JEDEC STANDARD

Standard for the Measurement of Small-Signal Transistor Scattering Parameters

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JEDEC SOLID STATE TECHNOLOGY ASSOCIATION

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APRIL 1976

EIA STANDARD

STANDARD FOR THE MEASUREMENT OF SMALL-SIGNAL TRANSISTOR SCATTERING PARAMETERS

ELECTRONIC INDUSTRIES ASSOCIATION
STANDARD RS-435

Formulated by

JEDEC Solid State Products Council

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PREFACE

The symbols and terms of this document are contained in JEDEC Publication No. 77 and are not in conflict with those in IEC Publication 147-OC. The measurement procedures are similar to those published in IEC.

STANDARD FOR THE MEASUREMENT OF SMALL-SIGNAL TRANSISTOR SCATTERING PARAMETERS

(From JEDEC Tentative Standard No. 10 and Standards Proposal No. 1178, formulated by JEDEC Committee JC-24 on High Frequency Signal Diodes and Transistors and approved by the JEDEC Solid State Products Council.)

1. DEFINITIONS

1.1 Definition of the Scattering Parameters

Given a two-port network as shown in Figure 1, the scattering parameters may be defined as the elements of the matrix (1 and 2)[⊕]

$$S = \begin{vmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{vmatrix} \tag{1}$$

associated with the linear equations

$$b_1 = s_{11} a_1 + s_{12} a_2 \tag{2}$$

$$b_2 = s_{21} a_1 + s_{22} a_2 \tag{3}$$

where

$$a_i = \frac{1}{2\sqrt{Z_0}} (V_i + Z_0 I_i) \tag{4}$$

$$b_i = \frac{1}{2\sqrt{Z_0}} (V_i - Z_0 I_i) \tag{5}$$

$$i = 1, 2$$

Here Z_0 is defined as a real impedance called the normalizing (or reference) impedance, usually taken to be 50 ohms. When other values are used, the value must be specified along with other conditions such as frequency, bias, temperature, etc.

[⊕]Bracketed numbers refer to references on page

Each of the scattering parameters may be individually defined as follows:

s_{11} is the voltage (or current) reflection coefficient (with respect to Z_0) at port one with port two terminated in Z_0; i.e.,

$$s_{11} = \left.\frac{b_1}{a_1}\right|_{a_2 = 0} = \left.\frac{(V_1/I_1) - Z_0}{(V_1/I_1) + Z_0}\right|_{Z_1 = Z_2 = Z_0} \quad (6)$$

s_{12} is the reverse transmission coefficient with port one terminated in Z_0 and port two driven with a generator of impedance Z_0; i.e.,

$$s_{12} = \left.\frac{b_1}{a_2}\right|_{a_1 = 0} = \left.\frac{V_1}{(V_o/2)}\right|_{Z_1 = Z_2 = Z_0} \quad (7)$$

where V_o is the open-circuit generator voltage.

s_{21} is the forward transmission coefficient with port two terminated in Z_0 and port one driven with a generator of impedance Z_0; i.e.,

$$s_{21} = \left.\frac{b_2}{a_1}\right|_{a_2 = 0} = \left.\frac{V_2}{(V_o/2)}\right|_{Z_1 = Z_2 = Z_0} \quad (8)$$

s_{22} is the reflection coefficient (with respect to Z_0) at port two with port one terminated in Z_0; i.e.,

$$s_{22} = \left.\frac{b_2}{a_2}\right|_{a_1 = 0} = \left.\frac{(V_2/I_2) - Z_0}{(V_2/I_2) + Z_0}\right|_{Z_1 = Z_2 = Z_0} \quad (9)$$

The scattering parameters of transistors are also represented by the following symbols:

$$s_{11} \longrightarrow s_{ix}$$

$$s_{12} \longrightarrow s_{rx}$$

$$s_{21} \longrightarrow s_{fx}$$

$$s_{22} \longrightarrow s_{ox}$$

where x is replaced by e, b, or c for bipolar transistors in common-emitter, common-base, or common-collector configuration, respectively; and by s, g, or d for field-effect transistors in common-source, commongate, or common-drain configuration, respectively.

1.2 Definition of Small-Signal Conditions

Transistors are essentially nonlinear devices which for sufficiently small applied signals behave as linear two-ports. Small-signal conditions may, therefore, be defined as the values of the voltage and current at ports one and two below which values the transistor may be considered a linear two-port.

For practical applications the following definition will be used: small-signal conditions are satisfied when a reduction of 50% in the amplitudes of V_1, I_1, V_2 or I_2 will not result in a variation of the ratio defined by (6), (7), (8), or (9) of more than 1%.*

1.3 Definition of the Transistor Terminal Reference Planes

1.3.1 Single-Ended Axial-Leaded Packages

The plane defined by points on the transistor leads at a distance of 1.5 mm (0.06 inch)* from the seating plane of the transistor package (see Figure 2a).

1.3.2 Stripline Packages †

The plane(s) transverse to the input and (or) output leads defined by the point on each transistor lead at a distance from the package body equal to or less than the dimensional tolerance range of the package body at the lead-body interface (see Figure 2B).

1.3.3 Coaxial Packages†

A transverse plane whose distance from the centerline of the seating flange is equal to the maximum dimension from the centerline of the seating flange to the body end of the input or output terminal (see Figure 2c).

For other packages not defined here, the transistor terminal reference planes must be similarly defined for each particular package.

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* All asterisks in this document refer to the following footnote:
The numerical values quoted have been agreed upon by the JEDEC JC-24 committee as those representing a practical compromise between the usual requirements of circuit design applications of scattering parameters and the measurement technology at the time of writing this document. (See Appendix 1).

† Stripline -- any transistor package with its leads in a single plane (this includes beam leads).
Coaxial -- any transistor package designed to mount directly into coaxial lines.

2. MOUNTS

The transistor mount must satisfy the following requirements:

2.1 It shall have well-designed terminals to which ports one and two of the transistor-under-test are connected. It shall also have well-designed ground connections to which the common terminal of the transistor package is connected. The SWR introduced by the transistor mount with the 50-ohm feedthrough shall be less than [1.02 + (0.02/GH_z (f_{GHz})],* with respect to the defining reference to which the "S" parameters are referred. The expression f_{GHz} represents the test frequency in gigahertz.

2.2 The magnitude of the transfer scattering parameter between the input-output terminals (when no device is inserted in the mount) shall be less than 5% (−26 dB) * of the magnitude of the reverse transfer of the transistor under test.

