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Semiconductor Measurement Technology:

Measurement of Transistor Scattering Parameters

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Measurement of Transistor Scattering Parameters

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Abstract: Results of an interlaboratory comparison of transistor scattering-parameter measurements are reported for transistor types 2N709, 2N918 and 2N3960. From these results it is estimated that, for such devices, between-laboratory variability of transistor S-parameter measurements in the frequency range between 200 and 2000 MHz could be held to a maximum relative sample standard deviation of 7.5 percent in the measurement of magnitude and a maximum sample standard deviation of 8 degrees in the measurement of s_{11} phase and 3.5 degrees in the measurement of phase of other S-parameters. This could be done if all participants were required to use the same calibration procedure and to limit their test signal to a level that would assure small-signal operation. In a separate study, the equivalent circuit of high-frequency probes used in characterizing the parameters of integrated circuits was evaluated by measuring S parameters at the input connectors with the probe tips in contact with known loads. These measurements revealed a resonance which would limit the usefulness of the probes for measurements in the vicinity of 1.2 GHz. Work is under way to determine design changes needed to eliminate this resonance.

Key Words: Electronics; high-frequency probes; interlaboratory comparison; scattering parameters; S parameters; transistors

1. INTRODUCTION

In response to a request from the Air Force Weapons Laboratory (AFWL), the National ureau of Standards in 1971 undertook a project to assist in improving instrumentation nd procedures utilized in measurements associated with the prediction of the effects f nuclear radiation on semiconductor devices. The work during the period January 1971 o August 1972 was reported in AFWL Report AFWL-TR-73-54, Measurement of Transit Time nd Related Transistor Characteristics [1][1].

That report discussed some of the causes of discrepancies in the measurement of ransistor transit time, particularly when h_{fe} is degraded as happens when transistors re irradiated by neutrons, and suggested techniques for improving transit-time measureents. In addition, scattering parameters were defined, a test plan for an interaboratory comparison of transistor scattering-parameter measurements was outlined, pecial probes for measuring the high-frequency characteristics of transistors in integrated-circuit wafers were described, and techniques were developed for determining he equivalent circuit of these probes in the 0.2 to 2 GHz frequency range.

This report covers the work from September 1972 to July 1973. It describes the esults of the interlaboratory comparison of transistor S-parameter measurements, and hows how the equivalent circuit of the high-frequency probes can be characterized by eans of S parameters using the previously-described techniques. The S-parameter easurements on the high-frequency probes disclosed resonances which limit the usefuless of the probes in the vicinity of 1.2 GHz. As a result, additional work has been ndertaken by the NBS Boulder Laboratories[2] to determine design changes needed to liminate these resonances and to further refine the probing technique.

Figures in brackets refer to references on page 48.
AFWL Project Order PO-74-144, AC Probe Characterization.

2. S-PARAMETER MEASUREMENTS

2.1 Introduction

The interlaboratory comparison of transistor scattering-parameter measurements conducted by the National Bureau of Standards for the Air Force Weapons Laboratory was designed to determine the extent of the agreement between transistor measurements made in different laboratories using each laboratory's own equipment and personnel. Measurement and calibration procedures were not specified; the procedures used were those normally employed by the participating laboratory for this type of measurement. Six organizations took part in the experiment. In addition to the National Bureau of Standards, these included one other government laboratory, three transistor suppliers, and one transistor user. All but one made the measurements on the same type of automatic network analyzer; the other used the manually-operated equivalent. (Table 1)

To provide the necessary data, each laboratory measured the scattering parameters [1,2,3] of a set of selected transistors of types 2N709, 2N918 and 2N3960 over the frequency range from 200 to 2000 MHz. In addition, each laboratory measured a number of passive devices to provide data for the assessment of within-laboratory variability and to provide information on between-laboratory variability for comparison with the transistor data.

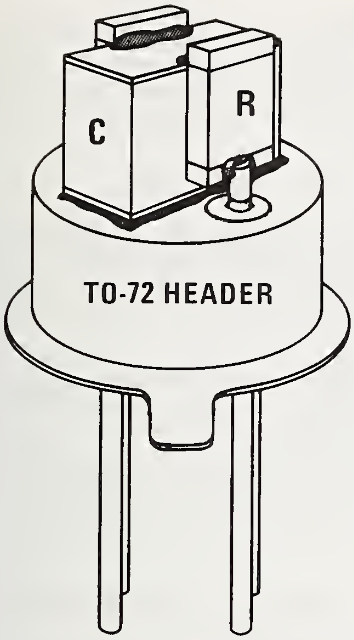
Analysis of the transistor data taken by the five laboratories which used automatic network analyzers revealed that the relative sample standard deviation of measurements of the magnitude of s_{21}, s_{12} and s_{22} was 10% or less, and that the sample standard deviation of phase measurements did not exceed 3.5 deg. In the measurement of s_{11}, relative sample standard deviations as high as 46% were recorded in the measurement of magnitude and sample standard deviations as large as 34 deg occurred in the measurement of phase. S-parameter measurements made manually by the sixth laboratory were in general agreement with those made by the other five.

The variability of the s_{11} measurements was due in large part to the variability introduced by the differences in calibration procedures employed by the participants when using the transistor fixture. The variability of the s_{21} measurements was exaggerated because the signal level applied to the transistor by one of the participants exceeded the requirements for small-signal conditions, resulting in overdriving the transistor when measuring the forward characteristics. If these sources of variability were eliminated by specifying the calibration method to be used and by specifying a maximum signal level to the transistor under test, a considerable reduction in the variability of S-parameter measurements could be expected.

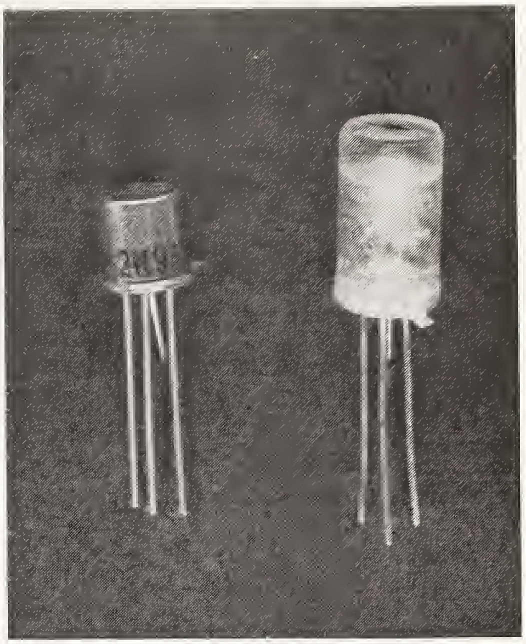
TABLE 1 - EQUIPMENT USED BY PARTICIPANTS

	LAB 1	LAB 2	LAB 3	LAB 4	LAB 5	LAB 6
Equipment	ANA[a]	ANA[a]	ANA[a]	ANA[a]	ANA[a]	MANUAL[b]
Frequency accuracy[c]	±7kHz	±7kHz	±7kHz	±7kHz	±7kHz	±5MHz (f<1Ghz) ±1% (1<f≤2)GHz
Signal level to transistor	-27dBm	-34dBm	-17dBm[d]	-30dBm	-30dBm	-30dBm
Type of bias meter	Panel[e]	Panel[e]	Digital[f]	Panel[e]	V_{CE} Panel[e] I_E Digital[f]	Panel[e]
Frequency of calibration of bias meters	Quarterly	Quarterly	No fixed schedule	Annually	Annually	Annually
Laboratory temperature	24°-24.5°C	24°C	23°-24°C	24°C	24°-26°C	24°C

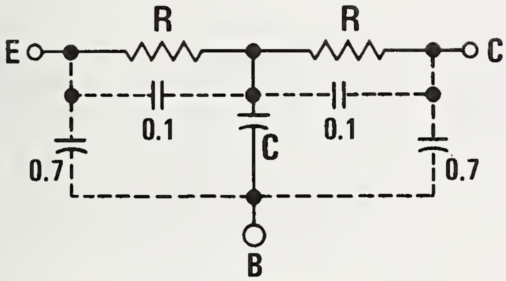
a automatic network analyzer
b manually operated S-parameter test set
c specified by manufacturer
d exceeds small-signal conditions
e 2-inch panel meter (accuracy ±4% of full scale)
f V_{CE}: 5 digit; I_E: 3-1/2 digit



a. Construction



b. External appearance



Capacitance in pF
Values are approximate

NETWORK	R,Ω	C,pF
R-C 2	10	20
R-C 3	20	5.1
R-C 4	20	10

Tolerance: ± 10%

c. Circuit

Figure 1. R-C networks.

2.2 Test Plan

The test plan for the interlaboratory comparison was adopted after consultation with the participants to determine the type of measuring equipment they intended to use. It provided for the measurement of 18 transistors (6 of each type) at 7 biases. In addition, five passive devices were circulated for measurement; these were three R-C networks mounted on TO-72 headers (Fig. 1) and two 10-dB coaxial attenuators. The test plan is summarized in figure 2, and the complete test plan is reproduced in Appendix 1.

The R-C networks were used to provide stable devices of known characteristics which could be measured at the transistor socket. No attempt was made to duplicate the equivalent circuit of a transistor. One terminal of a porcelain UHF capacitor was bonded to the TO-72 header and to the base lead of the package, and glass-passivated chip resistors were connected between the other terminal of the capacitor and the emitter and collector terminals of the package. The temperature coefficient of the R-C product is between +50 and +250 ppm/°C. Because of the construction, the R-C networks were measured in the grounded-base configuration.

Included with these devices were a transistor fixture to adapt the S-parameter test set for the measurement of transistors in TO-18 and TO-72 packages, the calibration standards for use with this transistor fixture, and a U-shaped coaxial line fitted with precision 7-mm connectors. The coaxial line was used to connect the output ports of the network analyzers for calibration, and was also used to connect the two 10-dB attenuators in series for measurement.

The following instructions were used to implement the test plan:

1. Calibrate at the output ports of the network analyzer and measure the 20-dB coaxial attenuator (actually two 10-dB attenuators connected in series by means of a length of coaxial line) at frequencies between 200 and 2000 MHz in 100-MHz increments.

2. Calibrate the system using the common transistor fixture and measure the three R-C networks at frequencies between 200 and 2000 MHz in 100-MHz increments.

3. Calibrate the system with each participant using his own transistor fixture and measure the three R-C networks, nine of the transistors (three of each type), and the three R-C networks a second time.

4. Calibrate the system using the common transistor fixture and repeat the measurements on the three R-C networks.

5. Calibrate the system at the output ports of the network analyzer and repeat the measurements on the 20-dB attenuator.

6. Repeat the entire series of measurements, 1 through 5 above, but substitute the second group of nine transistors in step 3.

Measurements made on the 20-dB attenuator provided a basis for determining both the within- and between-laboratory variability of measurements made by the basic measurement system, independently of adapters and auxiliary equipment needed for the measurement of transistors. Measurement of the R-C networks using a common transistor fixture for adapting the network analyzer for the measurement of transistors provided an estimate of the variability introduced by the transistor fixture. Finally, measurement of the R-C networks in the participant's own transistor fixture provided a measure of the variability introduced by the change in transistor fixtures as well as data which are independent of bias for comparison with the transistor measurements.

Each laboratory obtained the following data:

Four sets of measurements on the 20-dB attenuator.

Four sets of measurements on each of the three R-C networks measured in a common transistor fixture.

Four sets of measurements on each of the three R-C networks measured in each participant's own transistor fixture.

One set of measurements on each of the selected transistors. The 2N709s and 2N918s were measured in 100-MHz increments over the frequency range from 200 to 1000 MHz; the 2N3960s were measured at frequencies between 200 and 1800 MHz.

All transistor measurements were made at a collector-emitter bias of 5 V. Most participants took data at emitter currents of 1.6, 2.0, 2.5, 4.0 5.0, 8.0 and 10.0 mA. To shorten the time required, one participant measured at every other emitter current and measured only three each of the 2N709s and 2N918s.

The participant who used a manual system for measurement measured the transistors at only one bias, a collector-emitter voltage of 5 V and an emitter current of 2.5 mA, and measured both the transistors and passive devices at fewer frequencies than the laboratories which used automatic systems.

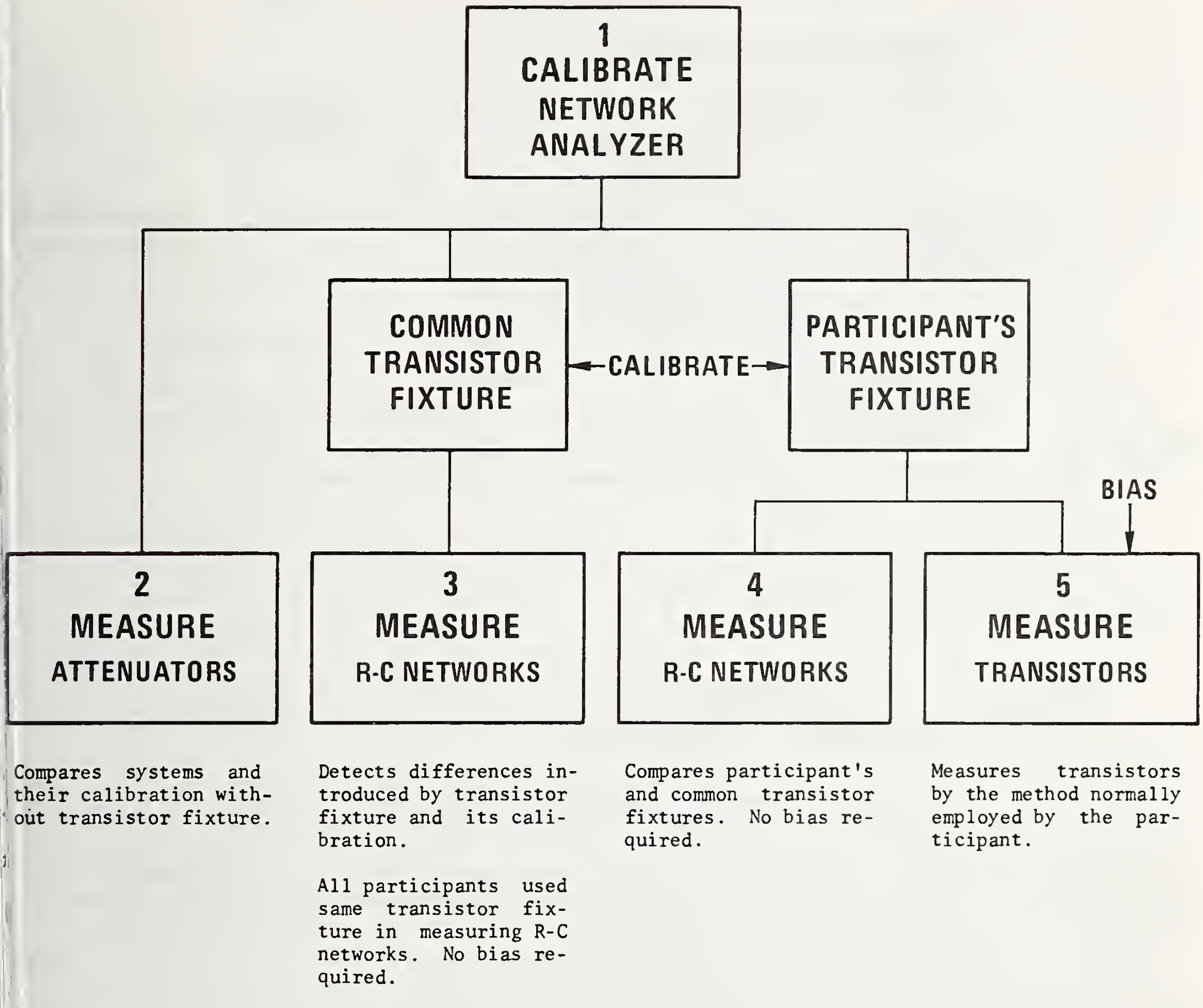


Figure 2. The test plan at a glance.

2.3 Transistors and Biases

The transistors selected for the interlaboratory comparison, types 2N709, 2N918 and 2N3960, are all *n-p-n* silicon types with either TO-18 or TO-72 cases. The units used were either JAN-TX types, which had been burned in for 168 hours, or devices which were burned in at NBS. The S parameters of a group of transistors were measured over a period of several months and the six most stable units of each type were selected for measurement in the round robin.

To detect any change in transistor characteristics during the course of the interlaboratory comparison, the S parameters of each of the transistors were measured at a collector-emitter bias of 5 V and an emitter current of 2.5 mA on the NBS network analyzer before the testing was begun, again after every second laboratory had completed its measurements, and finally at the conclusion of the tests. Transistor h_{fe} calculated from the S-parameter measurements remained stable during this period. During these control measurements, collector-emitter voltage was maintained within ±0.2% and emitter current within ±0.4% of the selected values.

The test plan did not specify how accurately the transistor biases were to be measured or maintained. All participants set the biases manually. Most participants used the two-inch panel meters on the power supply for the measurement of collector-emitter voltage and emitter current. Collector voltage was measured on the 10-V scale and emitter current on the 3-mA or 10-mA scales of these meters, which had a specified

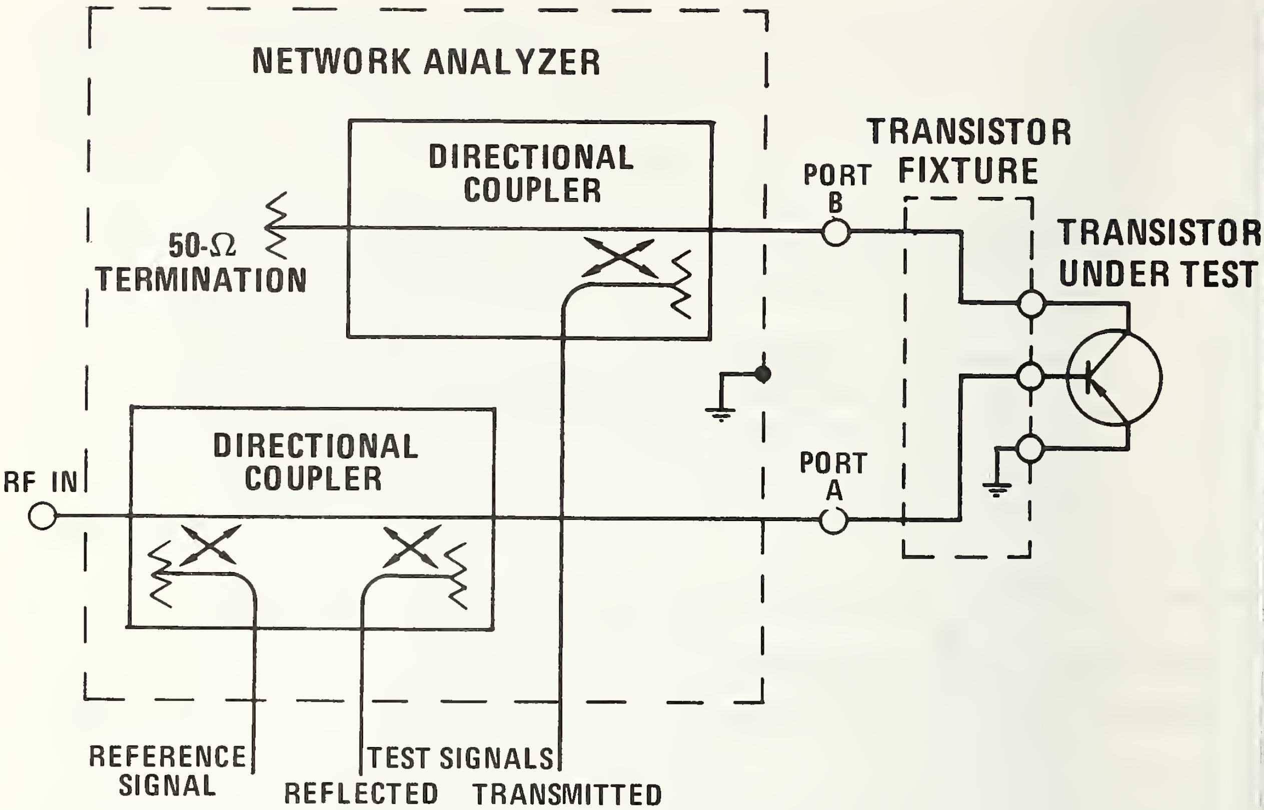


Figure 3. Basic S-parameter measurement circuit.

accuracy of ±4% of full scale. Two of the participants used 3-1/2 digit digital meters to set the emitter current within 0.01 mA, and one of these participants also used a 5-digit meter for the measurement of collector-emitter voltage to 0.01 V.

