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Analysis of Surface Moisture Variations Within Large Field Sites

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

"ANALYSIS OF SURFACE MOISTURE VARIATIONS WITHIN LARGE FIELD SITES"

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ABSTRACT

In the past several years, 1974 to 1977, NASA has conducted several research studies to develop an extensive collection of ground truth soil moisture data. As a result of these experiments, moisture data were available from 58 "large field sites," each being 400 m X 400 m (40 acre). The field locations were one field in Phoenix, Arizona (sampled four times); 28 fields in Jefferson County, Kansas; 23 fields in Finney County, Kansas and 5 fields in Hand County, South Dakota. At the first three locations, samples were taken in specific vertical increments or horizons (i.e. 0-1 cm, 1-2 cm, 2-5 cm, 5-9 cm, and 9-15 cm). In the South Dakota study, moisture samples were taken in increments from the surface (i.e. 0-2.5 cm, 0-5 cm, and 0-10 cm).

A detailed statistical analysis was made to define the general relationship and ranges of values of the field moisture relative to both the variance (standard deviation) and coefficient of variation (CV) for a given test site and depth increment.

Based upon the results of the variability study, it was concluded that, 1) moisture variations within any given "large field" area are inherent and can neither be controlled nor reduced, 2) neither a single (constant) value of the standard deviation nor coefficient of variation uniquely define the variability over the complete range of mean field moisture contents examined and 3) using an upper bound standard deviation parameter clearly defines the maximum range of anticipated moisture variability. It was found that 87% of all "large field" moisture content standard deviations were less than 3% while about 96% of all the computed values had an upper bound of σ=4% for these intensively sampled fields. Using these upper bound magnitudes and a preselected confidence level, limit of accuracy curves of mean soil moisture measurements for large field sites relative to the required number of samples were determined.

ANALYSIS OF SURFACE MOISTURE VARIATIONS WITHIN LARGE FIELD SITES

INTRODUCTION

There have been a number of recent papers indicating the importance of knowledge of the moisture content of the soil. Idso et. al. (1975) have described several applications in the field of agriculture such as improved yield forecasting and irrigation scheduling. Charney et. al. (1977) have studied its effect on the desertification process using general circulation models. Gannon (1977) has shown that the moisture content of the soil is the dominant parameter in modeling studies of the sea breeze in central Florida. Thus any techniques which could remotely sense soil moisture would be of great benefit for these applications. There are three methods that have shown promise for achieving this goal (Schmugge, 1978). They are: thermal inertia techniques using the diurnal range of surface temperature, active microwave or radar, and passive microwave. These approaches have been studied using sensors operating from aircraft platforms, by comparing the sensor response with ground measurements of soil moisture. These observations were typically made for fields 400m on a side (40 acres) with uniform surface conditions. Early experiments of this type used a value determined by the average of samples from 4 points per field (Schmugge et. al., 1974; Schmugge et.al., 1976; Burke et.al., 1979). However, because of the natural variability of soil moisture there has been considerable uncertainty in these ground determinations, and because the statistical variability of the data has a direct bearing on the outcome of the experiment it became essential that the magnitude and cause of any variability must be clearly defined if such a technique is to have widespread applications. In order to gain a better understanding of the in-situ variability of soil moisture within large field sites, a statistical analysis of available data obtained from previous NASA missions was performed. For purposes of this report, a "large field" area is defined as a soil area comprised of 16 hectares (40 acres). Inherent to this study was the desire to develop a statistically based sampling system relative to soil moisture variability which would accurately define the soil moisture regime of a given area.

BACKGROUND

Hills and Reynolds (1969), in a study of soil moisture variability for various size plots have found that the Coefficient of Variation (CV = standard deviation/mean) ranges from 6 to 16% for

60 samples from 1 X 1 m plots and from 8 to 15% for 30 X 30 m plots. The average soil moisture ranged from 30 to 70% for these plots. In another experiment they took 10 samples from plots ranging in size from 15 X 15 cm up to 31 X 31 m, all having average moisture levels of approximately 70% by weight. The standard deviations ranged from 3.2 to 6.5% yielding a range of CV from 4 to 9% with no correlation to plot size. Hills and Reynolds concluded from these results that for the smaller plots the magnitude of variability is not reduced when the plot size is reduced. However, they did find an increase when they studied the variability over an entire drainage basin, ($6 km^2$), for these cases the CV went up to 30% or more. Thus one cannot expect a CV of less than 5% in any situation and generally the CV is greater than 10%. They found that for larger samples, forty or more, the soil moisture values were normally distributed. A normal distribution was also observed in a plot study by Nielsen et.al. (1973) on a 150 hectare field. Therefore in the current analysis a normal distribution of soil moisture values will be assumed.

The data from one of the sites (Jefferson County, Kansas), included in this report, have been studied by Rao and Ulaby (1977) who sought to statistically estimate the number of samples required to reduce the uncertainty of the mean to 10% of its value. The data showed considerable segregation in that the surface layers were much drier (generally 6–7% or less for the 0-1 cm layer compared to 17 – 20% for the 9-15 cm layer) and had larger values of CV. As a result they came to the conclusion that more samples were required for the surface layer. One of the findings of this report is that CV is not a function of soil depth, i.e. surface layers have the same degree of variation as deeper layers when the moisture profiles are uniform.

DATA COLLECTION

In recent years NASA has sponsored a number of aircraft experiments studying the remote sensing of soil moisture. The experiments were conducted in Phoenix, Arizona (Blanchard, 1975); Jefferson County, Kansas (Dobson & Batlivala, 1976); Finney County, Kansas (Dobson, 1977); and Hand County, South Dakota (Jones, 1977 abc, 1978 abc).

At all four test sites gravimetric soil moisture samples were collected at various depth increments along a predetermiend grid system. The actual grid system and depth increments differed at each test site. The one common feature among the four sites was the areal extent of the fields, which was 16 hectares (40 acres). The general details of each location are described below and summarized in Table 1.

TABLE 1 SUMMARY OF TEST SITES

Location	Number of fields	Sampling Dates	Number of Samples	Sampling Putter	Depths	Comments
Phoenix, Ariz	1	4/ /74 3/13/75 3/16/75 3/21/75	36	6X6 Grid See Fig. 1	0-1, 1-2, 2-5, 5-9, 9-15 cm	Just Irrigated
Jefferson Cty Kansas	29	4/12/76	19	See Fig. 2		Relatively Dry
Finney Cty Kansas	24	10/13/76	9 to 35	See Fig. 3	0-1, 1-2 cm (35 pts) 2-5 cm (15 pts) 5-9, 9-15 (9 pts)	"
Hand Cty South Dakota	3	5/ /77	36	3X12 grid	0-2.5, 0-5, 0-10 cm	
	2	6/ /77	"	6X6 grid		
	1	5/2/78	"	"		
	1	5/31/78 (3)	"	"		Sampled at 3 different times of day
	1	7/26/78	"	"		

Phoenix Study

One field (260B) in the Phoenix area was extensively sampled to gain an understanding of the spatial variation of the soil moisture. A thirty-six point square grid system, Figure 1, was used to sample the field. At each grid point, samples were taken at depth increments of 0-1 cm, 1-2 cm, 2-5 cm, 5-9 cm and 9-15 cm. The field was furrowed to a depth of 15 to 20 cm with a 1 m separation for irrigation purposes, therefore separate moisture measurements were taken from both the top and bottom of the furrows. Field 260B was sampled on four occasions, April, 1974 and March 13, 16, and 21, 1975.

Figure 1 also shows a sample of the range of variation that can be expected. The mean moisture for this case was 7.1%, with a low of 4% near the center to 14% at the upper left hand corner, and a standard deviation of 2.5%

Jefferson County Study

The test site in Jefferson County consisted of 29 forty acre fields. Each of the forty acre fields were sampled at the 19 locations shown in Figure 2. The grid was selected to maximize the probability of adequate sampling for a diversity of sensor ground footprints. Twenty-eight of the twenty-nine fields sampled in Jefferson County were used in this study.

Moisture samples were taken from depths of 0-2 cm, 1-2 cm, 2-5 cm, 5-9 cm, and 9-15 cm at each of the 19 grid locations. The mission in Jefferson County Kansas took place on April 12, 1976. Bulk density measurements were also made for these fields.

Finney County Study

This NASA mission was carried out on October 13, 1976 over Finney County in Western Kansas. Twenty-four fields were sampled at this site. Based on the analysis of the Jefferson County data, discussed earlier, Rao and Ulaby(12)statistically estimated the number of soil samples taken at this site were a function of depth. Thus, 35 samples were taken at depths of 0-1 cm, and 1-2 cm, while 15 samples were taken from the 2-5 cm horizon, and only nine samples from both the 5-9 cm and 9-15 cm layers. The grid system used for the Finney County location is shown in Figure 3.

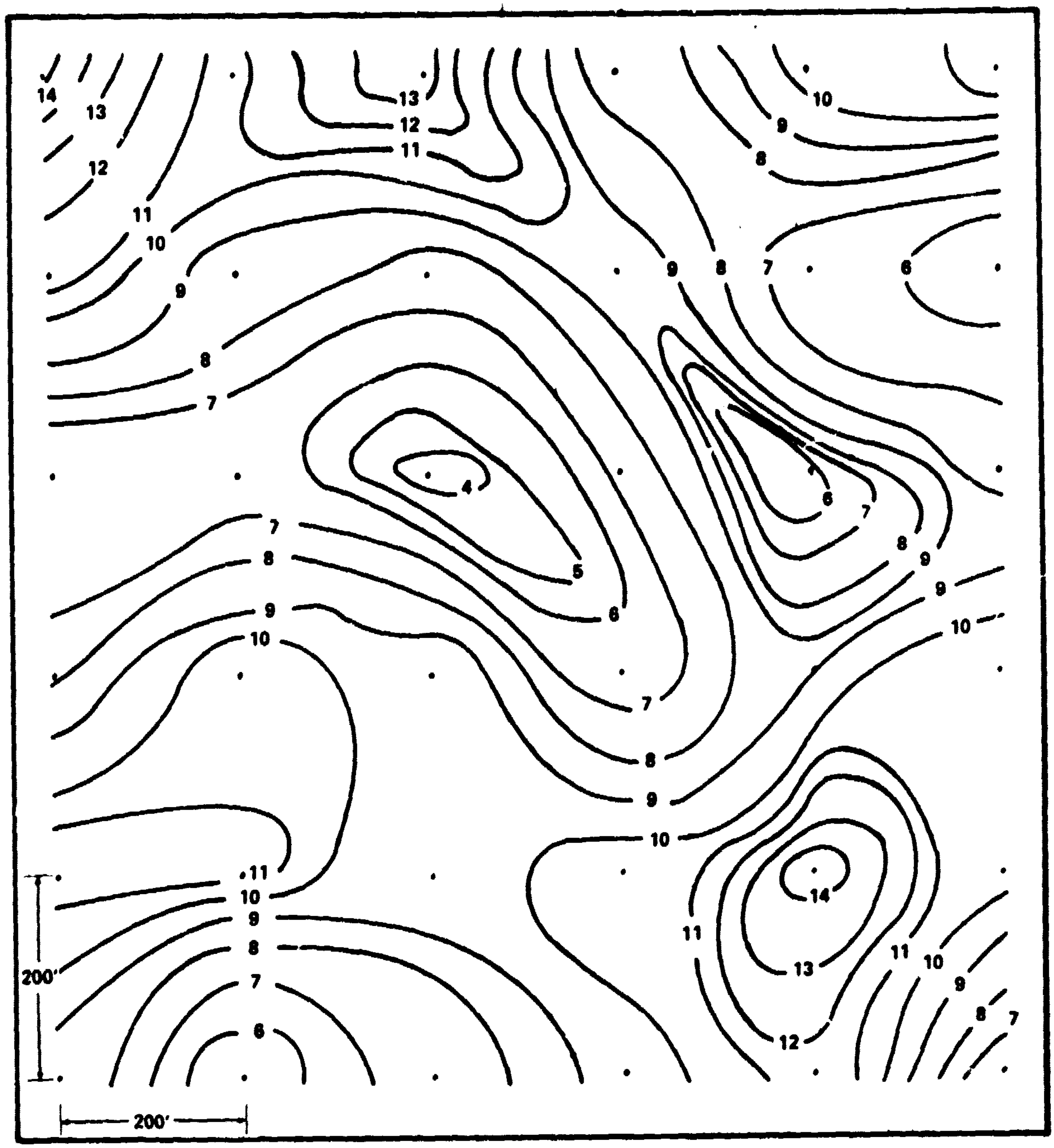

Figure 1. Iso-Moisture Contour Profile (0-1 cm) (Field 260 B, Phoenix, 4/74).

