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Coaxial Intrinsic Impedance Standards

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COAXIAL INTRINSIC IMPEDANCE STANDARDS

Robert T. Adair
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This paper discusses how impedance standards are derived from the basic definition of impedance, constructed and used in metrology with coaxial air-line systems. Basic transmission line equations are reviewed with emphasis given to intrinsic or derived standards for obtaining the impedance in low-loss transmission line systems. A brief description is given of how impedance standards are used to calibrate the vector automatic network analyzer, and specifically, the six-port system automatic network analyzer used at the National Institute of Standards and Technology for calibration services in the radio frequency, microwave, and millimeter wave areas. Measurement uncertainties are given for 7 mm coaxial devices measured with the National Institute of Standards and Technology six-port system. The resolution of our six-port system is several orders more precise than that of the present impedance standards from which it is calibrated. Required improvements in the physical dimensions of air-line standards which permit the automatic network analyzer's capability to be more fully utilized are given.

Key words: automatic network analyzer; calibration services; coaxial line; impedance; intrinsic; measurement uncertainties; metrology; microwave; radio frequency; reflection coefficient; scattering parameters; six-port systems; standards; transmission line; 7 mm coaxial devices.

1.0 INTRODUCTION

Although the resolution of today's state-of-the-art automatic network analyzers (ANAs) is approximately two orders of magnitude greater than what can be used, the measurement accuracy of these ANAs have been limited because of the lack of well-defined impedance standards. Impedance is one of the basic electrical parameters used to describe and quantify electrical systems and components. Historically, impedance standards have been one of the most important and widely used standards in radio frequency (rf), microwave (μw), and millimeter wave (mmw) metrology. Sections of precision air line are the basis for calculable impedance standards. They are nearly reflectionless and represent the ultimate in adherence to design principles in maintaining a constant characteristic impedance (Z_0) throughout the precision air-line sections. Today, ANAs are widely used in metrology because of their versatility, sensitivity, resolution, and potential accuracy. Moreover, their accuracy is directly dependent upon the quality of the impedance standards used to characterize and evaluate the system parameters of the ANAs. Therefore, it is necessary to develop, characterize, and propagate a new class of rf, μw, and mmw impedance standards.

2.0 GENERAL BACKGROUND

Coaxial impedance standards can be used from dc to above 60 GHz, but are widely used from audio frequencies up through 50 GHz. Propagation is ordinarily restricted to the TEM (transverse electromagnetic) mode. Impedance (Z) in a linear constant-parameter system can be defined [1,2] as the ratio of the phasor equivalent of a steady-state sine-wave voltage or voltage-like quantity (driving force) to the phasor equivalent of a steady-state sine-wave current or current-like quantity (response). The real part of impedance is the resistance (R). The imaginary part is the reactance (X). For dc and low frequencies below a few megahertz, impedances are easily modeled as shown in Figure 1 by discrete parameters. However, at higher frequencies, such impedances are more difficult to define since they do not maintain their low frequency characteristics and therefore have to be represented as distributed parameters for a unit length of line as shown in Figure 2.

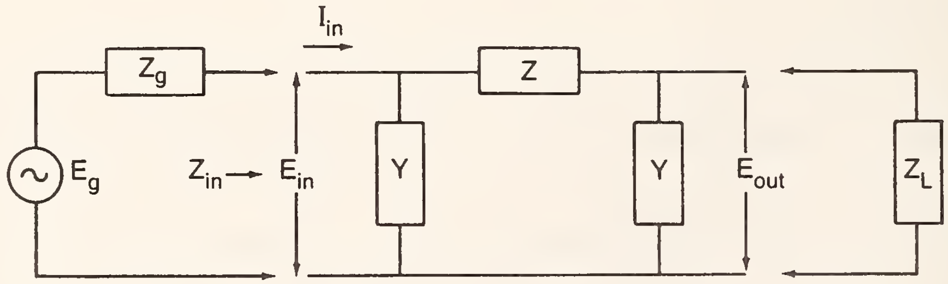


Figure 1. Typical discrete-parameter circuit.

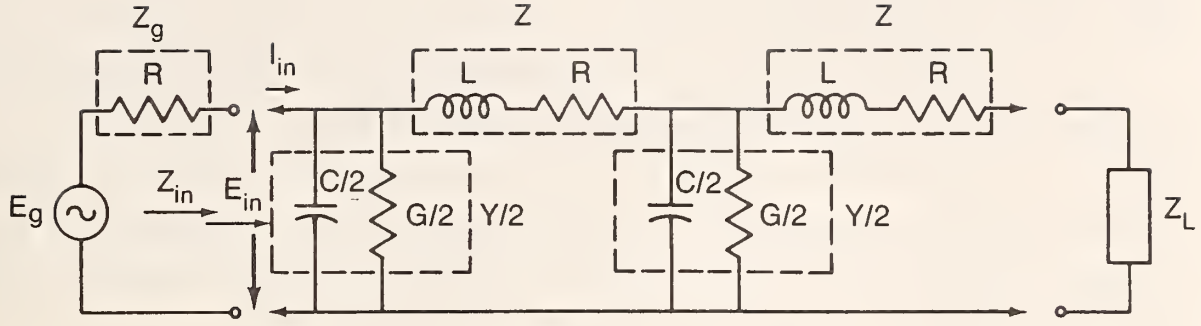


Figure 2. Equivalent circuit of a transmission line showing distributed circuit parameters in discrete form per unit length of line.

In the rf, μw, and mmw frequency ranges where the wavelengths are relatively short, the electric and magnetic fields vary over small distances. For coaxial transmission line systems, the electric field is restricted to the region between the inner and outer conductors. When the dominant mode is the TEM mode, the electric fields are radial and the magnetic fields concentric circles. The impedance can be defined as the ratio of the electric field to the magnetic field as they cross a plane perpendicular to the direction of propagation [3]. This impedance is often called the intrinsic or characteristic impedance of the device and is designated Z_0. The term "intrinsic" or "derived" is used to describe the impedance of a device by itself and is determined by the physical properties of that device [4]. In the case of a coaxial transmission line, Z_0 is determined from the diameters of the inner and outer conductors.

Finally, definitions [1] of accuracy, precision and resolution are presented as follows: accuracy - the degree of correctness with which a measured value agrees with the true value; precision - the degree of mutual agreement among individual measurements, namely repeatability and reproducibility; resolution - the degree to which nearly equal values of a quantity can be discriminated.

