rain, and rain-rate mapping, and surveying of forest heights.

In addition it has been demonstrated that altimeter data can supply precise satellite pointing information and surface reflectivity data. This information is valuable for calibrating the altimeter, and other satellite radars as well as for the design of future radar systems.

ACKNOWLEDGMENT

The author wishes to thank The NASA Wallops Island personnel involved in altimetry for contribution of some of the techniques and data presented in this paper. Particularly, C. Leitao, H. R. Stanley, W. F. Townsend, Dr. E. J. Walsh, C. L. Parsons, and Dr. F. E. Hoge have made substantial contributions. Also, Dr. J. D. Oberholtzer has contributed the plot of the pass over the eastern shore of Maryland and Virginia.

Dr. L. S. Miller, G. S. Hayne, and Dr. G. S. Brown of Applied Sciences Associates, Apex, N. C., have developed techniques for recovering wave height and satellite pointing and have produced some of the S-193 Skylab data results utilized in this paper.

Dr. W. T. Wells of Wolf Research and Development Corporation, Riverdale, Md., has supplied some of the methods used for geoid recovery.

E. Hofmeister and T. Godbey of General Electric, Utica, N. Y., have supplied various instrument data from which typical altimeter performance and errors were extracted.

B. Yaplee, D. Hammond, and A. Shapiro of the Naval Research Laboratory have provided technical assistance for all the present satellite altimeters and are the designers of the nanosecond radar utilized for aircraft studies.

REFERENCES

[1] W. M. Kaula, "The terrestrial environment: Solid earth and ocean physics," NASA Rep. Study at Williamstown, Mass., NASA CR-1579, Aug. 1969.

[2] R. P. Dooley, F. E. Nathanson, and L. W. Brooks, "Study of radar pulse compression for high resolution satellite altimetry," NASA CR-137474, Dec. 1974.

[3] E. L. Hofmeister, "Analysis and measurements of the performance of a signal tracking loop for a satellite radar altimeter when excited by a random process," Ph.D. dissertation, Syracuse Univ., Syracuse, N. Y., 1973.

[4] J. T. McGoogan, "Precision satellite altimetry," 1974 IEEE INTERCON Technical Papers, Mar. 26–29, 1974.

[5] J. T. McGoogan, L. S. Miller, G. S. Brown, and G. S. Hayne, "The S-193 radar altimeter experiment," *Proc. IEEE* (*Special Issue on Modern Radar Technology and Applications*), vol. 62, pp. 793–803, June 1974.

[6] J. T. McGoogan, C. D. Leitao, and W. T. Wells, "Summary of skylab S-193 altimeter altitude results," NASA TMX-69355, Mar. 1975.

[7] E. J. Walsh, "Analysis of experimental NRL radar altimeter data," *Radio Sci.*, vol. 9, pp. 711–722, Aug.–Sept. 1974.

[8] C. C. Goad and C. F. Martin, "Effects of tropospheric and ionspheric refraction errors in the utilization of GEOS-C altimeter data," Planetary Sciences Dep., Rep. 008-74, prepared for NASA Contract NAS6-2173, Oct. 1974.

[9] S. Vincent and J. G. Marsh, "Global detailed gravimetric geoid," NASA Goddard Space Flight Center, Rep. X-592-73-266, Sept. 1973.

[10] C. Bowin, "Catalogue of geoidal variations for simple sea floor topographic features," Tech. Rep., NASA Contract NAS6-2585.

[11] C. L. Parsons, "Cloud physics measurements by satellite altimeter," to be published in *J. Appl. Meteorol.*

[12] C. T. Swift and W. F. Jones, Jr., "Satellite radar scatterometry," 1974 IEEE INTERCON Technical Papers, Mar. 1974.

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.**

Manuscript received April 14, 1975. This work was partially supported by the Naval Sea Systems Command, USAFSAM, and the Army Metrology and Calibration Center.

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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

$$b_i = A_ia_1 + B_ia_2, \qquad i = 3\cdots 6 \tag{3}$$

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

$$|b_i|^2 = |A_i|^2|a_1|^2 + A_iB_i^*a_1a_2^* + A_i^*B_ia_1^*a_2 + |B_i|^2|a_2|^2, \qquad i = 3\cdots 6 \tag{4}$$

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

$$\frac{P_i}{K_i} = |A_i|^2|a_1|^2 + (A_iB_i^* + A_i^*B_i)|a_1a_2|\cos\phi + |B_i|^2|a_2|^2 + j(A_i^*B_i - A_iB_i^*)|a_1a_2|\sin\phi, \qquad i = 3\cdots 6 \tag{6}$$

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

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

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

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

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

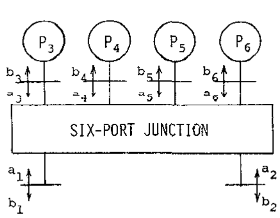

Fig. 1. An arbitrary six-port junction with power meters on four of the six ports.

