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# NINE-CONDUCTOR VLF ANTENNA AT CHINA LAKE

## Part 1. INITIAL MEASUREMENTS

by

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**ABSTRACT.** Measurements on the performance of a 9-conductor VLF antenna, 10.5 km long, laid on a lava bed at China Lake Naval Weapons Center, are presented. Theoretical curves are presented to show the improvement in radiation efficiency and bandwidth that can be realized if the antenna is elevated a few feet above the lava and the individual conductors are loaded with the proper series capacitance to increase the antenna wave velocity.



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## INTRODUCTION

A VLF transmitting antenna has been constructed on a lava bed at the Naval Weapons Center, China Lake, California, to be used in conjunction with an existing VLF antenna in Hawaii for measuring nonreciprocal east-west propagation. The China Lake antenna consists of nine parallel conductors originating in a lake bed on the east side of a lava flow and terminating on the west side of the lava flow. In Fig. 1 a diagram of the antenna is superimposed on a relief map of the area. The conductors, which are 6.5 mi long, are spaced 1,500 ft apart to minimize the losses due to mutual resistance. The conductors were laid down with a  $253^\circ$  true bearing so that radiation off the end of the antenna is directed toward the island of Hawaii, where the other Corona Laboratories antenna used in these propagation tests is located. A helicopter was used to lay the conductors on the lava bed. The development of the construction techniques used in laying the antenna is discussed in the appendix.

This report describes preliminary measurements of the conductivity of the lava bed, the installation of the antenna, and impedance measurements made on the antenna conductors. These measurements provide the basis for calculating wave propagation parameters and values of radiation efficiency, which are used to evaluate the performance of the antenna. Finally some planned improvements in the antenna are described.

## CONDUCTIVITY MEASUREMENTS

After the lava bed had been selected as a good possibility for a low-conductivity site for a VLF antenna and before the antenna was constructed, conductivity measurements were made at eight locations on the lava bed. The dots numbered 1 through 8 on the map in Fig. 2 show the locations of these measurement points with respect to surrounding terrain and with respect to the subsequently installed antenna.

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The ground conductivity measurements were made by means of the standard four-stake right-angle method. At all eight locations measurements were made with 100-m legs, which measured the effective conductivity to a depth of 100 m. In addition, legs of 305 m were used at locations No. 2 and No. 8 to increase the measurement depth to 305 m.

The lowest values of conductivity were measured in the center of the lava bed where, as may be seen in Fig. 3, the lava is deepest and is unfractured. The variation of conductivity with frequency at each of the eight locations is shown in Fig. 4. The variation of conductivity with distance from the west end of the lava bed is shown in Fig. 5. The higher conductivity near the east and west edges of the lava bed can be attributed to fracturing and shallow lava depths. In Airport Lake, on the east side of the lava bed where the feed point ground plane was eventually constructed, the conductivity was very high (0.1 mho/m) because of the presence of moist saline deposits.

At locations No. 2 and No. 8 the conductivity measured at 305 m was considerably different from that measured at 100 m (see Fig. 4), especially at the lower frequencies where the skin depth is greater than the measurement depth. At location No. 2, the conductivity decreases with depth, indicating either very deep lava or lava spread over unfractured granite. Just the opposite occurred at location No. 8 on the west edge of the lava, where the greater depths are more conductive (as Fig. 4 shows), indicating that the lava flow there is shallow and is spread over a conductive substructure.

The conductivity values averaged over the length of the antenna are plotted against frequency in Fig. 6. These average values were used to compute the radiation efficiency.

Mutual resistance measurements between two conductors on the lava indicate that these derived average values of conductivity may be lower than actual values for frequencies below 15 kHz and higher than actual values above 15 kHz. The mutual resistance, as measured by two different methods, is less at lower frequencies and greater at higher frequencies than the mutual resistance computed using average conductivity values, as shown in Fig. 7.

## IMPEDANCE MEASUREMENTS

### CONDUCTOR IMPEDANCE

Impedance measurements were made on each conductor to determine the propagation constants along the conductors. These constants were then used to compute the efficiency and radiation patterns.

The measured resonant frequency and resonant input resistance are tabulated in Table 1 along with values of the propagation parameter  $c/v$ , which were computed from the measured values of resonant frequency and resistance. Plots of  $c/v$  and another parameter  $\alpha\lambda$  as functions of frequency (Fig. 8 and 9) show that the points are quite scattered. This scatter results from the conductor being laid on the lava where, because of variations in proximity of the conductor to the ground, the wave velocity and attenuation may vary considerably from point to point. An average of these propagation parameters for any given frequency is the best obtainable value to use for predicting the performance of the antenna. (If the conductors were elevated a few feet above the ground, however, there would be very little variation in the propagation parameters.) The only other parameter needed to compute the radiation efficiency patterns is the distributed capacitance to ground,  $C_p$ . The measurements of distributed capacitance at a frequency of 100 Hz are tabulated in Table 1. The values of the distributed capacitance vary considerably from conductor to conductor.

### ANTENNA IMPEDANCE

Impedance measurements were also made on all nine conductors at the transmitter van located 1 mi from the feedpoint, as is indicated in Fig. 1. The west end of each conductor was terminated with a resistive load approximating the characteristic impedance of the conductor; the load was adjusted to have minimum pulse reflection when a burst of 4 cycles of VLF was applied to the east end. With these terminations, the input impedance of all nine conductors in parallel was reasonably constant over the VLF band, as is shown in Fig. 10.

## Part I

## ANTENNA PERFORMANCE

## RADIATION EFFICIENCY

The radiation efficiency of the China Lake antenna was found to be quite low. This is due not so much to high attenuation as to slow wave velocity along the antenna. The efficiency loss resulting from antenna attenuation is compensated for by an increase in distributed capacitance to ground along the antenna.

Theoretical and measured field strengths of the two antennas, as tabulated in Table 2, show that the China Lake antenna is roughly comparable to the stagger-tuned antenna in Hawaii. At lower VLF, the field strength of the China Lake antenna measured in Hawaii is less than the field strength of the Hawaii antenna measured in California because the propagation attenuation is greater in the westerly direction than the easterly. At 9.33 kHz, the field strength of radiation from the China Lake antenna measured at a range of 17 km is 5 dB below that of radiation from the Hawaii antenna, while at a range of 4,200 km the field strength of westerly radiation from the China Lake antenna is 8.2 dB below that of easterly radiation from the Hawaii antenna (see Table 2). The difference of 3.2 dB is approximately the theoretical difference in attenuation between westerly and easterly propagation over the path between California and Hawaii. At this frequency, the shape of the elevation patterns of the China Lake and Hawaii antennas are similar.

## PROPAGATION EFFICIENCY

As the frequency is increased, the China Lake antenna sky-wave beam becomes more narrow and depressed toward the horizon (Fig. 11). In Table 3 are listed the ratios of China Lake to Hawaii antenna ground wave and sky wave field strengths and also the difference between these ratios, which is designated the propagation efficiency. The propagation efficiency is the ratio of field strengths of the China Lake antenna to the Hawaii antenna at a range of 4,200 km when both antennas have equal ground-wave radiation. This propagation efficiency includes the effects of nonreciprocal east-west propagation attenuation, which are most prominent at lower VLF, and the effects of the shape of the radiation pattern in the elevation plane, which are most prominent at the higher VLF. The propagation efficiency listed in Table 3 is plotted in Fig. 12. The large increase in propagation efficiency at the higher VLF

TABLE 1. Measured Resonance Frequency,  $f_0$ , Resonance Input Resistance,  $R_0$ , and Wave Velocity,  $c/v$ , for the Nine Antenna Conductors.

Conduc- tor No.	Length, km	1st Resonance			2nd Resonance			3rd Resonance			4th Resonance			5th Resonance			6th Resonance			7th Resonance			8th Resonance			$C_p$ , pF/m
		$f_{01}$ , kHz	$R_{01}$ , $\Omega$	$\frac{c}{v_1}$	$f_{02}$ , kHz	$R_{02}$ , $\Omega$	$\frac{c}{v_2}$	$f_{03}$ , kHz	$R_{03}$ , $\Omega$	$\frac{c}{v_3}$	$f_{04}$ , kHz	$R_{04}$ , $\Omega$	$\frac{c}{v_4}$	$f_{05}$ , kHz	$R_{05}$ , $\Omega$	$\frac{c}{v_5}$	$f_{06}$ , kHz	$R_{06}$ , $\Omega$	$\frac{c}{v_6}$	$f_{07}$ , kHz	$R_{07}$ , $\Omega$	$\frac{c}{v_7}$	$f_{08}$ , kHz	$R_{08}$ , $\Omega$	$\frac{c}{v_8}$	
1	12.44	3.11	45	1.94	5.95	1785	2.03	9.4	110	1.92	12.23	860	1.97	15.946	194	2.11	17.653	480	2.29	22.438	187	2.10	24.446	400	2.21	30.
2	11.12	2.827	43	2.39	6.043	1785	2.23	9.373	114.5	2.16	12.158	883	2.22	15.955	170	2.13	18.759	620	2.17	22.954	187	2.07	25.646	468	2.11	29.1
3	11.03	2.923	42	2.32	6.257	1888	2.17	9.695	93	2.11	12.626	810	2.15	16.843	150	2.08	20.331	722	2.07	24.239	245	2.02	26.154	489	2.14	25.1
4	10.67	3.542	35	1.984	6.801	1923	2.07	10.11	83	2.09	13.924	1220	2.02	17.459	148	1.97	20.196	640	2.04	25.45	332	1.89	27.273	505	2.96	22.4
5	10.61	3.551	37	1.99	6.690	1870	2.11	10.36	76	2.05	14.087	1030	2.01	16.168	167	2.06	18.658	589	1.92	25.027	249	1.98	28.326	709	2.00	22
6	10.72	3.398	37	2.06	6.950	1475	2.02	9.423	74	2.23	13.577	990	2.06	15.502	182	2.12	16.705	415	2.07	24.239	245	2.02	26.154	489	2.14	25.1
7	10.9	3.383	38	2.034	6.383	1640	2.16	9.923	70	2.08	13.756	1042	2.00	17.459	148	1.97	20.196	640	2.04	25.45	332	1.89	27.273	505	2.96	22.4
8	11.1	2.929	42	2.28	5.722	1587	2.33	9.329	72	2.17	12.871	925	2.07	16.168	167	2.06	18.658	589	1.92	25.027	249	1.98	28.326	709	2.00	22
9	11.62	2.675	46	2.41	5.284	1390	2.44	8.843	81.5	2.19	11.637	837	2.22	15.502	182	2.12	16.705	415	2.32	20.194	182	2.24	24.478	489	2.18	28.6
Average	---	---	---	2.15	---	---	2.17	---	---	2.11	---	---	2.06	---	---	2.05	---	---	2.11	---	---	2.05	---	---	2.11	26.8

TABLE 2. Field Strengths of Ground and Sky Waves Radiated From China Lake Antenna and Hawaii Antenna With 5 kW Input Power.

f, kHz	Field strength of ground wave at 17 km ( $\phi = 10^\circ$ ), <sup>a</sup> $\mu\text{V}/\text{m}$				Sky wave			
	Hawaii antenna		China Lake antenna		Hawaii antenna (west-to-east propagation)		China Lake antenna (east-to-west propagation)	
	Measured	Theoret- ical	Measured	Theoret- ical	Measured field strength at 4200 km, $\mu\text{V}/\text{m}$	Theoret- ical effi- ciency ( $\theta = 15^\circ$ ); %	Measured field strength at 4200 km, $\mu\text{V}/\text{m}$	Theoret- ical effi- ciency ( $\theta = 15^\circ$ ); %
9.33	1705	1673	950	2070	16.7	0.18	6.46	0.22
10.9	1530	1673	1192	2250	17.1	0.09	5.73	0.26
14.0	1680	1813	1410	2370	13.1	0.08	11.2	0.28
15.5	1970	1890	1375	2380	11.7	0.15	6.92	0.28
17.1	2200	1930	1403	2335	15.6	0.15	11.26	0.26
21.78	4190	2230	1623	1860	5.6	0.07	8.00	0.14
24.9	3315	2870	1683	1215	4.2	0.12	5.14	0.06
26.45	3860	---	1650	---	---	0.16	9.5	---
28.1	4340	3440	1525	788	5.5	0.23	2.83	0.03
31.1	4450	3830	1600	1183	4.3	0.33	1.75	0.10

<sup>a</sup>  $\phi$  is azimuthal angle.

<sup>b</sup>  $\theta$  is elevation angle.

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TABLE 3. Comparison of Measured Radiation from  
China Lake Antenna and Hawaii Antenna  
With 5-kW Input Power.

