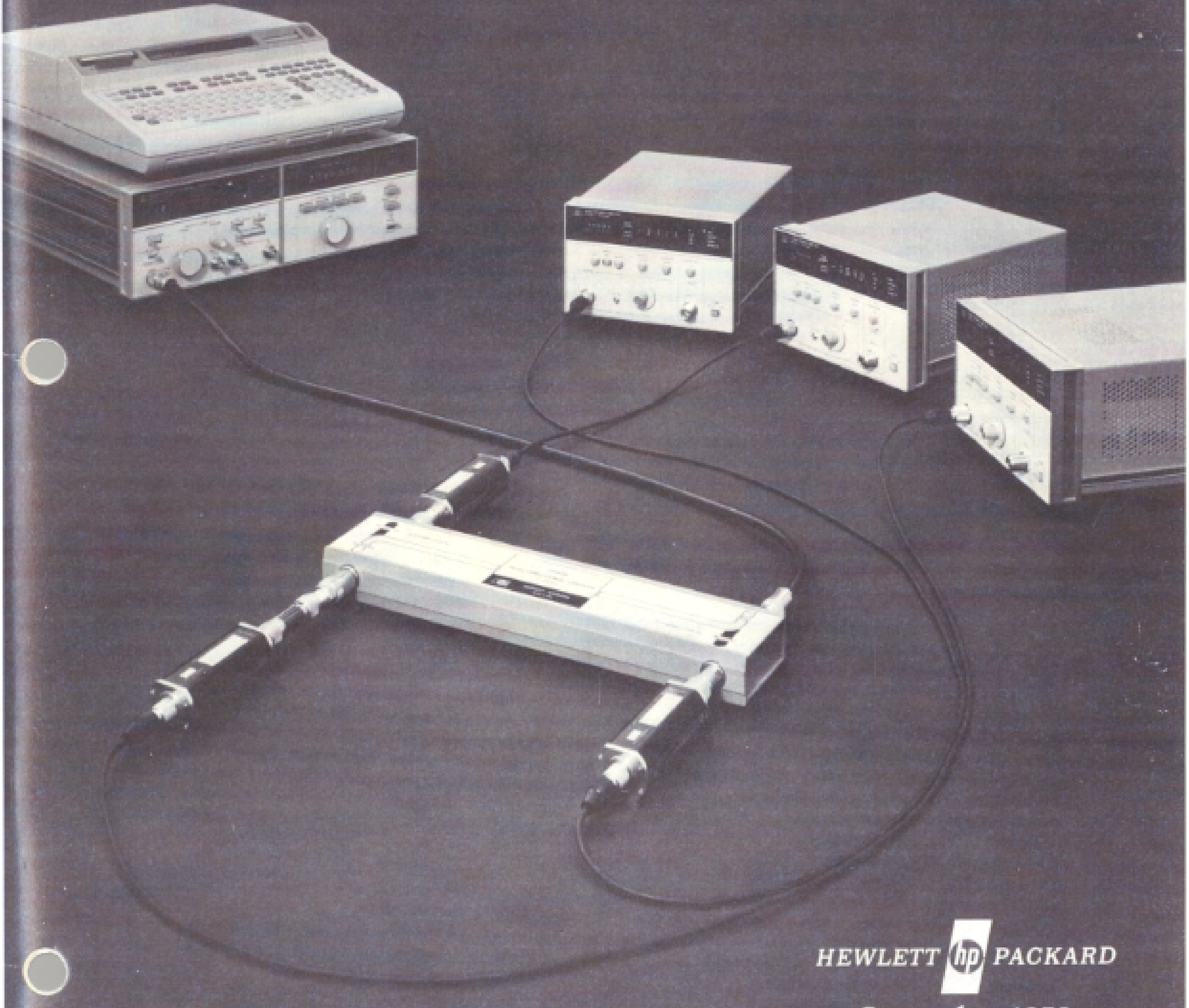
Application Note 64-2

Extended Applications of Automatic Power Meters



HEWLETT PACKARD

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HEWLETT hp PACKARD
1501 Page Mill Road, Palo Alto, California 94304

Contents

Introduction

Power measurements made under automatic control offer new flexibility, speed, and accuracy. Naturally, the straightforward power measurements of sources, transmitters, and amplifiers first come to mind. But other important and difficult measurements, such as power sensor calibration factor and high-accuracy attenuation measurements can also be made.

The purpose of this note is to facilitate and expand the usefulness of automatic power meters – especially the HP 436A Power Meter using the HP Interface Bus (HP-IB)*. The note is divided into three independent sections. There is no reason that Section I needs to be read before Section II or Section II before Section III.

Section I is a comprehensive treatment about programming the 436A Power Meter. This section is not needed by the person who operates the systems but only by the programmer. Example subroutines are given for zero-setting and making accurate measurements in optimum time. The discussion of these subroutines, of triggering power meters, and of some subtle aspects of automatic power meters will help eliminate the practice, that some programmers have, of unnecessarily throwing away several power meter readings before considering one as valid.

Section II describes a ready-to-run system for accurate and broad-range attenuation measurements. No programming is necessary to use the system, but the programs can be easily modified for tailoring the output format or plotting the results. The components of the system are of the general purpose type and likely to be around many measurement facilities. The accuracy of the measurement system results from the low SWR of modern power sensors. Small reflections from the power sensor mean small re-reflections from the device under test—thereby decreasing the uncertainty in attenuation measurements. (Most people are surprised when they realize that the reflections from good power sensors are already so low that, when a coaxial attenuator is used to pad the reflection, the reflection coefficient usually gets larger—not smaller.) To get higher accuracy than this systems gives, skilled personnel would have to adjust reflections to zero, on a frequency by frequency basis—an expensive, time consuming process with poor repeatability.

The broad range of attenuation values that can be measured (0 to at least 65 dB and often 80 dB), results from being able to program generator output power. Here the automatic system is valuable because the procedure for setting the proper generator level is too tedious and involved for repeated, mistake-free manual operation.

Section III of this note discusses the automatic calibration of power sensors. The programs are ready-to-run and use substantially the same equipment as the attenuation measurement system in Section II. With this measurement technique, power sensors can be calibrated without an expensive automatic network analyzer or without the special equipment and skilled personnel at a few of the national calibration laboratories of the world. Sending power sensors to such laboratories is usually expensive and often time consuming, especially if international boundaries must be crossed. Now local calibration can be performed on a routine basis to correct for aging effects or to detect connector wear and other damage. One big advantage of this system is that it is useful for other measurements, such as the attenuation and reflection coefficient measurements described in Section II. A very comprehensive analysis of measurement uncertainty is included in Section III.

The programs and examples shown in this note are not the only way of accomplishing a specific goal. They are the result of some programming experience and may be used to increase the effective experience level of the newcomer to automatic power measurements. The best way of accomplishing a specific measurement is usually a matter of judgment. Factors that often enter into the judgment of a program's effectiveness include execution speed, measurement accuracy, ease of running the program, and the conciseness and simplicity of the program code. The programs and examples used here are believed to satisfy a broad range of measurement objectives.

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* HP-IB is Hewlett-Packard's implementation of IEEE Standard 488-1975. A copy of this standard can be ordered from the IEEE Standard's Office, 345 East 47th Street, New York, N.Y. 10017. Adequate information for programming instruments is usually found in the appropriate instrument and computer manuals that operate on the HP-IB.

I. General Programming Considerations for the HP 436A Power Meter

Before writing extensive programs that use an instrument like the HP 436A Power Meter, the programmer should be familiar with the operation of the instrument as explained in the instrument manual. Then **Figure 1-1** can be used as a convenient reference for remote operation of the 436A. **Figure 1-1**(a) shows the commands used to control the 436A when it is a "listener" * on the bus. The 436A will respond to most other characters in various ways; therefore, care should be exercised in formating messages to the 436A to assure that extra characters are not transmitted. **Figure 1-1**(b) is a guide for interpreting the data string from the 436A when it is the "talker" on the bus. **Figure 1-1**(c) shows the response time of the analog circuits of the 436A.

When the 436A Power Meter is first turned on, it is in manual (local) operation and its mode (watts, dBm, etc.) is determined by the front panel controls. The 436A goes into remote operation by first receiving a "remote" message on the bus and then being addressed as a listener. The factory-set listen address is "M" and the talk address is "–" (the 5 bit decimal code is 13). The procedure for changing the address is in the 436A Operating and Service Manual.

It is impossible to discuss all the measurement situations that may arise or to anticipate the questions a programmer may have about automatic power measurements. Searching for an answer by finding the proper document or by sending the question through a chain of people, is often time consuming, expensive, and frustrating. The answer as to whether or not something works is often best found by experimenting with a short program. This is especially convenient with desktop computers that use an interpretive language like BASIC or HPL.

Several aspects of using the HP 436A Power Meter, especially for automatic power measurements, will now be discussed.

Zero-Setting

When considering automatic power measurements, the question arises "How often should the power meter be zero-set?" The essential rule for when to zero-set is: The power meter should be zero-set whenever the meter indication, for no applied RF power, is suspected of being in error. By gaining experience in several applications, each programmer will interpret this rule in the form of several recommendations that apply to the measurement environments he encounters.

The importance of being accurately zero-set is much more critical when measuring powers on the lower ranges of the power meter. A zero that reads 5 percent up scale on the most sensitive range, for example, causes a 50 percent error for a reading that is 10 percent up scale, a 5 percent error for a full-scale reading, and a 0.5 percent error for a reading that is 10 dB above full scale of the most sensitive range. If operation is only on the upper ranges of a power meter, frequent resetting of the power meter zero is seldom necessary.

The primary cause of zero-set drift is that the power sensing element experiences a temperature change or temperature gradient since the last zero-setting. Likely sources of temperature change include atmospheric changes, thermal conduction down the RF transmission line, and sources of heat near the power sensing element.

A sample set of recommendations about zero-setting from the above discussion is:

(1) After moving the power sensor to a new RF port, significant thermal gradients near the sensor are likely to exist. It is usually necessary to wait at least two minutes before zero-setting and measuring.

(2) In a steady environment and after one hour of operation, zero-setting every ten minutes is usually adequate. During the first hour of operation zero-setting may be necessary every minute or two.

(3) If accurate readings are desired on the most sensitive range of the power meter, zero-setting should be done every two minutes or so.

The answer to the question, "On what range should the power meter be zero-set?" is to zero on the most sensitive range. Some power meter operators, in an attempt to eliminate zero-carryover errors from one range to another, zero-set on the range of measurement. With the HP 436A Power Meter, as well as with the HP 432A and 435A Power Meters, this practice is not recommended. The

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* The specific method of sending various messages such as remote, local, device clear, talk, and listen can be found in the manuals of the computer being used.

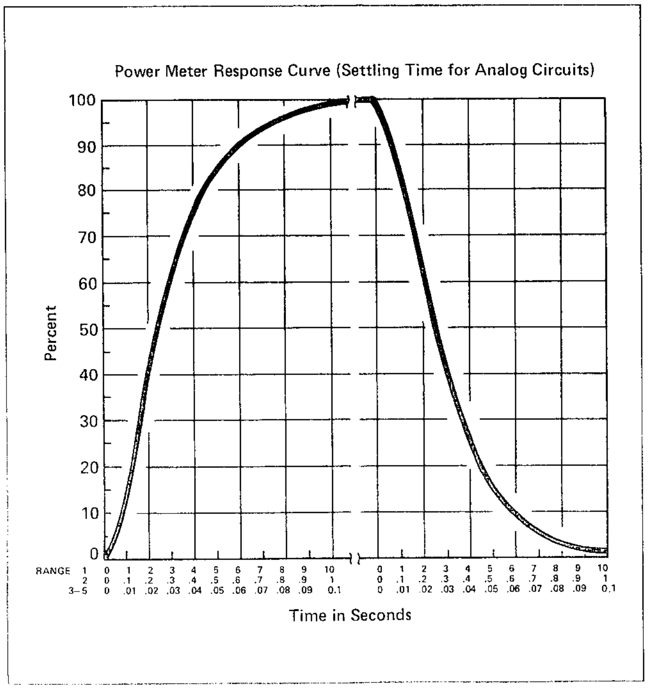
(a)

Input Program Codes		
Function	Program Codes	
	ASCII	Decimal
Range		
Least sensitive	5	53
	4	52
	3	51
	2	50
Most sensitive	1	49
Auto	9	57
MODE		
Watt	A	65
dB (Rel)	B	66
dB [Ref]	C	67
dBm	D	68
Sensor auto-zero	Z	90
CAL FACTOR		
Disable (100%)	+	43
Enable (front-panel switch setting)	—	45
Measurement Rate		
Hold	H	72
Trigger with settling time	T	84
Trigger, immediate	I	73
Free Run at maximum rate	R	82
Free Run with settling time	V	86

(b)

Output Data String			
	Definition	Character	
		ASCII	Decimal
STATUS	Measured value valid	P	80
	Watts Mode under Range	Q	81
	Over Range	R	82
	Under Range dBm or dB [REL] Mode	S	83
	Power Sensor Auto Zero Loop Enabled; Range 1 Under Range (normal for auto zeroing on Range 1)	T	84
	Power Sensor Auto Zero Loop Enabled; Not Range 1, Under Range (normal for auto zeroing on Range 2-5)	U	85
	Power Sensor Auto Zero Loop Enabled Over Range (error condition—RF power applied to Power Sensor; should not be)	V	86
RANGE	Most Sensitive 1	I	73
	2	J	74
	3	K	75
	4	L	76
	Least Sensitive 5	M	77
MODE	Watt	A	65
	dB REL	B	66
	dB REF (switch pressed)	C	67
	dBm	D	68
SIGN	space (+)	SP	32
	— (minus)	—	45
DIGIT	0	0	48
	1	1	49
	2	2	50
	3	3	51
	4	4	52
	5	5	53
	6	6	54
	7	7	55
	8	8	56
	9	9	57

(c)



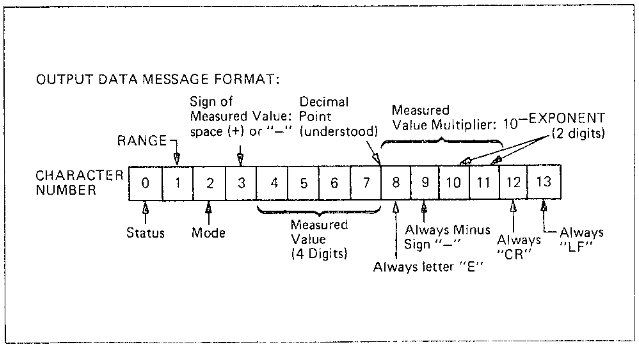


Figure 1-1. Reference data for operation of the 436A Power Meter on HP-IB.

zero-carryover for these power meters is typically much less than the data sheet specification. Furthermore, the auto-zero circuits operate more satisfactorily on the most sensitive range.

Most of the programs that follow contain the several steps of zero-setting a power meter. The proper sequence is: (1) turn the RF power "off", (2) continue to auto-zero until the meter reading is effectively zero, (3) remove the auto-zero function by programming the power meter to the Watts or dBm mode, and (4) before applying RF power, be sure the power meter is no longer in the auto-zero mode. This last step is extremely important. The 436A auto-zero circuits continue to operate for about four seconds after another mode is programmed. If any power enters the sensor during this time, including transients, the remaining power meter readings will be in error.

Noise, Bandwidth, and Settling Time

Although smaller power levels can be measured now than ever before, power measurements at low levels are limited by noise. The HP 8484A Power Sensor, for example, measures as low as —70 dBm over the 10 MHz to 18 GHz frequency range. The thermal noise power available from a transmission line termination at room temperature over that frequency range is about —71 dBm. Thus power measurements at the most sensitive levels are somewhat obscured by noise.

The IEEE Standards Committee has recommended that power meter noise be defined as the peak change of a power meter reading over any one-minute interval. The HP 8484A Power Sensor typically has about 20 pW of peak noise over any one-minute interval. When small signal levels are measured in dBm, the uncertainty in dB varies with level. For 20 pW variations, the variation in dB is shown in the upper part of **Figure 1-2.** The HP 8481A Power Sensor typically has about 40 nW of peak noise over any one-minute interval. For 40 nW variations, the dB uncertainty when making a dBm measurement is shown in the lower part of **Figure 1-2.**

Noise should not be confused with drift. Drift is often due to temperature effects and tends to be in a consistent direction at a somewhat uniform rate. The effects of drift can be removed by zero-setting the power meter.

Noise is a random phenomenon, equally likely to cause a reading to be high or low. It is sometimes said that the noise level can be effectively lowered by averaging a number of readings. The statistical principle is that the standard deviation of a population of readings should decrease as the square root of the number of readings. Unfortunately, the principle does not always apply to power measurements. In several sets of experiments conducted

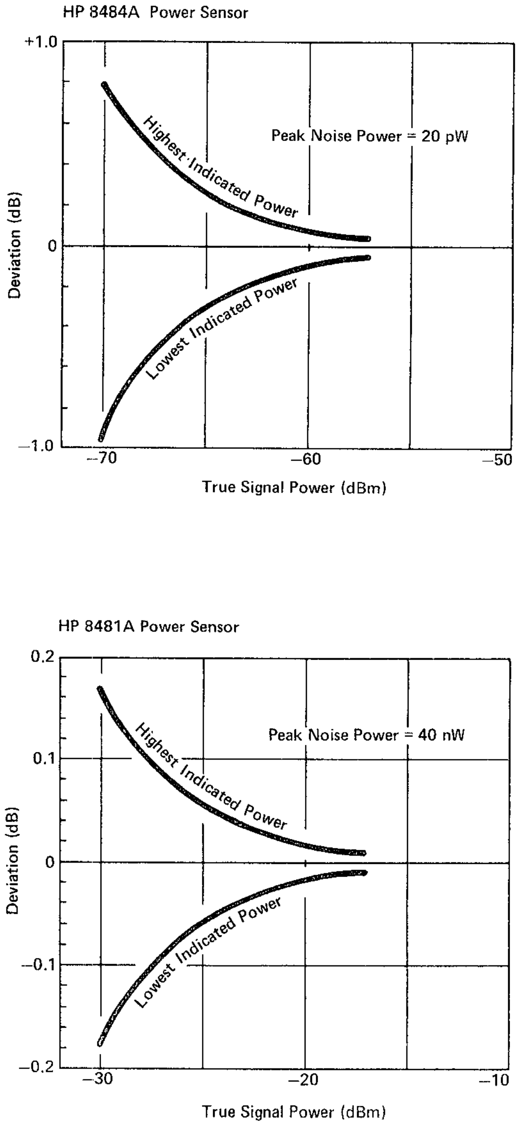


Figure 1-2. Typical excursion of the indicated power output in dBm from the true signal level due to the presence of noise for the HP 8484A Power Sensor (top), and the HP 8481A Power Sensor (bottom).

at Hewlett-Packard, the standard deviation was substantially the same, whether two readings were averaged or whether fifty readings were averaged. The readings were taken one second apart.

One explanation for the lack of noise level improvement by averaging is that a second noise limit has been reached—the flicker noise, or 1/f noise, of the electronic circuits. Flicker noise has the property that the noise voltage increases as the frequency of observation decreases. When more and more power-meter readings are averaged, the total observation time is increased. This means that the low frequency limit of the measurement bandwidth is decreased—resulting in an increase in the effective noise level. The increased noise level with observation time tends to offset the decrease in effective noise level due to averaging. If this is the proper explanation, then power measurements are limited by two different noise phenomena simultaneously: (1) the thermal noise generated by the power sensor, and (2) the flicker noise associated with the circuitry for metering the power sensor output.

The bandwidth of the electronic circuits also affects the noise level. If the observations of the detector output are made over a narrow bandwidth, then less noise is transferred and smaller signal powers can be measured without being obscured by noise. But a narrow bandwidth implies a long response time. The 436A Power Meter has available an internally generated delay that helps to assure that enough time has elapsed for the reading to be stable. On all ranges of the power meter, except the most sensitive range that will be discussed separately, the internal delay time is enough to assure that each power meter reading has settled to within 1 percent of its final value. The programmer should use the internal delay because it leads to simple programs.

On the most sensitive range the 0 to 99 percent response time is about ten seconds but the internal delay time is only about one second. A simple, but sometimes unnecessarily time consuming, method of assuring that each reading is within 1 percent of its final value is to first sense whether the power meter is on the most sensitive range. If it is, wait ten seconds before making a reading.

A second method is to make several power meter readings and not consider them as settled until they are the same. Waiting for two low-level readings to be the same has its own problems. One problem is that because of noise, the probability of two successive readings being identical on the most sensitive range is small—too long a measurement time is needed. This excessive time can be reduced considerably by continuing to take readings until successive readings are within 0.05 dB (±1.2 percent) of each other. An additional problem is that in the dBm mode, the under-range limit of −70 dBm could be sent out for several successive readings, even though the final reading will be considerably up-scale. The testing of two successive power meter readings should accommodate this possibility—it does in the sample programs that follow.

Kinds of Triggers

A feature available via remote programming is selection of standby, triggered, or free-running operation of the 436A Power Meter. The specific capabilities are:

(a) **Hold (H).** When programmed to hold, the power meter is inhibited from taking measurements.

(b) **Trigger immediate (I).** This programming command directs the power meter to make one measurement and output the data in the minimum possible time. It then goes into HOLD until the next trigger command is received.

(c) **Trigger with delay (T).** This programming command is identical to the "I" command except that this command causes the power meter to delay taking the measurement by an internally generated time. The delay time is sufficient to assure that the power meter has settled to within 1 percent of its final reading before outputting data on all but the most sensitive range. Programming for the most sensitive range requires proper wait times or the testing of successive readings.

(d) **Free run at maximum rate (R).** This command is used for asynchronous operation. It directs the power meter to continuously take measurements and output data in the minimum possible time. It does not allow for settling time prior to measurement.

(e) **Free run with delay (V).** This command is like the "R" command except that it causes the power meter to delay taking each measurement by the internally generated time explained above for the "T" command.

A flow chart of the measurement sequences of the 436A Power Meter is shown in **Figure 1-3.** Many programming difficulties can be avoided through an understanding of **Figure 1-3.** The measurement sequence can be thought of as consisting of four parts: (1) Configure, (2) Delay, (3) Analog-to-Digital Conversion, and (4) Data Output.

