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A MICROWAVE VECTOR VOLTMETER SYSTEM

Keith C. Roe
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Institute for Basic Standards
National Bureau of Standards
Boulder, Colorado 80302

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A MICROWAVE VECTOR VOLTMETER SYSTEM

Keith C. Roe and Cletus A. Hoer

This report presents a system description and operating procedure for a vector voltmeter system which covers the frequency range .5 to 12 GHz. The design is based upon a seven-port junction where phase and amplitude information is obtained using only power detectors. The system is computer controlled and self-calibrating for ratio measurements.

KEY WORDS: Amplitude; computer controlled; diode detectors; microwave measurements; phase angle; self-calibration; seven-port junction; vector voltmeter.

I. INTRODUCTION

The theory for using six, seven, and eight-port junctions to measure circuit parameters has developed rapidly at the National Bureau of Standards in the past three years [1 - 7]. One of the applications of that theory is a microwave vector voltmeter (MVV) used to make measurements of complex substitution loss, or gain, ratios.

This report describes a complete MVV system which includes a seven-port junction, computer, digital voltmeter, multiplexing unit, switching circuits, and self-calibration devices.

II. DESCRIPTION

General

The MVV system has two input ports or channels (labeled "reference" and "test") for comparison of voltage level changes in the test channel while the reference channel level is maintained constant. The complex ratio of the voltage change in the test channel may be measured at any frequency in the 0.5 to 12 GHz range with power levels not exceeding +10 dBm at either of the two input ports. The lower limit of power at the reference port is -20 dBm and at the test port is -70 dBM.

The basic design of the MVV is based upon the six-port concept [1 - 7] where phase and amplitude information can be obtained from a set of amplitude measurements. (In the MVV, diode detectors whose output voltages are very nearly a linear function of the square of their respective input voltages are used to indicate amplitude levels.) The seven-port approach may be regarded as an augmented version of the six-port technique. This was motivated by preliminary experiments, which indicated an improvement in measurement precision with one additional power detector.

A block diagram in figure 1 shows the interrelationship between the major parts of the complete system. All interconnecting lines in figure 1 represent interface cables for switching control or data transfer.

The computer is used for data storage and calculation as well as automatic control of the system to minimize operator involvement and reduce the time required for the calibration and measurement processes. The switch driver, multiplexer and DVM are necessary for automatic control and data handling.

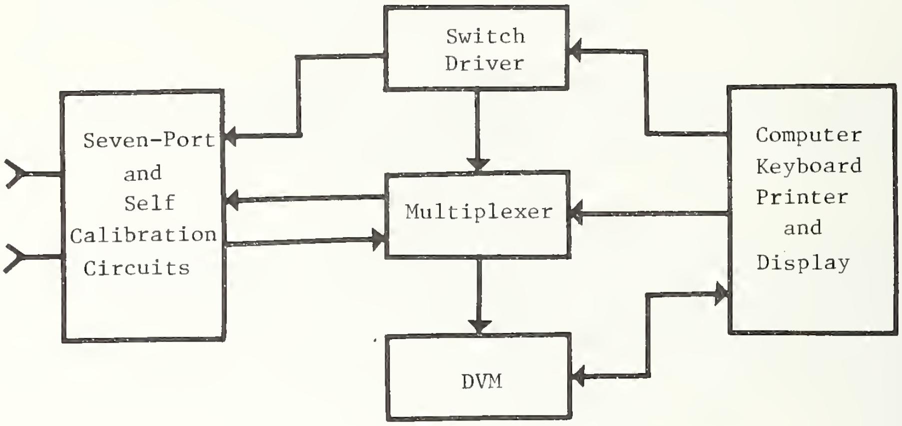

Figure 1. The microwave vector voltmeter system.

More detail is given in the following sections concerning the operation and functions of the MVV components shown in figure 1. Figure 2 shows the assembled system where the multiplexer, DVM, switch driver, seven-port and self-calibration circuits are contained within the cabinet on the right and the computer and keyboard are in the cabinet at the left.

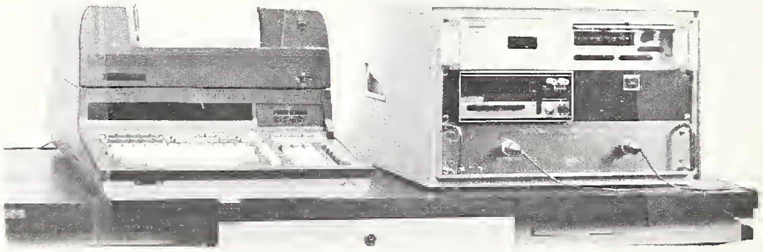

Figure 2. A front view of the microwave vector voltmeter.

Seven-Port Junction

The seven-port junction is constructed using quadrature hybrid 3 dB couplers (Q) and 3 dB power dividers as shown in figures 3 and 4.

For incident waves a_1 and a_2 at ports 1 and 2 the ideal response at each of the power detectors P_3, P_5, P_6, P_7 and P_8 would be proportional to the quantities indicated in figure 3. The ratio of the two incident waves would be

$$\frac{a_2}{a_1} \propto \frac{(P_5 - P_7) + j(P_6 - P_8)}{P_3} \quad . \tag{1}$$

Since non-ideal components are used resulting in reflections, losses and uneven power division, the seven-port junction must be analyzed in a more general way. This is done in Appendix A for a six-port junction. A minor extension of that analysis can be performed for a seven-port junction resulting in equations (1) through (10), (Appendix A) where the summations are taken over 5 detectors instead of 4. The result is (from (10), Appendix A)

$$\frac{a_2}{a_1} = K \frac{\sum z_i P_i}{\sum w_i P_i} \quad , \quad i = 3, 5, 6, 7, 8^* \tag{2}$$

The terms K, z_i, and w_i, are constants of proportionality that can be determined in calibration. For measurements of the ratio of two different values of a_2 (a_1 remains constant) the complex constant, K, does not need to be known. Since one of the $z_i = 1$ and one of the $w_i = 1$, this leaves four complex z_i and four real w_i, to be determined by the calibration. The self calibration process is described in Section III of this report.

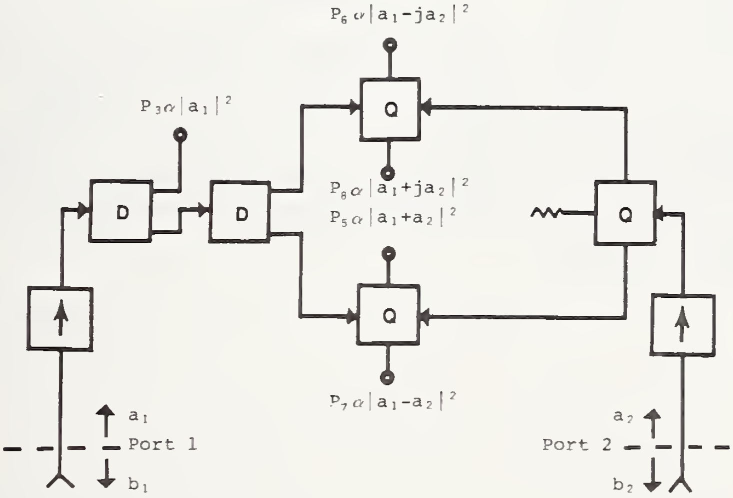

Figure 3. The seven-port junction and isolators used in the MVV.

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[*] The subscripts are so labeled to be consistent with previous publications.

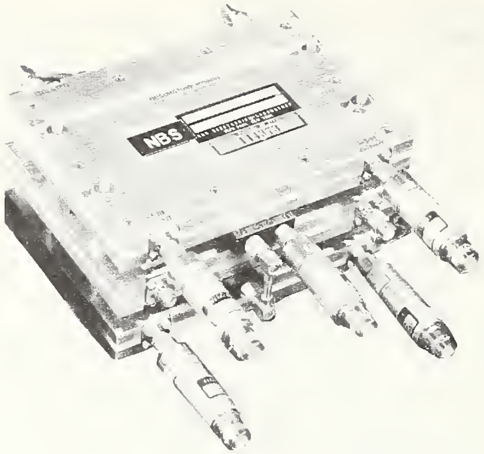

Figure 4. The seven-port junction and diode detectors.

System Operation

To make measurements the seven-port junction must first be calibrated, and then switched into a measurement routine. Three routines are available through software (Appendix C) supplied with the system. These routines are:

1. Self Calibration
2. Measurement
3. Diagnostic.

These routines contain control commands (Appendix B) which set the switches shown in figures 5 and 6. The four outer switches (1, 3, 6, 7) are set to "M" to measure or position "C" to calibrate the seven-port junction. The three inner switches (2, 4, and 5) are set to "S" for calibration and measurement or to "D" for diagnostics and diode linearity.

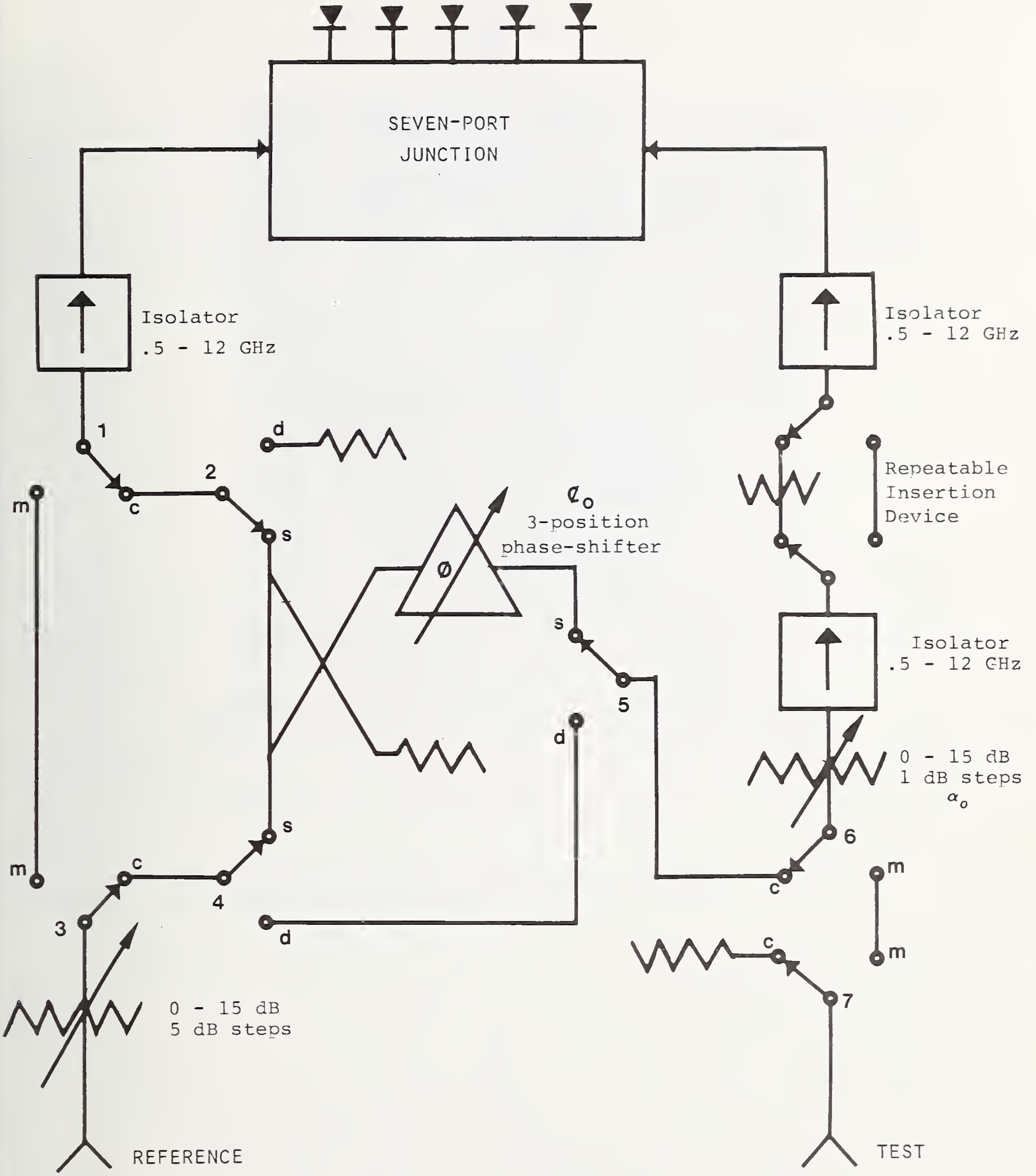

Figure 5. Circuit used for self-calibration, measurement and diode linearity in the MVV system.

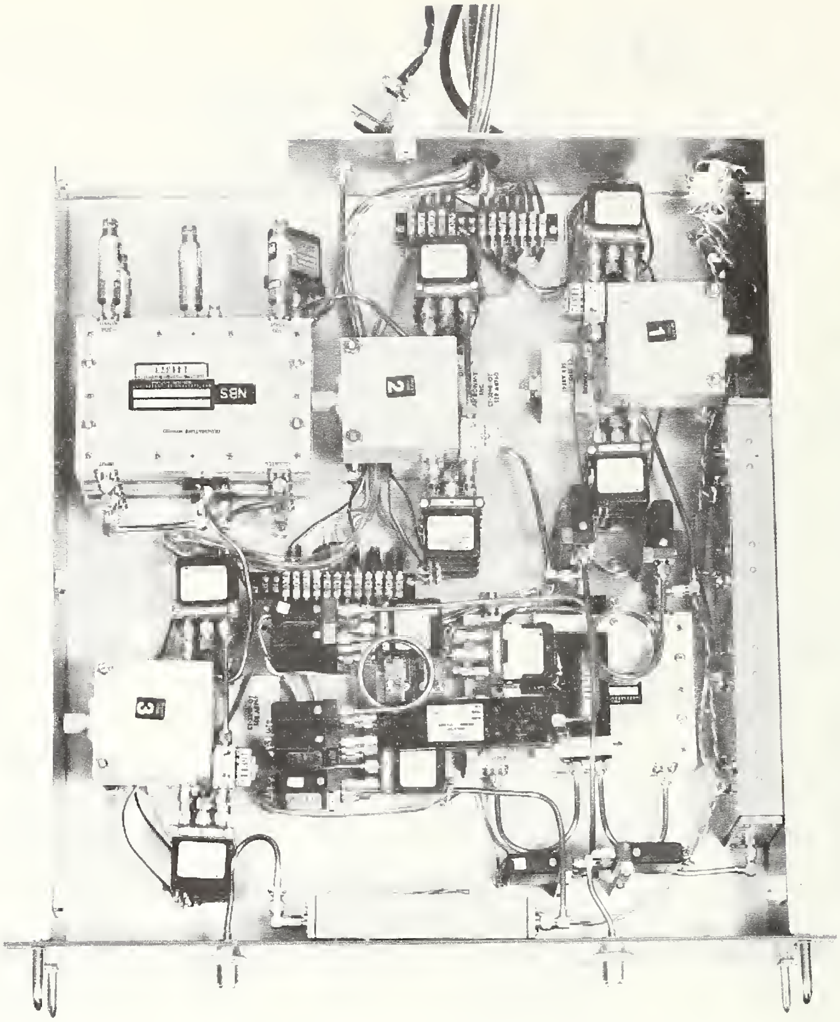

Figure 6. A view of the chassis containing the seven-port junction and self calibration circuitry.

III. SEVEN-PORT CALIBRATION

General

The self-calibration procedure is almost identical to the procedure outlined in [7] and reproduced in Appendix A. The only change is that i goes from 3 to 7 instead of 3 to 6.

Six independent measurements of the repeatable insertion device are obtained corresponding to these six nominal settings of ϕ_0 (three-position phase shifter) and α_0 (0 - 15 dB, 1 dB step).

α_0 (dB)	ϕ_0 (degrees)
0	0°
0	120°
0	240°
3	240°
3	120°
3	0°

These values of attenuation and phase shift for α_0 and ϕ_0 were chosen to obtain six symmetrically spaced points in the complex plane. The values are only approximate and need not be known for the self-calibration process. The only requirement is that no two points coincide for any frequency in the range 0.5 to 12 GHz.

The attenuation change, α_0, is easily obtained using commercially available equipment, however, the phase shifter (ϕ_0) and the repeatable insertion device (L) are specially constructed to obtain broadband operation. More detail is provided about those circuits and their operation in the following sections.

Broadband two-position insertion device

In calibrating the seven-port junction, the complex insertion ratio L of the repeatable two-position insertion device must not have a phase angle of 0° or multiples of 90°. A phase shift of 45° is probably optimum, but doesn't need to be exact or known. One way of getting 45° phase shift over a broad frequency range is shown in figure 7. The two outputs of the quadrature hybrid (Q) are equal in amplitude but 90° out of phase. Adding these two signals with an in-phase power divider. (D) gives a signal that is shifted 45° relative to the input signal. In addition to this 45° there will be some phase shift θ due to the lengths of line through Q and D. The length of the lower path can be adjusted to give a phase shift equal to θ. The phase difference in the two switch positions will be 45° over the complete frequency range of the hybrid and divider, which is the same as the frequency range of the seven-port. The amplitude of the insertion ratio will be approximately 3 dB. The assembled two-position insertion device is shown in figure 8. Measurements of the phase and insertion ratio are shown in the graph of figure 9.

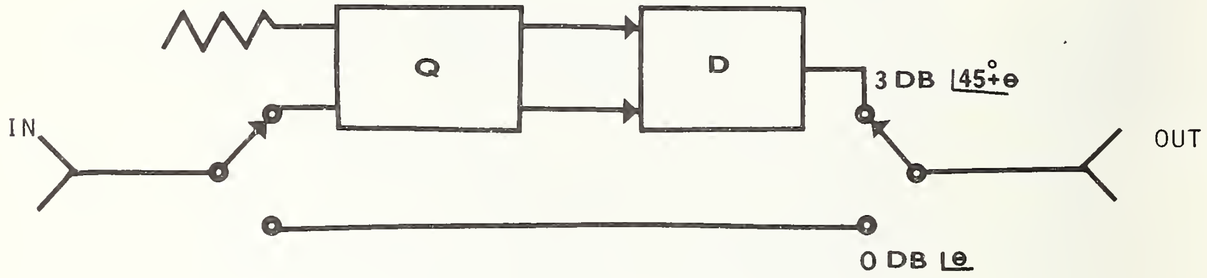

Figure 7. Using a quadrature hybrid (Q) and a power divider (D) to make an insertion ratio of 3 dB with 45° phase shift.

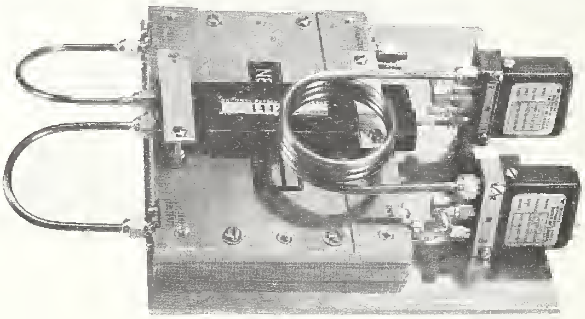

Figure 8. A two-position repeatable insertion device.