2.3 The input-output terminals shall be designed to eliminate the high-frequency effects of that part of each lead extending from the transistor terminal defined in 1.3 to the physical extremity of said lead. This is normally achieved by the use of tubular inputs in the case of axial- or coaxial-leaded transistors; for stripline transistors the width of the center or stripline conductor of the fixture shall be equal to or greater than that of the transistor lead.

2.4 The location of the reference plane(s) of the input-output terminals shall be known within less than ± one thousandth* of the wave length at the test frequency or 0.003 inch*, whichever is greater.

2.5 Electrical contact between the transistor leads and the terminals of the mount shall be made within 0.5 mm (0.02 inch)* of the specified reference planes and should have low enough resistance to assure repeatability of the intended measurement.

2.6 For axial-leaded transistors, no portion of the input or output shall extend beyond the reference plane defined in clause 1.3 and no material shall be placed in the air-gap between the seating plane of the transistor package and the reference plane of the transistor mount (see Figure 2a).

2.7 The mount insertion loss with its feedthrough shall be equal to or less than [0.3 dB + (0.05 dB/GHz) (f_{GHz})] *.

2.8 The following suggested feedthrough comments are useful in minimizing losses and electrical discontinuities:

(a) Approximately the same material and geometry should be used as in the transmission line of the fixture.

(b) In case of stripline packages the physical dimensions should be the same as that of the space which the transistor will occupy. Leads should have sufficient length and should have widths slightly narrower than both the fixture and feedthrough transmission lines.

3. THE MEASURING SYSTEMS FOR SCATTERING PARAMETERS

3.1 General

The measuring system must provide a means for applying bias to the transistor under test. The bias system must be such as not to influence the accuracy of the measurements.

The signal applied by the measuring system to the transistor must be sufficiently small to satisfy the small-signal conditions defined in 1.2. In addition, any spurious signals which might appear at the transistor terminals and, in particular the local oscillator feedthrough when a superheterodyne receiver is used, must be kept at least 30 dB* below the applied desired signal.

3.2 Input and Output Source Match

Ideally, the measurement of scattering parameters would require that system source and load impedances at the two-port-reference planes be precisely equal to Z_0, the defining reference impedance. In practice, these impedances must satisfy the following conditions:

Input Source Match:

$$\left|\Gamma_1\right| = \left|\frac{Z_1 - Z_0}{Z_1 + Z_0}\right| < [0.1 + (0.02/GH_z)(f_{GHz})]^*$$

Output Source Match:

$$\left|\Gamma_2\right| = \left|\frac{Z_2 - Z_0}{Z_2 + Z_0}\right| < [0.1 + (0.02/GH_z)(f_{GHz})]^*$$

3.3 Directivity

In reflectometer systems used for the measurement of s_{11} and s_{22}, the directivity, D, of the directional couplers used must meet the following conditions:

$$\left|D\right| > 40\,dB^*$$

3.4 Transmission lines may be used to make connection between the transistor mount and the measuring system. These lines may include adjustable-length sections for phase compensation. However, the SWR created by residual reflections in the lines must not exceed $[1.01 + (0.01/GH_z)(f_{GHz})]^*$ where f_{GHz} represents the test frequency expressed in gigahertz. Also, the errors in the measured parameters caused by losses in the lines must be less than 3%*. If these errors exceed 3%*, appropriate corrections should be made.

APPENDIX I

INSTRUMENT ACCURACY, DYNAMIC RANGE, AND SENSITIVITY FOR TRANSISTOR SCATTERING PARAMETER MEASUREMENT FROM 0.01 to 12 GHz OUTSIDE TEST FIXTURE

Three basic types of instruments are used for transistor measurements above 100MHz:

1. Bridge circuits, where the unknown is compared to standard impedances using impedance ratios but no directional devices;

2. Slotted sections where the unknown is compared to a characteristic impedance using voltage rations; and

3. Reflectometers, including network analyzers, where power levels and phase are compared to a reference signal assuming an impedance reference.

In general, over the range of concern, reflection coefficients can be measured[1] to 0.01 and phase angles to $1^{o}/s_{mm}$ using typical equipment and techniques (see Figures 3 and 4). Using the best equipment and technique this can be improved to 0.001 and $0.1^{o}/s_{mm}$ (see Figures 5 and 6). [3] Using either typical or the best equipment, attenuation or gain can be measured to 0.2 dB + $0.01s_{mn}$ (in dB). The phase angle of attenuation can be measured to 1^{o} + (0.01^{o}/dB) (s_{mn} in dB). See Figures 7 and 8. For low power levels these are degraded as shown in Table I. A summary of error versus power level using optimum and typical equipment and techniques is shown in this table.

The effect of power level on the test terminals can be estimated as follows. Noise and detector sensitivity will be the primary limiting factors on the measurement at low power levels. While detectors can be improved in sensitivity at the expense of response time and cost, typical detectors used for measurements have sensitivities of about −80 dBm. The slotted line or reflectometer has about 20 dB coupling in the probe or directional coupler giving roughly −60 dBm sensitivity. A typical generator will have about 10 dBm output decoupled by pads or power splitters by around 10 dB providing roughly 1 mW to the test terminals. The 60 dBdifference then allows a sensitivity of 60 dB in return loss or 0.0003 in Γ, which is about the best found in practice. This is subject to considerable variation but can serve as a general limitation. Not all of the error at low reflection coefficients is due to noise limitation so the power level can probably be reduced by 10 dB before the general 0.01 limit given above is exceeded. The bridge circuit is usually limited by errors other than noise at low reflections but a similar treatment will show that for 0.01 error in Γ, the bridge will require about −10dBm on the test terminals.

At lower signal levels, the slotted line with the generator feeding the probe appears most practical.[2] With such a system it is possible to obtain errors as low as 0.003 in Γ and 0.1^{o} in phase angle at 8 GHz using −50 dBm on the test terminals (see Figures 5 and 6). [4]

a rigorous error analysis would not be feasible for the following reasons:

1. Insufficient data is available on the various instruments, particularly the interaction of phase and magnitude values and errors.

2. Some instruments measure the parameters of two ports under matched conditions, others under open - and short-circuit conditions, and others approximate these conditions to different degrees. Thus, they cannot be directly compared.

3. For comparison, errors should be given for the same quantity while different instruments measure variously: impedances, scattering parameters, reflection coefficients, or standing wave ratios.

4. While the above quantities are mathematically related, four independent measurements are required to describe the two port device. These four complex measured values and their errors interact in the transformation.

