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Calculated and Measured S_{11}, S_{21}, and Group Delay for Simple Types of Coaxial and Rectangular Waveguide 2-Port Standards

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Calculated and Measured S_{11}, S_{21}, and Group Delay for Simple Types of Coaxial and Rectangular Waveguide 2-Port Standards

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CALCULATED AND MEASURED S_{11}, S_{21}, AND GROUP DELAY FOR SIMPLE TYPES OF COAXIAL AND RECTANGULAR WAVEGUIDE 2-PORT STANDARDS

by

R.W. Beatty

ABSTRACT

Formulas, simple computer programs, graphs and tables are given to aid in the design and construction of 2-port standards for rectangular waveguide and coaxial line. Only standards consisting of reduced height waveguide, increased ODIC (outside diameter of inner conductor), or reduced IDOC (inside diameter of outer conductor) coaxial line are considered. Examples of the calculation of S_{11}, S_{21} and group delay, and their measurement with automatic network analyzers are given. Some of the important sources of error in the standards are discussed and design data are presented for specific standards.

Key words: Automatic network analyzers; coaxial; coaxial line step discontinuities; group delay; scattering coefficients; standards; 2-ports; waveguide; waveguide discontinuities.

1. INTRODUCTION

One can calculate the complex scattering coefficients S_{11} and S_{22} and the group delay τ_G of 2-port standards having simple geometries. These standards are useful for monitoring the performance of computer-controlled automatic network analyzers (A.N.A.) and for evaluating the accuracy of their measurements over broad frequency ranges. They may have additional uses in future developments.

There are many possible types of 2-port standards for which the above parameters may be calculated. Some examples of simple steps in diameters of inner and outer conductors of coaxial line and in the heights of rectangular waveguide are illustrated in figure 1(a-j). However, only three types are considered here [1]. They are the reduced IDOC (inside diameter of outer conductor) type of figure 1(b), the increased ODIC (outside diameter of inner conductor) of figure 1(c), and the reduced height (h_R) type of figure 1(j). These three types are chosen for their simplicity, ease of construction, and accuracy. For a given value of $|S_{11}|$ in the range $0 > |S_{11}| > 0.6$, the increased ODIC type of 2-port (used by Whinnery and Jamieson in 1944 [2]), has a somewhat greater sensitivity to dimensional error than the reduced IDOC type but is easier to make and more economical.

In use, the 2-port standards are inserted into a standard coaxial line or rectangular waveguide system at the output of an A.N.A. and their parameters measured over broad frequency ranges. One then compares the calculated and measured values in order to assess the performance and accuracy of the A.N.A.

In the following, formulas and simple computer programs are given, as well as some examples of calculated and measured results.

The accuracy of the calculated results are discussed. Means of estimating uncertainties due to the more important sources of error are described. Finally, design data is given for specific standards.

2. FORMULAS FOR CALCULATION

As shown in figure 2, an equivalent circuit for the above types of 2-port standards includes the normalized equivalent discontinuity susceptance $\frac{B}{Y_{OR}}$ and the attenuation α_R of the section of coaxial line or waveguide.

Using straightforward circuit analysis [3], one can derive the following formulas for S_{11} and S_{21}.

$$S_{11} = \frac{(1 + r - jbr)(1 - \frac{1}{r} - jb)e^{-2\gamma L} + (1 - r - jbr)(1 + \frac{1}{r} + jb)}{(1 - r + jbr)(1 - \frac{1}{r} - jb)e^{-2\gamma L} + (1 + r + jbr)(1 + \frac{1}{r} + jb)} \quad (1)$$

$$S_{21} = \frac{4e^{-\gamma L}}{(1 - r + jbr)(1 - \frac{1}{r} - jb)e^{-2\gamma L} + (1 + r + jbr)(1 + \frac{1}{r} + jb)} \quad (2)$$

where

$$r = \frac{Y_{OR}}{Y_{ON}}, \qquad b = \frac{B}{Y_{OR}}, \qquad \gamma = \alpha_R + j\,\frac{2\pi}{\lambda_G},$$

L = length of 2-port,

r = the ratio of the characteristic admittances of the 2-port's waveguide and of the external waveguide system,

and λ_G = waveguide wavelength.

Additional parameters used in calculating S_{11} and S_{21} for rectangular waveguide ($TE_{1,0}$ mode) and for coaxial line (TEM mode) are given in table 1.

The group delay parameter, τ_G, is defined in terms of ψ_{21}, the argument of S_{21}, as follows.

$$\tau_G = \frac{-d\,\psi_{21}}{d\omega} = \frac{-1}{2\pi}\,\frac{d\,\psi_{21}}{df}. \quad (3)$$

Alternately, we can write

$$\tau_G = \frac{-1}{2\pi}\,\lim_{\Delta f\to 0}\left(\frac{\Delta\,\psi_{21}}{\Delta f}\right), \quad (4)$$

where $\Delta \psi_{21}$ is the increment in ψ_{21} in degrees corresponding to a given increment Δf. For finite Δf,

$$\tau_G \cong \frac{(\psi_{21})_L - (\psi_{21})_H}{360\ (f_H - f_L)}, \tag{5}$$

where

$$f_H = f + 1/2\ (\Delta f), \quad f_L = f - 1/2\ (\Delta f), \text{ and } \Delta f << f.$$

We use eq (5) in calculating τ_G for 2-port standards, choosing $\Delta f < 0.1$ f. (One can test whether or not Δf has been chosen to be sufficiently small by recalculating with a still smaller Δf and comparing the differences in the τ_G's obtained in the two calculations. Of course, if Δf is made too small, errors in calculation will result as one reaches the limits of computer capability. It is not usually difficult to tell when this happens.)

3. COMPUTER PROGRAMS

In order to make the results widely useful, simple computer programs have been developed in BASIC language. These have been designated as CS11, CS21, ICS11, and ICS21 for coaxial 2-ports, and WS11 and WS21 for rectangular waveguide. They are reproduced in the appendix to this note and are based on eqs (1), (2), and (5).

At the beginning of the programs the required input data and the calculated parameters are listed. Note that the computer programs WS11 and WS21 calculate the discontinuity susceptance from published formulas [7], but one must presently determine this separately in the case of coaxial lines[1] and insert the correct value into the program. Programs CS21 and WS21 calculate group delay τ_G as well as both magnitudes and arguments of S_{21}.

[1]Calculation of coaxial line step capacitances is based upon the analysis of Whinnery, Jamieson, and Robbins, 1944 [8] and is aided by the work of Somlo, 1967 [9] and Jurkus, 1972 [10]. The step capacitances vary slowly with frequency up to the highest recommended frequencies for coaxial line and this frequency variation is presently neglected in computer programs CS11, CS21, ICS11, and ICS21. The step capacitances can also be determined by measuring the frequencies where $|S_{11}|$ is going through deep minima.

4. EXAMPLES OF CALCULATED AND MEASURED DATA

4.1 Reduced IDOC Coaxial 2-Port
(IDOC = 0.5135 inch, Length = 30.000 cm.)

The 2-port used in this example is shown in figure 3. Note that it is fitted with connectors which permit it to be inserted into a standard 50-ohm 9/16 inch (14 mm) coaxial system. Calculated values using programs CS11 and CS21 of S_{11}, S_{21} and τ_G for frequencies from 0.1 to 0.5 GHz are shown in figures 4 and 5. Measurements made on two automatic network analyzers "A" and "B" of different manufacturers are plotted with calculated data on figure 6 through 12, inclusive.

Figure 6 is a plot of S_{11} in polar coordinates.
Figure 7 shows return loss = $-20 \log_{10}|S_{11}|$ versus frequency.
Figure 8 shows ψ_{11} versus frequency.
Figure 9 is a polar plot of $-20 \log_{10}|S_{21}|$ and ψ_{21} at various frequencies.
Figure 10 shows $|S_{21}|$ versus frequency.
Figure 11 shows ψ_{21} versus frequency.
Figure 12 shows τ_G versus frequency.

4.2 Increased ODIC Coaxial 2-Port
(ODIC = 0.2651 inch, Length = 30.000 cm.)

The 2-port used in this example is shown in figure 13. Calculated values using programs ICS11 and ICS21 of S_{11}, S_{21}, and τ_G for frequencies from 0.1 to 0.5 GHz are shown in figures 15 and 15. Calculations and measured values are plotted in figures 16 to 22, inclusive.

4.3 Reduced Height Rectangular Waveguide 2-Port
(h_R = 0.0918 inch, Length = 0.4052 inch)

The 2-port used in this example[2] is shown in figure 23. Note that it has flanges for connection to a WR-90 (R-100) rectangular system. Calculated values using programs WS11 and WS21 of S_{11}, S_{21}, and τ_G for frequencies from 8 to 13 GHz are shown in figures 24 and 25. Measurements made on an automatic network analyzer are compared with calculated data in figures 26 to 31, inclusive.

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[2]For the value of h_R in this example, measurements gave a value of discontinuity susceptance 4 percent higher than that calculated from [7]. Programs WS11 and WS21 were appropriately modified to include a factor of 1.04.

Figure 26 shows a plot of S_{11} and S_{21} in polar coordinates. Figure 27 shows return loss versus frequency. Figure 28 shows ψ_{11} versus frequency. Figure 29 shows attenuation versus frequency. Figure 30 shows ψ_{21} versus frequency. Figure 31 shows τ_G versus frequency.

4.4 Discussion

The examples of calculated and measured data are presented in various forms in order to show discrepancies between measurements and calculations. The purpose of showing the data is not to evaluate or compare automatic network analyzers. More data would be required in order to average out non-repeatable results due to operator errors, etc. The data shown does demonstrate the usefulness of 2-port standards in quickly checking all of the parameters measured by an A.N.A. over a broad frequency range.

In the examples shown, the length of the 2-port is less than a half-wavelength so that there can be no cyclical variations due to multiple reflections superimposed on the calculated curves. Any such variations observed in measured data must be due to error in measurement. Also, any sudden departures of measured data from the frequency variation of the calculated curves must be due to error in measurement. (This can be observed in figure 17, for example.)

In order to use 2-port standards to evaluate the accuracies of A.N.A. measurements, all of the errors in the standards should be carefully evaluated, and this has not been done. However, some measurements of $|S_{11}|$ have been made at fixed frequencies using tuned reflectometers with quarter-wave short-circuit standards. These measurements indicate that the curves of figure 33 represent the main source of error for $|S_{11}|$ values near the 2-port's quarter-wavelength frequencies.

The stability of the 2-port standards is of a high order so that non-repeatable results are due to non-repeatable connectors or waveguide joints, and to other insertion problems, operator error in calibrating the A.N.A., or A.N.A. instability. This is demonstrated in figure 7, where the results of two runs differ by about 0.2 decibel at 0.26 GHz. Non-repeatability effects have been observed which are much larger than this.

One should be cautious in drawing conclusions from the limited amount of data presented here. It does appear from figure 10 that A.N.A. "B" yields less scatter and more accurate values of $|S_{21}|$ over the frequency range 0.1 to 0.5 GHz and for $|S_{21}|$ near unity. Both "A" and "B" give accurate phase measurements of S_{21}. In the measurement of group delay, neither A.N.A. has sufficient resolution to show any variation with frequency. It would appear that "B" has less scatter than "A" for this particular 2-port over the frequency range 0.1 to 0.5 GHz. The results of figure 31 show that for a different 2-port, measurements of group delay with A.N.A. "A" still exhibit considerable scatter, but show the correct frequency dependence of group delay.

5. DISCUSSION OF ERRORS

Although a complete investigation of all sources of error in S_{11}, S_{21}, and τ_G of the standards is desirable, it is not included in this report in order not to delay publication of useful information. The error in S_{11} due to uncertainty in the discontinuity capacitance is very small at frequencies for which the length of the 2-port is $\lambda_G/4$, but becomes large at $\lambda_G/2$ frequencies. Similarly, the value of S_{11} is insensitive to variations in the resistivity of the metal, except at and near $\lambda_G/2$ frequencies. The actual surface resistivity will vary with the fabrication process used. One can by trial and error make the calculated data fit the measured data at and near the $\lambda_G/2$ frequencies by choosing suitable values of resistivity and step capacitance and inserting these values in the appropriate computer programs CS11, ICS11, or WS11. The error in S_{21} due to uncertainty in the resistivity of the metal is also greatest at $\lambda_G/2$ frequencies. Thus, the best accuracy is expected to occur at and near $\lambda_G/4$ frequencies. It is felt that at present, the errors in calculated results are likely to be less than the errors in measured results at most frequencies, except near frequencies at which $|S_{11}|$ is going through deep minima.

Some of the sources of error are the following:

1. Dimensional tolerances in construction
   a. uncertainty in reduced height or reduced IDOC,
   b. uncertainty in width or in ODIC,
   c. uncertainty in length.
2. Approximations in calculation of equivalent discontinuity susceptance
   a. lack of rigor in theory,
   b. errors in formulas,
   c. errors in computer programs.
3. Faulty construction of standard
   a. poor surface finish,
   b. burrs,
   c. lack of surface flatness or circularity.
4. Uncertainty in dissipative loss
   a. attenuation,
   b. losses at discontinuities,
   c. losses at flanges or connectors.

5. Insertion errors

   a. misalignment

   b. system into which 2-port is inserted has non-standard dimensions and is different on one side of insertion point than the other.

A few of the major sources of uncertainty will be discussed as follows. A given uncertainty in the reduced height or reduced IDOC produces a corresponding uncertainty in the calculated value of $|S_{11}|$ at frequencies for which the length of the 2-port is an odd number of quarter wavelengths.

For small errors, we may use the following expressions.

For reduced height rectangular waveguide the fractional error in $|S_{11}|$ is

$$\frac{d|S_{11}|}{|S_{11}|} = -\frac{1 - |S_{11}|^2}{|S_{11}|} \cdot \frac{d\ h_R}{h_R}. \tag{6}$$

This is derived by differentiating the relationship

$$S_{11} = -\frac{\left(\frac{h_N}{h_R}\right)^2 - 1}{\left(\frac{h_N}{h_R}\right)^2 + 1} \tag{7}$$

from [1], which holds closely at frequencies where L is an odd number of $\lambda_G/4$. For reduced IDOC coaxial line, the corresponding fractional error in $|S_{11}|$ is

$$\frac{d|S_{11}|}{|S_{11}|} = -\frac{1 - |S_{11}|^2}{|S_{11}|} \quad \frac{d(Z_{OR})}{Z_{OR}}, \text{ or} \tag{8}$$

$$\frac{d|S_{11}|}{|S_{11}|} = -\frac{1 - |S_{11}|^2}{|S_{11}|} \cdot \frac{59.9392}{Z_{OR}} \cdot \frac{d(IDOC_R)}{IDOC_R}. \tag{9}$$

Using eqs (6) and (9), data for the curves of figures 32 and 33 were obtained. The percent error in $|S_{11}|$ corresponding to a dimensional tolerance of 0.001 inch is shown in figure 32 for several standard sizes of rectangular waveguide and coaxial line. Figure 33 shows the effect of a smaller tolerance of 0.0001 inch.

One can easily determine the limits of uncertainty in S_{11} at other frequencies by perturbing the input data to computer programs CS11 and WS11, and observing the effect on uncertainties in S_{11}, S_{21}, and τ_G due to uncertainties in various input parameters with the exception of the inside width of the rectangular waveguide.

If the inside width of the rectangular waveguide 2-port is different than the width of the waveguide system into which the 2-port is inserted, unwanted reflections will be produced which can cause error. Evaluation of the uncertainty due to this error source can be accomplished using published formulas [7], but will not be discussed further in this note.

6. DESIGN INFORMATION

A design technique which has been used is to select values of $|S_{11}|$ that one would like to produce and then calculate the reduced height h_R, increased ODIC, or reduced IDOC required to obtain these values of $|S_{11}|$ at frequencies for which the length L of the 2-port is an odd number of $\lambda_G/4$, neglecting the effects of discontinuity susceptance.

Table II gives values of h_R corresponding to various values of $|S_{11}|$ for WR90 (R-100) rectangular waveguide. Table III gives values of increased ODIC and reduced IDOC for 9/16 inch (14 mm) coaxial 2-ports and table IV gives values of increased ODIC and reduced IDOC for 7 mm coaxial 2-ports. Table V gives approximate[3] step capacitances versus $|S_{11}|$ for quarter wavelength 7 mm and 9/16 inch (14 mm) coaxial 2-ports using either increased ODIC or reduced IDOC.

The choice of length of the 2-port is arbitrary and some choices which have proven convenient are the following: for WR90 (R-100) rectangular waveguide, L = 0.4052 inch, $\sim\lambda_G/4$ @ 9.8 GHz, L = 0.8104 inch, $\sim\lambda_G/2$ @ 9.8 GHz. Figure 34 shows how $|S_{11}|$ varies across the frequency range for 2-ports having a length L = 0.4052 inch. A flatter frequency response may be obtained as shown in figure 35 by choosing L = 0.3150 inch (80 mm), $\sim\lambda_G/4$ @ 11.43067 GHz.

In order to facilitate design for still other standard sizes of rectangular waveguide or coaxial line, simple computer programs may be used. Programs IDOC and ODIC calculate the reduced IDOC and increased ODIC for quarter wavelength coaxial line 2-ports corresponding to chosen values of $|S_{11}|$. Program HR calculates values of reduced height h_R of quarter guide-wavelength rectangular waveguide 2-ports for chosen values of $|S_{11}|$. These programs appear in the appendix.

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[3] The approximate values of step capacitance were obtained by interpolating in the tables of Somlo, 1967 [9], for τ = 2.3025 which corresponds to Z_0 = 50 ohms. More accurate values will be available later both from measurements and from the computer programs of Somlo [9] and Jurkus [10].

In designing coaxial 2-ports to have many odd numbers of quarter-wave resonances, figure 36 is useful. At present, the calculated values of S_{11} are most accurate near these resonances and least accurate at frequencies where $|S_{11}|$ is minimum. Therefore, it might be advantageous to have a second 2-port standard for which $|S_{11}|$ is nearly maximum at frequencies where $|S_{11}|$ is minimum for the first 2-port standard.

7. CONCLUSION

Two-port standards in rectangular waveguide or coaxial line may be produced by reducing the height of a waveguide section, increasing the ODIC or reducing the IDOC of a coaxial line section. They may be designed to produce desired $|S_{11}|$ values at chosen frequencies. After design, the complex S_{11} and S_{21} and the group delay may readily be calculated over any desired frequency range. The accuracy of the calculated data at and near $\lambda_G/4$ frequencies is better than present measurement accuracy with many automatic network analyzers. At and near the $\lambda_G/2$ frequencies, the measured data may be assumed to be more accurate, and used to adjust the values of surface resistivity and shunt susceptance in the calculations. The 2-port standards are very stable and can be used for quickly checking performance and accuracy of automatic network analyzers over broad frequency ranges.

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9. APPENDIX

The following computer programs are given in the appendix; CS11, CS21, ICS11, ICS21, WS11, WS21, ODIC, IDOC, and HR. The purpose of each program is described in the REM statements, and use of the programs is intended to be evident to those having an elementary knowledge of computer BASIC language.

For reduced IDOC coaxial 2-port standards:

CS11 calculates return loss in decibels, magnitudes of S_{11}, and argument of S_{11} in degrees;

CS21 calculates attenuation in decibels, magnitude of S_{21}, argument of S_{21} in degrees and group delay time in nanoseconds.

For increased ODIC coaxial 2-port standards:

ICS11 calculates return loss in decibels, magnitude of S_{11}, and argument of S_{11} in degrees;

ICS21 calculates attenuation in decibels, magnitude of S_{21}, argument of S_{21} in degrees, and group delay time in nanoseconds.

For decreased height rectangular waveguide 2-port standards:

WS11 calculates return loss in decibels, magnitude of S_{11}, and argument of S_{11} in degrees;

WS21 calculates attenuation in decibels, magnitude of S_{21}, argument of S_{21} in degrees, and group delay time in nanoseconds.

ODIC: For given values of $|S_{11}|$, calculates return loss, VSWR, and the corresponding increased ODIC of $\lambda_G/4$ coaxial 2-port standards.

IDOC: For given values of $|S_{11}|$, calculates return loss, VSWR, and the corresponding reduced IDOC of $\lambda_G/4$ coaxial 2-port standards.

HR: For given values of $|S_{11}|$, calculates return loss, VSWR, and the corresponding reduced height of $\lambda_G/4$ rectangular waveguide 2-port standards.

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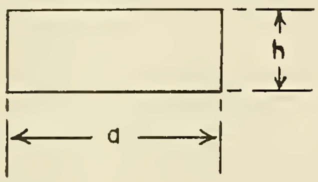
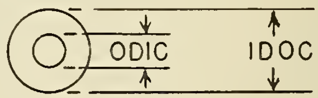
TABLE I. ADDITIONAL PARAMETERS USED IN CALCULATING S_{11}, S_{21}, and τ_G of RECTANGULAR WAVEGUIDE and COAXIAL LINE 2-PORTS.

PARAMETER	RECTANGULAR WAVEGUIDE	COAXIAL LINE
r	$\frac{h_N}{h_R}$	$\frac{\ln\left(\frac{IDOC_N}{ODIC}\right)}{\ln\left(\frac{IDOC_R}{ODIC}\right)}$
λ_G inches	$\left[\left(\frac{f}{v}\right)^2 - \left(\frac{1}{a}\right)^2\right]^{-1/2}$	$\frac{v}{f}$
$\frac{\alpha_{dB}}{ft.}$	$\frac{5.967\sqrt{\rho}\left(\frac{1}{h_R} + \frac{\lambda^2}{2a^3}\right)}{\sqrt{\lambda}\sqrt{1 - \left(\frac{\lambda}{2a}\right)^2}}$ See [4]	$\frac{13.64\sqrt{\epsilon_r}\left(\frac{\mu_{RI}\delta_I}{ODIC} + \frac{\mu_{RO}\delta_o}{IDOC_R}\right)}{\lambda_G \cdot \ln\left(\frac{IDOC_R}{ODIC}\right)}$ See [5]





a = nominal inside width (inches) of rectangular waveguide.

h_N = nominal inside height (inches) of rectangular waveguide system.

h_R = reduced inside height (inches) of waveguide 2-port.

ODIC = outer diameter (inches) of inner conductor of coaxial line.

$IDOC_N$ = nominal inside diameter (inches) of outer conductor of coaxial system.

$IDOC_R$ = reduced inside diameter (inches) of inner conductor of 2-port.

c = 2.997925×10^{10} cm/sec.

f = frequency (Hz or cycles per second).

ϵ_R = permittivity of air at 20°C, 760 mm pressure, 9° dewpoint temperature = 1.00064, see [6].

v = $c/2.54\sqrt{\epsilon_R}$ inches/sec.

λ = v/f inches.

ρ = resistivity of waveguide or coaxial line conductors (ohm-cm).

ρ_1 = resistivity of outer conductor (ohm-cm).

ρ_2 = resistivity of inner conductor (ohm-cm).

μ_{RO} = relative permeability of outer conductor.

μ_{RI} = relative permeability of inner conductor.

δ = skin depth (inches) of waveguide or coaxial line conductors. $[1/2\pi(2.54)]\sqrt{\rho/f}$ inches.

δ_o = skin depth (inches) of outer conductor of 2-port.

δ_I = skin depth (inches) of inner conductor of 2-port.

TABLE II. REDUCED HEIGHT h_R VERSUS MAGNITUDE OF S_{11} for QUARTER-GUIDE WAVELENGTH WR-90 (R-100) RECTANGULAR WAVEGUIDE 2-PORTS.

MAGNITUDE OF S_{11}	RETURN LOSS IN DECIBELS	VSWR	REDUCED HEIGHT IN INCHES
0	Infinity	1	.4
.05	26.0206	1.10526	.380476
.1	20.	1.22222	.361814
.15	16.4782	1.35294	.343891
.2	13.9794	1.5	.326599
.25	12.0412	1.66667	.309839
.3	10.4576	1.85714	.29352
.35	9.11864	2.07692	.277555
.4	7.9588	2.33333	.261861
.45	6.93575	2.63636	.246353
.5	6.0206	3.	.23094
.55	5.19275	3.44444	.215526
.6	4.43698	4.	.2
.65	3.74173	4.71429	.184226
.7	3.09804	5.66667	.168034
.75	2.49878	7.	.151186
.8	1.9382	9.	.133333
.85	1.41162	12.3333	.113899
.9	.91515	19.	9.17663E-2
.95	.445528	39.	6.40513E-2

TABLE III. INCREASED ODIC and REDUCED IDOC VERSUS $|S_{11}|$ for 9/16 INCH (14 mm) QUARTER-WAVELENGTH COAXIAL 2-PORTS.

MAGNITUDE OF S_{11}	RETURN LOSS, DECIBELS	VSWR	CHARACTERISTIC IMPEDANCE, IN OHMS	REDUCED IDOC IN INCHES	INCREASED ODIC IN INCHES
0	Infinity	1	50.0012	.5625	.24425
.05	26.0206	1.10526	47.5606	.540056	.2544
.1	20.	1.22222	45.2278	.519441	.264497
.15	16.4782	1.35294	42.9874	.500384	.27457
.2	13.9794	1.5	40.8258	.48266	.284653
.25	12.0412	1.66667	38.7308	.466081	.294778
.3	10.4576	1.85714	36.6909	.450486	.304983
.35	9.11864	2.07692	34.6953	.435735	.315308
.4	7.9588	2.33333	32.7335	.421704	.325799
.45	6.93575	2.63636	30.7948	.408283	.336508
.5	6.0206	3.	28.8682	.395368	.347501
.55	5.19275	3.44444	26.9414	.382861	.358853
.6	4.43698	4.	25.0006	.370662	.370662
.65	3.74173	4.71429	23.0289	.358668	.383058
.7	3.09804	5.66667	21.0047	.346758	.396215
.75	2.49878	7.	18.8987	.334785	.410384
.8	1.9382	9.	16.6671	.32255	.425951
.85	1.41162	12.3333	14.2377	.309738	.44357
.9	.91515	19.	11.4711	.295767	.464524
.95	.445528	39.	8.00661	.279156	.492164

TABLE IV. INCREASED ODIC and REDUCED IDOC VERSUS $|S_{11}|$ for 7 mm QUARTER-WAVELENGTH COAXIAL 2-PORTS.

MAGNITUDE OF S_{11}	RETURN LOSS, DECIBELS	VSWR	CHARACTERISTIC IMPEDANCE IN OHMS	REDUCED IDOC IN INCHES	INCREASED ODIC IN INCHES
0	Infinity	1	50.0522	.2759	.1197
.05	26.0206	1.10526	47.6092	.264881	.12468
.1	20.	1.22222	45.2739	.254759	.129633
.15	16.4782	1.35294	43.0312	.245403	.134575
.2	13.9794	1.5	40.8675	.236702	.139522
.25	12.0412	1.66667	38.7703	.228564	.14449
.3	10.4576	1.85714	36.7283	.220908	.149497
.35	9.11864	2.07692	34.7307	.213667	.154564
.4	7.9588	2.33333	32.7669	.20678	.159712
.45	6.93575	2.63636	30.8263	.200193	.164967
.5	6.0206	3.	28.8977	.193854	.170361
.55	5.19275	3.44444	26.9689	.187715	.175932
.6	4.43698	4.	25.0261	.181728	.181728
.65	3.74173	4.71429	23.0524	.175842	.187812
.7	3.09804	5.66667	21.0261	.169997	.19427
.75	2.49878	7.	18.918	.164122	.201224
.8	1.9382	9.	16.6841	.158118	.208865
.85	1.41162	12.3333	14.2522	.151831	.217513
.9	.91515	19.	11.4828	.144975	.227799
.95	.445528	39.	8.01477	.136825	.241368

TABLE V. APPROXIMATE STEP CAPACITANCES VERSUS $|S_{11}|$ FOR QUARTER WAVELENGTH 7 mm and 9/16 INCH (14 mm) COAXIAL 2-PORTS USING EITHER INCREASED ODIC or DECREASED IDOC.

