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RF Material Characterization Using a Large-Diameter (76.8 mm) Coaxial Air Line

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We report on the development of a 76.84 mm (3.025 in) diameter coaxial air line system whose purpose is to measure the dielectric and magnetic properties of bulk dielectric and ferrite materials over a frequency range of approximately 0.3 MHz to 2000 MHz. We summarize the relative advantages and disadvantages of using large-diameter coaxial air lines for material characterization, and we discuss the particular problems associated with calibrating vector network analyzers in this form of transmission line. We also present broadband measurement data for low-loss polymer and ceramic dielectrics as well as for lossy materials that included a ferrite-loaded polymer and carbon-loaded concrete.

Keywords: coaxial air line; dielectrics; ferrites; loss tangent; materials; measurements; permittivity; permeability; radio-frequency.

1. INTRODUCTION

The transmission/reflection (T/R) method in coaxial air lines is a widely used broadband technique for measuring the dielectric and magnetic properties of certain bulk materials at radio/microwave frequencies. It has recently been documented as a standardized measurement method by ASTM [1]. In this method, a toroidal sample of the material under test is precisely machined to the air-line dimensions and positioned inside the line. Two-port scattering (S-)parameters, both reflected and transmitted, are then measured over a broad frequency range, usually by means of an automatic vector network analyzer (VNA). Data on the complex dielectric permittivity, $\epsilon_r^* = \epsilon_r' - j\epsilon_r''$ and complex magnetic permeability, $\mu_r^* = \mu_r' - j\mu_r''$ are derived from the measured S-parameter data using various available reduction algorithms [2-5]. Coaxial air lines of 7 mm outer diameter are generally used for this purpose because they nominally cover a broad frequency range of 0 GHz to 18 GHz, and because they are readily available from commercial sources.

The broadband transmission-line measurement techniques suffer from two principal disadvantages. The first is that they cannot satisfactorily measure the dielectric or magnetic loss of low-loss materials (i.e., ϵ_r'', $\mu_r'' < 0.05$) due to the low-Q characteristics of transmission-line structures and resulting insensitivity for loss measurements. Such methods work satisfactorily when measuring the complex permittivity and permeability of medium- to high-loss materials. Transmission-line techniques generally suffice for measuring the real part ϵ_r' and μ_r' only of low-loss materials, in cases where loss data are not needed.

Any transmission-line or resonator technique, that involves placement of a material specimen under test in very close proximity to metal conductors, is prone to serious air-gap errors caused by field depolarization. Such errors constitute the technique's second major disadvantage. Air-gap effects occur whenever a normal component of the E- or H-field exists at the air-material interface. Since the normal component of electric or magnetic flux density must be continuous at the air-material interface, a discontinuity in the normal E- or H-fields results owing to the differences in ϵ^* and μ^* for the material and air. The resulting depolarization error always causes measured permittivity or permeability data to be biased lower than actual values. For the coaxial air line operated in the fundamental transverse electromagnetic (TEM) mode, normal electric field and tangential magnetic components exist at the air-material interfaces. As a result, electric- but not magnetic-field depolarization occurs at the interfaces. This means that the technique is very prone to air-gap errors when used to measure dielectric permittivity, but much less so for magnetic permeability. The 7 mm coaxial air line method has been shown to be generally accurate to within better than ±2 % in μ_r' and ±0.01 in μ_r'' when measuring the complex permeability of lossy polycrystalline ferrites at frequencies below their gyromagnetic resonance [5,6].

1.1 Methods of Reducing Air-Gap Errors

There exist five principal methods for reducing and correcting air-gap errors when performing T/R measurements of material permittivity. These can be used separately or in combination with each other [5,7]:

1. Copper electroplating of the curved surfaces of the toroidal specimen.
2. Split "clam shell" coaxial air line holder to ensure improved contact with specimen under test.
3. Application of conductive fillers such as pastes, solders, etc. in the air-gap region.
4. Correction using theoretical models; this requires an accurate knowledge of the air-gap dimension.
5. Use of coaxial air lines of larger diameter .

Each one of these approaches has its advantages and disadvantages. Not all materials can be electroplated and good electrical contact between plated specimens and conductor walls is still essential. Excessive pressure applied to fragile specimens in the "clam shell" holder can easily fracture them. Use of conductive fillers will bias loss-factor data upwards when measuring lower-loss materials because the fillers are themselves very lossy. Error correction using theoretical models works well provided that the inner and outer air-gap dimensions have been accurately estimated. Best accuracy requires use of coordinate-measuring or air-gauge instrumentation. This is the approach favored by NIST. The air-gap correction used by NIST is based on a simple concentric capacitor model and is included in our iterative-based EPS_MU3 transmission-line software [5]. Because uncertainties remain in the dimensional metrology process, NIST does not guarantee accuracies of better than $\epsilon_r' = \pm 5$ % for materials with $\epsilon_r' < 10$ during T/R dielectric measurements performed in 7 mm coaxial air lines. These accuracies degrade rapidly for materials of $\epsilon_r' > 10$.

This publication deals with the fifth option listed above for reducing air-gap errors: use of larger-diameter coaxial air lines. Figure 1 shows a cross-sectional representation of the dielectric specimen symmetrically mounted in a coaxial air line, plus uniform concentric air gaps between the specimen and the inner and outer conductors.

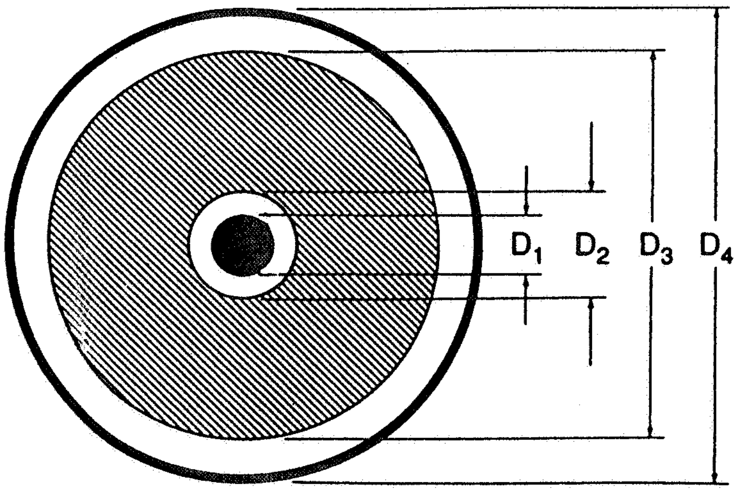


Figure 1. Cross-sectional representation of coaxial air line containing dielectric specimen with uniform and concentric air gaps.

Using a simple coaxial capacitor model [5, pp. 101-103] which employs three capacitors in series to represent the dielectric media and the two air gaps, we can readily derive values for observed or measured real permittivity $\epsilon_m{}'$ in terms of the actual or nominal ϵ' of the material under test, given the dimensions D_1, D_2, D_3, D_4. In Table 1, values of $\epsilon_m{}'$ have been derived for measurements of materials with nominal ϵ' values of 10, 100, and 1000 in different-sized 50 Ω coaxial air lines with $D_4 / D_1 = 2.3$ and a uniform air-gap width of 0.0254 mm (1 mil) throughout.

From the data of Table 1, we see that large differences exist between $\epsilon_m{}'$ and ϵ' and that this error becomes significantly reduced as the diameter of the coaxial air line increases. For example, the error for a measurement performed on the $\epsilon' = 100$ material in the 7 mm diameter air line is −59 %, whereas that for the 76.8 mm diameter line is only −11.2 %. Physically, this difference can be explained by the reduced capacitance across the air gap existing in air lines of larger diameter caused by the increase in surface area. The significant improvement in measurement accuracy realized through use of larger diameter air lines is gained at the expense of reduced frequency coverage and much-increased specimen volume needed for the material under test. However, machining tolerances for the larger-sized specimens can be relaxed. The frequency coverage of the coaxial line is dictated by the frequency where the first higher-order TE_{11} mode will start to propagate within the dielectric under test and depends on the line's diameter and the material's real permittivity. For example, assuming a nominal ϵ' value of 4 for the material under test, the upper frequency limit for measurements performed in a 7 mm line is approximately 19 GHz, that for the 14 mm line is approximately 9.5 GHz, and that for the 76.8 mm line is only about 1.73 GHz. However, for many materials such as high-loss ferrites, only the low-frequency properties are of interest. Therefore, the larger diameter coaxial air lines are well suited to cases where broadband measurements are needed only for a frequency range below about 1000 MHz. Consequently, this report will emphasize measurements at lower radio frequencies covering almost a four-decade range of 300 kHz to 2000 MHz

TABLE 1: Values of measured real permittivity $\epsilon_m{}'$ for materials of three different nominal permittivities, as measured in 50 Ω coaxial air lines of varying outer diameter; air gap = 0.025 mm.

D_4 (mm)	$\epsilon_m{}'$		
	$\epsilon' = 10$	$\epsilon' = 100$	$\epsilon' = 1000$
7	8.85	41.2	67.1
14	9.39	58.4	122
25.4 (1 in)	9.65	71.5	199
41.3 (1⅝ in)	9.78	80.5	291
76.8 (3 in)	9.88	88.8	441

The authors are aware that large-diameter coaxial air line systems are being routinely used for characterizing materials in industrial and academic measurement laboratories. However, few details of these systems appear to have been published, other than a report on the broadband characterization of Portland cement concrete, using a 150 mm diameter coaxial air line [8].

2. EXPERIMENTAL METHODOLOGY

2.1 Coaxial Air Line Hardware

We elected to construct our system using 76.8 mm (3.025 in) diameter coaxial components because some of these are commercially available for high-power applications [9] and because NIST had on hand two double-sectioned 50 Ω tapered reducers of total length 435 mm, which transition from the 76.8 mm diameter coaxial air line down to a 14 mm coaxial connector. However, many additional components were needed, which were designed and fabricated in our in-house machine-shop facilities. These included two 150 mm long coaxial extenders (mode filters) which are permanently attached to the adapters (the reason why the extenders are needed is discussed in Section 3) plus a 102 mm (4 in) long coaxial air line section in which the specimens under test are mounted (see Figure A1). The air line and extender sections were fabricated using 76.8 mm ID and 33.4 mm OD copper tubing of 1 mm wall thickness. Copper flanges, 133 mm in diameter and 6.3 mm thick, were soldered onto the outer conductor tube at both ends of the air line section (Figure A2). Figure 2 shows the tapered transition assembly with extender section attached. The center conductor is held in place using three polytetrafluoroethylene (PTFE) posts spaced 120° apart and the center conductors of the transition and extender sections are permanently connected using a connection bullet and small machine screws. To connect sections of the outer conductor together, the flanges are aligned with each other using two 6.3 mm pins and fastened together using six nominally 1.5 in long ⅜-20 machine screws and nuts. Center conductors were connected using a unique stainless steel male bullet containing slotted flowers at both ends, which is partially inserted inside the center conductor tubing (see Figure A3). In the photograph of Figure 3, the 102 mm coaxial air-line section is shown on the right with a material specimen partially inserted inside it and a connection bullet mounted in the center conductor. Additional components were needed to calibrate the VNA in this transmission line system (see Section 2.1 below), including 175 and 203 mm long air-line sections, two shorting plates with half-bullets attached (see Figure A4), plus two 50 Ω loads with transitions, which were procured from a commercial source [9]. Figure 4 illustrates the calibration components together with some of the connection bullets. The fully assembled transmission line system is illustrated in figure 5.

2.2 Calibration Techniques

Use of a VNA to perform two-port S-parameter measurements, requires that the instrument be first calibrated in the transmission-line system being used; i.e., in our case, in the 76.8 mm coaxial air line system. This process is required in order to correct for the imperfections and systematic errors inherent in the VNA system including impedance mismatches, RF leakage, and the finite directivity and bandwidth of the instrument's reflectometer couplers, etc. Calibration is achieved by measuring

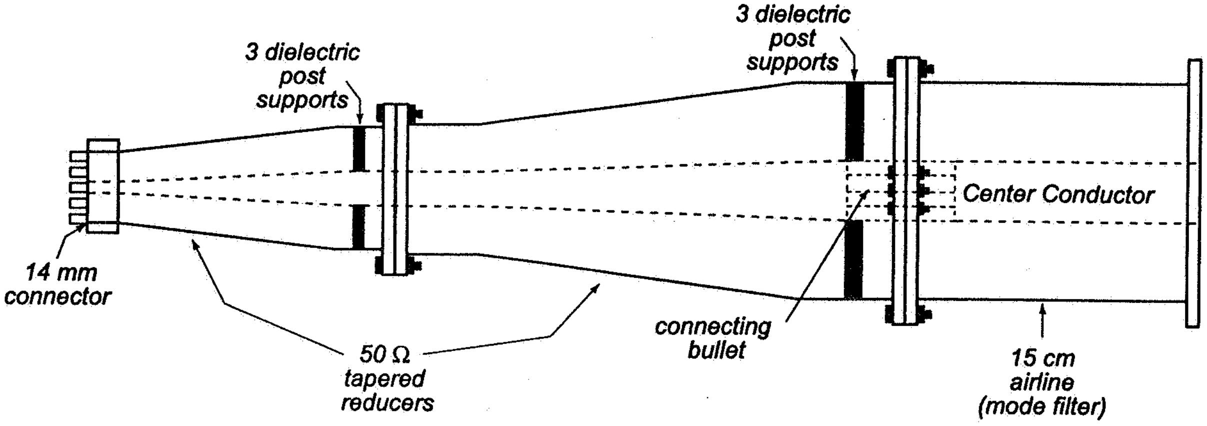


Figure 2. Tapered reducer assembly with 150 mm extender section.

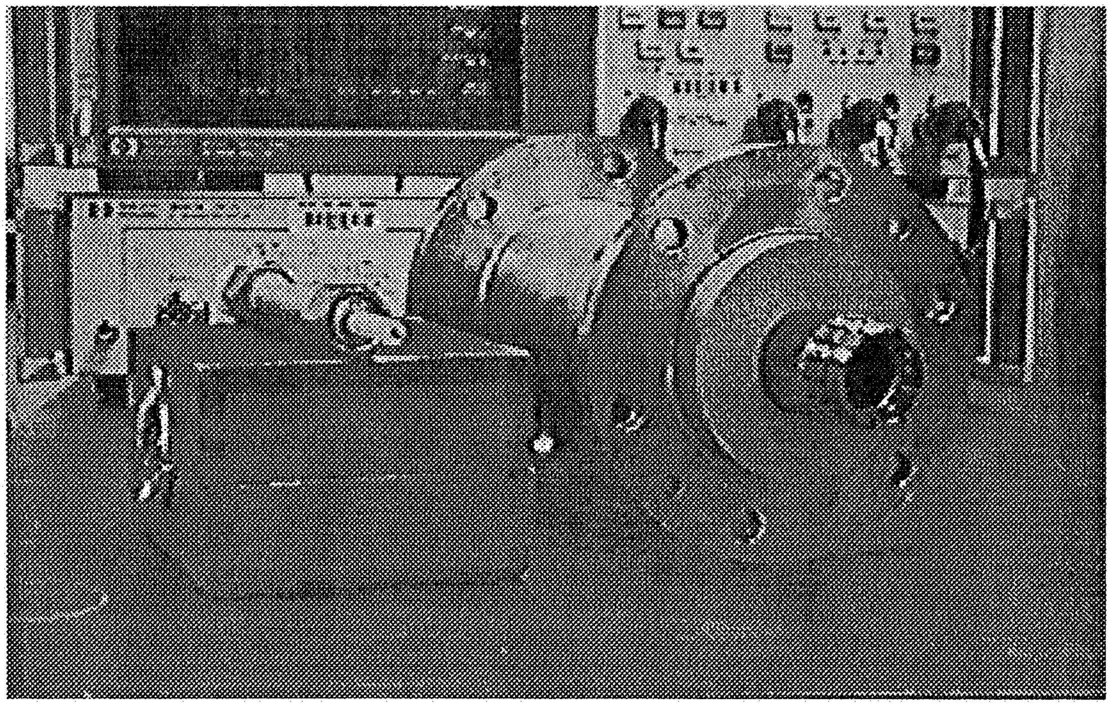


Figure 3. 102 mm long specimen holder section, showing alumina specimen partially inserted (on right). A standard 7 mm diameter coaxial air line, with specimen, is shown on left.

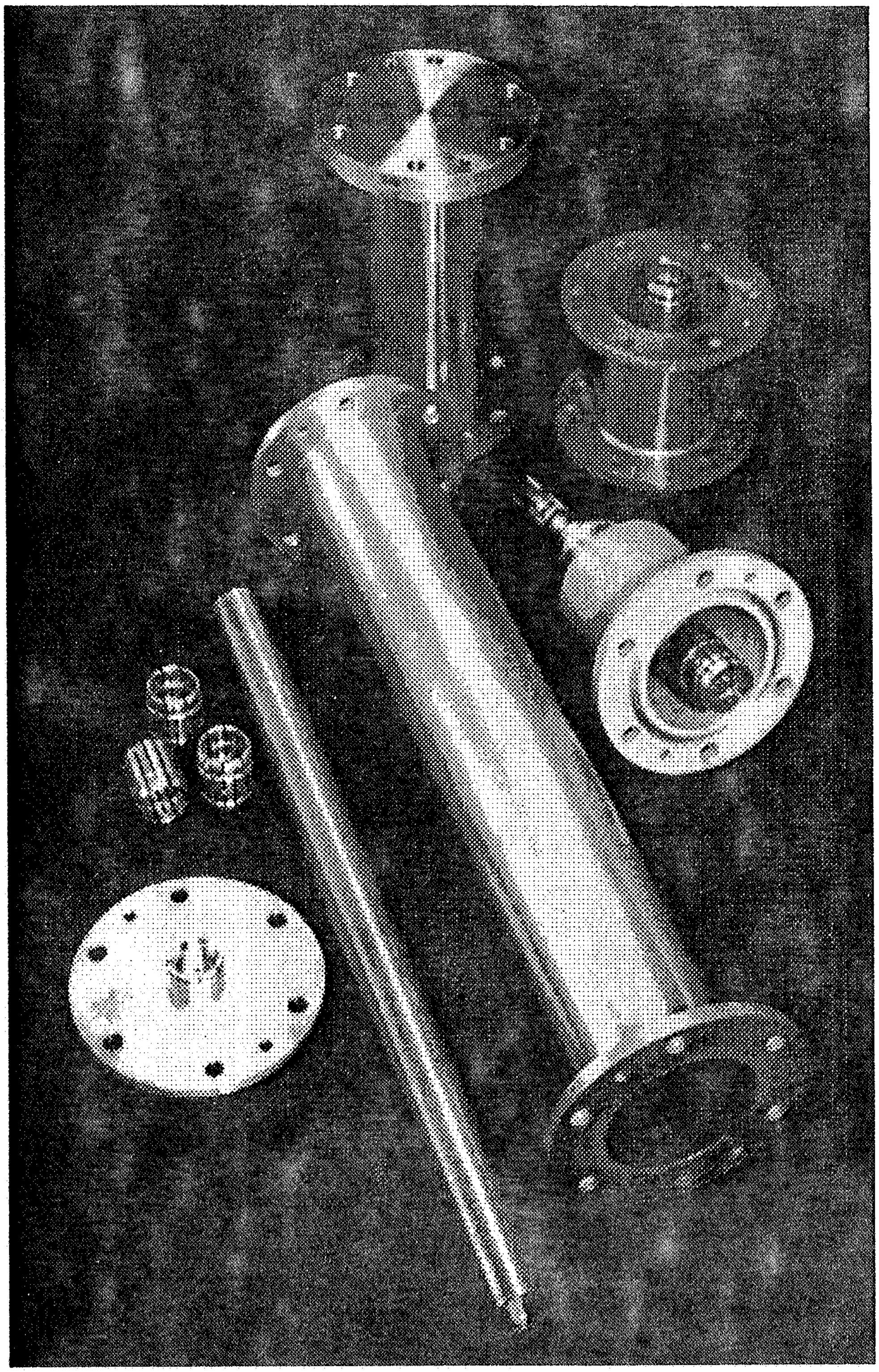


Figure 4. Calibration and other components; the 200 mm line is shown at top, the specimen holder at top right, the tapered load at right center and a shorting plate at bottom left. The long line diagonally positioned in the center was later cut in two and used for the mode-filter extenders.