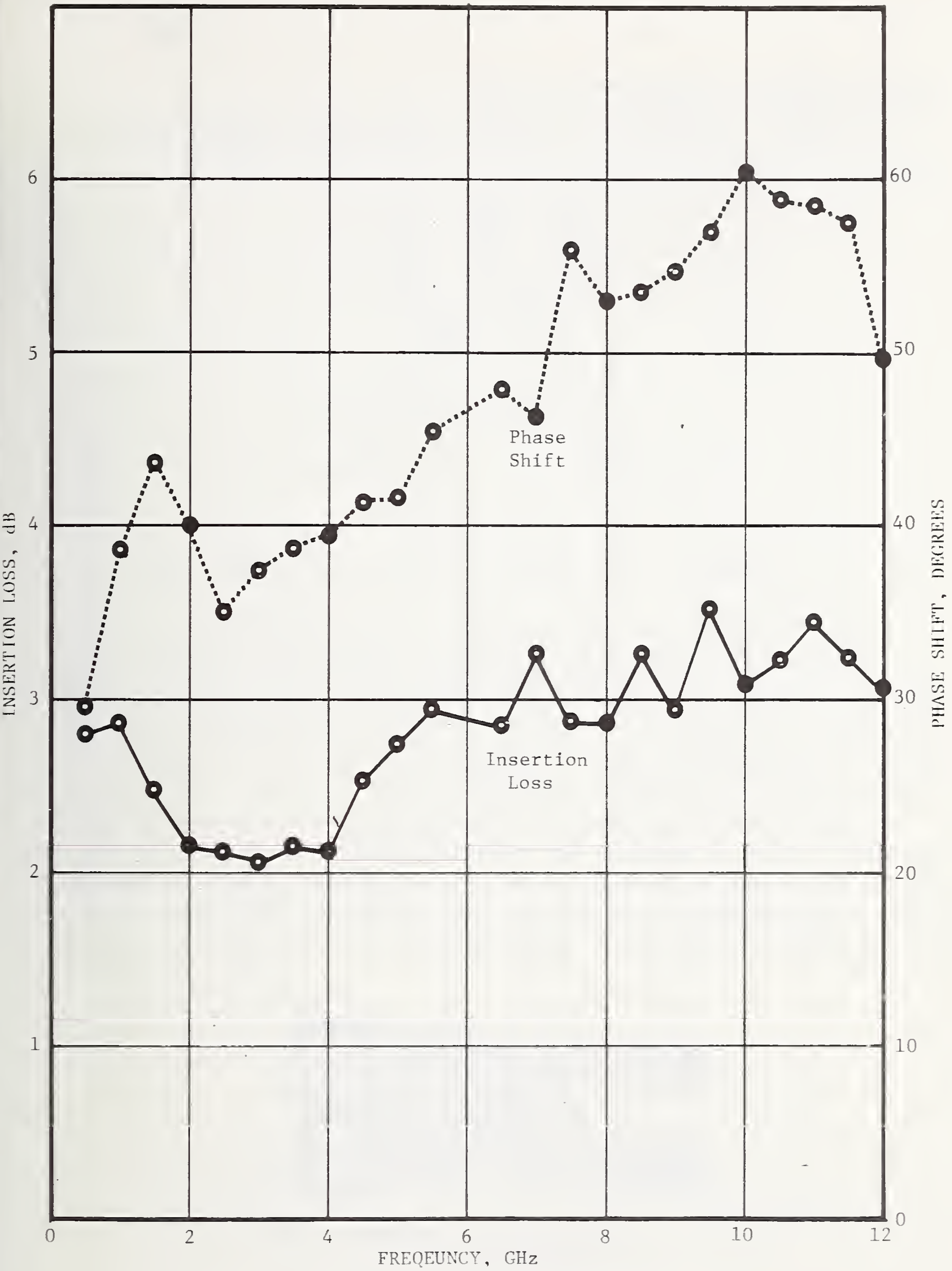

Figure 9. Insertion loss and phase shift of the broadband two-position insertion device.

Broadband three-position phase shifter

The phase shifter shown in figure 10 gives three different values of phase over the usable frequency range of the quadrature hybrid (Q).

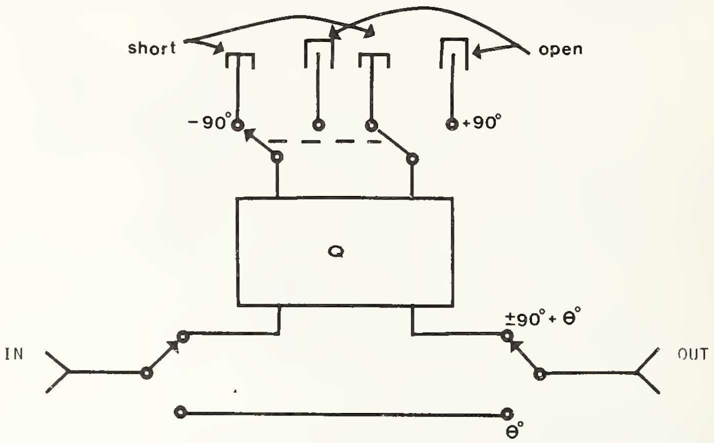

Figure 10. A broadband three-position phase shifter.

Going through the hybrid (Q) the phase shift is theoretically either θ - 90° or θ + 90° depending on whether the outputs are shorted or open. The phase shift θ is a residual phase shift due to the length of line through the hybrid. The electrical length of the lower path is adjusted to equal θ, so the three relative values of phase are 0°, -90° and +90° over the bandwidth at the hybrid coupler.

The center conductors at the two open circuited terminal planes were recessed 1.65 mm to equalize the electrical lengths of the shorted and open paths. The assembled three-position phase shifter is shown in figure 11. Results of measurements for both the shorted and open conditions relative to the bottom path are shown in figure 12.

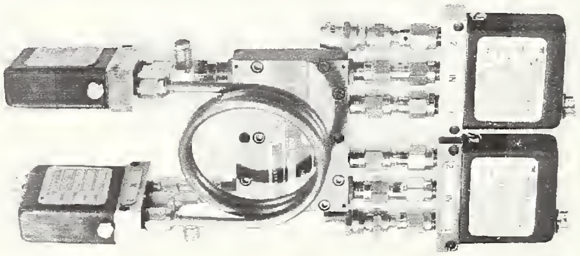

Figure 11. Photograph of a broadband three-position phase shifter.

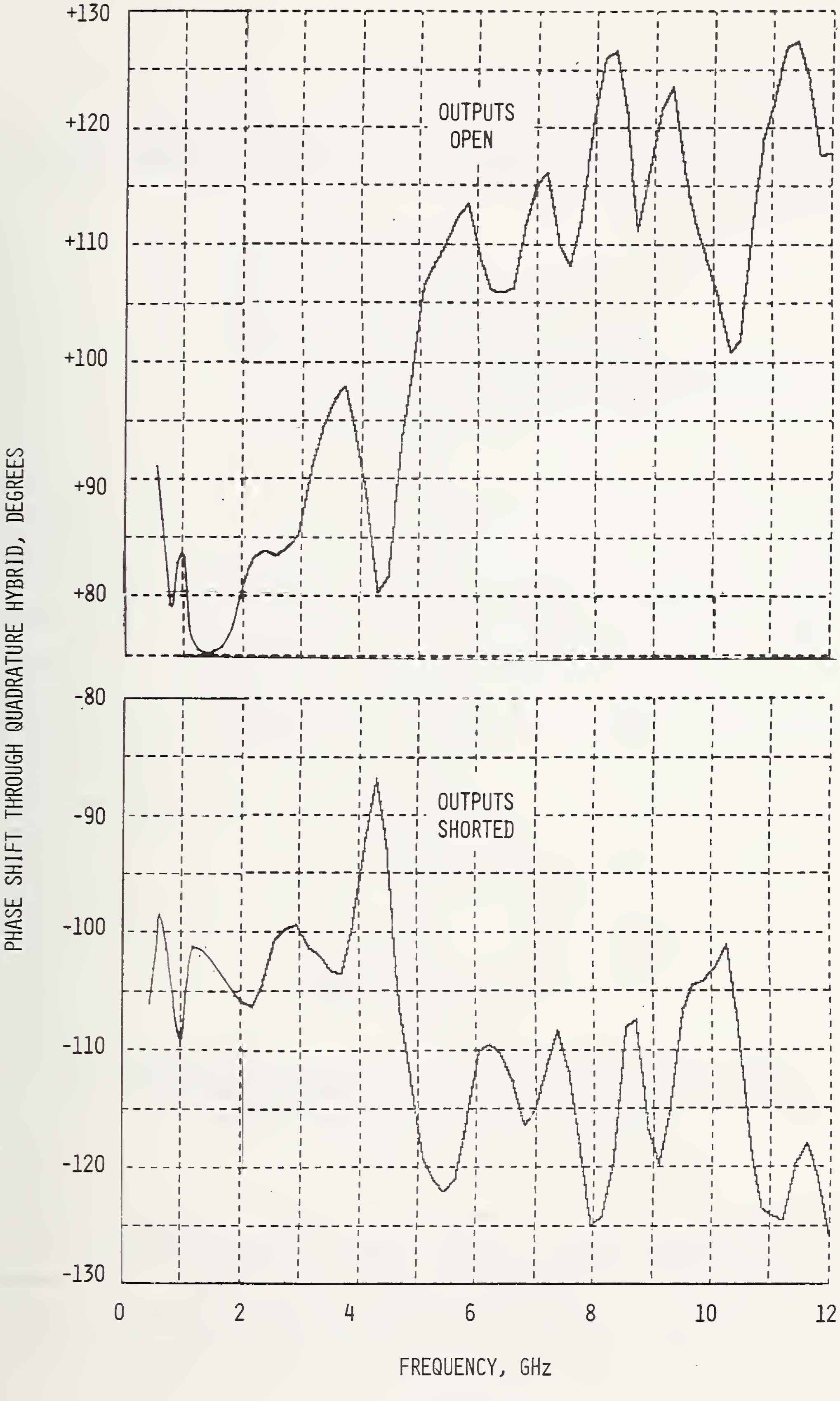

Figure 12. Phase shift through the quadrature hybrid shown in figure 1 relative to the bottom coax line, measured on the NBS automatic network analyzer.

IV. MEASUREMENT

Applications

Several types of measurement can be performed using the MVV. Three types are shown in figure 13. Some additional applications are described in [8] and [9].

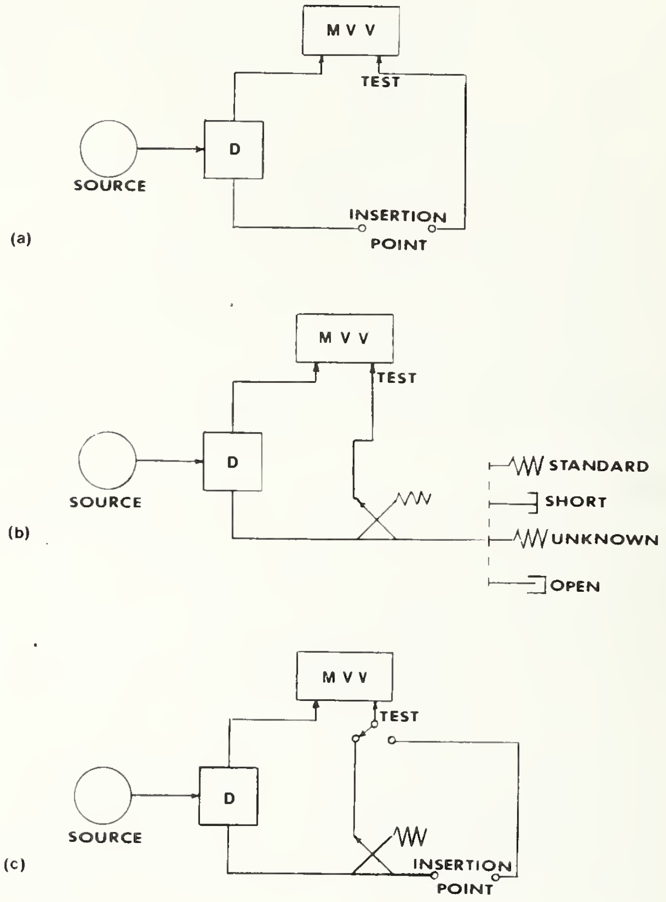

Figure 13. Some measurement configurations using the microwave vector voltmeter. Device D may be either a power divider or a directional coupler.

For the measurement shown in figure 13(a), the item under test must be a two-port device or system connected at the insertion point. The measurement configuration shown in figure 13(b) is for one-port devices and the configuration of figure 13(c) may be used for either one-port or two-port devices.

Tasks

Appendix C contains a listing of the program used to calibrate the seven-port junction and make measurements. This program contains a list of eight tasks which can be performed individually or sequentially. These tasks are:

1. Calibrate
2. Measure reference
3. Measure test device
4. Measure DVM offset voltages
5. Measure R_0 and C
6. Monitor reference diode voltage
7. Measure insertion step value
8. To determine K for absolute ratio measurements
9. To measure and average ratios with test device inserted.

Tasks 1, 2, and 3 are intended to be used most frequently where task 1 (calibrate) must, of course, be used before any measurements are made. Task 2 establishes a reference voltage ratio and task 3 measures a test voltage ratio relative to the reference voltage ratio. Any number of test voltage ratios may be measured relative to a reference or the option exists to reestablish a new reference ratio at any time by selecting task 2. Each time a task is completed the system will pause and wait for a new task selection which may be selected by entering the number of the task at the keyboard followed by an execute command.

The reference ratio is the value

$$\frac{a_2}{a_1} = K \frac{\sum z_i P_i}{\sum w_i P_i} , \quad i = 3 \ . \ . \ . \ 7 \tag{3}$$

and the test ratio is the value

$$\frac{a_2'}{a_1'} = K \frac{\sum z_i P_i'}{\sum w_i P_i'} , \quad i = 3 \ . \ . \ . \ 7 \tag{4}$$

The insertion ratio R is computed from these two ratios

$$R = \frac{a_2'/a_1'}{a_2/a_1} . \tag{5}$$

Tasks 4 (measure DVM offset voltages), 6 (monitor reference diode voltage), and 7 (measure insertion step value) are available for general information about the complete system in case there is some question about the measurement results.

Task 5 (measure R_0) is performed at the end of the calibration procedure automatically, however it may also be performed at any other time when applicable. Its purpose is to establish a zero input reference at the terminal plane of the test device insertion point. Establishing a zero reference value increases the reliability of the measurements for high values of insertion ratio, 40 to 60 dB. The need for this measurement is due to non-ideal isolation between input ports 1 and 2 which allows some of the signal at port 1 to go through the seven-port junction and appear at port 2. Portions of this leakage signal are then reflected from discontinuities in the transmission line leading from port 2 to the insertion point. The effect of this leakage signal is measured and cancelled out of the measurements of the test signals.

Task 5 also allows the operator to input a value for the absolute power, P_r, incident at the input reference terminal of the MVV. Measurement of the incident power can be accomplished using a calibrated bolometer-coupler. The program then calculates a value for C in

$$P_r = C\sum_{i=3}^{i=7} w_i \; P_i \tag{6}$$

so that the reference power can be monitored and printed by the calculator. If this is not useful information, simply input $P_r = 1$ when the calculator asks for P_r and then ignore the P_r column. Ratio accuracy is not affected by the value input for P_r.

Task 8 allows K in (3) to be determined. The operator is instructed to apply two signals equal in amplitude and phase to the test port and to the reference port so that $a_2/a_1 = 1 + j0$. Other reference ratios of a_2/a_1 are then calculated relative to this first one.

Task 9 is a special routine to be used where source power stability is a problem. This task changes the sequence of reading the diode output voltages on the seven-port junction. All diode voltages are measured as fast as possible taking one reading from each diode. The voltage ratio a_2'/a_1' is measured 2 to 25 times depending on the value of K6 in line 5140 of the MVV program. The average ratio is then computed. Results of the measurement are calculated using (5).

V. OPERATING PROCEDURE

Turn-on

First make sure that excessive microwave power levels are not present which could damage the diode detectors. Fifty milliwatts is considered excessive, however power levels of 10 milliwatt or less are recommended.

Turn on the ac power switch on the front panel of the voltmeter chassis and the computer and high-speed printer.

The front panel push button controls on the DVM should be set to "DC" and "Auto". The multiplexer push button controls should be set at "PWR", "REM" and "EXT". The multiplexer first point and last point thumbwheel switches should be set to 0 and 30 respectively.

Program

Load the program stored on file 2 of the cassette tape by pressing consecutively:

Load
2
Execute.

Operating

When the program has been loaded into computer memory it may be executed by pressing "Run" and "Execute". The computer will display or print questions and instructions. Questions can be answered through the keyboard while instructions can be acknowledged after completion by pressing "Cont" (continue) and "Execute". For example: The first question displayed when running the program is "Frequency (GHz)?" The operator responds by typing the frequency and pressing execute. The computer responds by setting the switches for the correct isolators in the MVV and then lists the eight available tasks on the high-speed printer. The operator may then select the appropriate task by typing the number of the task and pressing execute.

In general, it is desirable to set the power levels so that the test and reference channel power levels are approximately the same magnitude. The reference channel may be monitored by selecting task 6 and should be set so that the reference diode output level is between 5 and 10 millivolts.

When the frequency is changed the program should be started over (press Run, Execute) so that the isolators will be reset. The system will need to be recalibrated also. The system can be stopped at any time and returned to the "Next Operation" question by pressing:

Stop
Cont 400
Execute.

VI. ERRORS

The major sources of error are:

1. Detector nonlinearities
2. Step attenuator nonrepeatability
3. Frequency drift
4. Leakage signals
5. Signal level variation

The following is a description of these errors and of methods used to reduce them.

Detector nonlinearity

This is the largest single source of error in the MVV. Diode detectors are used because of their small size, availability, simplicity, and ease of instrumentation; however, the output voltage response is not proportional to input power over a wide dynamic range. Some major factors affecting diode response are diode loading impedance and ambient temperature.

To improve the diode response curve each diode detector has an output loading resistor which was selected for the most optimum square-law response by comparing the diode output with known input power levels measured using a bolometer bridge power meter.

In addition, the diodes are temperature controlled to within approximately ±0.1 degree Celsius using an aluminum block with a heater and temperature sensor controlled by a proportional oven temperature control circuit.

Step attenuator nonrepeatability

Self calibration of the seven-port junction is a process where six equations are produced relating the step attenuator value to two groups of power measurements. A basic assumption in solving the six simultaneous equations is that the step attenuator value is the same for each equation. If this is not true then the results may not fit to any lower value of precision than the precision of repeatability of the step attenuator.

Repeatability tests on the step attenuator produced standard deviations for groups of 10 steps of about 0.001 dB. A major factor which can increase the nonrepeatability is connector loosening due to vibrations from repeated switch closures. To reduce this effect a periodic check using the diagnostic routine (file 4 on cassette tape) is recommended which monitors the step repeatability for groups of five step closures. The connectors on the step may be retightened to improve the repeatability. Do not overtighten, since excessive torque may ruin the connectors on the switches.

Frequency Drift

Frequency variations from a microwave source will affect any phase measurement in a two-channel system if the two channels do not have equal electrical lengths. For example, a path length difference (Δd) of one meter in air dielectric coaxial line will result in a phase change (ΔP) of 12 degrees when the frequency varies by 10 MHz. The relationship is

$$\Delta P = \frac{360\ \Delta d\ \Delta f}{c}$$

where Δf is the frequency variation during the measurement period and c is the velocity of propagation.

Within the MVV, electrical lengths have been equalized for both channels in the measurement and calibration circuits; however, electrical path length differences external to the MVV can contribute to phase changes as well, so this effect must be considered. Both frequency control and equalization of external path lengths are recommended to minimize this source of error.

Leakage Signals

Isolation between the input ports 1 and 2 at the seven-port junction is required so that any change in Γ_1 or Γ_2 due to a change in a_1 or a_2 is negligible. (See Appendix A, eq. 18).

$$\frac{V_2}{V_1} = \frac{a_2\ (1 + \Gamma_2)}{a_1\ (1 + \Gamma_1)}$$

Isolation across the seven-port junction is greater than 40 dB, however this small amount produces significant errors when the measured insertion loss is 40 dB or greater. This effect has been reduced to approximately 60 dB by using the "measure R_0" routine described previously in Section IV.

