HF GROUND CONSTANT MEASUREMENTS AT THE LAWRENCE LIVERMORE NATIONAL LABORATORY (LLNL) FIELD SITE

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ABSTRACT

The SRI International open-wire-line (OWL) kit was used 3-5 July 1987 to measure the HF ground constants at the Lawrence Livermore National Laboratory (LLNL) field site in Livermore, CA. Data were acquired at 11 locations about 250 ft west of the LLNL facility fence in the vicinity where a longwire and broadband dipole were erected in August 1987 for making impedance measurements for the purpose of validating the Numerical Electromagnetics Code (NEC). An additional location was measured to the north of the antenna site where field strength data were to be taken. Several samples were taken at most locations. Best estimates of the conductivity, relative permittivity (relative dielectric constant), dissipation factor and skin depth were computed as the median values versus frequency for 2 through 30 MHz. Data were acquired at 1-MHz intervals from 2 MHz through 8 MHz, and the interval was increased to 2 MHz from 8 MHz to 30 MHz. The maximum and minimum values were also determined as bounds on the conductivity and relative permittivity values for use in parameter sensitivity analyses. The conductivity values for the relatively dry, densely packed light brown clay fell between those typical of pastoral land and rich agricultural land at about 4×10^{-2} S/m. The relative permittivity values exhibited more variation with frequency. At the low end of the HF band, the relative permittivity values exceeded those of a non-flooded rice paddy (e.g., about 150 at 2 MHz); whereas, at the high end of the band, the relative permittivity approximated values typical of rich agricultural land (about 17 at 30 MHz). The skin depth varied from about 2 m at 2 MHz to 0.7 m at 30 MHz. The dissipation factor was about 1.5, so the soil acted almost as a semiconductor rather than as a lossy conductor or a lossy dielectric. Both the relative dielectric constant and conductivity are important in modeling antennas and propagation over the ground at the LLNL site. Data from nearby wells indicated that the water table was at least 20 m below the surface. Therefore, a one-layer slab model adequately described the ground at this site for HF down to the skin depth.

1. INTRODUCTION

The Lawrence Livermore National Laboratory (LLNL) has developed a method-of-moments model, the Numerical Electromagnetics Code (NEC),[1-3] for modeling antenna characteristics over real ground. The model requires the specification of the wire geometry and the electrical characteristics of the ground over which the antenna is installed. The most recent version, NEC-3,[3] which handles wires that penetrate the earth's surface, has had only limited validation with field measurements. The antenna measurement possibilities include:

- Input impedance;
- Directivity pattern shape;
- Absolute gain; and,
- Ground-wave field strength versus distance from the antenna.

During a previous group of studies, the first three quantities were modeled with NEC-3 and measured in the HF band by SRI International (SRI) for a 7.5-ft vertical monopole with sixteen 40-ft radials buried 7 inches at several sites with different soils.[4-6] The NEC model predictions compared favorably with the measurements when measured ground conductivity and permittivity (i.e., relative dielectric constant) values were used.[7] These values of "ground constants" were obtained using the SRI open-wire-line (OWL) kit designed for this purpose.[8-10]

The LLNL has planned additional NEC validation work at their field site near Livermore, CA, using a broadband dipole and a sloping long-wire.[11] Input impedance and ground-wave field strength values will be measured in the HF band (2-30 MHz). SRI was asked to measure the ground constants in the HF band at the LLNL site for use by LLNL in this validation effort.[12] This paper describes the SRI measurements and presents the ground constants results. The NEC validation results are presented in Ref. 11.

2. DESCRIPTION OF EQUIPMENT

The SRI open-wire line (OWL) ground constants kit consists of a set of 0.5-inch diameter aluminum probes of various lengths from 3 inches to 36 inches, a probe adapter, an HP 4193A Vector Impedance Meter, an HP85B computer, and appropriate software. The kit is powered from generators, and a metered variac is used to maintain the correct voltage at the instrumentation when a long power cord is used. A power-line filter with spike suppression is sometimes used. The kit is shown schematically in Figure 2.1, and it is shown in use at Livermore in Figure 2.2.

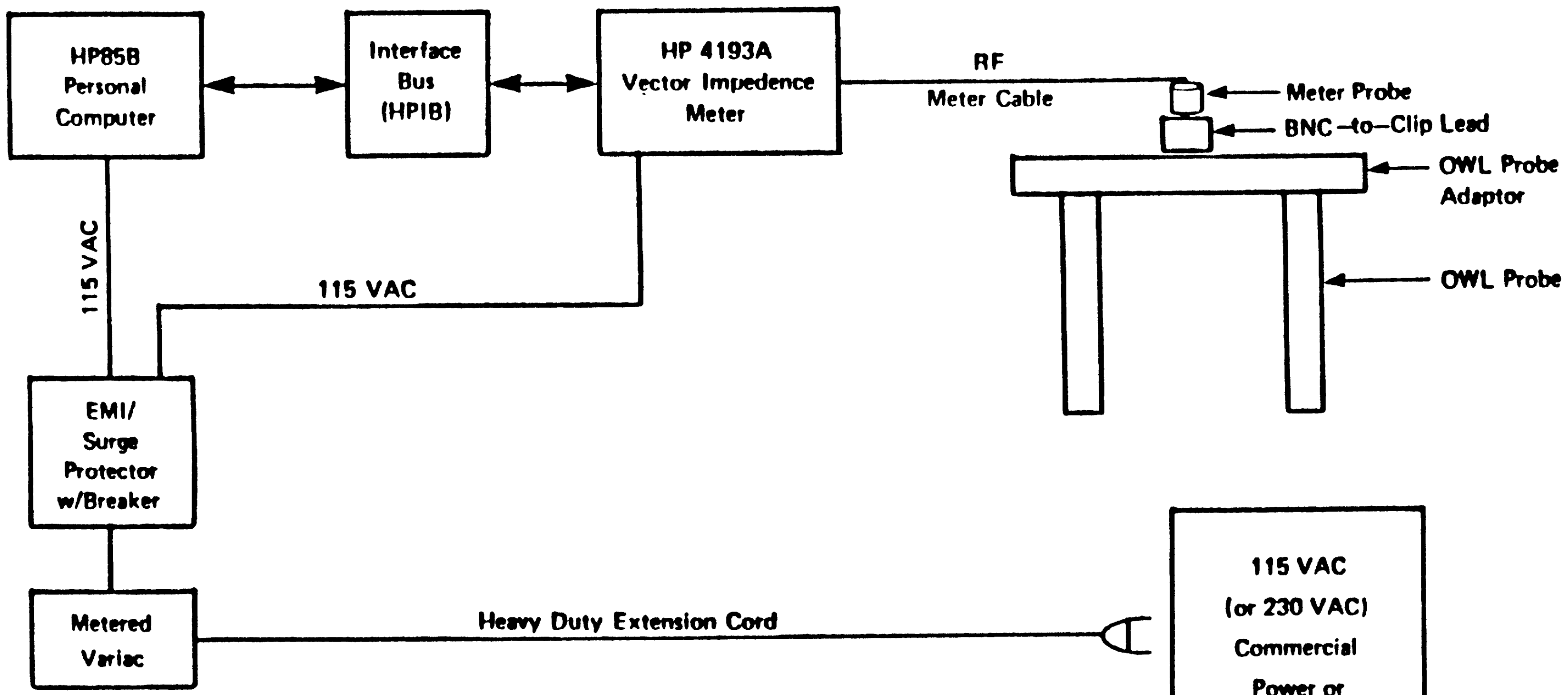
The SRI OWL kit semiautomatically measures the soil conductivity and relative permittivity vs frequency in the band 0.5 to 110 MHz. The frequency spacing for measurements between 0.5 and 2 MHz is 0.5 MHz, from 2 MHz to 8 MHz the spacing is 1 MHz, and from 8 to 30 MHz the spacing is 2 MHz. A 4-MHz spacing is used from 30 MHz to 110 MHz.