(1) **Configure.** Unless in a free-run state, the power meter stays in the REMOTE/HOLD loop until a trigger is

received. The power meter then adjusts itself as necessary, to assure that it is configured according to the last received instruction. It then proceeds to the Delay portion of the measurement sequence. If the power meter receives new configuration instructions after passing into the Delay portion of the sequence but before the Output portion of the sequence, the first output of data will be according to the old configuration instructions. This possibility is avoided by using the "T" and "I" trigger just before each measurement.

(2) **Delay.** During the Delay part of the sequence, the power meter initializes circuits to make a new analog-to-digital (A to D) conversion. These preparations take 17 ms (in the WATTS mode) or 33 ms (in the dBm mode) even if no delay is programmed. If delay is programmed, the preparations for A to D conversion are made while the delay clock is running.

(3) **A to D Conversion.** The conversion takes 35 to 53 ms depending on what portion of the measurement range the meter reading falls. In the dB relative mode, an additional 70 ms is needed for measurement.

(4) **Output.** If the power meter is assigned to talk on the bus, it will output its data to the assigned listeners. If no other instruments on the bus are ready to receive data, but the 436A is the assigned talker, the 436A keeps going around the TALK/BUS READY loop at the bottom-right of **Figure 1-3.** The fact that the power meter will keep going around the TALK/BUS READY loop could be a source of difficulty to the unsuspecting user. What sometimes happens is that a program is halted before the data is read. But the power meter keeps waiting for a listener and will not take a new reading. The power meter appears locked-up to the operator. There are several ways of exiting the TALK/BUS READY loop. The first is to make some other instrument the talker on the bus, then the power meter will exit the loop because the answer to "TALK?" is "NO". A second method is to send the "Abort" message or the "Clear" message over the interface bus. A third method is to push the power meter line switch to OFF and then ON again; the power meter always comes ON in the manual mode.

It should be pointed out that the 436A will respond to a command to send its data on the bus even if it is not in remote operation. The TALK decision at the bottom of the flow chart in **Figure 1-3** is always made, even in local operation. This means the 436A can be in the TALK/BUS READY loop even if the REMOTE light on the front panel is extinguished. In this state the front panel appears "locked out." The solution is one of the following: read the data on the bus, assign some other instrument on the bus as the talker, send the "Clear" message, or turn the power meter OFF and then ON again.

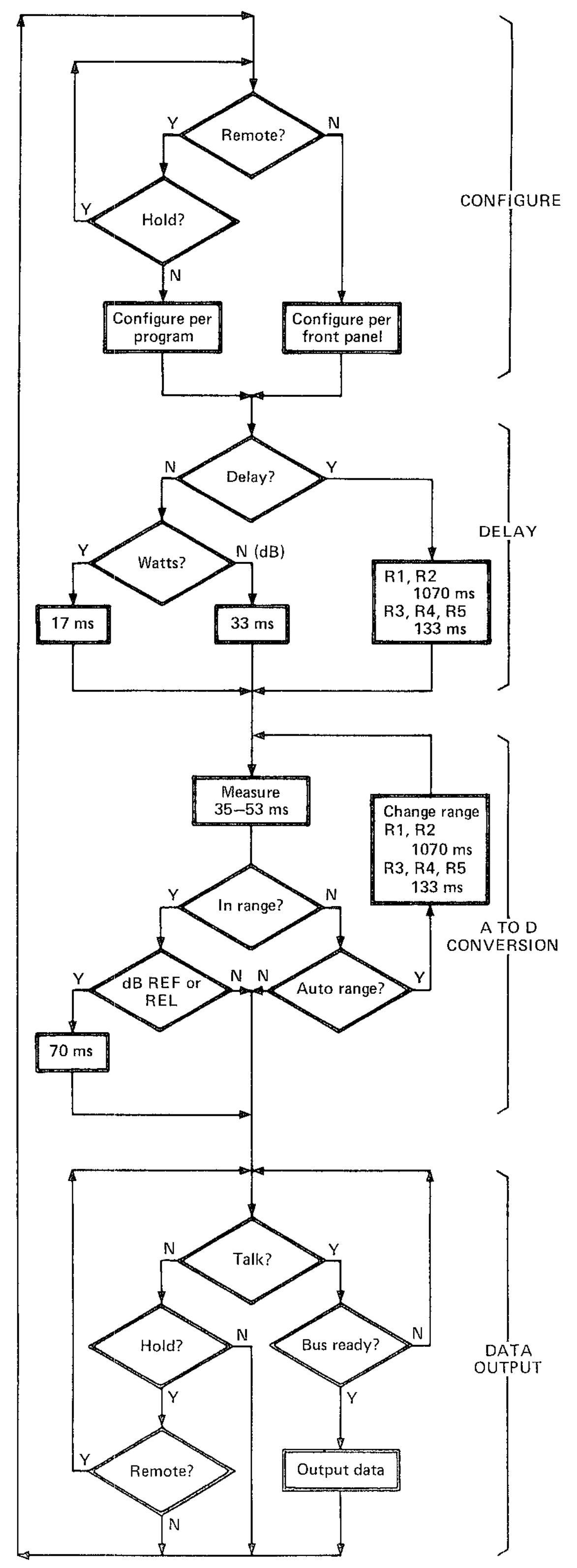
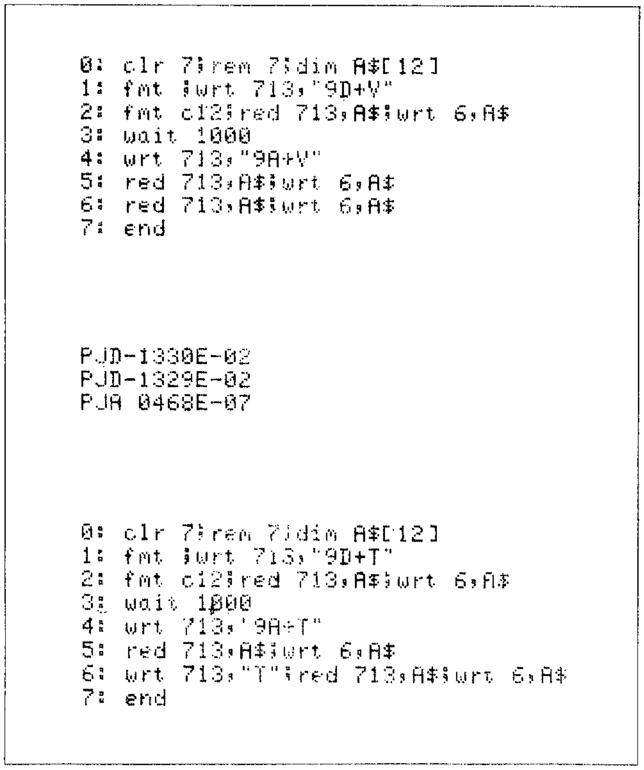


Figure 1-3. 436A operating program and measurement timing flow chart (simplified).

The top of **Figure 1-4** shows an example of difficulty from not understanding the flow chart of **Figure 1-3.** The goal is to make one dBm reading of power, then two readings in watts. The program is written for the HP 9825A Desktop Computer. In LINE 1, the power meter is programmed to read in dBm under free-run trigger with delay. In LINE 2, the power meter is read and the result is printed on the line printer. While the wait of LINE 3 is going on, the 436A proceeds to take the next reading. After the new measurement, the 436A is still the talker but there is no listener, so the 436A remains in the TALK/BUS READY loop at the bottom of **Figure 1-3.** In LINE 4, the calculator takes over as talker. As soon as that happens, even before the entire "9A+V" message is received by the power meter, the power meter begins another measurement sequence. The new "9A+V" message was not totally received, so the new measurement will be in the old "9D+V" mode of operation. By the time the 436A internal delay elapses, the computer is in LINE 5 and the power meter is again the assigned talker. When the data is ready, it is sent to the calculator and then printed. Note that the second set of data is in dBm as indicated by the "D" in the output string. The next reading is finally in absolute watts as desired.



```
0: clr 7;rem 7;dim A$[12]
1: fmt ;wrt 713,"9D+V"
2: fmt c12;red 713,A$;wrt 6,A$
3: wait 1000
4: wrt 713,"9A+V"
5: red 713,A$;wrt 6,A$
6: red 713,A$;wrt 6,A$
7: end
```

```
PJD-1330E-02
PJD-1329E-02
PJA 0468E-07
```

```
0: clr 7;rem 7;dim A$[12]
1: fmt ;wrt 713,"9D+T"
2: fmt ci2;red 713,A$;wrt 6,A$
3: wait 1000
4: wrt 713,'9A+T"
5: red 713,A$;wrt 6,A$
6: wrt 713,"T";red 713,A$;wrt 6,A$
7: end
```

Figure 1-4. (Top) An example of a program and its output that performs differently than the programmer's intention. The second reading was meant to be in watts but it is in dBm. (Bottom) A proper way to make the measurement intended.

An easy method of preventing such undesired readings is to use triggered operations (T or I) as shown in the lower part of **Figure 1-4.** Then the power meter will hold in the REMOTE/HOLD loop at the beginning of the measurement sequence. Now the new mode of operation will be received before the trigger (providing the trigger is the last character transmitted) and the measurement will be made in the desired way. A second method is to read the power meter one extra time, throwing away the first reading after each program change to the power meter.

When operating the 436A with either the T or I mode of triggering, it is very important to precede each attempt to read the power meter with a trigger. Attempting to read the power meter when there is no corresponding trigger, will often tie-up the interface bus so it is difficult for anything else to become the talker on the bus. One solution is to turn the power meter OFF and then ON again.

Power Meter Subroutines

Measurements under computer control are almost always a set of measurements. Each measurement usually consists of a sequence of instructions and responses that are made several times during the program. A process that can be accessed repetitively from several parts of a program is often called a subroutine.

Subroutines for making measurements with the 436A Power Meter and for zero-setting are included here. Other subroutines can be found in the latest instrument manual and within the measurement programs that follow. The subroutines are different because they are individualized according to the application and the preferences of the programmer. One reason for having such a selection is to give potential programmers of power meters a lot of experience in a short time. A detailed study of each subroutine will likely answer some questions that the new programmer of power meters is not likely to think of.

The dBm mode of operation is preferred in the following programs. One advantage is that, for a broad range of powers, it is easy to format print statements with two decimal places and to plot graphs without being complicated by the use of such exponential prefixes as milliwatts, microwatts, and nanowatts. Furthermore, the inevitable ± half-count uncertainty from digitizing is ±0.005 dB or ±0.12 percent of the power while reading in the dBm mode. In absolute watts the percent error from the ± half-count uncertainty depends on the reading. The main penalty for making measurements in dBm is an additional 16 ms measurement time if the internal delay is not used. The use of the dB relative mode for computer based systems is not advised because it is easy, usually faster, and essentially as accurate to calculate the difference between two dBm readings.

Trigger with delay (T) is also preferred in the following subroutines. The advantage of using internal delay is that, except on the most sensitive range, the first reading returned is always proper within at least 1 percent of the final reading due to power meter response time. If internal delay were not used, additional software would be needed to make at least two measurements and then test those measurements to make sure that the power meter reading had stabilized. The increased time it takes to use the internal delay is usually a small percentage of the total test time and is felt to be worth the simplicity of the programs in most cases. The advantage of using triggered as opposed to free-run operation is that in free-run the returned reading can sometimes be an obsolete reading as discussed above. The one possible disadvantage of triggered operation is that the power meter will not begin to change its range until the trigger occurs.

The CAL FACTOR dial of the 436A is disabled in these routines because the frequency range is likely to be so broad that no single setting is appropriate. The correction for CAL FACTOR can be made in software as necessary and interpolated between the frequencies where the calibration factor is known.

Flow Charts

Flow charts for two widely used subroutines are shown in **Figure 1-5.** The zero-setting subroutine assumes that the RF power has already been turned OFF before the subroutine is called. It furthermore assumes that the power will be turned back ON only after the zero-setting subroutine is completed. Besides zero-setting, this routine also places the 436A Power Meter in the dBm mode of operation and disables the CAL FACTOR switch for remote operation.

Several parts of the flow diagram require special comment. There is no advantage in using the internal delay when triggering the 436A during the zeroing operation because each measurement is tested anyway. With the immediate trigger, there is a possibility of saving one second of elapsed time. When in automatic operation with

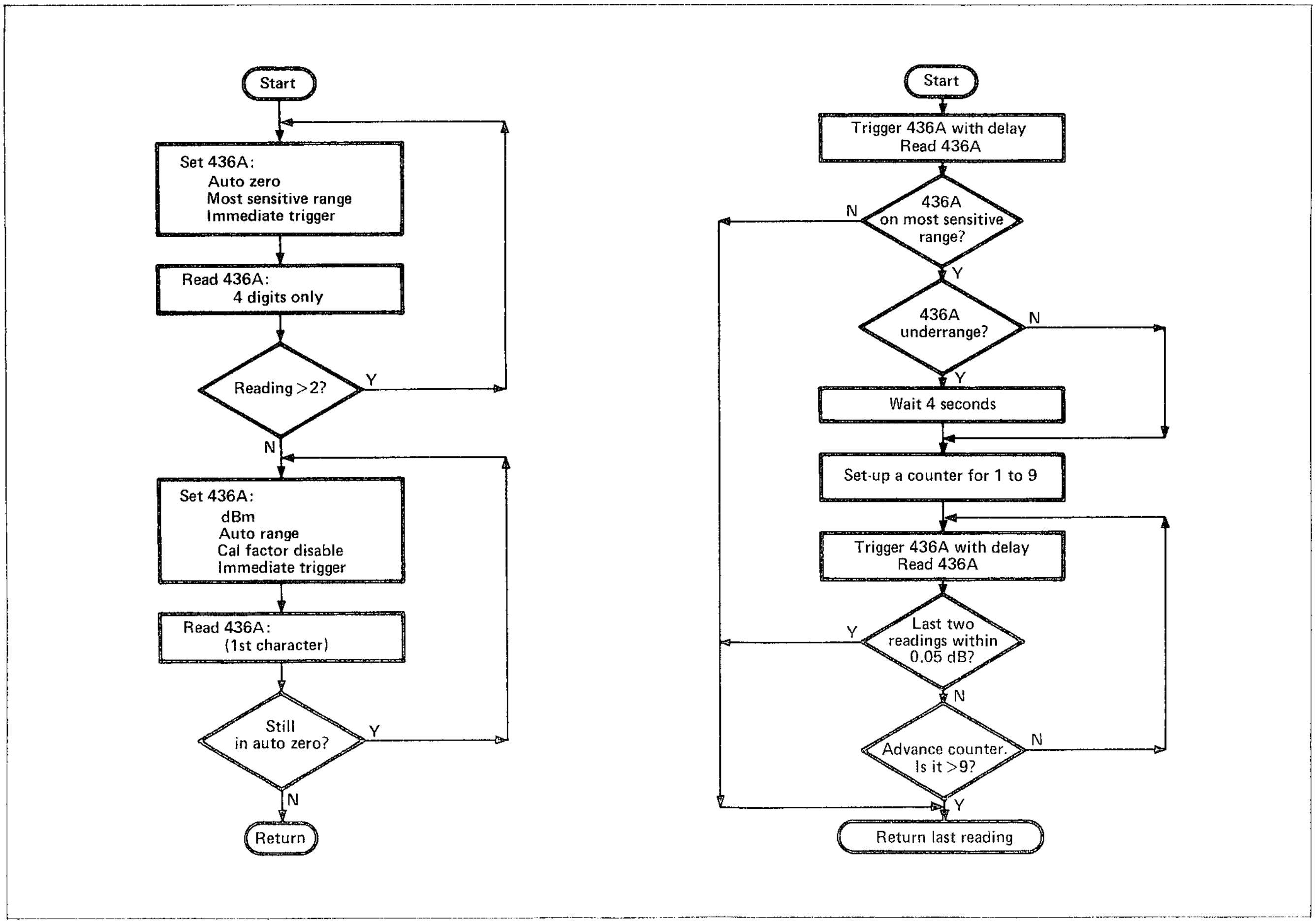


Figure 1-5. Flow chart of subroutines for zero-setting the 436A and for making a measurement.

HP-IB, the only way to remove the power meter from the auto-zero mode is to program it to another mode—in this case to dBm. Even then, the power meter will continue to zero for about another four seconds. If RF power is applied during that four seconds or if transients occur, the 436A will attempt to auto-zero with that power applied and cause an erroneous zero-set. To protect from premature application of power, the power meter is kept in this subroutine until its output string indicates that it is no longer in the auto-zero mode.

The subroutine to trigger and read the power meter is straightforward except when the power meter is reading on the most sensitive range. On that range the subroutine keeps making readings until either (1) two successive readings are within 0.05 dB of each other (1.16 percent), or (2) until ten readings are taken—whichever occurs first. That way, if the signal itself is unstable, the power meter is not kept reading indefinitely. It takes about 10 seconds to make ten readings. The subroutine allows for the fact that the 436A can remain in the under-range condition for several seconds when on the most sensitive range and the final result still not be under range. Such a condition is likely to occur when the power meter has just down-ranged from a higher range.

9830 Basic Subroutines

Subroutine listings for operating the 436A from the HP 9830A/B Desktop Computer are shown in **Figure 1-6.** The flow charts for the listing are those in **Figure 1-5.** The 9830A/B is assumed to be equipped with the Extended I/O ROM.

```
2800 REM
2810 REM       POWER METER ZERO SUBROUTINE
2820 CMD "?U-","Z1I","?M5"
2830 FORMAT 4X,F4.0
2840 FORMAT B
2850 ENTER (13,2830)Z
2860 IF Z>2 THEN 2820
2870 CMD "?U-","9D+I","?M5"
2880 ENTER (13,2840)Z
2890 IF Z >= 84 THEN 2870
2900 RETURN
3000 REM
3010 REM       POWER METER READ SUBROUTINE
3020 CMD "?U-","T","?M5"
3030 FORMAT 3B,E9.0
3040 ENTER (13,3030)X,Y,Z,P
3050 IF Y>73 THEN 3140
3060 IF X#83 THEN 3080
3070 WAIT 4000
3080 FOR W=1.TO 9
3090 V=P
3100 CMD "?U-","T","?M5"
3110 ENTER (13,3030)X,Y,Z,P
3120 IF ABS(P-V)<0.05 THEN 3140
3130 NEXT W
3140 RETURN
```

Figure 1-6. Listing of example BASIC language subroutines for controlling the 436A Power Meter with the HP 9830A/B Desktop Computer.

The zero-set subroutine is accessed from the main program by the statement

140 GOSUB 2800

where 140 is an example line number.

The auto-zero mode is enabled in LINE 2820. While reading the meter (LINE 2850) and testing for closeness to zero (LINE 2860), only the actual four digits of output are evaluated without regard to sign or to exponent. The subroutine continues to loop through LINES 2820 to 2860 until the reading is near zero. Then the dBm mode is programmed (LINE 2870). The auto-zero mode of the 436A continues to remain active until roughly four seconds after the dBm mode is programmed. The power meter indicates its status by the first character of its output string—read by the 9830A/B as variable Z in LINE 2880. After LINE 2880, Z contains the decimal equivalent of the octal number that represents the first character. The decimal value for the ASCII T is 84 (octal value 124 or binary 01010100). If the first character is the ASCII T, U, or V, as evaluated in LINE 2890, then the 436A is still in the auto-zero mode, and the program loops back to LINE 2870 for another reading. When the first returned character is less than the ASCII T, the auto-zero mode is terminated and the subroutine returns to the line after the calling GOSUB statement.

The subroutine for reading the power meter begins in LINE 3000. This subroutine is accessed by the statement

340 GOSUB 3000

where 340 is an example line number. After the subroutine is executed, the variable P will contain the power meter reading. Each command that addresses the 436A as a talker is preceded by a trigger command (LINES 3020 and 3100) to assure the 436A will have something "to say" and not hold on to the interface bus. After LINE 3040, the variables X and Y contain the decimal equivalent of the octal numbers that represent the first two characters from the data string of the 436A. In LINE 3050 the range of the 436A is evaluated. If the variable Y is greater than 73, which is the decimal value for the ASCII I (octal value 111 or binary 01001001), then the power meter is not on its most sensitive range and the power meter reading is within 1 percent of its final value. In LINE 3060, the under-range condition of the 436A is evaluated. If the variable X contains 83, which is the decimal value for the ASCII S (octal value 123 or binary 01010011), then the power meter reading is in an under-range condition and the 9830A/B waits four seconds before taking the next reading. Four seconds is sufficient time for the output of the analog circuits of the 436A to be above the under-range threshold, provided that signal power is above that threshold. The latest two readings from the 436A are compared in LINE 3120. If they are not within 0.05 dB of each other, then the subroutine loops back to LINE 3080 for another reading, up to a maximum of nine additional readings. Nine additional readings allow enough time for the analog circuits of the 436A to be settled. If the readings still are not within 0.05 dB, the signal level must be varying, so the subroutine returns to the calling portion of the program with the latest 436A reading in P.

The programmer should be aware that the zero-setting subroutine will change the values of the X and Z variables. The power meter read subroutine changes the values of the X, Y, Z, and P variables and possibly the W and V variables as well.

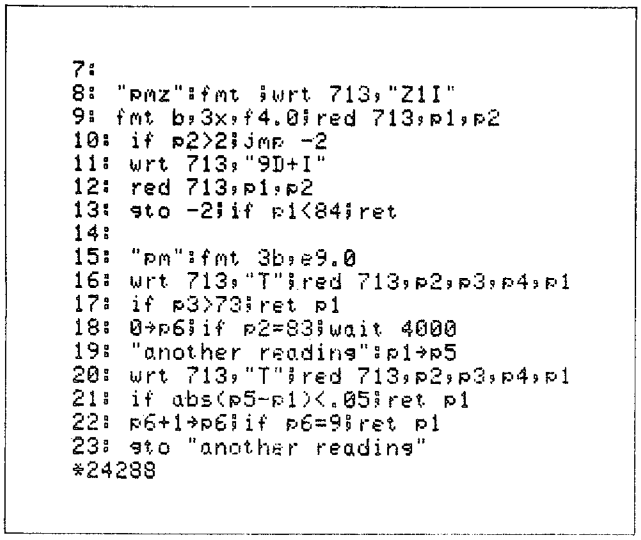
9825A HPL Subroutines

Subroutine listings for operating the HP 436A Power Meter from the 9825A Desktop Computer are shown in **Figure 1-7**. The flow charts for the listings are in **Figure 1-5**. The 9825A is assumed to be equipped with the General I/O ROM and the Advanced Programming ROM.