$\|S_{11}\|$ for Quarter Wavelength 2-Port	STEP CAPACITANCE--femtofarads			
	7 mm		9/16 inch (14 mm)	
	Decreased IDOC	Increased ODIC	Decreased IDOC	Increased ODIC
0	0	0	0	0
.05	0.62	0.40	1.3	0.82
.1	1.9	1.2	3.8	2.56
.15	3.6	2.5	7.4	5.1
.2	5.7	4.1	11.7	8.3
.25	8.2	6.0	16.8	12.2
.3	11.	8.3	22.5	16.9
.35	14.	11	28.6	22.3
.4	17.3	14	35.3	28.6
.45	20.8	17.6	42	36
.5	24.6	21.7	50	44
.55	28.8	26.3	59	54
.6	33.3	31.8	68	65
.65	38	38	78	78
.7	44	46	89	93
.75	50	55	102	112
.8	58	67	118	136
.85	67	82	137	167
.9	80	104	163	213
.95	101	144	206	294

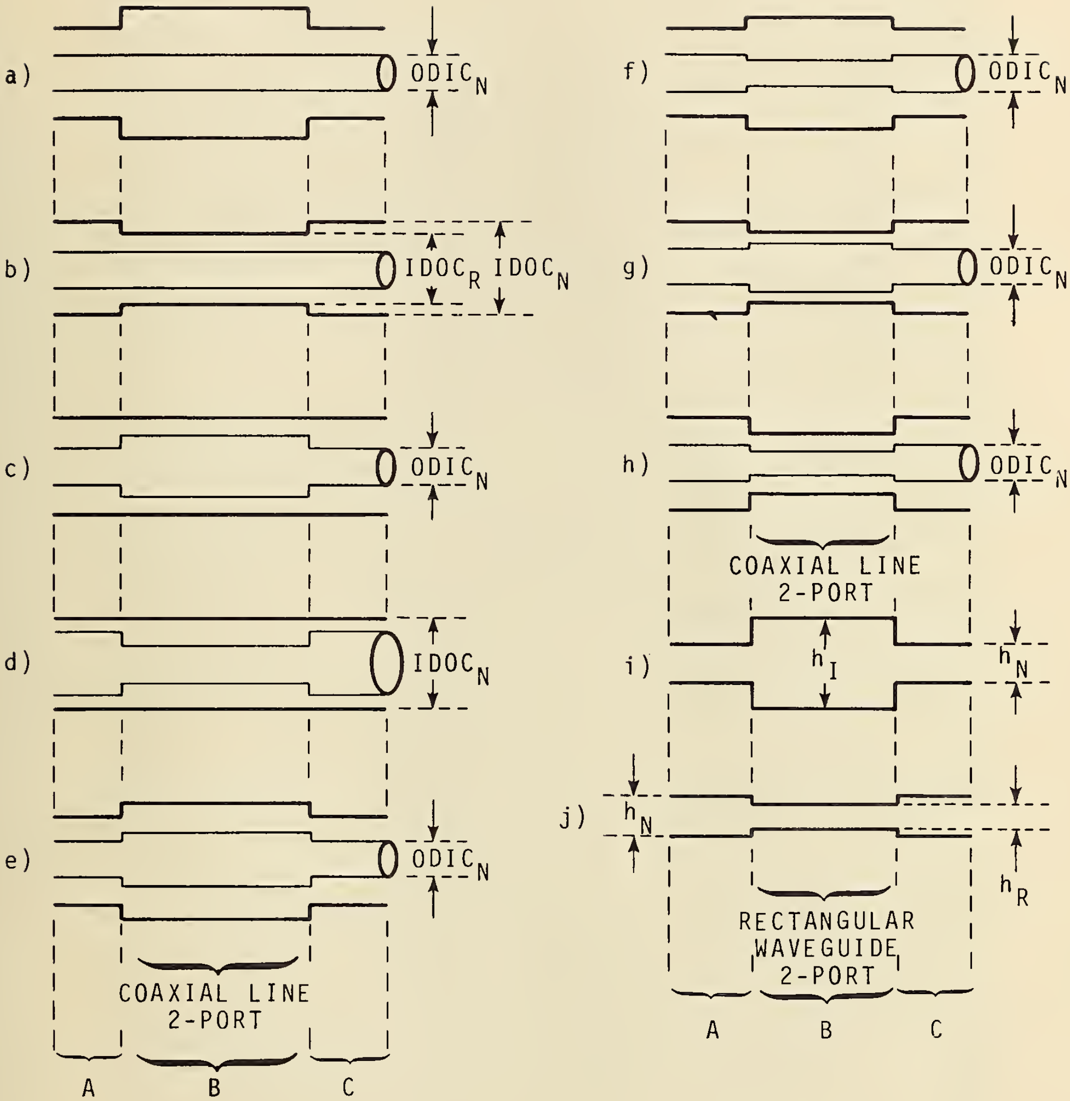


Figure 1. Examples of 2-port standards incorporating simple discontinuities in coaxial line (a-h) and rectangular waveguide (i-j). Regions A and C denote nominal coaxial cross-sectional dimensions specified by well-known standards, and region B denotes the 2-port sections having modified dimensions.

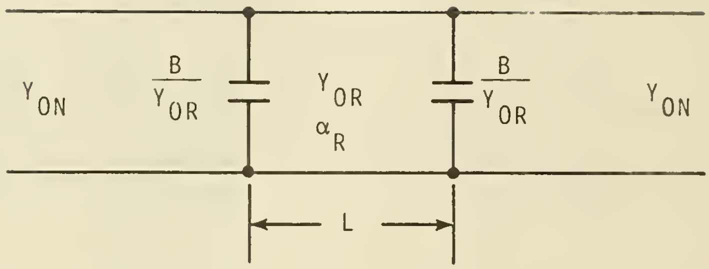


Figure 2. Equivalent circuit for dominant mode propagation in coaxial or rectangular waveguide 2-port standards of the types shown in figure 1. The characteristic admittances Y_{ON} and Y_{OR} are for the nominal standard waveguide and the 2-port section, respectively. The equivalent discontinuity susceptance is B, and the real part of the propagation constant is denoted by α_R.

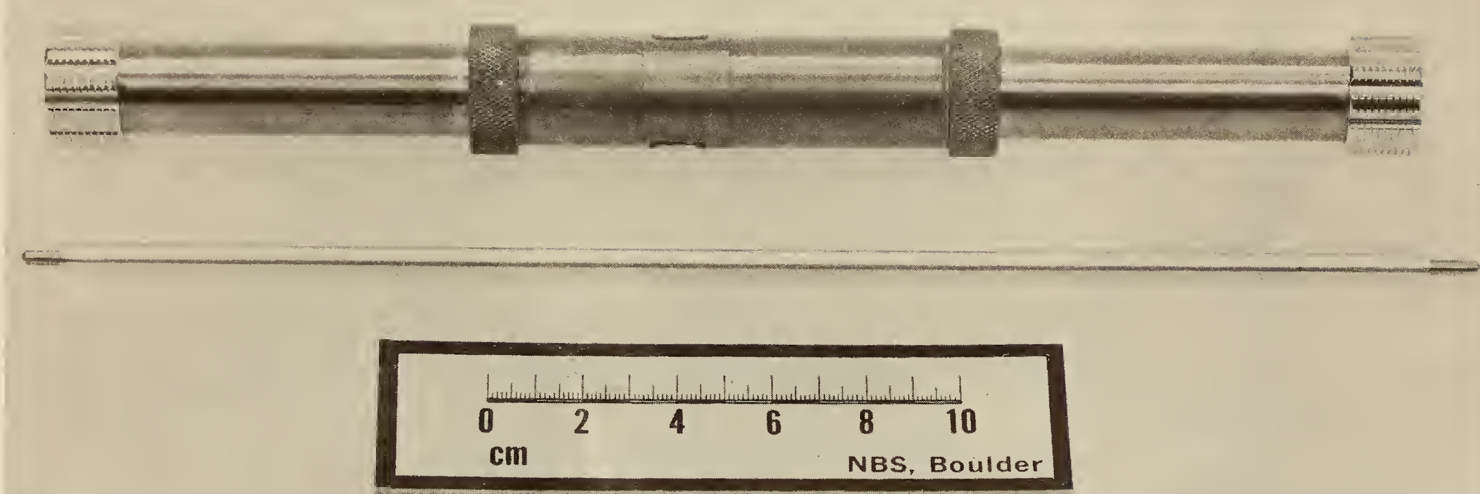


Figure 3. Photograph of reduced IDOC coaxial 2-port designed to be inserted into a 9/16 inch (14 mm) 50-ohm coaxial system.

CS11 08:56 06/04/74

FOR 9/16 INCH (14 MM) COAXIAL SYSTEM:

ODIC	.24425 INCHES
IDOC	.5625 INCHES
TEM-MODE CHARACTERISTIC IMPEDANCE	50.0012 OHMS

FOR 2-PORT:

ODIC	.24425 INCHES
IDOC	.5185 INCHES
LENGTH	11.811 INCHES
TEM-MODE CHARACTERISTIC IMPEDANCE	45.1191 OHMS
DISCONTINUITY CAPACITANCE	3.8E-15 FARADS
RELATIVE PERMITTIVITY OF AIR	1.00064
IC RESISTIVITY	.000002 OHM-CM.
OC RESISTIVITY	.000008 OHM-CM.

FREQUENCY GHZ	RETURN LOSS DECIBELS	MAG(S11)	ARG(S11) DEGREES
.1	24.368	6.04782E-2	233.74
.11	23.6677	.065556	230.137
.12	23.0523	7.03697E-2	226.536
.13	22.5103	7.49005E-2	222.937
.14	22.0331	7.91311E-2	219.34
.15	21.6137	8.30454E-2	215.746
.16	21.2468	8.66287E-2	212.153
.17	20.9279	8.98675E-2	208.563
.18	20.6537	9.27498E-2	204.974
.19	20.4213	.095265	201.387
.2	20.2285	9.74039E-2	197.802
.21	20.0734	9.91587E-2	194.219
.22	19.9547	.100523	190.637
.23	19.8714	.101492	187.055
.24	19.8227	.102062	183.475
.25	19.8083	.102231	179.894
.26	19.8281	.101999	176.314
.27	19.8822	.101366	172.734
.28	19.971	.100335	169.154
.29	20.0953	9.89088E-2	165.573
.3	20.2562	9.70936E-2	161.991
.31	20.4551	9.48956E-2	158.409
.32	20.6938	9.23228E-2	154.825
.33	20.9747	8.93848E-2	151.24
.34	21.3007	8.60924E-2	147.654
.35	21.6753	.082458	144.067
.36	22.1032	.078495	140.478
.37	22.5897	7.42187E-2	136.889
.38	23.1422	6.96453E-2	133.299
.39	23.7695	6.47923E-2	129.709
.4	24.4836	5.96787E-2	126.12
.41	25.3001	5.43245E-2	122.533
.42	26.2404	4.87506E-2	118.948
.43	27.3348	4.29793E-2	115.37
.44	28.6281	3.70335E-2	111.802
.45	30.1903	3.09373E-2	108.252
.46	32.1407	2.47152E-2	104.735
.47	34.7071	1.83926E-2	101.288
.48	38.4197	1.19954E-2	98.0246
.49	45.1127	5.55092E-3	95.5923
.5	60.4747	9.46813E-4	256.706

Figure 4. Computer printout of program CS11 for reduced IDOC coaxial 2-port.

CS21 09:18 06/04/74

FOR 9/16 INCH (14 MM) COAXIAL SYSTEM:

ODIC	.24425 INCHES
IDOC	.5625 INCHES
TEM-MODE CHARACTERISTIC IMPEDANCE	50.0012 OHMS

FOR 2-PORT:

ODIC	.24425 INCHES
IDOC	.5185 INCHES
LENGTH	11.811 INCHES
TEM-MODE CHARACTERISTIC IMPEDANCE	45.1191 OHMS
DISCONTINUITY CAPACITANCE	3.8E-15 FARADS
RELATIVE PERMITTIVITY OF AIR	1.00064
IC RESISTIVITY	.000002 OHM-CM.
OC RESISTIVITY	.000008 OHM-CM.

DELTA F FOR CALCULATION OF GROUP DELAY .005 GHZ

FREQUENCY GHZ	ATTENUATION DECIBELS	MAG(S21)	ARG(S21) DEGREES	GROUP DELAY NANOSECONDS
.1	2.40454E-2	.997235	-36.1865	1.00279
.11	2.72331E-2	.99687	-39.7954	1.00214
.12	3.04672E-2	.996498	-43.4019	1.00148
.13	3.37052E-2	.996127	-47.0061	1.00082
.14	.036902	.99576	-50.6078	1.00016
.15	4.00152E-2	.995404	-54.2072	.999523
.16	4.30018E-2	.995061	-57.8044	.99891
.17	4.58207E-2	.994739	-61.3994	.998335
.18	4.84335E-2	.994439	-64.9925	.997804
.19	5.08046E-2	.994168	-68.5837	.997328
.2	.052903	.993928	-72.1733	.996912
.21	5.46994E-2	.993722	-75.7615	.996565
.22	5.61722E-2	.993554	-79.3486	.996291
.23	5.73021E-2	.993425	-82.9349	.996093
.24	5.80768E-2	.993336	-86.5206	.995977
.25	5.84886E-2	.993289	269.894	.995942
.26	5.85352E-2	.993284	266.309	.99599
.27	5.82205E-2	.99332	262.723	.996119
.28	5.75534E-2	.993396	259.136	.996329
.29	5.65482E-2	.993511	255.549	.996614
.3	5.52252E-2	.993662	251.961	.996973
.31	5.36085E-2	.993847	248.371	.997399
.32	5.17276E-2	.994062	244.779	.997883
.33	4.96155E-2	.994304	241.186	.998422
.34	4.73094E-2	.994568	237.591	.999002
.35	4.48492E-2	.99485	233.993	.99962
.36	4.22769E-2	.995145	230.393	1.00026
.37	3.96372E-2	.995447	226.791	1.00092
.38	3.69755E-2	.995752	223.187	1.00158
.39	3.43365E-2	.996055	219.58	1.00224
.4	3.17664E-2	.996349	215.971	1.00288
.41	2.93091E-2	.996631	212.359	1.0035
.42	.027007	.996896	208.746	1.00407
.43	2.49004E-2	.997137	205.13	1.00461
.44	2.30264E-2	.997352	201.512	1.00508
.45	2.14177E-2	.997537	197.893	1.0055
.46	2.01037E-2	.997688	194.273	1.00585
.47	.019108	.997803	190.651	1.00612
.48	1.84505E-2	.997878	187.029	1.00632
.49	1.81443E-2	.997913	183.406	1.00643
.5	1.81976E-2	.997907	179.783	1.00646

Figure 5. Computer printout of program CS21 for reduced IDOC coaxial 2-port.

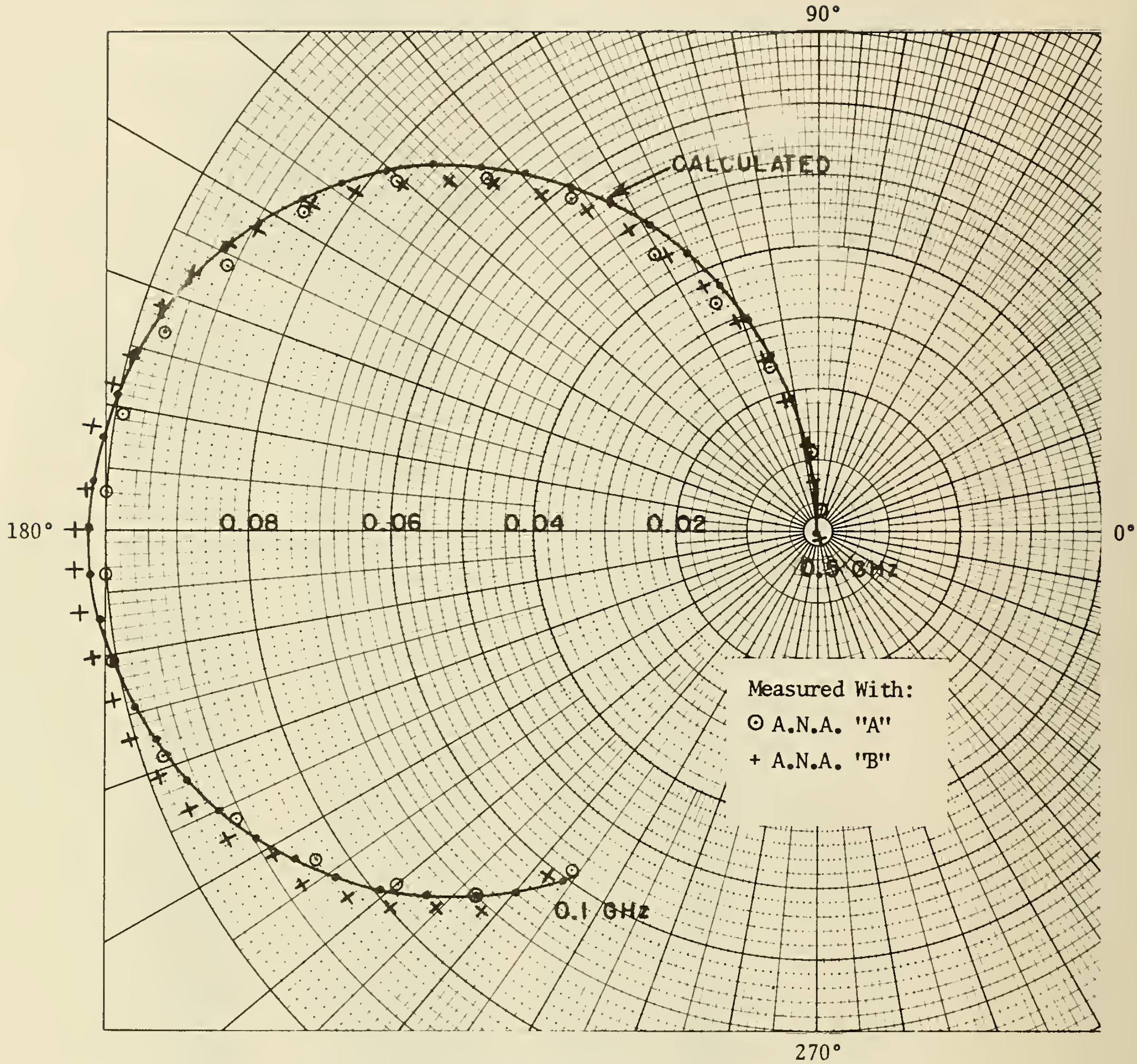


Figure 6. Polar plot of calculated and measured S_{11} of reduced IDOC coaxial 2-port for frequencies from 0.1 to 0.5 GHz.

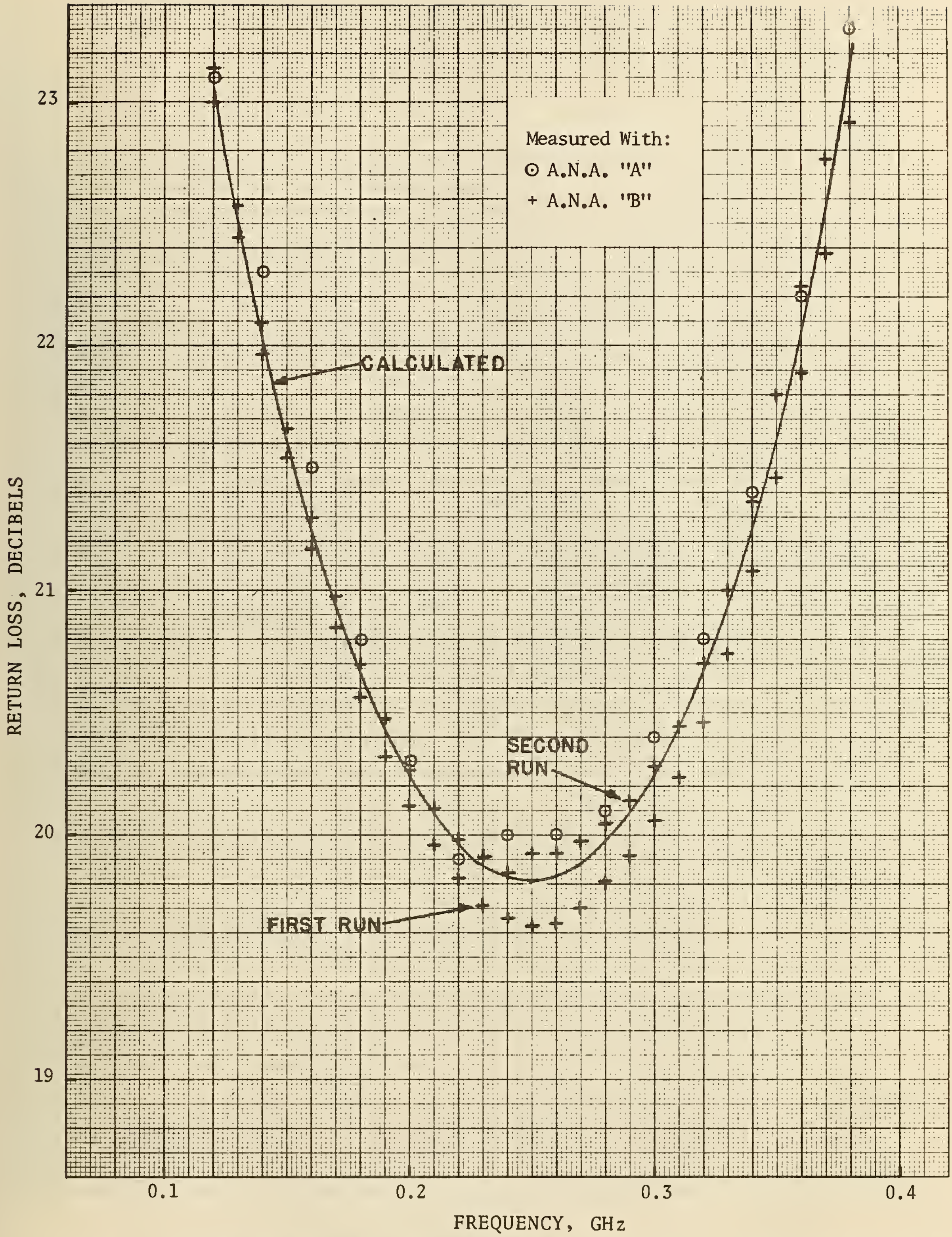


Figure 7. Calculated and measured return loss = $-20 \log_{10} |S_{11}|$ versus frequency for reduced IDOC coaxial 2-port.

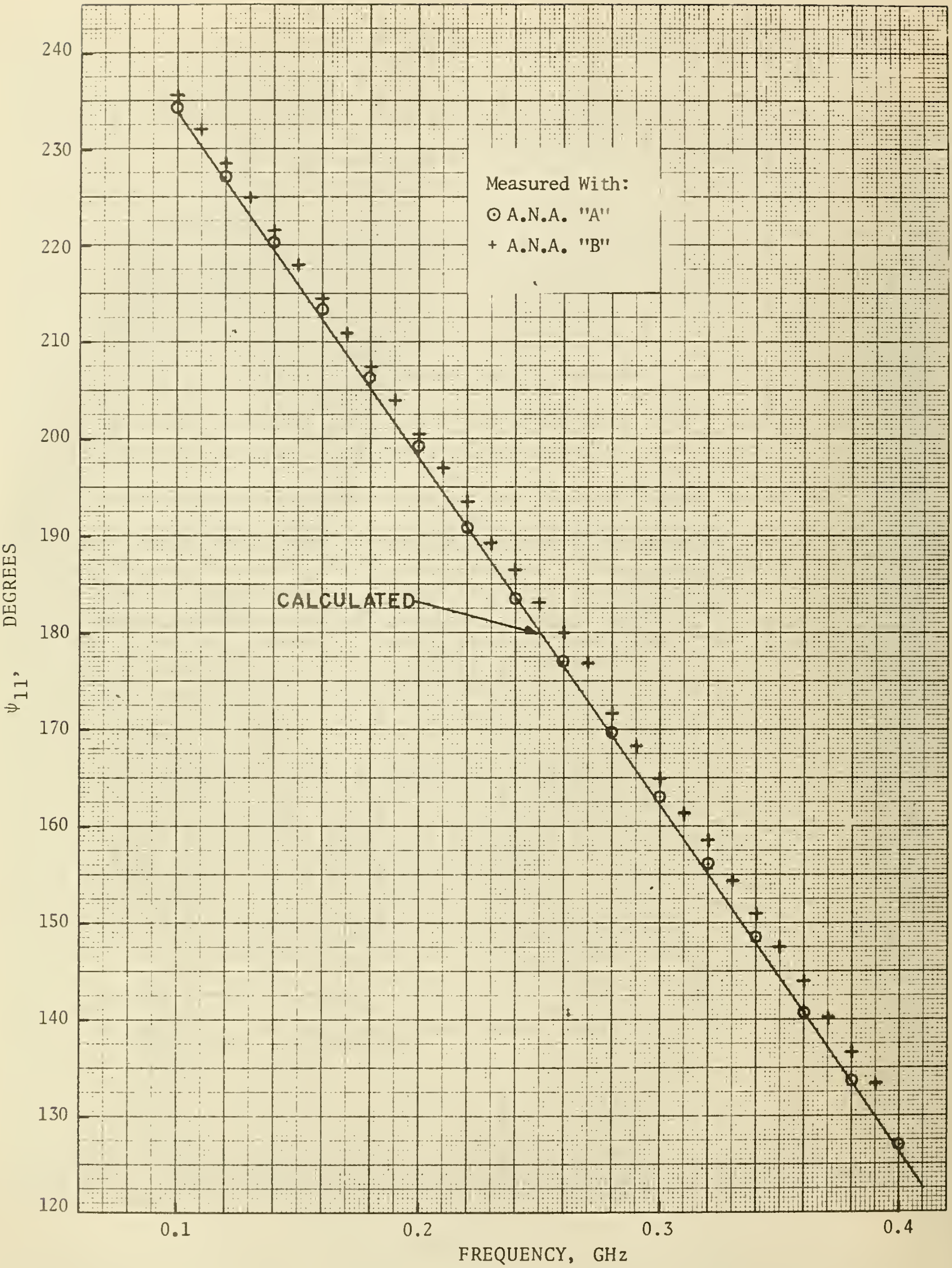


Figure 8. Calculated and measured arg $(S_{11}) = \psi_{11}$ in degrees versus frequency for reduced IDOC coaxial 2-port.

