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Detection of Moisture and Moisture Related

Phenomena from Skylab

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LITERATURE REVIEW

The dielectric constant of water at microwave frequencies is quite large, as much as 80, while that of dry soil is typically less than 5 (Schmugge et al., 1972). Therefore, the water content of a soil can greatly affect its dielectric properties.

A number of studies have been conducted recently in which microwave emissions from various soils have been examined and a number of frequencies and wavelengths have been evaluated.

In 1970, Edgerton and Trexler, using a truck mounted radiometer undertook the study of various geologic phenomena. The purpose of this study was "to establish the microwave properties of representative rocks and minerals and to examine the feasibility of utilizing microwave radiometry for various geologic mapping problems". Twenty-nine sites in 9 areas of the western United States were investigated using the microwave radiometer. Dual polarized radiometers of 0.81, 2.2, 6.0 and 21 cm wavelengths were utilized. Microwave brightness temperature measurements were used to determine the emissivities of several common rocks and minerals.

Correlation was noted between computed emissivities and physical characteristics of the materials. The authors determined that the characteristics included surface roughness, moisture content, and specific gravity. It was also found that a majority of outcrops examined during the study were "distinctly

non-specular" relative to the 0.81 cm observational wavelength and corresponding emissivities were generally ($\gtrsim 0.9$). It was also determined that practically no correlation exists between moisture content of rough outcrops and corresponding 0.81 cm emissivities.

At the 21 cm wavelength scattering due to roughness was greatly diminished, emissivities were low and the polarization differences were quite large. The low emissivities were correlated highly with high moisture content in the outcrops.

In 1971, Poe et.al. undertook to study soil moisture of a plot at the U.S.D.A.'s U.S. Water Conservation Laboratory in Tempe, Arizona. Their study encompassed multiple wavelength microwave radiometer measurements (8.1 mm, 2.2, 6.0 and 21.4 cm), and the numerical modeling of dielectric mixtures (soil, air, water) and the emission characteristics of the soils. The primary variables subject to measurements and analysis were the distribution of moisture and temperature within the soil.

Radiometric measurements were performed for 3 angles: 30, 40, and 50 degrees from nadir. Twenty-five samples were taken from the upper 2 cm of soil, 15 from 0 to 4 cm, 10 from 0 to 8 cm, 7 from 0 to 16 cm and 5 from 0 to 32 cm.

Further, the researchers calculated effective emissivities for measured horizontally polarized temperatures at 30, 40, and 50 degree view angles for all wavelengths. Skin depths and total volume of water per unit area corresponding to effective emissivities were calculated for 12 experiments. It was

2

found that the agreement of measured and calculated temperature is better at 0.81 cm than at 6 and 21.4 cm, however, it was concluded that this was due to the fact that certain theoretical values were extrapolated from data taken previously. However, it was found that for certain experiments there was closer agreement between 21.4 cm radiometric temperature and calculated temperatures than between the other frequencies and calculated temperatures. It was concluded that this was due to greater skin depth, which means that warm soil temperatures in the first few centimeters had a very small effect on the 21.4 cm radiometric temperature.

On February 25 and March 1, 1971, NASA Goddard Space Flight Center performed airborne microwave radiometric measurements at 1.42, 4.99, 19.35, 37 and 94 GHz (λ, 21.4, 6.0, 1.55, 0.81, and 0.32 cm) over a portion of the Phoenix Valley Arizona (Poe and Edgerton, 1971). The 1.42 and 4.99 GHz radiometers were aligned 45 degrees aft. The 19.35 GHz data were obtained with an imaging system which measures the horizontally polarized brightness temperatures in the plane perpendicular to the direction of flight at 50 degrees from nadir.

Ground based soil and moisture characteristics were obtained along the flight lines by Biospheric Inc. and Aerojet General Corp.(A.G.C.). Biospherics moisture measurements were obtained from soil samples taken in the 0-15 cm depth interval. Temperature measurements were performed at 7.5 cm below the soil's surface. About 200 soil plots were investigated by Biospherics. Aerojet performed detailed soil moisture and temperature

measurements at four locations along the north-south flight lines. Normal depth intervals at which soil and temperature measurements were performed at A.G.C. were surface to 1, 2, 4, 8, 16 and 32 cm. A.G.C. also performed 13.4 GHz measurements on each of the sites.

It was found that atmospheric attenuation effects at 1.42, 4.99, 19.35, 37 GHz were relatively unimportant, however effects were important at 94 GHz.

The A.G.C. microwave field laboratory was used to obtain 13.4 GHz (2.2 cm) brightness temperature and supporting soil data on several sites along the flight path. However, no comparison was made between the ground-based 13.4 GHz measurements and aircraft brightness temperatures.

The authors concluded that the 1.42 and 4.99 GHz measured brightness temperatures exhibited statistically meaningful agreement with those predicted by the theory of uniform media. Less agreement occurred between the measured and computed 37 and 94 GHz data.

Also, the apparent penetration of 1.42 and 4.99 GHz through alfalfa and wheat (25 cm and 15 cm., respectively) was noted in several cases. 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). It was concluded that the lack of detectable penetration of vegetal cover over relatively dry soil was probably due to the lack of significant contrast in the emissivities of vegetal

4

cover and dry soil. Further, the authors did not observe vegetal penetration with any consistency at higher frequencies.

Estimates of the depth of penetration indicated the emission at 37 and 94 GHz is controlled by the moisture contained in the near-surface regions of soil.

Values of correlation coefficients were consistently larger in magnitude at 1.42 and 4.99 GHz than at 37 and 94 GHz. Values obtained at 19.35 GHz for selected view angles varied widely.

Schmugge, Gloersen and Wilheit (1972) used microwave radiometers to measure surface temperatures. Measurements were by a nadir viewing infrared radiometer operating in the 10 to 12 μ atmospheric windows.

Agricultural test sites were located in the vicinity of Phoenix, Arizona; Weslaco, Texas; and the Imperial Valley, California. The majority of the selected fields were without vegetative cover and at least 400 meters on a side. In the Imperial Valley and Phoenix area four 15-cm soil samples were taken in each field to yield the average soil moisture for the top 15 cm in the soil.

More detailed surface truth data were available for flights over Weslaco, Texas. A surface sample 1-3 cm deep and a sub-surface sample at a depth of 15 cm were taken. The study was conducted at frequencies of 1.42 GHz (21.1 cm), 4.99 GHz (6.01 cm), 19.35 H (1.55 cm), 37 V (0.81 cm) and 37 H (0.81 cm).

A linear regression analysis was performed on the bright-

5

ness soil moisture data on each data set. In general, it was found that the correlation coefficient decreases with decreasing wavelength, as does the slope of the regression curve, indicating a greater sensitivity to soil moisture with longer wavelength radiometers. The brightness temperature at 21.1 cm decreased with increasing soil moisture, although the relationship was different for the California and Arizona data. At higher moisture contents there appeared to be a linear decrease at about $2^{\circ}K/\%$ soil moisture. It was concluded that longer wavelength radiometers (6 and 21 cm) have greater sensitivity to soil moisture.

The Soil Moisture vs. Brightness Temperature generated by Schmugge et. al. for selected sites are shown in Figures 1 and 2.

BACKGROUND PREPARATION

To thoroughly understand and evaluate sensor output, some means of referencing the real result to a theoretical result is essential. Therefore, an essential part of recent activity has been the calculation of expected brightness temperatures for a range of soil moistures from 0 to 30 percent.

The calculation of the expected brightness temperatures was based upon theoretical developments from a variety of sources.