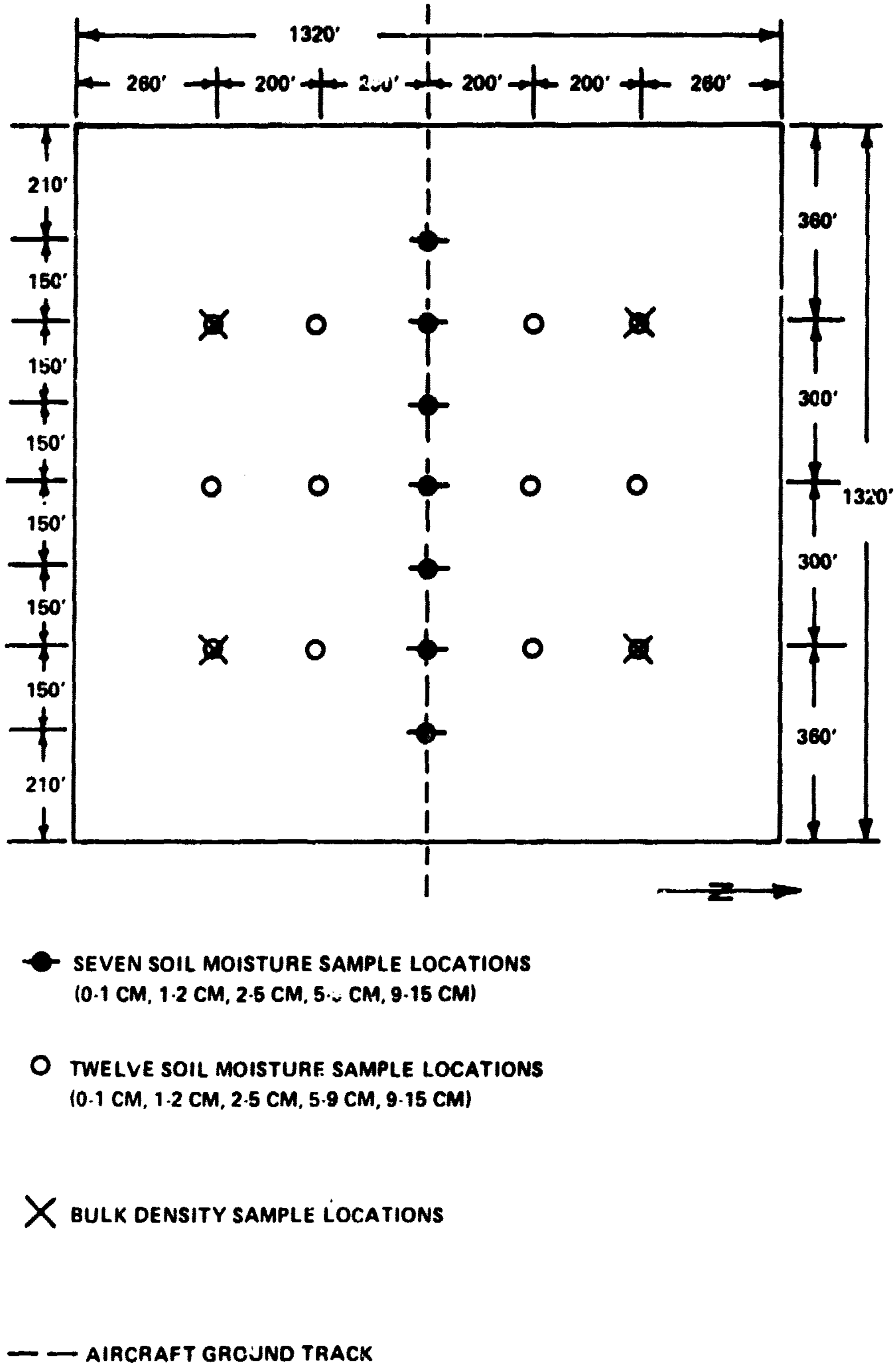

Figure 2. Jefferson County Study Sample Grid.

The data from field 129A appeared to be an extreme outlier and therefore was eliminated from the study.

<u>Hand County Study</u>

The Hand County, South Dakota site has been a test location for NASA for nine missions over the past three years. On the last five missions (May 1977, June 1977, May 1978, June 1978 and July 1978) a few fields were chosen for intensive studies. Three fields were sampled during May 1977, two fields were sampled in June 1977, and one field was sampled during each of the 1978 missions. Each field was sampled at depth increments of 0-1 inch, 0-2 inch, and 0-4 inch. During May 1977 a total of 36 samples were collected at each depth increment along three parallel lines at 100 foot spacing. For the remainder of the intensive sampling studies a square grid system covering the 40 acres, used in the Phoenix mission (Figure 1), was employed. In addition the field (175) was sampled on three occasions over a 24 hour period in May 1978.

<u>Summary</u>

A total of 58 fields (40 acre sites) were included in this study. One of these fields (260 B Phoenix) was sampled on four occasions and one field (175 Hand County) was sampled on five occasions. At the first three test sites soil samples were taken from individual layers (i.e. 0-1 cm, 1-2 cm, 2-5 cm, 5-9 cm and 9-15 cm). It was felt that the results of this and future studies would be more useful with respect to the microwave data if the moisture data were in increments from the surface, or integrated layers (i.e. 0-1 cm, 0-2 cm, 0-5 cm, 0-9 cm, and 0-15 cm). Therefore, data from the first three missions was transformed accordingly by summing the individual layers and calculating an average value. Each layer was given a weighted value depending on its thickness. Table 2 summarizes the mean field moisture, standard deviation and coefficient of variation for the soil moisture from the specific layers of each field.

In general, the two Kansas experiments were characterized by very dry surface layers (0-1 cm), generally around 5-7% or less and rather sharp increases of moisture content with depth. The Phoenix case had more uniform profiles, especially for the bottoms of the furrows, while the South Takota also had more uniform profiles, however in this case 0-1 cm samples were not taken.

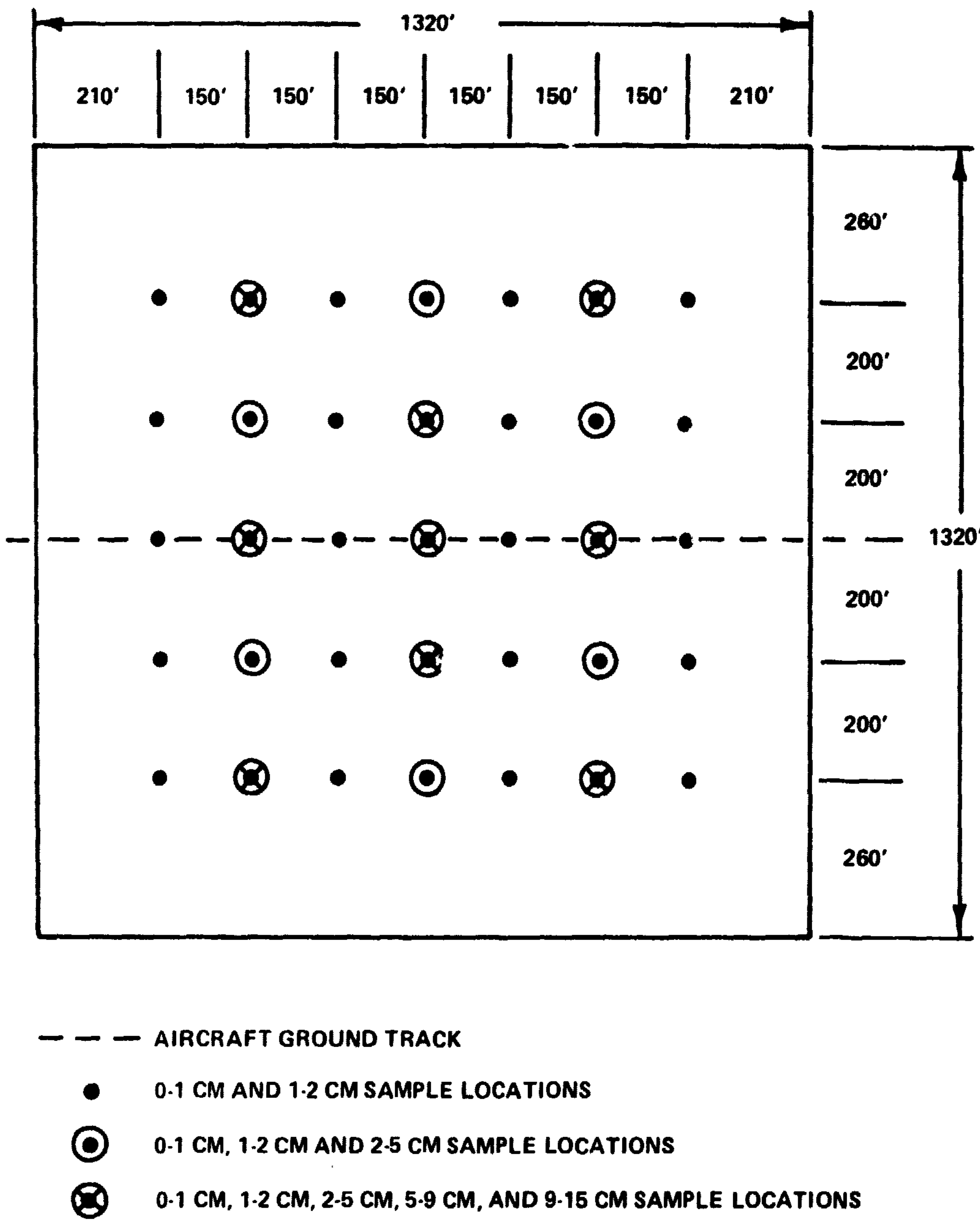

Figure 3. Finney County Study Sampling Grid.