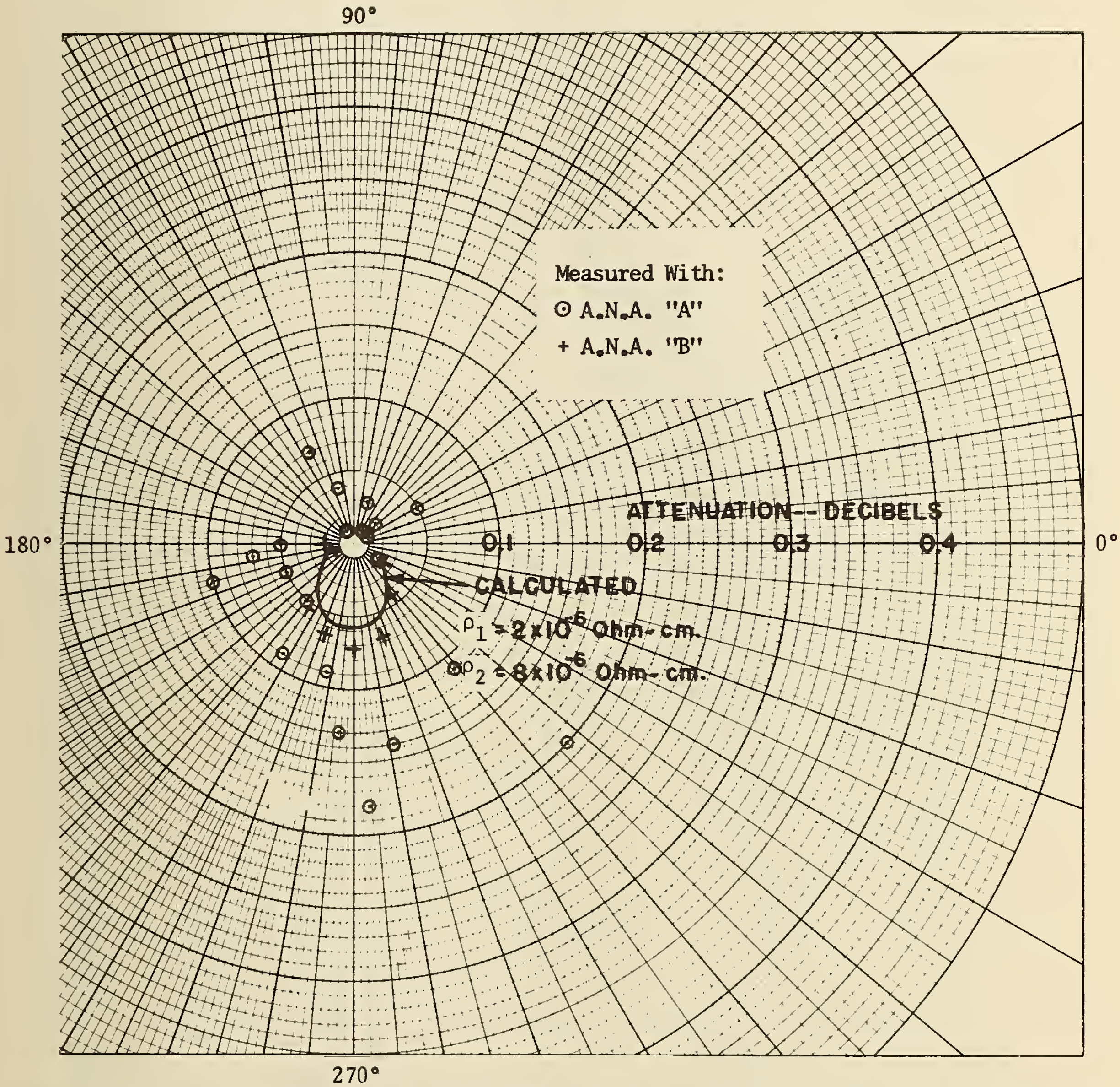


Figure 9. Polar plot of calculated and measured attenuation in decibels = $-20 \log_{10} |S_{21}|$ and arg $(S_{21}) = \psi_{21}$ at frequencies from 0.1 to 0.5 GHz for reduced IDOC coaxial 2-port.

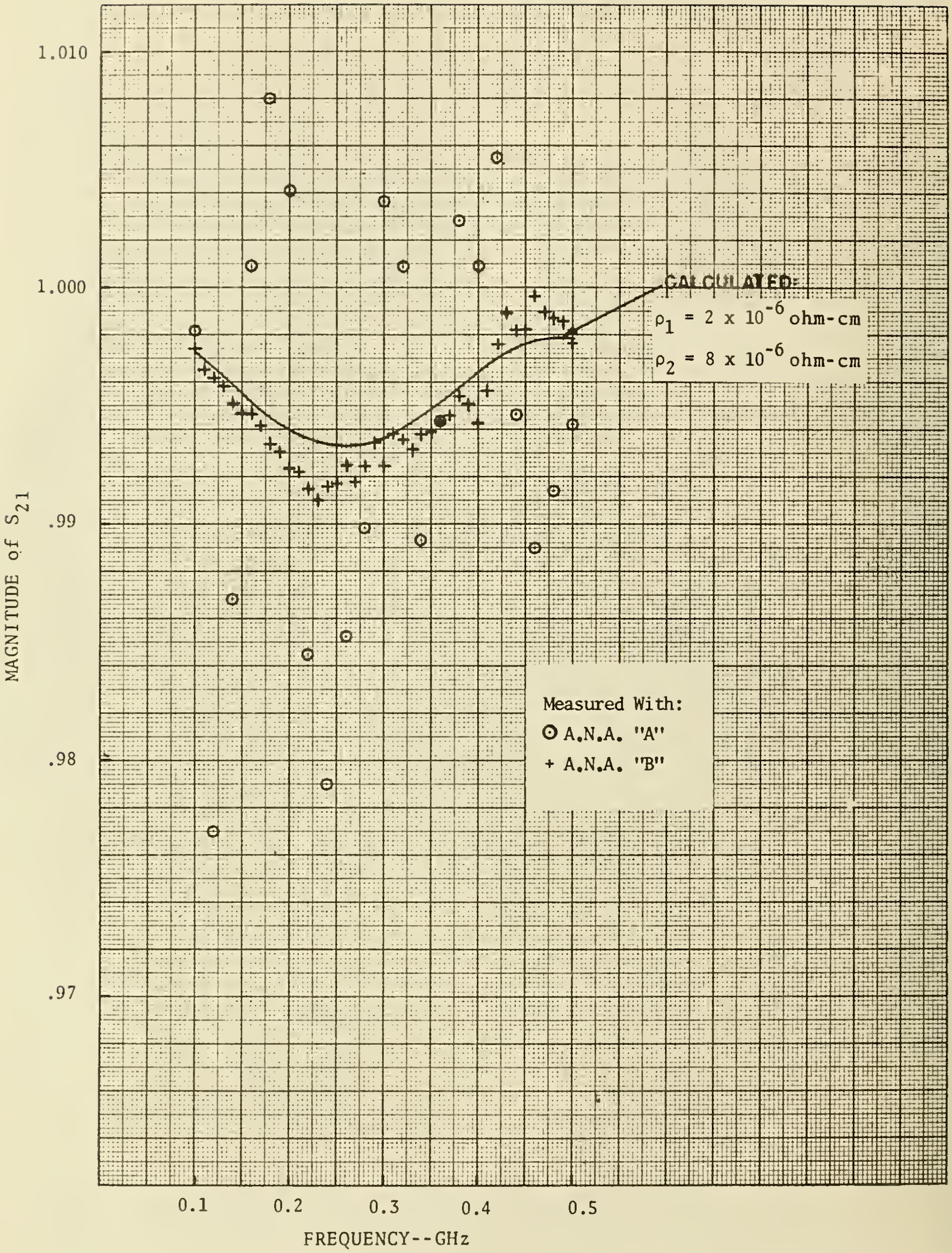


Figure 10. Calculated and measured $|S_{21}|$ versus frequency for reduced IDOC coaxial 2-port.

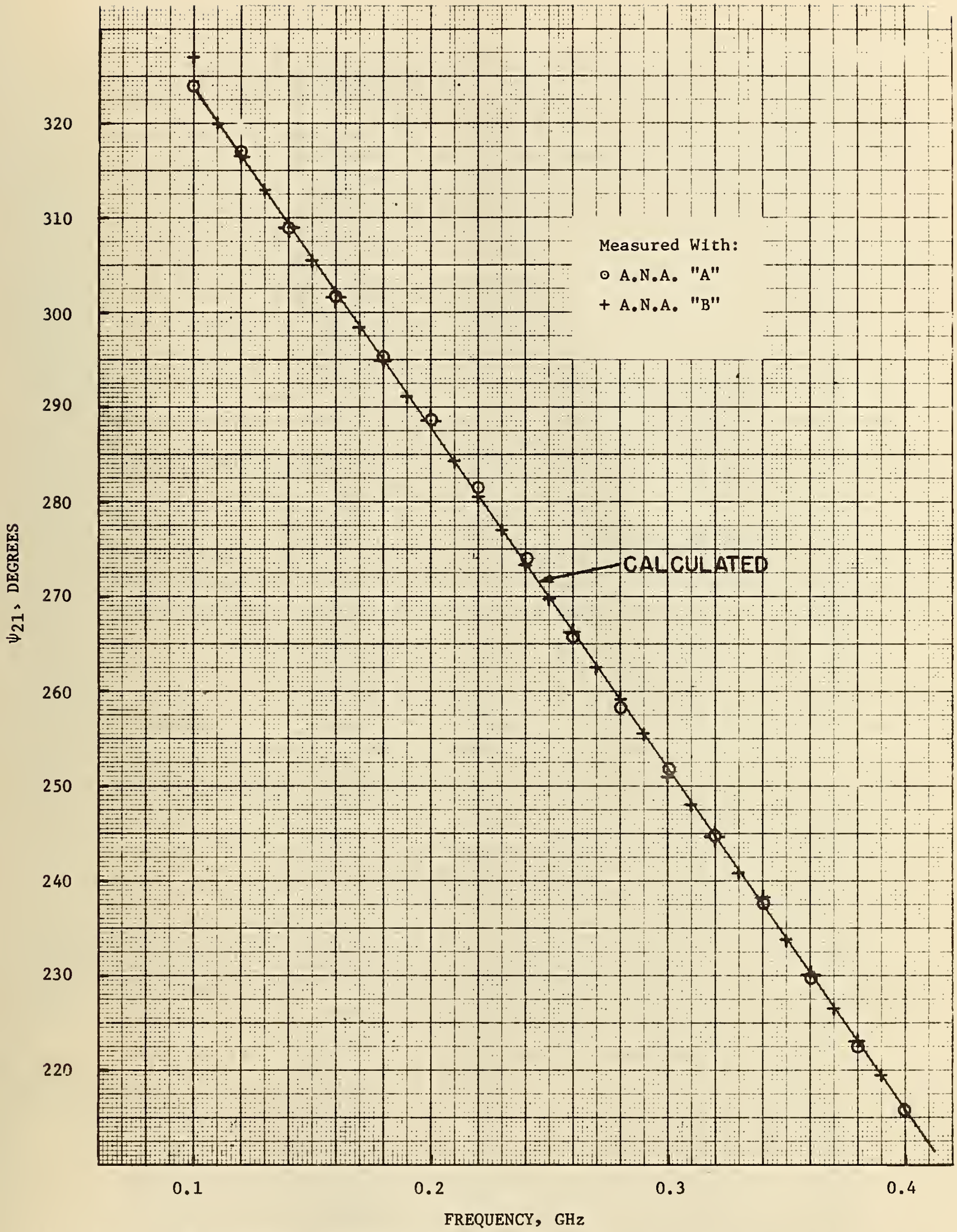


Figure 11. Calculated and measured arg (S_{21}) = ψ_{21} versus frequency for reduced IDOC coaxial 2-port.

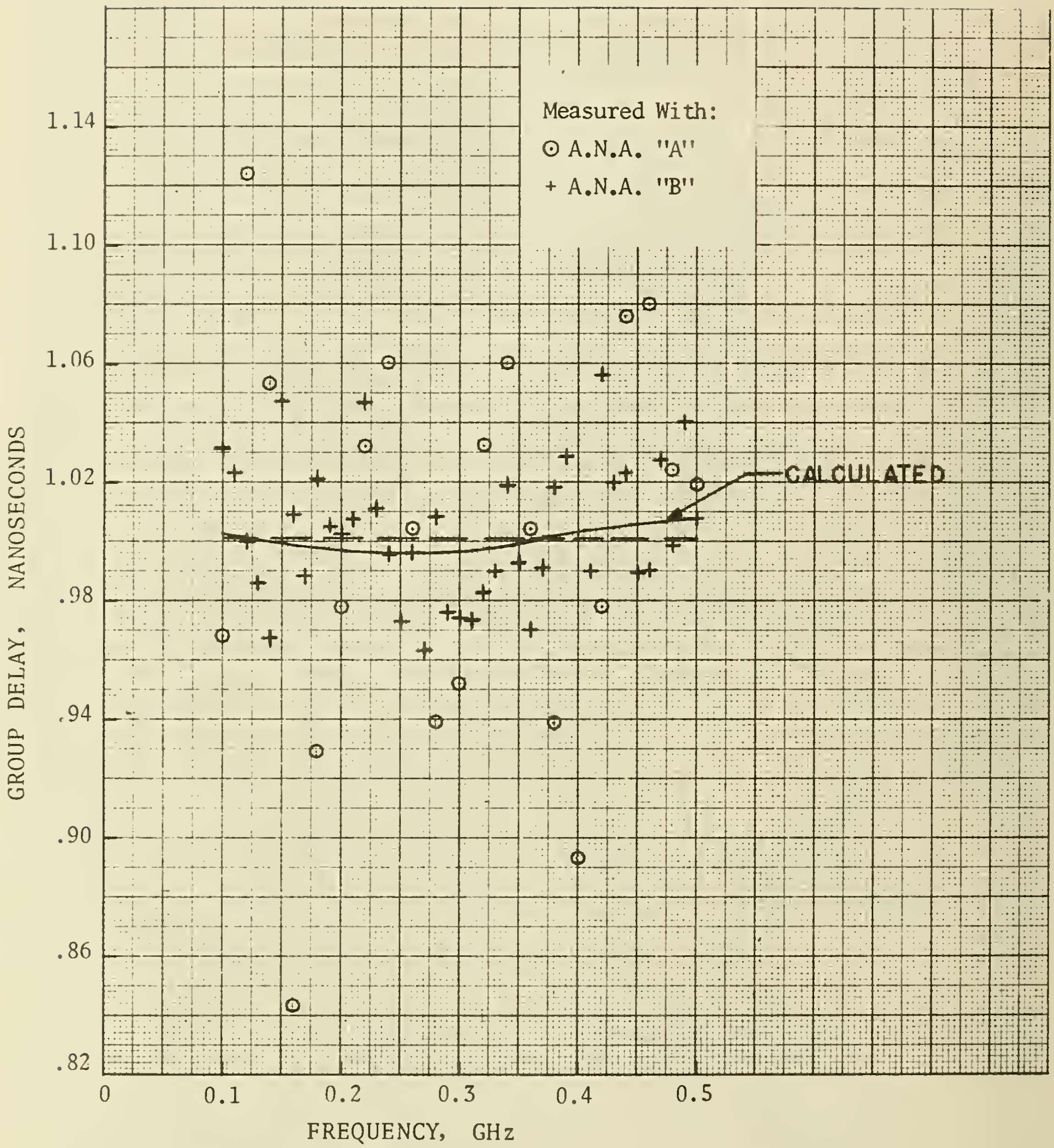


Figure 12. Calculated and measured group aelay time versus frequency for reduced IDOC coaxial 2-port.

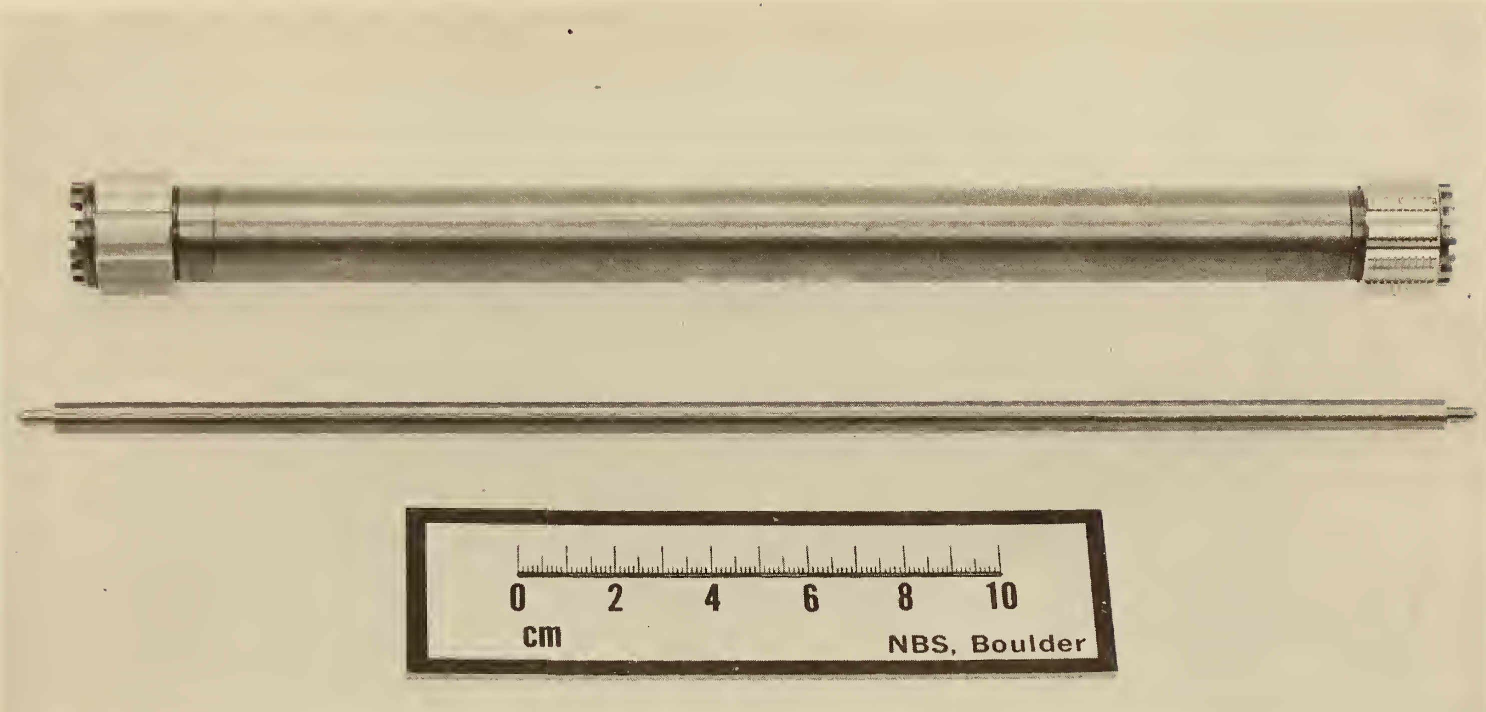


Figure 13. Photograph of increased ODIC coaxial 2-port designed to be inserted into a 9/16 inch (14 mm) 50-ohm coaxial system.

ICS11 08:30 06/07/74

FOR 9/16 INCH (14 MM) COAXIAL SYSTEM:

ODIC	.24425 INCHES
IDOC	.5625 INCHES
TEM-MODE CHARACTERISTIC IMPEDANCE	50.0012 OHMS

FOR 2-PORT:

ODIC	.2651 INCHES
IDOC	.5625 INCHES
LENGTH	11.811 INCHES
TEM-MODE CHARACTERISTIC IMPEDANCE	45.0913 OHMS
DISCONTINUITY CAPACITANCE	2.55531E-15 FARADS
RELATIVE PERMITTIVITY OF AIR	1.00064
IC RESISTIVITY	.000008 OHM-CM.
OC RESISTIVITY	.000008 OHM-CM.

FREQUENCY GHZ	RETURN LOSS DECIBELS	MAG(S11)	ARG(S11) DEGREES
.1	24.3239	6.07863E-2	233.712
.11	23.6236	6.58898E-2	230.111
.12	23.0082	7.07278E-2	226.512
.13	22.4662	7.52819E-2	222.916
.14	21.9889	7.95344E-2	219.321
.15	21.5695	8.34693E-2	215.728
.16	21.2025	8.70717E-2	212.138
.17	20.8835	9.03283E-2	208.55
.18	20.6092	.093227	204.963
.19	20.3766	9.57571E-2	201.379
.2	20.1835	9.79094E-2	197.796
.21	20.0282	.099676	194.215
.22	19.9092	.101051	190.635
.23	19.8256	.102028	187.056
.24	19.7766	.102606	183.477
.25	19.7618	.10278	179.9
.26	19.7811	.102552	176.322
.27	19.8347	.101922	172.745
.28	19.9229	.100891	169.167
.29	20.0466	9.94644E-2	165.589
.3	20.2068	9.76468E-2	162.011
.31	20.405	9.54448E-2	158.431
.32	20.6428	9.28664E-2	154.851
.33	20.9228	8.99211E-2	151.27
.34	21.2476	8.66199E-2	147.688
.35	21.6211	.082975	144.105
.36	22.0474	7.90002E-2	140.521
.37	22.5324	7.47103E-2	136.937
.38	23.0829	7.01219E-2	133.354
.39	23.7081	6.52524E-2	129.77
.4	24.4195	6.01209E-2	126.189
.41	25.2328	5.47472E-2	122.611
.42	26.1691	4.91527E-2	119.039
.43	27.2583	4.33594E-2	115.475
.44	28.5448	3.73904E-2	111.927
.45	30.0975	3.12698E-2	108.403
.46	32.0334	2.50223E-2	104.926
.47	34.5755	1.86734E-2	101.543
.48	38.2379	1.22492E-2	98.4103
.49	44.7642	5.77818E-3	96.3691
.5	62.0733	7.87655E-4	247.325

Figure 14. Computer printout of program ICS11 for increased ODIC coaxial 2-port.

ICS21 08:13 06/07/74

FOR 9/16 INCH (14 MM) COAXIAL SYSTEM:

ODIC	.24425 INCHES
IDOC	.5625 INCHES
TEM-MODE CHARACTERISTIC IMPEDANCE	50.0012 OHMS

FOR 2-PORT:

ODIC	.2651 INCHES
IDOC	.5625 INCHES
LENGTH	11.811 INCHES
TEM-MODE CHARACTERISTIC IMPEDANCE	45.0913 OHMS
DISCONTINUITY CAPACITANCE	2.55531E-15 FARADS
RELATIVE PERMITTIVITY OF AIR	1.00064
IC RESISTIVITY	.000008 OHM-CM.
OC RESISTIVITY	.000008 OHM-CM.

DELTA F FOR CALCULATION OF GROUP DELAY .005 GHZ

FREQUENCY GHZ	ATTENUATION DECIBELS	MAG(S21)	ARG(S21) DEGREES	GROUP DELAY NANOSECONDS
.1	2.74383E-2	.996846	-36.1859	1.00275
.11	3.08121E-2	.996459	-39.7947	1.0021
.12	3.42262E-2	.996067	-43.401	1.00143
.13	3.76386E-2	.995676	-47.005	1.00076
.14	4.10044E-2	.99529	-50.6065	1.0001
.15	4.42807E-2	.994915	-54.2057	.999451
.16	4.74251E-2	.994555	-57.8026	.998832
.17	5.03967E-2	.994215	-61.3973	.998251
.18	5.31572E-2	.993899	-64.99	.997714
.19	5.56706E-2	.993611	-68.5809	.997233
.2	5.79051E-2	.993356	-72.1702	.996813
.21	5.98333E-2	.993135	-75.758	.996462
.22	6.14317E-2	.992952	-79.3448	.996184
.23	6.26821E-2	.992809	-82.9306	.995984
.24	6.35715E-2	.992708	-86.5159	.995866
.25	6.40928E-2	.992648	269.899	.99583
.26	6.42432E-2	.992631	266.314	.995876
.27	6.40271E-2	.992656	262.729	.996006
.28	6.34527E-2	.992721	259.143	.996216
.29	6.25361E-2	.992826	255.556	.996504
.3	6.12962E-2	.992968	251.968	.996865
.31	5.97578E-2	.993144	248.378	.997293
.32	5.79507E-2	.99335	244.787	.997781
.33	5.59086E-2	.993584	241.194	.998324
.34	5.36687E-2	.99384	237.599	.99891
.35	.051271	.994115	234.002	.999532
.36	4.87585E-2	.994402	230.403	1.00018
.37	4.61758E-2	.994698	226.801	1.00084
.38	4.35682E-2	.994997	223.197	1.00151
.39	4.09822E-2	.995293	219.59	1.00218
.4	3.84636E-2	.995581	215.981	1.00282
.41	3.60566E-2	.995857	212.37	1.00344
.42	.0338805	.996116	208.756	1.00403
.43	3.17485E-2	.996351	205.141	1.00457
.44	2.99247E-2	.996561	201.523	1.00505
.45	2.83672E-2	.996739	197.904	1.00548
.46	2.71055E-2	.996884	194.284	1.00583
.47	2.61641E-2	.996992	190.662	1.00611
.48	2.55623E-2	.997061	187.04	1.00631
.49	2.53142E-2	.99709	183.417	1.00642
.5	.025428	.997077	179.794	1.00646

Figure 15. Computer printout of program ICS21 for increased ODIC coaxial 2-port.

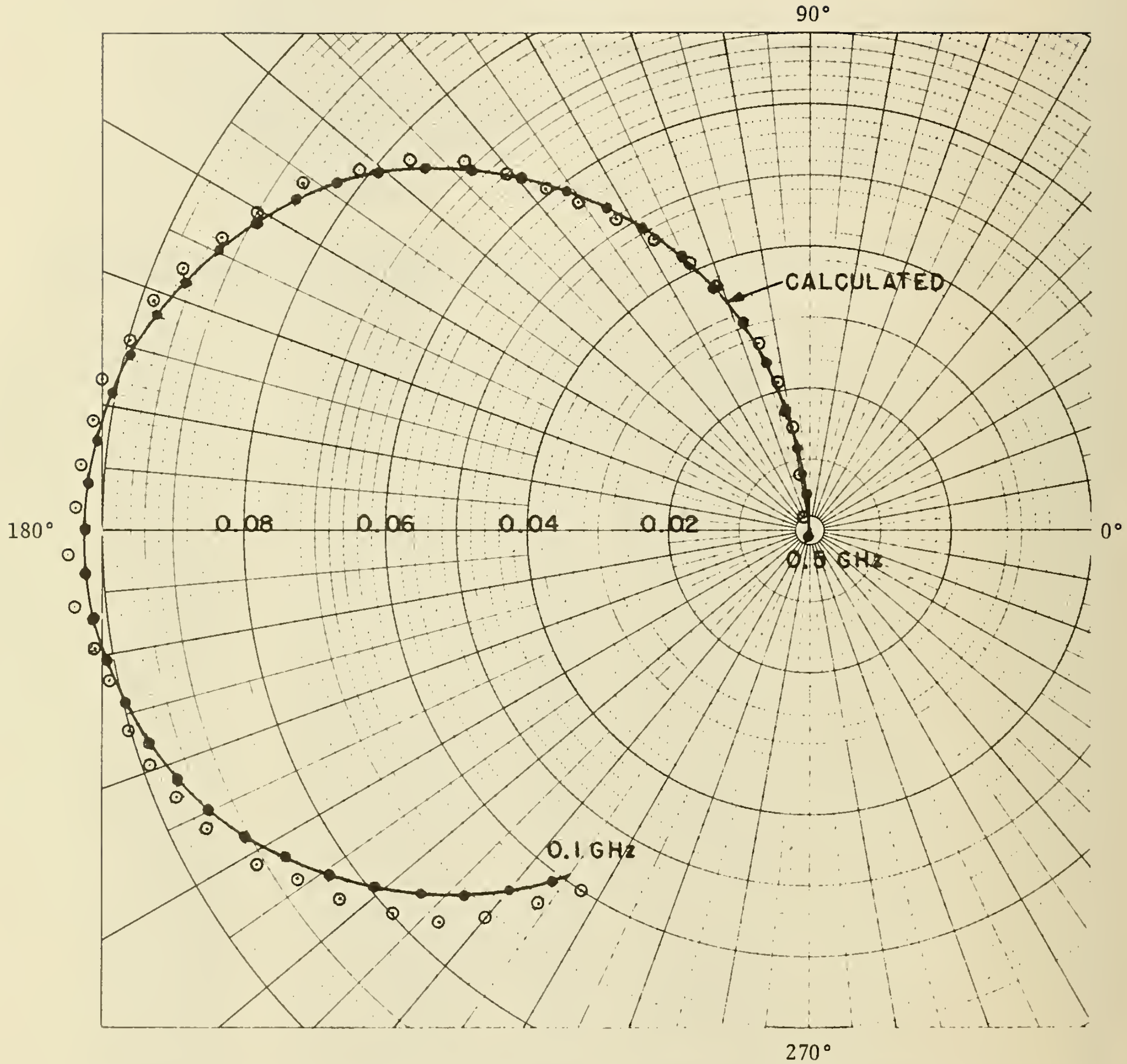


Figure 16. Polar plot of calculated and measured S_{11} of increased ODIC coaxial 2-port for frequencies from 0.1 to 0.5 GHz.

