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The open sleeve broadband antenna.

Barkley, Henry Brock

Monterey, California. Naval Postgraduate School

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THE OPEN SLEEVE BROADBAND ANTENNA

Henry B. Barkley, Jr.

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H. B. Barkley, Jr.

THE

OPEN SLEEVE

BROADBAND ANTENNA

by

Henry Brock Barkley, Jr.

Lieutenant, United States Navy

Submitted in partial fulfillment
of the requirements
for the degree of
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IN
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PREFACE

The open sleeve antenna was originally conceived and patented by Dr. J. T. Bolljahn of Stanford Research Institute, Menlo Park, California. During the fall of 1954 it was suggested to the writer as a possible subject of investigation for an eleven week industrial tour with Stanford Research Institute to be performed from 3 January 1955 through 18 March 1955. The work was to consist of developing a theory for the open sleeve antenna and extending and increasing the experimental data for its broadband performance.

The subject was given some consideration during the term preceding the industrial tour, but the major portion of the material was developed and obtained while working during the winter school term at Stanford Research Institute. The results were rather ideally suited for thesis material.

My sincere appreciation goes to Dr. J. T. Bolljahn for suggesting this interesting and useful device as a topic and providing cooperation, encouragement, and suggestions during the work on it and the preparation of the report. I am also grateful to Dr. John Taylor of Stanford Research Institute, under whose direct cognizance the project was pursued and whose cooperation proved invaluable in carrying out the work, and to Prof. J. G. Chaney of the U. S. Naval Postgraduate School, who served as my faculty advisor and who first stimulated my interest in antennas and electromagnetic theory. I further consider myself indeed fortunate to have had the opportunity of working at Stanford Research Institute for eleven weeks and to have this paper published as one of their regular reports.

STANFORD RESEARCH INSTITUTE

STANFORD, CALIFORNIA

JUNE 1955

SRI PROJECT 1197

A TECHNICAL MEMORANDUM ON

THE OPEN SLEEVE AS A BROADBAND ANTENNA

by

LT. H. B. BARKLEY, JR., USN

AIR FORCE CONTRACT No. AF 19(604)-1296
AIR FORCE CAMBRIDGE RESEARCH CENTER
CAMBRIDGE, MASSACHUSETTS

APPROVED:

This investigation was undertaken by Lt. H. B. Barkley, Jr., who was temporarily assigned to Stanford Research Institute from the U. S. Naval Postgraduate School at Monterey, California, in connection with the Naval Industrial Experience Program.

ABSTRACT

This report is concerned with the broadband impedance characteristics of the open sleeve antenna. The investigation is partly analytical, and partly experimental. A theory is derived for the simplest form of the antenna; this theory provides a qualitative explanation of the impedance behavior and permits systematic changes in antenna parameters during the experimental investigation. Experimental data are given which show that the antenna can be designed for a 2:1 VSWR on a 50-ohm transmission line over a 2:1 frequency band.

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ILLUSTRATIONS

THE OPEN SLEEVE AS A BROADBAND ANTENNA

CHAPTER 1

INTRODUCTION

The open sleeve antenna consists of a dipole with two closely-spaced parasites, one on each side of the dipole; (Fig. 1) the lengths of the parasites are of the order of one-half that of the center dipole. This antenna was first studied at the Naval Research Laboratory by Dr. J. T. Bolljahn,* now of Stanford Research Institute. The data obtained in Dr. Bolljahn's investigation were not very extensive and no report was published. However, these data indicated that the antenna had good impedance characteristics over a broad band of frequencies.

The investigation described in this report is partly analytical, partly experimental. In Chap. 2 a theory is derived which provides a qualitative explanation of the impedance behavior of the open sleeve antenna. This theory is applied in Chaps. 3 and 4 to find the effect of varying the physical parameters of the antenna structure. These parameters are then adjusted in accordance with the theory to achieve a maximum bandwidth for several values of VSWR.

Since the theory is somewhat qualitative, the experimental investigation described in Chaps. 5 and 6 is necessary to obtain quantitative results. The theory, however, permits the experimental study to be conducted in a more systematic manner than could otherwise be done.

There are a sufficient number of easily varied design parameters in the open sleeve to allow a rather wide range of compromise between the VSWR and the bandwidth. Because of the close spacing and comparatively short lengths of the elements, this bandwidth is realized while still retaining the radiation pattern of a dipole. The simplicity of the design of this radiator permits the construction of a rugged antenna which, in view of the broadband impedance characteristics it is shown to have, should be adaptable to many uses.

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* J. T. Bolljahn, "Broad Band Antenna," Pat. No. 2505751 issued May 2, 1950.

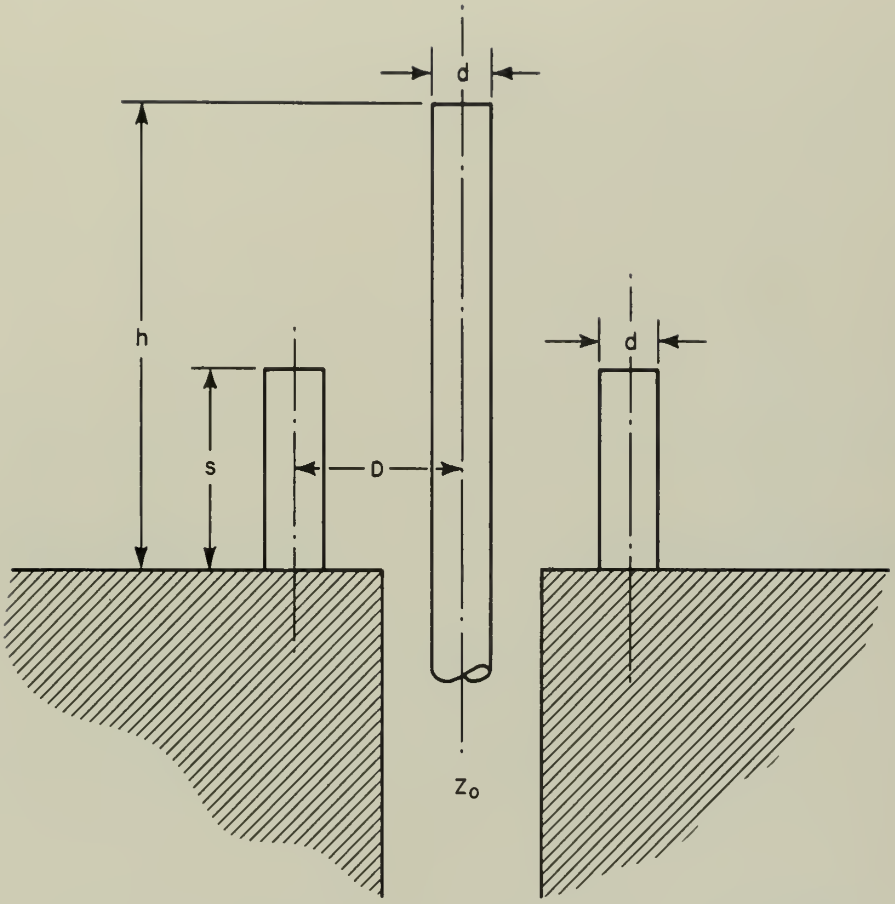

FIG. 1

DRAWING OF OPEN SLEEVE ANTENNA

CHAPTER 2

ANALYSIS AND BASIC THEORY

A. FUNDAMENTAL MODES OF OPERATION

The open sleeve antenna may be represented schematically as in Fig. 2(a), with the dipole element being driven against the ground plane by a generator V. An equivalent representation is that of Fig. 2(b), obtained by the superposition theorem. With

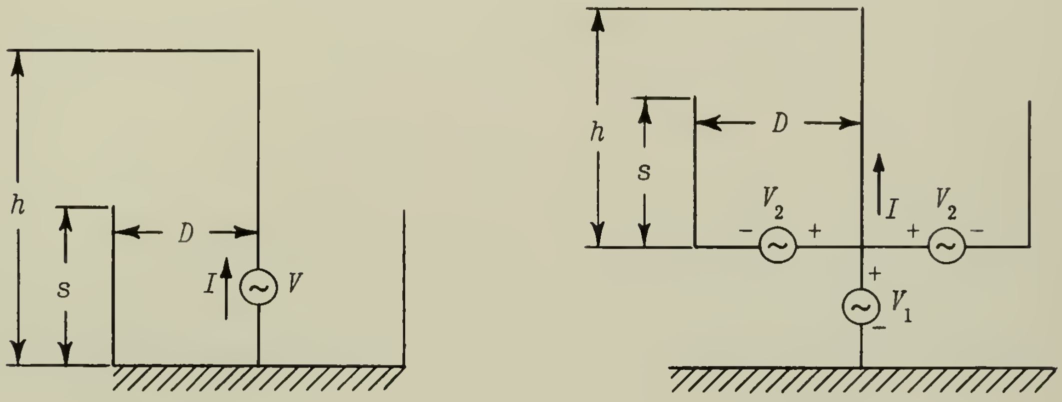

FIG. 2(a) FIG. 2(b)

SCHEMATIC DIAGRAMS OF OPEN SLEEVE ANTENNA

$$V_1 = V_2 = V \tag{1}$$

the dipole is still excited with a voltage V when the parasites are grounded, and the combination of V_1 and V_2 in opposition maintains the base of the parasites at ground potential. This latter manner of excitation permits the operation of the open sleeve to be broken down into two modes, an antenna mode and a transmission line mode. This procedure is similar to that employed by Roberts[1][*] with the folded dipole and modified by Bolljahn[2] for shunt excited cylinders. The problem here is somewhat more complex, however, since the effective termination of the transmission

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[*] References are listed at the end of the report.

line mode is not immediately obvious and the division of the antenna mode currents is difficult to determine theoretically. For the present, the nature of this termination and the current distribution may be ignored and an equivalent circuit derived for the open sleeve antenna in terms of the two fundamental modes of operation.

The driving point impedance is

$$Z_{in} = \frac{V}{I} \tag{2}$$

where I is the total current flowing into the base of the dipole. The current I may be broken down into two components, that contributed by the antenna mode, I_A, and that contributed by the transmission line mode, I_T. Then

$$I = I_A + I_T. \tag{3}$$

Generator V_1 excites the antenna mode, causing a current to flow which must divide among the three elements. If the impedance presented by the antenna mode to V_1 is called Z_A, the antenna mode current flowing into the base of the dipole is

$$I_A = \frac{V}{kZ_A}, \tag{4}$$

where k is a quantity introduced to account for the fraction of the total antenna mode current which flows into the dipole. Similarly, the transmission line mode current flowing into the dipole is

$$I_T = \frac{V}{Z_T} \tag{5}$$

where Z_T is the transmission line impedance presented to generators V_2. This, of course, implies a current of $I_T/2$ in each of the parasites.

Combining Eqs. (2) through (5) yields

$$Z_{in} = \frac{V}{I_A + I_T} = \frac{1}{\dfrac{1}{kZ_A} + \dfrac{1}{Z_T}} . \tag{6}$$

The driving point impedance is thus expressed as an impedance kZ_A in shunt with an impedance Z_T, as in Fig. 3. The next step is the evaluation of Z_A, k, and Z_T. This will be simplified by a consideration of the actual current distributions on the open sleeve antenna.

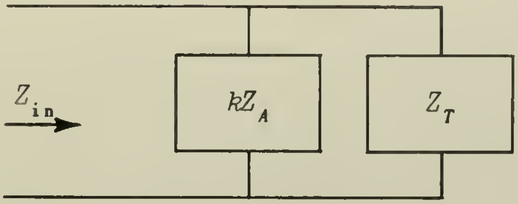

FIG. 3

EQUIVALENT CIRCUIT OF OPEN SLEEVE ANTENNA

B. APPROXIMATE CURRENT DISTRIBUTION

An approximation to the current distribution on the three elements of the open sleeve antenna may be obtained by analogy to the sleeve antenna. Taylor[3] gives experimental curves showing the current distribution on the outside of the sleeve and on the protruding part of the center dipole for various sleeve and dipole lengths. These currents correspond to the antenna mode, or to radiating currents in the open sleeve, with the restriction that the entire dipole of the open sleeve can radiate. Transmission line currents flow within the coaxial sleeve but do not correspond directly to the transmission line mode currents of an approximately open-ended line assumed in the open sleeve.

By analogy to the resulting distributions of total current on the sleeve antenna, the currents on the open sleeve become simply those which would be predicted for a dipole with two parasitic elements. Specifically, to a first approximation the resultant of assumed sinusoidal antenna and transmission line mode currents on the parasites is a sinusoidal current distribution of comparatively small magnitude. The resultant distribution on the dipole yields a variation from the sinusoid in the region of the parasites, as would be expected. More important, the total radiating, or antenna mode, current on the sleeve antenna is very nearly equivalent to the superposed effect of sinusoidal antenna mode currents on each of the three elements of the open sleeve antenna. It is this latter resolution which permits a reasonable evaluation of k and Z_A. It should be

noted however, that the resultant separation into antenna and transmission line modes on the open sleeve is not the same as that on the sleeve antenna because of radiating currents along the entire length of the dipole of the open sleeve antenna.

Another approach to the distribution of the antenna mode current is to note its similarity to the current on a single dipole whose lower half is of a larger diameter than the upper half. Because of the close spacing of the parasites in the open sleeve antenna, its behavior in an antenna mode will be quite similar to that of the dipole described. The current distribution on the dipole is sinusoidal in nature, with the magnitude of the sinusoid greater in the region of increased diameter, but with no discontinuity in current magnitude along the antenna. This is very nearly what the experimental current distribution of the sleeve antenna indicated for the antenna lengths of interest. Again, this type of current distribution may be represented on the open sleeve, to a first approximation, by currents on each element sinusoidally distributed from the ends.

C. EVALUATION OF Z_A

From the preceding discussion, it is clear that the antenna mode impedance, Z_A, should essentially be that of a dipole with the lower half of larger diameter than the upper half. In the open sleeve, as long as the spacing of the parasites from the dipole is not too great and the current flowing in the parasites is not too large, this impedance will not differ excessively from that of a uniform dipole. Since the spacings are to be kept electrically quite small, and the excitation of the parasites in the antenna mode relative to the dipole is not great, the impedance variation of Z_A will be assumed to be the same as that of the center dipole of the open sleeve. The values for this will be taken from King's[4] second order impedance curves for $\Omega = 10$. The antenna mode impedance, Z_A, is hence quite readily obtained.

D. EVALUATION OF k

Although the current in the parasites is small and does not have much effect on Z_A, the fact that one component of it comes from a shunting of part of the total antenna mode current must be accounted for in the determination of the driving point impedance. The quantity k has previously been introduced for this purpose. Since it has been shown that the

antenna mode current in each of the three elements may be considered sinusoidal from the ends, the evaluation of k simply requires the postulation of some relative magnitude between the sinusoids in the dipole and the parasites. It has also been stated that the current magnitude in the parasites is small. Accordingly, the peak value of the current sinusoid in each parasite is chosen as one-fourth that in the dipole. Admittedly the theoretical justification for this specific choice is somewhat weak. However, it turns out that the dependence of the driving point impedance upon the choice of the relative sizes of the current sinusoids is not at all critical, and the particular choice made gives the best agreement between theoretical and experimental values obtainable with this simple theory.

Proceeding on this basis, then, with I_m representing the peak value of the current distribution on the dipole, $I_m/4$ representing the peak value of the current on each parasite, and I_{Ap} representing the base current on each parasite,

$$I_A = I_m \sin \beta h \tag{7}$$

and

$$I_{Ap} = \frac{I_m}{4} \sin \beta s \tag{8}$$

since

$$I_A = \frac{V}{Z_A} - 2I_{Ap} , \tag{9}$$

and, from Eq. (4)

$$\frac{V}{Z_A} = kI_A ,$$

$$k = \frac{I_A + 2I_{Ap}}{I_A} \tag{10}$$

Substituting Eqs. (7) and (8) in Eq. (10),

$$k = 1 + \frac{|\sin \beta s|}{2|\sin \beta h|} . \tag{11a}$$

The absolute value signs are used to keep k always greater than unity, in other words, the base currents in parasites and dipole are always approximately in phase because of the extremely close coupling between elements. Since sinusoidal currents were postulated, this evaluation of k does not apply for frequencies in the region where $|\sin \beta h| = 0$ (i.e., for $\beta h = \pi$), but this limitation is of little concern.

For frequencies greater than for $\beta h = \pi$, a somewhat better approximation for k may be made on the basis of King's[4] theoretical current distribution curves by noting that the base current on an antenna is closely approximated by assuming a sinusoidal current distribution, but with the effective electrical length 0.5 rad longer than the actual electrical length. This gives for k, with $\beta h > \pi$

$$k = 1 + \frac{|\sin \beta s|}{2|\sin(\beta h + 0.5)|} . \qquad (11b)$$

E. EVALUATION OF Z_T AND EFFECTIVE LOADING

The only complications in the evaluation of the transmission line mode impedance are the length and termination of the transmission line. Although this mode is excited with antisymmetrical currents at its driving point, it does not follow that the line terminates with an open circuit at the end of the sleeve, since the center conductor extends beyond the sleeve. It will be shown, however, that Z_T may be evaluated to a good approximation by considering the transmission line to be of length s (Fig. 2) plus normal fringing, with a resistive termination to account for all radiation and losses of the transmission line.