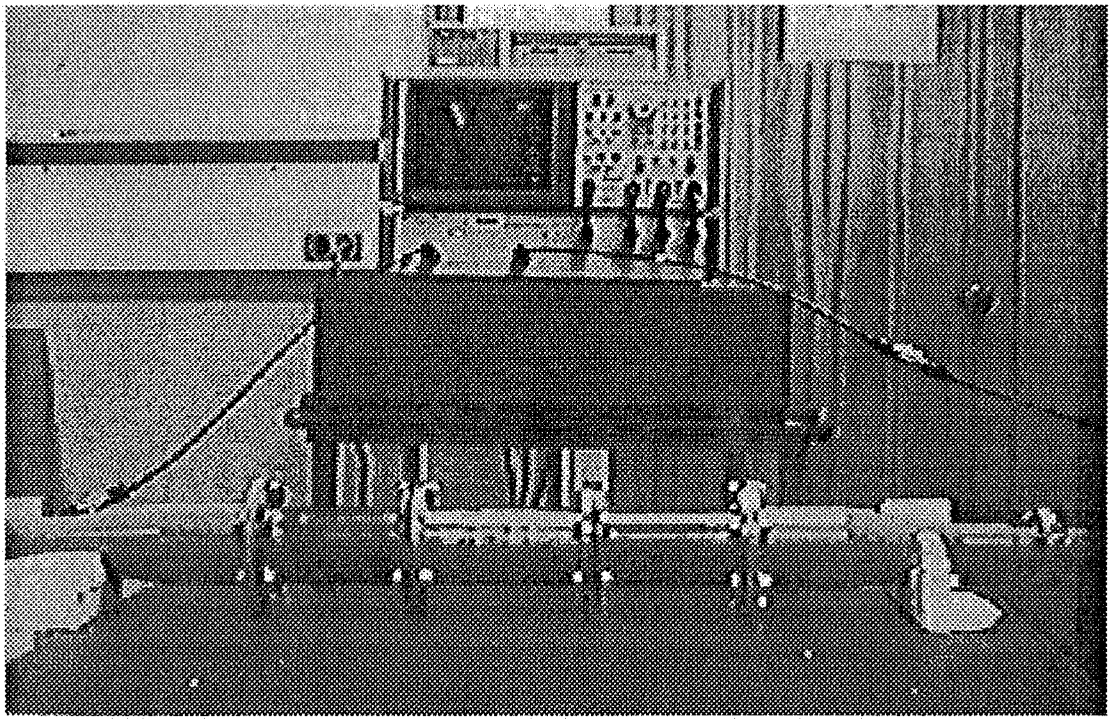


Figure 5. Fully assembled transmission-line system

the S-parameters of a set of known impedance standards, such as a "Short" (or "Reflect"), an "Open", a matched "Load", a "Thru" or a known length of transmission "Line". A set of 12 error correction coefficients are then derived in the VNA's internal firmware by solving a set of 12 simultaneous equations that describe the reflectometer system using a flow-diagram representation [10]. The performance of the standards is typically described by a lumped-element equivalent circuit, termed the "Calibration Kit Parameters" by the instrument manufacturer. The correction coefficients are subsequently applied to the S-parameter measurements, thereby yielding fully corrected data.

Over the years, many different types of calibration techniques have been developed. One of the most widely used and accurate techniques is the "Thru-Reflect-Line" (TRL) method [10]. A capability for processing the TRL calibration data is usually provided in the VNA instrument's firmware. A TRL calibration involves three different connection configurations, which are illustrated in figure 6 for our large-diameter coaxial system. In the first "Thru" configuration, the two reference planes at the ends of the extender sections are fastened together to form a through connection. In the second "Reflect" configuration, both reference planes are terminated by shorting plates, while in the third "Line" configuration, another section of transmission line of the same characteristic impedance is connected between the reference planes. The length of transmission line l required for the "Line" configuration is computed using the following relationship:

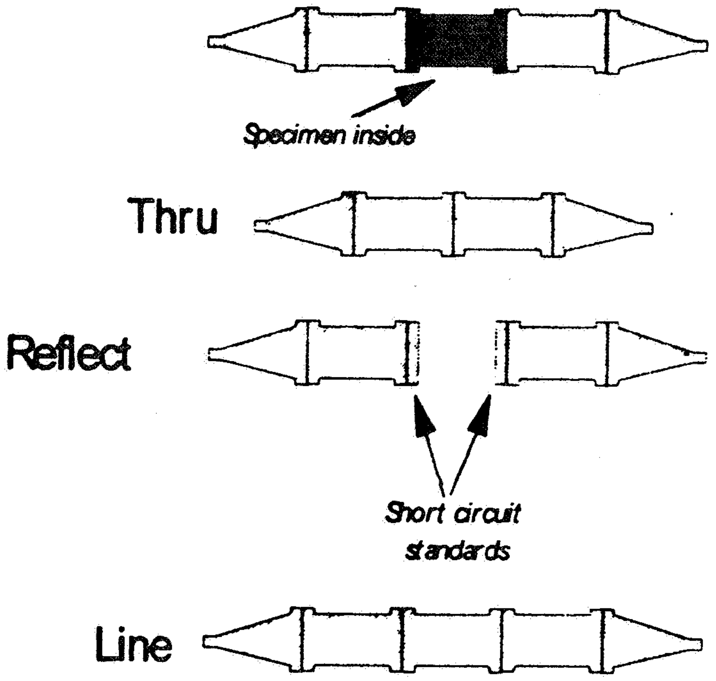


Figure 6. Connection configurations for TRL calibration (reproduced from Reference [8], with permission from Elsevier Science).

$$l = \frac{\phi\lambda_g}{2\pi}, \tag{1}$$

where ϕ is the desired phase delay of the line and λ_g is the guide wavelength for the transmission line used (identical to the free-space wavelength λ_0 in a lossless coaxial line). The value of l is normally chosen to give a minimum phase delay of 20° at the lowest measurement frequency and a phase delay of 160° or more at the highest frequency of interest [11]. We used the 203 mm long line section for performing TRL calibrations in this transmission line system. Using eq (1), the minimal 20° phase shift is obtained at approximately 82 MHz for this line length, which gives an approximate lower-frequency limit for which a TRL calibration is valid. Hence, measurements based on TRL calibrations are generally limited to a frequency range of 45 MHz to approximately 1500 MHz, depending on the dielectric material under test.

Because we were particularly interested in obtaining material characterization data at frequencies below 45 MHz, we needed to use another form of calibration that is valid at these lower frequencies. The "Open-Short-Load-Thru" (OSLT) technique is capable, in theory, of providing accurate calibrations at frequencies down to the kilohertz range, because it does not involve trying to measure small phase delays for a "Line" measurement. In the OSLT method, each end of the extender section is initially terminated in a shielded open, where the line's outer conductor continues beyond the end of the center conductor. In our system, a shielded open was realized by connecting only the outer shield of an air-line section to the extender section. In the second step, the extender sections are terminated by shorting plates at the reference planes. In the third step, the tapered loads are connected at the reference planes. The final step involves a "thru" measurement in which the reference planes are connected together.

The OSLT technique is also supported by internal firmware in the VNA instrument and is usually referred to as a "full two-port calibration" by instrument manufacturers [10]. The physical characteristics of the three standards used in the OSLT method, based on approximate equivalent circuit parameters, are stored in this firmware. The effective capacitance C_{eff} of the shielded open is generally described by a polynomial function in frequency f:

$$C_{eff} = C_0 + C_1 f + C_2 f^2 + C_3 f^3 \quad , \tag{2}$$

where C_0, C_1, C_2, C_3 are capacitive fitting coefficients derived from a full-field solution of the shielded open problem [12]. Similarly, the effective inductance L_{eff} of the coaxial short is described by an identical polynomial containing inductive fitting coefficients L_0, L_1, L_2, L_3. For the 0.3 MHz to 6000 MHz VNA instrument used for these measurements, estimates are provided in the internal firmware of the effective capacitance for the open standard used during OSLT calibration in both 7 mm and 14 mm diameter coaxial air lines. However, there are no provisions in the firmware for calibrating the instrument in coaxial air-line systems of larger diameter. Because of this, we had to develop our own external calibration program in order to perform OSLT calibrations in the 76.8 mm diameter coaxial air-line system. This included an estimate we derived for the effective capacitance of the shielded open standard, using some theory and software developed earlier on another project involving permittivity measurements of solids and fluids in a coaxial shielded open-circuit configuration [13]. The external calibration program was written in HP BASIC and is listed in Appendix B.

2.3 Material Characterization Measurements

2.3.1 Materials Tested

In order to validate our measurement system and determine its accuracy, we prepared specimens of four different materials, whose dielectric/magnetic properties had been measured at NIST by other techniques of equal or better accuracy. The specimens were prepared according to the specifications given in Figure A5 to fit precisely inside the sample holder. The specimen thickness, l was arbitrary and varied over a range of approximately 13 mm to 20 mm. These materials are listed below, together with their nominal dielectric and magnetic properties at 100 MHz.

1. Cross-linked polystyrene (CLP), $\epsilon' = 2.55$
2. Debased alumina ceramic,* $\epsilon' = 8.85$
3. Calcium-strontium-titanate (CST) ceramic, $\epsilon' = 275$
4. Ferrite-loaded polymer (FLP), $\epsilon' = 16.1$, $\mu' = 4.5$

* 88 % alumina with additions of SiO_2, MgO, CrO_2 and CaO; porosity 2 % to 3 %

In June 1997, we were approached by a NIST customer with a request to characterize some samples of carbon-loaded concrete at low frequencies (0.3 MHz to 50 MHz). This is a commercially made material used to attenuate ground currents in power line and broadcast installations. Since this material is known to be very lossy, it is well suited to T/R measurements in a transmission line. However, concrete often contains aggregate components of significant size (> 1 mm). Consequently, it is difficult to accurately machine small samples of this material that can be inserted into, for example, a 7 mm coaxial air line. Because the customer was primarily interested in measurements at low frequencies and not in the microwave region, our 76.8 mm diameter coaxial air-line system represented an ideal match to this requirement. The customer provided us with four samples, that had been machined according to Figure A5, and we labeled them CLC1, CLC2, CLC3, and CLC4.

2.3.2 Measurement Methodology

Material characterization measurements were performed in the manner usually followed for T/R transmission-line measurements. Two-port S-parameter data were measured by a VNA, following system calibration, and the data subsequently processed using our EPS_MU_3 data reduction algorithm [5]. This algorithm originally contained provisions for correcting the measured data for the inevitable presence of air gaps in 7- and 14-mm diameter coaxial sample holders and was later modified to perform the same correction in our 76.8-mm diameter geometry. Most of the measurements performed during the three-year time period during which this development effort took place (1991-1994), were restricted to the frequency range of approximately 45 MHz to 2000 MHz, because only a higher-frequency VNA was available to us. Regrettably, the Project's only low-frequency VNA was fully dedicated to other higher-priority tasks, so that we were unable to perform measurements at frequencies below 45 MHz at this time.

Three years later, the Project had acquired a second low-frequency VNA, so that we were able to characterize the carbon-loaded concrete samples over a full 0.3 MHz to 2000 MHz frequency range. We used both the internal TRL and the external OSLT calibration program for these measurements. The customer also asked us to repeat our measurement of specimen CLC3 one week after the original measurement.

3. EXPERIMENTAL RESULTS

3.1 Early Measurements

Following initial fabrication of the various hardware components and calibration standards, we sought to verify the performance of the standards over the frequency range 45 MHz to 1000 MHz by measuring the magnitude of S_{11} and S_{22} for the short, load and the 102 mm line standards. These data were all within acceptable limits; $|S_{11}|$ and $|S_{22}|$ for the load standards were about −30 dB. However, when we measured the phase of S_{12} and S_{21} for the line standard, we noted a serious anomaly. Figure 7 shows that the phase of S_{21}, which should not normally change by more than a few millidegrees with frequency, varied by +0.7° to −1.5° relative to the 0° reference at frequencies above about 585 MHz.

We subsequently attempted to measure the dielectric properties of the CLP sample over the frequency range 45 MHz to 2000 MHz, following a TRL calibration of the system. The measured ϵ' data for CLP, which are shown in Figure 8, should be compared with a well-established reference value of $\epsilon' = 2.55 \pm 0.013$ over this frequency range [14]. We see that good agreement is evident at frequencies below about 500 MHz, but that significant deviations occur above this frequency. It is apparent that the TRL calibration was unsatisfactory above 600 MHz owing to the significant phase deviations shown in Figure 7, and that this leads, in turn, to the poor data of Figure 8. Upon further investigation, we concluded that this problem was caused by the presence of higher-order transmission-line modes that are incident on the specimen. Such modes are generated in the tapered

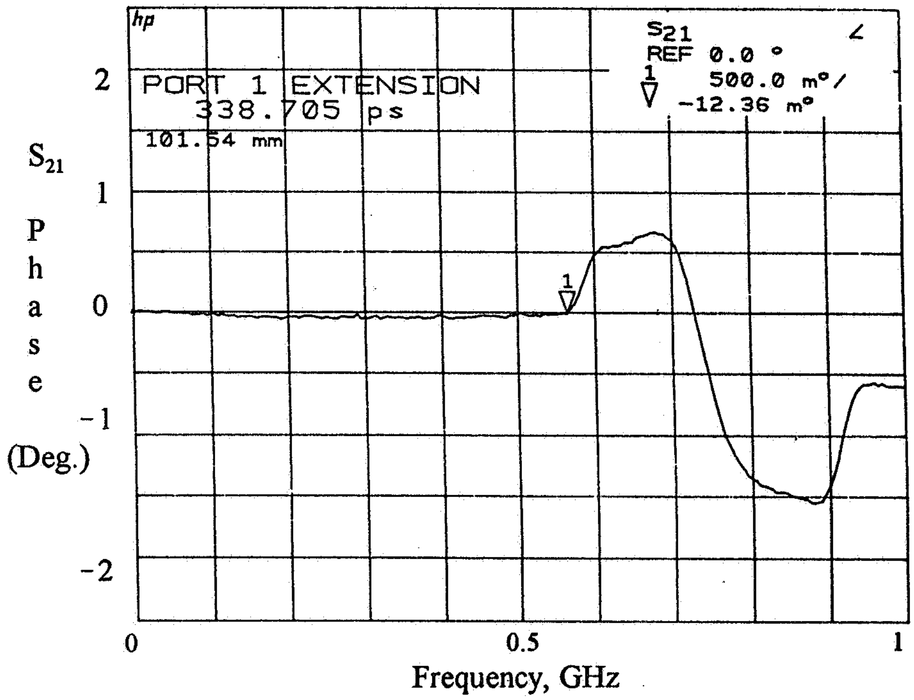
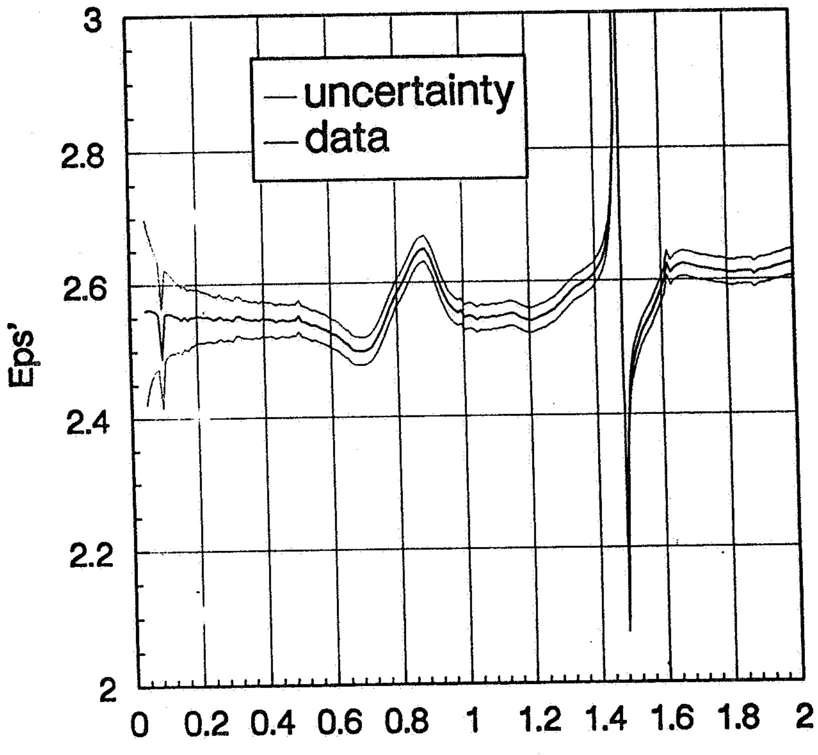


Figure 7: Plot of S_{21} phase versus frequency for the 102 mm line standard.



Frequency, GHz

Figure 8. Early Measured Real Permittivity Data for Cross-Linked Polystyrene, following TRL Calibration

adapter sections and are not sufficiently attenuated in the relatively short length (102 mm) of air line used to hold the specimen. The solution for this problem was to design and fabricate the two 150 mm long extenders which are permanently attached to the adapters. These sections ensure that any higher-order modes are completely attenuated before reaching the specimen under test.

