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, \( \varepsilon_r' = \epsilon_r' - j\epsilon_r'' \) 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., $\varepsilon^\prime\prime$, $\mu^\prime\prime < 0.05$) 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 $\varepsilon^\prime$ and $\mu^\prime$ 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 $\varepsilon^\prime\prime$ and $\mu^\prime\prime$ 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 $\pm 2\%$ in $\mu^\prime$, and $\pm 0.01$ in $\mu^\prime\prime$ 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 $\varepsilon_r' = \pm 5\%$ for materials with $\varepsilon_r' < 10$ during T/R dielectric measurements performed in 7 mm coaxial air lines. These accuracies degrade rapidly for materials of $\varepsilon_r' > 10$.

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.](image-url)
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 \( \varepsilon_m' \) in terms of the actual or nominal \( \varepsilon' \) of the material under test, given the dimensions \( D_1, D_2, D_3, D_4 \). In Table 1, values of \( \varepsilon_m' \) have been derived for measurements of materials with nominal \( \varepsilon' \) values of 10, 100, and 1000 in different-sized 50 \( \Omega \) 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 \( \varepsilon_m' \) and \( \varepsilon' \) 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 \( \varepsilon' = 100 \) 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 \( \text{TE}_{11} \) 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 \( \varepsilon' \) 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 \( \varepsilon_m' \) for materials of three different nominal permittivities, as measured in 50 \( \Omega \) coaxial air lines of varying outer diameter; air gap = 0.025 mm.

<table>
<thead>
<tr>
<th>( D_4 ) (mm)</th>
<th>( \varepsilon' = 10 )</th>
<th>( \varepsilon' = 100 )</th>
<th>( \varepsilon' = 1000 )</th>
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<tr>
<td>7</td>
<td>8.85</td>
<td>41.2</td>
<td>67.1</td>
</tr>
<tr>
<td>14</td>
<td>9.39</td>
<td>58.4</td>
<td>122</td>
</tr>
<tr>
<td>25.4 (1 in)</td>
<td>9.65</td>
<td>71.5</td>
<td>199</td>
</tr>
<tr>
<td>41.3 (1% in)</td>
<td>9.78</td>
<td>80.5</td>
<td>291</td>
</tr>
<tr>
<td>76.8 (3 in)</td>
<td>9.88</td>
<td>88.8</td>
<td>441</td>
</tr>
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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 3/8-20 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).

\[ l = \frac{\phi \lambda_g}{2\pi} \]  \hspace{1cm} (1)

where \( \phi \) is the desired phase delay of the line and \( \lambda_g \) is the guide wavelength for the transmission line used (identical to the free-space wavelength \( \lambda_0 \) 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 $C_{\text{eff}}$ of the shielded open is generally described by a polynomial function in frequency $f$:

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

(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 $L_{\text{eff}}$ 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), \( \varepsilon' = 2.55 \)
2. Debased alumina ceramic, \( \varepsilon' = 8.85 \)
3. Calcium-strontium-titanate (CST) ceramic, \( \varepsilon' = 275 \)
4. Ferrite-loaded polymer (FLP), \( \varepsilon' = 16.1, \mu' = 4.5 \)

* 88 % alumina with additions of \( \text{SiO}_2 \), \( \text{MgO} \), \( \text{CrO}_2 \) and \( \text{CaO} \); 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 \(+0.7^\circ\) to \(-1.5^\circ\) relative to the \(0^\circ\) 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 \( \varepsilon' \) data for CLP, which are shown in Figure 8, should be compared with a well-established reference value of \( \varepsilon' = 2.55 \pm 0.013 \) 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 S21 phase versus frequency for the 102 mm line standard.](image)
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 $\varepsilon' = 2.55$ 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 $\varepsilon' = 9.1$ is constant up to about 800 MHz. Compare this with a reference value of $\varepsilon' = 8.85 \pm 0.3$ 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 $\varepsilon'$ 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 $\varepsilon'$ 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 $\varepsilon' = 275$, 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](image.png)

Figure 11. Measured real permittivity data for calcium-strontium-titanate, following TRL Calibration.
We also measured the dielectric loss $\varepsilon''$ 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 $\delta = \varepsilon \varepsilon'' = 0.01$ 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 $\pm 2.5\%$ for the $\varepsilon$' reference data and $\pm 1.5\%$ for the $\mu$' reference data are included in Figures 12 and 13. The uncertainty bounds for the $\varepsilon''$ and $\mu''$ reference data are $\pm 0.01$. In Figure 12a, note that the measured data for $\varepsilon$' lie within the uncertainty limits of the reference data, whereas the agreement for $\varepsilon''$ (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 $\varepsilon' = 3.85 \pm 0.02$ at 5 GHz [14]. We see that there is very close agreement between the $\varepsilon$' 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 $\varepsilon' = 2.54$. In contrast, the data obtained following external OSLT calibration are seen to be unstable and vary by approximately $\pm 3\%$, 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 $\varepsilon'$ data for fused silica glass measured in a 7 mm coaxial air line following internal 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 $\varepsilon'$ 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 $\varepsilon'$ 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 $\varepsilon'$ 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 to 100 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 $C_{\text{eff}}$ 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.