The input reflection coefficient of a two-port, Γ_1, is related to the scattering parameters by [1]

$$\Gamma_1 = s_{11} + \frac{s_{12} s_{21} \Gamma_L}{1 - s_{22} \Gamma_L}$$

where Γ_L is the reflection coefficient of the load.

Therefore, if the two port is terminated in a matched impedance

$$\Gamma_L = 0$$

and

$$\Gamma_1 = s_{11}$$

then the power incident on a two-port, P_1, is

$$P_1 = \frac{|a_1|^2}{Z_{01}} \quad (1 - |\Gamma_1|^2)$$

where Z_{01} is the input impedance of the two-port.

The transmitted power, P_2, is

$$P_2 = \frac{|b_2|^2}{Z_{02}} \quad (1 - |\Gamma_L|^2)$$

where Z_{02} is the output impedance of the two-port.

The ratio of P_2/P_1 as would be measured by a reflectometer or ratio meter is

$$\frac{P_2}{P_1} = \frac{Z_{01}|b_2|^2}{Z_{02}|a_1|^2} \quad \frac{(1 - |\Gamma_L|^2)}{(1 - |\Gamma_1|^2)}$$

For the case where the input and output are matched and the terminal planes are at the same impedance

$$\frac{P_2}{P_1} = \frac{|b_2|^2}{|a_1|^1} = |s_{21}|^2$$

Approximate comparison of the methods can be obtained by letting

$$s_{mm} = \Gamma_{mm} = \frac{r-1}{r+1} = \left[\frac{R_N - 1}{R_N + 1}\right] R > R_0 \qquad \text{or} \qquad \left[\frac{1 - R_N}{1 + R_N}\right] R < R_0$$

where r is the SWR and R_N is the normalized resistance, R/R_0.

This is true only if the two-port is terminated in a matched load which is purely resistive. [5] Then

$$\Delta s = \Delta\Gamma = \frac{2\,\Delta r}{(r+1)^2} = \left[\frac{2\,\Delta R_N}{(R_N + 1)^2}\right] R > R_0 \qquad \text{or} \qquad \left[\frac{-2\,\Delta R_N}{(R_N + 1)^2}\right] R < R_0$$

INSTRUMENT ERRORS AS A FUNCTION OF TEST TERMINAL POWER LEVEL OVER THE FREQUENCY RANGE 0.1 to 12 GHz

TABLE I

Using Optimum Equipment and Technique

Test	s_{mm} Error		s_{mn} Error	
Power	Magnitude	Phase	Magnitude ††	Phase
10^{-3}W	0.001	$0.1°/s_{mm}$	$0.2\,dB + 0.01 s_{mn}$ dB	$1° + (0.1°/dB)$ (s_{mn} in dB)
10^{-4}W	0.001	$0.1°/s_{mm}$#	$0.2\,dB + 0.1 s_{mn}$ dB	$1° + (1°/dB)$ (s_{mn} in dB)
10^{-5}W†	0.003	$0.1°/s_{mm}$		
10^{-6}W†	0.003	$0.1°/s_{mm}$		
10^{-7}W†	0.003	$0.1°/s_{mm}$		
10^{-8}W†	0.003	$0.1°/s_{mm}$#		

TABLE II

Using Typical Equipment and Technique

Test	s_{mm} Error		s_{mn} Error	
Power	Magnitude	Phase	Magnitude ††	Phase
10^{-3}W	0.01	$1°/s_{mm}$	$0.2\,dB + 0.01 s_{mn}$ dB	$1° + (0.1°/dB)$ (s_{mn} in dB)
10^{-4}W	0.01	$1°/s_{mm}$	$0.2\,dB + 0.1 s_{mn}$ dB	$1° + (1°/dB)$ (s_{mn} in dB)
10^{-5}W †	0.01	$1°/s_{mm}$		
10^{-6}W †	0.01	$1°/s_{mm}$		
10^{-7}W †	0.01	$1°/s_{mm}$		
10^{-8}W †	0.01	$1°/s_{mm}$		

Requires detector sensitivity better than −90 dBm.

† For power levels below 10^{-4}W, the reverse slotted line technique is required.

†† Range of s_{mn} 0 to ± 60 dB.

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5. "Microwave Measurement" E.L. Ginzton, p. 223, McGraw-Hill Book Company, Inc. 1957.