3.0 BASIC TRANSMISSION LINE EQUATIONS

Traveling waves are set up when voltage, E_{in}, is applied to the input of a transmission medium and input current, I_{in}, flows in the line as shown in Figure 2 [5]. If the transmission line is sufficiently long then Z, Y, L, R, G, and C are defined as uniformly distributed constants of the complex series impedance Z in ohms, complex shunt admittance Y in siemens, inductance L in henries, dc resistance R in ohms, series conductance G in siemens and capacitance C in farads, respectively, per unit length. These components are shown in Figure 2 and presented for a coaxial transmission line in Figure 3. The series resistance and inductance are shown in the equivalent circuits in Figure 2 and can be distributed equally or unequally in the transmission line [6]. Under these conditions, Z_o of the line is equal to Z_{in} where

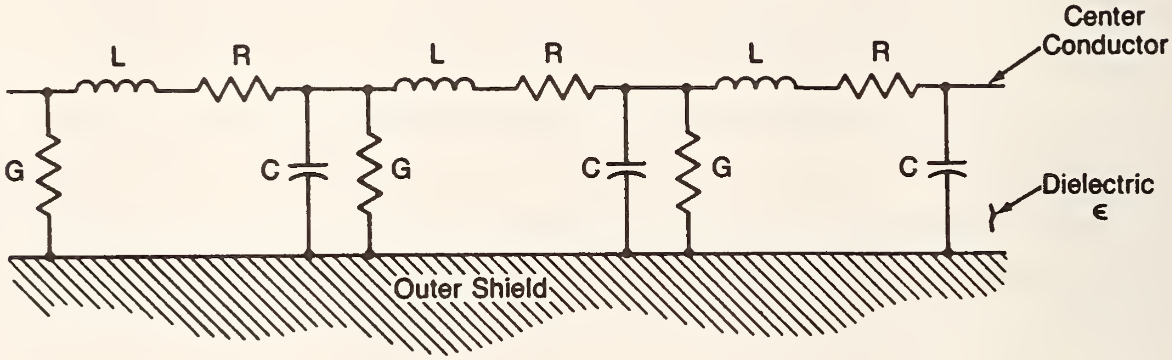


Figure 3. Distributed inductance, resistance, conductance, and capacitance of a coaxial transmission line.

$$Z_{in} = E_{in}/I_{in} = \sqrt{Z/Y}. \tag{1}$$

Since

$$Z = R + j\omega L$$

and

$$Y = G + j\omega C,$$

then

$$Z_o = \sqrt{\frac{R + j\omega L}{G + j\omega C}}. \tag{2}$$

The input voltage, E_{in}, requires a finite time to propagate along the transmission line. The complex propagation constant, γ, [6] describes the effect of the transmission line on the propagation of the traveling voltage wave where α = attenuation constant in nepers per unit length and β = phase constant in radians per unit length.

$$\gamma = \sqrt{ZY} = \sqrt{(R + j\omega L)(G + j\omega C)} = \alpha + j\beta. \tag{3}$$

The velocity of propagation [7] of the voltage wave is the phase velocity, ν_p, where

$$\nu_p = \omega/\beta = 2\pi f/\beta. \tag{4}$$

The voltage and current at any distance, ℓ, along the line are given respectively by $E_\ell = E_{in}e^{-\gamma\ell}$ and $I_\ell = I_{in}e^{-\gamma\ell}$, and they are related by the characteristic impedance, Z_o, of the line:

$$Z_o = E_{in}e^{-\gamma\ell}/I_{in}e^{-\gamma\ell}. \tag{5}$$

Standing waves [6] result when we do not have the ideal transmission line terminated in its characteristic impedance, Z_o. A portion of the incident voltage wave is reflected at the line's terminating load, Z_L, and reacts or interferes with the incident wave to set up a standing wave as shown in Figure 4. The reflected wave carries energy that is not delivered to the load. Reflection coefficient, Γ [3], is the term used to quantify this reflected voltage wave. Its magnitude is the ratio of the amplitude of the reflected voltage wave, E_r, to that of the incident voltage wave, E_i.

Thus
$$|\Gamma| = E_r/E_i. \tag{6}$$

The complex reflection coefficient can be expressed in terms of Z_o and Z_L [3].

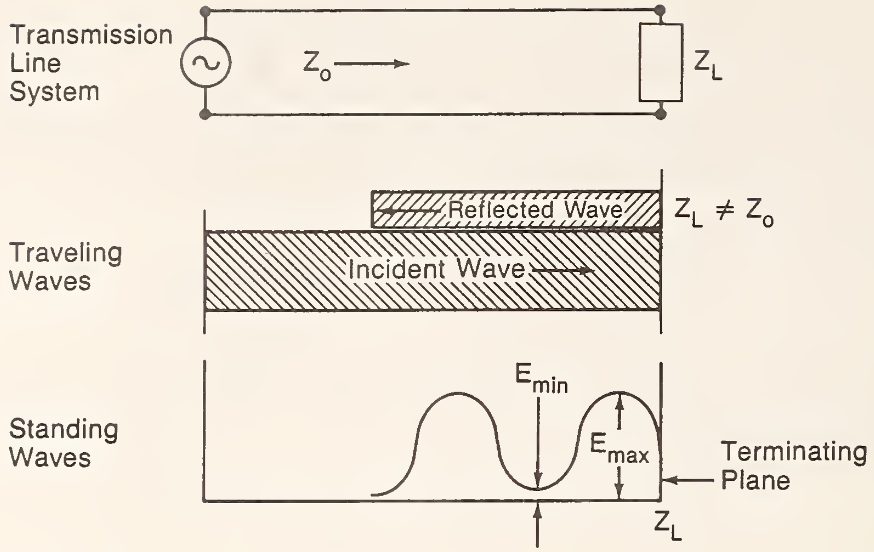


Figure 4. Incident and reflected wave of a transmission line terminated in a mismatched condition showing the resulting standing wave.

Thus $$\Gamma = (Z_L - Z_o)/(Z_L + Z_o) \qquad (7)$$

or $$\Gamma = |\Gamma| \angle \phi \qquad (8)$$

where ϕ is the angle by which the reflected wave is displaced from the incident wave.