The case temperature of the transistors was not controlled during the measurements. Results of qualitative tests to determine the effect of case temperature on S-parameter values indicated that temperature effects are not a problem at the bias levels used. Laboratory temperatures ranged between 23° and 26°C (74° and 79°F).

2.4 Calibration Procedures

The S-parameter measurement system, figure 3, includes two directional couplers for sampling the incident (reference) signal and the reflected and transmitted test signals. Devices which are equipped with coaxial connectors are measured at ports A and B. For the measurement of transistors, the transistor fixture is used to provide the transition between the coaxial terminals, ports A and B, and a transistor socket. The transistor is connected as shown for the measurement of forward characteristics; the functions of ports A and B are transposed for the measurement of reverse characteristics.

To calibrate the measurement system, loads of known characteristics are measured to determine correction factors for minimizing errors caused by mismatch, directivity of the directional couplers, cross-talk, and frequency response. The loads employed for this purpose are a 50-Ω termination, a short circuit, an open circuit, and a through line which connects either ports A and B or the emitter and collector terminals of the transistor socket, depending on the location of the reference plane to be used for device measurement. In the manual system only one of the calibration standards is used, and the corrections are made by manually setting the magnitude and phase meters to the correct value for the standard in use. In the automatic systems, a series of tests is made using each of the calibration standards in turn; corrections obtained from these measurements are stored in the computer and applied to the data when device measurements are made.

TABLE 2 -- COMPARISON OF CALIBRATION PROCEDURES

STEP	SPECIFIED LOAD	REFERENCE PLANE AT WHICH LOAD IS CONNECTED FOR MEASUREMENT OF: 20-dB ATTENUATOR	TRANSISTORS AND R-C NETWORKS LAB 5	LAB 4	LAB 2	LAB 1	LAB 3
1,2	50Ω at input and output	Output ports	Transistor socket	Thru line at[a] transistor socket	Output ports	Output ports	Output ports
3	50Ω at both[b] terminals	Output ports[c]	Transistor socket	Transistor socket	Transistor socket	Transistor socket	Output ports
4,5	Short at input and output	Output ports	Transistor socket	Transistor socket	Transistor socket	Output ports	Output ports
6,7	Open at input and output	Output ports	Transistor socket	Not measured[d]	Transistor socket	Output ports	Output ports
	Capacitance	0.21 pF[e]	-0.6 pF[e]		-0.195 pF[f]	0.21 pF[e]	0.21 pF[e]
8	Through line	Output ports	Transistor socket	Transistor socket	Transistor socket	Transistor socket	Transistor socket
	Length	46.525 cm[g]	0.1 cm[h]	0.1 cm[h]	0.1 cm[h]	49.05 cm[i]	49.05 cm[i]

a Line terminated in 50Ω at output of directional coupler
b Terminals left open when calibrating at transistor socket
c One participant left terminals open when making this measurement
d Not measured because at least 10-dB of isolation provided between output ports and transistor socket
e Specified by manufacturer of test equipment
f Empirically determined by participant
g Through line and data on length furnished by NBS
h Length of through line for TO-18 socket (specified by manufacturer)
i Total length of transistor fixture with through line

Since they must be connected at the measurement reference plane, two sets of calibration standards are required, one for connection at the output ports of the network analyzer when the device to be measured is equipped with coaxial connectors, and one for connection at the transistor socket when the device to be measured plugs into a transistor socket. Each of the participants had a complete set of calibration standards for use at the output ports of the system. Instead of a flexible coupling, which would ordinarily be used as a through line to join ports A and B, NBS furnished a length of coaxial line fitted with suitable connectors (shown attached to the 10-dB attenuators in figure 4) to eliminate errors that might have been caused by rotating joints. This coaxial line was also used to connect the 10-dB attenuators in series, thus eliminating the use of flexible couplings in their measurement. Terminals of both the through line and coaxial attenuators were labeled A and B to assure that they were connected to the network analyzer in the same way each time to minimize errors caused by asymmetry. With a minor exception (see table 2), all participants used the same procedure for calibration at ports A and B of the automatic network analyzer.

Laboratory 5, the only participant who had a complete set of calibration standards for the transistor socket, was able to use the same calibration procedure at both the coaxial terminals and the transistor socket (table 2). The other laboratories lacked a 50-Ω termination for the transistor fixture. This posed no difficulty in the case of the manual system, since with the manual system only one of the calibration standards is used. The other laboratories using automatic systems varied the calibration procedure to compensate for the lack of a 50-Ω termination, but no two performed this calibration in exactly the same way.

Laboratories 1, 2 and 3 used similar, but not identical procedures. Each performed the first two calibration steps, which call for the use of a 50-Ω termination, at the coaxial terminals of the analyzer using the coaxial 50-Ω termination. Laboratory 3 continued to calibrate at the coaxial terminals until the final step when the transistor fixture with through line inserted in the transistor socket was connected. At the third step, Laboratory 2 connected the transistor fixture with the transistor terminals open and completed the calibration with the transistor fixture in place, using the short, open and through line at the transistor socket. Laboratory 1 connected the transistor fixture with the transistor terminals open at the third calibration step, then went back to the coaxial terminals for calibration with the open and short, and completed the calibration with the transistor fixture in place and the through line in the transistor socket.

Table 3 - Effect of Calibration Method on s_{11} Measurements

R-C NETWORK 4 DATA TAKEN ON NBS ANALYZER AFTER IT WAS CALIBRATED BY METHOD OF:

FREQUENCY MHz	LAB 1 s_{11} MAG	LAB 1 s_{11} PHASE DEG	LAB 2 s_{11} MAG	LAB 2 s_{11} PHASE DEG	LAB 3 s_{11} MAG	LAB 3 s_{11} PHASE DEG	LAB 4 s_{11} MAG	LAB 4 s_{11} PHASE DEG
100	0.297	-28	0.296	-27	0.296	-28	0.266	-29
200	0.298	-56	0.305	-54	0.298	-56	0.329	-56
300	0.305	-80	0.313	-78	0.304	-80	0.288	-73
400	0.309	-101	0.320	-99	0.309	-101	0.273	-104
500	0.313	-119	0.322	-117	0.312	-119	0.319	-118
600	0.313	-135	0.324	-133	0.314	-135	0.307	-141
700	0.315	-148	0.326	-147	0.314	-148	0.292	-154
800	0.314	-161	0.324	-159	0.312	-161	0.322	-168
900	0.310	-173	0.322	-171	0.310	-173	0.303	-179
1000	0.312	174	0.321	177	0.312	173	0.315	169
1100	0.318	162	0.329	166	0.321	162	0.346	165
1200	0.333	153	0.343	157	0.336	154	0.360	149
1300	0.347	147	0.354	150	0.346	147	0.363	146
1400	0.353	141	0.357	144	0.351	141	0.385	135
1500	0.347	134	0.353	137	0.347	134	0.390	126
1600	0.342	125	0.353	129	0.347	125	0.387	123
1700	0.349	116	0.366	121	0.359	116	0.398	117
1800	0.369	110	0.386	115	0.378	110	0.405	111
1900	0.390	106	0.399	112	0.393	105	0.396	110
2000	0.398	102	0.398	109	0.399	102	0.445	102

Laboratory 4 performed the entire calibration with the transistor fixture in place but used a completely different approach to compensate for the lack of a 50-Ω termination for the transistor socket. Instead of the 50-Ω termination called for in the first two steps, Laboratory 4 connected the through line at the transistor socket. This procedure relies on the 50-Ω termination at the output of the directional coupler to provide the reflectionless termination required. The transistor socket was left open for the third calibration step and the calibration short was inserted in the transistor socket for the fourth and fifth steps. Steps 6 and 7 were unnecessary because of isolation provided by attenuators between the coaxial terminals and the transistor fixture. The final calibration step was performed using the through line in the transistor socket.

The entire calibration procedure used by Laboratory 4 was performed with the transistor fixture in place using the calibration standards for the transistor socket which were furnished with the equipment. In this respect it is the same as the procedure employed when the 50-Ω termination for the transistor socket is available. It is quicker and easier than the procedure employed by laboratories 1, 2 and 3, which procedures require connecting and disconnecting the transistor fixture. The results obtained in the measurement of the transmission parameters, s_{21} and s_{12}, were in good agreement with those obtained when the other methods of calibration were used, but the results obtained in the measurement of the reflection parameters, s_{11} and s_{22}, were considerably different. In addition, the within-laboratory variability of the reflection parameter measurements was two to eight times greater than the within-laboratory variability of the measurements made after calibration by one of the other methods.

These differences are illustrated by the data in tables A5 through A8 in Appendix 2, which summarize the measurements of s_{11} and s_{21} made on R-C network 4 when all participants used the same transistor fixture. All the s_{21} data are in good agreement. The mean values of s_{11} obtained by Laboratories 1, 2 and 3 in most cases agree very closely with each other, while the means obtained by Laboratories 4 and 5 are frequently different from each other and from the results obtained by the other three laboratories. Furthermore, at most frequencies the within-laboratory standard deviation of the Laboratory 4 data was so high that Cochran's test for homogeneity of variance was not satisfied [4].

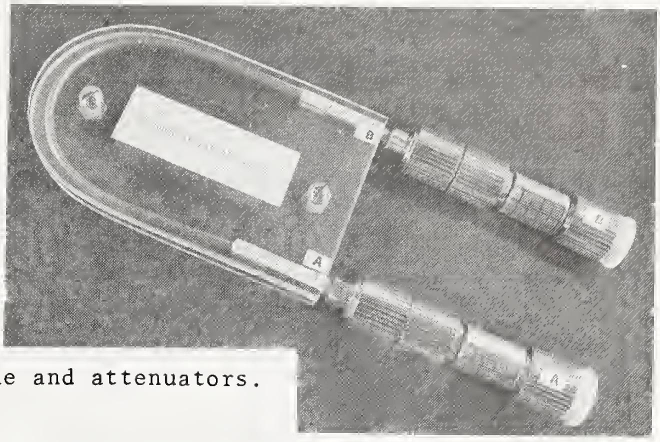


Figure 4. Coaxial through line and attenuators.

Differences in transistor fixtures cannot account for these differences because ach of the participants used the same transistor fixture for this measurement. Since he results obtained by Laboratory 4 in measuring the 20-dB attenuator were in good greement with the measurements made by the other laboratories (tables A1 through A4), he method of calibration used for measurements at the transistor socket is probably he source of the discrepancy. To determine if the differences in calibration proedures contribute to the differences in reflection parameter measurements, the measrements on the R-C networks were repeated on the NBS analyzer after calibration by the ethods of Laboratories 1, 2, 3 and 4 in turn. Lack of a 50-Ω termination prevented rying the method of Laboratory 5.

The R-C networks were measured in 100-MHz increments over the frequency range from 00 to 2000 MHz after each calibration. The magnitude and phase of s_{11} and s_{21} shown or R-C network 4 in tables 3 and 4 are typical of the results of these measurements. gain, s_{11} data obtained by the methods of Laboratories 1, 2 and 3 agree more closely ith each other than with the data obtained after calibration by the method of Labortory 4.

To simulate the results that might be expected if all participants calibrated by

TABLE 4 - EFFECT OF CALIBRATION METHOD ON s_{21} MEASUREMENTS

R-C NETWORK 4 DATA TAKEN ON NBS ANALYZER AFTER IT WAS CALIBRATED BY METHOD OF:

	LAB 1		LAB 2		LAB 3		LAB 4	
	s_{21}		s_{21}		s_{21}		s_{21}	
FREQUENCY MHZ	MAG	PHASE DEG	MAG	PHASE DEG	MAG	PHASE DEG	MAG	PHASE DEG
100	0.690	-14	0.689	-15	0.688	-15	0.695	-16
200	0.649	-29	0.651	-29	0.645	-29	0.664	-28
300	0.593	-41	0.601	-41	0.591	-41	0.591	-41
400	0.537	-53	0.545	-53	0.534	-53	0.530	-53
500	0.478	-63	0.483	-64	0.475	-63	0.483	-64
600	0.424	-72	0.429	-74	0.422	-72	0.419	-73
700	0.374	-80	0.377	-82	0.372	-80	0.374	-80
800	0.334	-87	0.337	-89	0.334	-87	0.330	-88
900	0.302	-94	0.301	-96	0.299	-94	0.302	-94
1000	0.270	-101	0.268	-103	0.267	-101	0.272	-101
1100	0.239	-107	0.240	-109	0.237	-108	0.239	-108
1200	0.215	-113	0.214	-115	0.212	-113	0.218	-114
1300	0.192	-118	0.190	-121	0.189	-119	0.194	-120
1400	0.174	-124	0.170	-127	0.172	-125	0.178	-125
1500	0.160	-130	0.153	-133	0.158	-131	0.164	-132
1600	0.146	-135	0.141	-138	0.144	-137	0.147	-137
1700	0.135	-141	0.131	-144	0.133	-142	0.136	-148
1800	0.127	-146	0.122	-149	0.125	-148	0.127	-149
1900	0.120	-151	0.115	-154	0.118	-153	0.116	-154
2000	0.114	-157	0.107	-160	0.113	-159	0.113	-160

the same method when using the common transistor fixture, a second statistical comparison of the original data was made using only the data from Laboratories 1, 2 and 3. Tables A13 through A16, which summarize this data for R-C network 4, show that the vari ability has been reduced from the corresponding values shown in tables A5 through A8 by a factor ranging between 10% and 40% in between-laboratory standard deviation and between 30% and 80% in within-laboratory standard deviation.

The data obtained from the interlaboratory comparison also provided a means for determining if any one of the calibration methods was significantly better than the others in compensating for anomalies introduced by the transistor fixtures. Before measuring the transistors, each participant measured the R-C networks in both the common transistor fixture and his own. In each case the same devices were measured on the same analyzer immediately after calibration of the system; the drift in calibratio should be minimal since the entire series of measurements on the three R-C networks required less than 15 minutes. The two series of measurements differed in the following respects:

> Different transistor fixtures were used, although both transistor fixtures were of the same construction.
>
> Different calibration standards, but of the same construction, were used with the two transistor fixtures. Each participant used the common set of calibration standards to calibrate the common fixture, but his own standards to calibrate his own fixture.

For each frequency and device, these data were grouped into pairs, one measuremen made with the R-C network mounted in the common transistor fixture and the other made with the device in the participant's fixture. A paired test [4] used to compare these measurements indicated that none of the calibration methods completely compensated for the effects introduced by the transistor fixture and that none had any advantage over the others in this respect.

From these tests it was concluded that a significant improvement in measurement precision could be obtained by specifying the calibration procedure to be used by the round-robin participants. In selecting this procedure, consideration should be given to the fact that most laboratories do not have a 50-Ω termination for the transistor socket. The calibration method of Laboratory 4 is simpler and faster than that used by the other participants who lacked a 50-Ω termination for the transistor socket, but the precision of Laboratory 4 reflection-parameter measurements was poor.

2.5 Results of Measurements

Analyses of some of the data taken by the five participants in the interlaborator comparison who used automatic systems for the measurement of transistor scattering parameters are tabulated in Appendix 2. These tables, which summarize the results of measurements made on the 20-dB attenuator, R-C network 4, and three of the transistors are representative of the measurements made on both transistors and passive devices, and illustrate the variability found in the measurements.

Statistics similar to those shown in Appendix 2 were compiled for all measurement To further condense these statistics, tables 5 and 6 show the mean, minimum and maximu variability of the S-parameter measurements made in the participant's transistor fixtu by the laboratories which used automatic equipment. Sample standard deviation is usec as a measure of the variability of phase measurements. Sample standard deviation expressed as a percentage of the overall mean to obtain relative standard deviation, or coefficient of variation, is used as an indication of the variability of amplitude measurements. The latter facilitates comparison of the variability of R-C network anc transistor measurements in which there are large differences in the magnitudes of the corresponding S parameters.

Note that the means listed in tables 5 and 6 are the means of the sample standarc deviations (relative sample standard deviations in the case of amplitude measurements). These were obtained by averaging the sample standard deviations of the measurements at all the measurement frequencies. Signal frequency is thus included as one of the variables which contribute to the dispersion of the measurements. As can be seen fron the data in Appendix 2, the standard deviation of some of the S-parameter measurements does tend to increase with frequency. The minimum and maximum values of standard deviation are also listed in the tables to indicate the extremes of variability encount ed in the measurements. The maximum value is the one quoted when a single number is used to indicate overall variability.

TABLE 5 - SUMMARY OF 51[a] VALUES OF THE SAMPLE STANDARD DEVIATION OF THE S-PARAMETER MEASUREMENTS OF THREE R-C NETWORKS AT 17[a] FREQUENCIES

MEASUREMENTS MADE BY[b]:		FIVE LABORATORIES		THREE LABORATORIES			
		BETWEEN-LABORATORY STANDARD DEVIATION		BETWEEN-LABORATORY STANDARD DEVIATION		WITHIN-LABORATORY STANDARD DEVIATION	
OF S-PARAMETER:		MAGNITUDE	PHASE	MAGNITUDE	PHASE	MAGNITUDE	PHASE
		%[c]	DEG	%[c]	DEG	%[c]	DEG
s_{11}	maximum	14.8	10.6	10.7	9.0	1.8	3.7
	mean	6.9	4.2	3.7	3.6	0.8	0.3
	minimum	2.2	1.1	0.1	0.1	0.3	0.2
s_{21}	maximum	9.6	4.6	10.2	3.5	2.8	2.0
	mean	2.3	1.8	2.6	1.7	0.7	0.8
	minimum	0.4	0.4	0.3	0.4	0.2	0.2
s_{12}	maximum	10.6	4.2	11.6	3.3	2.3	1.8
	mean	2.3	1.6	2.6	1.6	0.8	0.8
	minimum	0.3	0.5	0.1	0.5	0.3	0.2
s_{22}	maximum	10.2	7.6	5.9	6.1	1.6	2.0
	mean	5.0	4.1	2.8	3.2	0.7	0.8
	minimum	2.2	1.8	0.5	0.2	0.3	0.2

[a] Data for three laboratories are a summary of 48 measurements at 16 frequencies
[b] All measurements made in participant's transistor fixture
[c] Relative sample standard deviation is listed for measurements of magnitude

Table 5 summarizes the variability of the S-parameter measurements made on all the -C networks by the laboratories which used automatic test equipment. Each of the five aboratories made four measurements on each of the networks at each frequency. These our measurements were averaged to obtain a mean for the laboratory, and these means ere compared with those of the other laboratories to determine the between-laboratory ample standard deviation at each measurement frequency. In general this resulted in different sample standard deviation for each of the 17 measurement frequencies from 00 to 1800 MHz -- a total of 51 values for the three networks. Table 5 indicates the ange of this variability by recording the highest, lowest and mean values of these 1 standard deviations.