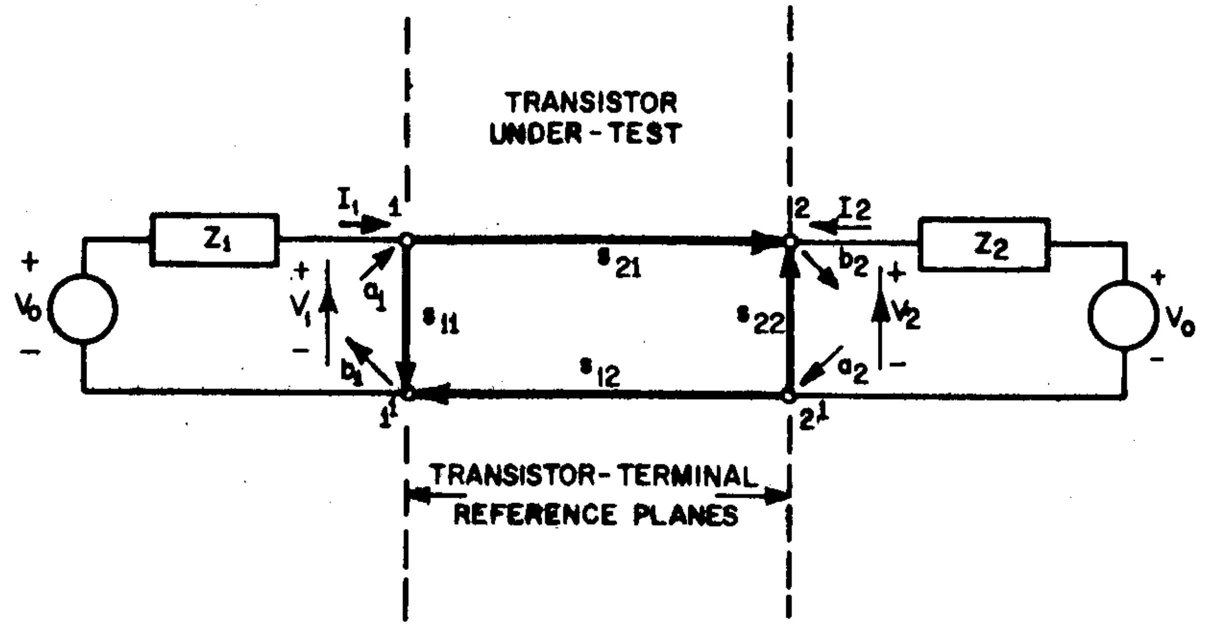
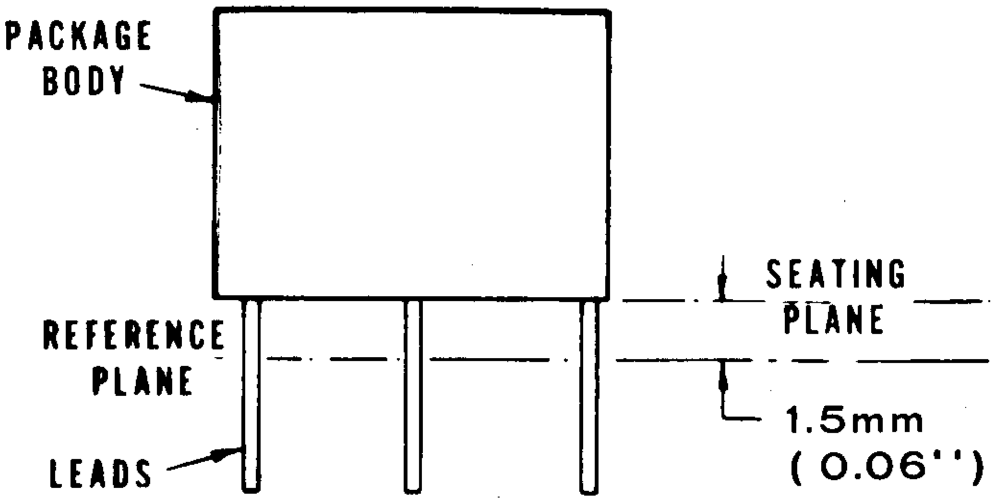
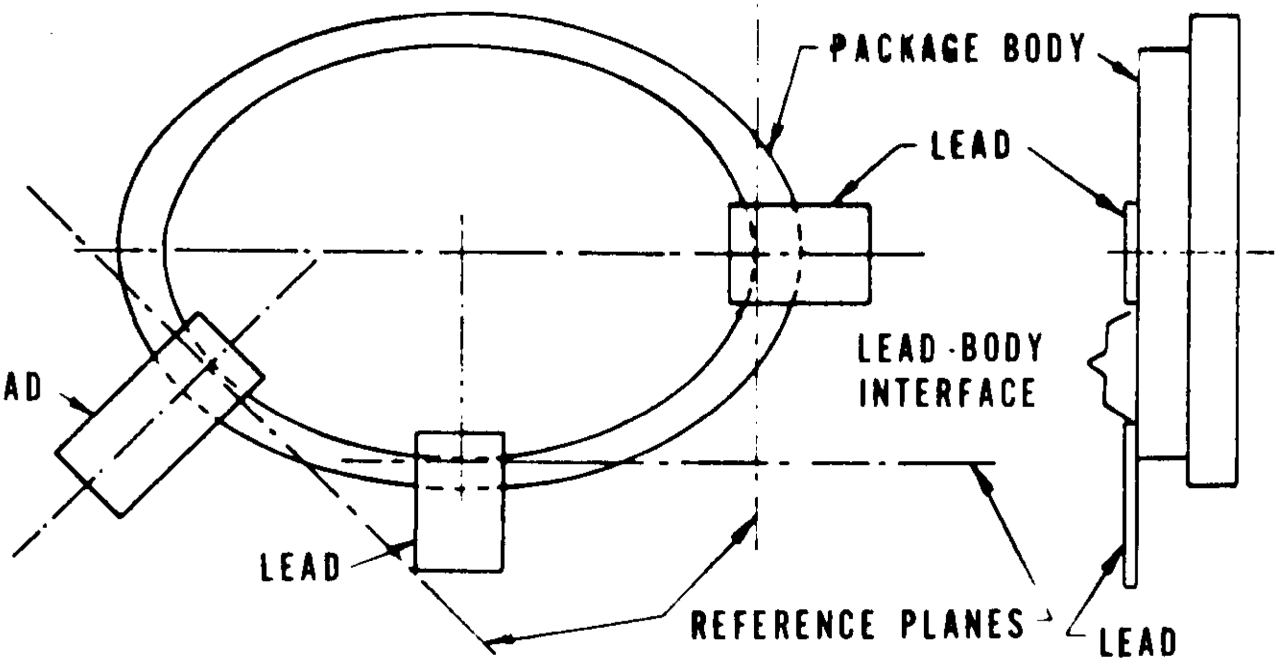