REFERENCES


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APPENDIX A.

Machine Drawings of Coaxial Air Line System Hardware
Figure A1. 102 mm long specimen-holder assembly.

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).
Figure A4. Details of short-circuit standard (all dimensions in inches).
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
TWOPORT Version 1.0  Last Revision 08/12/94  14:35

purge "a:\twooport"
re-save "a:\twooport3"
re-save "b:\twooport3"
re-save "c:\jones\twooport2"

Init_com!:  

RAD

OPTION BASE 1

COM /Measurement/ COMPLEX J
COM /Measurement/ REAL Cap(801),Beta(801)
COM /Measurement/ COMPLEX S11m(801),S21m(801),S12m(801),S22m(801)
COM /Measurement/ COMPLEX S11c(801),S21c(801),S12c(801),S22c(801)
COM /Measurement/ INTEGER Datacount,REAL Freq(801)
COM /Calibration/ COMPLEX S11m_short(801),S11m_open(801),S11m_load(801)
COM /Calibration/ COMPLEX S22m_short(801),S22m_open(801),S22m_load(801)
COM /Calibration/ COMPLEX S11t_short(801),S11t_open(801),S11t_load(801)
COM /Calibration/ COMPLEX S22t_short(801),S22t_open(801),S22t_load(801)
COM /Calibration/ COMPLEX S12m_thru(801),S12m_rev(801),S12m_isol(801)
COM /Calibration/ COMPLEX S21m_thru(801),S21m_rev(801),S21m_isol(801)
COM /Calibration/ COMPLEX S12t_thru(801),S12t_rev(801),S12t_isol(801)
COM /Calibration/ COMPLEX S21t_thru(801),S21t_rev(801),S21t_isol(801)
COM /Calibration/ REAL Short_re(801),Short_im(801),Open_re(801),Open_im(801)
COM /Calibration/ REAL Load_re(801),Load_im(801),Thru_re(801),Thru_im(801)
COM /Calibration/ REAL Rev_re(801),Rev_im(801),Isol_re(801),Isol_im(801)
COM /Error_terms/ COMPLEX Edf(801),Ern(801),Esf(801),Eodf(801),Eirt(801)
COM /Error_terms/ COMPLEX Ede(801),Err(801),Esr(801),Eor(801),Ebt(801)
COM /Substitutions/ COMPLEX Cl(801),C2(801),C3(801),C4(801)
COM /Addresses/ INTEGER Plotter_addr,Printer_addr,Nwa_addr
COM /File/Filename$(30),Diskdrive$(30),Path$(200),Description$(40),INTEGER

Init_var!:  

INTEGER Preamble,Size
DIM T1$(5500),T2$(5500),T3$(5500),T4$(5500)
DIM Freq_data(340),Real_open(340),Imag_open(340),Xa(20),Ya(20),Ya2(20)

Init_const!:  

J=CMPLX(0,1)

Init_keys!:  

CONTROL KBD,15;1
CONTROL CRT,12;0
SET KEY 0, " "
SET KEY 1, " "
SET KEY 2, " "
SET KEY 3, " "
SET KEY 4, " "
SET KEY 5, " "
SET KEY 6, " "
SET KEY 7, " "
SET KEY 8, " "
SET KEY 9, " "
SET KEY 10, " "

Main_menu!:  

OFF KEY
CLEAR SCREEN
Prty=VAL(SYSTEM$("SYSTEM PRIORITY")+1)
ON KEY 0 TARET. "End program",Prty GOSUB End program
ON KEY 2 LABEL "Read NWA", Prty GOSUB Read_nwa
ON KEY 3 LABEL "Calibrate NWA", Prty GOSUB Calibrate_nwa
ON KEY 4 LABEL "Calc errors", Prty GOSUB Calc_errors
ON KEY 5 LABEL "load stan", Prty GOSUB Load_stan
ON KEY 6 LABEL "load errors", Prty GOSUB Load_cal
ON KEY 7 LABEL "Read S-parms", Prty GOSUB Read_sparsms
ON KEY 8 LABEL "Correct S-parms", Prty GOSUB Correct_sparsms
ON KEY 9 LABEL "Save data", Prty GOSUB Save_data
Done=0
Prior_menu=0
DISP "Please Select One of the Softkeys..."
LOOP
IF Done THEN GOTO Main_menu
END LOOP