The zero-setting subroutine is accessed from the main program by a statement like

cll 'pmz'

LINE 8 places the 436A in the auto-zero mode and LINE 9 monitors the 436A output. The first character from the 436A, indicating the mode of operation, is read into p1 but is not used during this portion of the subroutine. The next three 436A output characters are not used at all. The following four characters, forming the mantissa of the 436A reading, are read into variable p2. The auto-zero mode continues until p2 is near zero as evaluated in LINE 10. LINE 11 programs the dBm mode but the auto-zero mode remains in operation for about another four seconds. LINES 11 through 13 form a loop that continues until the 436A is no longer in the auto-zero mode. In that loop, the status of the 436A, as indicated by the first character of the output string in variable p1, is evaluated. The decimal equivalent for the ASCII T is 84 (octal code 124 or binary 01010100). If the first character is the ASCII T, U, or V then the 436A is still in the auto-zero mode and the "gto −2" at the beginning of LINE 13 is executed. If p1 is less than 84, then the 436A is no longer in the auto-zero mode. Then the return in LINE 13 is executed instead of the "gto −2" because "ret" is the last valid "go to" type of statement in LINE 13. This is according to 9825A protocol which states that only the last valid "go to" type of statement on each line is executed.



```
7:
8: "pmz":fmt ;wrt 713,"Z1I"
9: fmt b,3x,f4.0;red 713,p1,p2
10: if p2>2;jmp -2
11: wrt 713,"9D+I"
12: red 713,p1,p2
13: gto -2;if p1<84;ret
14:
15: "pm":fmt 3b,e9.0
16: wrt 713,"T";red 713,p2,p3,p4,p1
17: if p3>73;ret p1
18: 0→p6;if p2=83;wait 4000
19: "another reading":p1→p5
20: wrt 713,"T";red 713,p2,p3,p4,p1
21: if abs(p5-p1)<.05;ret p1
22: p6+1→p6;if p6=9;ret p1
23: gto "another reading"
*24288
```

Figure 1-7. Listing of example HPL language subroutines for controlling the 436A Power Meter with the HP 9825A Desktop Computer.

The subroutine for reading the power meter is actually a function. For the subroutine in **Figure 1-7**, the function is accessed by using 'pm' in an expression. For example, the statement

$$20 + \text{'pm'} \rightarrow P$$

would add 20 dB to whatever the power meter reads when the statement is executed, and places the total in variable P.

The subroutine function for reading the power meter begins in LINE 15. A trigger command precedes each statement that addresses the power meter as a talker (LINES 16 and 20). This assures that the 436A will have a reading to return and not hold on to the interface bus. After LINE 16, the variables p2 and p3 contain the decimal equivalent of the octal numbers that represent the first two characters from the data string of the 436A. LINE 17 evaluates the range of the 436A. If p3 is greater than 73, which is the decimal value for the ASCII I (octal value 111 or binary 01001001), then the power meter is not on its most sensitive range and the power meter reading is within 1 percent of its final value. The power meter reading in p1 is therefore valid and p1 is returned to the program in place of the calling characters 'pm'.

If the reading is on the most sensitive range then the under-range condition, indicated by p2, must be evaluated (LINE 18). If under-ranged, a four-second wait is programmed. If it is still under-ranged after four seconds, the rest of the subroutine will return the under-range reading. LINES 19 to 23 comprise a loop where successive power meter readings are evaluated to see if they are almost the same. The old reading is stored in variable p5 (LINE 19). The new reading, p1 from LINE 20, is compared to p5 in

LINE 21). If p1 and p5 are within 0.05 dB of each other, the latest reading, p1, is returned to the main program in place of the calling characters 'pm'. If they are not within 0.05 dB, then another reading (up to the ninth repeated reading) is made. After the ninth consecutive reading, enough time has elapsed for the 436A analog circuits to have settled to a final value for any steady signal. The signal must therefore be unsteady and the latest reading is returned to the main program in place of the calling characters 'pm'.

HP 1000 Device Subroutines

Although the desktop computer is convenient and popular for constructing measurement systems, general purpose computers are also seeing increased usage—especially in distributed computer centers. This section shows subroutines for the 436A, written for the HP 1000 system. The measurement subroutines for the 436A are written in FORTRAN, and can be included in a library of subroutines used by the RTE operating system. The source listing is shown in **Figure 1-8.** Subroutines for both zero-

```
FTN4,L
           SUBROUTINE PZSET(MLU), POWER METER ZERO
C          THIS IS A SUBROUTINE TO ZERO AND SET UP AN HP436A POWER METER.
C          THE ROUTINE SETS THE POWER METER TO AUTOZERO WITH IMMEDIATE
C          TRIGGER.  THEN, IT READS AND LOOPS UNTIL THE METER IS ZEROED.
C          ONCE ZEROED, THIS ROUTINE TAKES THE POWER METER OUT OF THE AUTO-
C          ZERO MODE BY PROGRAMMING THE DBM MODE AND TESTING THE 436A OUTPUT
C          UNTIL THE AUTO-ZERO MODE HAS TERMINATED.
           INTEGER MLU,A
C          SET METER TO ZERO
401        WRITE(MLU,101)
101        FORMAT("Z1I")
           READ(MLU,102) A
102        FORMAT(4X,I4)
C          CHECK TO SEE IF READING IS CLOSE TO ZERO. IF NOT, TRY AGAIN.
           IF (A.GT.2) GO TO 401
C          SET UP METER TO MAKE READINGS
402        WRITE(MLU,103)
103        FORMAT("D9+I")
C          NOW, CHECK TO SEE THAT METER IS READY
           READ(MLU,104) A
104        FORMAT(1A2)
C          IF NOT, TRY AGAIN
           IF (A.GT.2HSM) GO TO 402
           RETURN
           END
C
C
           SUBROUTINE PMR(MLU,P), POWER METER READ
C
C          THIS IS A DEVICE SUBROUTINE TO TAKE A READING FROM THE HP436A POWER
C          METER.  IF NECESSARY, THE SUBROUTINE CONTINUES TO TAKE READINGS
C          UNTIL THE READING IS STABLE OR UNTIL 10 READINGS HAVE BEEN TAKEN.
C          THE LAST READING TAKEN IS THE VALUE RETURNED.
           INTEGER MLU,A,B,C
C          TRIGGER THE 436 TO TAKE A READING
           WRITE(MLU,101)
101        FORMAT("T")
C          TAKE A READING
           READ(MLU,102) A,B,C,P
102        FORMAT(3A1,E9.0)
C          IF THE SECOND CHARACTER IS NOT AN "I" THE READING IS GOOD--RETURN
           IF(B.NE.1HI) GO TO 999
C          IF THE FIRST CHARACTER IS "S" THEN THE 436 IS IN AN UNDER-RANGE
C          CONDITION-- LET 4 SECONDS ELAPSE AND TRY AGAIN
           IF(A.NE.1HS) GO TO 401
           CALL EXEC(12,0,1,0,-400)
401        DO 888 I=1,9
           WRITE(MLU,101)
           E=P
           READ(MLU,102) A,B,C,P
           IF(ABS(P-E).LT..05) GO TO 999
888        CONTINUE
999        RETURN
           END
END$
```

Figure 1-8. Example Fortran subroutine source listing for controlling the 436A Power Meter with the HP 1000 system.

setting and measuring are in the same source file. Refer to **Figure 1-5** for the program flowcharts.

The device subroutines can also be loaded for use in the RTE BASIC interpreter. BASIC accesses these subroutines through linkages in Branch and Mnemonic Tables. Construction of these tables is explained in detail in the BASIC manual. A brief description of the table entries for the 436A device subroutines appears at the end of this section.

The zero-setting subroutine is accessed from a BASIC program by a subroutine call statement like

```
10 CALL PZSET (30)
```

The parameter 30 is an example logical unit number that was assigned to reference the I/O slot and HP-IB address of the power meter.

The PZSET subroutine (**Figure 1-8**) places the power meter in the auto-zero mode by the write statement in LINE 11. The four digits forming the mantissa of the power meter reading are then read into variable A in LINE 13. If the mantissa is greater than 2 (LINE 16), the program loops back to the auto-zero/trigger instruction for another reading. If the mantissa is close to zero (less than 2), LINE 18 programs the 436A to the dBm mode. The auto-zero mode, however, will remain in operation for approximately four seconds. LINES 18 to 24 form a loop that repeats until the 436A is actually out of the auto-zero mode. The mode of the 436A is indicated by the first character in its output message. The first two characters from the 436A data message are read in LINE 21 because the HP 1000 has a 16-bit data word and it is more memory efficient to read two 8-bit characters into each word. The characters are tested in LINE 24. If the first character is greater than S (i.e. T, U, or V), the power meter is still in the auto-zero mode and the program loops back to LINE 18 to trigger and reread the 436A. When the first character is equal to or less than the ASCII S, then the auto-zero mode has terminated and the subroutine returns to the calling program. The second character cannot be greater than the ASCII M since the allowable second characters for the 436A are only I through M.

The subroutine for reading the 436A Power Meter, which begins in LINE 29, is accessed from a program by a subroutine call statement like:

```
130 CALL PMR (30,P)
```

Once again, the 30 refers to the logical unit number for the power meter. After the above subroutine is executed, the result of the power meter measurement is contained in P.

Just prior to each reading of the 436A (LINES 40 and 51), the power meter is triggered (LINES 37 and 49). After the reading in LINE 40, variables A and B contain the first two characters from the 436A data string. If the second character is not equal to the ASCII I (LINE 43), the power meter is not on the most sensitive range. The power meter reading is within 1 percent of its final value and the subroutine returns back to the calling program with the power meter reading (in dBm) stored in P.

If the second character is I (meaning the 436A is on the most sensitive range), the first character is evaluated (LINE 46) to see if the power meter is in an under-range condition. If the first character is equal to S (meaning under range), the subroutine suspends operation for four seconds by the call to EXEC in LINE 47. Another reading is taken (LINE 51) and it is examined to see if it is within 0.05 dB of the first reading (LINE 52). If so, the 436A has apparently stabilized and the subroutine returns back to the calling program. If the reading has not stabilized, the program loops back to LINE 48 for another reading. This process can repeat up to nine times. Nine additional readings allow enough time for the 436A analog circuits to be settled. If the readings still are not within 0.05 dB, the signal level must be varying so the last power meter reading is returned to the calling program.

Before a subroutine can be called from an HP 1000 BASIC program, a linkage must be declared to the Branch and Mnemonic Tables. The RTE Table Generator will create these tables and produce overlays for the subroutines to reside in. The proper entries for the power meter subroutines are:

```
PZET(I), OV=7, ENT=PZSET, FIL=%PM436
PMR(I,RV), OV=7, ENT=PMR, FIL=%PM436
```

The subroutines will reside in, for this example, overlay number 7. %PM436 is the file where the relocatable version of the subroutines is stored.

The major purpose of this chapter was to acquaint the reader with the automatic operation of the 436A Power Meter on the Hewlett-Packard Interface Bus. Some programs will now be presented that accomplish tasks with power meters that would be quite difficult without HP-IB, and a computing controller.

II. Automatic, High-Accuracy Attenuation Measurement

Power meters are designed to accurately measure absolute power over a broad range of levels. Attenuation measurements require the accurate measurement of the ratio of power over a broad range of levels. Modern power meters have such a broad dynamic range and power sensors have such low SWR, that they can be used to make attenuation measurements more accurately than most other popular techniques to more than 65 dB.

This section describes an attenuation measurement system for attenuations of 0 to at least 65 dB over the 2 to 18 GHz frequency range. The instrumentation uncertainty of the system is under ±0.08 dB. Because the power sensors have such a low SWR, the mismatch uncertainty is also low, yielding, for example, ±0.3 dB worst-case uncertainty when measuring an HP 8491B Attenuator at 3 GHz. For attenuations smaller than about 55 dB, measurement time is usually less than one second per frequency. The instruments and components in the measurement system are also used in the power sensor calibration system of the next section. With the addition of a single 8484A Power Sensor, the system will also measure the reflection coefficient magnitude at the input port of the attenuator under test.

Some devices, like filters, have low attenuation at some frequencies and large attenuation at other frequencies. If accurate large values of attenuation are to be measured on components that have low attenuations at other frequencies, then the system signal source must be free of spurious frequencies. Some extra equipment, that will be discussed later, will assure that spurious signals do not occur at the low attenuation frequencies while measuring at high attenuation frequencies.

This system takes particular advantage of being able to program the signal level from a microwave signal generator. The effective dynamic range of the power sensor is expanded by raising and lowering the signal-generator level. The range of attenuations that can be accurately measured by the system is the difference between (1) the maximum power in dBm that the generator can deliver to a Z_0 load and (2) the minimum power in dBm that can be accurately measured by the power sensor. If the generator can put out +13 dBm and the power sensor can accurately sense −68 dBm, then 81 dB of attenuation can be measured.

The system operates under the automatic control of a desktop computer. Although the measurements could be performed manually, the decision making process for setting the signal-generator level is involved and tedious; human execution is prone to errors.

Equipment Suggested

The hardware suggested for the power sensor calibration system of the next chapter can be used for this attenuation measurement system. An HP 8484A needs to be added only if it is desired to measure the reflection coefficient of the attenuator under test. If a system is to be built only for measuring attenuation, the following equipment is suggested:

Desktop Computer (with 16k Byte Memory)	HP 9825A Opt. 001
HP-IB Interface with 4 m Cable	HP 98034A
String-Advanced Programming ROM	HP 98210A
General I/O, Ext. I/O ROM	HP 98213A
Synthesized Signal Generator	HP 8672A
Power Meter with HP-IB (2 each)	HP 436A Opt. 022
Dual-Directional Coupler	HP 11692D
10 dB Attenuator (Type N connectors)	HP 8491B Opt. 010
Power Sensors (2 each)	HP 8484A
Type N Cable (61 cm)	HP 11500B
HP-IB Cable (1 m, 2 each)	HP 10631A

The following additional equipment is needed if the reflection coefficient is also to be measured:

Power Meter with HP-IB (bringing the total to 3 Power Meters)	HP 436A Opt. 022
Power Sensor (bringing the total to 3 Power Sensors)	HP 8484A
Type N Short	HP 11512A
HP-IB Cable (1 m, bringing the total to 3 cables)	HP 10631A

A data cartridge that contains the measurement program is also needed. The data cartridge of the 436A-E10 system, that is discussed in the next chapter of this note, contains the attenuation measurement program. If that cartridge is not available, the listing at the end of this section may be entered in the 9825A Desktop Computer and recorded on a spare cartridge.

For measuring components like filters that have large values of attenuation (greater than 30 dB) at some frequencies, but have low loss at other frequencies, some additional equipment is needed. The problem is that signals at harmonic and subharmonic frequencies of the test frequency may be present that are only about 30 dB below the desired output. Consider a component, for example, that actually has 50 dB of loss at the test frequency but only 1 dB of loss at half that frequency where the generator subharmonic output is only 30 dB down. Then only 31 dB of attenuation would be measured at the test frequency.

Harmonics and subharmonics of the 8672A can be reduced by >70 dB to at least 95 dB below the desired output using the HP 8445B Option 004, 005 Tracking Preselector. The 8445B is a YIG-tuned filter whose passband can be externally tuned with a 2 to 18 V dc level. Because the 8445B has a narrow pass band, its tracking of the signal frequency is critical. For automatic operation, a system such as that shown in **Figure 2-1** can be constructed. In this system, proper tracking is accomplished using the following procedure:

(1) Program the input voltage to the 8445B to 2 V and the 8672A to +3 dBm internal leveling and 2 GHz. Adjust the 8445B FREQ OFFSET to maximize the signal through the system.

(2) Program the input voltage to 18 V and the 8672A to 18 GHz. Adjust the 8445B TRACKING for maximum signal through the system.

(3) Repeat steps 1 and 2 until no improvement can be made.

(4) Periodic readjustment may be necessary for minimum insertion loss.

Because of hysteresis, whenever a new, lower frequency is selected, the voltage to the 8445B should first be programmed to 2 volts and then to the new level.

The 8445B limits the output level for input signals >+5 dBm. This limits the maximum output level even though the 8672A typically has much higher available power. Although the 8445B limits the dynamic range of the system, attenuations of at least 60 dB can still be measured. For frequency ranges less than an octave, a bandpass filter may be more desirable because of lower insertion loss.

System Description

A block diagram of the system for measuring attenuation is shown in **Figure 2-2.** The suggested source of microwave energy is the HP 8672A Synthesized Signal Generator. This general purpose synthesizer is used because of its broad frequency range and the ease of power level programming. A sweep oscillator with an external programmable attenuator can be substituted with suitable changes to the measurement program.

The microwave source drives the input port of the dual-directional coupler. One HP 436A Power Meter and its HP 8484A Power Sensor is connected to the incident port of the coupler. This 436A is called the *incident power meter* because it monitors the incident power. Another 436A and 8484A is connected to the test port of the coupler during calibration and to the output of the device under test during attenuation measurement. This power meter is called the *test power meter.* If reflection coefficient is to be measured, another 436A and 8484A, called the *reflected power meter,* is connected to the reflected port of the coupler.

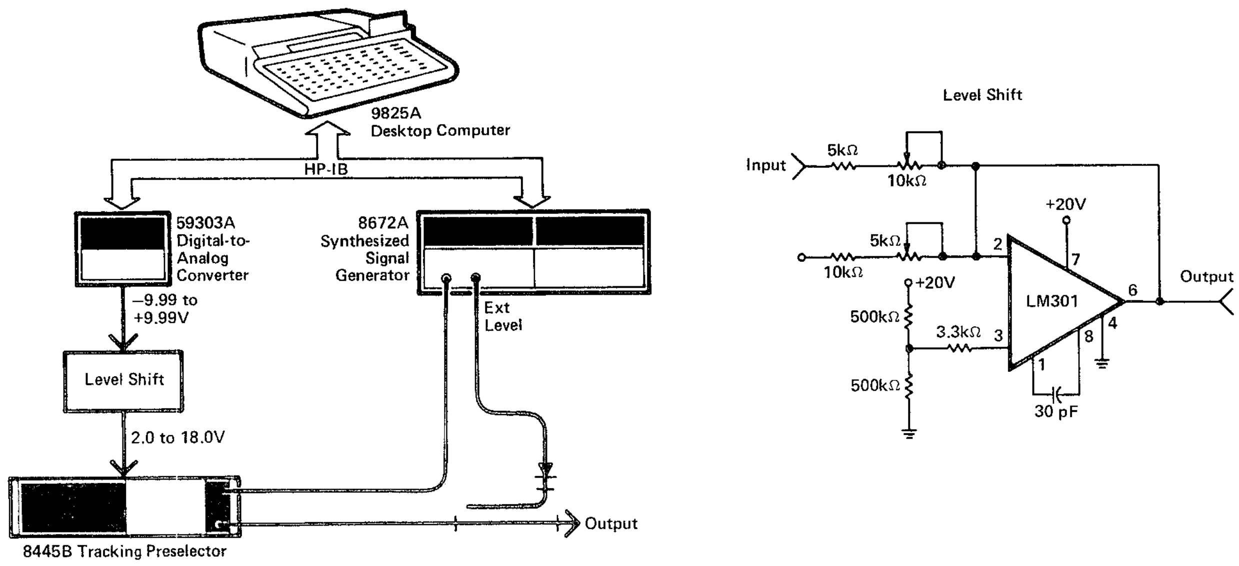


Figure 2-1. Equipment needed for reducing harmonics and subharmonics of the HP 8672A to at least 95 dB below the signal level.

For maximum dynamic range, the 8484A Power Sensor of the *incident power meter* is preceded by a 10 dB attenuator. The maximum power that can be sensed by the 8484A is −20 dBm. With a coupling factor of 22 dB and the 10 dB attenuator, powers on the mainline up to about +12 dBm can then be monitored. Without that attenuator, the mainline power would be limited to about +2 dBm. Larger values of attenuation in the auxiliary arm would permit larger generator levels, where available, and therefore a larger attenuation measurement range.

An HP 9825A Desktop Computer controls the system by means of the Hewlett-Packard Interface Bus (HP-IB). The computer commands the signal generator, operates and reads the power meters, processes the data and outputs the results. To perform these functions, the 9825A should have the ROM's shown in the equipment list.

In order for the computer to separately command the system instruments and receive data, each item operating on the bus must have a different HP-IB address. The addresses of the equipment to operate the program are shown in **Figure 2-3.** Special care is needed for the power meter(s), where the addresses of the *reflected power meter* and *test power meter* need to be changed. The 436A Operating and Service Manual describes how to change the address on the A6 Assembly (one of the printed-circuit boards inside the power meter). If the address is set by the use of jumper wires, do not be confused by the least significant bit being on the left. The proper position of the power meter jumper wires is pictured in the bottom of **Figure 2-3.** If the address is set by the use of a switch on the printed-circuit board, then the least significant bit is on the right so that the binary address reads from left to right.

Instrument	Decimal Address Code	Octal Address Code	Binary Address Code	ASCII Talk Address	ASCII Listen Address
9825A Desktop Computer	21	25	10101	U	5
8672A Synthesized Signal Generator	19	23	10011	S	3
436A Incident Power Meter	13	15	01101	M	—
436A Reflected Power Meter (Optional)	12	14	01100	L	,
436A Test Power Meter	29	35	11101	]	=

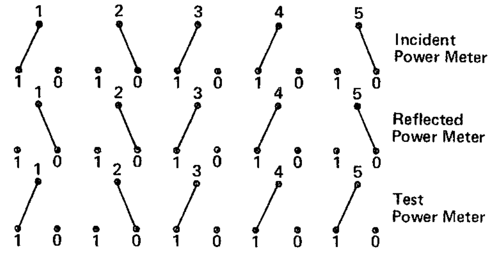


Figure 2-3. Table of HP-IB addresses for the attenuation measurement system. The bottom portion sketches the jumper wiring necessary for some 436A Power Meters.