TABLE 2

SUMMARY OF LARGE FIELD MOISTURE DATA: Individual Layers

Location	Date	Field	0-1 cm			1-2 cm			2-5 cm			5-9 cm			9-15		
			$\overline{X}$	S	CV	$\overline{X}$	S	CV	$\overline{X}$	S	CV	$\overline{X}$	S	CV	$\overline{X}$	S	CV
Jefferson	4/76	1	5.9	1.3	22	16.0	2.3	14	21.6	1.8	8	24.7	1.3	4	24.9	1.9	8
County		2	4.5	1.4	30	9.9	2.2	23	15.5	2.1	14	18.2	2.3	13	20.1	2.6	13
Kansas		3	4.7	1.3	28	9.6	1.8	18	13.8	2.6	17	17.0	2.4	14	19.7	1.6	8
		4	9.9	2.0	19	14.8	2.8	18	18.1	2.9	16	21.3	2.4	11	23.8	2.0	8
		5	6.2	1.2	18	14.0	1.6	11	16.0	1.1	7	17.2	1.8	11	17.3	1.4	8
		6	7.5	1.5	19	15.3	1.7	11	19.5	1.7	8	22.2	1.3	6	22.1	1.9	8
		7	3.7	.9	24	8.6	3.3	37	15.8	2.5	16	19.0	2.0	11	20.4	1.2	6
		8	4.6	1.2	26	9.0	2.8	30	15.0	2.6	16	18.5	2.6	9	20.0	2.7	13
		9	4.2	1.0	25	11.0	1.9	17	15.4	2.1	14	18.8	3.7	14	20.3	1.9	8
		10	4.8	1.0	22	10.8	1.6	15	13.0	1.7	13	15.5	2.0	13	18.8	1.5	8
		11	2.2	.7	32	8.4	2.0	24	15.2	1.5	9	17.6	2.1	12	18.9	1.7	8
		12	4.0	1.2	28	12.1	2.1	17	16.9	2.0	12	19.4	2.4	12	19.4	2.2	11
		13	4.4	1.9	42	11.9	3.4	28	16.8	2.2	13	20.1	1.7	8	20.9	1.8	8
		14	13.9	4.7	33	19.1	2.2	11	19.4	1.6	8	19.1	1.4	7	20.0	1.6	8
		15	11.8	4.0	33	15.1	2.4	16	15.6	1.4	8	14.7	1.2	8	15.3	1.0	7
		16	6.4	2.1	32	11.1	1.9	16	13.7	.9	6	14.5	1.6	11	14.9	1.6	11
		17	11.4	3.0	26	14.4	1.4	9	15.1	.9	6	15.6	.7	4	15.8	.9	6
		18	7.3	1.9	25	12.0	2.3	18	17.8	2.7	15	18.6	3.8	19	17.5	3.6	19
		19	2.9	.9	32	6.3	2.5	39	12.3	2.4	18	16.5	2.0	12	19.1	1.4	7
		20	3.2	1.2	35	8.8	5.1	57	13.0	2.0	15	15.9	2.1	13	19.0	1.8	8
		21	2.9	1.0	33	4.8	1.4	28	11.6	2.6	22	16.2	2.3	14	17.8	2.4	14
		22	4.9	1.3	26	7.9	2.7	33	11.6	3.8	32	16.8	2.9	16	18.5	2.2	12
		23	3.7	1.1	28	6.4	1.5	23	13.3	3.1	23	17.5	1.6	8	22.4	3.4	15
		24	2.2	.7	33	5.7	2.4	42	12.4	2.8	23	17.7	1.5	8	19.0	1.6	8
		25	4.4	.9	19	12.3	2.6	21	18.5	1.7	8	19.5	2.1	11	21.6	1.3	6
		26	5.1	1.6	30	11.3	3.2	28	15.4	1.8	12	18.6	1.5	8	19.1	1.7	8
		27	2.0	.6	30	3.0	.9	28	9.5	3.6	37	17.4	3.1	17	18.2	1.6	8
		28	2.6	.5	18	3.7	.7	17	10.5	3.6	33	15.2	4.0	26	20.0	3.1	15
		29	5.4	1.7	30	9.6	2.4	25	16.5	2.3	14	19.3	2.1	11	21.3	1.2	4

TABLE 2 (Continued)

SUMMARY OF LARGE FIELD MOISTURE DATA: Individual Layers

Location	Date	Field	0-1 cm			1-2 cm			2-5 cm			5-9 cm			9-15		
			$\overline{X}$	S	CV	$\overline{X}$	S	CV	$\overline{X}$	S	CV	$\overline{X}$	S	CV	$\overline{X}$	S	CV
Finney	10/76	18	4.6	1.8	39	10.5	5.6	53	20.6	2.2	11	22.0	.9	4	23.2	1.3	6
County,		21	4.9	1.3	26	11.3	3.7	32	22.3	3.1	14	22.9	2.0	8	23.1	2.0	9
Kansas		30A	6.9	1.8	25	14.4	3.6	25	22.0	1.7	8	23.1	2.1	8	24.1	1.1	4
		30B	5.0	1.6	30	10.2	3.2	30	18.6	2.5	13	20.8	4.1	19	21.5	4.0	18
		30C	3.9	1.0	26	10.6	3.9	37	20.4	2.2	11	23.2	1.7	7	24.1	2.6	11
		33A	3.7	1.1	28	5.4	2.2	41	15.2	3.3	21	21.5	2.2	9	21.2	2.9	14
		33B	2.5	.6	24	3.8	1.3	35	12.4	2.2	17	19.8	2.0	9	21.8	2.1	9
		35A	5.3	.9	16	8.8	2.7	30	14.6	4.2	28	21.0	4.2	19	23.0	2.9	13
		35B	4.5	1.0	24	10.0	3.9	39	16.7	3.1	18	20.5	2.8	14	21.8	1.2	6
		37A	4.4	1.4	32	10.4	5.2	50	17.2	4.7	26	22.6	2.2	8	22.9	3.0	13
		37B	4.4	1.3	28	11.1	5.1	46	17.6	5.7	32	21.8	1.1	4	22.1	1.6	7
		38A	5.1	1.7	33	11.0	4.1	37	21.9	2.5	12	23.5	1.5	6	24.1	1.5	6
		38B	5.8	2.3	39	14.7	4.1	28	22.3	2.5	11	24.0	2.0	8	25.1	1.4	4
		50A	6.2	2.3	35	13.0	4.7	32	19.8	3.5	17	22.7	2.8	14	23.3	3.2	13
		50B	6.2	2.7	42	13.8	4.6	32	21.0	2.5	12	25.2	3.2	13	26.0	3.1	12
		50C	5.8	2.5	44	13.4	5.1	37	18.6	2.5	13	22.1	2.2	9	23.8	1.8	8
		57A	4.1	.9	21	10.0	4.3	42	17.8	2.5	14	23.6	1.7	7	26.2	1.9	7
		57B	3.7	.8	22	9.5	3.5	37	19.8	3.5	17	22.1	2.5	11	22.2	2.1	9
		129B	4.2	1.1	26	8.3	3.5	42	18.8	4.3	23	22.6	2.5	11	22.8	1.6	7
		129C	5.6	1.2	21	11.9	5.3	44	20.4	4.2	21	23.9	2.4	9	25.5	2.2	8
		129D	6.3	1.5	24	13.4	4.5	33	20.1	4.1	21	23.8	1.8	7	25.6	1.8	7
		148A	4.9	2.1	42	9.0	3.7	42	19.2	4.3	22	23.7	2.2	8	24.8	2.4	9
		148B	4.8	1.3	26	9.3	4.8	52	23.2	2.9	12	23.8	3.0	13	23.7	3.6	15
Phoenix,	4/74	260T	7.1	2.5	35	16.0	4.7	28	21.9	2.5	11	23.5	1.9	8	25.0	2.5	9
Arizona		260B	24.3	6.5	26	26.1	4.5	16	26.1	3.5	14	25.7	2.7	11	25.1	1.8	7
	3/13/75	260T	27.6	3.4	12	28.1	2.5	8	28.8	2.3	8	30.1	2.3	7	31.1	2.8	8
		260B	44.4	3.5	8	41.6	3.0	7	40.7	3.9	9	37.5	3.9	9	35.9	3.0	8
		260T	19.8	3.9	18	25.5	2.1	8	26.7	2.3	8	27.6	1.9	7	28.0	1.7	6

TABLE 2 (Continued)

SUMMARY OF LARGE FIELD MOISTURE DATA: Individual Layers

Location	Date	Field	0-1 cm $\overline{X}$	0-1 cm S	0-1 cm CV	1-2 cm $\overline{X}$	1-2 cm S	1-2 cm CV	2-5 cm $\overline{X}$	2-5 cm S	2-5 cm CV	5-9 cm $\overline{X}$	5-9 cm S	5-9 cm CV	9-15 $\overline{X}$	9-15 S	9-15 CV
Phoenix,	3/16/75	260B	37.5	4.2	11	37.9	3.0	8	36.6	4.2	11	32.0	3.7	12	31.4	2.4	8
Arizona	3/21/75	260T	9.4	2.4	25	20.2	2.9	14	23.4	1.9	8	24.5	1.9	8	24.7	2.5	9
		260B	29.4	3.8	13	30.0	3.5	12	29.6	3.2	11	28.6	3.2	11	26.5	2.5	8

SURFACE TO DEPTH LAYERS

Location	Date	Field	0-1 cm $\overline{X}$	0-1 cm S	0-1 cm CV	0-1 cm $\overline{X}$	0-1 cm S	0-1 cm CV	0-5 cm $\overline{X}$	0-5 cm S	0-5 cm CV	0-9 cm $\overline{X}$	0-9 cm S	0-9 cm CV	0-15 cm $\overline{X}$	0-15 cm S	0-15 cm CV
Jefferson	4/76	1	5.9	1.3	22	11.0	1.8	16	17.4	1.8	9	20.6	1.5	7	22.3	1.7	8
County,		2	4.5	1.4	30	7.2	1.8	25	12.2	2.1	16	14.8	1.7	12	17.0	1.9	11
Kansas		3	4.7	1.3	28	7.2	1.7	23	11.1	2.3	21	13.8	2.6	18	16.1	2.0	13
		4	9.9	2.0	19	12.3	2.6	21	15.8	2.9	17	18.2	2.7	15	20.4	2.4	12
		5	6.2	1.2	18	10.1	1.5	14	13.6	1.2	8	15.2	1.7	11	16.1	1.6	9
		6	7.5	1.5	19	11.4	1.7	15	16.3	1.7	9	18.9	1.4	8	20.4	1.5	7
		7	3.7	.9	24	6.1	2.2	37	11.9	2.3	18	15.1	1.9	13	17.2	1.7	9
		8	4.6	1.2	26	6.8	2.1	30	11.7	2.4	19	14.7	2.2	15	16.8	2.2	13
		9	4.2	1.0	25	7.6	1.6	21	12.2	2.1	16	15.2	2.2	15	17.2	1.9	11
		10	4.8	1.0	22	7.8	1.6	19	10.9	1.6	14	13.0	1.9	14	15.3	1.6	9
		11	2.2	.7	32	5.3	1.4	26	11.2	1.4	12	14.1	1.7	12	16.0	1.3	8
		12	4.0	1.2	28	8.1	1.7	21	13.4	1.9	14	16.1	1.9	11	17.4	1.7	9
		13	4.4	1.9	42	8.2	2.8	35	13.4	2.8	21	16.4	2.3	14	18.2	2.1	12
		15	11.8	4.0	33	13.5	3.5	26	14.7	2.1	14	14.7	1.3	8	14.9	1.0	7
		16	6.4	2.1	32	8.6	2.4	44	11.7	1.2	9	12.9	1.1	8	13.7	1.3	8
		17	11.4	3.0	26	12.9	2.5	18	14.2	1.5	11	14.9	1.1	8	15.2	1.0	6
		18	7.3	1.9	25	9.7	2.1	22	14.6	2.4	16	16.4	2.4	15	16.8	2.5	15
		19	2.9	.9	32	4.6	2.0	42	9.2	2.2	24	12.5	2.1	16	15.1	1.6	9
		20	3.2	1.2	35	5.0	1.6	32	9.8	1.6	16	12.5	1.7	14	15.1	1.7	11
		21	2.9	1.0	33	3.9	1.4	37	8.5	2.2	26	11.9	2.3	18	14.2	2.3	16