The first two columns of table 5 summarize the between-laboratory variability of he measurements made by all five laboratories. The third and fourth columns record imilar data for laboratories 1, 2 and 3, which laboratories differed least in their alibration procedures. These data simulate the results that would be obtained if all aboratories had used the same procedure in calibrating with the transistor fixture. ey are a summary of 48 values of standard deviation rather than 51 because the 200-Hz data were discarded to provide a comparison with the transistor statistics for the ame three laboratories.

The final two columns of table 5 summarize the within-laboratory variability of e measurements made by Laboratories 1, 2 and 3. The within-laboratory sample stand-rd deviation is a measure of the dispersion of the four measurements made by each of e laboratories about the mean for that laboratory. The values obtained by each of e laboratories at each frequency were pooled to obtain a single sample standard de-iation for each of the devices at each of the measurement frequencies. Table 5 ecords the largest, smallest and mean values of these 48 pooled values. These data ow that the laboratories are capable of repeating their measurements within a maximum elative sample standard deviation of 3% in the measurement of magnitude and within a ximum sample standard deviation of 2 deg in the measurement of phase, except for the ase of s_{11} for which the sample standard deviations are within 4 deg.

The first two columns of table 6 summarize the variability of the 102 measurements de on the six 2N3960 transistors at an emitter current of 2.5 mA. In addition, the riability of h_{fe} and h_{ie} values calculated from the S-parameter measurements made by ch of the participants is listed. The 2N3960s were picked for this comparison be-

TABLE 6 - SUMMARY OF 102 VALUES OF THE BETWEEN-LABORATORY SAMPLE STANDARD DEVIATION OF MEASUREMENTS MADE ON TRANSISTOR TYPE 2N3960 AT AN EMITTER CURRENT OF 2.5 mA

MEASUREMENTS MADE BY[a]:		FIVE LABORATORIES		THREE LABORATORIES	
STANDARD DEVIATION OF S PARAMETER:		MAGNITUDE %[b]	PHASE DEG	MAGNITUDE %[b]	PHASE DEG
s_{11}	maximum	45.9	34.2	7.5	8.2
	mean	12.6	8.8	4.5	1.8
	minimum	3.5	0.7	0.6	0.1
s_{21}	maximum	9.9	3.3	5.4	1.7
	mean	2.9	1.1	2.7	0.7
	minimum	0.9	0.2	0.7	0.1
s_{12}	maximum	5.2	1.7	6.6	2.2
	mean	2.4	0.9	3.0	0.9
	minimum	0.9	0.2	0.2	0.1
s_{22}	maximum	8.9	3.1	4.8	3.5
	mean	4.4	2.0	2.8	2.0
	minimum	1.6	0.7	0.8	0.5
h_{fe}	maximum	8.6	5.0	7.0	3.0
	mean	3.4	1.6	2.2	1.1
	minimum	0.8	0.4	0.2	0.2
h_{ie}	maximum	23.1	12.0	2.6	3.0
	mean	5.2	3.1	1.0	1.6
	minimum	1.1	0.5	0.0	0.3

a All measurements made in participant's transistor fixture
b Relative sample standard deviation is listed for measurements of magnitude

cause they were measured over the same frequency range as the R-C networks and becaus all six transistors were measured by all participants. These data are typical of tha obtained at other biases and from the measurement of the other transistor groups (tables A23 and A24, Appendix 2).

The variability of the transistor S-parameter data compares favorably with that the R-C networks except for measurements of s_{11}. It is also noticeable that, in most cases, transistor phase measurements are less variable than the phase measurements on the R-C networks. A possible explanation for the latter is the diffuse nature of the resistive and capacitive elements in the transistor. These may have less effect on phase measurements than the lumped elements of the R-C networks when the location of the reference plane varies by a small amount as it may because of differences in the measurement systems, the calibration standards, or the seating of the device under te in the transistor socket.

The variability of the s_{11} measurements is mainly the result of differences in calibration procedures employed when using the transistor fixture. In addition, the variability of transistor s_{11} and s_{21} measurements was affected by the signal level used by Laboratory 3, which exceeded requirements for small-signal conditions. This resulted in overdriving the transistor under test when the signal was applied to the base of the transistor for the measurement of s_{11} and s_{21}. The effect was most notic able at the lower measurement frequencies where transistor beta is highest. The ove drive had a negligible effect on measurements of s_{12} and s_{22}, which are made with the drive applied to the collector of the transistor, and had no effect on the measureme of any of the S parameters of the R-C networks.

Since the calibration procedures used by Laboratories 1, 2 and 3 were nearly id tical, their data were analyzed to estimate the improvement that might be realized i differences in calibration procedures were eliminated. The 200-MHz measurements wer discarded from these data to eliminate the frequency at which the effects of the ove drive were most severe.

These data, listed in the final two columns of table 6, show a general improvement in the variability of the transistor S-parameters and considerable reduction in the variability of s_{11} measurements. Based on these results it is estimated that between-laboratory variability of s_{11} measurements could be held to a maximum relative sample standard deviation of 7.5% in the measurement of magnitude and a maximum sample standard deviation of 8 deg in the measurement of phase, and that the variability of the other S-parameter measurements could be reduced to a relative sample standard deviation of 6.5% in the measurement of magnitude and a maximum sample standard deviation of 3.5 deg in the measurement of phase. This would require that the calibration procedure for use with the transistor fixture be agreed upon and that a maximum signal to the transistor under test be specified.

Since the variabilities of the transistor and R-C network measurements are comparable under these conditions, it is probable that closer control of transistor test conditions such as bias and temperature would not by itself significantly improve the precision of the transistor measurements.

2.6 Conclusions

The following conclusions are based on the results of measurements made on automatic measurement systems. A similar assessment of the variability of measurements made manually was not feasible because of the time that would have been required for a set of replicate measurements using manual equipment. The S-parameter measurements made manually by one of the laboratories, although more limited in scope, were in good agreement with those reported here for the automatic systems.

The results of the interlaboratory comparison of transistor scattering parameter measurements can be summarized as follows:

1. In general, scattering parameter measurements made by the participants in the interlaboratory comparison were in good agreement except for the measurement of s_{11}. The relative sample standard deviation of measurements of the magnitude of s_{21}, s_{12} and s_{22} was 10% or less, and the sample standard deviation of phase measurements did not exceed 3.5 deg. In the measurement of s_{11}, relative sample standard deviations as high as 46% were recorded in the measurement of magnitude and sample standard deviations as large as 34 deg occurred in the measurement of phase.
2. The variability was aggravated by the differences in calibration procedures used by the participants and by an excessively high test signal level used by one of the laboratories. The former affected measurements of s_{11} and the latter measurements of both s_{11} and s_{21}.
3. If differences in calibration procedures and signal levels were eliminated, it is estimated that the between-laboratory variability of s_{11} measurements could be reduced to a maximum relative sample standard deviation of 7.5% in the measurement of magnitude and a maximum sample standard deviation of 8 deg in the measurement of phase. The variability of all other S-parameter measurements could be reduced to a maximum relative sample standard deviation of 6.5% in the measurement of magnitude and a maximum sample standard deviation of 3.5 deg in the measurement of phase.
4. Measurements made on the R-C networks under the same conditions as the transistor measurements (except that no bias was required) indicate that the laboratories are capable of repeating their measurements within a relative standard deviation of better than 3% in the measurement of S-parameter magnitude and a standard deviation of less than 4 deg in the measurement of s_{11} phase and 2 deg in the measurement of the phase of the other S parameters.
5. Since the variabilities of the transistor and R-C network measurements are so nearly alike, it is not probable that more accurate setting of transistor biases or better control of case temperature, by itself, would increase precision significantly.
6. Better agreement among laboratories would be obtained if the calibration procedure to be used with the transistor fixture were agreed upon in advance. The calibration procedure chosen should not depend on the use of a 50-Ω termination at the transistor socket, unless a 50-Ω termination is known to be available to the participating laboratories. The maximum signal applied to the transistor under test should also be limited to a level that will assure small-signal operation.

3. ELECTRICAL CHARACTERIZATION OF TRANSISTOR PROBE ASSEMBLIES

3.1 Background

Probe assemblies for making contact with transistor contact pads embedded in integrated circuit wafers were described in the previous report and are illustrated in figure 5. These were designed to measure the S parameters at ultra-high frequencies of individual integrated-circuit transistors at the wafer stage of assembly. The mechanical characterization of the probe assemblies, the steps preparatory to determination of the equivalent electrical circuit, and the probe reference units required for this determination were all described in the previous report [1]. The final task, that of electrically characterizing the probe assemblies, is reported here.

The characteristics of the probes must be separated from the measured S parameters of a device to determine the intrinsic characteristics of the device when it is connected to the measurement system by means of the probe assembly. This can be done if the S parameters of the probe assembly are known. These can be determined by making measurements at the input ports of the probes with the probe tips in contact with elements having known impedance values. The probe reference units chosen for this purpose permitted termination of the assemblies in an open circuit, a short circuit, and a known resistance.

3.2 Measurements and Results

A probe assembly with adaptors for connection to the 7-mm precision coaxial connectors at the output ports of the network analyzer can be represented as two sections of transmission line as shown in figure 6. The problem is to evaluate the probe assembly by measurements at ports A and B when known impedances are connected to ports C and D. The probe assemblies were of two different configurations, three with the center probe grounded and three with one of the end probes grounded. Different probe reference units were used for testing the two types, but electrically the methods were identical. Stray coupling between the ungrounded conductors of ports C and D was shown to be negligible and does not affect the results.

Initially, it was planned to determine the probe-assembly characteristics at three or four discrete frequencies by bridge and slotted-line techniques. Once the probe assemblies were received and one was set up in the slotted-line measurement system, however, it became very apparent that this would be a difficult and time-consuming task. It was also seen that measurements at more than three or four frequencies would be required to analyze and characterize the probe assemblies properly. Therefore, it was decided to use the automatic network analyzer to measure the S parameters of the probe assemblies.

It would have been desirable to establish a reference plane for these measurements at the input connectors of the probes. Since the miniature coaxial connectors used for

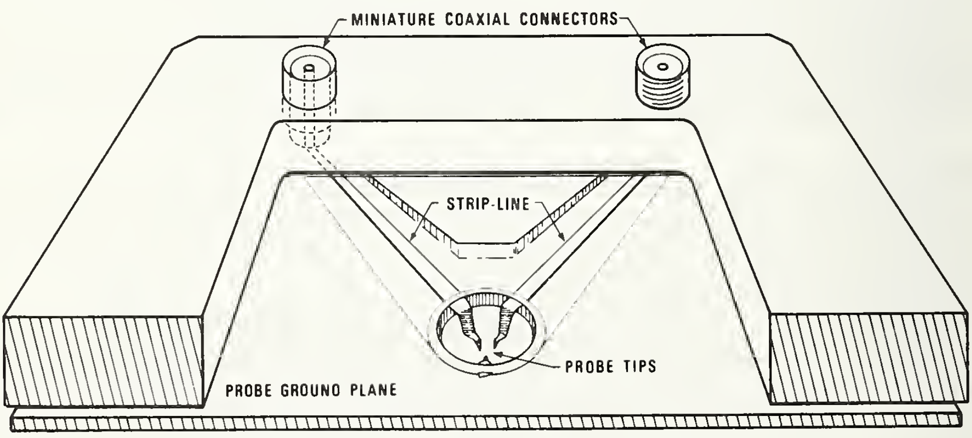


Figure 5. Special probe assembly.

Drawing is not to scale. The probe tips are in line on 0.003-in. (0.08-mm) centers, the diameter of the hole in the sapphire plate is 0.1 in. (2.5 mm), and the miniature coaxial connectors are on 0.6-in. (1.5 cm) centers.

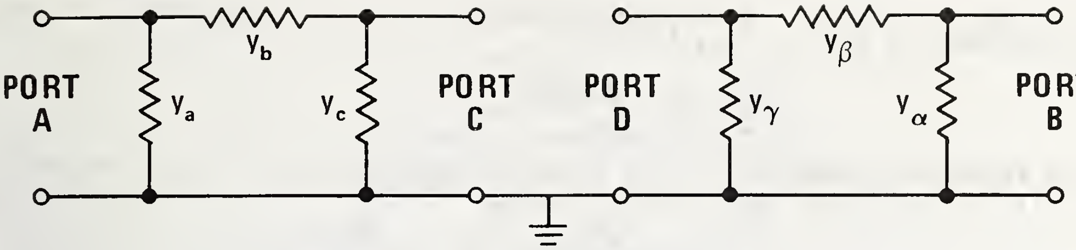


Figure 6. Schematic diagram of probe assembly.

his purpose do not have a well-defined reference plane and suitable reference standards ere not available for them, an adaptor from miniature to 7-mm connector was used. The eference plane used for all measurements was established by a short-circuit termination t the 7-mm connector. The loads connected to the probe tips were those designated 0,3) in the first quadrant of probe reference unit wafer number 6.[3]

The probe assemblies were connected to the network analyzer and the S parameters easured in 0.1-GHz increments from 0.2 to 2 GHz with the probe tips in contact with a hort circuit, an open circuit, and a resistance, in turn (Fig. 7). From the measured parameters, the input admittances at ports A and B of the probes were determined for hree different loads at the probe tips, ports C and D. This provided the three equations necessary to determine the three unknown admittances in the equivalent circuit of ach of the probes.

When the probes are terminated by the short-open load configuration with short at ort C (Fig. 7a), the input admittance at port A, Y_{As}, is given by

$$Y_{As} = y_a + y_b$$

The probe reference units are described in Reference 1.

a. Short-open termination; short circuit at port C.

b. Short-open termination; open circuit at port C.

c. Resistor-short termination; resistor connected to port C.

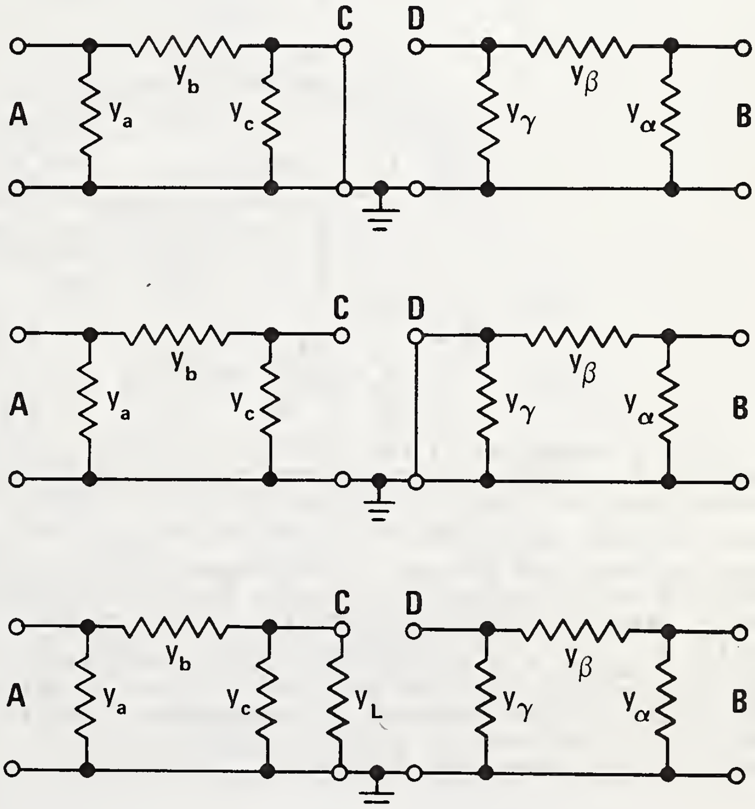


Figure 7. Circuits used for determination of admittances of the probe assemblies.

