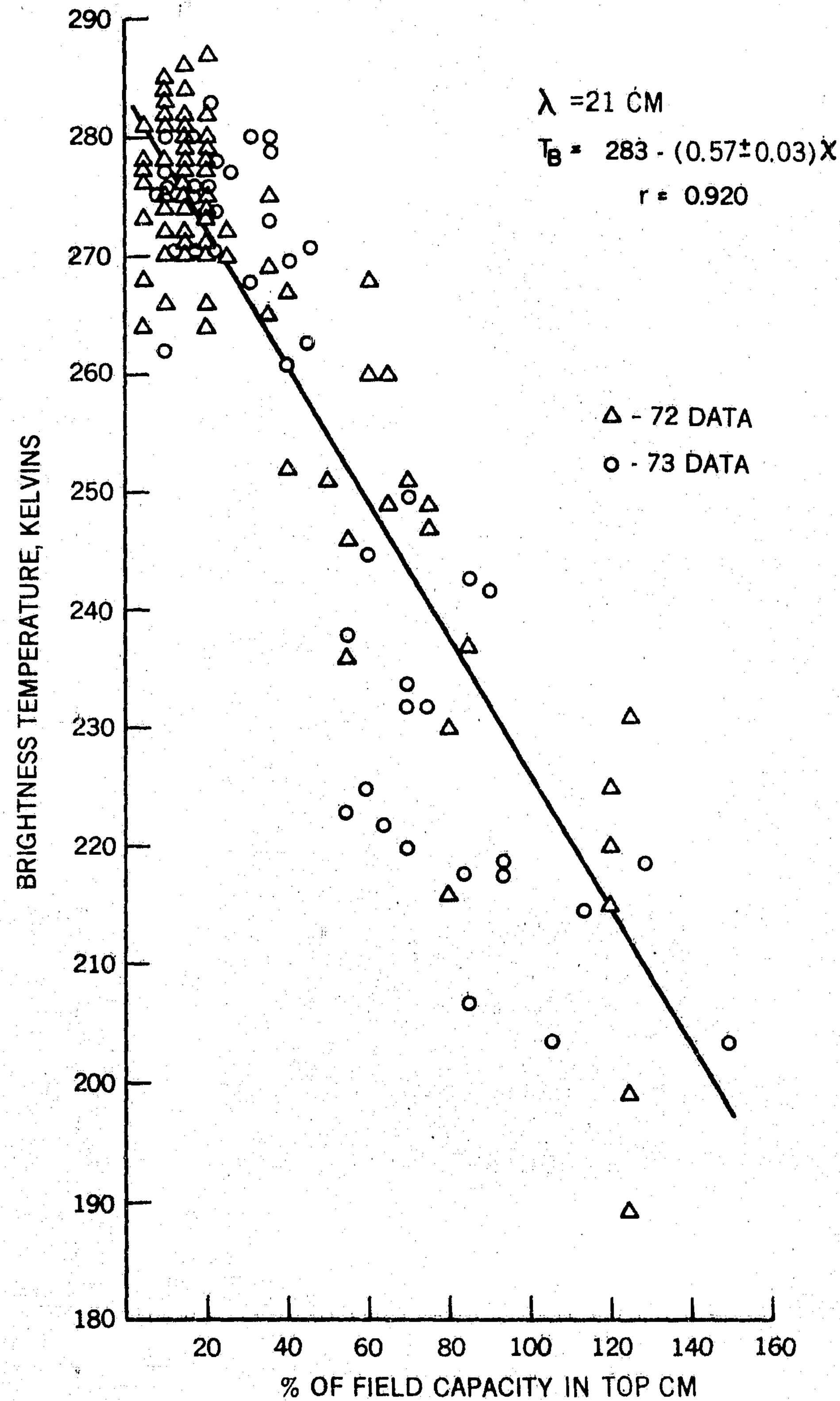


Figure 8. Plot of 21 cm brightness temperatures versus soil moisture expressed as a percent of field capacity for bare fields