! 250 !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
252 ! Setup keys so the person can decide when they want to do
254 ! which calibration
256 !
258 Calibrate_nwa: 
260 !
REDIM S1lm short(Datacount),S1lt short(Datacount)
REDIM S1lm open(Datacount),S1lt open(Datacount)
REDIM S1lm load(Datacount),S1lt load(Datacount)
REDIM S22m short(Datacount),S22t short(Datacount)
REDIM S22m open(Datacount),S22t open(Datacount)
REDIM S22m load(Datacount),S22t load(Datacount)
REDIM S12m thru(Datacount),S12t thru(Datacount)
REDIM S12m rev(Datacount),S12t rev(Datacount)
REDIM S12m isol(Datacount),S12t isol(Datacount)
REDIM S21m thru(Datacount),S21t thru(Datacount)
REDIM S21m rev(Datacount),S21t rev(Datacount)
REDIM S21m isol(Datacount),S21t isol(Datacount)

Menu: 
OFF KEY
CLEAR SCREEN
Prty=VAL(SYSTEM$("SYSTEM PRIORITY"))+1
ON KEY 0 LABEL "Prior menu", Prty GOSUB Prior_menu
ON KEY 7 LABEL "Reflection", Prty GOSUB Reflection
IF Flag7=1 THEN
ON KEY 7 LABEL "Reflection*", Prty GOSUB Reflection
END IF

ON KEY 8 LABEL "Transmission", Prty GOSUB Transmission
IF Flag8=1 THEN
ON KEY 8 LABEL "Transmission*", Prty GOSUB Transmission
END IF

ON KEY 9 LABEL "Isolation", Prty GOSUB Isolation
IF Flag9=1 THEN
ON KEY 9 LABEL "Isolation*", Prty GOSUB Isolation
END IF

Done=0
Prior_menu=0
DISP "Please select One of the Softkeys..."
LOOP
IF Done THEN GOTO Menu

35
EXIT IF Prior_menu
END LOOP
Done=1
Prior_menu=0
RETURN
!
Read_nwa: !
DISP "Reading data from NWA, Please wait...";
ASSIGN @Nwa TO 716
ASSIGN @Nwa_data TO 716;FORMAT OFF
ASSIGN @Nwa_sysb TO 717
Calc_freq: !
OUTPUT @Nwa;"STAR;OUTPACTI;"
ENTER @Nwa;Start_freq
OUTPUT @Nwa;"STOP;OUTPACTI;"
ENTER @Nwa;Stop_freq
OUTPUT @Nwa;"POIN;OUTPACTI;"
ENTER @Nwa;Num_points
!
Datacount=Num_points
for testing
Datacount=201
Start_freq=4.5E+7
Stop_freq=1.8E+9
!
FOR I=1 TO Datacount
Freq(I)=Start_freq+((Stop_freq-Start_freq)/(Datacount-1))*(I-1))
NEXT I
WAIT 1.5
Done=1
RETURN
!
Reflection: !
Menu_1: !
OFF KEY
CLEAR SCREEN
Prty=VAL(SYSTEM$("SYSTEM PRIORITY")+1
ON KEY 0 LABEL "Prior menu",Prty GOSUB Prior_menu
!
ON KEY 2 LABEL "Port 1 Short",Prty GOSUB Meas_prt1_short
IF Flag2=1 THEN
ON KEY 2 LABEL "Port 1 Short*",Prty GOSUB Meas_prt1_short
END IF
!
ON KEY 3 LABEL "Port 2 Short",Prty GOSUB Meas_prt2_short
IF Flag3=1 THEN
ON KEY 3 LABEL "Port 2 Short*",Prty GOSUB Meas_prt2_short
END IF
!
ON KEY 4 LABEL "Port 1 Open ",Prty GOSUB Meas_port1_open
IF Flag4=1 THEN
ON KEY 4 LABEL "Port 1 Open*",Prty GOSUB Meas_port1_open
END IF
!
ON KEY 5 LABEL "Port 2 Open ",Prty GOSUB Meas_port2_open
IF Flag5=1 THEN
ON KEY 5 LABEL "Port 2 Open*",Prty GOSUB Meas_port2_open
END IF
!
ON KEY 6 LABEL "Port 1 Load ",Prty GOSUB Meas_port1_load
IF Flag6=1 THEN
ON KEY 6 LABEL "Port 1 Load++",Prty GOSUB Meas_port1_load
END IF