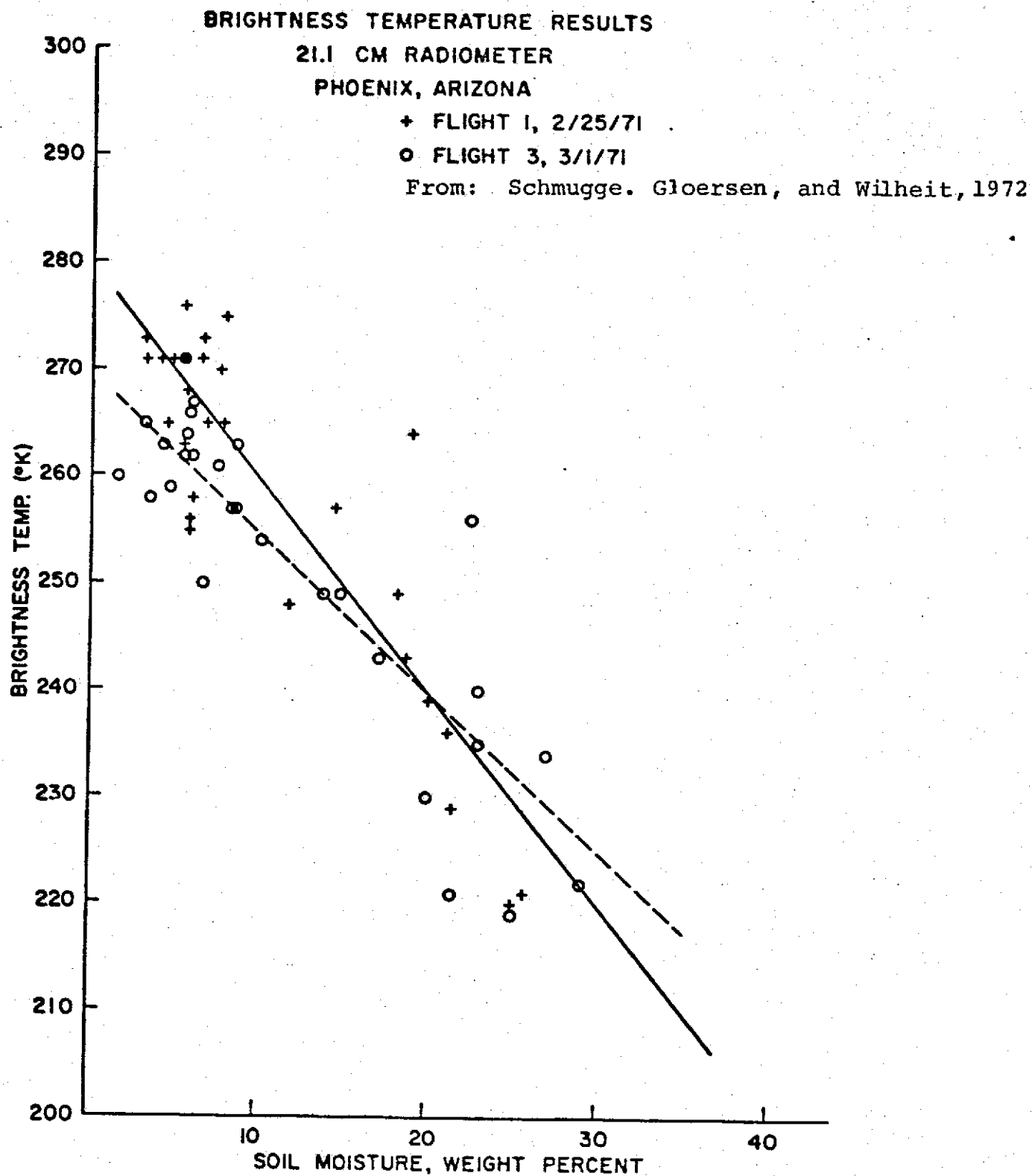The initial procedure involved the use of an equation

Figure 1. Plot of 21.1 cm Brightness Temperatures vs Soil Moisture from Phoenix, Arizona
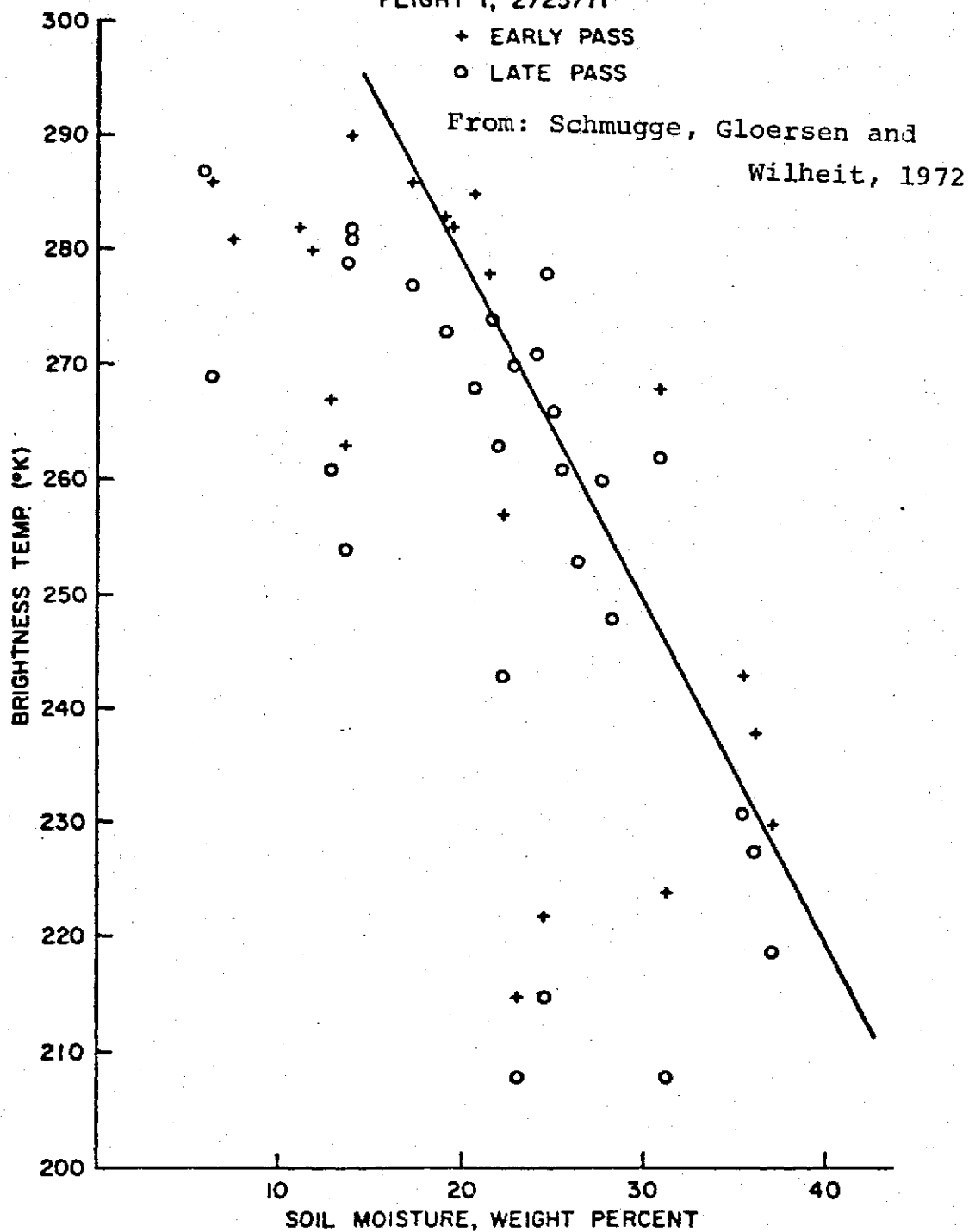
Figure 2. Plot of 21.1 cm Brightness Temperature vs Soil Moisture from the Imperial Valley

and empirically derived data generated by Teschanskii et al (1971).

The equation which was employed was given as:

$$\alpha = \frac{Q}{8.66} = \frac{2\pi}{\lambda}\left[\sqrt{\frac{\epsilon'}{2}\left(\sqrt{1+\left(\frac{\epsilon''}{\epsilon'}\right)^2}-1\right)}\right]$$

where Q, the attenuation coefficient, and
ϵ', the real part of the dielectric were
given for soil moistures at several wave-
lengths (λ).

This equation is easily manipulated algebraically to give
ϵ''(the imaginary part of the complex dielectric)which can
then be used in the standard formula for the complex dielectric
given by; $\epsilon_r = \epsilon' - j\epsilon''$.