3.2 Improved Characterization Measurements

3.2.1 Higher-Frequency Measurements Using Internal TRL Calibration

We repeated characterization measurements for the CLP sample, after installation of the extender sections. The repeat data (see Figure 9) now exhibit a constant value $\epsilon' = 2.55$ at frequencies up to 1400 MHz. The instability evident at about 1475 MHz represents a measurement artifact caused by an unwanted half-wavelength resonance within the 102 mm long specimen holder section of the transmission-line system. Figure 10 shows similar data for the debased alumina sample. The measured value of $\epsilon' = 9.1$ is constant up to about 800 MHz. Compare this with a reference value of $\epsilon' = 8.85 \pm 0.3$ as measured by both NIST in a 14 mm diameter air line and by the University of Nottingham, UK [15]. The somewhat higher value measured here is likely due to over-correction for the air gap error, but is still within the uncertainty bounds of the reference data. The instability seen

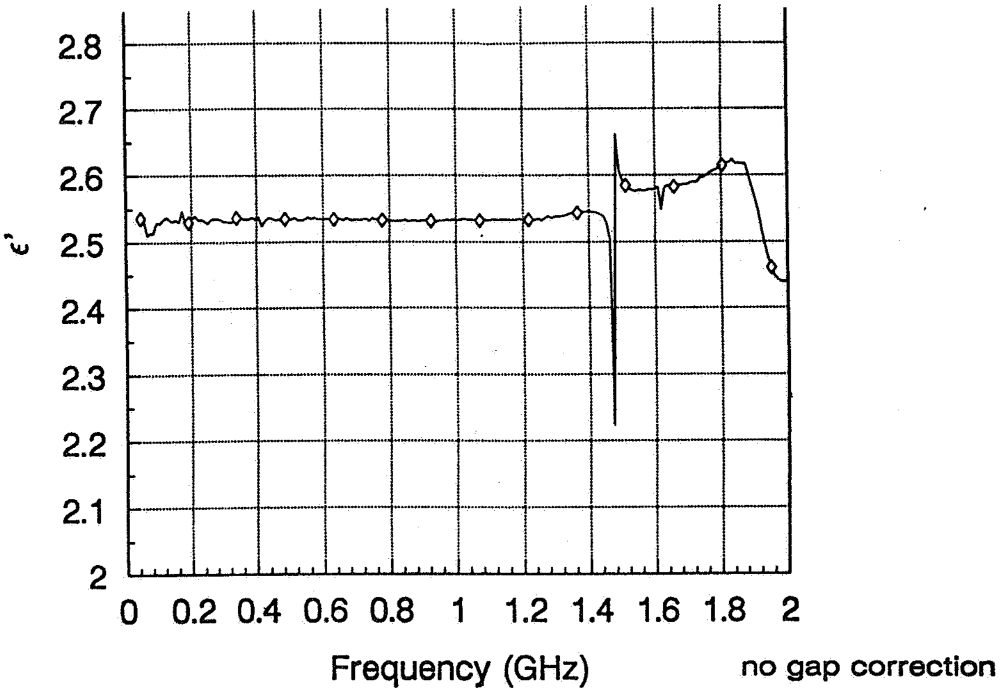


Figure 9: Measured Real Permittivity Data for Cross-Linked Polystyrene, following TRL Calibration, and using extender sections.

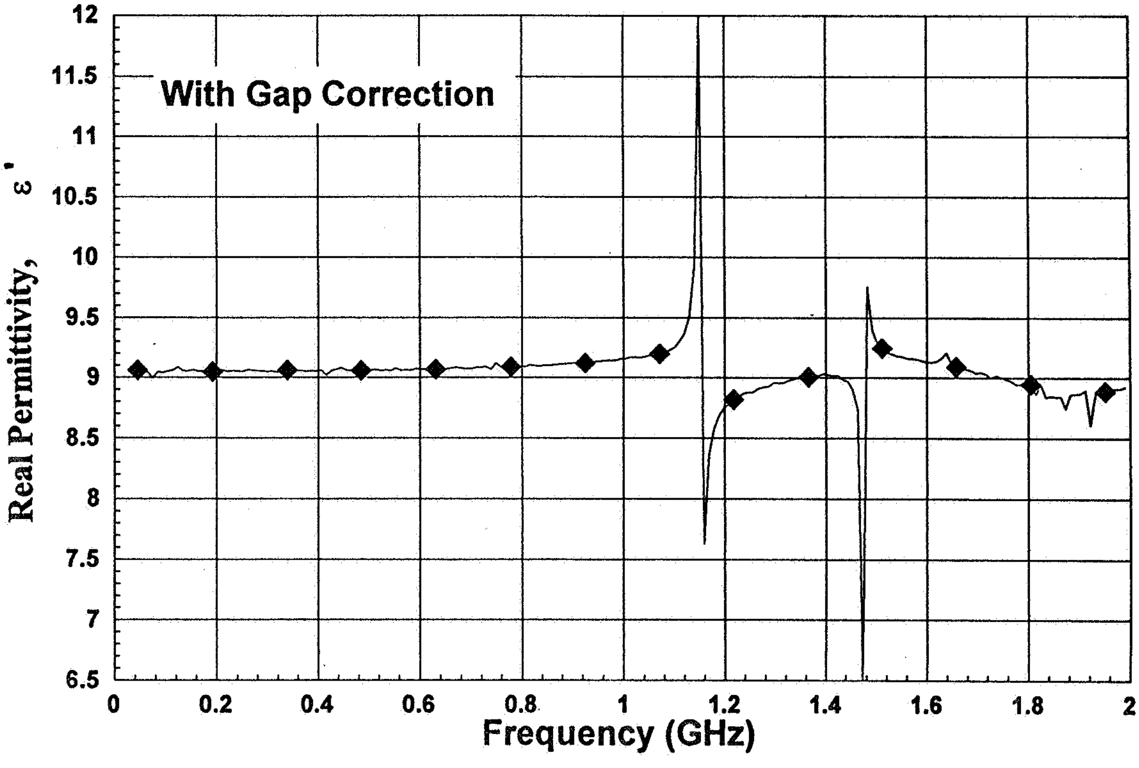


Figure 10: Measured Real Permittivity Data for Debased Alumina, following TRL Calibration.

in the data of Figure 10 at 1150 MHz is probably due to propagation of the first higher-order mode in the sample. This is a common problem that frequently occurs when performing T/R measurements of low-loss dielectrics with ϵ' values of 10 or more. The system artifact at 1475 MHz is again evident in Figure 10.

Past attempts to characterize very high-permittivity and low-loss ceramics in 7 and 14 mm diameter coaxial air lines had been unsuccessful owing to a number of problems. These included an inability of the EPS_MU_3 algorithm to converge on the correct solution, as well as the very large air-gap error that resulted. Consequently, we sought to determine whether a meaningful measurement of this type of material could be realized using this system. Figure 11 shows measured ϵ' data for a sample of calcium-strontium-titanate (CST), both without and with air-gap correction. The corrected values at frequencies below about 250 MHz are seen to compare well with the nominal value of $\epsilon' = 275$, provided by the manufacturer. At higher frequencies, the data are clearly not reliable due to the presence of many higher-order modes within the specimen, which occur at much lower frequencies than usual owing to the very high permittivity of this material.

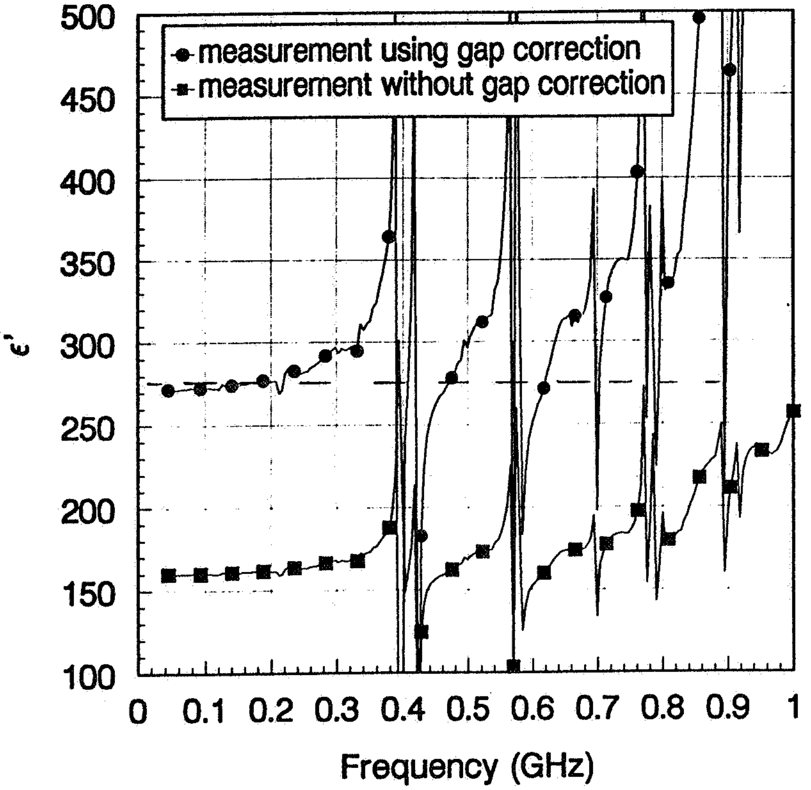


Figure 11. Measured real permittivity data for calcium-strontium-titanate, following TRL Calibration.

We also measured the dielectric loss ϵ'' for the CLP, alumina and CST samples, but these data are not included here because they are not meaningful. As discussed earlier, the sensitivity limit for measuring loss factor in any transmission line system is approximately $\tan\delta = \epsilon''/\epsilon' = 0.01$ and all three materials exhibit loss factor values that are at least ten times less.

A final measurement in this series involved a ferrite-loaded polymer with medium dielectric and magnetic loss. Figures 12 and 13 show the measured dielectric and magnetic properties, respectively. The solid line represents data measured in this system, while the dotted lines represent reference data obtained in a 7 mm coaxial air line measurement of this material [6]. Uncertainty bounds of ±2.5 % for the ϵ' reference data and ±1.5 % for the μ' reference data are included in Figures 12 and 13. The uncertainty bounds for the ϵ'' and μ'' reference data are ±0.01. In Figure 12a, note that the measured data for ϵ' lie within the uncertainty limits of the reference data, whereas the agreement for ϵ'' (see Figure 12b) is clearly not good, particularly at frequencies above 900 MHz. In Figure 13, the agreement with reference data is seen to be excellent for both real and imaginary parts.

3.2.2 Verification of External OSLT Calibration Program

After completing the external OSLT calibration program, we needed to verify that it was providing satisfactory measurement data. We compared dielectric characterization data of air, CLP, and fused-silica glass as measured in a 7 mm diameter coaxial air line system that had been calibrated using either the VNA's internal full two-port calibration program or the external OSLT calibration program; the effective capacitance of the 7 mm shielded open standard was separately estimated by the external program. Data taken for the fused-silica glass are shown in Figure 14. These data were not corrected for air-gap errors and are therefore somewhat lower than the accepted reference value of $\epsilon' = 3.85 \pm 0.02$ at 5 GHz [14]. We see that there is very close agreement between the ϵ' data obtained following the two different methods of calibration up to about 1 GHz. At frequencies above this, the data obtained using the external calibration program appear increasingly unstable, and the agreement deteriorates to a maximum of about 2.4 % near 2 GHz. The good agreement seen at lower frequencies gave us confidence in the validity of the external calibration routine at frequencies below 45 MHz, but we were unable to actually verify this due to the instrumentation availability problems discussed in Section 2.3. We subsequently performed a 45 MHz to 1000 MHz measurement on CLP in our 76.8 mm coaxial air line system, following external OSLT calibration. We compared these data with similar data obtained earlier in this system, following internal TRL calibration (see Figure 15). As was seen in Figure 9, the data obtained following internal TRL calibration are flat with frequency and compare well with a reference value of $\epsilon' = 2.54$. In contrast, the data obtained following external OSLT calibration are seen to be unstable and vary by approximately ±3 %, relative to the TRL data.

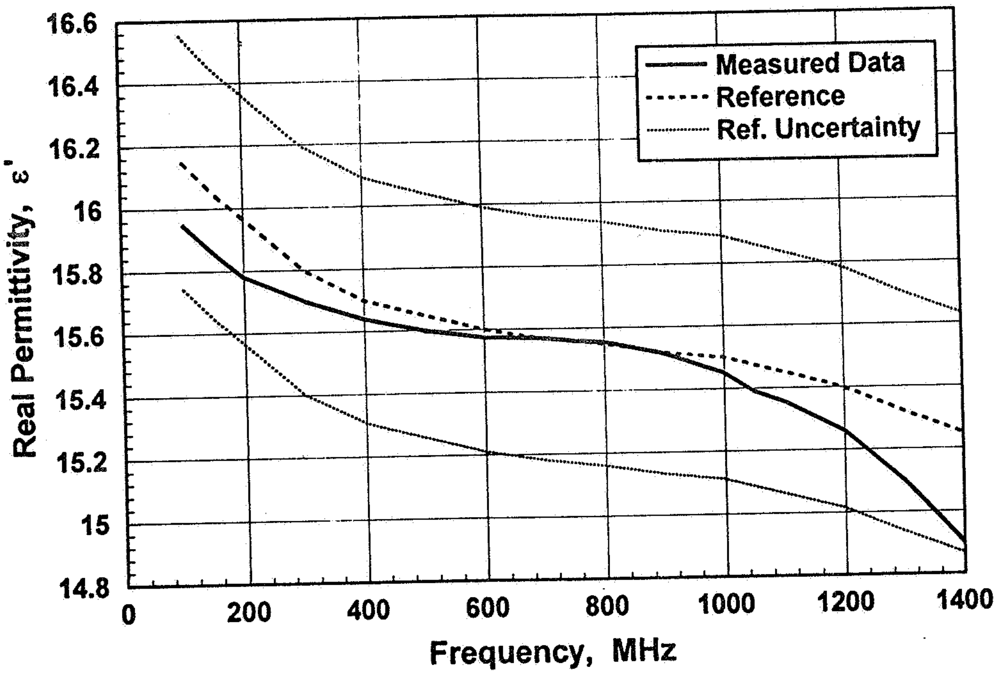


Figure 12a. Comparison of measured real permittivity data with reference data for the ferrite loaded polymer.

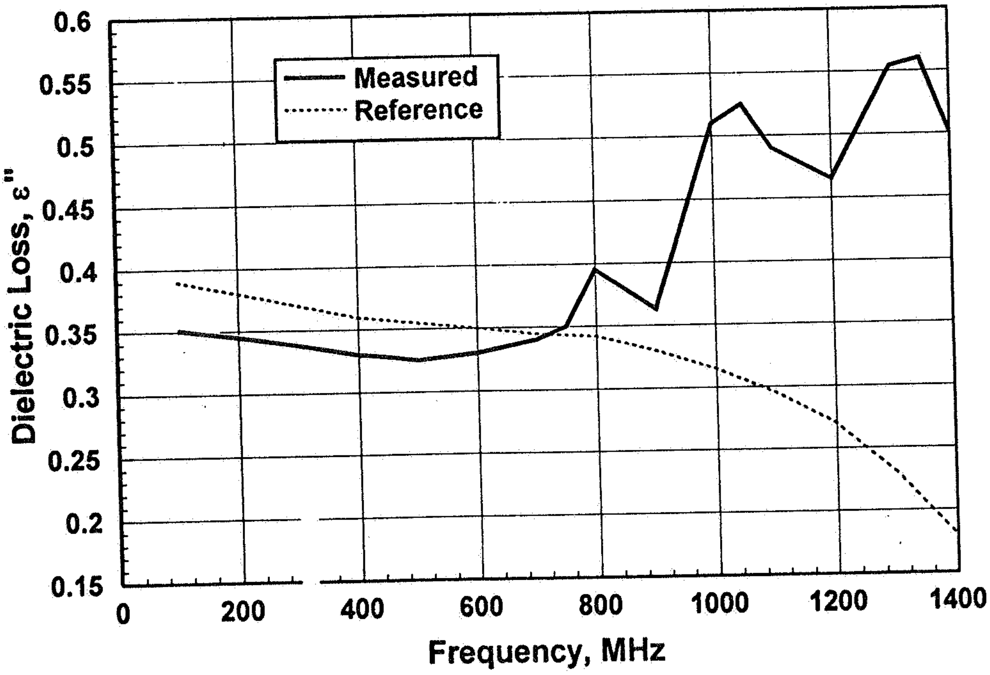


Figure 12b. Comparison of measured dielectric loss data with reference data for the ferrite loaded polymer.

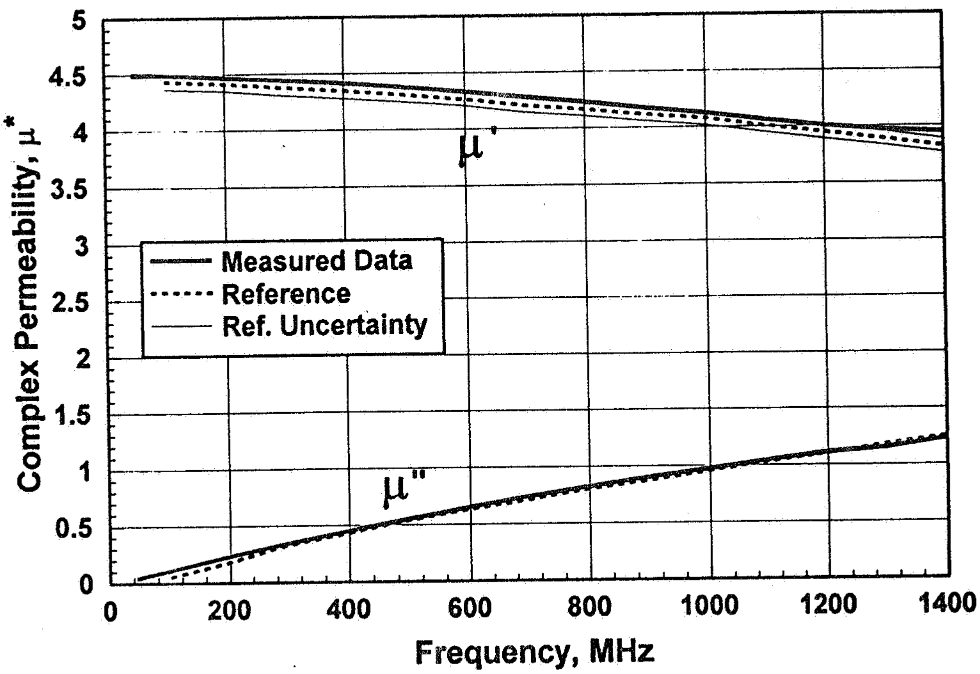


Figure 13. Comparison of measured complex permeability data with reference data for the ferrite-loaded polymer.