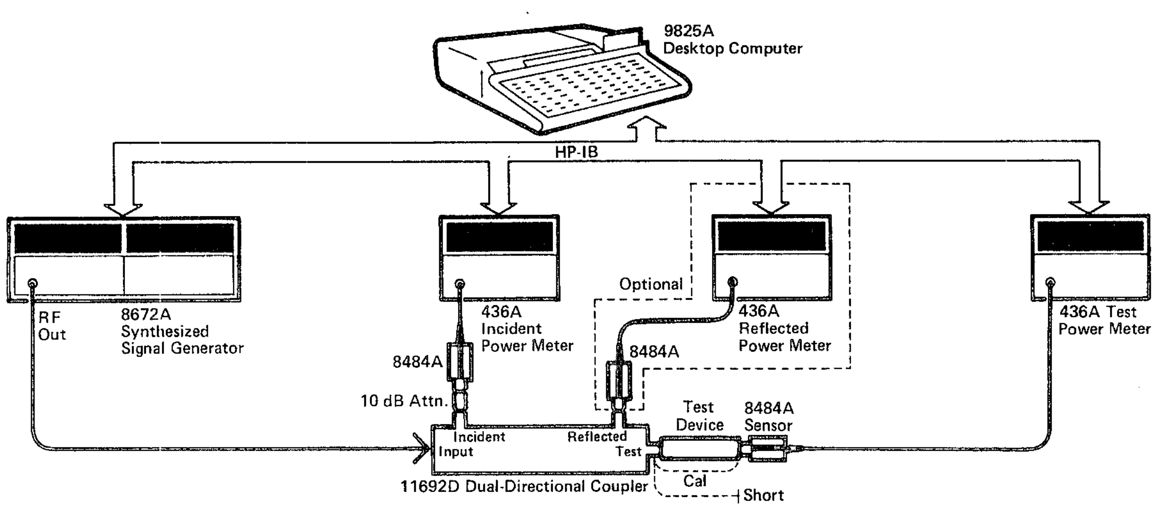


Figure 2-2. Block diagram of attenuation measurement system.

Figure 2-4 shows the nominal programmed signal levels at several points in the system as a function of the attenuation being measured. For simplicity, it is assumed there are no parasitic losses and that levels change continuously. The program only changes the signal level when there is good reason for doing so—namely so that each power meter is making measurements as fast as it can. This way, time is not wasted changing the generator level and waiting for the power meter readings to stabilize. The power meters read at the fastest rate for levels in the range of −49 to −20 dBm.

According to **Figure 2-4**, for attenuations less than 32 dB, the generator level and the *incident power meter* reading change with attenuation but the *test power meter* reading remains constant. For attenuation greater than about 32 dB, the generator level and *incident power meter* reading remain constant, but the *test power meter* reading changes with attenuation.

When measuring reflection coefficient, the signal generator is programmed to +1 dBm. The *reflected power meter* is then close to its highest measurement level for reflection coefficients of one. For attenuations less than 20 dB, the test power meter is over-ranged but it is not monitored during that time and it is still well below its maximum allowed level of 200 mW (+23 dBm).

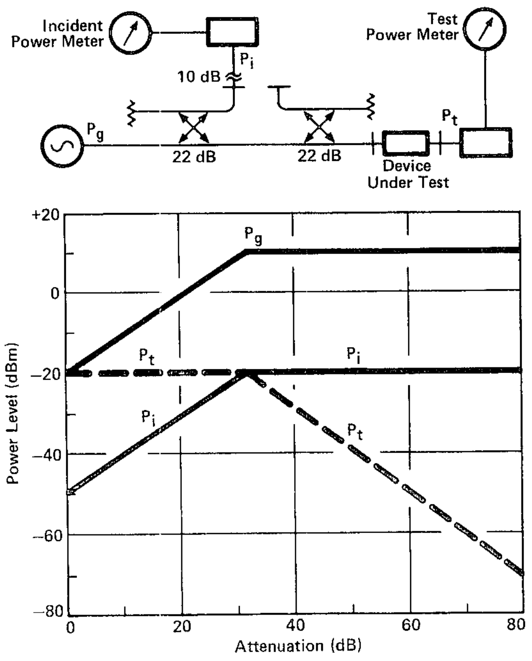


Figure 2-4. The adjusted power levels at various points of the system for different values of attenuation being measured.

Accuracy

The overall attenuation measurement accuracy is mainly determined by three sources of uncertainty: (1) instrumentation uncertainty caused by the power meters; (2) noise associated with low-level signals when measuring large attenuations; and (3) mismatch uncertainty caused by re-reflections among the measurement components and the device under test. These three sources of uncertainty will soon be discussed separately.

There are two popular methods of combining the various uncertainties to yield an overall measurement accuracy—the worst-case method and the root-sum-of-the-squares method.

The worst-case uncertainty for any measurement system is calculated by considering each error to be at its extreme value and in such a direction as to accumulate directly with all the other errors. The result is a very conservative estimate of measurement accuracy. If, by comparison to some much more accurate measurement technique, it is demonstrated that system accuracy is close to its calculated worst-case uncertainty, the system engineer should be advised to look for faulty equipment or for some other large source of error that was overlooked. Perhaps that is why worst-case uncertainty is so popular—it is so conservative that it might cover up faulty equipment and other undiscovered sources of error.

A more realistic method of combining uncertainties that is gaining in popularity, is the root-sum-of-the-squares (RSS) method. The RSS uncertainty is based on the fact that most of the errors in power measurements, although systematic and not random, are independent of each other. Since they are independent, they are random with respect to each other and combine like random variables. The RSS method of combining random variables is justified by statistical considerations that are beyond the scope of this Application Note. The calculation is made by squaring the individual uncertainties, summing them, and then taking the square root. The total RSS uncertainty is usually less than half the total worst-case uncertainty.

Power Meter Uncertainty

The power meter uncertainty for this system is especially low because the power meters and power sensors make relative measurements. This means that the desired measurement is the ratio of two readings from the same power meter and such things as the calibration factor uncertainty and power reference oscillator uncertainty, affect the numerator and denominator in the same way. The effect cancels out, resulting in no uncertainty from those causes.

Another source of power meter uncertainty is the zero-set and zero-carryover accuracy. The accuracy of the zero-setting, if the proper procedure is used, is primarily noise and will soon be considered separately. Zero-carryover, although loosely specified on the data sheet, is not detectable on the 436A Power Meter. Its effect is smaller than the noise soon to be discussed and smaller than the ± half-count accuracy of the analog-to-digital converter. Zero-carryover is therefore not considered here.

The instrumentation uncertainty accounts for the linearity of the power meter and the range-to-range accuracy. Linearity includes the ± half-count resolution characteristic of the analog-to-digital converter in each power meter. The 436A accuracy for relative measurements is ±0.02 dB for within range measurements and another ±0.02 dB for different ranges. This uncertainty needs to be included for two power meters, the *incident power meter* and the *test power meter*. Thus, there are four sources of instrumentation uncertainty, each equal to ±0.02 dB. The worst-case instrumentation uncertainty is therefore ±0.08 dB and the RSS uncertainty is ±0.04 dB.

There is still one more source of error—the response time of the analog circuits in the power meters. The program is constructed to always allow enough time for the circuits to reach 99 percent of their final value before considering a power meter reading valid. It is therefore possible for a power meter reading to be 1 percent away from its final value. Since each attenuation measurement consists of four power meter readings, two at calibration and two at measurement, the worst-case uncertainty is ±4 percent (±0.18 dB). If the RSS calculation method is applied to response time uncertainties, the answer is ±2 percent (±0.09 dB).

There are several reasons for the actual uncertainty to be smaller than the worst-case value of ±0.18 dB. The maximum 1 percent error applies only when two successive power meter readings are at the extremes of a range—for example, when one reading is at the minimum of a range and the next at a maximum. For this to happen to all four power meter readings is very unlikely. Furthermore, the *test power meter* and *incident power meter* will tend to be off in the same direction because the signal level to both is likely to have increased or decreased together since the previous reading. But the ratio of the two meter indications is calculated, so the numerator and denominator will tend to be in error in the same direction. The effects tend to cancel. Still another reason for the uncertainty to be small, is that the analog circuits usually have more time to stabilize than the built-in delay time. Therefore, ±0.09 dB is felt to be plenty of allowance for uncertainty due to response time.

Noise

The measurement of large attenuations is also limited by the noise level of the *test power meter*. The typical *test power meter* indication only fluctuates by 20 pW peak over a one-minute interval. But this fluctuation is significant when measuring small signal levels at the output of the device under test.

Figure 2-5 graphs the uncertainty caused by a 20 pW variation in the indicated power as a function of the attenuation being measured. Various curves are shown in **Figure 2-5,** each for a different maximum attenuation measurement capability of the system. The maximum attenuation measurement capability, at each frequency, can easily be found by measuring an open circuit as the device under test, that is, to have the *test power meter* disconnected from the coupler. For attenuations under 50 dB, noise is insignificant.

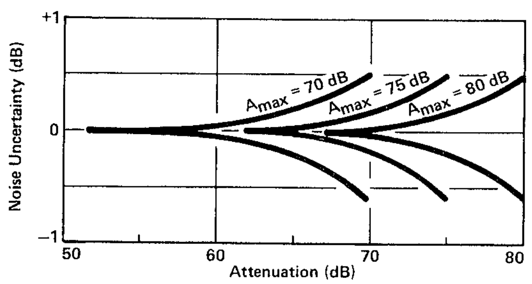


Figure 2-5. The uncertainty caused by noise when measuring large values of attenuation. Different curves apply for different values of maximum attenuation measurement capability.

Mismatch Uncertainty

The theory of mismatch uncertainty is discussed in Chapter V of Hewlett-Packard Application Note 64-1. The uncertainty arises because re-reflections change the incident waves so they are different than they would be for a zero-reflection attenuator, generator, and power sensor.

Although this uncertainty is usually the largest source of error in well-designed microwave measurements, it is also the most overlooked. It is probably overlooked for a combination of reasons: (1) it is often forgotten; (2) it is complicated to evaluate; (3) it depends on the reflection from several components, including the device under test, and these are seldom known; and (4) there are so many variables that the effect is difficult to summarize. Summaries of the mismatch uncertainty are considered here.

The worst-case mismatch uncertainty limits for attenuation measurements are derived in Appendix C of Hewlett-Packard Application Note 183. The limits are sometimes called the Mismatch Error Limits. The limits depend on the magnitudes of (1) the equivalent generator reflection coefficient seen by the device under test, ρ_g; (2) the reflection coefficient of the sensor for the test power meter, ρ_t; (3) the device under test input reflection coefficient, ρ_1; and (4) the device under test output reflection coefficient, ρ_2. It also depends on the forward and reverse transmission coefficients of the device under test, τ_1 and τ_2. The expression that defines the limits of mismatch uncertainty is

$$M_u = 20 \log \frac{1 \pm \rho_g \rho_t}{(1 \mp \rho_1 \rho_g)(1 \mp \rho_2 \rho_t) \mp \tau_1 \tau_2 \rho_g \rho_t} \qquad (2\text{-}1)$$

Figure 2-6 plots the upper limit of M_u for several values of attenuation; the lower limit is slightly smaller. The calculations are made by considering that (1) the actual source and power sensor reflection coefficients are given by the data sheet limits of the components; (2) the device under test reflection is the same at both ports—that is, $\rho_1 = \rho_2$; and (3) the device under test is bilateral so that $\tau_1 = \tau_2$. The expression used to evaluate ρ_g, taken from Appendix A of the next section of this note, is

$$\rho_g = \rho_c + TD_i \qquad (2\text{-}2)$$

where ρ_c is the mainline reflection coefficient of the coupler, T is the transmission coefficient, and D_i is the directivity of the incident arm of the coupler. The mismatch uncertainty limits for the different values of attenuation in **Figure 2-6** allow easy interpolation to other values.

It has already been mentioned that the worst-case uncertainty is a conservative estimate of the actual accuracy. For the calculations in **Figure 2-6**, the results are even more conservative because data sheet specification limits are used for the calculations. These specifications are partially established to assure a reasonable yield from the production line. Specifications are conservative in two ways. First, they have a guard band to allow for measurement uncertainty in production. Second, the guarded specification limit is usually approached at only a few frequencies and met with considerable allowance at the other frequencies. Which particular frequencies are close to specification limits depends on manufacturing tolerances, so actual performance could vary from unit to unit. It is highly unlikely that those few frequencies would coincide for the coupler, the device under test, and test power meter. It seems especially reasonable, therefore, to use a root-sum-of-the-squares method to calculate mismatch uncertainty. Such calculations are graphed in **Figure 2-7.** Some comments are needed about how the calculations are made.

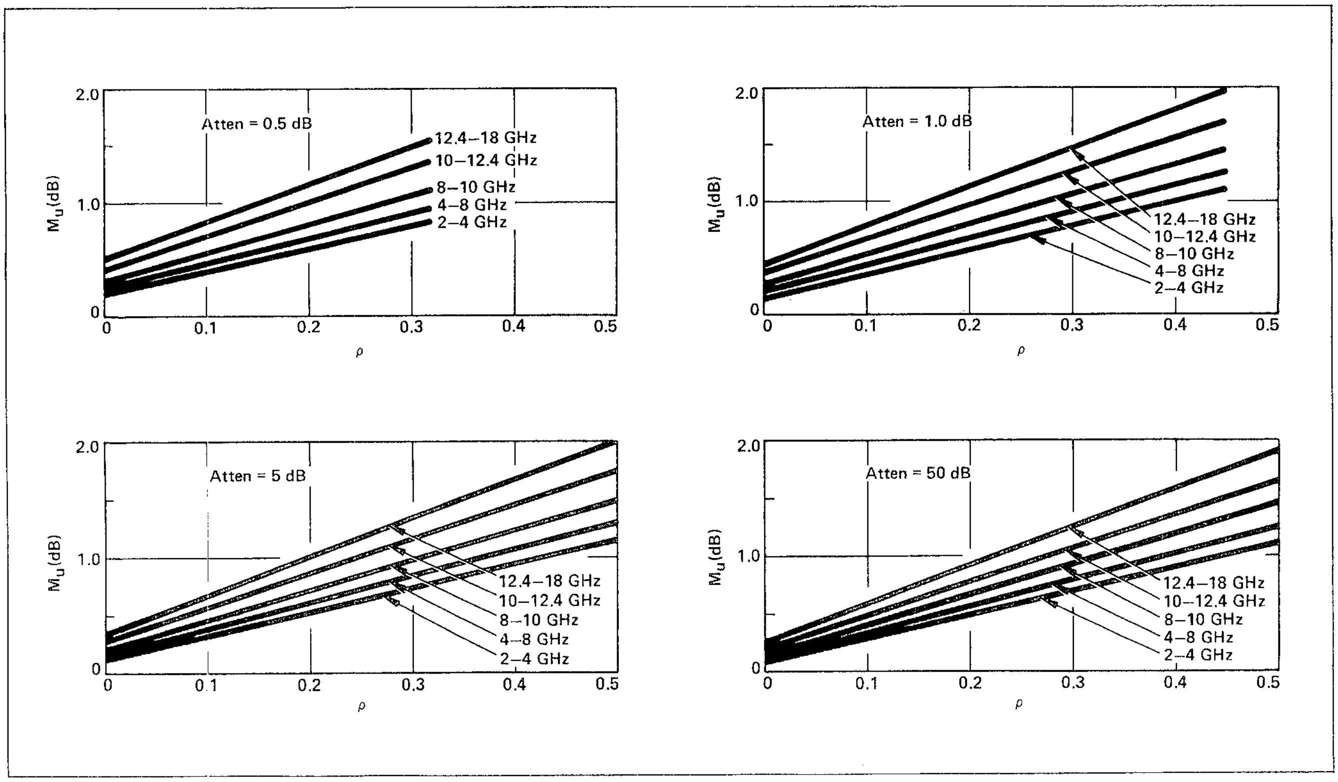


Figure 2-6. Worst-case positive mismatch uncertainty limit, M_u, vs. the reflection coefficient, ρ, of the device under test for several values of measured attenuation.

The mismatch uncertainty of equation (2-1) is primarily composed of four different re-reflected waves: (1) from the *test power meter* and the signal source during calibration; (2) from the device under test input and the signal source during measurement; (3) from the *test power meter* and the device under test output during measurement; and (4) from the *test power meter* and the signal source through the device under test during measurement. Each of these re-reflections is considered independent of the others and combine in RSS fashion. The equation used is

$$M_{RSS} = 20 \log \left[1 + \sqrt{\rho_g^2 \rho_t^2 + \rho_g^2 \rho_1^2 + \rho_t^2 \rho_2^2 + \rho_g^2 \rho_t^2 \tau_1^2 \tau_2^2}\right] \tag{2-3}$$

A second modification is made for the RSS calculation because equation (2-2) is too conservative an estimate of the equivalent source match. The equivalent complex source reflection coefficient, from Appendix A of this note is

$$\Gamma_g = \Gamma_C - TD_i \tag{2-4}$$

where Γ_C is the complex value of the mainline reflection coefficient of the 11692D coupler, T is the complex mainline transmission coefficient, and D_i is the complex directivity of the incident coupler. Sources of mainline reflections that occur at the generator end of the coupler contribute to both Γ_C and D_i in equation (2-4). Those sources of reflection, however, are inside the generator loop monitored by the *incident power meter* and do not contribute to measurement errors. It is too pessimistic, therefore, to take the magnitude of each term on the right of equation (2-4) in order to find the magnitude of the effective source reflection coefficient. Furthermore, the remaining contributors to D_i and Γ_C are independent of each other in phase because the reference planes for measuring Γ_C and D_i are different and independent. It is reasonable, therefore, to combine the terms in RSS fashion when calculating the effective source reflection coefficient magnitude:

$$\rho_g = \sqrt{|D_i|^2 + (0.75\ \rho_c)^2} \tag{2-5}$$

The 0.75 is used because, on the average, $0.25\rho_c$ represents reflections inside the generator loop monitored by the *incident power meter*—those reflections do not contribute to the uncertainty.

The RSS mismatch uncertainty in **Figure 2-7** is calculated for several values of attenuation to allow easy interpolation to other values. The negative value of the mismatch uncertainty is a little larger so that is the value plotted.

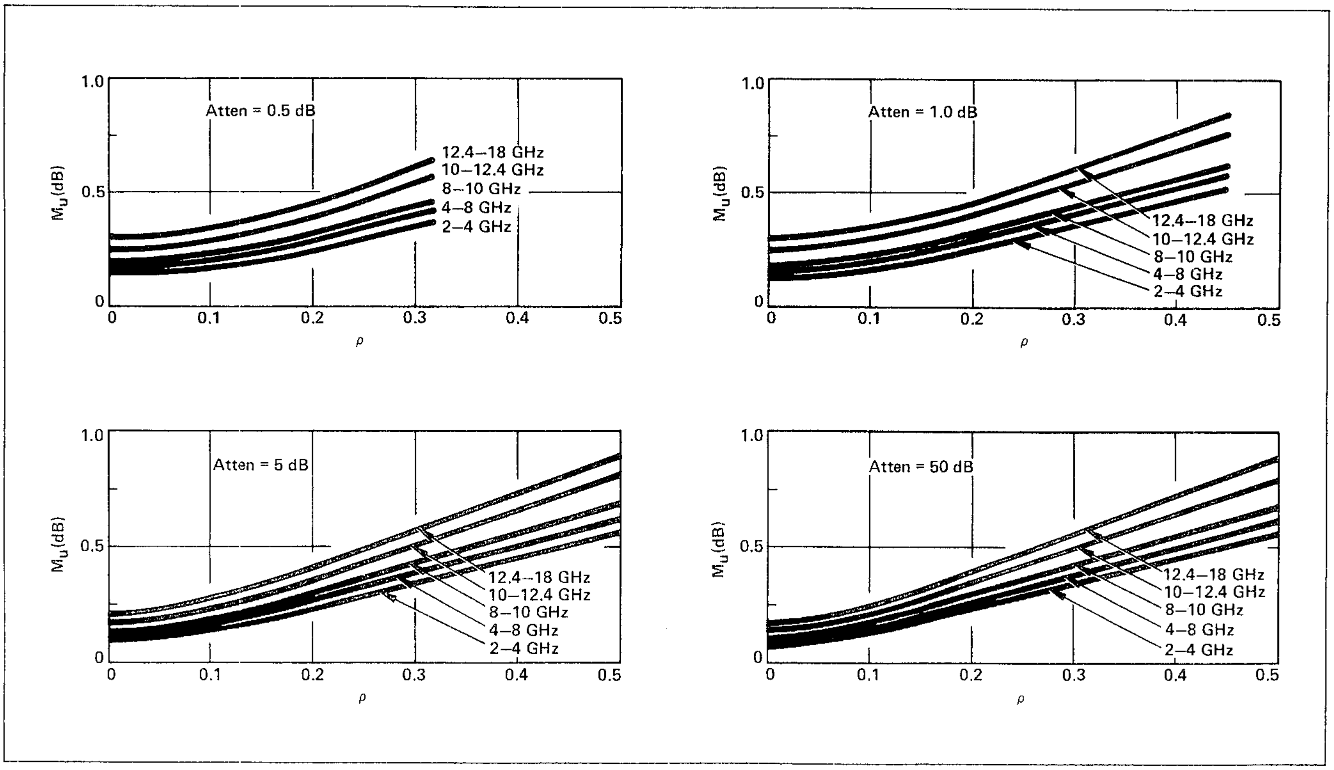


Figure 2-7. RSS mismatch uncertainty limit, M_u, vs. the reflection coefficient, ρ, of the device under test for several values of measured attenuation.