Signal Level Variation

An error can appear in calibration of the seven-port junction if the signal level varies during the time between measurements with the step in and the step out. From Appendix A equation (20)

$$L = \frac{a_2'}{a_2} = \frac{\sum Z_i P_i'}{\sum Z_i P_i}, \quad i = 3 \ . \ . \ . \ 7, \tag{7}$$

L is the insertion ratio of the two-position insertion step attenuator. A change in signal level from the microwave source between measurements of a_2 and a_2' will introduce an error in the calculation of L and therefore an error in the calculation of the seven-port constants. This error will have the same effect as the previously described error from step attenuator non-repeatability.

VII. EVALUATION

System Repeatability

Measurement precision and accuracy may vary from time to time depending on such factors as microwave source stability, step repeatability, and operating power levels. A reliable check on measurement precision appears in sigma of the self-calibration printout. Sigma is the standard deviation of differences between the calculated and measured values of the step attenuator for each of the six calibration measurements. If sigma is less than 0.03 dB the calibration is good and measurements should repeat to about the same value for insertion ratios up to about 20 dB. Above 20 dB the errors should increase approximately one order of magnitude for each 20 dB increment of insertion change in the test channel.

Intercomparison

A measurement comparison between the MVV and the NBS network analyzer has been performed using a 0 - 70 dB (10 dB steps) attenuator. Isolators were connected on both sides of the attenuator and measurements were made in the octave frequency range between 4 and 8 GHz using both systems. Results of that intercomparison are given in table I and table II.

Table I.

Attenuation Measurement Difference (dB)

ANA - MVV

Frequency GHz	10 dB	20 dB	30 dB	40 dB	50 dB
4.0	0.35	.07	.07	.49	1.7
4.5	0.27	.03	.31	.07	1.1
5.0	0.10	.08	.06	.15	0.2
5.5	0.05	.04	.13	.06	0.5
6.0	0.02	.07	.14	.41	1.5
6.5	0.02	.01	.00	.26	0.8
7.0	0.01	.05	.31	.17	0.0
7.5	0.01	.01	.01	.11	0.6
8.0	0.07	.04	.32	.42	1.3

Table II.

Phase Shift Measurement Difference (degrees)

ANA - MVV

Frequency GHz	10 dB	20 dB	30 dB	40 dB	50 dB
4.0	0.6	1.1	5.7	8.6	32.3
4.5	0.01	0.1	1.8	0.8	6.5
5.0	0.3	0.6	0.2	6.2	10.5
5.5	0.3	1.1	3.9	11.2	37.8
6.0	0.5	0.6	2.1	3.9	59.1
6.5	0.2	0.6	0.2	1.4	1.0
7.0	0.5	0.5	2.2	0.3	0.3
7.5	0.7	0.6	1.1	1.1	2.3
8.0	0.2	0.3	7.3	2.4	3.0

VIII. TROUBLESHOOTING

The following table lists some troubles that may occur during operation of the MVV system, their probable cause and cure.

Those troubles due to malfunctioning commercial equipment contained within the system should be referred to the respective manuals (supplied with the system) covering that equipment.

Trouble	Probable cause and/or cure
Program won't converge to correct solution in self-calibration procedure.	CAUSE: 1. Data incorrect due to power level--too high or too low. 2. Switches not functioning. 3. Data transfer error caused by transient noise or interface cable trouble. CURE: 1. Compare data with samples of good data that did converge. 2. Check switches by running diagnostic program to measure step repeatability and cycle the switches. 3. Check for adequate signal level in both the reference and test channels in the calibration and measurement modes. 4. Rerun the self-calibration routine.
Bad data	CAUSE: 1. Equipment not on. 2. Interface cables loose. 3. Scanner not setting correctly. 4. DVM malfunction or controls at wrong setting 5. Attenuators not switching correctly. 6. Switches sticking on phase shifter or repeatable step. CURE: 1. Check equipment and cables. 2. Cycle switches. 3. Watch scanner during self-calibration routine to see if the scanner is changing channels properly. 4. Check data from the DVM, display data transferred to the computer and make sure it is the same as that displayed on the DVM. 5. Monitor diode voltage levels to see if there is sufficient signal present in both channels in the measurement and calibration modes.

Trouble	Probable cause and/or cure
Improper Switching	CAUSE: 1. Switch sticking 2. Switch driver malfunctioning 3. Interface cable disconnected. CURE: 1. Cycle switches several times using the diagnostic routines and listen for audible switching noise. If no switches work, check the switch driver, interface cables, and statements in the program which control the switching functions. See Appendix C. If some switches work but others do not the switches may be bad or the driver output power level may be low. If possible substitute switches.
Program won't load	CAUSE: 1. Bad tape 2. Dirt or residue on tape reader 3. Computer out CURE: 1. Clean the tape reader then reload the program. 2. Load program from another tape. 3. Check computer manual.

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APPENDIX A

USING AN ARBITRARY SIX-PORT JUNCTION TO MEASURE COMPLEX VOLTAGE RATIOS

The following report is reproduced in its entirety because it provides the theoretical background for the MVV system. All work in this Appendix and in the main body of the report represents the same effort, therefore repetition can be avoided by referral to portions of this Appendix which cover the applicable subject.

Using an Arbitrary Six-Port Junction to Measure Complex Voltage Ratios

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Abstract—**An arbitrary six-port junction is analyzed as a microwave vector voltmeter, measuring the amplitudes and phase differences of two input signals in terms of power readings taken at the remaining four ports. The junction may be calibrated for measuring the complex ratio of these two signals using a self-calibration procedure which requires no attenuation or phase standards.**

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INTRODUCTION

PERHAPS the greatest impact in the field of UHF and microwave measurement in recent years has been the introduction of the automatic network analyzer (ANA). In contrast with the prior art where the key to improved accuracy was usually an improved hardware item, the procedure now is to measure the hardware imperfections and adjust the measurement results in such a way as to account for them. The key to this correction process is in the measurement of the phase as well as amplitude of the complex parameters involved. The measurement of this phase has generally involved conversion to a lower frequency which complicates the detection process. Although phase detection circuits which operate at microwave frequencies are well known, these have generally assumed ideal components, and are not particularly suitable for automation.

Recent theoretical studies of an arbitrary six-port have provided an alternative method of obtaining the phase information without requiring either frequency conversion or ideal components. [1], [2], [7]. One of the unexpected results of this study is that most of the earlier six-port designs for getting phase information provide a set of data which is ill conditioned from the viewpoint of the more general theory. Fortunately, the theory also suggests how to design the six-port junction to eliminate this condition.

This paper shows how the ratio of two complex voltages or two complex wave amplitudes can be measured using an arbitrary six-port junction where four of the ports are terminated with power meters. If two coherent signals of the same frequency are applied to the remaining two ports, the junction gives the phase angle between the two signals as well as the amplitude of both in terms of the four power meter readings. The six-port junction thus becomes a vector voltmeter in which phase and amplitude information are calculated from power measurements.

The six-port junction can be calibrated for making complex ratio measurements without using any standards. The only precision component needed in the calibration or measurement setup is a two-position step attenuator whose change in insertion ratio must be highly repeatable, but need not be known. Its value is determined in the calibration process along with other unknown constants describing the six-port. The complete calibration process is readily automated, requiring no operator involvement.

Accuracy of ratio measurements is determined primarily by the linearity of the four detectors. Precision components are not required to make precise ratio measurements.

The analysis of a six-port junction as a vector voltmeter is similar to that of a six-port junction used for power [1] or impedance [2] measurements.

GENERAL THEORY

Consider an arbitrary six-port junction shown in Fig. 1, where four ports are terminated with power meters. If the junction is linear and only one mode is present at each port, the scattering equations for the junction can be written

$$b_i = \sum_{j=1}^{6} S_{ij}a_j, \qquad i = 1 \cdots 6 \tag{1}$$

where a_j and b_i are the complex incident and emergent wave amplitudes and the S_{ij} are the scattering parameters of the junction. Assuming that the power meters on arms $3 \cdots 6$ are permanently connected

$$a_j = b_j \Gamma_j, \qquad j = 3 \cdots 6 \tag{2}$$

where Γ_j is the reflection coefficient of the power meter on port j. Equations (1) and (2) represent a collection of ten linear equations in terms of the twelve variables a_i, b_i, $i = 1 \cdots 6$. This system of equations may be solved for any ten of these variables as functions of the remaining two. In particular, it is possible to write

$$b_i = A_i a_1 + B_i a_2, \qquad i = 3 \cdots 6 \tag{3}$$

where A_i and B_i are functions of the scattering parameters of the junction and the reflection coefficients of the power meters. Multiplying (3) by its complex conjugate yields

$$|b_i|^2 = |A_i|^2 |a_1|^2 + A_i B_i^* a_1 a_2^* + A_i^* B_i a_1^* a_2 + |B_i|^2 |a_2|^2, \qquad i = 3 \cdots 6 \tag{4}$$

where (*) indicates complex conjugate.

If the phase angles ϕ_1, ϕ_2, and ϕ are defined such that

$$a_1 = |a_1| \exp(j\phi_1), \qquad a_2 = |a_2| \exp(j\phi_2) \tag{5}$$

and

$$\phi = \phi_2 - \phi_1$$

then (4) becomes

$$\frac{P_i}{K_i} = |A_i|^2 |a_1|^2 + (A_i B_i^* + A_i^* B_i) |a_1 a_2| \cos\phi + |B_i|^2 |a_2|^2 + j(A_i^* B_i - A_i B_i^*) |a_1 a_2| \sin\phi, \qquad i = 3 \cdots 6 \tag{6}$$

where $P_i \equiv K_i |b_i|^2$ is the power indicated by the meter on the ith port, and K_i is a constant. This expression represents a linear system of four equations in the four unknowns $|a_1|^2$, $|a_2|^2$, $|a_1a_2| \cos\phi$, and $|a_1a_2| \sin\phi$. If these equations are independent[1] they may be inverted to obtain each of the four unknowns as a linear function of the four P_i $(i = 3 \cdots 6)$. The result is

$$|a_1|^2 = \sum \rho_i P_i \tag{7a}$$

$$|a_2|^2 = \sum \sigma_i P_i, \qquad i = 3 \cdots 6 \tag{7b}$$

$$|a_1a_2| \cos\phi = \sum x_i P_i \tag{7c}$$

$$|a_1a_2| \sin\phi = \sum y_i P_i \tag{7d}$$

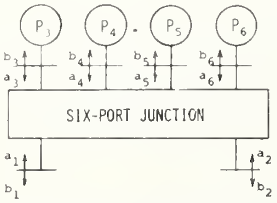

Fig. 1. An arbitrary six-port junction with power meters on four of the six ports.

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[1] It is this condition that is not satisfied by most older six-port designs used for getting phase information from amplitude measurements. See the section on "Six-Port Design Criteria."

where each sum in (7) and throughout this paper is over the four sidearm power readings, $i = 3\cdots 6$. The coefficients of P_i are real numbers which are functions of the parameters S_{ij} and Γ_j. Equations (7) constitute the desired result and are valid for any linear six-port junction subject to the conditions mentioned. The ratio a_2/a_1 can be written

$$\frac{a_2}{a_1} = \frac{|a_2|}{|a_1|} \exp(j\phi) = \frac{|a_1 a_2|}{|a_1|^2} (\cos\phi + j\sin\phi). \quad (8)$$

Using (7) this becomes

$$\frac{a_2}{a_1} = \frac{\sum (x_i + jy_i) P_i}{\sum \rho_i P_i}. \quad (9)$$

A more useful form of (9) for calibration purposes is obtained by factoring $x_m + jy_m$ out of the top sum and factoring ρ_n out of the bottom sum to get

$$\frac{a_2}{a_1} = K \frac{\sum z_i P_i}{\sum w_i P_i} \quad (10)$$

where

$$K = \frac{x_m + jy_m}{\rho_n} \quad (11)$$

$$z_i = \frac{x_i + jy_i}{x_m + jy_m} \quad (12)$$

$$w_i = \frac{\rho_i}{\rho_n} \quad (13)$$

and where m and n can each be either 3, 4, 5, or 6. For many applications the complex constant K does not need to be known. Since $z_i = 1$ when $i = m$, and $w_i = 1$ when $i = n$, this leaves only three complex z_i and three real w_i to be determined.

COMPLEX VOLTAGE RATIOS

The voltage at the two input ports can be written

$$v_i = a_i + b_i, \qquad i = 1,2 \quad (14)$$

$$= a_i(1 + \Gamma_i) \quad (15)$$

where Γ_i is the complex ratio b_i/a_i at port i

$$\Gamma_1 = S_{11} + S_{12} \frac{a_2}{a_1} \quad (16)$$

$$\Gamma_2 = S_{22} + S_{21} \frac{a_1}{a_2}. \quad (17)$$

The scattering parameters in (16) and (17) are those of the equivalent two-port which results when the four sidearms of the six-port junction are terminated with power meters. The ratio of the two input voltages is

$$\frac{v_2}{v_1} = \frac{a_2(1 + \Gamma_2)}{a_1(1 + \Gamma_1)}. \quad (18)$$

The voltage ratio will be proportional to a_2/a_1 provided that there is sufficient isolation between input ports 1 and 2 so that any change in Γ_1 or Γ_2 due to a change in a_1 or a_2 is negligible.

SELF-CALIBRATION PROCEDURE

All of the constants in (10) except K can be determined by a self-calibration technique which does not require any standards. The technique is based on earlier work described by Allred and Manney [3]. A calibration circuit such as shown in Fig. 2 is used. A signal is divided into two channels which are connected to the inputs of the six-port junction. The signal a_1 in one channel is held constant by internally leveling the generator and isolating it from the signal a_2 in the other channel which contains a level set attenuator α_0, phase shifter ϕ_0, and a two-position insertion device. Data for calibrating the six-port junction are obtained by noting the value of all P_i for the two positions of the insertion device at different settings of α_0 and ϕ_0. The value of the insertion device does not need to be known, but it must be highly reproducible and independent of signal level.

The initial value of a_2 relative to a_1 is determined by the setting of α_0 and ϕ_0, which also need not be known. When the insertion device is switched to its second position, a_2 changes to a_2' and the power readings change from P_i to P_i'. Assuming that a_1 is constant during the time it takes to read the P_i and P_i', (7a) and (13) give

$$\sum w_i P_i = \sum w_i P_i'. \quad (19)$$

The ratio of a_2'/a_2 obtained from (10) is

$$L \equiv \frac{a_2'}{a_2} = \frac{\sum z_i P_i'}{\sum z_i P_i}. \quad (20)$$

This L is the change in insertion ratio of the two-position insertion device. The ratio of $|a_2'|^2/|a_2|^2$ obtained from (7b) is

$$|L|^2 = \frac{\sum u_i P_i'}{\sum u_i P_i} \quad (21)$$

where $u_i \equiv \sigma_i/\sigma_l$ and l is either 3, 4, 5, or 6. Since $u_l = 1$, there are only three u_i to be determined in (21).

The measurements of P_i and P_i' are repeated for four

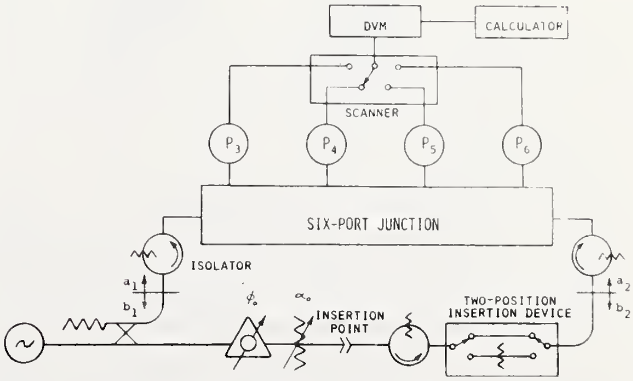

Fig. 2. Setup for calibrating and using a six-port junction to measure complex voltage ratios.

or more different settings of α_0 and ϕ_0. Each different setting gives additional equations like (19)–(21), where L is the same for each measurement. These three sets of equations can be solved for the calibration constants z_i, w_i, and u_i and also for L.

To assure that L remains constant when α_0 and ϕ_0 are changed, and that a_1 remains constant at the two positions of L, isolators are added as shown in Fig. 2. Further analysis may show that not all of the isolators are needed.

CALCULATING SIX-PORT CONSTANTS

When the complex insertion ratio L is known, it can be thought of as a ratio standard in calibrating the six-port junction to obtain the constants z_i, w_i, and u_i. However, it is not necessary that L be known; L can be treated as simply one more unknown constant to be determined. When L is not known, (20) is a nonlinear equation which can be solved by writing it in the form

$$f = \sum z_i(LP_i - P_i') = 0 \tag{22}$$

and expanding f in a Taylor series about the best estimates of z_i and L

$$f \simeq f_0 + \sum_{i \neq m} \frac{\partial f}{\partial z_i} \Delta z_i + \frac{\partial f}{\partial L} \Delta L = 0 \tag{23}$$

where f_0 is the value of f calculated from (22) using best estimates of z_i and L. The partial derivatives

$$\frac{\partial f}{\partial z_i} = LP_i - P_i' \tag{24}$$

$$\frac{\partial f}{\partial L} = \sum z_i P_i \tag{25}$$

are also calculated using best estimates of z_i and L.

Initial estimates of z_i to use in (25) and in calculating f_0 can be determined by solving (22) for the z_i using an estimate of L as a known value. A set of four or more equations like (23), which is linear in the unknowns Δz_i and ΔL, is solved for these four unknowns which are then used to improve the estimates of z_i and L

$$\text{new} \quad Z_i = \text{old} \quad Z_i + \Delta Z_i \tag{26}$$

$$\text{new} \quad L = \text{old} \quad L + \Delta L. \tag{27}$$

These new estimates of z_i and L are used in (23) and the iteration repeated until the Δ's become insignificant. Once L is determined, (21) becomes linear in the three unknown u_i so that three or more equations like (21) can be solved directly for the u_i.

The constants ρ_n, σ_l, and $x_m + jy_m$ cannot be determined by this calibration process. However, for measuring complex insertion ratios, these constants are not needed. Complex insertion ratios of a_2'/a_2 can now be measured using the known z_i in (20). If only the amplitude of L is desired, it is somewhat simpler to calculate $|L|^2$ using the real u_i in (21) rather than the complex z_i in (20). Using the z_i and w_i in (10), ratios of a_2/a_1 can be measured to within a constant K.

BROAD-BAND TWO-POSITION INSERTION DEVICE

In calibrating the six-port junction, the complex insertion ratio L of the repeatable two-position insertion device must not have a phase angle of 0° or multiples of 90°. A phase shift of 45° is probably optimum. One way of getting 45° phase shift over a broad frequency range is shown in Fig. 3. The two outputs of the quadrature hybrid (Q) are equal in amplitude but 90° out of phase. Adding these two signals with an in-phase power divider (D) gives a signal that is shifted 45° relative to the input signal. In addition to this 45° there will be some phase shift θ due to the lengths of line. The length of the lower path can be adjusted to give a phase shift equal to θ. The phase difference in the two switch positions will be 45° over the complete frequency range of the hybrid and divider, which can be the same as the frequency range of the six-port. The amplitude of the insertion ratio will be 3 dB.

The optimum value of $|L|$ has not been determined. Values near 3 and 8 dB have been used with no noticeable difference in results.