ON KEY 7 LABEL "Port 2 Load ",Prty GOSUB Meas_port2_load
IF Flag7=1 THEN
ON KEY 7 LABEL "Port 2 Load++",Prty GOSUB Meas_port2_load
END IF
Done=0
Prior_menu=0
DISP "Please select One of the Softkeys..."
LOOP
IF Done THEN GOTO Menu_1
EXIT IF Prior_menu
END LOOP
Done=1
Prior_menu=0
RETURN

DISP "Connect Ports 1 and 2 together and press Enter...";
INPUT Dummy$
Menu_2: 0
OFF KEY
Prty=VAL(SYSTEM$("SYSTEM PRIORITY")+1
ON KEY 0 LABEL "Prior menu",Prty GOSUB Prior_menu

ON KEY 2 LABEL "Port 1 for",Prty GOSUB Meas_s21_thru
IF Flag8=1 THEN
ON KEY 2 LABEL "Port 1 for++",Prty GOSUB Meas_s21_thru
END IF

ON KEY 3 LABEL "Port 2 for",Prty GOSUB Meas_s12_thru
IF Flag9=1 THEN
ON KEY 3 LABEL "Port 2 for++",Prty GOSUB Meas_s12_thru
END IF

ON KEY 4 LABEL "Port 1 rev",Prty GOSUB Meas_s21_rev
IF Flag10=1 THEN
ON KEY 4 LABEL "Port 1 rev++",Prty GOSUB Meas_s21_rev
END IF

ON KEY 7 LABEL "Port 2 rev",Prty GOSUB Meas_s12_rev
IF Flag11=1 THEN
END IF

Done=0
Prior_menu=0
DISP "Please Select One of the Softkeys..."
LOOP
IF Done THEN GOTO Menu_2
EXIT IF Prior_menu
END LOOP
Done=1
RETURN

Isolation: 0

37
568 DISP "Attach 50 ohm loads to port 1 and 2 and press Enter...";
569 INPUT Dummy$
570 !
572 Menu 3: !
574 OFF KEY
576 Prty=VAL(SYSTEM$("SYSTEM PRIORITY"))+1
578 ON KEY 0 LABEL "Prior menu",Prty GOSUB Prior_menu
580 ON KEY 2 LABEL "Port 1 Isol",Prty GOSUB Meas_s21_isol
582 IF Flag12=1 THEN
584 ON KEY 2 LABEL "Port 1 Isol*",Prty GOSUB Meas_s21_isol
588 END IF
590 !
592 ON KEY 3 LABEL "Port 2 Isol",Prty GOSUB Meas_s12_isol
594 IF Flag13=1 THEN
596 ON KEY 3 LABEL "Port 2 Isol*",Prty GOSUB Meas_s12_isol
598 END IF
600 !
602 Done=0
604 Prior_menu=0
606 DISP "Please Select One of the Softkeys..."
608 LOOP
610 IF Done THEN GOTO Menu_3
612 EXIT IF Prior_menu
614 END LOOP
616 Done=1
618 RETURN
620 Prior_menu: !
622 Prior menu=1
624 RETURN
626 !
628 Meas_port1_short: !
630 DISP "Please Connect the Short at Port 1 and Press Enter...";
632 INPUT Dummy$
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;Framble;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;Framble;Size,S11m_open(*)
678 OUTPUT @Nwa;"TITL "";"
680 Flag4=1
682 Done=1
684 RETURN
686 !
Meas_port1_load: !
DISP "Please Connect the Load at Port 1 and Press Enter...";
INPUT Dummy$
DISP "Measuring the Load at Port 1...
OUTPUT @Nwa;"S11;"
OUTPUT @Nwa;"TITL "MEASURING STANDARD, PLEASE WAIT..."" ;
! OUTPUT @Nwa;"NUMG 64;"
OUTPUT @Nwa;"SING;"
OUTPUT @Nwa;"FORM3;OUTLPDATA;"
ENTER @Nwa_data;Preamble;Size,S11m_load(*
OUTPUT @Nwa;"TITL ****;"
Flag6=1
Done=1
RETURN

Meas_port2_short: !
DISP "Please Connect the Short at Port 2 and Press Enter...";
INPUT Dummy$
DISP "Measuring the Short at Port 2...
OUTPUT @Nwa;"S22;"
OUTPUT @Nwa;"TITL "MEASURING STANDARD, PLEASE WAIT..."" ;
! OUTPUT @Nwa;"NUMG 64;"
OUTPUT @Nwa;"SING;"
OUTPUT @Nwa;"FORM3;OUTLPDATA;"
ENTER @Nwa_data;Preamble;Size,S22m_short(*
OUTPUT @Nwa;"TITL ****;"
Flag3=1
Done=1
RETURN