This value can then be used directly in Peakes' (1969)
equations to calculate the Fresnel coefficients for horizontal
(R_h) and vertical (R_v) polarizations,

$$R_h = \frac{\cos\theta_0 - \sqrt{\epsilon_r - \sin^2\theta_0}}{\cos\theta_0 + \sqrt{\epsilon_r - \sin\theta_0}}$$

$$R_v = \frac{\epsilon_r\cos\theta_0 - \sqrt{\epsilon_r - \sin^2\theta_0}}{\epsilon_r\cos\theta_0 + \sqrt{\epsilon_r - \sin^2\theta_0}}$$

These absolute values are equal in the case of the S194, since
incidence angles (θ_0) of zero provide that Rh=-Rv. Thus, the
calculation of emissivity, done irrespective of polarization
characteristics, becomes: $\epsilon = (1 - |R_p|^2)$ and the final expected
brightness temperature $T_B = \epsilon T_g$ for each soil moisture where T_g
is Ground Temperature in $^\circ$A.

The curves (A and A') in Figure 3 are the results of these
calculations for soil moistures of zero to thirty percent for
loam and sand for 80°F. The differences in the two curves are
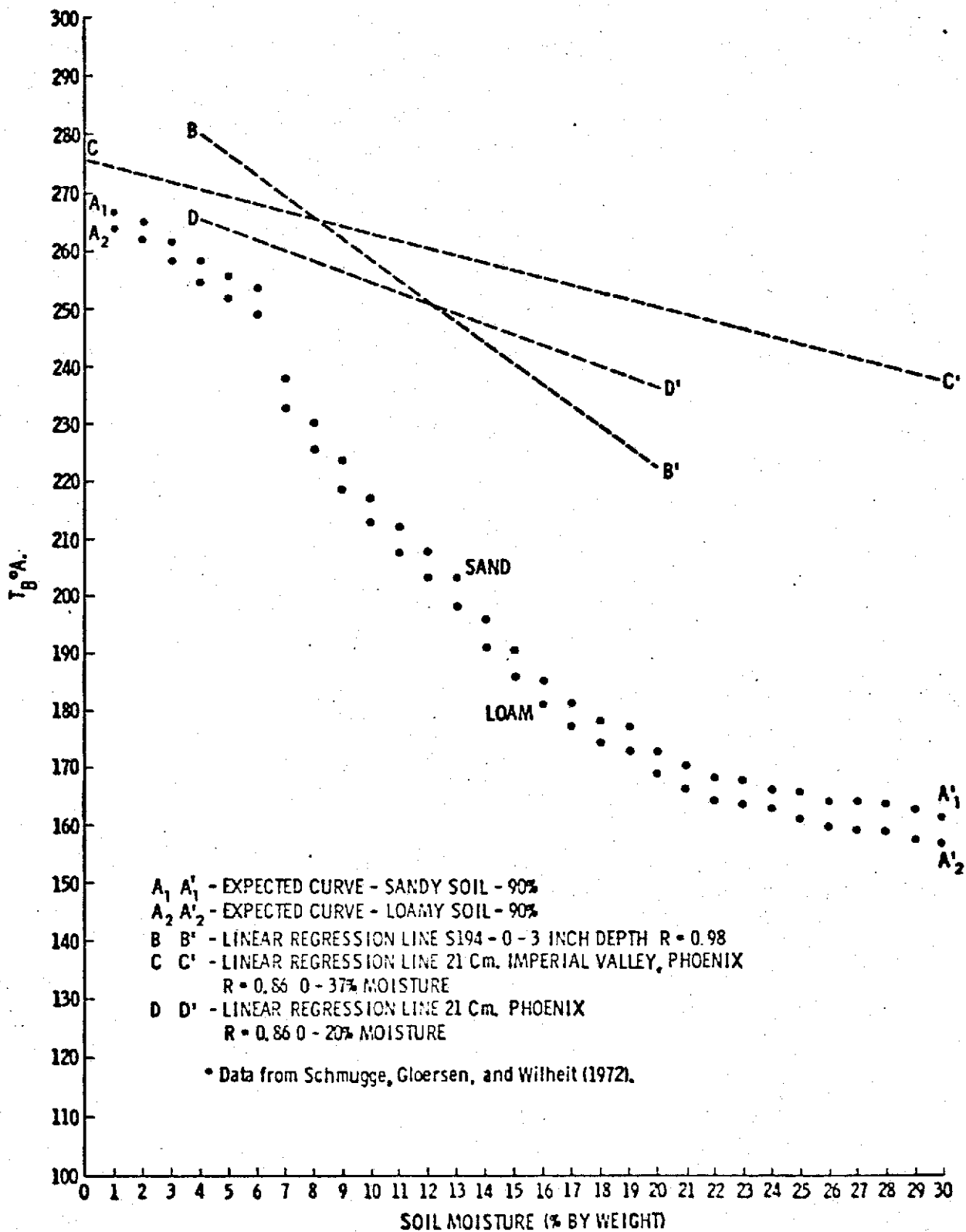the result of differences in Q for different soil types.

7

Figure 3.

Curve B is the regression line based upon Skylab II June 5, 1973 data (Texas site) for which the soil moisture ranged from approximately four to twenty percent. In general, the slope of the line is as expected over the appropriate range of moistures, although absolute magnitudes are somewhat greater for the real than for the predicted. There has been no attempt to determine why this is the case.

Curve C is the regression line based upon the data set published by Schmugge et al. (1972), and processed using the routine used for processing S194 data. Thus, it was assumed that a degree of comparability of results could be maintained.

Curve D represents the linear regression on Schmugge's data from 4-20% moisture, the same spread as for the June 5, 1973 S194 Skylab II data. In both cases, the slope tends to be much lower than that for the S194 data, or the predicted curves. This very obvious difference has not yet been satisfactorily explained, although analysis of these data is currently under way.

Therefore, Skylab II data for June 5, 1973 (Texas site) relates favorably with previously calculated aircraft data when correlating Brightness Temperature to Soil Moisture, however, more detailed work is needed to determine the corrected surface temperature.

Additional work has been completed on soil site locations and S194-Soil Moisture correlations. The remainder of this report updates these parts of the project.

8

SOIL SITE MAPS

Maps showing soil sample locations have been made for each
of the 6 test sites (Figures 4-9). For each map the width of the
test site as shown by solid black lines is 50 nautical miles
either side of the center line. S194 coverage is indicated by
a dashed line. This represents a 30 nautical mile range away
from the center line.

Soil samples were taken every 3 to 5 miles for the length
of the test sites. Soil samples falling outside the S194
coverage area were not used in the S194-Soil Moisture correl-
ations. Rainfall terminated soil sample collections for the
9-18-73 Kansas site, therefore, only 9 soil samples were
obtained.

ADDITIONAL S194 MEASUREMENTS AND SOIL MOISTURE

S194 temperatures and soil moisture data have been
analyzed for two additional test sites, Texas 9-13-73 and
Kansas 9-13-73. This makes a total of five sites analyzed
to date.

Actual variations in antenna temperature for the Sept.
13, 1973 Texas site are shown in Figure 10. Antenna temp-
erature remained high and constant for 70 nautical miles
(271 degrees K) then it dropped off sharply throughout the
remaining portion of the test site reaching a low of 248.4
degrees K.