Since the total current on the parasites is the resultant of currents from the antenna and transmission line modes, the vanishing of the antenna mode current at the ends of the parasites also requires the vanishing of the transmission line mode current, which implies an open circuited transmission line. However, it is apparent that a three-wire transmission line in which all three conductors do not terminate at the same point has some radiation. This radiation may be attributed to the presence of higher order modes existing on the transmission line, primarily near the end, which do not directly affect the driving point impedance Hence, the current of the dominant mode does not entirely vanish at the end of the line, but must assume such a value that the total transmission line mode current

vanishes. The effect of the higher order modes and radiation may then be accounted for in a manner similar to that employed by Schelkunoff[5] with the biconical antenna. The dominant mode may be assumed to be terminated at the end of the line, in the impedance necessary to match the current required to flow at the ends to cancel that from the higher order modes. If the amount of radiation is small, which is the case for closely spaced parasites, the currents of the higher order modes are quite small, and the deviation of the transmission line from the open circuited condition may be accounted for by a large resistive termination. The value of Z_T is then merely the terminal resistive impedance, Z_{Tt}, transformed along a lossless three-wire transmission line to the driving point. The characteristic impedance, Z_{OT}, of the three-wire transmission line is given by a formula derived by Duncan[6]

$$Z_{OT} = 207 \log\left(\frac{2}{2^{\frac{1}{3}}}\,\frac{D}{d}\right) . \tag{12}$$

It is probably possible to compute a theoretical value for Z_{Tt}, but this computation would be rather involved. Inasmuch as this theory must be relatively simple if it is to yield any significant amount of quantitative or qualitative results, it is more practical to establish an empirical value for Z_{Tt} for some average case and then let it vary in accordance with theory. The value chosen for a specific case is given in Chap. 3. Only the nature of its variation needs to be discussed at this point.

Since the losses from the transmission line mode are associated with radiation from the end of a transmission line, radiation along a transmission line, and radiation of a short antenna, the variation of the terminal impedance should be of the same type as that of radiation under the above conditions. The radiation from the end of a coaxial cable is approximately proportional to the fourth power of the electrical spacing; with a two- or three-wire transmission line, since circular symmetry is not present, it is reasonable to consider that radiation from the end would be roughly proportional to the square of the electrical spacing. Radiation from a two-wire transmission line is shown by Storer and King[7] to be proportional to the square of the electrical spacing. Additionally, radiation of a short antenna is approximately proportional to the square of the electrical length or frequency. Therefore, the variation of the terminal loading of the transmission line mode is taken as proportional

to the square of the frequency or the electrical spacing of the parasites; or the terminal resistance Z_{Tt}, is inversely proportional to the square of the electrical spacing or the frequency. Any variation in the end loading with parasite length for a fixed frequency and spacing is neglected.

F. LIMITATIONS OF THEORY

Most of the cases where the application of the theory fails have been mentioned in the discussion of the various quantities involved. A brief recapitulation of the essential limitations is given here.

When the dipole length becomes materially greater than a half wavelength, or the electrical spacing of the parasites becomes too great, departure of the current distributions from those assumed causes errors in k and Z_A. Too great an electrical spacing of the parasites causes errors in Z_A, and in the variation and nature of Z_{Tt}. The formula for k is not applicable for dipole lengths very close to a half wavelength. When these restrictions are observed, the theory provides a reasonably good and easily calculated representation of the driving point impedance of the open sleeve antenna. Quantitative comparisons between theoretical and experimental values are given in Chap. 3.

CHAPTER 3

APPLICATION OF BASIC THEORY AND THEORETICAL RESULTS

A. QUALITATIVE PREDICTIONS FROM THEORY

With the theory for the open sleeve antenna developed in Chap. 2 it is possible to describe qualitatively the expected behavior of the antenna and the effects of variation of the design parameters. The results are most readily discussed in terms of the shape of the driving point impedance curves on the Smith chart.

The frequency range of interest, and the range over which the theory is generally applicable, is from frequencies somewhat below resonance to somewhat above antiresonance, corresponding to lengths of the dipole above a ground plane from somewhat less than a quarter wavelength to somewhat greater than a half wavelength. The basic impedance to be modified is that of the dipole and is identical to that used for Z_A. Its locus is the familiar one of a large, approximately circular curve. The addition of the two short parasites, by magnifying Z_A through multiplication by k, and by shunting with a resistive loaded transmission line impedance, causes the driving point impedance curve to break away from Z_A and make a small loop through the region of low VSWR, at frequencies near the resonant frequency of the transmission line. The size and general location of the loop can be controlled primarily by a variation of the shunting impedance of the transmission line mode, since the amount by which the impedance deviates from Z_A is inversely related to the magnitude of Z_T.

A change in the spacing of the parasites or in the diameters of the three elements causes a change in Z_{0T}, the mode characteristic impedance, for the transmission line and in Z_{Tt}, the quantity representing the transmission line mode losses and radiation. A reduction of the spacing or an increase in element diameters decrease Z_{0T} and increase Z_{Tt}. The decrease of Z_{0T} causes the values of Z_T to be of smaller magnitude, while the reduction of the losses gives a smaller value of input resistance at the resonant frequency of the transmission line. Since Z_T is capacitive

below resonance and inductive above, the net effect of the increased shunting is to enlarge the impedance loop and cause a general capacitive shift.

The length of the parasites controls the length of the transmission line and, hence, the frequency at which resonance occurs or the range of frequencies over which the shunting by Z_T is effective. With the longer lengths resonance is reached at low frequencies, and the impedance loop is small and covers a somewhat restricted frequency range, although the VSWR is quite low and has little variation over this range. With shorter parasites, resonance is not reached until higher frequencies; the impedance loop is much larger in size and covers a wide frequency range. The variation of VSWR is greater through the frequency range.

B. COMPUTATIONS AND CURVES FROM THEORY

The theory developed allows the numerical computation of driving point impedance over a wide range of conditions. Calculations have been carried out for several cases for which some experimental data were available before the theory was developed. It was these data which permitted the establishment of a proper average value for Z_{Tt}, as discussed in Sec. E of Chap. 2. The particular antenna dimensions chosen and cases investigated theoretically and experimentally were picked because of the simplicity of construction of models for a convenient frequency range. They also covered a range of values which includes most of the conditions that appeared promising.

The physical dimensions for the cases considered theoretically under the theory are, (see Fig. 1)

$$D = 1 \text{ in.} \qquad h = 22 \text{ cm}$$

$$d = \frac{1}{4} \text{ in.} \qquad s = 0,\ 9,\ 11, \text{ and } 13 \text{ cm},$$

and

$$D = \frac{1}{2} \text{ in.} \qquad h = 22 \text{ cm}$$

$$d = \frac{1}{4} \text{ in.} \qquad s = 11 \text{ cm}$$

The frequency range is approximately 250 to 800 Mc. The basic value

chosen for Z_{Tt}, which is used as the reference for the other computed values, is

$$Z_{Tt} = 500 \text{ ohms}, \qquad \text{for} \quad f = 600 \text{ Mc}, \ \frac{D}{d} = 4 .$$

All impedances are normalized to 67 ohms.

The above conditions yield the impedance data shown in Figs. 4 and 5. The behavior predicted in Sec. A is clearly demonstrated in these curves. For the 1-in. spacing the shorter lengths of parasites give the largest impedance loops over the widest frequency range, but the variation of VSWR is rather marked. On the other hand, the longer parasites give a small impedance loop over a somewhat restricted frequency range, but the variation of VSWR is much less. When spacing is reduced to 1/2 in., the impedance curve shifts capacitively and toward smaller impedance values, with a resulting enlargement of the loop from the case of the corresponding parasite length at 1-in. spacing. The variation of Z_A is plotted as a reference for both cases.

VSWR as a function of frequency is plotted in Fig. 6 for the case of 1-in. spacing. These values are taken directly from the impedance curves, with extrapolation for higher frequencies, but show somewhat more vividly the nature of the variation of VSWR. It is clear that the larger the maximum value of VSWR which can be permitted, the greater the bandwidth which can be achieved. It is also interesting to note that the effect of the parasites is to cause a second dip in the VSWR vs. frequency curves as compared to the single sharp dip which is characteristic of the dipole.

To indicate the type of accuracy achievable with this theory, theoretical and experimental results for 11-cm parasites are plotted on the same Smith chart; Fig. 7 is for 1-in. spacing, and Fig. 8 for 1/2-in. spacing. Although the agreement is not particularly good, the trends in the impedance curve are clearly shown. The discrepancy is the greatest for frequencies over 600 Mc, as anticipated in the theoretical development; there is also a capacitive shift in the theoretical curves. The agreement, however, is sufficient to show qualitatively the effect of varying the physical parameters of the antenna.

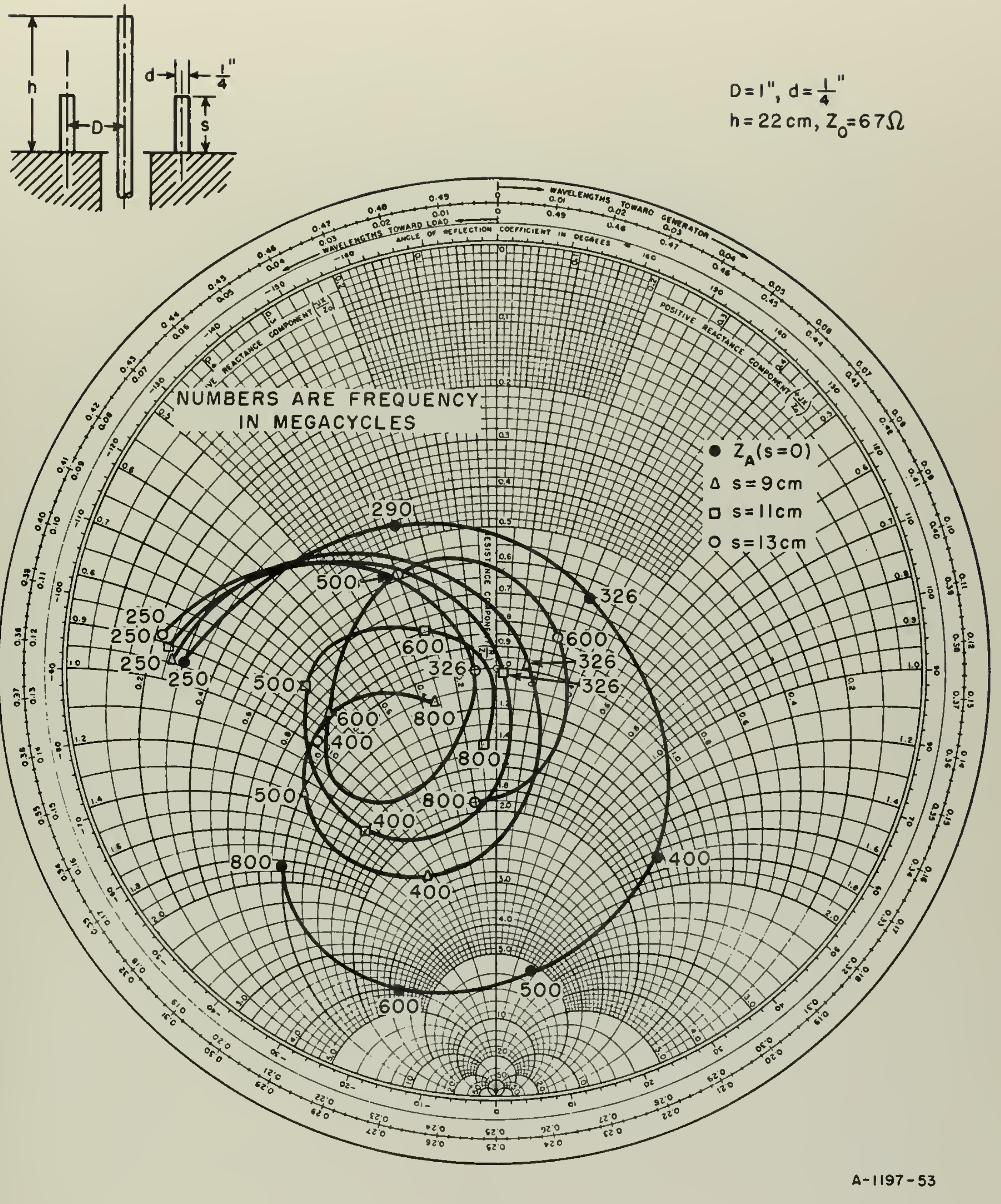

FIG. 4

THEORETICAL DRIVING POINT IMPEDANCE OF OPEN SLEEVE ANTENNA WITH PARASITES SPACED 1 INCH FROM DIPOLE

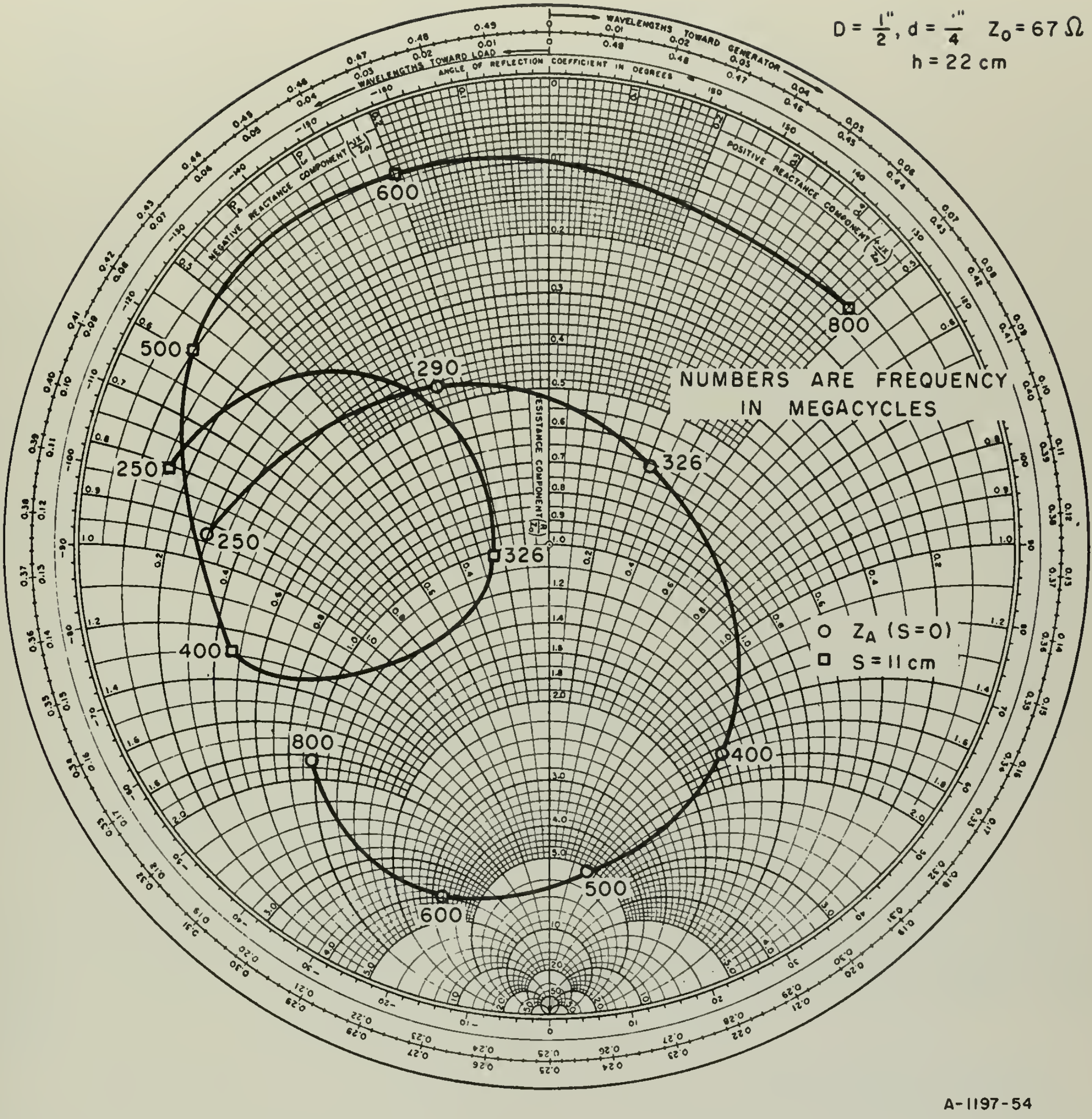

FIG. 5

THEORETICAL DRIVING POINT IMPEDANCE OF OPEN SLEEVE ANTENNA WITH PARASITES SPACED 1/2 INCH FROM DIPOLE

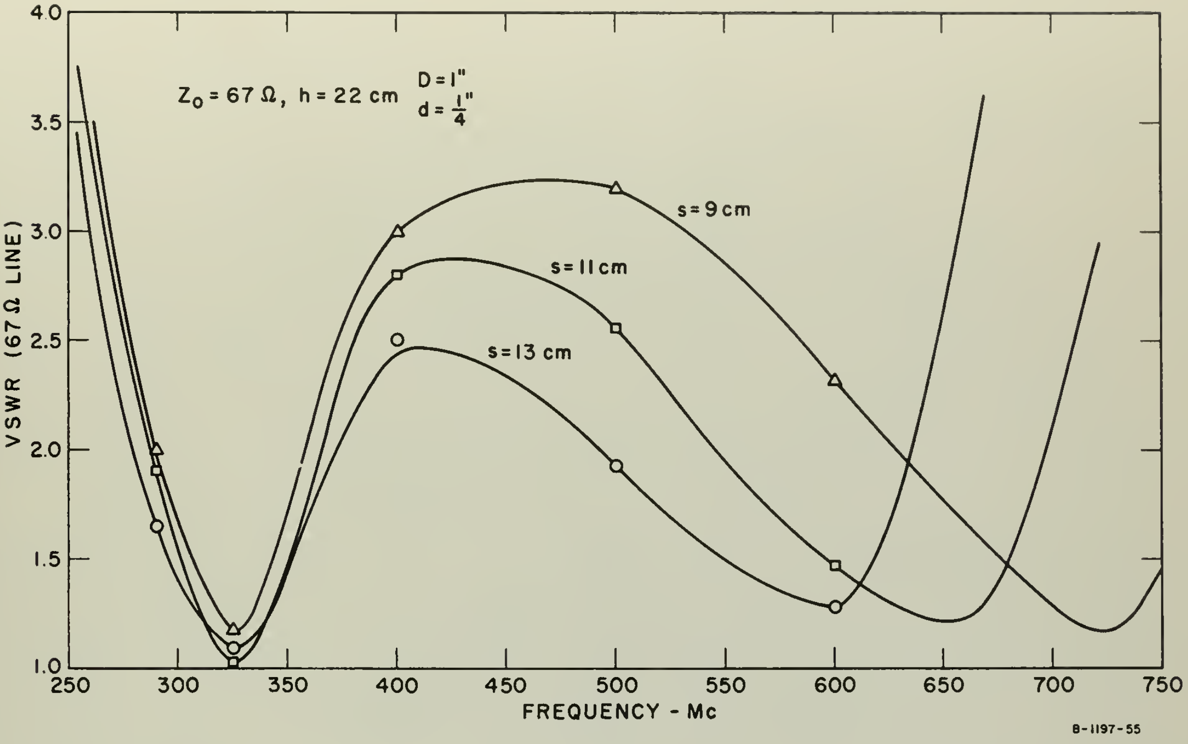

FIG. 6

THEORETICAL VSWR ON 67-OHM LINE FOR OPEN SLEEVE ANTENNA WITH PARASITES SPACED 1 INCH FROM DIPOLE

C. METHODS FOR IMPROVING THEORETICAL RESULTS

The several improvements which could be made in the theoretical computations are evident from the discussion of the limitations of the theory in Chap. 2. There are a few minor changes that would improve the theory, however, which will be mentioned here.