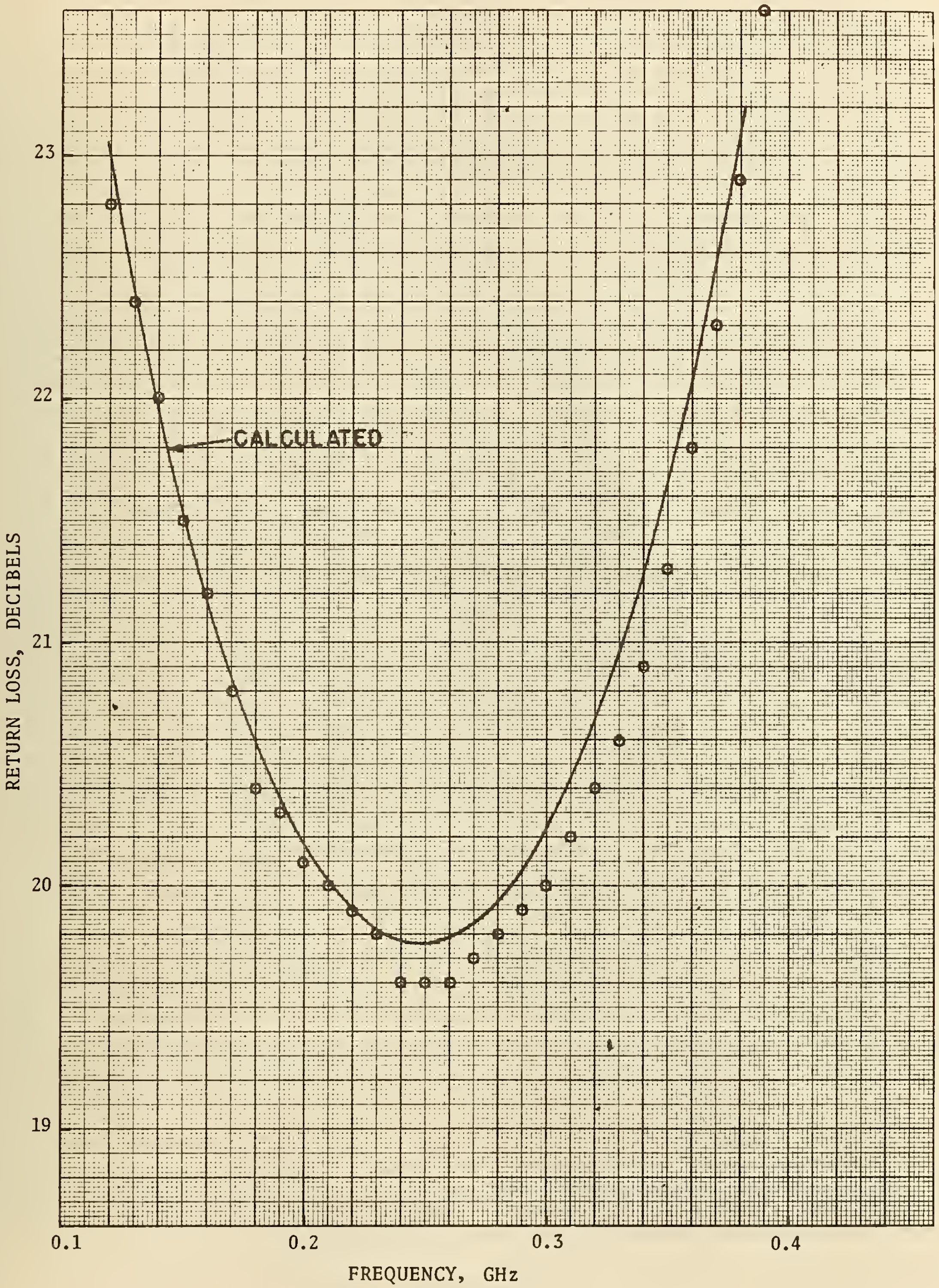


Figure 17. Calculated and measured return loss = $-20 \log_{10} |S_{11}|$ versus frequency for increased ODIC coaxial 2-port.

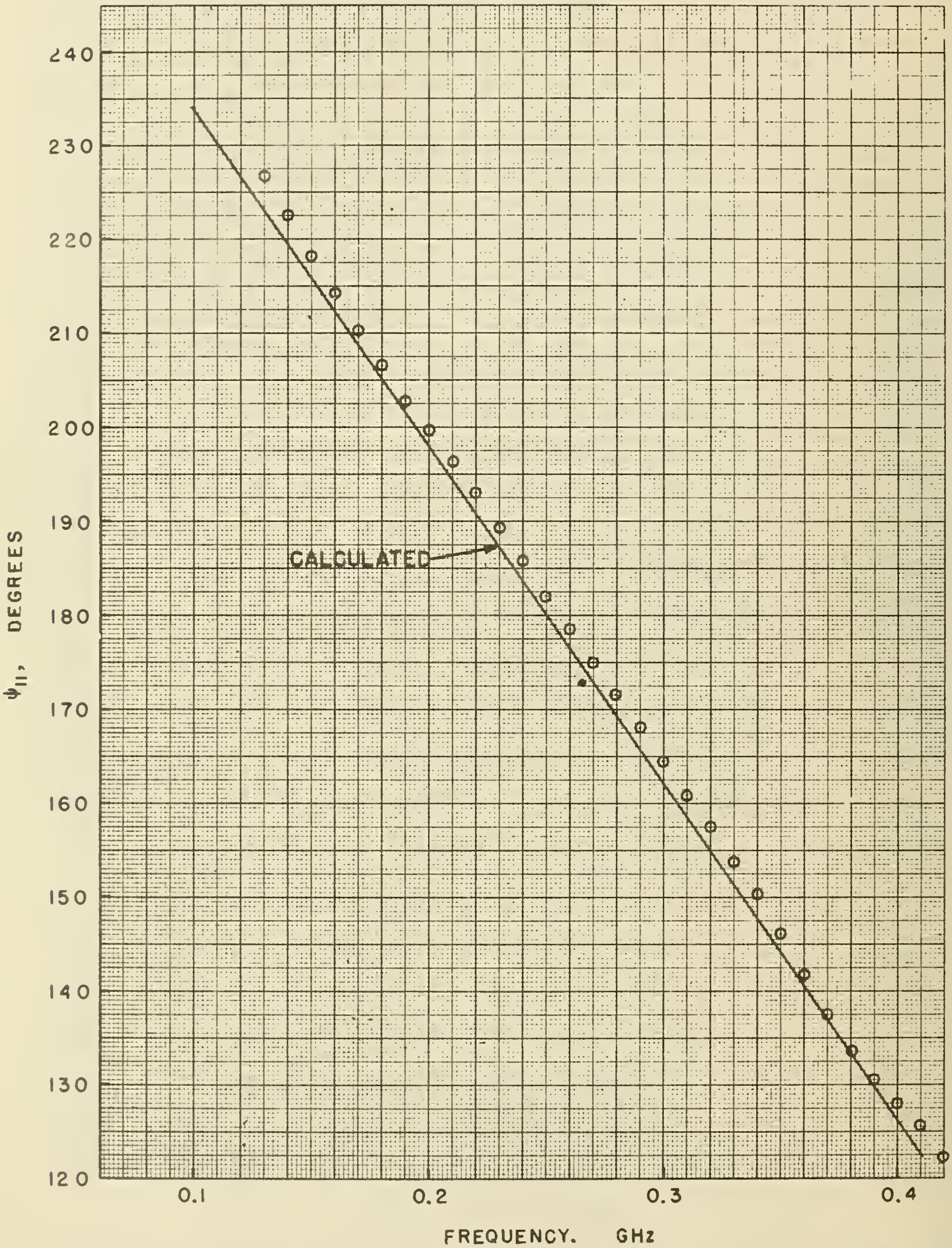


Figure 18. Calculated and measured arg $(S_{11}) = \psi_{11}$ in degrees versus frequency for increased ODIC coaxial 2-port.

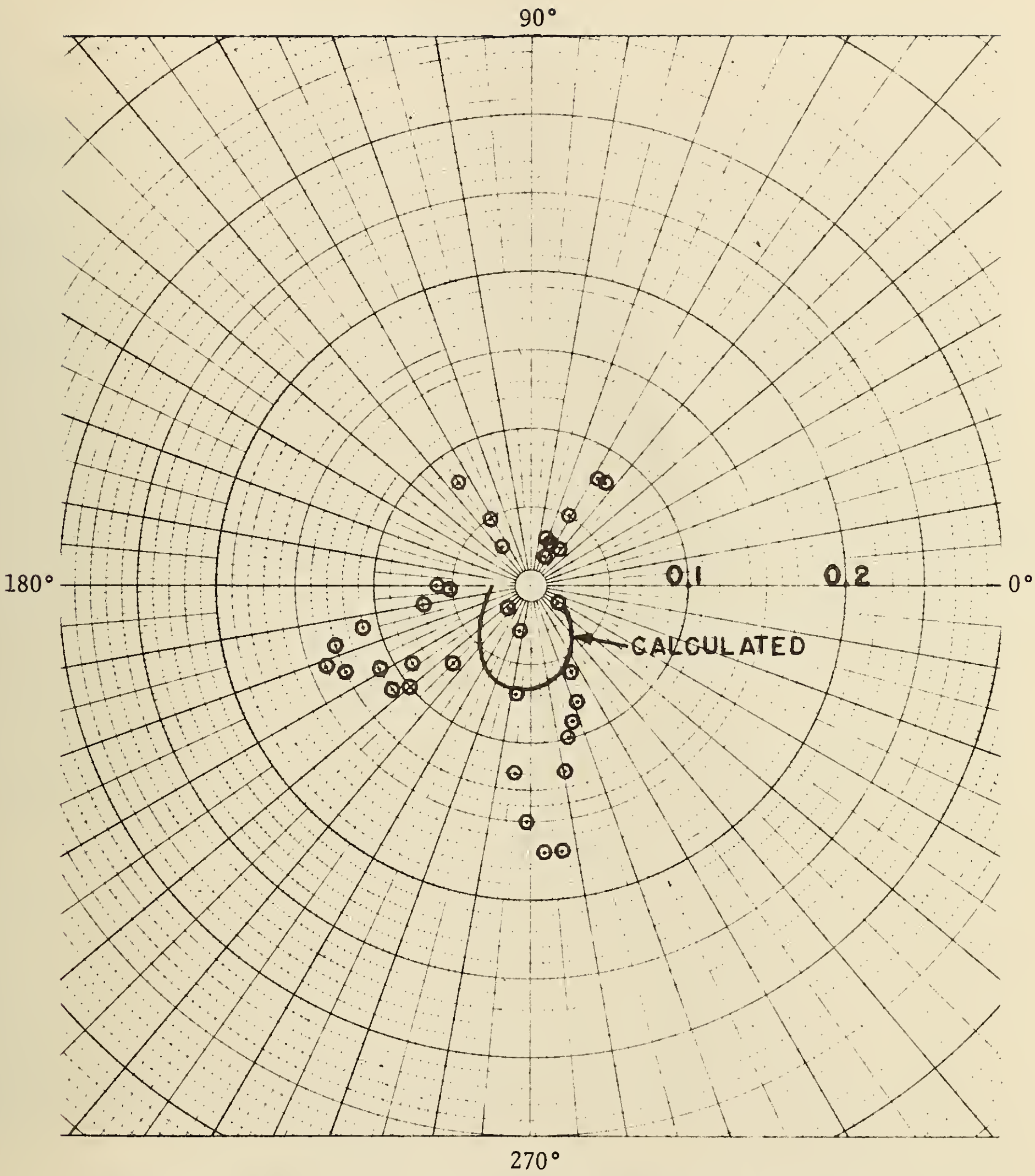


Figure 19. Polar plot of calculated and measured attenuation in decibels = $-20 \log_{10} |S_{21}|$ and arg $(S_{21}) = \psi_{21}$ of increased ODIC coaxial 2-port for frequencies from 0.1 to 0.5 GHz.

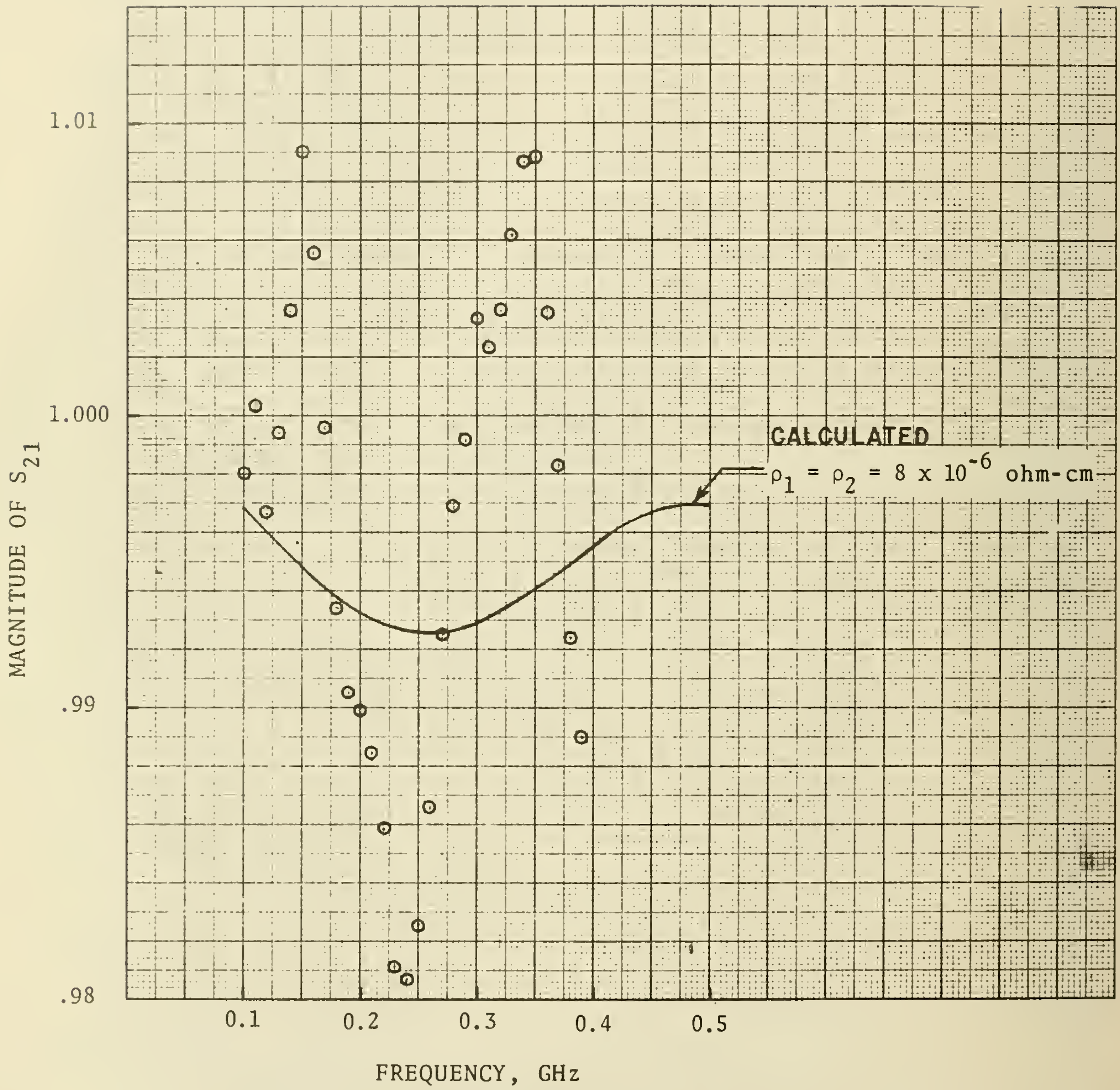


Figure 20. Calculated and measured $|S_{21}|$ versus frequency for increased ODIC coaxial 2-port.

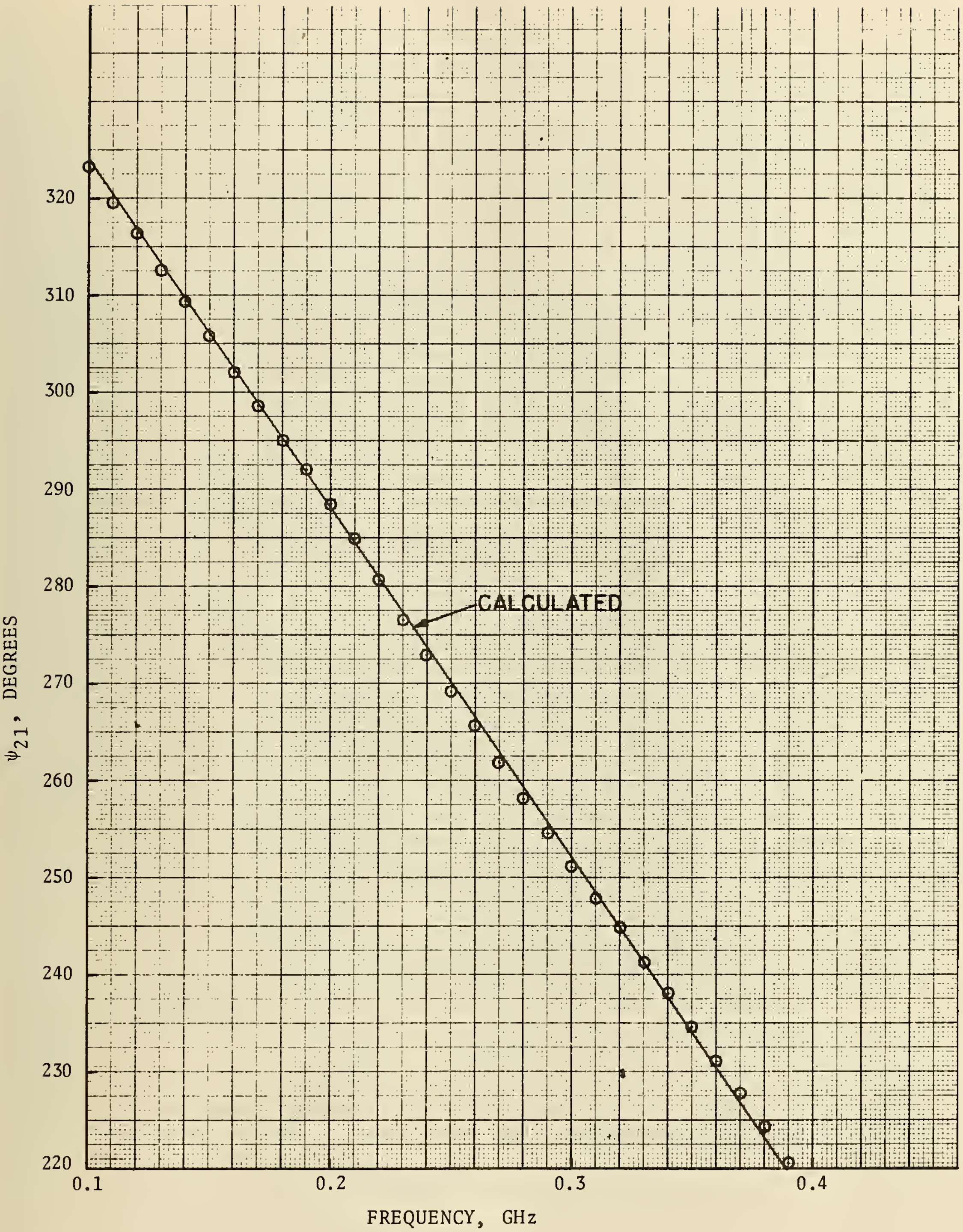


Figure 21. Calculated and measured arg (S_{21}) = ψ_{21} versus frequency for increased ODIC coaxial 2-port.

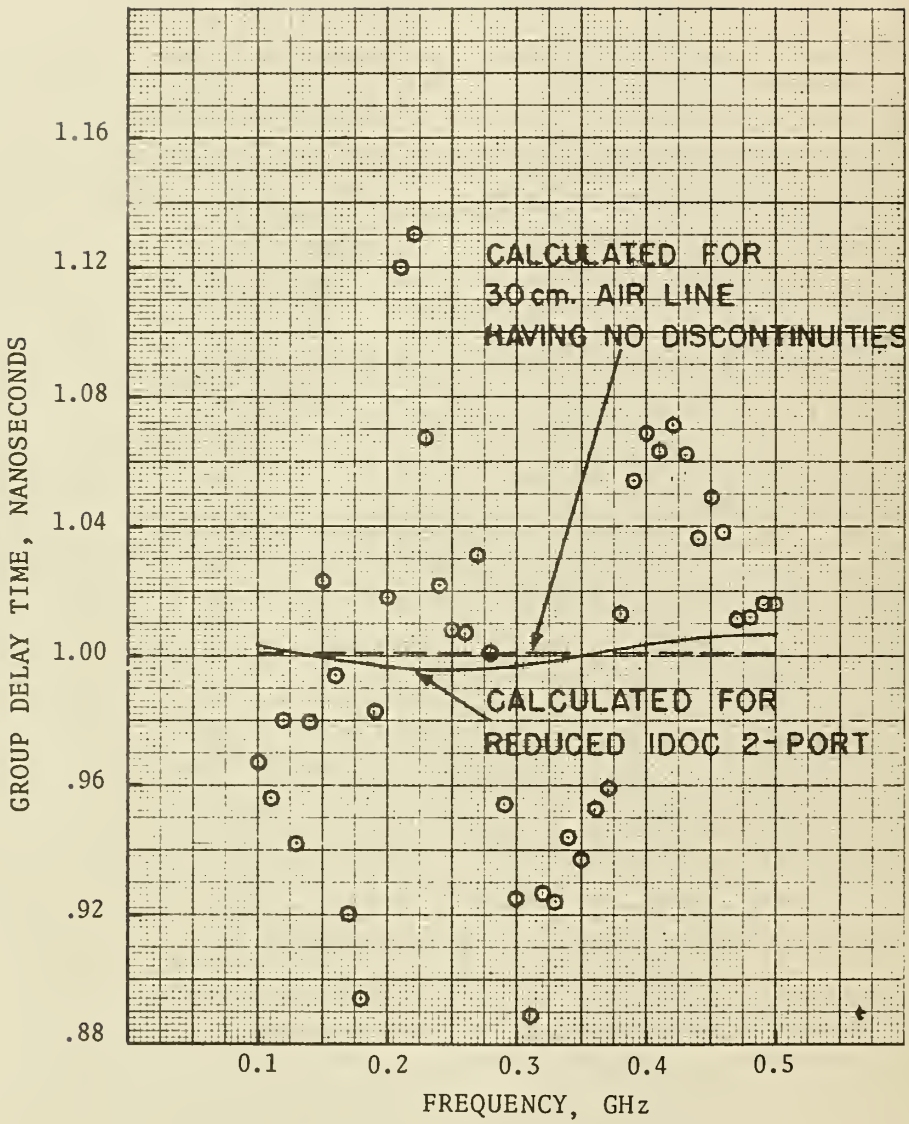


Figure 22. Calculated and measured group delay time versus frequency for increased ODIC coaxial 2-port.