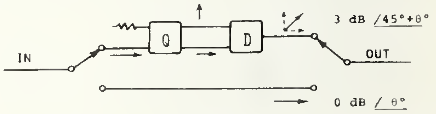

Fig. 3. Using a quadrature hybrid (Q) and a power divider (D) to make an insertion ratio of 3 dB with 45° phase shift.

SIX-PORT DESIGN CRITERIA

As one might expect, not all six-port junctions are equally useful in making measurements of $|a_1|$, $|a_2|$, and ϕ. One useful design is an extension of the phase discriminator or correlator circuit which is a six-port device often used to get phase information from amplitude measurements [4]. Fig. 4 shows a correlator constructed from three quadrature hybrids and one in-phase power divider. If the components are ideal, the phase angle is calculated from $P_5 \cdots P_8$ using

$$4|a_1 a_2| \cos\phi = |a_1 + a_2|^2 - |a_1 - a_2|^2 \tag{28}$$

$$= k(P_5 - P_7) \tag{29}$$

$$4|a_1 a_2| \sin\phi = |a_1 - ja_2|^2 - |a_1 + ja_2|^2 \tag{30}$$

$$= k(P_6 - P_8) \tag{31}$$

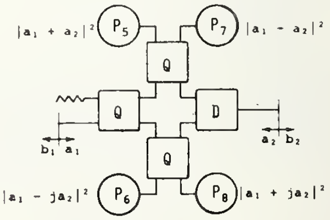

Fig. 4. A correlator constructed from one power divider (D) and three quadrature hybrids (Q). Ideal components would give outputs proportional to the values shown.

where k is a constant. Although the correlator is a six-port device, the equations in (7) do not apply in the limit when the correlator becomes ideal because the four outputs are not linearly independent. The identity

$$|a_1 + a_2|^2 + |a_1 - a_2|^2 = |a_1 - ja_2|^2 + |a_1 + ja_2|^2 \tag{32}$$

shows that the correlator has only three independent outputs since any one output can be obtained from the other three. In a sense, the correlator by itself is only a five-port junction. One more independent output must be added to the correlator to have (7) apply. Since the correlator alone cannot give $|a_1|^2$ and $|a_2|^2$ which do come out of (7), we might expect that adding an output proportional to $|a_1|^2$ or $|a_2|^2$ would make a valid set of four independent outputs. This is indeed the case. Fig. 5 shows a correlator with two power dividers and two more detectors added to make $|a_1|^2$ and $|a_2|^2$ available. The six outputs are listed in Table I. It can be shown that a set of four independent outputs is obtained by choosing one from each group in Table I, plus a fourth output which can be any one of the six not already chosen. For example, if $|a_1| \simeq |a_2|$, a six-port vector voltmeter could have outputs approximately proportional to

$$|a_1|^2, \qquad |a_1 + a_2|^2, \qquad |a_1 - ja_2|^2, \qquad |a_2|^2. \tag{33}$$

Or if $|a_2| \ll |a_1|$ one might design the outputs to approximate

$$|a_1|^2, \qquad |a_1 + a_2|^2, \qquad |a_1 - ja_2|^2$$

and

$$|a_1 - a_2|^2$$

or

$$|a_1 + ja_2|^2. \tag{34}$$

Here $|a_1 - a_2|^2$ or $|a_1 + ja_2|^2$ is used instead of $|a_2|^2$ because $|a_2|^2$ might be too small to measure, but $|a_1 - a_2|^2$ or $|a_1 + ja_2|^2$ would still contain useful information about a_2.

As with other six-port applications, the outputs listed in Table I are only design goals. The actual outputs of a six-port junction can depart considerably from these values and still be quite useful. For example, the output $|a_1 + ja_2|^2$ indicates that ideally a_1 and a_2 would be 90° apart at detector 8. But the output is still useful even though the phase difference is ±60° from the ideal 90°. When the outputs depart greatly from those in Table I, the coefficients of P_i in (7) become large so that the desired information is obtained from the difference between large terms in the sum. As the individual terms in the sum become significantly larger than the quantity on the left of the corresponding equal sign in (7), greater precision is required in measuring each P_i to obtain a given accuracy.

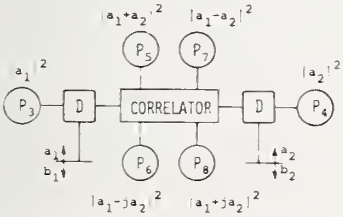

Fig. 5. Adding two power dividers (*D*) to a correlator to make an eight-port junction having several combinations of four independent outputs.

TABLE I

Group 1	Group 2	Group 3
$\|a_1\|^2$	$\|a_1 + a_2\|^2$	$\|a_1 - ja_2\|^2$
$\|a_2\|^2$	$\|a_1 - a_2\|^2$	$\|a_1 + ja_2\|^2$

Note: A set of four independent outputs is obtained by choosing one from each group plus a fourth which can be any one of the six not already chosen.

EXPERIMENTAL SETUP

An eight-port junction following the design shown in Fig. 5 was constructed from commercially available miniature coaxial X-band components with SMA connectors. This was converted to a six-port by terminating ports 7 and 8 with 50-Ω loads so that the remaining four outputs are approximately proportional to those in (33). A photograph of the junction is shown in Fig. 6. The components in the photograph are identified in Fig. 7 which also shows how the signals are combined to get the desired outputs. Four diode-type power meters having a linearity of ±1 percent from 10 nW to 10 μW were used as detectors. The power level into each diode was kept less than 10 μW to assure square-law operation.

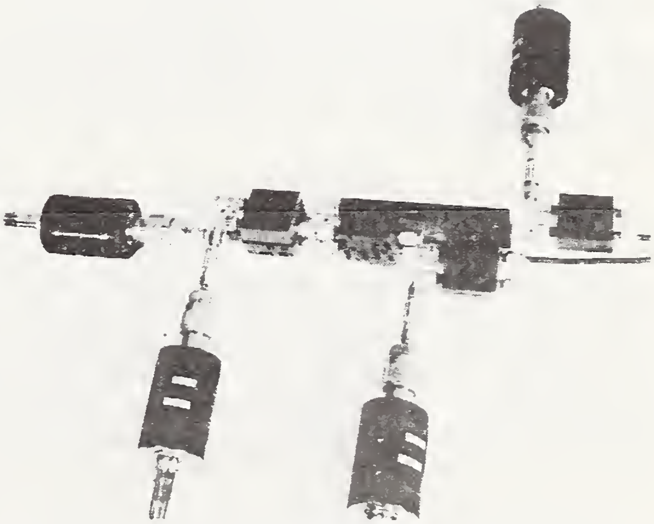

Fig. 6. Experimental six-port junction and power detector mounts.

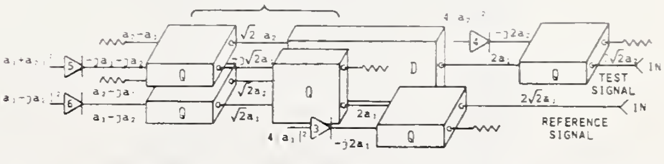

Fig. 7. Identifying the components in Fig. 6, where *Q* indicates quadrature hybrids, and *D* indicates an in-phase power divider. The signals labeled at different parts of the circuits are those obtained from ideal components if the two input signals are $2\sqrt{2}a_1$ and $2\sqrt{2}a_2$.

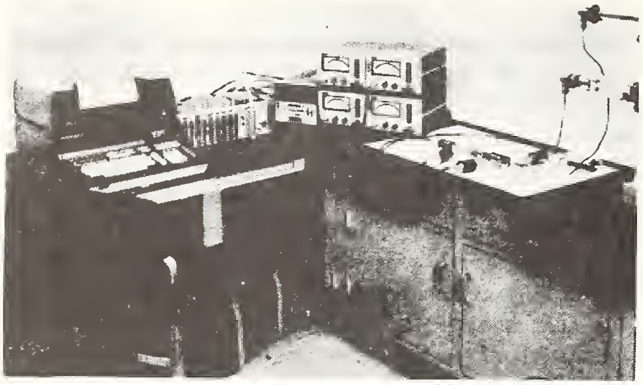

Fig. 8. Experimental six-port *X*-band vector voltmeter setup. From left to right: programmable calculator, input/output expander, DVM and scanner, four-power meters, six-port junction (on white paper), and two-input signal lines.

Since the six-port calibration and measurement process requires taking many sidearm power measurements, it is most desirable to have the data read directly into a computer which can then process the data. A programmable calculator is capable of taking the necessary sidearm power readings under program control, and then processing the data to give the calibration constants and measurement results.

Basic language programs have been written for calibrating the junction as a microwave vector voltmeter, and also for using it to measure complex insertion ratio. After calibrating the six-port junction using the setup in Fig. 2, the same setup is used to measure complex insertion ratios by either changing or inserting something in the test (lower) channel, and using (20) to calculate the ratio.

A picture of the setup is shown in Fig. 8. The same setup can be used with any type power detectors that have an output dc voltage which is a known function of the input power level.

RESULTS

Preliminary measurements have been made on this setup at 8–12 GHz. The complex insertion ratio of the two-position step attenuator *L*, was measured with the six-port junction and then measured by the National Bureau of Standards ANA. The results are shown in Table II. The agreement is within what one would expect using detectors linear to only 1 percent. Better power detectors should give greater accuracy. The comparison shows that the theory of using an arbitrary six-port junction as a vector voltmeter is correct. It also shows that the six-port junction can be calibrated without using any standards. The only precision component in the setup is the two-position step attenuator whose change in insertion ratio is repeatable to ±0.001 dB.

TABLE II
Amplitude and Phase Change in the Two-Position Step Attenuator as Measured by the Six-Port with Diode Power Meters and by the National Bureau of Standards ANA

	FREQUENCY, GHz.	8	9	10	11	12
ATTENUATION DB	SIX-PORT	7.82	7.58	7.52	7.91	8.53
	ANA	7.75	7.57	7.48	7.92	8.36
	DIFFERENCE	.07	.01	.04	-.01	.17
PHASE DEG.	SIX-PORT	38.15	34.13	33.19	31.49	31.00
	ANA	38.09	34.81	32.45	31.73	30.91
	DIFFERENCE	.06	-.68	.74	-.24	.09

Note: Six-port versus ANA.

OTHER APPLICATIONS

Once the six-port vector voltmeter has been calibrated, it can be used to measure the complex reflection coefficient of a one-port device by using it on the sidearms of a reflectometer. The setup in Fig. 2 can be converted to a reflectometer by inserting a directional coupler at the "insertion point" as shown in Fig. 9. The resulting reflectometer can be calibrated to measure Γ at the reference plane using established techniques [5], [6]. If it is desired to measure only Γ with the setup, the six-port vector voltmeter can be calibrated as before with the directional coupler permanently fixed at the insertion point. A sliding short at the reference plane could then take the place of ϕ_0. The reflection coefficient is calculated from

$$\Gamma = \frac{A(a_2/a_1) + B}{1 + C(a_2/a_1)} \qquad (35)$$

where *A*, *B*, and *C* are complex constants. Note that although *K* in (10) is not known, it can be thought of as being part of *A* and *C* which are determined in calibrating the reflectometer. It is, therefore, not necessary to know *K* for this application. If the only application of the six-port junction is to measure Γ, it is probably better to calibrate the junction directly as a reflectometer using other techniques which do not require isolators [7].

DISCUSSION

The experimental system described here could be simplified to make a relatively inexpensive automatic measurement system of moderate accuracy. The six-port component and diode detectors could be fabricated in one stripline package. Since measurements are made directly at the test frequency, no local oscillator (LO) or phase-locked sources are required to heterodyne the signal to some lower frequency. The six-port concepts should be useful into the millimeter-wave region where it becomes difficult to measure phase by other techniques. The complete calibration process can be controlled by a programmable calculator or small computer.

Accuracy of the six-port measurements is determined primarily by the linearity of the detectors. Bolometric- or thermoelectric-type power detectors would give greater accuracy than that achieved in our experiment, but that

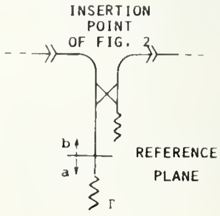

Fig. 9. Adding a directional coupler to the setup in Fig. 2 to make complex reflection coefficient measurements.

would increase the measurement time somewhat. Another approach to increased accuracy would be to model the diodes and mathematically correct for their nonlinearity with the computer. This latter approach is presently under investigation.

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APPENDIX B

CONTROL COMMANDS USED IN THE COMPUTER OPERATING PROGRAM

The following tables list commands that are used in the operating programs to control specific functions in the microwave vector voltmeter. These commands are located in various parts of the program listed in Appendix C. Use of these tables is intended to be an aid in understanding the program and in writing other software routines or modifying existing routines.

IMPORTANT NOTICE

Certain commercial equipment is identified in this report. This does not imply endorsement by the National Bureau of Standards nor does it imply that the equipment identified is necessarily the best available for the purpose.

Control Commands from Computer to MVV

Effect	Device under Control	Command
Insertion Step Out	Scanner Model 1200	Write (1,*) WBYTE 47;
	Driver 120-1	Write (2,*) WBYTE 1;
Insertion Step In	Scanner Model 1200	Write (1,*) WBYTE 46;
	Driver 120-1	Write (2,*) WBYTE 1;
Phase Shifter +90°	Scanner Model 1200	Write (1,*) WBYTE 43;
	Driver 120-1	Write (2,*) WBYTE 1;
	Scanner Model 1200	Write (1,*) WBYTE 45;
	Driver 120-1	Write (2,*) WBYTE 1;
Phase Shifter -90°	Scanner Model 1200	Write (1,*) WBYTE 43;
	Driver 120-1	Write (2,*) WBYTE 1;
	Scanner Model 1200	Write (1,*) WBYTE 44;
	Driver 120-1	Write (2,*) WBYTE 1;
Phase Shifter 0°	Scanner Model 1200	Write (1,*) WBYTE 42;
	Driver 120-1	Write (2,*) WBYTE 1;
Switches 2, 4, 5 to D	Scanner Model 1200	Write (1 *) WBYTE 41;
	Driver 120-1	Write (2,*) WBYTE 1;
Switches 2, 4, 5, to S	Scanner Model 1200	Write (1,*) WBYTE 40;
	Driver 120-1	Write (2,*) WBYTE 1;
Switches 1, 3, 6, 7 to C	Scanner Model 1200	Write (1,*) WBYTE 39;
	Driver 120-1	Write (2,*) WBYTE 1;
Switches 1, 3, 6, 7 to M	Scanner Model 1200	Write (1,*) WBYTE 38;
	Driver 120-1	Write (2,*) WBYTE 1;

Control Commands from Computer to MVV

Effect	Device under Control	Command
Test Atten: 0 db	Driver 120-1	Write (2,*) WBYTE (0 or 1);
1 db	" "	" " " (2 or 3);
2 db	" "	" " " (4 or 5);
3 db	" "	" " " (6 or 7);
4 db	" "	" " " (8 or 9);
5 db	" "	" " " (10 or 11);
6 db	" "	" " " (12 or 13);
7 db	" "	" " " (14 or 15);
8 db	" "	" " " (16 or 17);
9 db	" "	" " " (18 or 19);
10 db	" "	" " " (20 or 21);
11 db	" "	" " " (22 or 23);
12 db	" "	" " " (24 or 25);
13 db	" "	" " " (26 or 27);
14 db	" "	" " " (28 or 29);
15 db	" "	" " " (30 or 31);
Reference Atten: 5 db	" "	" " " (32 or 33);
10 db	" "	" " " (64 or 65);
15 db	" "	" " " (96 or 97);

Control Commands from Computer to MVV

Effect	Device under Control	Command
Isolators to 8-12 GHz	Scanner Model 1200	Write (1,*) WBYTE 31;
	Driver 120-1	Write (2,*) WBYTE 1;
	Scanner Model 1200	Write (1,*) WBYTE 26;
	Driver 120-1	Write (2,*) WBYTE 1;
	Scanner Model 1200	Write (1,*) WBYTE 25;
	Driver 120-1	Write (2,*) WBYTE 1;
	Scanner Model 1200	Write (1,*) WBYTE 22;
	Driver 120-1	Write (2,*) WBYTE 1;
Isolators to 4-8 GHz	Scanner Model 1200	Write (1,*) WBYTE 30;
	Driver 120-1	Write (2,*) WBYTE 1;
	Scanner Model 1200	Write (1,*) WBYTE 29;
	Driver 120-1	Write (2,*) WBYTE 1;
	Scanner Model 1200-1	Write (1,*) WBYTE 24;
	Driver 120-1	Write (2,*) WBYTE 1;
	Scanner Model 1200-1	Write (1,*) WBYTE 23;
	Driver 120-1	Write (2,*) WBYTE 1;
Isolators to 2-4 GHz	Scanner Model 1200-1	Write (1,*) WBYTE 30;
	Driver 120-1	Write (2,*) WBYTE 1;
	Scanner Model 1200-1	Write (1,*) WBYTE 28;
	Driver 120-1	Write (2,*) WBYTE 1;
	Scanner Model 1200-1	Write (1,*) WBYTE 24;
	Driver 120-1	Write (2,*) WBYTE 1;
	Scanner Model 1200-1	Write (1,*) WBYTE 22;
	Driver 120-1	Write (2,*) WBYTE 1;
Isolators to .5-2 GHz	Scanner Model 1200	Write (1,*) WBYTE 31;
	Driver 120-1	Write (2,*) WBYTE 1;
	Scanner Model 1200	Write (1,*) WBYTE 27;
	Driver 120-1	Write (2,*) WBYTE 1;
	Scanner Model 1200	Write (1,*) WBYTE 25;
	Driver 120-1	Write (2,*) WBYTE 1;
	Scanner Model 1200	Write (1,*) WBYTE 23;
	Driver 120-1	Write (2,*) WBYTE 1;
Take Voltage Readings from the 5 detectors in the MVV	Scanner Model 1200	Write (1,*) WBYTE 58;
	DVM Model 3500	Enter (4,*) A, B
	Scanner Model 1200	Write (1,*) WBYTE 59;
	DVM Model 3500	Enter (4,*) A, B
	Scanner Model 1200	Write (1,*) WBYTE 60;
	DVM Model 3500	Enter (4,*) A, B
	Scanner Model 1200	Write (1,*) WBYTE 61;
	DVM Model 3500	Enter (4,*) A, B
	Scanner Model 1200	Write (1,*) WBYTE 62;
	DVM Model 3500	Enter (4,*) A, B

APPENDIX C

COMPUTER PROGRAM DESCRIPTION AND LISTING WITH SAMPLE PRINTOUT

Appendix C

Computer program description and listing.

Equations (22) - (27) in Appendix A are solved using matrix algebra. Before expressing these equations in matrix notation, add a subscript j to indicate the measurement number, where j = 1 ... 6 in the present calibration routine which takes six measurements. Equation (22) of Appendix A then becomes

$$f_j = \sum_{i=1}^{5} (LP_{ji} - P'_{ji})\, z_i = 0 \qquad \text{(C-1)}$$

Subscript i refers to the detector numbers which are relabeled 1 ... 5 in the program. The following table relates the detector number used by the program to that shown in Figure 3.