Fre- quency, kHz	Ratios of field strengths of China Lake antenna to Hawaii antenna, dB		(3) Propagation efficiency, dB (Col. 2 minus col. 1)
	(1) Ground wave at 17 km ( $\phi = 10^\circ$ )	(2) Sky wave at 4,200 km	
9.33	-5.0	-8.2	-3.2
10.9	-2.2	-9.5	-7.3
14.0	-1.5	-1.4	+0.1
15.5	-3.1	-4.5	-1.4
17.1	-3.9	-2.8	+1.1
21.78	-8.2	+3.1	+11.3
24.9	-4.9	+1.7	+6.6
26.45	-7.4	---	---
28.1	-9.1	-5.8	+3.3
31.1	-8.9	-7.8	+1.1

where the beam launch angle is very low (see Fig. 11) indicates that low-loss propagation modes or hops are being excited.

#### INCREASING RADIATION EFFICIENCY

The radiation efficiency could be increased considerably by inserting series capacitors at regular intervals along the conductors to increase the wave velocity. The longer the antenna is electrically, the more the efficiency would be increased by this method.

Radiation patterns based on measured conductor propagation parameters have been computed for the China Lake antenna both with and without series capacitance. Beamwidth of the ground wave, beam launch angle of the sky wave, and maximum efficiency of both, as taken from the radiation patterns, are plotted as a function of frequency in Fig. 11 and 13. The efficiency can be more than doubled at low VLF by inserting  $0.2 \mu\text{F}$  at 2,500-ft intervals. This series capacitance is sufficient to increase the antenna wave velocity to that of free space at 10 kHz (see Fig. 14), but at some lower frequency the propagation along the conductor approaches cutoff. As the frequency increases, the effect of the series capacitance decreases until about 25 kHz, where the antenna performance becomes equal to that of the antenna with no series capacitance (compare Fig. 11, 13, and 14). In general, the best performance can be realized when sufficient series capacitance is used to increase the antenna wave velocity to that of free space at the low end of the band of frequencies to be used.

A much larger increase in efficiency can be realized at the higher VLF when the proper amount of series capacitance is used. If  $0.1\text{-}\mu\text{F}$  capacitors were inserted in the China Lake antenna at intervals of 1,025 ft, the radiation efficiency would be improved by a factor of 12 at 20 kHz (see Fig. 15). Below 20 kHz, propagation cutoff is approached, and above 20 kHz the improving effects diminish rapidly, as is shown in Fig. 16. A large increase in the radiation efficiency of an antenna lying on a lava bed and having an initial slow wave velocity, such as the China Lake antenna, can be effected only over a narrow band of frequencies. By such a narrow-band increase a half-power bandwidth of 40% can be realized. This relatively narrow bandwidth, caused by rapid change in propagation parameters with frequency, also causes rapid changes in ground-wave beam width and sky-wave launch angle (see Fig. 17 and 18), which are undesirable for broadband operation.

Considerable improvement in bandwidth could be achieved by elevating the antenna a few feet above the lava bed on poles. Both im-

proved efficiency and improved beamwidth and launch angle beamwidth would result if the China Lake antenna were elevated 4 ft above the lava (see Fig. 19 and 20). Then, if the antenna conductors were loaded with 0.1  $\mu$ F capacitance per 1,510 ft, the propagation parameters would vary much more slowly with frequency, as is shown in Fig. 21. In this case, the amount of series capacitance would be selected so as to optimize the efficiency at 20 kHz.

### CONCLUSIONS

Measurements made on the individual conductors of the 9-conductor horizontal antenna lying loosely on the lava bed showed that there was considerable variation among conductors in the propagation parameters, due to the proximity of the wire to the ground. Average values of these parameters were obtained by measuring mutual impedance between conductors and measuring resonant frequencies and resistances. These average propagation parameters were used to compute the radiation patterns. The radiation patterns show that the radiation efficiency is greatly reduced by the slow wave velocity along the conductors.

This conductor wave velocity can be increased, however, by inserting series capacitance in the conductors and thereby greatly increasing the radiation efficiency over a relatively narrow bandwidth (40%). Theoretical radiation patterns indicate that the antenna should be elevated a few feet above the ground to increase the bandwidth over which large increases in radiation efficiency can be obtained by using series capacitance.

### FUTURE PLANS

It is planned to insert the proper amount of series capacitance in the conductors of the antenna and then measure the field strengths as well as the impedance to determine whether the expected increase in radiation efficiency is realized.

It is also planned to elevate the conductors of the antenna on 4-ft poles, to insert the proper series capacitance in the conductors, and to make impedance and radiation measurements over the VLF band to confirm the expected increase in bandwidth.

## Appendix

DEVELOPMENT OF ANTENNA CONSTRUCTION  
TECHNIQUES

Because of the special problems encountered in the construction of this VLF horizontal antenna, various construction techniques had to be developed as the antenna was being built. The construction involved laying down many miles of parallel conductors over rough terrain, and in future work these conductors will be elevated on poles a few feet above the ground. It was necessary that the conductors be stretched taut and, generally, that series capacitors be connected to the conductors at regular intervals of about one-half mile. Since most of the terrain was not accessible by ordinary land vehicles, a helicopter provided the fastest and lowest-cost means of accomplishing these construction tasks. Using a helicopter to install the conductors required that some method be developed for marking the straight lines to be followed by the helicopter.

The three major tasks to be accomplished in the construction were establishing straight survey lines or marking straight parallel lines, devising means of dispensing wire rapidly, and putting poles into the ground and laying wire on the poles. Before arriving at the techniques ultimately used to install the antenna, several methods of performing these tasks were tried. One of the methods that was tried to mark lines to guide the helicopter pilot in dispensing the wire was dropping first flour and then whitewash from the helicopter, which was guided by a survey transit operator in radio communication with the pilot. The method proved unsatisfactory because in rough terrain, when the pilot flew low enough to dispense the wire, he lost sight of the white guide line in the depressions ahead. Next an attempt was made to use balloon markers to designate the straight parallel lines. Although these markers worked well during calm periods, they were easily pushed to the ground by the wind. The method that proved best was marking the straight lines with flags. However, another method worked well when construction requirements were less exacting. Where the antenna would be operated with the conductors on the ground, the requirement for straightness of the conductors could be relaxed and

## Part 1

lateral variations of  $\pm 100$  ft tolerated. In this case, the most efficient method of guiding the helicopter to dispense the wire was to have a man sight through a transit or gun scope and by radio talk the pilot along a straight line indicated by a hair line. For this method to work well, the helicopter had to increase its altitude as it receded from the transit or gun scope.

Several methods of dispensing the wire were tried. At first coiled wire was dispensed from the center of the coil without being wound on reels. This method proved unsatisfactory in that when most of the wire had been dispensed, the outer shell of the coil would collapse and cause the wire to tangle. Moreover, the wire could not easily be laid taut by this method. An improved method of dispensing the wire resulted from the use of a reel and dispenser apparatus, as is shown in Fig. 22. The reel, designed to hold 2,500-ft coils of wire, was suspended from the helicopter so that the reel axis was vertical, as may be seen in Fig. 23. By this method it was possible to lay wire at the rate of 5 mi/hr, including the time for pickup and transport of the wire. The main difficulty experienced with this method was that occasionally, when the helicopter changed speed rapidly, the wire tangled. Although this is the best method of dispensing wire yet developed, it is felt a horizontal-axis dispenser with a braking system that maintains the wire at constant tension should be developed.

Clearly the helicopter is almost indispensable to the construction of the antenna. Not only does it serve to mark the surveyed lines and to dispense wire along the surface of the terrain, but even in such operations as putting poles in holes drilled in the ground and putting wire on the poles, where the work must be done either by ground crews or ground vehicles, the helicopter can save much time and labor by transporting people, material, and equipment to and from the construction site.

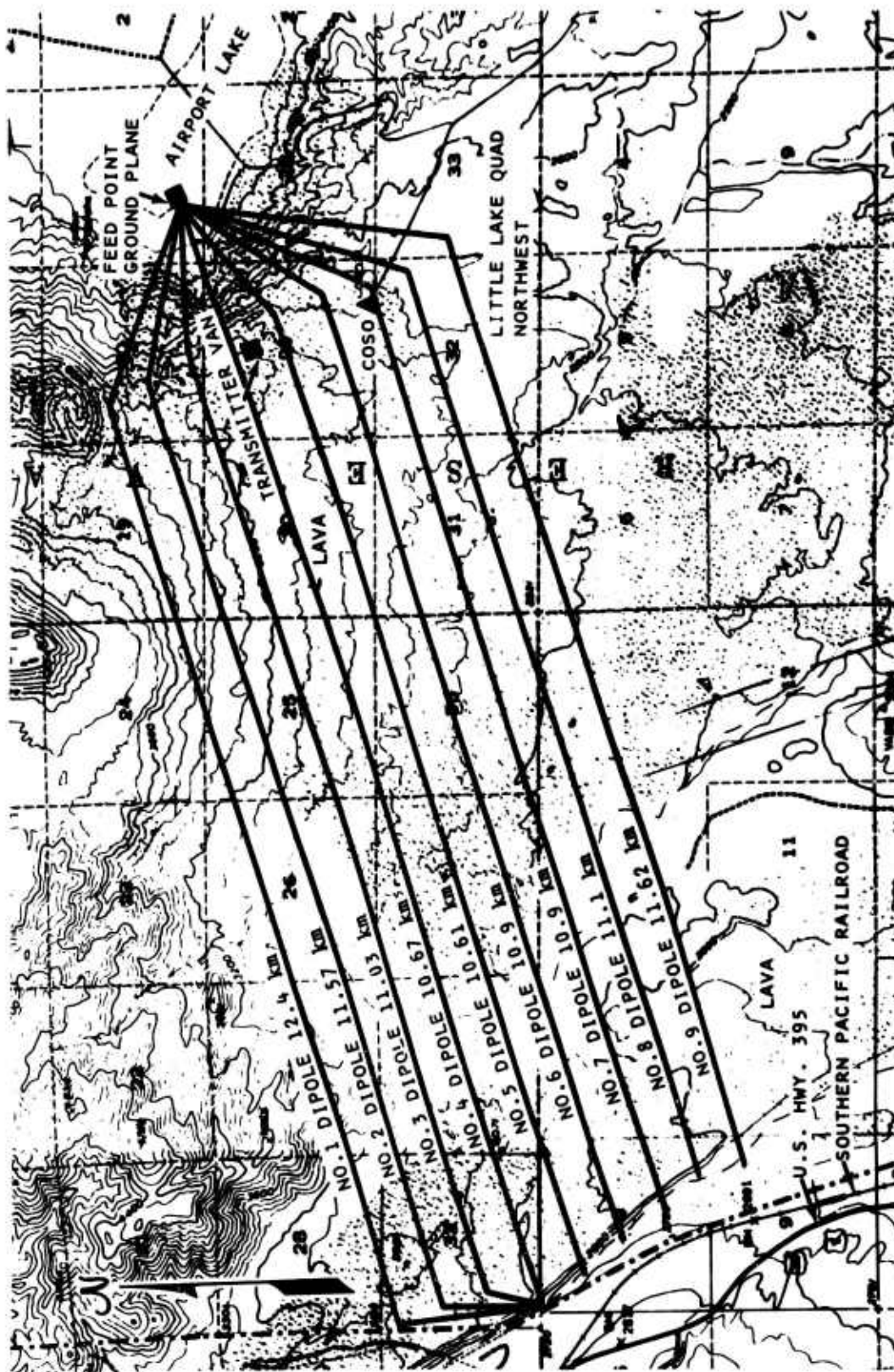


FIG. 1. Layout of Nine-Conductor VLF Antenna.