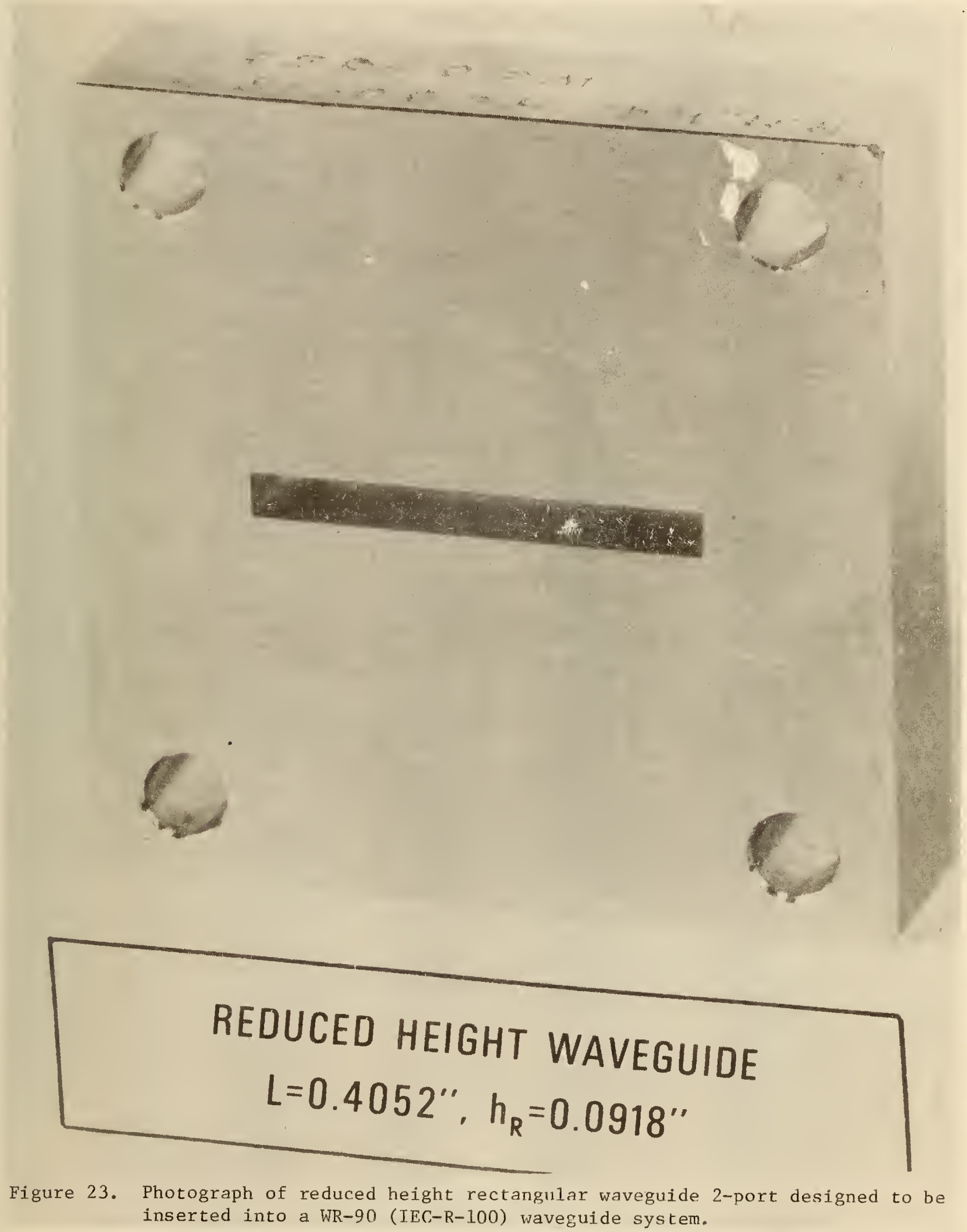


Figure 23. Photograph of reduced height rectangular waveguide 2-port designed to be inserted into a WR-90 (IEC-R-100) waveguide system.

```
WS11    13:54    06/05/74

FOR WR-90 (R-100) WAVEGUIDE SYSTEM:
   INTERNAL WIDTH                                   .9 INCHES
   INTERNAL HEIGHT                                  .4 INCHES

FOR 2-PORT:
   INTERNAL WIDTH                                   .9 INCHES
   INTERNAL HEIGHT                                  .0918 INCHES
   LENGTH                                           .4052 INCHES
   RESISTIVITY                                      8.5E-6 OHM-CM.
   RELATIVE PERMITTIVITY OF AIR                     1.00064
```

FREQUENCY GHZ	RETURN LOSS DECIBELS	MAG(S11)	ARG(S11) DEGREES
8	1.05701	.88542	192.856
8.1	1.02289	.888905	191.71
8.2	.994234	.891843	190.621
8.3	.970268	.894307	189.583
8.4	.950387	.896356	188.586
8.5	.934112	.898037	187.624
8.6	.92106	.899388	186.693
8.7	.910931	.900437	185.788
8.8	.903484	.90121	184.904
8.9	.898529	.901724	184.038
9.	.89592	.901995	183.187
9.1	.895548	.902033	182.347
9.2	.897331	.901848	181.517
9.3	.901219	.901445	180.693
9.4	.907183	.900826	179.873
9.5	.91522	.899993	179.055
9.6	.925345	.898944	178.236
9.7	.937597	.897677	177.416
9.8	.952034	.896186	176.591
9.9	.968736	.894465	175.759
10.	.987805	.892503	174.919
10.1	1.00936	.890291	174.068
10.2	1.03356	.887814	173.205
10.3	1.06058	.885056	172.327
10.4	1.09062	.882001	171.431
10.5	1.12392	.878626	170.517
10.6	1.16075	.874908	169.58
10.7	1.20144	.870819	168.619
10.8	1.24635	.866328	167.631
10.9	1.2959	.8614	166.613
11.	1.35058	.855995	165.561
11.1	1.41093	.850067	164.473
11.2	1.47761	.843566	163.345
11.3	1.55136	.836434	162.174
11.4	1.63304	.828606	160.954
11.5	1.72364	.820008	159.681
11.6	1.82433	.810557	158.352
11.7	1.93646	.80016	156.959
11.8	2.06163	.788712	155.499
11.9	2.20171	.776094	153.964
12.	2.35891	.762175	152.349
12.1	2.53584	.746806	150.646
12.2	2.73562	.729826	148.847
12.3	2.96198	.711051	146.946
12.4	3.21941	.690287	144.934
12.5	3.51333	.667319	142.803
12.6	3.85036	.641922	140.544
12.7	4.23865	.613858	138.149
12.8	4.68828	.582889	135.612
12.9	5.21199	.548783	132.925
13.	5.82604	.511326	130.083

Figure 24. Computer printout of program WS11 for rectangular waveguide 2-port.

WS21 14:00 06/05/74

FOR WR-90 (R-100) WAVEGUIDE SYSTEM:

INTERNAL WIDTH	.9 INCHES
INTERNAL HEIGHT	.4 INCHES

FOR 2-PORT:

INTERNAL WIDTH	.9 INCHES
INTERNAL HEIGHT	.0918 INCHES
LENGTH	.4052 INCHES
RESISTIVITY	8.5E-6 OHM-CM.
RELATIVE PERMITTIVITY OF AIR	1.00064

DELTA F FOR CALCULATION OF GROUP DELAY .05 GHZ

FREQUENCY GHZ	ATTENUATION DECIBELS	MAG(S21)	ARG(S21) DEGREES	GROUP DELAY NANOSECONDS
8	6.67891	.463505	-77.1143	3.28741E-2
8.1	6.80454	.456849	-78.2646	3.11083E-2
8.2	6.91374	.451142	-79.3565	2.96136E-2
8.3	7.00779	.446283	-80.3988	2.83439E-2
8.4	7.08778	.442192	-81.399	2.72637E-2
8.5	7.15464	.438801	-82.3633	.026345
8.6	7.20917	.436055	-83.2971	2.55655E-2
8.7	7.25206	.433907	-84.2051	2.49077E-2
8.8	7.28389	.43232	-85.0914	2.43571E-2
8.9	7.30517	.431262	-85.9596	2.39024E-2
9.	7.31635	.430708	-86.8131	2.35343E-2
9.1	7.3178	.430635	-87.6548	2.32451E-2
9.2	7.30987	.431029	-88.4874	2.30289E-2
9.3	7.29283	.431875	-89.3135	2.28808E-2
9.4	7.26693	.433165	269.865	2.27972E-2
9.5	7.23239	.434891	269.045	2.27748E-2
9.6	7.18938	.43705	268.224	2.28119E-2
9.7	7.13807	.439639	267.402	2.29067E-2
9.8	7.07857	.442661	266.574	2.30588E-2
9.9	7.011	.446118	265.741	2.32676E-2
10.	6.93545	.450015	264.899	2.35337E-2
10.1	6.85199	.454361	264.046	2.38577E-2
10.2	6.76066	.459163	263.18	.024241
10.3	6.66151	.464434	262.3	2.46857E-2
10.4	6.55457	.470188	261.402	2.51937E-2
10.5	6.43986	.476439	260.485	2.57683E-2
10.6	6.31738	.483205	259.546	2.64126E-2
10.7	6.18714	.490505	258.583	2.71308E-2
10.8	6.04913	.49836	257.592	2.79275E-2
10.9	5.90336	.506795	256.572	2.88077E-2
11.	5.74982	.515833	255.517	2.97774E-2
11.1	5.58852	.525502	254.427	3.08432E-2
11.2	5.41945	.53583	253.296	3.20122E-2
11.3	5.24266	.546849	252.121	3.32928E-2
11.4	5.05817	.558588	250.898	3.46936E-2
11.5	4.86606	.57108	249.622	3.62244E-2
11.6	4.66642	.584358	248.288	3.78958E-2
11.7	4.45939	.598454	246.892	3.97188E-2
11.8	4.24517	.613397	245.427	4.17054E-2
11.9	4.02402	.629215	243.887	4.38683E-2
12.	3.79627	.645931	242.267	.04622
12.1	3.56238	.663561	240.558	4.87729E-2
12.2	3.3229	.682111	238.753	5.15394E-2
12.3	3.07855	.701573	236.845	5.45295E-2
12.4	2.8302	.721922	234.825	5.77519E-2
12.5	2.57895	.743109	232.685	6.12109E-2
12.6	2.32613	.765056	230.416	6.49053E-2
12.7	2.07333	.78765	228.009	6.88268E-2
12.8	1.82246	.810731	225.458	.072957
12.9	1.57575	.834089	222.755	7.72647E-2
13.	1.33576	.857456	219.894	8.17034E-2

NOW AT 999
SRU'S:1.1
READY

Figure 25. Computer printout of program WS21 for rectangular waveguide 2-port.

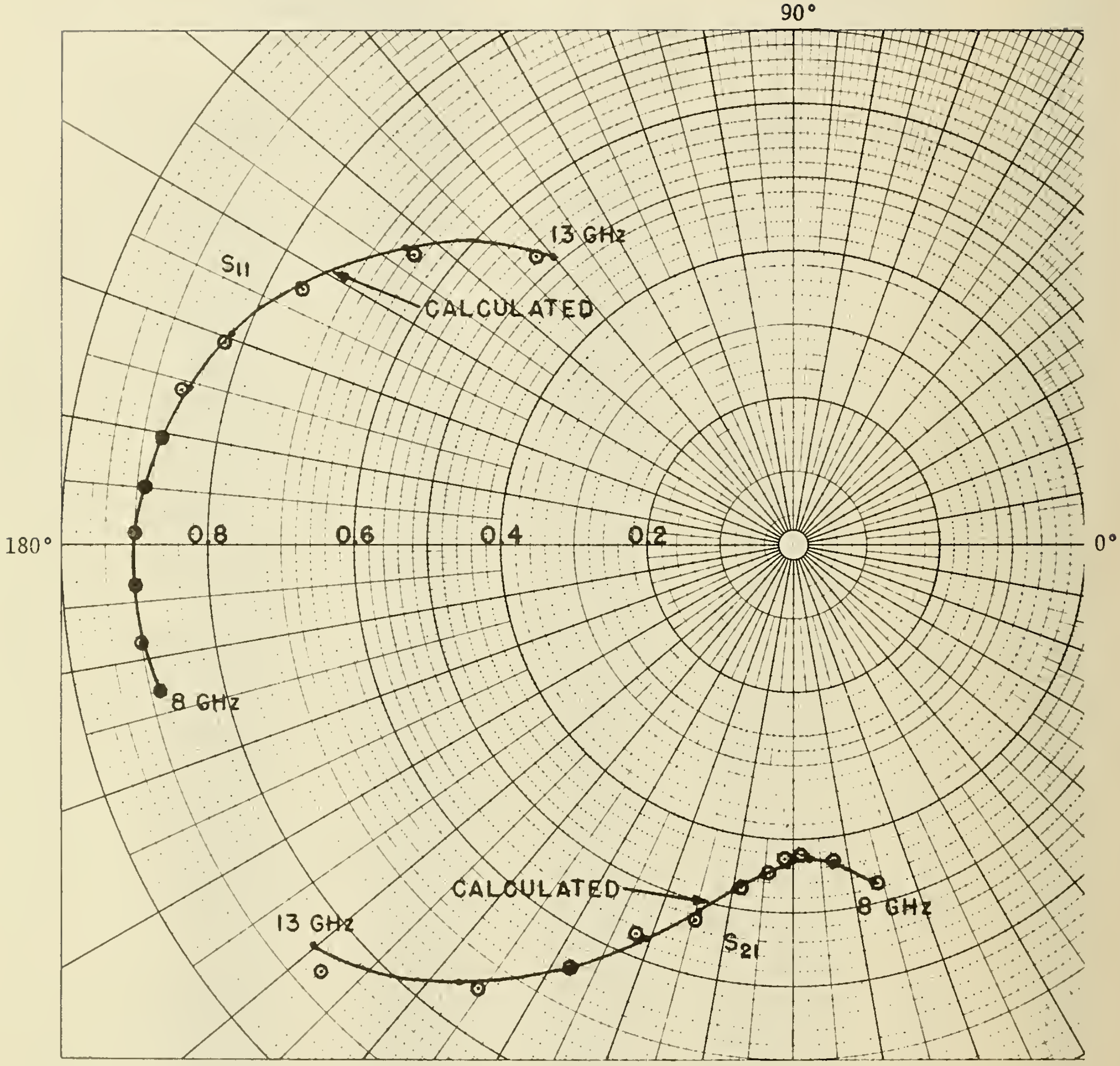


Figure 26. Polar plot of calculated and measured S_{11} and S_{21} of rectangular waveguide 2-port for frequencies from 8 to 13 GHz.

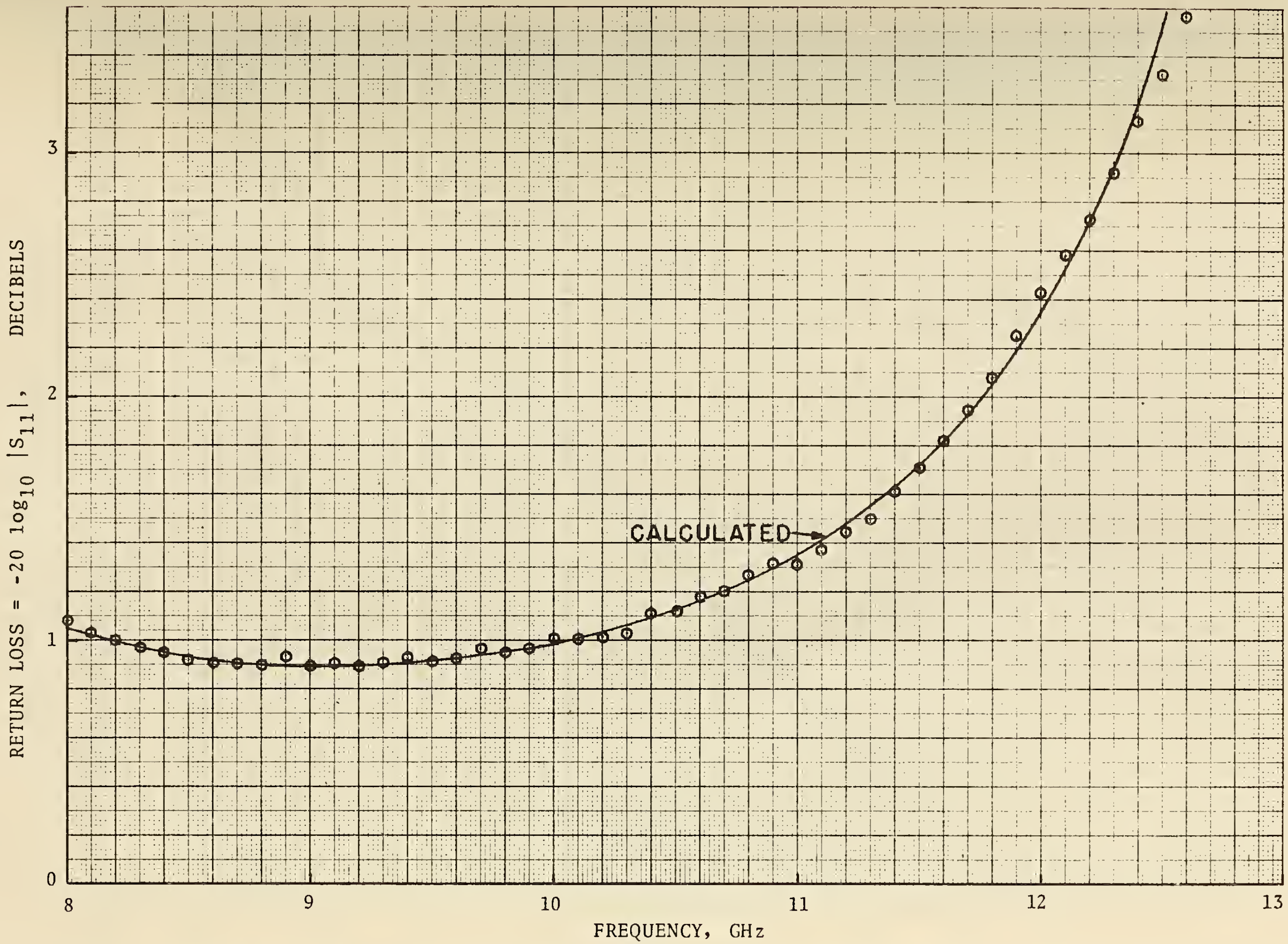


Figure 27. Calculated and measured return loss = -20 $\log_{10}$ $|S_{11}|$ versus frequency for rectangular waveguide 2-port.

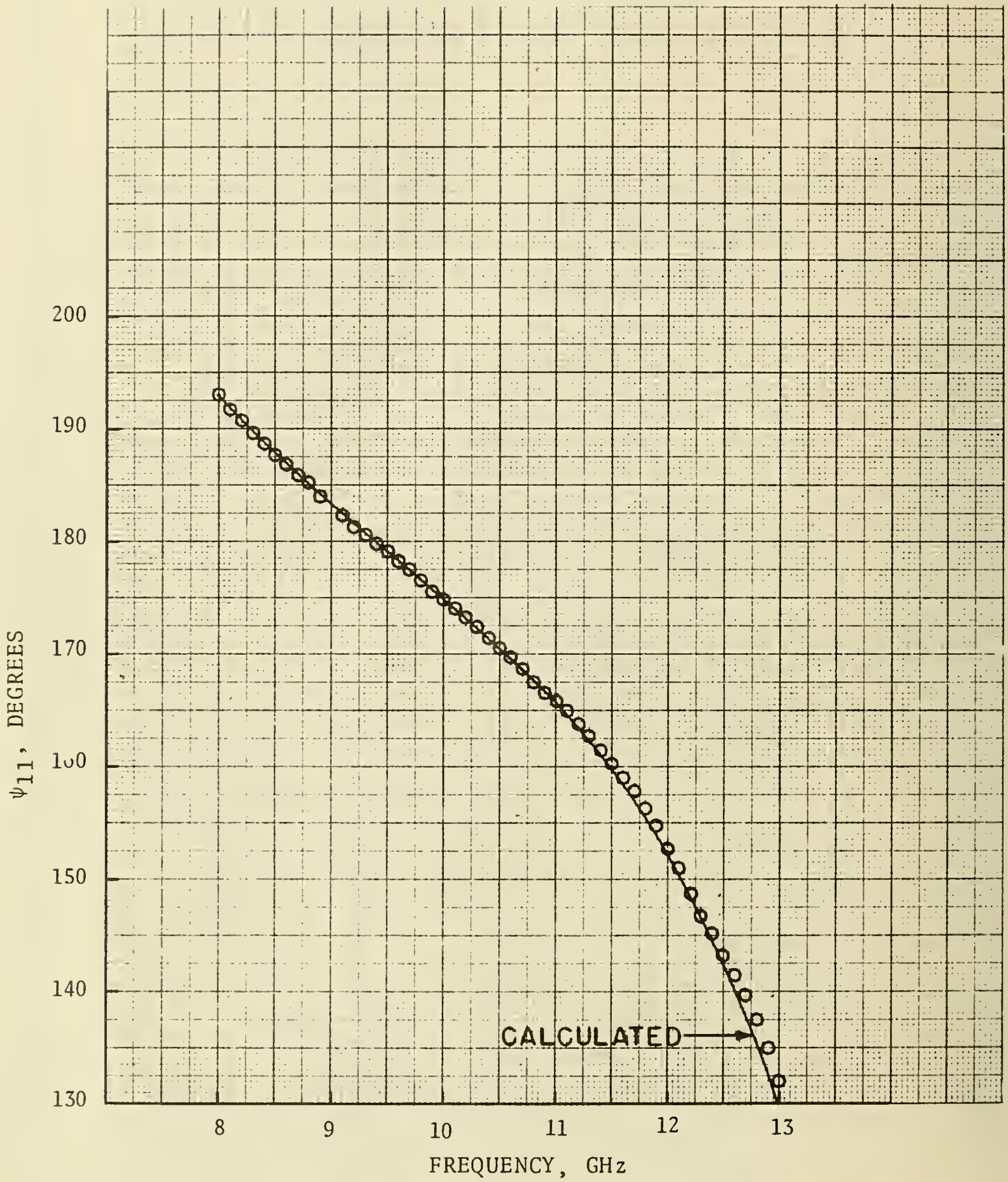


Figure 28. Calculated and measured arg $(S_{11}) = \psi_{11}$ in degrees versus frequency for rectangular waveguide 2-port.

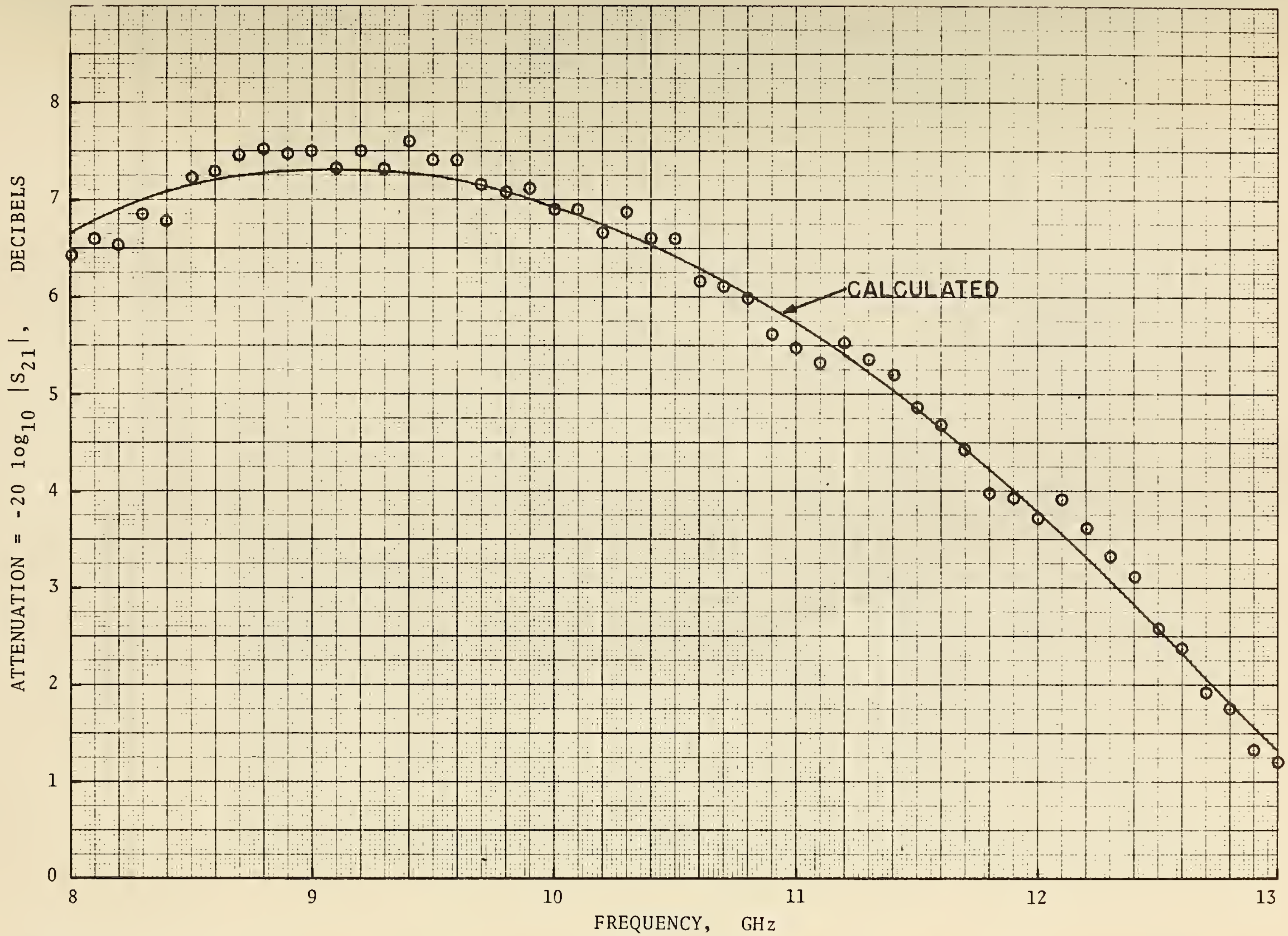


Figure 29. Calculated and measured attenuation = $-20 \log_{10} |S_{21}|$ versus frequency for rectangular waveguide 2-port.

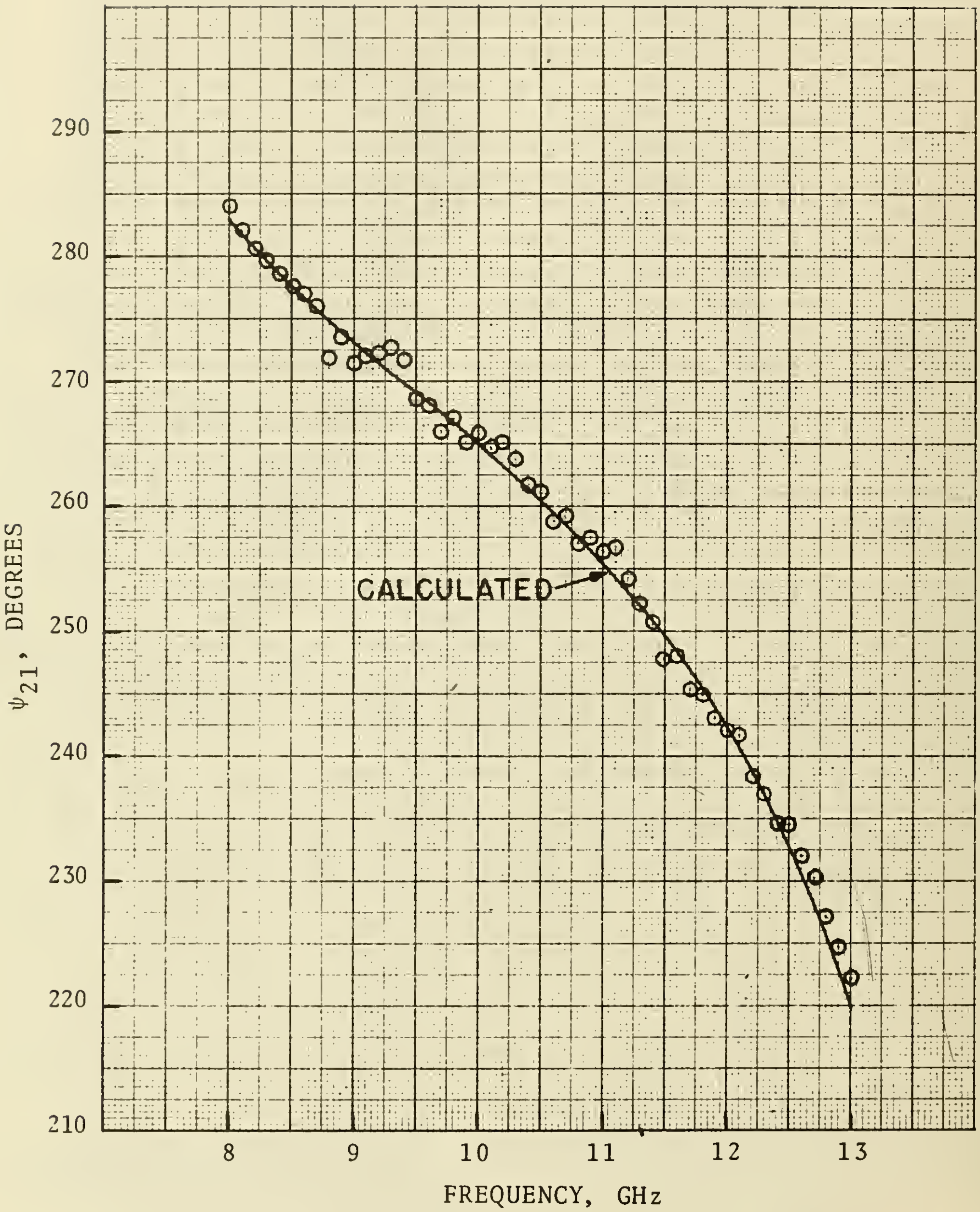


Figure 30. Calculated and measured arg $(S_{21}) = \psi_{21}$ in degrees versus frequency for rectangular waveguide 2-port.