Above 600 Mc, Z_{T_t} no longer decreases at a rate inversely proportional to the square of the frequency. Therefore, if a larger value for Z_{T_t} were used at 800 Mc, for example, the impedance would be improved; however, the choice of this value would have to be somewhat arbitrary, and any positive theoretical justification would be difficult to establish. To maintain the theory in the form that suffices for the lower frequency calculations, Z_{T_t} is retained as it has been described.

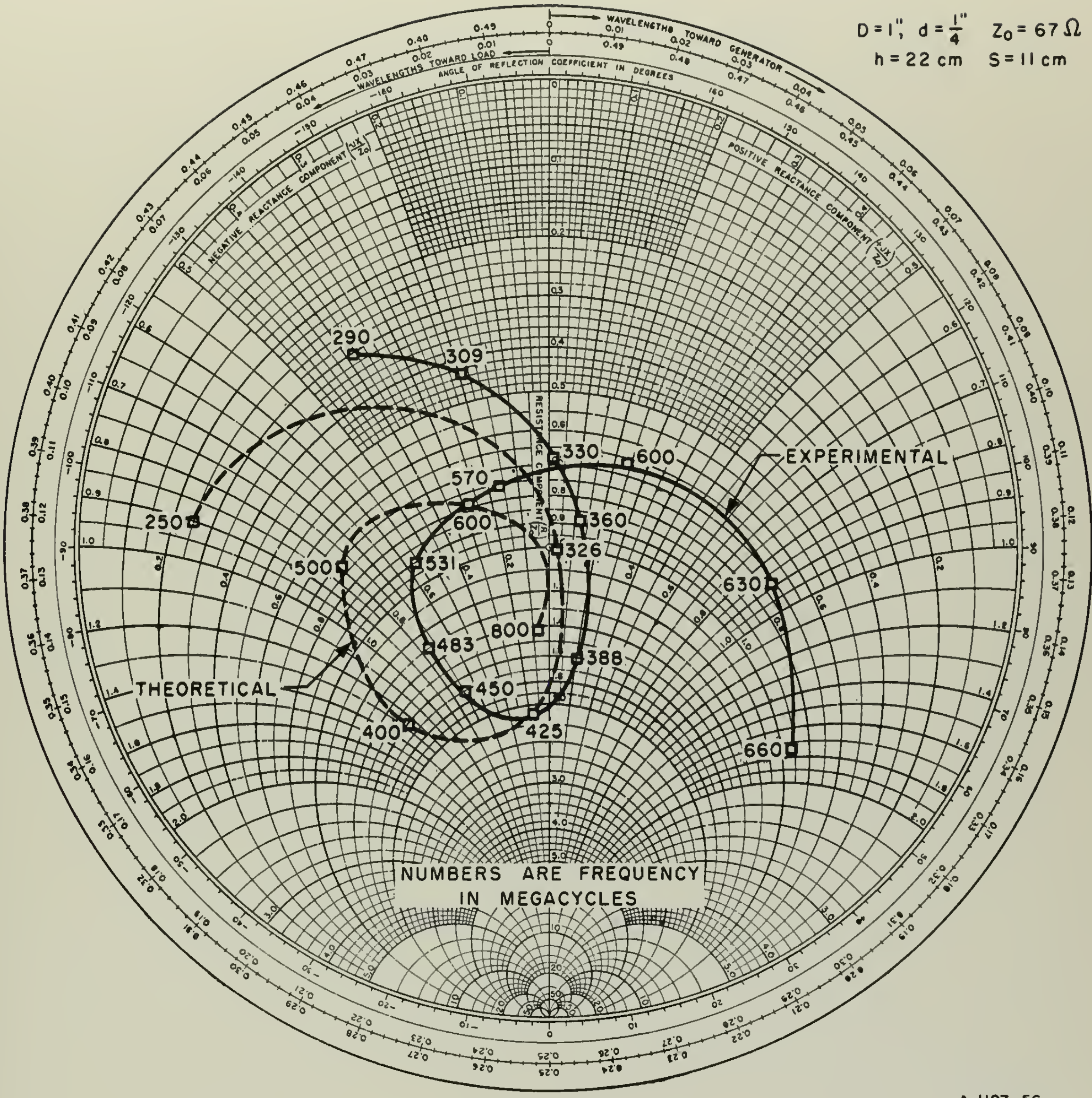

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FIG. 7

COMPARISON OF THEORETICAL AND EXPERIMENTAL DRIVING POINT IMPEDANCES OF OPEN SLEEVE ANTENNA WITH PARASITES SPACED 1 INCH FROM DIPOLE

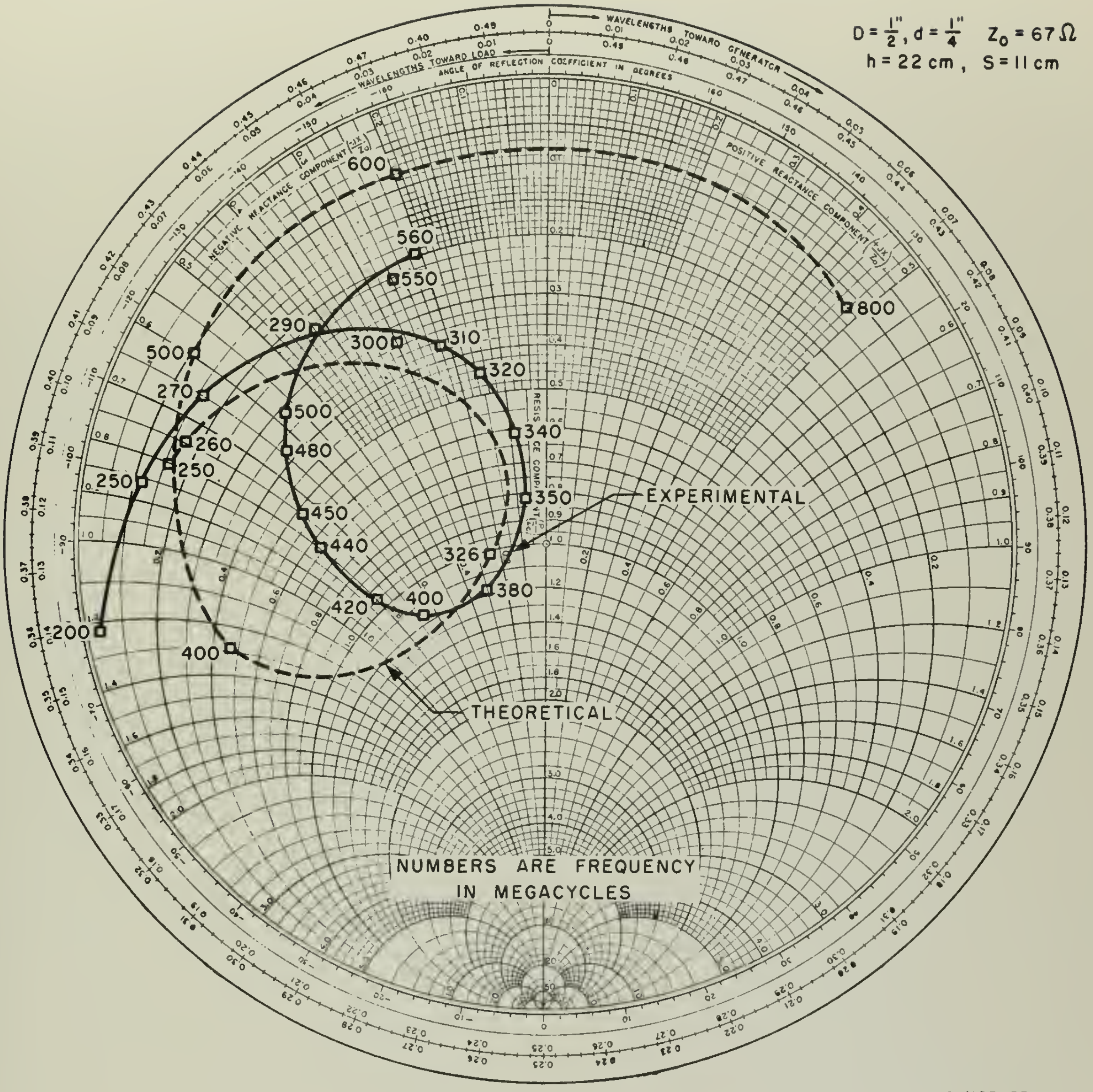

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FIG. 8

COMPARSISON OF THEORETICAL AND EXPERIMENTAL DRIVING POINT IMPEDANCES OF OPEN SLEEVE ANTENNA WITH PARASITES SPACED 1/2 INCH FROM DIPOLE

Although it was implied in the theoretical development for Z_T that the normal fringing effect on a transmission line would be included in the computations, it was neglected for these theoretical curves. Inclusion of this effect would slightly improve the data.

A reduction in the small capacitive shift of the theoretical curves relative to the experimental curves could be achieved by the use of values for Z_A nearer the experimental impedance for the dipole. The theoretical values are somewhat larger than the corresponding experimental ones, allowing the capacitive shunting by the transmission line mode to be somewhat more pronounced than it would be for lower Z_A. However, the second order impedance curves of King [4] are about as good theoretical values as can be obtained. Hence there is little justification for going to other values in a theoretical treatment, though notice can be taken of the differences.

CHAPTER 4

EXTENSION OF THEORY TO GENERAL CASE OF UNEQUAL SPACINGS AND UNEQUAL LENGTHS OF PARASITES

A. RELATIONS BETWEEN THREE-WIRE AND TWO-WIRE TRANSMISSION LINES

An extension of the theory to include the cases of unequal spacings and unequal lengths of parasites necessitates a means of treating the effects of the parasites separately. This requirement leads to a consideration of relationships between three-wire and two-wire transmission lines.

The fields of the dominant TEM wave on a transmission line are conveniently examined by reference to the static field distributions along the line. If the static electric field along a two-wire line is considered, it would not be expected that the introduction of a third wire in the same plane, a distance away equal to the spacing of the other two and carrying an opposite charge to the adjacent wire, would appreciably change the original field distribution between the two wires. This is particularly true if the diameter of the center wire is increased to maintain approximately the same surface charge density. (This presupposes, of course, a source of charge on each of the wires so that the net charge on the three wires is zero.) That is, the result is very nearly the superposition of the fields of two similar two-wire lines, where the wires of like polarity coincide, with negligible distortion of the original fields. This is equivalent to saying that the charge distribution on the two wires is unaltered by proximity to another two-wire line in the same plane, with wires of like polarity adjacent. This consideration leads to the concept of a three-wire line as the superposition of two two-wire lines. In order to extend the analogy to the case of a three-wire line with equal diameter conductors, it is apparent that the two-wire lines must consist of conductors of different diameters. Figure 9 illustrates this concept. Then, if the coupling between the two transmission lines is neglected, and insofar as the above relationship remains valid, the two parasites of the open sleeve may be treated independently, and in any case as two.wire lines excited in shunt.

The mathematical justification for this relationship is rather simply indicated. An extension of the conformal transformation method of obtaining a solution to Laplace's equation for the case of three coplanar line charges yields the transformation

$$W = b \ln \frac{Z^2}{(Z - 2a)(Z + 2a)} . \tag{13}$$

This is the direct superposition of a pair of two line charges, with two lines of like polarity coincident at the origin and the other two lines located at ±$2a$. The question is, what are the equipotential surfaces and how much do they differ from those of the individual two-wire cases? The condition to be satisfied in choosing equipotentials to represent the three-wire line as two independent two-wire lines in shunt is simply that the voltage difference between the two-wire lines be the same as that

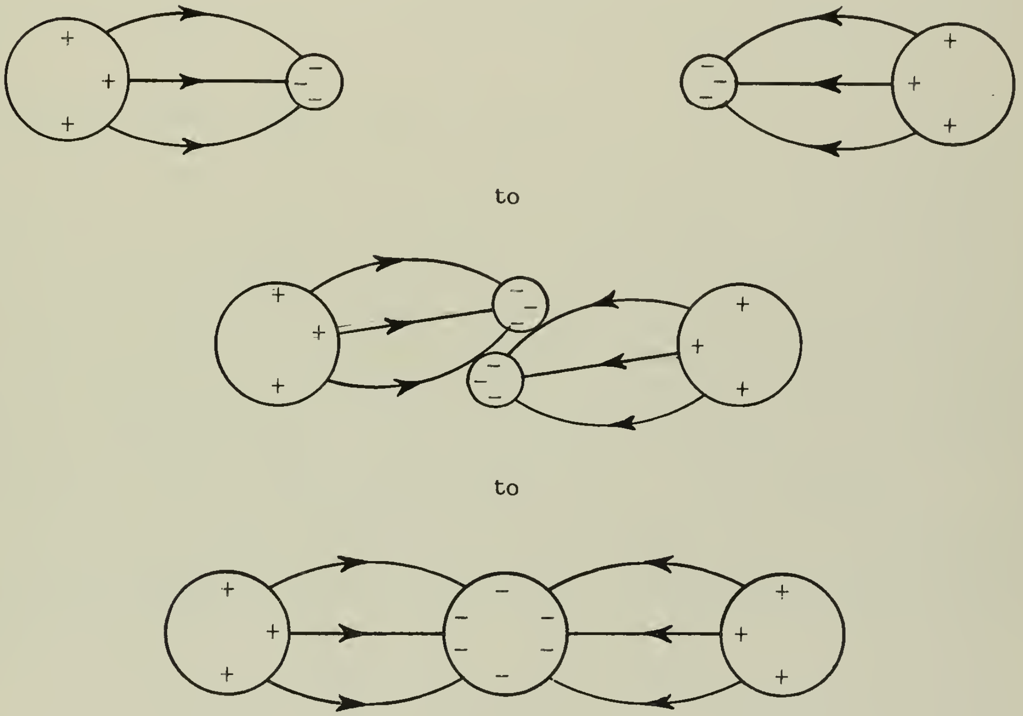

FIG. 9

EQUIVALENCE OF TWO-WIRE AND THREE-WIRE TRANSMISSION LINES

between conductors of the three-wire line. Under this condition, it turns out that the equipotential surfaces near the outer charges are nearly circles while those around the center charge are elliptical. The elliptical shape results from the non-coincidence of the center of the equipotential circles from the separate two-wire lines when the line charges do coincide. Thus, the direct superposition of two-wire lines does not result in the three-wire case except in the limiting case of line charges. However, if the spacing between conductors is not too small compared to their diameter, a reasonably good approximation to cylindrical conductor three-wire lines may be had. Knowledge of the precise nature of the breakdown of the three-wire line is actually not required, merely an indication of the degree of isolation existing between the two-wire lines, and their physical form.

B. GENERALIZED EQUIVALENT CIRCUIT

If the effect of the two parasites on the open sleeve antenna is separated into the effects produced by each parasite independently, by using the relationship described between the two-wire and three-wire transmission lines, an equivalent circuit results which is less restricted in its applicability than that of Fig. 3. The behavior of a dipole with a single parasite, or with two parasites of unequal length or unequal spacing may be explained. This extension is desirable for a broader investigation of the possibilities of the open sleeve antenna.

Withe the transmission line mode expressible as two transmission line modes in shunt, the equivalent circuit obviously becomes that of Fig. 10.