TEXAS SITE (6-5-73)

Soil Site Map

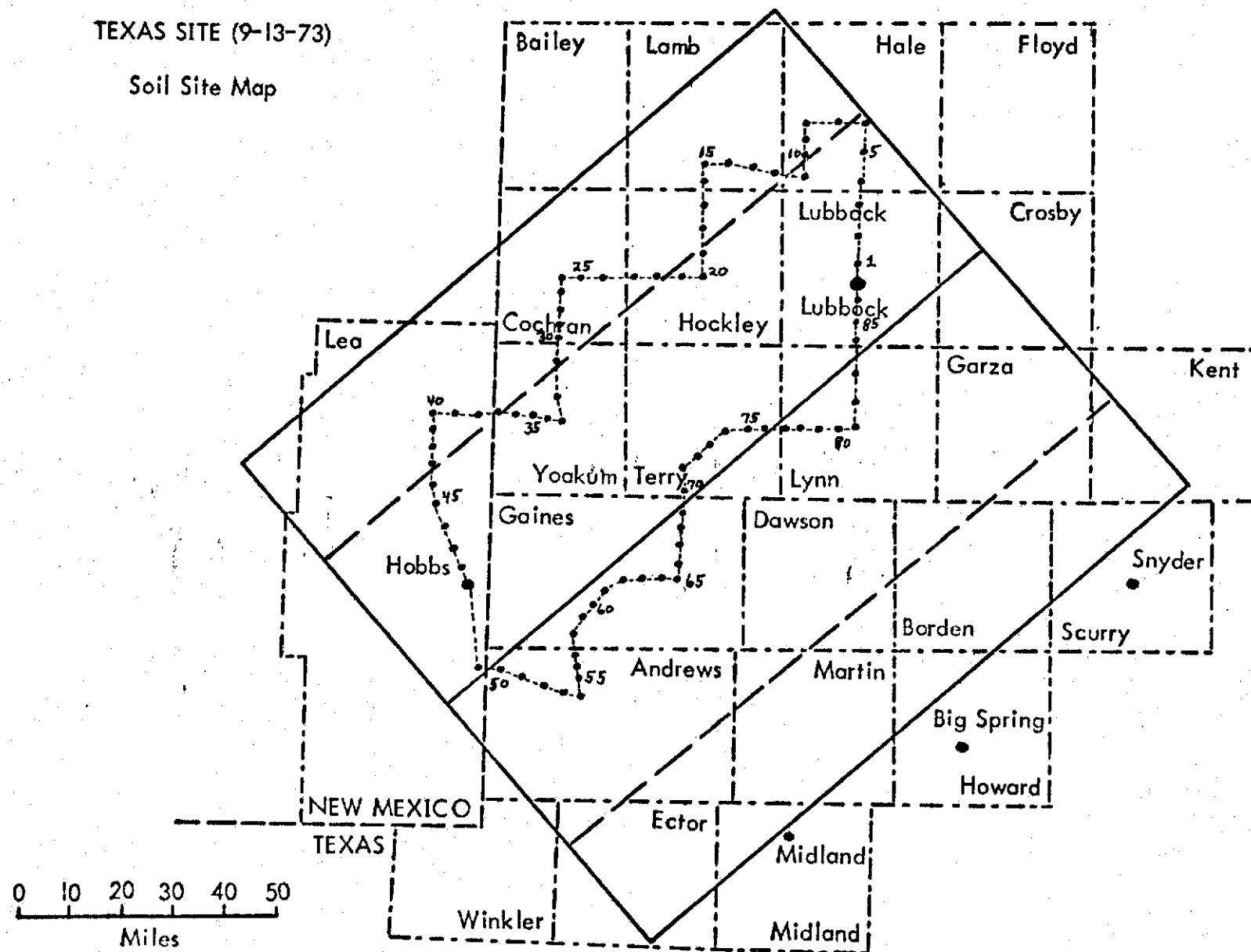Figure 4.

Figure 5.

KANSAS SITE (8-5-73)

Soil Site Map

Scale: 1:2,000,000

Figure 6

TEXAS SITE (9-13-73)

Soil Site Map

Figure 7.

KANSAS SITE (9-13-73)

Soil Site Map

Figure 8.

KANSAS SITE(9-18-73)

Soil Site Map

Franklin Miami

MISSOURI

Coffey

Anderson Linn

Bates

— 38

Bourbon

Vernon

Fort
Scott

Woodson Allen

5

?

Wilson Neosho

Crawford

Barton

Dade

Cherokee

Jasper

Joplin

KANSAS

OKLAHOMA Labette

— 37

Lawrence

0   10   20   30   40   50

Miles

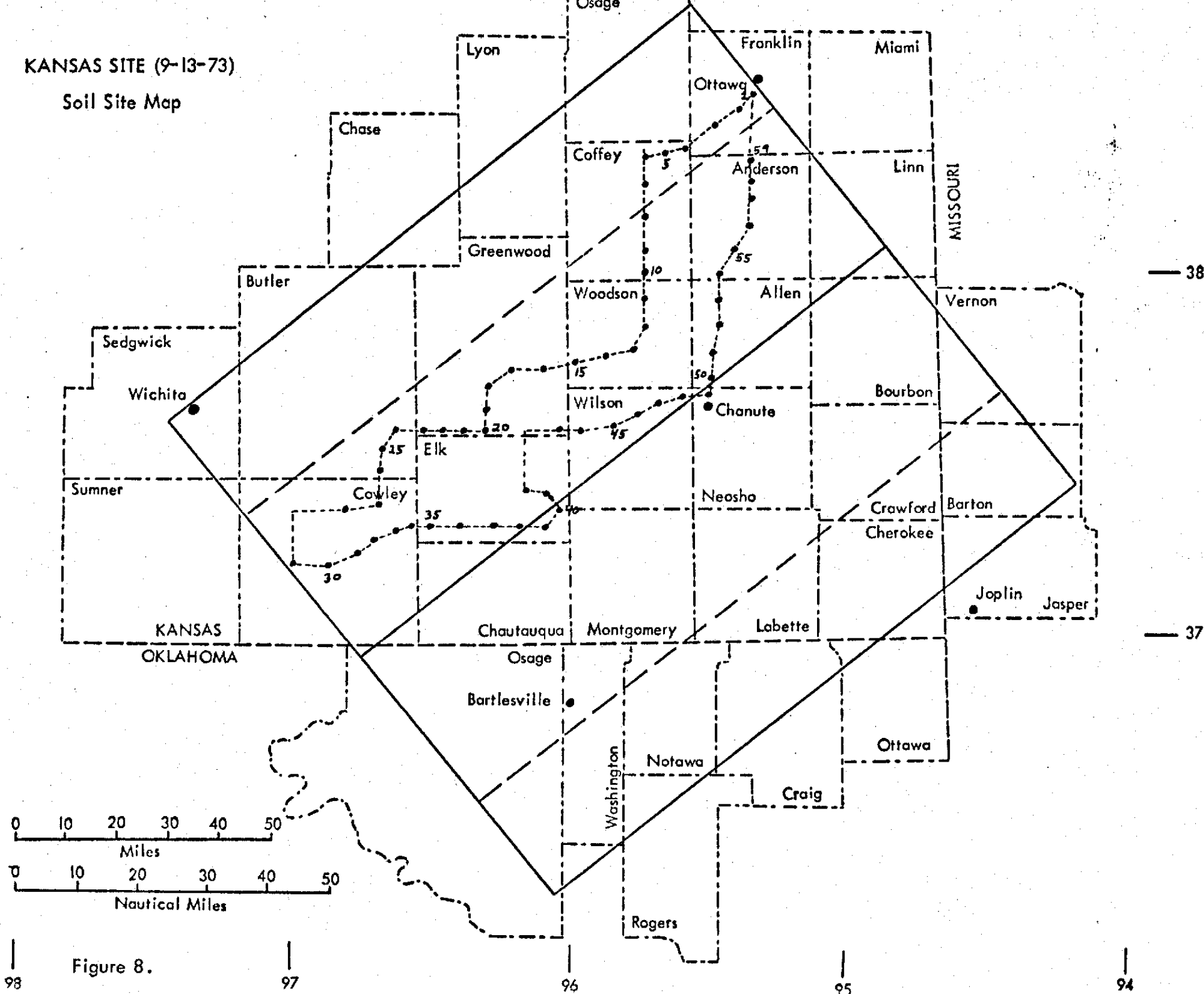0   10   20   30   40   50

Nautical Miles

Newton

Ottawa

Figure 9.