3. SAMPLING STRATEGY AND MEASUREMENT SITE AND LOCATION DESCRIPTIONS

3.1 Sampling Strategy

The general sampling strategy evolved from consideration of the following:

- Sampling Locations:
  - Proposed antenna locations;
  - Proposed field strength measurement location;
  - Land accessability;
  - Possibility of small-scale lateral inhomogeneities;
  - Availability of water well data; and,
  - Surface vegetation differences.
- Sample Depths:
  - The need for observing variations (if any) in soil electrical properties with depth; and,
  - The depth to which it was possible to penetrate the soil and retrieve the probes.



Note: The Variac and EMI/surge protector are used only for 115 VAC.

Figure 2.1 BLOCK DIAGRAM OF THE SRI OWL KIT FOR MEASURING RF GROUND CONSTANTS

a) Probe Insertion

b) Data Acquisition

Figure 2.2 SRI OWL KIT IN USE AT LIVERMORE

- Selection of Test Frequencies:

  - Band in which the test antennas operate; and,

  - Added frequencies to mitigate possible interference and facilitate interpolation.

- Choice of Measurement Day:

  - Antenna setup schedule;
  - Personnel availability; and,
  - Suitable weather conditions.

Mr. Al Christman of Ohio University selected the proposed antenna locations and the radial for the field strength measurements. Some land was not available for field strength measurements due to use by livestock. Several water wells had been drilled for test purposes,[13] and one location was selected to be near a well. At a given general location, several sample points usually were identified within about 1 m of each other to check for small-scale variations. Differences (if any) that might relate to changes in surface vegetation were also a consideration.

Probe lengths up to 36 inches were used; however, it was not possible to get the longest probes into the ground (or back out of the ground) at every location.

The basic test frequencies were in the HF band (defined for the OWL measurements as 2-30 MHz). As previously noted, these data were taken at a 1-MHz interval from 2-8 MHz and at 2-MHz intervals from 8 MHz to 30 MHz. This provided enough samples on different frequencies so that data taken on interference- contaminated frequencies (if any) could be discarded without impacting the ability to estimate the ground constant values versus frequency.

The measurement day was a possible variable. Data were taken on three consecutive days (3-5 July 1987) in order to sample all the locations selected. No locations were repeated on different days at this site due to the extreme difficulty in getting the probes into and out of the ground.

There was no rain during the test period, and it had not rained for some weeks before. Therefore, no significant change in ground constant values with measurement day was expected.

At a given location (an area within a radius of several meters of the stake marking the location), samples were taken at several sample points within about 1 m of each other in order to check the small-scale variations. The 3-inch probe spacing was used, and this approximates a 300-ohm line. An alphanumeric coding system was used to identify the location number, probe configuration, and sample number at that location. For example, L1P3S2 indicates Location 1, a probe spacing of 3 inches and Sample 2. Two identical OWL kits were used at most of the locations, and the data from Kit 1 was assigned odd sample numbers and Kit 2 was assigned even sample numbers.

3.2 General Site Description

The LLNL Livermore, CA test site was located to the west of the scientific compound about 250 feet from the outer security fence. The land is quite flat, and it is covered with dry grass about 1-2 feet high (see Figure 3.1). Occasional green thistles are present and a few small leafless bushes about 3-4 feet high were the tallest vegetation on the site. The soil was a light brown clay containing occasional small rocks.

3.3 Specific Measurement Locations

Twelve measurement locations were selected (see Figure 3.2). Locations 1, 2 and 3 represent the feedpoint, center and termination point where the longwire antenna was erected. Locations 4, 5, 6 and 7 are 25 ft away from the longwire, 75 ft from its center, and Locations 8, 9, 10 and 11 are 75 ft from the longwire at 25 ft from its center. Locations 4 through 11 are symmetrically located around Location 2 to document the area where the broadband dipole was erected. Location 12 was along the line of the longwire beyond Location 3 at the end of the lab fence. It was selected to be along a radial where the field strength data would be taken.

Figure 3.1 PHOTO OF LLNL FIELD SITE

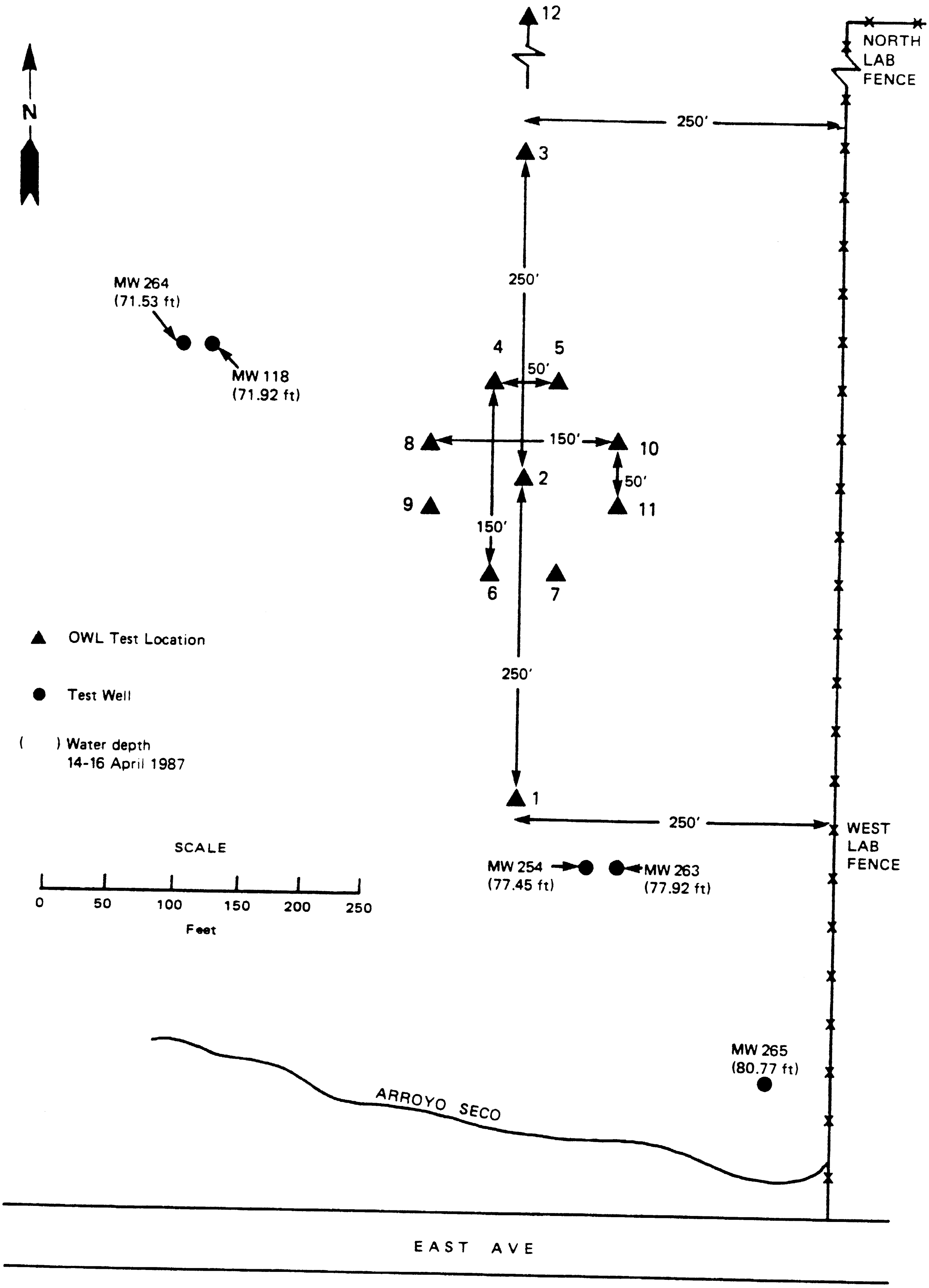


Figure 3.2 LOCATIONS OF OWL MEASUREMENTS AND TEST WELLS AT LIVERMORE SITE

All of the locations appeared very similar to the eye. The 0.5-inch steel rod used to create the hole for the aluminum OWL probe was very difficult to drive into the dry ground using a sledge hammer (see Figure 3.3). Frequently the pointed steel rod would only penetrate less than 1 inch per hit, although it was somewhat easier to drive at Locations 1 (beside a road near the well), 4 and 8.