Combining Uncertainties

The three major components of uncertainty may be combined in worst-case fashion by merely adding the separate effects. An approximate total RSS uncertainty of the three major components of uncertainty may be found by squaring the individual dB uncertainties, adding them together, and then taking the square root. For example, the RSS combination of ±0.04 dB instrumentation uncertainty, ±0.09 dB for settling time, ±0.1 dB noise, and ±0.3 dB mismatch uncertainty yields a total RSS uncertainty of

$$U \approx \pm\sqrt{0.04^2 + 0.09^2 + 0.1^2 + 0.3^2} = \pm 0.33 \text{ dB} \qquad (2\text{-}6)$$

Program Operation

(1) Set up the measurement system as shown in **Figure 2-2.**

- It is recommended that the system be allowed 1 hour minimum warm-up time.
- During operation of the program, the 8672A Synthesized Signal Generator should have its front panel RF switch in the OFF position and the RANGE dBm switch set to a maximum of —40. This protects against the possibility of the power meters going into an over-range condition when changing the component being measured. The recovery from over-range could take longer than the program allows.
- The CAL FACTOR dials on the Power Meters should be set to 100 percent.
- Zero-set and set the CAL ADJ of the 436A/8484A's according to the Operating Instructions in the 436A Operating Manual. Be sure to connect the 11708A Reference Attenuator to the 436A Power Reference Output when calibrating.

(2) Insert the data cartridge with the attenuation measurement program, rewind, and load file 3 (or whatever file contains the program).

(3) Examine LINE 3 of the program to see if flag 2 is set properly. If the reflection coefficient measurement is desired then

```
sfg 2
```

should end LINE 3. If reflection coefficient measurement is not wanted then

```
cfg 2
```

should end LINE 3.

(4) Begin the program by pressing RUN. When "START FREQ (MHz)?" appears in the display, type the desired first test frequency and press CONTINUE.

(5) When "STOP FREQ (MHz)?" appears in the display, type the desired last test frequency and press CONTINUE.

(6) "FREQ STEP (MHz)?" next appears. Type the frequency increment between the test points and press CONTINUE.

Note: The program, as written, only measures at a maximum of 101 different frequencies. If the START, STOP, and STEP inputs correspond to more than 101 frequencies, the program will loop back to the start of step number 4, requesting new frequency data.

(7) (Only for reflection measurements). Follow the "CONNECT SHORT TO COUPLER" instruction and press CONTINUE when completed. This calibration part of the program will measure and save the difference in dB between the *reflected* and *incident power meter* readings at each frequency.

(8) "CONNECT POWER SENSOR TO COUPLER" refers to the power sensor on the *test power meter*. When completed, press CONTINUE. This calibration part of the program measures and saves the difference in dB between the *test* and *incident power meter* readings at each frequency.

(9) The next instruction is, "INSERT TEST DEVICE. DESCRIBE!". Connect the device to be tested and describe it with up to 70 alphanumeric characters including spaces. Model and serial numbers are frequent descriptions. The first 16 characters will be output at the top of the measurement results. Press CONTINUE when finished.

(10) The program then measures, at each frequency, the attenuation by measuring the difference in dB between the *test* and *incident power meter* readings. If necessary, the program adjusts the generator power level. By comparison to the saved calibration reading made in step number 8, the attenuation is calculated and saved.

(11) (Only for reflection measurements). The program measures, at each frequency, the difference in dB between the *reflected* and *incident power meter* readings. This is done with the generator output power adjusted to about 1 dBm. By comparison to the same quantity for the short circuit measured in step number 7, the reflection coefficient is calculated and saved.

(12) The program prints the saved results from the above measurements.

(13) The program then loops back to step number 9 for the measurement of another device.

Measurement Results

An example of the accuracy of the attenuation measurement system is shown in **Figure 2-8.** It compares the attenuation as measured on this system and as measured on the more accurate, elaborate, and expensive 8542B Automatic Network Analyzer. Any deviations in the data are well within the total RSS uncertainties calculated for this system.

Freq (GHz)	Power Meter Attenuation System (dB)	8542B (dB)	Reflection Coefficient	
			Power Meter System	8542B
2	10.02	9.95	0.007	0.003
3	9.97	9.91	0.021	0.014
4	10.02	9.95	0.003	0.017
5	10.01	9.98	0.011	0.013
6	9.99	9.96	0.030	0.010
7	9.96	9.95	0.021	0.011
8	10.00	9.98	0.028	0.014
9	10.01	9.93	0.058	0.025
10	9.95	9.93	0.033	0.036
11	10.01	9.93	0.041	0.040
12	9.87	9.96	0.050	0.037
13	9.93	9.87	0.041	0.051
14	9.95	9.87	0.078	0.078
15	10.04	9.89	0.092	0.097
16	9.96	9.88	0.110	0.098
17	9.95	9.82	0.117	0.086
18	9.83	9.82	0.086	0.086

Figure 2-8. A comparison of attenuation and reflection coefficient measurements of a 10 dB attenuator as measured by this system and an HP 8542B Automatic Network Analyzer.

```
0pen circuit
 FREQ         ATTEN
 (GHz)         (dB)                (GHZ)        RHO

  2.00    >  76.95                  2.00       0.966
  3.00    >  77.36                  3.00       0.984
  4.00    >  79.27                  4.00       0.994
  5.00    >  78.95                  5.00       1.030
  6.00    >  78.79                  6.00       1.002
  7.00    >  72.19                  7.00       0.945
  8.00    >  75.02                  8.00       0.948
  9.00    >  78.92                  9.00       0.999
 10.00    >  75.75                 10.00       1.030
 11.00    >  77.46                 11.00       0.963
 12.00    >  78.22                 12.00       1.022
 13.00    >  71.80                 13.00       1.022
 14.00    >  73.26                 14.00       0.967
 15.00    >  69.63                 15.00       1.064
 16.00    >  71.50                 16.00       1.040
 17.00    >  74.02                 17.00       0.991
 18.00    >  70.05                 18.00       1.045
```

Figure 2-9. Measured attenuation and reflection coefficient for an open circuit. This demonstrates the attenuation measurement range and the uncertainty of measured reflection coefficient, RHO, for large reflections. The reflection coefficient should be approximately 1.0.

Figure 2-9 shows the measurement of attenuation and reflection coefficient of an open circuit. The actual attenuation approaches infinity, but the system only detects that the attenuation is greater than the dynamic range of the system. The small deviation of the measured reflection coefficient from unity shows that the reflection coefficient measurement is also good.

Program Structure

The program structure will now be explained to make changes easier. A flow chart of the main program is shown in **Figure 2-10. Figure 2-11** shows a detailed flow chart of the subroutine that tests and adjusts the level of the signal generator. At the end of this section there is an annotated listing of the program.

The variables used in this program are assigned as follows:

Matrices:

A[101]	Array for storing the measured attenuation. There is one number for each frequency. If the measurement is beyond the dynamic range of the system, the stored number is 1000 dB smaller than the dynamic range.
C[101]	Array for storing the difference, in dB, between the output power from the main line of the coupler, as read by the *test power meter,* and the reading of the *incident power meter.* This difference is measured during the calibration portion of the program. There is one number for each measurement frequency.
R[101]	Array for storing measured reflection coefficient. There is one number for each frequency.
S[101]	Array for storing the indicated return loss of a short circuit at each frequency. This is measured during the calibration portion of the program.

String Variable:

K$[70]	A string array for holding a description of the device under test.

Simple Variables:

A	Attenuation in dB.

B	The decimal value for the ASCII "space" or for the ASCII ">" sign used to print values of attenuations that exceed the dynamic range of the system.
C	The latest reading of the *test power meter.*
E	Start frequency in MHz.
G	The latest reading of the *incident power meter.*
H	Stop frequency in MHz.
I	The number of the frequency at which data is being measured. This results in I being the index to the matrices of calibration data, C[I] and S[I].
L	Variable that contains the level, in dBm, to which the generator is programmed.
M	Variable for temporarily holding the new level, in dBm, to which the generator may be programmed.
N	The total number of frequencies at which measurements are to be made.
Q	Frequency increment in MHz.
S	The status word sent to the program from the 8672A. Used to tell whether the 8672A has more power output available.

flag:

2	(0) Reflection coefficient measurements and calibration are not desired. (1) Reflection coefficient measurements and calibration are desired.

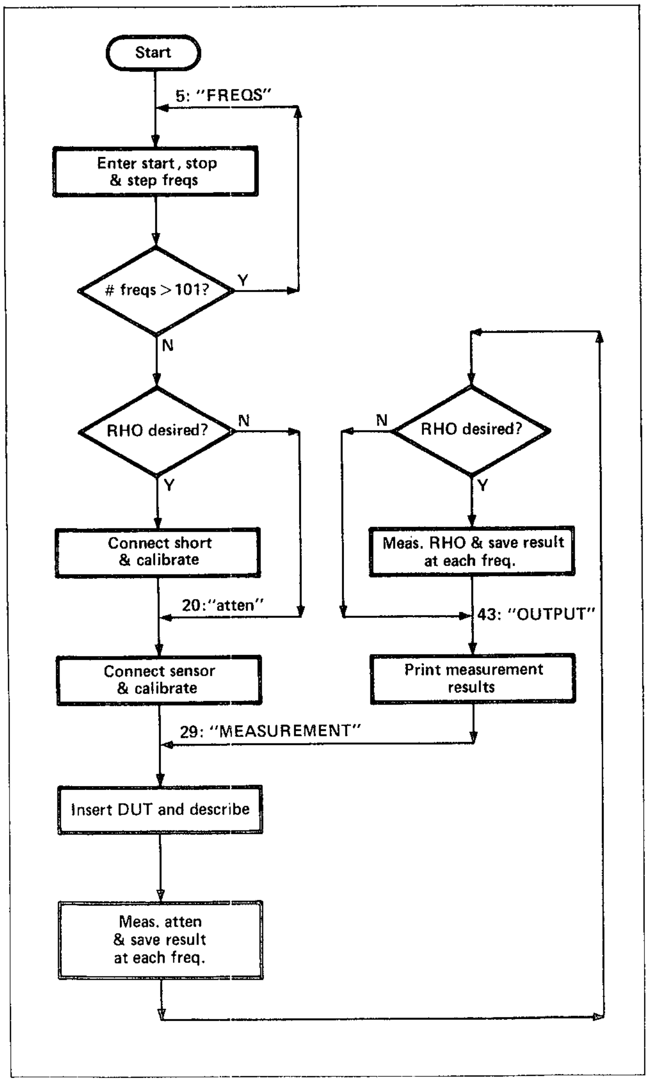


Figure 2-10. A flow chart of the attenuation measurement program.

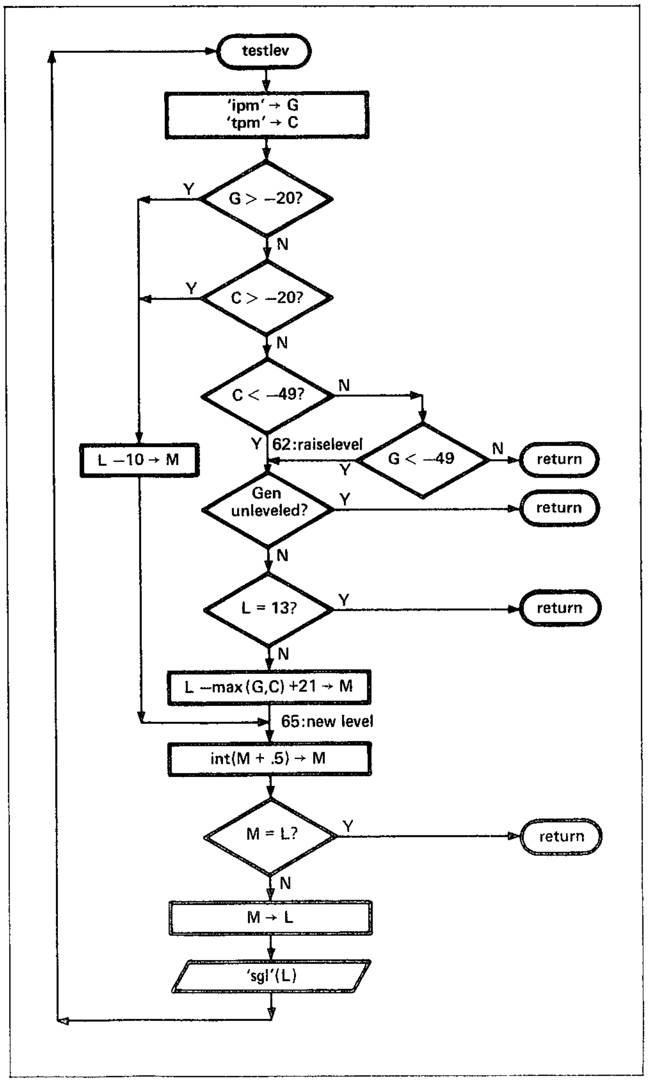


Figure 2-11. A flow chart of the subroutine that tests and adjusts the level of the signal generator.

Program and System Variations

This program was written to utilize the same equipment as the power sensor calibration system to be described in the next section. The program was also written with the idea that it would be changed by the user to suit special output data format requirements or different equipment. A likely change to the system includes the addition of a line printer and a graphic plotter.

A power splitter, such as the HP 11667A, could be substituted for the directional coupler at the sacrifice of some measurement range and of reflection measurement capability. The power splitter would allow accurate attenuation measurements down to 10 MHz with a suitable source.

Other signal sources may be substituted for the 8672A. The HP 8620C/86290A/B Sweep Oscillator with the HP-IB option could be used instead. The sweep oscillator, however, would require a programmable attenuator and associated power supply driver and HP-IB circuitry. The portion of the program entitled SIG GEN SUBROUTINES, for both frequency and level, would also have to be changed.

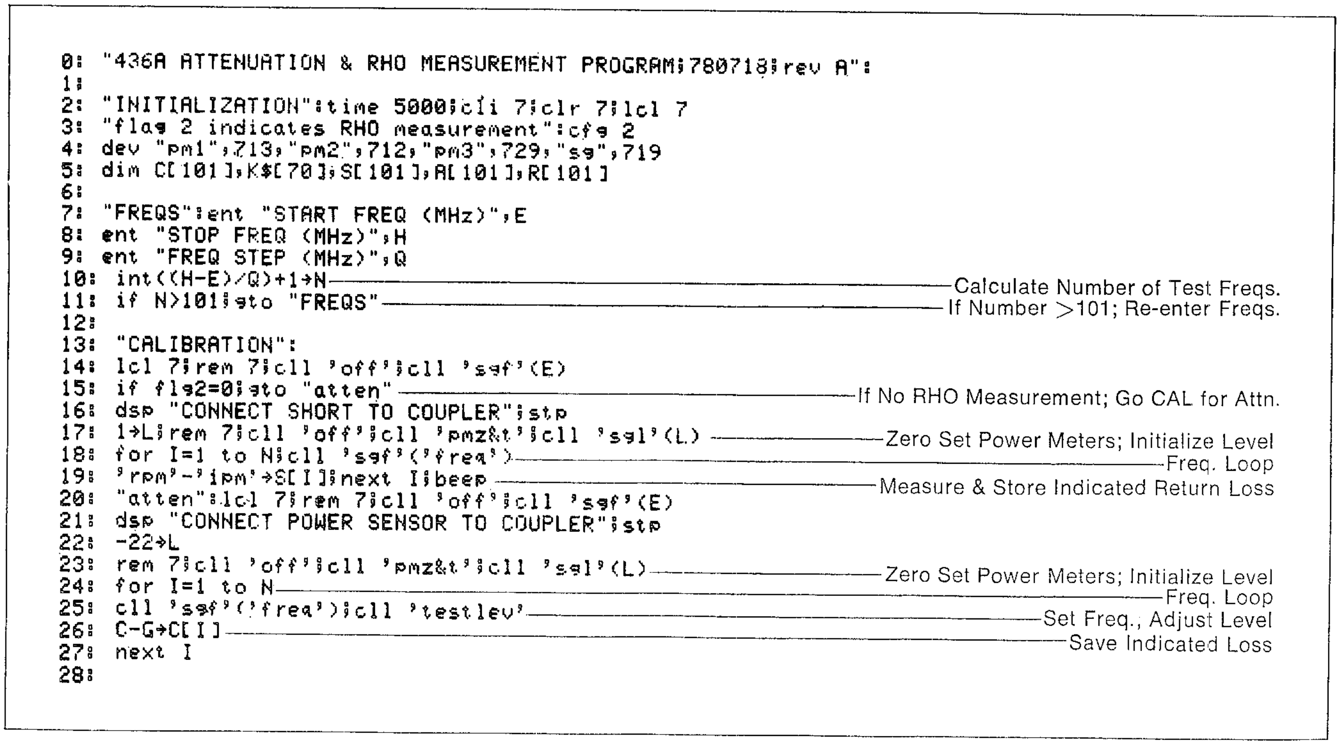
A preselector, described in the EQUIPMENT SUGGESTED portion of this section, is another possible improvement. Although the preselector limits the output power somewhat, the true dynamic range is still at least 60 dB. The system can then measure components like filters that have large variations of loss with frequency.

The maximum power that can be monitored by the *incident power meter* is −20 dBm. The loss between the generator output and the *incident power meter* limits the maximum generator power. If the system is assembled as in **Figure 2-2,** that loss is nominally 32 dB, 10 dB for the attenuator and 22 dB for the coupling factor. This means the maximum generator output is limited to about +12 dBm (−20 dBm +32 dB). More powerful generators will need a larger attenuator at that position before the extra power can be utilized.

Removing that 10 dB attenuator limits the generator output to about +2 dBm. That means that the attenuation measurement range is limited to about 70 dB. But there is one advantage to removing that attenuator. The measurement of small losses, under about 3 dB, will also be performed at the quicker speed of about 1 frequency per second. The measurement program does not need to be changed when the attenuator at the *incident power meter* changes.

The dynamic range of the system can be increased another way. An additional 15 dB of RF gain may be added just before the *test power meter.* The amplifier needs a low noise figure and the bandwidth would have to be reduced so that the amplifier total poise power output is less than −70 dBm.

The same equipment used to measure attenuation can also automatically measure gain and gain saturation. This is just another example of the broad range of applications that can be met by this general purpose equipment.



```
0: "436A ATTENUATION & RHO MEASUREMENT PROGRAM;780718;rev A":
1:
2: "INITIALIZATION":time 5000;cli 7;clr 7;lcl 7
3: "flag 2 indicates RHO measurement":cfg 2
4: dev "pm1",713,"pm2",712,"pm3",729,"sg",719
5: dim C[101],K$[70],S[101],A[101],R[101]
6:
7: "FREQS":ent "START FREQ (MHz)",E
8: ent "STOP FREQ (MHz)",H
9: ent "FREQ STEP (MHz)",Q
10: int((H-E)/Q)+1→N---------------------------------Calculate Number of Test Freqs.
11: if N>101;gto "FREQS"------------------------------If Number >101; Re-enter Freqs.
12:
13: "CALIBRATION":
14: lcl 7;rem 7;cll 'off';cll 'sgf'(E)
15: if flg2=0;gto "atten"-----------------------If No RHO Measurement; Go CAL for Attn.
16: dsp "CONNECT SHORT TO COUPLER";stp
17: 1→L;rem 7;cll 'off';cll 'pmz&t';cll 'sgl'(L) ---------Zero Set Power Meters; Initialize Level
18: for I=1 to N;cll 'sgf'('freq')---------------------------------------------Freq. Loop
19: 'rpm'-'ipm'→S[I];next I;beep ----------------Measure & Store Indicated Return Loss
20: "atten":lcl 7;rem 7;cll 'off';cll 'sgf'(E)
21: dsp "CONNECT POWER SENSOR TO COUPLER";stp
22: -22→L
23: rem 7;cll 'off';cll 'pmz&t';cll 'sgl'(L)----------Zero Set Power Meters; Initialize Level
24: for I=1 to N-------------------------------------------------------------Freq. Loop
25: cll 'sgf'('freq');cll 'testlev'---------------------------Set Freq., Adjust Level
26: C-G→C[I]-------------------------------------------------Save Indicated Loss
27: next I
28:
```

