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Practical Matching Techniques on the Smith Chart

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THE PROBLEM

Present in an assembled form the techniques used with the Smith Chart when developing matching networks for broadband antennas.

RESULT

The basic problems involved in the application of these techniques are covered in detail, with illustrations showing each step on the Smith Chart.

RECOMMENDATION

Disseminate this information to naval shipyards and other activities throughout the Armed Forces where the work is concerned with antennas and their operation.

ADMINISTRATIVE INFORMATION

Work was performed in the Electromagnetics Division in conjunction with SC 06301, S-F006 03 04, Task 7046 (NEL B1-27). This report covers work done at intervals during 1960 and was approved for publication 31 March 1961.

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ILLUSTRATIONS

INTRODUCTION

Among the least understood phases of radio engineering, as far as the majority of engineers are concerned, are the techniques by which an antenna is matched to the transmission line. In the case of broadband antennas, a relatively few know the methods by which a matching network is developed and, to make the situation even more unfortunate, the published information on the techniques used has been sketchy. This report is intended to fill the need for a detailed explanation of these techniques.

PROPERTIES OF THE SMITH CHART

Much has been written about the Smith Chart, its construction and its uses. Its properties are therefore well known. However, one of these particularly important with chart techniques is the following:

> A normalized impedance lying anywhere within the limits of the chart will have its corresponding normalized admittance given at a point lying diametrically opposite.

This useful attribute stems (1) from the fact that points located in this manner are separated by a quarter wavelength, and (2) from the normalization inherent in the chart. To illustrate, the input impedance of a quarter wavelength of line is:

$$Z_{in} = \frac{Z_o^2}{Z_L}$$

$$\frac{Z_{in}}{Z_o} = \frac{1}{Z_L \frac{1}{Z_o}}$$

$${}_{in}z_1 = \frac{Y_L}{Y_o} = {}_L y_1$$

USE OF OVERLAY FOR FACILITATING WORK ON CHARTS

From what has just been said, an antenna impedance curve, for instance, could be changed to an admittance curve by moving point by point. Actually, this process would be too time-consuming in cases when it is constantly necessary to change back and forth. Hence, the impedance curve is plotted on an overlay. A practical way to go from one position to another using this overlay is by means of a heavy cardboard of convenient size with a thumbtack pushed through it. The Smith Chart is placed on the board and carefully centered on the thumbtack. Finally, the overlay is added. To permit return to the exact position, the $\frac{R}{Z_0}$ axis is drawn on the overlay and marked for position identification. An impedance curve plotted on this overlay can now be rapidly changed to an admittance curve (or vice versa by simply turning it 180 degrees. The selection of a matching component and its arrangement in the circuit are important to successive steps and the preliminary estimates of a move are made easier by being able to see the curve in either position as required.

SIGNS OF REACTANCES AND SUSCEPTANCES

It is necessary to keep in mind the sign of the reactance or susceptance to be added, and to make the addition algebraically. Thus, if a point has a susceptive component of +0.25 "chartmho" (normalized susceptance), and an inductive element the susceptance of which is -0.4 chartmho is added to it in parallel, the resulting susceptance would be:

$$b_1 = 0.25 + (-0.4) = -0.15 \text{ chartmho}$$

While this bit of algebra will give the new location of the point without difficulty, it is important, when studying the over-all attack on the impedance or admittance curve, to observe that positive values in each case move the points clockwise along the constant resistance (conductance) circles on which they are located while negative values move them counterclockwise.

Finally, if the reactance component of an impedance has been changed by adding at some frequency an increment of either inductive or capacitive reactance, this increment will differ at other frequencies. To illustrate, if the change in reactance is -2 chart ohms at 3 Mc/s, find the change at 6 Mc/s. The minus sign in front of 2 indicates that the change is "capacitive."

From $$X_c = \frac{1}{2\pi fC} \tag{1}$$

it is seen that the change at other frequencies (f_x) will be

$$-2\,\frac{f_3}{f_x}$$

and, specifically, for 6 Mc/s

$$-2\,\frac{3}{6} = -1$$

What has just been said about reactances and their dependence on the frequency applies to susceptances as well. Thus, if +1.5 is a change in capacitive susceptance of a point, the change at other frequencies will be proportional to these frequencies, as shown by the expression:

$$b = 2\pi fC \tag{2}$$

SOLVING A TYPICAL PROBLEM

The problem chosen to show matching techniques on the Smith Chart for the case of a broadband antenna starts with a typical impedance curve of such an antenna, except that the number of frequencies at which the impedances were measured has been reduced to nine to avoid cluttering the chart. Ordinarily, in the range from 2-6 Mc/s it is good practice to measure the impedance every two-tenths of a megacycle, corresponding to a total of 21 measurements. It is also of interest that impedance data are often obtained on models, particularly in the Navy. Model ships, for instance, are scaled down to $\frac{1}{48}$ of full size. In order to maintain full scale impedance-frequency relationships, the frequencies are correspondingly scaled up 48 times.

The impedance data are as shown in the following table:

Freq.(Mc/s)	Z	θ
2	143	-46
2.5	71	-13
3	70	+22
3.5	104	+47
4	150	+48
4.5	94	+31
5	115	+62
5.5	187	+33
6	54	-22

As will be seen, the data are given in polar coordinates ($Z\underline{/\theta}$). In order to plot the impedance curve on a Smith Chart these data have to be changed into rectangular form ($R+jX$). Conventionally, this would mean tedious slide-rule work. Fortunately, there is a simple technique which gets the curve onto the Smith Chart without any calculations, even to the extent of "automatic" normalization. Thus, if the data in the table are plotted on an overlay on a Z-θ chart (fig. 1A) designed for the characteristic impedance of the line feeding the antenna (it must also be of the same size as the Smith Chart being used), then this overlay can be used with the normalized Smith Chart without any more processing. Figure 1B shows the overlay on the Smith Chart in the impedance position.

The matching specification in this problem is that the standing wave ratio (SWR) on the coaxial cable shall not exceed 3. The first step, therefore, is to draw a circle centered on the Smith Chart center and passing through 3 on the $\frac{R}{Z_0}$ axis. Any impedance lying within this circle will comply with the requirement. The aim, then, is to maneuver the curve into this circle with the fewest possible moves. It should be mentioned that often a curve will defy all efforts. In such cases the antenna will have to be experimented with further. Its location relative to surrounding structures will be changed or its configuration altered. The goal is finally to obtain a curve which can be coaxed inside the limiting circle.

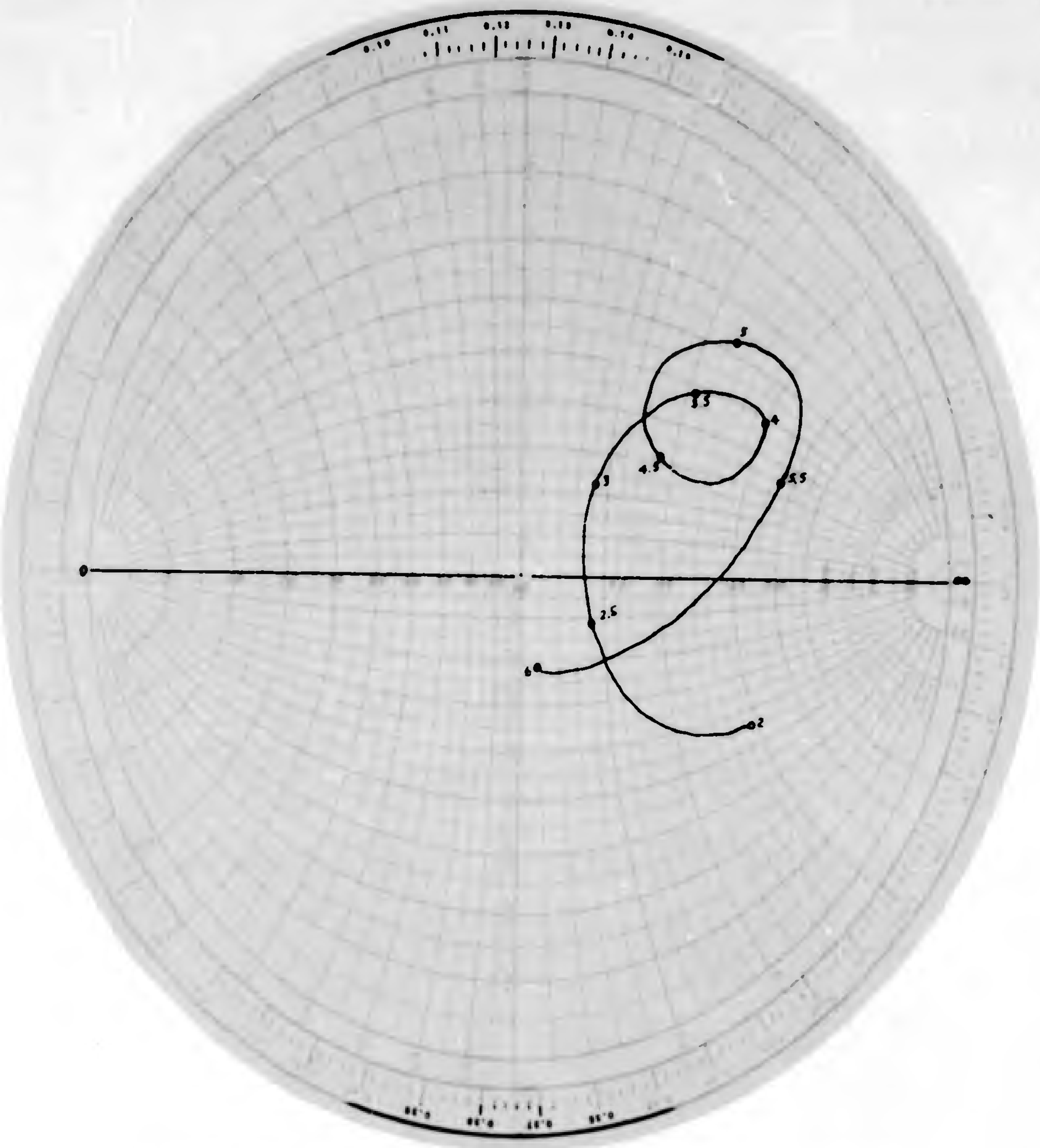


Figure 1A. Antenna impedance curve plotted on an overlay on a Z-θ chart.