Meas_port2_open: !
DISP "Please Connect the Open at Port 2 and Press Enter...";
INPUT Dummy$
DISP "Measuring the Open at Port 2...
OUTPUT @Nwa;"S22;"
OUTPUT @Nwa;"TITL "MEASURING STANDARD, PLEASE WAIT..."" ;
! OUTPUT @Nwa;"NUMG 64;"
OUTPUT @Nwa;"SING;"
OUTPUT @Nwa;"FORM3;OUTLPDATA;"
ENTER @Nwa_data;Preamble;Size,S22m_open(*
OUTPUT @Nwa;"TITL ****;"
Flag5=1
Done=1
RETURN

Meas_port2_load: !
DISP "Please Connect the Load at Port 2 and Press Enter...";
INPUT Dummy$
DISP "Measuring the Load at Port 2...
OUTPUT @Nwa;"S22;"
OUTPUT @Nwa;"TITL "MEASURING STANDARD, PLEASE WAIT..."" ;
! OUTPUT @Nwa;"NUMG 64;"
OUTPUT @Nwa;"SING;"
OUTPUT @Nwa;"FORM3;OUTLPDATA;"
ENTER @Nwa_data;Preamble;Size,S22m_load(*
OUTPUT @Nwa;"TITL ****;"
Flag7=1
Done=1
RETURN

!
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; outdata;"
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; outdata;"
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; outdata;"
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; outdata;"
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_s1lm: !
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 S1lm(Datacount),S1lc(Datacount)
996     REDIM S2lm(Datacount),S2lc(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,S1lm(*)
1024    OUTPUT @Nwa;"TITL ***;"
1026    !
1028    Read_s21:!
1030    DISP "Measuring s21..."
1032    OUTPUT @Nws;"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),Etf(Datacount)
1108 REDIM Edz(Datacount),Err(Datacount),Esr(Datacount),Etr(Datacount)
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
ENTER @File;Dummy
PRINT "dummy number is ",Dummy
ENTER @File;Description$
DISP "Loading table for S11 data for open"
FOR I=1 TO Counter
    ENTER @File;Freq_data(I),Real_open(I),Imag_open(I)
    S11t_open(I)=CMPLX(Real_open(I),Imag_open(I))
    S22t_open(I)=CMPLX(Real_open(I),Imag_open(I))
NEXT I
GOTO Reflect_errors
!
Hp_open_model:!
Theory_open:!
!
! Coeff_7mm: !
! Capn=1.5092E-12
! Cap1=8.92E-27
! Cap2=5.8051E-33
! Cap3=6.310E-43
!
! Coeff_3_1_8: !
! Capn=1.3007E-12
! Cap1=2.4563E-24
! Cap2=6.0290E-32
! Cap3=1.9978E-41
!
Znot=50
FOR I=1 TO Datablock
    Cap(I)=Capn+Cap1*Freq(I)+Cap2*(Freq(I))^2+Cap3*(Freq(I))^3
    Beta(I)=2*(ATN(2*PI*Freq(I)))*Cap(I)*Znot
    S11t_open(I)=EXP(-J*Beta(I))
    S22t_open(I)=EXP(-J*Beta(I))
NEXT I
PRINT "cap(I) is ",Cap(I)
PRINT "beta(I) is ",Beta(I)
PRINT "s11t_open is ",S11t_open(I)
WAIT 1.4
!
Reflect_errors:!
Theory_short:!
DISP "Calculating theoretical S11 (short) for point ";I
S11t_short(I)=CMPLX(-1,0)
NEXT I
FOR I=1 TO Datablock
DISP "Calculating theoretical S22 (short) for point ";I
S22t_short(I)=CMPLX(-1,0)
NEXT I
Theory_load:!
FOR I=1 TO Datablock
DISP "Calculating theoretical S11 (load) for point ";I
S11t_load(I)=CMPLX(0,0)
NEXT I
FOR I=1 TO Datablock
DISP "Calculating theoretical S22 (load) for point ";I
S22t_load(I)=CMPLX(0,0)
NEXT I
!
Calc_error_net:!
DISP "Calculating error terms for port 1..."
FOR I=1 TO Datacount
  T1=S11t_short(I)
  T2=S11t_open(I)
  T3=S11t_load(I)
  M1=S11m_short(I)
  M2=S11m_open(I)
  M3=S11m_load(I)
  Edf(I)=(T1*T2*M3*(M1-M2)+T1*T3*M2*(M3-M2)+T2*T3*M1*(M2-M3))/(T1*T2*(M2-M1))
  Esf(I)=(T1*(M2-Edf(I)))+T2*(Edf(I)-M1))/(T1*T2*(M2-M1))
  Erf(I)=((M1-Edf(I))*(1-T1*Esf(I)))/T1)
NEXT I