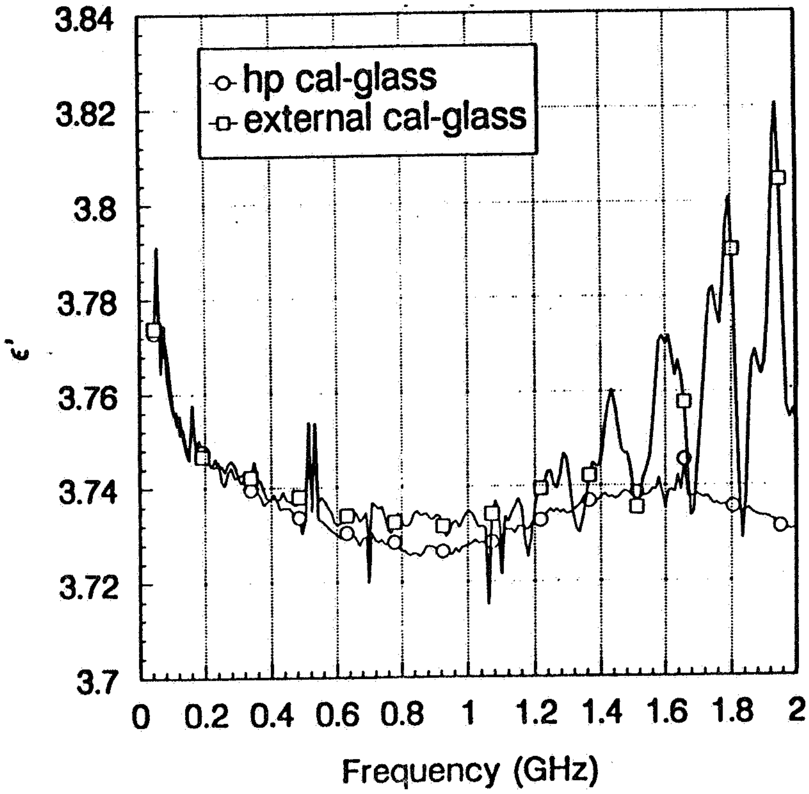


Figure 14. Comparison of ε'data for fused silica glass measured in a 7 mm coaxial air line following internal and external OSLT calibration.

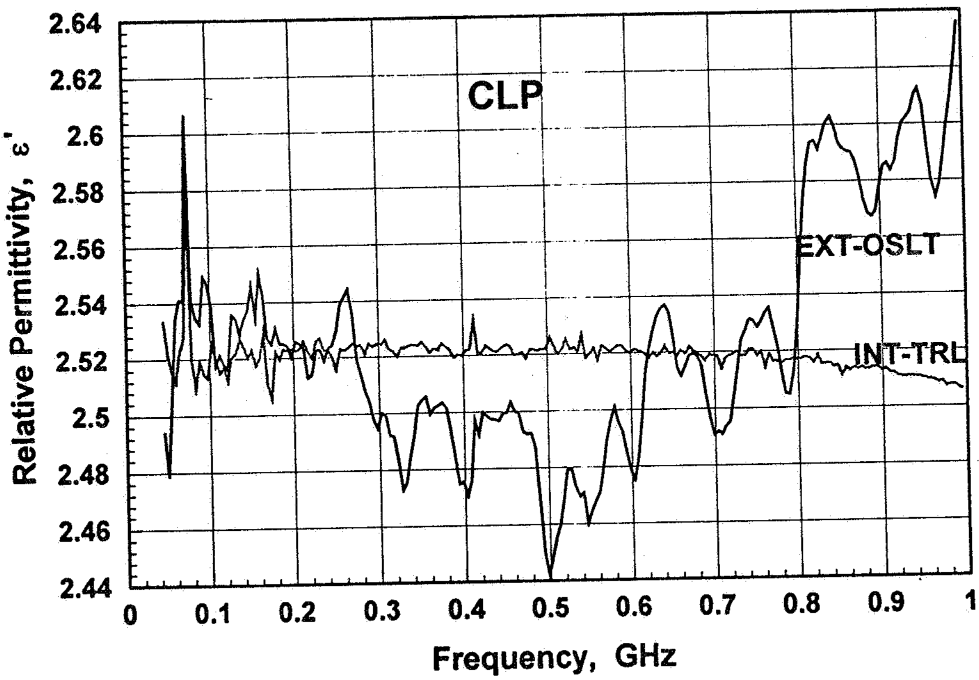


Figure 15. Comparison of ϵ'data for CLP measured in the 76.8 mm coaxial air line following internal TRL and external OSLT calibration.

3.2.3 Low-Frequency Measurements of Carbon-Loaded Concrete.

Permittivity data, including loss factor, for the four carbon-loaded samples CLC1, CLC2, CLC3, and CLC4 are given in Figure 16 over the frequency range 0.3 MHz to 50 MHz. Wide variations in dielectric properties are evident between the four samples. The differences between specimens were not disclosed to us but are likely due to differences in carbon content as well as differences in curing time for each specimen. Measured data were not included in Figure 16 for samples CLC2 and CLC3 below 5 MHz, nor for CLC4 below 20 MHz, because these data became increasingly unreliable at low frequencies. Similarly, the measured ϵ'data for specimen CLC4 appeared to be inconsistent with the other data and have not been included in Figure 16a. Most of the measured data at higher frequencies above 100 MHz were very unstable and have generally not been included. However, the higher-frequency data for Specimen CLC1 are shown in Figure 16d which shows ϵ'data as a function of frequency over parts of four decades, 0.3-500 MHz. The unstable nature of the measurement at frequencies above 100 MHz is clearly evident in Figure 16d.

Figure 16e compares the loss factor data for Specimen CLC3 at the time of initial measurement and after a further week of curing time. The decrease seen in loss factor with increased curing time agrees closely with the results of Al-Qadi et al. [8].

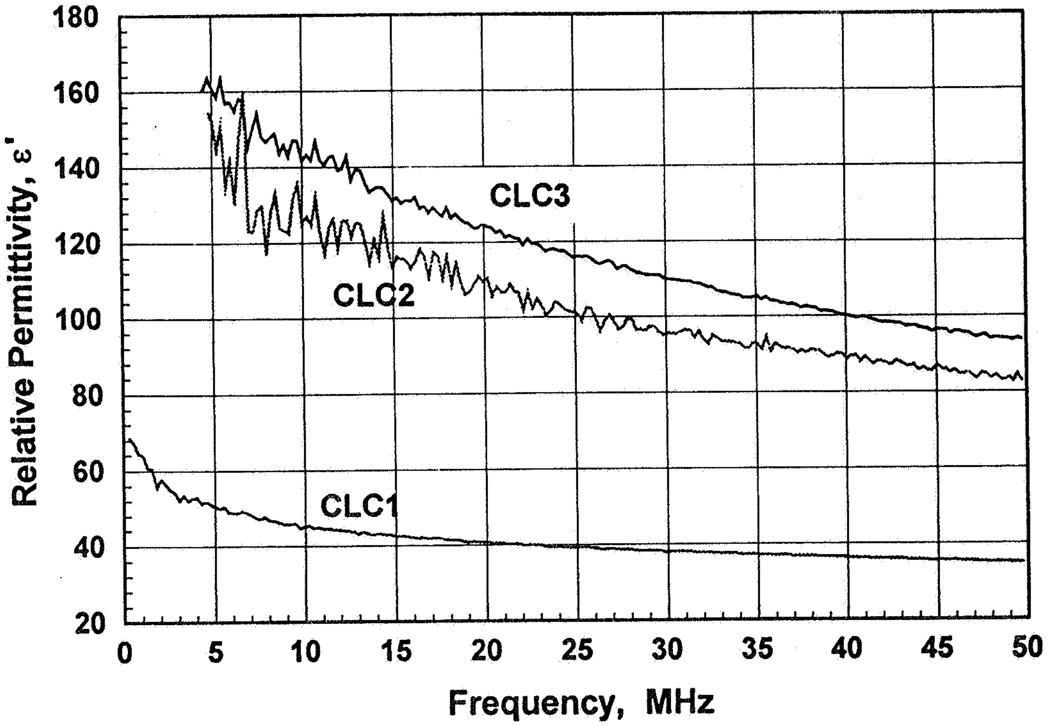


Figure 16a: Relative Permittivity Data for the Carbon-Loaded Concrete.

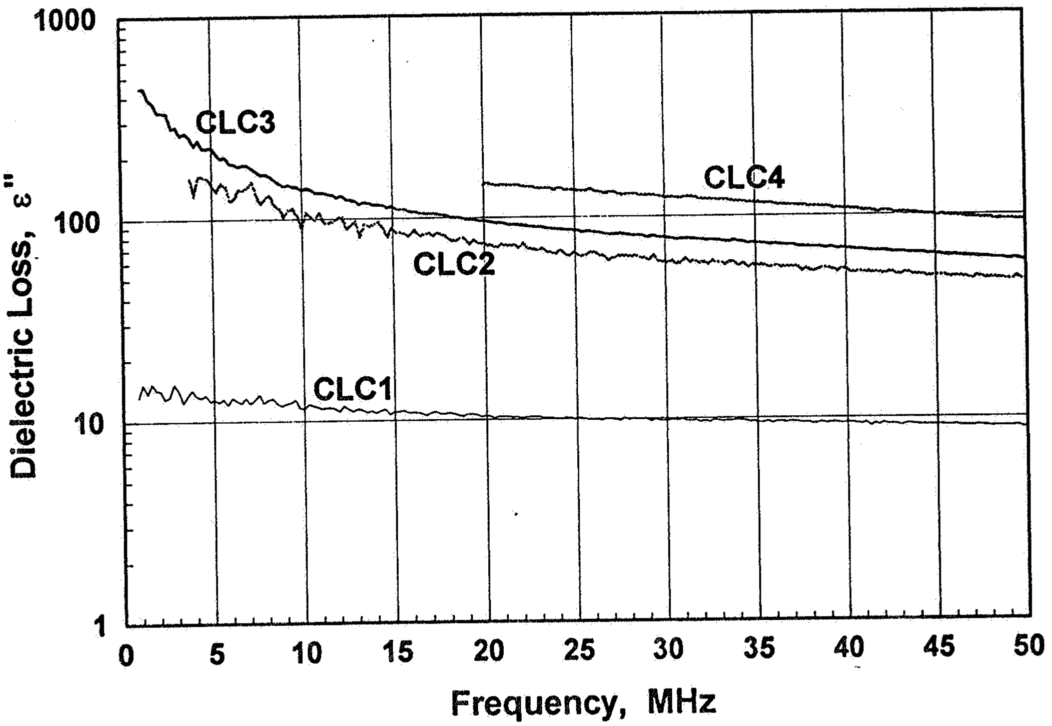


Figure 16b: Dielectric Loss Data for the Carbon-Loaded Concrete.

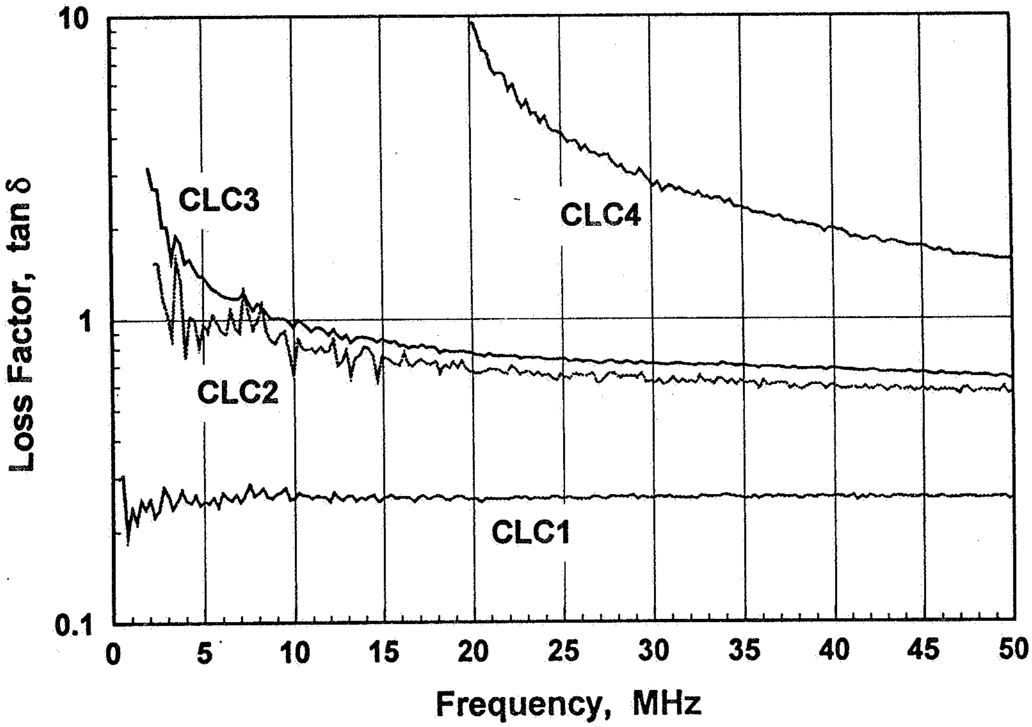


Figure 16c: Loss Factor Data for the Carbon-Loaded Concrete

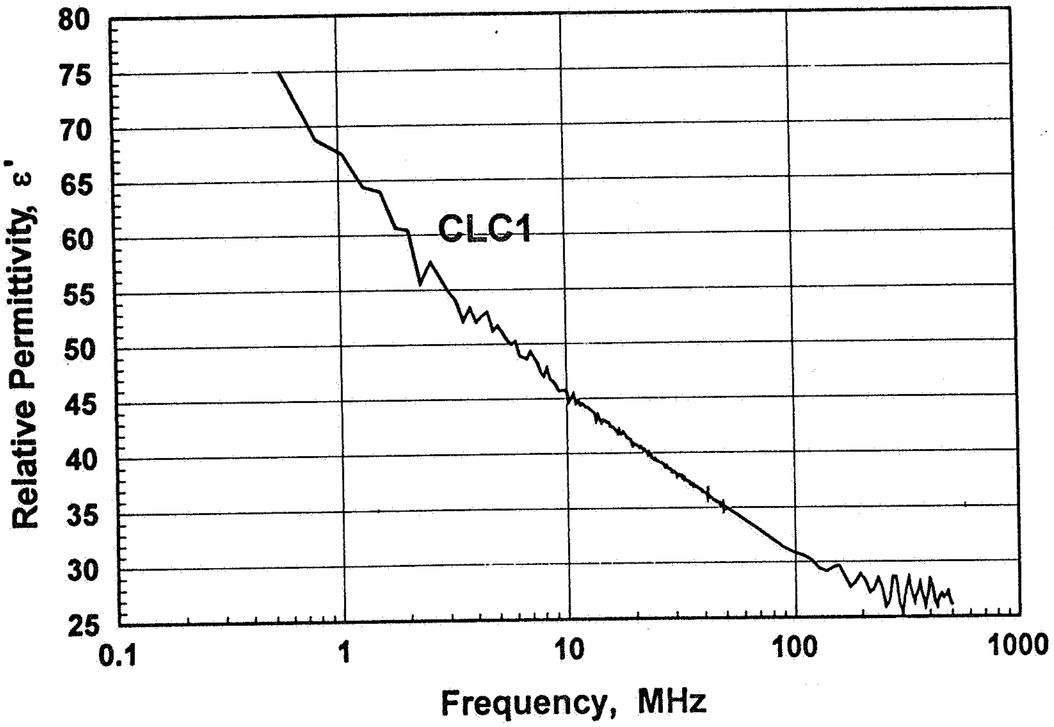


Figure 16d: Relative Permittivity Data for Specimen CLC1 over an Extended Frequency Range

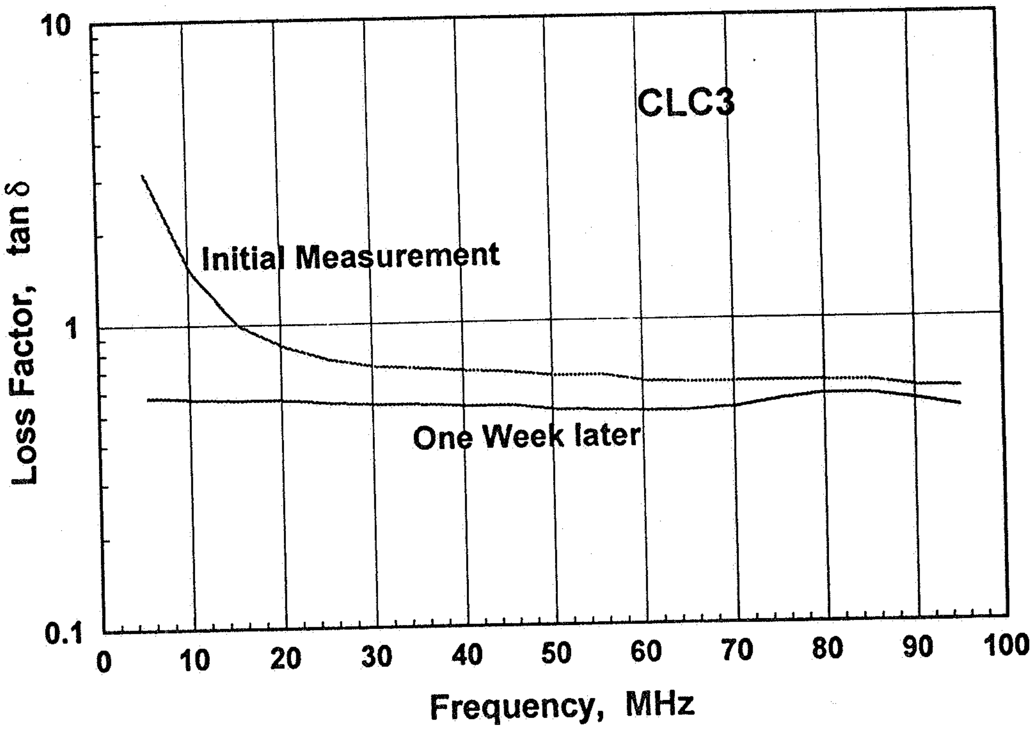


Figure 16e. Change of loss factor with curing time for specimen CLC3.

No comparison data for this material were available to us so that we cannot draw any conclusions regarding the validity or accuracy of these data. However, they are consistent with measurements performed at NIST on other carbon-loaded materials such as the carbon-loaded urethane foam used in anechoic chambers.

4. DISCUSSION AND CONCLUSIONS

We conclude that the measurements performed above 50 MHz following TRL calibration were generally satisfactory, provided that the extender sections were used. In particular, measured ϵ'data for high- and very high-permittivity ceramics appeared to be more stable and accurate than corresponding data obtained in a 7 mm or 14 mm coaxial air line measurement. Air-gap errors still needed to be corrected for, but the relative correction was much smaller, compared to that for the smaller diameter air lines. The complex permeability data measured on the ferrite-loaded polymer agreed very closely indeed with reference data, further demonstrating that the coaxial air line method is one of the most accurate available for measuring the magnetic properties of demagnetized ferrites at RF frequencies below gyromagnetic resonance.