FIG. 1—SCATTERING PARAMETER DEFINITION SCHEMATIC



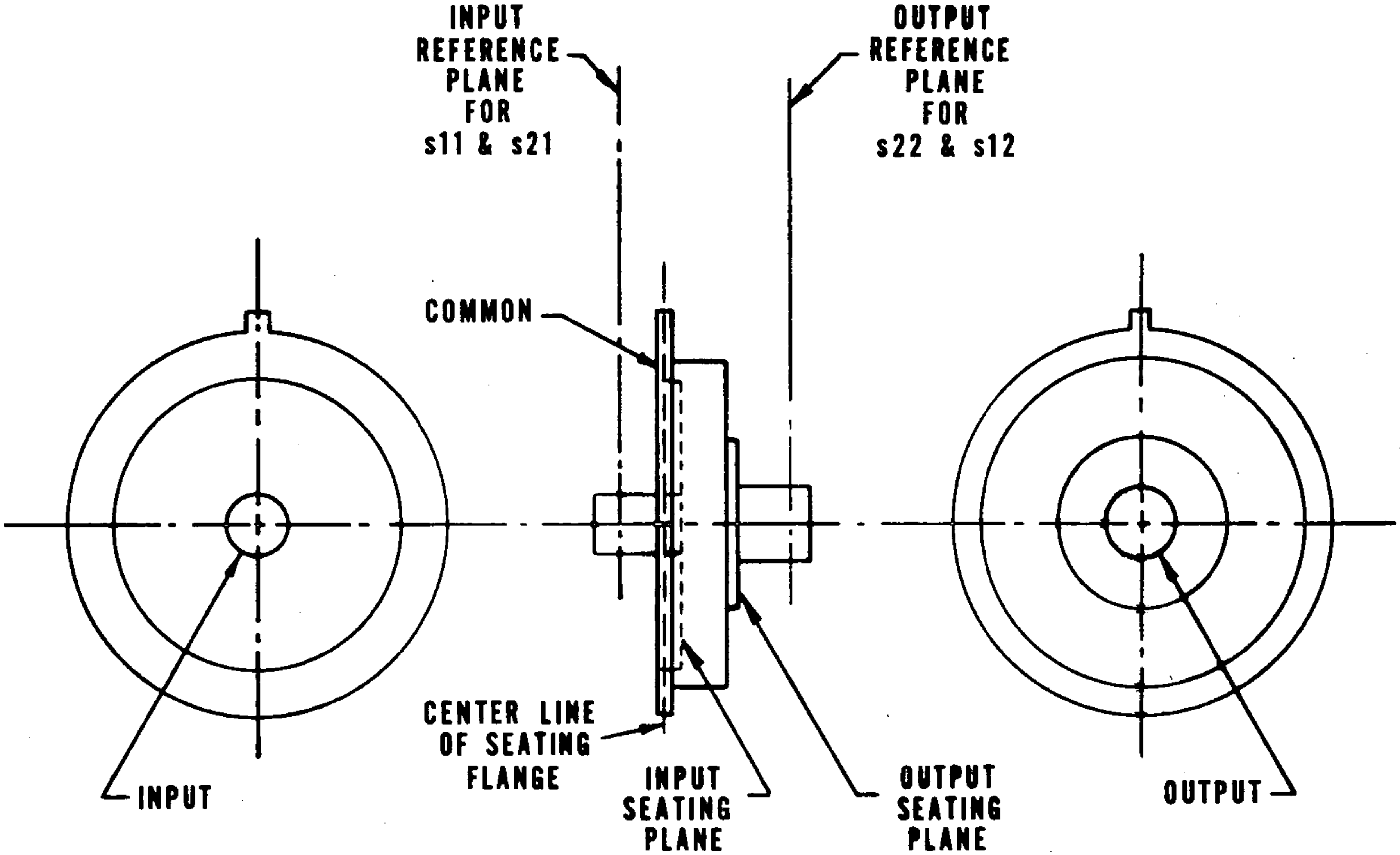
(a)SINGLE-ENDED
AXIAL-LEAD PACKAGE

FIGURE 2a



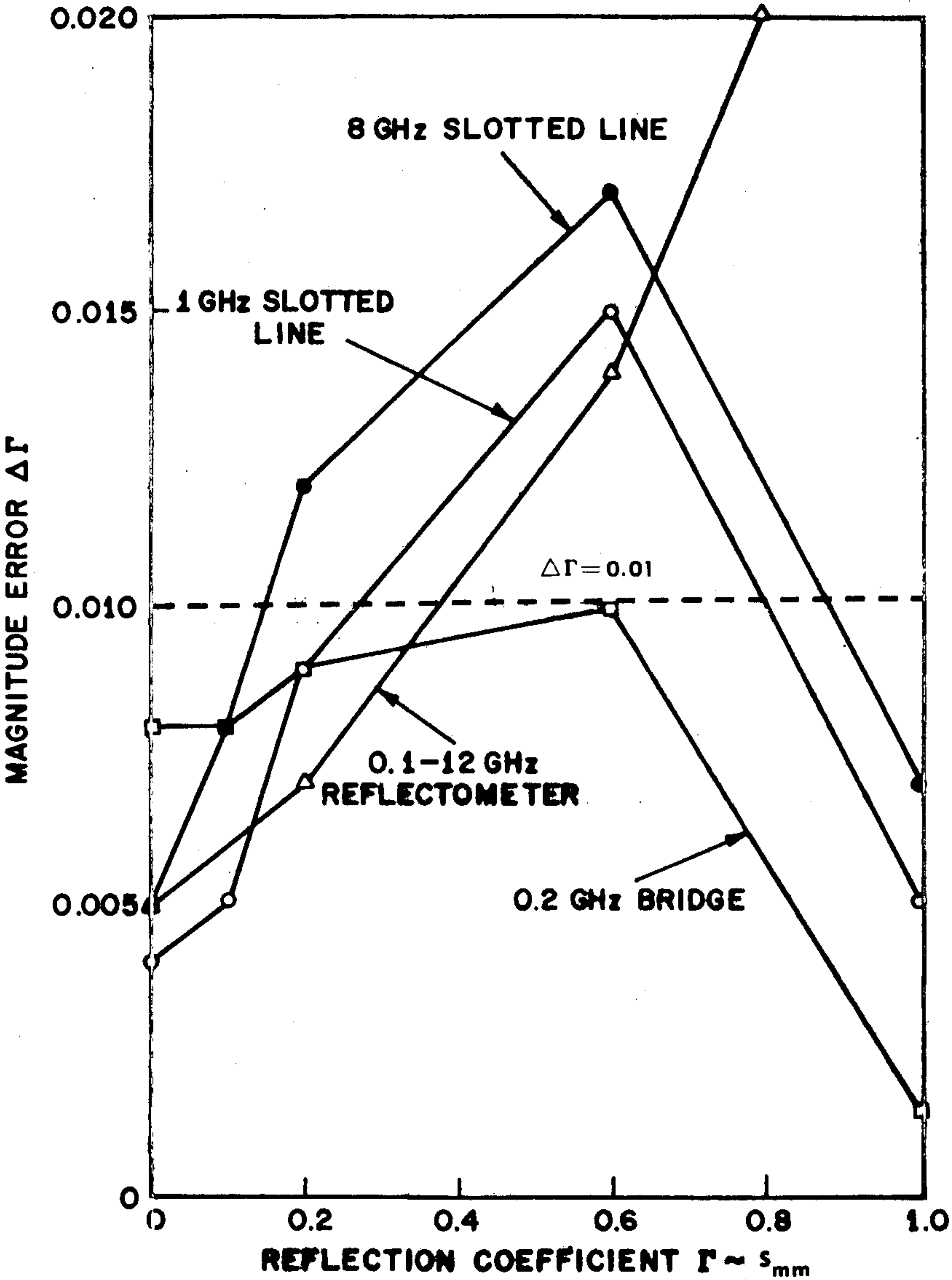
STRIP-LINE PACKAGE