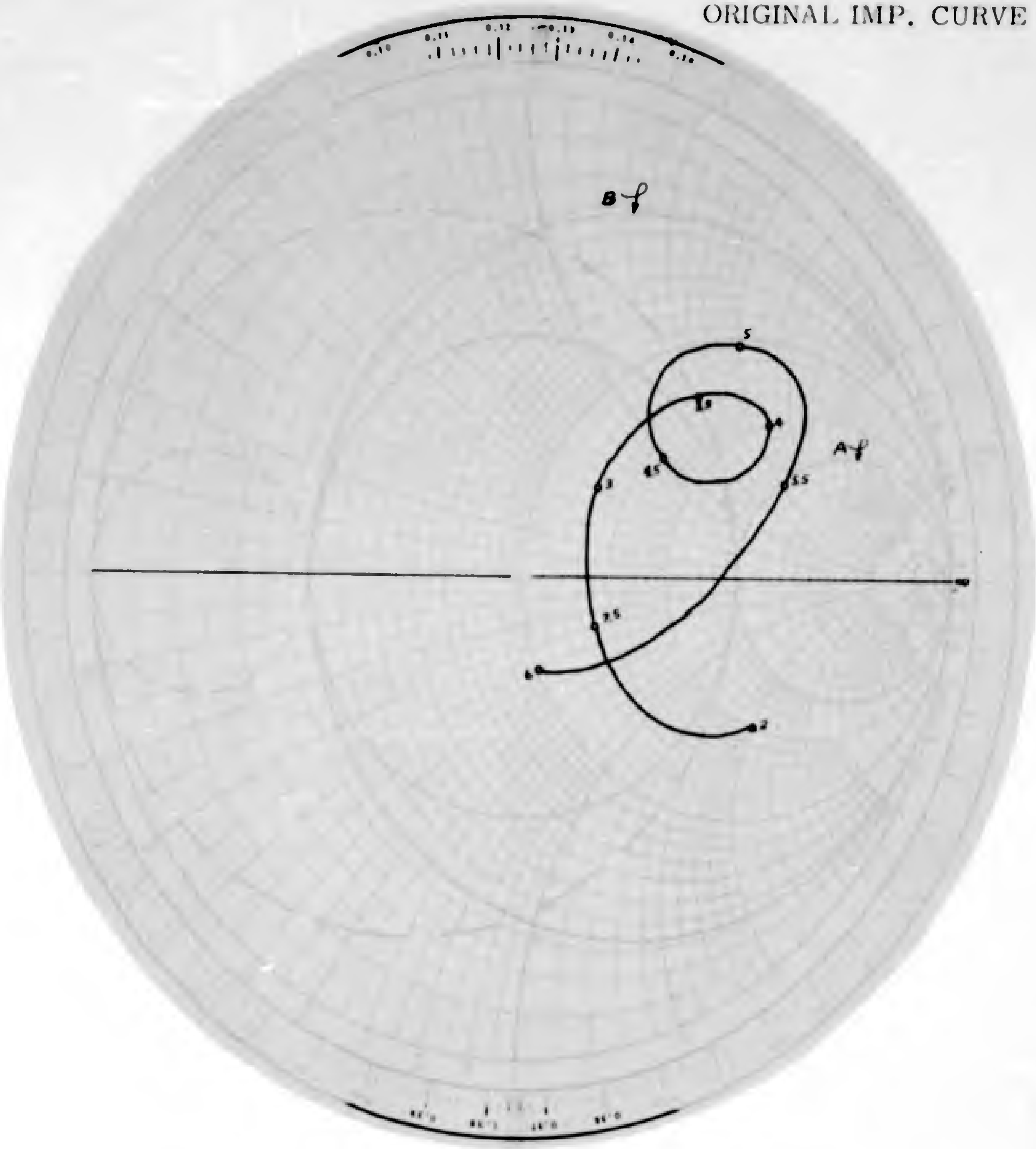


Figure 1B. Overlay from figure 1 transferred to the Smith Chart.

Assume that the curve in this problem is of such a type. A study of it in its impedance position on the Smith Chart reveals that neither an inductive nor a capacitive reactance added in series with the antenna will put it inside the circle, as the former would push the upper right-hand portion farther away while the latter would do the same with the 2 Mc/s point. Turning the overlay and studying the graph in the admittance position (fig. 2) reveals that the 2 Mc/s point can be brought closer to the others by adding an inductive susceptance. It is true that the other points will move in the same direction, but the 2 Mc/s being the lowest frequency will move the farthest ($b = \frac{1}{2\pi f L}$). Thus squeezing or "bunching" the curve, and at the same time moving it counterclockwise, will locate it in a strategic area for the next move in the impedance position.

It is not easy to decide the size of the move. However, certain limits on the extent of these movements are taken advantage of. Thus, it is impossible for any point in the area inside the circle *A* (tangent to the SWR circle on one side and to the outside boundary circle of the chart proper on its other side) to be moved inside the accepted SWR circle (fig. 1B). The point must first be moved out of circle *A* and, as a study of the chart will show, this can be accomplished only in the admittance position. Likewise, a point has to be inside the big circle *B*, tangent to the same circles in the manner shown. Both of these circles are also drawn (dashed) in their admittance position. The validity of these statements concerning the limiting boundaries should become apparent with a little study of any of the figures and need not be further elaborated on here.

The first move (fig. 2) is indicated by the dashed lines (in actual practice these lines are not drawn). The extent of the move was decided upon after a preliminary try indicated that point 5 controlled how much of a shift could be made in that it would be the first point to cross the outer boundary circle. By placing it as indicated (end of dashed line) it will be in a fairly good position for the next step. This thinking ahead was, of course, aided by turning the overlay back and forth. The 5 Mc/s point, then, has been located such that its inductive susceptance now is -0.59.

The extent of its move therefore is

$$-0.59 - (-0.39) = -0.2$$

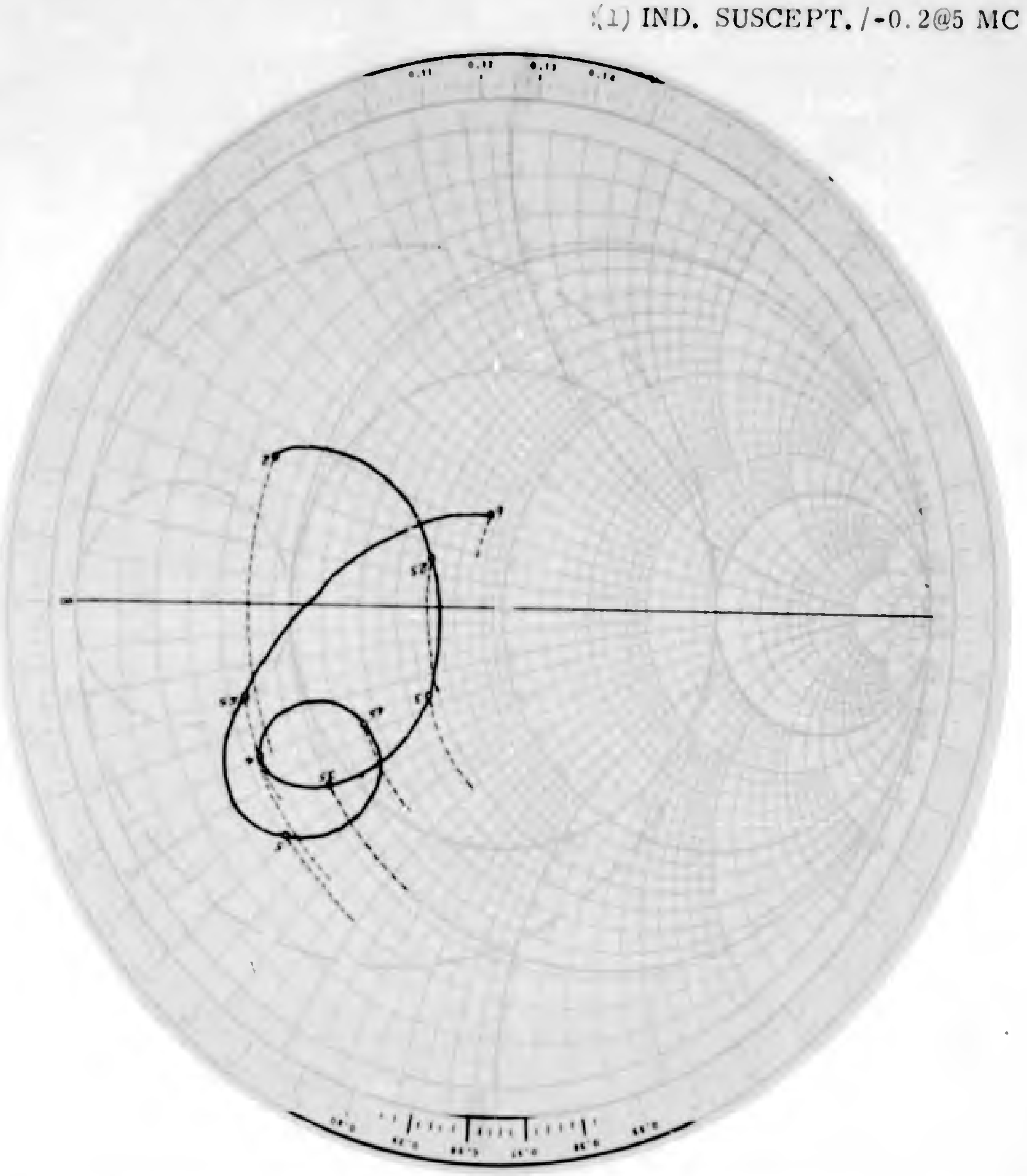


Figure 2. Overlay turned 180° showing curve in admittance position. First step indicated.