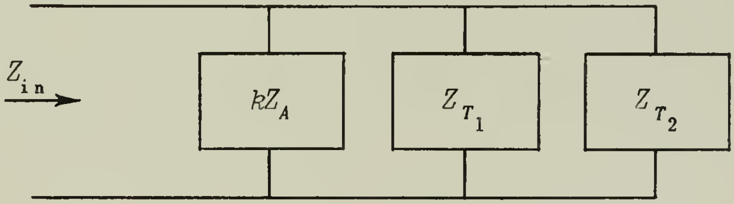

FIG. 10

GENERALIZED EQUIVALENT CIRCUIT FOR OPEN SLEEVE ANTENNA

C. EVALUATION OF GENERALIZED TRANSMISSION LINE MODE PARAMETERS

Where there are parasites equally spaced but of unequal length, there is a discontinuity in the longer transmission line at the point where the shorter line ends. This discontinuity may effectively be attributed to a change in diameter of one of the conductors, since it was shown that the two-wire lines equivalent to the three-wire line consist of elements of unequal diameter. Alternatively, the discontinuity may be explained by a change in the coupling effect of the shorter line on the longer line, since practically the coupling terminates at the end of the shorter line. The calculation of the specific diameter required for the smaller element, or determination of the exact nature of the discontinuity may be avoided by taking the characteristic impedance of each line in the region where both are present to be twice the characteristic impedance of the three-wire line. In the region where only the longer line exists, the characteristic impedance for a two-wire line of equal diameter elements may be computed directly.

For parasites with unequal spacings, the characteristic impedance of the individual lines may be obtained as a logarithmic variation from that of the equally spaced case, since characteristic impedance is proportional to the logarithm of a constant times D.

The reference value for effective loading on the end of each line, $Z_{T_{t1}}$ and $Z_{T_{t2}}$, is most conveniently obtained from the value for the three-wire line, with the division of magnitude determined in the same manner as for the characteristic impedance. This method introduces some error, since even for equal spacings the radiation and losses from lines with one conductor of variable length are somewhat dependent upon the variable length. However, inclusion of this effect would be exceedingly difficult. The variation of the loading impedance will be the same as for the three-wire case—inversely with the square of the electrical spacing or the frequency.

The computation of Z_{T1} and Z_{T2} with the above values determined is a straight application of transmission line theory. It should be noted also that these values cause the generalized equivalent circuit to reduce to the previously developed basic equivalent circuit when the parasites are of equal length and equally spaced; (i.e., $Z_{T1} = Z_{T2} = 2Z_T$).

D. EVALUATION OF GENERALIZED VALUE FOR k

A more general expression for k must be derived to use with parasites of unequal length. Since no account was taken previously of the effect of spacing upon k, there is no need to consider any change caused by unequal spacing of elements.

With s_1 and s_2 representing the two parasite lengths, and using a procedure entirely analogous to that originally used for k, the general expression for k becomes,

$$k = 1 + \frac{|\sin \beta s_1| + |\sin \beta s_2|}{4|\sin \beta h|} \qquad (f < 600 \text{ Mc})$$

$$k = 1 + \frac{|\sin \beta s_1| + |\sin \beta s_2|}{4|\sin(\beta h + 0.5)|} \qquad (f > 600 \text{ Mc}) \tag{14}$$

This reduces to the case for a single parasite when $s_2 = 0$.

E. USE OF A SINGLE PARASITIC ELEMENT

The qualitative behavior of an open sleeve antenna with a single parasite can be discussed from the theory without actually carrying out theoretical computations. One case is calculated to illustrate the predictions.

With the single parasite, the characteristic impedance for the two-wire line is about 1.5 times that for the three-wire line with the same parasite spacing. The normalized end loading is taken to be the same as for the three-wire case, since the end loading is changed in the same proportion as the characteristic impedance. The normalized value of the transmission line mode impedance is thus the same, but the impedance itself is 1.5 times as large. Hence, the shunting effect of the transmission line impedance, Z_T, is reduced. Actually, the specific change in end loading is somewhat indefinite, since the relative predominance of the three types of losses previously described is not apparent. The radiation from the end of a two-wire line should be greater than from a three-wire line. On the other hand, the total radiation from the unbalanced two-wire line might well be less than from the three-wire line.

Later experiment did show the VSWR to behave essentially as predicted, so that the assumption used appears substantiated.

Z_A varies the same as for the two-parasite case, but kZ_A is reduced by the smaller value of k, since there is only one element into which the base current can be shunted from the center dipole.

The resulting driving point impedance should then follow more nearly the curve of Z_A. Some broadbanding effect would be anticipated as the curve breaks somewhat away from Z_A, but the useful range would not be so great as with two parasites. In terms of standing wave ratio, the first dip should be somewhat broader than for the dipole, but the second dip should either be completely eliminated or materially reduced. Thus the single parasite, though physically simpler, is not as effective as two parasites.

If an attempt is made to increase the effect of the single parasite by reducing the spacing, thus decreasing Z_{OT} and the shunting impedance of the transmission line mode, the smaller impedance magnitude and capacitive shifts are present as in the case of two parasites. These shifts result from the decrease in loading on the transmission line with the decreased spacing. This case is illustrated in Fig. 11, where theoretical values have been plotted for a single parasite, with

$$D = \frac{1}{2} \text{ in.} \qquad h = 22 \text{ cm}$$

$$d = \frac{1}{4} \text{ in.} \qquad s = 11 \text{ cm}$$

The computations for this case do include the fringing effect of the transmission line. The curves are plotted normalized to 50 ohms since all measurements except the very first ones for equally spaced parasites of equal length were taken on a 50-ohm slotted line.

For marked broadband operation, at least two parasites are required for the open sleeve antenna.

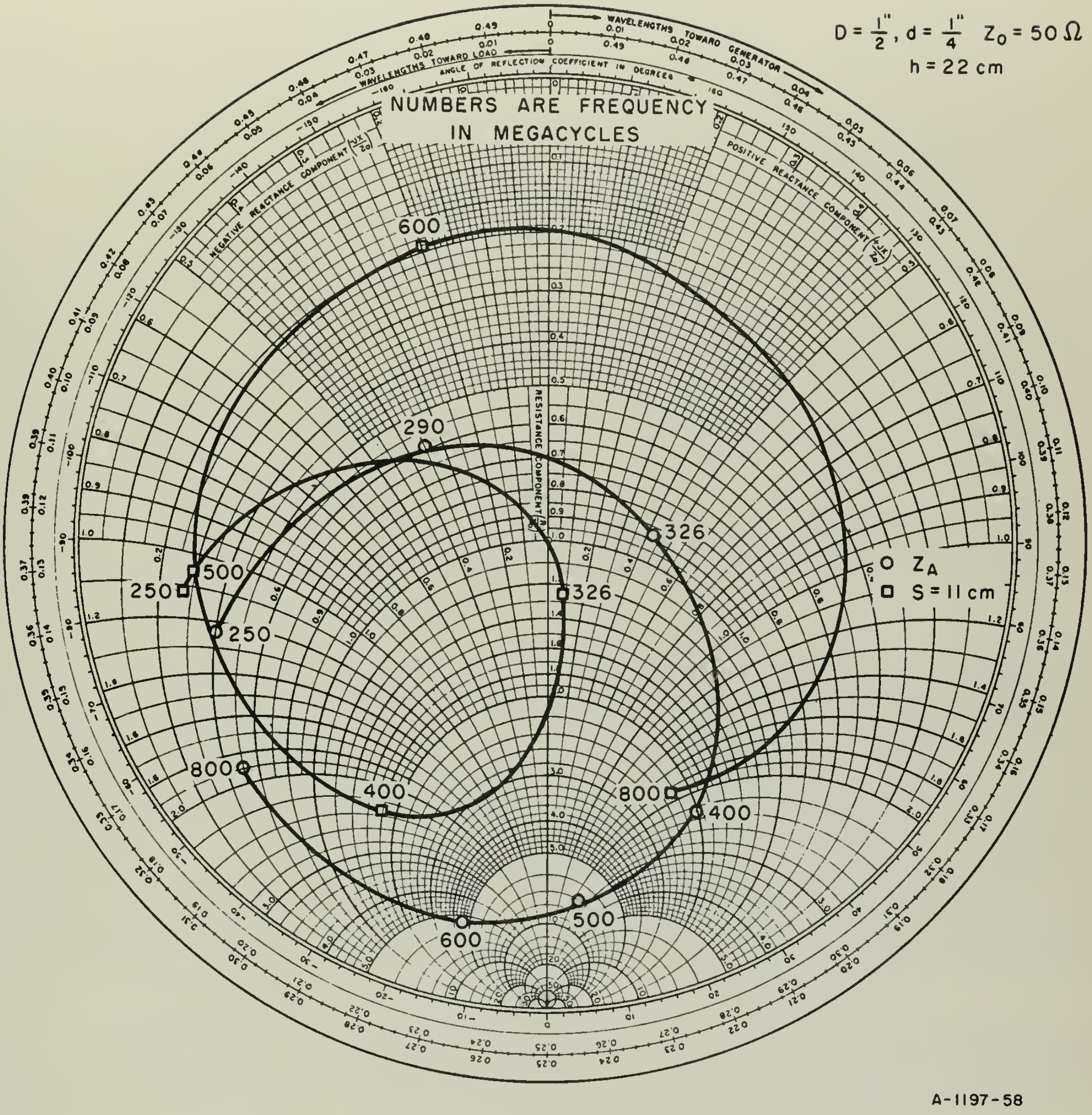

FIG. 11

THEORETICAL DRIVING POINT IMPEDANCE OF OPEN SLEEVE ANTENNA WITH SINGLE PARASITE SPACED 1/2 INCH FROM DIPOLE

F. USE OF TWO PARASITES OF UNEQUAL LENGTH WITH EQUAL SPACINGS

The use of two parasites of unequal length but equal spacing is discussed, not just because it is one of the various possible arrangements for the open sleeve antenna, but rather because there are considerations which suggest its superiority over the equal length cases. The Smith chart impedance plot shows that with equal length elements a fairly severe increase in VSWR must be accepted near the middle of the frequency band if wide bandwidth is desired. On the other hand, this hump in the VSWR curve can be made rather small if the frequency band may be restricted. The behavior of the VSWR vs. frequency curves thus resembles very closely that of the impedance curves for two tuned, coupled, low frequency circuits. The procedure which thus suggests itself is the use of parasites with different lengths to correspond to the low frequency case of triple tuned, coupled circuits. If one of the shorter parasites can be used to give the general folding desired of the Z_{in} locus, a longer element may be able to cause a reduced hump of the VSWR or perhaps a double hump. This approach appears quite intriguing and warrants thorough investigation.

There is one point of caution which must be observed in pursuing this analogy. In the open sleeve antenna there can be significant interchange of energy between all three elements and various modes set up, as the theoretical analysis implies. Specifically, the problem of concern is the possible excitation of a mode between the two transmission lines at a frequency where the longer line is inductive and the shorter capacitive, yielding an antiresonant condition with a high antiresonant impedance. The magnitude of this impedance is a function of the Q of the transmission lines, or of the ratio of energy stored to energy dissipated.

To investigate the theoretical behavior of the open sleeve with elements of unequal length, computations by the methods previously explained were carried out for the following conditions, (see Fig. 12)

$D_1 = D_2 = 1$ in. $\qquad s_1 = 13$ cm

$d = \frac{1}{4}$ in. $\qquad s_2 = 9$ cm

Fringing effects were considered, and driving point impedance is normalized to 50 ohms. The results are shown in Fig. 13.

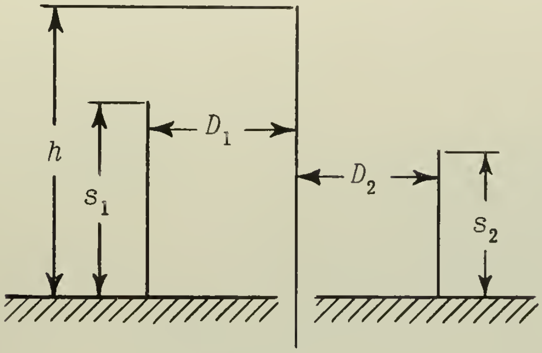

FIG. 12
SCHEMATIC DIAGRAM OF GENERALIZED OPEN SLEEVE ANTENNA

The theoretical results indicate a substantial improvement in the performance of the open sleeve antenna for the above case. Unfortunately, however, experiment does not bear out the entire range of theory very well. The problem of the antiresonant mode between the shunt-excited transmission lines is actually far more evident than the theory predicts, as may be seen by reference to the experimental data in Chap. 6. On the other hand, the variation of the impedance at the lower frequencies is fairly accurately predicted, and detailed consideration of the calculation procedures and the theoretical assumptions made permits the behavior at the higher frequencies to be explained qualitatively quite well. In fact, the theory is fully adequate for indicating the types of changes which can lead to the optimum performance of the antenna with unequal parasites. A discussion of these various methods is the subject of the next section.

G. METHODS OF IMPROVING PERFORMANCE OF OPEN SLEEVE ANTENNA WITH UNEQUAL LENGTHS, UNEQUAL SPACINGS OF PARASITES

The problem involved in the improvement of the performance is the removal, reduction, or shifting of the transmission line antiresonant effect from the frequency band of interest while leaving undisturbed the satisfactory low frequency performance. The complete removal of the antiresonant effect through the use of unequal length parasites is impractical. Furthermore, although a reduction in the magnitude of the antiresonant impedance is definitely practical, there is a question of the degree of improvement possible. Shifting the antiresonant frequency may also be accomplished, although there is a limit to how much the frequency can be changed while still retaining the low frequency characteristics of the antenna. The following changes to accomplish these improvements are ones which were tried because the theory indicated their propriety.

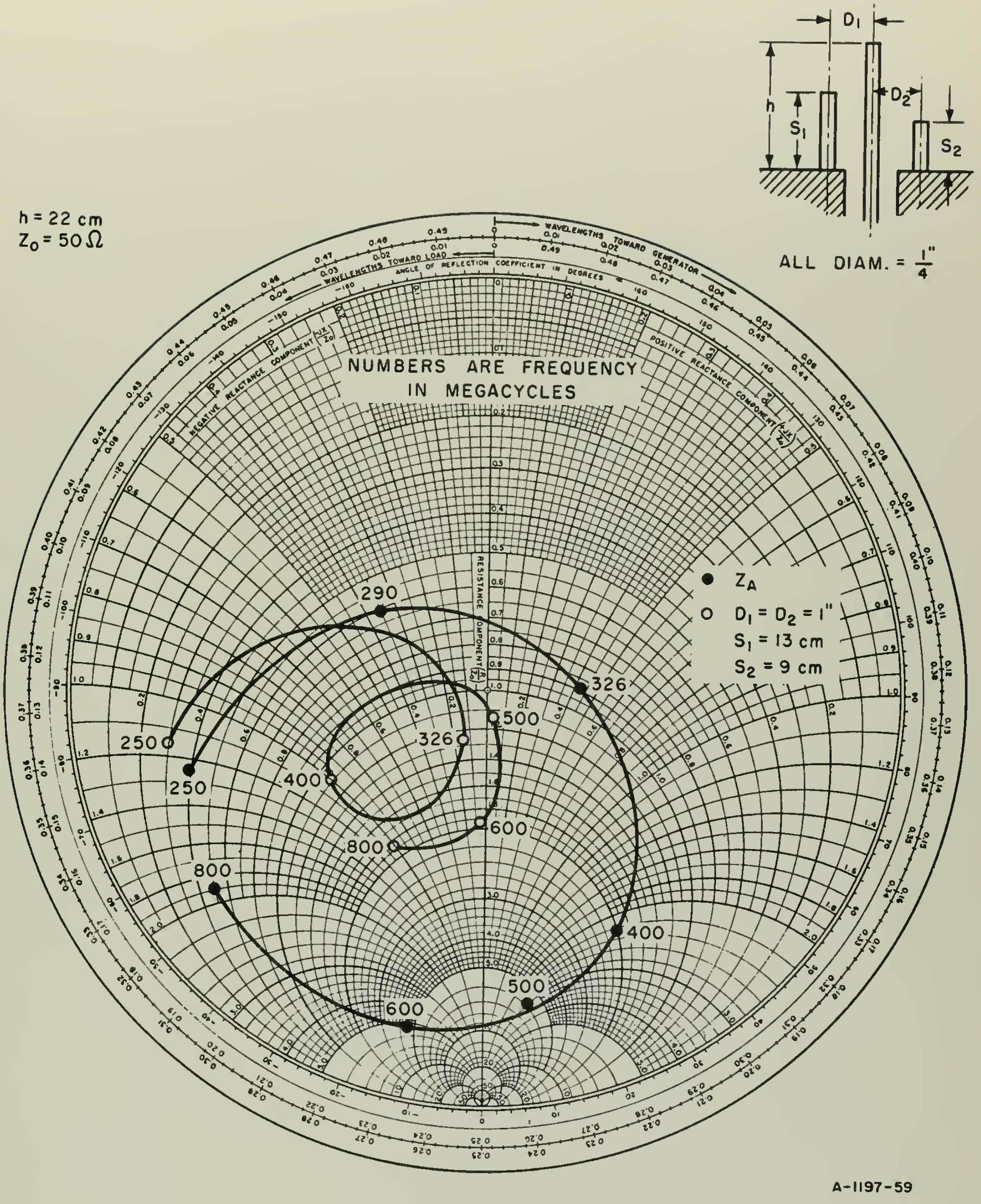

FIG. 13

THEORETICAL DRIVING POINT IMPEDANCE OF OPEN SLEEVE ANTENNA WITH PARASITES OF UNEQUAL LENGTH SPACED 1 INCH FROM DIPOLE

The reduction of the antiresonant impedance must be accomplished by either a reduction of the reactance of each transmission line at antiresonance or an increase in the losses. Either of these changes may be effected by several methods, although some of the methods exclude the simultaneous accomplishment of both. The improvement then becomes dependent upon the predominance of one effect over the other.