DISP "Calculating error terms for port 2..."
FOR I=1 TO Datacount
  T1=S22t_short(I)
  T2=S22t_open(I)
  T3=S22t_load(I)
  M1=S22m_short(I)
  M2=S22m_open(I)
  M3=S22m_load(I)
  Edr(I)=(T1*T2*M3*(M1-M2)+T1*T3*M2*(M3-M2)+T2*T3*M1*(M2-M3))/(T1*T2*(M2-M1))
  Esr(I)=(T1*(M2-Edr(I)))+T2*(Edr(I)-M1))/(T1*T2*(M2-M1))
  Err(I)=((M1-Edr(I))*(1-T1*Esr(I)))/T1)
NEXT I

Isol_errors:
FOR I=1 TO Datacount
  Exf(I)=S11m_isol(I)
NEXT I

Calc_s12_isol:
FOR I=1 TO Datacount
  Exr(I)=S12m_isol(I)
NEXT I

Trans_errors:
FOR I=1 TO Datacount
  M1=S11m_thru(I)
  M2=S12m_thru(I)
  M3=S11m_rev(I)
  M4=S12m_rev(I)
  Elf(I)=(M3-Edf(I))/(M3*Esf(I)+Erf(I)-Edf(I)*Esf(I))
  Elr(I)=(M4-Edr(I))/(M4*Esr(I)+Err(I)-Edr(I)*Esr(I))
  Ef(I)=(M1-Exf(I))*(1-Esf(I)*Elf(I))
  Etr(I)=(M2-Exr(I))*(1-Esr(I)*Elr(I))
NEXT I

Done=1
RETURN
Correct_sparms:!
Actual_sparms:!

Substitutions:
DISP "Calculating corrections for S-parms...";
FOR I=1 TO Datacount
    CI(I)=S11m(I)-Edf(I)
    C2(I)=S22m(I)-Edf(I)
    C3(I)=S21m(I)-Exr(I)
    C4(I)=S12m(I)-Exr(I)
    Denom(I)=(1+(C1(I)*Esf(I))/Err(I)) * (1+(C2(I)*Esr(I))/Err(I))) - (C3
    S11c(I)=(C1(I)/Err(I)) * (1+(C2(I)*Esr(I))/Err(I))) - (Elr(I)*C3(I)/Etf
    S22c(I)=(C2(I)/Err(I)) * (1+(C1(I)*Esf(I))/Err(I))) - (Elf(I)*C3(I)/Etf
    S12c(I)=(C1(I)/Err(I)) * (1+(C2(I)*Esr(I))/Err(I))) / Denom(I)
    S21c(I)=(C3(I)/Etf(I)) * (1+(C2(I)*Err(I)) * (Esf(I)-Elr(I)))) / Denom(I)
NEXT I
WAIT 2
Done=1
RETURN
!
Save_data:!
!
OFF KEY
CLEAR SCREEN
Prty=VAL(SYSTEM$("SYSTEM PRIORITY")+1
ON KEY 0 LABEL "Prior menu", Prty GOSUB Prior_menu
ON KEY 6 LABEL "Save calibration", Prty GOSUB Save_cal
ON KEY 7 LABEL "Save standards", Prty GOSUB Save_std
ON KEY 8 LABEL "Save meas", Prty GOSUB Save_meas
ON KEY 9 LABEL "Save sparms", Prty GOSUB Save_sparms
Done=0
Prior_menu=0
DISP "Please select One of the Softkeys..."
LOOP
EXIT IF Prior_menu
END LOOP
Done=1
Prior_menu=0
RETURN
!
Save_sparms:
!
Dut:!
OFF KEY
CLEAR SCREEN
DISP "Please enter a description of the corrected data (<40 chars.)..."
LINPUT Test$
Test$=TRIM$(Test$)
Description$=Test$
Bitflag=0
ALLOCATE Array(Datacount,5,2)
FOR I=1 TO Datacount
    Array(I,1,1)=Freq(I)
    Array(I,2,1)=REAL(S11c(I))
    Array(I,2,2)=IMAG(S11c(I))
    Array(I,3,1)=REAL(S22c(I))
    Array(I,3,2)=IMAG(S22c(I))
Array(I,4,1)=REAL(S21c(I))
Array(I,4,2)=IMAG(S21c(I))
Array(I,5,1)=REAL(S12c(I))
Array(I,5,2)=IMAG(S12c(I))
NEXT I