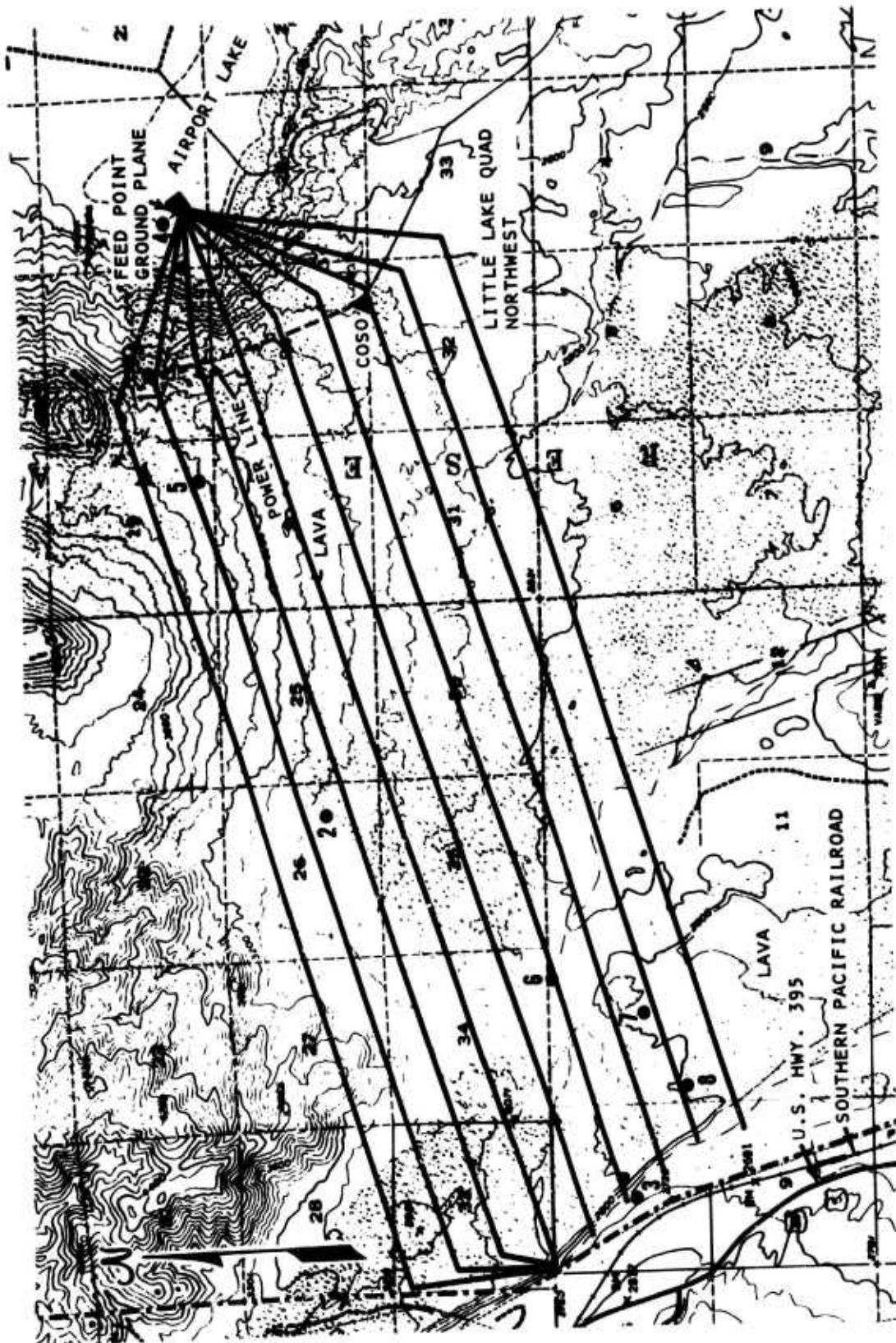


FIG. 2. Locations of Conductivity Measurements.

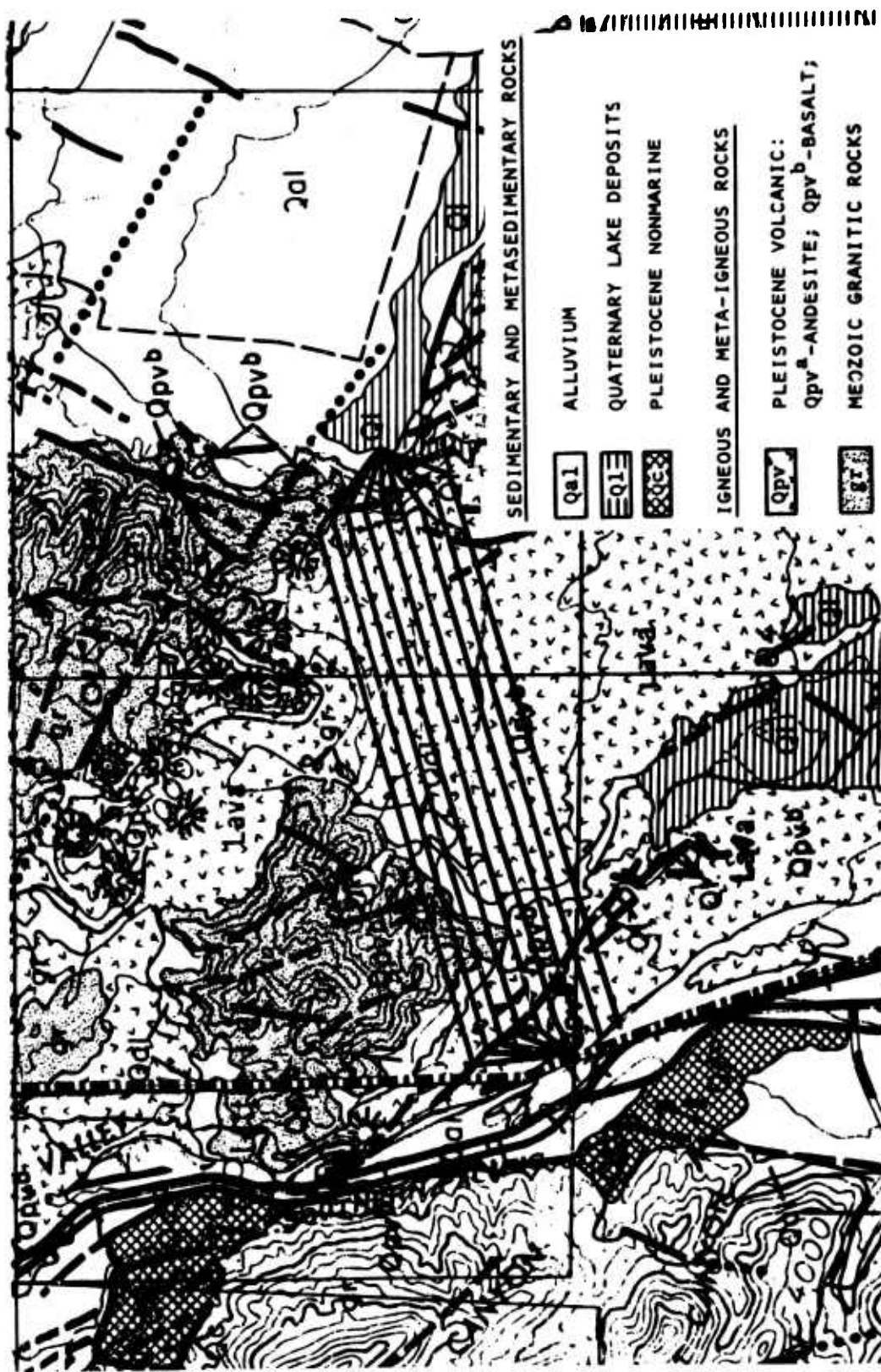


FIG. 3. Geological Structure of Antenna Site Showing Antenna Located Mainly on Pleistocene Volcanic (Basalt).

Part 1

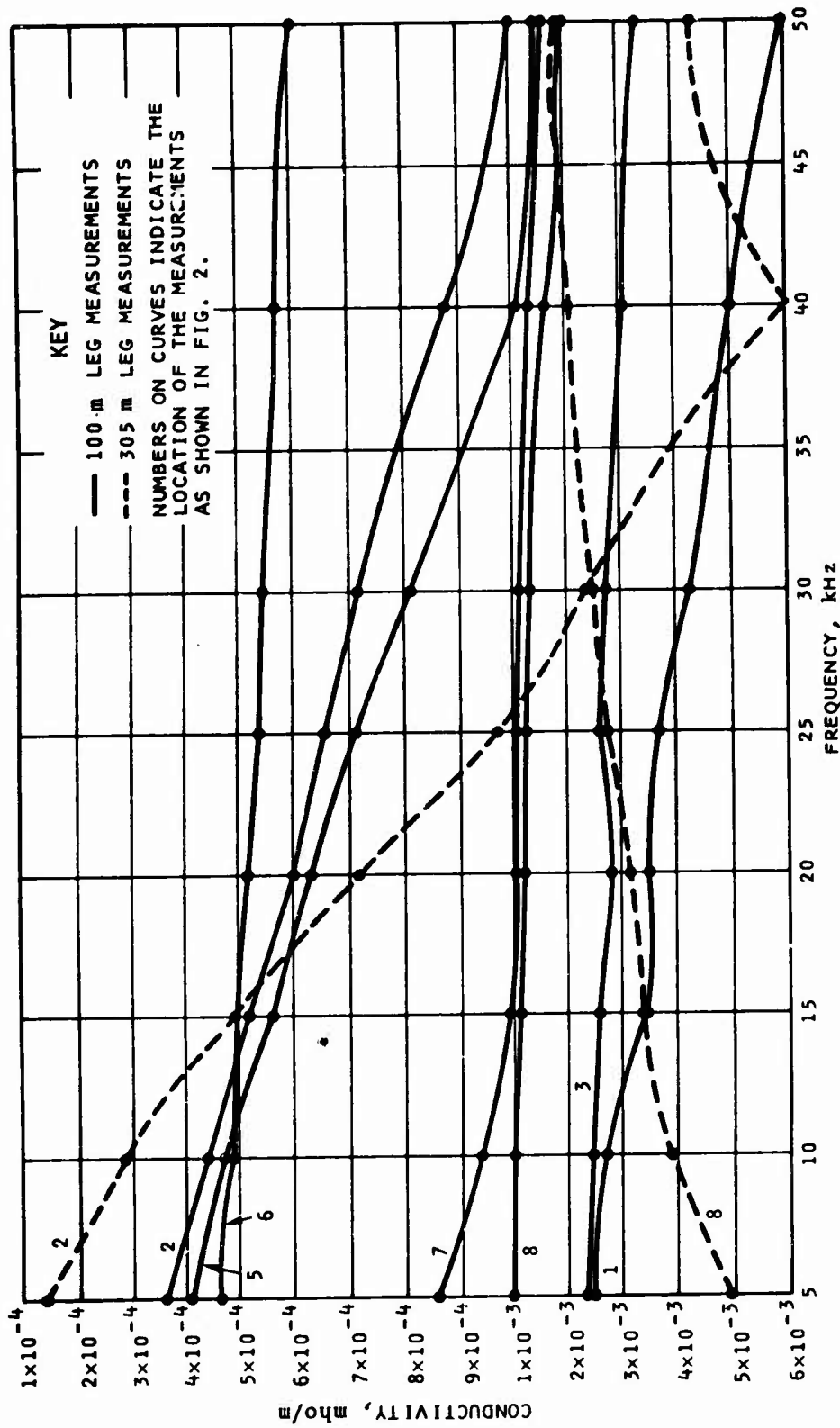


FIG. 4. Ground Conductivity of Lava Bed Measured at Eight Locations.

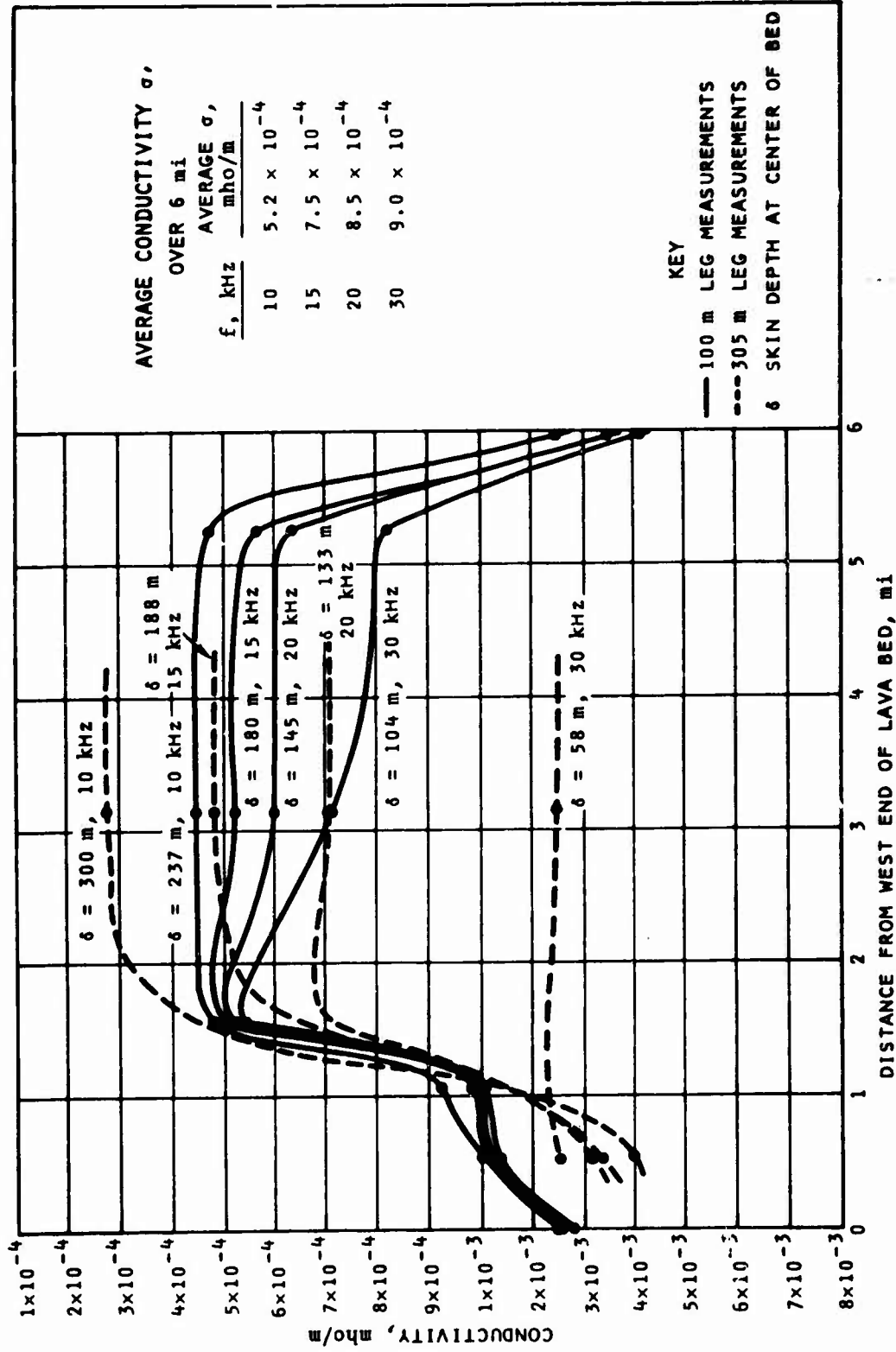


FIG. 5. Variation of Ground Conductivity with Skin Depth and Frequency Along Antenna Length.