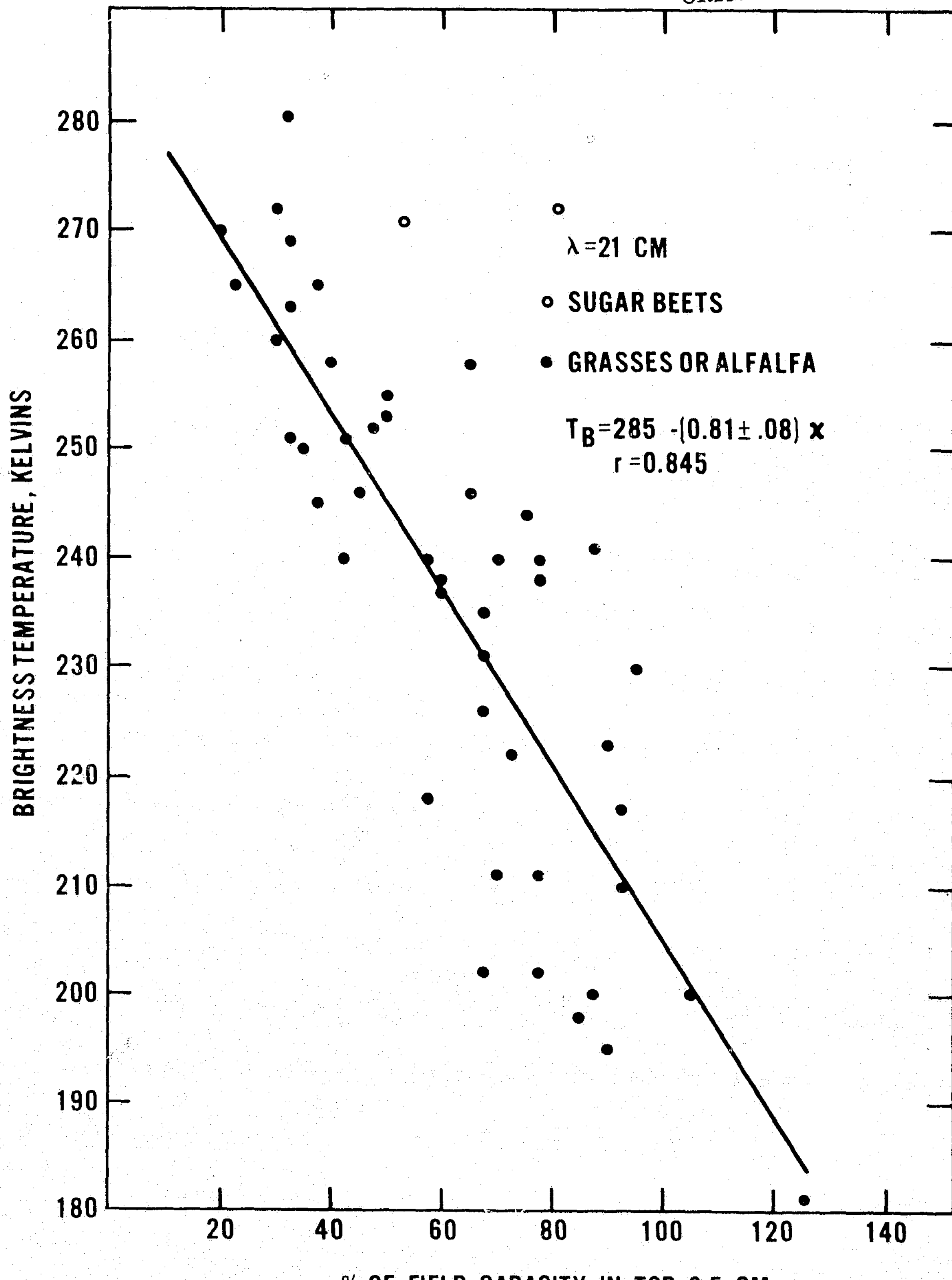
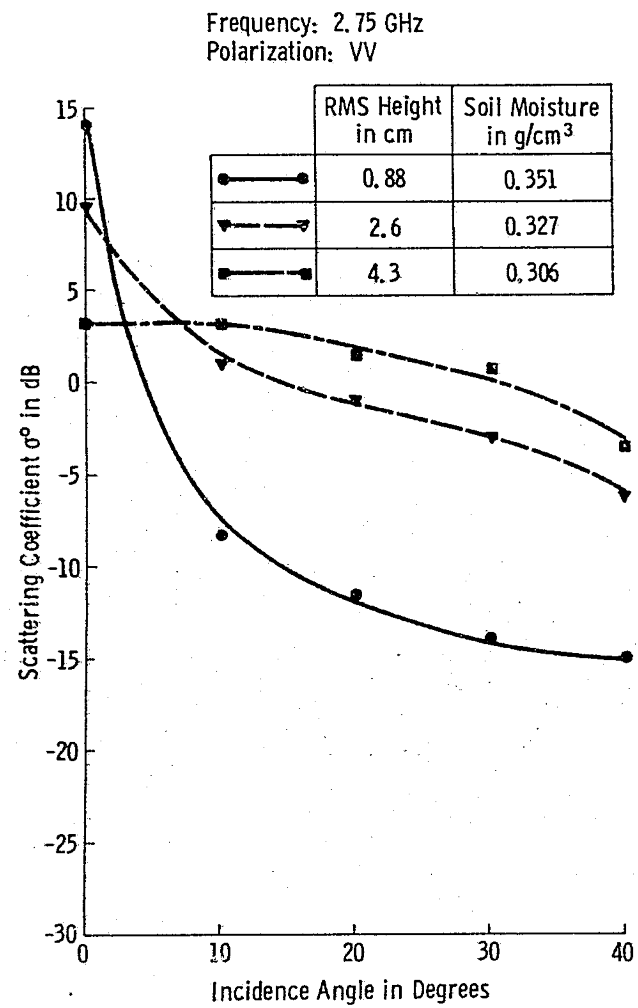