From this the change in positions of the other frequencies are calculated $b = \frac{1}{2\pi fL}$. The result is given in the following table:

Freq. (Mc/s)	$-0.2 \frac{f_5}{f}$
2	-0.5
2.5	-0.4
3	-0.33
3.5	-0.28
4	-0.25
4.5	-0.22
5	-0.2
5.5	-0.18
6	-0.17

The new locations of all points are shown in figure 2 (end of dashed lines).

Turning the overlay to its impedance position (fig. 3) will show that a capacitive reactance of proper magnitude, connected in series with the antenna, has a fairly good chance of moving the curve inside the SWR circle. Further study will reveal that the 5 Mc/s point has a considerable way to go, meaning that one will have to reckon with relatively formidable changes in the lower frequency range; thus, the 2.5 Mc/s point will go twice as far reactance-wise. A test calculation of these two points shows that it is a close decision between the two of them. The 5.5 Mc/s point is also critical, but will qualify.

The end result of the preliminaries is that, if the 5 Mc/s point is moved -0.86 chartohm, both it and the 2.5 Mc/s point will just make it with the 5.5 Mc/s point an uneasy step ahead of them. The rest of the points cause no difficulties. The results of the calculations for all points are shown in the following table:

Freq. (Mc/s)	$-0.86 \frac{f_5}{f}$
2	-2.15
2.5	-1.72
3	-1.43
3.5	-1.23
4	-1.08
4.5	-0.96
5	-0.86
5.5	-0.78
6	-0.72

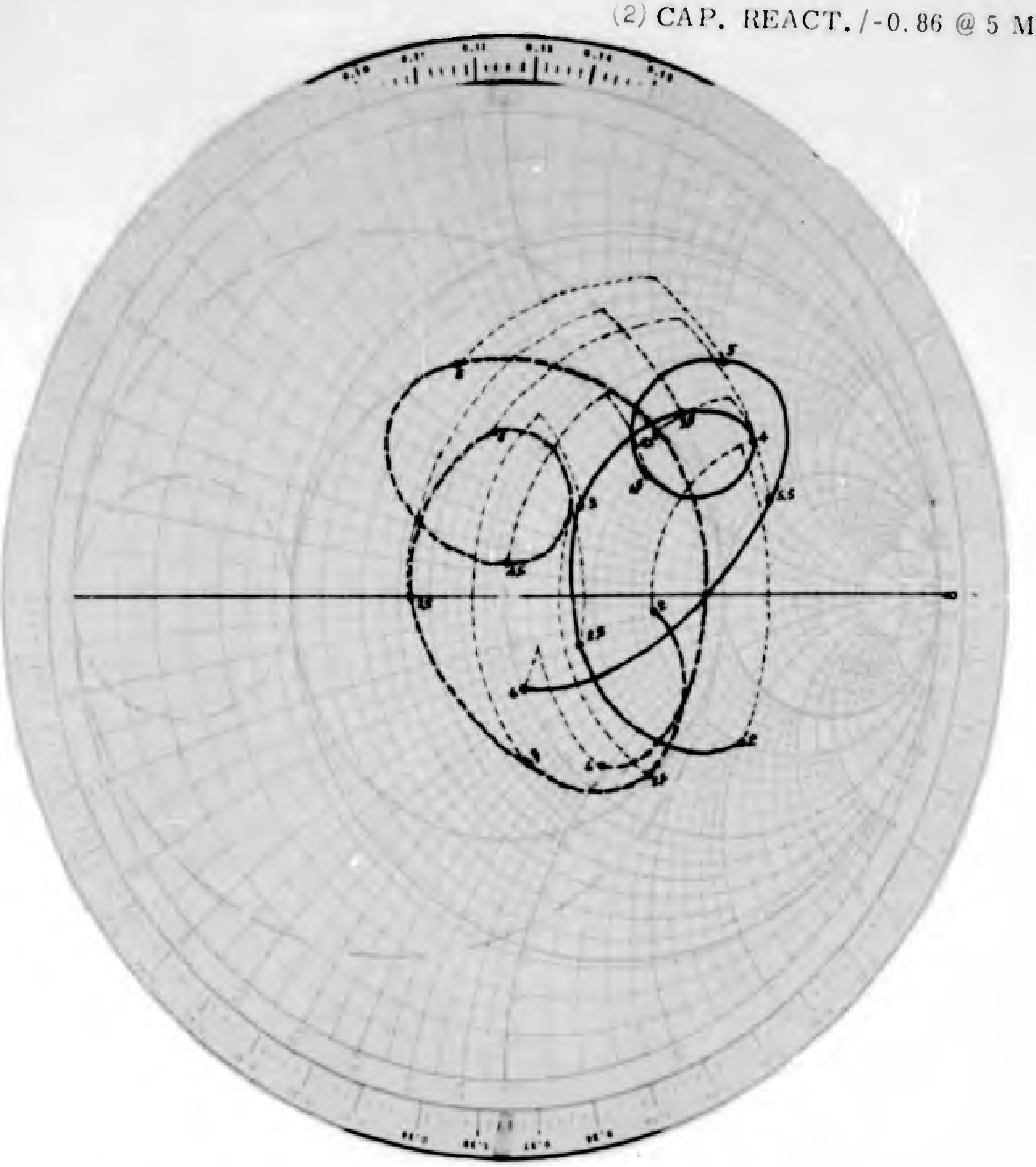


Figure 3. Overlay back in impedance position. Original and final curves shown as solid and dashed respectively.

The dashed curve in figure 3 is the final location.

The problem is now solved in regard to the requirement of a SWR of 3 or less over the range of frequencies. Whether it is the best solution or not is difficult to answer. It is only fair to state that the chances of it being the best are remote. If the requirement had been stricter the effort would have been towards a "tighter" solution (although, as it happens, it does not look as if the solution of this problem could be much improved on). This would involve more components with a consequent increase in the complexity of the problem.

In figures 4 and 5 the same initial curve has been subjected to three moves. The difference between these two solutions is that in figure 5 the first move of the 2 Mc/s point is only half that for the same point in figure 4. The second step in both figures is the same, and the difference in magnitude in the third step is only slight. Thus these figures give a good idea of the effects on the final result when a step in an early move has been altered. It will be noticed that in both of these the SWR has been improved somewhat over the first, but hardly enough to warrant the use of one or more components in the matching network. It should also be observed that this trend (decreasing the first step of the 2 Mc/s point in fig. 4) could hardly continue because, while the points for 2 and 6 Mc/s have moved inward, that for 5.5 Mc/s has gone outward.

All that now remains is to calculate the inductance and capacitance, the susceptance and reactance of which were determined graphically. This is done as follows:

$$\frac{1}{2\pi f_5 L} = b_1 Y_0$$

where

b_1 = -0.2 chartmho at 5 Mc/s as obtained in first move

Y_0 = characteristic admittance of the cable $= \frac{1}{Z_0}$

f_5 = 5 Mc/s

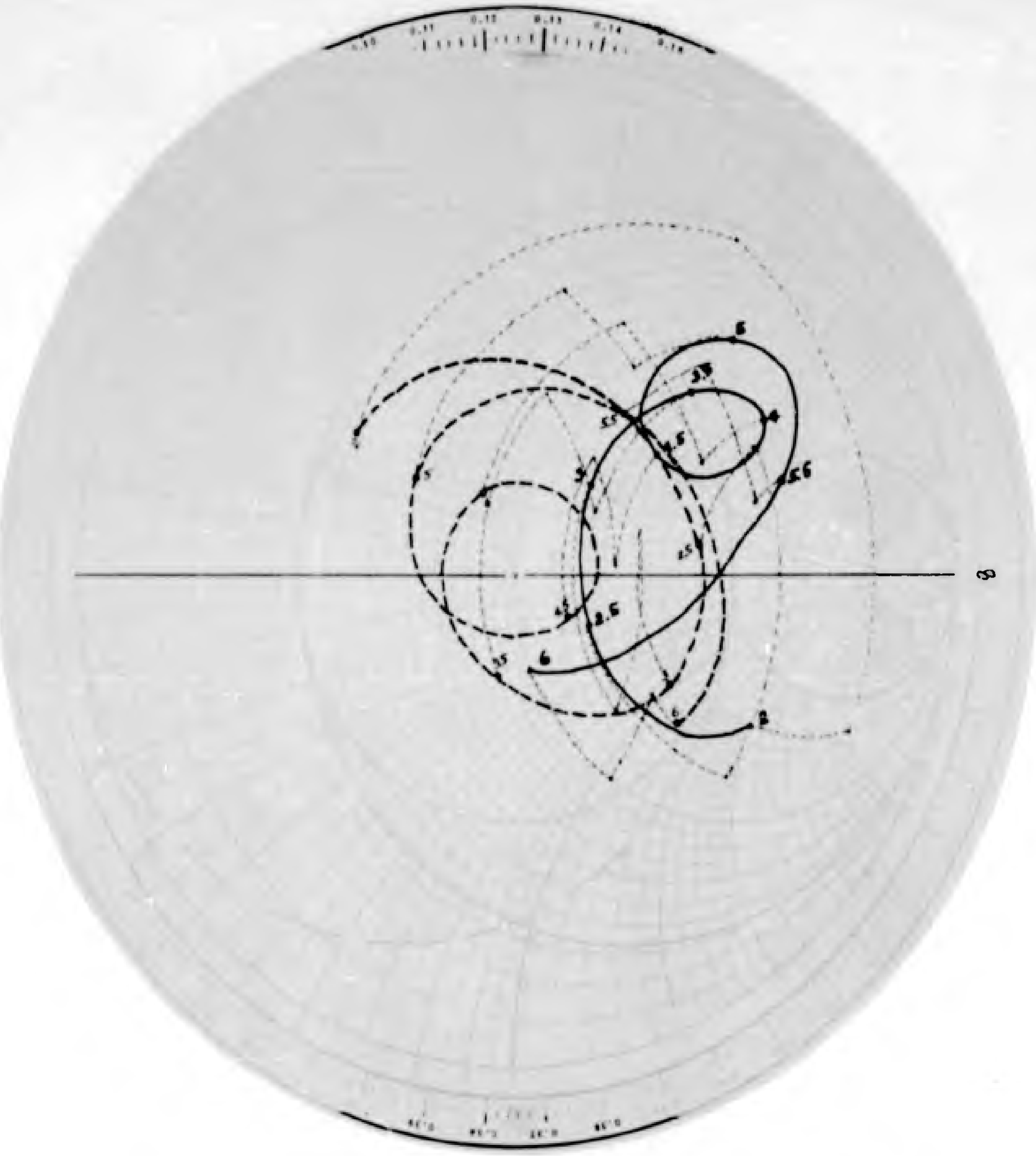


Figure 4 How a change of the initial attack on the same impedance curve affects the final curve.