96

95
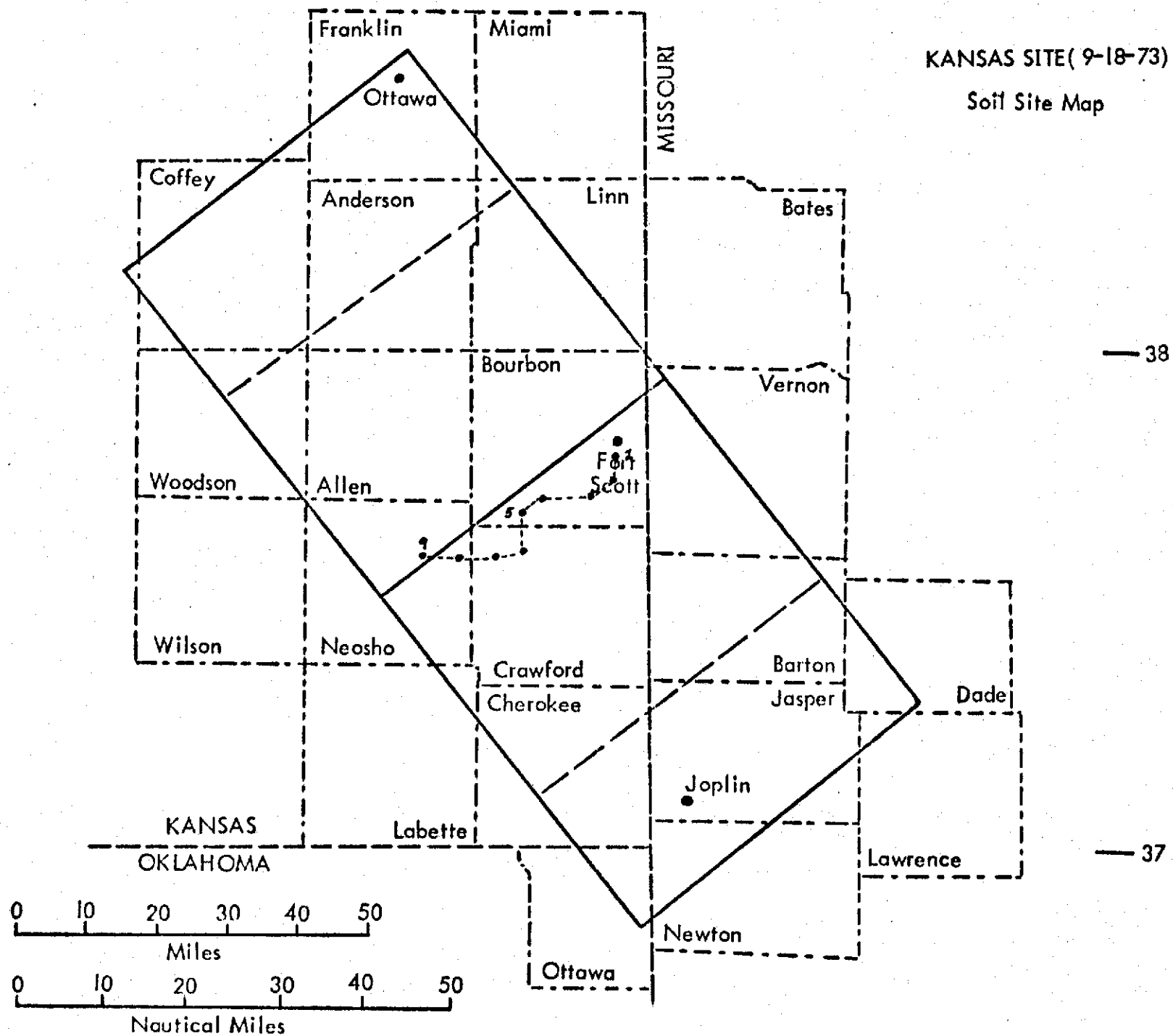
94

Actual variations in average soil moisture (0-1 inch layer) for the same site are shown in Figure 11. Moisture by % of weight was low for the first 35 nautical miles (less than 2%), then it started increasing slowly and continued to increase until 16.8% was reached at the end of the test site. Figures 10 and 11 reveal a 15% soil moisture variation with lower antenna temperatures corresponding to higher moisture content.

Correlation coefficients were calculated using the S194 antenna temperature measured every 3.5 nautical miles from Skylab on Sept. 13, 1973 over the Texas test site. Table 1 gives the correlation coefficients and regression equations determined for various soil depths. Table 1 was obtained by correlating single antenna temperatures measured every 3.5 nautical miles with the average measured soil moisture within a 30 nautical mile radius (not 3.0 as indicated in a previous report) of the center of the radiometric measurement. The antenna temperature is correlated highest (-0.90) with the moisture content of the 0-1 inch layer. Figure 12 shows a scatter diagram for the 0-1 inch layer.

A similar analysis of Skylab data obtained on Sept. 13, 1973 over the Kansas site is shown in Figures 13, 14, 15 and Table 2. Figure 13 shows that antenna temperature began high at 231.2 degrees K then dropped sharply to 219.4 degrees where it remained constant for 40 nautical miles before rising sharply to 223.9 degrees. Average soil moisture (0-1 inch layer) for the same site are shown in Figure 14.

10

Moisture by % of weight was about 23% at the beginning of the test site. This increased to the 35-36% range after about 70 nautical miles where it remained relatively constant. As with the Sept. 13, 1973 Texas site, Figures 13 and 14 for the Sept. 13, 1973 Kansas site reveal lower antenna temperatures correspond to higher soil moisture content.

Correlation coefficients and regression equations for the Sept. 13, 1973 Kansas site are shown in Table 2. The best correlation between the antenna temperature and soil moisture existed for the 0-1 inch layer (-0.808) with the 0-2 inch layer second, (-0.804). Figure 15 shows a scatter diagram for the 0-1 inch layer.

SUMMARY OF SIGNIFICANT RESULTS

Skylab II data for June 5, 1973 (Texas site) relates favorably with previously calculated aircraft data when correlating Brightness Temperature to Soil Moisture. However, more detailed work is needed to determine the corrected surface temperature.

In addition, correlations between the S194 antenna temperature and soil moisture have been obtained for five sets of Skylab data. The best correlations were obtained for the surface to one inch depth in four cases and for the surface to two inches depth for the fifth case. Correlation coefficients for the surface to one inch depth were -0.98, -0.95, -0.90, -0.82, and -0.80.