[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

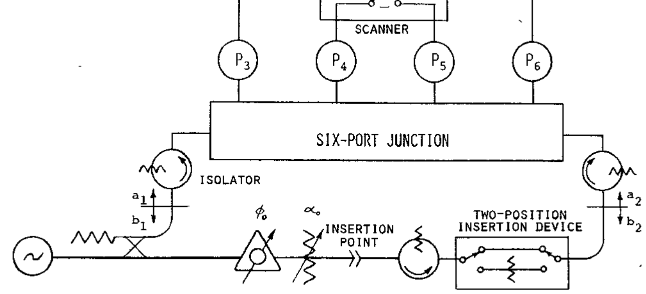

Fig. 2. Setup for calibrating and using a six-port junction to measure complex voltage ratios.

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.

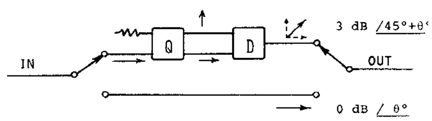

Fig. 3. Using a quadrature hybrid (Q) and a power divider (D) to make an insertion ratio of 3 dB with 45° phase shift.

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

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

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

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

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

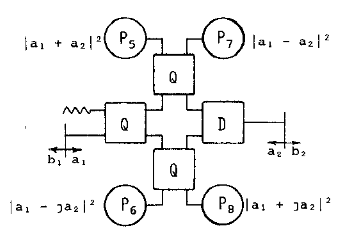

Fig. 4. A correlator constructed from one power divider (D) and three quadrature hybrids (Q). Ideal components would give outputs proportional to the values shown.

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.

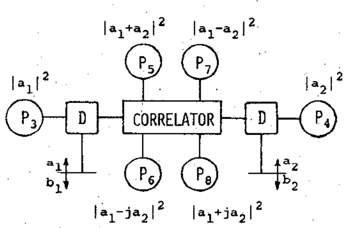

Fig. 5. Adding two power dividers (D) to a correlator to make an eight-port junction having several combinations of four independent outputs.

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.

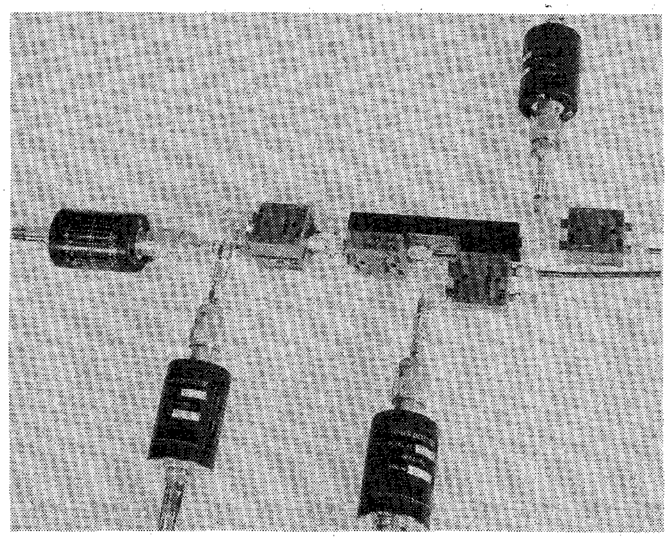

Fig. 6. Experimental six-port junction and power detector mounts.

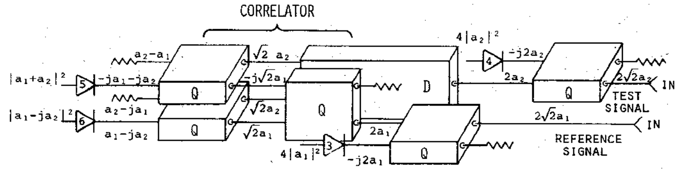

Fig. 7. Identifying the components in Fig. 6, where Q indicates quadrature hybrids, and D indicates an in-phase power divider. The signals labeled at different parts of the circuits are those obtained from ideal components if the two input signals are $2\sqrt{2}a_1$ and $2\sqrt{2}a_2$.

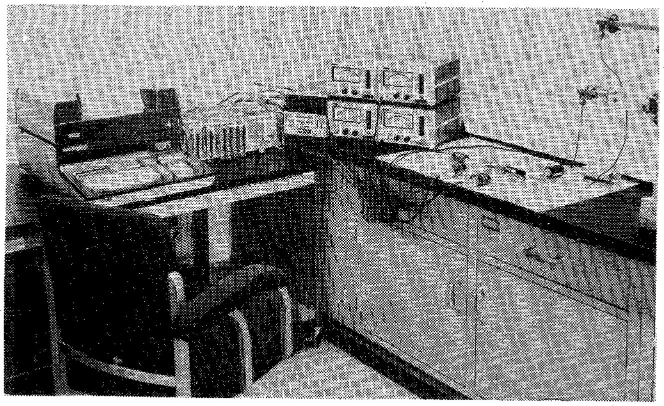

Fig. 8. Experimental six-port X-band vector voltmeter setup. From left to right: programmable calculator, input/output expander, DVM and scanner, four-power meters, six-port junction (on white paper), and two-input signal lines.