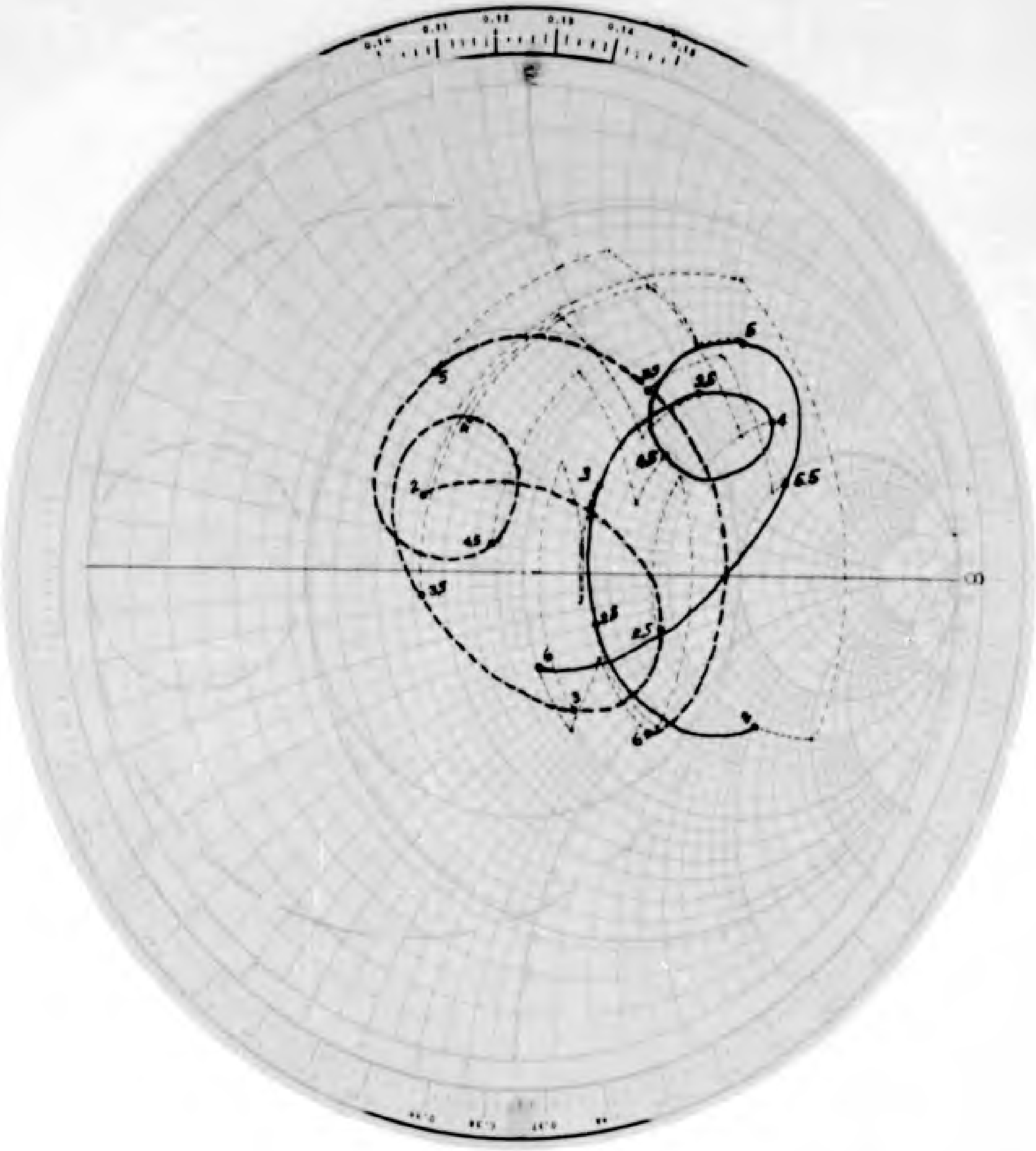


Figure 5. Similar moves to those in figure 4, except that the first step is twice as large.

Substituting,

$$\frac{1}{2\pi(5)L} = 0.2\left(\frac{1}{50}\right)$$

$$L = \frac{50}{2\pi(5)(0.2)} = 7.96\ \mu h$$

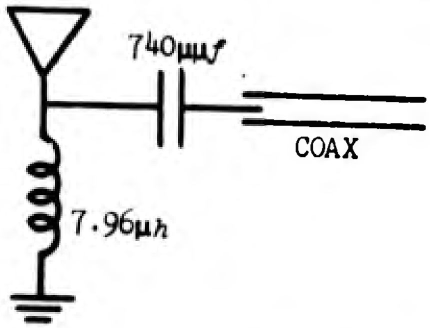
The capacitance is likewise calculated from the data obtained in the second move:

$$\frac{1}{2\pi f_5 C} = x_1 Z_0$$

$$\frac{1}{2\pi(5)C} = 0.86(50)$$

$$C = \frac{1}{2\pi(5)(0.86)(50)} = 740\ \mu\mu f$$

The antenna and the network are shown schematically below.



Figures 6 to 11 show another example of the problem. The impedance was measured at 21 frequencies in the range of 2 to 6 Mc/s (scaled up for model work purpose by 48). Normally, instead of using a separate overlay for each step, as has been done in these figures, all steps would be shown on one overlay, using colored pencils to keep track of the points. The separate overlays are used here as an aid to the reader.

In all these illustrations (figs. 6 to 11) the initial curve is represented by dots and the result of a move by small circles. Thus, the starting curve in figure 8, for instance, would be dots copied from the circles in figure 7.

ORIGINAL IMP. CURVE

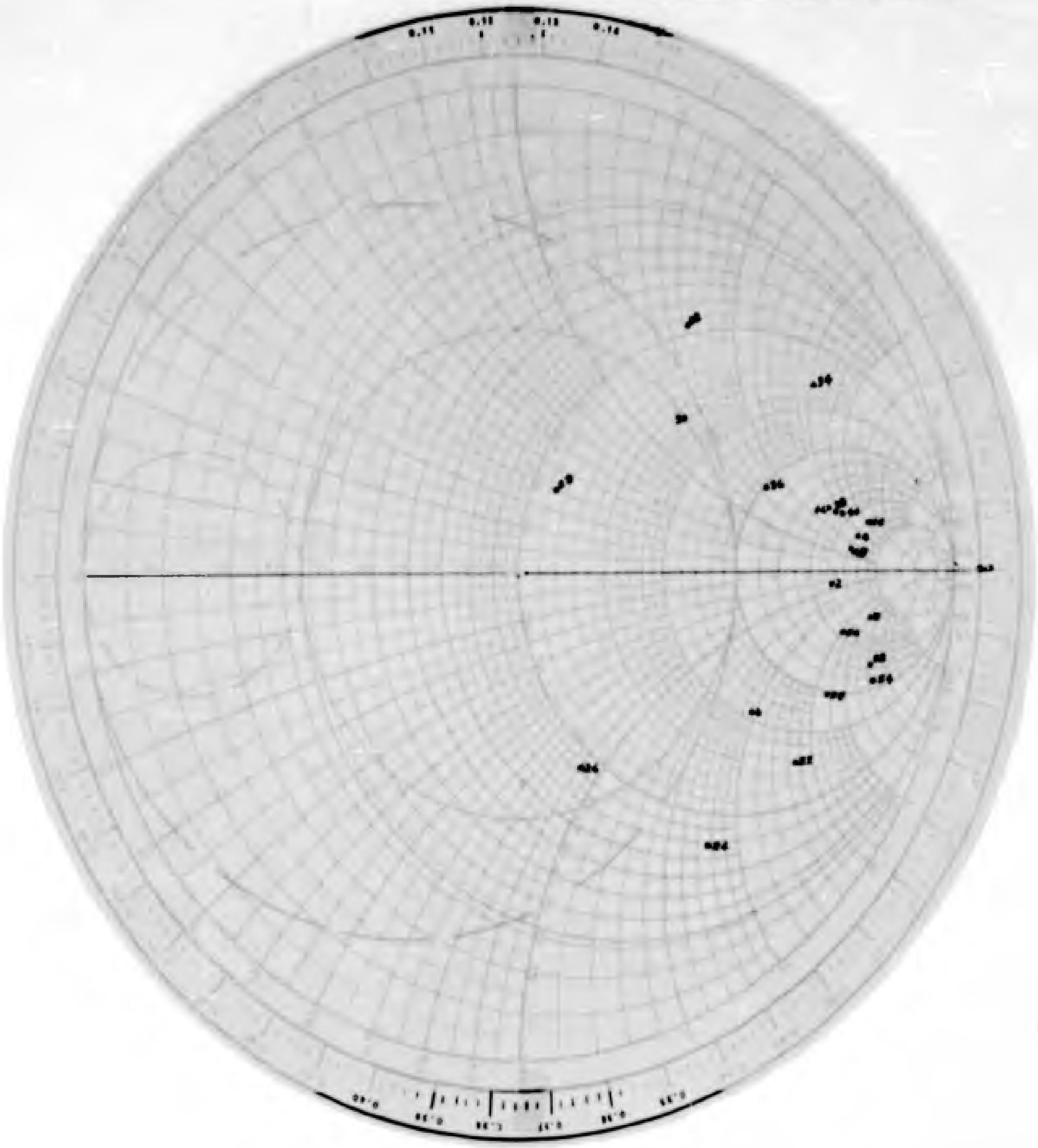


Figure 6. An impedance plot with 21 points between 2 and 6 Mc/s (to avoid cluttering, the curve in this and the following illustrations have not been drawn in: likewise, the decimal points in the frequency designations have been left out).