Although the performance of the external OSLT program was never verified at frequencies below 50 MHz, the measurements performed on the carbon-loaded concrete appear to demonstrate that it generated satisfactory data for frequencies in the range 5 MHz to100 MHz, depending on how lossy the material is. Below about 5 MHz, the measured data often became unstable. This problem is consistent with all T/R measurements performed in transmission lines and is caused by difficulty in resolving small phase differences at these low frequencies. When this program was used at frequencies above about 100 MHz, the results were also unstable. We believe that this problem was caused by inaccurate estimates of the open standard capacitance C_{eff} at these frequencies, due to including insufficient higher-order TM_{0n} modes in the full-field analysis. At 1000 MHz, the 76.8 mm open standard has a diameter $d = 0.26\lambda$. Contrast this with the 7 mm open standard, where $d = 0.023\lambda$. Because the diameter of the open standard represents a significant fraction of the wavelength at these frequencies, accurate computation of the fringing capacitance using a full-field solution requires that many modes be included in the field analysis. For our estimate, we included only four modes and it is apparent that this was insufficient. Because of this problem, the NIST measurement software that utilizes the coaxial shielded-open technique has since been modified to incorporate additional modes up to a total of eight, yielding more stable and reliable data [13].

The authors gratefully acknowledge the contributions of James Baker-Jarvis and Michael Janezic, who provided software and technical guidance for estimating the fringing capacitance of the open standard used during OSLT calibrations. We also acknowledge the assistance of Douglas Gallagher and James Boyd of the NIST Instrument Shop for fixture design and fabrication, of Bud O'Connor of Colorado Precision Optics, Longmont, CO for specimen preparation and of Glen Sherwood for dimensional metrology of the specimens. We also acknowledge the help of Eric Medaugh, of the Lockheed Martin Corporation, for providing the copper tubing used in hardware fabrication.

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APPENDIX A.

Machine Drawings of Coaxial Air Line System Hardware

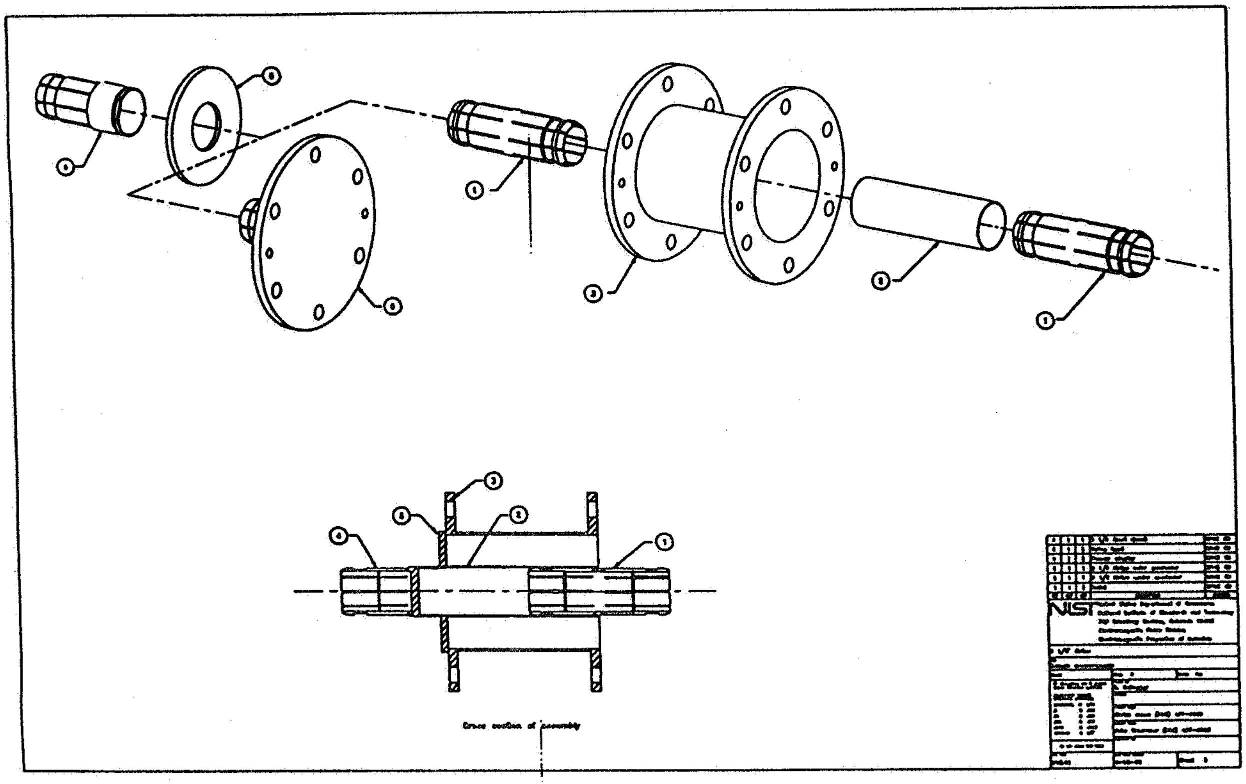
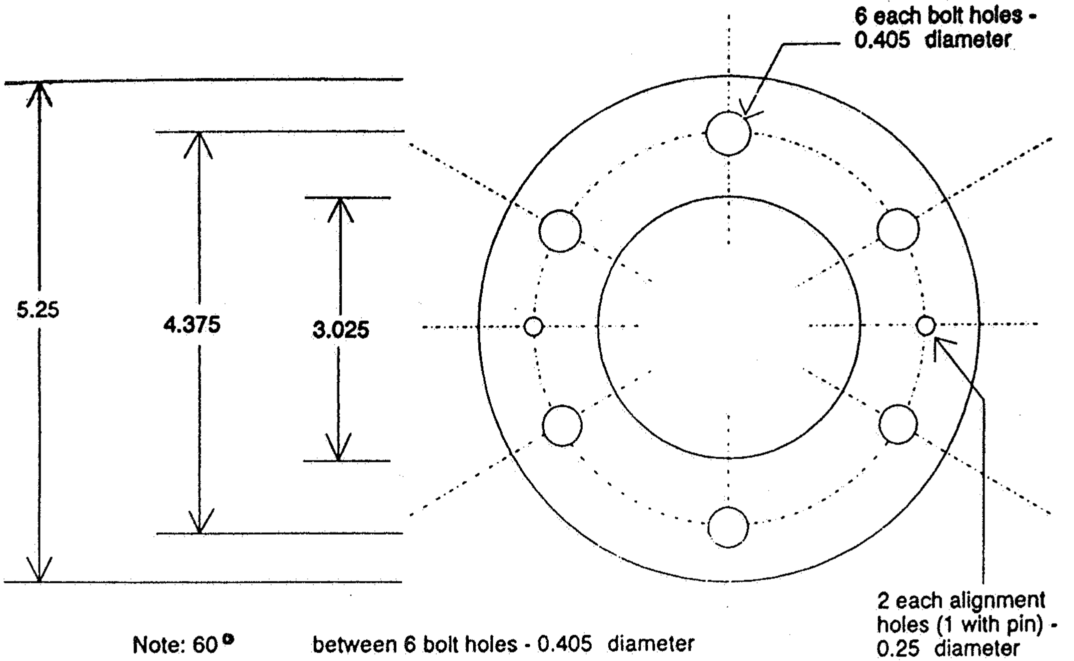


Figure A1. 102 mm long specimen-holder assembly.



Note: 60° between 6 bolt holes - 0.405 diameter
180° between alignment holes - 0.25 diameter

Figure A2. Flange for 76.8 mm (3.025 in) diameter coaxial air-line components (all dimensions in inches).

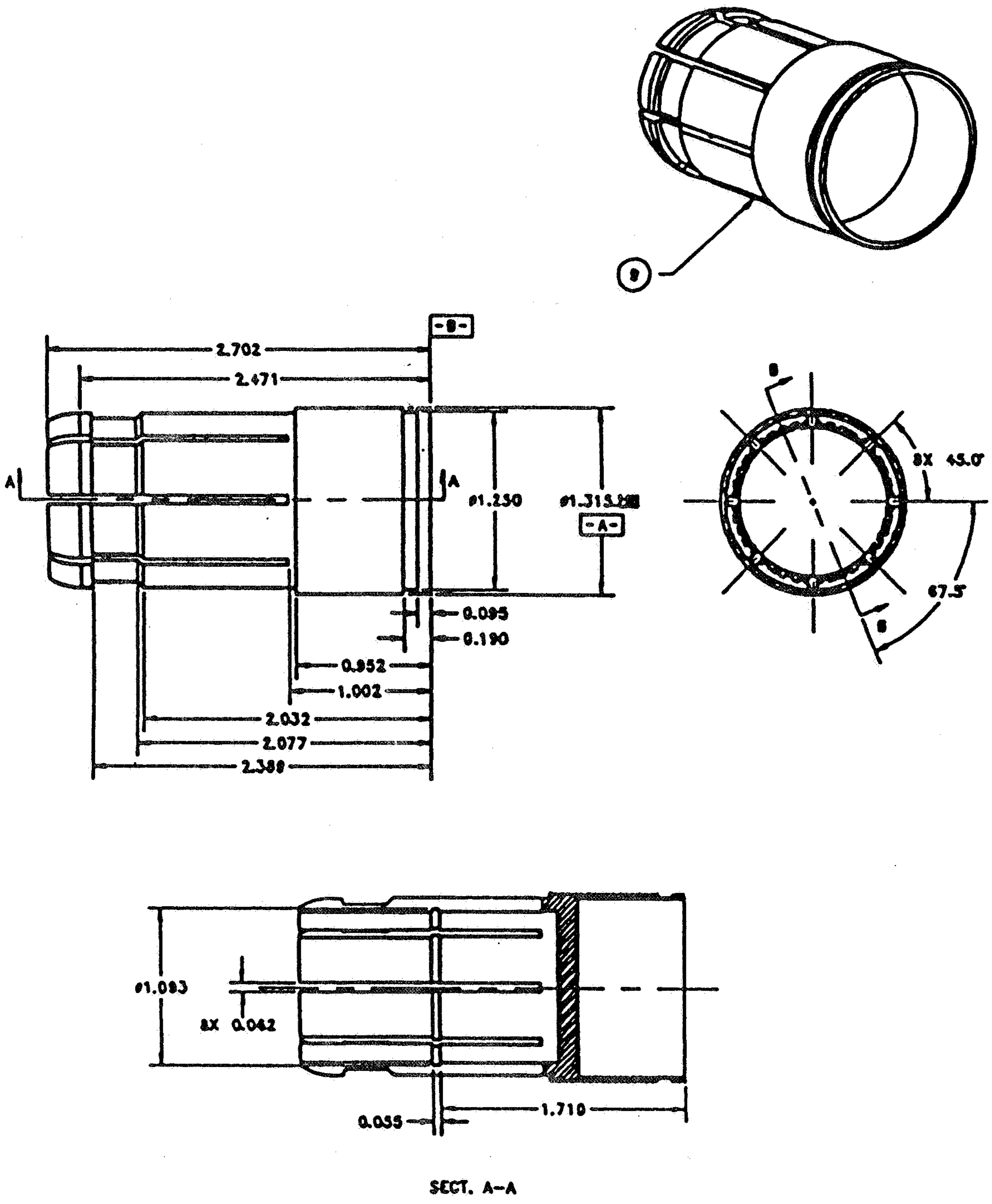
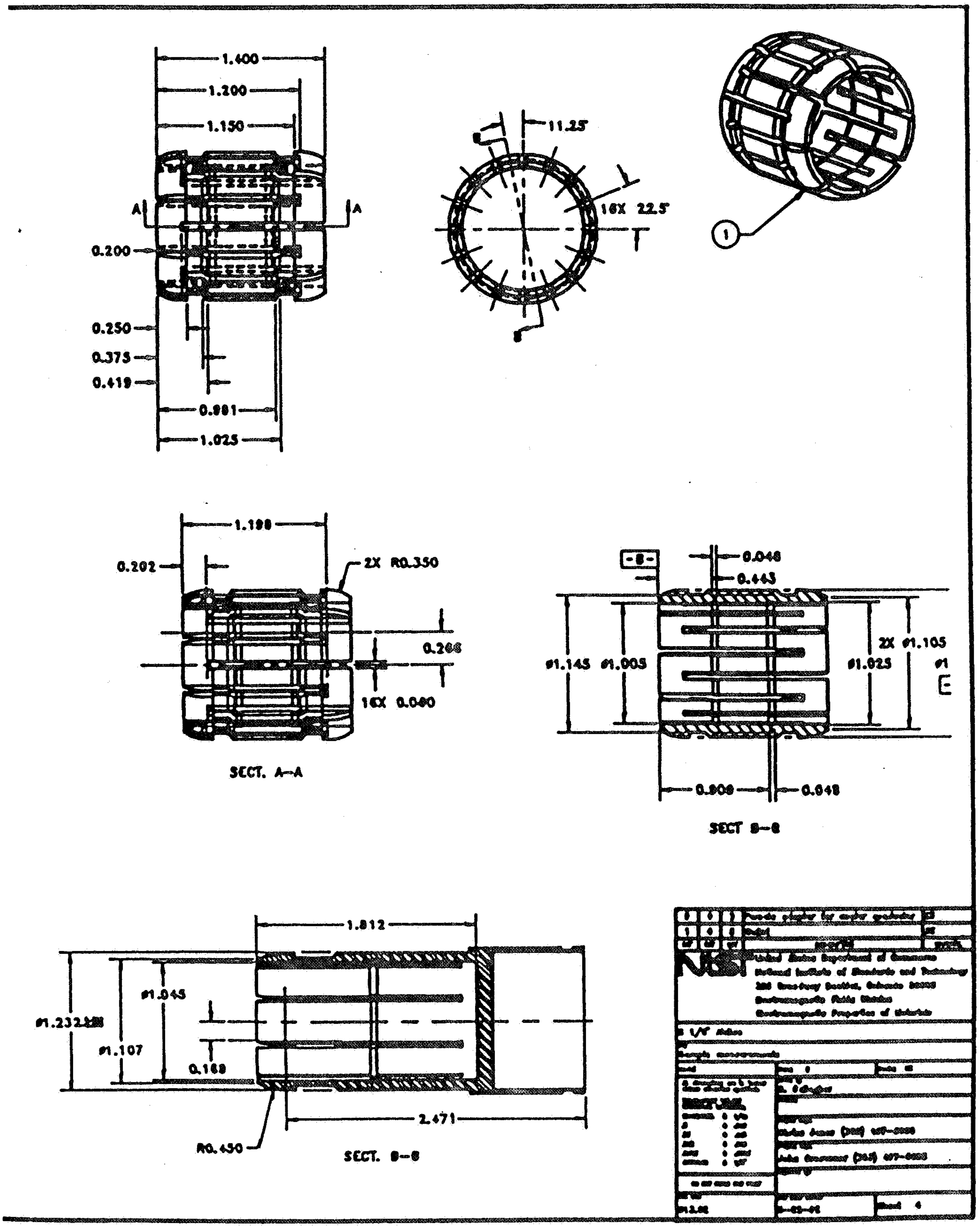


Figure A3. Details of connection bullet (all dimensions in inches).



1.400
1.200
1.150
A
A
0.200
0.250
0.375
0.419
0.981
1.025
11.25°
16X 22.5°
1
1.198
0.202
2X R0.350
0.266
16X 0.060
SECT. A—A
0.048
0.443
ø1.145
ø1.005
2X ø1.105
ø1.025
0.808
0.048
SECT B—B
1.812
ø1.045
ø1.232
ø1.107
0.169
2.471
R0.450
SECT. B—B