A decrease of reactance at antiresonance may be brought about by decreasing the spacing of the parasites. The decrease of Z_{0T} causes a decrease of reactance at all frequencies, including antiresonance. There will also be a decrease of the resistance component because of less radiation, but the reactive decrease can predominate when the resistance is originally quite small. By making the parasites nearly the same length, the individual transmission lines are more nearly a quarter wavelength at antiresonance, and their reactances are smaller. This condition tends to imply a return to the case of equal length parasites.

One method of increasing the resistive term of each transmission line is to increase the effective resistive end loading or radiation losses, by a greater parasite spacing. This greater spacing has a detrimental effect on the reactance term, but the resistance can predominate for spacings greater than a certain minimum (as it apparently did in the theoretical curve). There is a maximum limit to the spacing usable, above which the low frequency behavior suffers, or severe pattern distortion occurs. An alternative method may be to flare the parasites outward from the dipole, increasing the losses of the transmission line mode by radiation. This, of course, is essentially reverting to the idea of the gradual taper to free space as a means of achieving broadbanding, but the explanation of the resistive loading of the transmission lines originates the suggestion. However, the taper appears to destroy the analogy to the antenna mode of operation, so that analysis by the present theory would be questionable, and the results of this technique would most readily be determined experimentally. One further means of increasing losses is by a reduction of parasite diameter, but some intrinsic broadbanding effect would undoubtedly be lost.

There is one method for reducing the antiresonant impedance which is presented merely to permit the objections to its use to be pointed out. This consists of end loading of the transmission lines with lumped constant resistance to increase the losses. The addition of physical resistance to

antennas is usually questionable, although at times advantages may be had such as the increase in gain obtained by terminating a rhombic antenna with its characteristic resistance. In this particular case, aside from the problem of obtaining a good physical resistor at uhf, the antenna efficiency is bound to suffer. Whether or not sufficient improvement in broadband operation could compensate for the lower efficiency would have to be investigated. In this regard it might be pointed out that the ultimate in broadbanding would be the addition of a resistor across the generator terminals, but effective radiation would hardly result. Another situation to be coped with is the power rating obtainable for resistors in various frequency ranges. In any case the problem would be somewhat difficult to handle analytically with the present theory, since the antenna mode of operation would be disturbed. Evaluation of k particularly would be difficult, although the qualitative behavior could be predicted, especially if the end resistor were reasonably large.

There are two basic approaches possible for shifting the antiresonant frequency. The obvious one is to shorten the parasites to raise the antiresonant frequency above the range of interest. However, a significant shift of frequency requires a considerable shortening of elements; but if the elements are made too short, the highly desirable low frequency response is changed. Nevertheless, there is possible a compromise whereby some increase in the antiresonant frequency may be obtained with a still satisfactory low frequency variation. An indication of a practical lower limit is the impedance locus variation with parasite length for equal length parasites. The length of the longer parasite can not be made shorter than that of the equal parasite case which gives the maximum tolerable variation of VSWR in the low frequency loop.

The other approach for increasing the antiresonant frequency consists of a change of parasite spacing. A simple decrease of spacing causes some upward shift of the frequency by virtue of an apparent shortening of the transmission lines from reduced fringing. This effect is noticeable but not too significant. If the spacings of the parasites are made unequal, however, the difference between the characteristic impedances of the two transmission lines may be adjusted to cause a rise in the antiresonant frequency. Some insight into the magnitude of change possible and the proper choice of spacings may be obtained by considering the case of antiresonant, lossless transmission lines. For the open circuited line,

$$Z_T = -jZ_{OT} \operatorname{ctn} \beta s \quad . \tag{15}$$

For the two lines at antiresonance,

$$Z_{OT_1} \operatorname{ctn} \beta s_1 = -Z_{OT_2} \operatorname{ctn} \beta s_2$$

or

$$Z_{OT_1} \operatorname{ctn} \frac{\omega_r s_1}{c} = -Z_{OT_2} \operatorname{ctn} \frac{\omega_r s_2}{c} \tag{16}$$

and the value of ω_r is established by the lengths and characteristic impedances. It is readily shown that when $s_1 > s_2$

ω_r for $Z_{OT_1} > Z_{OT_2}$ is less than

ω_r for $Z_{OT_1} = Z_{OT_2}$; and

ω_r for $Z_{OT_1} < Z_{OT_2}$ is greater than

ω_r for $Z_{OT_1} = Z_{OT_2}$.

Hence, in order to raise the antiresonant frequency, D_1 should be less than D_2 to make $Z_{OT_1} < Z_{OT_2}$; the longer parasite should be closer to the center element than the shorter parasite. However, it is also true that even a sizable difference between Z_{OT_1} and Z_{OT_2} does not in general cause a marked change in the antiresonant frequency; but any change is an improvement.

Thus, the theory provides very definite information on changes that should be made in the antenna setup to give the best attainable performance with unequal lengths and unequal spacings of parasites. The actual magnitude of the effects achieved by these changes will be discussed with the experimental data in Chap. 6.

H. USE OF TWO PAIRS OF PARASITES OF UNEQUAL LENGTH

The same line of reasoning that suggested the use of two parasites of unequal length leads to the idea of two pairs of parasites of unequal length. From the standpoint of the reduced effect of a single parasite

compared to two parasites (discussed in Sec. E of this chapter) one might feel that the logical progression would have been to two pairs of unequally long parasites rather than the single pair discussed. The single pair was chosen because of its simpler analysis and physical construction, however, and it should be apparent that the same basic limitation of high antiresonant impedance exists with the two pairs as with the single pair. Although the matter was not investigated in any detail, it appears that the use of two pairs does not warrant further consideration.

EXPERIMENTAL CONDITIONS AND PROCEDURES

A. DESCRIPTION OF PHYSICAL SETUP

The test equipment and physical setup used in obtaining the experimental data are shown schematically in Fig. 14. The arrangement is typical of that usually employed for antenna impedance measurements. The slotted line was three 20-in. Hewlett-Packard lines bolted end to end, with a continuous center conductor supported at two points along the line by Styrofoam slabs All of the equipment was bonded together with 1/2-in. metal braid and all leads were kept as short as possible.

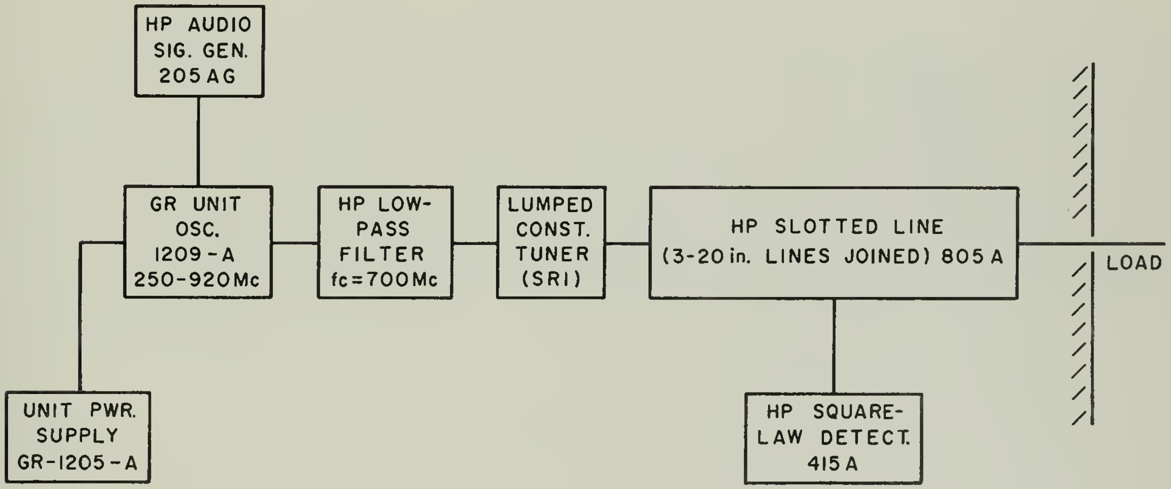

FIG. 14

EXPERIMENTAL SETUP

The antenna construction was quite simple. A 1/4-in. diameter aluminum rod 22 cm long was mounted on an N-type coaxial fitting and erected over a ground plane to serve as the center dipole. Four lengths of parasites—7, 9, 11, and 13 cm—were constructed out of the same 1/4-in.

aluminum stock used for the center element. Their bases were tapped to permit mounting on the ground plane through holes drilled at spacings of 1/2, 1, and 1-1/2 in. from the center of the dipole. Two parasites of each length were available, so that any combinations of lengths or spacings of interest could be investigated.

B. MEASUREMENT TECHNIQUES EMPLOYED

One of the standard techniques for determining impedance with a slotted line was employed. This consited of measuring the shift of minimum from a short to load condition and the determination of VSWR on the line with a Hewlett-Packard square-law standing-wave indicator, using a bolometer for the detector to insure square-law operation. The short circuit was inserted right at the antenna so that impedance measurements computed on the Smith chart were referred directly to the base of the antenna. Minima were located by taking the average of readings for equal VSWR slightly to each side.

C. ACCURACY

The accuracy of impedance values (R and X) generally achievable,and expected with measurements of this type and in this frequency range, is from 5 to 10%. Since reasonable precautions were taken with the present data, it is felt that the values obtained generally fall within the above limits of precision. However, there are a few frequency ranges in which slightly more error is present because of some limitations of the measuring equipment.

CHAPTER 6

EXPERIMENTAL DATA AND RESULTS

A. DRIVING POINT IMPEDANCE AND VSWR OF OPEN SLEEVE ANTENNA WITH PARASITES OF EQUAL LENGTH

The impedance data shown in Figs. 15 and 16, and the VSWR data in Fig. 17, all normalized to 67 ohms, are experimental values previously obtained by Bolljahn (see Chap. 1) and were used in evaluating the first part of the theoretical data. Figures 18 and 19 are plots of impedance data taken with the equipment setup described in this report for some of the same conditions as those of Figs. 15-17. A normalizing impedance of 50 ohms was used in Figs. 18 and 19. It should be noted that the symbols of Figs. 15-17 are slightly different from those used throughout the rest of the report; the diagrams provide the proper key.

The agreement of the 67-ohm data with that computed from the theory has already been shown (Figs. 7 and 8) and discussed in Chap. 3. The VSWR curves of Fig. 17 may be compared with the theoretical ones of Fig. 6. The agreement between the 50-ohm data and the 67-ohm data is seen to be quite good when allowance is made for the different value of normalizing impedance.

The main points to note with this data are the size and frequency range of the impedance loop as a function of parasite length, and the capacitive, low impedance shift of the loop in going from 1-in. to 1/2-in. parasite spacing. The plot of VSWR shows quite clearly the possible compromise between bandwidth and VSWR through the frequency band.

B. DRIVING POINT IMPEDANCE OF OPEN SLEEVE ANTENNA WITH EQUALLY SPACED PARASITES OF UNEQUAL LENGTH

Figure 20 shows the experimental impedance curve for the case corresponding to the theoretical curve and conditions of Fig. 13. There is considerable disparity between the two curves, particularly the higher frequency portion of the band. As mentioned in Chap. 4, the discrepancy arises primarily because of the inadequacy of the theory in predicting the impedance at the transmission-line antiresonant frequency. The theory

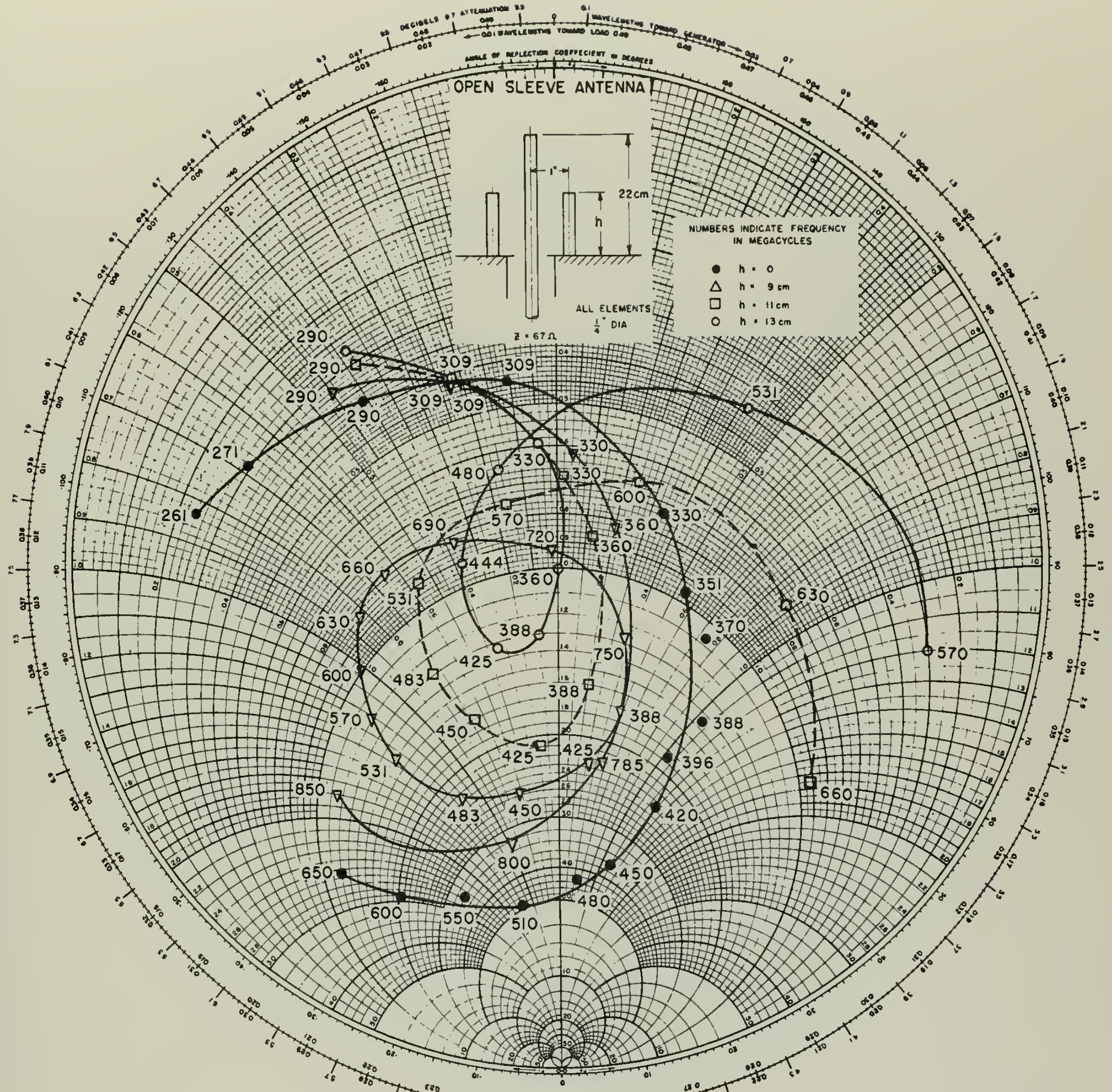

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FIG. 15

EXPERIMENTAL DRIVING POINT IMPEDANCE OF OPEN SLEEVE ANTENNA WITH PARASITES SPACED 1 INCH FROM DIPOLE

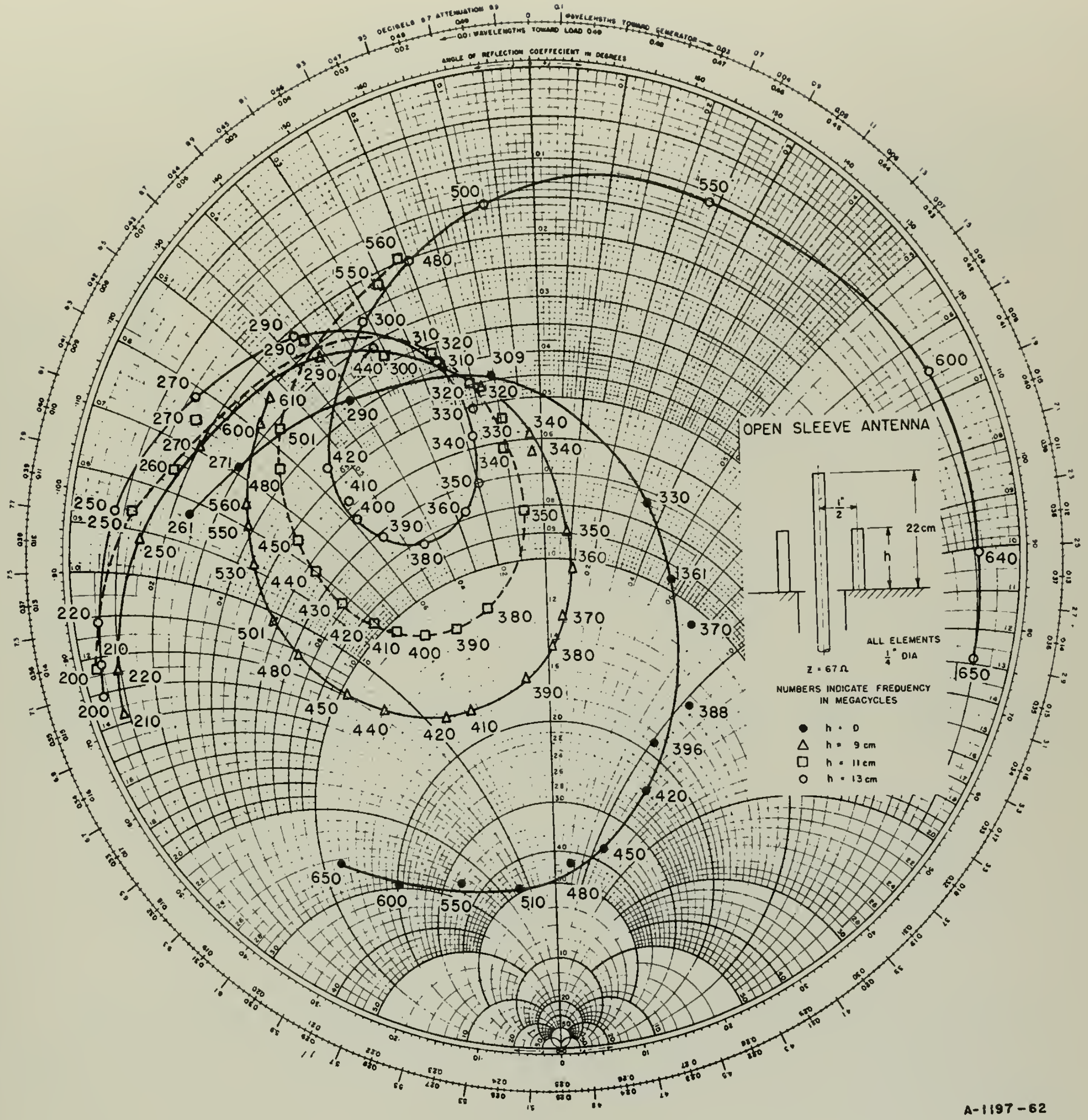

FIG. 16

EXPERIMENTAL DRIVING POINT IMPEDANCE OF OPEN SLEEVE ANTENNA WITH PARASITES SPACED 1/2 INCH FROM DIPOLE

does, however, adequately predict the effect of dimensional change on the form of the impedance curve and hence provides a useful guide to the designer.