Equation (7) can be rewritten in a different form which is also useful:

$$Z_L = Z_o\ (1 + \Gamma)/(1 - \Gamma). \qquad (9)$$

Voltage standing wave ratio (VSWR) is defined as the resultant peak-to-trough variation of the amplitude of the periodic standing wave created when a line is not terminated in Z_o. Specifically, VSWR, ρ, is the ratio of E_{max} to E_{min} of the standing wave [8]. VSWR can be expressed in terms of Γ, so

$$\rho = (1 + |\Gamma|)/(1 - |\Gamma|). \qquad (10)$$

Equation (10) can be solved for $|\Gamma|$ and yields a useful equation for calculating $|\Gamma|$ from VSWR:

$$|\Gamma| = \frac{\text{VSWR} - 1}{\text{VSWR} + 1}. \tag{11}$$

Return loss, RL, is the ratio of the incident power, P_i, to the reflected power, P_r, at a point on the transmission line, expressed in decibels.

$$\text{RL} = 10 \log \frac{P_i}{P_r}. \tag{12}$$

Equation (12) can also be expressed in terms of $|\Gamma|$ and VSWR:

$$\text{RL} = 20 \log \frac{1}{|\Gamma|} = 20 \log \frac{\text{VSWR} + 1}{\text{VSWR} - 1}. \tag{13}$$

4.0 THE MEASUREMENT OF IMPEDANCE

Historically, slotted lines and reflectometers have been the most accurate means available to measure impedance.

Precision slotted transmission lines [6] are excellent means of impedance measurement. They are designed to measure the standing-wave pattern of the electric field intensity as a function of the longitudinal position along a line. They determine the maximum and minimum magnitudes of voltage from which VSWR is calculated. A matched impedance standard (such as a sliding load) is used to calibrate (or evaluate) the slotted line since any residual VSWR due to the slotted line must be separated from the value measured by the slotted line. The impedance of the device under test (DUT) can then be calculated. However, the effects of connectors on the measurement results cannot be separated from those of the slotted line or of the DUT.

Tuned reflectometers [9,10] and untuned (broadband) reflectometers [11] are typically more precise (and more complex) than slotted lines for measuring the magnitude and phase of the characteristic impedance. Their use requires a precision section of transmission line, a precision quarter-wave short-circuit termination, and a precision quarter-wave offset open-circuit termination as the impedance standards. Very precise measurements can be performed on these systems but typically these are performed manually and hence are time-consuming and cumbersome.

Current and future methods of precise impedance measurements most certainly lie in the realm of the computer-controlled ANA. In order to treat the difficult area of rf, μw, and mmw parameters more effectively both magnitude and phase information is included. The following discussion is based on the vector ANA rather than the scalar ANA. The recent publication of the IEEE standard on network analyzers [12] is proof of the wide acceptance and present use of vector ANAs for the major portion of complex measurements.

The National Institute of Standards and Technology (NIST) has done considerable work in the design, development, and refinement of the six-port automatic network analyzer [13,14]. The six-port ANA incorporates two six-port reflectometers, one on either side of the measurement insertion point. The high precision and resolution of these systems demands a more accurate standard than those currently available. The absolute accuracy of the impedance standards used to calibrate these systems appears to be the limiting factor in ANA measurement abilities.

Several commercially available ANAs demonstrate excellent complex measurement capabilities, and they also require more accurate standards than those currently available. See for example, [15,16].

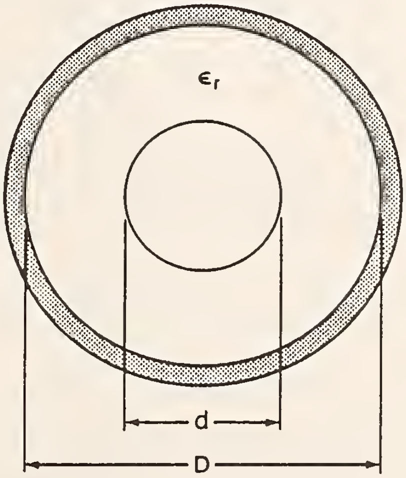
5.0 TYPICAL IMPEDANCE STANDARDS

Important impedance standards can be placed into three major categories: (1) matched terminations; (2) mismatched terminations; and (3) precision sections of air-dielectric transmission lines.

Matched terminations are designed and constructed to match as precisely as possible the characteristic impedance of the system in which they are to be used. These are usually broadband devices. They can be fixed or they can be adjustable terminations such as sliding loads [17, 18].

Mismatched terminations designed for specific values of impedance mismatch are available. They are used to test the measurement system's ability to correctly measure impedances other than the characteristic impedance of the system. These terminations [19] typically fall into three categories: (1) short-circuit terminations (either flat or quarter-wavelength); (2) open-circuit terminations (either flat or quarter-wavelength offset), and (3) mismatches with fixed precise values of VSWR such as 1.2, 1.5, and 2.0. These standard mismatch terminations furnish precisely calculated values of reflection coefficient magnitude and phase. When connected to the system of interest they provide a means of testing the measurement system's accuracy.

Precision air-dielectric transmission line sections, commonly called "air lines," provide calculable values of Z_0 based on physical dimensions of the individual air lines [20]. The dimensions of interest for ideal coaxial transmission lines are (1) the inner diameter, D, of the outer conductor and (2) the outer diameter, d, of the inner conductor. Figure 5 shows the relationship of the conductor's dimensions to the characteristic impedance of a coaxial transmission line [20].



$$Z_0 \cong \frac{60}{\sqrt{\epsilon_r}} \ell n \frac{D}{d}$$

Figure 5. Dimensional relations for an ideal coaxial air line.

The following equations provide a rapid and accurate means of determining the electrical parameters of precision, air-dielectric, coaxial transmission lines. For a dielectric medium of air, the relative permeability, $\mu_r = \mu_0$, and the relative permittivity, $\epsilon_r = \epsilon_o$. When the line can be considered lossless ($R = G = 0$), eq. (2) becomes

$$Z_o = \sqrt{L/C} \tag{14}$$

where $L = (\mu_o/2\pi)\ \ell n\ (D/d)$

and $C = (2\pi\epsilon_o)(\epsilon/\epsilon_o)/(\ell n(D/d))$.