(1) PAR. CAP/+0.37 @ 5.4 MC

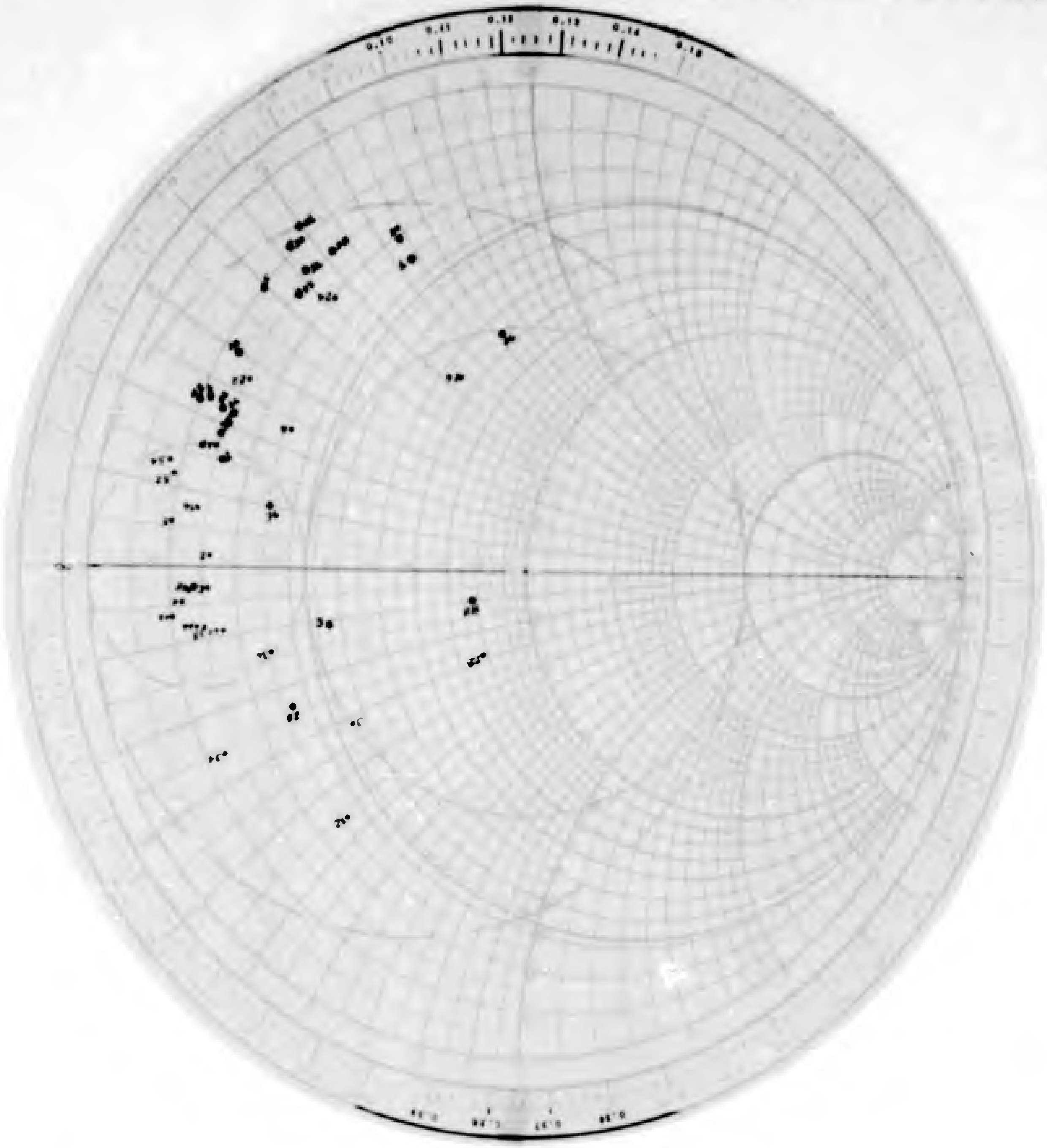
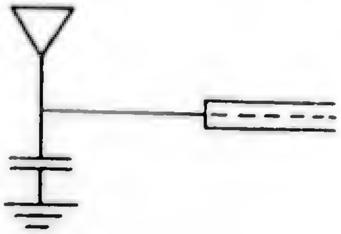
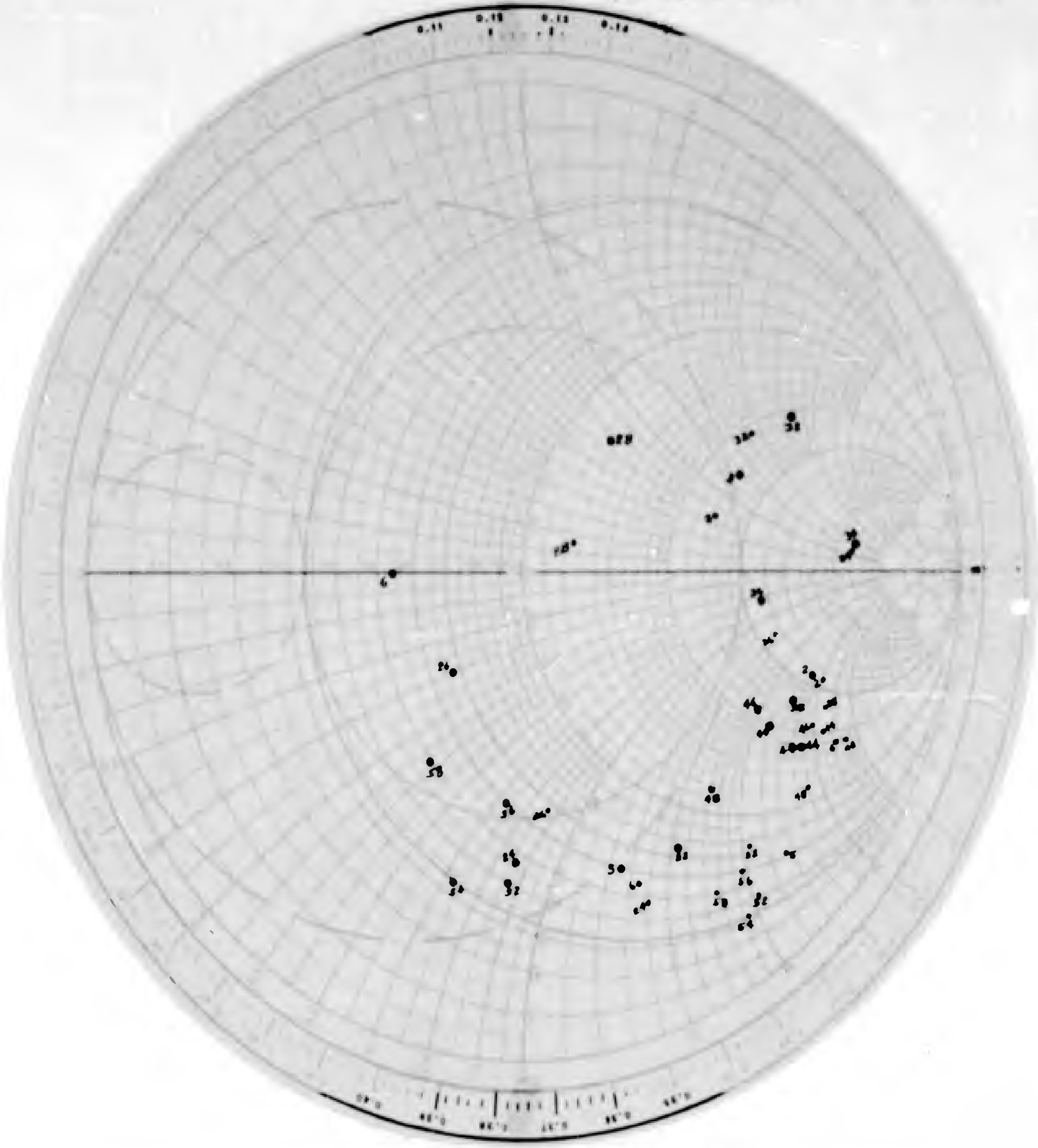


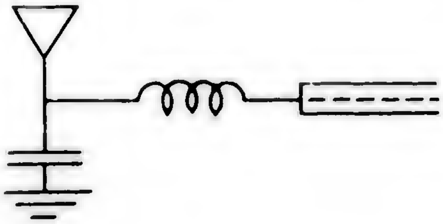
Figure 7. First step: capacitor added in parallel with antenna.