Annotated Program Listing (1 of 2)

```
29:"MEASUREMENT":lcl 7;rem 7;cll 'off';cll 'sgf'(E);beep
30:ent "INSERT TEST DEVICE, DESCRIBE!",K$
31:-22→L;rem 7;cll 'off';cll 'pmz&t';cll 'sgl'(L) ———— Zero Set Power Meters; Initialize Level
32:for I=1 to N ——————————————————————————————————————————— Freq. Loop
33:cll 'sgf'('freq');cll 'testlev' ——————————————————————— Set Freq.; Adjust Level
34:C[I]-C+G→A[I];if C<-68;A[I]-1000→A[I] —————————————— Calc. Attn; If Noisy –1000
35:next I
36:if flg2=0;gto "OUTPUT" ————————————————— If No RHO Measurement; Go Output Results
37:1→L;cll 'sgl'(L);cll 'sgf'(E) ——————————— Set Level for RHO Measurement; Initialize Freq.
38:for I=1 to N;cll 'sgf'('freq') ————————————————————— Freq. Loop; Set Freq.
39:tn↑(('rpm'-'ipm'-S[I])/20)→R[I];next I ————————————— Measure & Calculate RHO
40:gto "OUTPUT"
41:
42:"OUTPUT SUBROUTINES":
43:"OUTPUT":spc ;prt K$[1,16];prt "FREQ       ATTEN" ——————— Print ATTN. Headings
44:prt " (GHz)       (dB)";spc
45:fmt x,f5.2,2x,b,f6.2
46:for I=1 to N ——————————————————————————————————————————— Freq. Loop
47:32→B;A[I]→A;if A<-500;62→B;A+1000→A ——————————————— Set Space or > Sign
48:wrt 16,'freq'/1000,B,A;next I ———————————————————————— Print Freq. & Attn.
49:if flg2=0;gto "MEASUREMENT" ———————————— If No RHO Measurement; Go to Next Measurement
50:spc ;prt " (GHz)      RHO";spc ————————————————————————— Print RHO Headings
51:fmt x,f5.2,3x,f6.3
52:for I=1 to N ——————————————————————————————————————————— Freq. Loop
53:wrt 16,'freq'/1000,R[I];next I ——————————————————————— Print Freq. & RHO
54:gto "MEASUREMENT" —————————————————————————————————————— Go to Next Measurement
55:
56:"SUBROUTINES":
57:"testlev":'tpm'→C;'ipm'→G;if G>-20;L-10→M;gto "newlevel" \
58:if C>-20;L-10→M;gto "newlevel"                             |
59:if C<-49;gto "raiselevel"                                  |    Adjust Level, if
60:if G<-49;gto "raiselevel"                                  |    Necessary, for Accuracy,
61:ret                                                        |
62:"raiselevel":rdb("sg")→S;if bit(2,S);ret                   }——— Noise, and Speed.
63:if L=13;ret                                                |    See Flow Chart
64:L-(max(G,C)+21)→M                                          |    in Figure 2-11.
65:"newlevel":int(M+.5)→M;if M=L;ret                          |
66:M→L;cll 'sgl'(L);gto "testlev"                             /
67:
68:"freq":E+(I-1)Q→p1;max(2000,p1)→p1;min(18000,p1)→p1;ret p1 ——— Calculate Freq. in MHz
69:
70:"POWER METER SUBROUTINES":
71:"pmz&t":fmt ;wrt "pm1","Z1I";wrt "pm3","Z1I";if flg2;wrt "pm2","Z1I" ——— Set to Zero
72:fmt 4x,f4.0;red "pm1",p1;red "pm3",p3;if flg2;red "pm2",p2 ——— Read Power Meters
73:if p1>2 or p3>2;jmp -2 }——————————————————— { Are Power Meters Approx. Zero?
74:if flg2;if p2>2;jmp -3 }                      { If Not, Zero Again
75:wrt "pm1","9D+I";wrt "pm3","9D+I";if flg2;wrt "pm2","9D+I" ——— Change to dBm
76:if flg2;if rdb("pm2")>83;gto -1                }——— { Keep Changing to dBm Until Power
77:gto -2;if rdb("pm1")<84;if rdb("pm3")<84;ret   }     { Meters Are Not in Auto Zero
78:"ipm":fmt x,b,x,e9.0;wrt "pm1","T";red "pm1",p1,p2;if p1>73;ret p2 }   { Trigger & Read
79:if p2=-70;wait 4000                                                  }——{ Incident
80:p2→p3;wrt "pm1","T";red "pm1",p1,p2;gto -0;if abs(p2-p3)<.05;ret p2 }   { Power Meter
81:"rpm":fmt x,b,x,e9.0;wrt "pm2","T";red "pm2",p1,p2;if p1>73;ret p2 }   { Trigger & Read
82:if p2=-70;wait 4000                                                  }——{ Reflected
83:p2→p3;wrt "pm2","T";red "pm2",p1,p2;gto -0;if abs(p2-p3)<.05;ret p2 }   { Power Meter
84:"tpm":fmt x,b,x,e9.0;wrt "pm3","T";red "pm3",p1,p2;if p1>73;ret p2 }   { Trigger & Read
85:if p2=-70;wait 4000                                                  }——{ Test
86:p2→p3;wrt "pm3","T";red "pm3",p1,p2;gto -0;if abs(p2-p3)<.05;ret p2 }   { Power Meter
87:"SIG GEN SUBROUTINES":
88:"off":cll 'sgl'(-60);fmt ;wrt "sg","00";ret ——————————— Turns RF Power OFF
89:"sgl":fmt "K",2b,"07",b;if p1>13;13→p1 ——————— Sets Generator Level; Max. is 13 dBm
90:if p1>3;wrt "sg",48,61-p1,51;ret ————————— Special Instructions for Top Level Range
91:if p1<-120;wrt "sg",59,61,48;ret ——————————————— Min Generator is –120 dBm
92:int(abs(p1/10))→p2;wrt "sg",p2+48,51-10p2-p1,49;wait 300;ret ——— Send Level on HP-IB
93:"sgf":fmt "P",fz9.3,"Z9";wrt "sg",p1;wait 300;ret ————————— Send Freq. on HP-IB
94:end
*17862
```

Annotated Program Listing (2 of 2)

III. Automatic Power Sensor Calibration

The validity of any absolute power measurement depends strongly on the characteristics of the power sensor. The main parameter that characterizes the power sensor accuracy is the calibration factor. This figure of merit shows the ability of the sensor to (1) absorb the RF power incident upon it (this means it has a low reflection coefficient) and (2) convert the power absorbed into a measureable dc value (this means it has a high effective efficiency). The accurate measurement of calibration factor has either been very tedious or it has required expensive equipment, such as an error-correcting Automatic Network Analyzer. Calibration factor has normally been measured only by manufacturers and by the most well-equipped calibration laboratories. Sending power sensors to such facilities for recalibration is time consuming, expensive, and often complicated by international import/export regulations. Consequently, the calibration factor is usually measured only during manufacture or after major repair. Yet, because the calibration factor can change due to factors like connector wear, aging, or the application of excessive power, it should be measured more frequently. Once each year is felt to be adequate for average usage.

This section describes a system for measuring calibration factor. A desktop computer operates the equipment and processes the data to achieve an easy-to-operate and accurate measurement system. Most of the measuring instruments that make up the system will be standard equipment in calibration laboratories. Some of the components are special in that measured data expressing their performance is stored on the system computer. The physical construction of the special components is standard. This particular system measures calibration factor over the 2 to 18 GHz frequency range, for sensors with Type N connectors, and over a power range from 1 mW to 1 μW. This allows calibration of the HP 8481A, 8481H, 8484A, 8478B, and 478A Power Sensors. The basic method can, however, be adapted to other conditions.

One of the advantages of this calibration system is that it can be used for other purposes. Since the system is composed of general purpose equipment, it might be used for calibration factor measurement a few months each year. Other times it might be used for such things as the accurate attenuation measurements discussed in the previous section.

The goals of this section are (1) to describe the principles of the measurement, including a derivation of the uncertainties of measurement; (2) to enable an operator to set-up and run the system; and (3) to enable a programmer to rewrite sections of the software for special applications.

Calibration factor is measured by comparing the power *sensor under test* to a *standard power sensor* that was previously calibrated by a standards laboratory. When a power sensor is calibrated in a standards laboratory by tuning reflections at each frequency, the calibration factor is typically known within an uncertainty of ±1.5 percent. That same power sensor, calibrated by the manufacturer on his production line with a suitably equipped Automatic Network Analyzer, would typically have an uncertainty of ±3 percent. When calibrated on this system, at the same frequencies as the *standard power sensor*, the power *sensor under test* would typically have an uncertainty of ±4 percent. The low uncertainty for this system is achieved by calculating the uncertainty for each measurement using stored data about system components. The uncertainty printed for each measurement is traceable to the U.S. National Bureau of Standards. If the calibration factor were measured manually, using the same general technique used by this system (where no tedious tuning adjustments are required at each frequency), and using data sheet specifications for system components, the uncertainty would be about ±10 percent.

At frequencies different than those where the *standard power sensor* was calibrated, the calibration factor is found by interpolating the calibration factor of the *standard power sensor*. At those frequencies the calibration factor uncertainty is not printed because there is no longer traceability to the U.S. National Bureau of Standards. The principal causes of worst-case uncertainty vary slowly as a function of frequency, so the uncertainty at an arbitrary frequency is often approximated by the uncertainty at the closest frequency where the system was calibrated.

The Basic Technique

The basic technique is to measure the power from a carefully controlled generator, first with a *standard power sensor* and then with the *sensor under test*. In the ideal case, with constant generator output, the ratio of the calibration factors is identical to the ratio of those two power readings. One essential contribution of this system is that it computes its own departure from an ideal system. It computes its own worst-case uncertainty for each measurement. A magnetic tape cartridge contains measured data about the system components that is used in the calculation. The calculation does not correct for system errors using the stored data, it only uses that data to calculate the measurement uncertainty.

Stored data about the system components is typically much better than the manufacturer's data sheet specification of the same component. Data sheet specifications are usually established to assure a reasonable yield from the manufacturer's production line with allowance for measurement uncertainty. A directional coupler, for example, might barely achieve its directivity specification of 30 dB at 5 GHz, but its other pertinent characteristics would typically be well within the data sheet specifications. Furthermore, the directivity at other frequencies would be well within its specification. Using actual measured data about the coupler and other system components to find the measurement uncertainty yields more accurate and more realistic results than the data sheet specifications.

The system operates under automatic control of a desktop computer. An automatic system is necessary because the procedure would be so long and complicated under human control that errors would be likely and the skilled labor costs would be prohibitive.

Equipment Suggested

Desktop Computer (with 16k Byte Memory)	HP 9825A Opt. 001
HP-IB Interface with 4 m Cable	HP 98034A
String-Advanced Programming ROM	HP 98210A
General I/O Ext. I/O ROM	HP 98213A
Synthesized Signal Generator	HP 8672A
Digital Multimeter with HP-IB	HP 3455A or HP 3490A Opt. 030
Power Meter System[*] typically consisting of:	HP 436A-E10 Series[*]
Power Meter with HP-IB (3 each)	HP 436A Opt. 022
Dual-Directional Coupler with Computer Characterization	HP 11692D–H04
10 dB Type N Attenuator (selected for low SWR) with Computer Characterization	HP 8492A–H33
Power Sensors (2 each)	HP 8484A
Power Sensor with Standards Lab Calibration	HP 8481A–H11
Power Meter	HP 432A
Thermistor Mount with Standards Lab Calibration	HP 8478B–H28
Type N Cable (61 cm)	HP 11500B
Type N Short	HP 11512A
HP-IB Cable (1 m, 3 each)	HP 10631A
BNC-Dual Banana Cable (112 cm)	HP 11001A
436A-E10 System Tape[**]	HP Part No. 00436-10xxx[**]

System Description

Figure 3-1 shows the two principal methods of assembling the system. The upper block diagram is for testing thermistor mounts and the lower block diagram is for testing thermocouple and diode detector power sensors. The major difference is that the thermistor mounts need a bridge-type power meter. The recorder output of the bridge-type power meter is digitized with a digital voltmeter.

The RF stimulus suggested for the calibration system is an HP 8672A Synthesized Signal Generator. This general purpose synthesizer is likely to be available in many calibration facilities and is preferred in this system because of the ease in setting the power level. A broad range sweep oscillator, such as the HP 8620C Option 011 with the HP 86290A/B 2 to 18 GHz Sweep Oscillator Plug-in, and a programmable attenuator, such as the HP 8495H Option 001 Attenuator with a programmable power supply to drive it, can be substituted along with suitable changes to the calculator program.

An important characteristic of any signal source is its output at harmonics and subharmonics of the desired output frequency. The HP 8672A is specified to have such spurious outputs at least 25 dB below the output at the desired frequency. For calibrating power sensors, this level is adequate. For example, consider a *standard power sensor* that responds to the −25 dB spurious frequency with 100 percent efficiency. Furthermore, consider that the power *sensor under test* does not respond at all to the spurious frequency. The error in calibration factor would be 25 dB down or only 0.3 percent. Even this extreme case is not likely to occur because, if it did, the *sensor under test* would have a calibration factor of 0 at the spurious frequency where the *standard power sensor* would be 100 percent.

The microwave source drives the input port of the dual-directional coupler. One HP 436A Power Meter and its HP 8484A Power Sensor is connected to the incident port of the coupler. This 436A is called the *incident power meter* because it monitors the incident power from the generator. A second 436A and 8484A, connected to the reflected port of the coupler, is used to measure the reflected wave from the *sensor under test*. This power meter

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[*] HP 436A-E10 is a generic number. The actual model number may change because of deletions and additions to suit growth in the state-of-the-art of coaxial components, special customer requirements, etc.

[**] A special part number is assigned at the factory for each complete system. The special number is a reference to the specially stored data.

is called the *reflected power meter*. Power meters are used to monitor the incident and reflected power levels because of ease in programming, accuracy, and sensitivity (down to −70 dBm) while still covering the complete frequency range. Furthermore, power meters are likely to be available around most calibration facilities.

A third power meter, called the *test power meter,* uses the *standard power sensor* during calibration and the *sensor under test* during measurement. The *test power meter* and its power sensor is sometimes connected to the test port of the directional coupler through a 10 dB attenuator and sometimes it is connected directly to the coupler test port. The computer is programmed to always inform the operator whether or not to use the 10 dB attenuator.

With the 10 dB attenuator, the generator reflection coefficient presented to the *standard power sensor* and the *sensor under test,* is as low as practical without tedious tuning at each measurement frequency. When measuring the 8481H Power Sensor, however, the 10 dB attenuator would lower the output power too much, so it is not used. Nor is the attenuator used when measuring reflection coefficient because it obscures the reflected wave from the *sensor under test.*

A 9825A Desktop Computer controls the system by means of the Hewlett-Packard Interface Bus (HP-IB). The computer also processes the measured and stored data. To perform these functions the 9825A should have the ROM's shown in the equipment list.

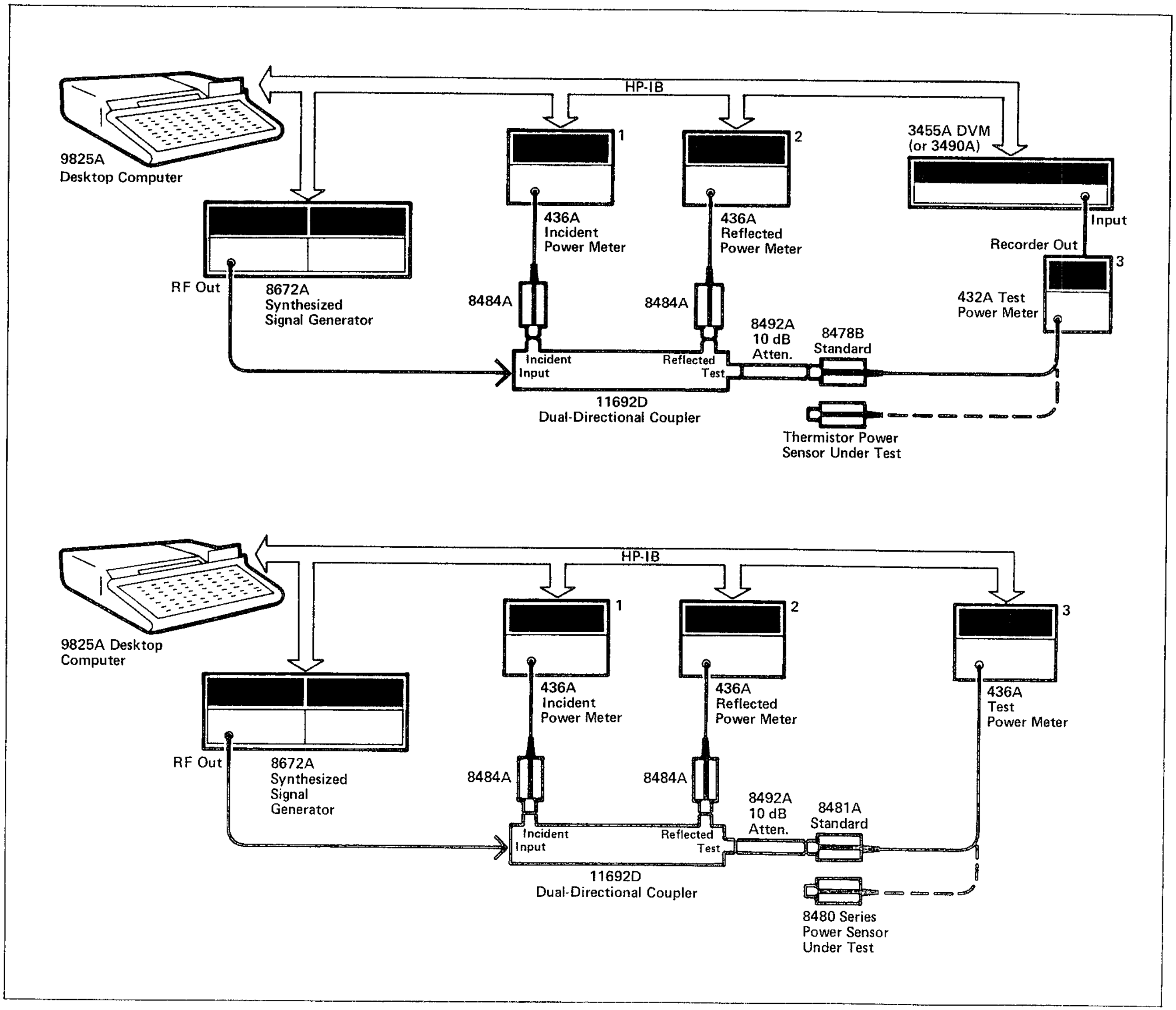

Figure 3-1. Block diagrams for calibrating power sensors: (top) thermistor mounts, (bottom) thermocouple and diode detector power sensors.

For the computer to separately command the system instruments and receive data, each item operating on the bus must have a different address. The addresses used for the 436A-E10 system are indicated in **Figure 3-2.** Special care is needed for the power meters, where the addresses of the *reflected power meter* and *test power meter* need to be changed. The 436A Operating and Service Manual describes how to change the address on the A6 Assembly (one of the printed-circuit boards inside the power meter). If the address is set by the use of jumper wires, do not be confused by the least significant bit being on the left. The proper position of the power meter jumper wires is pictured in the bottom of **Figure 3-2.** If the address is set by the use of a switch on the printed-circuit board, then the least significant bit is on the right so that the binary address reads from left to right.

Instrument	Decimal Address Code	Octal Address Code	Binary Address Code	ASCII Talk Address	ASCII Listen Address
9825A Desktop Computer	21	25	10101	U	5
8672A Synthesized Signal Generator	19	23	10011	S	3
436A Incident Power Meter	13	15	01101	M	—
436A Reflected Power Meter	12	14	01100	L	,
436A Test Power Meter	29	35	11101	]	=
3455A Digital Voltmeter (or 3490A Option 001 Multimeter)	22	26	10110	V	6

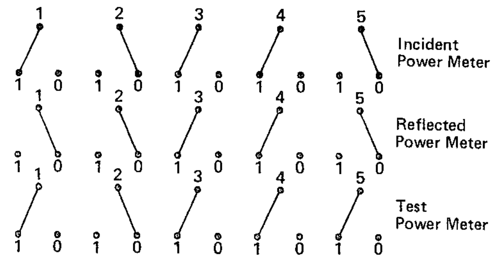

Figure 3-2. Table of HP-IB address for the 436A-E10 system. The bottom portion sketches the jumper wiring necessary for some 436A Power Meters.

Measurement of K_b

The calibration factor K_b of a power sensor is defined as

$$K_b = \frac{P_{sub}}{P_{inc}} \qquad (3\text{-}1)$$

where P_{inc} is the RF power incident upon the sensor and P_{sub} is the substituted low frequency equivalent of the RF power being measured. For thermistors, P_{sub} is the change in bias power required to bring the thermistor back to the same resistance as before the application of RF power. For thermocouple and diode sensors, P_{sub} is the amount of power from a reference power source, at a specified frequency, that yields the same voltage to the metering circuits as caused by the RF power. For the HP family of thermocouple and diode sensors the reference power source is at a frequency of 50 MHz. The gain of the circuits in the power meter is adjusted so that when P_{sub} is 1 mW, the power meter reads 1 mW. For the HP 8484 Power Sensor, the reading is adjusted to 1 μW. From then on, the meter indication is equal to P_{sub} within the instrumentation uncertainty of the power meter. This means that

$$M = P_{sub}\,(1 \pm i) \qquad (3\text{-}2)$$

where M is the power meter indication and i is the instrumentation uncertainty (for 1 percent uncertainty, i would be 0.01).

Figure 3-3 shows the two measurements made to find the calibration factor K_b of a *sensor under test.* "P" symbolizes

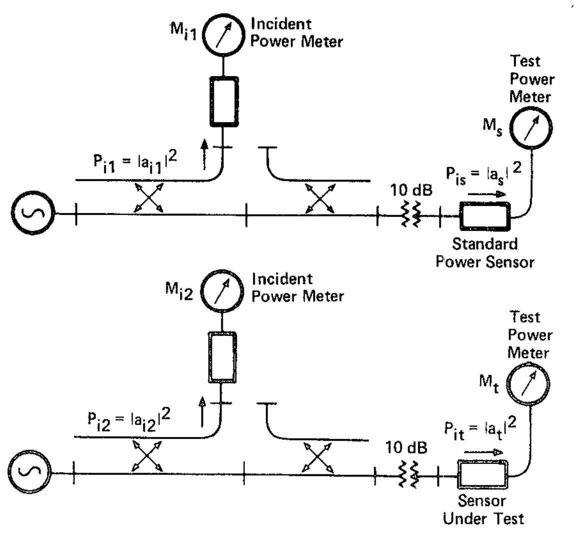

Figure 3-3. Schematic diagram of calibration factor measurement showing the measured powers for (top) the *standard power sensor* and (bottom) the *sensor under test.*

power flow and "a" symbolizes the amplitude of incident waves. In the upper figure, the *standard power sensor* is connected to the measurement port. Two power meter readings, M_s (for *standard power sensor*) and M_{i1} (for the *first* measurement with the *incident power meter*), are observed. In the lower figure the same measurements are made except that the *sensor under test* is connected to the measurement port. The respective meter readings are M_t (for *sensor under test*) and M_{i2}.