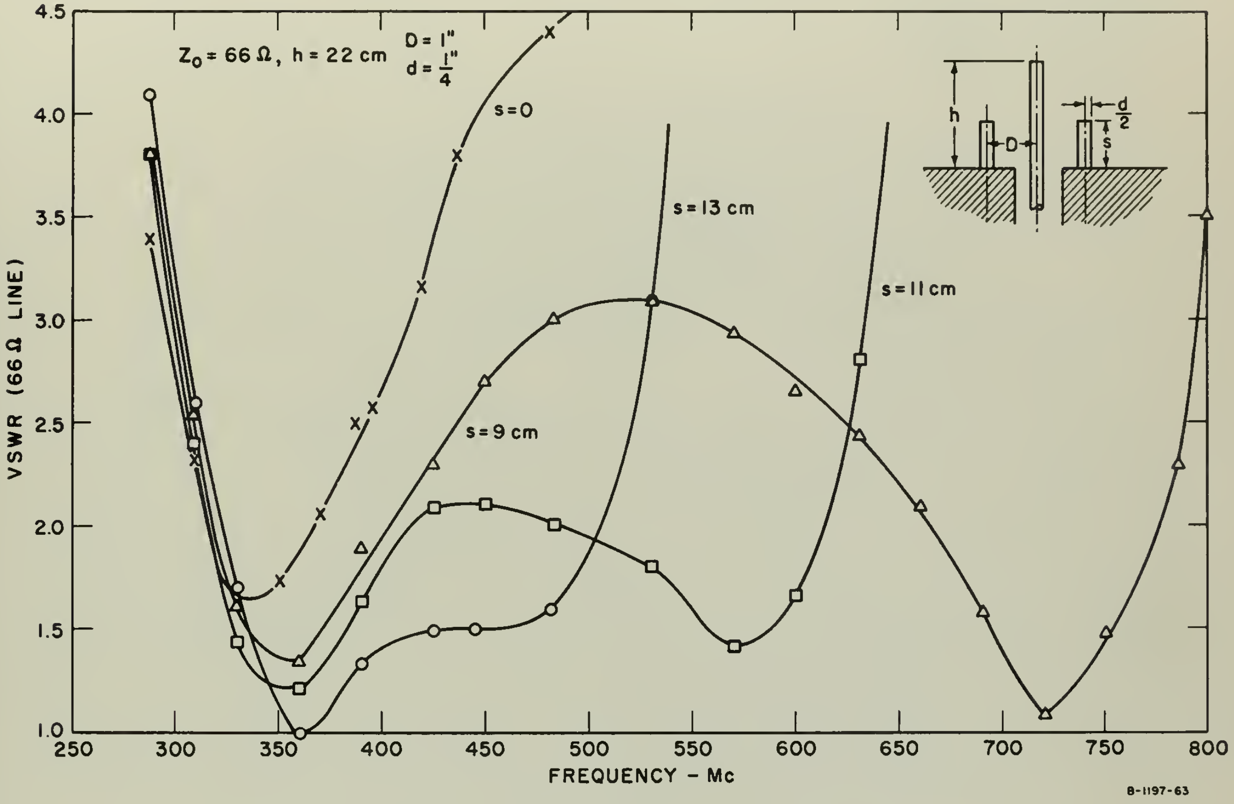

FIG. 17

EXPERIMENTAL VSWR ON 67-OHM LINE FOR OPEN SLEEVE ANTENNA WITH PARASITES SPACED 1 INCH FROM DIPOLE

The impedance variation below 500 Mc is very similar to that obtained with two parasites 13 cm long. Generally, the lower-frequency impedance variation for the open sleeve with parasites of unequal length is very similar to the variation which would be found if both parasites were of the same length and spacing as the longer one.

The rapid increase of the impedance toward values of extremely large magnitude as the frequency is raised above 500 Mc is the result of two factors. The quantity k becomes quite large and multiplies the already large value of Z_A. In addition, the two transmission lines set up an antiresonant mode, yielding a very high antiresonant impedance. It

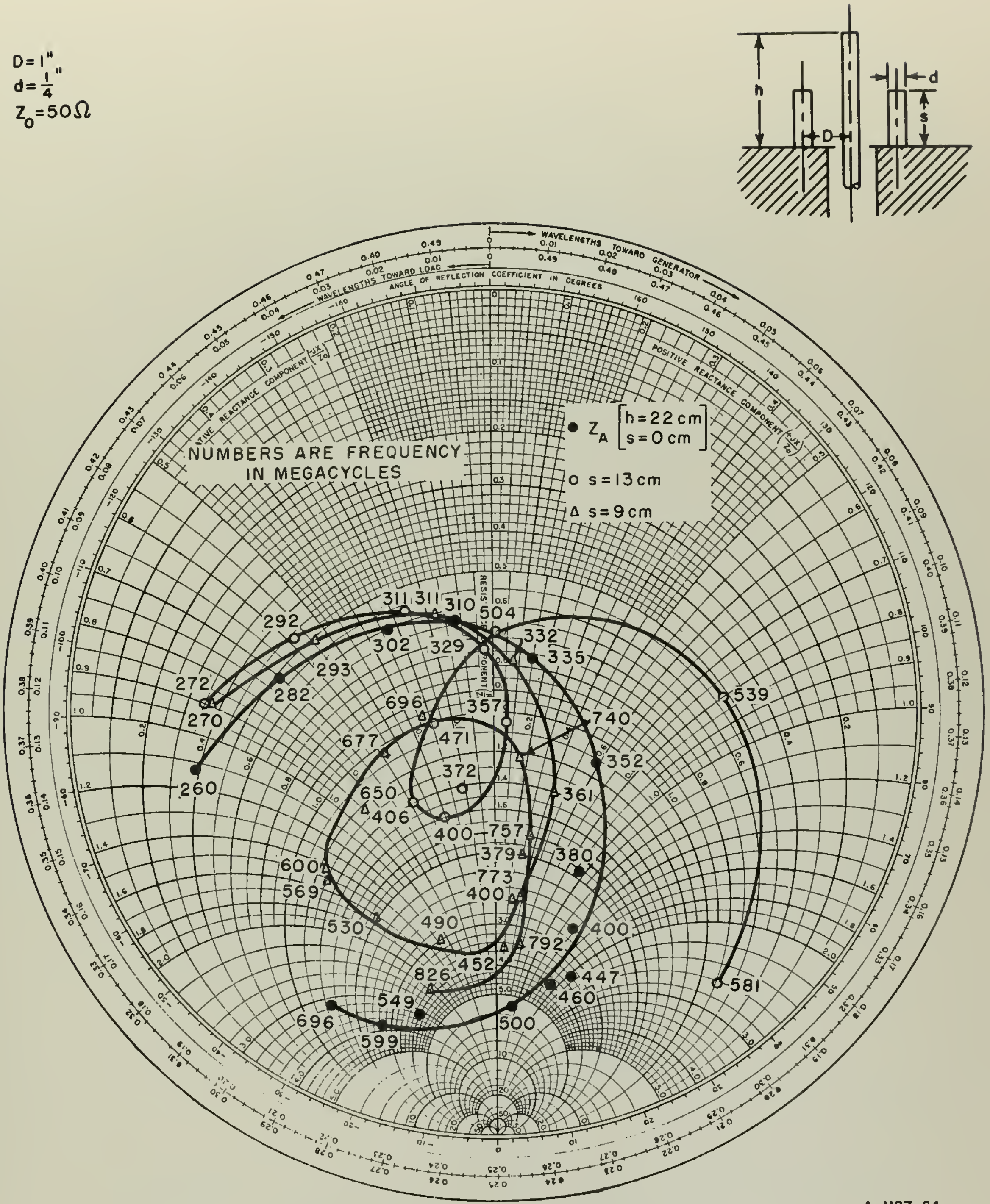

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FIG. 18

EXPERIMENTAL DRIVING POINT IMPEDANCE OF OPEN SLEEVE ANTENNA WITH PARASITES SPACED 1 INCH FROM DIPOLE

D = 1/2"
d = 1/4"
Z_0 = 50Ω

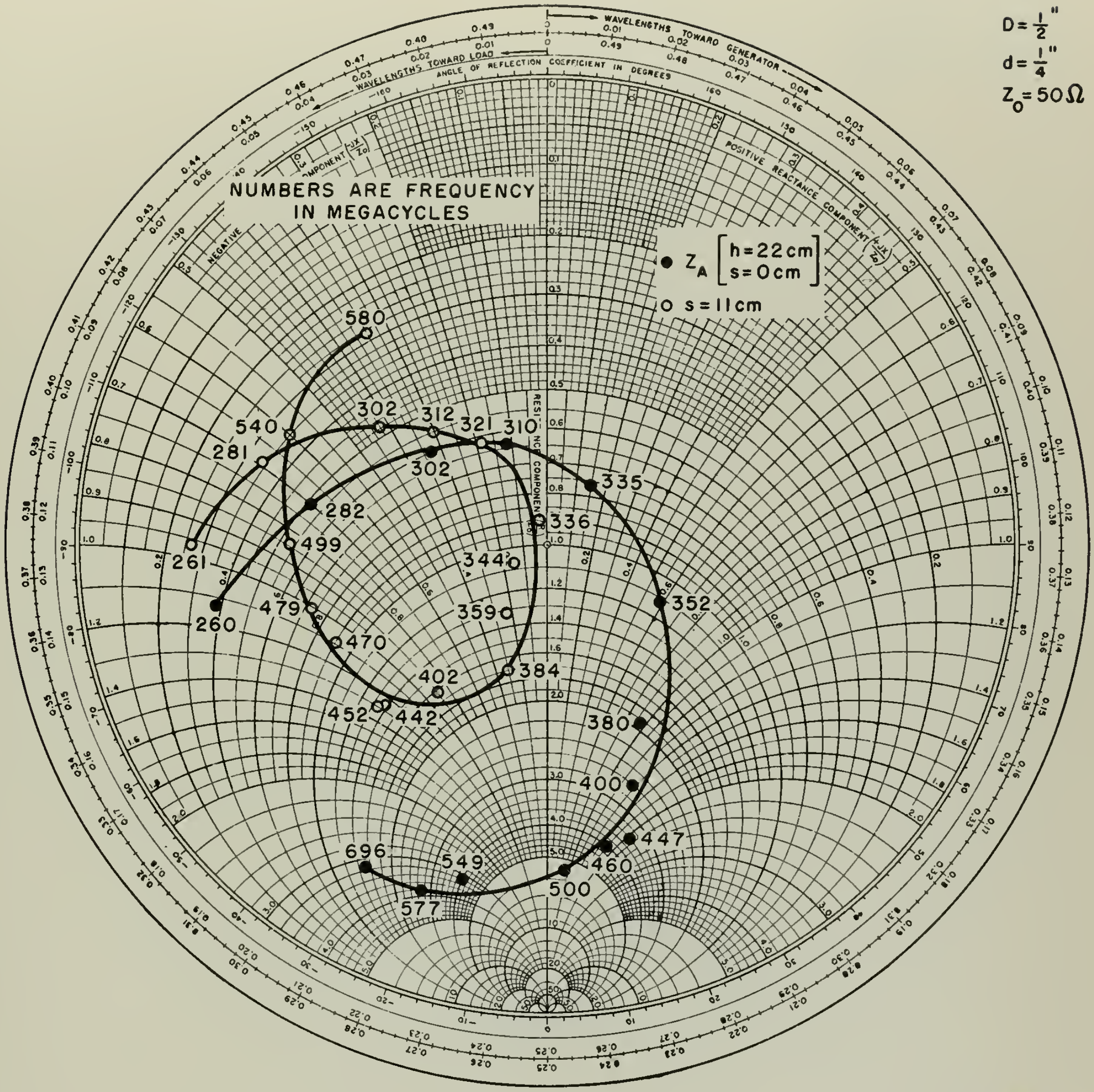

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FIG. 19

EXPERIMENTAL DRIVING POINT IMPEDANCE OF OPEN SLEEVE ANTENNA WITH PARASITES SPACED 1/2 INCH FROM DIPOLE

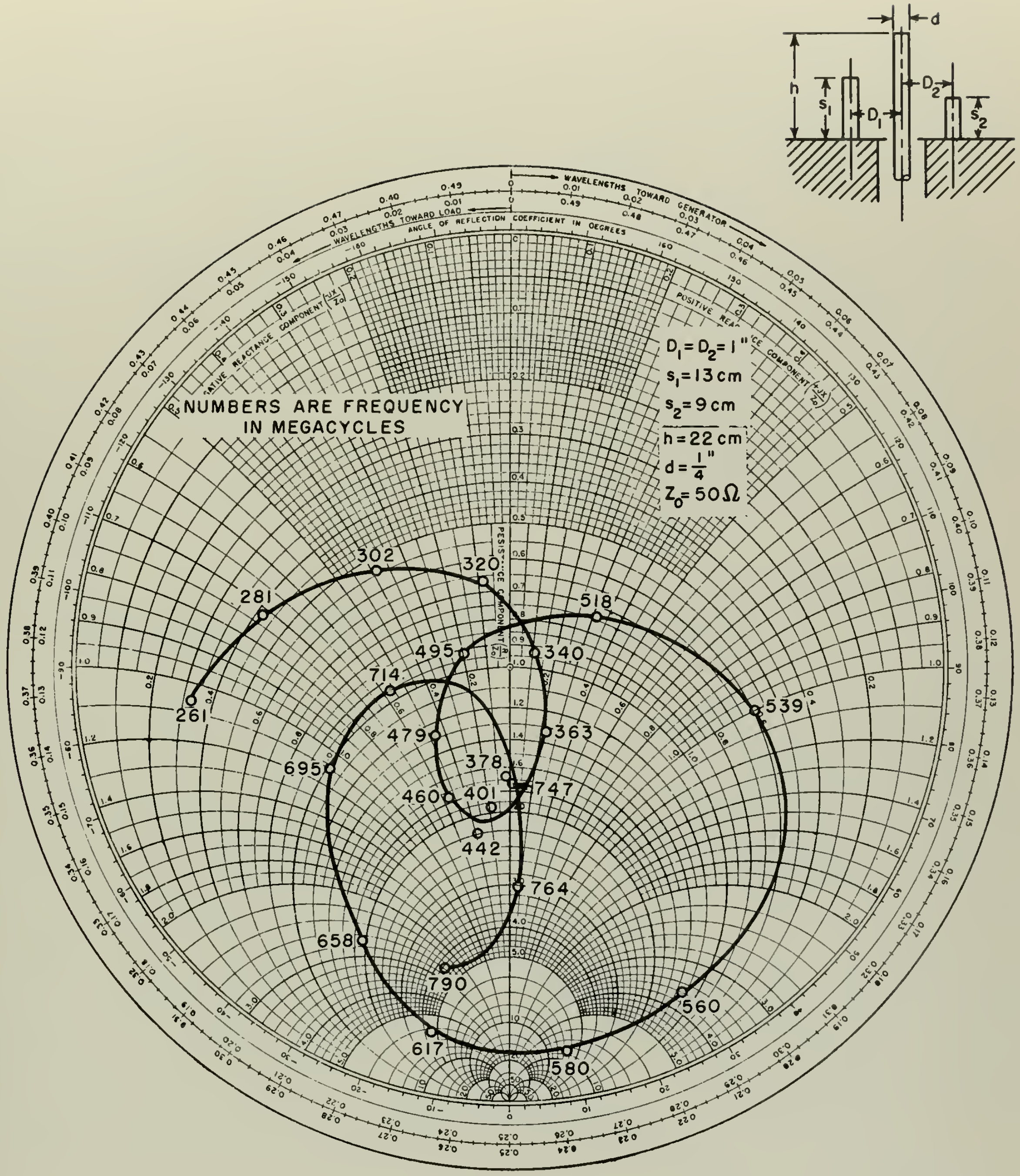

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FIG. 20

EXPERIMENTAL DRIVING POINT IMPEDANCE OF OPEN SLEEVE ANTENNA WITH PARASITES OF UNEQUAL LENGTH SPACED 1 INCH FROM DIPOLE

is primarily the exceptionally large size of this antiresonant impedance that the theory fails to give, since the antiresonant condition from the experimental curve does occur at very nearly the theoretical antiresonant frequency. As the theoretical losses in the transmission lines are lumped together in the resistive end loading, the failure of the theory can be attributed to errors in Z_{T_t}. This quantity has caused difficulty at the higher frequencies before, but it was chosen to vary strictly in accordance with theory. In this case, as in the case of the parasites of equal length, if the rate of decrease of Z_{T_t} were lessened as the electrical spacing increased, closer agreement could be had between theory and experiment. The important point, however, already alluded to, is that one needs only keep in mind the deficiency of the end loading while employing the theory to direct the changes necessary for improvement of antenna performance.