There was a band about 10 yards wide with no vegetation at Location 5. The ground at this site was very hard, and 3 driving rods were broken trying to drive into it. At the other locations, it was necessary to clear the vegetation prior to making the holes for the probes (see Figure 3.4 taken at Location 12). The vegetation at Location 8 consisted of dried grasses 1-2 ft high, and several 3- to 4-ft bushes (the tallest at the site) were nearby. Several green thistles about 3 ft high were near Location 12, and they were the only green vegetation at the entire site (exclusive of trees along the security fence).

4. SOIL DESCRIPTION

The soil was highly compacted light brown clay with some occasional small (1-2 inch) smooth rocks. The surface moisture content, temperature and pH were measured at each location. These results are summarized in Table 4.1. Surface soil samples were taken at Locations 1, 2 and 3 for use in estimating soil moisture content by measuring the percent of change in weight before and after heating, but the ground was so hard that it was not practical with only a pick and shovel to take samples at different depths except at Location 1 (where additional samples were taken at 1 ft and 2 ft). Regretably, these soil samples were lost when the sample pans melted in the microwave oven. It was observed that the samples were successively more moist as the sample depth increased. The sealed pan for the sample taken at 2 ft had condensation on the inside several days later. Therefore, it is assumed that there was a gradient of moisture content which increased with depth.

Figure 3.3 DRIVING STEEL AT LIVERMORE

Figure 3.4 CLEARING THE VEGETATION AT LOCATION 12
(With Supervision from Advisors)

TABLE 4.1

Summary of Soil Measurements at LLNL Site

Location Number	M.C.*	Temp. (°C)	pH	Comments
1	1	24.5	7.0	Soil less compacted
2	1	23.0	6.9	Soil very compacted
3	1	22.0	6.9	
4	1	28.5	7.0	Soil less compacted
5	1	27.0	7.0	Soil very compacted
6	1	28.0	7.0	
7	1	28.5	7.0	
8	1	28.0	7.0	Soil less compacted
9	1	28.0	7.0	
10	1	30.0	7.0	
11	1	27.5	7.0	
12	1	24.0	7.0	Soil very compacted

* M.C. = Moisture Content (on a scale from 1 = dry to 8 = wet)

The water table can cause a very significant change in effective ground constants if it occurs closer to the surface than a skin depth at the radio frequency of interest. Fortunately, the LLNL site has been recently surveyed using the test wells shown in Figure 3.2.[13] The water table was between 71 and 81 feet below the surface at the test site. The water depth, measured on 14-16 April 1987, is given in parentheses beside each test well shown on the map of ground constant measurement locations (Figure 3.2).

5. DATA REDUCTION AND ANALYSIS

5.1 Data Reduction

Data were taken at 12 locations. The number of samples per location ranged from one to four. Thirty-one samples were taken in all, but two were discarded due to excessive separation of the soil from the probes near the surface or the inability to get the probes completely into the ground (see Table 5.1). OWL probe lengths up to 36 inches were used at 8 locations, and lengths up to 24 inches were used at 4 locations due to the difficulty in probe insertion and extraction. The data were recorded on thermal printer paper and on magnetic cassettes using the HP 85B. Figure 5.1 is an example of the raw data for the 3- and 6-inch probe lengths, and Figure 5.2 shows the reduced data for these samples.

TABLE 5.1

Summary of Data Samples

Location Number	Number of Samples	Longest Probe (Inches)
1	4	36
2	4	36
3	2	36
4	1	24
5	2	36
6	4	36
7	3	36
8	1	24
9	1	24
10	2	36
11	2	24
12	3	36

There was a considerable spread in the measured results for a given frequency, so a statistical data reduction was required.

5.2 Data Analysis

Three types of estimates of the ground constants versus frequency are required for subsequent use by LLNL in the NEC validation:

- Estimate for sloping longwire;
- Estimate for broadband dipole; and,
- Estimate for field strength.

SITE NAME	LIV
LOCATION NUMBER	5
SAMPLE NUMBER	1
DATE	07-05-87
TIME (HOURS)	16.30
OPERATOR'S ID	GHH
PROBE CONFIG NO.	3
PROBE KIT NUMBER	1

3 INCH PROBES IN GROUND

FREQ.	/Z/	θ	Er	SD
2.0	1856	-48.7	45	7.32
3.0	1431	-50.8	37	5.59
4.0	1197	-49.9	34	4.15
5.0	1073	-52.3	28	3.83
6.0	934	-51.7	28	3.11
7.0	871	-51.0	26	2.63
8	781	-52.4	24	2.45
10	759	-39.0	33	.97
12	731	-62.2	14	2.76
14	620	-60.0	15	2.09
16	525	-62.7	14	2.19
18	475	-60.2	14	1.72
20	449	-61.0	13	1.63
22	400	-59.6	14	1.39
24	375	-56.7	14	1.09
26	364	-53.3	15	.83
28	352	-51.9	16	.71
30	369	-49.4	16	.55

6 INCH PROBES IN GROUND

FREQ.	/Z/	θ	Er	SD
2.0	783	-48.1	55	7.26
3.0	585	-47.4	48	5.00
4.0	493	-42.2	48	3.19
5.0	467	-42.2	40	2.73
6.0	404	-40.6	41	2.15
7.0	410	-38.7	36	1.80
8	355	-36.6	39	1.43
10	471	-46.6	18	2.06
12	360	-51.4	18	2.09
14	308	-53.6	17	1.99
16	256	-57.0	16	2.04
18	232	-50.8	18	1.42
20	212	-51.3	17	1.34
22	200	-46.7	17	1.03
24	199	-43.5	18	.84
26	203	-42.6	16	.76
28	210	-41.8	15	.69
30	218	-46.8	12	.83

Figure 5.1 EXAMPLE OF RAW DATA

LIV

LOCATION # 5
SAMPLE # 1
PROBE CONFIGURATION 3 in.
PROBE LENGTH 3 in.

FREQ	Er	COND.	D.F.	S.D.
2	45	5.39E-003	1.08	7.32
3	37	6.36E-003	1.04	5.59
4	34	8.28E-003	1.11	4.15
5	28	8.11E-003	1.04	3.83
6	28	9.95E-003	1.08	3.11
7	26	1.15E-002	1.15	2.63
8	24	1.19E-002	1.16	2.45
10	33	4.17E-002	2.26	.97
12	14	7.64E-003	.84	2.76
14	15	1.06E-002	.92	2.09
16	14	9.53E-003	.79	2.19
18	14	1.24E-002	.89	1.72
20	13	1.27E-002	.87	1.63
22	14	1.53E-002	.92	1.39
24	14	2.05E-002	1.07	1.09
26	15	2.88E-002	1.29	.83
28	16	3.43E-002	1.41	.71
30	16	4.73E-002	1.80	.55

LIV

LOCATION # 5
SAMPLE # 1
PROBE CONFIGURATION 3 in.
PROBE LENGTH 6 in.