TABLE 2 (Continued)
SURFACE TO DEPTH LAYERS

Location	Date	Field	0-1 cm			0-2 cm			0-5 cm			0-9 cm			0-15		
			$\overline{X}$	σ	CV	$\overline{X}$	σ	CV	$\overline{X}$	σ	CV	$\overline{X}$	σ	CV	$\overline{X}$	σ	CV
Jefferson County, Kansas	4/76	22	4.9	1.3	26	6.4	2.3	35	9.5	3.4	35	12.6	3.4	26	15.0	2.8	18
		23	3.7	1.1	28	5.1	1.3	26	10.0	2.4	24	13.3	1.9	15	16.3	1.5	8
		24	2.2	.7	33	3.9	1.7	44	9.0	2.6	28	12.8	2.0	15	15.3	1.8	12
		25	4.4	.9	19	8.4	2.0	23	14.5	1.8	12	16.7	2.0	12	18.7	1.7	8
		26	5.1	1.6	30	8.2	2.8	33	12.5	2.2	16	15.2	2.0	13	16.8	1.7	9
		27	2.0	.6	30	2.5	.6	26	6.7	2.5	37	11.5	2.4	21	14.1	1.7	12
		28	2.6	.5	18	3.2	.7	21	7.6	2.8	37	10.9	3.4	30	14.6	3.2	22
		29	5.4	1.7	30	7.5	2.3	30	12.9	2.4	18	15.8	2.1	13	20.0	1.5	8
Finney County Kansas	10/76	18	4.6	1.8	39	7.6	3.6	48	15.8	3.3	21	17.9	1.2	7	20.0	1.1	6
		21	4.9	1.3	26	8.0	2.3	28	16.5	2.1	13	19.4	1.9	9	20.5	2.6	13
		30A	6.9	1.8	25	10.7	2.5	23	17.4	1.8	9	19.7	1.8	8	21.6	1.7	8
		38B	5.0	1.6	30	7.7	2.2	28	14.0	1.8	13	16.8	1.9	11	18.7	1.7	8
		30C	3.9	1.0	26	6.7	2.6	37	15.8	2.2	14	19.2	1.7	8	21.2	1.9	8
		33A	3.7	1.1	28	4.6	1.4	32	10.5	2.3	22	15.5	2.4	15	17.8	2.4	14
		33B	2.5	.6	24	3.2	.8	24	8.5	1.4	16	13.2	1.4	11	16.7	1.5	8
		35A	5.3	.9	16	7.0	1.6	22	11.4	2.7	24	15.4	2.9	18	18.5	2.8	15
		35B	4.5	1.0	24	7.3	2.2	30	12.7	2.3	17	16.1	1.7	11	18.4	.9	4
		37A	4.4	1.4	32	7.4	3.0	41	12.8	3.3	26	17.2	2.5	15	19.2	2.3	12
		37B	4.4	1.3	28	7.8	3.0	37	13.3	4.1	30	17.1	2.3	13	19.1	1.6	8
		38A	5.1	1.7	33	7.9	2.6	32	16.4	2.2	13	19.8	1.8	8	21.5	1.6	7
		38B	5.8	2.3	39	10.2	3.0	28	18.1	2.8	16	20.1	2.3	11	22.4	1.6	7

TABLE 2 (Continued)

SUMMARY OF LARGE FIELD MOISTURE DATA

			0-1 cm			0-2 cm			0-5 cm			0-9 cm			0-15		
Location	Date	Field	$\overline{X}$	σ	CV	$\overline{X}$	σ	CV	$\overline{X}$	σ	CV	$\overline{X}$	σ	CV	$\overline{X}$	σ	CV
Finney	10/76	50A	6.2	2.3	35	9.4	3.1	32	14.8	2.6	17	17.9	2.5	14	20.1	2.6	13
County		50B	6.2	2.7	42	10.0	3.4	33	15.6	1.8	11	20.0	2.4	12	22.4	2.6	12
Kansas		50C	5.8	2.6	44	9.6	3.6	37	13.7	2.5	17	17.7	2.2	12	20.1	1.9	8
		57A	4.1	.9	21	7.1	2.4	33	12.7	1.8	14	17.7	1.4	8	21.2	1.5	7
		57B	3.7	.8	22	6.6	2.0	30	14.8	2.5	16	17.9	1.7	8	19.8	1.7	8
		129B	4.2	1.1	25	6.0	1.5	25	13.7	2.9	21	17.2	2.6	15	19.4	1.9	9
		129C	5.6	1.2	21	8.7	2.8	32	16.6	2.5	15	20.6	2.0	9	22.6	1.9	8
		129D	6.3	1.5	24	9.8	2.7	35	16.5	3.5	21	20.2	2.4	12	22.4	2.0	8
		148A	4.9	2.1	42	7.0	2.8	39	13.8	2.9	21	17.8	2.4	14	20.6	2.2	11
		148B	4.8	1.3	26	7.2	2.8	39	16.5	2.2	13	19.6	2.5	13	21.1	2.9	14
Phoenix,	4/76	260T	7.1	2.5	35	11.6	3.3	28	17.7	2.6	15	20.3	2.2	11	22.2	2.1	8
Arizona		260B	24.3	6.5	26	25.2	5.5	22	25.7	2.1	8	25.7	2.1	8	25.5	2.6	9
	3/13/75	260T	27.6	3.4	12	27.8	2.7	9	28.4	2.4	8	29.2	2.1	7	30.0	2.2	7
		260B	44.4	3.5	8	42.5	3.2	7	41.4	3.2	8	39.4	3.2	8	37.7	2.9	8
	3/16/75	260T	19.8	3.7	18	22.7	2.8	12	25.0	2.4	9	26.0	1.9	7	26.8	1.7	6
		260B	37.5	4.2	11	37.5	3.1	8	37.1	3.5	8	34.6	3.4	9	33.7	3.0	8
	3/21/75	260T	9.4	2.4	25	14.8	2.4	16	19.9	1.8	8	22.0	1.8	8	23.0	1.7	7
		260B	29.4	3.8	13	29.3	3.9	13	29.5	3.1	11	29.1	3.0	9	28.1	2.6	8

TABLE 2 (Continued)

SUMMARY OF LARGE FIELD MOISTURE DATA

Location	Date	Field	0-1 in			0-2 in			0-4 in		
			$\overline{X}$	σ	CV	$\overline{X}$	σ	CV	$\overline{X}$	σ	CV
Hand County, South Dakota	5/77	126	4.1	2.9	71	10.5	4.6	44	16.1	3.6	22
		177	3.3	1.4	42	5.0	2.0	39	8.6	2.7	32
		191				6.5	1.9	28	8.3	1.8	22
	5/77	119	9.5	2.9	30	13.6	2.9	21	13.8	3.3	24
		210	14.5	3.4	23	18.7	2.2	12	21.8	2.4	11
	5/78	175	16.6	4.7	28	19.9	3.4	16	22.7	2.7	12
		175	19.0	5.2	26	21.0	3.9	18	23.6	3.2	14
		175	18.2	5.4	30	21.2	3.9	18	23.6	3.2	18
	6/78	175	24.5	4.2	16	26.1	4.5	16	27.3	3.3	12
	7/78	175	10.2	3.5	35	14.2	2.3	16	17.8	2.4	14

DATA ANALYSIS

Using these data a statistical study was made to define the general relationships and ranges of values for the mean field moisture ($\bar{x}$), standard deviation (σ) and coefficient of variation (CV) for a given forty acre field. Emphasis was placed on the CV analysis because preliminary NASA studies of microwave response data have shown that a coefficient of variation less than 15% would be most desirable for soil moisture-Brightness Temperature correlations.

The statistical analyses were performed for both the integrated layers (0-1, 0-2, . . ., 0-15 cm) and for the individual layers (0-1, 1-2, 2-5, . . ., 9-15 cm) data. A comparison of the results for the two approaches will be made.

Integrated Layers

The initial step in this study was the collection and tabulation of all data by field location and depth increment. Using the data in Table 2 an analysis was then made to investigate the relationship between mean moisture content and CV. Figure 4 shows the arithmetic relationship between these variables. As can be seen the data is highly non linear. In addition the data from the Hills & Reynolds (1969) are plotted for comparison and to extend the moisture range of the data. It should be noted that their data were for smaller plots, (31 X 31 m was the largest), and the sample depth was 0-8 cm. Even for their smaller plots the values of CV were in the same range as those observed for 16 hectare fields. As can be seen from Figure 4 the CV is greater than 5% and for soil moistures greater than 20% the CV is generally less than 15%.

A log-log model was also evaluated. This result, shown in Figure 5 and 6. now generally appears to be linear. Figure 5 shows the data as a function of location while Figure 6 shows the data as a function of soil layer. Note especially that the results for the 0-1 and 0-2 cm layers, Figure 6, are distributed over the same range of CV and soil moisture as the deeper layers and that CV for the surface layers decreases with increased moisture content.