From equations (3-1) and (3-2), the ratio of the *sensor under test* calibration factor K_b to the *standard power sensor* calibration factor K_s is

$$\frac{K_b}{K_s} = \frac{\dfrac{M_t}{(1 \pm i_t)\,P_{it}}}{\dfrac{M_s}{(1 \pm i_s)\,P_{is}}} = \frac{M_t}{M_s} \cdot \frac{P_{is}}{P_{it}} \cdot \frac{1 \pm i_s}{1 \pm i_t} \qquad (3\text{-}3)$$

where P_{is} and P_{it} are the true values of the power incident on the *standard power sensor* and *sensor under test.* From **Figure 3-3**

$$\frac{P_{is}}{P_{it}} = \left|\frac{a_s}{a_t}\right|^2 \qquad (3\text{-}4)$$

In Appendix A, equation (A-8), an expression for the output at the test port is derived in terms of a_i, the wave on the auxiliary arm of the coupler that monitors the incident wave. Substituting equation (A-8) for a_s and for a_t yields

$$\frac{a_s}{a_t} = \frac{a_{i1}}{a_{i2}} \cdot \frac{1 - \Gamma_t \Gamma_e}{1 - \Gamma_s \Gamma_e} \qquad (3\text{-}5)$$

In this equation Γ_e is the effective source reflection coefficient looking back into the measurement port and Γ_s and Γ_t are the reflection coefficients of the *standard power sensor* and *sensor under test.* From **Figure 3-3** and equations (3-1) and (3-2) it is also true that

$$\frac{P_{i1}}{P_{i2}} = \left|\frac{a_{i1}}{a_{i2}}\right|^2 = \frac{\dfrac{M_{i1}}{(1 \pm i_1)\,K_i}}{\dfrac{M_{i2}}{(1 \pm i_2)\,K_i}} = \frac{M_{i1}}{M_{i2}} \cdot \frac{1 \pm i_2}{1 \pm i_1} \qquad (3\text{-}6)$$

where i_1 and i_2 refer to the *incident power meter* uncertainties during the two measurements and K_i is the calibration factor of the power sensor connected to the *incident power meter.* When equations (3-4), (3-5), and (3-6) are substituted in equation (3-3), the result is

$$\frac{K_b}{K_s} = \frac{M_t}{M_{i2}} \cdot \frac{M_{i1}}{M_s} \left|\frac{1 - \Gamma_t \Gamma_e}{1 - \Gamma_s \Gamma_e}\right|^2 \frac{1 \pm i_2}{1 \pm i_1}\,\frac{1 \pm i_s}{1 \pm i_t} \qquad (3\text{-}7)$$

If the measurement system were ideal, the power meters would have no instrumentation error (all the i's would be zero) and the equivalent source reflection, Γ_e, would be zero. Then the calibration factor would be given by

$$K_b = \frac{\dfrac{M_t}{M_{i2}}}{\dfrac{M_s}{M_{i1}}}\,K_s \qquad (3\text{-}8)$$

This is the value of K_b that is calculated by the program that follows. M_s/M_{i1}, expressed in dB, is stored in array C[N]. M_t/M_{i2}, expressed in dB, is stored in array K[N].

The proper value of K_s is either read directly from the array or interpolated. Equation (3-8) is then solved and the result is stored in array K[N].

Calculating Worst-Case Uncertainty

The percent worst-case uncertainty of the calibration factor U_{Kb} is defined as

$$U_{Kb} = \frac{K_{b\,max} - K_b}{K_b}\,100 = \left(\frac{K_{b\,max}}{K_b} - 1\right) 100 \qquad (3\text{-}9)$$

where $K_{b\,max}$ is the largest possible value of K_b.* $K_{b\,max}$ is calculated by maximizing the separate terms of equation (3-7) to give

$$K_{b\,max} = K_{s\,max} \underbrace{\frac{\dfrac{M_t}{M_{i2}}}{\dfrac{M_{i1}}{M_s}}}_{\textstyle = K_{s\,max}\ \frac{K_b}{K_s}} \underbrace{\left|\frac{1 - \Gamma_t \Gamma_e}{1 - \Gamma_s \Gamma_e}\right|^2_{max}}_{M} \underbrace{\left(\frac{1 \pm i_2}{1 \pm i_1}\right)_{max} \left(\frac{1 \pm i_s}{1 \pm i_t}\right)_{max}}_{W} \qquad (3\text{-}10)$$

The substitution of K_b/K_s comes from equation (3-8). The procedure for finding M and W will soon be discussed. $K_{s\,max}/K_s$ can be found by applying equation (3-9) to the *standard power sensor*

$$\frac{K_{s\,max}}{K_s} = \frac{U_{Ks}}{100} + 1 \qquad (3\text{-}11)$$

where U_{Ks} is the calibration factor uncertainty of the *standard power sensor.* When equations (3-10) and (3-11) are substituted in (3-9) the result is

$$U_{Kb} = \left[\left(\frac{U_{Ks}}{100} + 1\right) MW - 1\right] 100 \qquad (3\text{-}12)$$

This is the equation used in the program that follows.

---

* It is true that $K_{b\,max} - K_b$ is larger than $K_b - K_{b\,min}$ but usually by a very small amount.

Mismatch Uncertainty

The M of equations (3-10) and (3-12) is the maximum total mismatch uncertainty caused by (1) re-reflections between the *standard power sensor* and the effective source looking back into the test port of the coupler and (2) re-reflections between the *sensor under test* and the effective source looking back into the test port of the coupler. The worst-case value occurs when the reflection coefficient magnitudes are at their largest and the reflections combine in phase to give the largest value to M. M can be written as

$$M = \left(\frac{1 + \rho_{t\ max}\, \rho_{e\ max}}{1 - \rho_s\, \rho_{e\ max}} \right)^2 \tag{3-13}$$

where ρ refers to magnitude of corresponding reflection coefficients. The *standard power sensor* reflection coefficient magnitude, ρ_s, is taken from the calibration lab report data that is stored in array A[I,J] of the computer program. Values of $\rho_{t\ max}$ and $\rho_{e\ max}$ will now be discussed.

The worst-case equivalent source reflection coefficient, $\rho_{e\ max}$ (labeled G in the sample program), is calculated from equation (A-6) of Appendix A.

$$\rho_{e\ max} = |S_{22}| + \frac{|S_{21}|^2 (\rho_c + |TD_i|)_{max}}{1 - |S_{11}|_{max} (\rho_c + |TD_i|)_{max}} \tag{3-14}$$

The S parameters refer to the attenuator that is used on the coupler output. $|S_{22}|$ and $|S_{21}|$ are stored as calibration data in A[I,10] and A[I,11] respectively. $|S_{11}|_{max}$ is read from the attenuator data sheet and is indicated by the symbol U in the program. The $(\rho_c + |TD_i|)_{max}$ term is given the label C and is also used later in calculating $\rho_{t\ max}$. The coupler mainline reflection coefficient, ρ_c, is read from the data array A[I,8]. The coupler used with the system consists of two 22 dB couplers. An upper bound on T, found by considering only coupling loss, is $T = 1 - (0.1)^2 = 0.99$. The incident arm directivity, D_i, is stored in array A[I,9]. This allows the calculation of C and of the effective source reflection coefficient G. To conserve power when measuring the high power HP 8481H Power Sensor, the 10 dB attenuator at the measurement port is not used. In this case G = C.

Sensor Under Test Reflection Coefficient

The reflectometer measures the reflection coefficient magnitude of the *sensor under test* (**Figure 3-4**). This reflection coefficient is used mainly to calculate mismatch uncertainty M. Reflection coefficient is the ratio of the reflected wave to the incident for the *sensor under test.* The procedure for using the reflectometer is to first measure the magnitude of that ratio for a short circuit, which has a reflection coefficient of −1, and then to measure it for the *sensor under test.* The ratio of those ratios is taken as the reflection coefficient magnitude of the *sensor under test.* In terms of **Figure 3-4**

$$R = \frac{\left.\dfrac{|a_r|}{|a_i|}\right|_{\text{sensor under test}}}{\left.\dfrac{|a_r|}{|a_i|}\right|_{\Gamma = -1}} \tag{3-15}$$

The denominator, expressed in dB, is measured and stored in array, S[N]. The numerator, in dB, is measured and stored in array R[N]. The value of the reflection coefficient is calculated and stored in array R[N].

The worst-case error in considering R of equation (3-15) as the reflection coefficient is evaluated in Appendix B and given in equations (B-8) and (B-9) as

$$\Delta\rho_{max} = A + B\rho + C\rho^2 \tag{3-16}$$

where

$$A = \frac{|D_r|}{|T|}$$

$$B = \rho_c + |TD_i| + \frac{|D_r|}{|T|}$$

$$C = \rho_c + |TD_i|$$

The reflected arm directivity D_r is inserted from data sheet specification limits. T and C were already evaluated above so $\Delta\rho_{max}$ of equation (3-16) is calculated and stored in array Q[N].

The highest possible reflection coefficient of the *sensor under test* is the sum of the indicated value and the worst-case error

$$\rho_{d\ max} = \rho + \Delta\rho_{max} = R[N] + Q[N] \tag{3-17}$$

This is the value used to calculate the total mismatch uncertainty M in the program for the system.

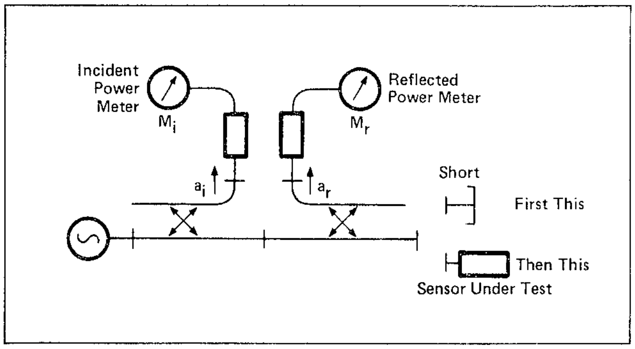

Figure 3-4. Schematic diagram of reflection coefficient measurement.

Power Meter Uncertainty

There are two possible sources of power meter uncertainty besides the basic accuracy of the power meters symbolized by i. They are noise and reference oscillator mismatch uncertainty. These sources will be individually evaluated. All the sources of power meter uncertainty are then tabulated and combined in **Figure 3-5.** The results are used in the program that follows as the variable W.

The first part of W from equation (3-10), $((1 \pm i_2)/(1 \pm i_1))_{max}$, accounts for the instrumentation uncertainty of the *incident power meter.* The *incident power meter* actually measures the ratio of the generator output for the *standard power sensor* to the output for the *sensor under test.* Many sources of instrumentation error cancel when the ratio of two power meter readings is taken. For example, if a power meter has too high a gain in its metering circuits, so that the output consistently reads twice as high as it should, the numerator and denominator are each too high but the ratio is still correct. Another example of error canceling is the power reference oscillator output. If it is too high for the *standard power sensor,* it is also too high for the *sensor under test.* The HP 436A Power Meter is especially good for relative power measurements. If the two measurements of incident power are on the same range, as they are for the calibration factor measurement of the HP 8481A and 8481H Power Sensors and for the 8478B Thermistor Mounts, the uncertainty of the ratio is ±0.02 dB. For the HP 8484A Power Sensor, the meter range for the measurement with the *standard power sensor* is different than the meter range for the *sensor under test* measurement. There is an additional ±0.02 dB range-to-range uncertainty so the total uncertainty of the ratio is ±0.04 dB.

The last part of W from equation (3-10), $((1 \pm i_s)/(1 \pm i_t))_{max}$, involves the identical concern for the *test power meter* that meters the *standard power sensor* and the *sensor under test.* If both sensors are the HP 8481A, the power meter will read on the same range and the uncertainty is ±0.02 dB. If the *sensor under test* is the 8484A or 8481H, the power meter range for the *standard power sensor* and the *sensor under test* are different and the uncertainty is therefore ±0.04 dB.

The HP 432A Power Meter, used for calibrating thermistor mounts, has no specification for relative power measurements or ratios. If specifications for absolute power measurements were applied twice, once for the standard and once for the unknown, the result would be about ±0.14 dB. This uncertainty is overly conservative and large enough to restrict the usefulness of the system. A separate evaluation of several HP 432A Power Meters showed, at levels between full scale and 3 dB below full scale, that the power ratio was accurate to within ±0.03 dB.

	8481A Sensor	8481H Sensor	8484A Sensor	478A 8478B Sensor
$\left(\frac{1 \pm i_2}{1 \pm i_1}\right)_{max}$	±0.02 dB	±0.02 dB	±0.04 dB	±0.02 dB
$\left(\frac{1 \pm i_s}{1 \pm i_t}\right)_{max}$	±0.02	±0.04	±0.04	±0.03
Noise	2(±0.0028)	±0.028	±0.003	2(±0.017)
Ref. Osc. M_u	±0.017	±0.017	±0.017	0
Total Uncertainty	±0.063 dB	±0.105 dB	±0.100 dB	±0.084 dB
Absolute Ratio	1.0146	1.02447	1.02329	1.01953

Figure 3-5. A chart of the measurement error components that make up the total power meter uncertainty.

The effect of noise is to increase or decrease the desired signal. It could affect the result both during the measurement of the *standard power sensor* and during the measurement of the *sensor under test.* Each of the "Noise" entries in **Figure 3-5** will now be discussed. The HP 432A Power Meter for use with the thermistor mounts has a specified noise level of ±0.25 percent of full scale. For measurements 2 dB down from full scale this could contribute ±0.4 percent or ±0.017 dB. For the HP 8481A Power Sensor the noise level is typically 40 nW. For measurements at −12 dBm the noise could change the signal by ±0.063 percent or ±0.0028 dB. For measurements at −2 dBm, the noise could contribute ±0.0063 percent which is negligible. The HP 8481H Power Sensor has a typical noise level of 4 μW. For measurements at −2 dBm, the noise could contribute ±0.63 percent or ±0.028 dB. For the HP 8484A Power Sensor the typical noise level is ±20 pW. At a signal level of −32 dBm (630 nW) the noise could contribute ±0.003 percent.

For the HP 8480 Series of power sensors there is still another uncertainty: the mismatch uncertainty between the power reference oscillator and the *standard power sensor* as well as the *sensor under test.* Each of these mismatch uncertainties contributes an additional ±0.017 dB (±0.0087 dB for each sensor) to the instrumentation uncertainty.

When setting the CAL ADJ for the 8484A Sensor, a 30 dB attenuator is used on the power reference output. If this attenuator will always be dedicated to the 8484A being calibrated, then it adds no error. If it is not dedicated, then an additional ±0.05 dB or 1 percent should be added. The example program used here does not include this possible source of error.

Effective Efficiency

Once the calibration factor and reflection coefficient of a power sensor are known, the effective efficiency can be calculated according to the equation

$$\eta_e = \frac{K_b}{1-\rho^2} \qquad (3\text{-}18)$$

This is the relationship used in the sample program.

The uncertainty of η_e is defined in the same manner as the uncertainty of K_b given in equation (3-9)

$$U_\eta = \left(\frac{\eta_{e\,max}}{\eta_e} - 1\right)100 \qquad (3\text{-}19)$$

Equation (3-18) can be extended to find $\eta_{e\,max}$

$$\eta_{e\,max} = \frac{K_{b\,max}}{1-\rho_{max}^2} = \frac{K_{b\,max}}{1-(\rho+\Delta\rho)^2} \qquad (3\text{-}20)$$

Now by combining equations (3-18), (3-19) and (3-20)

$$U_\eta = \left(\frac{K_{b\,max}\,(1-\rho^2)}{K_b\,(1-(\rho+\Delta\rho)^2)} - 1\right)100 \qquad (3\text{-}21)$$

But $K_{b\,max}/K_b$ has already been evaluated by means of equations (3-9) and (3-12) so that

$$U_\eta = \left(\left(\frac{U_{Kb}}{100}+1\right)\frac{1-\rho^2}{1-(\rho+\Delta\,\rho)^2}-1\right)100 \qquad (3\text{-}22)$$

This is the uncertainty calculated in the sample program.

Program Operation

(1) Set up measurement system as shown in **Figure 3-1.**

- It is recommended that the system be allowed 1 hour warm-up time.
- During operation of the program, the 8672A Synthesized Signal Generator should have the RF switch on the front panel in the OFF position and the RANGE dBm switch set a maximum of −40. This protects against the possibility of power meters going into an over-range condition. The recovery from such a condition may take a longer time than the program allows.
- The CAL FACTOR dials on all Power Meters should be set to 100 percent.
- Zero-set and set the CAL ADJ of the two 436A/8484A's that connect to the incident and reflected coupler ports according to the Operating Instructions in the 436A Operating Manual. Be sure to connect the 11708A Reference Attenuator to the 436A Power Reference Output when calibrating.

(2) Insert the 436A–E10 System Tape, rewind, load file 0 (or whatever file contains the main program) and press RUN. "TODAY'S DATE?" will appear in the display. Type the date in the manner desired for the final report and press CONTINUE.

(3) When "FILE # of CALIBRATION DATA?" appears, type in the proper file number (usually file 1) and press CONTINUE.

(4) When "START FREQ (MHz)?" appears, there are two choices of answers.

  (a) If CONTINUE is pressed without entering anything on the keyboard, the program will measure at those frequencies where there is calibration data–usually 2 to 18 GHz in 1 GHz steps plus 12.4 GHz. Furthermore, the next two program prompts, for STOP FREQ and FREQ STEP, are skipped.

  (b) If some other frequency set is desired, enter the lowest frequency of the set in MHz and then press CONTINUE.

(5) When "STOP FREQ (MHz)?" appears in the calculator display, type the last test frequency and press CONTINUE.

(6) "FREQ STEP (MHz)?" next appears. Type the frequency increment between test points and press CONTINUE.

Note: The program as written only calibrates at 41 frequencies. If the START, STOP, and STEP inputs correspond to more than 41 frequencies, the program will loop back to the start of step number 4, requesting new frequency data.

(7) "SHORT TO COUP. OUTPUT" tells the operator to place a short circuit on the test port of the coupler. When this is done, press CONTINUE. The program will measure and save the difference in dB between the *reflected* and *incident power meter* readings at each frequency.

(8) "SENSOR UNDER TEST MODEL #?" requires a proper model number of an HP sensor. The standard program accepts the following: 478A, 8478B, 8481A, 8481H, and 8484A. If the answer is unacceptable, the program loops back and re-asks the question. In order for the program to handle other power sensors the program must be changed.

(9) "SENSOR UNDER TEST SERIAL #?" will next appear. A reply of up to 11 alphanumeric characters is allowed. Press CONTINUE when ready.

(10) If the *sensor under test* is an HP 8484A Power Sensor, a 30 dB attenuator is used for setting the CAL ADJ on the 436A. The serial number of this attenuator is entered next in answer to the prompt, "SER

OF 30 dB 11708A ATTEN." Press CONTINUE when the serial number is entered. This step is skipped if the *sensor under test* is other than the 8484A.

Note: If a 436A and this 8484A is used without that particular attenuator for CAL ADJ, an additional uncertainty of ±0.05 dB (1 percent) should be added to the results printed.

(11) **FOR THERMISTOR MOUNTS**

- The program prompts "STD 8478B to 432A POWER METER!" This refers to the thermistor mount with the Standards Lab calibration. Press CONTINUE when accomplished.
- The next prompt is "STD 8478B TO COUP. VIA SPECIAL ATTN". Press CONTINUE when accomplished.
- The next prompt is "ZERO 432A POWER METER–CHECK DRIFT!" After zeroing on the lowest power range, observe whether the needle moves less than 0.4 μW (about 2 divisions) in one minute. If the drift is greater than this, do not proceed until the thermistor reaches thermal equilibrium and the drift subsides. This could take an hour but is usually only a few minutes. Once the drift is low enough, press the FINE ZERO toggle on the 432A once more and press CONTINUE on the calculator.
- The next prompt is "SET 432A to 0.1 mW RANGE". Press CONTINUE when the power meter range is proper.

FOR 8480 FAMILY POWER SENSORS

- "STD 8481A TO TEST POWER METER!" refers to the 8481A *standard power sensor* with the special Standards Lab calibration. Press CONTINUE when the sensor is connected to the power meter.
- When "ZERO-SET & CALIBRATE TO 1mW" is displayed, the *standard power sensor* should be connected to the 436A, 50 MHz, Power Reference Output. The Power Reference Oscillator on any of the 436A Power Meters may be used. It is important, however, to use the same Power Reference Oscillator for the *standard power sensor* and for the *sensor under test*. Once the sensor is connected, but with the Power Reference Oscillator turned off, the *test power meter* is to be zero-set by depressing the SENSOR ZERO button until the meter reads zero. The Power Reference Oscillator is not to be turned ON until the ZERO light goes out. The CAL ADJ must be set to 1 mW. When this operation is completed, press CONTINUE.
- The next instruction displayed is either "STD 8481A TO COUP. DIRECT" (for the case of calibrating to test the 8481H), or "STD 8481A TO COUP VIA SPEC. ATTN" (for the case of calibrating to test the 8481A or 8484A Power Sensors). Press CONTINUE when the *standard power sensor* is connected. The program will wait about 2 minutes before beginning measurement to allow the power sensor temperature to stabilize. If this wait is eliminated, the zero-set will often have drifted significantly by the tenth or fifteenth frequency of measurement. After the wait the system measures and stores the dB difference between the *test power meter reading* and *incident power meter* reading at each frequency. This completes the calibration process.

(12) The next step is to make the same measurement with the *sensor under test* as was made with the *standard power sensor* in step number 11. The instructions are much the same. Connect the *sensor under test* to the *test power meter* and follow the instruction prompts. Press CONTINUE after each instruction is followed.

- For thermistor mounts, part of zero-setting is to wait until thermal drift is below 0.4 μW/minute as described in step number 11 for the *standard power sensor*. When the drift has settled, press FINE ZERO on the 432A once more and then press CONTINUE.
- If the *sensor under test* is an 8484A Power Sensor, it is connected to the Power Reference Output of the 436A through an 11708A, 30 dB attenuator and the CAL ADJ on the *test power meter* is set to 1 μW. Be sure to use the same Power Reference Oscillator as was used for the *standard power sensor* in step number 11.
- If the *sensor under test* is the 8481H, during CAL ADJ the meter reading has a long settling time. The meter reading is also somewhat noisy. This is normal and accounted for in the uncertainty that will be printed for this sensor. The average reading should be 1 mW (or 0.00 dBm) with a typical deviation of up to ±0.004 mW (or ±0.02 dBm).

(13) The next part of the program measures the reflection coefficient of the *sensor under test*. Again press CONTINUE after each instruction is followed.

- If the *sensor under test* is the 8481H, no 10 dB attenuator needs to be removed. The test set-up is exactly the same as in step number 12 and the program continues automatically with no prompts.
- For all other *sensors under test*, the 10 dB attenuator is to be removed.
- For Thermistor Mounts, the 432A Power Meter should have its range switch set to the highest range.

- For the 8484A, the *test power meter* will be overranged during this measurement. The power incident upon the *sensor under test* is close to 0 dBm, but it is not enough to damage the 8484A nor enough to significantly change its reflection coefficient.

(14) After all the measurements and calculations are complete, the calculator outputs the data on its strip printer.

(15) The program loops back to step number 8, "SENSOR UNDER TEST MODEL #?". If the new model number is such that the calibration is still valid, step number 11 is skipped.

Measurement Results

The purpose of this system is to economically and periodically measure the calibration factor of power sensors with better accuracy than would be achieved by considering data sheet specifications of the system components. When compared to an Automatic Network Analyzer, this system is almost as accurate but has much lower cost.