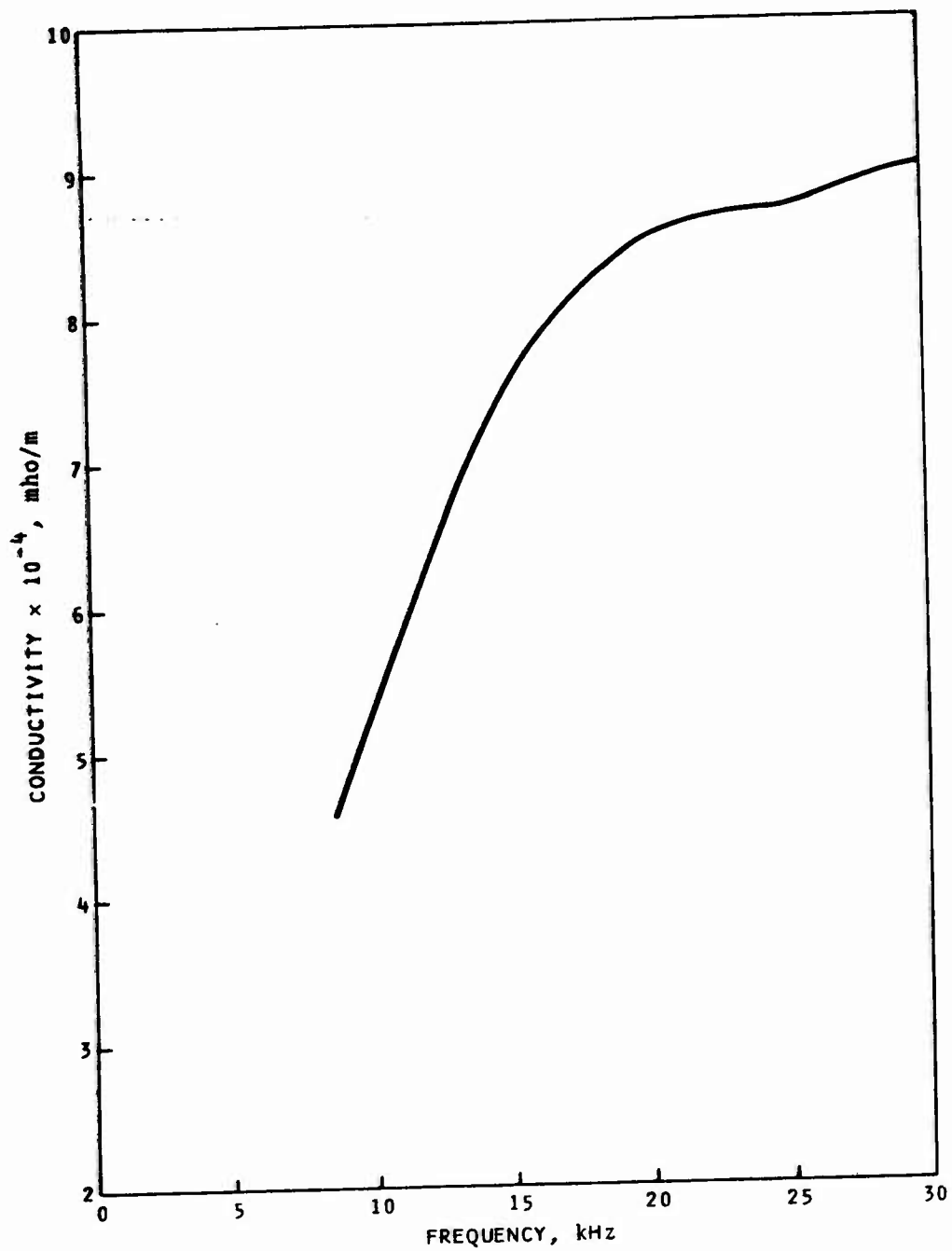


FIG. 6. Variation of Average Ground Conductivity with Frequency.

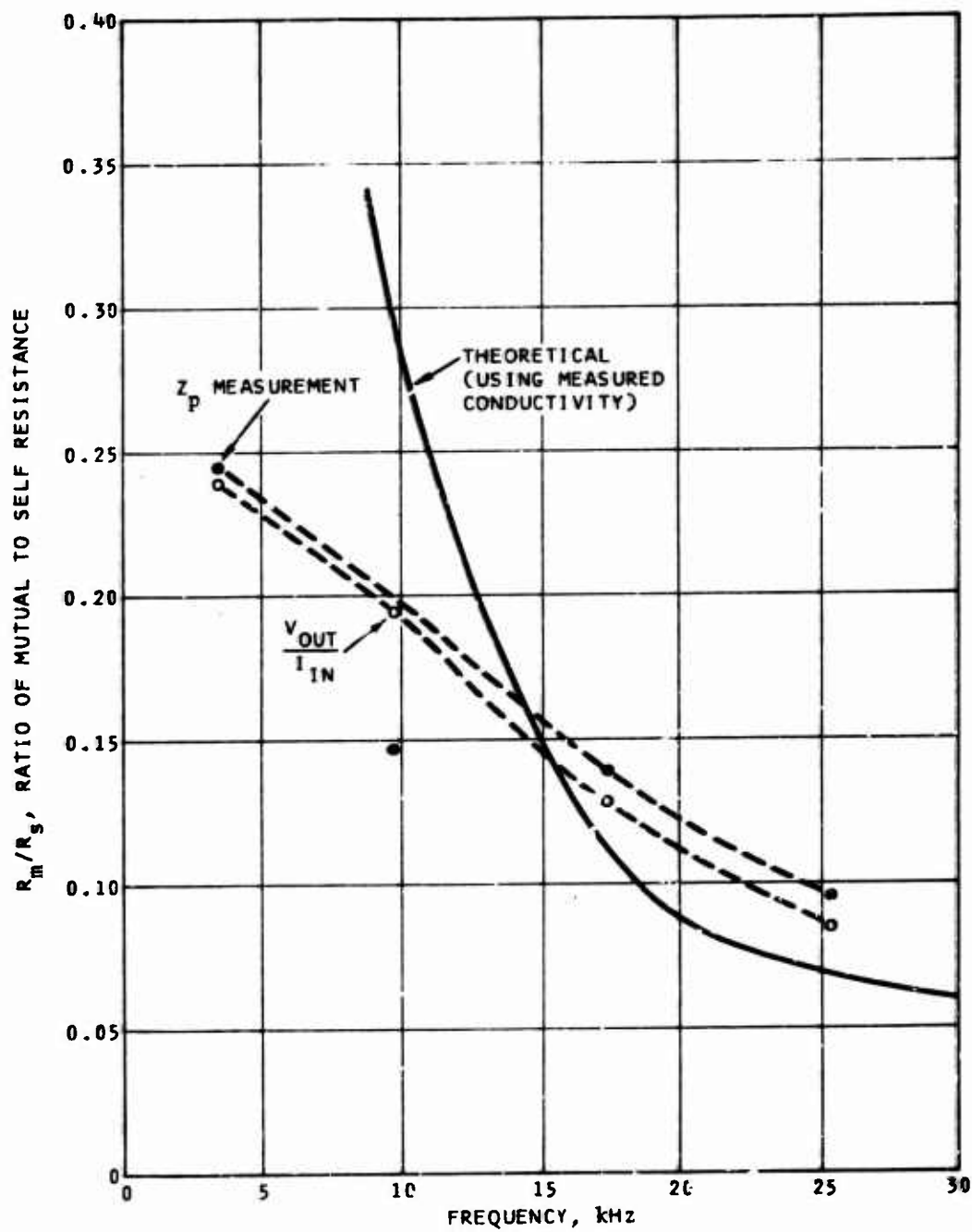


FIG. 7. Mutual Resistance Between Conductors No. 6 and No. 7 Lying 1500 ft Apart on Lava Bed.

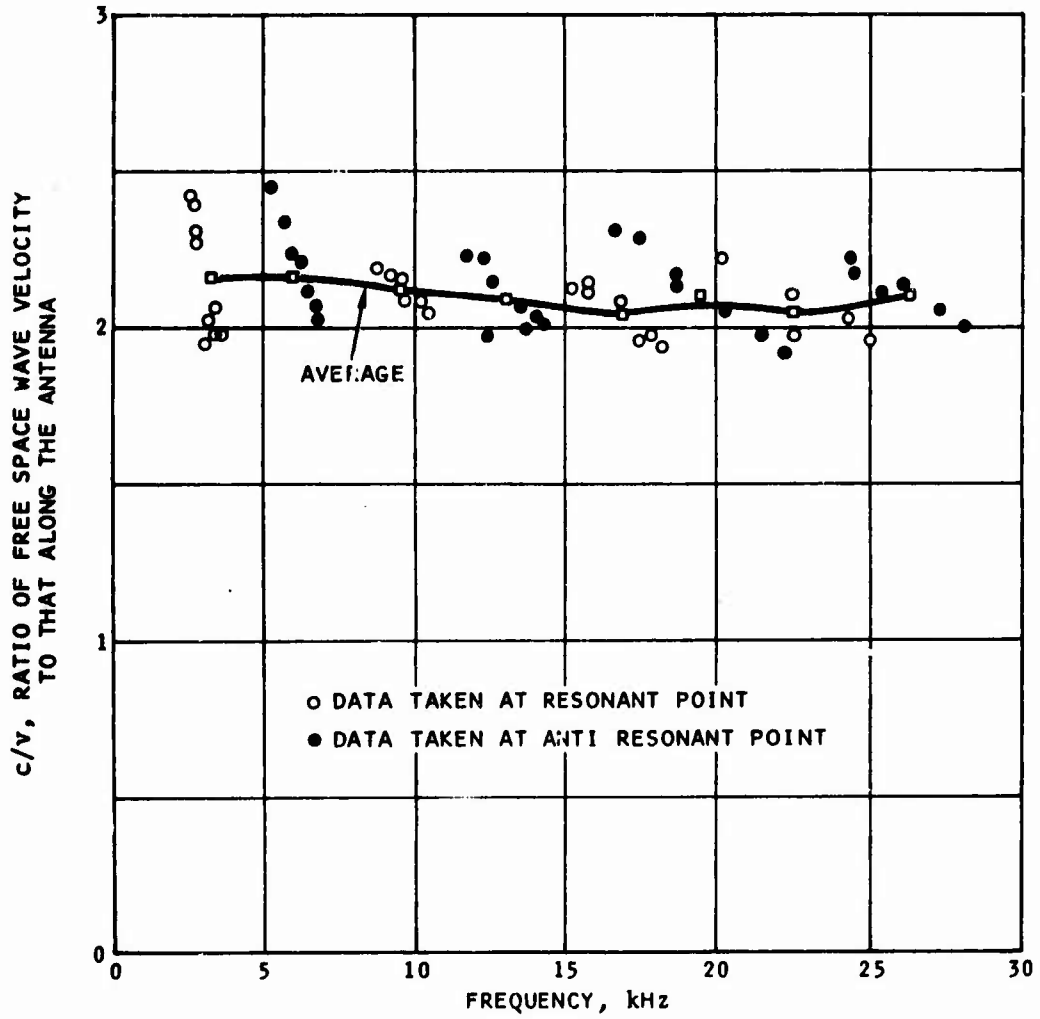


FIG. 8. Wave Velocity vs Frequency for Each Conductor.