FREQ.	Er	COND.	D.F.	S.D.
2	55	5.90E-003	.97	7.26
3	48	8.11E-003	1.01	5.00
4	48	1.31E-002	1.23	3.18
5	40	1.40E-002	1.26	2.73
6	41	1.82E-002	1.34	2.15
7	36	2.10E-002	1.49	1.80
8	39	2.78E-002	1.61	1.43
10	18	1.25E-002	1.23	2.06
12	18	1.18E-002	.99	2.09
14	17	1.19E-002	.90	1.99
16	16	1.12E-002	.77	2.04
18	18	1.72E-002	.97	1.42
20	17	1.78E-002	.95	1.34
22	17	2.41E-002	1.13	1.03
24	18	3.05E-002	1.30	.84
26	16	3.29E-002	1.39	.76
28	15	3.54E-002	1.51	.69
30	12	2.50E-002	1.29	.83

Figure 5.2 EXAMPLE OF REDUCED DATA

The estimate for the sloping longwire was made by computing the median values for each frequency from Locations 1 through 7. The estimate for the broadband dipole was obtained by computing the comparable median values from Locations 2 and 4 through 11. The estimate for the field strength was obtained by computing the site median values using data from all 12 locations. For each of these types of estimates, the appropriate data (taken as a set) were used to perform the following steps:

- Compute the median values of conductivity and relative dielectric constant for each measurement frequency used;
- Compute median dissipation factor and skin depth using the median relative dielectric constant and conductivity; and,
- Tabulate and plot the results vs frequency.

6. DISCUSSION OF RESULTS

6.1 Results

The results for Locations 1-7, pertinent to the longwire, are given in Table 6.1. The upper and lower bounds (i.e., the maximum and minimum observed values) are given for the conductivity and relative dielectric constant. The median conductivity was approximately 4×10^{-2} S/m across the band; whereas, the median relative dielectric constant decreased from 182 at 2 MHz to 17 at 30 MHz. The upper and lower bounds were separated by about one order of magnitude for the conductivity and about half that separation was typical for the relative dielectric constant. The dissipation factor was about 1.5 and the skin depth varied from about 1.5 m at 2 MHz down to about 0.7 m at 30 MHz.

Comparable data were obtained for the area where the broadband dipole is to be erected (Locations 2, 4-11). These data are summarized in Table 6.2 for the conductivity and relative dielectric constant. The overall site median values (Locations 1-12) for these same parameters are tabulated in Table 6.3.

TABLE 6.1

Summary of Data for Longwire Antenna
(Locations 1 through 7)

Frequency (MHz)	Best Estimate		Lower Bound		Upper Bound	
	ε_r	σ (S/m)	ε_r	σ (S/m)	ε_r	σ (S/m)
2	182	4.72 X 10-2	82	1.16 X 10-2	455	1.56 X 10-^{1}
3	141	7.10 X 10-2	71	2.15 X 10-2	371	2.04 X 10-1
4	92	6.09 X 10-2	73	2.55 X 10-2	328	2.73 X 10-^{1}
5	71	3.93 X 10-2	52	2.10 X 10-2	301	3.36 X 10-^{1}
6	71	4.98 X 10-2	49	2.51 X 10-2	293	4.35 X 10-^{1}
7	62	5.45 X 10-2	38	2.62 X 10-2	217	3.06 X 10-^{1}
8	51	5.00 X 10-2	22	2.67 X 10-2	213	3.68 X 10-^{1}
10	46	5.18 X 10-2	28	2.01 X 10-2	78	1.12 X 10-^{1}
12	39	4.32 X 10-2	19	1.56 X 10-2	58	8.38 X 10-2
14	31	3.67 X 10-2	19	1.59 X 10-2	54	9.59 X 10-2
16	30	3.54 X 10-2	19	1.87 X 10-2	52	1.04 X 10-^{1}
18	24	3.09 X 10-2	17	1.91 X 10-2	46	8.83 X 10-2
20	23	3.11 X 10-2	16	2.08 X 10-2	44	9.32 X 10-2
22	22	3.80 X 10-2	14	1.03 X 10-2	28	5.55 X 10-2
24	20	3.91 X 10-2	12	1.53 X 10-2	31	6.80 X 10-2
26	20	4.48 X 10-2	10	1.32 X 10-2	27	6.43 X 10-2
28	18	4.45 X 10-2	10	1.22 X 10-2	26	6.98 X 10-2
30	17	4.33 X 10-2	9	1.26 X 10-2	24	7.23 X 10-2

TABLE 6.2

Summary of Data Broadband Dipole
(Locations 2, 4 through 11)

Frequency (MHz)	Best Estimate ε_r	Best Estimate σ (S/m)	Lower Bound ε_r	Lower Bound σ (S/m)	Upper Bound ε_r	Upper Bound σ (S/m)
2	137	2.72×10^{-2}	54	1.16×10^{-2}	314	9.22×10^{-2}
3	112	3.52×10^{-2}	49	1.00×10^{-2}	230	1.10×10^{-1}
4	87	3.73×10^{-2}	45	1.17×10^{-2}	266	2.14×10^{-1}
5	71	3.93×10^{-2}	42	1.78×10^{-2}	189	1.63×10^{-1}
6	63	3.49×10^{-2}	33	1.01×10^{-2}	205	2.73×10^{-1}
7	57	4.46×10^{-2}	28	1.27×10^{-2}	163	2.36×10^{-1}
8	48	3.70×10^{-2}	22	1.47×10^{-2}	150	2.48×10^{-1}
10	45	4.66×10^{-2}	22	1.18×10^{-2}	78	1.12×10^{-1}
12	39	4.37×10^{-2}	19	1.46×10^{-2}	58	8.38×10^{-2}
14	32	4.24×10^{-2}	19	1.81×10^{-2}	54	9.59×10^{-2}
16	32	4.55×10^{-2}	19	1.87×10^{-2}	52	1.04×10^{-1}
18	23	2.99×10^{-2}	17	1.91×10^{-2}	46	8.83×10^{-2}
20	22	3.11×10^{-2}	16	2.08×10^{-2}	44	9.32×10^{-2}
22	20	3.41×10^{-2}	10	1.01×10^{-2}	28	5.55×10^{-2}
24	22	4.80×10^{-2}	11	1.40×10^{-2}	31	7.09×10^{-2}
26	20	5.05×10^{-2}	10	1.28×10^{-2}	27	6.53×10^{-2}
28	18	4.26×10^{-2}	9	1.22×10^{-2}	26	6.98×10^{-2}
30	17	3.80×10^{-2}	9	1.26×10^{-2}	24	6.67×10^{-2}

TABLE 6.3

Summary of Data for Field Strength Tests
(Locations 1 through 12)

Frequency (MHz)	Best Estimate		Lower Bound		Upper Bound	
	ε_r	σ (S/m)	ε_r	σ (S/m)	ε_r	σ (S/m)
2	153	3.55×10^{-2}	54	6.37×10^{-3}	455	1.56×10^{-1}
3	129	4.18×10^{-2}	49	1.00×10^{-2}	371	2.04×10^{-1}
4	109	4.74×10^{-2}	45	1.17×10^{-2}	328	2.73×10^{-1}
5	77	3.82×10^{-2}	42	1.78×10^{-2}	301	3.36×10^{-1}
6	60	3.41×10^{-2}	33	1.01×10^{-2}	293	4.35×10^{-1}
7	56	4.43×10^{-2}	28	1.27×10^{-2}	217	3.06×10^{-1}
8	48	3.91×10^{-2}	22	1.47×10^{-2}	213	3.68×10^{-1}
10	45	4.34×10^{-2}	22	1.18×10^{-2}	78	1.12×10^{-1}
12	39	4.35×10^{-2}	19	1.46×10^{-2}	58	8.38×10^{-2}
14	32	4.10×10^{-2}	19	1.59×10^{-2}	54	9.59×10^{-2}
16	29	3.34×10^{-2}	19	1.87×10^{-2}	52	1.04×10^{-1}
18	23	3.03×10^{-2}	17	1.91×10^{-2}	46	8.83×10^{-2}
20	23	3.07×10^{-2}	16	2.08×10^{-2}	44	9.32×10^{-2}
22	21	3.59×10^{-2}	10	1.01×10^{-2}	28	5.55×10^{-2}
24	22	4.14×10^{-2}	11	1.40×10^{-2}	31	7.09×10^{-2}
26	20	4.61×10^{-2}	10	1.28×10^{-2}	27	6.53×10^{-2}
28	18	4.36×10^{-2}	9	1.22×10^{-2}	26	6.98×10^{-2}
30	17	3.96×10^{-2}	9	1.26×10^{-2}	24	7.23×10^{-2}

6.2 Horizontal Homogeneity

There are two scales of horizontal homogeneity to consider: variations among samples taken on a given frequency with the probes inserted within about 1 m of each other at a given location, and variations with location across the entire antenna field. The small-scale variations seemed rather large (see the bounds given in Appendix A of Ref. 12 for the data on a given frequency at each location), but the small-scale variation seemed to decrease with increasing measurement frequency. The median values for each location showed relatively little variation (for this type of data) across the entire antenna field (with a few minor exceptions), as discussed below.