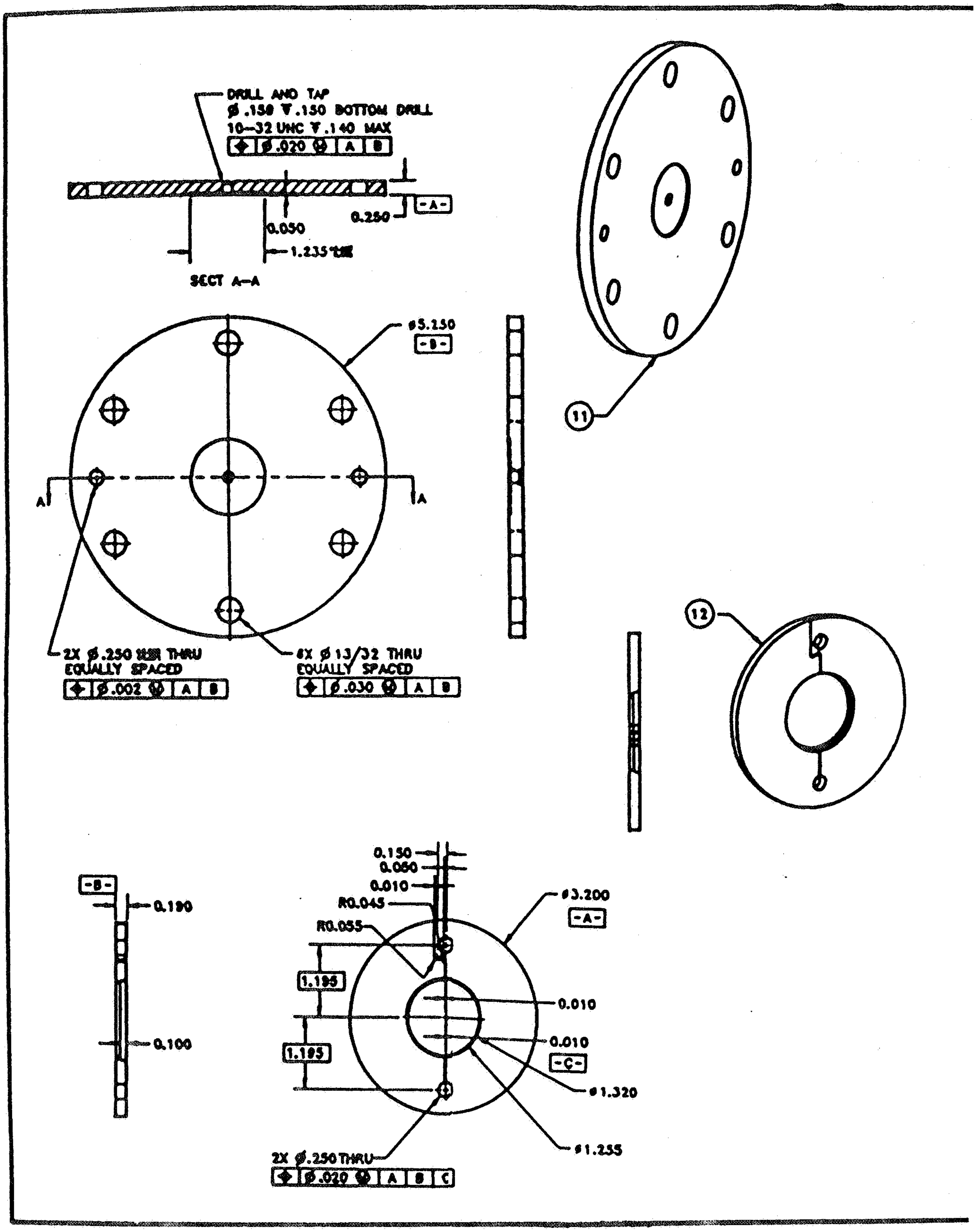
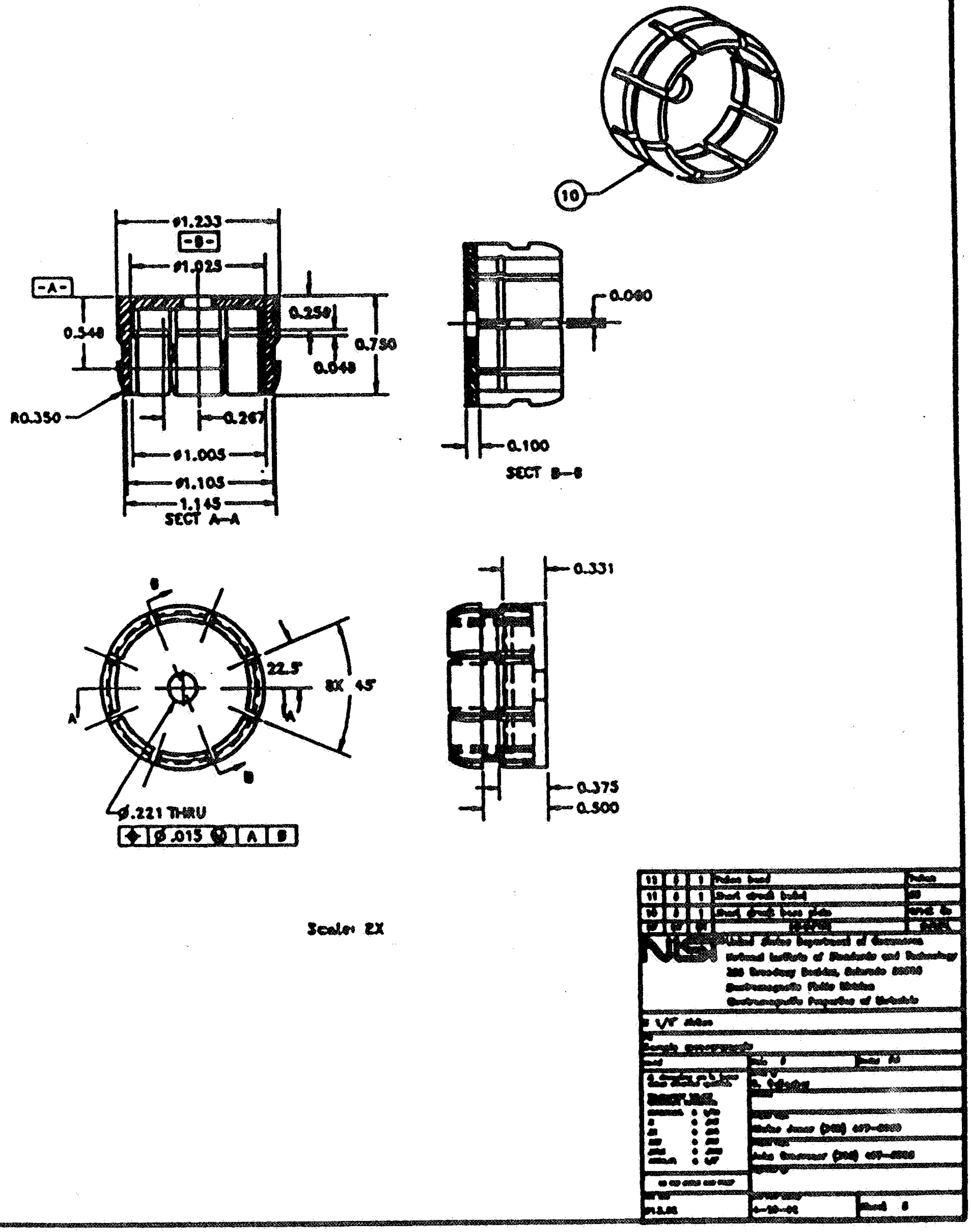
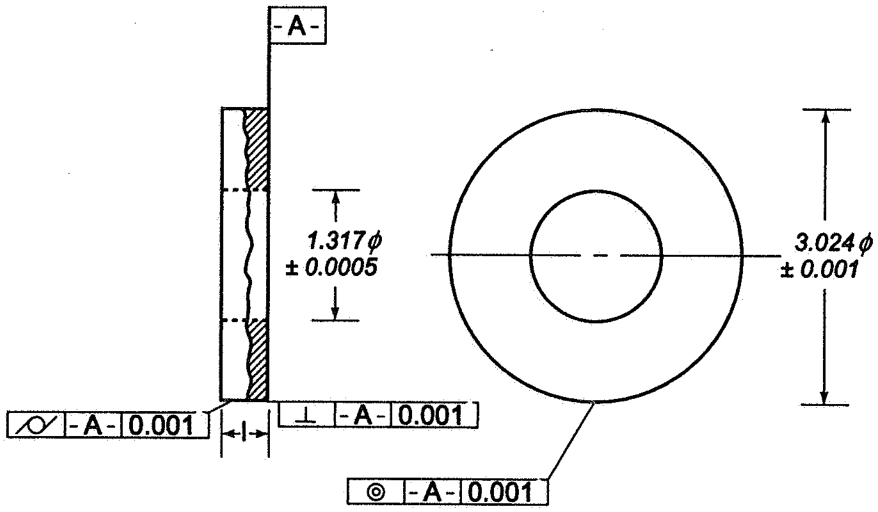


Figure A4. Details of short-circuit standard (all dimensions in inches).


10
ø1.233
-B-
ø1.025
-A-
0.548
0.250
0.750
0.048
R0.350
0.267
ø1.005
ø1.105
1.145
SECT A–A
0.060
0.100
SECT B–B
B
22.5°
8X 45°
A
A
B
ø.221 THRU
⌖ ø.015 Ⓜ A B
0.331
0.375
0.500
Scale: 2X
12 Teflon bead
11 Short circuit bead
10 Short circuit base plate
United States Department of Commerce
National Institute of Standards and Technology
325 Broadway Boulder, Colorado 80303
Electromagnetic Fields Division
Electromagnetic Properties of Materials



Sample Thickness: $0.25 \leq l \leq 0.75$

Figure A5. Specifications for material specimen (all dimensions in inches).

APPENDIX B.