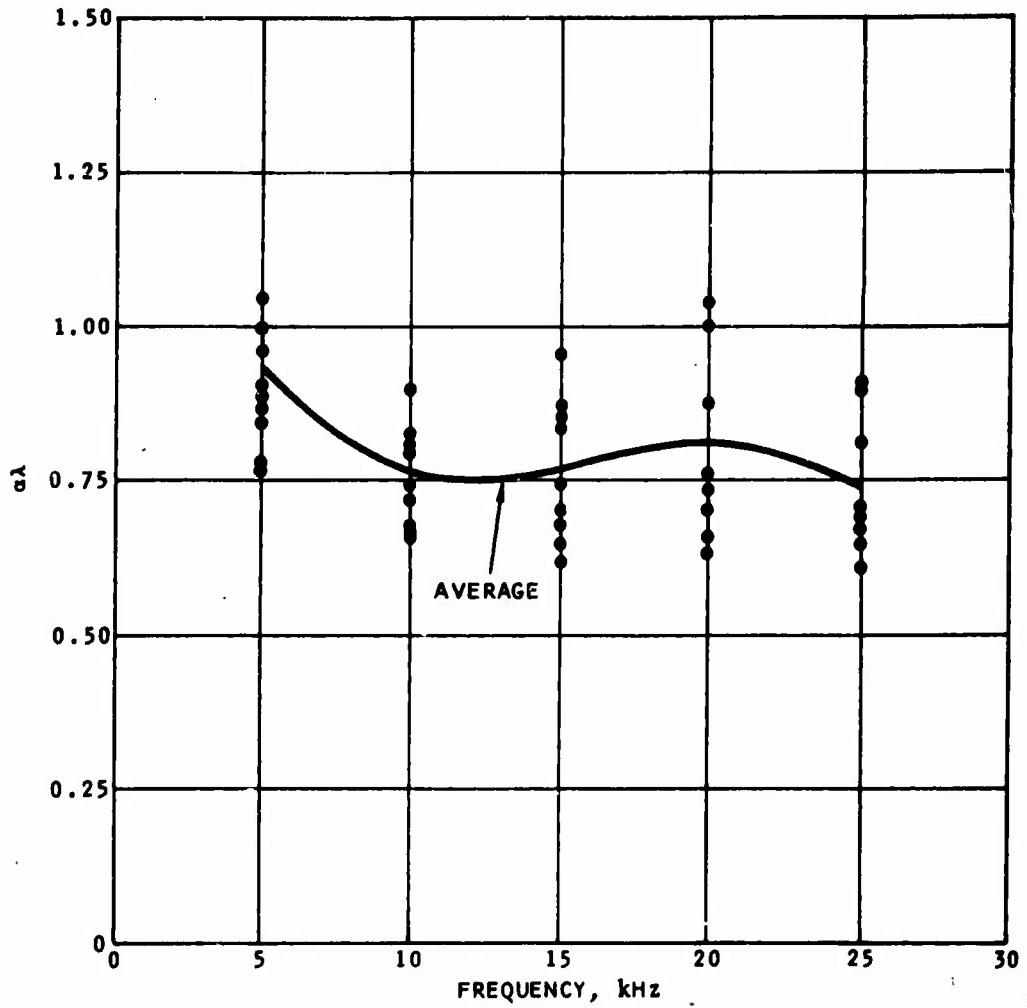


FIG. 9. Attenuation (not including mutual resistance) vs Frequency Along Each Conductor.

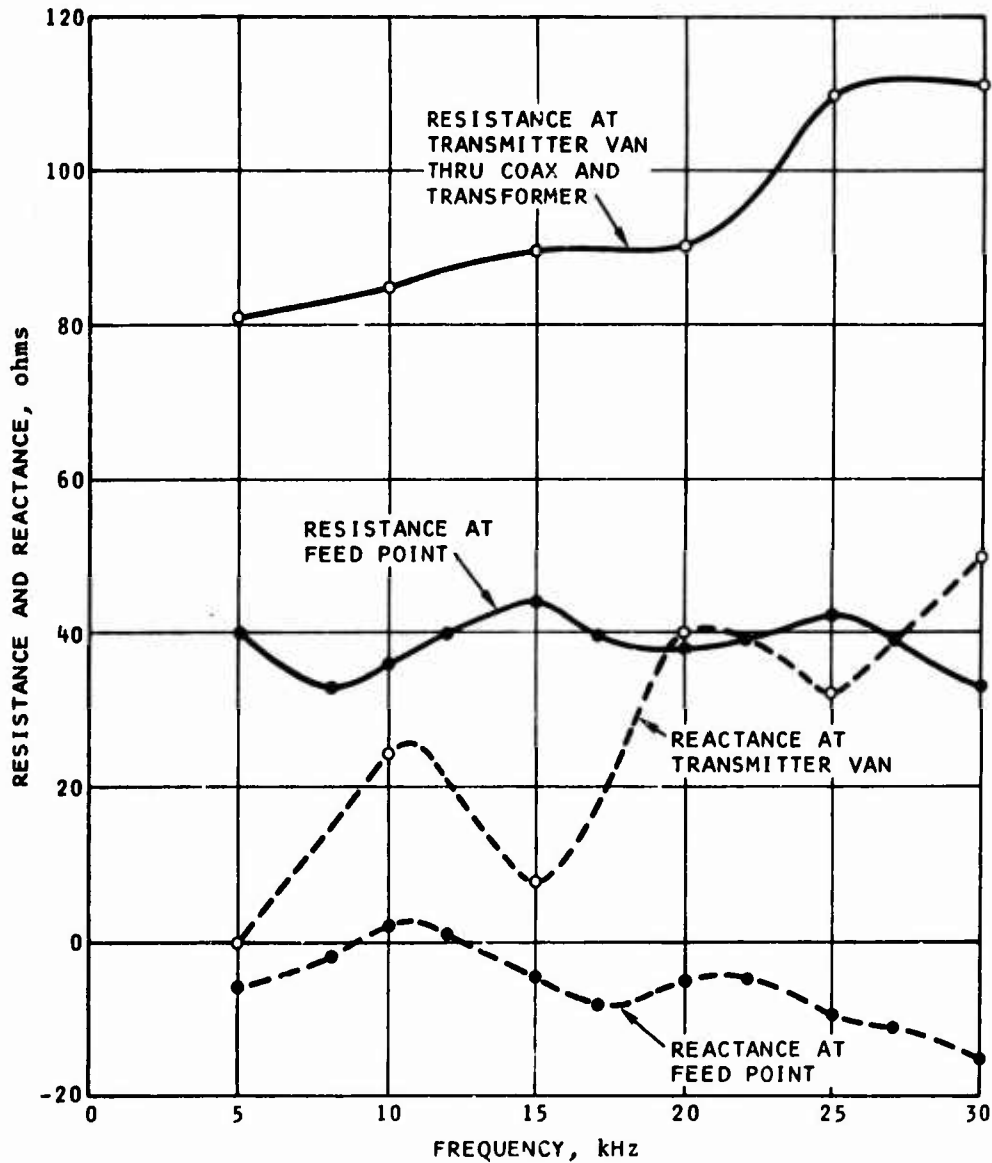


FIG. 10. Antenna Resistance and Reactance vs Frequency Measured at Feed Point and Transmitter for Antenna Lying on Lava and Terminated with its Characteristic Impedance.

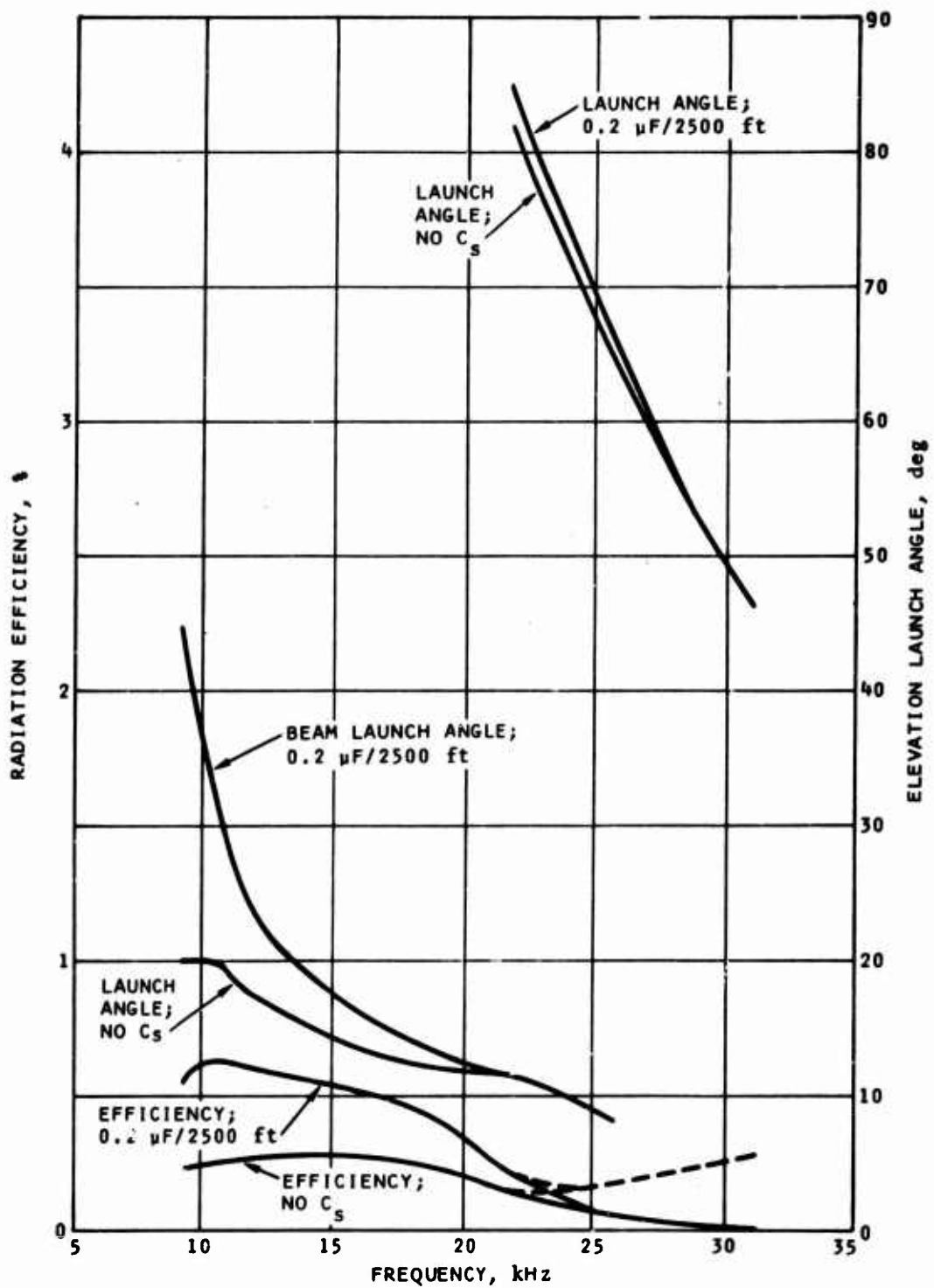


FIG. 11. Sky-Wave Launch Angle and Radiation Efficiency vs Frequency for 10.5-km Antenna Lying on Lava Bed.