Diskdrive$="c:\jones\programs\"
DISP "Please enter a filename for the corrected data (<=30 chars.)... ";
LINPUT Filename$
Path$=Diskdrive$&Filename$
CREATE Path$,0
ASSIGN @File TO Path$;FORMAT ON
DISP "Saving File...";Path$
OUTPUT @File;Datacount
OUTPUT @File;Bitflag
OUTPUT @File;Description$
OUTPUT @File;Array(*)
ASSIGN @File TO *
DISP "File saved... 
WAIT 5
DEALLOCATE Array(*)
Done=1
RETURN

1611 !
1612 Save_meas:
1613 Before_corr:
1614 OFF KEY
1615 CLEAR SCREEN
1616 DISP "Please enter a description of the measured data (<=40 chars.)... ";
1618 LINPUT Test$
Test$=TRIM$(Test$)
Description$=Test$
Bitflag=0
ALLOCATE Array(Datacount,5,2)
FOR I=1 TO Datacount
Array(I,1,1)=Freq(I)
Array(I,2,1)=REAL(S11m(I))
Array(I,2,2)=IMAG(S11m(I))
Array(I,3,1)=REAL(S22m(I))
Array(I,3,2)=IMAG(S22m(I))
Array(I,4,1)=REAL(S21m(I))
Array(I,4,2)=IMAG(S21m(I))
Array(I,5,1)=REAL(S12m(I))
Array(I,5,2)=IMAG(S12m(I))
NEXT I

Diskdrive$="c:\jones\programs\"
DISP "Please enter a filename for the measured data (<=30 chars.)... ";
LINPUT Filename$
Path$=Diskdrive$&Filename$
CREATE Path$,0
ASSIGN @File TO Path$;FORMAT ON
DISP "Saving File...";Path$
OUTPUT @File;Datacount
OUTPUT @File;Bitflag
OUTPUT @File;Description$
OUTPUT @File;Array(*)
ASSIGN @File TO *
DISP "File saved... 
WAIT 5
DEALLOCATE Array(*)
Done=1

46
RETURN
!
Save_cal:!
OFF KEY
CLEAR SCREEN
ALLOCATE Array(Datacount, 13, 2)
FOR I=1 TO Datacount
  Array(I, 1, 1) = Freq(I)
  Array(I, 2, 1) = REAL(Edf(I))
  Array(I, 2, 2) = IMAG(Edf(I))
  Array(I, 3, 1) = REAL(Esf(I))
  Array(I, 3, 2) = IMAG(Esf(I))
  Array(I, 4, 1) = REAL(Ezf(I))
  Array(I, 4, 2) = IMAG(Ezf(I))
  Array(I, 5, 1) = REAL(Exf(I))
  Array(I, 5, 2) = IMAG(Exf(I))
  Array(I, 6, 1) = REAL(Etf(I))
  Array(I, 6, 2) = IMAG(Etf(I))
  Array(I, 7, 1) = REAL(Elf(I))
  Array(I, 7, 2) = IMAG(Elf(I))
  Array(I, 8, 1) = REAL(Edr(I))
  Array(I, 8, 2) = IMAG(Edr(I))
  Array(I, 9, 1) = REAL(Err(I))
  Array(I, 9, 2) = IMAG(Err(I))
  Array(I, 10, 1) = REAL(Esr(I))
  Array(I, 10, 2) = IMAG(Esr(I))
  Array(I, 11, 1) = REAL(Erx(I))
  Array(I, 11, 2) = IMAG(Erx(I))
  Array(I, 12, 1) = REAL(Etr(I))
  Array(I, 12, 2) = IMAG(Etr(I))
  Array(I, 13, 1) = REAL(Elr(I))
  Array(I, 13, 2) = IMAG(Elr(I))