The median data were quite similar for the three groupings. This is to be expected because the data sets were not mutually exclusive. The horizontal (lateral) homogeneity across the entire site can be considered by focussing on a few selected frequencies. Table 6.4 summarizes the conductivity and relative dielectric constants data for 7, 14 and 30 MHz.

TABLE 6.4

Summary of Median Data for 7, 14 and 30 MHz

Location No.	7 MHz ϵ_r	7 MHz σ (S/m)	14 MHz ϵ_r	14 MHz σ (S/m)	30 MHz ϵ_r	30 MHz σ (S/m)
1	55	4.35×10^{-2}	23	1.86×10^{-2}	16	4.12×10^{-2}
2	62	5.77×10^{-2}	32	4.31×10^{-2}	17	4.33×10^{-2}
3	63	5.56×10^{-2}	41	5.45×10^{-2}	21	5.56×10^{-2}
4	54	4.00×10^{-2}	31	3.61×10^{-2}	12	2.42×10^{-2}
5	67	5.45×10^{-2}	39	4.84×10^{-2}	22	5.48×10^{-2}
6	50	3.38×10^{-2}	29	2.77×10^{-2}	16	3.18×10^{-2}
7	66	5.91×10^{-2}	31	3.67×10^{-2}	21	5.54×10^{-2}
8	54	4.46×10^{-2}	31	3.96×10^{-2}	14	3.59×10^{-2}
9	41	2.10×10^{-2}	33	4.24×10^{-2}	11	2.07×10^{-2}
10	59	5.02×10^{-2}	37	4.91×10^{-2}	16	3.80×10^{-2}
11	57	4.40×10^{-2}	34	4.24×10^{-2}	21	5.57×10^{-2}
12	37	1.99×10^{-2}	22	1.80×10^{-2}	17	3.62×10^{-2}

These frequencies are approximately octavely related across the HF band. At 7 MHz, the location median values are very similar except at Locations 9 and 12. At each of these locations there was some difficulty with the soil breaking away from the top of the probe holes as the holes were being made. This added air may have caused the OWL kit readings to be biased to the low side. The data reduction equations assume that the soil is touching the rods for their full length. The suspicion that the air holes caused reduced readings was verified by using the same set of probe holes twice. The second readings, taken in the enlarged holes (with more air), gave lower values. The problem caused by the dry brittle soil was not unique to these two locations, but it was more pronounced there. Excluding these two locations, the conductivity values varied between 3.38 X 10^{-2} S/m and 5.91 X 10^{-2} S/m, and the relative dielectric constant values varied between 50 and 67. At 14 MHz, the data from Locations 1 and 12 were low relative to the other locations. Excluding these two locations, the conductivity values varied from 2.77 X 10^{-2} S/m to 5.45 X 10^{-2} S/m, and the relative dielectric constant values varied from 29 to 41. At 30 MHz, the data at Locations 4 and 9 were lower for both the conductivity and relative dielectric constant. At Location 9, the problem of air around the probes was probably responsible for the values being lower. At Location 4, the surface soil (pertinent to the 9-inch probes used to obtain the data at 30 MHz) was much less compacted, and this resulted in the lower values. As noted in Table 4.1, the soil was less compacted at Locations 1, 4 and 8. The Location 8 data for all three frequencies seems to be very similar to the data from the other locations even though the steel rods were somewhat easier to drive at this location.

The conclusion is that the site is relatively horizontally homogeneous from a statistical standpoint--with the possible exception of Locations 9 and 12.

6.3 Vertical Homogeneity

As mentioned in Section 3, there was a vertical gradient of moisture content with the soil getting more moist with increasing depth down to 2 or 3 ft. The water table was at 71 to 81 feet below the surface. Therefore, it was not a factor since the skin depth was only about 3 to 6 feet. Next, the variation of the relative dielectric constant (most closely correlated with volumetric moisture content)[14] with depth at the same location is considered by comparing the results obtained for several probe lengths on the same frequency at Location 2.

The relative dielectric constant data for Location 2 are given in Table 6.5 for the seven probe lengths for the following frequencies: 2, 4, 7, 14 and 30 MHz. These data show that there is a variation of relative

TABLE 6.5

Examples of Variation of Relative Dielectric Constant with Depth for Selected Samples and Frequencies at Location 2

Loc. No.	Sample No.	Freq. (MHz)	Probe Length (inches)						
			3	6	5	12	18	24	36
2	1	2	32	59	59	84	138	95	141
2	1	4	24	45	45	74	99	85	i.d.*
2	1	7	23	63	47	65	53	55	i.d.
2	1	14	12	15	17	22	30	39	i.d.
2	1	30	16?	17	12	17	i.d.	i.d.	i.d.
2	2	2	20	37	45	128	212	266	197
2	2	4	16	28	35	73	114	176	169
2	2	7	14	25	24	40	71	94	i.d.
2	2	14	11	13	16	27	54	i.d.	i.d.
2	2	30	10	9	11	20	i.d.	i.d.	i.d.
2	3	2	22	97	72	100	63	76	89
2	3	4	17	64	74	126?	68	81	i.d.
2	3	7	16	80	76	101	36	38	i.d.
2	3	14	10	18	18	22	18	19	i.d.
2	3	30	16?	16	12	15	18	i.d.	i.d.
2	4	2	25	29	65	51	104	92	250
2	4	4	18	22	41	41	54	79	i.d.
2	4	7	15	20	32	35	34	62	i.d.
2	4	14	11	12	16	17	26	45	i.d.
2	4	30	13?	10	10	11	i.d.	i.d.	i.d.

* i.d. = invalid data; ? = questionable data.

dielectric constant with probe depth for a given frequency that generally increases with increasing probe depth up to 18 or 24 inches, except at 30 MHz where little real variation is apparent. All four samples were obtained within 2 meters of each other; Samples 1 and 3 (Kit 1) and Samples 2 and 4 (Kit 2) were within 1 meter of each other for a given kit. The conclusion is that the moisture content and the resulting ground constants varied considerably over relatively short distances, and that it would be necessary to sample several times at a given location and use some measure of central tendency (e.g., the median) to describe the soil as it would be seen by a passing radio wave with a wavelength in the medium which is larger than the scale of variation being observed.

6.4 Comparison of Livermore Data with Generic Curves and Data from Other Sites

In 1980, the author developed some "generic curves" for the ground constants vs frequency, and they were first published in 1982.[15] These curves provide estimates of the ground constants for different terrain categories of the types described in handbooks.[16,17] These curves for the HF band for conductivity, relative dielectric constant, dissipation factor and skin depth, are reproduced here (from Ref. 5) as Figures 6.1 through 6.4, respectively. Also shown on these curves are data taken at other sites as presented and discussed in Ref. 18. The Livermore median values for all 12 locations are shown on Figures 6.1 through 6.4 to facilitate the comparison. The closest fit for the Livermore data to the generic curves is with rich agricultural land. The Livermore data are almost identical to the results obtained earlier by SRI on a farm near Delta, UT, where again rich agricultural land seemed an apt description.[4,5]

A useful parameter for NEC modeling is the wavelength in the soil at the radio frequency of interest. This parameter is needed in order to determine the number of segments needed for NEC-3 for the wire which has penetrated the air-ground interface. A set of generic curves for this parameter were developed recently by Hagn.[19] using the equations in Table 6 of Ref. 18 or Table 1 of Ref. 19. The curves of wavelength in the soil