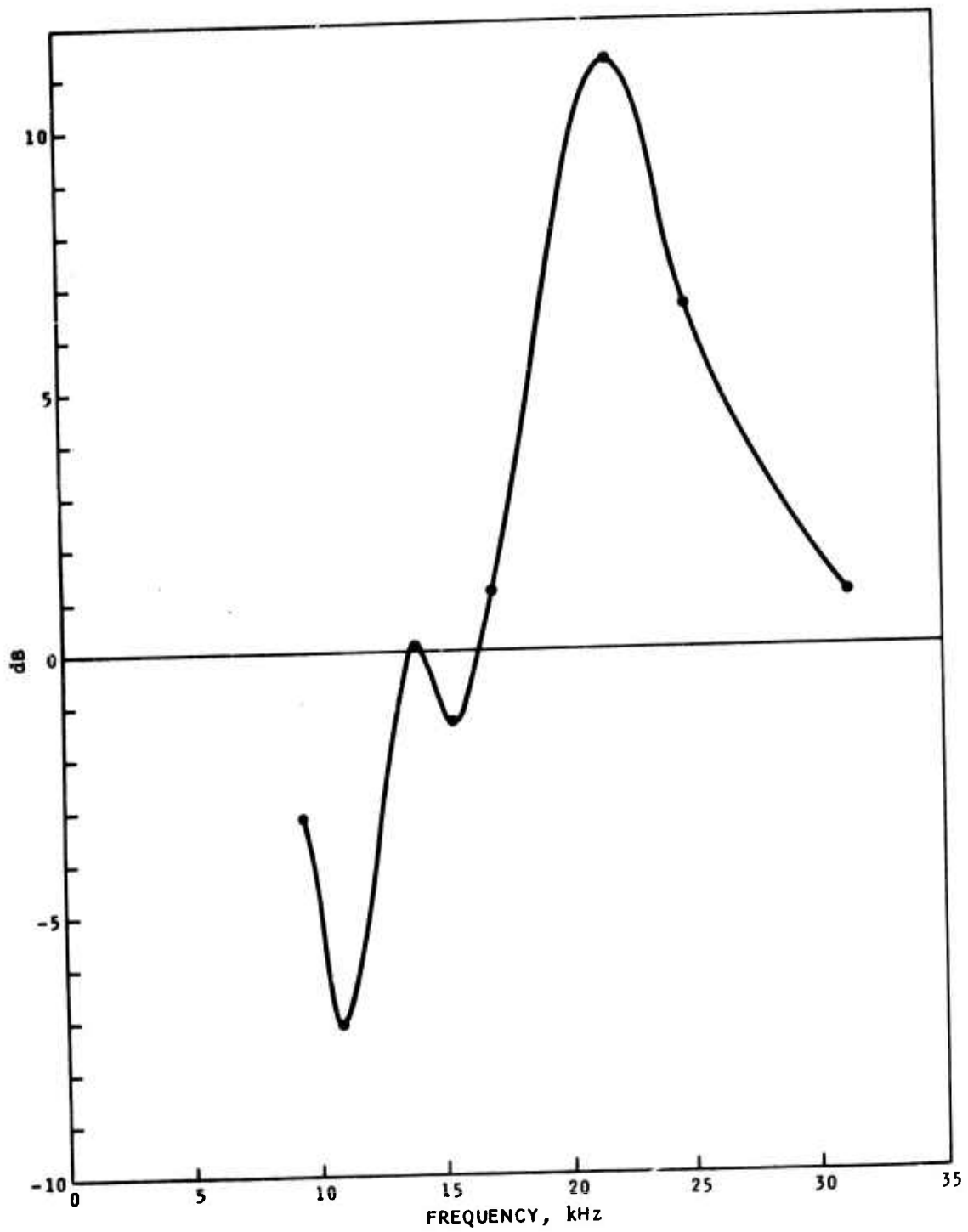


FIG. 12. Ratio of Propagation Efficiency of China Lake Antenna Radiating Westerly to that of Hawaii Antenna Radiating Easterly.

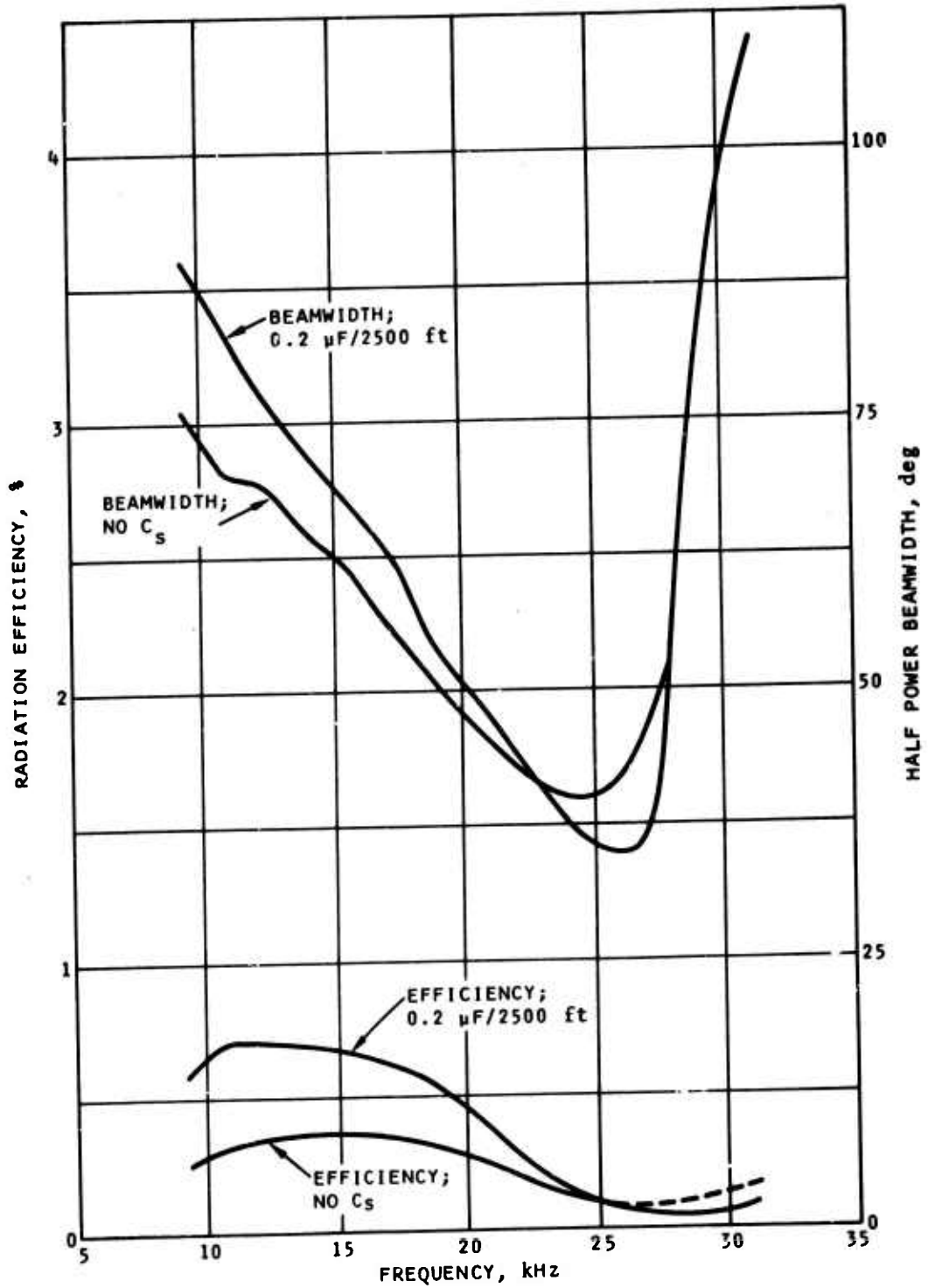


FIG. 13. Ground-Wave Beamwidth and Radiation Efficiency vs Frequency for 10.5-km Antenna Lying on Lava Bed.

Part 1

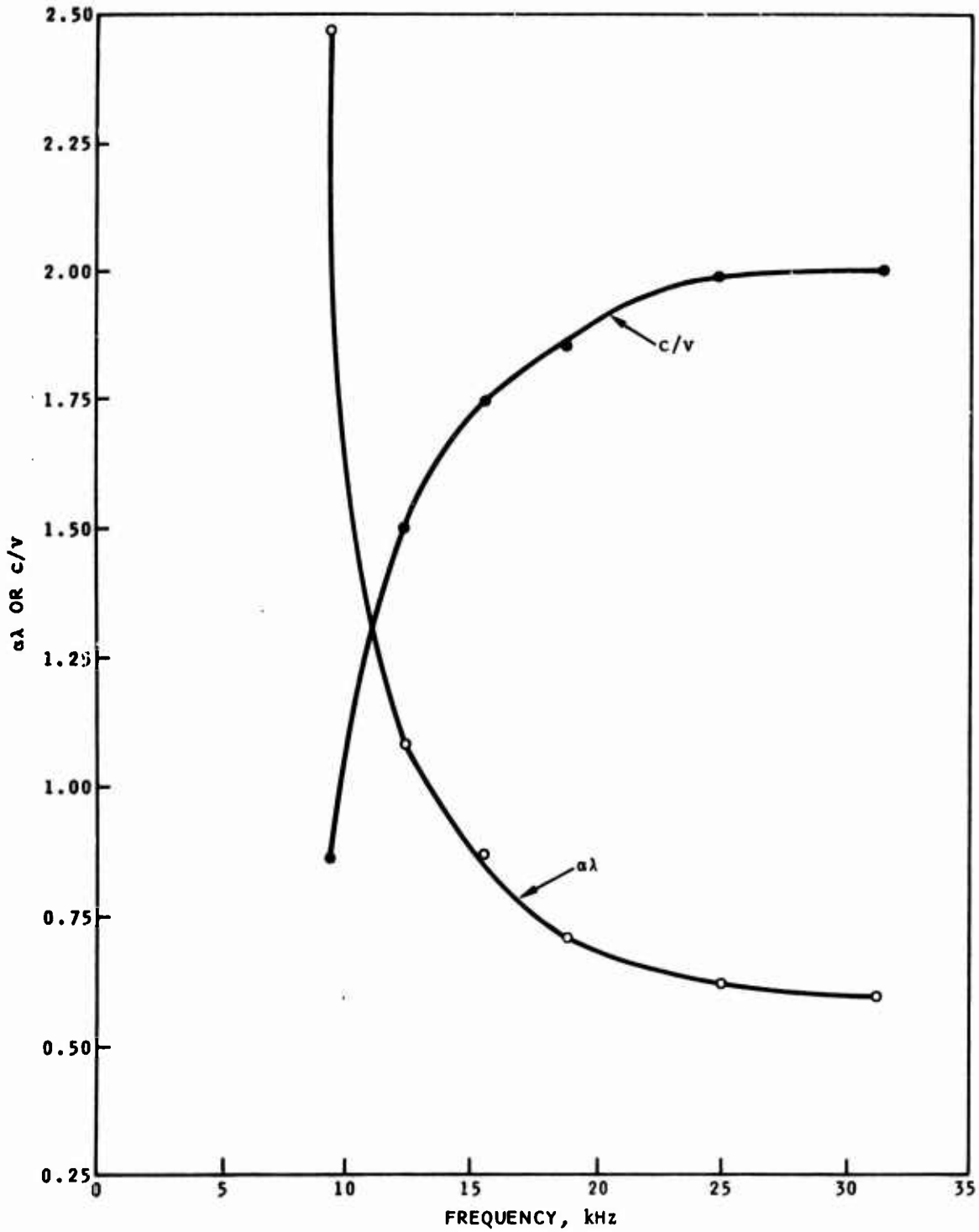


FIG. 14. Wave Velocity and  $\alpha\lambda$  vs Frequency for Antenna Loaded with  $0.2 \mu\text{F}/2500 \text{ ft}$ . Values are based on measured values with  $C_p = 22 \text{ pF/m}$  and  $L = 2.34 \mu\text{H/m}$ .

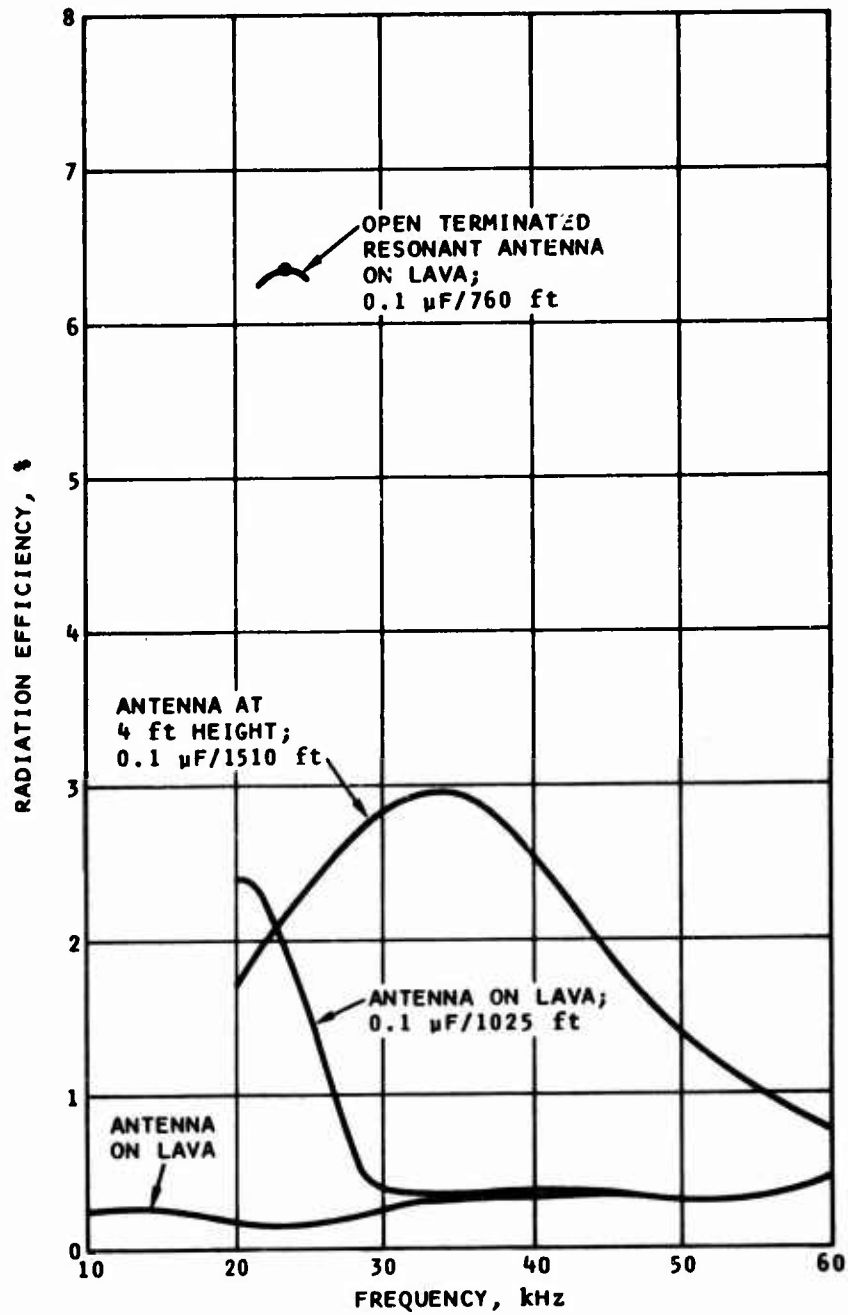


FIG. 15. Sky-Wave Radiation Efficiency vs Frequency.