11

S-194 TEMPERATURE VARIATIONS IN DEGREES K
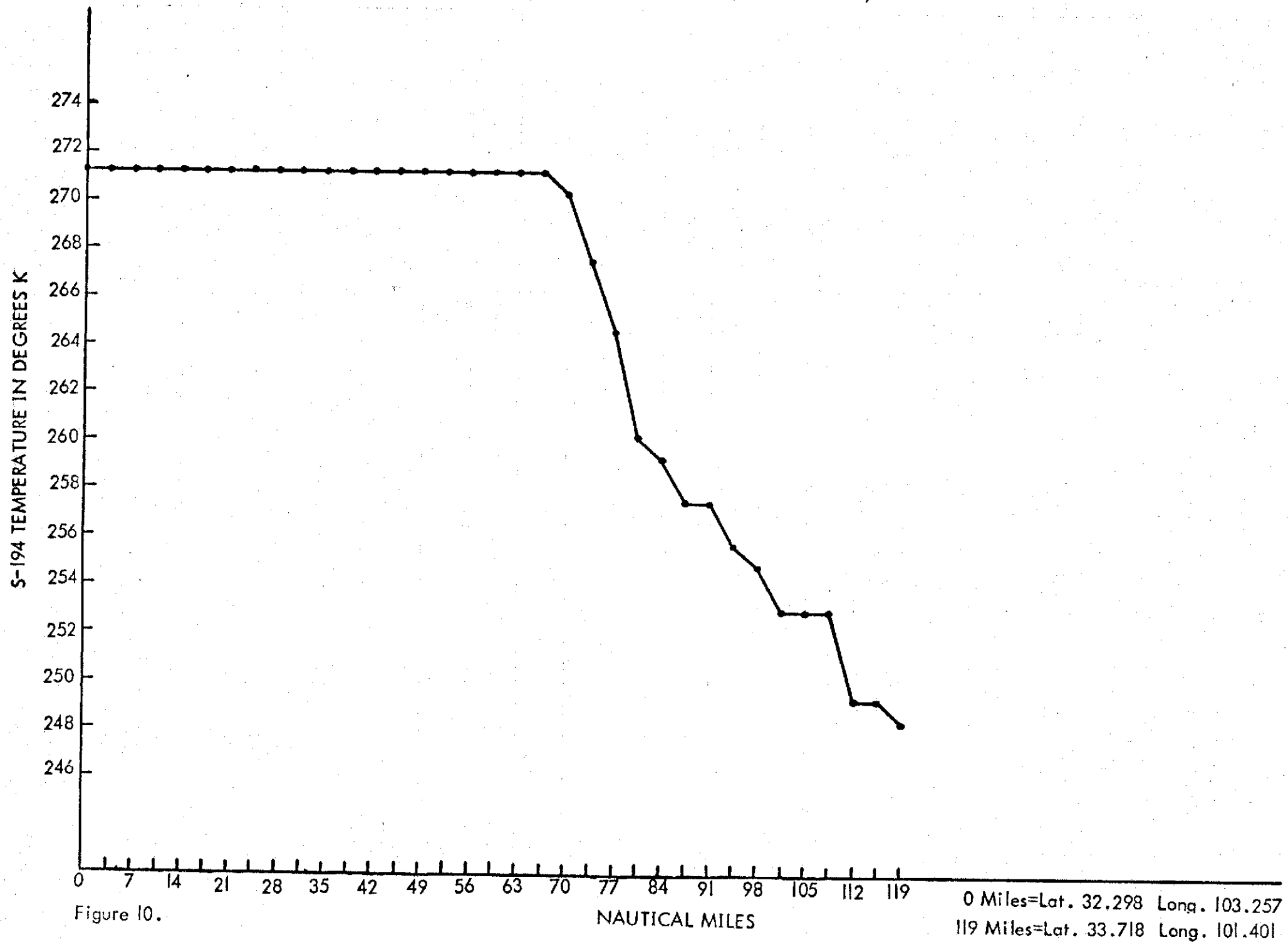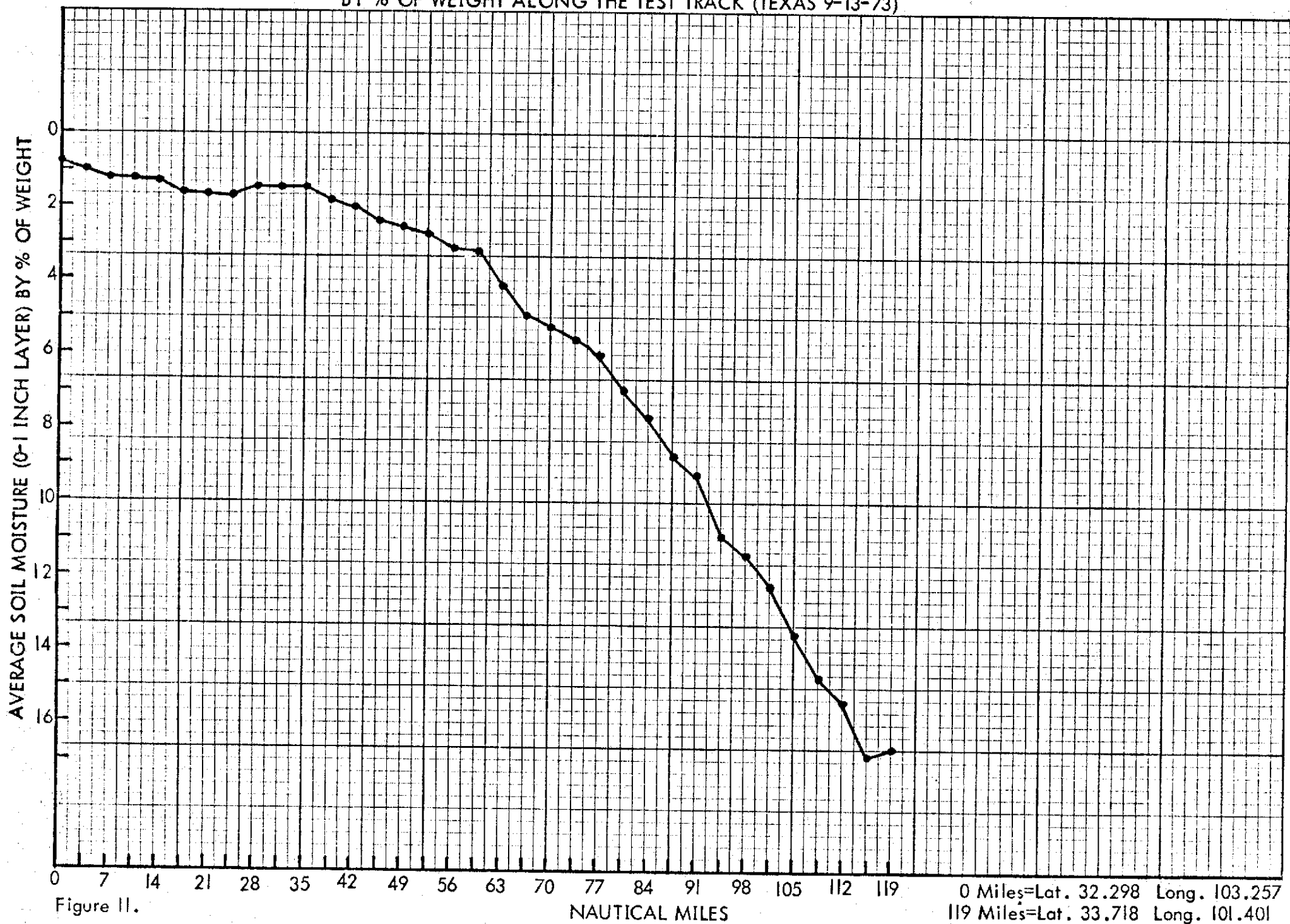ALONG THE TEST TRACK (TEXAS 9-13-73)

Figure 10.

NAUTICAL MILES

0 Miles=Lat. 32.298 Long. 103.257
119 Miles=Lat. 33.718 Long. 101.401

VARIATION OF THE AVERAGE SOIL MOISTURE (0-1 INCH LAYER)
BY % OF WEIGHT ALONG THE TEST TRACK (TEXAS 9-13-73)

AVERAGE SOIL MOISTURE (0-1 INCH LAYER) BY % OF WEIGHT

NAUTICAL MILES

Figure 11.

0 Miles = Lat. 32.298 Long. 103.257
119 Miles = Lat. 33.718 Long. 101.401

CORRELATION BETWEEN SOIL MOISTURE AND S-194 ANTENNA TEMPERATURE

<div style="text-align: right">9-13-73 Texas</div>

Soil Moisture Layer	Correlation Coefficient	Regression Equation
0-1 inch	-0.900	SM=142.92-0.5160AT
1-2 inch	-0.881	SM=126.86-0.4489AT
2-3 inch	-0.852	SM=123.92-0.4376AT
3-4 inch	-0.868	SM=122.49-0.4328AT
4-5 inch	-0.872	SM=115.92-0.4092AT
5-6 inch	-0.874	SM=120.84-0.4273AT
0-2 inch	-0.892	SM=134.87-0.4824AT
0-3 inch	-0.881	SM=131.21-0.4674AT
3-6 inch	-0.871	SM=119.75-0.4232AT
0-6 inch	-0.877	SM=125.47-0.4453AT