C. DISCUSSION OF VSWR DATA FOR IMPROVED OPEN SLEEVE WITH PARASITES OF UNEQUAL LENGTHS AND SPACINGS

Since the theory indicated various means for improving the bandwidth of the open sleeve antenna by reducing or shifting the antiresonant effect, but did not predict much about the degree of improvement offered, it was desired to try out as many of the simple changes as possible. The single factor which gives most information about the performance of an antenna on the end of a transmission line is VSWR, especially if the general nature of impedance variation is already known. The measurement of VSWR by itself is much more rapid on the slotted line than when minimum shift is also required, so that only VSWR was investigated for the various changes. Full impedance data were taken and plotted for the one arrangement that showed the most promise, and a VSWR curve was plotted. Only the results of particular interest will be given here, although all the various changes suggested by the theory were investigated.

An increase in spacing from 1 to 1.5 in. for the 9- and 13-cm parasites increased the resistive end loading by radiation and reduced the maximum value of VSWR at antiresonance from 18.0/1 to 15.0/1. The frequency of maximum VSWR was reduced from 580 to 560 Mc because of the effective lengthening of the transmission line by increased fringing with the greater spacing. Both of these changes were as predicted by theory, but were inadequate to yield significant improvement.

A cumulation of changes was also tried. To keep different the characteristic impedances of the two lines, and to reduce fringing in order to raise the antiresonant frequency, the spacings were made unequal and as small as possible. The small spacings would also result in a decrease of reactance at antiresonance, and decrease the antiresonant impedance. To raise the antiresonant frequency, the parasite lengths were made as short as feasible; but to decrease the antiresonant reactance, they were made as nearly equal as possible. One compromise reached with all of these changes was

D_1 = 1/2 in. s_1 = 11 cm

D_2 = 1 in. s_2 = 9 cm.

The net effect was a further reduction in maximum VSWR to 9.0/1 and an increase in the antiresonant frequency to 680 Mc. This was a decided improvement, with both changes fully in accord with theory; however, the resulting performance was still not so good as some of those achieved with parasites of equal length. There was a range of rather high values of VSWR that apparently resulted from a general capacitive shift of impedance such as that in the 0.5-in. spacing for the parasites of equal length.

To try to retain the advantages of the above arrangement but remove the capacitive shift, the relative spacings and lengths were maintained about the same but the actual spacings increased. This led to the condition considered the optimum attainable with unequal parasites and is discussed in the next section.

D. DISCUSSION AND COMPARISON OF PERFORMANCE FOR OPTIMUM CONDITIONS WITH UNEQUAL AND EQUAL PARASITES

The conditions considered optimum for unequal parasites are

D_1 = 1 in. s_1 = 11 cm

D_2 = 1.5 in. s_2 = 9 cm.

Impedance data were taken for these conditions and are shown in Fig. 21; VSWR curves for the same case are shown in Fig. 22. It should be noted that the lower frequency impedance loop still looks very much like that for the case for parasites 11 cm long with equal 1-in. spacing, again verifying the statement made previously that the lower-frequency impedance

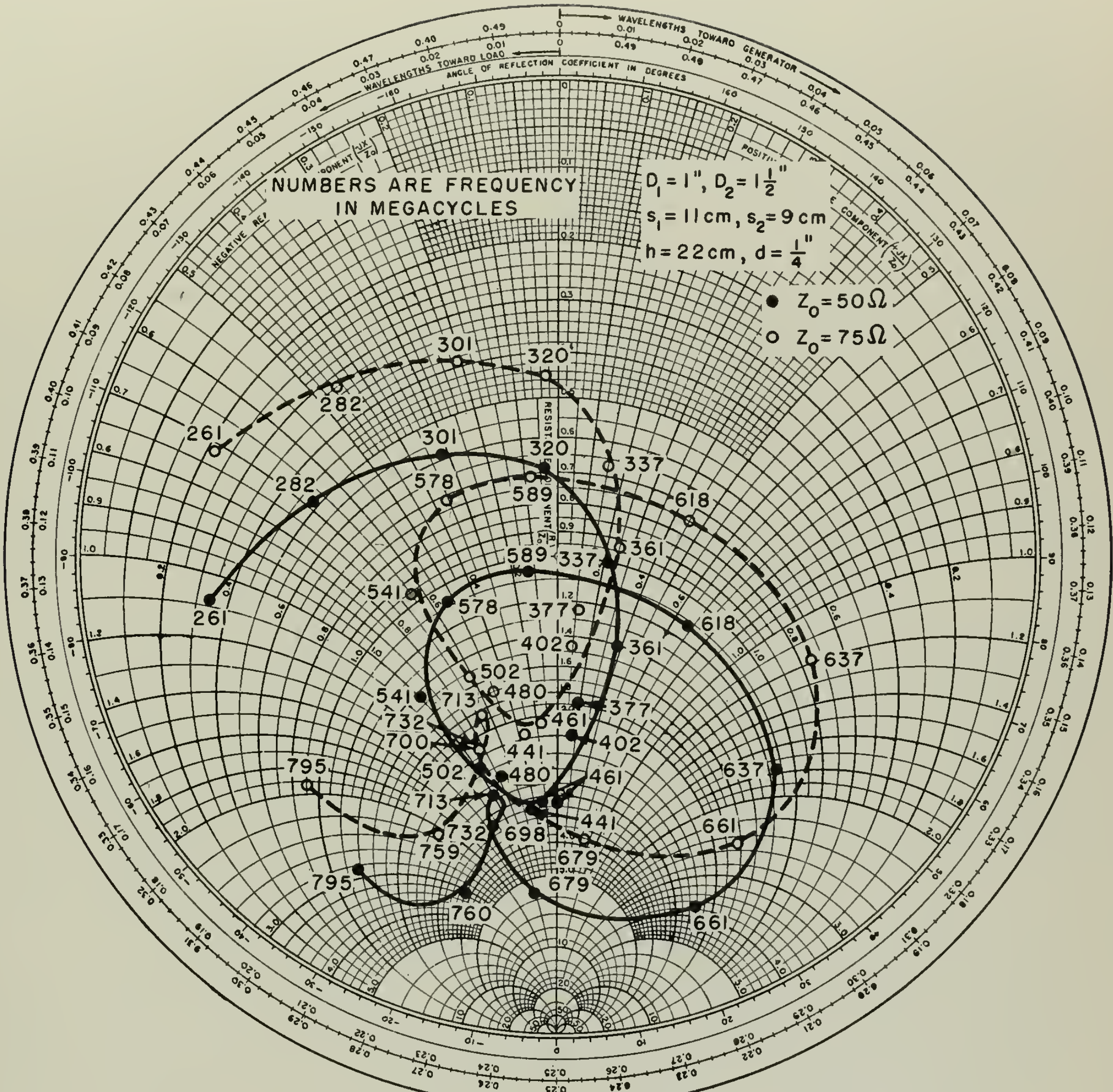

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FIG. 21

EXPERIMENTAL DRIVING POINT IMPEDANCE OF OPEN SLEEVE ANTENNA WITH PARASITES OF UNEQUAL LENGTH UNEQUALLY SPACED

variation is predominantly determined by the length and spacing of the longer parasite. Furthermore, the use of unequal parasites shows no material improvement in the higher frequency range over the use of equal parasites. Thus, even by making use of all the various improvements suggested by the theory, the optimum case with unequal parasites is limited in performance to that achievable with equally spaced parasites of equal length. It does appear, however, that if a frequency range much greater than two to one must be used with an antenna of this type, some improvement results from the use of unequal parasites. This point was not investigated specifically in detail.

It is apparent from all of the impedance curves that the open sleeve antenna will give a better impedance match to a transmission line of higher characteristic impedance than 50 ohms, since the larger value will shift the impedance curve upward on the Smith chart. Accordingly, the impedance data for the unequal parasite case just discussed is shown in Fig. 21 also normalized to 75 ohms, such as is typical for RG-11/U or RG-12/U coaxial cable. VSWR values taken from this curve are also plotted in Fig. 22. A definite improvement is readily discernable.

Figure 22 also has, for additional comparison, plotted the VSWR data of the case of parasites of equal length corresponding to the unequal parasite conditions where D = 1 in. and s = 11 cm. These values are for a transmission line with characteristic impedance of 67 ohms. It is seen that this latter curve behaves very similarly to the case of unequal parasites normalized to 75 ohms, except that at the high frequency end the rise in VSWR is not quite so abrupt.

To illustrate further the improvement possible with a higher impedance transmission line, the driving point impedance for 9-cm parasites spaced 1 in. apart is normalized to 75 ohms in Fig. 23. The resulting VSWR is plotted in Fig. 24 along with that for the 50-ohm transmission line. It is not to be inferred from these curves, however, that no sizable improvement in matching results with a 50-ohm cable and the open sleeve, as compared to a dipole, for even in this case the improvement in matching is rather marked.

It may frequently be desirable to use the open sleeve antenna with a 50-ohm coaxial cable, particularly in aircraft and u-h-f applications. It is easily verified that if a quarter-wave matching section tuned to the mid frequency range of the pass band of the antenna, with characteristic

impedance chosen to match 75-ohm and 50-ohm cables, is inserted between the antenna and 50-ohm coaxial cable, results entirely comparable to those with a 75-ohm cable can be achieved. This procedure is recommended in general for lower impedance cables to make maximum use of the capabilities of the open sleeve antenna.

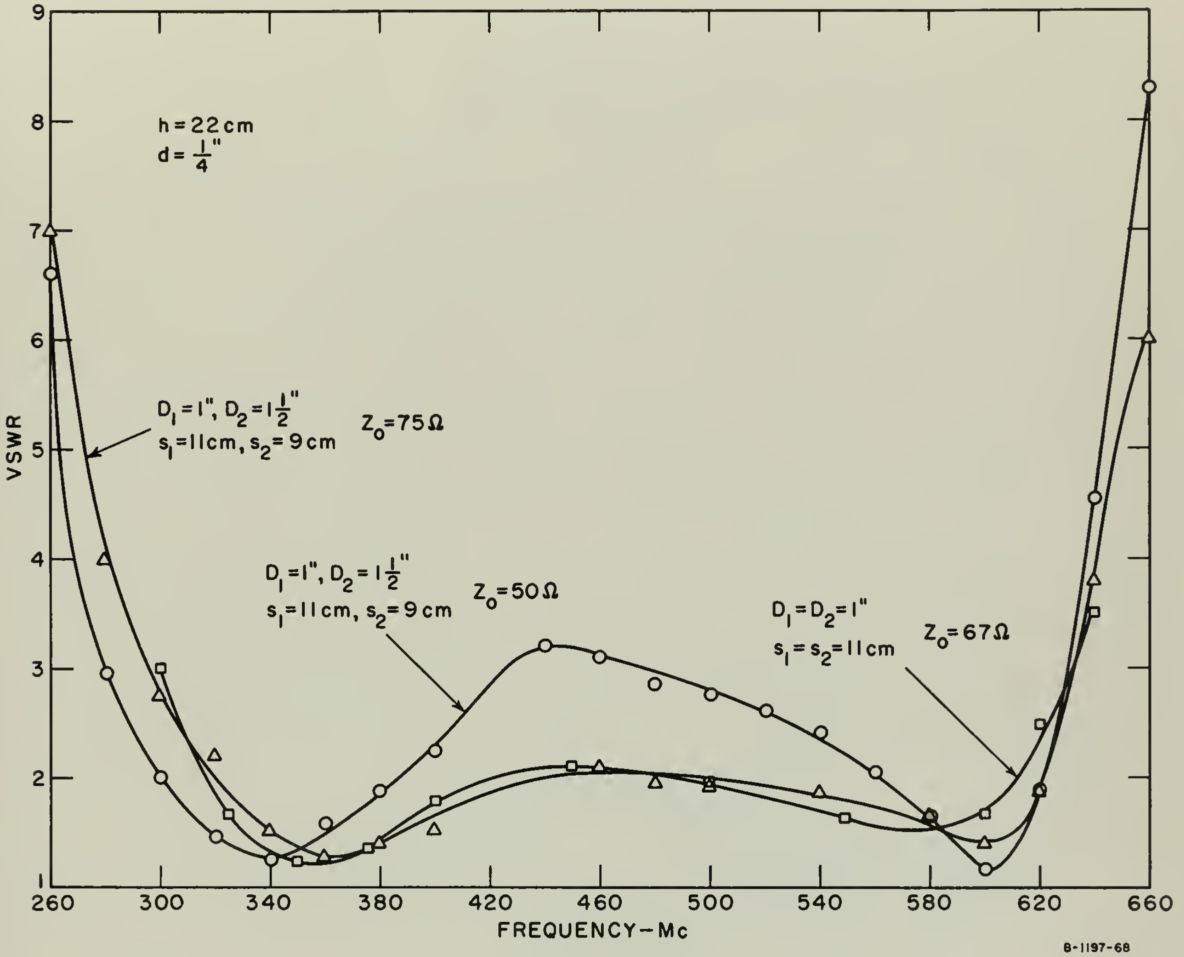

FIG. 22

COMPARISON OF EXPERIMENTAL VSWR ON VARIOUS IMPEDANCE LINES FOR OPEN SLEEVE ANTENNA WITH EQUALLY AND AND UNEQUALLY SPACED PARASITES OF EQUAL AND UNEQUAL LENGTHS

A summary of the best results obtained under varying conditions for the particular model investigated is given in Table I. Other results are readily apparent from the curves.