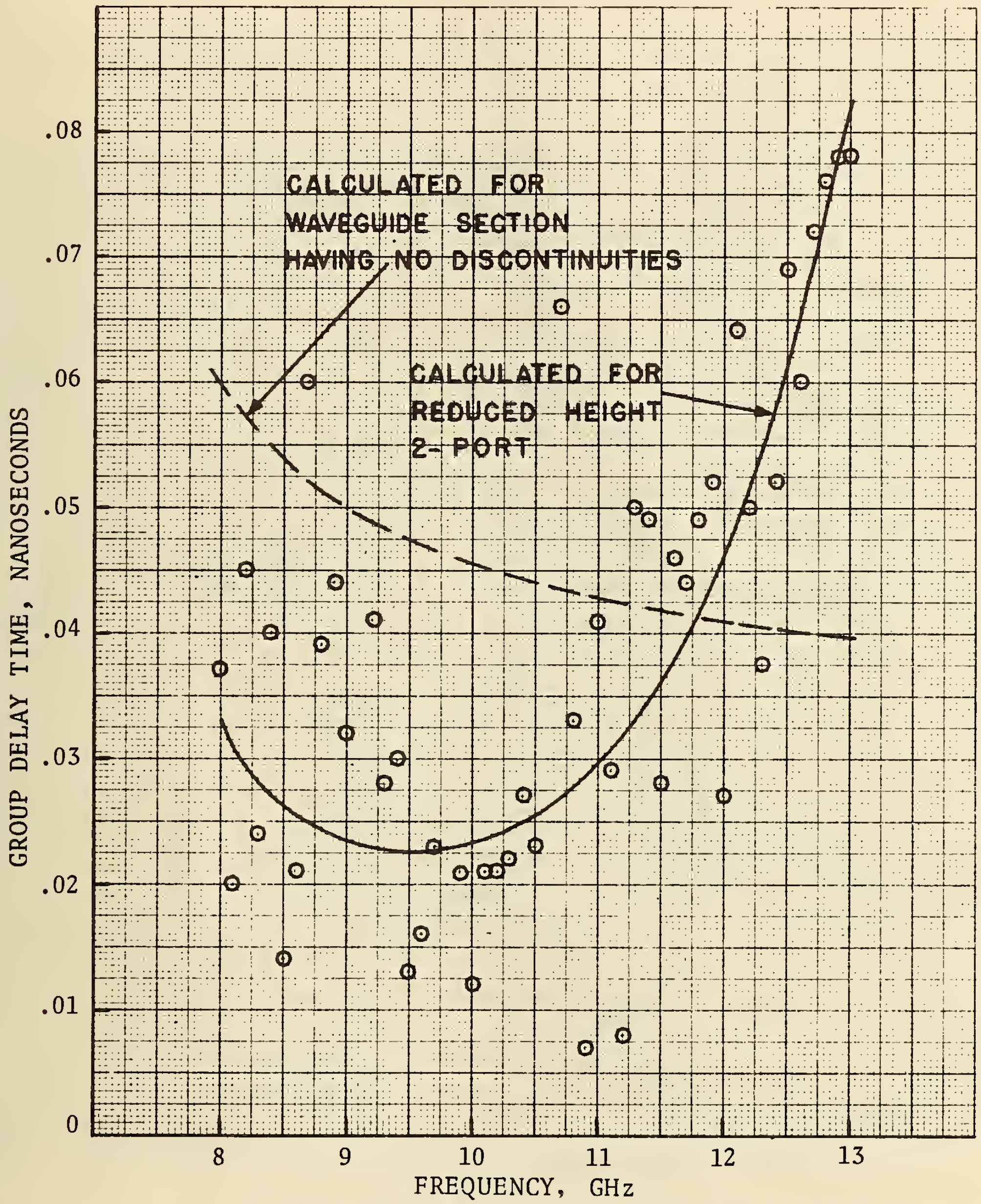


Figure 31. Calculated and measured group delay time versus frequency for rectangular waveguide 2-port.

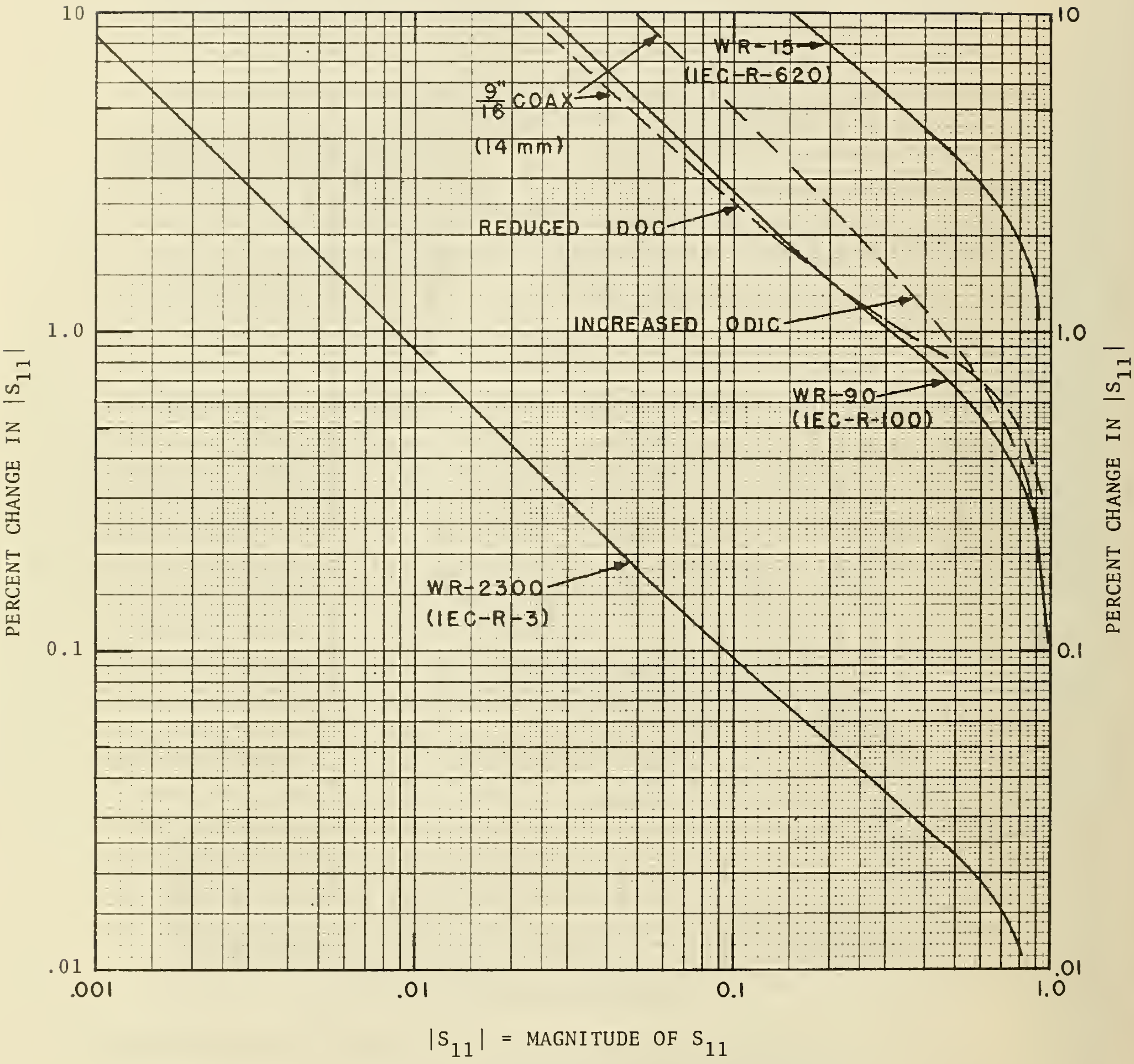


Figure 32. Percent change in $|S_{11}|$ versus $|S_{11}|$ of $\lambda_G/4$ 2-port standards corresponding to a change of 0.001 inch in the increased ODIC or reduced IDOC of 9/16 inch (14 mm) coaxial 2-ports or reduced height rectangular waveguide 2-ports.

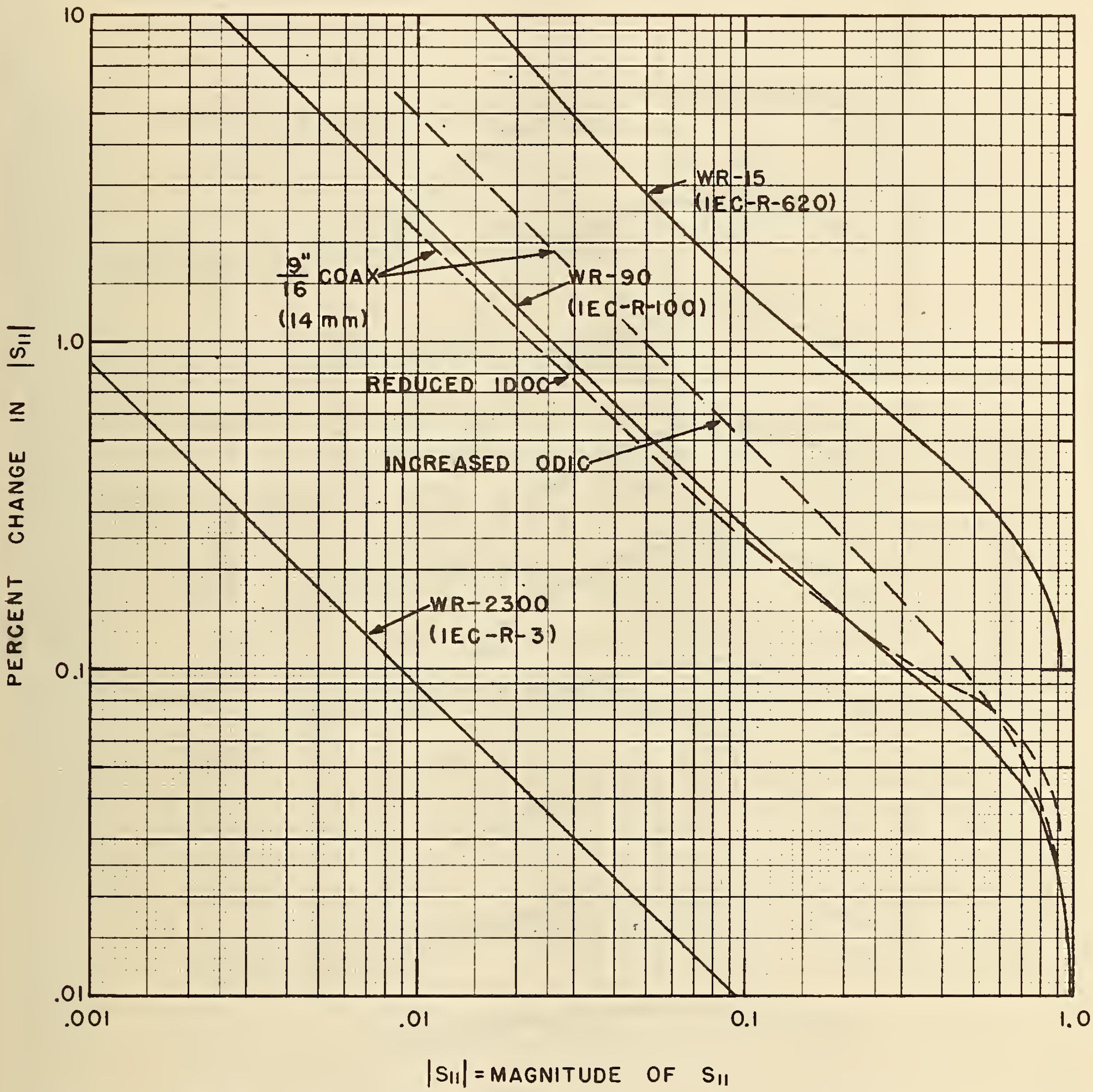


Figure 33. Percent change in $|S_{11}|$ versus $|S_{11}|$ of $\lambda_G/4$ 2-port standards corresponding to a change of 0.0001 inch in the increased ODIC or reduced IDOC of 9/16 inch (14 mm) coaxial 2-ports, or reduced height rectangular waveguide 2-ports.

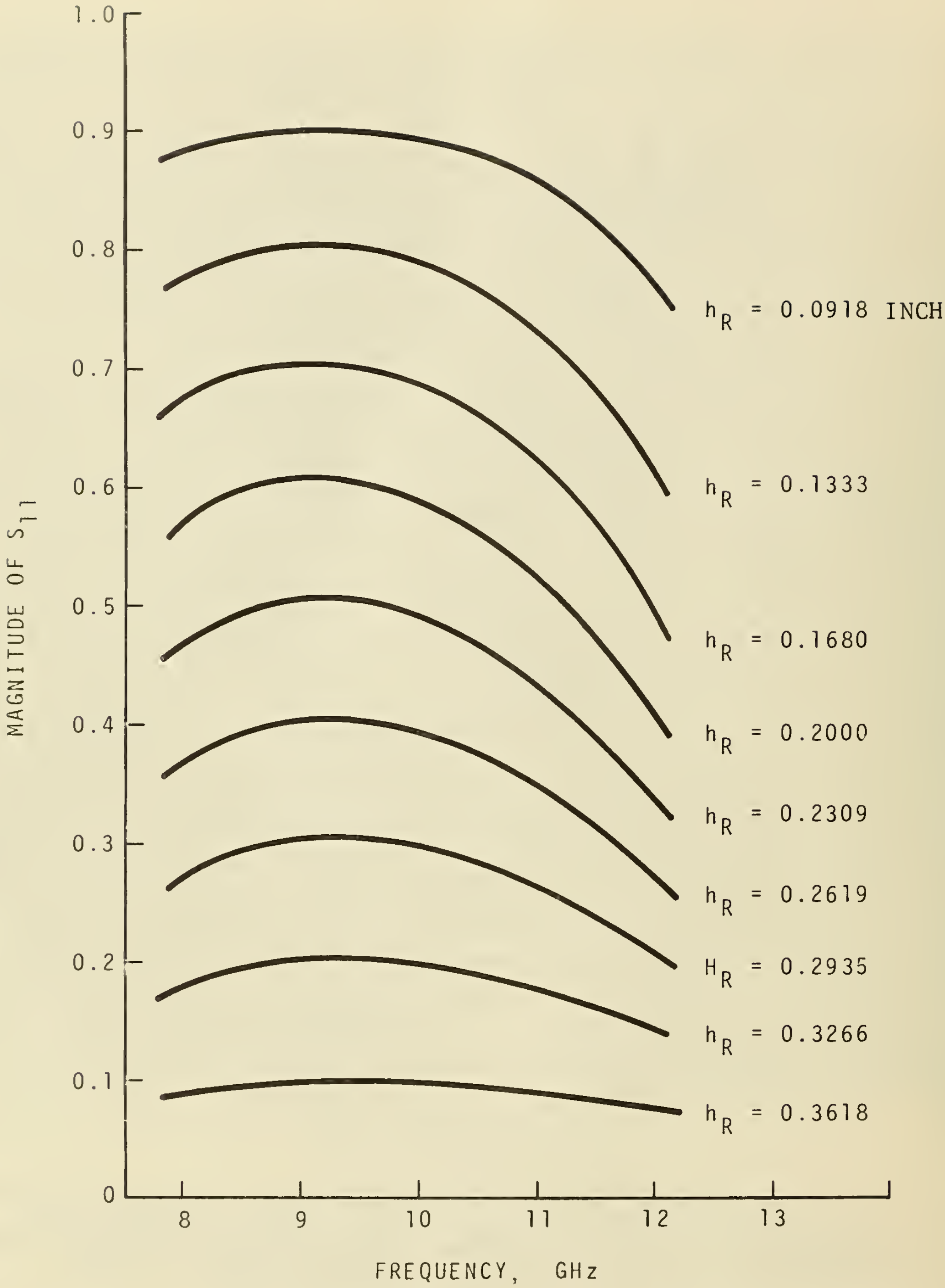


Figure 34. Calculated $|S_{11}|$ versus frequency for various reduced height WR-90 (IEC-R-100) rectangular waveguide 2-port standards all having a length of 0.4052 inch.

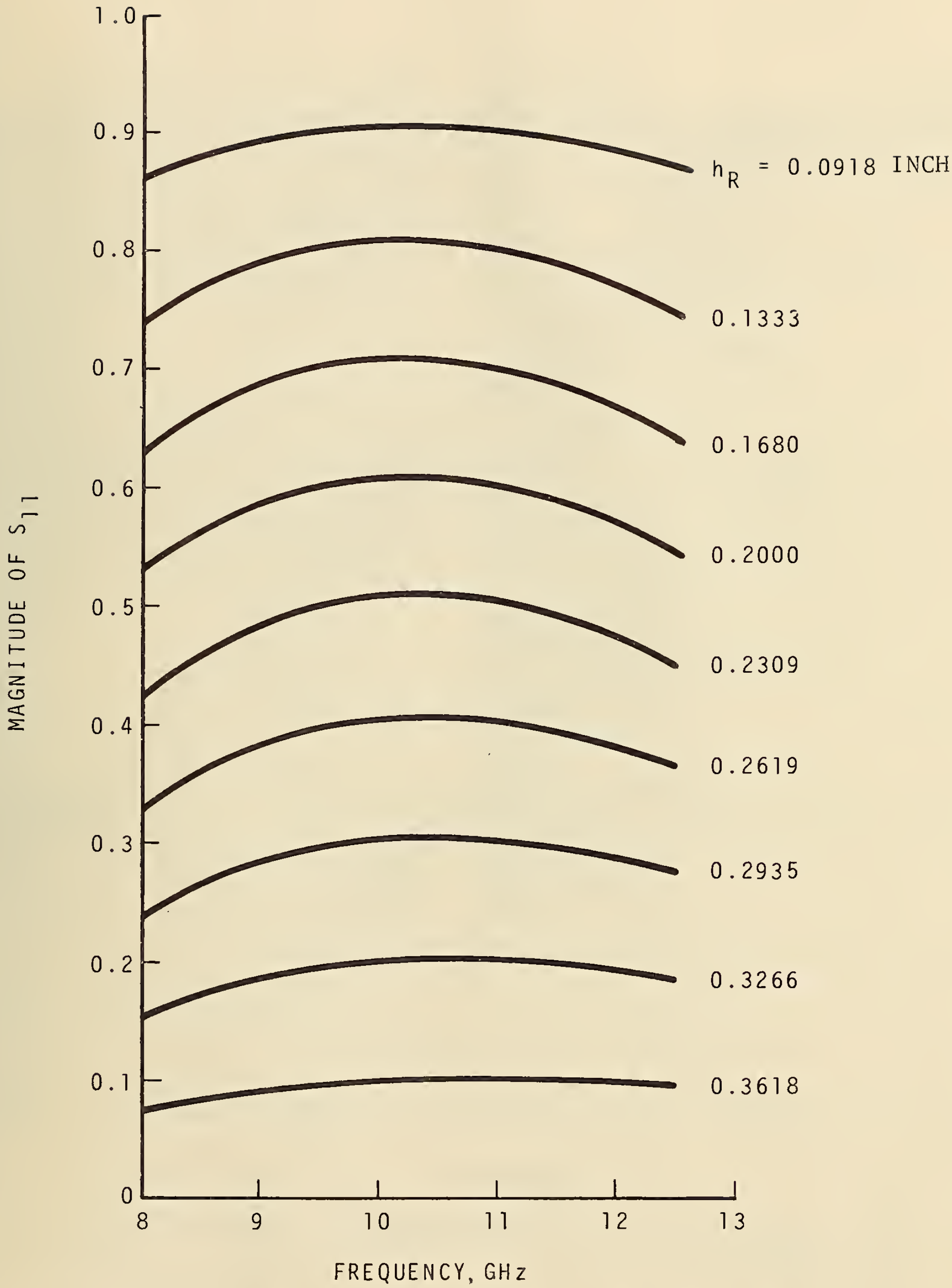


Figure 35. Calculated $|S_{11}|$ versus frequency for various reduced height WR-90 (IEC-R-100) rectangular waveguide 2-port standards all having a length of 0.3150 inch (80 mm).