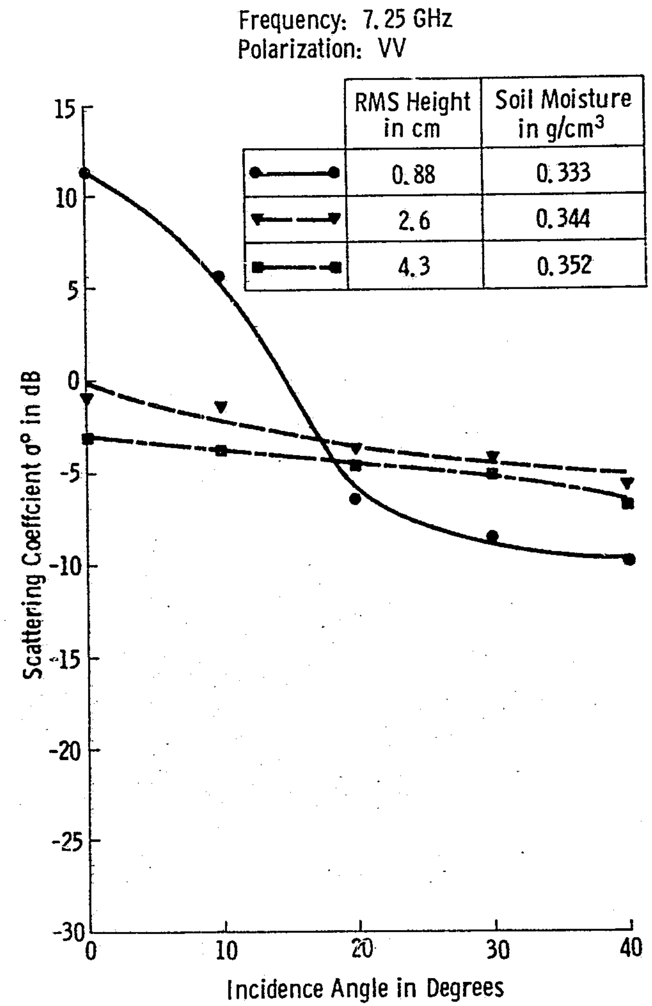