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

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

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

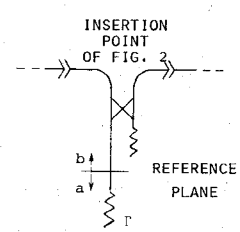

Fig. 9. Adding a directional coupler to the setup in Fig. 2 to make complex reflection coefficient measurements.

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.

ACKNOWLEDGMENT

The authors wish to thank C. M. Allred for assistance in working out the self-calibration techniques. They also wish to thank G. F. Engen for his helpful discussions throughout the project.

REFERENCES

[1] G. F. Engen and C. A. Hoer, "Application of an arbitrary 6-port junction to power-measurement problems," *IEEE Trans. Instrum. Meas.* (*1972 Conferecne on Precision Electromagnetic Measurements*), vol. IM-21, pp. 470–474, Nov. 1972.

[2] C. A. Hoer and G. F. Engen, "Analysis of a six-port junction for measuring v, i, a, b, z, Γ, and phase," presented at the Proc. IMEKO Symp. Acquisition and Processing of Measurement Data for Automation, Dresden, Germany, June 17–23, 1973.

[3] C. M. Allred and C. H. Manney, "Self-calibration of complex ratio measuring systems," presented at the Proc. IMEKO Symp. Acquisition and Processing of Measurement Data for Automation, Dresden, Germany, June 17–23, 1973.

[4] S. B. Cohn and N. P. Weinhouse, "An automatic microwave phase measurement system," *Microwave J.*, vol. 7, pp. 49–56, Feb. 1964.

[5] R. A. Hachborn, "An automatic network analyzer system," *Microwave J.*, vol. 11, pp. 45–62, May 1968.

[6] G. F. Engen, "Calibration technique for automated network analyzers with application to adaptor evaluation," *IEEE Trans. Microwave Theory Tech.* (*Part II of Two Parts*), vol. MTT-22, pp. 1255–1260, Dec. 1974.

[7] ——, "Calibration of an arbitrary six-port junction for measurement of active and passive circuit parameters," *IEEE Trans. Instrum. Meas.* (*Special Issue on 1973 EEMTIC and IM Symposium*). vol. IM-22, pp. 295–299, Dec. 1973.

Automated Calibration of Directional-Coupler–Bolometer-Mount Assemblies

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Abstract—**Although the application of automated methods to power calibration problems in the UHF and microwave region has been described by a number of authors, the primary orientation has been towards the calibration of bolometer mounts and similar items. Little has been published on the problem of calibrating directional-coupler–bolometer-mount assemblies, which also play a major role in the calibration and measurement of UHF and microwave power.**

This paper develops a theoretical basis for several different approaches to this measurement problem.

I. BACKGROUND

MICROWAVE power calibrations tend to center around devices of two basic types. The first is the terminating power meter, a common example of which is the bolometer or thermistor. The second basic device is the feedthrough power meter which often takes the form of a directional coupler with a power meter (frequently of the bolometric type) attached to its sidearm. Although a number of authors [1]–[3] have described the application of automated techniques to the calibration of bolometer mounts, little has been done in the area of automating the calibration of directional-coupler–bolometer-mount assemblies. It is to this problem that this paper addresses itself.

II. INTRODUCTION

As already noted, it is possible to regard the directional-coupler–power-meter assembly as a feedthrough power meter. It is perhaps more instructive, however, to visualize the assembly in the context of Fig. 1, where a feedback loop is employed to maintain the sidearm power at a constant level. Under this mode of operation, the Thevenin equivalent generator, which obtains at the coupler output port, has a source impedance which is usually close to a Z_0 (reflectionless) match and, in any case, depends *only* on the directivity and other properties of the coupler [4]. The voltage associated with the equivalent generator is

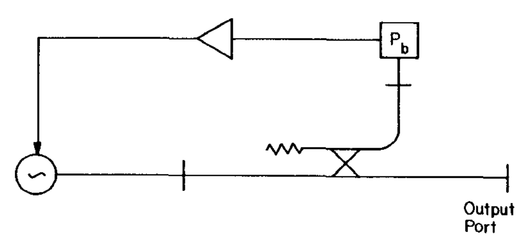

Fig. 1. Basic circuit for discussion of calibration problem.

Manuscript received April 14, 1975; revised July 7, 1975. This work was supported in part by the Department of Defense Calibration Coordination Group, and in part by the U. S. Army Metrology and Calibration Center.

The author is with the U. S. Department of Commerce, National Bureau of Standards, Boulder, Colo. 80302.