Table C-1

Computer Number	Figure 3
1	$P_3 \; \alpha \; \lvert a_1 \rvert^2$
2	$P_5 \; \alpha \; \lvert a_1 + a_2 \rvert^2$
3	$P_8 \; \alpha \; \lvert a_1 + ja_2 \rvert^2$
4	$P_6 \; \alpha \; \lvert a_1 - ja_2 \rvert^2$
5	$P_7 \; \alpha \; \lvert a_1 - a_2 \rvert^2$

In matrix notation (C-1) becomes

$$\begin{bmatrix} f_1 \\ \cdot \\ \cdot \\ \cdot \\ f_6 \end{bmatrix} = \begin{bmatrix} LP_{11} - P'_{11} & LP_{12} - P'_{12} & \cdots & LP_{15} - P'_{15} \\ \cdot & & & \cdot \\ \cdot & & & \cdot \\ \cdot & & & \cdot \\ LP_{61} - P'_{61} & LP_{62} - P'_{62} & \cdots & LP_{65} - P'_{65} \end{bmatrix} \begin{bmatrix} z_1 \\ \cdot \\ \cdot \\ \cdot \\ z_5 \end{bmatrix} \qquad \text{(C-2)}$$

Since L and z_i are complex numbers, all matrices in (C-2) are complex. Let $L = L_1 + jL_2$ and $z_i = x_i + jy_i$ where L_1, L_2, and x_i and y_i are real numbers. Write (C-2) as

$$F_o = [P + jQ][X + jY] \tag{C-3}$$

where F_o is a complex matrix but P, Q, X, and Y are real matrices;

$$P = \begin{bmatrix} L_1P_{11} - P'_{11} & \dots & L_1P_{15} - P'_{15} \\ \cdot & & \cdot \\ \cdot & & \cdot \\ \cdot & & \cdot \\ L_1P_{61} - P'_{61} & \dots & L_1P_{65} - P'_{65} \end{bmatrix}, \quad Q = \begin{bmatrix} L_2P_{11} & \dots & L_2P_{15} \\ \cdot & & \cdot \\ \cdot & & \cdot \\ \cdot & & \cdot \\ L_2P_{61} & \dots & L_2P_{65} \end{bmatrix} \tag{C-4}$$

$$X = \begin{bmatrix} x_1 \\ \cdot \\ \cdot \\ \cdot \\ x_5 \end{bmatrix}, \quad Y = \begin{bmatrix} y_1 \\ \cdot \\ \cdot \\ \cdot \\ y_5 \end{bmatrix} \quad . \tag{C-5}$$

The P and Q matrices can be written

$$P = L_1O - I \quad , \qquad Q = L_2O \tag{C-6}$$

Where the O matrix contains the data with the step "out", and the I matrix contains the data with the step "in" (3 dB inserted).

$$O = \begin{bmatrix} P_{11} & \dots & P_{15} \\ \cdot & & \cdot \\ \cdot & & \cdot \\ \cdot & & \cdot \\ P_{61} & \dots & P_{65} \end{bmatrix} \quad , \qquad I = \begin{bmatrix} P'_{11} & \dots & P'_{15} \\ \cdot & & \cdot \\ \cdot & & \cdot \\ \cdot & & \cdot \\ P'_{61} & \dots & P'_{65} \end{bmatrix} \tag{C-7}$$

The program first takes the data to fill in the O and I matrices. It then asks for an estimate of L (approximately -3 dB and 45 degrees) from which it calculates L_1 and L_2. The P and Q matrices in (C-4) are then calculated.

Initial estimates of the z_i are obtained by solving (C-1) using the estimated value of L. Since any one of the z_i can be set equal to 1, we choose to set $z_5 = 1 + j0$ since this tends to simplify the mathematics. Equation (C-1) then becomes

$$\sum_{i=1}^{4} (LP_{ji} - P'_{ji})\, z_i = -(LP_{j5} - P'_{j5}) \qquad \text{(C-8)}$$

In matrix notation this becomes

$$\begin{bmatrix} LP_{11} - P'_{11} & \cdots & LP_{14} - P'_{14} \\ \vdots & & \vdots \\ LP_{61} - P'_{61} & \cdots & LP_{64} - P'_{64} \end{bmatrix} \begin{bmatrix} z_1 \\ \vdots \\ z_4 \end{bmatrix} = - \begin{bmatrix} LP_{15} - P'_{15} \\ \vdots \\ LP_{65} - P'_{65} \end{bmatrix} \qquad \text{(C-9)}$$

Let N, Z, and R be the three complex matrices in (C-9) so that (C-9) becomes

$$NZ = R \qquad \text{(C-10)}$$

Note that N is identical to P + jQ if the last column of P + jQ is deleted. The column matrix R is the negative of the last column of P + jQ. Since N is not a square matrix, it cannot be inverted. To solve (C-10), first premultiply by N transpose to get

$$N^T NZ = N^T R \qquad \text{(C-11)}$$

Since $N^T N$ is a square matrix, it can be inverted to give

$$Z = (N^T N)^{-1} N^T R \qquad \text{(C-12)}$$

The elements of Z are only estimates of the z_i since in general L used in C-9 is not known. The correct values of the z_i are obtained by using the estimates in equation (23) of Appendix A.

Adding a subscript j to (23) of Appendix A gives

$$f_j = f_{oj} + \sum_{i=1}^{4} \frac{\partial f_j}{\partial z_i} \Delta z_i + \frac{\partial f_j}{\partial L} \Delta L = 0 \qquad \text{(C-13)}$$

The sum in (C-13) is from 1 to 4 since $z_5 = 1 + j0$. In matrix notation (C-13) becomes

$$- \begin{bmatrix} f_{01} \\ \cdot \\ \cdot \\ \cdot \\ f_{06} \end{bmatrix} = \begin{bmatrix} \frac{\partial f_1}{\partial z_1} & \frac{\partial f_1}{\partial z_2} & \cdots & \frac{\partial f_1}{\partial z_4} & \frac{\partial f_1}{\partial L} \\ \cdot & \cdot & & \cdot & \cdot \\ \cdot & \cdot & & \cdot & \cdot \\ \frac{\partial f_6}{\partial z_1} & \frac{\partial f_6}{\partial z_2} & \cdots & \frac{\partial f_6}{\partial z_4} & \frac{\partial f_6}{\partial L} \end{bmatrix} \begin{bmatrix} \Delta z_1 \\ \cdot \\ \cdot \\ \cdot \\ \Delta z_4 \\ \Delta L \end{bmatrix} \qquad \text{(C-14)}$$

where from (24) and (25) of Appendix A

$$\frac{\partial f_j}{\partial z_i} = LP_{ji} - P'_{ji} \qquad \text{(C-15)}$$

$$\frac{\partial f_j}{\partial L} = \sum_{i=1}^{5} z_i P_{ji} \qquad \text{(C-16)}$$

Let F_o, M, and ΔZ be the three complex matrices in (C-14) so that (C-14) becomes

$$-F_o = M\Delta Z \qquad \text{(C-17)}$$

Substituting (C-15) and (C-16) in (C-14) shows that M is identical to P + jQ except for the last column which contains the $\partial f_j/\partial L$. These terms are calculated from (C-16) which can be written

$$\frac{\partial f_j}{\partial L} = \sum_{i=1}^{5} P_{ji}(x_i + jy_i) \qquad \text{(C-18)}$$

or

$$\begin{bmatrix} \frac{\partial f_1}{\partial L} \\ \cdot \\ \cdot \\ \cdot \\ \frac{\partial f_6}{\partial L} \end{bmatrix} = \begin{bmatrix} P_{11} & \ldots & P_{15} \\ \cdot & & \\ \cdot & & \\ \cdot & & \\ P_{61} & \ldots & P_{65} \end{bmatrix} \begin{bmatrix} x_1 + jy_1 \\ \cdot \\ \cdot \\ \cdot \\ x_5 + jy_5 \end{bmatrix} \qquad \text{(C-19)}$$

$$= \quad 0\ [X + jY] \qquad \text{(C-20)}$$

Therefore M is obtained by substituting the complex column matrix (C-20) in column 5 of the P + jQ matrix.

Initial estimates of z_i to use in calculating F_o and M are obtained from (C-12). With these estimates, F_o and M can be calculated so that (C-17) can be solved for ΔZ. The solution is

$$\Delta Z = -(M^T M)^{-1} M^T F_o \qquad \text{(C-21)}$$

The elements of ΔZ are used to correct the estimated values of z_i and L;

$$\text{new } z_i = \text{old } z_i + \Delta z_i \qquad \text{(C-22)}$$

$$\text{new } L = \text{old } L + \Delta L \qquad \text{(C-23)}$$

The iteration is now repeated, calculating a new P and Q matrix using the new L, and calculating a new F_o and M matrix using the new z_i. Then (C-21) is solved to get a new ΔZ. The iteration continues until $\Delta L_1 < 10^{-6}$. Usually ΔL_1 will be less than 10^{-6} after four iterations.

Equation (19) of Appendix A is also solved using matrix algebra, but no iteration is required. Adding a subscript j to indicate the measurement number as before, that equation becomes

$$\sum_{i=1}^{5} w_i\ (P_{ji} - P'_{ji}) = 0 \qquad \text{(C-24)}$$

For an ideal seven-port junction, all of the $w_i = 0$ except for the w corresponding to P_3 in figure 3. Since P_3 is on channel #1, we choose $w_1 = 1$ in the program. Therefore (C-24) becomes

$$\sum_{i=2}^{5} w_i \left(P_{ji} - P'_{ji}\right) = P'_{j1} - P_{j1} \qquad \text{(C-25)}$$

which can be written

$$\begin{bmatrix} P_{12} - P'_{12} & P_{13} - P'_{13} & \cdots & P_{15} - P'_{15} \\ \vdots & & & \vdots \\ P_{62} - P'_{62} & & \cdots & P_{65} - P'_{65} \end{bmatrix} \begin{bmatrix} w_2 \\ \vdots \\ w_5 \end{bmatrix} = \begin{bmatrix} P'_{11} - P_{11} \\ \vdots \\ P'_{61} - P_{61} \end{bmatrix} \qquad \text{(C-26)}$$

or simply

$$DW = C \qquad \text{(C-27)}$$

whose solution is

$$W = (D^T D)^{-1} D^T C \qquad \text{(C-28)}$$

```
100 PRINT "SAM TAPE #1, FILE 6, REVISED 7 MAY 1976"
110 REM .5-12 GHZ MICROWAVE VECTOR VOLTMETER CALIBRATION & MEASUREMENT PROGRAM
115 REM SAME AS FILE 2 BUT WITH OPTION 9 ADDED
116 REM
120 DIM A[6,6],B[6,6],C[6,5],D[6,5],E[5,5],F[5,5],G[5,5],H[5,5],R[5]
130 DIM I[6,5],O[6,5],P[6,5],Q[6,5],S[5,5],T[5,6],U[6],V[6],X[5],Y[5],M[7]
140 DIM W[5],K[6,5],L[6,5]
150 S7=50                           Scale factor to keep determinants reasonable
160 M[6]=-10*S7         }
170 M[5]=-100*S7        }           Range constants for DVM
180 M[7]=M[3]=-1000*S7  }
190 DEG                             All angles are in degrees
200 PRINT "PRESS CONT EXECUTE AFTER COMPLETING EACH INSTRUCTION"
210 PRINT
220 K1=1                            K = k1 + jK2 is set to 1 + j0 to start
230 K2=K9=C1=0                      K9 = 0 indicates 0 dB added to measurement channel
240 K5=3                            K5 = number of DVM readings to be averaged for each
250 DISP "FREQUENCY IN GHZ ";
260 INPUT F7
270 GOSUB 3650                      Switch in appropriate isolators
280 WRITE (1,*)WBYTE40; }
290 GOSUB 3350          }           Set calibration switches to "S" (six-port) position
300 PRINT "ENTER 1 TO CALIBRATE VECTOR VOLTMETER"                                   }
310 PRINT "ENTER 2 TO MEASURE REFERENCE RATIO"                                      }
320 PRINT "ENTER 3 TO MEASURE RATIO WITH TEST DEVICE INSERTED"                      } Instruc-
330 PRINT "ENTER 4 TO MEASURE DVM OFFSET VOLTAGES"                                  } tions
340 PRINT "ENTER 5 TO MEASURE  R0 & C"                                              } to
350 PRINT "ENTER 6 TO MONITOR REFERENCE DIODE"                                      } Operator
360 PRINT "          PRESS STOP CONT 400 WHEN DONE"                                 }
370 PRINT "ENTER 7 TO MEASURE STEP VALUE (L) "                                      }
380 PRINT "ENTER 8 TO DETERMINE K FOR ABSOLUTE RATIO MEASUREMENTS"                  }
385 PRINT "ENTER 9 TO MEASURE & AVERAGE RATIOS WITH TEST DEVICE INSERTED"           }
390 PRINT
400 DISP "NEXT OPERATION (ENTER 1 THRU 9)";
410 INPUT I9
420 GOSUB I9 OF 440,3000,3110,4080,2720,3960,3400,3230,5110
430 GOTO 400
-------------------------------------------------------------------------------------
440 REM CALIBRATING VECTOR VOLTMETER
450 N=5                             N = number of diodes used
460 M=M1=6                          M = number of measurements made during calibration
470 N1=N-1
480 REDIM I[M,N],O[M,N],K[M,N],L[M,N]
490 MAT I=ZER
500 MAT O=ZER
510 GOSUB 4300                      Set switches to calibration mode
530 GOSUB 4080                      Read diode offset voltages
540 WRITE (1,*)WBYTE42; }
550 GOSUB 3350          }           Set phase shifter to 0°
560 I=1
570 GOSUB 3550                      Take data for measurement #1
580 WRITE (1,*)WBYTE43; }
590 GOSUB 3350          }           Set phase shifter to ±90° position
600 WRITE (1,*)WBYTE45; }
610 GOSUB 3350          }           Set phase shifter to +90°
620 I=2
630 GOSUB 3550                      Take data for measurement #2
640 WRITE (1,*)WBYTE44; }
650 GOSUB 3350          }           Set phase shifter to -90°
660 I=3
670 GOSUB 3550                      Take data for measurement #3
680 K9=K9+6                         Add 3 dB to measurement channel
690 I=4
700 GOSUB 3550                      Take data for measurement #4
710 WRITE (1,*)WBYTE45; }
720 GOSUB 3350          }           Set phase shifter to +90°
730 I=5
740 GOSUB 3550                      Take data for measurement #5
750 WRITE (1,*)WBYTE42; }
760 GOSUB 3350          }           Set phase shifter to 0°
770 I=6
780 GOSUB 3550                      Take data for measurement #6
790 K9=0                }
800 GOSUB 3350          }           Take out all attenuation in measurement channel
810 MAT K=O
820 MAT L=I
-------------------------------------------------------------------------------------
830 DISP "ESTIMATED RATIO, DB & DEGREES =";
840 INPUT L,T        }
850 L=10↑(L/20)      }      L = L1 + jL2 is now a voltage ratio
860 L1=L*COST        }
870 L2=L*SINT        }      Calibration data is stored in matrices K and L
880 DISP "USING HOW MANY DIODES?";
890 INPUT N
895 N1=N-1                  N = 4 or 5 diodes can be used
900 M=M1
```

```
910 REM CALCULATE THE W(I
920 REDIM D[M,N1],T[N1,M],P[N1,N1],U[N1],C[M,1],W[N1]
930 REDIM O[M,N],I[M,N]
940 GOSUB 4980
```

Put calibration data in O and I matrices

```
950 FOR J=1 TO M
960 FOR I=2 TO N
970 D[J,I-1]=O[J,I]-I[J,I]
980 NEXT I
990 C[J,1]=I[J,1]-O[J,1]
1000 NEXT J
```

Caculate D and C matrices

```
1010 MAT T=TRN(D)
1020 MAT P=T*D
1030 MAT P=INV(P)
1040 MAT U=T*C
1050 MAT W=P*U
```

Solve for $W = (D^TD)^{-1}D^TC = \begin{bmatrix} w_2 \\ \vdots \\ w_5 \end{bmatrix}$

```
1060 REDIM W[N]
1070 FOR I=N1 TO 1 STEP -1
1080 W[I+1]=W[I]
1090 NEXT I
1100 W[1]=1
```

Change W to $W = \begin{bmatrix} 1 \\ w_2 \\ \vdots \\ w_5 \end{bmatrix}$

```
1110 REM SOLVING FOR Z(I) & L
1120 GOSUB 4650
```

Calculate initial estimate of the z_i

```
1130 IF N=5 THEN 1160
1140 PRINT " -----DELTA X(I)-----    -----DELTA Y(I)-----     DELTA L
1150 GOTO 1170
1160 PRINT " --------DELTA X(I)--------    --------DELTA Y(I)--------     DELTA L
1170 PRINT
1180 REM ITERATION BEGINS
1190 REDIM A[M,N],B[M,N],E[M,1],F[M,1],G[M,1],U[M],V[M]
1200 MAT A=P
1210 MAT B=Q
1220 GOSUB 2090
```

Calculate $F_0 = (P + jQ)(X + jY)$, store in E + jF

```
1230 MAT U=E
1240 MAT V=F
```

F_0 stored in U + jV

```
1250 REDIM C[M,N],D[M,N]
1260 MAT C=P
1270 MAT D=Q
```

M except for last column

```
1280 MAT E=O*X
1290 MAT F=O*Y
```

Last column of M

```
1300 FOR I=1 TO M
1310 C[I,N]=E[I,1]
1320 D[I,N]=F[I,1]
1330 NEXT I
```

Filling in last column of M

```
1340 REDIM A[N,M],B[N,M],E[N,N],F[N,N],G[N,N]
1350 MAT A=TRN(C)
1360 MAT B=TRN(D)
```

M^T stored in A + jB

```
1370 GOSUB 2090
```

Calculate M^TM, store in E + jF

```
1380 GOSUB 2170
```

Calculate $(M^TM)^{-1}$, store in S + jT

```
1390 REDIM C[M,1],D[M,1],E[N,1],F[N,1],G[N,1]
1400 MAT C=U
1410 MAT D=V
```

Put F_0 in C + jD

```
1420 GOSUB 2090
```

Calculate M^TF_0, store in E + jF

```
1430 REDIM C[N,1],D[N,1]
1440 GOSUB 2260
```

Calculate $-\Delta Z = (M^TM)^{-1}M^TF_0$, store in C + jD

```
1450 FOR I=1 TO N1
1460 WRITE (15,1520)C[I,1];
1470 NEXT I
1480 FOR I=1 TO N1
1490 WRITE (15,1520)D[I,1];
1500 NEXT I
1510 WRITE (15,1520)C[I,1];D[I,1]
1520 FORMAT 4E7.0,2X,4E7.0,2X,2E7.3
1530 PRINT
```

Print $-\Delta Z$

```
1540 L1=L1-C[N,1]
1550 L2=L2-D[N,1]
```

New L = old L + ΔL

```
1560 X4=C[N,1]
```

X4 + ΔL_1

```
1570 MAT C=X-C
1580 MAT D=Y-D
```

New z_i = old z_i + Δz_i

```
1590 MAT X=C
1600 MAT Y=D
1610 X[N]=C[N,1]=+1
1620 Y[N]=D[N,1]=0
```