Regression equations were calculated for each depth increment and collectively for the entire data set. Table 3 summarizes the regression equations and their respective correlation coefficients squared (R^2). The regression equation for the entire data set is shown as the solid line on Figures 5 and 6. In addition lines showing a standard deviation of 1%, 2%, 3%, and 5% were added to show the limits of variability of the data set. In Table 3 low R^2 values exist for several of the soil layers. This

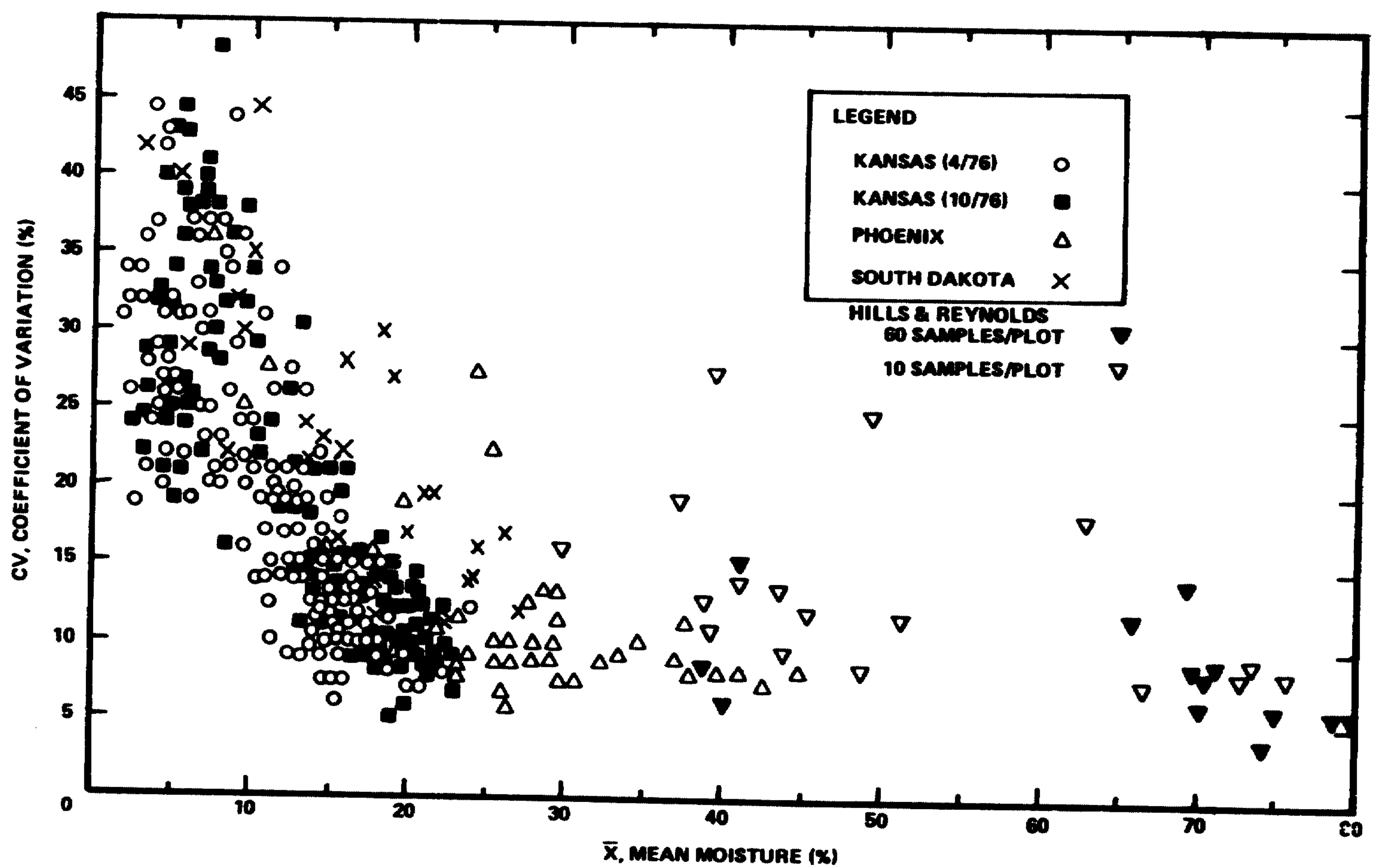

Figure 4. Arithmetic Plot of CV Versus Mean Moisture (Integrated Layers).

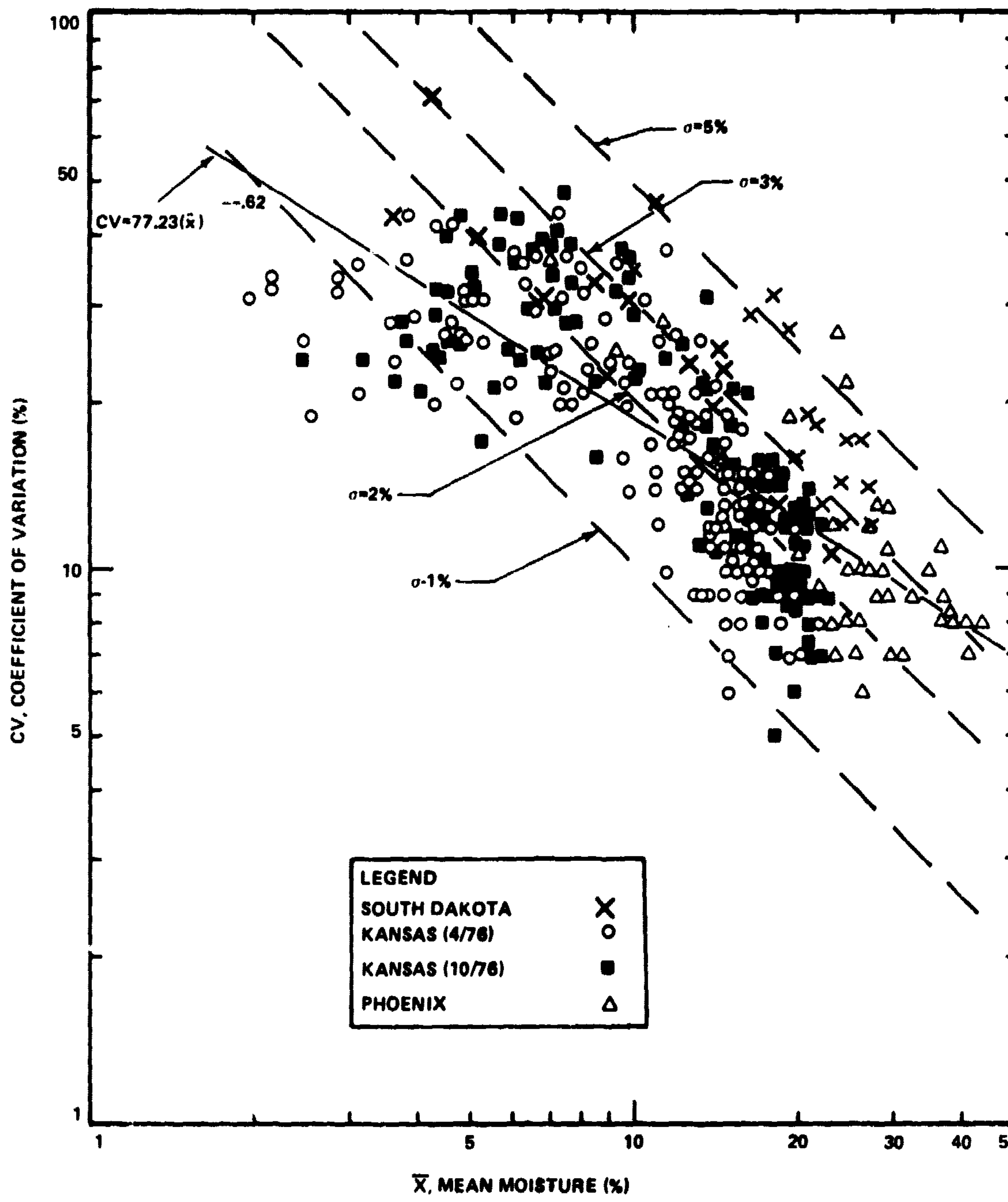

Figure 5. Log-Log plot of CV Versus Mean Moisture (Integrated Layer's by Location). The dashed lines are the curves that would be obtained for the indicated values of σ.

TABLE 3

SUMMARY OF REGRESSION EQUATIONS

DEPTH INCREMENT (cm)	EQUATION	R^2
0-1	$CV = 55.0(\overline{X})^{-0.36}$	.42
0-2	$CV = 80.3(\overline{X})^{-0.52}$	.48
0-5	$CV = 150(\overline{X})^{-0.84}$	.57
0-9	$CV = 151(\overline{X})^{-0.89}$	.47
0-15	$CV = 44.9(\overline{X})^{-0.52}$	.14
ALL	$CV = 77.2(\overline{X})^{-0.62}$	.62

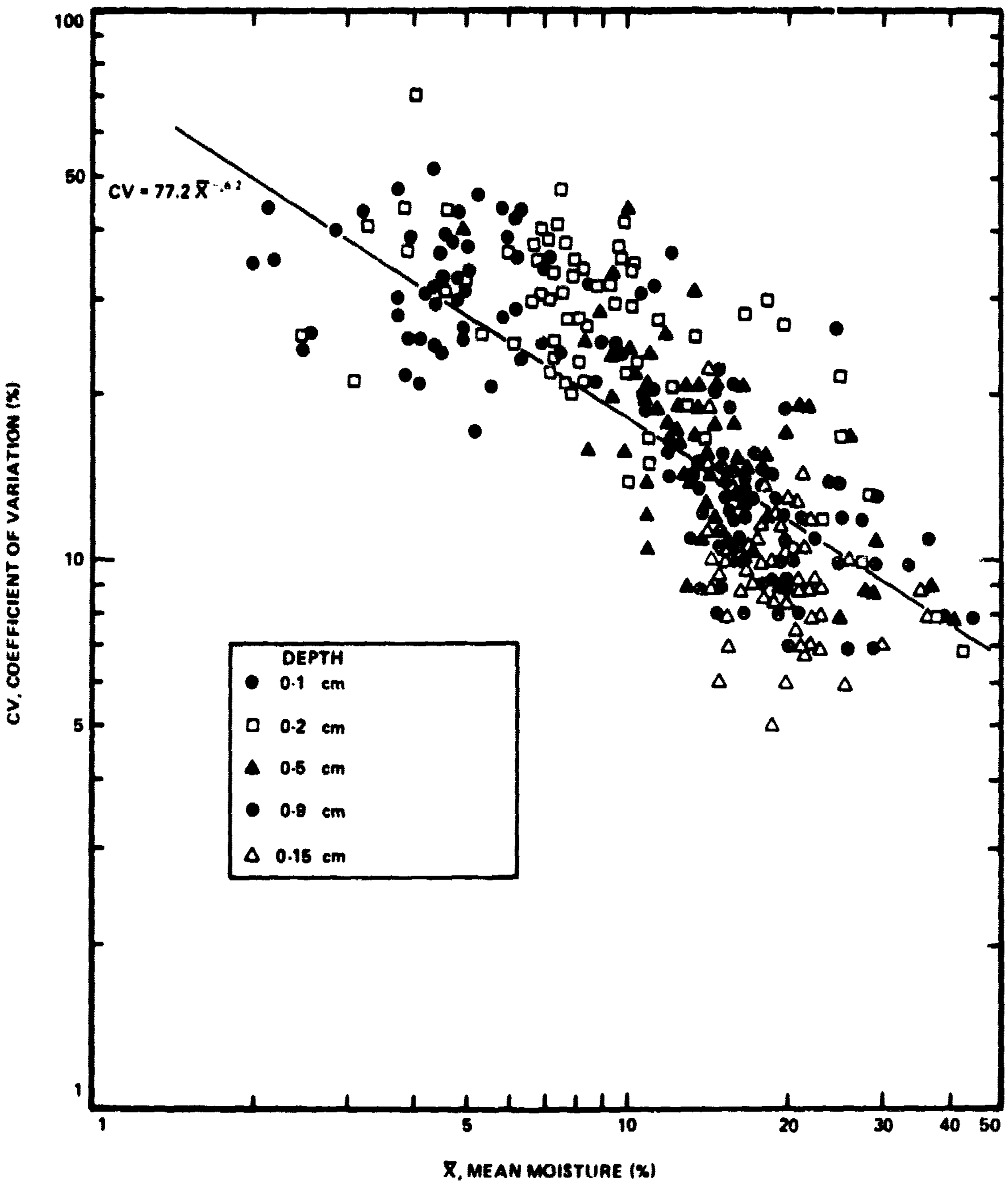

Figure 6. Log-Log Plot of CV Versus Mean Moisture (Integrated Layers by Depth).

is due to the strong segregation in the moisture content levels associated with a given soil layer. In Figure 6 the moisture contents for 0-1 cm are clustered between 3-5%; 0-2 cm layer near 7-9%; 0-5 cm at 10-14%; 0-9 cm at 17%; and 0-15 cm near 20% moisture content. The only data that was consistently outside these main clusters was obtained from the Phoenix test site where the highest moisture levels and most uniform profiles were observed.