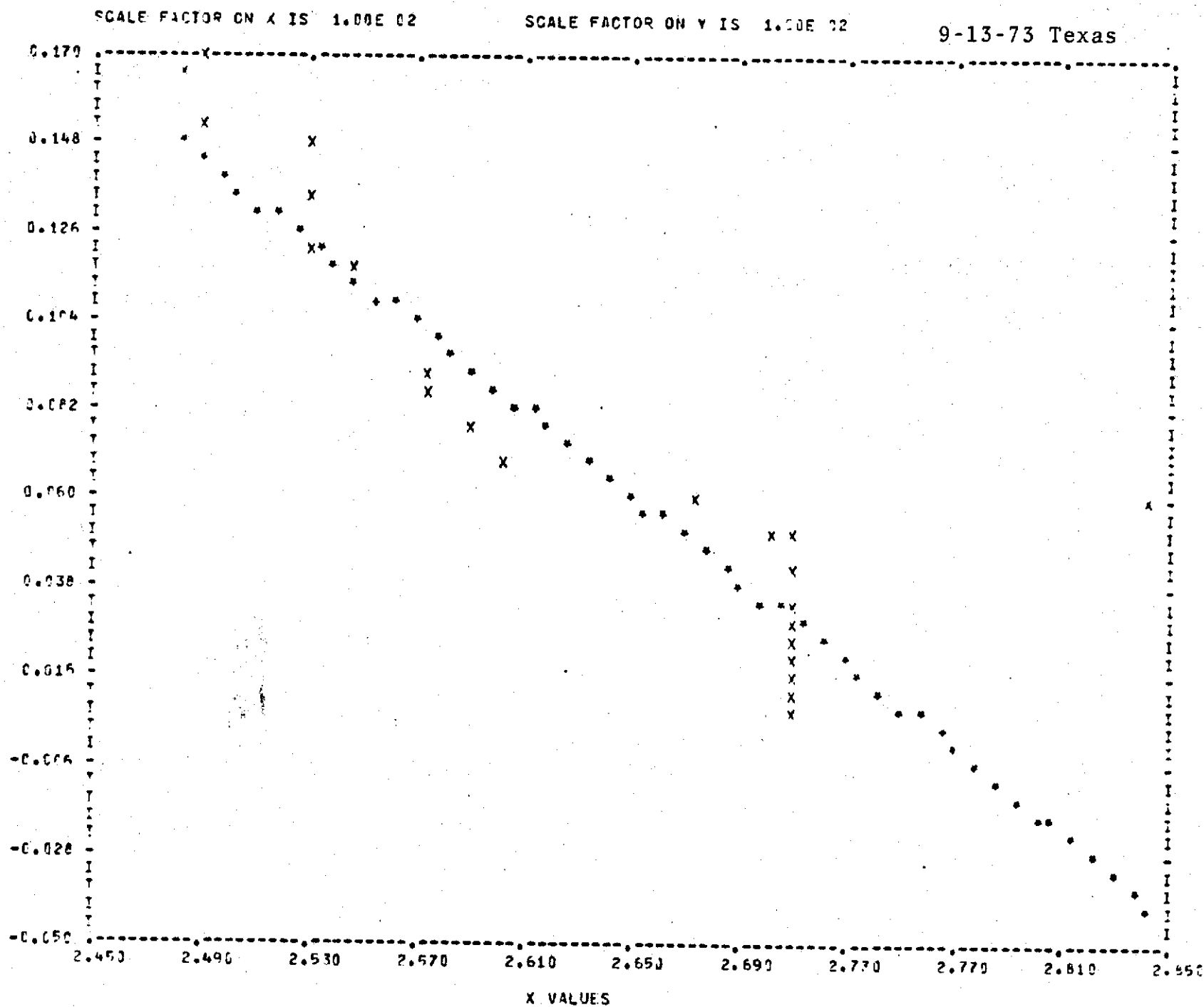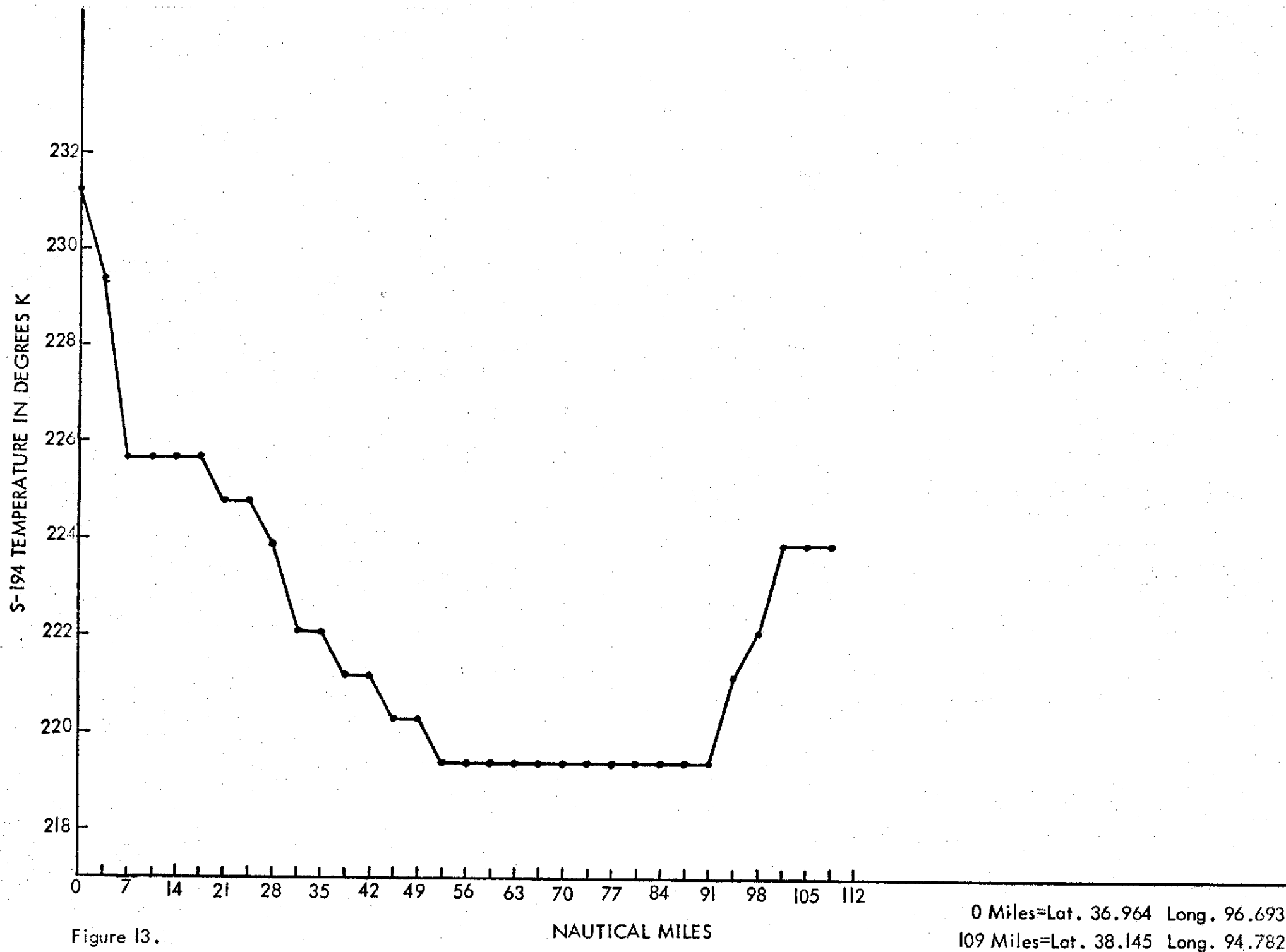Sample Size= 35
SM=Soil Moisture
AT=Antenna Temperature

Table I.

Figure 12.

S-194 TEMPERATURE VARIATIONS IN DEGREES K
ALONG THE TEST TRACK (KANSAS 9-13-73)

Figure 13.

NAUTICAL MILES

0 Miles=Lat. 36.964 Long. 96.693
109 Miles=Lat. 38.145 Long. 94.782

VARIATION OF THE AVERAGE SOIL MOISTURE (0-1 INCH LAYER)
BY % OF WEIGHT ALONG THE TEST TRACK (KANSAS 9-13-73)

Figure 14.