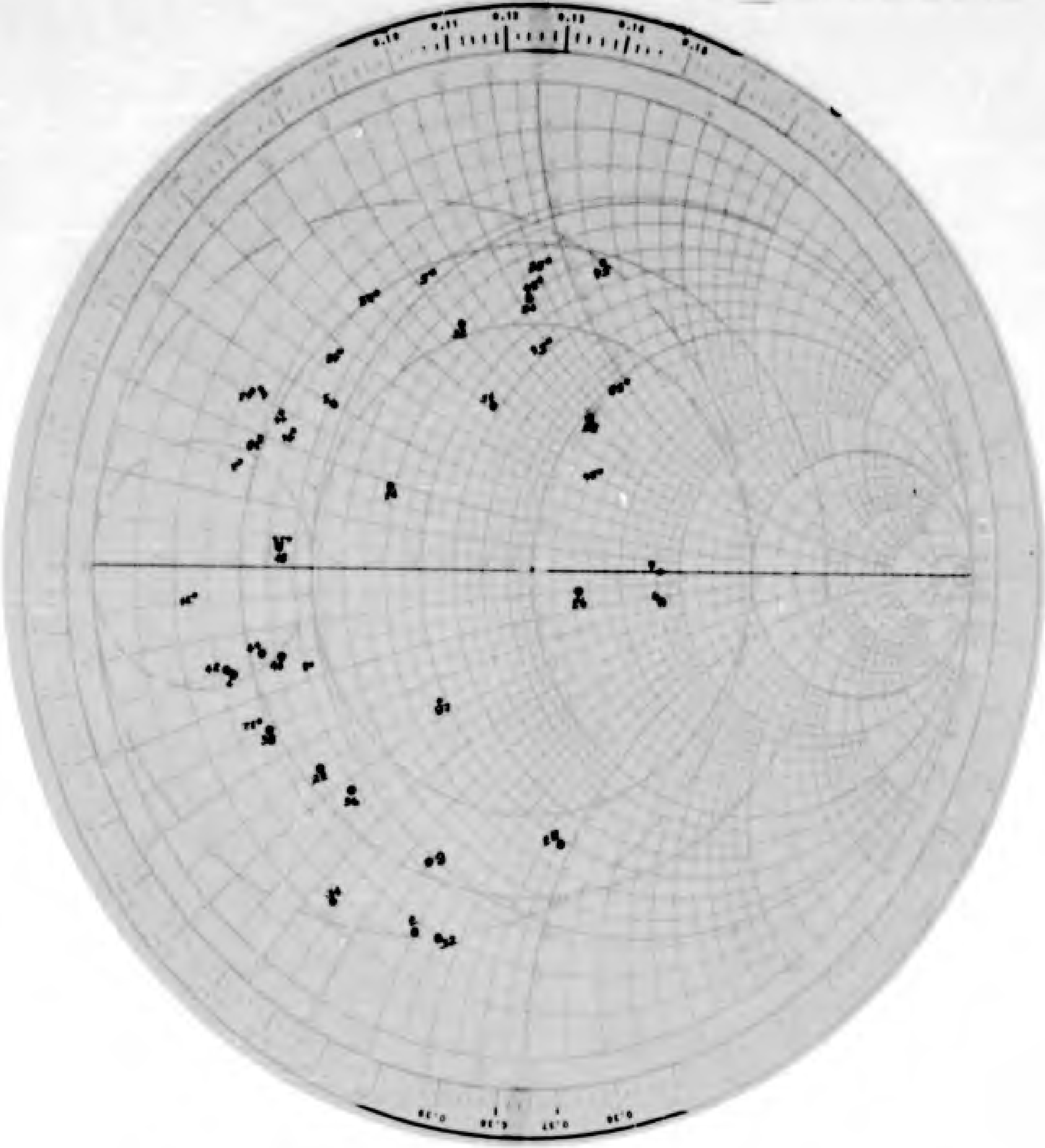




(2) SER. IND. /+1.35 @ 6 MC

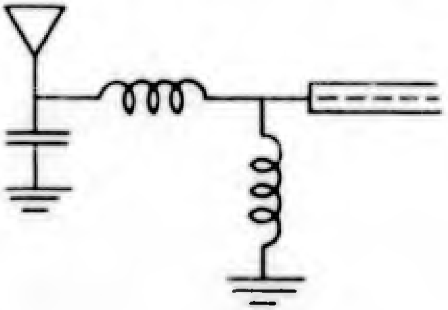
Figure 8. Second step: inductor added in series with antenna.

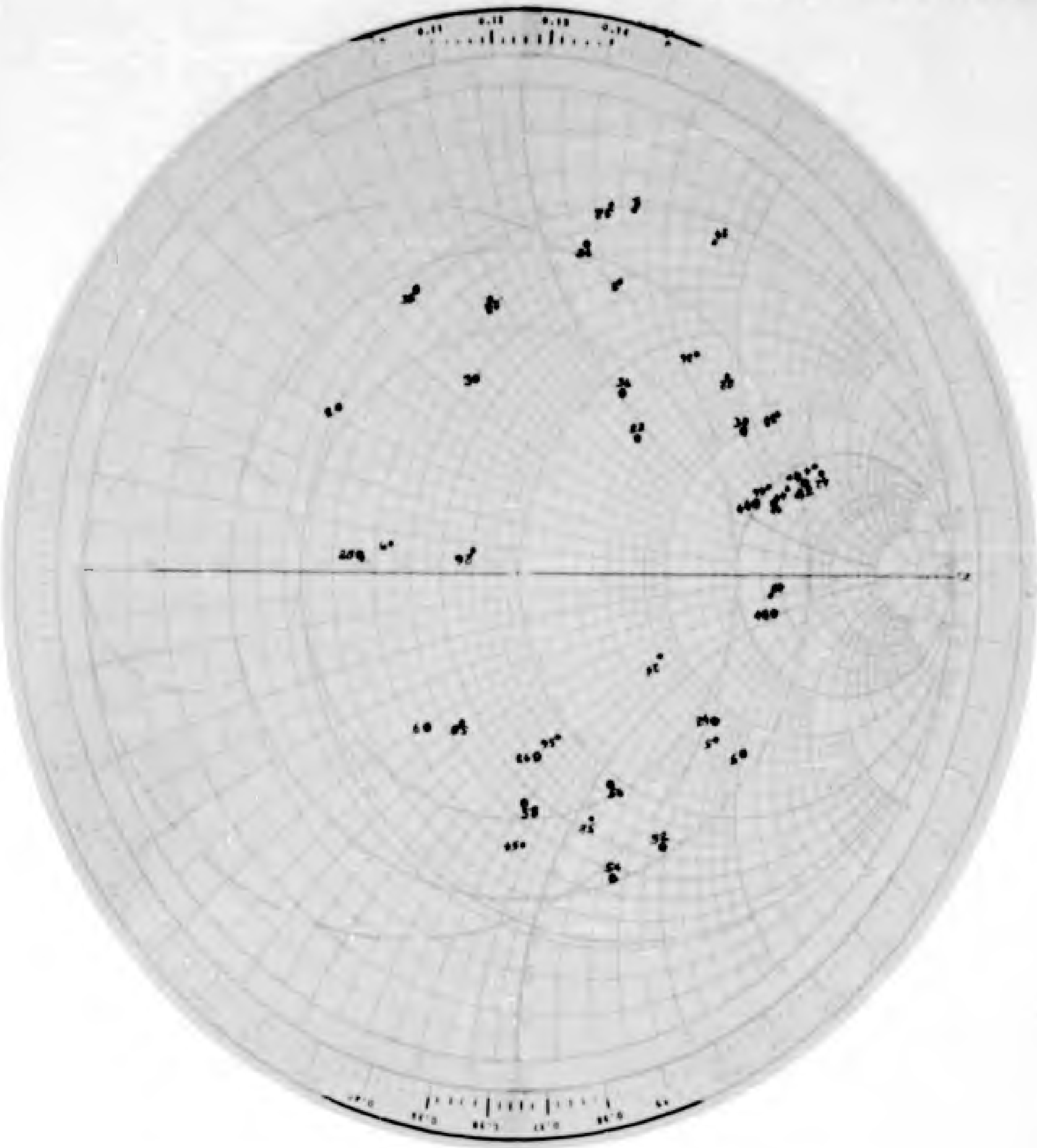




(3) PAR. IND. /-0.85 @ 2 MC

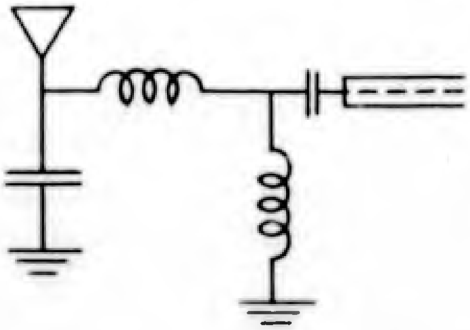
Figure 9. Third step: inductor added in parallel.





(4) SER. CAP. /-0.38 @ 5.4 MC

Figure 10. Fourth step: Capacitor added in series.



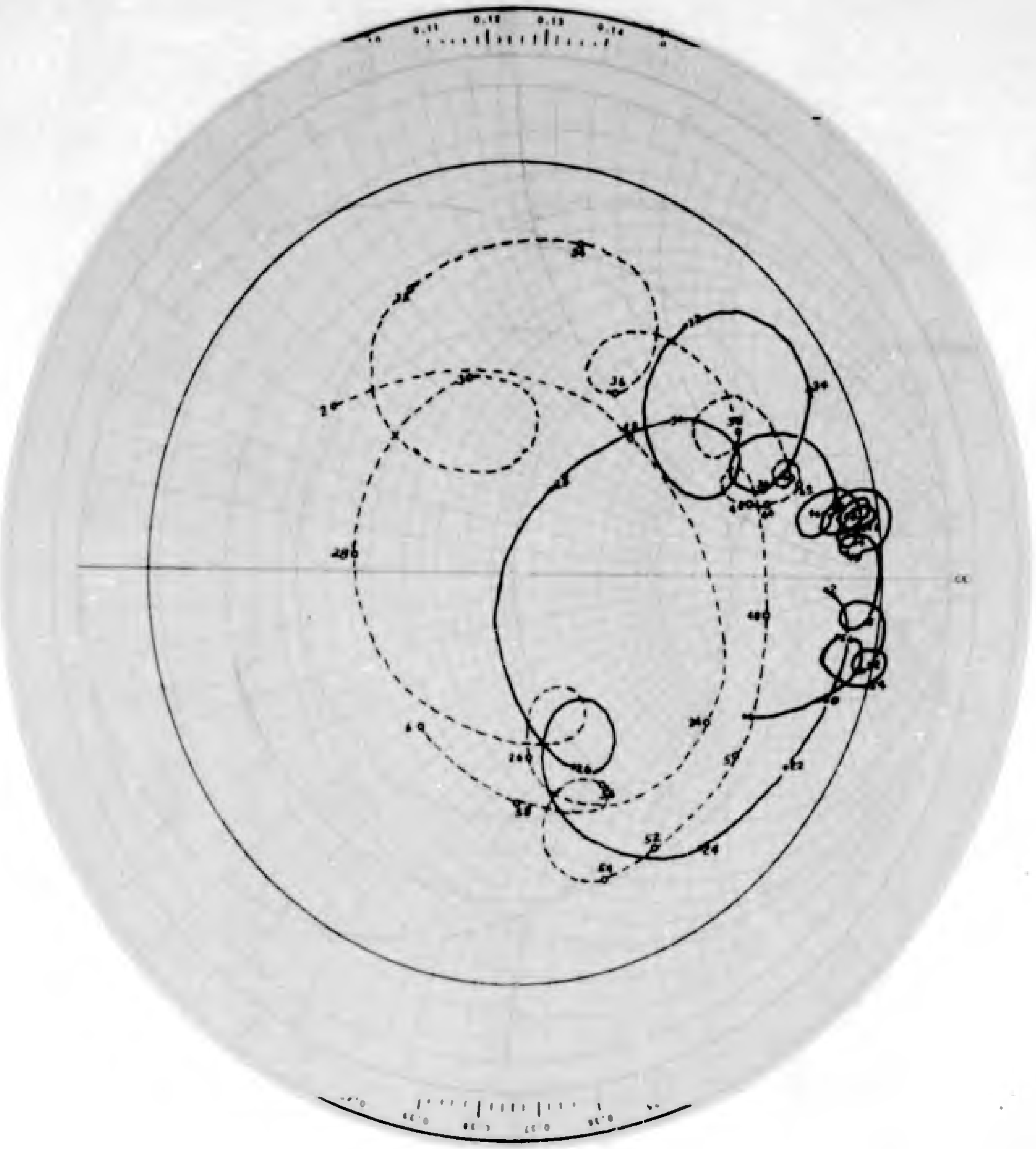


Figure 11. Original (——) and final curve (----).