It was also found that for the Phoenix location (Field 260B) where they were near equal moisture contents throughout the entire profiel below the bottoms of the furrows, the CV remained nearly constant with depth as shown in Table 4. This result would strongly indicate that CV is more dependent on moisture level than on depth.

The values of σ were also compared to the mean moisture. The plot of these data in arithmetic form is shown in Figure 7. There are several observations that can be made concerning this plot. At low moisture levels (below 10%) there is a linear increase of the upper limit for σ given approximately by: $\sigma = 0.5\bar{x}$. Furthermore, 87% of the values have σ's below 3% and about 96% have σ's below 4%. Therefore it can be concluded with a high degree of confidence that σ will be less than 4%.

With this estimate of the upper limit for the standard deviation (σ) it is possible to make estimates of the number of samples required to determine the average soil moisture for a field within certain limits of accuracy (L). To be 95% confident that the true mean is within plus or minus L of the observed mean, the number of samples (n) required is (Snedecor & Cochran, 1967)

$$n = (1.96\,\sigma/L)^2 = 4(\sigma/L)^2 = 4\left(\frac{CV}{L/\bar{x}}\right)^2$$

for $L/\bar{x}$ and CV expressed in %. This relationship is plotted in Figure 8 for σ = 3, and 4. Thus for a σ of 4% and a L of 2%, which is a reasonable level of accuracy for soil moistures greater than 10%, an n of 16 would be required. To make a significant reduction in L (e.g., to 1%) would require quadrupling the number of samples and would be of questionable value.

Individual Layers

The first step in the individual layer analysis, as in the weighted layer analysis, was the study of the relationship between an individual layer's (depth increment) mean moisture and the Coefficient of Variation. Applying the information obtained from the first study, the CV data was only investigated in a log-log format as shown in Figure 9. The resulting plot is very similar

TABLE 4

VARIATION OF CV AND STANDARD DEVIATION FOR PHOENIX, ARIZONA

DATA	DEPTH INCREMENT	MEAN MOISTURE		STANDARD DEVIATION		CV%	
		Top	Bottom	Top	Bottom	Top	Bottom
3/13/75	0-1 cm	27.6	44.4	3.4	3.5	12	8
	0-2 cm	27.8	42.5	2.7	3.2	10	8
	0-5 cm	28.4	41.4	2.4	3.2	9	8
	0-9 cm	29.2	39.4	2.1	3.2	8	8
	0-15 cm	30.0	37.7	2.2	2.9	7	8
3/16/75	0-1 cm	19.8	37.5	3.7	4.2	19	11
	0-2 cm	22.7	37.5	2.8	3.1	12	8
	0-5 cm	25.0	37.1	2.4	3.5	10	9
	0-9 cm	26.0	34.6	1.9	3.4	7	10
	0-15 cm	26.8	33.7	1.7	3.0	6	9
3/21/75	0-1 cm	9.4	29.4	2.4	3.8	25	13
	0-2 cm	14.8	29.3	2.4	3.9	[illegible]	13
	0-5 cm	19.9	29.5	1.8	3.1	[illegible]	11
	0-9 cm	22.0	29.1	1.8	3.0	8	10
	0-15 cm	23.0	28.1	1.7	2.6	7	9

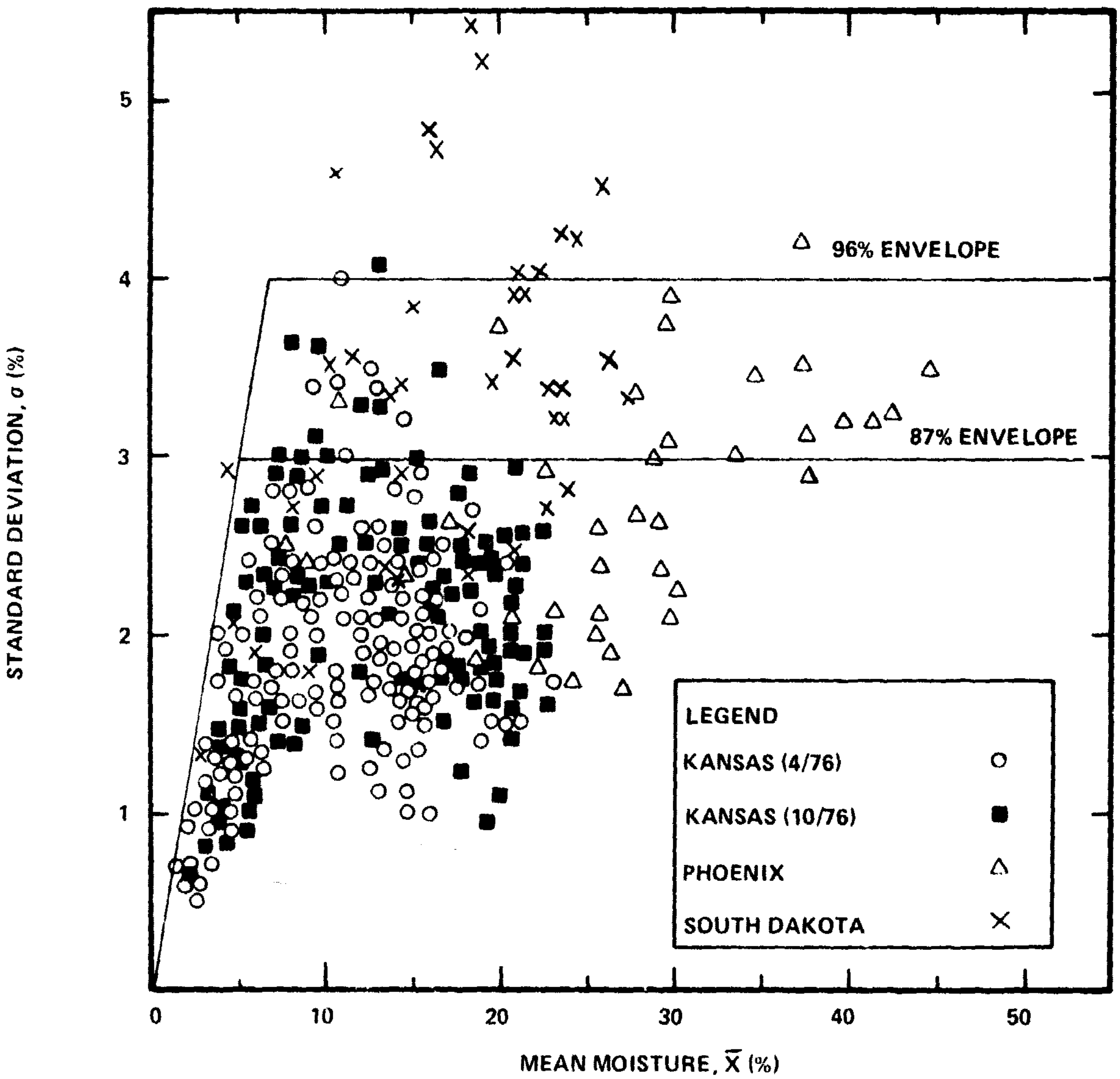

Figure 7. Arithmetic Plot of Standard Deviation Versus Mean Moisture (Integrated Layers).

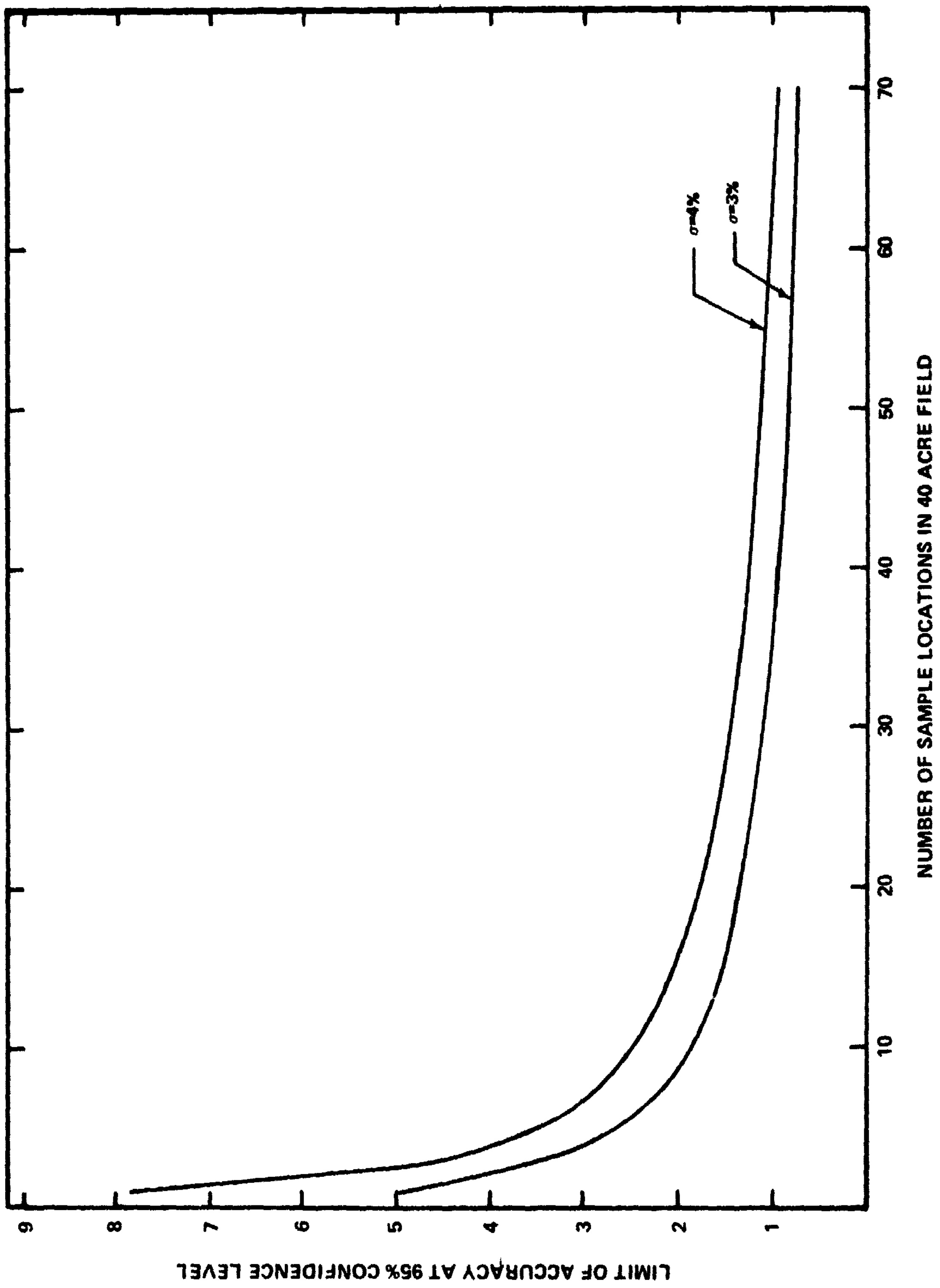

Figure 8. Limit of Accuracy Curves (Integrated Layers)