FIGURE 2b



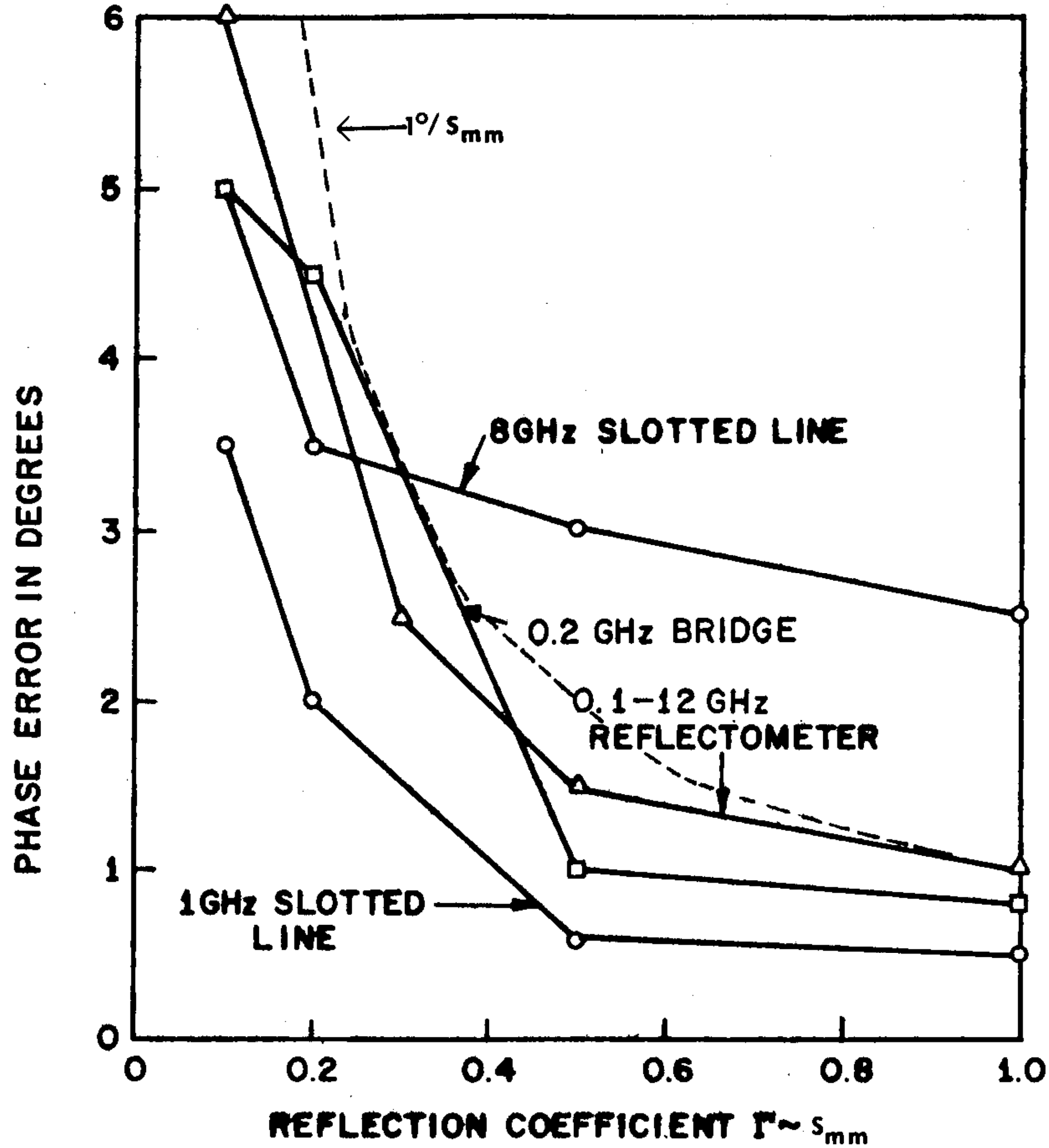
COAXIAL PACKAGE

FIGURE 2c



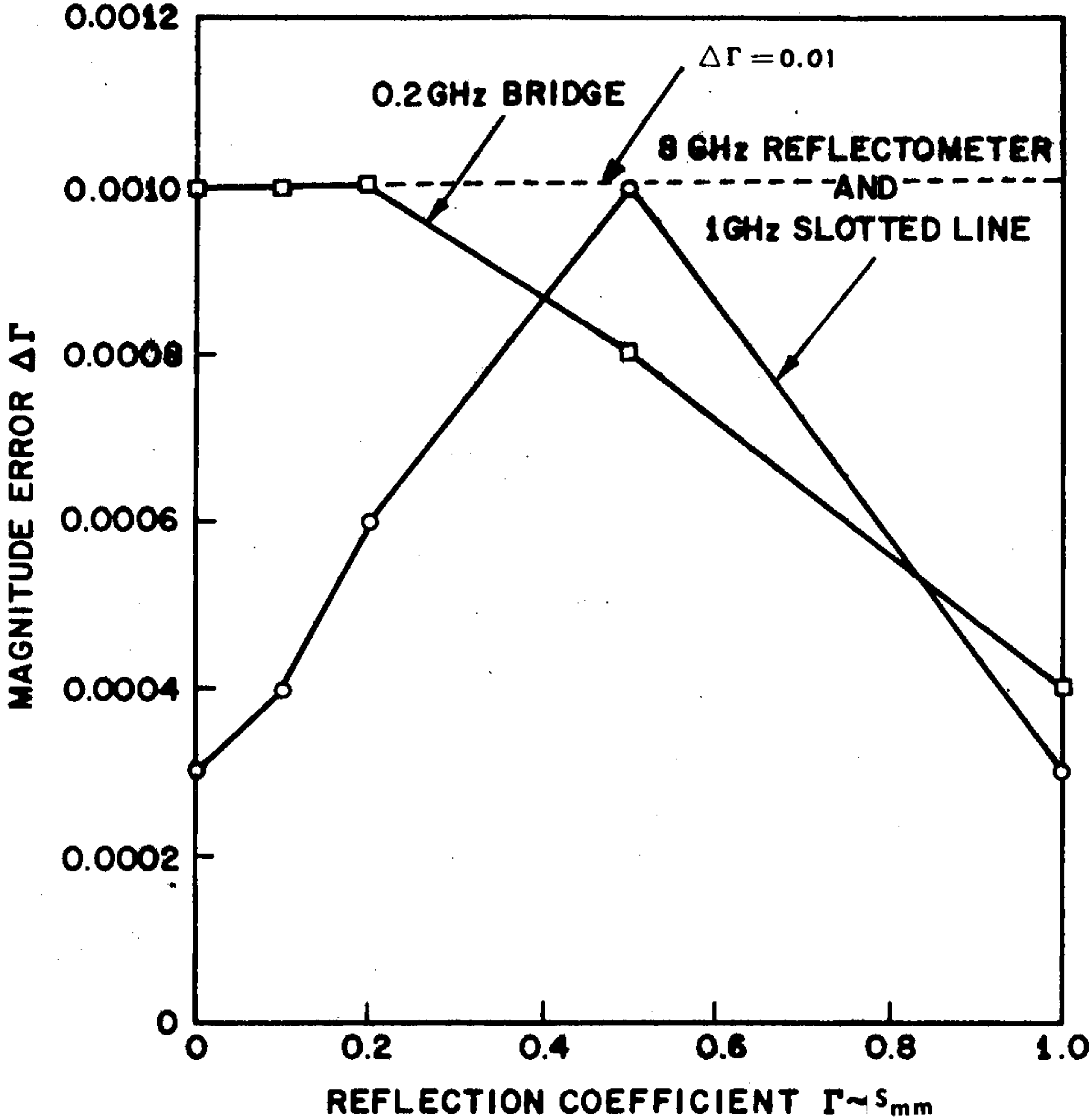
TYPICAL MEASUREMENT ERROR
MAGNITUDE ERROR

FIGURE 3