$z_5 = 1 + jo$

```
1630 GOSUB 4930
1640 IF ABS(X4)>1E-06 THEN 1190
```

If $\Delta L_1 > 10^{-6}$ then continue iterating

```
1650 PRINT
```

```
1660 PRINT "FREQUENCY =  "F7;" GHZ, USING DIODES ";
1670 FOR I=1 TO N
1680 PRINT I;
1690 NEXT I
1700 PRINT
1710 PRINT
1720 PRINT "   L(REAL)        I(IMAGINARY)     L(DB)          P(DEGREES)"
1730 PRINT
1740 L=20*LGT(SQR(L1*L1+L2*L2))
1750 P=ATN(L2/L1)+180*(L1<0)*(2*(L2 >= 0)-1)
1760 PRINT L1,L2,L,P
1770 PRINT
1780 WRITE (15,1790)"  I ="1,2,3,4,5
1790 FORMAT F7.0,4F10.0
1800 PRINT "X(I)=";
1810 FOR I=1 TO N                                                     Print
1820 WRITE (15,1950)X[I];                                             Constants
1830 NEXT I
1840 PRINT
1850 PRINT "Y(I)=";
1860 FOR I=1 TO N
1870 WRITE (15,1950)Y[I];
1880 NEXT I
1890 PRINT
1900 PRINT "W(I)=";
1910 FOR I=1 TO N
1920 WRITE (15,1950)W[I];
1930 NEXT I
1940 PRINT
1950 FORMAT 5F10.4
1960 GOSUB 2340      Calculate and print value of L for each of the 6 measurements
1970 IF N=5 THEN [illegible]
1980 DISP "RECALCULATE WITH 5 DIODES? [illegible]";
1990 INPUT C1
2000 IF C1=1 THEN 880
2010 M=1
2020 REDIM A[M,1],B[M,1],C[M,1],D[M,1],E[M,1],F[M,1],I[M,N],U[M,N]
2030 PRINT
2040 PRINT "   TYPE            ---RATIO---       PHASE      PR(DBM)   PR: [illegible]
2050 PRINT "MEASUREMENT      MAGNITUDE     DB       DEGREES "
2060 PRINT
2070 GOSUB 2710      Measure ρ0 and C
2080 RETURN
----------------------------------------------------------------------------
2090 REM MULTIPLYING 2 COMPLEX MATRICES (A+JB)*(C+JD)=E+JF
2100 MAT G=B*D
2110 MAT E=A*C
2120 MAT E=E-G
2130 MAT G=B*C
2140 MAT F=A*D
2150 MAT F=F+G
2160 RETURN
----------------------------------------------------------------------------
2170 REM INVERTING A COMPLEX MATRIX S+JT=INV(E+JF)
2180 MAT G=INV(E)
2190 MAT H=G*F
2200 MAT S=F*H
2210 MAT S=E+S
2220 MAT S=INV(S)
2230 MAT T=H*S
2240 MAT T=(-1)*T
2250 RETURN
----------------------------------------------------------------------------
2260 REM MULTIPLYING 2 COMPLEX MATRICES (S+JT)*(E+JF)=C+JD
2270 MAT G=T*F
2280 MAT C=S*E
2290 MAT C=C-G
2300 MAT G=T*E
2310 MAT D=S*F
2320 MAT D=D+G
2330 RETURN
```

```
2340 REM CALCULATING INDIVIDUAL VALUES OF L
2350 REDIM A[M,1],B[M,1],C[M,1],D[M,1],E[M,1],F[M,1],I[M,N],O[M,N]
2360 MAT A=O*X
2370 MAT B=O*Y
2380 MAT C=I*X
2390 MAT D=I*Y
2400 MAT E=O*W
2410 MAT F=I*W
```

$$A = \begin{bmatrix} \Sigma x_i P_{1i} \\ \vdots \\ \Sigma x_i P_{6i} \end{bmatrix}, \quad B = \begin{bmatrix} \Sigma y_i P_{1i} \\ \vdots \\ \Sigma y_i P_{6i} \end{bmatrix}, \quad C = \begin{bmatrix} \Sigma x_i P'_{1i} \\ \vdots \\ \Sigma x_i P'_{6i} \end{bmatrix}, \text{ etc.} \left\{ \begin{array}{l} \text{each sum} \\ \text{is over} \\ i = 1 \text{ to } 5 \end{array} \right.$$

```
2420 PRINT "       L(I),DB    L-L(I),DB    P(I),DEG    P-P(I),DEG";
2430 PRINT "    PR=REF PORT POWER"
2440 WRITE (15,2450)
2450 FORMAT 54X,"PR1/C    PR2/PR1-1"
2460 L5=P5=0
2470 FOR J=1 TO M          For each measurement j calculate:
2480 E=E[J,1]
2490 F=F[J,1]
2500 A=A[J,1]/E
2510 B=B[J,1]/E
2520 C=C[J,1]/F
2530 D=D[J,1]/F
2540 G=A*A+B*B
2550 X=(A*C+B*D)/G
2560 Y=(A*D-B*C)/G
2570 R=SQR(X*X+Y*Y)
2580 L3=20*LGT(R)
2590 L4=L-L3
2600 L5=L5+L4*L4
2610 P3=ATN(Y/X)+180*(X<0)*(1-2*(Y<0))
2620 P4=P-P3
2630 P5=P5+P4*P4
2640 WRITE (15,2690)L3,L4,P3,P4,E*1000/ST,F/E-1
2650 NEXT J
2660 PRINT
2670 WRITE (15,2680)"   STD. DEV. = ",SQR(L5/(M-1)),SQR(P5/(M-1))
2680 FORMAT F10.4,F24.3
2690 FORMAT 2F12.4,3F12.3,1F12.6
2700 RETURN
```

$$\rho = \frac{\Sigma x_i P_i + j\,\Sigma y_i P_i}{\Sigma w_i P_i} = \frac{A + jB}{E}$$

$$\rho' = \frac{\Sigma x_i P_i' + j\,\Sigma y_i P_i'}{\Sigma w_i P_i'} = \frac{C + jD}{F}$$

$X + jY = \rho'/\rho$ = step insertion ratio

```
2710 REM SUBROUTINE TO MEASURE RHO-ZERO
2720 GOSUB 4350            Set switches to measurement mode
2730 DISP "CONNECT 50 OHM LOAD TO TEST PORT"
2740 STOP
2750 C3=-1
2760 D=I=1
2770 C0=D0=0
2780 DISP "INCIDENT POWER (MW) = ";
2790 INPUT P1
2800 GOSUB 4350            Read diode output voltages
2810 GOSUB 2880            Calculate voltage ratio
2820 C0=X
2830 D0=Y
2840 C3=P1/F
2850 WRITE (15,2860)"Z0",Z,L,T,10*LGT P1
2860 FORMAT F8.4,F12.3,F12.3,F12.3,F12.6
2870 RETURN
```

$C_0 + jD_0 = \rho_0$

```
2880 REM CALCULATING VOLTAGE RATIO
2890 MAT A=O*X
2900 MAT B=O*Y
2910 MAT E=O*W
2920 F=E[I,1]
2930 X=A[I,1]/F-C0
2940 Y=B[I,1]/F-D0
2950 Z=SQR(X*X+Y*Y)*K1
2960 L=20*LGT(Z)
2970 P1=10*LGT(C3*F)
2980 T=ATN(Y/X)+180*(X<0)*(1-2*(Y<0))
2990 RETURN
```

$= \Sigma x_i P_i$

$= \Sigma y_i P_i$

$= \Sigma w_i P_i$

$$\rho = K \frac{\Sigma x_i P_i + j\,\Sigma y_i P_i}{\Sigma w_i P_i}$$

$X + jY = \rho - \rho_0$

$K = K1 + jK2 = 1 + j0$ unless calibrated for absolute ratio measurements

---

```
3000 REM  MEASURING THE REFERENCE RATIO
3010 DISP "SET DEVICE TO REFERENCE VALUE"
3020 STOP
3030 I=D=I
3040 GOSUB 4350            Read diode output voltages
3050 GOSUB 2880            Calculate voltage ratio
3060 R=Z
3070 S=L                   Store results in R, S, & P
3080 P=T
3090 WRITE (15,2860)"REFERENCE RATIO",R,L,P,P1
3100 RETURN
```

```
3110 REM MEASURING RATIO WITH TEST DEVICE INSERTED
3120 DISP "INSERT TEST ITEM OR SET DEVICE"
3130 STOP
3140 I=D=1
3150 GOSUB 4350          Read diode output voltages
3160 GOSUB 2880          Calculate voltage ratio
3170 P1=T-P
3180 P1=P1+360*((P1<-180)-(P1>180))
3190 GOTO 3210
3200 WRITE (15,2860)"TEST RATIO      "Z,L,T,F1
3210 WRITE (15,2860)"INSERTION RATIO"Z/R,L-S,P1,F1
3220 RETURN
3230 REM DETERMINE K=K1+J*K2 FOR ABSOLUTE RATIO MEASUREMENTS
3240 DISP "APPLY SAME SIGNAL TO BOTH PORTS"
3250 STOP
3260 GOSUB 4250          Set switches to measurement mode
3270 K1=I=D=1
3280 K2=0
3290 GOSUB 4350          Read diode output voltages
3300 GOSUB 2880          Calculate voltage ratio
3310 K1=1/Z        }
3320 K2=-T         }     K1 + jK2 = K
3330 WRITE (15,2860)"K                "K1,-L,K2,F1
3340 RETURN
3350 REM SUBROUTINE  TO RUN SWITCH DRIVER
3360 WAIT 50
3370 WRITE (2,*)WBYTEK9+1;
3380 WAIT 50
3390 RETURN
3400 REM MEASURING STEP VALUE AFTER CALIBRATION
3410 I=1
3420 GOSUB 3540          Measure diode voltages with step "out", step "in"
3430 GOSUB 2880          Calculate voltage ratio for step out.
3440 R=Z        |
3450 S=L        |
3460 P=T        |        Store results in R, S, P, E.
3470 E=F        |
3480 MAT O=I
3490 GOSUB 2880          Calculate voltage ratio for step "in"
3500 P1=T-P
3510 P1=P1+360*((P1<-180)-(P1>180))
3520 WRITE (15,2860)"STEP RATIO (L) "Z/R,L-S,P1,F1,F/E-1
3530 RETURN
3540 REM SUBROUTINE SETS STEP OUT- GETS VOLTAGES- SETS STEP IN- GETS VOLTAGES
3550 WRITE (1,*)WBYTE47;  }
3560 D=1                  }   Set step "out"
3570 GOSUB 3350           }
3580 GOSUB 4350               Read diode outputs, store in O matrix
3590 WRITE (1,*)WBYTE46;  }
3600 D=2                  }
3610 GOSUB 3350           }   Set step "in"
3620 GOSUB 4350               Read diode outputs, store in I matrix
3630 RETURN
3640 REM SWITCH IN ISOLATORS FOR CHOSEN FREQUENCY
3650 IF F7>8 THEN 3730
3660 IF F7<2 THEN 3780
3670 IF F7>4 THEN 3830
3680 N6=28
3690 N5=30
3700 N7=24                  For 2 ≤ f ≤ 4
3710 N8=22
3720 GOTO 3870
3730 N5=31
3740 N6=26                  For 8 < f < 12
3750 N7=25
3760 N8=22
3770 GOTO 3870
3780 N5=31
3790 N6=27
3800 N7=25                  For 0.5 ≤ f < 2
3810 N8=23
3820 GOTO 3870
3830 N5=30
3840 N6=29
3850 N7=24                  For 4 < f ≤ 8
3860 N8=23
3870 WRITE (1,*)WBYTEN5;  }
3880 GOSUB 3350           }
3890 WRITE (1,*)WBYTEN6;  }
3900 GOSUB 3350           }  Set isolator switches
3910 WRITE (1,*)WBYTEN7;  }
3920 GOSUB 3350           }
3930 WRITE (1,*)WBYTEN8;  }
3940 GOSUB 3350           }
3950 RETURN               }
```

```
3960 REM MONITOR DIODE #1
3970 DISP "MEASUREMENT(1) OR CALIBRATION(2)";
3980 INPUT J
3990 GOSUB J OF 4250,4300       Set switches to measurement or calibration mode
4000 I=1                        Note:  Change I to monitor a diode other than #1
4010 WRITE (1,*)WBYTE63-I;      Connect output of diode #I to DVM
4020 ENTER (4,*)A,B             Read DVM range code (A) and digits (B)
4030 B=B*M[A]                   Multiply B by proper range constant
4040 DISP "V AT POSITION"I;"=" B/87
4050 WAIT 1000
4060 GOTO 4020                  Repeat readings until stop is pressed
4070 RETURN
4080 REM SUBROUTINE TO READ DIODE OFFSET VOLTAGES
4090 DISP "TURN POWER OFF";
4100 STOP
4110 MAT R=ZER                  Set all offset voltage readings to zero
4120 FIXED 1
4130 FOR J=1 TO N
4140 WRITE (1,*)WBYTE63-J;      Connect output of diode #J to DVM
4150 WAIT 50
4160 GOSUB 4470                 Read diode offset voltage
4170 R[J]=B
4180 DISP "DIODE"J;"OFFSET ="B*1E+06/87  Display offset in microvolts
4190 WAIT 500
4200 NEXT J
4210 DISP "SET POWER LEVEL TO START"
4220 STOP
4230 STANDARD
4240 RETURN
4250 REM SET SWITCHES TO MEASUREMENT MODE
4260 K9=32
4270 WRITE (1,*)WBYTE38;
4280 GOSUB 3350
4290 RETURN
4300 REM SET SWITCHES TO CALIBRATION MODE
4310 K9=0
4320 WRITE (1,*)WBYTE39;
4330 GOSUB 3350
4340 RETURN
4350 REM READ DIODE OUTPUT VOLTAGES
4360 FOR J=1 TO N
4370 WRITE (1,*)WBYTE63-J;      Connect output of diode #J to DVM
4380 WAIT 150
4390 GOSUB 4470                 Read DVM
4400 IF D=2 THEN 4440       )
4410 O[I,J]=B               |
4420 NEXT J                 |   Store data in 0 matrix if D = 1,
4430 GOTO 4460              |       or in I matrix if D = 0.
4440 I[I,J]=B               |
4450 NEXT J                 )
4460 RETURN
4470 REM READ DVM K5 TIMES & AVERAGE
4480 ENTER (4,*)A,B         )
4490 B1=B*M[A]              |
4500 ENTER (4,*)A,B         |   See line 4020
4510 B=B*M[A]               )
4520 IF ABS(B)<1E-05 THEN 4560        }  Program discards DVM readings until two
4530 IF ABS((B-B1)/B)<0.01 THEN 4560  >  consecutive readings agree to better than
4540 B1=B                             }  1%. Program then accepts next K5 readings.
4550 GOTO 4500                        }
4560 S1=0
4570 FOR N4=1 TO K5         )
4580 ENTER (4,*)A,B         |
4590 WAIT 50                |
4600 B=B*M[A]               |   Read DVM K5 times, compute average,
4610 S1=S1+B                |   then subtract offset voltage.
4620 NEXT N4                |
4630 B=S1/K5-R[J]           )
4640 RETURN
```

```
4650 REM CALCULATE INITIAL ESTIMATE OF THE Z(I) FROM ESTIMATE OF L
4660 REM
4680 REDIM A[N,M],B[N,M],P[M,N],Q[M,N],X[N],Y[N]
4690 GOSUB 4930          Calculate P and Q matrices
4700 MAT A=TRN(P)
4710 MAT B=TRN(Q)
4720 REDIM A[N1,M],B[N1,M],C[M,N1],D[M,N1],E[N1,N1]   A + jB now = N^T
4730 REDIM F[N1,N1],G[N1,N1],H[N1,N1],S[N1,N1],T[N1,N1]
4740 MAT C=TRN(A)  }
4750 MAT D=TRN(B)  }  C + jD = N
4760 GOSUB 2090          Calculate N^TN, store in E + jF
4770 GOSUB 2170          Calculate (N^TN)^-1, store in S + jT
4780 REDIM C[M,1],D[M,1],E[N1,1],F[N1,1],G[N1,1]
4790 FOR I=1 TO M  }
4800 C[I,1]=-P[I,N] }  C + jD = R
4810 D[I,1]=-Q[I,N] }
4820 NEXT I
4830 GOSUB 2090             Calculate N^TR, store in E + jF
4840 REDIM C[N1,1],D[N1,1]
4850 GOSUB 2260             Calculate Z = (N^TN)^-1 N^TR, store in C + jD
4860 REDIM C[N,1],D[N,1]
4870 C[N,1]=+1    }
4880 D[N,1]=0     }     z5 = 1 + j0
4890 MAT X=C      }
4900 MAT Y=D      }     X + jY = initial estimate of Z
4910 REDIM H[N,N],S[N,N],T[N,N]
4920 RETURN
4930 REM CALCULATE THE P AND Q MATRICES
4940 MAT P=(L1)*O
4950 MAT P=P-I
4960 MAT Q=(L2)*O
4970 RETURN
4980 REM CALIBRATION DATA IN K & L MATRICES TRANSFERRED TO O & I MATRICES
4990 FOR I=1 TO N
5000 D=I
5010 REM DELETE NEXT LINE TO USE DIODES IN ANY ORDER
5020 GOTO 5050
5030 DISP "USE DIODE #(1...5)";
5040 INPUT D
5050 FOR J=1 TO M
5060 O[J,I]=K[J,D]
5070 I[J,I]=L[J,D]
5080 NEXT J
5090 NEXT I
5100 RETURN
```

```
110 REM MEASURING RATIO K6 TIMES WITH TEST DEVICE INSERTED, & AVERAGE
120 DISP "INSERT TEST ITEM OR SET DEVICE"
130 STOP
140 K6=10          Change K6 (2 to 25) to change number of times ratio is measured
200 REDIM G[K6,1],H[K6,1]
210 S1=S2=0
220 FOR N4=1 TO K6
5230 GOSUB 5600       Read diode output voltages
5240 GOSUB 2880       Calculate voltage ratio
5250 G[N4,1]=X        Real part of ratio stored in G matrix         Repeat K6 times
5260 S1=S1+X
5270 H[N4,1]=Y        Imaginary part of ratio stored in H matrix
5280 S2=S2+Y
5290 NEXT N4
5293 X=S1/K6      }   Average ratio = X + jY
5296 Y=S2/K6
5300 S3=S4=0
5310 FOR N4=1 TO K6
5320 S1=X-G[N4,1]
5330 S3=S3+S1*S1          Calculating sum of the squares of the deviation
5340 S2=Y-H[N4,1]         of individual measurements from the average
5350 S4=S4+S2*S2
5360 NEXT N4
5370 S1=SQR(S3/(K6-1))     Standard deviation of X
5380 S2=SQR(S4/(K6-1))     Standard deviation of Y
5390 S3=S4=X0=Y0=0
5400 FOR N4=1 TO K6
5410 IF ABS(G[N4,1]-X)>2*S1 THEN 5440
5420 S3=S3+G[N4,1]
5430 X0=X0+1                             Discarding any measurement whose deviation
5440 IF ABS(H[N4,1]-Y)>2*S2 THEN 5470    from the average is greater than two
5450 S4=S4+H[N4,1]                       standard deviations
5460 Y0=Y0+1
5470 NEXT N4
5480 X=S3/X0     }     Average ratio with bad points discarded = X + jY
5490 Y=S4/Y0
5500 Z=SQR(X*X+Y*Y)*K1
5510 L=20*LGT(Z)                                     Calculate amplitude and
5520 F1=10*LGT(C2*F)                                 phase of insertion ratio
5530 T=ATN(Y/X)+180*(X<0)*(2*(Y >= 0)-1)-K2
5540 P1=T-P
5550 P1=P1+360*((P1<-180)-(P1>180))
5560 WRITE (15,2860)"AVG. INS.  RATIO"Z/R,L-S,P1,F1
5570 PRINT "FOR AVERAGE OF"X0"REAL TERMS &"Y0"IMAGINARY TERMS OUT OF POSSIBLE"K6
5580 RETURN
5600 REM READ DIODE OUTPUT VOLTAGES ONLY ONCE
5610 FOR J=1 TO N
5620 WRITE (1,*)WBYTE63-J;       Connect diode #J to DVM
5625 WAIT 10
5630 ENTER (4,*)A,B              Read DVM
5640 O[I,J]=B*M[A]-R[J]          Subtract offset voltage and store reading in O matrix
5650 NEXT J
5660 RETURN
```