NAUTICAL MILES
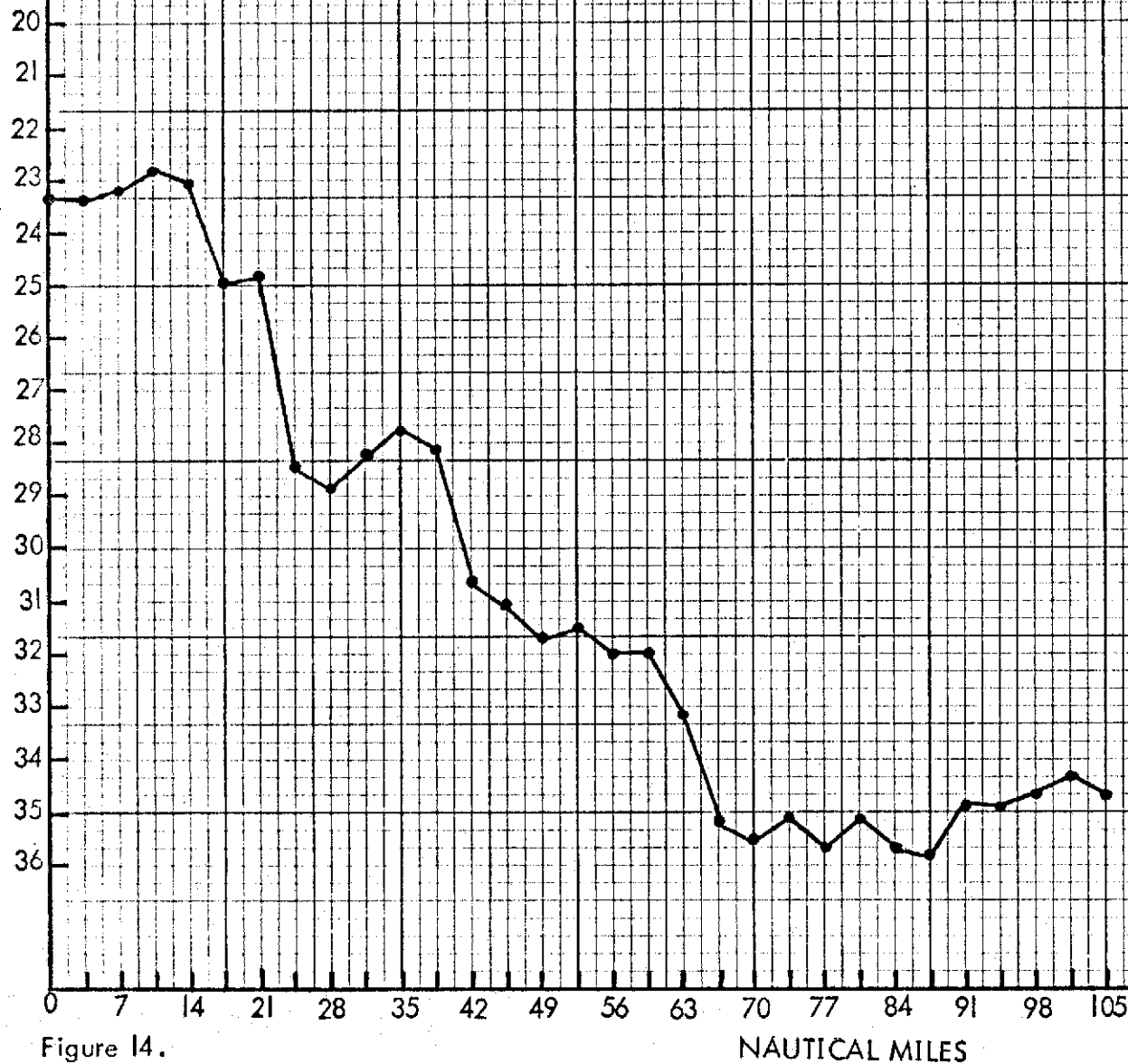
0 Miles=Lat. 36.964 Long. 96.693
109 Miles=Lat. 38.145 Long. 94.782
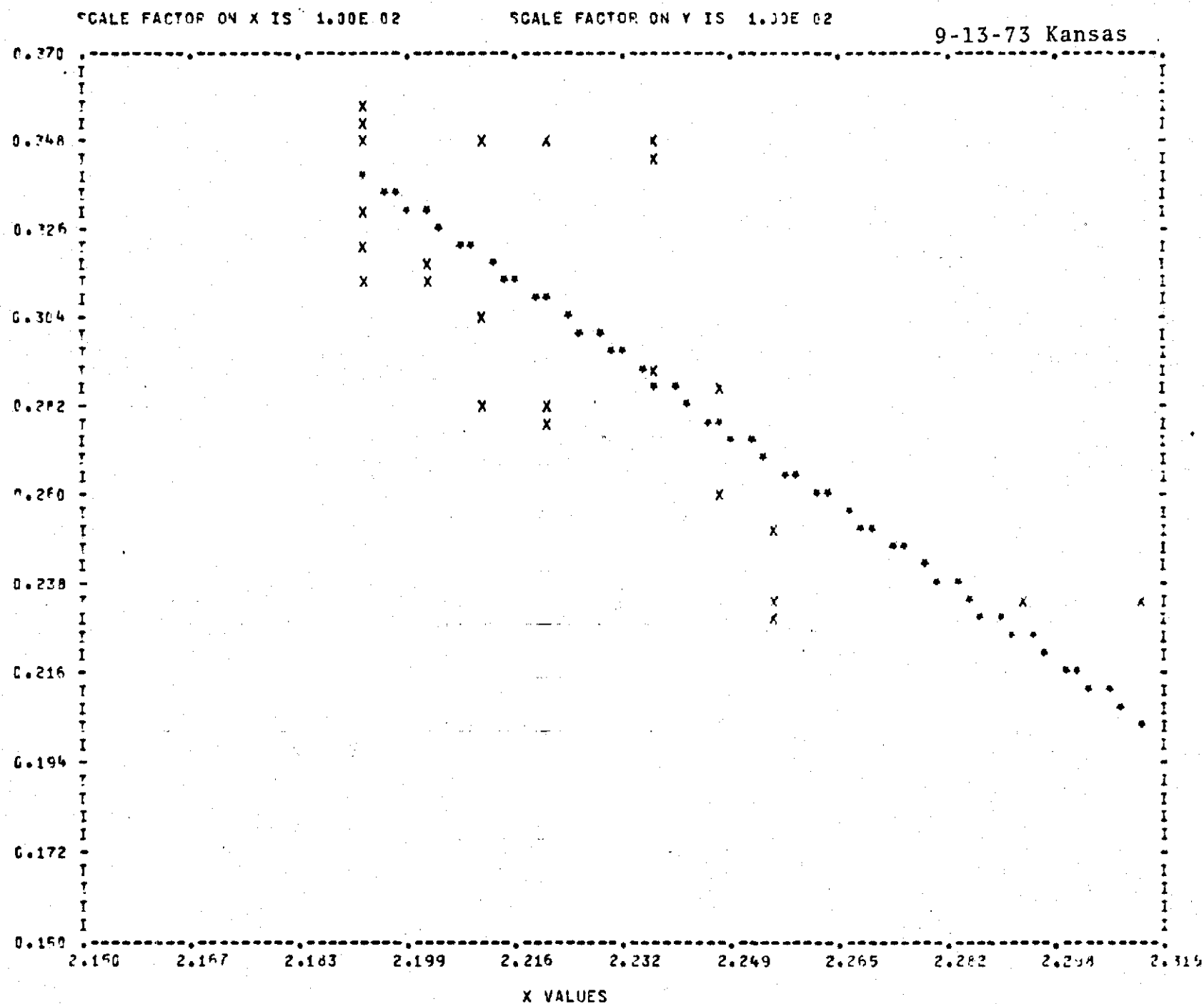
Figure 15.

CORRELATION BETWEEN SOIL MOISTURE AND S-194 ANTENNA TEMPERATURE

Soil Moisture Layer	Correlation Coefficient	Regression Equation
0-1 inch	-0.808	SM=284.20-1.1409AT
1-2 inch	-0.788	SM=260.55-1.0380AT
2-3 inch	-0.625	SM=158.85-0.5915AT
3-4 inch	-0.661	SM=132.06-0.4772AT
4-5 inch	-0.635	SM=108.50-0.3742AT
5-6 inch	-0.604	Sm= 98.57-0.3309AT
0-2 inch	-0.804	SM=272.35-1.0893AT
0-3 inch	-0.765	SM=234.53-0.9234AT
3-6 inch	-0.637	SM=113.01-0.3940AT
0-6 inch	-0.725	SM=173.80-0.6588AT

Sample Size= 31
SM=Soil Moisture
AT=Antenna Temperature

Table 2.

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