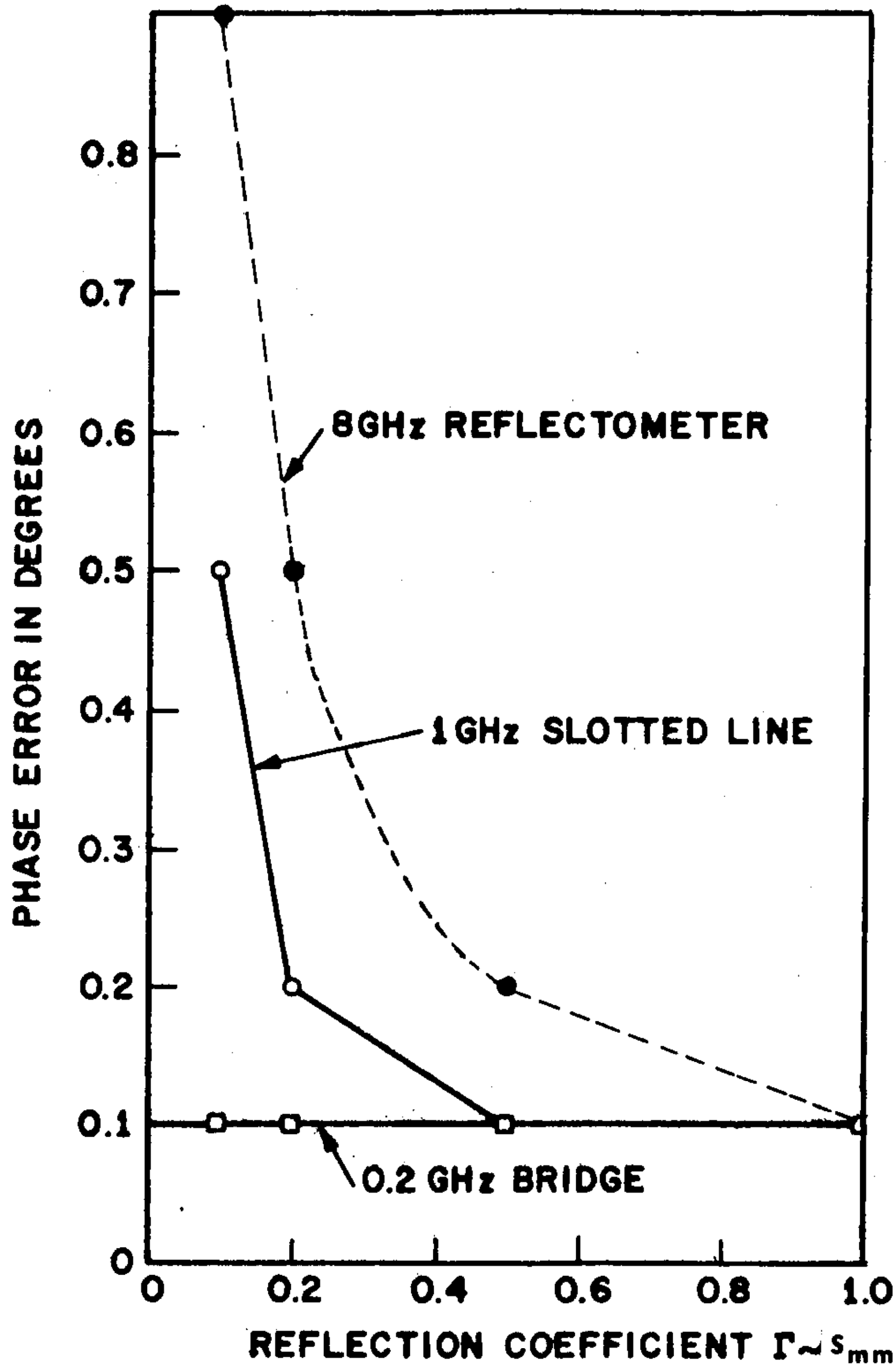
TYPICAL MEASUREMENT ERROR
PHASE ERROR

FIGURE 4



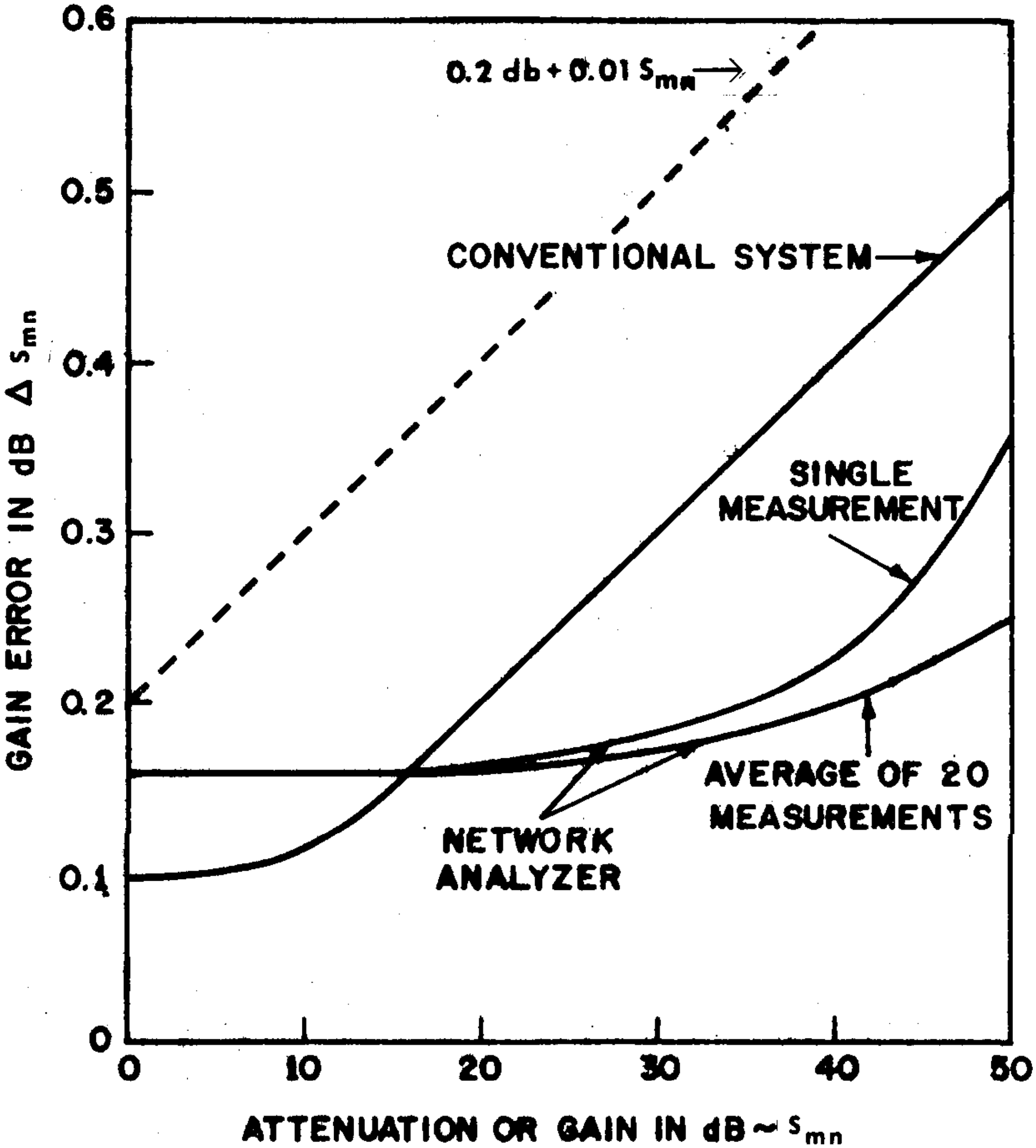
MINIMUM MEASUREMENT ERROR
MAGNITUDE ERROR

FIGURE 5