SAMPLE PRINTOUT

```
SAM TAPE #1, FILE 2, REVISED 25 APR 1976
PRESS CONT EXECUTE AFTER COMPLETING EACH INSTRUCTION

ENTER 1 TO CALIBRATE VECTOR VOLTMETER
ENTER 2 TO MEASURE REFERENCE RATIO
ENTER 3 TO MEASURE RATIO WITH TEST DEVICE INSERTED
ENTER 4 TO MEASURE DVM OFFSET VOLTAGES
ENTER 5 TO MEASURE  R0
ENTER 6 TO MONITOR REFERENCE DIODE
        PRESS STOP CONT 400 WHEN DONE
ENTER 7 TO MEASURE STEP VALUE (L)
ENTER 8 TO DETERMINE K FOR ABSOLUTE RATIO MEASUREMENTS
 ---------DELTA X(I)----------   ---------DELTA Y(I)---------    DELTA L

 -2E-04 -1E-04  3E-05 -4E-04  5E-04  7E-04  1E-04  5E-05
 -8E-08  2E-07  2E-07  5E-08 -6E-08  1E-07  4E-09 -5E-08

FREQUENCY =   3.99     GHZ, USING DIODES  1     2     3     4

   L(REAL)        L(IMAGINARY)      L(DB)         P(DEGREES)

 0.601393772     0.504685579   -2.1015005       40.00314672

  I =       1          2          3          4          5
X(I)=    -0.0557    -0.9527     0.0162     1.0000
Y(I)=    -0.0424     1.0257    -0.6448     0.0000
W(I)=     1.0000    -0.0076     0.0067     0.0046
      L(I),DB     L-L(I),DB    P(I),DEG    P-P(I),DEG     PR=REF  PORT POWER
                                                          PR1/C     PR2/PR1-1
     -2.0909      -0.0106       40.030       -0.027      -11.235    0.000145
     -2.0812      -0.0203       40.054       -0.051      -10.690   -0.000094
     -2.0895      -0.0120       40.108       -0.105      -10.975   -0.000131
     -2.1179       0.0164       39.762        0.241      -10.980    0.000125
     -2.1278       0.0263       39.952        0.051      -10.704    0.000200
     -2.1339       0.0324       39.962        0.041      -11.195   -0.000197

   STD. DEV. =     0.0231                     0.124
 ---------DELTA X(I)----------   ---------DELTA Y(I)---------    DELTA L

  5E-03 -4E-02 -2E-02  4E-02  2E-03  5E-02 -4E-02 -9E-03 -1E-03  3E-03
  7E-05  3E-04  6E-05 -5E-04  3E-05 -7E-04  2E-04  1E-04   1E-04  2E-04
 -4E-06 -4E-05 -1E-05  6E-05 -1E-06  9E-05 -4E-05 -2E-05  8E-08  2E-07

FREQUENCY =   3.99     GHZ, USING DIODES  1     2     3     4     5

   L(REAL)        L(IMAGINARY)      L(DB)         P(DEGREES)

 0.602651388     0.501276445   -2.115015992     39.7531794

  I =       1          2          3          4          5
X(I)=    -0.1006    -0.1301    -0.2728    -0.2557     1.0000
Y(I)=    -0.0606     0.0528    -0.3889     0.6144     0.0000
W(I)=     1.0000     0.0435    -0.0254    -0.0366     0.0471
      L(I),DB     L-L(I),DB    P(I),DEG    P-P(I),DEG     PR=REF  PORT POWER
                                                          PR1/C     PR2/PR1-1
     -2.1160       0.0010       39.740        0.013      -11.286    0.000136
     -2.1157       0.0006       39.741        0.012      -10.736   -0.000154
     -2.1136      -0.0014       39.747        0.007      -11.018   -0.000071
     -2.1159       0.0009       39.769       -0.016      -11.028    0.000022
     -2.1144      -0.0006       39.779       -0.026      -10.750    0.000234
     -2.1140      -0.0010       39.773       -0.020      -11.244   -0.000120

   STD. DEV. =     0.0010                     0.018

   TYPE             ------RATIO------      PHASE       PR(DBM)   PR2/PR1-1
 MEASUREMENT        MAGNITUDE     DB       DEGREES

 R0   .             0.0022     -53.087    -126.75       0.000                    Attenuation in
 REFERENCE RATIO    0.7479      -2.523    -138.22       0.000                     Test Channel
 INSERTION RATIO    0.9999      -0.001      -0.04       0.001                         0 dB
 INSERTION RATIO    0.3315      -9.592      -6.25      -0.005                        10
 INSERTION RATIO    0.1031     -19.736      -2.42      -0.002                        20
 INSERTION RATIO    0.0328     -29.696      -8.67      -0.004                        30
 INSERTION RATIO    0.0108     -39.325      10.65      -0.005                        40
 INSERTION RATIO    0.0035     -49.232       5.34      -0.006                        50
 INSERTION RATIO    0.0012     -58.335      41.97      -0.007                        60
 INSERTION RATIO    0.0003     -70.144     107.36      -0.007                        70
 STEP RATIO (L)     0.7780      -2.181      40.28      -0.007     0.001681           0
 STEP RATIO (L)     0.7835      -2.119      39.88      -0.009     0.000027          10
 STEP RATIO (L)     0.7807      -2.150      39.93      -0.010    -0.000017          20
 STEP RATIO (L)     0.7780      -2.181      40.29      -0.009     0.000054          30
 STEP RATIO (L)     0.8233      -1.688      41.14      -0.012    -0.000024          40
 STEP RATIO (L)     0.7613      -2.369      46.98      -0.011     0.000309          50
 STEP RATIO (L)     0.8311      -1.607      61.74      -0.013     0.000297          60
```

APPENDIX D

INTERFACE CABLE PIN CONNECTIONS

These tables list pin connections for the interface cables indicated in figure 1 (page 2). The tables can be found at the rear of the chassis of each unit indicated. A brief description of the signal present at those pins is given to aid in understanding or troubleshooting.

Monitor Labs To MVV

Model 1200A Scanner

Board	Channel	Pin No.		Switch	Pin No.	Function
No. 2	10	B	→	step	2	Step out
2	10	E	→		Com	Common
2	11	D	→	step	1	Step in
2	11	C	→		Com	Common
2	12	J	→	ϕ shifter	1	+90
2	12	H	→		Com	
2	13	N	→	ϕ shifter	2	-90
2	13	M	→		Com	
2	14	T	→	ϕ shifter	1	Thru hybrid
2	14	S	→		Com	
2	15	X	→	ϕ shifter	2	Thru Coax
2	15	W	→		Com	
2	16	V	→	2, 4, 5	2	Cal. Diodes
2	16	Y	→		Com	
2	17	R	→	2, 4, 5	1	Cal. 6-port
2	17	U	→		Com	
2	18	L	→	1, 3, 6, 7	2	Calibrate
2	18	P	→		Com	
2	19	F	→	1, 3, 6, 7	1	Measure
2	19	K	→		Com	
3	20	B	→	Isolators (1 & 2)	1	1-2, 8-12 GHz
3	20	E	→	" " "	Com	
3	21	D	→	" " "	2	2-4, 4-8 GHz
3	21	C	→	" " "	Com	
3	22	J	→	" " "	2	4-8 GHz
3	22	H	→	" " "	Com	
3	23	N	→	" " "	1	2-4 GHz
3	23	M	→	" " "	Com	
3	24	T	→	" " "	2	1-2 GHz
3	24	S	→	" " "	Com	
3	25	X	→	" " "	1	8-12 GHz
3	25	W	→	" " "	Com	
3	26	V	→	Isolator 3	1	1-2, 8-12 GHz
3	26	Y	→	" "	Com	
3	27	R	→	" "	2	2-4, 4-8 GHz
3	27	U	→	" "	Com	
3	28	L	→	" "	2	4-8, 1-2 GHz
3	28	P	→	" "	Com	
3	29	F	→	" "	1	8-12, 2-4 GHz
3	29	K	→	" "	Com	

Weinschel Switch Driver Model 120-1	To	MVV
Output Data Connector		Pin Connection on device
Pin 2	→	+ on 1 db Step in Test Channel
Pin 20	→	- on 1 db Step " " "
Pin 3	→	+ on 2 dB Step " " "
Pin 21	→	- on 2 dB Step " " "
Pin 4	→	+ on 4 dB Step " " "
Pin 22	→	- on 4 dB Step " " "
Pin 5	→	+ on 8 dB Step " " "
Pin 23	→	- on 8 dB Step " " "
Pin 6	→	+ on 5 dB Step in Reference Channel
Pin 24	→	- on 5 dB Step " " " "
Pin 7	→	+ on 10 dB Step " " " "
Pin 25	→	- on 10 dB Step " " " "
Pin 8	→	Terminal strip (Not used)
Pin 26	→	Terminal strip (Not used)
Pin 1	→	Monitor Labs Scanner Pin 4 (J2 Boards 2 & 3)
Pin 19	→	Monitor Labs Scanner Pin 2 (J2 Boards 2 & 3)

Interface connections from Data Precision Model 3500 DVM to HP computer interface cable 11203A BCD Interface

Data Precision Model 3500 Connector Pin #	Information Direction	Hewlett Packard 11203A Interface Wire #	Comments on description
1	↔	968	ground
2	→	907	Digit 9 "8" (LSD)
3	→	96	Digit 9 "4"
4	→	90	Digit 9 "2"
5	→	1	Digit 9 "1"
6		N.C.	
7	→	906	Digit 8 "8"
8	→	95	Digit 8 "4"
9	→	9	Digit 8 "2"
10	→	2	Digit 8 "1"
11	→	913	1000 V Range to Exp. "5"
12		N.C.	
13		N.C.	
14	→	967	Flag from Read Output (Invert Flag
15	→	912	5th digit "8" MSD
16	→	902	5th digit "4"
17	→	91	5th digit "2"
18	→	5	5th digit "1"
19	→	925	4th digit "1" 1/2 digit (1 or 0)
20	→	901	
21	→	957	
22	↔	968	ground

915 - 97 +5 volts to Exp. "4"

Data Precision Model 3500 Connector Pin #	Information Direction	Hewlett-Packard 11203A Interface Wire #	Comments on description
A	↔	968	ground
B	→	98	10 volt range to Function "4"
C	→	908	Digit 6 "8"
D	→	93	Digit 6 "4"
E	→	7	Digit 6 "2"
F	→	4	Digit 6 "1"
H	→	92	1 volt range to Function "2"
J	←	958	Control 1 to Enable
K		N.C.	
L		N.C.	
M		N.C.	
N	→	905	Digit 7 "8"
P	→	94	Digit 7 "4"
R	→	8	Digit 7 "2"
S	→	3	Digit 7 "1"
T	→	0	100 volt Range to Exp "1"
U		N.C.	
V		N.C.	
W		N.C.	
X	→	6	100 mv Range to Function "1"
Y	→	916	Overload to Exp. sign
Z	↔	968	ground

Ground: 903; 908; 917; 918; 923; 924; 926; 927; 928;
934; 935; 936; 937; 938; 946; 947; 948; 956.

Monitor Labs Model 1200 Scanner Connector J2	To	Data Precision Model 3500 DVM Rear Panel Input Connectors
Pin 2	→	High
Pin 4	→	Low
Pin 3	→	Guard

Weinschel Switch Driver Model 120-1 Connector Pin No.	To	Monitor Labs Model 1200 Scanner Pin No. on J2 (Boards 2 and 3)
Pin 1	→	Pin 4
Pin 19	→	Pin 2

HP 11202 Connections to Monitor Labs Scanner

Model 1200 Pin Connections		HP 11202 Interface	
1	←	Output "4"	Orange
2	←	Output "2"	Red
3	←	Output "0"	Blue
4	←	Output "1"	Brown
5	↔	Ground	
6	↔	Ground	
7	←	Output "8"	(Green)
8	←	Output "16"	(Yellow)
9 ↓ 16	↔	Ground	
22	↔	Ground	
21	→	(98) Control ($\overline{\text{Cntrl}}$) line (pin H on 11202)	
All other pins open		on 11202 - short outputs to inputs (1-1, 2-2, etc.), short flag to Cntrl	

HP 11202A Interface Unit to HP 9830		To	Weinschel Switch Driver Model 120-1
Pins 16→T	(Jumper)	→	Pin 11 (Control Pin 1)
15→S	"	→	12 (Control Pin 2)
14→R	"	→	13 (Control Pin 3)
13→P	"	→	14 (Control Pin 4)
12→N	"	→	15 (Control Pin 5)
11→M	"	→	16 (Control Pin 6)
10→L	"	→	17 (Control Pin 7)
9→K	"	→	18 (Control Pin 8)
H→C	"		
Pin 3 of UI0B		→	9 Strobe
U → V		↔	27 Signal ground

APPENDIX E

DIAGNOSTIC PROGRAM LISTING WITH SAMPLE PRINTOUTS

This appendix contains a listing of the diagnostic program stored on file 4 of the MVV cassette tape.

Three separate tasks can be selected when using program. They are:

1. Measure step repeatability
2. Measure diode linearity
3. Monitor source stability.

The program was written to be an aid for setting up the system and for troubleshooting. Remarks have been added to the program listing to explain the functions of the program statements.

```
100 PRINT "SAM TAPE #1, FILE 4, REVISED 27 APRIL 1976"
110 REM DIAGNOSTIC ROUTINES FOR MICROWAVE VECTOR VOLTMETER
120 DIM M[7],O[16,5],I[16,5],R[4],V[4]
130 M[6]=-10
140 M[5]=-100                          DVM range constants
150 M[7]=M[3]=-1000
160 K9=0                               K9 = 0 indicates 0 dB added to measurement channel
170 MAT C=ZER
180 MAT R=ZER
190 MAT O=ZER
200 MAT I=ZER
210 DISP "FREQ. IN GHZ";
220 INPUT F7
230 PRINT "FREQ ="F7"GHZ"
240 PRINT
250 GOSUB 1510                         Switch in appropriate isolators
260 PRINT "ENTER 1 TO MEASURE STEP REPEATABILITY"
270 PRINT "ENTER 2 TO MEASURE DIODE LINEARITY"
280 PRINT "ENTER 3 TO MONITOR SOURCE STABILITY"
290 PRINT
300 DISP "TASK";
310 INPUT I
320 GOSUB I OF 340,850,2080
330 GOTO 300
340 REM SUBROUTINE TO MEASURE STEP REPEATABILITY
350 GOTO 410
360 DISP "TURN OFF POWER";
370 STOP
380 GOSUB 2000                         Measure diode offset voltages
390 DISP "TURN ON  POWER";
400 STOP
410 GOSUB 430                          Choose which diode to monitor
420 GOTO 570
430 DISP "MONITOR WHICH DIODE (2-5)";
440 INPUT J1
450 PRINT
460 PRINT "DIODE NO.  "J1
470 PRINT
480 J=J1-1                             Set attenuation in measurement channel to zero
490 K9=0
500 K2=39
510 GOSUB 1830                         Set switches to calibration mode
520 K2=41
530 GOSUB 1830                         Set switches to calibrate diodes
540 K2=47
550 GOSUB 1830                         Set step out
560 RETURN
570 PRINT "     -.06%     -.04%     -.02%     A0    ";
580 PRINT TAB35"     +.02%     +.04%     +.06%"
590 PRINT " N    +----+----+----+----+----+----0----+----+----+----+----+----+";
600 WRITE (15,610)
610 FORMAT 5X,"SIGMA, %"
620 K1=1
630 N=5
640 GOSUB 1300                         Measure step ratio N times, compute average and std. dev.
650 A0=A                               A0 = initial average
660 WRITE (15,670)N,A0
670 FORMAT F3.0,24X,"A0 =",F11.6,27X,F8.4
680 GOSUB 1300                         Measure step ratio N times again
690 WRITE (15,700)N;
700 FORMAT F3.0
710 A=(A-A0)/A0*100                    Compute % deviation from initial average
720 IF A<-0.001 THEN 760
730 IF A>0.001 THEN 780
740 PRINT TAB32"+"TAB67;
750 GOTO 790                                     Plot deviations
760 PRINT TAB(32+500*A)"*"TAB32"."TAB67;
770 GOTO 790
780 PRINT TAB32"."TAB(32+500*A)"*"TAB67;
790 WRITE (15,800)G
800 FORMAT F7.4
810 IF ABS(A)>0.05 THEN 640            If deviation > .05%, compute new initial average
820 K1=K1+1
830 IF K1<20 THEN 680                  Repeat measurement 20 times
840 RETURN
```

```
850 REM SUBROUTINE TO MEASURE DIODE LINEARITY
860 DISP "TURN OFF POWER";
870 STOP
880 GOSUB 2000           Measure diode offset voltages
890 DISP "TURN ON POWER";
900 STOP
910 N=5
920 K2=39
930 GOSUB 1830      }    Set switches to calibration mode
940 K2=41
950 GOSUB 1830      }    Set switches to calibrate diodes
960 PRINT
970 WRITE (15,980)"DIODE NO."2,3,4,5
980 FORMAT F6.0,3F16.0
990 PRINT "          RATIO  VOLTS    RATIO  VOLTS    RATIO  VOLTS    RATIO  VOLTS
1000 FOR K9=30 TO 2 STEP -2
1010 D=1
1020 K2=47
1030 GOSUB 1830     }    Set step out
1040 GOSUB 1170          Read all diodes
1050 K2=46
1060 D=2
1070 GOSUB 1830     }    Set step in
1080 GOSUB 1170          Read all diodes
1090 FOR J=1 TO 4
1100 V[J]=-O[K9/2,J]
1110 R[J]=O[K9/2,J]/I[K9/2,J]
1120 NEXT J
1130 WRITE (15,1140)K9/2;"DB";R[1],V[1],R[2],V[2],R[3],V[3],R[4],V[4]
1140 FORMAT F4.0,F8.1,F8.4,F8.3,F8.4,F8.3,F8.4,F8.3,F8.4
1150 NEXT K9
1160 GOTO 2800
-----------------------------------------------------------------------------
1170 REM SUBROUTINE TO SCAN AND READ DIODE VOLTAGES
1180 S=0
1190 FOR J=1 TO 4
1200 WRITE (1,*)WBYTE82-J          Connect diode #J + 1 to DVM
1210 GOSUB 1890                    Read DVM
1220 A=B
1230 IF D=2 THEN 1270   )
1240 O[K9/2,J]=A        |
1250 NEXT J             |          Store data in O matrix if D = 1 for step out
1260 RETURN             |             or in I matrix if D = 2 for step in
1270 I[K9/2,J]=A        )
1280 NEXT J
1290 RETURN
-----------------------------------------------------------------------------
1300 REM MEASURE STEP RATIO N TIMES, COMPUTE AVERAGE & % STD. DEV.
1310 S=S2=0
1320 FOR I=1 TO N
1330 K2=47
1340 GOSUB 1830          }  Set step out
1350 WRITE (1,*)WBYTE82-J   }  Read diode #J + 1 five times
1360 GOSUB 1940
1370 V1=B
1380 K2=46
1390 GOSUB 1830          }  Set step in
1400 WRITE (1,*)WBYTE82-J   }  Read diode #J + 1 five times
1410 GOSUB 1940
1420 V2=B
1430 V=V1/V2                V = ratio of step out to step in
1440 S=S+V
1450 S2=S2+V*V
1460 NEXT I
1470 A=S/N
1480 G=SQR(ABS((S2-A*S)/(N-1)))   }  Compute average and % standard deviation
1490 G=100*G/A
1500 RETURN
```

```
1510 REM SUBROUTINE TO SET ISOLATORS TO THE CORRECT FREQUENCY RANGE
1520 IF F7>8 THEN 1600
1530 IF F7<2 THEN 1650
1540 IF F7>4 THEN 1700
1550 N6=28
1560 N5=30
1570 N7=24
1580 N8=22
1590 GOTO 1740
1600 N5=31
1610 N6=26
1620 N7=25
1630 N8=22
1640 GOTO 1740
1650 N5=31
1660 N6=27
1670 N7=25
1680 N8=23
1690 GOTO 1740
1700 N5=30
1710 N6=29
1720 N7=24
1730 N8=23
1740 WRITE (1,*)WBYTEN5;
1750 GOSUB 1850
1760 WRITE (1,*)WBYTEN6;
1770 GOSUB 1850
1780 WRITE (1,*)WBYTEN7;
1790 GOSUB 1850
1800 WRITE (1,*)WBYTEN8;
1810 GOSUB 1850
1820 RETURN
----------------------------------------------------------------------
1830 REM SUB ROUTINE TO RUN SWITCH DRIVER
1840 WRITE (1,*)WBYTEK2;
1850 WAIT 50
1860 WRITE (2,*)WBYTEK9+1;
1870 WAIT 50
1880 RETURN
----------------------------------------------------------------------
1890 REM SUBROUTINE TO READ DIODE VOLTAGES
1900 B=0
1910 ENTER (4,*)A1,B4
1920 FOR K=1 TO 5
1930 ENTER (4,*)A1,B1
1940 WAIT 50
1950 B2=B1*M[A1]-C[J]          Subtract offset from each DVM reading
1960 B=B+B2
1970 NEXT K
1980 B=B/5
1990 RETURN
----------------------------------------------------------------------
2000 REM SUBROUTINE TO MEASURE OFFSET VOLTAGES
2010 MAT C=ZER
2020 FOR J=1 TO 4
2030 WRITE (1,*)WBYTE62-J;     Connect diode #J + 1 to DVM
2040 GOSUB 1890                Read DVM
2050 C[J]=B
2060 NEXT J
2070 RETURN
----------------------------------------------------------------------
2080 REM MEASURING A VOLTAGE ON THE DATA PRECISION 3500 DVM & PLOTTING
2090 REM OR DISPLAYING DEVIATIONS FROM THAT VOLTAGE WITH TIME.
2100 GOSUB 430                   Monitor which diode?
2110 WRITE (1,*)WBYTE62-J;       Connect diode #J + 1 to DVM
2120 FOR I=1 TO 6          }
2130 ENTER (4,*)A1,V       }     Discard six DVM readings
2140 NEXT I                }
2142 DISP "ENTER 1,2,OR3 FOR .05%,.5%,OR 5%";   }    Choose range of deviations
2144 INPUT S7                                   }    as ±0.05%, ±0.5%, or ±5%
2150 DISP " PRINT(1) OR DISPLAY(2) ";
2160 INPUT K                                    }    Input 1 to plot deviations on printer
2170 IF K=2 THEN 2580                           }    Input 2 to display deviations
2175 GOTO S7 OF 2180,2193,2197
2180 PRINT "     -.06%.     -.04%      -.02%      A0     ";   )
2190 PRINT TAB35"     +.02%      +.04%      +.06% "           )
2192 GOTO 2200                                                 )
2193 PRINT "      -.6%       -.4%       -.2%      A0     ";   )   Headings for
2194 PRINT TAB35"     +.2%       +.4%       +.6%  "           )   different ranges
2196 GOTO 2200                                                 )
2197 PRINT "    -6.0%      -4.0%      -2.0%      A0     ";   )
2198 PRINT TAB35"    +2.0%      +4.0%      +6.0%  "           )
2200 PRINT " N    *----*----*----*----*----*----0----*----*----*----*----*----*";
2210 WRITE (15,2220)
2220 FORMAT 5X,"SIGMA, %"                           { S7 = 1 for ±0.05% range
2225 S7=10↑(S7-1)          S7 is now a scale factor  { S7 = 10 for ±0.5% range
2230 N=10                                           { S7 = 100 for ±5.0% range
```

```
2240 GOSUB 2450          Read DVM
2250 A0=A                A0 = initial average
2260 WRITE (15,2270)N,A0,G
2270 FORMAT F3.0,24X,"A0 =",F11.6,27X,F8.4
2280 N=10
2290 GOSUB 2450          Read DVM
2300 WRITE (15,2310)N;
2310 FORMAT F3.0
2320 A=100*(A-A0)/(A0*S7)  Compute % deviation from initial average and divide by S7
2330 IF A<-0.001 THEN 2370                  )
2340 IF A>0.001 THEN 2390                   |
2350 PRINT TAB32"*"TAB67;                   |
2360 GOTO 2400                              >  Plot deviation
2370 PRINT TAB(32+500*A),"*"TAB32,"."TAB67; |
2380 GOTO 2400                              |
2390 PRINT TAB32"."TAB(32+500*A)"*"TAB67;   )
2400 WRITE (15,2410)G
2410 FORMAT F7.4
2420 IF ABS(A)<0.05 THEN 2290 {  If deviation is greater than the chosen
2430 GOTO 2230                }  range, compute new initial average
2440 END
```