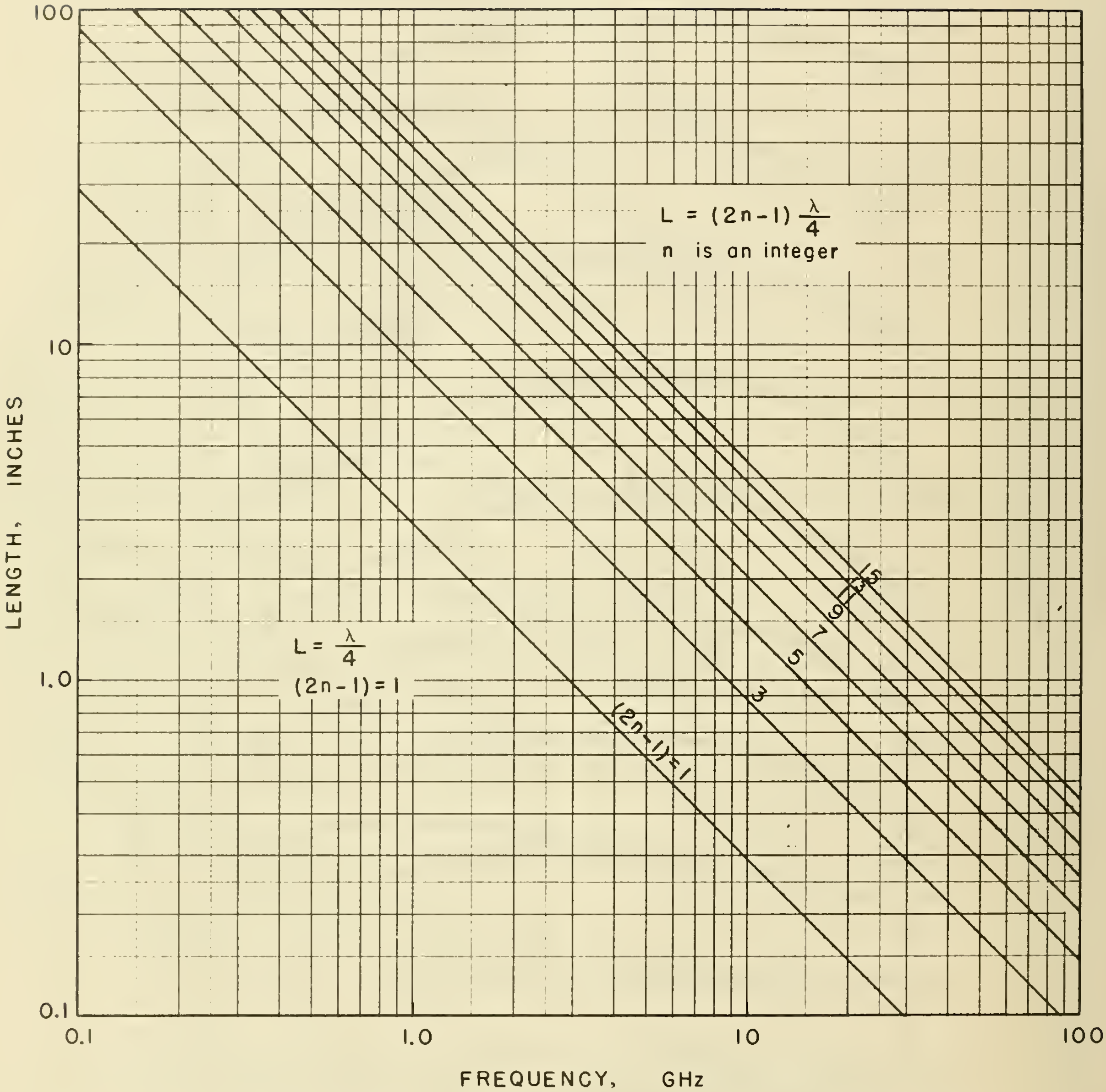


Figure 36. Plot of L = (2n-1) $\lambda_G/4$ versus frequency for TEM mode propagation in coaxial line.

```
CS11   09:01   06/04/74

1REM
2REM   INPUT DATA REQUIRED:
4REM
6REM      FOR COAXIAL SYSTEM INTO WHICH 2-PORT IS INSERTED:
7REM         COAXIAL SYSTEM DESIGNATOR.........LINE 250
8REM         ODIC (INCHES)......................LINE 205 A1
10REM        IDOC (INCHES)......................LINE 215 B1
12REM      FOR REDUCED IDOC 2-PORT STANDARD:
14REM        ODIC (INCHES)......................LINE 210 A2
16REM        IDOC (INCHES)......................LINE 220 B2
18REM        LENGTH (INCHES)....................LINE 225 L
20REM        IC RESISTIVITY (OHM-CM.)...........LINE 230 P1
22REM        OC RESISTIVITY (OHM-CM.)...........LINE 235 P2
24REM        DISCONTINUITY CAPACITANCE DIVIDED BY CIRCUMFER-
26REM           ENCE OF IC (FARADS/CM.).........LINE 240 C1
28REM           (NOTE THAT C1 IS ASSUMED INDEPENDENT OF
30REM           FREQUENCY AND IS NOT CALCULATED BY THIS PRO-
32REM           GRAM BUT MUST BE OBTAINED BY OTHER MEANS)
34REM        RELATIVE PERMITTIVITY OF AIR.......LINE 200 E
36REM        FREQUENCIES (GHZ)..................LINE 329 F
38REM
40REM
42REM   CALCULATED PARAMETERS:
44REM
46REM      TEM MODE Z0 OF COAXIAL SYSTEM (OHMS)..LINE305 Z1
48REM      TEM MODE Z0 OF 2-PORT (OHMS)..........LINE 310 Z2
50REM      DISCONTINUITY CAPACITANCE (FARADS)....LINE 360 C2
52REM      DISCONTINUITY SUSCEPTANCE/Y02.........LINE 370 E7
54REM         (NOTE THAT Y02=1/Z02)
56REM      GUIDE WAVELENGTH (INCHES).............LINE 330 W
58REM      IC SKIN DEPTH (CM.)...................LINE 335 K1
60REM      OC SKIN DEPTH (CM.)...................LINE 340 K2
62REM      ATTENUATION CONSTANT OF 2-PORT(N/CM)..LINE 345 A
64REM      (ATTEN. CONST.)*(LENGTH)---(DB).......LINE 355 A7
65REM      RETURN LOSS (DB) CORRESPONDING TO S11..LINE 481 T5
66REM      MAGNITUDE OF S11......................LINE 480 S
68REM      ARGUMENT OF S11 (DEGREES).............LINE 500 T3
70REM         (NOTE THAT IF G1<0 THEN T3+180)
100P=3.14159265
105 C=2.997925*10↑10
110N=8.68589
115N1=2.54
125 N3=.5/P
200E=1.00064
205A1=.24425
210A2=.24425
215B1=.5625
220B2=.5185
225 L=30/N1
230 P1=2/10↑6
235 P2=8/10↑6
240 C1=1.94969/10↑15
245V=C/(N1*SQR(E))
246Z1=59.9392*LOG(B1/A1)
247Z2=59.9392*LOG(B2/A2)
248C9=2.302585093
250PRINT"FOR 9/16 INCH (14 MM) COAXIAL SYSTEM:"
251PRINT"   ODIC                                   ",A1;"INCHES"
252PRINT"   IDOC                                   ",B1;"INCHES"
253PRINT"   TEM-MODE CHARACTERISTIC IMPEDANCE ",Z1;"OHMS"
254PRINT
255PRINT"FOR 2-PORT:"
256PRINT"   ODIC                                   ",A2;"INCHES"
257PRINT"   IDOC                                   ",B2;"INCHES"
258PRINT"   LENGTH                                 ",L;"INCHES"
259PRINT"   TEM-MODE CHARACTERISTIC IMPEDANCE ",Z2;"OHMS"
260PRINT"   DISCONTINUITY CAPACITANCE          ",C1*P*A1*N1;"FARADS
261PRINT"   RELATIVE PERMITTIVITY OF AIR  ",E
262PRINT"   IC RESISTIVITY                         ",P1;"OHM-CM."
263PRINT"   OC RESISTIVITY                         ",P2;"OHM-CM."
264PRINT
315R1=Z1/Z2
320R2=R1↑2
323PRINT
324PRINT"FREQUENCY","RETURN LOSS","        ","ARG(S11)"
325PRINT"  GHZ   ","DECIBELS","MAG(S11)","DEGREES"
326PRINT
329FOR F=.1 TO.5STEP.01
330 W=V/(F*10↑9)
335K1=N3*SQR(P1/F)
340K2=N3*SQR(P2/F)
345 A=2*P*F*((K1/A2)+(K2/B2))/(N1*Z2)
350 A6=2*A*L*N1
355A7=A6*N/2
360C2=P*A1*N1*C1
365 B3=2*P*F*C2*10↑9
370 E7=Z2*B3
375 B=4*P*L/W
380S5=SIN(B)
385C5=COS(B)
390A9=1-A6
395C6=E7*E7*R2
400R3=(1-R2+C6)*(1-A9*C5)
405R4=-2*E7*R2*A9*S5
410R5=R3+R4
415I1=-2*E7*R2*(1+A9*C5)
420I2=(1-R2+C6)*A9*S5
425I3=I1+I2
430M1=SQR(R5↑2+I3↑2)
435R6=(1+R1)↑2-C6
440R7=((1-R1)↑2-(E7*R1)↑2)*C5
445R8=(2*E7*R1)*(1-R1)*S5
450R9=R6-A9*(R7+R8)
455I4=(2*E7*R1)*(1+R1)
460I5=R7*TAN(B)
465I6=-2*E7*R1*(1-R1)*C5
470I7=I4+(1-A6)*(I5+I6)
475M2=SQR(R9↑2+I7↑2)
480S =M1/M2
481T5=(20*LOG(1/S))/C9
485G1=(R5*R9+I3*I7)/(R9*R9+I7*I7)
490G2=(I3*R9-R5*I7)/(R9*R9+I7*I7)
495G3=ATN(G2/G1)
500T3=G3*180/P
505IF G1<0 THEN 520
510PRINT F,T5,S,T3
515IF G1>0 THEN 525
520PRINT F,T5,S,T3+180
525NEXT F
```

```
2REM    INPUT DATA REQUIRED:
4REM
6REM    FOR COAXIAL SYSTEM INTO WHICH 2-PORT IS INSERTED:
7REM        COAXIAL SYSTEM DESIGNATOR...........LINE 296
8REM        ODIC (INCHES).......................LINE 135 A1
10REM       IDOC (INCHES).......................LINE 145 B1
12REM     FOR REDUCED IDOC 2-PORT STANDARD:
14REM       ODIC (INCHES).......................LINE 140 A2
16REM       IDOC (INCHES).......................LINE 150 B2
18REM       LENGTH (INCHES).....................LINE 155 L
20REM       IC RESISTIVITY (OHM-CM.)............LINE 160 P1
22REM       OC RESISTIVITY (OHM-CM.)............LINE 165 P2
24REM       DISCONTINUITY CAPACITANCE DIVIDED BY CIRCUMFER-
26REM       ENCE OF IC (FARADS/CM.).............LINE170 C5
28REM          (NOTE THAT C5 IS ASSUMED INDEPENDENT OF FRE-
30REM          QUENCY AND IS NOT CALCULATED BY THIS PRO-
32REM          GRAM BUT MUST BE OBTAINED BY OTHER MEANS)
34REM       RELATIVE PERMITTIVITY OF AIR.......LINE 130 E
36REM       FREQUENCIES (GHZ)...................LINE 400 F
37REM
38REM     DELTA F FOR GROUP DELAY CALCULATION...LINE 205 M3
40REM
41REM
42REM     CALCULATED PARAMETERS:
44REM
46REM       TEM MODE Z0 OF COAXIAL SYSTEM (OHMS)..LINE 180 Z1
48REM       TEM MODE Z0 OF 2-PORT (OHMS)..........LINE 185 Z2
50REM       DISCONTINUITY CAPACITANCE (FARADS)....LINE 190 C2
52REM       DISCONTINUITY SUSCEPTANCE/Y02.........LINE 480 E7
54REM          (NOTE THAT Y02=1/Z02)
56REM       GUIDE WAVELENGTH (INCHES).............LINE 420 W
58REM       IC SKIN DEPTH (CM.)...................LINE 435 K1
60REM       OC SKIN DEPTH (CM.)...................LINE 440 K2
61REM       ATTENUATION OF 2-PORT (DECIBELS)....LINE 811 T5
62REM       ATTENUATION CONSTANT OF 2-PORT (N/CM)  .LINE 445 A
63REM       ATTENUATION CONSTANT*LENGTH (DB)....LINE 460 A7
64REM       MAGNITUDE OF S21......................LINE 810 S
66REM       ARGUMENT OF S21 (DEGREES).............LINE 860 T3
68REM          (NOTE THAT IF G1<0 THEN T3+180)
70REM       GROUP DELAY (NANOSECONDS)..........LINE 830 K9
72REM          (NOTE THAT IF K6*K5>0 THEN LINE LINE 840)
74REM
100P=3.14159265
105C=2.997925*10↑10
110N=8.68589
115N1=2.54
125N3= .5/P
130E=1.00064
135A1=.24425
140A2=.24425
145B1=.5625
150B2=.5185
155L=30/N1
160 P1=2/10↑6
165 P2=8/10↑6
170 C5=1.94969/10↑15
175V=C/(N1*SQR(E))
180Z1=59.9392*LOG(B1/A1)
185Z2=59.9392*LOG(B2/A2)
190C2=P*A1*N1*C5
195R1=Z1/Z2
200R2=R1↑2
205M3=.005
210C9=2.302585093
296PRINT"FOR 9/16 INCH (14 MM) COAXIAL SYSTEM:"
300 PRINT"   ODIC                          ",A1;"INCHES"
305PRINT"   IDOC                          ",B1;"INCHES"
310 PRINT"   TEM-MODE CHARACTERISTIC IMPEDANCE",Z1;"OHMS"
315PRINT
318PRINT"FOR 2-PORT:"
319 PRINT"   ODIC                          ",A2;"INCHES"
320PRINT"   IDOC                          ",B2;"INCHES"
325PRINT"   LENGTH                        ",L;"INCHES"
330 PRINT"   TEM-MODE CHARACTERISTIC IMPEDANCE",Z2;"OHMS"
335PRINT"   DISCONTINUITY CAPACITANCE         ",C5*P*A1*N1;"FARADS"
340PRINT"   RELATIVE PERMITTIVITY OF AIR      ",E
345PRINT"   IC RESISTIVITY                   ",P1;"OHM-CM."
350PRINT"   OC RESISTIVITY                   ",P2;"OHM-CM."
355PRINT
360 PRINT"DELTA F FOR CALCULATION OF GROUP DELAY",M3;"GHZ"
365PRINT
366PRINT
370PRINT"FREQUENCY","ATTENUATION","          ","ARG(S21)","GROUP DELAY"
375PRINT"  GHZ  ","DECIBELS","MAG(S21)","DEGREES","NANOSECONDS"
380PRINT
400FOR F=.1 TO .5 STEP .01
410F1=F-M3
415F2=F+M3
420W=V/(F*10↑9)
425W1=W*F/F1
430W2=W*F/F2
435K1=N3*SQR(P1/F)
440K2=N3*SQR(P2/F)
445 A=2*P*F*((K1/A2)+(K2/B2))/(N1*Z2)
450A6=2*A*L*N1
460A7=A6*N/2
465A8=A6*SQR(F1/F)
470A9=A6*SQR(F2/F)
475B5=2*P*F*C2*10↑9
480E7=Z2*B5
485E8=E7*(F1/F)
490E9=E7*(F2/F)
495B=4*P*L/W
500B3=B*W/W1
505B4=B*W/W2
600Q1=4*R1*(1-A6/2)*COS(B/2)
605Q6=4*R1*(1-A8/2)*COS(B3/2)
610Q7=4*R1*(1-A9/2)*COS(B4/2)
615H1=4*R1*(1-A6/2)*SIN(B/2)
620M1=SQR(Q1↑2+H1↑2)
625D1=ATN(H1/Q1)
630Q2=-((1-R1)↑2-E7*E7*R2)*(1-A6)
635Q8=-((1-R1)↑2-E8*E8*R2)*(1-A8)
640Q9=-((1-R1)↑2-E9*E9*R2)*(1-A9)
645Q3=((1+R1)↑2-E7*E7*R2)*COS(B)
650D3=((1+R1)↑2-E8*E8*R2)*COS(B3)
655D4=((1+R1)↑2-E9*E9*R2)*COS(B4)
660H6=Q6*TAN(B3/2)
665H7=Q7*TAN(B4/2)
670 Q4=-2*E7*R1*(1+R1)*SIN(B)
675D5=-2*E8*R1*(1+R1)*SIN(B3)
680D6=-2*E9*R1*(1+R1)*SIN(B4)
685Q5=Q2+Q3+Q4
690D7=Q8+D3+D5
695D8=Q9+D4+D6
700H3=((1+R1)↑2-E7*E7*R2)*SIN(B)
705J1=((1+R1)↑2-E8*E8*R2)*SIN(B3)
710J2=((1+R1)↑2-E9*E9*R2)*SIN(B4)
715H2=2*E7*R1*(1+R1)*COS(B)
720H8=2*E8*R1*(1+R1)*COS(B3)
725H9=2*E9*R1*(1+R1)*COS(B4)
730H4=2*E7*R1*(R1-1)*(1-A6)
735J3=2*E8*R1*(R1-1)*(1-A8)
740J4=2*E9*R1*(R1-1)*(1-A9)
745H5=H2+H3+H4
750J5=H8+J1+J3
755J6=H9+J2+J4
760M2=SQR(Q5↑2+H5↑2)
765D2=ATN(H5/Q5)
770T1=D1*180/P
775J7=(Q6*D7+H6*J5)/(D7*D7+J5*J5)
780J8=(Q7*D8+H7*J6)/(D8*D8+J6*J6)
785K3=(H6*D7-Q6*J5)/(D7*D7+J5*J5)
790K4=(H7*D8-Q7*J6)/(D8*D8+J6*J6)
795T2=D2*180/P
800K5=ATN(K3/J7)
805K6=ATN(K4/J8)
810S=M1/M2
811T5=(20*LOG(1/S))/C9
815IF (K6*K5)↑2<1 THEN 840
820IF K6*K5<0 THEN 830
825IF K6*K5>0 THEN 840
830K9=(K5+P-K6)/(4*P*M3)
835IF K6*K5<0 THEN 845
840K9=(K5-K6)/(4*P*M3)
841IF K5>K6 THEN 845
842K9=-K9
845G1=(Q1*Q5+H1*H5)/(Q5*Q5+H5*H5)
850G2=(H1*Q5-Q1*H5)/(Q5*Q5+H5*H5)
855G3=ATN(G2/G1)
860T3=G3*180/P
865IF G1<0 THEN 880
870PRINT F,T5,S,T3,K9
875IF G1>0 THEN 885
880PRINT F,T5,S,T3+180,K9
885NEXT F
999END
```

```
ICS11   08:35   06/07/74

1REM
2REM   INPUT DATA REOUIREO:
4REM
6REM      FOR COAXIAL SYSTEM INTO WHICH 2-PORT IS INSERTED:
7REM         COAXIAL SYSTEM OESIGNATOR..........LINE 250
8REM        ODIC (INCHES)........................LINE 205 A1
10REM        IDOC (INCHES)........................LINE 215 B1
12REM     FOR INCREASEO ODIC 2-PORT STANOARO:
14REM        DDIC (INCHES)........................LINE 210 A2
16REM        IDOC (INCHES)........................LINE 220 B2
18REM        LENGTH (INCHES)......................LINE 225 L
20REM        IC RESISTIVITY (OHM-CM.)............LINE 230 P1
22REM        DC RESISTIVITY (OHM-CM.)............LINE 235 P2
24REM        OISCONTINUITY CAPACITANCE OIVIOEO BY CIRCUMFER-
26REM           ENCE OF OC (FARADS/CM.)..........LINE 240 C1
28REM           (NOTE THAT C1 IS ASSUMED INDEPENDENT OF
30REM           FREOUENCY ANO IS NOT CALCULATEO BY THIS PRO-
32REM           GRAM BUT MUST BE DETAINEO BY OTHER MEANS)
34REM        RELATIVE PERMITTIVITY OF AIR.......LINE 200 E
36REM        FREGUENCIES (GHZ)...................LINE 329 F
38REM
40REM
42REM   CALCULATED PARAMETERS:
44REM
46REM      TEM MODE Z0 DF CDAXIAL SYSTEM (DHMS)..LINE305 Z1
48REM      TEM MOOE Z0 OF 2-PORT (OHMS)..........LINE 310 Z2
50REM      OISCONTINUITY CAPACITANCE (FARADS)....LINE 360 C2
52REM      OISCONTINUITY SUSCEPTANCE/Y02.........LINE 370 E7
54REM         (NOTE THAT Y02=1/Z02)
56REM      GUIDE WAVELENGTH (INCHES).............LINE 330 W
58REM      IC SKIN DEPTH (CM.)...................LINE 335 K1
60REM      OC SKIN OEPTH (CM.)....................LINE 340 K2
62REM      ATTENUATIDN CONSTANT OF 2-PORT(N/CM)..LINE 345 A
64REM      (ATTEN. CDNST.)*(LENGTH)---(OB).......LINE 355 A7
65REM      RETURN LOSS (OB) CORRESPONDING TO S11..LINE 481 T5
66REM      MAGNITUOE OF S11......................LINE 480 S
68REM      ARGUMENT OF S11 (OEGREES).............LINE 500 T3
70REM         (NOTE THAT IF G1<0 THEN T3+180)
100P=3.14159265
105 C=2.997925*10↑10
110N=8.68589
115N1=2.54
125 N3=.5/P
200E=1.00064
205A1=.24425
210 A2=.2651
215B1=.5625
220B2=B1
225 L=11.811
230P1=8/10↑6
235P2=P1
240 C1=.569295/10↑15
245V=C/(N1*SQR(E))
246Z1=59.9392*LOG(B1/A1)
247Z2=59.9392*LDG(B2/A2)
248C9=2.3025850 93
250PRINT"FOR 9/16 INCH (14 MM) COAXIAL SYSTEM:"
251PRINT"   OOIC                                    ",A1;"INCHES"
252PRINT"   IOOC                                    ",B1;"INCHES"
253PRINT"   TEM-MOOE CHARACTERISTIC IMPEDANCE ",Z1;"OHMS"
254PRINT
255PRINT"FDR 2-PORT:"
256PRINT"   DOIC                                    ",A2;"INCHES"
257PRINT"   IDOC                                    ",B2;"INCHES"
258PRINT"   LENGTH                                  ",L;"INCHES"
259PRINT"   TEM-MODE CHARACTERISTIC IMPEDANCE ",Z2;"OHMS"
260 PRINT"   OISCONTINUITY CAPACITANCE         ",C1*P*B1*N1;"FARAOS"
261PRINT"   RELATIVE PERMITTIVITY DF AIR  ",E
262PRINT"   IC RESISTIVITY                          ",P1;"OHM-CM."
263PRINT"   OC RESISTIVITY           .              ",P2;"OHM-CM."
264PRINT
315R1=Z1/Z2
320R2=R1↑2
323PRINT
324PRINT"FREQUENCY","RETURN LORS","        ","ARG(S11)"
325PRINT"  GHZ    ","OECIBELS","MAG(S11)","OEGREES"
326PRINT
329 FOR F=.1TO.5STEP.01
330 W=V/(F*10↑9)
335K1=N3*SOR(P1/F)
340K2=N3*SDR(P2/F)
345A=2*P*F*((K1/A2)+(K2/B2))/(N1*Z2)
350 A6=2*A*L*N1
355A7=A6*N/2
360C2=P*B1*N1*C1
365 B3=2*P*F*C2*10↑9
370 E7=Z2*B3
375 B=4*P*L/W
380S5=SIN(B)
385C5=COS(B)
390A9=1-A6
395C6=E7*E7*R2
400R3=(1-R2+C6)*(1-A9*C5)
405R4=-2*E7*R2*A9*S5
410R5=R3+R4
415I1=-2*E7*R2*(1+A9*CS)
420I2=(1-R2+C6)*A9*S5
425I3=I1+I2
430M1=SOR(R5↑2+I3↑2)
435R6=(1+R1)↑2-C6
440R7=((1-R1)↑2-(E7*R1)↑2)*C5
445R8=(2*E7*R1)*(1-R1)*S5
450R9=R6-A9*(R7+R8)
455I4=(2*E7*R1)*(1+R1)
460I5=R7*TAN(B)
465I6=-2*E7*R1*(1-R1)*C5
470I7=I4+(1-A6)*(I5+I6)
475M2=SQR(R9↑2+I7↑2)
480S =M1/M2
481T5=(20*LOG(1/S))/C9
485G1=(R5*R9+I3*I7)/(R9*R9+I7*I7)
490G2=(I3*R9-R5*I7)/(R9*R9+I7*I7)
495G3=ATN(G2/G1)
500T3=G3*180/P
505IF G1<0 THEN 520
510PRINT F,T5,S,T3
515IF G1>0 THEN 525
520PRINT F,T5,S,T3+180
525NEXT F
999END
```

```
ICS21    08:20    06/07/74

2REM    INPUT DATA REQUIRED:
4REM
6REM    FOR COAXIAL SYSTEM INTO WHICH 2-PORT IS INSERTED:
7REM        COAXIAL SYSTEM DESIGNATOR............LINE 296
8REM      ODIC (INCHES)........................LINE 135 A1
10REM       IDOC (INCHES)........................LINE 145 B1
12REM    FOR INCREASED ODIC 2-PORT STANDARD:
14REM       ODIC (INCHES)........................LINE 140 A2
16REM       IDOC (INCHES)........................LINE 150 B2
18REM       LENGTH (INCHES)......................LINE 155 L
20REM       IC RESISTIVITY (OHM-CM.)............LINE 160 P1
22REM       OC RESISTIVITY (OHM-CM.)............LINE 165 P2
24REM       DISCONTINUITY CAPACITANCE DIVIDED BY CIRCUMFER-
26REM       ENCE OF OC (FARADS/CM.)      .......LINE 170 C5
28REM          (NOTE THAT C5 IS ASSUMED INDEPENDENT OF FRE-
30REM          QUENCY AND IS NOT CALCULATED BY THIS PRO-
32REM          GRAM BUT MUST BE OBTAINED BY OTHER MEANS)
34REM       RELATIVE PERMITTIVITY OF AIR.......LINE 130 E
36REM       FREQUENCIES (GHZ)...................LINE 400 F
37REM
38REM    DELTA F FOR GROUP DELAY CALCULATION...LINE 205 M3
40REM
41REM
42REM    CALCULATED PARAMETERS:
44REM
46REM       TEM MODE Z0 OF COAXIAL SYSTEM (OHMS)..LINE 180 Z1
48REM       TEM MODE Z0 OF 2-PORT (OHMS)..........LINE 185 Z2
50REM       DISCONTINUITY CAPACITANCE (FARADS)....LINE 190 C2
52REM       DISCONTINUITY SUSCEPTANCE/Y02.........LINE 480 E7
54REM          (NOTE THAT Y02=1/Z02)
56REM       GUIDE WAVELENGTH (INCHES).............LINE 420 W
58REM       IC SKIN DEPTH (CM.)...................LINE 435 K1
60REM       OC SKIN DEPTH (CM.)...................LINE 440 K2
61REM       ATTENUATION OF 2-PORT (DECIBELS)....LINE 811 T5
62REM       ATTENUATION CONSTANT OF 2-PORT (N/CM)...LINE 445 A
63REM       (ATTEN. CONST.)*(LENGTH)---(DB)..........LINE 460 A7
64REM       MAGNITUDE OF S21......................LINE 810 S
66REM       ARGUMENT OF S21 (DEGREES).............LINE 860 T3
68REM          (NOTE THAT IF G1<0 THEN T3+180)
70REM       GROUP DELAY (NANOSECONDS).........LINE 830 K9
72REM          (NOTE THAT IF K6*K5>0 THEN LINE LINE 840)
74REM
100P=3.14159265
105C=2.997925*10↑10
110N=8.68589
115N1=2.54
125N3= .5/P
130E=1.00064
135A1=.24425
140 A2=.2651
145B1=.5625
150 B2=B1
155L=30/N1
160 P1=8/10↑6
165 P2=P1
170 C5=.569295/10↑15
175V=C/(N1*SQR(E))
180Z1=59.9392*LOG(B1/A1)
185Z2=59.9392*LOG(B2/A2)
190 C2=P*B1*N1*C5
195R1=Z1/Z2
200R2=R1↑2
205M3=.005
210C9=2.30258 5093
296PRINT"FOR 9/16 INCH (14 MM) COAXIAL SYSTEM:"
300 PRINT"    ODIC                                    ",A1;"INCHES"
305PRINT"    IDOC                                    ",B1;"INCHES"
310 PRINT"    TEM-MODE CHARACTERISTIC IMPEDANCE",Z1;"OHMS"
315PRINT
318PRINT"FOR 2-PORT:"
319 PRINT"    ODIC                                    ",A2;"INCHES"
320PRINT"    IDOC                                    ",B2;"INCHES"
325PRINT"    LENGTH                                  ",L;"INCHES"
330 PRINT"    TEM-MODE CHARACTERISTIC IMPEDANCE",Z2;"OHMS"
335PRINT"    DISCONTINUITY CAPACITANCE          ",C5*P*B1*N1;"FARADS"
340PRINT"    RELATIVE PERMITTIVITY OF AIR       ",E
345PRINT"    IC RESISTIVITY                     ",P1;"OHM-CM."
350PRINT"    OC RESISTIVITY                     ",P2;"OHM-CM."
355PRINT
360 PRINT"DELTA F FOR CALCULATION OF GROUP DELAY",M3;"GHZ"
365PRINT
366PRINT
370PRINT"FREQUENCY","ATTENUATION","          ","ARG(S21)","GROUP DELAY"
375PRINT"   GHZ   ","DECIBELS","MAG(S21)","DEGREES","NANOSECONDS"
380PRINT
400FOR F=.1 TO .5 STEP .01
410F1=F-M3
415F2=F+M3
420W=V/(F*10↑9)
425W1=W*F/F1
430W2=W*F/F2
435K1=N3*SQR(P1/F)
440K2=N3*SQR(P2/F)
445 A=2*P*F*((K1/A2)+(K2/B2))/(N1*Z2)
450A6=2*A*L*N1
460A7=A6*N/2
465A8=A6*SQR(F1/F)
470A9=A6*SQR(F2/F)
475B5=2*P*F*C2*10↑9
480E7=Z2*B5
485E8=E7*(F1/F)
490E9=E7*(F2/F)
495B=4*P*L/W
500B3=B*W/W1
505B4=B*W/W2
600Q1=4*R1*(1-A6/2)*COS(B/2)
605C6=4*R1*(1-A8/2)*COS(B3/2)
610Q7=4*R1*(1-A9/2)*COS(B4/2)
615H1=4*R1*(1-A6/2)*SIN(B/2)
620M1=SQR(C1↑2+H1↑2)
625D1=ATN(H1/Q1)
630C2=-((1-R1)↑2-E7*E7*R2)*(1-A6)
635Q8=-((1-R1)↑2-E8*E8*R2)*(1-A8)
640Q9=-((1-R1)↑2-E9*E9*R2)*(1-A9)
645Q3=((1+R1)↑2-E7*E7*R2)*COS(B)
650D3=((1+R1)↑2-E8*E8*R2)*COS(B3)
655D4=((1+R1)↑2-E9*E9*R2)*COS(B4)
660H6=Q6*TAN(B3/2)
665H7=Q7*TAN(B4/2)
670 Q4=-2*E7*R1*(1+R1)*SIN(B)
675D5=-2*E8*R1*(1+R1)*SIN(B3)
680D6=-2*E9*R1*(1+R1)*SIN(B4)
685Q5=Q2+C3+Q4
690D7=Q8+D3+D5
695D8=Q9+D4+D6
700H3=((1+R1)↑2-E7*E7*R2)*SIN(B)
705J1=((1+R1)↑2-E8*E8*R2)*SIN(B3)
710J2=((1+R1)↑2-E9*E9*R2)*SIN(B4)
715H2=2*E7*R1*(1+R1)*COS(B)
720H8=2*E8*R1*(1+R1)*COS(B3)
725H9=2*E9*R1*(1+R1)*COS(B4)
730H4=2*E7*R1*(R1-1)*(1-A6)
735J3=2*E8*R1*(R1-1)*(1-A8)
740J4=2*E9*R1*(R1-1)*(1-A9)
745H5=H2+H3+H4
750J5=H8+J1+J3
755J6=H9+J2+J4
760M2=SQR(Q5↑2+H5↑2)
765D2=ATN(H5/Q5)
770T1=D1*180/P
775J7=(Q6*D7+H6*J5)/(D7*D7+J5*J5)
780J8=(Q7*D8+H7*J6)/(D8*D8+J6*J6)
785K3=(H6*D7-Q6*J5)/(D7*D7+J5*J5)
790K4=(H7*D8-Q7*J6)/(D8*D8+J6*J6)
795T2=D2*180/P
800K5=ATN(K3/J7)
805K6=ATN(K4/J8)
810S=M1/M2
811T5=(20*LOG(1/S))/C9
815IF (K6*K5)↑2<1 THEN 840
820IF K6*K5<0 THEN 830
825IF K6*K5>0 THEN 840
830K9=(K5+P-K6)/(4*P*M3)
835IF K6*K5<0 THEN 845
840K9=(K5-K6)/(4*P*M3)
841IF K5>K6 THEN 845
842K9=-K9
845G1=(Q1*Q5+H1*H5)/(Q5*Q5+H5*H5)
850G2=(H1*Q5-Q1*H5)/(Q5*Q5+H5*H5)
855G3=ATN(G2/G1)
860T3=G3*180/P
865IF G1<0 THEN 880
870PRINT F,T5,S,T3,K9
875IF G1>0 THEN 885
880PRINT F,T5,S,T3+180,K9
885NEXT F
999END
```

```
WSII    14:57    06/04/74

2REM     INPUT DATA REDUIRED:
4REM
6REM        FDR WAVEGUIDE SYSTEM:
7REM           WAVEGUIDE DESIGNATDR.....................LINE 200
8REM           INTERNAL WIDTH (INCHES)..................LINE 75 A1
10REM          INTERNAL HEIGHT (INCHES).................LINE 80 B1
12REM
14REM       FDR REDUCED HEIGHT 2-PDRT:
16REM          INTERNAL WIDTH (INCHES)..................LINE 82 A2
18REM          INTERNAL HEIGHT (INCHES).................LINE 85 B2
20REM          LENGTH (INCHES)..........................LINE 87 L
22REM          RESISTIVITY (DHM-CM.)....................LINE 90 P1
24REM          RELATIVE PERMITTIVITY DF AIR.............LINE 70 E
26REM          FREDUENCIES (GHZ)........................LINE 320 F
28REM
30REM
32REM    CALCULATED PARAMETERS:
34REM
36REM       GUIDE WAVELENGTH (INCHES)...................LINE 580 W
38REM       NDRMALIZED (TD Y0 DF 2-PORT) SUSCEPTANCE
40REM       DF DISCDNTINUITY............................LINE 685 E7
42REM       NDRMALIZED (TD Y0 DF WG SYSTEM) SUSCEPTANCE
44REM       DIVIDED BY RATID DF INTERNAL HEIGHT DF WG SYSTEM
46REM       TD GUIDE WAVELENGTH.........................LINE 690 E8
48REM       SKIN DEPTH (CM.)............................LINE 325 K1
50REM       ATTENUATIDN CDNSTANT DF 2-PDRT (DB/FT.).....LINE 600 A5
52REM       ATTENUATIDN DF 2-PDRT (DECIBELS)............LINE 607 A7
53REM       RETURN LDSS (DB) CDRRESPONDING TD S11 ......LINE 506 T5
54REM       MAGNITUDE DF S11 ...........................LINE 505 S
56REM       ARGUMENT DF S11 (DEGREES)...................LINE 525 T3
58REM          (NDTE THAT IF G1<0 THEN T3+180)
60REMM
64 P=3.14159265
65C=2.997925*10↑10
70E=1.00064
75A1=0.9
80B1=0.4
82A2=0.9
85B2=0.0918
87 L=.4052
90 P1=8.5/10↑6
95N=2*4.342945
100N1=2.54
105V=C/SQR(E)
110V1=V/N1
115N2=5.963
120C9=2.302585093
160 N3=.5/P
200PRINT"FDR WR-90 (R-100) WAVEGUIDE SYSTEM:"
205PRINT"   INTERNAL WIDTH                        ",A1:"INCHES"
210PRINT"   INTERNAL HEIGHT                       ",B1;"INCHES"
215PRINT
220PRINT"FDR 2-PDRT:"
225PRINT"   INTERNAL WIDTH                        ",A2:"INCHES"
230PRINT"   INTERNAL HEIGHT                       ",B2;"INCHES"
235PRINT"   LENGTH                                ",L;"INCHES"
240PRINT"   RESISTIVITY                           ",P1;"DHM-CM."
245PRINT"   RELATIVE PERMITTIVITY DF AIR          ",E
250V=C/(N1*SQR(E))
255R1=B1/B2
260R2=R1↑2
295PRINT
300PRINT
305PRINT"FREQUENCY","RETURN LDSS","          ","ARG(S11)"
310PRINT"   GHZ    ","DECIBELS","MAG(S11)","DEGREES"
315PRINT
320FDR F=8 TD 13 STEP .1
325K1=N3*SQR(P1/F)
405GDSUB 560
410
420 B=4*P*L/W
425 R3=(1-R2+(E7↑2)*R2)*(1-(1-A6)*CDS(B))
430R4=-2*E7*R2*(1-A6)*SIN(B)
435R5=R3+R4
440I1=-2*E7*R2*(1+(1-A6)*CDS(B))
445 I2=(1-R2+E7*E7*R2)*(1-A6)*SIN(B)
450I3=I1+I2
455M1=SDR(R5↑2+I3↑2)
460R6=(1+R1)↑2-(E7↑2)*R2
465 R7=((1-R1)↑2-(E7*R1)↑2)*CDS(B)
470R8=(2*E7*R1)*(1-R1)*SIN(B)
475R9=R6-(1-A6)*(R7+R8)
480I4=(2*E7*R1)*(1+R1)
485 I5=((1-R1)↑2-(E7*R1)↑2)*SIN(B)
490I6=-2*E7*R1*(1-R1)*CDS(B)
495I7=I4+(1-A6)*(I5+I6)
500M2=SQR(R9↑2+I7↑2)
505S=M1/M2
506T5=(20*LDG(1/S))/C9
510 G1=(R5*R9+I3*I7)/(R9*R9+I7*I7)
515 G2=(I3*R9-R5*I7)/(R9*R9+I7*I7)
520 G3=ATN(G2/G1)
525 T3=G3*180/P
530 IF G1<0 THEN 545
535 PRINT F,T5,S,T3
540 IF G1>0 THEN 550
545 PRINT F,T5,S,T3+180
550NEXT F
555END
560L1=SQR(E)
565L2=C/(10↑9)
570L3=(N1*F*L1/L2)↑2
575L4=(1/(2*A1))↑2
580W=1/SQR(L3-L4)
585 A2=1/L3
590 A3=SQR(SQR(A2))
595A4=N2*SQR(P1)
600 A5=((A4/A3)*((1/B2)+A2/(2*A1↑3)))/SQR(1-A2/((2*A1)↑2))
605 A6=(L/(6*N))*A5
607 A7=A6*N
610D1=B2/B1
615D2=(4*D1/(1-D1↑2))↑2
620D3=((1+D1)/(1-D1))↑(2/D1)
625D4=(1+SQR(1-((B2/W)↑2)))/(1-SQR(1-((B2/W)↑2)))
630D5=D3*D4+(3+(D1)↑2)/(1-(D1)↑2)
635D6=D3↑((D1)↑2)
640D7=(1+SQR(1-(B1/W)↑2))/(1-SQR(1-(B1/W)↑2))
645D8=D6*D7-(1+3*(D1↑2))/(1-(D1)↑2)
650D9=((1-D1↑2)/(4*D1))*((1+D1)/(1-D1))↑((1/2)*(D1+1/D1))
655E1=LDG(D9)
660E2=2*(D8+D5+2*D2)/(D8*D5-D2↑2)
665 E3=((B1/(4*W))↑2)*((1-D1)/(1+D1))↑(4*D1)
670E4=((5*(D1↑2))-1)/(1-D1↑2)
675E5=(4*(D1↑2)*D2)/(3*D8)
680E6=E3*(E4+E5)↑2
685E7=2*(E1+E2+E6)*(B2/W)
686 E7=1.04*E7
690E8=E7*W/B2
695RETURN
```

```
10REM   INPUT DATA:
12REM
13REM        WAVEGUIDE DESIGNATOR....................LINE 200
14REM      FOR WAVEGUIDE SYSTEM:
16REM        INTERNAL WIDTH (INCHES)..................LINE 100 A1
18REM        INTERNAL HEIGHT (INCHES).................LINE 105 B1
20REM
22REM      FOR 2-PORT:
24REM        INTERNAL WIDTH (INCHES)..................LINE 110 A2
26REM        INTERNAL HEIGHT (INCHES).................LINE 115 B2
28REM        LENGTH (INCHES)..........................LINE 120 L
30REM        RESISTIVITY (OHM-CM.)....................LINE 125 P1
32REM        RELATIVE PERMITTIVITY OF AIR ............LINE 130 E
34REM
36REM      FREQUENCIES (GHZ) ..........................LINE 300 F
38REM      DELTA F FOR CALCULATION OF GROUP DELAY.....LINE 135 D
40REM
42REM
44REM   CALCULATED PARAMETERS:
46REM
48REM      MAGNITUDE OF S21...........................LINE 395 S
50REM      ARGUMENT OF S21 (DEGREES)..................LINE 415 T3
52REM                                            ALSO LINE 475 T3+180
54REM      GROUP DELAY (NANOSECONDS)..................LINE 435 K9
56REM                                            ALSO LINE 445 K9
58REM                                            ALSO LINE 455 -K9
60REM      GUIDE WAVELENGTH (INCHES)..................LINE 1010 W
62REM      SKIN DEPTH (CENTIMETERS)...................LINE 480 K1
64REM      ATTENUATION OF 2-PORT (DECIBELS)...........LINE 396 T5
65REM      ATTENUATION CONSTANT OF 2-PORT (DB/FT.)....LINE 1030 A5
66REM      ATTENUATION CONSTANT*LENGTH (DECIBELS).....LINE 1125 A7
68REM      NORMALIZED (TO Y0 OF 2-PORT) SUSCEPTANCE
70REM      OF DISCONTINUITY...........................LINE 1115 E7
72REM      NORMALIZED (TO Y0 OF WG SYSTEM)SUSCEPTANCE
74REM      OF DISCONTINUITY DIVIDED BY RATIO B1/W ....LINE 1120 E8
76REM
78REM
80REM
100A1=0.9
105B1=0.4
110A2=0.9
115B2=0.0918
120L=0.4052
125 P1=8.5/10↑6
130E=1.00064
135D=0.05
140P=3.14159265
145N=8.68589
150N1=2.54
155N2=5.963
160N3=0.5/P
165C=2.997925*10↑10
170R1=B1/B2
175R2=R1↑2
180L1=SQR(E)
185L2=C/10↑9
190C9=2.302585093
200PRINT"FOR WR-90 (R-100) WAVEGUIDE SYSTEM:"
205PRINT"   INTERNAL WIDTH                          ",A1;"INCHES"
210PRINT"   INTERNAL HEIGHT                         ",B1;"INCHES"
215PRINT
220PRINT"FOR 2-PORT:"
225PRINT"   INTERNAL WIDTH                          ",A2;"INCHES"
230PRINT"   INTERNAL HEIGHT                         ",B2;"INCHES"
235PRINT"   LENGTH                                  ",L;"INCHES"
240PRINT"   RESISTIVITY                             ",P1;"OHM-CM."
245PRINT"   RELATIVE PERMITTIVITY OF AIR            ",E
250PRINT
255PRINT"DELTA F FOR CALCULATION OF GROUP DELAY",D;"GHZ"
260PRINT
265PRINT
270PRINT"FREQUENCY","ATTENUATION","        ","ARG(S21)","GROUP DELAY"
275PRINT"  GHZ  ","DECIBELS","MAG(S21)","DEGREES","NANOSECONDS"
280PRINT
300FOR F=8 TO 13 STEP 0.1
301F1=F-D
302F2=F+D
305GOSUB 1000
310B=4*P*L/W
311B3=4*P*L/W1
312B4=4*P*L/W2
315Q1=4*R1*(1-A6/2)*COS(B/2)
316Q6=4*R1*(1-A8/2)*COS(B3/2)
317Q7=4*R1*(1-A9/2)*COS(B4/2)
320H1=4*R1*(1-A6/2)*SIN(B/2)
321H6=4*R1*(1-A8/2)*SIN(B3/2)
322H7=4*R1*(1-A9/2)*SIN(B4/2)
325M1=SQR(Q1↑2+H1↑2)
330M3=ATN(H1/Q1)
335Q2=-((1-R1)↑2-E7*E7*R2)*(1-A6)
336Q8=-((1-R1)↑2-F3*F3*R2)*(1-A8)
337Q9=-((1-R1)↑2-F4*F4*R2)*(1-A9)
340Q3=((1+R1)↑2-E7*E7*R2)*COS(B)
341R3=((1+R1)↑2-F3*F3*R2)*COS(B3)
342R4=((1+R1)↑2-F4*F4*R2)*COS(B4)
345Q4=-2*E7*R1*(1+R1)*SIN(B)
346R5=-2*F3*R1*(1+R1)*SIN(B3)
347R6=-2*F4*R1*(1+R1)*SIN(B4)
350Q5=Q2+Q3+Q4
351 R7=Q8+R3+R5
352R8=Q9+R4+R6
355H3=Q3*TAN(B)
356J1=R3*TAN(B3)
357J2=R4*TAN(B4)
360H2=-Q4/TAN(B)
361H8=-R5/TAN(B3)
362H9=-R6/TAN(B4)
365H4=2*E7*R1*(R1-1)*(1-A6)
366J3=2*F3*R1*(R1-1)*(1-A8)
367J4=2*F4*R1*(R1-1)*(1-A9)
370H5=H2+H3+H4
371J5=H8+J1+J3
372J6=H9+J2+J4
375M2=SQR(Q5↑2+H5↑2)
380M4=ATN(H5/Q5)
385T1=M3*180/P
390T2=M4*180/P
395S=M1/M2
396T5=(20*LOG(1/S))/C9
400G1=(Q1*Q5+H1*H5)/(Q5↑2+H5↑2)
401J7=(Q6*R7+H6*J5)/(R7↑2+J5↑2)
402J8=(Q7*R8+H7*J6)/(R8↑2+J6↑2)
405G2=(H1*Q5-Q1*H5)/(Q5↑2+H5↑2)
406K3=(H6*R7-Q6*J5)/(R7↑2+J5↑2)
407K4=(H7*R8-Q7*J6)/(R8↑2+J6↑2)
410G3=ATN(G2/G1)
411K5=ATN(K3/J7)
412K6=ATN(K4/J8)
415T3=G3*180/P
420IF (K6*K5)↑2 <1 THEN 445
425IF K6*K5<0 THEN 435
430IF K6*K5>0 THEN 445
435K9=(K5+P-K6)/(4*P*D)
440IF K6*K5<0 THEN 460
445K9=(K5-K6)/(4*P*D)
450IF K5>K6 THEN 460
455K9=-K9
460IF G1<0 THEN 475
465PRINT F,T5,S,T3,K9
470IF G1>0 THEN 480
475PRINT F,T5,S,T3+180,K9
480K1=N3*SQR(P1/F)
485NEXT F
999END
1000L3=(N1*F*L1/L2)↑2
1001L5=(N1*F1*L1/L2)↑2
1002L6=(N1*F2*L1/L2)↑2
1005L4=(1/(2*A1))↑2
1010W=1/SQR(L3-L4)
1011W1=1/SQR(L5-L4)
1012W2=1/SQR(L6-L4)
1015M5=1/L3
1016M6=1/L5
1017M7=1/L6
1020A3=SQR(SQR(M5))
1021S1=SQR(SQR(M6))
1022S2=SQR(SQR(M7))
1025A4=N2*SQR(P1)
1030A5=((A4/A3)*((1/B2)+M5/(2*A1↑3)))/SQR(1-M5/((2*A1)↑2))
1031S5=((A4/S1)*((1/B2)+M6/(2*A1↑3)))/SQR(1-M6/((2*A1)↑2))
1032S6=((A4/S2)*((1/B2)+M7/(2*A1↑3)))/SQR(1-M7/((2*A1)↑2))
1035A6=(L/(6*N))*A5
1036A8=(L/(6*N))*S5
1037A9=(L/(6*N))*S6
1040D1=B2/B1
1045D2=(4*D1/(1-D1↑2))↑2
1050D3=((1+D1)/(1-D1))↑(2/D1)
1055D4=(1+SQR(1-((B2/W)↑2)))/(1-SQR(1-((B2/W)↑2)))
1056S7=(1+SQR(1-((B2/W1)↑2)))/(1-SQR(1-((B2/W1)↑2)))
1057S8=(1+SQR(1-((B2/W2)↑2)))/(1-SQR(1-((B2/W2)↑2)))
1060D5=D3*D4+(3+D1↑2)/(1-D1↑2)
1061P3=D3*S7+(3+D1↑2)/(1-D1↑2)
1062P4=D3*S8+(3+D1↑2)/(1-D1↑2)
1065D6=D3↑((D1)↑2)
1070D7=(1+SQR(1-(B1/W)↑2))/(1-SQR(1-(B1/W)↑2))
1071P7=(1+SQR(1-(B1/W1)↑2))/(1-SQR(1-(B1/W1)↑2))
1072P8=(1+SQR(1-(B1/W2)↑2))/(1-SQR(1-(B1/W2)↑2))
1075D8=D6*D7-(1+3*(D1↑2))/(1-D1↑2)
1076K7=D6*P7-(1+3*(D1↑2))/(1-D1↑2)
1077K8=D6*P8-(1+3*(D1↑2))/(1-D1↑2)
1080D9=((1-D1↑2)/(4*D1))*((1+D1)/(1-D1))↑((1/2)*(D1+1/D1))
1085E1=LOG(D9)
1090E2=2*(D8+D5+2*D2)/(D8*D5-D2↑2)
1091B7=2*(K7+P3+2*D2)/(K7*P3-D2↑2)
1092B8=2*(K8+P4+2*D2)/(K8*P4-D2↑2)
1095E3=((B1/(4*W))↑2)*((1-D1)/(1+D1))↑(4*D1)
1096C1=((B1/(4*W1))↑2)*((1-D1)/(1+D1))↑(4*D1)
1097C2=((B1/(4*W2))↑2)*((1-D1)/(1+D1))↑(4*D1)
1100E4=((5*(D1↑2))-1)/(1-D1↑2)
1105E5=(4*(D1↑2)*D2)/(3*D8)
1106C5=(4*(D1↑2)*D2)/(3*K7)
1107C6=(4*(D1↑2)*D2)/(3*K8)
1110E6=E3*(E4+E5)↑2
1111C7=C1*(E4+C5)↑2
1112C8=C2*(E4+C6)↑2
1115E7=2*(E1+E2+E6)*(B2/W)
1116F3=2*(E1+B7+C7)*(B2/W1)
1117F4=2*(E1+B8+C8)*(B2/W2)
1118 E7=1.04*E7
1119 F3=1.04*F3
1120E8=E7*W/B2
1121 F4=1.04*F4
1125A7=A6*N/2
1130RETURN
```

```
2REM     INPUT DATA:
4REM        MAG(S11)............................LINE 160 S
6REM        COAXIAL LINE DESIGNATOR.............LINE 100
8REM        IDOC OF COAXIAL SYSTEM..............LINE 110 B1 (INCHES)
10REM       ODIC OF COAXIAL SYSTEM..............LINE 105 A1 (INCHES)
12REM
14REM    CALCULATED PARAMETERS:
16REM       RETURN LOSS.........................LINE 200 R2 (DB)
18REM       VSWR................................LINE 165 R
19REM       TEM-MODE CHARACTERISTIC IMPEDANCE...LINE 175 Z2 (OHMS)
20REM       REDUCED IDOC OF 2-PORT..............LINE 180 B2 (INCHES)
22REM
80A1=.24425
85B1=.5625
90A2=.24425
95Z1=59.9392*LOG(B1/A1)
100PRINT"FOR 9/16-INCH (14 MM) COAXIAL SYSTEM:"
105PRINT"   ODIC                                 ",A1;"INCHES"
110PRINT"   IDOC                                 ",B1;"INCHES"
112 PRINT"   TEM-MODE CHARACTERISTIC IMPEDANCE",Z1;"OHMS"
115PRINT
120PRINT"FOR 2-PORT:"
125PRINT"   ODIC                                 ",A2;"INCHES"
130PRINT
135PRINT
140PRINT"        ","RETURN","        ","CHARACTERISTIC","REDUCED"
145 PRINT"        "," LOSS ","        ","IMPEDANCE"," IDOC"
150PRINT"MAG(S11)","DECIBELS","VSWR"," OHMS ","INCHES"
155PRINT
160 FOR S=0 TO 0.95 STEP 0.05
165R=(1+S)/(1-S)
170R1=SQR(R)
175 Z2=Z1/R1
180 B2=A2*EXP(Z2/59.9392)
185C1=2.302585093
190R2=0
195IF S=0 THEN 210
200R2=(20*LOG(1/S))/C1
205IF S>0 THEN 220
210PRINT S,"INFINITY",R,Z2,B2
215 IF S=0 THEN 225
220 PRINT S,R2,R,Z2,B2
225NEXT S
999END
READY
RUN

IDOC    09:40    06/04/74

FOR 9/16-INCH (14 MM) COAXIAL SYSTEM:
   ODIC                                          .24425 INCHES
   IDOC                                          .5625 INCHES
   TEM-MODE CHARACTERISTIC IMPEDANCE             50.0012 OHMS

FOR 2-PORT:
   ODIC                                          .24425 INCHES
```