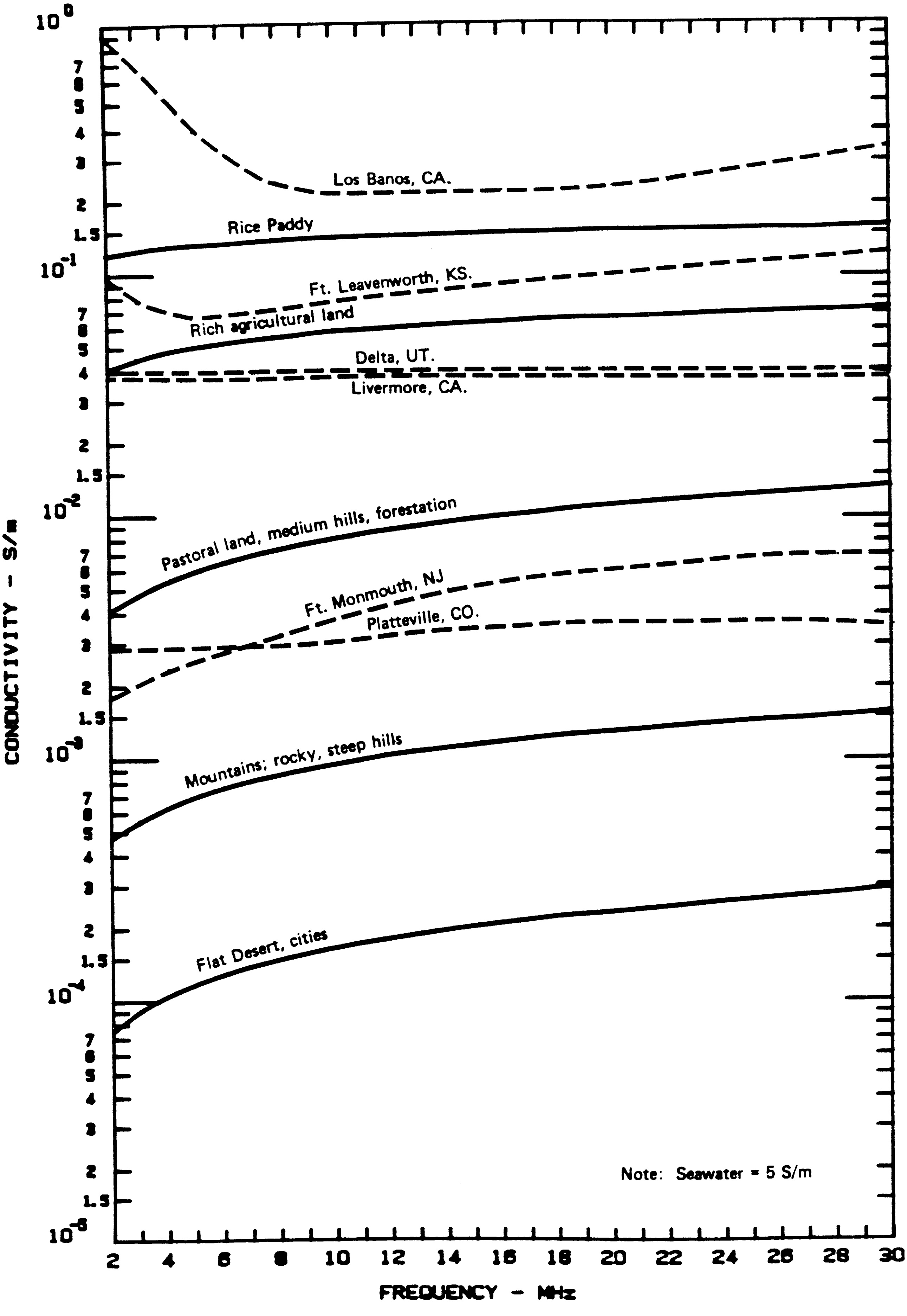


Figure 6.1 EFFECTIVE GROUND CONDUCTIVITY FOR SIX ANTENNA TEST FIELD SITES VS SRI GENERIC CURVES FOR SELECTED TERRAIN CATAGORIES

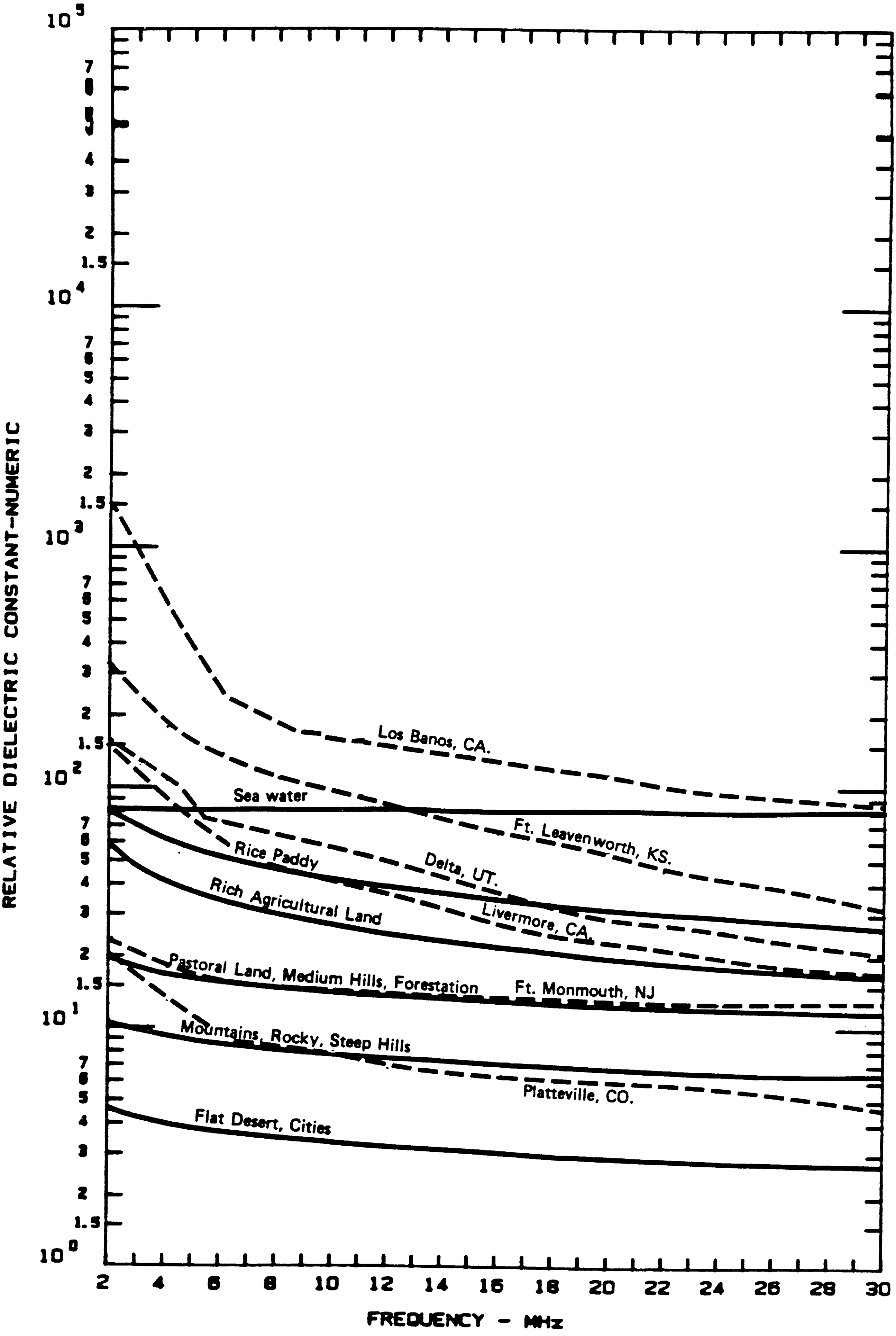


Figure 6.2 EFFECTIVE RELATIVE DIELECTRIC CONSTANT FOR SIX ANTENNA TEST FIELD SITES VS SRI GENERIC CURVES FOR SELECTED TERRAIN CATAGORIES