Figure 9. Plot of 21 cm brightness temperatures for vegetated fields



(A)



(B)

Figure 10a. Angular response of σ° for three bare fields with similar moisture conditions but different surface roughnesses (2.75GHz)

Figure 10b. Angular response of σ° for three bare fields with similar moisture conditions but different surface roughnesses (7.25GHz)

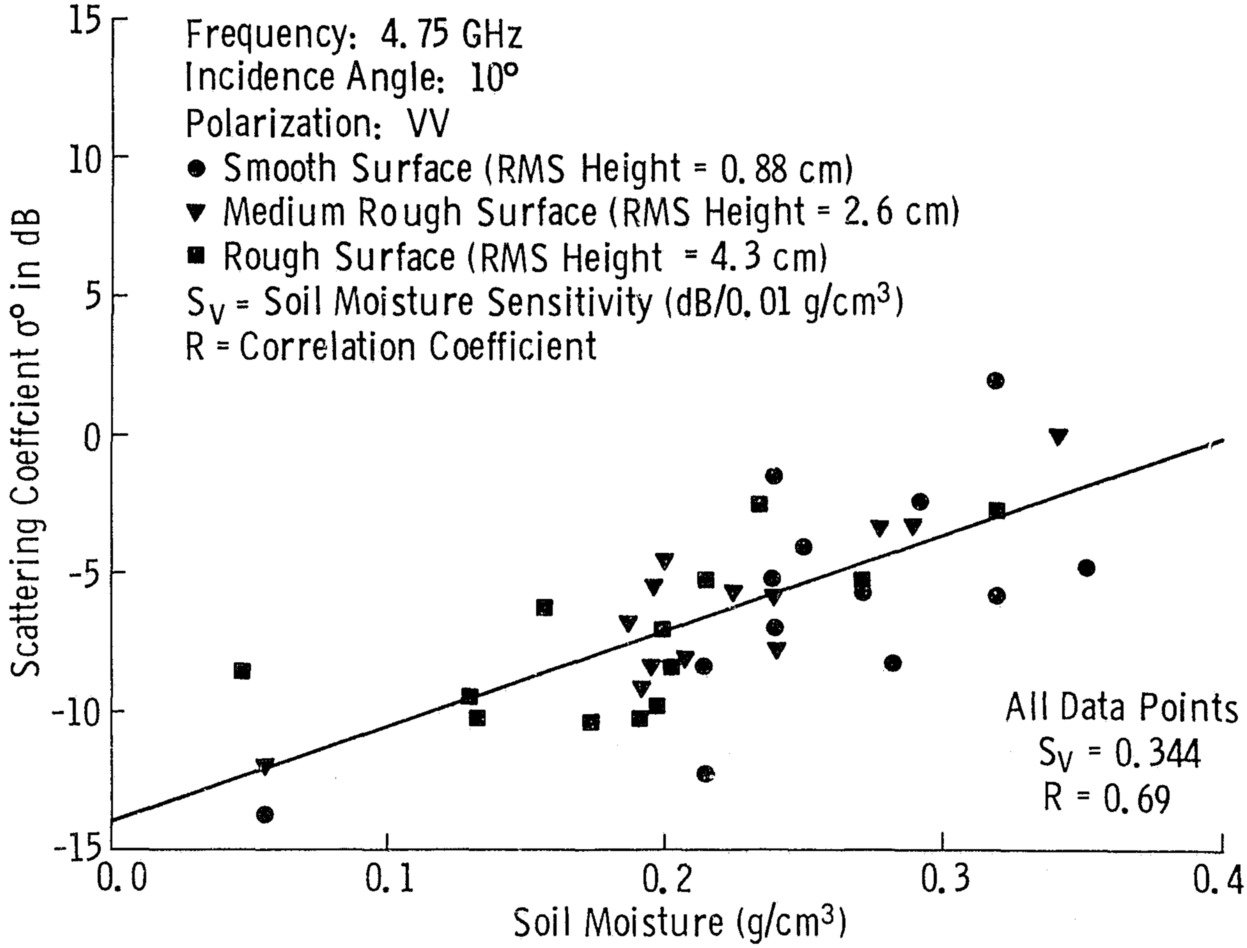


Figure 11. Soil moisture response of σ° for the three surface roughnesses