MAG(S11)	RETURN LOSS DECIBELS	VSWR	CHARACTERISTIC IMPEDANCE OHMS	REDUCED IDOC INCHES
0	INFINITY	1	50.0012	.5625
.05	26.0206	1.10526	47.5606	.540056
.1	20.	1.22222	45.2278	.519441
.15	16.4782	1.35294	42.9874	.500384
.2	13.9794	1.5	40.8258	.48266
.25	12.0412	1.66667	38.7308	.466081
.3	10.4576	1.85714	36.6909	.450486
.35	9.11864	2.07692	34.6953	.435735
.4	7.9588	2.33333	32.7335	.421704
.45	6.93575	2.63636	30.7948	.408283
.5	6.0206	3.	28.8682	.395368
.55	5.19275	3.44444	26.9414	.382861
.6	4.43698	4.	25.0006	.370662
.65	3.74173	4.71429	23.0289	.358668
.7	3.09804	5.66667	21.0047	.346758
.75	2.49878	7.	18.8987	.334785
.8	1.9382	9.	16.6671	.32255
.85	1.41162	12.3333	14.2377	.309738
.9	.91515	19.	11.4711	.295767
.95	.445528	39.	8.00661	.279154

```
2REM    INPUT DATA:
4REM       MAG(S11)..............................LINE 160 S
6REM       COAXIAL LINE DESIGNATOR...............LINE 100
8REM       IDOC OF COAXIAL SYSTEM................LINE 110 B1 (INCHES)
10REM      ODIC OF COAXIAL SYSTEM................LINE 105 A1 (INCHES)
12REM
14REM   CALCULATED PARAMETERS:
16REM      RETURN LOSS...........................LINE 200 R2 (DB)
18REM      VSWR..................................LINE 165 R
19REM      TEM-MODE CHARACTERISTIC IMPEDANCE.....LINE 175 Z2 (OHMS)
20REM      INCREASED ODIC OF 2-PORT..............LINE 180 A2 (INCHES)
22REM
80A1=.24425
85B1=.5625
90B2=.5625
95Z1=59.9392*LOG(B1/A1)
100PRINT"FOR 9/16-INCH (14 MM) COAXIAL SYSTEM:"
105PRINT"   ODIC                               ",A1;"INCHES"
110PRINT"   IDOC                               ",B1;"INCHES"
112 PRINT"   TEM-MODE CHARACTERISTIC IMPEDANCE",Z1;"OHMS"
115PRINT
120PRINT"FOR 2-PORT:"
125 PRINT"   IDOC                               ",B2;"INCHES"
130PRINT
135PRINT
140PRINT"        ","RETURN","        ","CHARACTERISTIC","INCREASED"
145PRINT"        "," LOSS","        ","IMPEDANCE","  ODIC"
150PRINT"MAG(S11)","DECIBELS","VSWR"," OHMS ","INCHES"
155PRINT
160 FOR S=0 TO 0.95 STEP 0.05
165R=(1+S)/(1-S)
170R1=SQR(R)
175 Z2=Z1/R1
180A2=B2/(EXP(Z2/59.9392))
185C1=2.302585093
190R2=0
195IF S=0 THEN 210
200R2=(20*LOG(1/S))/C1
205IF S>0 THEN 220
210 PRINT S,"INFINITY",R,Z2,A2
215 IF S=0 THEN 225
220PRINT S,R2,R,Z2,A2
225NEXT S
999END
READY
RUN

ODIC    09:47    06/04/74

FOR 9/16-INCH (14 MM) COAXIAL SYSTEM:
   ODIC                                        .24425 INCHES
   IDOC                                        .5625 INCHES
   TEM-MODE CHARACTERISTIC IMPEDANCE           50.0012 OHMS

FOR 2-PORT:
   IDOC                                        .5625 INCHES
```

MAG(S11)	RETURN LOSS DECIBELS	VSWR	CHARACTERISTIC IMPEDANCE OHMS	INCREASED ODIC INCHES
0	INFINITY	1	50.0012	.24425
.05	26.0206	1.10526	47.5606	.2544
.1	20.	1.22222	45.2278	.264497
.15	16.4782	1.35294	42.9874	.27457
.2	13.9794	1.5	40.8258	.284653
.25	12.0412	1.66667	38.7308	.294778
.3	10.4576	1.85714	36.6909	.304983
.35	9.11864	2.07692	34.6953	.315308
.4	7.9588	2.33333	32.7335	.325799
.45	6.93575	2.63636	30.7948	.336508
.5	6.0206	3.	28.8682	.347501
.55	5.19275	3.44444	26.9414	.358853
.6	4.43698	4.	25.0006	.370662
.65	3.74173	4.71429	23.0289	.383058
.7	3.09804	5.66667	21.0047	.396215
.75	2.49878	7.	18.8987	.410384
.8	1.9382	9.	16.6671	.425951
.85	1.41162	12.3333	14.2377	.44357
.9	.91515	19.	11.4711	.464524
.95	.445528	39.	8.00661	.492164

```
HR    09:32    06/04/74        Appendix  HR

2REM    INPUT DATA:
4REM        MAG(S11)............................LINE 150 S
6REM        WAVEGUIDE DESIGNATOR................LINE 100
8REM        NOMINAL HEIGHT OF WG SYSTEM.........LINE 95 H1 (INCHES)
9REM        NOMINAL WIDTH OF WG SYSTEM..........LINE 90 W (INCHES)
10REM
12REM   CALCULATED PARAMETERS:
14REM       RETURN LOSS.........................LINE 175 R2 (DB)
16REM       VSWR................................LINE155 R
18REM       REDUCED HEIGHT OF 2-PORT............LINE 165 H2 (INCHES)
20REM
90 W=.9
95 H1=.4
100PRINT"FOR WR-90 (R-100) WAVEGUIDE SYSTEM:"
105PRINT"   INTERNAL WIDTH                    ",W;"INCHES"
110PRINT"   INTERNAL HEIGHT                   ",H1;"INCHES"
115PRINT
120PRINT"FOR 2-PORT:"
125PRINT"   INTERNAL WIDTH                    ",W;"INCHES"
130PRINT
135PRINT
140 PRINT"        ","RETURN","        ","REDUCED"
142 PRINT"        "," LOSS ","        ","HEIGHT"
144 PRINT"MAG(S11)","DECIBELS"," VSWR","INCHES"
145 PRINT
150 FOR S=0 TO 0.95 STEP 0.05
155R=(1+S)/(1-S)
160R1=SQR(R)
165 H2=H1/R1
170C1=2.302585093
172 R2=0
173 IF S=0 THEN 180
175 R2=(20*LOG(1/S))/C1
176 IF S>0 THEN 182
180 PRINT S,"INFINITY",R,H2
181 IF S=0 THEN 185
182 PRINT S,R2,R,H2
185NEXT S
999END
READY
RUN

HR   09:34   06/04/74

FOR WR-90 (R-100) WAVEGUIDE SYSTEM:
   INTERNAL WIDTH                              .9 INCHES
   INTERNAL HEIGHT                             .4 INCHES

FOR 2-PORT:
   INTERNAL WIDTH                              .9 INCHES


               RETURN                         REDUCED
                LOSS                          HEIGHT
MAG(S11)       DECIBELS        VSWR           INCHES

 0             INFINITY        1               .4
 .05            26.0206        1.10526         .380476
 .1             20.            1.22222         .361814
 .15            16.4782        1.35294         .343891
 .2             13.9794        1.5             .326599
 .25            12.0412        1.66667         .309839
 .3             10.4576        1.85714         .29352
 .35            9.11864        2.07692         .277555
 .4             7.9588         2.33333         .261861
 .45            6.93575        2.63636         .246353
 .5             6.0206         3.              .23094
 .55            5.19275        3.44444         .215526
 .6             4.43698        4.              .2
 .65            3.74173        4.71429         .184226
 .7             3.09804        5.66667         .168034
 .75            2.49878        7.              .151186
 .8             1.9382         9.              .133333
 .85            1.41162        12.3333         .113899
 .9             .91515         19.             9.17663E-2
 .95            .445528        39.             6.40513E-2
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15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Formulas, simple computer programs, graphs and tables are given to aid in the design and construction of 2-port standards for rectangular waveguide and coaxial line. Only standards consisting of reduced height waveguide, increased ODIC (outside diameter of inner conductor), or reduced IDOC (inside diameter of outer conductor) coaxial line are considered. Examples of the calculation of S_{11}, S_{21} and group delay, and their measurement with automatic network analyzers are given. Some of the important sources of error in the standards are discussed and design data are presented for specific standards.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Automatic network analyzers; coaxial; coaxial line step discontinuities; group delay; scattering coefficients; standards; 2-ports; waveguide; waveguide discontinuities.

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