Listing for External OSLT Calibration Program

Language: HT BASIC
Author: C.A. Jones
Date: August 1994

```
100 !   TWOPORT  Version 1.0  Last Revision 08/12/94  14:35
102 !   purge "a:\twoport"
104 !   re-save "a:\twoport3"
106 !   re-save "b:\twoport3"
108 !   re-save "c:\jones\twoport2"
110 !
112 Init_com:!
114     RAD
116     OPTION BASE 1
118     COM /Measurement/ COMPLEX J
120     COM /Measurement/ REAL Cap(801),Beta(801)
122     COM /Measurement/ COMPLEX S11m(801),S21m(801),S12m(801),S22m(801)
124     COM /Measurement/ COMPLEX S11c(801),S21c(801),S12c(801),S22c(801)
126     COM /Measurement/ INTEGER Datacount,REAL Freq(801)
128     COM /Calibration/ COMPLEX S11m_short(801),S11m_open(801),S11m_load(801)
130     COM /Calibration/ COMPLEX S22m_short(801),S22m_open(801),S22m_load(801)
132     COM /Calibration/ COMPLEX S11t_short(801),S11t_open(801),S11t_load(801)
134     COM /Calibration/ COMPLEX S22t_short(801),S22t_open(801),S22t_load(801)
136     COM /Calibration/ COMPLEX S12m_thru(801),S12m_rev(801),S12m_isol(801)
138     COM /Calibration/ COMPLEX S21m_thru(801),S21m_rev(801),S21m_isol(801)
140     COM /Calibration/ COMPLEX S12t_thru(801),S12t_rev(801),S12t_isol(801)
142     COM /Calibration/ COMPLEX S21t_thru(801),S21t_rev(801),S21t_isol(801)
144     COM /Calibration/ REAL Short_re(801),Short_im(801),Open_re(801),Open_im(8
146     COM /Calibration/ REAL Load_re(801),Load_im(801),Thru_re(801),Thru_im(801
148     COM /Calibration/ REAL Rev_re(801),Rev_im(801),Isol_re(801),Isol_im(801)
150     COM /Error_terms/ COMPLEX Edf(801),Erf(801),Esf(801),Exf(801),Etf(801),El
152     COM /Error_terms/ COMPLEX Edr(801),Err(801),Esr(801),Exr(801),Etr(801),El
154     COM /Error_terms/ COMPLEX T1,T2,T3,M1,M2,M3,Denom(801)
156     COM /Substitutions/ COMPLEX C1(801),C2(801),C3(801),C4(801)
158     COM /Addresses/ INTEGER Plotter_addr,Printer_addr,Nwa_addr
160     COM /File/Filename$[30],Diskdrive$[30],Path$[200],Description$[40],INTEGE
162 !
164 Init_var:!
166     INTEGER Preamble,Size
168     DIM T1$[5500],T2$[5500],T3$[5500],T4$[5500]
170     DIM Freq_data(340),Real_open(340),Imag_open(340),Xa(20),Ya1(20),Ya2(20)
172 !
174 Init_const:!
176     J=CMPLX(0,1)
178 !
180 Init_keys:!
182     CONTROL KBD,15;1
184     CONTROL CRT,12;0
186     SET KEY 0," "
188     SET KEY 1," "
190     SET KEY 2," "
192     SET KEY 3," "
194     SET KEY 4," "
196     SET KEY 5," "
198     SET KEY 6," "
200     SET KEY 7," "
202     SET KEY 8," "
204     SET KEY 9," "
206     SET KEY 10," "
208 !
210 Main_menu:!
212     OFF KEY
214     CLEAR SCREEN
216     Prty=VAL(SYSTEM$("SYSTEM PRIORITY"))+1
218     ON KEY 0 LABEL "End program",Prty GOSUB End_program
```

```
220    ON KEY 2 LABEL "Read NWA",Prty GOSUB Read_nwa
222    ON KEY 3 LABEL "Calibrate NWA",Prty GOSUB Calibrate_nwa
224    ON KEY 4 LABEL "Calc errors",Prty GOSUB Calc_errors
225    ON KEY 5 LABEL "load stan",Prty GOSUB Load_stan
227    ON KEY 6 LABEL "Load errors",Prty GOSUB Load_cal
228    ON KEY 7 LABEL "Read S-parms",Prty GOSUB Read_sparms
230    ON KEY 8 LABEL "Correct S-parms",Prty GOSUB Correct_sparms
232    ON KEY 9 LABEL "Save data",Prty GOSUB Save_data
234    Done=0
236    Prior_menu=0
238    DISP "Please Select One of the Softkeys..."
240    LOOP
242        IF Done THEN GOTO Main_menu
244    EXIT IF Prior_menu
246    END LOOP
248 !
250 !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
252  ! Setup keys so the person can decide when they want to do
254  ! which calibration
256  !
258 Calibrate_nwa: !
260  !
262    REDIM S11m_short(Datacount),S11t_short(Datacount)
264    REDIM S11m_open(Datacount),S11t_open(Datacount)
266    REDIM S11m_load(Datacount),S11t_load(Datacount)
268    REDIM S22m_short(Datacount),S22t_short(Datacount)
270    REDIM S22m_open(Datacount),S22t_open(Datacount)
272    REDIM S22m_load(Datacount),S22t_load(Datacount)
274    REDIM S12m_thru(Datacount),S12t_thru(Datacount)
276    REDIM S12m_rev(Datacount),S12t_rev(Datacount)
278    REDIM S12m_isol(Datacount),S12t_isol(Datacount)
280    REDIM S21m_thru(Datacount),S21t_thru(Datacount)
282    REDIM S21m_rev(Datacount),S21t_rev(Datacount)
284    REDIM S21m_isol(Datacount),S21t_isol(Datacount)
286  !
288 Menu: !
290    OFF KEY
292    CLEAR SCREEN
294    Prty=VAL(SYSTEM$("SYSTEM PRIORITY"))+1
296    ON KEY 0 LABEL "Prior menu",Prty GOSUB Prior_menu
298    ON KEY 7 LABEL "Reflection",Prty GOSUB Reflection
300    IF Flag7=1 THEN
302        ON KEY 7 LABEL "Reflection*",Prty GOSUB Reflection
304    END IF
306  !
308    ON KEY 8 LABEL "Transmission",Prty GOSUB Transmission
310    IF Flag11=1 THEN
312        ON KEY 8 LABEL "Transmission*",Prty GOSUB Transmission
314    END IF
316  !
318    ON KEY 9 LABEL "Isolation",Prty GOSUB Isolation
320    IF Flag13=1 THEN
322        ON KEY 9 LABEL "Isolation*",Prty GOSUB Isolation
324    END IF
326  !
328    Done=0
330    Prior_menu=0
332    DISP "Please select One of the Softkeys..."
334    LOOP
336        IF Done THEN GOTO Menu
```

```
338     EXIT IF Prior_menu
340     END LOOP
342     Done=1
344     Prior_menu=0
346     RETURN
348   !
350 Read_nwa: !
352     DISP "Reading data from NWA, Please wait...";
354     ASSIGN @Nwa TO 716
356     ASSIGN @Nwa_data TO 716;FORMAT OFF
358     ASSIGN @Nwa_sysb TO 717
360 Calc_freq: !
362    OUTPUT @Nwa;"STAR;OUTPACTI;"
364     ENTER @Nwa;Start_freq
366     OUTPUT @Nwa;"STOP;OUTPACTI;"
368     ENTER @Nwa;Stop_freq
370     OUTPUT @Nwa;"POIN;OUTPACTI;"
372     ENTER @Nwa;Num_points
374 !
376     Datacount=Num_points
377 !
378 !   for testing
379 !   Datacount=201
380 !   Start_freq=4.5E+7
381 !   Stop_freq=1.E+9
383   !
384     FOR I=1 TO Datacount
385         Freq(I)=Start_freq+(((Stop_freq-Start_freq)/(Datacount-1))*(I-1))
386     NEXT I
387     WAIT 1.5
388     Done=1
390     RETURN
392   !
394 Reflection: !
396 Menu_1: !
398     OFF KEY
400     CLEAR SCREEN
402     Prty=VAL(SYSTEM$("SYSTEM PRIORITY"))+1
404     ON KEY 0 LABEL "Prior menu",Prty GOSUB Prior_menu
406   !
408     ON KEY 2 LABEL "Port 1 Short",Prty GOSUB Meas_prt1_short
410     IF Flag2=1 THEN
412         ON KEY 2 LABEL "Port 1 Short*",Prty GOSUB Meas_prt1_short
414     END IF
416   !
418     ON KEY 3 LABEL "Port 2 Short",Prty GOSUB Meas_prt2_short
420     IF Flag3=1 THEN
422         ON KEY 3 LABEL "Port 2 Short*",Prty GOSUB Meas_prt2_short
424     END IF
426   !
428     ON KEY 4 LABEL "Port 1 Open ",Prty GOSUB Meas_port1_open
430     IF Flag4=1 THEN
432         ON KEY 4 LABEL "Port 1 Open*",Prty GOSUB Meas_port1_open
434     END IF
436   !
438     ON KEY 5 LABEL "Port 2 Open ",Prty GOSUB Meas_port2_open
440     IF Flag5=1 THEN
442         ON KEY 5 LABEL "Port 2 Open*",Prty GOSUB Meas_port2_open
444     END IF
446   !
```

```
448    ON KEY 6 LABEL "Port 1 Load ",Prty GOSUB Meas_port1_load
450    IF Flag6=1 THEN
452        ON KEY 6 LABEL "Port 1 Load*",Prty GOSUB Meas_port1_load
454    END IF
456  !
458    ON KEY 7 LABEL "Port 2 Load ",Prty GOSUB Meas_port2_load
460    IF Flag7=1 THEN
462        ON KEY 7 LABEL "Port 2 Load*",Prty GOSUB Meas_port2_load
464    END IF
466    Done=0
468    Prior_menu=0
470    DISP "Please select One of the Softkeys..."
472    LOOP
474        IF Done THEN GOTO Menu_1
476    EXIT IF Prior_menu
478    END LOOP
480    Done=1
482    Prior_menu=0
484    RETURN
486  !
488 Transmission: !
490    DISP "Connect Ports 1 and 2 together and press Enter...";
492    INPUT Dummy$
494 Menu_2: !
496    OFF KEY
498    Prty=VAL(SYSTEM$("SYSTEM PRIORITY"))+1
500    ON KEY 0 LABEL "Prior menu",Prty GOSUB Prior_menu
502  !
504    ON KEY 2 LABEL "Port 1 for",Prty GOSUB Meas_s21_thru
506    IF Flag8=1 THEN
508        ON KEY 2 LABEL "Port 1 for*",Prty GOSUB Meas_s21_thru
510    END IF
512  !
514    ON KEY 3 LABEL "Port 2 for",Prty GOSUB Meas_s12_thru
516    IF Flag9=1 THEN
518        ON KEY 3 LABEL "Port 2 for*",Prty GOSUB Meas_s12_thru
520    END IF
522  !
524    ON KEY 4 LABEL "Port 1 rev",Prty GOSUB Meas_s21_rev
526    IF Flag10=1 THEN
528        ON KEY 4 LABEL "Port 1 rev*",Prty GOSUB Meas_s21_rev
530    END IF
532  !
534    ON KEY 7 LABEL "Port 2 rev",Prty GOSUB Meas_s12_rev
536    IF Flag11=1 THEN
538        ON KEY 7 LABEL "Port 2 rev*",Prty GOSUB Meas_s12_rev
540    END IF
542  !
544    Done=0
546    Prior_menu=0
548    DISP "Please Select One of the Softkeys..."
550    LOOP
552        IF Done THEN GOTO Menu_2
554    EXIT IF Prior_menu
556    END LOOP
558    Done=1
560    RETURN
562  !
564 Isolation: !
566  !
```

```
568    DISP "Attach 50 ohm loads to port 1 and 2 and press Enter...";
570    INPUT Dummy$
572  !
574 Menu_3: !
576    OFF KEY
578    Prty=VAL(SYSTEM$("SYSTEM PRIORITY"))+1
580    ON KEY 0 LABEL "Prior menu",Prty GOSUB Prior_menu
582    ON KEY 2 LABEL "Port 1 Isol",Prty GOSUB Meas_s21_isol
584    IF Flag12=1 THEN
586        ON KEY 2 LABEL "Port 1 Isol*",Prty GOSUB Meas_s21_isol
588    END IF
590  !
592    ON KEY 3 LABEL "Port 2 Isol",Prty GOSUB Meas_s12_isol
594    IF Flag13=1 THEN
596        ON KEY 3 LABEL "Port 2 Isol*",Prty GOSUB Meas_s12_isol
598    END IF
600  !
602    Done=0
604    Prior_menu=0
606    DISP "Please Select One of the Softkeys..."
608    LOOP
610        IF Done THEN GOTO Menu_3
612    EXIT IF Prior_menu
614    END LOOP
616    Done=1
618    RETURN
620 Prior_menu:  !
622    Prior_menu=1
624    RETURN
626  !
628 Meas_prt1_short: !
630    DISP "Please Connect the Short at Port 1 and Press Enter...";
632    INPUT Dummy$
634    DISP "Measuring the Short at Port 1..."
636    OUTPUT @Nwa;"S11;"
638    OUTPUT @Nwa;"TITL ""MEASURING STANDARD, PLEASE WAIT..."";"
640  !  OUTPUT @Nwa;"NUMG 64;"
642    OUTPUT @Nwa;"SING;"
644    OUTPUT @Nwa;"FORM3;OUTPDATA;"
646    ENTER @Nwa_data;Preamble;Size,S11m_short(*)
648    OUTPUT @Nwa;"TITL """";"
650    Flag2=1
652    Done=1
654    RETURN
656  !
658 Meas_port1_open: !
660    DISP "Please Connect the Open at Port 1 and Press Enter...";
662    INPUT Dummy$
664    DISP "Measuring the Open at Port 1..."
666    OUTPUT @Nwa;"S11;"
668    OUTPUT @Nwa;"TITL ""MEASURING STANDARD, PLEASE WAIT..."";"
670  !  OUTPUT @Nwa;"NUMG 64;"
672    OUTPUT @Nwa;"SING;"
674    OUTPUT @Nwa;"FORM3;OUTPDATA;"
676    ENTER @Nwa_data;Preamble;Size,S11m_open(*)
678    OUTPUT @Nwa;"TITL """";"
680    Flag4=1
682    Done=1
684    RETURN
686  !
```

```
688 Meas_port1_load: !
690    DISP "Please Connect the Load at Port 1 and Press Enter...";
692    INPUT Dummy$
694    DISP "Measuring the Load at Port 1..."
696    OUTPUT @Nwa;"S11;"
698    OUTPUT @Nwa;"TITL ""MEASURING STANDARD, PLEASE WAIT..."";"
700  !  OUTPUT @Nwa;"NUMG 64;"
702    OUTPUT @Nwa;"SING;"
704    OUTPUT @Nwa;"FORM3;OUTPDATA;"
706    ENTER @Nwa_data;Preamble;Size,S11m_load(*)
708    OUTPUT @Nwa;"TITL """";"
710    Flag6=1
712    Done=1
714    RETURN
716  !
718 Meas_prt2_short: !
720    DISP "Please Connect the Short at Port 2 and Press Enter...";
722    INPUT Dummy$
724    DISP "Measuring the Short at Port 2..."
726    OUTPUT @Nwa;"S22;"
728    OUTPUT @Nwa;"TITL ""MEASURING STANDARD, PLEASE WAIT..."";"
730  !  OUTPUT @Nwa;"NUMG 64;"
732    OUTPUT @Nwa;"SING;"
734    OUTPUT @Nwa;"FORM3;OUTPDATA;"
736    ENTER @Nwa_data;Preamble;Size,S22m_short(*)
738    OUTPUT @Nwa;"TITL """";"
740    Flag3=1
742    Done=1
744    RETURN
746  !
748 Meas_port2_open: !
750    DISP "Please Connect the Open at Port 2 and Press Enter...";
752    INPUT Dummy$
754    DISP "Measuring the Open at Port 2..."
756    OUTPUT @Nwa;"S22;"
758    OUTPUT @Nwa;"TITL ""MEASURING STANDARD, PLEASE WAIT..."";"
760  !  OUTPUT @Nwa;"NUMG 64;"
762    OUTPUT @Nwa;"SING;"
764    OUTPUT @Nwa;"FORM3;OUTPDATA;"
766    ENTER @Nwa_data;Preamble;Size,S22m_open(*)
768    OUTPUT @Nwa;"TITL """";"
770    Flag5=1
772    Done=1
774    RETURN
776  !
778 Meas_port2_load: !
780    DISP "Please Connect the Load at Port 2 and Press Enter...";
782    INPUT Dummy$
784    DISP "Measuring the Load at Port 2..."
786    OUTPUT @Nwa;"S22;"
788    OUTPUT @Nwa;"TITL ""MEASURING STANDARD, PLEASE WAIT..."";"
790  !  OUTPUT @Nwa;"NUMG 64;"
792    OUTPUT @Nwa;"SING;"
794    OUTPUT @Nwa;"FORM3;OUTPDATA;"
796    ENTER @Nwa_data;Preamble;Size,S22m_load(*)
798    OUTPUT @Nwa;"TITL """";"
800    Flag7=1
802    Done=1
804    RETURN
806  !
```

```
808  !
810 Meas_s21_thru: !
812     DISP "Measuring the s21 thru..."
814     OUTPUT @Nwa;"S21;"
816     OUTPUT @Nwa;"TITL ""MEASURING STANDARD, PLEASE WAIT..."";"
818  !   OUTPUT @Nwa;"NUMG 64;"
820     OUTPUT @Nwa;"SING;"
822     OUTPUT @Nwa;"FORM3;OUTPDATA;"
824     ENTER @Nwa_data;Preamble;Size,S21m_thru(*)
826     OUTPUT @Nwa;"TITL """";"
828     Flag8=1
830     Done=1
832     RETURN
834  !
836 Meas_s12_thru: !
838     DISP "Measuring the s12 thru..."
840     OUTPUT @Nwa;"S12;"
842     OUTPUT @Nwa;"TITL ""MEASURING STANDARD, PLEASE WAIT..."";"
844  !   OUTPUT @Nwa;"NUMG 64;"
846     OUTPUT @Nwa;"SING;"
848     OUTPUT @Nwa;"FORM3;OUTPDATA;"
850     ENTER @Nwa_data;Preamble;Size,S12m_thru(*)
852     OUTPUT @Nwa;"TITL """";"
854     Flag9=1
856     Done=1
858     RETURN
860  !
862 Meas_s21_rev: !
864     DISP "Measuring the s21 reverse transmission..."
866     OUTPUT @Nwa;"S11;"
868     OUTPUT @Nwa;"TITL ""MEASURING STANDARD, PLEASE WAIT..."";"
870  !   OUTPUT @Nwa;"NUMG 64;"
872     OUTPUT @Nwa;"SING;"
874     OUTPUT @Nwa;"FORM3;OUTPDATA;"
876     ENTER @Nwa_data;Preamble;Size,S21m_rev(*)
878     OUTPUT @Nwa;"TITL """";"
880     Flag10=1
882     Done=1
884     RETURN
886  !
888 Meas_s12_rev: !
890     DISP "Measuring the s12 reverse transmission..."
892     OUTPUT @Nwa;"S22;"
894     OUTPUT @Nwa;"TITL ""MEASURING STANDARD, PLEASE WAIT..."";"
896  !   OUTPUT @Nwa;"NUMG 64;"
898     OUTPUT @Nwa;"SING;"
900     OUTPUT @Nwa;"FORM3;OUTPDATA;"
902     ENTER @Nwa_data;Preamble;Size,S12m_rev(*)
904     OUTPUT @Nwa;"TITL """";"
906  !
908     Flag11=1
910     Done=1
912     RETURN
914  !
916  !
918  !
920 Meas_s21_isol: !
922     DISP "Measuring the s21 isolation..."
924     OUTPUT @Nwa;"S21;"
926     OUTPUT @Nwa;"TITL ""MEASURING STANDARD, PLEASE WAIT..."";"
```

```
928  !  OUTPUT @Nwa;"NUMG 64;"
930    OUTPUT @Nwa;"SING;"
932    OUTPUT @Nwa;"FORM3;OUTPDATA;"
934    ENTER @Nwa_data;Preamble;Size,S21m_isol(*)
936    OUTPUT @Nwa;"TITL """";"
938    Flag12=1
940    Done=1
942    RETURN
944  !
946 Meas_s12_isol: !
948    DISP "Measuring the s12 isolation..."
950    OUTPUT @Nwa;"S12;"
952    OUTPUT @Nwa;"TITL ""MEASURING STANDARD, PLEASE WAIT..."";"
954  !  OUTPUT @Nwa;"NUMG 64;"
956    OUTPUT @Nwa;"SING;"
958    OUTPUT @Nwa;"FORM3;OUTPDATA;"
960    ENTER @Nwa_data;Preamble;Size,S12m_isol(*)
962    OUTPUT @Nwa;"TITL """";"
964  !
966  !
968    Flag13=1
970    Done=1
972    RETURN
974  !
976  !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
978  !
980 Read_sparms: !  For device under test
982 Read_s11m: !
984    OFF KEY
986    CLEAR SCREEN
988    ASSIGN @Nwa TO 716
990    ASSIGN @Nwa_data TO 716;FORMAT OFF
992    ASSIGN @Nwa_sysb TO 717
994    REDIM S11m(Datacount),S11c(Datacount)
996    REDIM S21m(Datacount),S21c(Datacount)
998    REDIM S12m(Datacount),S12c(Datacount)
1000   REDIM S22m(Datacount),S22c(Datacount)
1002 !
1004   DISP "Please connect the device under test and press Enter...";
1006   INPUT Dummy$
1008 !
1010   DISP "Measuring s11..."
1012   OUTPUT @Nwa;"s11;"
1014   OUTPUT @Nwa;"TITL ""MEASURING S11..."";"
1016 ! OUTPUT @Nwa;"NUMG 64;"
1018   OUTPUT @Nwa;"SING;"
1020   OUTPUT @Nwa;"FORM3;OUTPDATA;"
1022   ENTER @Nwa_data;Preamble;Size,S11m(*)
1024   OUTPUT @Nwa;"TITL """";"
1026 !
1028 Read_s21:!
1030   DISP "Measuring s21..."
1032   OUTPUT @Nwa;"s21;"
1034   OUTPUT @Nwa;"TITL ""MEASURING S21..."";"
1036 ! OUTPUT @Nwa;"NUMG 64;"
1038   OUTPUT @Nwa;"SING;"
1040   OUTPUT @Nwa;"FORM3;OUTPDATA;"
1042   ENTER @Nwa_data;Preamble;Size,S21m(*)
1044   OUTPUT @Nwa;"TITL """";"
1046 !
```

```
1048 Read_s12:!
1050   DISP "Measuring s12..."
1052   OUTPUT @Nwa;"s12;"
1054   OUTPUT @Nwa;"TITL ""MEASURING S12..."";"
1056 ! OUTPUT @Nwa;"NUMG 64;"
1058   OUTPUT @Nwa;"SING;"
1060   OUTPUT @Nwa;"FORM3;OUTPDATA;"
1062   ENTER @Nwa_data;Preamble;Size,S12m(*)
1064   OUTPUT @Nwa;"TITL """";"
1066 !
1068 Read_s22:!
1070   DISP "Measuring s22..."
1072   OUTPUT @Nwa;"s22;"
1074   OUTPUT @Nwa;"TITL ""MEASURING S22..."";"
1076 ! OUTPUT @Nwa;"NUMG 64;"
1078   OUTPUT @Nwa;"SING;"
1080   OUTPUT @Nwa;"FORM3;OUTPDATA;"
1082   ENTER @Nwa_data;Preamble;Size,S22m(*)
1084   OUTPUT @Nwa;"TITL """";"
1086 !
1088   DISP "Device under test has been measured...";
1090 !
1092   Done=1
1094   RETURN
1096 !
1098 !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
1100 !
1102 Calc_errors:!
1104 !
1106   REDIM Edf(Datacount),Erf(Datacount),Esf(Datacount),Exf(Datacount),Etf(Dat
1108   REDIM Edr(Datacount),Err(Datacount),Esr(Datacount),Exr(Datacount),Etr(Dat
1110   REDIM C1(Datacount),C2(Datacount),C3(Datacount),C4(Datacount)
1112   REDIM Denom(Datacount)
1114   REDIM Short_re(Datacount),Short_im(Datacount),Open_re(Datacount),Open_im(
1116   REDIM Load_re(Datacount),Load_im(Datacount),Thru_re(Datacount),Thru_im(Da
1118   REDIM Rev_re(Datacount),Rev_im(Datacount),Isol_re(Datacount),Isol_im(Data
1120   REDIM Cap(Datacount),Beta(Datacount)
1122 !
1124 !//////////////////
1126 !
1128   DISP "Are you working with the open circuit model (O), or"
1130   WAIT 1
1132   INPUT "Stuchly's model? (S) (O=1,S=0)",Answer