Part 1

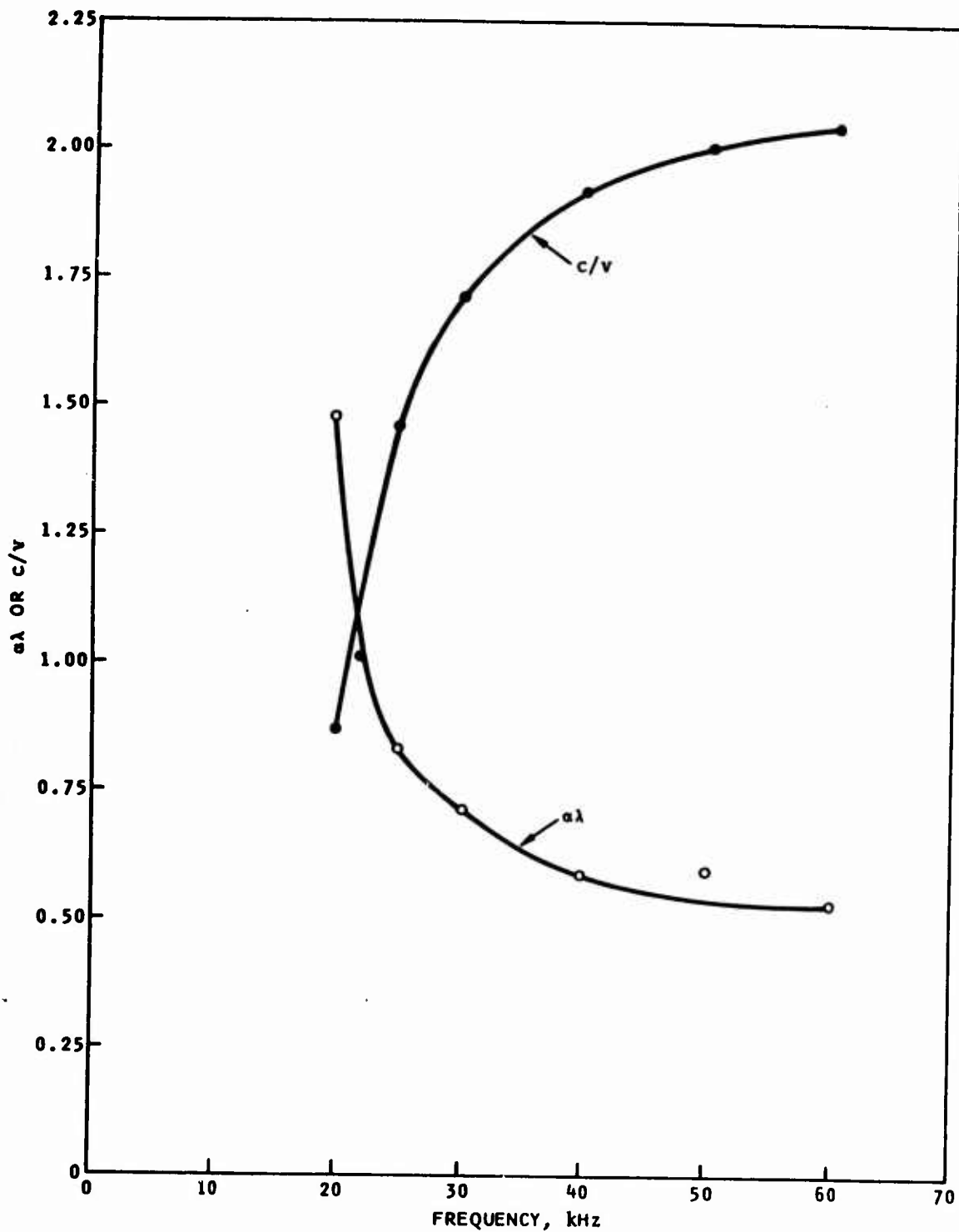


FIG. 16. Wave Velocity and  $a\lambda$  vs Frequency for Antenna Loaded with  $0.032 \mu\text{F}/\text{km}$  or  $0.1 \mu\text{F}/1025 \text{ ft}$  and Having  $C_p = 22 \text{ pF}/\text{m}$  and  $L = 2.34 \mu\text{H}/\text{m}$ .

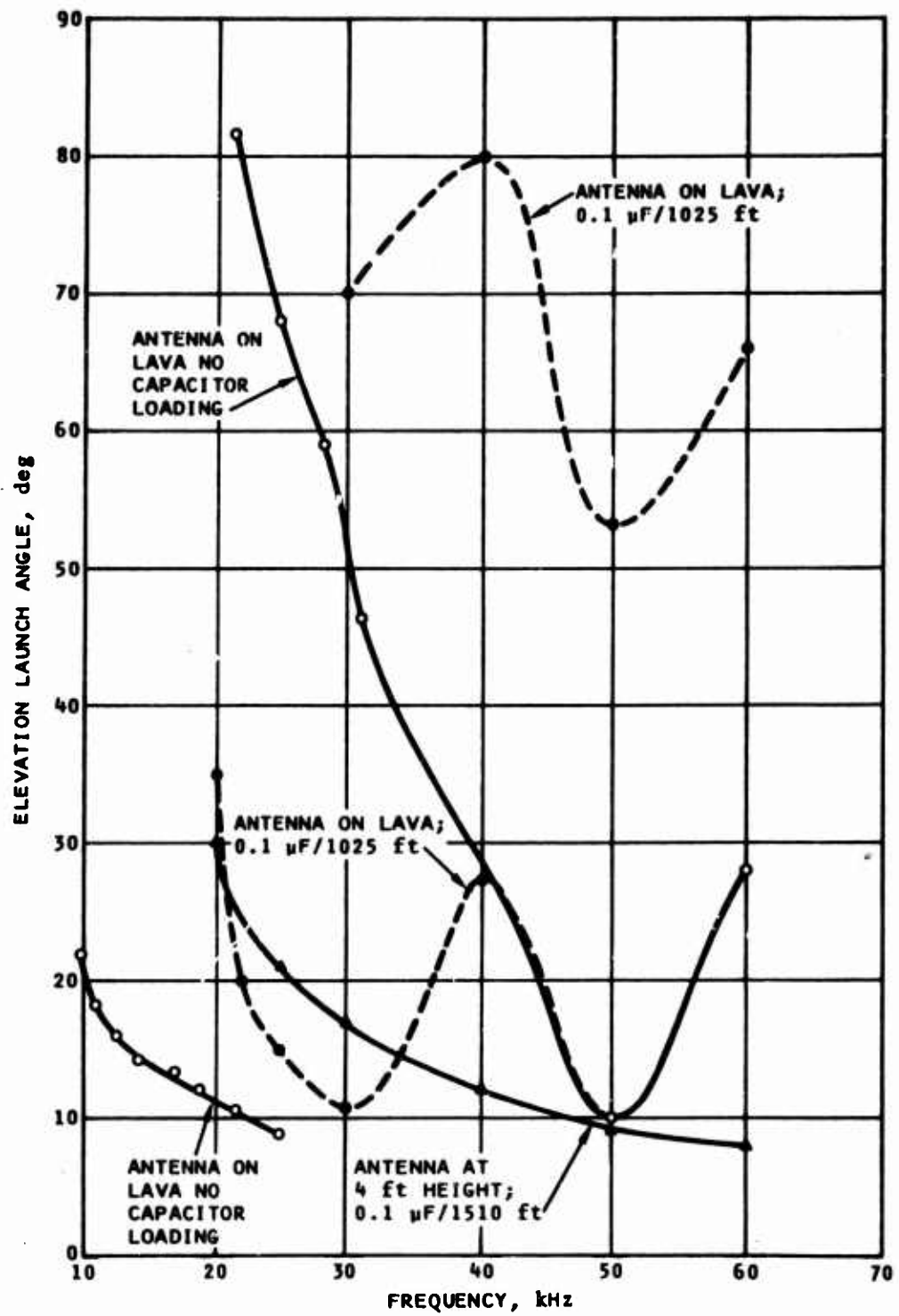


FIG. 17. Beam Launch Angle vs Frequency for Various Antenna Conditions.

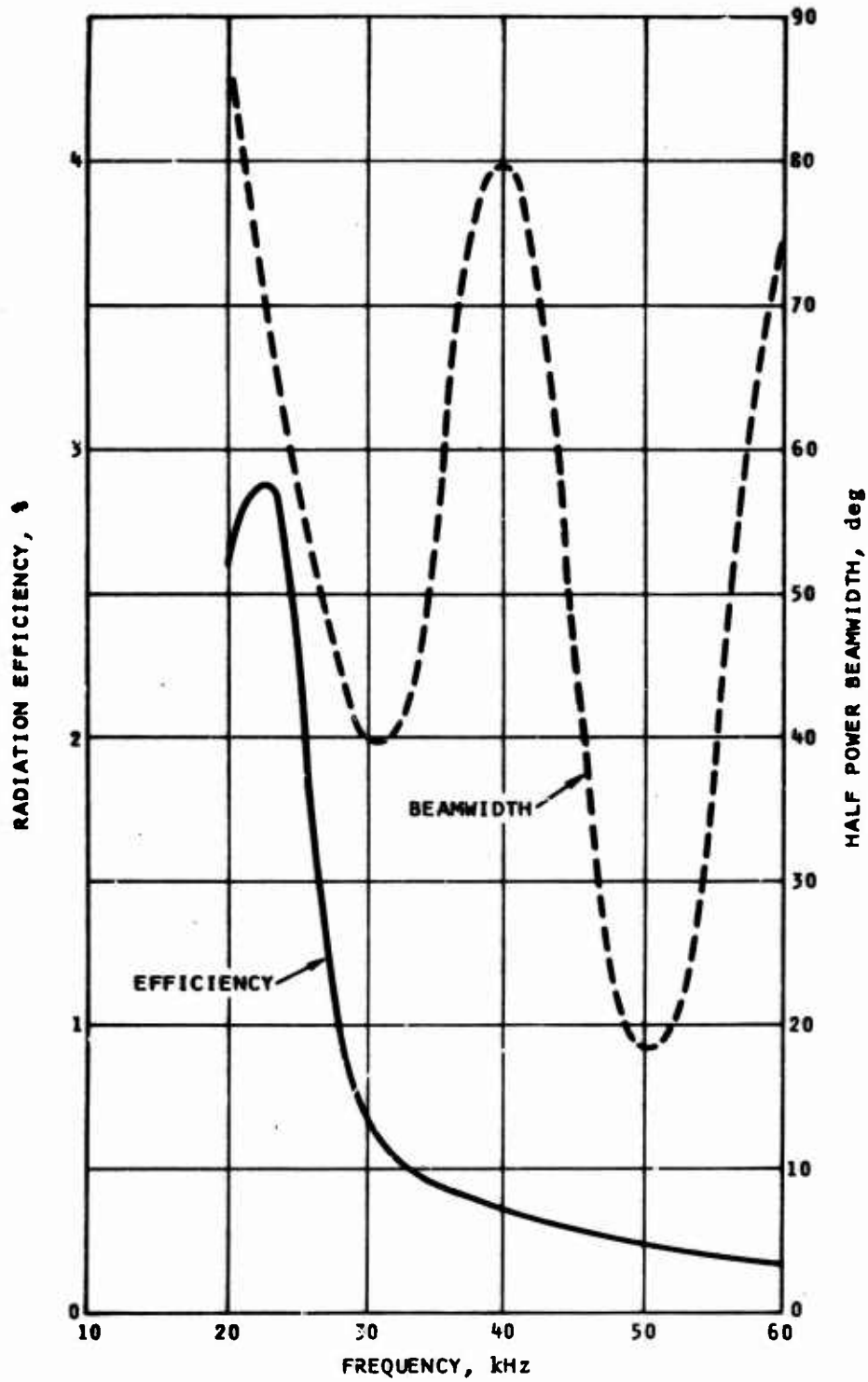


FIG. 18. Ground-Wave Radiation Efficiency and Half-Power Beamwidth vs Frequency for Antenna Loaded with 0.1 UF/1025 ft.