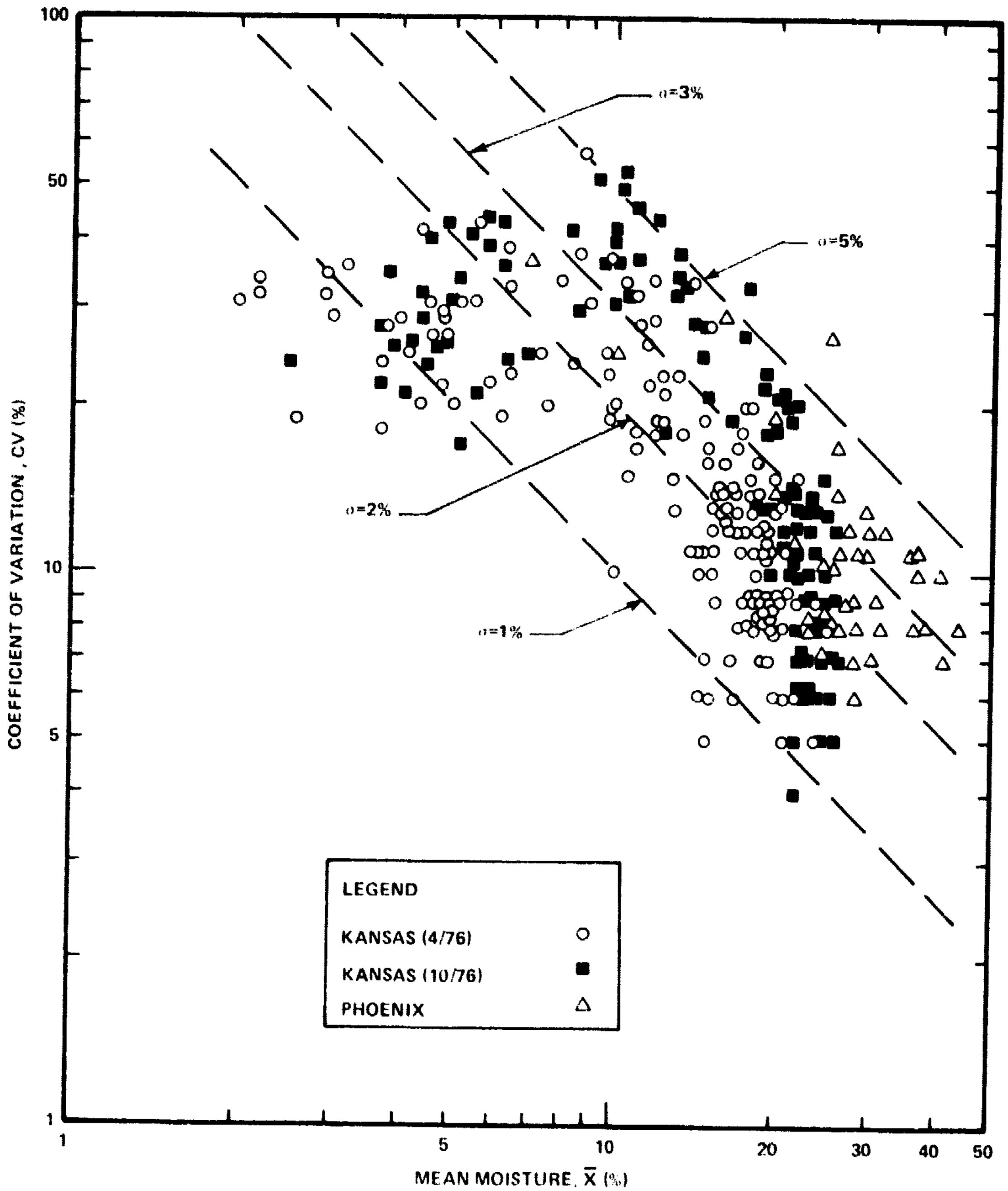

Figure 9. Log-Log Plot of CV Versus Mean Moisture (Individual Layers).

to the weighted layer plot (Figures 6 and 7) except that the data is slightly more scattered. This caused the R^2 to drop to .60 as compared to the .62 for the weighted layers. In addition it can be also observed by a comparison of the two figures that the standard deviations for the individual layer are slightly larger than the weighted values.

The plot of the standard deviation versus the moisture content for the individual layers, shown in Figure 10, appears very similar to the one of the weighted layers. The only major difference again is that the data appears slightly more scattered. Therefore to include 90% of the data in this case an upper bound of 4% on σ must be set and an upper bound of 5% will include 98% of the data for all layers except, as indicated earlier, the upper bound envelope linearly approaches zero at a zero moisture content. Figure 12 shows the resulting limit of accuracy curves for the individual layers. Assuming an upper bound of 5.0 for a 36 point sampling plan, it can be concluded with 95% confidence that the true mean moisture will be within ±1.6% of the sample mean moisture as opposed to the ±1.3% found for the weighted layers. For a four point sampling plan, the limit of accuracy increases from ±3.9% to ±4.9%. It can therefore be concluded that by sampling the individual layers (depth increments) with an equal number of sample points the limit of accuracy increases by 25% over the weighted layer moisture approach.

CONCLUSIONS

Soil moisture data from 58 intensively sampled fields were analyzed to determine the relationship between the soil moisture variability represented by either σ or CV and mean field moisture $\bar{x}$. The principle conclusions were:

1. Moisture variations, at predefined depths or depth increments, within 40 acre fields are a form of inherent variation that can neither be controlled nor reduced. Many intrinsic and extrinsic factors are responsible for this variation. In their study of the spatial variability of soil-water properties Nielsen et.al. found that bulk density, soil texture and water content had the same level of variability but that hydraulic conductivity had significantly larger variability. For example, they obtained CV's of greater than 100% for hydraulic conductivity compared with 10-15% for the water content measured at the same time. These results were for a field considered to be generally uniform to most cultural practices and indicate the intrinsic level of variability of soil-water properties. Other factors such as

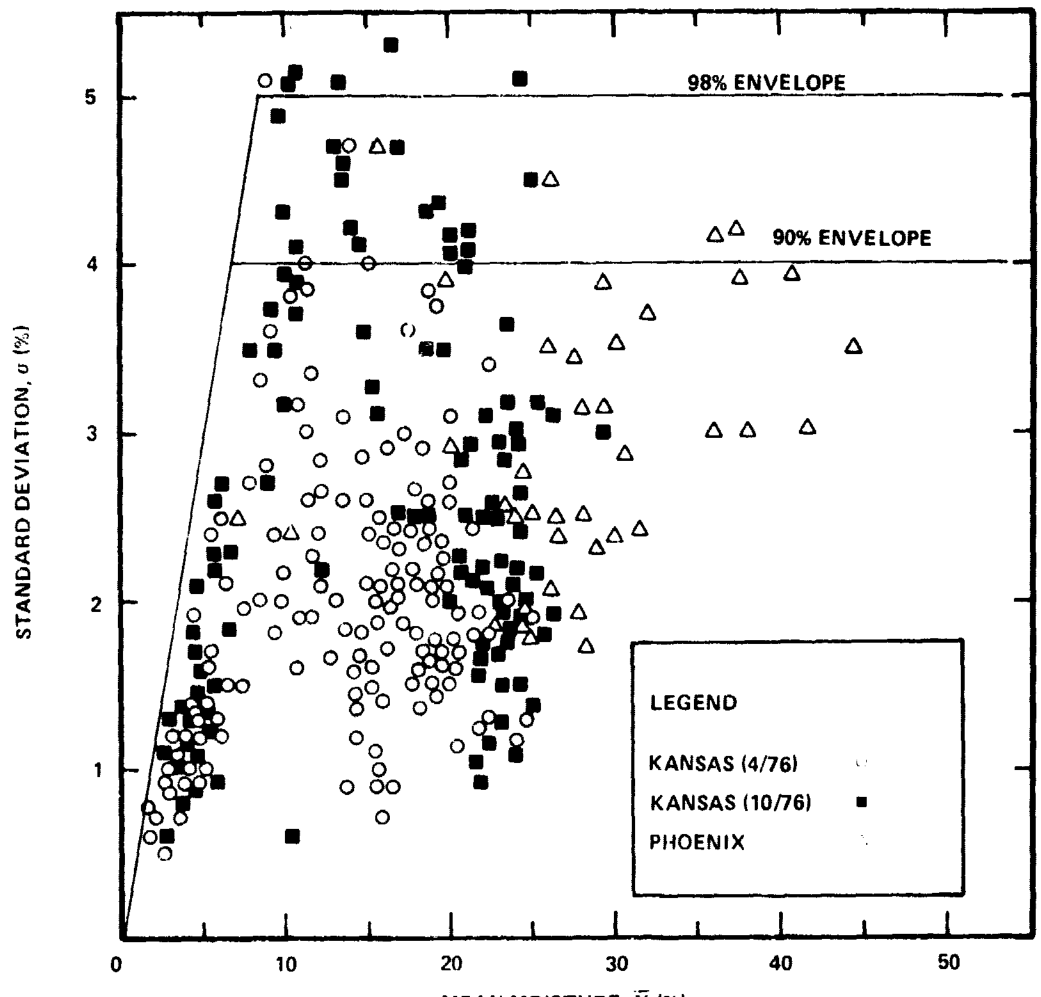

Figure 10. Arithmetic Plot of Standard Deviation Versus Mean Moisture (Indivudal Layers).