1134   IF (Answer=1) THEN
1136       DISP "Correcting error coefficients, Please wait...";
1138       WAIT 1
1140       GOSUB Jims_open_model
1142   ELSE
1144       DISP "Correcting error coefficients, Please wait...";
1146       WAIT 1
1148       GOSUB Hp_open_model
1150   END IF
1152   Done=1
1154   RETURN
1156 !
1158 Jims_open_model:!
1160 Theory_open:!
1162   ASSIGN @File TO "a:\oc77mm2.dat";FORMAT ON
1163   ENTER @File;Counter
1164   PRINT "counter is ",Counter
```

```
1166   ENTER @File;Dummy
1167   PRINT "dummy number is ",Dummy
1168   ENTER @File;Description$
1170       DISP "Loading table for S11 data for open..."
1171       FOR I=1 TO Counter
1172          ENTER @File;Freq_data(I),Real_open(I),Imag_open(I)
1173          S11t_open(I)=CMPLX(Real_open(I),Imag_open(I))
1174          S22t_open(I)=CMPLX(Real_open(I),Imag_open(I))
1175       NEXT I
1299   GOTO Reflect_errors
1300 !
1301 Hp_open_model:!
1302 Theory_open1:!
1303 !
1304 !Coeff_7mm:  !
1306 ! Capnot=1.5092E-12
1307 ! Cap1=8.92E-27
1308 ! Cap2=5.8051E-33
1309 ! Cap3=8.310E-43
1310 !
1311 Coeff_3_1_8: !
1312   Capnot=1.3007E-12
1313   Cap1=2.4563E-24
1314   Cap2=8.0290E-32
1315   Cap3=1.9978E-41
1316 !
1318   Znot=50
1319   FOR I=1 TO Datacount
1320       Cap(I)=Capnot+Cap1*Freq(I)+Cap2*(Freq(I))^2+Cap3*(Freq(I))^3
1321       Beta(I)=2*(ATN(2*PI*Freq(I)*Cap(I)*Znot))
1322       S11t_open(I)=EXP(-J*Beta(I))
1323       S22t_open(I)=EXP(-J*Beta(I))
1324   NEXT I
1325   PRINT "cap(1) is ",Cap(1)
1326   PRINT "beta(1) is ",Beta(1)
1327   PRINT "s11t_open is ",S11t_open(1)
1328   WAIT 1.4
1329 !
1330 Reflect_errors:!
1331 Theory_short:!
1332   FOR I=1 TO Datacount
1333       DISP "Calculating theoretical S11 (short) for point # ";I
1334       S11t_short(I)=CMPLX(-1,0)
1335   NEXT I
1336   FOR I=1 TO Datacount
1337       DISP "Calculating theoretical S22 (short) for point # ";I
1338       S22t_short(I)=CMPLX(-1,0)
1339   NEXT I
1340 Theory_load:!
1341   FOR I=1 TO Datacount
1342       DISP "Calculating theoretical S11 (load) for point # ";I
1343       S11t_load(I)=CMPLX(0,0)
1344   NEXT I
1345   FOR I=1 TO Datacount
1346       DISP "Calculating theoretical S22 (load) for point # ";I
1347       S22t_load(I)=CMPLX(0,0)
1348   NEXT I
1349 !
1350 !
1351 Calc_error_net:!
```

```
1352   DISP "Calculating error terms for port 1..."
1353   FOR I=1 TO Datacount
1354       T1=S11t_short(I)
1355       T2=S11t_open(I)
1356       T3=S11t_load(I)
1357       M1=S11m_short(I)
1358       M2=S11m_open(I)
1360       M3=S11m_load(I)
1364 !
1365       Edf(I)=(T1*T2*M3*(M1-M2)+T1*T3*M2*(M3-M1)+T2*T3*M1*(M2-M3))/(T1*T2*(M
1366       Esf(I)=(T1*(M2-Edf(I))+T2*(Edf(I)-M1))/(T1*T2*(M2-M1))
1367       Erf(I)=((M1-Edf(I))*(1-T1*Esf(I))/T1)
1368   NEXT I
1369 !
1370   DISP "Calculating error terms for port 2..."
1371   FOR I=1 TO Datacount
1372       T1=S22t_short(I)
1373       T2=S22t_open(I)
1374       T3=S22t_load(I)
1375       M1=S22m_short(I)
1376       M2=S22m_open(I)
1377       M3=S22m_load(I)
1378 !
1379       Edr(I)=(T1*T2*M3*(M1-M2)+T1*T3*M2*(M3-M1)+T2*T3*M1*(M2-M3))/(T1*T2*(M
1380       Esr(I)=(T1*(M2-Edr(I))+T2*(Edr(I)-M1))/(T1*T2*(M2-M1))
1381       Err(I)=((M1-Edr(I))*(1-T1*Esr(I))/T1)
1382   NEXT I
1384 !
1386 !///////////////
1388 Isol_errors:!
1390 Calc_s21_isol:!
1392   FOR I=1 TO Datacount
1394       Exf(I)=S21m_isol(I)
1396   NEXT I
1398 !
1400 Calc_s12_isol:!
1402   FOR I=1 TO Datacount
1404       Exr(I)=S12m_isol(I)
1406   NEXT I
1408 !
1410 !///////////////
1412 Trans_errors:!
1414 !
1416   FOR I=1 TO Datacount
1418       M1=S21m_thru(I)
1420       M2=S12m_thru(I)
1422       M3=S21m_rev(I)
1424       M4=S12m_rev(I)
1426 !
1428       Elf(I)=(M3-Edf(I))/(M3*Esf(I)+Erf(I)-Edf(I)*Esf(I))
1430       Elr(I)=(M4-Edr(I))/(M4*Esr(I)+Err(I)-Edr(I)*Esr(I))
1432       Etf(I)=(M1-Exf(I))*(1-Esf(I)*Elf(I))
1434       Etr(I)=(M2-Exr(I))*(1-Esr(I)*Elr(I))
1436 !
1438   NEXT I
1440 !
1442   Done=1
1444   RETURN
1446 !
1448 !//////////////////////
```

```
1450 Correct_sparms:!
1452 Actual_sparms:!
1454 !
1456 Substitutions:!
1458   DISP "Calculating corrections for S-parms...";
1460   FOR I=1 TO Datacount
1462       C1(I)=S11m(I)-Edf(I)
1464       C2(I)=S22m(I)-Edr(I)
1466       C3(I)=S21m(I)-Exf(I)
1468       C4(I)=S12m(I)-Exr(I)
1470       Denom(I)=(1+((C1(I)*Esf(I))/Erf(I)))*(1+((C2(I)*Esr(I))/Err(I)))-((C3
1472 !
1474       S11c(I)=(C1(I)/Erf(I))*(1+((C2(I)*Esr(I))/Err(I)))-(Elf(I)*(C3(I)/Etf
1476       S22c(I)=(C2(I)/Err(I))*(1+((C1(I)*Esf(I))/Erf(I)))-(Elr(I)*(C3(I)/Etf
1478       S12c(I)=(C4(I)/Etr(I))*(1+((C1(I)/Erf(I))*(Esf(I)-Elr(I))))/Denom(I)
1480       S21c(I)=(C3(I)/Etf(I))*(1+((C2(I)/Err(I))*(Esr(I)-Elf(I))))/Denom(I)
1482 !
1484   NEXT I
1486   WAIT 2
1488   Done=1
1490   RETURN
1492 !
1494 Save_data:!
1496 !
1498   OFF KEY
1500   CLEAR SCREEN
1502   Prty=VAL(SYSTEM$("SYSTEM PRIORITY"))+1
1504   ON KEY 0 LABEL "Prior menu",Prty GOSUB Prior_menu
1506   ON KEY 6 LABEL "Save calibration",Prty GOSUB Save_cal
1508   ON KEY 7 LABEL "Save standards",Prty GOSUB Save_stan
1510   ON KEY 8 LABEL "Save meas",Prty GOSUB Save_meas
1512   ON KEY 9 LABEL "Save sparms",Prty GOSUB Save_sparms
1514   Done=0
1516   Prior_menu=0
1518   DISP "Please select One of the Softkeys..."
1520   LOOP
1522       IF Done THEN GOTO Save_data
1524   EXIT IF Prior_menu
1526   END LOOP
1528   Done=1
1530   Prior_menu=0
1532   RETURN
1534 !
1536 Save_sparms:!
1538 !
1540 Dut:!
1542   OFF KEY
1544   CLEAR SCREEN
1546   DISP "Please enter a description of the corrected data (<=40 chars.)...";
1548   LINPUT Test$
1550   Test$=TRIM$(Test$)
1552   Description$=Test$
1554   Bitflag=0
1556   ALLOCATE Array(Datacount,5,2)
1558   FOR I=1 TO Datacount
1560       Array(I,1,1)=Freq(I)
1562       Array(I,2,1)=REAL(S11c(I))
1564       Array(I,2,2)=IMAG(S11c(I))
1566       Array(I,3,1)=REAL(S22c(I))
1568       Array(I,3,2)=IMAG(S22c(I))
```

```
1570        Array(I,4,1)=REAL(S21c(I))
1572        Array(I,4,2)=IMAG(S21c(I))
1574        Array(I,5,1)=REAL(S12c(I))
1576        Array(I,5,2)=IMAG(S12c(I))
1578    NEXT I
1580    Diskdrive$="c:\jones\programs\"
1582    DISP "Please enter a filename for the corrected data (<=30 chars.)...";
1584    LINPUT Filename$
1586    Path$=Diskdrive$&Filename$
1588    CREATE Path$,0
1590    ASSIGN @File TO Path$;FORMAT ON
1592    DISP "Saving File...";Path$
1594    OUTPUT @File;Datacount
1596    OUTPUT @File;Bitflag
1598    OUTPUT @File;Description$
1600    OUTPUT @File;Array(*)
1602    ASSIGN @File TO *
1604    DISP "File saved... "
1606    WAIT 5
1608    DEALLOCATE Array(*)
1610    Done=1
1612    RETURN
1614 !
1616 Save_meas:!
1618 Before_corr:!
1620    OFF KEY
1622    CLEAR SCREEN
1624    DISP "Please enter a description of the measured data (<=40 chars.)...";
1626    LINPUT Test$
1628    Test$=TRIM$(Test$)
1630    Description$=Test$
1632    Bitflag=0
1634    ALLOCATE Array(Datacount,5,2)
1636    FOR I=1 TO Datacount
1638        Array(I,1,1)=Freq(I)
1640        Array(I,2,1)=REAL(S11m(I))
1642        Array(I,2,2)=IMAG(S11m(I))
1644        Array(I,3,1)=REAL(S22m(I))
1646        Array(I,3,2)=IMAG(S22m(I))
1648        Array(I,4,1)=REAL(S21m(I))
1650        Array(I,4,2)=IMAG(S21m(I))
1652        Array(I,5,1)=REAL(S12m(I))
1654        Array(I,5,2)=IMAG(S12m(I))
1656    NEXT I
1658    Diskdrive$="c:\jones\programs\"
1660    DISP "Please enter a filename for the measured data (<=30 chars.)...";
1662    LINPUT Filename$
1664    Path$=Diskdrive$&Filename$
1666    CREATE Path$,0
1668    ASSIGN @File TO Path$;FORMAT ON
1670    DISP "Saving File...";Path$
1672    OUTPUT @File;Datacount
1674    OUTPUT @File;Bitflag
1676    OUTPUT @File;Description$
1678    OUTPUT @File;Array(*)
1680    ASSIGN @File TO *
1682    DISP "File saved... "
1684    WAIT 5
1686    DEALLOCATE Array(*)
1688    Done=1
```

```
1690   RETURN
1692 !
1694 Save_cal:!
1695   OFF KEY
1696   CLEAR SCREEN
1697   ALLOCATE Array(Datacount,13,2)
1698   FOR I=1 TO Datacount
1699       Array(I,1,1)=Freq(I)
1700       Array(I,2,1)=REAL(Edf(I))
1701       Array(I,2,2)=IMAG(Edf(I))
1702       Array(I,3,1)=REAL(Erf(I))
1703       Array(I,3,2)=IMAG(Erf(I))
1704       Array(I,4,1)=REAL(Esf(I))
1705       Array(I,4,2)=IMAG(Esf(I))
1706       Array(I,5,1)=REAL(Exf(I))
1707       Array(I,5,2)=IMAG(Exf(I))
1708       Array(I,6,1)=REAL(Etf(I))
1709       Array(I,6,2)=IMAG(Etf(I))
1710       Array(I,7,1)=REAL(Elf(I))
1711       Array(I,7,2)=IMAG(Elf(I))
1712       Array(I,8,1)=REAL(Edr(I))
1713       Array(I,8,2)=IMAG(Edr(I))
1714       Array(I,9,1)=REAL(Err(I))
1715       Array(I,9,2)=IMAG(Err(I))
1716       Array(I,10,1)=REAL(Esr(I))
1717       Array(I,10,2)=IMAG(Esr(I))
1718       Array(I,11,1)=REAL(Exr(I))
1719       Array(I,11,2)=IMAG(Exr(I))
1720       Array(I,12,1)=REAL(Etr(I))
1721       Array(I,12,2)=IMAG(Etr(I))
1722       Array(I,13,1)=REAL(Elr(I))
1723       Array(I,13,2)=IMAG(Elr(I))
1724   NEXT I
1725   Diskdrive$="c:\jones\programs\"
1726   DISP "Please enter a filename for the calibration (<30 chars.)...";
1727   LINPUT Filename$
1728   Path$=Diskdrive$&Filename$
1729   CREATE Path$,0
1730   ASSIGN @File TO Path$;FORMAT ON
1731   DISP "Saving File...";Path$
1732   OUTPUT @File;Start_freq
1733   OUTPUT @File;Stop_freq
1734   OUTPUT @File;Datacount
1735   OUTPUT @File;Array(*)
1736   ASSIGN @File TO *
1737   DISP "file saved... "
1738   DEALLOCATE Array(*)
1784   Done=1
1786   RETURN
1788 !
1790 Load_cal:!
1791   OFF KEY
1792   CLEAR SCREEN
1793   Diskdrive$="c:\jones\programs\"
1794   DISP "Please enter a filename for the cal file (<=30 chars.)...";
1795   LINPUT Filename$
1796   Path$=Diskdrive$&Filename$
1797   ASSIGN @File TO Path$;FORMAT ON
1798   DISP "Loading File...";Path$
1799   ENTER @File;Start_freq
```

```
1800   ENTER @File;Stop_freq
1801   ENTER @File;Datacount
1802   ALLOCATE Array(Datacount,13,2)
1803   ENTER @File;Array(*)
1804   ASSIGN @File TO *
1805   FOR I=1 TO Datacount
1806       Freq(I)=Array(I,1,1)
1807       Edf(I)=CMPLX(Array(I,2,1),Array(I,2,2))
1808       Erf(I)=CMPLX(Array(I,3,1),Array(I,3,2))
1809       Esf(I)=CMPLX(Array(I,4,1),Array(I,4,2))
1810       Exf(I)=CMPLX(Array(I,5,1),Array(I,5,2))
1811       Etf(I)=CMPLX(Array(I,6,1),Array(I,6,2))
1812       Elf(I)=CMPLX(Array(I,7,1),Array(I,7,2))
1813       Edr(I)=CMPLX(Array(I,8,1),Array(I,8,2))
1814       Err(I)=CMPLX(Array(I,9,1),Array(I,9,2))
1815       Esr(I)=CMPLX(Array(I,10,1),Array(I,10,2))
1816       Exr(I)=CMPLX(Array(I,11,1),Array(I,11,2))
1817       Etr(I)=CMPLX(Array(I,12,1),Array(I,12,2))
1818       Elr(I)=CMPLX(Array(I,13,1),Array(I,13,2))
1819   NEXT I
1820   DISP "File loaded.. "
1821   DEALLOCATE Array(*)
1822   Done=1
1823   RETURN
1858 !
1859 Load_stan:!
1860 Load_stan_port1:!
1862   OFF KEY
1863   CLEAR SCREEN
1864   Diskdrive$="a:\"
1865   DISP "Please enter a filename for the standards on port1(<=30 chars.)..."
1866   LINPUT Filename$
1867   Path$=Diskdrive$&Filename$
1868   ASSIGN @File TO Path$;FORMAT ON
1869   DISP "Loading File...";Path$
1870   ENTER @File;Start_freq
1871   ENTER @File;Stop_freq
1872   ENTER @File;Datacount
1873   ALLOCATE Array(Datacount,7,2)
1874   ENTER @File;Array(*)
1875   ASSIGN @File TO *
1876   FOR I=1 TO Datacount
1877       Freq(I)=Array(I,1,1)
1878       S11m_short(I)=CMPLX(Array(I,2,1),Array(I,2,2))
1879       S11m_open(I)=CMPLX(Array(I,3,1),Array(I,3,2))
1880       S11m_load(I)=CMPLX(Array(I,4,1),Array(I,4,2))
1881       S21m_thru(I)=CMPLX(Array(I,5,1),Array(I,5,2))
1882       S21m_isol(I)=CMPLX(Array(I,6,1),Array(I,6,2))
1883       S21m_rev(I)=CMPLX(Array(I,7,1),Array(I,7,2))
1884   NEXT I
1885   DISP "File loaded.. "
1886   DEALLOCATE Array(*)
1893 !
1896 Load_stan_port2:!
1897   OFF KEY
1898   CLEAR SCREEN
1899   Diskdrive$="a:\"
1900   DISP "Please enter a filename for the standards on port2(<=30 chars.)..."
1901   LINPUT Filename$
1902   Path$=Diskdrive$&Filename$
```

```
1903   ASSIGN @File TO Path$;FORMAT ON
1904   DISP "Loading File...";Path$
1905   ENTER @File;Start_freq
1906   ENTER @File;Stop_freq
1907   ENTER @File;Datacount
1908   ALLOCATE Array(Datacount,7,2)
1909   ENTER @File;Array(*)
1910   ASSIGN @File TO *
1911   FOR I=1 TO Datacount
1912       Freq(I)=Array(I,1,1)
1913       S22m_short(I)=CMPLX(Array(I,2,1),Array(I,2,2))
1914       S22m_open(I)=CMPLX(Array(I,3,1),Array(I,3,2))
1915       S22m_load(I)=CMPLX(Array(I,4,1),Array(I,4,2))
1916       S12m_thru(I)=CMPLX(Array(I,5,1),Array(I,5,2))
1917       S12m_isol(I)=CMPLX(Array(I,6,1),Array(I,6,2))
1918       S12m_rev(I)=CMPLX(Array(I,7,1),Array(I,7,2))
1919   NEXT I
1920   DISP "File loaded.. "
1921   DEALLOCATE Array(*)
1922   Done=1
1923   RETURN
1924 !
1925 Save_stan:!
1926   FOR I=1 TO Datacount
1927       Short_re(I)=REAL(S11m_short(I))
1928       Short_im(I)=IMAG(S11m_short(I))
1929       Open_re(I)=REAL(S11m_open(I))
1930       Open_im(I)=IMAG(S11m_open(I))
1931       Load_re(I)=REAL(S11m_load(I))
1932       Load_im(I)=IMAG(S11m_load(I))
1933       Thru_re(I)=REAL(S21m_thru(I))
1934       Thru_im(I)=IMAG(S21m_thru(I))
1935       Isol_re(I)=REAL(S21m_isol(I))
1936       Isol_im(I)=IMAG(S21m_isol(I))
1937       Rev_re(I)=REAL(S21m_rev(I))
1938       Rev_im(I)=IMAG(S21m_rev(I))
1939   NEXT I
1940   OFF KEY
1941   CLEAR SCREEN
1942   ALLOCATE Array(Datacount,7,2)
1943   FOR I=1 TO Datacount
1944       Array(I,1,1)=Freq(I)
1945       Array(I,2,1)=Short_re(I)
1946       Array(I,2,2)=Short_im(I)
1947       Array(I,3,1)=Open_re(I)
1948       Array(I,3,2)=Open_im(I)
1949       Array(I,4,1)=Load_re(I)
1950       Array(I,4,2)=Load_im(I)
1951       Array(I,5,1)=Thru_re(I)
1952       Array(I,5,2)=Thru_im(I)
1953       Array(I,6,1)=Rev_re(I)
1954       Array(I,6,2)=Rev_im(I)
1955       Array(I,7,1)=Isol_re(I)
1956       Array(I,7,2)=Isol_im(I)
1957   NEXT I
1958   Diskdrive$="c:\jones\programs\"
1959   DISP "Please enter a filename for standards on port 1 (<30 chars.)...";
1960   LINPUT Filename$
1961   WAIT 1.2
1962   Path$=Diskdrive$&Filename$
```

```
1963   CREATE Path$,0
1964   ASSIGN @File TO Path$;FORMAT ON
1965   DISP "Saving File...";Path$
1966   OUTPUT @File;Start_freq
1967   OUTPUT @File;Stop_freq
1968   OUTPUT @File;Datacount
1969   OUTPUT @File;Array(*)
1970   ASSIGN @File TO *
1971   DISP "file saved... "
1972   DEALLOCATE Array(*)
1973 !
1974   FOR I=1 TO Datacount
1975       Short_re(I)=REAL(S22m_short(I))
1976       Short_im(I)=IMAG(S22m_short(I))
1977       Open_re(I)=REAL(S22m_open(I))
1978       Open_im(I)=IMAG(S22m_open(I))
1979       Load_re(I)=REAL(S22m_load(I))
1980       Load_im(I)=IMAG(S22m_load(I))
1981       Thru_re(I)=REAL(S12m_thru(I))
1982       Thru_im(I)=IMAG(S12m_thru(I))
1983       Isol_re(I)=REAL(S12m_isol(I))
1984       Isol_im(I)=IMAG(S12m_isol(I))
1985       Rev_re(I)=REAL(S12m_rev(I))
1986       Rev_im(I)=IMAG(S12m_rev(I))
1987   NEXT I
1988   OFF KEY
1990   CLEAR SCREEN
1992   ALLOCATE Array(Datacount,7,2)
1994   FOR I=1 TO Datacount
1996       Array(I,1,1)=Freq(I)
1998       Array(I,2,1)=Short_re(I)
2000       Array(I,2,2)=Short_im(I)
2002       Array(I,3,1)=Open_re(I)
2004       Array(I,3,2)=Open_im(I)
2006       Array(I,4,1)=Load_re(I)
2008       Array(I,4,2)=Load_im(I)
2010       Array(I,5,1)=Thru_re(I)
2012       Array(I,5,2)=Thru_im(I)
2014       Array(I,6,1)=Rev_re(I)
2016       Array(I,6,2)=Rev_im(I)
2018       Array(I,7,1)=Isol_re(I)
2020       Array(I,7,2)=Isol_im(I)
2022   NEXT I
2024   Diskdrive$="c:\jones\programs\"
2026   DISP "Please enter a filename for the standards on port 2(<=30 chars.)...
2028   LINPUT Filename$
2030   WAIT 1.2
2032   Path$=Diskdrive$&Filename$
2034   CREATE Path$,0
2036   ASSIGN @File TO Path$;FORMAT ON
2038   DISP "Saving File...";Path$
2040   OUTPUT @File;Start_freq
2042   OUTPUT @File;Stop_freq
2044   OUTPUT @File;Datacount
2046   OUTPUT @File;Array(*)
2048   ASSIGN @File TO *
2050   DISP "file saved... "
2052   DEALLOCATE Array(*)
2054   Done=1
2056   RETURN
```

```
2058 !
2060 !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
2062 !
2064 End_program:!
2066   CLEAR SCREEN
2068   DISP "Program has ended..."
2070   END
2072 !
2074 !///////////////////////////////////////////////////////////////
2076   SUB Interpolate(Xa(*),Ya(*),N,X,Y)
2078 Init_com: !
2080 Init_const: !
2082       Nmax=10
2084 Init_var: !
2086       DIM C(1000),D(1000)
2088       REDIM C(Nmax),D(Nmax)
2090 Interpolate: !
2092       Ns=1
2094       Dif=ABS(X-Xa(1))
2096       FOR I=1 TO N
2098           Dift=ABS(X-Xa(I))
2100           IF (Dift<Dif) THEN
2102               Ns=I
2104               Dif=Dift
2106           END IF
2108           C(I)=Ya(I)
2110           D(I)=Ya(I)
2112       NEXT I
2114       Y=Ya(Ns)
2116       Ns=Ns-1
2118       FOR M=1 TO N-1
2120           FOR I=1 TO N-M
2122               Ho=Xa(I)-X
2124               Hp=Xa(I+M)-X
2126               W=C(I+1)-D(I)
2128               Den=Ho-Hp
2130               IF (Den=0) THEN PAUSE
2132               Den=W/Den
2134               D(I)=Hp*Den
2136               C(I)=Ho*Den
2138           NEXT I
2140           IF (2*Ns<N-M) THEN
2142               Dy=C(Ns+1)
2144           ELSE
2146               Dy=D(Ns)
2148               Ns=Ns-1
2150           END IF
2152           Y=Y+Dy
2154       NEXT M
2156   SUBEND
```

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