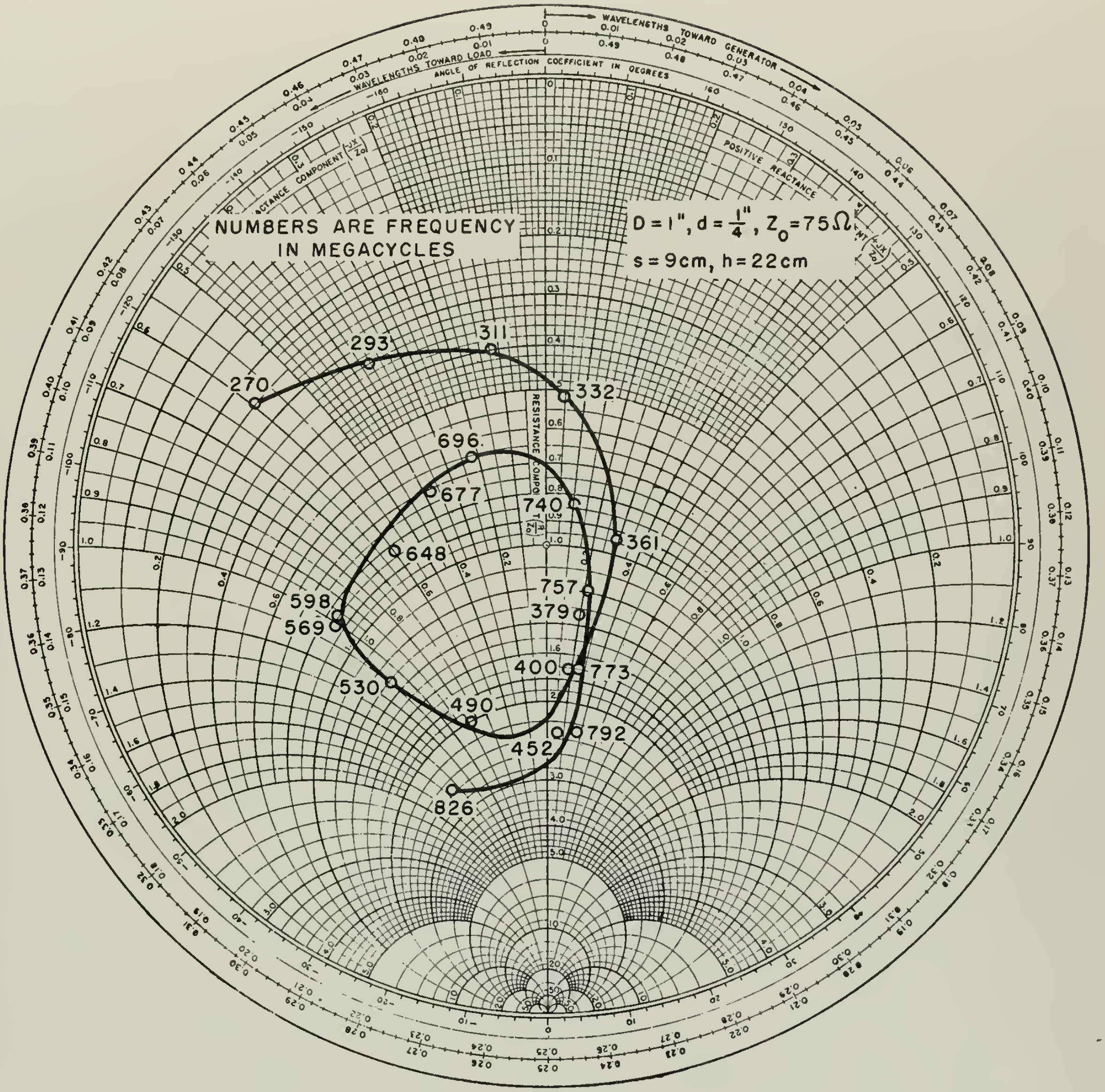

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FIG. 23

EXPERIMENTAL DRIVING POINT IMPEDANCE OF OPEN SLEEVE ANTENNA WITH PARASITES SPACED 1 INCH FROM DIPOLE — NORMALIZED TO 75-OHMS

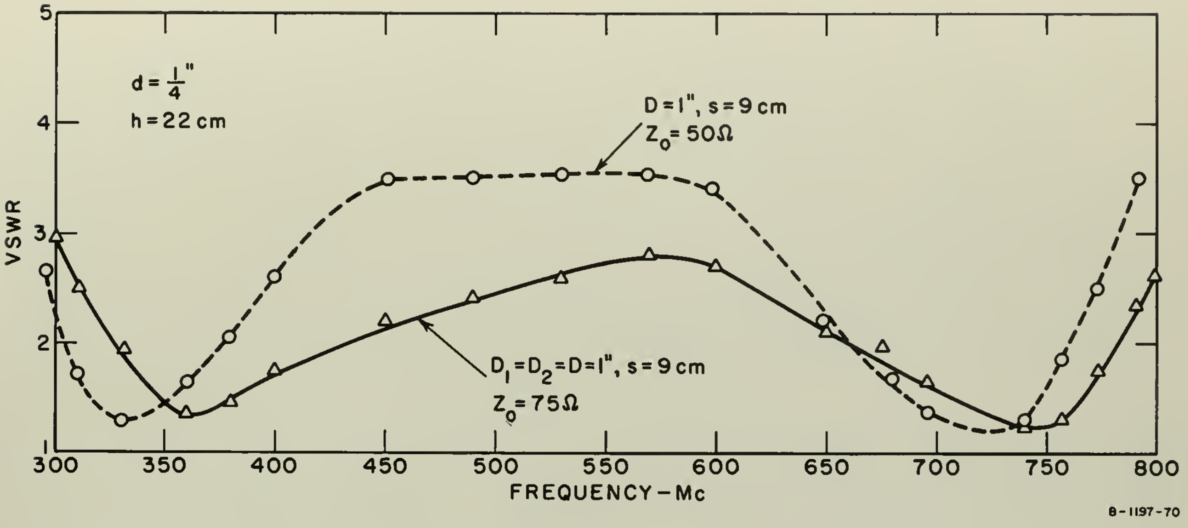

FIG. 24

COMPARISON OF EXPERIMENTAL VSWR ON 75- AND 50-OHM LINES FOR OPEN SLEEVE ANTENNA WITH PARASITES SPACED 1 INCH FROM DIPOLE

TABLE I

BANDWIDTH OF OPEN SLEEVE ANTENNA FOR VARIOUS PARASITE ARRANGEMENTS

OPTIMAL PARAMETERS WITH PARASITES*	D_1 (IN.)	D_2 (IN.)	s_1 (CM)	s_2 (CM)	Z_0 (OHMS)	MAX. VSWR	FREQUENCY RANGE (Mc)
Unequal	1	1½	11	9	75	2.05/1	1.96/1
					50	3 2/1	2.3/1
					50 (with 61 ohm λ/4 matching section)	2.4/1	2.2/1
Equal	1	1	9	9	75	2.8/1	2.64/1
			11	11	67	2.1/1	1.96/1

---

[*] All elements are of ¼-in. diameter.

E. GENERAL CONCLUSIONS ON DESIGN CRITERIA FOR OPEN SLEEVE ANTENNA

Comparison of both impedance and VSWR curves for equal and unequal parasites indicates that the case of equally long, equally spaced parasites allows as wide control over the results obtainable, and gives as desirable performance, as any combinations of unequal lengths or spacings, at least in the range of the first impedance loop. The general theory developed is applicable quantitatively to the equal parasite condition and qualitatively to the unequal parasite arrangements. Further improvement in the antenna is conceivably possible with any of the additional techniques mentioned but not fully investigated.

The case fully investigated used 1/4-in. diameter elements over frequencies from 250 to 800 Mc. Considerable control of the impedance loop shape and position is possible with the various design parameters. Increasing the parasite length from 9 to 13 cm causes a reduction in the size and frequency range of the impedance loop with a general vertical shift toward the low impedance region of the Smith chart. Changing the spacing D causes a diagonal displacement of impedance on the Smith chart, with smaller spacings yielding larger impedance loops having marked capacitive components. One inch was found to be the best spacing. From theoretical investigation it was learned that changing h causes primarily a vertical displacement of impedance on the Smith chart, implying that smaller parasites might help to match the antenna directly to 50-ohm coaxial cables.

If both D and d are changed while maintaining a constant D/d ratio, with Z_{0T} thus remaining constant, the performance of the antenna is not materially changed. This is illustrated in Fig. 25 where an experimental VSWR curve is plotted for increased D and d but the same characteristic impedance of the antenna transmission line mode as that reported throughout the paper. This type of change, along with appropriate length and spacing of parasites, allows the adaptation of the antenna to other frequency ranges.

In general, better performance of the antenna is realized when excited by a higher impedance transmission line than 50 ohms, with 75 ohms being a good figure. However, comparable results are possible with a 50 ohm-coaxial cable, using a quarter-wavelength matching section between antenna and line.

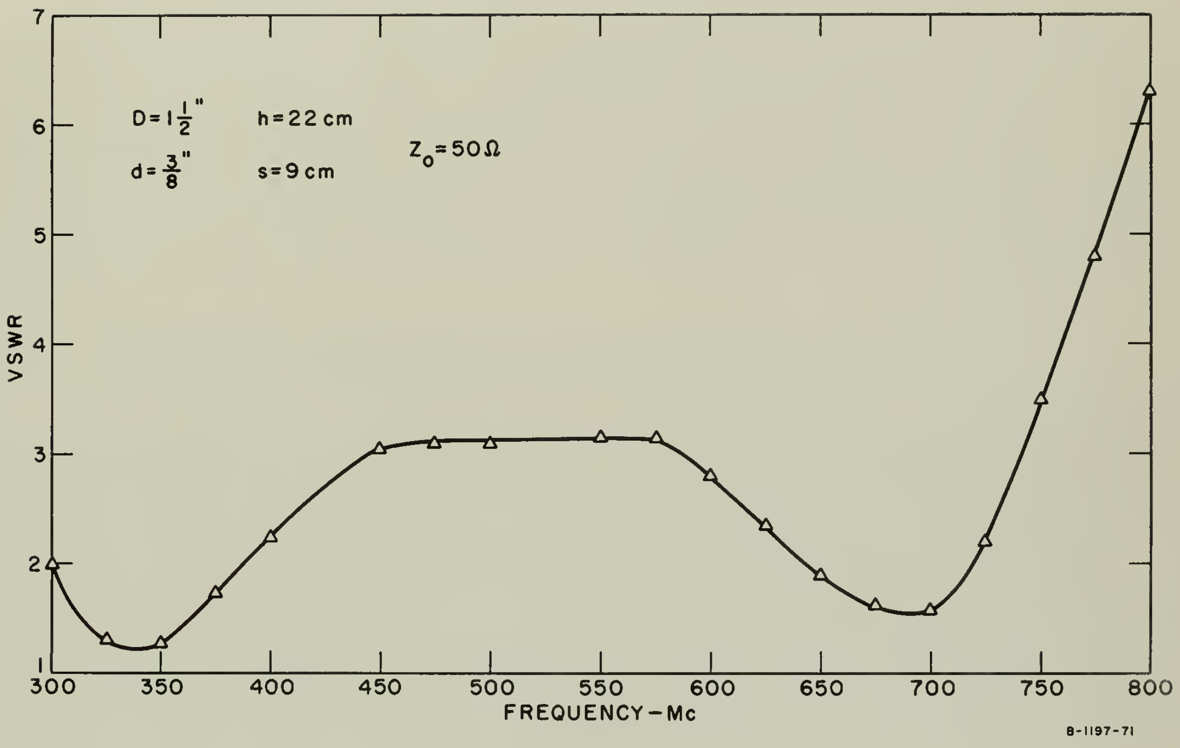

FIG. 25

EXPERIMENTAL VSWR ON 50-OHM LINE FOR
OPEN SLEEVE ANTENNA WITH ELEMENTS OF INCREASED DIAMETER

CHAPTER 7

ALTERNATE POSSIBILITIES FOR ANALYSIS OF OPEN SLEEVE ANTENNA

A. GENERAL

There are several other avenues of approach to the analysis of the open sleeve antenna, some merely giving qualitative indications of why broadband performance could be expected and others actually adaptable to quantitative development. The first section will discuss qualitative aspects which help to explain the broadband characteristics of the open sleeve, while the second section will consider other possible quantitative approaches.

B. QUALITATIVE APPROACHES TO BROADBANDING EFFECT

Because of the similarity of the open sleeve antenna to the ordinary sleeve antenna, most applications of the concepts of broadbanding are common to both. A gradual taper or outward flare of a transmission line may serve as an antenna to give an impedance match between the transmission line and free space, and is a very common broadband technique by virtue of the infinitely large number of cancelling reflections which are not frequency sensitive. The sleeve antenna can be imagined to be an extreme case of this technique, with the open sleeve as a degenerate form, yielding some broadband performance.

As the sleeve antenna may be considered a superposition of two asymmetrically fed antennas when its image in the ground plane is considered, so may the open sleeve antenna. King[8] shows how a single asymmetrically fed antenna may be considered as two monopoles excited in series; one monopole corresponds to the upper half and one to the lower half of the asymmetrical antenna. By a proper selection of lengths for the two halves, the combination can be made less sensitive to frequency variation than can either one independently. It would seem reasonable, then, that the superposition to the sleeve or open sleeve antenna would also exhibit broadband characteristics.

Another very similar concept of why the asymmetrically fed, and hence the open sleeve antenna, show broadband tendencies can be had from a consideration of the current distribution. If the feed occurs at such a point that the change of antenna electrical length with frequency produces compensating changes in current distribution, because of the requirement of current continuity at the feed point with a basically sinusoidal distribution from the ends, the driving point impedance will remain more steady.

The open sleeve antenna may also be thought of as only one of many techniques for broadbanding by using impedance transformers. Coleman[9] discusses many analogous types of devices. The actual excitation of the open sleeve antenna may be considered to be at the termination of the sleeve, with the sleeve nothing more than an extension of the feed transmission line. Broadbanding then results from the impedance of the sleeve antenna itself and the transformation of this impedance to the base of the antenna through the sleeve transmission line.

Thus there are many aspects of the open sleeve antenna which would lead one to expect some broadband performance, but most of the above techniques do not lead to quantitative answers without excessively involved computations.

C. QUANTITATIVE APPROACHES TO BROADBANDING EFFECT

Any antenna array theoretically can be analyzed by means of network equations using self and mutual impedances. The only problem which arises in general is the evaluation of the impedances involved. With the open sleeve antenna, the determination of the necessary impedances presents a particular obstacle. There is some published data available for the self impedance of single dipoles of varying length. Also some curves for mutual impedance between similar elements can be found for certain rather restricted cases.

Chaney[10] has derived more general formulas for assumed sinusoidal current distributions for the calculation of mutual impedance between like elements, and also elements of different length. Aside from the extreme tediousness of calculating any significant number of impedances from Chaney's formulas, the values obtained from his and the other published data would be questionable when applied to the open sleeve antenna because of the uncertainty of the current distributions of such closely spaced elements. Also,

since the values would be of interest over a considerable frequency range, many of the formulas and curves would be inapplicable. Even self impedance, which frequently is considered invariant for want of better information, would be subject to significant error because of the proximity of other elements, particularly for lengths near a half wavelength.

In short, an analysis based on mutual and self impedances would be a tremendously lengthy problem to obtain even relatively sketchy information, and the reliability of the answers obtained would be very questionable unless undue precaution were observed.

Computations were carried out for one particular case, where the dipole was very nearly a quarter wavelength and the longest parasites (13 cm) were used at 1-in. spacing. These are the conditions for which the current distributions should most nearly approximate those assumed in the formula derivations. The results are, for f = 330 Mc,

$$\text{Calculated} \quad Z_{in} = 38.0 + j\,3.8,$$

$$\text{Measured} \quad Z_{in} = 37.0 - j\,1.2\ .$$

Self impedance of the dipole works out to be

$$Z_{11} = 38.0 + j\,7.5\ .$$

The agreement is fair, and the effect of the coupled impedance does cause a change of the driving point impedance in the right direction. Larger discrepancies would be expected under most other conditions.

Probably the most promising quantitative approach (besides the one employed in this report) utilizes some of the experimental impedance data of Taylor[3] for the sleeve antenna. This method would consist of taking various values of sleeve impedance and transforming them to the base of the antenna through the transmission line formed by the sleeve. All of the values required in this case are readily calculable. The major problems in this regard, however, are the limited conditions which could be covered with the available data and the question of how much the open sleeve would depart from the behavior of the ordinary sleeve antenna. Nevertheless, at least a good indication of the expected performance should be obtainable.

CHAPTER 8

CONCLUSIONS

The open sleeve antenna provides an extremely simple method for materially increasing the bandwidth of an ordinary dipole antenna. The broadbanding is achieved with practically negligible distortion of the omnidirectional pattern in azimuth, and the antenna can still be made simple and rugged.

The theory presented permits a quantitative analysis of the basic antenna and a qualitative extension to more complex conditions. It was found theoretically, and proved experimentally, that for elements of 1/4-in. diameter, a center to center spacing of about one inch, using parasites of equal length, was optimum. For a variation in diameter of elements, the ratio of spacing to diameter should be kept relatively constant. By varying the length of the parasites, the bandwidth of the antenna can be controlled, although any increase in bandwidth brings a larger value of VSWR into the center range of the operating band. A compromise to meet any specific operating condition should be readily determinable from the data presented.

In general, better matching conditions are possible to feed lines of characteristic impedance greater than 50 ohms, such as the 75-ohm RG-11/U or RG-12/U coaxial cable; however, if requirements call for use with a 50-ohm line, such as in aircraft and u-h-f applications, results comparable to those attainable with a higher impedance line can be achieved by the insertion of a quarter-wave matching section. Even when used directly with a 50-ohm line, the performance is significantly better than that of an ordinary dipole.

The open sleeve antenna is not envisioned as the ultimate in broadband antennas. It is, however, considered extremely effective for its simplicity. This factor is one which makes it adaptable for use over a wide range of frequency bands. The addition of two parasites is a modification that quite readily could be made to existing v-h-f and u-h-f antennas in aircraft or ships. Furthermore, in the h-f band for shore

installations, the open sleeve would generally be simpler than existing procedures for broadbanding, particularly where omnidirectional patterns are desired. Thus, because of its versatility, ruggedness, and simplicity, it would not be surprising to find the open sleeve antenna used for numerous applications in the future.

SYMBOLS USED

c	speed of light
D	center to center spacing between dipole and parasites
d	diameter of all antenna elements
f	frequency
h	length of dipole above ground plane
hf	high frequency
I	total current flowing into base of dipole
I_A	antenna mode current in dipole
I_m	spatial peak value of antenna mode current in dipole
I_T	transmission line mode current in dipole
I_{Ap}	antenna mode current in each parasite
k	quantity to account for antenna mode current shunted to parasites
s	length of parasites above ground plane
TEM	transverse electromagnetic
uhf	ultra high frequency
V	voltage of exciting generator
V_1, V_2	voltage of equivalent exciting generators
vhf	very high frequency
VSWR	voltage standing wave ratio
W	complex variable in the W-plane
z	complex variable in the z-plane
Z_A	antenna mode impedance (presented to V_1)
Z_o	characteristic impedance of antenna feed transmission line
Z_T	transmission line mode impedance (presented to V_2)
Z_{in}	driving point impedance of open sleeve antenna
Z_{0_T}	characteristic impedance for antenna transmission line mode
Z_{T_t}	transmission line mode terminal impedance
β	wavelength constant, $2\pi/\lambda$
λ	wavelength
Ω	Hallen's constant, $2 \ln \frac{4h}{d}$
ω_r	antiresonant angular frequency

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