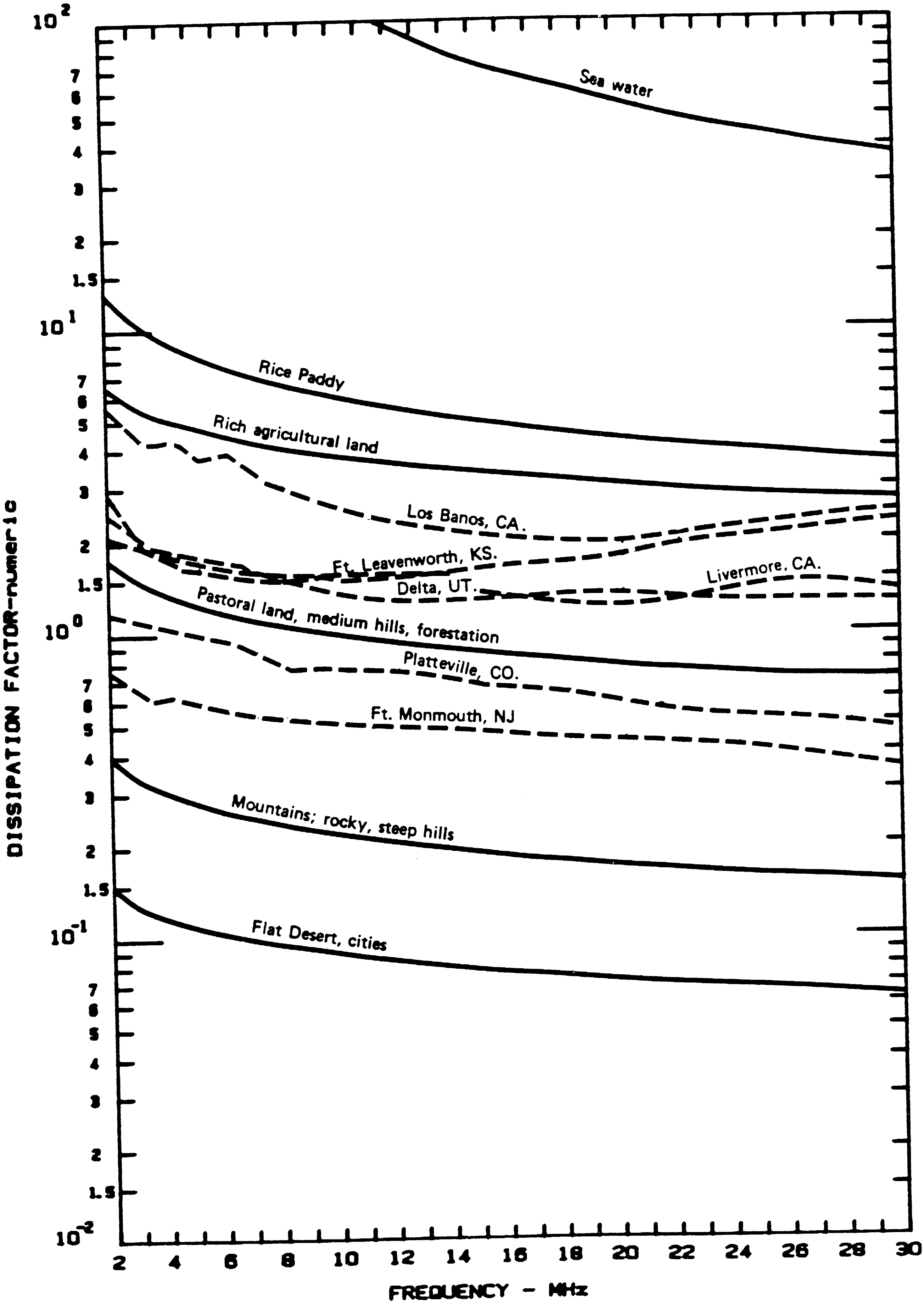


Figure 6.3 EFFECTIVE GROUND DISSIPATION FACTOR FOR SIX ANTENNA TEST FIELD SITES VS SRI GENERIC CURVES FOR SELECTED TERRAIN CATAGORIES