When the load is reversed, shorting port D and leaving port C open (Fig. 7b), the input admittance at port A, Y_{Ao}, is

$$Y_{Ao} = y_a + \frac{y_b\, y_c}{y_b + y_c}$$

When the probes are terminated by the resistor-short load with resistor at port C (Fig. 7c), the input admittance at port A, Y_{Ar}, is

$$Y_{Ar} = y_a + \frac{y_b\,(y_c + y_L)}{y_b + y_c + y_L}$$

Similarly, when port D is successively terminated in a short, an open, and a resistance, using the same load configurations but reversed, the admittances at port B are

$$Y_{Bs} = y_\alpha + y_\beta$$

$$Y_{Bo} = y_\alpha + \frac{y_\beta\, y_\gamma}{y_\beta + y_\gamma}$$

$$Y_{Br} = y_\alpha + \frac{y_\beta\,(y_\gamma + y_L)}{y_\beta + y_\gamma + y_L}$$

The values of these six admittances were then used to solve for the components c the equivalent network, y_a, y_b, y_c, y_α, y_β and y_γ, where

$$y_a = Y_{As} - y_b$$

$$y_b = \sqrt{\frac{(Y_{As} - Y_{Ao})\,(Y_{As} - Y_{Ar})}{(Y_{Ar} - Y_{Ao})}\, y_L}$$

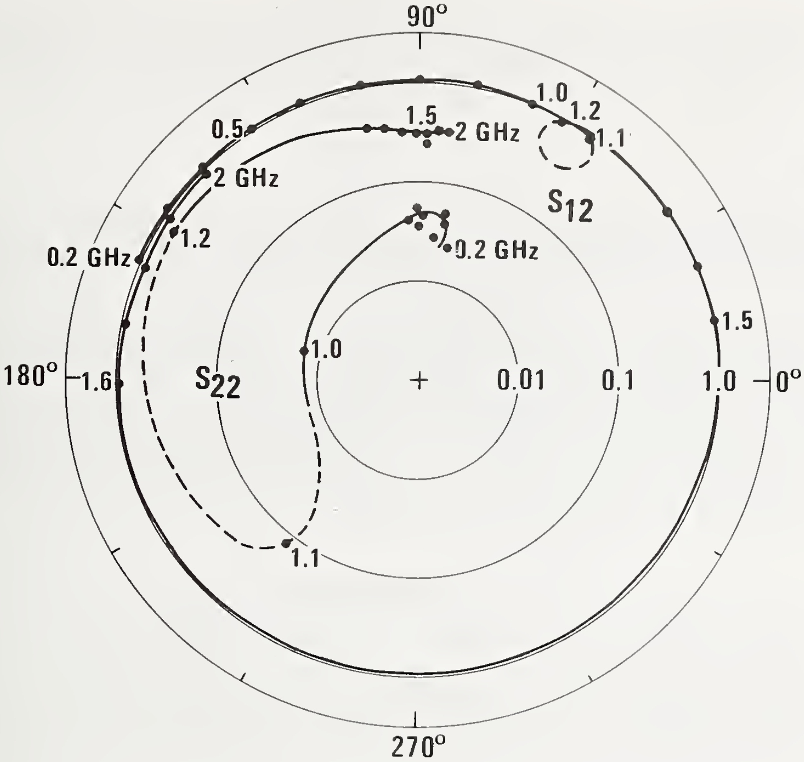
$$y_c = \frac{(Y_{As} - Y_{Ar})}{(Y_{Ar} - Y_{Ao})}\, y_L - y_b$$

$$y_\alpha = Y_{Bs} - y_\beta$$

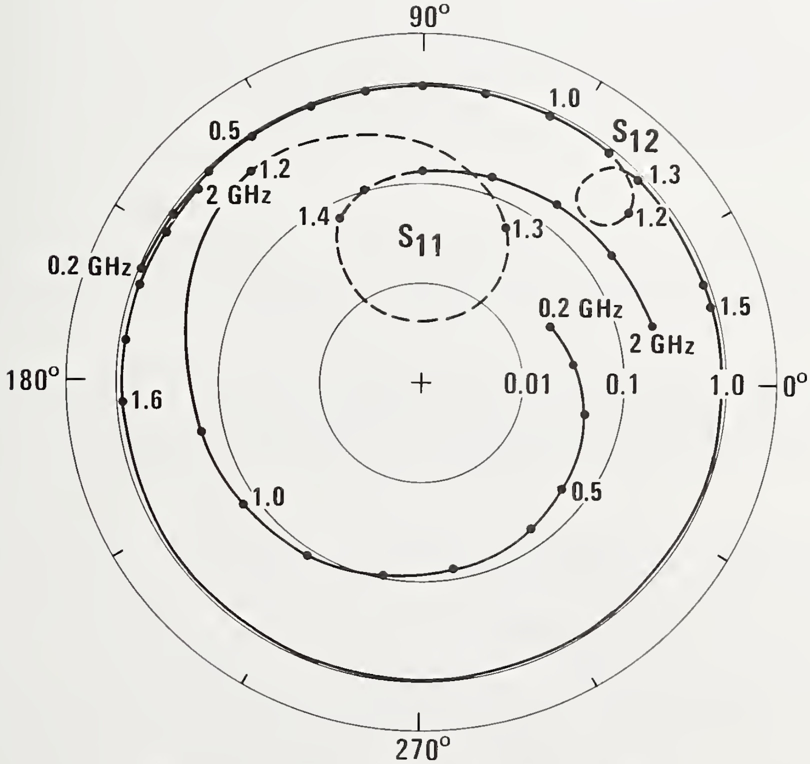
$$y_\beta = \sqrt{\frac{(Y_{Bs} - Y_{Bo})\,(Y_{Bs} - Y_{Br})}{(Y_{Br} - Y_{Bo})}\, y_L}$$

$$y_\gamma = \frac{(Y_{Bs} - Y_{Br})}{(Y_{Br} - Y_{Bo})}\, y_L - y_\beta$$

The S parameters of the probes were calculated from the admittances of the equivalent circuit. Typical values are plotted in polar form with a logarithmic radial scale in figure 8. In figure 8a, s_{22} and s_{12} of a typical center-ground probe assembly are shown, and in figure 8b, s_{11} and s_{12} of a typical end-ground probe assembly are plotted. A resonance in the vicinity of 1.2 GHz, which was observed on the monitor oscilloscope during measurements on all of the probe assemblies, results in abrupt changes in the S-parameter values over a 0.2-GHz interval in the 1.0- to 1.5-GHz frequency range. Within the range which is shown by dashed lines in figure 8, a more detailed plot of the probe characteristics could have bee obtained by decreasing the frequency interval at which measurements were made, but this would not have improved the measurement capabilities of the probes within abou ±0.1 GHz of the resonant frequency because of the very rapid change of S-parameter magnitude and phase with frequency in this region.



a. Center-ground probe assembly, serial number 103.



b. End-ground probe assembly, serial number 104.

Figure 8. S parameters of probe assemblies referred to port A.

For measurements at other frequencies, the intrinsic parameters of the measured device can be determined by multiplying the scattering matrix of the measured S parameters by the inverse of the scattering matrix of the probe [5]. If measurements are not made in a 50-Ω system, the difference in impedances must be taken into consideration.

3.3 Conclusions

While the objective to evaluate the probe assemblies in terms of their S parameters was achieved, it is apparent that resonances in the probe assemblies limit their usefulness for measurements in the vicinity of 1.2 GHz. The theoretical groundwork has been laid, however, for the development of a very accurate probe capability. Work is underway at the NBS Boulder laboratories[4] to further refine these techniques to obtain a more accurate model of the probe assembly, to determine design changes needed to eliminate resonances over the frequency range of interest, and to determine the limit of accuracy of the high-frequency probe technique. This later work has shown that there is a parasitic element in the ground probe lead, requiring modification of the schematic representation of figure 6 to include an additional element common to the ground leads of both ports C and D. By methods similar to those described here, the value of this parasitic element can be determined by measurements at ports A and B with suitable loads connected to ports C and D.

4. ACKNOWLEDGEMENTS

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4 AFWL Project Order PO-74-144, AC Probe Characterization.

APPENDIX 1

Plan for an interlaboratory comparison of transistor scattering-parameter measurements

October 29, 1972

Purpose:

To assess the variability of the S-parameter measurement systems as used by the participants.

The method employed is to measure selected transistors on each of the S-parameter measurement systems and to compare the results obtained. As a check against possible changes in the transistor parameters and variability introduced by auxiliary systems such as transistor fixtures and bias supplies, a coaxial attenuator and passive networks will be included in the measurements. For each device, both magnitude and phase of s_{11}, s_{21}, s_{12}, and s_{22} will be measured as a function of frequency. Each of the passive elements will be measured more than once on each system to obtain a measure of the variability of the individual systems.

Conditions being studied:

1. Differences in the results obtained from the S-parameter test sets when measuring the same device, including effects of the operator and the associated fixtures and bias supply systems.

2. Differences introduced by transistor fixtures.

3. The effect of transistor bias on the measurements. The measurements are relatively insensitive to changes in V_{CE}, but are very sensitive to changes in emitter current, especially at the lower values of emitter current. Five percent accuracy in the measurement of V_{CE} and 1 percent accuracy in the measurement of emitter current would be desirable. These accuracies are not specified for the round robin, however, because the intent is to measure the transistors by the procedure normally used by the participants. Measurement of the passive networks will provide a measure of the variability of the S-parameter measurement systems which is independent of bias levels. The tests may disclose that more accurate control of bias levels is required for repeatable transistor measurements.

Conditions not being studied:

1. The transistors, except to the extent necessary to be sure that their characteristics haven't changed during the round robin. NBS will record the characteristics of each transistor before the testing begins and will periodically check transistor performance against these characteristics.

2. The effect of transistor case temperature on the measurements. The sensitivity of the measurements to temperature changes is low enough to make special provisions for the control of transistor case temperature unnecessary at the power levels used in these tests provided the laboratory temperature is within the range 68° to 77°F (20° to 25°C).

Devices to be tested:

The following devices will be circulated for test to each of the participants (all participants will test the same devices):

a. Two coaxial attenuators with a length of semi-rigid coax for connecting them in series to the test set.

b. A transistor fixture to adapt the S-parameter test set for the measurement of transistors in TO-18 and TO-72 packages.

c. Three RC networks mounted on transistor TO-72 headers.

d. Six transistors of each of the following types: 2N709, 2N918, and 2N3960.

Test Procedure:

1. Record the manufacturer, model number and serial number of the equipment used in making the measurements.
2. Record the method of reducing the RF drive to the transistor under test if one is used.
3. Record the method of setting the transistor bias levels, their accuracy, and indicate how the accuracy is verified.

Measurements:

The transistors to be tested have been divided into two groups, A and B, each group comprising three transistors of each type. These are to be tested along with the passive elements as follows:

1. Record the laboratory ambient temperature.
2. Calibrate the S-parameter measurement system without the transistor fixture at frequencies between 200 MHz and 2 GHz in increments of 100 MHz and record the procedure used. Use the coaxial link furnished by NBS as the through line, connecting it so that the terminal marked A is connected to the A port of the S-parameter test set and the terminal marked B is connected to the B port. The electrical length of this link is 46.525 cm. After calibration, change the transmission linearization to 46.525 cm.
3. Connect the 10-dB attenuators to the output ports of the test set, with the end marked A connected to the A port and the end marked B to the B port. Connect the attenuators in series by means of the coaxial link, again connecting it so that the terminal marked A connects to the attenuator connected to the A port and the terminal marked B connects to the attenuator connected to the B port. Measure and record the S-parameters at frequencies between 200 MHz and 2 GHz in 100-MHz increments.
4. Using the calibration standards (THRU LINE and SHORT) provided by NBS where applicable, calibrate the S-parameter measurement system with the NBS transistor fixture connected to the output ports at frequencies between 200 MHz and 2 GHz in 100-MHz increments, and record the procedure used.
5. Measure and record the S-parameters of the RC networks at frequencies between 200 MHz and 2 GHz in 100-MHz increments using the common-base configuration on the NBS transistor fixture.
6. Connect the participant's transistor fixture to the output ports of the S-parameter system and calibrate the system using the participant's calibration standards at frequencies between 200 MHz and 2 GHz in 100-MHz increments.
7. Connect each of the devices in turn to the participant's transistor fixture and measure and record the S-parameter of the device.

   a. Measure the RC networks in the common-base configuration at frequencies between 200 MHz and 2 GHz in 100-MHz increments.

   b. Measure the transistors of Group A in the common-emitter configuration under the following conditions:

Type	V_{CE} (Volts)	I_E (mA)	FREQUENCY (MHz) START	STOP	INCREMENT
2N709	5	1.6, 2.0, 2.5, 4.0, 5.0, 8.0, 10.0	200	1000	100
2N918	5	1.6, 2.0, 2.5, 4.0 5.0 8.0 10.0	200	1000	100
2N3960	5	1.6, 2.0, 2.5, 4.0 5.0 8.0 10.0	200	1800	100

   c. Repeat the measurements on the RC networks in the common-base configuration at frequencies between 200 MHz and 1800 MHz in 100-MHz increments.

8. Recalibrate the system with the NBS transistor fixture connected to the output ports (using the same calibration procedure as in 4) and remeasure and record the S-parameters of the RC networks in the common-base configuration at frequencies between 200 MHz and 2 GHz in increments of 100 MHz.

9. Recalibrate the system without the transistor fixture (using the same calibration procedure as in 2) and remeasure and record the S-parameters of the 10-dB attenuators connected in series at frequencies between 200 MHz and 2 GHz in 100-MHz increments.

10. Record the laboratory ambient temperature.

11. On a different day, repeat the measurements outlined in 1 thru 10, but use the transistors of Group B in step 7, b.

ta to be furnished to NBS:

1. The manufacturer, model number and serial number of the equipment used for the measurements.

2. The step-by-step procedure used in calibrating the S-parameter measurement system. If the manufacturer's procedure is followed, a statement to this effect with a reference to the document (including date or edition) and page where the procedure is found is sufficient. Be sure to record any deviations from the stated procedure.

3. The step-by-step procedure used in calibrating the system when the transistor fixture is added. If the manufacturer's procedure is followed, a statement to this effect with a reference to the document (including date or edition) and page where the procedure is found is sufficient. Be sure to record any deviations from the stated procedure.

4. The method of reducing the RF drive to the transistor under test if one is used.

5. The method of setting the bias levels, the accuracy of these levels, and the method of verifying the accuracy.

6. A tabulation of S-parameters versus frequency for each of the devices. To reduce the time required for processing the data at NBS and to minimize errors, we would prefer to receive the data punched on teletype tape if this is possible; if this would entail extra work on the part of the participants, a data printout is acceptable. Each set of data should be identified with the name of the device tested (if a transistor include both the type number and the letter identifying the sample) and the conditions of test. This information should be written on the tape ahead of the data. Leave a gap of 3 or 4 inches on the tape between sets of data.

   The beginning of each tape must be visibly marked to identify the participant and the contents of the tape. This can be done by marking the tape with the identity of the participant and listing the contents of the tape, for example, NBS, passive devices, first set, first day; NBS, Group A, 2N709; etc. An alternate method would be to mark the tape with the identity of the participant and an identifying letter or number and provide the legend on a separate sheet.

APPENDIX 2

STATISTICAL SUMMARY OF REPRESENTATIVE S-PARAMETER MEASUREMENTS

The following are representative analyses of the data taken during the interlaboratory comparison using automatic measuring equipment. Included are a summary of the measurements of s_{11} and s_{21} for the 20-dB attenuator and R-C network 4, and a summary of all the S parameters of transistors 2N3960(f), 2N709(g) and 2N918(a) at an emitter current of 2.5 mA. The summaries are representative of those made on the other passive devices and transistors under similar conditions. Since the passive devices are symmetrical, the summaries are also typical of s_{22} and s_{12} data for these devices. Measurements made manually were in reasonable agreement with those made on the automatic systems.

The 20-dB attenuator data are summarized in tables A1 through A4. Measurements on R-C network 4 made in the common transistor fixture are summarized in tables A5 through A8, and those made in the participants' transistor fixtures in tables A9 through A12. In addition, the measurements on R-C network 4 by the three laboratories which used nearly identical calibration procedures are analyzed for the common transistor fixture in tables A13 through A16, and for the participants' transistor fixtures in tables A17 through A20.

Each participant measured the transistors in his own transistor fixture. Data on transistor 2N3960(f) at an emitter current of 2.5 mA are analyzed for both five and three laboratories in tables A21 and A22, respectively, and data on transistors 2N709(g) and 2N918(a) are given in tables A23 and A24.

In tables A1 through A20, which summarize the measurements on passive devices, the upper table lists the means of the four measurements made by each laboratory at each frequency in the columns headed MEAN OF 4 MEASUREMENTS. In the columns headed BETWEEN-LABORATORY, the means obtained by averaging the laboratory means are given in the column headed MEAN, and the standard deviation of the laboratory means about this overall mean are given in the column headed STD DEV. In addition, in the tables which describe the measurements of S-parameter magnitude (odd-numbered tables), the relative standard deviation, or percent coefficient of variation, is given in the column headed PCT C.V.

In these first 20 tables, the lower table shows the standard deviation of the four measurements made by each laboratory about the mean for that laboratory in the columns headed WITHIN-LABORATORY, the pooled value for all the within-laboratory standard deviations in the column headed STD DEV, and the relative standard deviation in the column headed PCT C.V. if the table is one which describes the variability of S-parameter magnitude.

The pooled standard deviation is listed only when the individual laboratory variances (squares of the standard deviations) are sufficiently similar to be considered homogeneous as determined by Cochran's test [4]. This test is designed to determine if one of the variances is sufficiently larger than the rest to invalidate an analysis of variance. For 5 sets of 4 measurements each, the largest variance must be equal to or less than 0.6329 times the sum of all the variances to satisfy Cochran's test at the 1 percent level of significance. For four laboratories the critical value is 0.7212, and for three laboratories it is 0.8335.

In tables A21 through A24, which summarize the results of transistor measurements, the S-parameters shown in the upper table are the means obtained by averaging the measurements made by all the laboratories; the corresponding between-laboratory sample standard deviations are listed in the lower table. Relative standard deviation is used to describe the variability of the measurements of S-parameter magnitude, and standard deviation is used to describe the variability of phase measurements.

TABLE A1. SUMMARY OF S_{11} MAGNITUDE MEASUREMENTS MADE BY FOUR[a] LABORATORIES ON 20-dB ATTENUATOR.

MEANS

FREQUENCY* MHZ *	MEAN OF 4 MEASUREMENTS LAB 2	LAB 3	LAB 4	LAB 5 *	BETWEEN-LABORATORY MEAN	STD DEV	PCT C.V.
200.	.009	.008	.009	.011	.0092	.0012	12.68
300.	.008	.008	.009	.010	.0088	.0012	14.19
400.	.006	.008	.008	.010	.0082	.0015	17.87
500.	.006	.007	.007	.009	.0075	.0015	19.63
600.	.008	.009	.009	.011	.0092	.0014	14.80
700.	.009	.008	.009	.011	.0091	.0011	12.15
800.	.007	.007	.007	.009	.0076	.0010	13.33
900.	.011	.010	.011	.013	.0113	.0010	8.72
1000.	.011	.010	.010	.012	.0109	.0011	9.76
1100.	.008	.008	.008	.010	.0085	.0009	10.47
1200.	.010	.010	.011	.012	.0109	.0011	9.76
1300.	.011	.009	.010	.011	.0102	.0008	8.11
1400.	.009	.008	.009	.010	.0090	.0006	7.17
1500.	.010	.009	.010	.011	.0101	.0008	7.68
1600.	.011	.007	.008	.008	.0088	.0015	17.24
1700.	.011	.009	.010	.010	.0100	.0005	5.40
1800.	.011	.008	.009	.010	.0095	.0012	12.34
1900.	.009	.007	.007	.008	.0080	.0008	10.52
2000.	.012	.011	.012	.011	.0119	.0004	3.65

STANDARD DEVIATION

FREQUENCY* MHZ *	WITHIN-LABORATORY LAB 2	LAB 3	LAB 4	LAB 5 *	ALL LABS POOLED[b] STD DEV	PCT C.V.
200.	.0013	.0006	.0005	.0000	*****	7.96
300.	.0005	.0012	.0005	.0006	.0007	8.41
400.	.0006	.0010	.0010	.0000	.0007	9.16
500.	.0014	.0012	.0010	.0006	.0011	14.40
600.	.0015	.0010	.0010	.0000	.0010	11.03
700.	.0005	.0005	.0005	.0005	.0005	5.48
800.	.0008	.0010	.0010	.0000	.0008	10.63
900.	.0008	.0006	.0014	.0005	.0009	7.97
1000.	.0017	.0010	.0010	.0005	.0011	10.31
1100.	.0014	.0010	.0010	.0005	.0010	12.01
1200.	.0010	.0005	.0013	.0006	.0009	8.03
1300.	.0005	.0005	.0013	.0000	*****	7.08
1400.	.0005	.0005	.0013	.0005	.0008	8.49
1500.	.0024	.0005	.0013	.0008	.0014	14.11
1600.	.0014	.0006	.0015	.0006	.0011	12.58
1700.	.0015	.0006	.0014	.0005	.0011	10.99
1800.	.0008	.0005	.0014	.0005	.0009	9.37
1900.	.0019	.0006	.0017	.0005	.0013	16.73
2000.	.0005	.0006	.0015	.0006	.0009	7.49

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a Laboratory 1 data were discarded. There were large discrepancies in the phase measurements made by Laboratory 1 because two different methods were used to compensate for the length of coaxial line which connected the two 10-dB attenuators.

b Pooled values of within-laboratory standard deviation are given only when the laboratory variances satisfy Cochran's test for homogeneity of variance at the 1 percent level of significance; i.e., when the largest variance is less than or equal to 0.7212 times the sum of the variances.