NEXT I
Diskdrive$ = "c:\ Jones\ Programs\"
DISP "Please enter a filename for the calibration (<30 chars.)... ";
INPUT Filename$
Path$ = Diskdrive$ & Filename$
CREATE Path$, 0
ASSIGN @File TO Path$; FORMAT ON
DISP "Saving File... "; Path$
OUTPUT @File; Start_freq
OUTPUT @File; Stop_freq
OUTPUT @File; Datacount
OUTPUT @File; Array(*)
ASSIGN @File TO *
DISP "file saved... 
DEALLOCATE Array(*)
Done=1
RETURN
!
Load_cal:!
OFF KEY
CLEAR SCREEN
Diskdrive$ = "c:\ Jones\ Programs\"
DISP "Please enter a filename for the cal file (<30 chars.)... ";
INPUT Filename$
Path$ = Diskdrive$ & Filename$
ASSIGN @File TO Path$; FORMAT ON
DISP "Loading File... "; Path$
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)=CPLX(Array(I,2,1),Array(I,2,2))
1808 Erf(I)=CPLX(Array(I,3,1),Array(I,3,2))
1809 Esf(I)=CPLX(Array(I,4,1),Array(I,4,2))
1810 Exf(I)=CPLX(Array(I,5,1),Array(I,5,2))
1811 Etf(I)=CPLX(Array(I,6,1),Array(I,6,2))
1812 Elf(I)=CPLX(Array(I,7,1),Array(I,7,2))
1813 Edr(I)=CPLX(Array(I,8,1),Array(I,8,2))
1814 Err(I)=CPLX(Array(I,9,1),Array(I,9,2))
1815 Esr(I)=CPLX(Array(I,10,1),Array(I,10,2))
1816 Exr(I)=CPLX(Array(I,11,1),Array(I,11,2))
1817 Etr(I)=CPLX(Array(I,12,1),Array(I,12,2))
1818 Elr(I)=CPLX(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)=CPLX(Array(I,2,1),Array(I,2,2))
1879 S11m_open(I)=CPLX(Array(I,3,1),Array(I,3,2))
1880 S11m_load(I)=CPLX(Array(I,4,1),Array(I,4,2))
1881 S21m_thru(I)=CPLX(Array(I,5,1),Array(I,5,2))
1882 S21m_isol(I)=CPLX(Array(I,6,1),Array(I,6,2))
1883 S21m_rev(I)=CPLX(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$
ASSIGN @File TO Path$; FORMAT ON
DISP "Loading File...",;Path$
ENTER @File; Start_freq
ENTER @File; Stop_freq
ENTER @File; Datacount
ALLOCATE Array(Datacount, 7, 2)
ENTER @File; Array(*)
ASSIGN @File TO *
FOR I=1 TO Datacount
  Freq(I)=Array(I,1,1)
  S22m_short(I)=CMPLX(Array(I,2,1),Array(I,2,2))
  S22m_open(I)=CMPLX(Array(I,3,1),Array(I,3,2))
  S22m_load(I)=CMPLX(Array(I,4,1),Array(I,4,2))
  S22m_thru(I)=CMPLX(Array(I,5,1),Array(I,5,2))
  S12m_isol(I)=CMPLX(Array(I,6,1),Array(I,6,2))
  S12m_rev(I)=CMPLX(Array(I,7,1),Array(I,7,2))
NEXT I
DISP "File loaded."
DEALLOCATE Array(*)
Done=1
RETURN

Save stan:!
FOR I=1 TO Datacount
  Short_re(I)=REAL(S11m_short(I))
  Short_im(I)=IMAG(S11m_short(I))
  Open_re(I)=REAL(S11m_open(I))
  Open_im(I)=IMAG(S11m_open(I))
  Load_re(I)=REAL(S11m_load(I))
  Load_im(I)=IMAG(S11m_load(I))
  Thru_re(I)=REAL(S21m_thru(I))
  Thru_im(I)=IMAG(S21m_thru(I))
  Isol_re(I)=REAL(S21m_isol(I))
  Isol_im(I)=IMAG(S21m_isol(I))
  Rev_re(I)=REAL(S21m_rev(I))
  Rev_im(I)=IMAG(S21m_rev(I))
NEXT I
OFF KEY
CLEAR SCREEN
ALLOCATE Array(Datacount, 7, 2)
FOR I=1 TO Datacount
  Array(I,1,1)=Freq(I)
  Array(I,2,1)=Short_re(I)
  Array(I,2,2)=Short_im(I)
  Array(I,3,1)=Open_re(I)
  Array(I,3,2)=Open_im(I)
  Array(I,4,1)=Load_re(I)
  Array(I,4,2)=Load_im(I)
  Array(I,5,1)=Thru_re(I)
  Array(I,5,2)=Thru_im(I)
  Array(I,6,1)=Rev_re(I)
  Array(I,6,2)=Rev_im(I)
  Array(I,7,1)=Isol_re(I)
  Array(I,7,2)=Isol_im(I)
NEXT I
Diskdrive$="c:\jones\programs"
DISP "Please enter a filename for standards on port 1 (<30 chars.)..."
LINPUT Filename$
WAIT 1.2
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  l
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)
1997    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(I))
2096 FOR I=1 TO N
2098 Dif=ABS(X-Xa(I))
2100 IF (Dif<Dif) THEN
2102 _Ns=I
2104 Dif=Dif
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