Then $Z_o \approx (60/\sqrt{\epsilon_r})\ \ell n(D/d)$,

where Z_o is in ohms. The value of the coefficient of $\ell_n(D/d)$ has been determined at NIST to seven decimal places [20], so

for $\mu_o = 4\pi \times 10^{-7}$ H/m,

and $\epsilon_o = 8.854\ 192 \times 10^{-12}$ F/m,

then $$Z_o = (59.958\ 4916/\sqrt{\epsilon_r})\ \ell n(D/d)\ \Omega. \tag{15}$$

For $\epsilon_r = 1.000\ 649$,

$$Z_o = 59.939\ 0446\ \ell n(D/d). \tag{16}$$

The value of ϵ_r is computed from the refractive index of air [17] for ambient conditions of 23°C, 50% relative humidity and an atmospheric pressure of $1.013\ 25 \times 10^5$ Pa (760 Torr). The value of ϵ_r varies as a function of the ambient conditions. For example, in Boulder, Colorado, where the atmospheric pressure is $0.903\ 92 \times 10^5$ Pa (678 Torr), the value for ϵ_r becomes 1.000 558.

Accurate, stable impedance standards are critically needed to characterize, calibrate, and support all ANAs including six-port ANAs. The equations above help to illustrate the requirements for precision in the physical dimensions of impedance standards, to produce the corresponding electrical precision for the new generation of ANAs.

6.0 BASIC DESCRIPTION OF SIX-PORT ANAs

Single-port and six-port ANAs can be assembled from readily available commercial components and instruments. Typical port configurations are shown in Figure 6. The basis of the system can be thought of as a directional coupler and three voltage probes connected as shown in Figure 7.

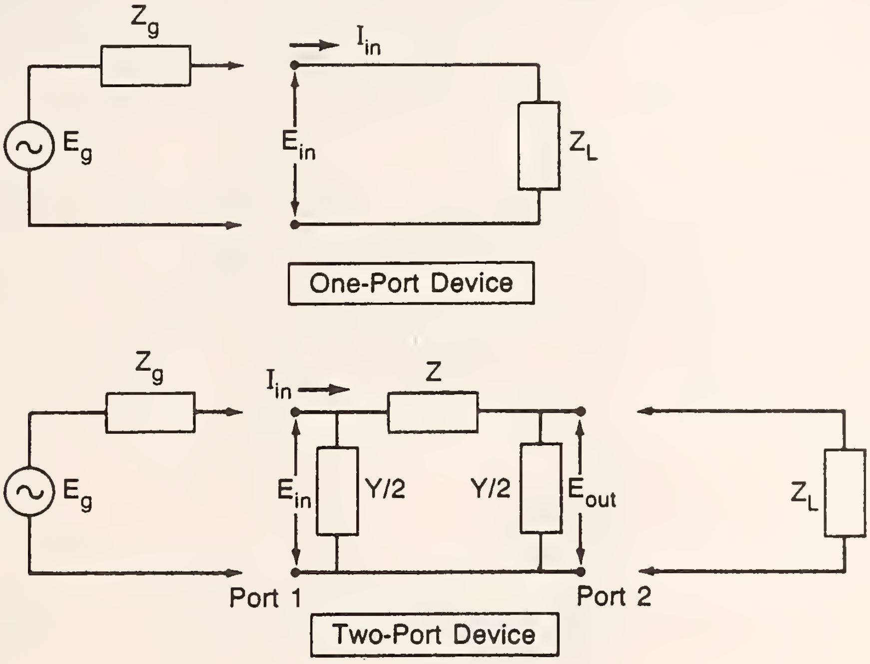


Figure 6. Typical circuit port configurations.

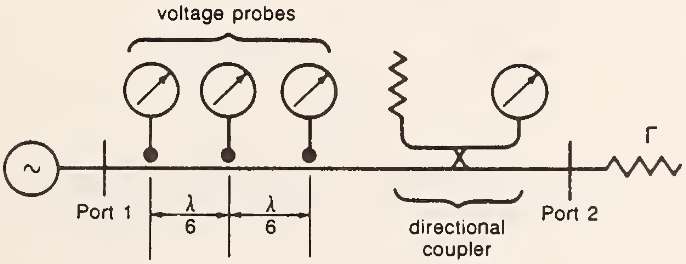


Figure 7. Basic six-port network analyzer

A six-port network analyzer is a linear passive microwave network with several ports. It is used to measure power and Γ. These parameters are measured at one port when a signal is applied to a second port, and the remaining sidearm ports are terminated with power detectors. The power and the reflection coefficient at the measurement port are calculated from the sidearm power detector readings. Usually four sidearm detectors are used, so the network has six ports in all and is called a six-port reflectometer. A typical six-port network analyzer consists of components such as directional couplers or probes that couple in different ways to the incident and reflected waves in a transmission line. Other designs are reported in the literature [22].

When power detectors are connected to each of the ports as shown in Figure 8, this device becomes a vector network analyzer. A major advantage of this technique is that both amplitude and phase information can be obtained from only amplitude information from the set of power detectors.

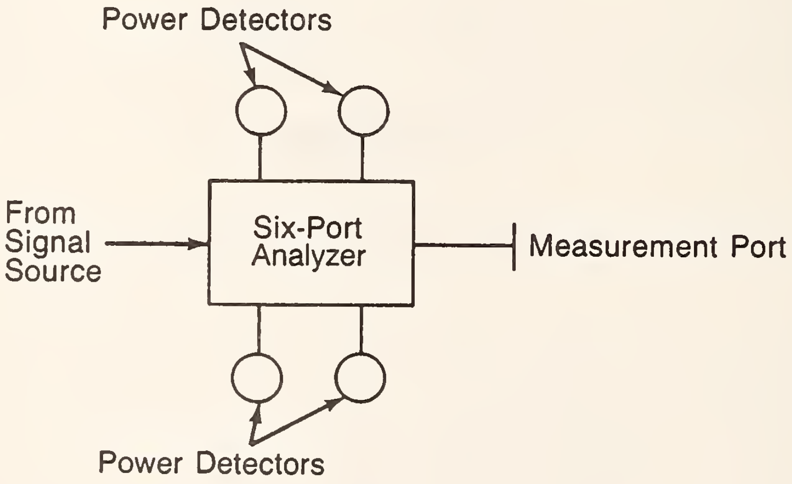


Figure 8. Single six-port vector network analyzer for measuring one-port parameters.