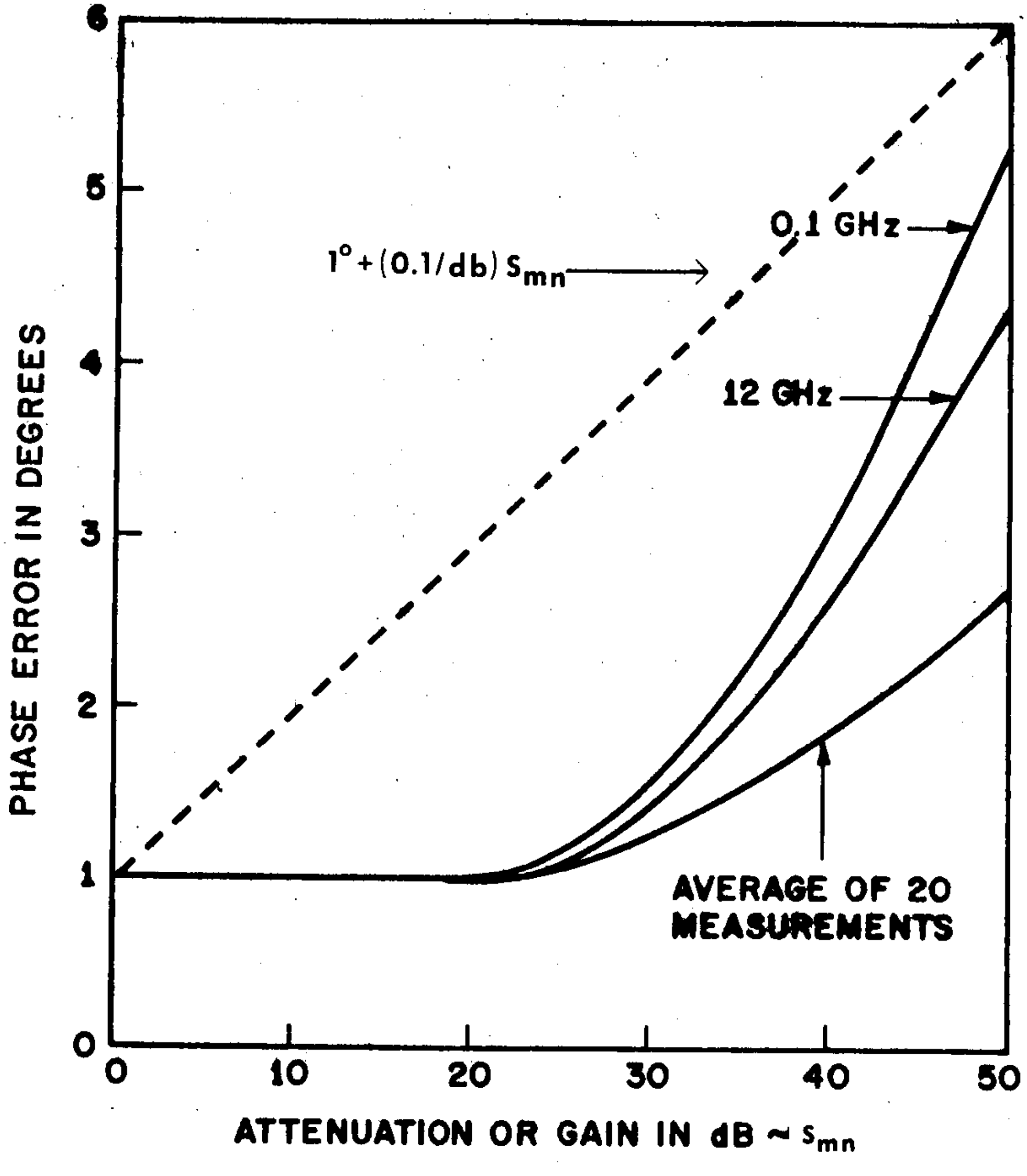
MINIMUM MEASUREMENT ERROR
PHASE ERROR

FIGURE 6



MEASUREMENT ERROR
AMPLITUDE OF ATTENUATION

FIGURE 7



MEASUREMENT ERROR
PHASE OF ATTENUATION

FIGURE 8

JEDEC