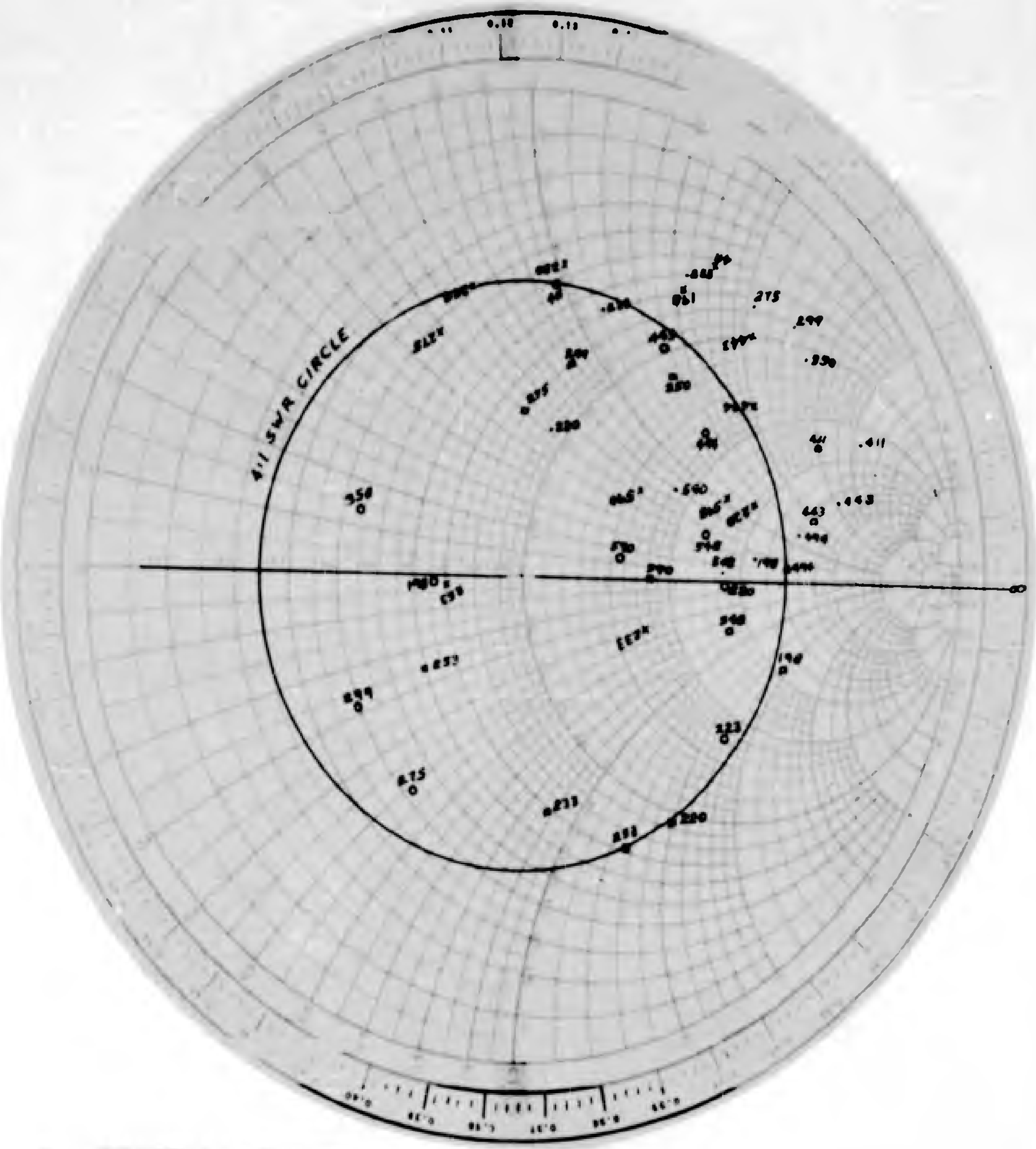
A study of figure 11 will reveal that a SWR of 3 was not achieved and probably could not be realized with any type of fixed matching network components, as any further reactance or admittance added would move points such as 5, 5.2, and 5.4 Mc/s inside but, at the same time, would drive points such as 4, 3.4, and 3.2 Mc/s farther outside, and vice versa.

As mentioned above all moves normally are made on one overlay. In figure 12 this has been done, but, instead of using colored pencils to identify each set of points, different symbols have been used. Also, in order to avoid confusion, the number of frequencies has been reduced to twelve. It can be readily seen that, if the normal number of points had been used, and the number of moves been greater, it would have been difficult to keep any single set by itself in view.

THE LINE TRANSFORMER

So far, only networks with lumped constants have been discussed, but networks with distributed constants are also used as matching components especially at the higher frequencies. The various techniques which make use of sections of lines will not be discussed here, except those associated with the line transformer which is occasionally also found in combination with lumped-constant networks. However, in what follows it will be the only matching component. As its name implies, the line transformer is a section of line, and it is placed between the load and the line when used alone. If used with a network having lumped parameters, it may be inserted in the circuit at any logical point. The input impedance of a line transformer with constant load and frequency is a function of its characteristic impedance and of its length, as given by the expression for input impedance of transmission lines:

$$Z_{in} = Z_0 \frac{\frac{Z_L}{Z_0} \cos\left(2\pi \frac{l}{\lambda}\right) + J\sin\left(2\pi \frac{l}{\lambda}\right)}{\cos\left(2\pi \frac{l}{\lambda}\right) + J \frac{Z_L}{Z_0} \sin\left(2\pi \frac{l}{\lambda}\right)}$$



● ORIGINAL CURVE
□ MOVE NO. 1 - SER. CAP. 2.12 @ 2.2 MC 650 μμf.
× MOVE NO. 2 - PAR. IND. 0.69 @ 1.98 MC 5.8 μh.
○ MOVE NO. 3 - SER. CAP. 0.75 @ 4.11 MC 1030 μμf.

NOTE: DECIMAL SIGNS ON FREQS.
OMITTED IN PLOT.

Figure 12. Performing all moves (three in this case) on one overlay. Frequency range 1.98-5.90 Mc/s.

In other words, as one proceeds up the line from the load, the measured input impedance continually changes. On the Smith Chart the locus of the input impedance as the line or transformer increases in length is given by circles centered on the chart center and, if the position of the curve is right, it is possible to swing it inside the line SWR circle (fig. 14).

Figure 13 shows the impedance curve normalized to the transmission line characteristic impedance. By drawing the outer boundary circle tangent to the definition (SWR) circle in such a manner as to include the desired portion of the curve one can determine the transformer characteristic impedance (Z'_0) by calculating the geometric mean of the "denormalized" maximum and minimum intercepts on the $\frac{R}{Z_0}$ axis. It is not to be understood that this alone will insure a transformer which will answer the purpose, because the manner in which the points of the various frequencies are located on the chart influences the choice. It does mean, however, that if there is an appropriate transformer, the characteristic impedance as obtained above will be a successful choice. In this problem

$$Z'_0 \quad \overline{(0.5)(50)\ (5.4)(50)} = 82 \text{ ohms}$$

The next step is to normalize the curve and the 2:1 SWR circle on figure 13 to this Z'_0. As the following table indicates, the impedance data are in polar form ($Z\underline{/\theta}$).

Freq. (Mc/s)	Z	θ	$\frac{Z}{Z'_0} = \frac{Z}{82}$
30	109	-45.4	1.33
40	95	-22.2	1.16
50	94	0	1.15
60	103	+20.4	1.26
70	127	+33.4	1.55
80	191	+29.5	2.33
90	148	+21.4	1.76
100	138	+60.5	1.68

This table shows that the normalization to Z'_0 = 82 ohms has been done in the polar form as this is obviously the simplest. It can now be plotted on a normalized $Z\underline{/\theta}$ chart using an overlay. This in turn is now transferred to a Smith Chart (fig. 14).