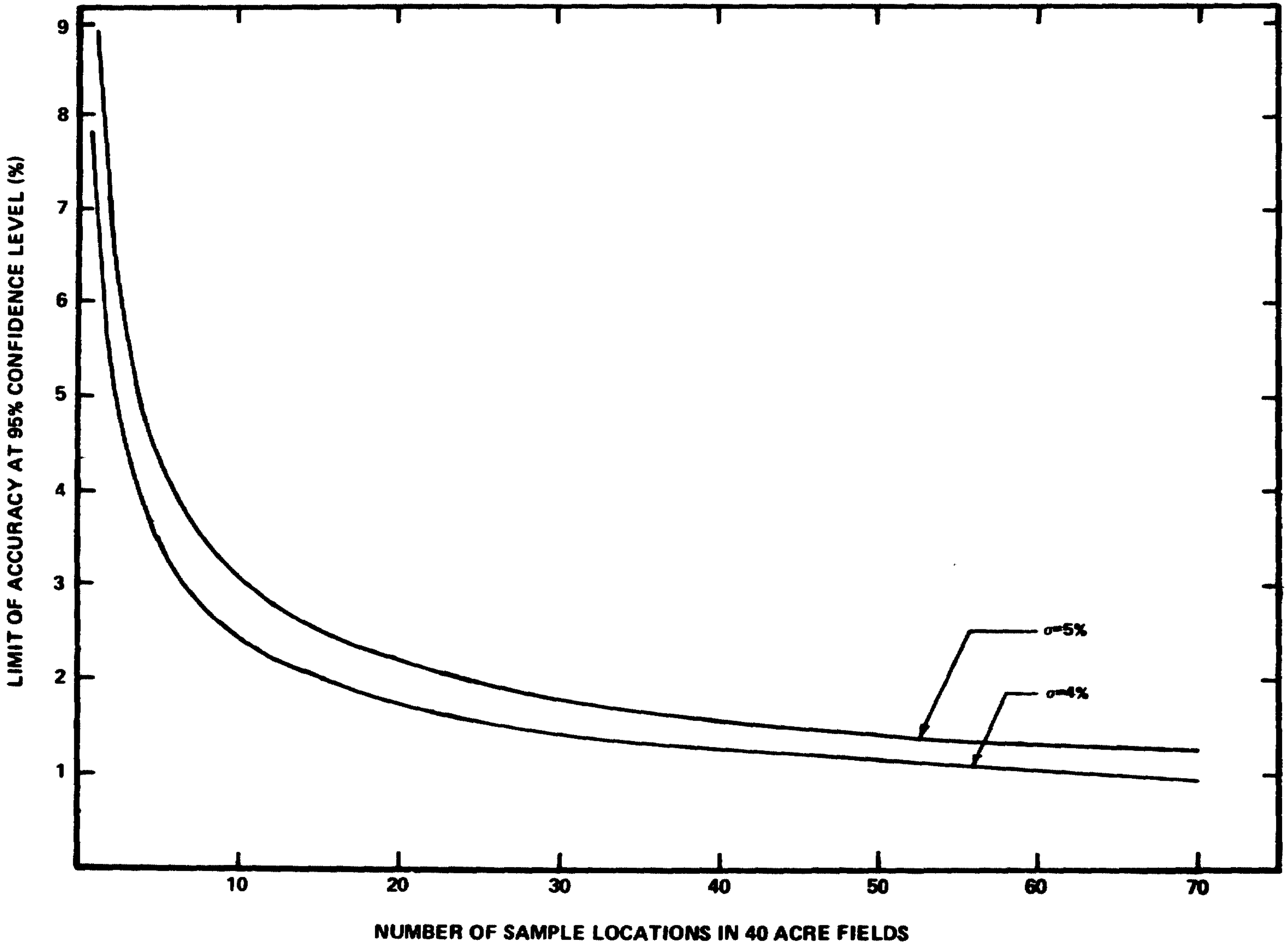

Figure 11. Limit of Accuracy Curves (Individual Layers).

topography and relief, aspect and vegetation cover appear to be relatively minor contributors to the variability observed in this study. All the fields were bare or had uniform vegetation cover and were relatively level. Field 175 in South Dakota was surveyed and found to have only 2 m of relief over the 16 hectare (40 acre) field.

2. In this report, a large statistical study of the variation of mean moisture contents at various depths (to 15 centimeters) was undertaken for numerous 40 acre field sites that served as the "sample population". While it can be said that neither a unique (constant) standard deviation(σ) nor Coefficient of Variation (CV) solely define variability over the complete range of mean field moisture contents examined, it appears that using an upper bound standard deviation parameter more clearly defines the maximum range of anticipated variability than does the CV parameter, particularly at the higher moisture levels.

3. Moisture variability was analyzed by two separate procedures. In one method an "integrated moisture content" from the surface to a given depth was determined at a given sample location (e.g., 0-2 cm, 0-5 cm, 0-9 etc.). The other technique used only the moisture content existing at a given depth increment (e.g. 0-1 cm, 1-2 cm, 2-5 cm, 5-9 cm etc.). For purposes of this report, these two methods were defined as the: (a) Integrated Layer and (b) Individual Layer Procedures, respectively. It was concluded that for the "Integrated Layer" approach, 87% of the observed values of σ were less than or equal to 3% and 96% of the observed values were less than 4%. Comparable values for the "Individual Layer" approach resulted in σ values of 4% and 5% for 90% and 98% of the data respectively. This increase is possibly due to measurement difficulties in obtaining samples from precise layers for a large number of locations. When these results from individual layers are used to obtain the integrated layer moisture values these errors are apparently averaged out. Thus for a given limit of accuracy the number of samples required to achieve a given confidence interval is smaller for the "Integrated Layer" technique compared to the "Individual Layer" approach.

4. Because the relevant variability parameter found in this study was the standard deviation for a large range of mean field moisture content, it can be concluded that limit of accuracy curves (and hence number of samples at a given location) are more a function of moisture

content than of depth, as shown by the Phoenix data. This dependence on depth observed by Rao & Ulaby arises from the dependence of CV on the moisture content which for the Kansas studies was a strong function of depth.

5. While many factors have been noted to influence the variability of mean field moisture; it should be noted that, in general, the family of observed standard deviations ranged from 2% to 4% for all of the large field (40 acre) sites studied.

RECOMMENDATIONS

It is recommended that future field studies be conducted using the following general guidelines deduced from this study.

1. In general, the number of samples obtained should be independent of the depth considered (in either the Integrated or Individual Layer approaches). The Kansas results however indicate that it may be necessary to adjust sampling patterns to reflect the existing moisture conditions, e.g., an increased number of samples may be required for the surface layers when steep moisture gradients are present.
2. While these results and conclusions were based on 40 acre fields, it seems reasonable to assume that similar levels of variability would be observed for larger fields provided that they had uniform soils and surface cover. Conversely the results from Hills and Reynolds indicate that the number of samples cannot be reduced for smaller fields.
3. The selection of the number of samples required is a tenous choice. It must be recognized that all limit of accuracy curves are functionally dependent upon the reciprocal of the square root of the number of samples. Thus, while significant reductions in the confidence interval may occur between relatively small sampling number, once a "threshold" number is reached, the benefit-cost rapidly decreases with increasing sample size. In addition, within this range, it is highly improbable to define the true significance of reducing the confidence range from, say, ±1.4% to ±1.0%. Because, the limit of accuracy curves defined in this report are based upon probable upper bounds; it is also logical to state that any one field may possess variability less than the values shown and thus actually result in a much lower confidence limit for a

predefined sample size than was originally estimated. Taking all of these complex factors into consideration, it is recommended that 16 to 25 points (per 40 acre field) be used as a basis for future testing.

The results and conclusions developed in this study have been based upon a statistical analysis of variability data from various sites. However, as noted, variability-mean moisture data pairs showed a very significant degree of clustering about a mean moisture for a given test site location. Additional research is needed that would develop moisture variability data for a given site over a long period of time (and thus a large range of mean field moisture contents). This would either substantiate the general range of standard deviations obtained in this study or subsequently form the basis for revised estimates of this parameter.

REFERENCES

Blanchard, B. J. 1975; Ground truth report 1975 Phoenix microwave experiment. Tech. Rept. RSC-70, Remote Sensing Center Texas A&M Univ. College Station, Texas.

Burke, W. J., T. Schmugge and J. F. Paris, 1979; Comparison of 2.8 and 21 cm microwave radiometer observations over soils with emission model calculations. J. Geophys. Res., 84, 287–294.

Charney, J., W. J. Quirk, S. Chow, and J. Kornfield, 1977: A comparative study of the effects of albedo change on drought in semi-arid regions. J. Atmos. Sci., 34, 1366-1385.

Dobson, C., P. P. Batlivala, 1976: Ground truth data for the joint soil moisture experiment April 12, 1976 mission Lawrence – Topeka site. RS.L. Tech. Rept. 264-9 of Remote Sensing Laboratory. University of Kansas, Lawrence, Kansas.

Dobson, C., 1977: Ground data documentation joint soil moisture experiment, October 13, 1976 mission, Finney County test site. RSL Tech. Rept. 264-14 of the Remote Sensing Laboratory, University of Kansas, Lawrence, Kansas.

Gannon, P. T., 1977: On the influence of surface thermal properties and clouds on the South Florida sea breeze. Ph.D. Dissertation, University of Miami. University Microfilms #77-21893.

Hills, R. C., S. G. Reynolds, 1969: Illustrations of soil moisture variability in selected areas and plots of different sizes. Journal of Hydrology, 8, 27-47.

Idso, S. D., R. D. Jackson, R. J. Reginato, 1975: Detection of soil moisture by remote surveillance. American Scientist, 63, 549–557.

Jones, E. B., 1977a: Soil-Moisture Ground Truth, Hand County, South Dakota, Mission Report for the April 19-20, 1977, Mission. NASA Contract: NAS5-23815, M. W. Bittinger & Associates, Inc., Fort Collins, Colo., 33 pp.

__________, 1977b: Soil-Moisture Ground Truth, Hand County, South Dakota, Mission Report for the May 10-11, 1977, Mission. NASA Contract: NAS5-12815, M. W. Bittinger & Associates, Inc., Fort Collins, Colo., 61 pp.

__________, 1977c: Soil-Moisture Ground Truth, Hand County, South Dakota, Mission Report for the June 15-16, 1977, Mission. NASA Contract: NAS5-23815, M. W. Bittinger & Associates, Inc., Fort Collins, Colo., 54 pp.

__________, 1978a: Soil-Moisture Ground Truth, Hand County, South Dakota, Mission Report for the May 2-3, 1978, Mission. NASA Contract: NAS5-24439, Resource Consultants, Inc., Fort Collins, Colo., 56 pp.

__________, 1978b: Soil-Moisture Ground Truth, Hand County, South Dakota, Mission Report for the May 31-June 1, 1978, Mission. NASA Contract: NAS5-24439, Resource Consultants, Inc., Fort Collins, Colo., 46 pp.

__________, 1978c: Soil-Moisture Ground Truth, Hand County, South Dakota, Mission Report for the July 25-26, 1978, Mission. NASA Contract: NAS5-24439, Resource Consultants, Inc., Fort Collins, Colo., 43 pp.

Nielsen, D. R., J. W. Biggar and K. T. Erh, 1973: Spatial variability of field-measured soil water properties. Hilgardia, 42, 215-259

Rao, R. G. S., and F. T. Ulaby, 1977: Optimal spatial sampling techniques for ground truth data in microwave remote sensing of soil moisture. Remote Sensing of the Environment, 6, pp 289-301, 1977.

Schmugge, T. J., P. Gloersen, T. Wilheit and F. Geiger, 1974: Remote sensing of soil moisture with microwave radiometers. J. Geophys. Res., 79, 317-323.

__________, T. Wilheit, W. Webster, Jr., and P. Gloersen, 1976: Remote sensing of soil moisture with microwave radiometers-II, NASA Tech. Note TN D-8321, [NTIS No. N76-32625].

__________, 1978: Remote sensing of surface soil moisture. J. Appl. Meteor., 17, 1550-1557.

Snedecor, George W., and William G. Cochran, Statistical Methods, Sixth Edition, The Iowa State University Press, Ames, Iowa, 593 pp, 1967.