TABLE A2. SUMMARY OF S_{11} PHASE MEASUREMENTS MADE BY FOUR[a] LABORATORIES ON 20-dB ATTENUATOR.

MEANS - DEGREES

FREQUENCY* MHZ *	MEAN OF 4 MEASUREMENTS LAB 2	LAB 3	LAB 4	LAB 5	* BETWEEN-LABORATORY * MEAN	STD DEV
200.	155.9	160.2	160.9	161.9	159.74	2.66
300.	145.6	153.6	154.0	155.6	152.22	4.47
400.	127.6	143.9	143.8	147.0	140.58	8.80
500.	122.4	142.5	141.9	145.4	138.05	10.54
600.	132.6	138.8	138.5	141.1	137.76	3.63
700.	107.6	119.0	119.4	122.4	117.13	6.52
800.	114.3	128.1	125.7	128.1	124.04	6.57
900.	104.0	118.7	117.4	121.1	115.30	7.69
1000.	72.7	92.2	91.4	95.4	87.92	10.28
1100.	71.2	93.7	94.6	96.0	88.89	11.83
1200.	68.5	85.5	84.5	93.9	83.10	10.63
1300.	51.9	64.1	63.4	70.0	62.37	7.57
1400.	48.4	65.4	63.5	73.4	62.69	10.46
1500.	38.3	52.4	52.4	63.8	51.73	10.41
1600.	24.9	49.1	45.8	60.7	45.11	14.93
1700.	26.7	47.9	44.1	54.0	43.19	11.73
1800.	3.3	26.6	24.0	39.3	23.31	14.94
1900.	14.5	44.7	37.8	50.7	36.92	15.86
2000.	13.0	29.3	25.7	43.5	27.87	12.57

STANDARD DEVIATION - DEGREES

FREQUENCY* MHZ *	WITHIN-LABORATORY LAB 2	LAB 3	LAB 4	LAB 5	*ALL LABS[b] * POOLED
200.	11.48	2.15	.49	2.14	****
300.	10.14	2.88	.74	4.21	****
400.	7.54	3.36	.72	2.22	****
500.	12.15	3.63	.48	.97	****
600.	11.06	3.60	.26	1.13	****
700.	6.79	4.42	1.03	1.79	4.18
800.	5.50	4.26	.99	2.87	3.80
900.	2.31	3.30	.22	1.23	2.11
1000.	7.40	5.40	1.89	1.54	4.74
1100.	11.91	6.13	1.54	5.30	7.24
1200.	11.45	5.52	1.89	2.05	****
1300.	8.77	6.39	3.74	3.95	6.07
1400.	6.92	7.91	4.09	3.97	5.98
1500.	6.08	7.85	5.00	2.91	5.74
1600.	8.11	9.28	5.97	7.92	7.91
1700.	3.94	8.09	4.73	3.27	5.34
1800.	7.04	9.00	8.62	3.25	7.34
1900.	6.92	9.15	5.88	1.54	6.49
2000.	7.43	6.77	4.74	5.31	6.16

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a Laboratory 1 data were discarded. There were large discrepancies in the phase measurements made by Laboratory 1 because two different methods were used to compensate for the length of coaxial line which connected the two 10-dB attenuators.

b Pooled values of within-laboratory standard deviation are given only when the laboratory variances satisfy Cochran's test for homogeneity of variance at the 1 percent level of significance; i.e., when the largest variance is less than or equal to 0.7212 times the sum of the variances.

Table A3. Summary of S_{21} magnitude measurements made by four[a] laboratories on 20-dB attenuator.

MEANS

FREQUENCY* MHZ *	MEAN OF 4 MEASUREMENTS LAB 2	LAB 3	LAB 4	LAB 5	* BETWEEN-LABORATORY * MEAN	STD DEV	PCT C.V.
200.	.103	.104	.103	.104	.1034	.0003	.32
300.	.103	.103	.103	.104	.1034	.0005	.44
400.	.103	.103	.103	.104	.1034	.0004	.37
500.	.103	.102	.103	.103	.1028	.0004	.38
600.	.102	.103	.102	.104	.1026	.0008	.79
700.	.103	.103	.103	.103	.1029	.0003	.33
800.	.103	.102	.103	.103	.1027	.0003	.28
900.	.101	.102	.102	.103	.1022	.0005	.52
1000.	.104	.102	.102	.102	.1025	.0010	.99
1100.	.104	.102	.101	.102	.1022	.0010	.94
1200.	.102	.102	.101	.102	.1021	.0004	.42
1300.	.102	.102	.102	.102	.1020	.0002	.24
1400.	.103	.102	.102	.102	.1022	.0007	.67
1500.	.103	.102	.102	.103	.1024	.0004	.42
1600.	.104	.103	.102	.103	.1031	.0009	.91
1700.	.102	.102	.102	.103	.1025	.0004	.39
1800.	.103	.102	.101	.103	.1023	.0009	.88
1900.	.104	.102	.101	.103	.1024	.0011	1.12
2000.	.103	.101	.102	.102	.1019	.0006	.57

STANDARD DEVIATION

FREQUENCY* MHZ *	WITHIN-LABORATORY LAB 2	LAB 3	LAB 4	LAB 5	* ALL LABS POOLED[b] * STD DEV	PCT C.V.
200.	.0009	.0002	.0001	.0005	*****	.50
300.	.0008	.0003	.0001	.0002	*****	.43
400.	.0010	.0006	.0000	.0003	.0006	.59
500.	.0016	.0005	.0001	.0005	*****	.84
600.	.0014	.0002	.0001	.0002	*****	.70
700.	.0010	.0005	.0001	.0003	*****	.54
800.	.0002	.0001	.0001	.0002	.0002	.15
900.	.0004	.0002	.0001	.0003	.0003	.26
1000.	.0008	.0002	.0001	.0002	*****	.41
1100.	.0020	.0002	.0001	.0008	*****	1.06
1200.	.0019	.0006	.0001	.0003	*****	1.00
1300.	.0008	.0003	.0000	.0002	*****	.44
1400.	.0013	.0004	.0001	.0003	*****	.71
1500.	.0017	.0002	.0001	.0002	*****	.86
1600.	.0011	.0001	.0001	.0004	*****	.60
1700.	.0007	.0002	.0001	.0005	.0005	.44
1800.	.0012	.0002	.0001	.0002	*****	.62
1900.	.0017	.0002	.0001	.0004	*****	.88
2000.	.0017	.0002	.0001	.0003	*****	.86

a Laboratory 1 data were discarded. There were large discrepancies in the phase measurements made by Laboratory 1 because two different methods were used to compensate for the length of coaxial line which connected the two 10-dB attenuators.

b Pooled values of within-laboratory standard deviation are given only when the laboratory variances satisfy Cochran's test for homogeneity of variance at the 1 percent level of significance; i.e., when the largest variance is less than or equal to 0.7212 times the sum of the variances.

Table A4. Summary of S_{21} phase measurements made by four[a] laboratories on 20-dB attenuator.

MEANS - DEGREES

FREQUENCY* MHZ *	MEAN OF 4 MEASUREMENTS LAB 2	LAB 3	LAB 4	LAB 5	* BETWEEN-LABORATORY MEAN	STD DEV
200.	323.7	324.8	325.2	324.6	324.60	.61
300.	306.2	306.8	307.4	306.6	306.74	.49
400.	288.4	288.7	289.3	288.9	288.86	.37
500.	271.5	271.2	271.2	271.5	271.36	.18
600.	253.1	253.6	253.6	254.0	253.59	.36
700.	235.6	235.9	235.9	236.4	235.97	.35
800.	217.9	218.1	217.7	219.0	218.17	.56
900.	199.9	200.5	199.6	201.5	200.39	.83
1000.	182.5	183.1	182.1	183.8	182.87	.73
1100.	165.2	165.4	164.8	165.7	165.29	.39
1200.	148.1	147.6	147.5	148.1	147.84	.34
1300.	130.7	130.1	130.1	130.1	130.26	.30
1400.	111.7	112.7	112.7	112.4	112.41	.47
1500.	95.1	95.1	95.2	94.8	95.07	.15
1600.	77.7	77.2	77.5	77.2	77.39	.25
1700.	59.6	59.0	59.4	59.9	59.49	.41
1800.	43.2	41.4	41.6	42.9	42.28	.91
1900.	24.8	23.9	24.1	25.9	24.71	.93
2000.	7.8	6.2	6.5	9.4	7.48	1.45

STANDARD DEVIATION - DEGREES

FREQUENCY* MHZ *	WITHIN-LABORATORY LAB 2	LAB 3	LAB 4	LAB 5	*ALL LABS[b] * POOLED
200.	1.11	.06	.10	.30	****
300.	.19	.32	.10	.10	.20
400.	.13	.17	.05	.19	.15
500.	.13	.26	.05	.29	.21
600.	.90	.35	.05	.08	****
700.	.38	.38	.05	.13	.28
800.	.22	.10	.05	.15	.14
900.	.51	.17	.05	.25	****
1000.	1.02	.39	.06	.12	****
1100.	.41	.38	.00	.37	.33
1200.	.57	.08	.00	.21	****
1300.	1.07	.08	.05	.25	****
1400.	.83	.13	.05	.13	****
1500.	.51	.32	.08	.17	.32
1600.	1.14	.15	.10	.08	****
1700.	.38	.28	.08	.10	.24
1800.	.67	.18	.08	.18	****
1900.	.87	.13	.10	.06	****
2000.	.39	.13	.10	.19	.23

a Laboratory 1 data were discarded. There were large discrepancies in the phase measurements made by Laboratory 1 because two different methods were used to compensate for the length of coaxial line which connected the two 10-dB attenuators.

b Pooled values of within-laboratory standard deviation are given only when the laboratory variances satisfy Cochran's test for homogeneity of variance at the 1 percent level of significance; i.e., when the largest variance is less than or equal to 0.7212 times the sum of the variances.

TABLE A5. SUMMARY OF S_{11} MAGNITUDE MEASUREMENTS MADE BY FIVE LABORATORIES ON R-C NETWORK 4 USING COMMON TRANSISTOR FIXTURE.

MEANS

FREQUENCY* MHZ *	MEAN OF 4 MEASUREMENTS LAB 1	LAB 2	LAB 3	LAB 4	LAB 5 *	BETWEEN-LABORATORY MEAN	STD DEV	PCT C.V.
200.	.298	.301	.297	.259	.296	.2902	.0177	6.10
300.	.305	.309	.305	.275	.306	.2999	.0142	4.73
400.	.312	.314	.309	.305	.316	.3112	.0044	1.41
500.	.315	.321	.312	.300	.322	.3144	.0088	2.80
600.	.312	.323	.310	.305	.329	.3159	.0099	3.12
700.	.308	.320	.310	.306	.337	.3163	.0129	4.08
800.	.302	.318	.312	.319	.346	.3193	.0163	5.12
900.	.308	.320	.312	.314	.354	.3217	.0187	5.81
1000.	.323	.325	.316	.306	.364	.3270	.0221	6.75
1100.	.332	.337	.323	.346	.373	.3421	.0192	5.61
1200.	.337	.351	.336	.361	.384	.3536	.0198	5.60
1300.	.339	.361	.345	.373	.393	.3624	.0218	6.00
1400.	.333	.364	.354	.414	.404	.3739	.0342	9.16
1500.	.342	.366	.352	.406	.415	.3764	.0327	8.68
1600.	.367	.373	.356	.379	.426	.3802	.0268	7.05
1700.	.375	.379	.367	.414	.435	.3940	.0291	7.40
1800.	.384	.398	.386	.402	.445	.4031	.0245	6.07
1900.	.397	.404	.397	.421	.455	.4150	.0245	5.89
2000.	.393	.423	.402	.498	.463	.4358	.0440	10.10

STANDARD DEVIATION

FREQUENCY* MHZ *	WITHIN-LABORATORY LAB 1	LAB 2	LAB 3	LAB 4	LAB 5 *	ALL LABS POOLED [a] STD DEV	PCT C.V.
200.	.0017	.0026	.0005	.0028	.0008	.0019	.66
300.	.0010	.0008	.0005	.0022	.0008	*****	.41
400.	.0010	.0022	.0010	.0059	.0008	*****	.93
500.	.0015	.0024	.0010	.0039	.0029	.0025	.81
600.	.0022	.0015	.0025	.0076	.0042	*****	1.34
700.	.0033	.0015	.0006	.0154	.0015	*****	2.25
800.	.0017	.0033	.0022	.0175	.0021	*****	2.54
900.	.0018	.0029	.0013	.0159	.0049	*****	2.38
1000.	.0019	.0029	.0014	.0258	.0042	*****	3.62
1100.	.0014	.0014	.0010	.0190	.0034	*****	2.54
1200.	.0026	.0026	.0015	.0125	.0048	*****	1.76
1300.	.0017	.0019	.0019	.0414	.0030	*****	5.14
1400.	.0016	.0047	.0013	.0233	.0034	*****	2.88
1500.	.0024	.0037	.0032	.0257	.0038	*****	3.16
1600.	.0045	.0008	.0031	.0429	.0029	*****	5.11
1700.	.0017	.0061	.0025	.0271	.0032	*****	3.20
1800.	.0034	.0059	.0043	.0282	.0033	*****	3.27
1900.	.0044	.0373	.0035	.0439	.0027	.0259	6.25
2000.	.0021	.0059	.0038	.0409	.0029	*****	4.27

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a Pooled values of within-laboratory standard deviation are given only when the laboratory variances satisfy Cochran's test for homogeneity of variance at the 1% level of significance; i.e., when the largest variance is less than or equal to 0.6329 times the sum of the variances.

Table A6. Summary of S_{11} phase measurements made by five laboratories on R-C network 4 using common transistor fixture.

MEANS - DEGREES

FREQUENCY* MHZ *	MEAN OF 4 MEASUREMENTS LAB 1	LAB 2	LAB 3	LAB 4	LAB 5 *	* BETWEEN-LABORATORY MEAN	STD DEV
200.	303.6	305.4	303.6	300.1	301.3	302.81	2.10
300.	278.9	280.5	279.5	281.0	275.5	279.09	2.15
400.	257.8	258.9	258.6	260.9	254.1	258.06	2.50
500.	240.9	240.8	240.7	239.2	235.2	239.40	2.42
600.	226.9	225.2	224.9	222.4	219.2	223.74	2.99
700.	211.9	211.5	211.1	203.3	205.3	208.61	4.02
800.	197.5	198.1	198.5	188.6	193.2	195.18	4.27
900.	183.9	185.4	186.4	178.7	182.1	183.30	3.05
1000.	172.8	173.5	174.5	169.2	172.5	172.51	1.98
1100.	163.7	163.2	163.9	161.1	163.2	163.05	1.11
1200.	155.2	154.1	155.3	156.8	155.3	155.37	.96
1300.	148.2	146.9	148.4	143.3	147.9	146.96	2.10
1400.	140.1	140.0	142.3	132.3	141.1	139.17	3.92
1500.	130.6	132.5	134.7	127.1	134.9	131.97	3.23
1600.	123.5	125.1	126.3	117.3	129.0	124.26	4.35
1700.	117.7	117.5	117.6	113.4	123.8	117.99	3.72
1800.	111.8	111.1	111.4	115.1	118.7	113.62	3.28
1900.	106.1	106.9	106.9	107.7	114.0	108.36	3.22
2000.	101.3	102.1	103.4	101.6	109.7	103.62	3.48

STANDARD DEVIATION - DEGREES

FREQUENCY* MHZ *	WITHIN-LABORATORY LAB 1	LAB 2	LAB 3	LAB 4	LAB 5	*ALL LABS [a] * POOLED
200.	.46	.46	.10	1.01	.51	.58
300.	.42	.26	.22	1.30	.58	****
400.	.44	.53	.17	1.22	.55	****
500.	.22	.25	.73	1.35	.66	.76
600.	.14	.19	.38	2.02	.43	****
700.	.25	.26	.62	.56	.24	.42
800.	.37	.35	.67	2.99	.22	****
900.	.48	.56	.54	4.99	.34	****
1000.	.24	.24	.68	1.01	.43	.60
1100.	.19	.35	.81	4.10	.64	****
1200.	.24	.17	.78	4.79	.81	****
1300.	.38	.26	.88	.75	.81	.67
1400.	.44	.90	.82	4.42	.83	****
1500.	.49	.92	.89	5.98	1.02	****
1600.	.17	.45	.78	1.70	1.11	1.00
1700.	.45	.33	.73	4.48	1.16	****
1800.	.21	.25	.75	5.24	.94	****
1900.	.21	1.78	.84	3.43	1.01	****
2000.	.29	.37	.79	2.28	1.09	****

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a Pooled values of within-laboratory standard deviation are given only when the laboratory variances satisfy Cochran's test for homogeneity of variance at the 1% level of significance; i.e., when the largest variance is less than or equal to 0.6329 times the sum of the variances.

Table A7. Summary of S_{21} magnitude measurements made by five laboratories on R-C network 4 using common transistor fixture.

MEANS

FREQUENCY*	MEAN OF 4 MEASUREMENTS					* BETWEEN-LABORATORY		
MHZ *	LAB 1	LAB 2	LAB 3	LAB 4	LAB 5 *	MEAN	STD DEV	PCT C.V.
200.	.649	.650	.650	.645	.658	.6503	.0049	.75
300.	.597	.598	.596	.582	.600	.5946	.0072	1.21
400.	.535	.538	.536	.533	.540	.5363	.0028	.52
500.	.478	.475	.475	.475	.477	.4759	.0013	.27
600.	.427	.424	.419	.424	.423	.4236	.0026	.62
700.	.381	.377	.372	.374	.372	.3752	.0035	.93
800.	.338	.339	.332	.336	.331	.3353	.0032	.95
900.	.300	.302	.297	.300	.296	.2988	.0027	.90
1000.	.267	.266	.264	.269	.262	.2655	.0026	.99
1100.	.238	.239	.235	.239	.234	.2371	.0024	1.03
1200.	.214	.214	.211	.215	.212	.2131	.0015	.72
1300.	.192	.192	.190	.196	.190	.1918	.0023	1.20
1400.	.173	.172	.172	.180	.172	.1739	.0033	1.91
1500.	.157	.156	.157	.166	.156	.1585	.0043	2.71
1600.	.144	.144	.143	.152	.143	.1453	.0038	2.64
1700.	.133	.135	.132	.138	.132	.1340	.0023	1.71
1800.	.125	.126	.123	.125	.123	.1245	.0014	1.11
1900.	.115	.123	.116	.119	.116	.1179	.0033	2.81
2000.	.109	.111	.111	.118	.110	.1116	.0035	3.18

STANDARD DEVIATION

FREQUENCY*	WITHIN-LABORATORY					* ALL LABS POOLED [a]	
MHZ *	LAB 1	LAB 2	LAB 3	LAB 4	LAB 5 *	STD DEV	PCT C.V.
200.	.0009	.0056	.0012	.0017	.0014	*****	.43
300.	.0006	.0047	.0008	.0007	.0020	*****	.39
400.	.0007	.0023	.0029	.0013	.0013	.0019	.35
500.	.0010	.0011	.0033	.0011	.0015	*****	.39
600.	.0007	.0040	.0008	.0013	.0008	*****	.46
700.	.0006	.0015	.0022	.0003	.0003	*****	.33
800.	.0006	.0014	.0020	.0008	.0008	.0012	.37
900.	.0007	.0003	.0007	.0010	.0008	.0008	.25
1000.	.0005	.0048	.0023	.0009	.0007	*****	.92
1100.	.0004	.0011	.0019	.0006	.0023	.0015	.62
1200.	.0004	.0021	.0013	.0015	.0003	.0013	.62
1300.	.0002	.0010	.0013	.0009	.0004	.0009	.46
1400.	.0003	.0010	.0015	.0006	.0007	.0009	.52
1500.	.0011	.0014	.0016	.0003	.0008	.0011	.71
1600.	.0008	.0019	.0017	.0015	.0006	.0014	.96
1700.	.0002	.0017	.0020	.0014	.0009	.0014	1.03
1800.	.0002	.0016	.0019	.0012	.0008	.0013	1.02
1900.	.0004	.0070	.0018	.0009	.0007	*****	2.78
2000.	.0006	.0021	.0020	.0016	.0008	.0015	1.39

a Pooled values of within-laboratory standard deviation are given only when the laboratory variances satisfy Cochran's test for homogeneity of variance at the 1% level of significance; i.e., when the largest variance is less than or equal to 0.6329 times the sum of the variances.