7.0 DUAL SIX-PORT ANA CALIBRATION TECHNIQUES

The addition of a second six-port reflectometer to the system, as shown in Figure 9, provides the means to measure two-port parameters in addition to one-port parameters. Suitable six-port calibration techniques have been sought for the past decade. Many techniques have been developed by many different scientists [23-30] to calibrate six-port reflectometers. As in most other developing technologies, the more we learn the more insights we have in ways to improve upon previous work.

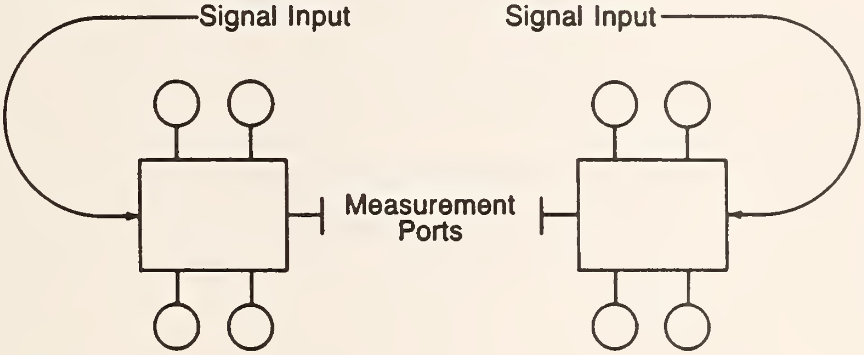


Figure 9. Dual six-port vector network analyzer for measuring two-port parameters.

Two distinctly preferred techniques for the calibration of six-port ANAs have evolved from the research work in this area: (1) the Thru-Reflect-Line (TRL) technique and (2) the Line-Reflect-Line (LRL) technique [31]. The LRL technique has been expanded from (1) the One-Line Technique to (2) the Two-Line Technique to (3) the Five-Line Technique [32].

Typically, the procedure for calibration of a dual six-port ANA consists of observation and analysis of the six-port's response to a set of suitably chosen, known excitation and reflection conditions at the measurement ports. This procedure yields a series of complex simultaneous equations which are then solved for the desired parameters in terms of scattering parameters [24].

8.0 NEED FOR MORE PRECISE IMPEDANCE STANDARDS

The advances in technology and metrology over the past decade have greatly improved the measurement capabilities and performance of ANAs. The precision and resolution of the current state-of-the-art computer-controlled network analyzers are sufficient to detect and quantify the effects of individual circuit components. The component of variation due to inadequacies of coaxial connectors and waveguide flanges can be seen and isolated from the rest of the measurands. The difficulty lies in the fact that the certifiable absolute accuracy of these ANAs is approximately two orders of magnitude less than their precision, based upon present impedance standards. Also, greatly improved connectors are becoming available. Table 1 summarizes the improvements in coaxial connectors over the past four decades [33]. The newer high-precision connectors allow more precise measurements than were possible in the past, and therefore require more accurate impedance standards than those currently available. Impedance standards with reflection coefficients less than 0.0002 are needed if ANA accuracies with two additional orders of magnitude are to be achieved.

TABLE 1

Summary of the improvement in connector performance over the past four decades.

Connector Type	Approximate Date of Introduction	VSWR at 5 GHz (Typical)	Approximate Maximum Usable Frequency (GHz)	Symmetrical	Well-Defined Mating Plane
GR 874	1948	1.035	7	Yes	No
GR 900	1963	1.005	8.5	Yes	Yes
Prec. N	1967	1.02	18	No	No
APC 7	1968	1.007	18	Yes	Yes
APC 3.5	1976	1.006	32	No	No
K 2.92	1983	1.01	40	No	No
PC 2.4	1986	1.01	50	No	No
PC 1.85	1987	<1.016	65	No	No

9.0 DEPENDENCE OF COMPUTED ELECTRICAL IMPEDANCE UPON PHYSICAL DIMENSIONS

Lengths of precision air-dielectric coaxial transmission lines have constant impedance and are nearly reflectionless. They actualize ideal design principles and are the bases for calculable impedance standards. The electrical performance of these air lines depends primarily on the diameters of the two conductors as illustrated in Figure 5. The effect of irregularities in the diameters of these conductors on the characteristic impedance of a 50 Ω coaxial line can be computed from $\Delta Z_0/Z_0$. Differentiation of (15) yields

$$\frac{\Delta Z_0}{Z_0} = \left(\frac{\Delta D}{D} - \frac{\Delta d}{d}\right) \frac{1}{\ell n\ (D/d)}, \tag{17}$$

where ΔZ_0 is the change in characteristic impedance, D is the inner diameter of the outer conductor, ΔD is the deviation of D, d is the outer diameter of the inner conductor, and Δd is the deviation of d [34].

The currently achievable dimensional tolerances in the fabrication of coaxial conductors in various sizes are listed in Table 2. The desired dimensional tolerances and frequency ranges are also listed. Table 3 shows typical and desired dimensional tolerances of coaxial conductors. The effect of air-line conductor's dimensional tolerances on Z_0 and on $|\Gamma|$ can be determined with equations (16) and (7), respectively (assuming that Z_L is constant), and with the dimensional tolerances found in Table 3.

The outer conductor tolerances, ΔD, are added to the outer conductor dimension, D, and the center conductor tolerances, Δd, are subtracted from the center conductor dimension, d, to obtain the "worst-case" effect on Z_0 of the precision air-line impedance standards. Equation (16) then takes the following form for these calculations:

$$Z_0 = 59.939\ 0446\ \ell n\ [(D+\Delta D)/(d-\Delta d)]. \tag{18}$$

Table 4 is a tabulation of the changes in Z_0 and $|\Gamma|$ as a function of ΔD and Δd for 14 mm, 7 mm, and 3.5 mm air lines, respectively, using a value of 50 Ω for Z_L.

TABLE 2

Summary of precision impedance standards (coaxial air lines) characteristics.