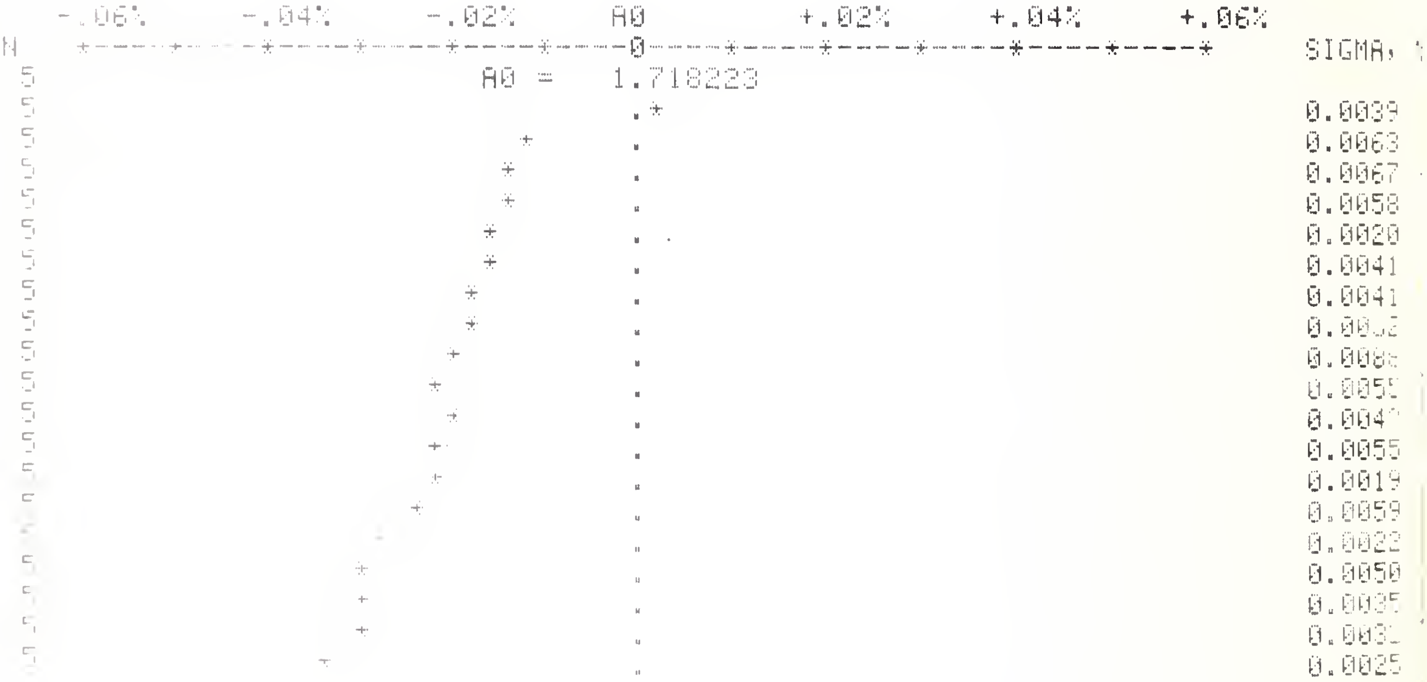
```
2450 REM READ DVM N TIMES, COMPUTE AVERAGE & % STD. DEV.
2460 S=G2=0
2470 FOR I=1 TO N
2480 ENTER (4,*)A1,B
2490 V=B*M[A1]
2500 S=S+V
2510 G2=G2+V↑2
2520 NEXT I
2530 A=S/N
2540 G=SQR((G2-A*S)/(N-1))
2550 G=100*G/A
2560 RETURN
2570 END
```

```
2580 REM SAME AS ABOVE EXCEPT DISPLAYING INSTEAD OF PLOTTING
2590 K=0
2600 N=5
2605 S7=10↑(S7-1)        See line 2225
2610 GOSUB 2450          Read DVM
2620 A0=A                A0 = initial average
2630 WRITE (15,2640)N,A0,"  TIME SINCE LAST REZERO ="K*0.807,G
2640 FORMAT F3.0,5X,"A0 =",F11.6,3X,F6.0," SEC.  SIGMA =",F8.4
2650 K=0
2660 ENTER (4,*)A1,B          )
2670 A=B*M[A1]                } Read DVM one time, compute
2680 A=100*(A-A0)/(A0*S7)     ) % deviation from initial average, divided by S7
2690 IF A<-0.001 THEN 2730     )
2700 IF A>0.001 THEN 2750      |
2710 DISP TAB16"*"             |
2720 GOTO 2760                 >  Display deviation
2730 DISP TAB(16+500*A),"*"TAB16,"."
2740 GOTO 2760                 |
2750 DISP TAB16"."TAB(16+500*A)"*"  )
2760 K=K+1
2770 IF ABS(A)<0.04 THEN 2660 {  If deviation is greater than the chosen
2780 GOTO 2610                }  range, compute new initial average
2790 END
```

```
2800 REM PLOTTING STEP RATIOS VS DIODE VOLTAGE
2810 DISP "PLOT (0=NO 1=YES) ";
2820 INPUT S
2830 IF S=0 THEN 2990
2840 FIXED 4
2850 S=0
2860 FOR D=1 TO 4              )  Compute average step ratio at lowest power setting.
2870 S=S+O[15,D]/I[15,D]       |
2880 NEXT D                    |  Use this average to determine scale.
2890 S=S/4                     )
2900 FOR D=1 TO 4
2910 PRINT "FOR DIODE"D+1
2920 PRINT "STEP RATIO ="TAB18;S-0.04;TAB[illegible];[illegible];TAB58;[illegible]  Scale ≈ .05%/division
2930 PRINT "            !+++++++++!+++++++++!+++++++++!+++++++++!+++++++++!+++++
2940 FOR J=15 TO 1 STEP -1
2950 PRINT O[J,D];TAB(60+1000*(O[J,D]/I[J,D]-S[illegible]   }   Plot ratios
2960 NEXT J
2970 PRINT
2980 NEXT D
2990 STANDARD
3000 RETURN
```

Sample Printout
Task #1, Step Repeatability

```
SAM TAPE #1, FILE 4, REVISED 27 APRIL 19
FREQ = 0.5  GHZ

ENTER 1 TO MEASURE STEP REPEATABILITY
ENTER 2 TO MEASURE DIODE LINEARITY
ENTER 3 TO MONITOR SOURCE STABILITY


DIODE NO.    3
```



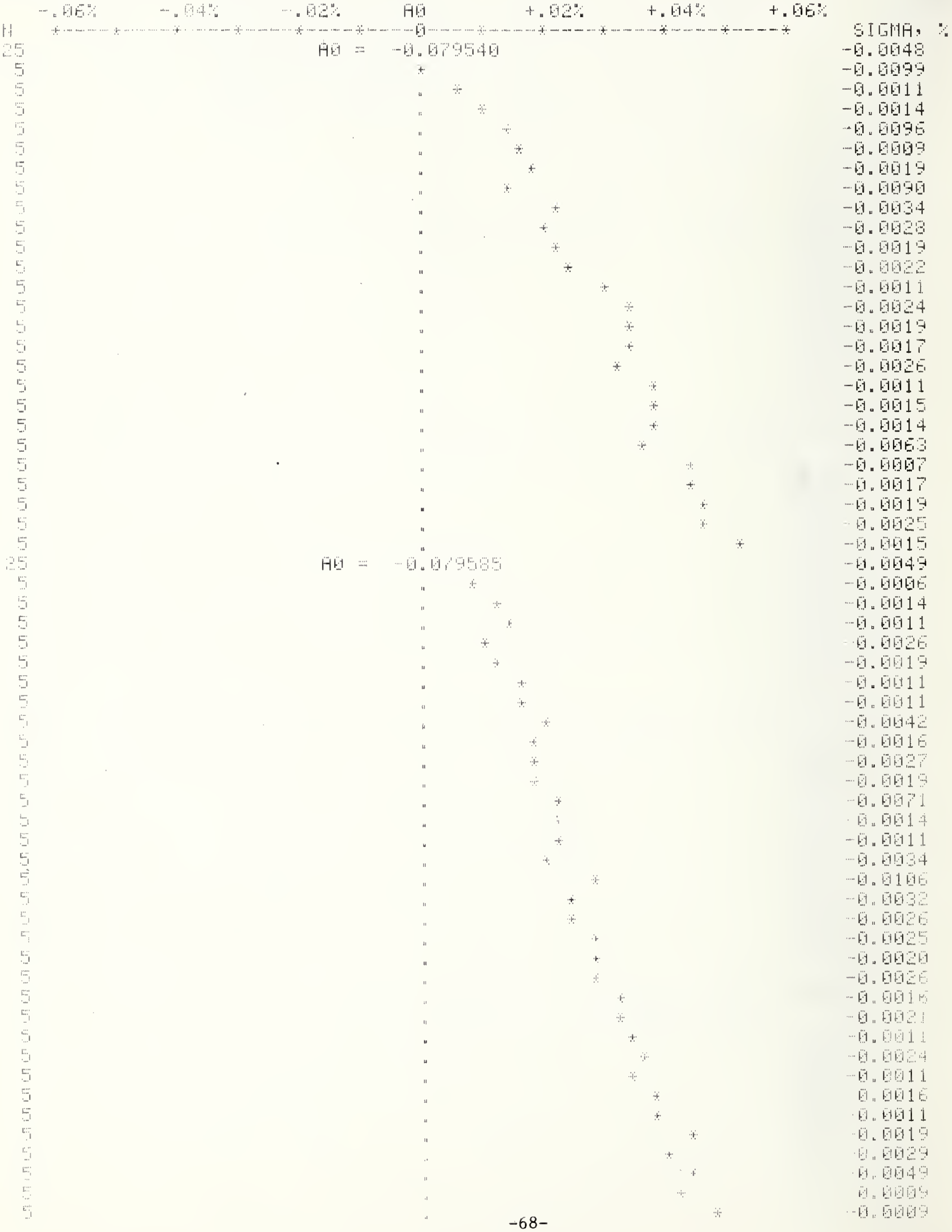
```
    -.06%     -.04%     -.02%     A0        +.02%     +.04%     +.06%
 N   +----+----+----+----+----+----0----+----+----+----+----+----+     SIGMA,
  5                        A0 =   1.718223
  5                                .+                                  0.0039
  5                          +     .                                   0.0063
  5                         +      .                                   0.0067
  5                         +      .                                   0.0058
  5                        +       .                                   0.0020
  5                        +       .                                   0.0041
  5                       +        .                                   0.0041
  5                       +        .                                   0.00[illegible]2
  5                      +         .                                   0.0086
  5                     +          .                                   0.0055
  5                      +         .                                   0.0047
  5                     +          .                                   0.0055
  5                     +          .                                   0.0019
  5                    +           .                                   0.0059
  5                  +             .                                   0.0022
  5                 +              .                                   0.0050
  5                 +              .                                   0.0035
  5                 +              .                                   0.0031
  5               +                .                                   0.0025
```

Sample Printout
Task 2, Diode Linearity

```
[illegible]

                                                       5
        [illegible]                     RATIO   VOLTS     RATIO  VOLTS
                                        1.741   0.0011    1.729  0.0011
                                        1.741   0.0013    1.738  0.0014
                                        1.745   0.0017    1.747  0.0018
                                        1.742   0.0021    1.739  0.0022
                                        1.744   0.0027    1.739  0.0028
                                        1.741   0.0031    1.740  0.0034
                                        1.741   0.0043    1.737  0.0044
                                        1.741   0.0051    1.737  0.0054
                                        [illegible]       1.737  0.0072
                                        1.741   0.0083    1.738  0.0086
                                        [illegible]       1.730  0.0111
                                        [illegible]       1.727  0.0133
                                        [illegible]       1.718  0.0173
                                        [illegible]       1.712  0.0207
                                        [illegible] 0.0251 1.698 0.0263
[illegible]
                                                         1.7393

-0.0011
-0.0014
-0.0018
-0.0022
-0.0028
-0.0034
-0.0044
-0.0054
-0.0072
```

```
SMM TAPE #1, FILE 4, REVISED 27 APRIL 1976
FREQ = 0.5  GHZ

ENTER 1 TO MEASURE STEP REPEATABILITY
ENTER 2 TO MEASURE DIODE LINEARITY
ENTER 3 TO MONITOR SOURCE STABILITY


DIODE NO.    3
```

Sample Printout
Task 3, Source Stability



```
     -.06%     -.04%     -.02%     A0        +.02%     +.04%     +.06%
N     +----+----+----+----+----+----+----0----+----+----+----+----+----+      SIGMA, %
25                         A0 =  -0.079540                                  -0.0048
 5                                                                          -0.0099
 5                                                                          -0.0011
 5                                                                          -0.0014
 5                                                                          -0.0096
 5                                                                          -0.0009
 5                                                                          -0.0019
 5                                                                          -0.0090
 5                                                                          -0.0034
 5                                                                          -0.0028
 5                                                                          -0.0019
 5                                                                          -0.0022
 5                                                                          -0.0011
 5                                                                          -0.0024
 5                                                                          -0.0019
 5                                                                          -0.0017
 5                                                                          -0.0026
 5                                                                          -0.0011
 5                                                                          -0.0015
 5                                                                          -0.0014
 5                                                                          -0.0063
 5                                                                          -0.0007
 5                                                                          -0.0017
 5                                                                          -0.0019
 5                                                                          -0.0025
 5                                                                          -0.0015
25                         A0 =  -0.079585                                  -0.0049
 5                                                                          -0.0006
 5                                                                          -0.0014
 5                                                                          -0.0011
 5                                                                          -0.0026
 5                                                                          -0.0019
 5                                                                          -0.0011
 5                                                                          -0.0011
 5                                                                          -0.0042
 5                                                                          -0.0016
 5                                                                          -0.0027
 5                                                                          -0.0019
 5                                                                          -0.0071
 5                                                                          -0.0014
 5                                                                          -0.0011
 5                                                                          -0.0034
 5                                                                          -0.0106
 5                                                                          -0.0032
 5                                                                          -0.0026
 5                                                                          -0.0025
 5                                                                          -0.0020
 5                                                                          -0.0026
 5                                                                          -0.0016
 5                                                                          -0.0021
 5                                                                          -0.0011
 5                                                                          -0.0024
 5                                                                          -0.0011
 5                                                                           0.0016
 5                                                                          -0.0011
 5                                                                          -0.0019
 5                                                                          -0.0029
 5                                                                          -0.0049
 5                                                                           0.0009
 5                                                                          -0.0009
```

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

This report presents a system description and operating procedure for a vector voltmeter system which covers the frequency range .5 to 12 GHz. The design is based upon a seven-port junction where phase and amplitude information is obtained using only power detectors. The system is computer controlled and self-calibrating for ratio measurements.

17. 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)*

Amplitude; computer controlled; diode detectors; microwave measurements; phase angle; self-calibration; seven-port junction; vector voltmeter.

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