Table A8. Summary of S_{21} phase measurements made by five laboratories on R-C network 4 using common transistor fixture.

MEANS - DEGREES

FREQUENCY* MHZ *	MEAN OF 4 MEASUREMENTS LAB 1	LAB 2	LAB 3	LAB 4	LAB 5	* BETWEEN-LABORATORY MEAN	STD DEV
200.	330.7	331.1	330.9	329.2	330.1	330.41	.73
300.	317.5	318.3	317.9	317.9	316.7	317.67	.61
400.	305.8	306.4	306.1	306.2	305.0	305.89	.55
500.	294.9	295.9	296.1	295.3	295.1	295.47	.53
600.	285.6	286.8	287.1	286.3	286.2	286.41	.58
700.	277.0	278.4	279.2	278.7	278.5	278.35	.80
800.	269.8	270.7	271.9	271.8	271.3	271.13	.86
900.	262.5	263.7	264.9	265.2	264.8	264.24	1.11
1000.	256.3	257.1	258.1	258.0	258.3	257.56	.84
1100.	249.9	251.0	252.1	251.2	252.4	251.33	1.01
1200.	244.4	245.0	246.3	245.4	246.5	245.51	.89
1300.	238.1	238.7	240.2	240.6	240.9	239.73	1.24
1400.	232.6	233.0	234.2	234.9	235.2	234.00	1.13
1500.	226.6	226.6	227.9	228.7	229.6	227.89	1.34
1600.	220.9	221.1	222.0	222.7	224.2	222.21	1.33
1700.	215.1	215.0	216.2	216.5	218.6	216.30	1.46
1800.	210.0	209.3	210.2	210.7	212.6	210.56	1.28
1900.	204.4	204.1	204.4	205.4	207.4	205.16	1.38
2000.	198.4	198.3	198.8	200.1	201.6	199.47	1.40

STANDARD DEVIATION - DEGREES

FREQUENCY* MHZ *	WITHIN-LABORATORY LAB 1	LAB 2	LAB 3	LAB 4	LAB 5	*ALL LABS [a] * POOLED
200.	.14	.19	.10	.13	.26	.17
300.	.10	.22	.21	.17	.17	.18
400.	.05	.15	.28	.14	.28	.20
500.	.10	.13	.29	.28	.32	.24
600.	.08	.26	.57	.10	.32	.32
700.	.10	.14	.19	.25	.32	.21
800.	.13	.25	.34	.29	.40	.30
900.	.17	.32	.47	.14	.49	.35
1000.	.14	.26	.31	.26	.51	.32
1100.	.22	.45	.43	.54	.90	.56
1200.	.22	.37	.52	.34	.71	.46
1300.	.24	.75	.39	.66	.85	.62
1400.	.10	.51	.71	.38	.77	.55
1500.	.26	1.08	.76	.34	.89	.74
1600.	.32	.44	.97	.29	.84	.64
1700.	.19	.41	1.01	.78	.92	.73
1800.	.28	.36	.90	.36	1.20	.72
1900.	.22	.87	.82	.52	1.24	.81
2000.	.32	.47	.78	.57	1.28	.76

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a Pooled values of within-laboratory standard deviation are given only when the laboratory variances satisfy Cochran's test for homogeneity of variance at the 1% level of significance; i.e., when the largest variance is less than or equal to 0.6329 times the sum of the variances.

Table A9. Summary of S_{11} magnitude measurements made by five laboratories on R-C network 4 using participant's transistor fixture.

MEANS

FREQUENCY* MHZ	LAB 1	LAB 2	LAB 3	LAB 4	LAB 5	BETWEEN-LABORATORY MEAN	STD DEV	PCT C.V.
	MEAN OF 4 MEASUREMENTS							
200.	.294	.301	.296	.251	.294	.2873	.0204	7.10
300.	.290	.305	.301	.284	.300	.2963	.0086	2.90
400.	.282	.313	.303	.309	.310	.3033	.0125	4.14
500.	.285	.322	.306	.293	.315	.3042	.0154	5.06
600.	.301	.327	.308	.329	.323	.3178	.0125	3.92
700.	.318	.331	.312	.296	.333	.3179	.0152	4.78
800.	.321	.338	.313	.344	.344	.3320	.0143	4.31
900.	.323	.343	.318	.367	.353	.3408	.0205	6.02
1000.	.327	.336	.320	.296	.365	.3289	.0251	7.63
1100.	.333	.339	.325	.378	.376	.3504	.0249	7.10
1200.	.346	.337	.336	.400	.389	.3617	.0304	8.40
1300.	.352	.338	.343	.338	.400	.3544	.0261	7.35
1400.	.346	.343	.349	.453	.414	.3811	.0497	13.05
1500.	.355	.341	.345	.432	.424	.3795	.0447	11.78
1600.	.380	.347	.348	.329	.436	.3682	.0423	11.48
1700.	.394	.356	.359	.476	.446	.4066	.0534	13.13
1800.	.399	.376	.381	.464	.457	.4155	.0421	10.14

STANDARD DEVIATION

FREQUENCY* MHZ	LAB 1	LAB 2	LAB 3	LAB 4	LAB 5	ALL LABS POOLED[a] STD DEV	PCT C.V.
	WITHIN-LABORATORY						
200.	.0012	.0015	.0008	.0135	.0010	*****	2.13
300.	.0005	.0029	.0000	.0100	.0013	*****	1.58
400.	.0005	.0008	.0013	.0089	.0021	*****	1.37
500.	.0010	.0015	.0000	.0138	.0037	*****	2.12
600.	.0015	.0022	.0012	.0244	.0049	*****	3.52
700.	.0022	.0025	.0043	.0263	.0032	*****	3.80
800.	.0014	.0005	.0038	.0197	.0047	*****	2.79
900.	.0024	.0024	.0005	.0522	.0033	*****	6.88
1000.	.0017	.0031	.0010	.0404	.0041	*****	5.54
1100.	.0017	.0022	.0026	.0349	.0037	*****	4.50
1200.	.0022	.0021	.0032	.0446	.0040	*****	5.56
1300.	.0008	.0030	.0032	.0689	.0024	*****	8.71
1400.	.0022	.0030	.0013	.0546	.0019	*****	6.43
1500.	.0006	.0020	.0014	.0454	.0038	*****	5.38
1600.	.0036	.0022	.0030	.0855	.0037	*****	10.41
1700.	.0064	.0022	.0050	.0794	.0031	*****	8.79
1800.	.0062	.0028	.0075	.0554	.0025	*****	6.07

a Pooled values of within-laboratory standard deviation are given only when the laboratory variances satisfy Cochran's test for homogeneity of variance at the 1% level of significance; i.e., when the largest variance is less than or equal to 0.6329 times the sum of the variances.

TABLE A10. SUMMARY OF S_{11} PHASE MEASUREMENTS MADE BY FIVE LABORATORIES ON R-C NETWORK 4 USING PARTICIPANT'S TRANSISTOR FIXTURE.

MEANS - DEGREES

FREQUENCY* MHZ *	MEAN OF 4 MEASUREMENTS LAB 1	LAB 2	LAB 3	LAB 4	LAB 5 *	BETWEEN-LABORATORY MEAN	STD DEV
200.	304.1	304.7	303.7	301.5	301.2	303.06	1.56
300.	279.4	279.2	279.3	277.8	275.4	278.22	1.70
400.	256.1	257.1	257.4	263.8	253.3	257.54	3.89
500.	234.8	238.7	238.5	235.8	234.0	236.38	2.14
600.	217.4	223.1	221.3	221.9	217.4	220.22	2.64
700.	203.4	209.1	206.6	206.1	202.9	205.61	2.51
800.	191.0	196.4	195.0	181.8	190.6	190.97	5.69
900.	180.4	185.9	184.2	179.2	179.4	181.84	3.04
1000.	169.6	176.4	173.0	170.3	169.7	171.77	2.92
1100.	158.8	166.7	162.6	154.6	160.6	160.67	4.49
1200.	149.8	157.2	153.9	158.6	152.7	154.48	3.54
1300.	143.6	148.5	146.9	141.0	145.4	145.06	2.92
1400.	136.2	139.7	140.5	125.8	138.9	136.24	6.05
1500.	126.9	131.3	132.4	131.9	132.7	131.06	2.37
1600.	119.9	122.6	123.2	112.9	127.0	121.11	5.25
1700.	114.5	113.5	114.0	108.0	122.3	114.46	5.12
1800.	109.3	105.8	107.7	121.4	117.3	112.31	6.71

STANDARD DEVIATION - DEGREES

FREQUENCY* MHZ *	WITHIN-LABORATORY LAB 1	LAB 2	LAB 3	LAB 4	LAB 5 *	ALL LABS[a] POOLED
200.	.32	.42	.05	1.89	1.00	****
300.	.19	.43	.21	4.09	1.04	****
400.	.35	.35	.24	3.45	1.02	****
500.	.39	.31	.87	3.80	.70	****
600.	.24	.64	.28	2.19	.42	****
700.	.26	.15	.90	4.09	.24	****
800.	.53	.28	.41	7.10	.15	****
900.	.55	.21	.26	4.98	.15	****
1000.	.32	.36	.17	3.86	.26	****
1100.	.73	.40	.59	6.34	.15	****
1200.	.34	.41	.26	7.69	.37	****
1300.	.33	.29	.34	2.93	.50	****
1400.	.48	.45	.30	6.10	.52	****
1500.	.43	.38	.48	11.29	.52	****
1600.	.46	.29	.56	4.96	.85	****
1700.	.67	.22	.56	6.21	.57	****
1800.	.64	.42	.51	11.60	.29	****

a Pooled values of within-laboratory standard deviation are given only when the laboratory variances satisfy Cochran's test for homogeneity of variance at the 1% level of significance; i.e., when the largest variance is less than or equal to 0.6329 times the sum of the variances.

APPENDIX

Table A11. Summary of S_{21} magnitude measurements made by five laboratories on R-C network 4 using participant's transistor fixture.

MEANS

FREQUENCY* MHZ	* LAB 1	LAB 2	LAB 3	LAB 4	LAB 5	* BETWEEN-LABORATORY MEAN	STD DEV	PCT C.V.
200.	.646	.650	.649	.647	.655	.6494	.0036	.55
300.	.593	.596	.596	.584	.598	.5933	.0058	.97
400.	.528	.537	.536	.531	.539	.5343	.0045	.84
500.	.471	.482	.475	.474	.476	.4758	.0041	.86
600.	.418	.428	.419	.424	.422	.4223	.0041	.97
700.	.373	.377	.367	.374	.376	.3734	.0040	1.07
800.	.331	.334	.331	.333	.336	.3329	.0024	.71
900.	.293	.297	.297	.297	.295	.2959	.0019	.64
1000.	.261	.260	.266	.267	.264	.2640	.0030	1.13
1100.	.234	.237	.238	.238	.237	.2370	.0018	.74
1200.	.210	.212	.216	.215	.213	.2133	.0022	1.02
1300.	.188	.192	.195	.197	.191	.1926	.0035	1.82
1400.	.170	.174	.178	.181	.175	.1753	.0041	2.37
1500.	.153	.158	.164	.166	.160	.1602	.0050	3.15
1600.	.141	.147	.150	.153	.147	.1475	.0046	3.12
1700.	.129	.134	.138	.140	.136	.1353	.0043	3.17
1800.	.120	.127	.129	.128	.126	.1261	.0034	2.72

STANDARD DEVIATION

FREQUENCY* MHZ	* WITHIN-LABORATORY LAB 1	LAB 2	LAB 3	LAB 4	LAB 5	* ALL LABS POOLED[a] STD DEV	PCT C.V.
200.	.0007	.0032	.0005	.0014	.0011	*****	.26
300.	.0016	.0034	.0007	.0009	.0018	.0020	.33
400.	.0005	.0018	.0030	.0007	.0010	*****	.31
500.	.0013	.0020	.0023	.0009	.0018	.0017	.36
600.	.0005	.0027	.0009	.0012	.0013	.0015	.36
700.	.0009	.0009	.0011	.0008	.0014	.0010	.28
800.	.0008	.0025	.0007	.0006	.0013	*****	.42
900.	.0013	.0027	.0004	.0002	.0013	*****	.50
1000.	.0008	.0034	.0021	.0005	.0012	*****	.72
1100.	.0008	.0023	.0024	.0009	.0021	.0018	.77
1200.	.0012	.0018	.0004	.0008	.0006	.0011	.51
1300.	.0007	.0010	.0010	.0005	.0010	.0009	.46
1400.	.0011	.0020	.0013	.0010	.0009	.0013	.74
1500.	.0007	.0015	.0006	.0010	.0008	.0010	.61
1600.	.0010	.0018	.0010	.0005	.0005	.0011	.72
1700.	.0012	.0011	.0003	.0007	.0004	.0008	.61
1800.	.0009	.0012	.0004	.0010	.0007	.0009	.71

a Pooled values of within-laboratory standard deviation are given only when the laboratory variances satisfy Cochran's test for homogeneity of variance at the 1% level of significance; i.e., when the largest variance is less than or equal to 0.6329 times the sum of the variances.

TABLE A12. SUMMARY OF S_{21} PHASE MEASUREMENTS
MADE BY FIVE LABORATORIES ON R-C NETWORK 4 USING PARTICIPANT'S TRANSISTOR FIXTURE.

MEANS - DEGREES

FREQUENCY*	MEAN OF 4 MEASUREMENTS					* BETWEEN-LABORATORY	
MHZ *	LAB 1	LAB 2	LAB 3	LAB 4	LAB 5 *	MEAN	STD DEV
200.	330.5	331.3	330.9	329.5	330.2	330.49	.66
300.	317.4	318.4	317.8	318.2	316.8	317.75	.64
400.	305.8	306.6	306.0	306.2	305.1	305.95	.55
500.	295.0	296.3	295.8	295.3	295.4	295.58	.53
600.	285.9	287.1	286.7	286.3	286.5	286.49	.43
700.	277.2	279.0	279.3	278.9	278.6	278.61	.83
800.	270.2	271.3	271.9	272.3	271.7	271.49	.81
900.	263.1	263.9	265.1	265.9	265.1	264.65	1.11
1000.	256.7	257.8	258.2	258.9	259.0	258.15	.93
1100.	250.5	251.3	252.4	252.5	252.7	251.87	.97
1200.	245.2	245.1	246.7	247.0	247.5	246.31	1.06
1300.	239.3	239.1	241.0	241.6	242.0	240.61	1.32
1400.	234.0	232.9	235.3	236.0	236.4	234.95	1.44
1500.	228.1	227.0	229.2	230.4	230.8	229.09	1.58
1600.	222.4	221.3	223.4	224.3	225.9	223.47	1.73
1700.	216.6	215.5	217.9	217.7	220.5	217.63	1.86
1800.	211.7	209.3	212.2	212.1	214.6	212.01	1.88

STANDARD DEVIATION - DEGREES

FREQUENCY*	WITHIN-LABORATORY					*ALL LABS [a]
MHZ *	LAB 1	LAB 2	LAB 3	LAB 4	LAB 5	* POOLED
200.	.17	.26	.10	.13	.29	.21
300.	.14	.17	.32	.10	.41	.26
400.	.17	.10	.29	.13	.28	.21
500.	.33	.25	.24	.10	.40	.28
600.	.43	.32	.52	.05	.29	.36
700.	.42	.08	.55	.17	.31	.35
800.	.49	.24	.05	.10	.29	.28
900.	.68	.59	.08	.28	.17	.43
1000.	.70	.17	.13	.37	.21	****
1100.	.59	.39	.61	.08	.30	.44
1200.	.81	.47	.64	.37	.24	.54
1300.	.85	.80	.54	.57	.21	.64
1400.	.97	.52	.24	.24	.25	****
1500.	.98	.82	.31	.14	.32	.61
1600.	1.45	.47	.43	.52	.22	****
1700.	1.23	.47	.34	.22	.28	****
1800.	.88	.66	.17	.17	.06	.50

a Pooled values of within-laboratory standard deviation are given only when the laboratory variances satisfy Cochran's test for homogeneity of variance at the 1% level of significance, i.e., when the largest variance is less than or equal to 0.6329 times the sum of the variances.

TABLE A13. SUMMARY OF S_{11} MAGNITUDE MEASUREMENTS MADE BY THREE[a] LABORATORIES ON R-C NETWORK 4 USING COMMON TRANSISTOR FIXTURE.