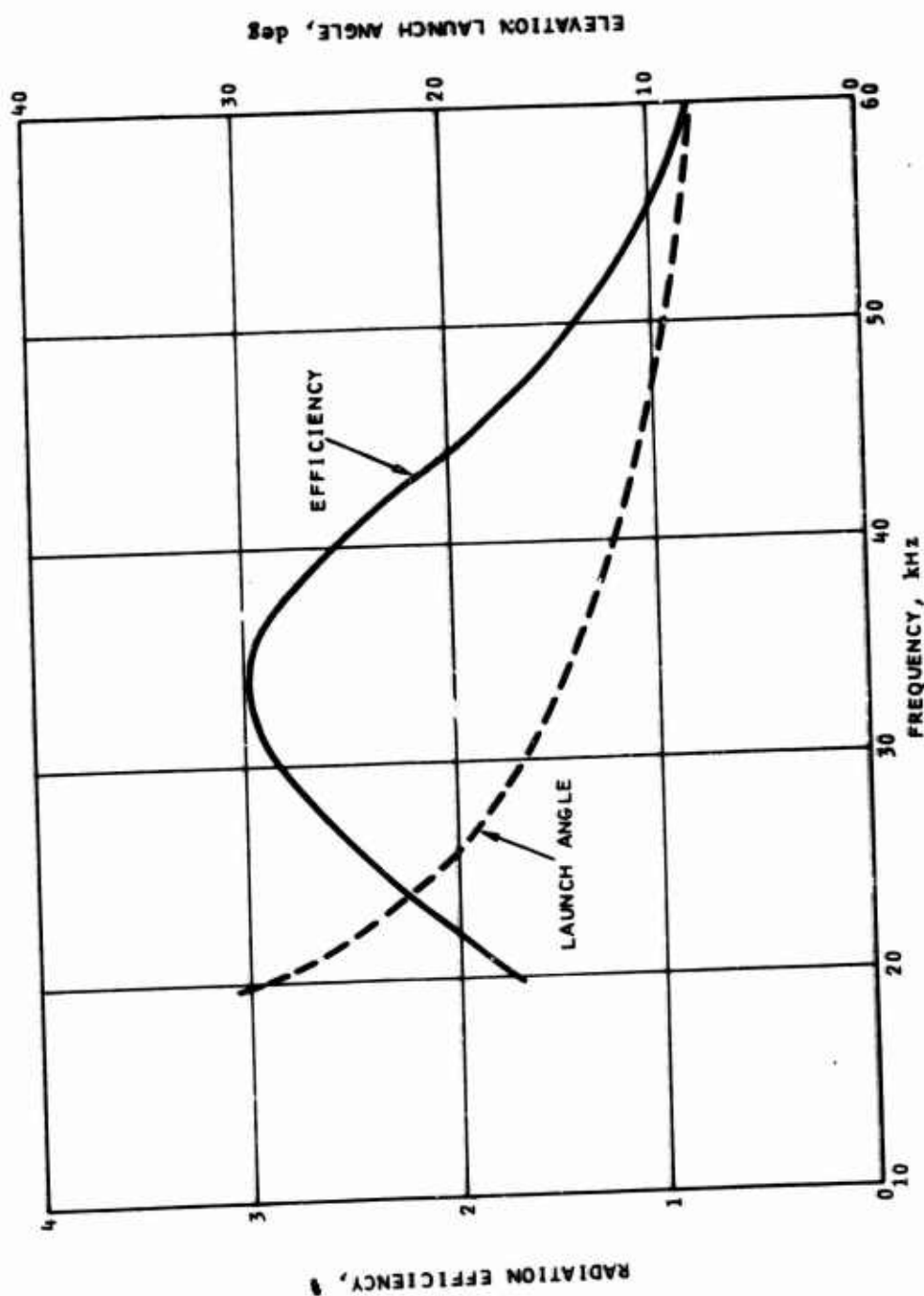


FIG. 19. Sky-Wave Radiation Efficiency and Beam Launch Angle vs Frequency for Antenna Mounted on 4-ft Poles and Loaded with 0.1  $\mu$ F/1510 ft.

Part 1

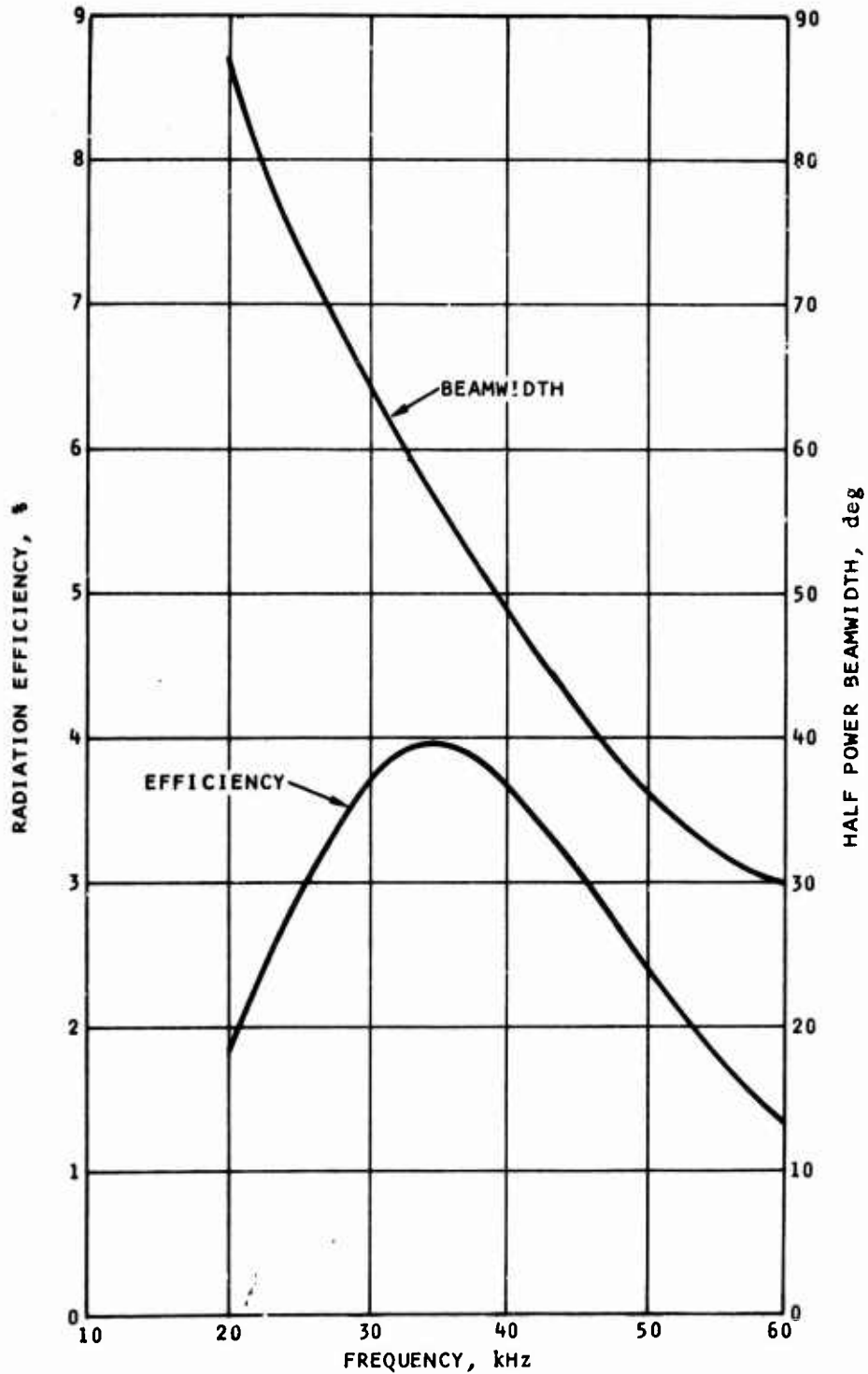


FIG. 20. Ground-Wave Radiation Efficiency and Half-Power Beamwidth vs Frequency for 10.5-km Antenna Mounted on 4-ft Poles and Loaded with 0.1  $\mu$ F/1510 ft.

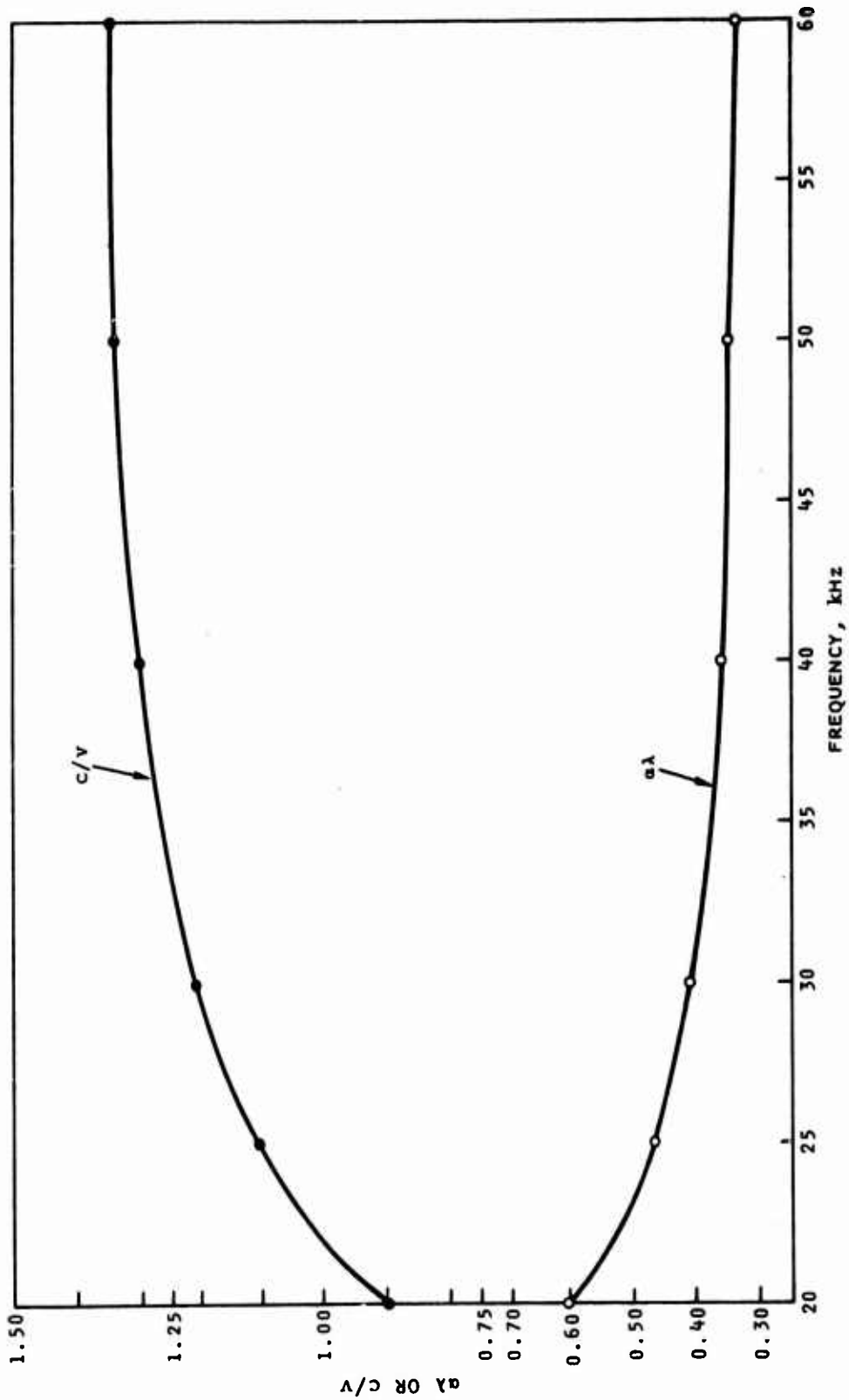


FIG. 21. Wave Velocity and  $a\lambda$  vs Frequency for Antenna Mounted on 4-ft Poles; Loaded with  $0.1 \mu\text{F}/1510 \text{ ft}$ ; and Having  $C_p = 9.35 \text{ pF/m}$ ,  $L = 2.34 \mu\text{H/m}$ , and  $Z_o = 500 \Omega$ .



FIG. 22. Dispensing Reel and Wire Used in Constructing Antenna.



FIG. 23. Helicopter Laying Antenna Wire by Means of Underslung Vertical-Axis Dispensing Reel.

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13. ABSTRACT Measurements of the performance of a nine-conductor VLF antenna, 10.5 km long, laid on a lava bed at the Naval Weapons Center China Lake, are presented. Theoretical curves are presented to show the improvement in radiation efficiency and bandwidth that can be realized if the antenna is elevated a few feet above the lava and the individual conductors are loaded with the proper series capacitance to increase the antenna wave velocity.			

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