Air-Line Diameter (mm)	Connector Type	Frequency Range (GHz)	Tolerance (μin.)*	
			Typical	Desired
14	PC 1.85	0 - 8.5	100-200	15-25
7	N	0 - 18	250-500	15-25
7	PC 7	0 - 18	100-200	15-25
3.5	SMA	0 - 25	100-500	10-20
3.5	PC 3.5	0 - 32	100-200	10-20
2.92	K	0 - 40	50-100	25-50
2.4	PC 2.4	0 - 50	100-200	10-20
1.85	PC 1.85	0 - 65	---	5-15

TABLE 3

Typical and desired dimensional tolerances in the fabrication of precision coaxial air-line conductors, where D is the inner diameter of the outer conductor and d is the outer diameter of the inner conductor.

Air-Line Diameter (in.)*	Dimensions (in.)	
	(Typical)	(Desired)
14 mm D = 0.562 500* d = 0.244 255	 Δd = ±0.000 100* ΔD = ±0.000 200	 ±0.000 015* ±0.000 025
7 mm D = 0.275 591 d = 0.119 670	 Δd = ±0.000 100 ΔD = ±0.000 200	 ±0.000 015 ±0.000 025
3.5 mm D = 0.137 795 d = 0.059 835	 Δd = ±0.000 100 ΔD = ±0.000 200	 ±0.000 010 ±0.000 020
2.4 mm D = 0.094 490 d = 0.041 064	 Δd = ±0.000 100 ΔD = ±0.000 200	 ±0.000 010 ±0.000 020

*Note: Dimensions are those given by the manufacturers and are not converted to SI to avoid round-off errors.

TABLE 4

Calculated characteristic impedance (Z_0), reflection coefficient magnitude ($|\Gamma|$), and return loss (RL) for precision 14 mm, 7 mm, and 3.5 mm coaxial air lines using ideal, existing and desired fabrication tolerances for conductor diameters D and d.

D = Inner diameter of outer conductor.

d = Outer diameter of inner conductor.

$Z_0 = 59.939\,0446 \ln (D + \Delta D/d - \Delta d)$.

$|\Gamma| = |(Z_0 - 50.000\,000)/(Z_0 + 50.000\,000)|$.

RL = Return Loss = $20 \log (1/|\Gamma|)$.

Tolerance	D (in.)	d (in.)	ΔD (μin.)	Δd (μin.)	Z_0 Ω	$\lvert\Gamma\rvert$	RL (dB)
14 mm diameter air line							
Ideal	0.562 500	0.244 255	0	0	49.999 85	0.000 001	120.0
Typical	0.562 700	0.244 155	+200	-100	50.045 71	0.000 457	66.8
Desired	0.562 525	0.244 240	+25	-15	50.006 20	0.000 062	84.2
7 mm diameter air line							
Ideal	0.275 591	0.119 670	0	0	49.999 95	0.000 0005	126.0
Typical	0.275 791	0.119 570	+200	-100	50.093 54	0.000 935	60.6
Desired	0.275 616	0.119 655	+25	-15	50.012 90	0.000 129	77.8
3.5 mm diameter air line							
Ideal	0.137 795	0.059 835	0	0	49.999 73	0.000 003	110.5
Typical	0.137 995	0.059 735	+200	-100	50.186 92	0.001 866	54.6
Desired	0.137 815	0.059 825	+20	-10	50.018 45	0.000 184	74.7

Figure 10 illustrates the relative resolution and uncertainties of the NIST six-port ANA measurements of $|\Gamma|$ on 7 mm coaxial devices. The random uncertainty includes the effect of the connectors on the standards and on the DUT. The resolution for the measurement of $|\Gamma|$ by the NIST six-port ANA ranges from a value of 0.000 02 at 2 GHz to a value of 0.000 05 at 18 GHz. The desired $|\Gamma|$ of 0.0002 for the new generation of precision coaxial air lines is compared to the value of $|\Gamma|$ of 0.001 for the existing air-line impedance standards. The present estimated uncertainty in the measurement of $|\Gamma|$ by the NIST six-port ANA is a few parts in 10^3.

The total uncertainty, U_T, is the sum of the random and systematic uncertainties. The NIST six-port ANA value of U_T for the measurement of $|\Gamma|$ of 7 mm coaxial devices can be determined using the equation

$$U_T = 3\left(S_{NIST} + \frac{S_c^2}{n}\right)^{1/2} + \Delta. \tag{19}$$

S_{NIST} is the random uncertainty associated with the calibration of the NIST dual six-port ANA and is given as one standard deviation. S_c is the standard deviation computed from n connections of the DUT, and Δ represents the systematic uncertainty of the NIST six-port ANA. Three standard deviations are taken as the overall random uncertainty; hence the factor of 3.

Typical values of U_T, S_{NIST}, and Δ are plotted in Figure 10. Values of S_c are not plotted since they are frequency dependent and are different for each DUT. Typical values of S_c range from 0.0001 at 1 GHz to 0.001 at 18 GHz under normal conditions.

The measurement of conductor diameters to achieve the desired accuracy is typically a tedious and difficult process. Air gauges [35,36], capacitance gauges [37], and laser micrometer gauges [38] provide excellent techniques to measure these diameters, but a number of problems must be solved during the measurement process. These include mechanical standards of diameter, uncertainties in the measuring system, measurement environment, and handling techniques, all of which directly affect the measurements.