MEANS

FREQUENCY*	MEAN OF 4 MEASUREMENTS *			BETWEEN-LABORATORY		
MHZ *	LAB 1	LAB 2	LAB 3 *	MEAN	STD DEV	PCT C.V.
200.	.298	.301	.297	.2987	.0022	.73
300.	.305	.309	.305	.3063	.0023	.76
400.	.312	.314	.309	.3118	.0023	.74
500.	.315	.321	.312	.3164	.0046	1.46
600.	.312	.323	.310	.3151	.0067	2.13
700.	.308	.320	.310	.3128	.0066	2.10
800.	.302	.318	.312	.3104	.0081	2.60
900.	.308	.320	.312	.3135	.0061	1.93
1000.	.323	.325	.316	.3214	.0048	1.48
1100.	.332	.337	.323	.3306	.0072	2.19
1200.	.337	.351	.336	.3412	.0083	2.44
1300.	.339	.361	.345	.3485	.0111	3.17
1400.	.333	.364	.354	.3504	.0160	4.57
1500.	.342	.366	.352	.3535	.0118	3.34
1600.	.367	.373	.356	.3654	.0085	2.32
1700.	.375	.379	.367	.3736	.0062	1.65
1800.	.384	.398	.386	.3896	.0076	1.94
1900.	.397	.404	.397	.3995	.0039	.98
2000.	.393	.423	.402	.4059	.0153	3.78

STANDARD DEVIATION

FREQUENCY*	WITHIN-LABORATORY			* ALL LABS POOLED[b]	
MHZ *	LAB 1	LAB 2	LAB 3	* STD DEV	PCT C.V.
200.	.0017	.0026	.0005	.0018	.61
300.	.0010	.0008	.0005	.0008	.26
400.	.0010	.0022	.0010	.0015	.48
500.	.0015	.0024	.0010	.0017	.54
600.	.0022	.0015	.0025	.0021	.67
700.	.0033	.0015	.0006	.0021	.68
800.	.0017	.0033	.0022	.0025	.81
900.	.0018	.0029	.0013	.0021	.68
1000.	.0019	.0029	.0014	.0022	.68
1100.	.0014	.0014	.0010	.0013	.39
1200.	.0026	.0026	.0015	.0023	.67
1300.	.0017	.0019	.0019	.0018	.53
1400.	.0016	.0047	.0013	*****	.84
1500.	.0024	.0037	.0032	.0031	.89
1600.	.0045	.0008	.0031	.0032	.88
1700.	.0017	.0061	.0025	.0039	1.05
1800.	.0034	.0059	.0043	.0047	1.20
1900.	.0044	.0373	.0035	*****	5.45
2000.	.0021	.0059	.0038	.0042	1.04

a Data from Laboratories 4 and 5 were omitted from this analysis; Laboratories 1, 2 and 3 used nearly identical calibration procedures.

b Pooled values of within-laboratory standard deviation are given only when the laboratory variances satisfy Cochran's test for homogeneity of variance at the 1% level of significance; i.e., when the largest variance is less than or equal to 0.8335 times the sum of the variances.

TABLE A14. SUMMARY OF S_{11} PHASE MEASUREMENTS MADE BY THREE[a] LABORATORIES ON R-C NETWORK 4 USING COMMON TRANSISTOR FIXTURE.

MEANS - DEGREES

FREQUENCY* MHZ *	MEAN OF 4 MEASUREMENTS LAB 1	LAB 2	LAB 3 *	BETWEEN-LABORATORY MEAN	STD DEV
200.	303.6	305.4	303.6	304.21	1.05
300.	278.9	280.5	279.5	279.62	.82
400.	257.8	258.9	258.6	258.43	.53
500.	240.9	240.8	240.7	240.83	.08
600.	226.9	225.2	224.9	225.69	1.06
700.	211.9	211.5	211.1	211.50	.36
800.	197.5	198.1	198.5	198.05	.52
900.	183.9	185.4	186.4	185.24	1.29
1000.	172.8	173.5	174.5	173.61	.87
1100.	163.7	163.2	163.9	163.62	.39
1200.	155.2	154.1	155.3	154.89	.64
1300.	148.2	146.9	148.4	147.86	.79
1400.	140.1	140.0	142.3	140.79	1.29
1500.	130.6	132.5	134.7	132.62	2.04
1600.	123.5	125.1	126.3	124.98	1.38
1700.	117.7	117.5	117.6	117.61	.09
1800.	111.8	111.1	111.4	111.43	.38
1900.	106.1	106.9	106.9	106.67	.45
2000.	101.3	102.1	103.4	102.28	1.07

STANDARD DEVIATION - DEGREES

FREQUENCY* MHZ *	WITHIN-LABORATORY LAB 1	LAB 2	LAB 3 *	ALL LABS[b] POOLED
200.	.46	.46	.10	.38
300.	.42	.26	.22	.31
400.	.44	.53	.17	.41
500.	.22	.25	.73	.46
600.	.14	.19	.38	.26
700.	.25	.26	.62	.42
800.	.37	.35	.67	.49
900.	.48	.56	.54	.53
1000.	.24	.24	.68	.44
1100.	.19	.35	.81	.52
1200.	.24	.17	.78	****
1300.	.38	.26	.88	.58
1400.	.44	.90	.82	.75
1500.	.49	.92	.89	.79
1600.	.17	.45	.78	.53
1700.	.45	.33	.73	.53
1800.	.21	.25	.75	****
1900.	.21	1.78	.84	1.14
2000.	.29	.37	.79	.53

a Data from Laboratories 4 and 5 were omitted from this analysis; Laboratories 1, 2 and 3 used nearly identical calibration procedures.

b Pooled values of within-laboratory standard deviation are given only when the laboratory variances satisfy Cochran's test for homogeneity of variance at the 1% level of significance; i.e., when the largest variance is less than or equal to 0.8335 times the sum of the variances.

Table A15. Summary of S_{21} magnitude measurements made by three[a] laboratories on R-C network 4 using common transistor fixture.

MEANS

FREQUENCY* MHZ *	MEAN OF 4 MEASUREMENTS * LAB 1	LAB 2	LAB 3 *	BETWEEN-LABORATORY MEAN	STD DEV	PCT C.V.
200.	.649	.650	.650	.6495	.0007	.11
300.	.597	.598	.596	.5969	.0010	.17
400.	.535	.538	.536	.5362	.0018	.34
500.	.478	.475	.475	.4760	.0015	.31
600.	.427	.424	.419	.4235	.0036	.86
700.	.381	.377	.372	.3766	.0041	1.08
800.	.338	.339	.332	.3362	.0033	.98
900.	.300	.302	.297	.2996	.0030	.99
1000.	.267	.266	.264	.2656	.0017	.66
1100.	.238	.239	.235	.2374	.0024	1.02
1200.	.214	.214	.211	.2131	.0015	.70
1300.	.192	.192	.190	.1910	.0012	.60
1400.	.173	.172	.172	.1724	.0008	.49
1500.	.157	.156	.157	.1566	.0006	.36
1600.	.144	.144	.143	.1437	.0005	.31
1700.	.133	.135	.132	.1333	.0013	.97
1800.	.125	.126	.123	.1248	.0014	1.12
1900.	.115	.123	.116	.1183	.0043	3.63
2000.	.109	.111	.111	.1102	.0012	1.11

STANDARD DEVIATION

FREQUENCY* MHZ *	WITHIN-LABORATORY LAB 1	LAB 2	LAB 3	* ALL LABS POOLED[b] * STD DEV	PCT C.V.
200.	.0009	.0056	.0012	*****	.51
300.	.0006	.0047	.0008	*****	.46
400.	.0007	.0023	.0029	.0022	.41
500.	.0010	.0011	.0033	.0021	.44
600.	.0007	.0040	.0008	*****	.57
700.	.0006	.0015	.0022	.0016	.42
800.	.0006	.0014	.0020	.0014	.43
900.	.0007	.0003	.0007	.0006	.21
1000.	.0005	.0048	.0023	.0031	1.16
1100.	.0004	.0011	.0019	.0013	.55
1200.	.0004	.0021	.0013	.0015	.69
1300.	.0002	.0010	.0013	.0010	.50
1400.	.0003	.0010	.0015	.0010	.61
1500.	.0011	.0014	.0016	.0014	.87
1600.	.0008	.0019	.0017	.0016	1.09
1700.	.0002	.0017	.0020	.0015	1.13
1800.	.0002	.0016	.0019	.0014	1.14
1900.	.0004	.0070	.0018	*****	3.54
2000.	.0006	.0021	.0020	.0017	1.55

a Data from Laboratories 4 and 5 were omitted from this analysis; Laboratories 1, 2 and 3 used nearly identical calibration procedures.

b Pooled values of within-laboratory standard deviation are given only when the laboratory variances satisfy Cochran's test for homogeneity of variance at the 1% level of significance; i.e., when the largest variance is less than or equal to 0.8335 times the sum of the variances.

TABLE A16. SUMMARY OF S_{21} PHASE MEASUREMENTS MADE BY THREE[a] LABORATORIES ON R-C NETWORK 4 USING COMMON TRANSISTOR FIXTURE.

MEANS - DEGREES

FREQUENCY* MHZ *	MEAN OF 4 MEASUREMENTS LAB 1	LAB 2	LAB 3 *	BETWEEN-LABORATORY MEAN	STD DEV
200.	330.7	331.1	330.9	330.88	.19
300.	317.5	318.3	317.9	317.89	.43
400.	305.8	306.4	306.1	306.09	.28
500.	294.9	295.9	296.1	295.64	.67
600.	285.6	286.8	287.1	286.50	.80
700.	277.0	278.4	279.2	278.20	1.09
800.	269.8	270.7	271.9	270.84	1.04
900.	262.5	263.7	264.9	263.73	1.20
1000.	256.3	257.1	258.1	257.19	.93
1100.	249.9	251.0	252.1	250.99	1.13
1200.	244.4	245.0	246.3	245.22	.97
1300.	238.1	238.7	240.2	239.03	1.10
1400.	232.6	233.0	234.2	233.29	.81
1500.	226.6	226.6	227.9	227.02	.76
1600.	220.9	221.1	222.0	221.37	.60
1700.	215.1	215.0	216.2	215.44	.64
1800.	210.0	209.3	210.2	209.81	.47
1900.	204.4	204.1	204.4	204.30	.20
2000.	198.4	198.3	198.8	198.52	.24

STANDARD DEVIATION - DEGREES

FREQUENCY* MHZ *	WITHIN-LABORATORY LAB 1	LAB 2	LAB 3 *	ALL LABS[b] POOLED
200.	.14	.19	.10	.15
300.	.10	.22	.21	.18
400.	.05	.15	.28	.18
500.	.10	.13	.29	.19
600.	.08	.26	.57	.36
700.	.10	.14	.19	.15
800.	.13	.25	.34	.26
900.	.17	.32	.47	.34
1000.	.14	.26	.31	.25
1100.	.22	.45	.43	.38
1200.	.22	.37	.52	.39
1300.	.24	.75	.39	.51
1400.	.10	.51	.71	.51
1500.	.26	1.08	.76	.78
1600.	.32	.44	.97	.64
1700.	.19	.41	1.01	****
1800.	.28	.36	.90	.58
1900.	.22	.87	.82	.70
2000.	.32	.47	.78	.56

a Data from Laboratories 4 and 5 were omitted from this analysis; Laboratories 1, 2 and 3 used nearly identical calibration procedures.

b Pooled values of within-laboratory standard deviation are given only when the laboratory variances satisfy Cochran's test for homogeneity of variance at the 1% level of significance; i.e., when the largest variance is less than or equal to 0.8335 times the sum of the variances.

TABLE A17. SUMMARY OF S_{11} MAGNITUDE MEASUREMENTS MADE BY THREE[a] LABORATORIES ON P-C NETWORK 4 USING PARTICIPANT'S TRANSISTOR FIXTURE.

MEANS

FREQUENCY* MHZ *	MEAN OF 4 MEASUREMENTS * LAB 1	LAB 2	LAB 3 *	BETWEEN-LABORATORY MEAN	STD DEV	PCT C.V.
200.	.294	.301	.296	.2971	.0037	1.26
300.	.290	.305	.301	.2988	.0077	2.59
400.	.282	.313	.303	.2994	.0160	5.35
500.	.285	.322	.306	.3043	.0188	6.18
600.	.301	.327	.308	.3121	.0134	4.28
700.	.318	.331	.312	.3203	.0095	2.97
800.	.321	.338	.313	.3238	.0127	3.93
900.	.323	.343	.318	.3279	.0131	4.01
1000.	.327	.336	.320	.3279	.0080	2.45
1100.	.333	.339	.325	.3326	.0069	2.08
1200.	.346	.337	.336	.3398	.0054	1.58
1300.	.352	.338	.343	.3446	.0068	1.99
1400.	.346	.343	.349	.3462	.0030	.88
1500.	.355	.341	.345	.3472	.0075	2.16
1600.	.380	.347	.348	.3584	.0187	5.22
1700.	.394	.356	.359	.3700	.0213	5.75
1800.	.399	.376	.381	.3854	.0120	3.11

STANDARD DEVIATION

FREQUENCY* MHZ *	WITHIN-LABORATORY LAB 1	LAB 2	LAB 3	* ALL LABS POOLED[b] * STD DEV	PCT C.V.
200.	.0012	.0015	.0008	.0012	.40
300.	.0005	.0029	.0000	*****	.56
400.	.0005	.0008	.0013	.0009	.31
500.	.0010	.0015	.0000	.0010	.34
600.	.0015	.0022	.0012	.0017	.53
700.	.0022	.0025	.0043	.0032	.99
800.	.0014	.0005	.0038	*****	.72
900.	.0024	.0024	.0005	.0020	.59
1000.	.0017	.0031	.0010	.0021	.64
1100.	.0017	.0022	.0026	.0022	.66
1200.	.0022	.0021	.0032	.0025	.74
1300.	.0008	.0030	.0032	.0026	.75
1400.	.0022	.0030	.0013	.0023	.66
1500.	.0006	.0020	.0014	.0015	.42
1600.	.0036	.0022	.0030	.0030	.83
1700.	.0064	.0022	.0050	.0049	1.31
1800.	.0062	.0028	.0075	.0059	1.52

a Data from Laboratories 4 and 5 were omitted from this analysis; Laboratories 1, 2 and 3 used nearly identical calibration procedures.

b Pooled values of within-laboratory standard deviation are given only when the laboratory variances satisfy Cochran's test for homogeneity of variance at the 1% level of significance; i.e., when the largest variance is less than or equal to 0.8335 times the sum of the variances.

TABLE A18. SUMMARY OF S_{11} PHASE MEASUREMENTS MADE BY THREE[a] LABORATORIES ON R-C NETWORK 4 USING PARTICIPANT'S TRANSISTOR FIXTURE.

MEANS - DEGREES

FREQUENCY* MHZ *	MEAN OF 4 MEASUREMENTS LAB 1	LAB 2	LAB 3 *	BETWEEN-LABORATORY MEAN	STD DEV
200.	304.1	304.7	303.7	304.17	.48
300.	279.4	279.2	279.3	279.29	.10
400.	256.1	257.1	257.4	256.87	.71
500.	234.8	238.7	238.5	237.33	2.22
600.	217.4	223.1	221.3	220.58	2.92
700.	203.4	209.1	206.6	206.35	2.86
800.	191.0	196.4	195.0	194.16	2.78
900.	180.4	185.9	184.2	183.52	2.83
1000.	169.6	176.4	173.0	172.98	3.40
1100.	158.8	166.7	162.6	162.72	3.96
1200.	149.8	157.2	153.9	153.67	3.73
1300.	143.6	148.5	146.9	146.32	2.50
1400.	136.2	139.7	140.5	138.82	2.32
1500.	126.9	131.3	132.4	130.22	2.92
1600.	119.9	122.6	123.2	121.88	1.76
1700.	114.5	113.5	114.0	114.00	.50
1800.	109.3	105.8	107.7	107.61	1.74

STANDARD DEVIATION - DEGREES

FREQUENCY* MHZ *	WITHIN-LABORATORY LAB 1	LAB 2	LAB 3 *	ALL LABS[b] POOLED
200.	.32	.42	.05	.31
300.	.19	.43	.21	.29
400.	.35	.35	.24	.32
500.	.39	.31	.87	.58
600.	.24	.64	.28	.42
700.	.26	.15	.90	****
800.	.53	.28	.41	.42
900.	.55	.21	.26	.37
1000.	.32	.36	.17	.29
1100.	.73	.40	.59	.59
1200.	.34	.41	.26	.34
1300.	.33	.29	.34	.32
1400.	.48	.45	.30	.42
1500.	.43	.38	.48	.43
1600.	.46	.29	.56	.45
1700.	.67	.22	.56	.52
1800.	.64	.42	.51	.53

a Data from Laboratories 4 and 5 were omitted from this analysis; Laboratories 1, 2 and 3 used nearly identical calibration procedures.

b Pooled values of within-laboratory standard deviation are given only when the laboratory variances satisfy Cochran's test for homogeneity of variance at the 1% level of significance; i.e., when the largest variance is less than or equal to 0.8335 times the sum of the variances.

Table A19. Summary of S_{21} magnitude measurements made by three[a] laboratories on R-C network 4 using participant's transistor fixture.

MEANS

FREQUENCY* MHZ *	MEAN OF 4 MEASUREMENTS * LAB 1	LAB 2	LAB 3 *	BETWEEN-LABORATORY MEAN	STD DEV	PCT C.V.
200.	.646	.650	.649	.6482	.0022	.35
300.	.593	.596	.596	.5951	.0017	.29
400.	.528	.537	.536	.5336	.0047	.87
500.	.471	.482	.475	.4761	.0056	1.18
600.	.418	.428	.419	.4219	.0056	1.32
700.	.373	.377	.367	.3723	.0051	1.36
800.	.331	.334	.331	.3319	.0019	.57
900.	.293	.297	.297	.2960	.0026	.87
1000.	.261	.260	.266	.2627	.0031	1.16
1100.	.234	.237	.238	.2365	.0022	.93
1200.	.210	.212	.216	.2127	.0028	1.31
1300.	.188	.192	.195	.1915	.0036	1.90
1400.	.170	.174	.178	.1737	.0040	2.29
1500.	.153	.158	.164	.1584	.0052	3.26
1600.	.141	.147	.150	.1458	.0048	3.30
1700.	.129	.134	.138	.1337	.0048	3.61
1800.	.120	.127	.129	.1256	.0047	3.74

STANDARD DEVIATION

FREQUENCY* MHZ *	WITHIN-LABORATORY LAB 1	LAB 2	LAB 3	* ALL LABS POOLED[b] * STD DEV	PCT C.V.
200.	.0007	.0032	.0005	*****	.29
300.	.0016	.0034	.0007	.0022	.38
400.	.0005	.0018	.0030	.0020	.38
500.	.0013	.0020	.0023	.0019	.41
600.	.0005	.0027	.0009	*****	.39
700.	.0009	.0009	.0011	.0009	.25
800.	.0008	.0025	.0007	.0016	.47
900.	.0013	.0027	.0004	.0017	.59
1000.	.0008	.0034	.0021	.0023	.89
1100.	.0008	.0023	.0024	.0019	.82
1200.	.0012	.0018	.0004	.0013	.60
1300.	.0007	.0010	.0010	.0009	.48
1400.	.0011	.0020	.0013	.0015	.87
1500.	.0007	.0015	.0006	.0010	.65
1600.	.0010	.0018	.0010	.0013	.90
1700.	.0012	.0011	.0003	.0009	.71
1800.	.0009	.0012	.0004	.0009	.72

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a Data from Laboratories 4 and 5 were omitted from this analysis; Laboratories 1, 2 and 3 used nearly identical calibration procedures.

b Pooled values of within-laboratory standard deviation are given only when the laboratory variances satisfy Cochran's test for homogeneity of variance at the 1% level of significance; i.e., when the largest variance is less than or equal to 0.8335 times the sum of the variances.

TABLE A20. SUMMARY OF S_{21} PHASE MEASUREMENTS MADE BY THREE[a] LABORATORIES ON R-C NETWORK 4 USING PARTICIPANT'S TRANSISTOR FIXTURE.