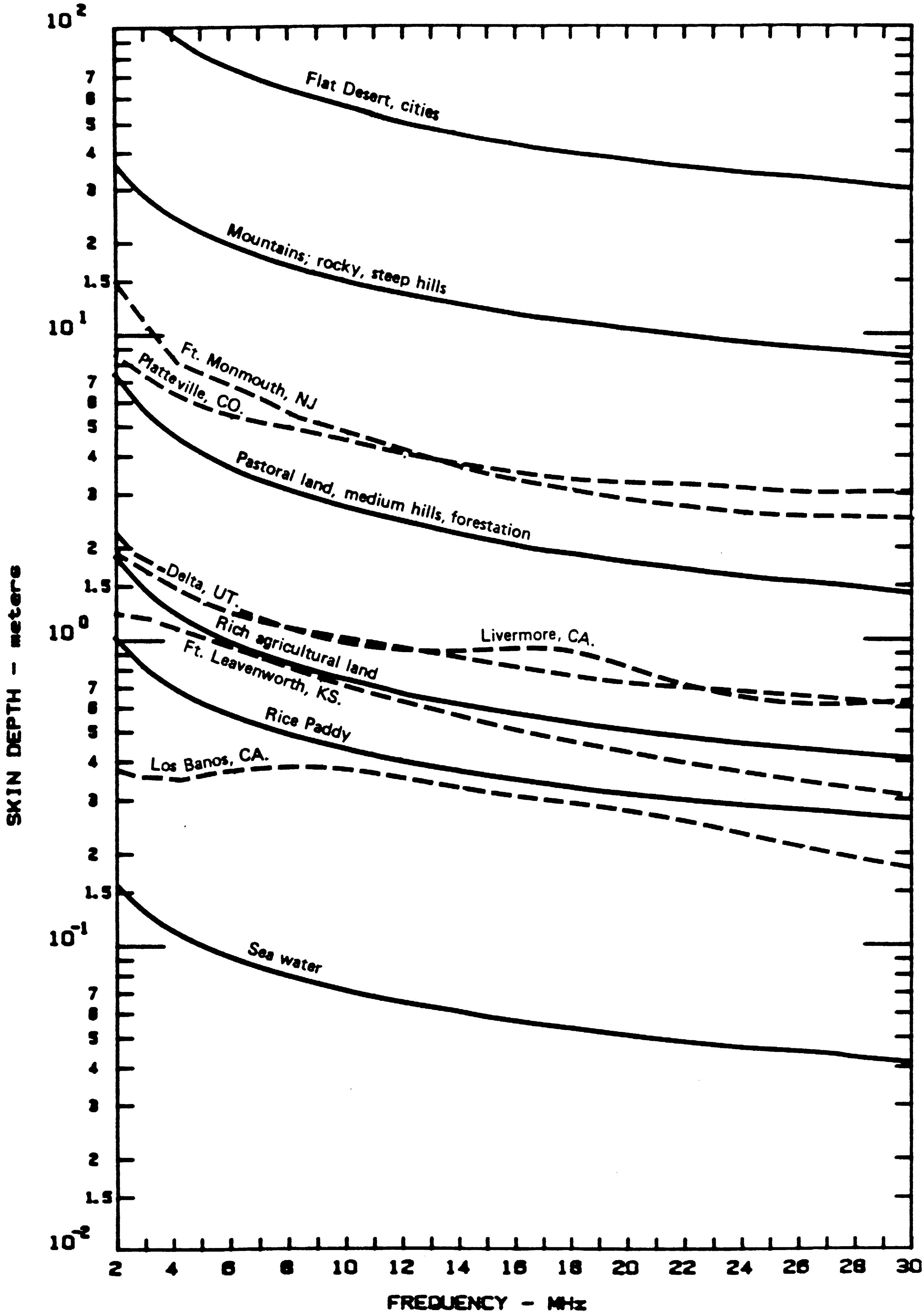


Figure 6.4 EFFECTIVE SKIN DEPTH FOR SIX ANTENNA TEST FIELD SITES VS SRI GENERIC CURVES FOR SELECTED TERRAIN CATAGORIES

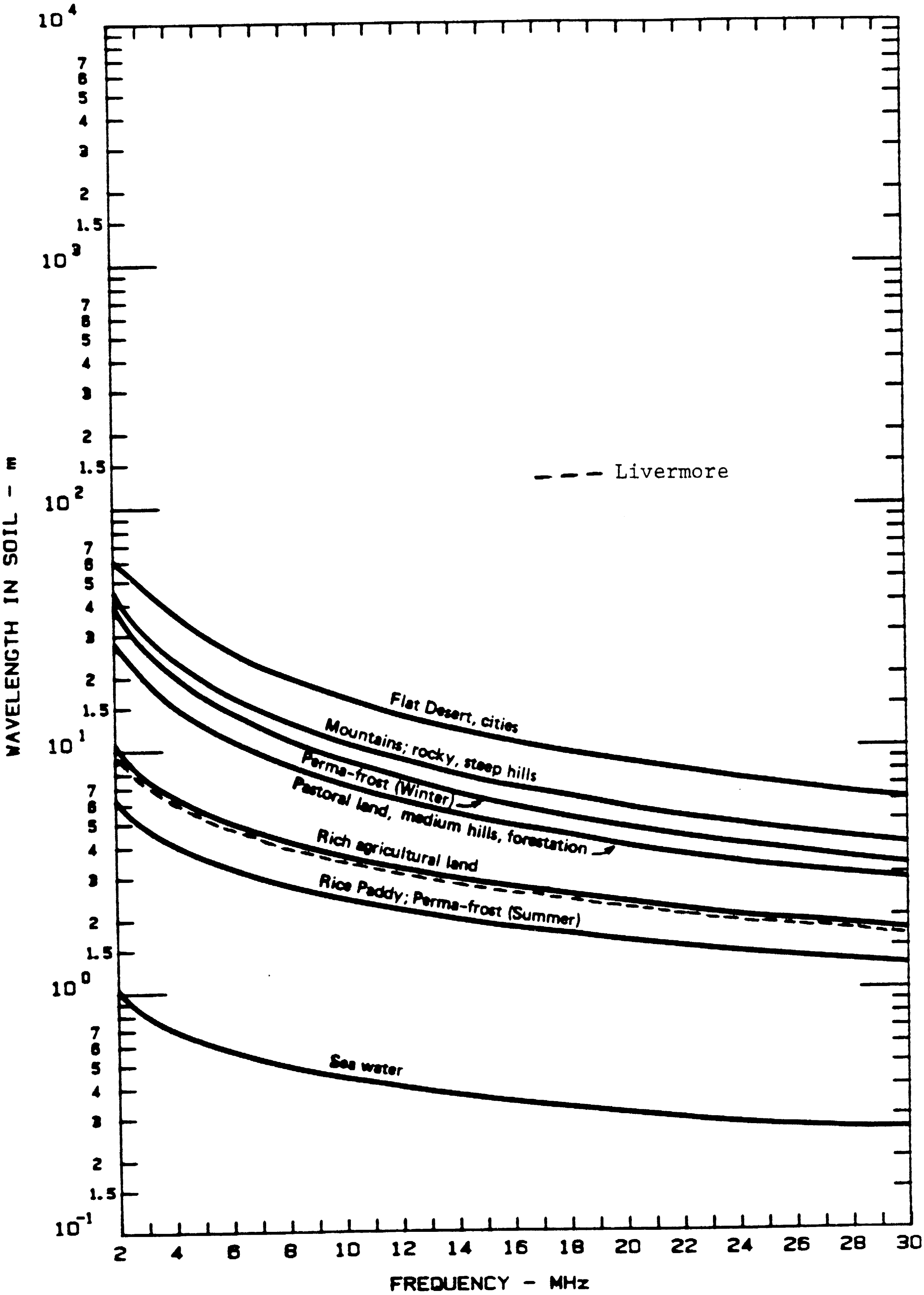


Figure 6.5 LIVERMORE DATA AND SRI GENERIC CURVES OF WAVELENGTH IN SOIL VS FREQUENCY FOR SELECTED TERRAIN CATEGORIES

(or sea water) vs frequency are plotted in Figure 6.5. The data from the Livermore site are plotted for comparison.

6.5 Accuracy Considerations

Accuracy checks with the HP 4193A on a 52.0-ohm dummy load, as measured at DC with a Micronta Model 2-211 two-jewel meter, provided values less than 0.6 ohm different across the HF band on the measurement frequencies. The phase angle difference was never more than 1.9 degrees, and it was 1 degree or less for frequencies below 16 MHz. The frequency accuracy is ± 0.01 percent. The HP 4193A features built-in test equipment (BITE), and the front-panel display flashes "PASS" or a "NOT READY" light comes on. This ensures that the instrument is operating properly prior to data acquisition.

The resulting accuracy of measurement of the ground constants is better than 25 percent.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The following conclusions were reached:

- The ground constants data were particularly difficult to obtain at Livermore due to the hardness (and brittle nature) of the soil at this site.
- There was a significant variation of the data for a given frequency at a given location and between locations, and this necessitated a statistical analysis to obtain best estimates of the ground constants at the Livermore site suitable for use in NEC validation.
- These small-scale variations could have been caused by localized variations in moisture content or by differing amounts of air around the probes (biasing the reading to be too low), or by both effects.
- The data from selected locations required grouping

together to obtain the sample set for the two antennas (longwire and broadband dipole) and for the field strength test.

- The location median values of the conductivity and relative dielectric constant were reasonably consistent across the antenna field.

- The spreads between the bounds about the median formed by the maximum and minimum observed values were about an order of magnitude for the conductivity and about half that for the relative dielectric constant. These are typical of the spreads observed at other locations where there was less of a problem with air around the probes.

- The effective skin depth is less than about 2 meters in the HF band at Livermore, and it decreases to about 0.7 m at 30 MHz. Therefore, the water table (which is over 20 m down) has no significant effect on HF antennas or propagation at this site.

- The ground at the Livermore site behaves as a lossy conductor in the HF band with an effective dissipation factor that is relatively constant with frequency at about 1.5.

- The conductivity also is relatively constant in the HF band at about 4×10^{-2} S/m; whereas, the relative dielectric constant decreases with increasing frequency from about 150 at 2 MHz to about 17 at 30 MHz.

- The SRI OWL kit, adapted from the approach of Kirkscether,[20] is an effective tool for estimating effective ground constant values for the HF band when appropriate sampling techniques are used and when appropriate statistical processing of the valid data is performed.

7.2 Recommendations

The following recommendations are offered:

- The median values of conductivity and relative dielectric constant given in Tables 6.1 through 6.3 should be used to estimate (by interpolation) the values for the NEC validation computations for the longwire and broadband dipole input impedance and the field strength vs distance.

- A parameter sensitivity analysis should be performed using the bounds given in Tables 6.1 through 6.3 of Ref. 11 as input values for NEC. Priority should be given to the upper bounds due to the problem with air around the top of the probes at some locations which probably biased those values low.

- The vertical electric field strength data vs distance from the longwire should be fit using an SRI program or the NEC while varying the ground constants. Any ground constant estimates obtained through such curve fitting should be compared with the data from the OWL kit.

- The moisture content vs depth should be measured and correlated with the relative dielectric constant data vs probe length of the type given in Table 6.5. The soil samples for this comparison should be taken from the same volume sampled by the OWL kit (a cylinder approximately twice the probe spacing and as deep as the probes) to check the small-scale variations in relative dielectric constant and to determine if they are caused by highly localized moisture content variations or by different amounts of air around the probes near the top of the holes. It may be necessary to carefully drill the holes for the probes and to use a core drill for the soil samples.

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