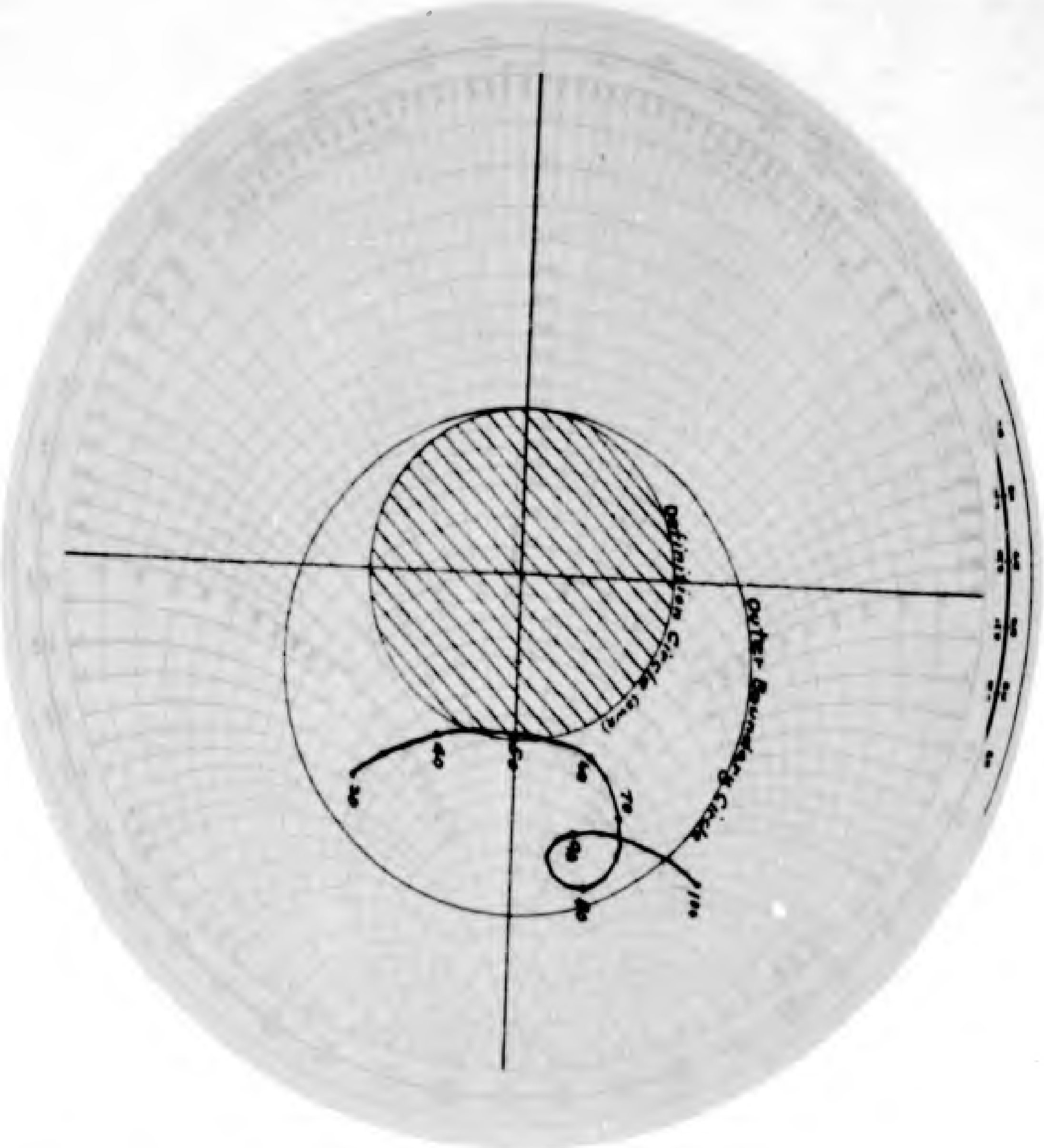


Figure 13. Obtaining the intercepts for calculating the line transformer characteristic impedance. Frequency range 30 to 100 Mc/s.

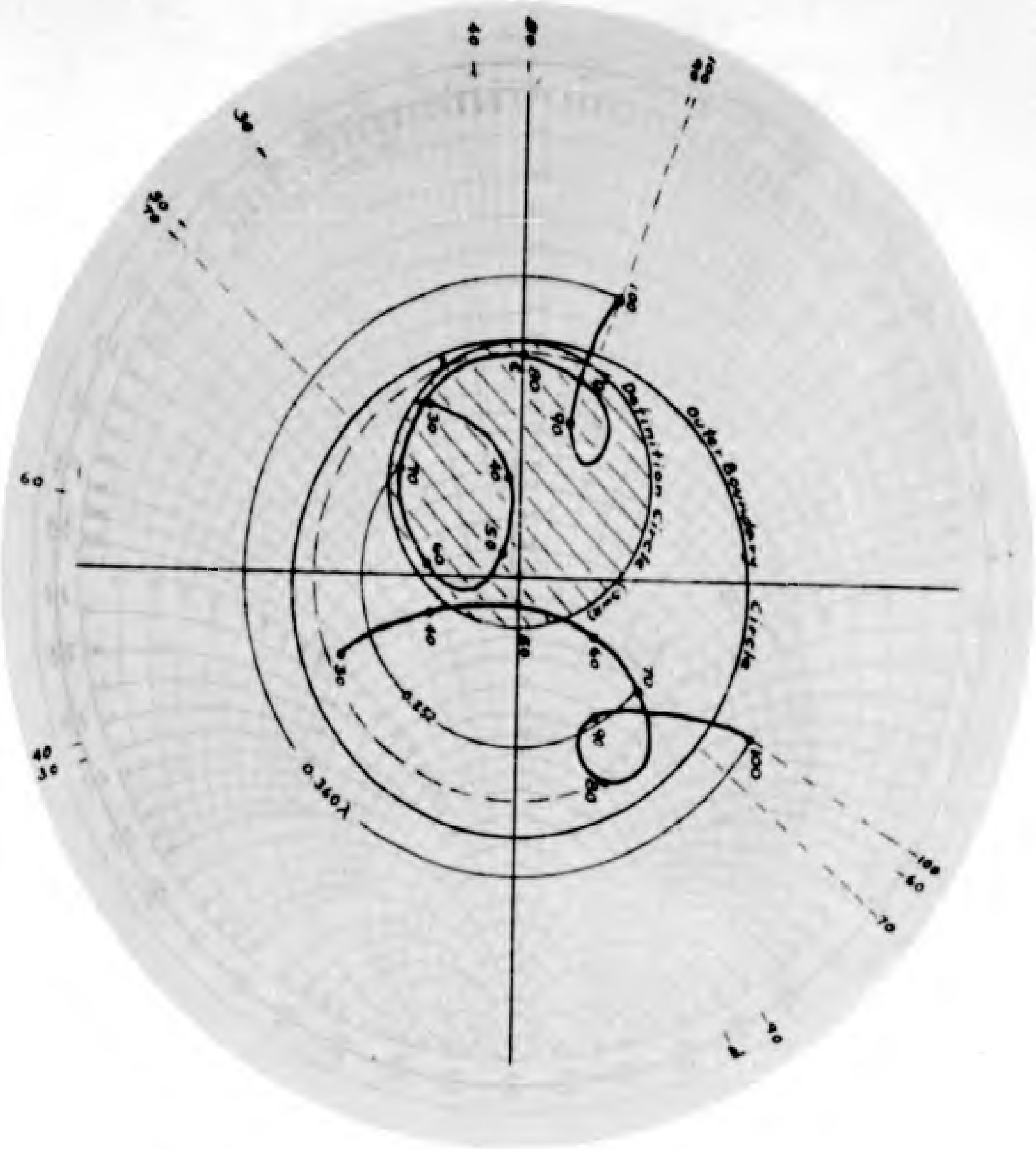
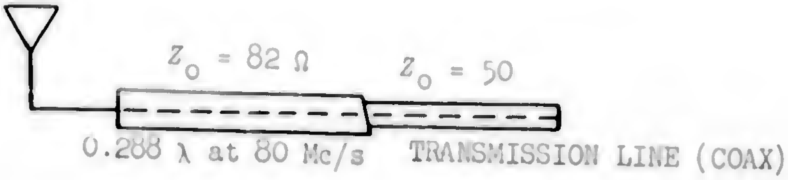


Figure 14. Original and "transformed" curve.



The 2:1 SWR circle is normalized to 82 ohms by noting that its maximum and minimum intercepts are given by $\sigma \cdot Z_o$ and $\frac{Z_o}{\sigma}$ respectively, where σ = SWR = 2. The respective intercepts are

$$\text{Max. intercept} = \frac{\sigma \cdot Z_o}{Z_o} = \frac{2(50)}{82} = 1.21$$

$$\text{Min. intercept} = \frac{Z_o/\sigma}{Z_o} = \frac{50/2}{82} = 0.35$$

The circle through these two points is then constructed as shown in figure 14.

We are now ready to determine the physical length of the line transformer, bearing in mind that once this length is decided upon, its electrical length will be different for every point on the curve. The question then is to which point should its physical length be tied. One rule is that a point where the curve departs from its general direction is considered critical. By tying the length to this point a quicker indication is obtained whether or not the other points can be moved inside. Figure 14 shows 80 Mc/s to be such a point.

After some exploratory trials it is found that an electrical length of 0.288λ at this frequency will be satisfactory. The electrical lengths at the other frequencies are given by

$$\lambda_f = \lambda_{80} \frac{f}{f_{80}}$$

The following table gives the calculated values of λ at the other frequencies:

Freq.	30	40	50	60	70	80	90	100
El. length(λ)	0.108	0.144	0.180	0.216	0.252	0.288	0.324	0.360

The dashed radial lines on figure 14 give the initial and final position on the wavelength scale of the various points. In practice they are not shown.

The result of this transformation is shown in figure 14.*

It was mentioned earlier that the line transformer sometimes is used in combination with lumped constants. The chart techniques, when used in this manner, are similar to those described above. It is of interest in this connection to note that, occasionally, it is not necessary to change to a Z_0 different from that of the line, as sometimes all that is needed is to rotate the curve to a better position on the chart for a subsequent easier attack with lumped constants of the network. Thus, the same overlay can be used, with consequent saving in time and labor.

CONCLUDING REMARKS

The various problems discussed in this report concern the matching of broadband antennas, but it should not be inferred that the chart techniques apply to such cases only. They are adapted to single frequency antennas as well. The only difference is that the problems then become considerably simpler and, instead of striving for a 3:1 standing wave ratio, one settles for nothing less than a 1:1. A problem of this type has not been included, because it is felt that, after the techniques have been mastered with broadband antennas, the procedure for obtaining a match for a single frequency antenna will suggest itself.

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*The location of each point is most easily ascertained by using the following: Simonsen, O., "Impedance Transfer Ring," Electronics, v.32, p.82, 84, 31 July 1959.

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PRACTICAL MATCHING TECHNIQUES ON THE SMITH CHART, by Ove Simonsen. 29p., 31 March 1961.

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2. Impedance matching
3. Smith Chart

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