MEANS - DEGREES

FREQUENCY* MHZ *	MEAN OF 4 MEASUREMENTS LAB 1	LAB 2	LAB 3 *	BETWEEN-LABORATORY MEAN	STD DEV
200.	330.5	331.3	330.9	330.90	.36
300.	317.4	318.4	317.8	317.89	.53
400.	305.8	306.6	306.0	306.14	.38
500.	295.0	296.3	295.8	295.72	.70
600.	285.9	287.1	286.7	286.57	.59
700.	277.2	279.0	279.3	278.50	1.14
800.	270.2	271.3	271.9	271.14	.86
900.	263.1	263.9	265.1	264.06	.99
1000.	256.7	257.8	258.2	257.61	.77
1100.	250.5	251.3	252.4	251.37	.95
1200.	245.2	245.1	246.7	245.69	.87
1300.	239.3	239.1	241.0	239.82	1.03
1400.	234.0	232.9	235.3	234.10	1.18
1500.	228.1	227.0	229.2	228.09	1.10
1600.	222.4	221.3	223.4	222.40	1.04
1700.	216.6	215.5	217.9	216.67	1.20
1800.	211.7	209.3	212.2	211.08	1.52

STANDARD DEVIATION - DEGREES

FREQUENCY* MHZ *	WITHIN-LABORATORY LAB 1	LAB 2	LAB 3 *	ALL LABS[b] POOLED
200.	.17	.26	.10	.19
300.	.14	.17	.32	.23
400.	.17	.10	.29	.20
500.	.33	.25	.24	.28
600.	.43	.32	.52	.43
700.	.42	.08	.55	.40
800.	.49	.24	.05	.32
900.	.68	.59	.08	.52
1000.	.70	.17	.13	****
1100.	.59	.39	.61	.54
1200.	.81	.47	.64	.65
1300.	.85	.80	.54	.74
1400.	.97	.52	.24	.65
1500.	.98	.82	.31	.76
1600.	1.45	.47	.43	****
1700.	1.23	.47	.34	.78
1800.	.88	.66	.17	.64

---

a Data from Laboratories 4 and 5 were omitted from this analysis; Laboratories 1, 2 and 3 used nearly identical calibration procedures.

b Pooled values of within-laboratory standard deviation are given only when the laboratory variances satisfy Cochran's test for homogeneity of variance at the 1% level of significance; i.e., when the largest variance is less than or equal to 0.8335 times the sum of the variances.

TABLE A21. SUMMARY OF S-PARAMETERS OF TRANSISTOR 2N3960(F) MEASURED IN PARTICIPANT'S TRANSISTOR FIXTURE $V_{CE} = 5V$, $I_E = 2.5$ mA

DATA FROM FIVE LABORATORIES

MEAN VALUES, 5 LABORATORIES

FREQUENCY	S11		S21		S12		S22	
MHZ	MAG	PHASE	MAG	PHASE	MAG	PHASE	MAG	PHASE
200.	.513	311.9	3.19	104.8	.121	59.8	.667	326.5
300.	.430	301.3	2.38	91.4	.160	55.4	.621	320.2
400.	.380	294.4	1.93	80.9	.195	51.3	.598	312.9
500.	.317	285.9	1.64	72.2	.224	47.4	.576	305.5
600.	.299	275.8	1.44	64.8	.249	43.6	.567	298.5
700.	.274	271.4	1.30	57.9	.265	40.9	.550	292.1
800.	.229	257.0	1.18	51.5	.284	37.7	.546	286.1
900.	.249	250.3	1.09	46.2	.292	35.3	.552	279.5
1000.	.230	251.8	1.02	40.9	.304	33.5	.551	273.9
1100.	.199	232.9	.96	36.0	.312	31.3	.553	267.3
1200.	.232	229.6	.90	31.6	.317	29.6	.561	261.3
1300.	.199	231.5	.85	27.6	.322	28.7	.565	256.3
1400.	.191	203.5	.81	24.3	.327	27.7	.568	251.3
1500.	.229	209.1	.78	20.9	.329	27.5	.583	246.6
1600.	.195	214.7	.74	18.4	.335	27.1	.591	243.1
1700.	.192	183.3	.71	15.7	.336	26.6	.593	237.4
1800.	.234	188.4	.68	13.2	.340	26.3	.610	231.8

BETWEEN-LABORATORY STANDARD DEVIATION [a]

	S11		S21		S12		S22	
FREQUENCY	MAG	PHASE	MAG	PHASE	MAG	PHASE	MAG	PHASE
MHZ	PCT	DEG	PCT	DEG	PCT	DEG	PCT	DEG
200.	9.33	2.12	6.61	2.48	1.07	1.25	3.98	1.05
300.	3.32	.68	3.69	.97	2.63	.85	2.34	2.27
400.	8.01	3.41	2.83	.52	1.48	.36	2.78	1.57
500.	7.83	2.16	2.17	.46	1.73	.91	2.25	1.25
600.	7.06	2.11	1.90	.78	1.97	.91	2.94	1.95
700.	6.50	7.36	1.72	.90	2.78	1.39	4.79	2.64
800.	21.79	7.69	1.87	.27	2.44	.48	5.70	2.36
900.	9.64	6.43	1.89	.32	2.15	.60	4.70	2.26
1000.	8.43	13.15	2.49	.40	2.39	.47	4.80	1.97
1100.	24.12	14.85	2.62	.41	3.18	.51	6.49	2.31
1200.	23.44	8.41	2.61	.64	2.28	1.05	5.20	2.72
1300.	7.38	17.95	2.16	.35	3.66	.83	6.68	1.98
1400.	13.82	31.47	2.95	.34	3.60	.41	8.91	2.05
1500.	28.91	9.52	2.56	.37	3.48	.27	7.56	1.80
1600.	3.91	22.98	2.85	.47	3.66	.41	6.08	1.33
1700.	8.69	34.19	3.23	.52	4.04	.61	5.54	2.06
1800.	45.88	9.02	3.42	1.18	2.97	1.07	2.59	2.73

a Relative standard deviation of S-parameter magnitude measurements; standard deviation of phase measurements.

Table A22. Summary of S-parameters of transistor 2N3960(F) measured in participant's transistor fixture

$V_{CE} = 5V, I_E = 2.5$ mA

Data from three[a] laboratories

MEAN VALUES, 3 LABORATORIES

FREQUENCY MHZ	S11 MAG	S11 PHASE	S21 MAG	S21 PHASE	S12 MAG	S12 PHASE	S22 MAG	S22 PHASE
200.	.536	311.2	3.13	105.9	.121	60.2	.679	326.3
300.	.435	301.8	2.37	91.8	.160	55.3	.629	319.1
400.	.372	293.1	1.91	80.9	.194	51.3	.600	312.1
500.	.331	285.1	1.63	72.4	.223	47.5	.582	304.9
600.	.299	276.9	1.43	65.0	.247	43.4	.572	297.9
700.	.283	268.4	1.30	58.2	.262	41.2	.566	290.9
800.	.258	261.0	1.17	51.6	.285	37.7	.563	285.2
900.	.249	254.3	1.09	46.1	.291	35.2	.566	278.8
1000.	.240	248.2	1.02	40.8	.302	33.3	.568	273.3
1100.	.227	242.0	.96	36.2	.309	31.3	.575	267.2
1200.	.215	235.6	.90	31.8	.315	29.6	.580	261.6
1300.	.206	227.9	.85	27.7	.320	28.6	.588	256.4
1400.	.204	221.5	.81	24.2	.324	27.7	.598	252.2
1500.	.200	215.9	.78	20.9	.326	27.5	.609	247.5
1600.	.194	210.3	.74	18.5	.331	27.4	.612	243.5
1700.	.182	203.0	.72	15.9	.329	27.1	.612	238.8
1800.	.176	194.1	.68	13.8	.335	26.9	.617	233.6

BETWEEN-LABORATORY STANDARD DEVIATION[b]

FREQUENCY MHZ	S11 MAG PCT	S11 PHASE DEG	S21 MAG PCT	S21 PHASE DEG	S12 MAG PCT	S12 PHASE DEG	S22 MAG PCT	S22 PHASE DEG
200.	6.38	1.50	8.19	2.40	.57	1.07	2.31	1.44
300.	3.57	.40	3.06	1.15	1.98	1.18	2.26	1.24
400.	4.28	.76	2.09	.70	1.19	.50	3.02	1.10
500.	5.83	.45	2.02	.50	1.83	1.12	1.98	1.32
600.	5.45	.69	1.71	1.03	2.41	1.25	3.01	2.33
700.	5.12	.90	1.15	1.02	3.09	1.81	2.41	2.95
800.	3.76	1.08	1.51	.10	2.91	.40	4.64	2.78
900.	3.79	.50	1.55	.40	2.49	.79	4.16	2.83
1000.	5.79	.90	2.63	.45	2.80	.56	3.11	2.56
1100.	6.70	1.37	3.08	.42	3.59	.72	2.96	2.81
1200.	7.27	2.93	3.53	.65	2.83	1.35	2.40	3.16
1300.	6.81	2.80	2.98	.47	4.93	1.15	2.93	2.72
1400.	5.19	2.05	4.12	.44	4.87	.53	3.11	1.69
1500.	1.32	1.50	3.49	.45	4.67	.35	3.86	1.00
1600.	3.65	.98	3.73	.60	4.73	.23	3.04	.70
1700.	6.24	3.37	4.36	.56	4.45	.23	2.46	.95
1800.	3.70	5.89	4.42	.84	3.06	.53	2.63	1.12

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a Data from Laboratories 4 and 5 were omitted from this analysis; Laboratories 1, 2 and 3 used nearly identical calibration procedures.

b Relative standard deviation of S-parameter magnitude measurements; standard deviation of phase measurements.

Table A23. Summary of S-parameters of transistor 2N709(g) measured in participant's transistor fixture. V_{CE} = 5V, I_E = 2.5 mA

A. Data from five laboratories

MEAN VALUES, 5 LABORATORIES

FREQUENCY	S11		S21		S12		S22	
MHZ	MAG	PHASE	MAG	PHASE	MAG	PHASE	MAG	PHASE
200.	.361	281.9	2.13	91.4	.062	54.1	.769	338.7
300.	.339	265.6	1.50	78.5	.076	52.8	.759	332.9
400.	.332	252.8	1.18	68.3	.091	51.3	.762	325.8
500.	.325	237.3	.97	58.6	.102	50.6	.767	318.4
600.	.347	226.3	.83	51.2	.109	50.8	.770	310.9
700.	.346	216.8	.73	44.2	.113	52.7	.762	303.8
800.	.364	204.0	.64	37.6	.120	54.3	.769	296.9
900.	.388	198.3	.57	33.0	.125	57.4	.779	289.6
1000.	.371	191.5	.51	28.6	.133	62.1	.787	283.2

BETWEEN-LABORATORY STANDARD DEVIATION [a]

FREQUENCY	S11		S21		S12		S22	
	MAG	PHASE	MAG	PHASE	MAG	PHASE	MAG	PHASE
MHZ	PCT	DEG	PCT	DEG	PCT	DEG	PCT	DEG
200.	10.25	1.82	3.45	1.61	1.43	1.37	2.25	.64
300.	1.13	1.54	2.58	.72	2.54	1.01	.97	1.70
400.	2.59	4.68	2.08	.78	1.53	.85	1.38	1.21
500.	5.52	2.08	1.34	.99	1.51	1.35	1.69	.90
600.	4.01	1.83	.83	1.24	1.55	1.63	1.59	1.43
700.	5.41	1.87	1.28	1.76	1.50	2.15	3.83	1.83
800.	1.86	8.21	1.34	.96	2.06	.72	3.64	1.86
900.	5.89	2.63	2.30	1.30	1.91	.99	3.07	2.12
1000.	9.06	1.80	3.24	1.73	1.04	1.46	4.83	2.57

B. Data from three[b] laboratories

MEAN VALUES, 3 LABORATORIES

FREQUENCY	S11		S21		S12		S22	
MHZ	MAG	PHASE	MAG	PHASE	MAG	PHASE	MAG	PHASE
200.	.379	282.9	2.10	92.3	.061	54.6	.777	338.7
300.	.340	266.5	1.50	78.9	.078	52.9	.762	332.4
400.	.329	251.4	1.18	68.5	.091	51.2	.760	325.6
500.	.332	238.5	.97	59.2	.101	50.9	.771	318.6
600.	.341	227.1	.83	51.7	.108	51.3	.770	311.2
700.	.354	217.0	.73	45.1	.114	53.4	.771	303.9
800.	.364	208.5	.64	38.0	.121	54.7	.777	297.2
900.	.375	200.1	.58	33.6	.125	57.8	.784	290.2
1000.	.380	192.5	.52	29.2	.132	62.6	.798	284.1

BETWEEN-LABORATORY STANDARD DEVIATION [a]

FREQUENCY	S11		S21		S12		S22	
	MAG	PHASE	MAG	PHASE	MAG	PHASE	MAG	PHASE
MHZ	PCT	DEG	PCT	DEG	PCT	DEG	PCT	DEG
200.	2.25	1.85	3.47	1.11	.91	1.30	.97	.86
300.	1.48	1.17	1.23	.51	1.84	1.39	.75	1.01
400.	3.00	.78	1.25	.80	.88	1.00	1.79	.59
500.	2.80	1.80	.92	.59	1.44	1.76	2.16	.81
600.	2.77	1.80	.69	1.29	1.56	1.87	2.21	1.76
700.	1.27	1.10	.48	1.69	1.61	2.69	3.19	2.16
800.	1.92	.46	1.33	.25	2.12	.32	3.23	2.06
900.	1.48	.46	1.56	.87	2.53	.21	3.06	2.31
1000.	1.45	.23	3.37	.68	1.39	.98	4.63	2.36

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a Relative standard deviation of S-parameter magnitude measurements; standard deviation of phase measurements.

b Data from Laboratories 4 and 5 were omitted from this analysis; Laboratories 1, 2 and 3 used nearly identical calibration procedures.

TABLE A24. SUMMARY OF S-PARAMETERS OF TRANSISTOR 2N918(A) MEASURED IN PARTICIPANT'S TRANSISTOR FIXTURE.

V_{CE} = 5V, I_E = 2.5 mA

A. DATA FROM FIVE LABORATORIES

MEAN VALUES, 5 LABORATORIES

FREQUENCY	S11		S21		S12		S22	
MHZ	MAG	PHASE	MAG	PHASE	MAG	PHASE	MAG	PHASE
200.	.486	308.4	2.37	100.5	.052	64.2	.871	348.4
300.	.421	293.5	1.71	89.2	.068	61.1	.856	345.4
400.	.374	281.3	1.38	80.5	.083	58.4	.850	341.8
500.	.315	266.8	1.16	72.1	.094	57.0	.848	338.1
600.	.298	252.9	1.01	65.1	.105	55.4	.842	333.9
700.	.267	242.3	.91	58.8	.112	55.6	.822	330.3
800.	.248	222.9	.82	51.8	.121	54.8	.820	326.4
900.	.256	214.6	.75	47.1	.127	55.0	.823	322.2
1000.	.222	206.8	.69	41.5	.133	57.0	.818	318.3

BETWEEN-LABORATORY STANDARD DEVIATION [a]

	S11		S21		S12		S22	
FREQUENCY	MAG	PHASE	MAG	PHASE	MAG	PHASE	MAG	PHASE
MHZ	PCT	DEG	PCT	DEG	PCT	DEG	PCT	DEG
200.	8.47	1.58	4.95	1.99	2.13	1.30	1.36	.69
300.	2.13	1.26	4.55	.68	2.96	.93	.77	1.22
400.	4.58	3.39	4.18	.68	1.84	.76	1.15	1.03
500.	8.52	1.14	3.27	.88	1.88	1.09	1.65	1.04
600.	5.02	2.72	2.72	1.14	2.13	1.32	1.56	1.12
700.	8.03	4.36	3.31	1.66	1.21	2.59	3.19	1.35
800.	8.73	12.82	2.75	.87	1.79	1.05	1.90	1.19
900.	7.86	6.26	3.05	1.40	1.28	.85	1.96	1.36
1000.	18.07	5.87	3.82	1.31	1.84	.70	3.06	1.29

B. DATA FROM THREE[b] LABORATORIES

MEAN VALUES, 3 LABORATORIES

FREQUENCY	S11		S21		S12		S22	
MHZ	MAG	PHASE	MAG	PHASE	MAG	PHASE	MAG	PHASE
200.	.505	308.0	2.33	101.6	.051	64.7	.876	348.1
300.	.425	294.4	1.71	89.7	.068	61.3	.858	344.7
400.	.368	280.4	1.37	80.8	.082	58.4	.847	341.4
500.	.327	267.3	1.15	72.7	.093	57.4	.852	337.8
600.	.297	254.6	1.01	65.8	.103	55.8	.843	333.5
700.	.277	241.8	.91	59.8	.112	56.3	.829	329.6
800.	.257	230.1	.82	52.3	.121	55.2	.823	325.8
900.	.247	218.9	.75	48.0	.126	55.1	.824	321.8
1000.	.235	207.9	.69	42.2	.133	57.4	.825	318.2

BETWEEN-LABORATORY STANDARD DEVIATION [a]

	S11		S21		S12		S22	
FREQUENCY	MAG	PHASE	MAG	PHASE	MAG	PHASE	MAG	PHASE
MHZ	PCT	DEG	PCT	DEG	PCT	DEG	PCT	DEG
200.	1.54	1.01	5.50	1.30	.91	1.48	.69	.70
300.	1.87	.76	3.18	.47	1.46	1.18	.79	.92
400.	4.02	.23	3.02	.72	.41	1.07	1.29	1.18
500.	5.90	.95	2.82	.30	1.59	1.21	2.13	1.14
600.	6.42	1.46	2.68	1.01	1.97	1.65	2.15	.50
700.	4.80	2.31	2.03	1.34	.49	3.41	3.03	1.01
800.	5.07	1.75	2.44	.72	2.02	1.31	2.09	.21
900.	6.08	2.00	2.52	.86	.51	1.07	2.69	.86
1000.	6.81	2.99	2.49	1.07	1.37	.46	2.94	.80

a Relative standard deviation of S-parameter magnitude measurements; standard deviation of phase measurements.

b Data from Laboratories 4 and 5 were omitted from this analysis; Laboratories 1, 2 and 3 used nearly identical calibration procedures.

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

Results of an interlaboratory comparison of transistor scattering-parameter measurements are reported for transistor types 2N709, 2N918 and 2N3960. From these results it is estimated that, for such devices, between-laboratory variability of transistor S-parameter measurements in the frequency range between 200 and 2000 MHz could be held to a maximum relative sample standard deviation of 7.5 percent in the measurement of magnitude and a maximum sample standard deviation of 8 degrees in the measurement of phase of s_{11} and 3.5 degrees in the measurement of phase of other S parameters. This could be done if all participants were required to use the same calibration procedure and to limit their test signal to a level that would assure small-signal operation. In a separate study, the equivalent circuit of high-frequency probes used in characterizing the parameters of integrated circuits was evaluated by measuring S parameters at the input connectors with the probe tips in contact with known loads. These measurements revealed a resonance which would limit the usefulness of the probes for measurements in the vicinity of 1.2 GHz. Work is underway to determine design changes needed to eliminate this resonance.

KEY WORDS (*six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons*) Electronics; high-frequency probes; interlaboratory comparison; scattering parameters; S parameters; transistors

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