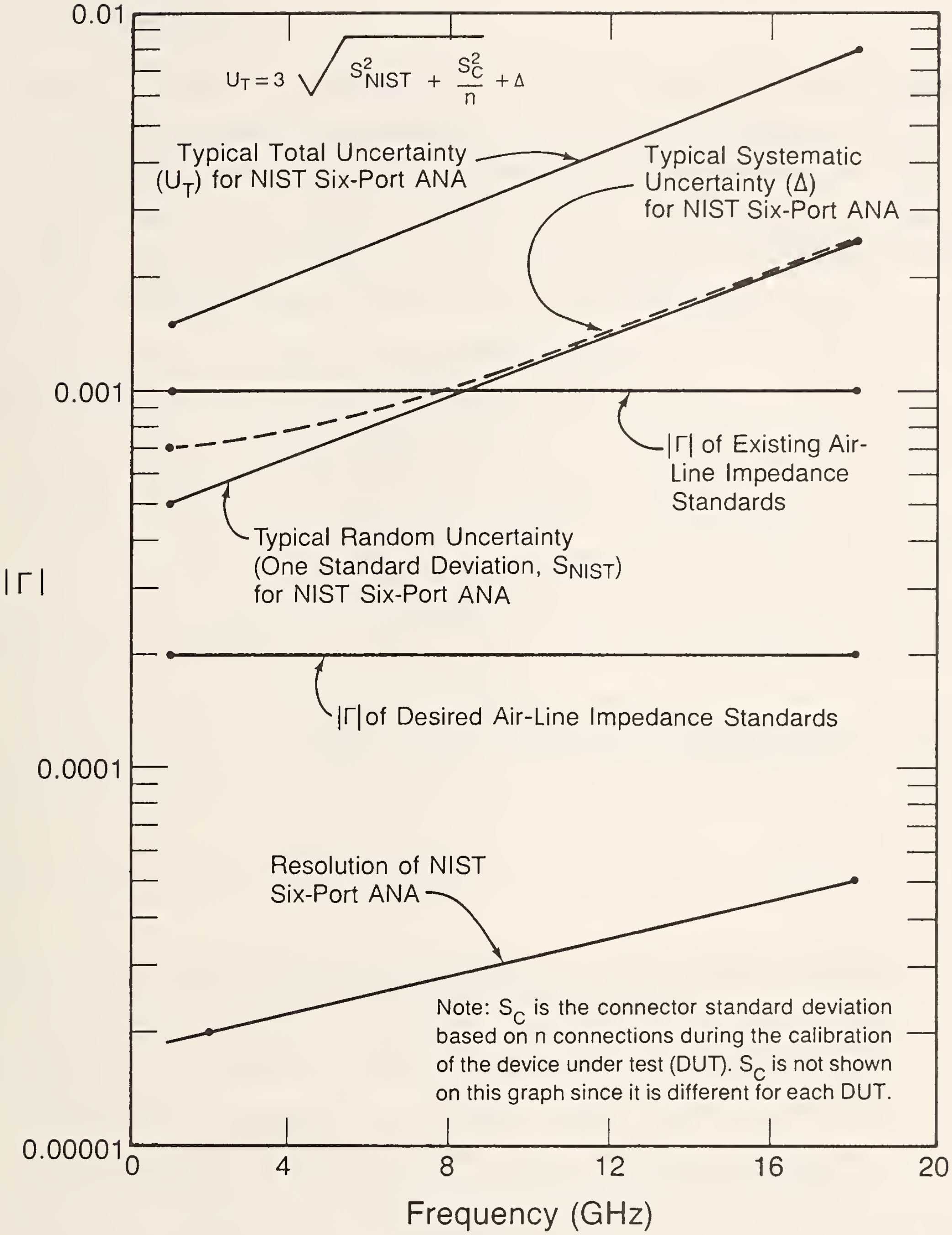


Figure 10. Values of reflection coefficient magnitude versus frequency for existing and desired precison 7 mm coaxial air-line impedance standards. Typical NIST six-port ANA resolution and uncertainties for reflection coefficient measurements on 7 mm coaxial devices are also included.

10.0 SUMMARY

Transmission line concepts are used in electronic measurement systems to provide an integral, vital part of rf, μw, and mmw measurements. Precision sections of coaxial air-dielectric transmission lines are the most precise impedance standards in existence [39]. They are necessary for the calibration and support of ANAs which now make up a majority of the active measurement systems. The accuracy and capability of ANAs depend directly upon the precision and accuracy of the physical dimensions of these air lines. The electrical parameters of these impedance standards are calculated from their physical properties and dimensions, and consequently depend directly upon the quality of their fabrication and the measurement of their physical properties.

The results presented in this report are best shown in terms of the parameter of interest which must be improved to achieve these goals -- the reflection coefficient of the impedance standard. The degree of improvement in the reflection coefficient is directly dependent upon improvements in the physical dimensions of the impedance standards. Data which quantitatively define the degree of uncertainty in reflection coefficient produced by specific values of uncertainty in each physical dimension of the impedance standard are presented.

11.0 CONCLUSIONS

The resolution of state-of-the-art ANAs now is approximately two orders of magnitude greater than their accuracy. Therefore, significantly greater accuracies in impedance standards than those currently available are needed to use the full capability of these ANAs. Impedance standards with reflection coefficients of less than 0.0002 are required to utilize the existing ANA resolution. The dimensional tolerances of the impedance standards necessary to achieve this level of reflection coefficient are now known, as presented in this document. Thus, a new generation of impedance standards which will provide the required accuracy and precision not currently available in the impedance standards of today must be developed. The results presented in this report provide a quantitative analysis of the methods needed to achieve the full capability of the present ANAs.

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13.0 REFERENCES

[1] Jay, F., ed. in chief. IEEE standard dictionary of electrical and electronic terms, ANSI/IEEE Std. 100-1984. 1174 pp.

[2] Jones, R.N. The measurement of lumped parameter impedance: A Metrology Guide. Natl. Bur. Stand. (U.S.) Monogr. 141; 1974 June. 211 pp.

[3] Kerns, D.M. Definitions of v, i, Z, Y, a, b, Γ, and S. Proceedings of the IEEE. 55(6): 892-900; 1967 June.

[4] Michels, W.C., ed. in chief. The international dictionary of physics and electronics. Second edition. D. Van Nostrand Company, Inc. 1961. 1356 pp.

[5] Beatty, R.W. Microwave impedance measurements and standards. Natl. Bur. Stand. (U.S.) Monogr. 82; 1965 August. Reprinted June 1969 with Errata. 32 pp.

[6] Lance, A.L. Introduction to microwave theory and measurements. New York: McGraw-Hill Book Company; 1964. 308 pp.

[7] Gardiol, F.E. Introduction to microwaves. Artech House, Inc.; 1984. 495 pp.

[8] Jesch, R.L.; Jickling, R.M. Impedance measurements in coaxial waveguide systems. Proc. IEEE. 55(6): 912-923; 1967 June.

[9] Engen, G.F.; Beatty, R.W. Microwave reflectometer techniques. IRE Trans. Microwave Theory Tech., MTT-7 (3): 351-355; 1959 July.

[10] Anson, W.J. A Guide to the use of the modified reflectometer technique of VSWR measurement.. J. Res. Natl. Bur. Stand. (U.S.) Engineering and Instrumentation. 65C (4): 217-223; 1961.

[11] Little, W.E.; Ellerbruch, D.A. Precise reflection coefficient measurements with an untuned refectometer. J. Res. Natl. Bur. Stand. (U.S.) Engineering and Instrumentation. 70C (3): 165-168; 1966 July-September.

[12] IEEE standard on network analyzers (100 kHz to 18 GHz). ANSI/IEEE Std. 378-1986. 15 pp.

[13] Hoer, C.A. A network analyzer incorporating two six-port reflectometers. IEEE Trans. Microwave Theory Tech., MTT-25 (12): 1070-1074; 1977 December.

[14] Juroshek, J.R. A technique for extending the dynamic range of the dual six-port network analyzer. IEEE Trans. Microwave Theory Tech., MTT-33 (6): 453-459; 1985 June.

[15] Hewlett-Packard. Millimeter wave vector measurements using the HP 8510A network analyzer. Product Note No. 8510-1. 1984 November. 15 pp.

[16] Wiltron Company. Wiltron 5600 Series automated network analyzer systems. 10 MHz to 40 GHz. Production Note. 1984 January. 14 pp.

[17] Little, W.E.; Wakefield, J.P. A coaxial adjustable sliding termination. IEEE Trans. Microwave Theory Tech., MTT-12 (2): 247-248; 1964 March.

[18] Weinschel, B.O.; Sorger, G.U.; Raff, S.J.; Ebert, J.E. Precision coaxial VSWR measurements by coupled sliding-load technique. IEEE Trans. Instrum. Meas., IM-13 (4): 292-300; 1964 December.

[19] Beatty, R.W.; MacPherson, A.C. Mismatch errors in microwave power measurements. Proc. I.R.E. 41 (9): 1112-1119; 1953 September.

[20] Nelson, R.E.; Coryell, M.R. Electrical parameters of precision coaxial, air-dielectric transmission lines. Natl. Bur. Stand. (U.S.) Monogr. 96; 1966 June. 104 pp.

[21] Essen, L.; Froome, K.D. Dielectric constant and refractive index of air and its principal constituents at 24 GHz. Nature. (167): 512; 1951 March.

[22] McGraw-Hill Yearbook of Science and Technology: NY 1986; 289-292.

[23] Engen, G.F.; Hoer, C.A. "Through-reflect-line": an improved technique for calibrating the dual six-port automatic network analyzer. IEEE Trans. Microwave Theory Tech., MTT-27 (12): 987-993; 1979 December.

[24] Hoer, C.A. Calibrating two six-port reflectometers with an unknown length of precision transmission line. IEEE MTT-S International Microwave Symposium Digest. June 27-29, 1978: 176-178.

[25] Engen, G.F.; Hoer, C.A., and Speciale, R.A. The application of "through-short-delay" to the calibration of the dual six-port. IEEE MTT-S International Microwave Symposium Digest. June 27-29, 1978: 184-185.

[26] Engen, G.F.; Hoer, C.A. "Through-load-delay": An improved technique for calibrating the dual six-port. IEEE MTT-S International Microwave Symposium Digest. April 30-May 4, 1979: 53.

[27] Engen, G.F. On-line accuracy assessment for the dual six-port ANA: background and theory. IEEE Trans. Instru. Meas. IM-36 (2): 501-506: 1987 June.

[28] Judish, R.M. On-line accuracy assessment for the dual six-port ANA: statistical methods for random errors. IEEE Trans. Instrum. Meas., IM-36 (2): 507-513; 1987 June.

[29] Hoer, C.A. On-line accuracy assessment for the dual six-port ANA: treatment of systematic errors. IEEE Trans. Instrum. Meas., IM-36 (2): 520-523; 1987 June.

[30] Juroshek, J.R. On-line accuracy assessment for the dual six-port ANA: experimental results. IEEE Trans. Instrum. Meas., IM-36 (2): 524-529; 1987 June.

[31] Hoer, C.A.; Engen, G.E. On-line accuracy assessment for the dual ANA: extension to non-mating connectors. (To be published.)

[32] Hoer, C.A. Some questions and answers concerning air lines as impedance standards. 29th Automatic RF Techniques Group (ARFTG) Conference, Las Vegas, NV. June 12-13, 1987. 161-173.

[33] Somlo, P.I.; Hunter, J.D. Microwave impedance measurement. Peter Peregrinus Ltd., London, UK. 1985; 213 pp.

[34] MacKenzie, T.E.; Sanderson, A.E. Some fundamental design principles for the development of precision coaxial standards and components. IEEE Trans. Microwave Theory Tech., MTT-14 (1): 29-39; 1966 January.

[35] Kirk, David B. Introduction to principles of pneumatic gaging. Tech. Paper 8101. American Society of Mechanical Engineers Annual Meeting, December 5, 1952.

[36] Kennedy, C.W. Inspection and gaging. 3rd ed. New York: Industrial Press, 1962. 580 pp.

[37] Sanderson, A.E.; Van Veen, F.T. The precise measurement of small dimensions by a capacitance bridge. Gen. Radio Exper. 38 (2): 1964 February.

[38] Hewlett-Packard. Traceability and the HP 8510 Network Analyzer. Publication No. 5954-1552. 1985 November. 11 pp.

[39] Weinschel, B.O. Air-filled coaxial lines as absolute impedance standards. Microwave J. 7 (4): 47-50; 1964 April.

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This paper discusses how impedance standards are derived from the basic definition of impedance, constructed and used in metrology with coaxial air-line systems. Basic transmission line equations are reviewed with emphasis given to intrinsic or derived standards for obtaining the impedance in low-loss transmission line systems. A brief description is given of how impedance standards are used to calibrate the vector automatic network analyzer, and specifically, the six-port system automatic network analyzer used at the National Institute of Standards and Technology for calibration services in the radio frequency, microwave, and millimeter wave areas. Measurement uncertainties are given for 7 mm coaxial devices measured with the National Institute of Standards and Technology six-port system. The resolution of our six-port system is several orders more precise than that of the present impedance standards from which it is calibrated. Required improvements in the physical dimensions of air-line standards which permit the automatic network analyzer's capability to be more fully utilized are given.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

automatic network analyzer; calibration services; coaxial line; impedance; intrinsic; measurement uncertainties; metrology; microwave; radio frequency; reflection coefficient; scattering parameters; six-port systems; standards; transmission line; 7 mm coaxial devices

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