The uncertainty of calibration factor measurement for this system is compared to the other alternatives in **Figure 3-6** for the 8484A Power Sensor. The uncertainty for this system, using stored data, is one-half to one-third the uncertainty calculated using data sheet specification limits of the system components.

Figure 3-6 also shows that this system is only slightly less accurate than the published specifications achieved with an Automatic Network Analyzer (ANA). It should be noted, however, that the ANA uncertainty is guaranteed for any and all HP 8484A Power Sensors. The ANA uncertainty is calculated assuming that the *sensor under test* has a reflection coefficient magnitude that corresponds to the data sheet specification limit. If the ANA uncertainty were individually calculated for each sensor at each frequency (such as is done by the 436A–E10 program), the ANA uncertainty would be significantly lower. The uncertainty listed for this desktop computer-based system, only applies to one particular power sensor. Another power sensor, even of the same type, will yield a different uncertainty.

The Automatic Network Analyzer System is more accurate than the 436A–E10 system because the ANA corrects for re-reflections between the power sensors and the measurement equipment. Such correction requires the capability to measure the phase angle of reflection coefficient. The 436A–E10 system does not measure phase, thus it is not an error correcting system. But it is an error evaluating system—it evaluates the limits of error, especially those due to re-reflection phenomena.

The measurement uncertainty printed by this system still seems to be quite conservative. **Figure 3-7** shows the calibration factor as measured by a Standards Laboratory and then the uncertainty as measured on this system. This was done for two sensors, an HP 8481A thermocouple type sensor and an HP 8478B thermistor type sensor. Note that any deviation between the Standards Lab result and the result with this system is well within the uncertainty limits printed by this system.

A sample of the complete system printout is printed in **Figure 3-8.** Also shown in **Figure 3-8** is a sample printout when non-standard and standard frequencies are chosen. For the non-standard frequencies, measurement uncertainty is not printed because there is no longer traceability to the National Bureau of Standards.

		Uncertainty (%)		
Freq (GHz)	Cal. Factor (%)	436A-E10 Using Measured Data for the System Components	Manufacturing Specifications Using the 8542B Automatic Network Analyzer	436A-E10 Using Published Data Sheet Specification Limits for the System Components
2.0	97.4	4.0	4.70	10.4
3.0	97.2	4.2		10.4
4.0	96.5	4.2	4.36	9.9
5.0	96.5	4.3		10.5
6.0	95.3	4.0	4.55	10.5
7.0	95.2	4.2		10.5
8.0	95.1	4.2	4.47	10.4
9.0	93.9	5.2		13.7
10.0	94.5	5.7	4.42	13.7
11.0	93.8	5.8		15.4
12.0	94.5	6.5		15.4
12.4	94.4	6.9	4.71	15.4
13.0	94.3	7.5		26.0
14.0	94.7	7.3	7.00	25.9
15.0	97.7	7.7		26.0
16.0	96.2	8.7	7.62	26.5
17.0	99.1	9.3		26.5
18.0	98.3	8.4	7.15	26.5

Figure 3-6. A table of the calibration factor uncertainty for an HP 8484A Power Sensor as measured with different techniques.

HP 8481A

Freq (GHz)	Standards Lab Data		436A-E10 Data	
	C.F.	% UNC	C.F.	% UNC
2.0	98.8	1.5	99.0	3.2
3.0	98.4	1.5	98.4	3.3
4.0	98.4	1.5	98.3	3.3
5.0	98.1	1.5	97.9	3.4
6.0	97.6	1.5	97.6	3.3
7.0	97.3	1.6	96.9	3.4
8.0	96.9	1.6	96.9	3.7
9.0	96.2	1.8	96.5	3.9
10.0	95.9	1.8	95.6	4.2
11.0	95.2	1.8	96.0	4.5
12.0	95.7	1.8	94.7	4.8
12.4	94.7	1.8	94.7	5.9
13.0	93.5	2.7	93.7	7.2
14.0	94.1	2.7	94.0	9.0
15.0	92.7	2.7	92.9	8.6
16.0	92.6	2.7	93.3	8.1
17.0	92.8	2.7	92.5	7.2
18.0	92.7	2.7	92.7	6.0

HP 8478B

Freq (GHz)	Standards Lab Data		436A-E10 Data	
	C.F.	% UNC	C.F.	% UNC
2.0	98.2	1.5	98.4	3.8
3.0	97.9	1.5	97.9	4.0
4.0	97.6	1.5	97.8	4.0
5.0	97.3	1.5	97.5	4.2
6.0	96.8	1.6	96.9	4.1
7.0	96.5	1.6	96.7	4.3
8.0	96.2	1.6	96.0	4.6
9.0	95.8	1.8	95.7	5.1
10.0	95.4	1.8	95.5	5.7
11.0	95.2	1.8	94.9	6.1
12.0	94.4	1.8	95.0	6.3
12.4	94.9	1.8	94.1	7.1
13.0	93.4	2.7	93.6	7.7
14.0	94.4	2.7	95.0	9.3
15.0	93.7	2.7	93.8	7.8
16.0	93.4	2.7	93.8	8.8
17.0	93.2	2.7	93.4	7.7
18.0	93.8	2.7	94.3	6.2

Figure 3-7. A comparison of calibration factor data as measured by a Standards Lab and by the 436A-E10 system for (upper) an HP 8481A and (lower) HP 8478B.

```
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 CALIBRATION DATA
 FOR POWER SENSOR
 HP MODEL# 8481H
 SER#  1234A3532
 USING STANDARD
 8481A SENSOR
 SER# 1234A03322

 REF. CAL FACTOR
 @ 50MHz=  97%

 FREQ
 GHz     CF%   %UNC
  2.0   94.5    4.3
  3.0   94.6    4.6
  4.0   95.7    4.2
  5.0   95.6    5.1
  6.0   95.5    4.4
  7.0   96.1    4.9
  8.0   97.3    5.5
  9.0   98.2    5.7
 10.0   98.5    5.3
 11.0   98.7    5.8
 12.0   99.0    6.4
 12.4   99.1    6.2
 13.0   97.6    6.7
 14.0   96.9    7.7
 15.0   96.6    7.0
 16.0   93.2    9.3
 17.0   88.2   10.1
 18.0   88.5    8.6

 FREQ
 GHz     EE%   %UNC
  2.0   94.5    4.4
  3.0   94.6    4.8
  4.0   95.7    4.5
  5.0   95.7    5.4
  6.0   95.5    4.5
  7.0   96.1    5.1
  8.0   97.5    6.0
  9.0   98.4    7.0
 10.0   98.7    6.5
 11.0   98.8    6.8
 12.0   99.2    7.5
 12.4   99.5    7.7
 13.0   98.1    8.2
 14.0   97.4    9.4
 15.0   97.1    8.7
 16.0   93.8   11.3
 17.0   88.8   12.2
 18.0   88.6    9.6

        REF
 FREQ COEFF DELTA
 GHz    RHO   RHO
  2.0 0.009 0.032
  3.0 0.020 0.033
  4.0 0.015 0.033
  5.0 0.030 0.035
  6.0 0.004 0.032
  7.0 0.006 0.032
  8.0 0.042 0.036
  9.0 0.053 0.069
 10.0 0.045 0.068
 11.0 0.035 0.068
 12.0 0.040 0.070
 12.4 0.061 0.071
 13.0 0.067 0.071
 14.0 0.073 0.073
 15.0 0.072 0.072
 16.0 0.078 0.076
 17.0 0.081 0.078
 18.0 0.034 0.069
```

```
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 CALIBRATION DATA
 FOR POWER SENSOR
 HP MODEL# 8481A
 SER# 1550A08189
 USING STANDARD
 8481A SENSOR
 SER# 1234A03322

 REF. CAL FACTOR
 @ 50MHz= 100%

 FREQ
 GHz     CF%   %UNC
  8.0   97.6    3.3
  8.5   97.2   $$$$
  9.0   97.3    4.0
  9.5   96.9   $$$$
 10.0   95.7    4.4
 10.5   95.1   $$$$
 11.0   95.0    5.2
 11.5   95.0   $$$$
 12.0   94.6    5.6
 12.5   93.6   $$$$

 FREQ
 GHz     EE%   %UNC
  8.0   97.7    3.6
  8.5   97.2   $$$$
  9.0   97.4    4.9
  9.5   97.1   $$$$
 10.0   95.7    5.2
 10.5   95.2   $$$$
 11.0   95.2    6.4
 11.5   95.2   $$$$
 12.0   94.9    7.0
 12.5   93.9   $$$$

        REF
 FREQ COEFF DELTA
 GHz    RHO   RHO
  8.0 0.029 0.035
  8.5 0.015 $$$$$
  9.0 0.034 0.067
  9.5 0.042 $$$$$
 10.0 0.022 0.066
 10.5 0.031 $$$$$
 11.0 0.046 0.070
 11.5 0.039 $$$$$
 12.0 0.052 0.072
 12.5 0.052 $$$$$
```

Figure 3-8. Typical printouts of data taken by the 436A-E10 system. $$$$ shows unavailable traceability to NBS.

Programs

The 436A–E10 System Tape consists of the following three files for measuring calibration factor:

File 0: Power Sensor Calibration Program
File 1: File of Measured Data about System Components
File 2: Power Sensor Data File Construction Program
File 3: Attenuation and Rho Measurement Program

The power sensor calibration program will now be explained to ease any changes that may be necessary for a particular application.

Main Program

The main power sensor calibration program is divided into the following sections and subsections:

- Initialization, data entry, frequency entry (LINES 0-17)
- Calibration with short circuit and Standard Sensor (LINES 18-58)
- Measurement of the *sensor under test* (LINES 59-95)
- Calculations and printing of results (LINES 96-157)
- Subroutines and Subfunctions (LINES 158-211)

The variables of the main program are assigned as follows:

Matrices:

A[18, 11]	Calibration data for system components that is read from the data file. Each row is data for a specific frequency. Each column consists of the following:
Column 1	Frequency in MHz.
Column 2	Calibration Factor in % of the Standard HP 8481A Power Sensor.
Column 3	Uncertainty of calibration factor data in column 2.
Column 4	Reflection-coefficient magnitude of the Standard 8481A Power Sensor.
Column 5	Calibration Factor in % of the Standard HP 8478B Thermistor Mount.
Column 6	Uncertainty of calibration factor data in column 5.
Column 7	Reflection-coefficient magnitude of the Standard 8478B Thermistor Mount.
Column 8	Mainline reflection coefficient of the dual-directional coupler as viewed from the test port.
Column 9	Directivity of the incident arm of the dual-directional coupler.
Column 10	Reflection coefficient of the special 10 dB attenuator as viewed from the female end (right end).
Column 11	Attenuation of the special 10 dB attenuator.
C[41]	Array for storing the difference in dB between coupler or attenuator output power, when the *standard power sensor* is connected, and the power monitored by the *incident power meter.* Each row corresponds to a selected frequency.
K[41]	Array for storing the difference in dB between coupler or attenuator output power, when the *sensor under test* is connected, and the power monitored by the *incident power meter.* During the calculation of the results, the data in this array gets changed to the calibration factor of the *sensor under test.*
Q[41]	Array for storing the uncertainty of the measured reflection coefficient of the *sensor under test.*
R[41]	Array for storing the dB difference between the *reflected power meter* and the *incident power meter* readings when the *sensor under test* is connected to the coupler output. During the calculation of the results, the data in this array gets changed to the reflection coefficient of the *sensor under test.*
S[41]	Array for storing the dB difference between the *reflected power meter* and the *incident power meter* readings when a short circuit is connected to the coupler output.
T[41]	Array for storing the worst-case uncertainty of the measured calibration factor.

String Variables:

A$[11]	Serial number of the 30 dB attenuator used to set CAL ADJ for an HP 8484A Power Sensor.
C$[4, 11]	Each row stores a serial number of a system component as follows: row 1 Standard HP 8481A Power Sensor. row 2 Standard HP 8478 Thermistor Mount. row 3 Dual-Directional Coupler. row 4 Special 10 dB attenuator.
D$[16]	Today's date.
K$[6]	Model number of the *sensor under test.*
L$[11]	Serial number of the *sensor under test.*

Simple Variables:

A	One of the calculated uncertainty terms pertaining to the measurement of reflection coefficient. A is also the maximum value of Calibration Factor used for renormalizing.
C	One of the calculated uncertainty terms pertaining to the measurement of reflection coefficient.
D	The desired power from a certain sensor that, if not achieved, is used to vary the signal generator power. D is also used as the reflected arm directivity of the coupler.
E	Start frequency in MHz.
F	Frequency in MHz.

G	Calculated source reflection coefficient magnitude.
H	Stop frequency in MHz.
I	Row index for the matrix A[*].
J	Column index for the matrix A[*].
K	Calibration Factor of *standard power sensor.*
L	Power level (dBm) to which the signal generator is programmed.
M	Mismatch uncertainty.
N	Counter for the current number of the frequency. Also the counter of the number of 30-second waiting periods to comprise a total waiting time.
Q	Frequency increment in MHz.
S	Code that identifies the model number of the *sensor under test.*
T	Transmission coefficient of coupler.
U	Reflection-coefficient magnitude of 10 dB attenuator from the male end (left end).
V	The number of frequencies at which measurements are made.
W	Total instrumentation uncertainty.
X	File number of calibration data. Also a variable to dump unwanted power meter readings. X is also used for the worst-case uncertainty of effective efficiency.

r Variables:

r0	A number that identifies the measurement cycle being performed: 1 for calibration with the short circuit, 2 for calibration with the *standard power sensor,* 3 for calibration factor measurement of the *sensor under test,* and 4 for reflection coefficient measurement.
r1	The value of the variable S during the last calibration. The same calibration is valid for any combination of HP 8478B and HP 478A *sensors under test.* The same calibration is valid for any combination of HP 8481A and 8484A *sensors under test.*

flags:

1	(0) Measurement frequencies are calculated from START, STOP, and STEP frequency inputs. (1) Measurement frequencies are chosen from the first column of matrix A; these are standard frequencies.
3	(0) The frequency being considered is a standard frequency and uncertainties are calculated. (1) The frequency being considered is not standard and therefore the uncertainty is not printed.
13	(0) Data was supplied during the last enter statement. (1) CONTINUE was pressed without entering data during the last enter statement.

Calibration Data File Construction Program

This program, normally stored on FILE 2 of the 436A–E10 System Tape, is used to construct, modify, print, or copy the calibration data file of the system. Operation of the program is as follows:

(1) Load the program, normally in FILE 2, and press RUN.

(2) Answer the prompt "OLD CALIBRATION FILE # = ?" with the data file number and press CONTINUE. If a completely new file is to be constructed simply press CONTINUE without entering any number.

- If a totally new file is being constructed, the program loads the standard frequencies of 2 to 18 GHz in 1 GHz steps and also 12.4 GHz. If other frequencies are desired, the program will have to be modified.
- If a totally new file is not being constructed, the old data is loaded. Then answer the prompt "CHANGE DATA (Y or N)?" with a Y for yes or N for no and press CONTINUE. If "N" is entered, proceed to step number 4 below.

(3) As the program prompts the operator through the various pieces of data the old data is displayed. If no change is to be made to the old data item, simply press CONTINUE to retain the old data item. The next data item is then prompted for entry. If a new value is to be entered, type in the value and press CONTINUE.

- The first four items of data are the serial numbers of the special system components.
- The remainder of the prompts proceed through the array of calibration data A [*], column by column from columns 2 through 11.
- If a mistake is made, write it down and proceed as if there were no mistake. There is an opportunity for further corrections later in the program.

(4) The next question is "PRINT CALIBRATION DATA (Y or N)?" If "Y" is answered, all the data items are printed.

(5) The next question is "ANY OTHER CHANGES (Y or N)?". If "Y" is answered the program goes back to the beginning of step number 3 above.

(6) The last prompt is "FILE # TO STORE NEW DATA." The program will print the data on whatever magnetic cartridge file is specified.

Extensions of the Basic System

There are many possible ways of changing this system to satisfy other needs such as using other signal sources, testing power sensors from other manufacturers, using a different computer, or using a different digital voltmeter for reading the thermistor mount power meter. One popular addition is to use a line printer instead of the narrow printer tape of the 9825A. The output portion of the program is consolidated into one section to facilitate such a change.

The program shown here utilizes the 2 to 18 GHz HP 8672A Synthesized Signal Generator. Other sources of RF energy could be used with suitable modifications to the program. A microwave sweep oscillator, for example, could be used for some of the sensors. For the sensitive HP 8484A Power Sensor, however, the power level must be reduced considerably so a programmable attenuator would be necessary for a completely automatic system. Manual attenuators could also be used for setting the power level if appropriate instructions are inserted into the program.

The system described here covers the frequency range of 2 to 18 GHz. Yet the power sensors normally operate down to 10 MHz. The question arises about checking performance over that entire frequency range. If an 8481A, 8481H, or 8484A Power Sensor has problems below 2 GHz, Hewlett-Packard production experience shows that the sensors will also have problems above 2 GHz, or they will not calibrate properly at 50 MHz. If the sensor is operating properly, any variation in the calibration factor over frequencies below 2 GHz will be small compared to the uncertainties of measurement. A linear interpolation of calibration factor from 50 MHz to 2 GHz is almost always adequate. For the HP 8478B and 478A Thermistor Mounts, a check of reflection coefficient magnitude at 10 MHz along with calibration factor measurements above 2 GHz is sufficient to insure proper operation and a low measurement uncertainty. Measurements below 2 GHz, therefore, are felt to be much less necessary than those above 2 GHz.

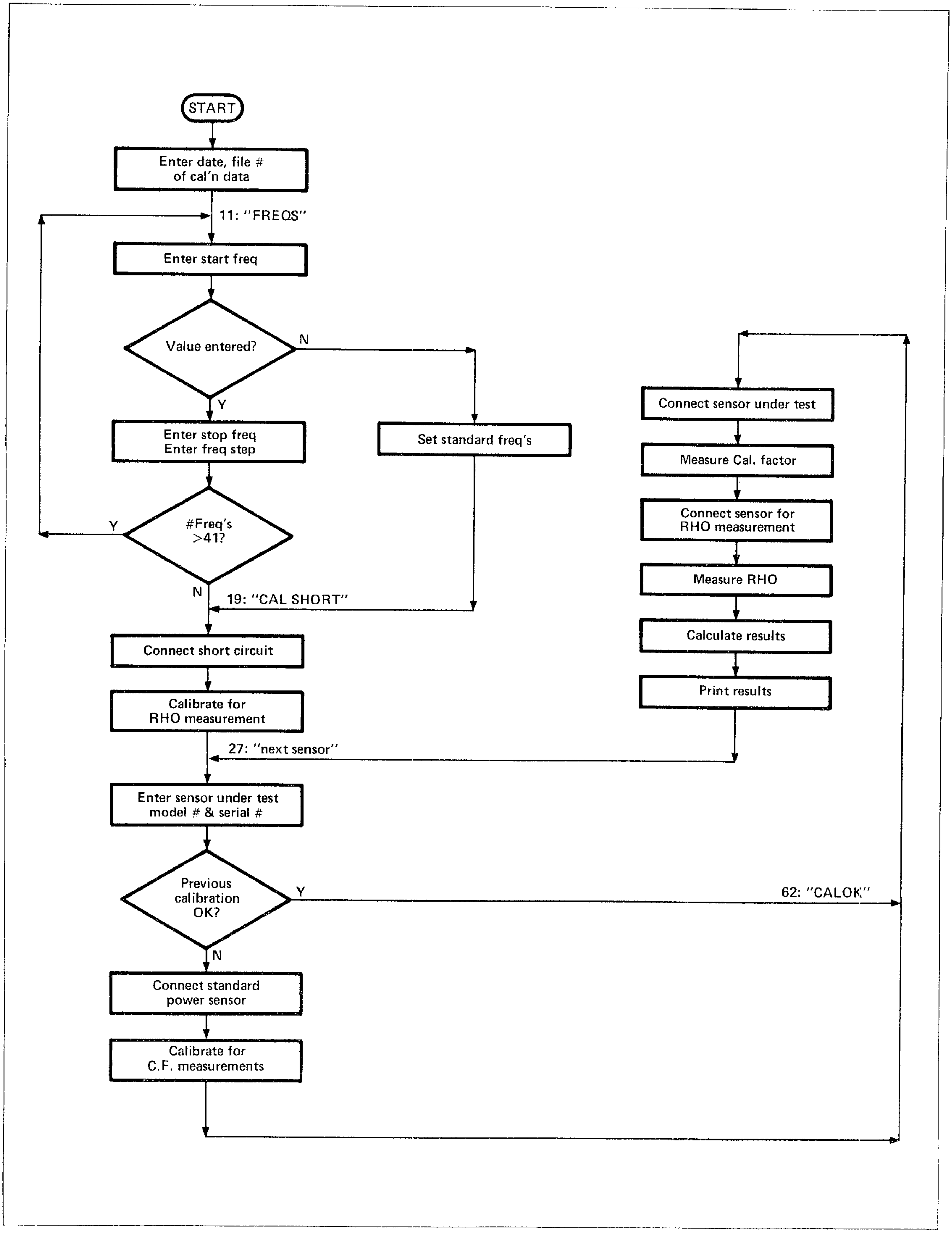
Measurements may still be desired below 2 GHz. Furthermore, there are power sensors designed for the 100 kHz to 4 GHz frequency range that may need to be checked. The power sensor calibration system described in Section 7 of Hewlett-Packard Application Note 196, "Automatic Measurements Using the 436A Power Meter," can be used as a starting point for a system that operates over the 110 kHz to 2.6 GHz range. By adding the ability to measure different sensors at various power levels, that program can be made quite general. It is even possible to combine the systems for 110 kHz to 18 GHz operation.

The programs listed here are for the HP 9825A Desktop Computer. Similar programs have been written for the 9830A/B Desktop Computer and are available. The programs already published in AN 196 are for the HP 9830A Desktop Computer.

There are several suitable digital voltmeters available for digitizing the output of thermistor power meters. The program is written for the HP 3455A Digital Voltmeter. The HP 3490A Option 030 Digital Multimeter can be used merely by changing LINE 198 to read:

```
198: "dvm": fmt; wrt "vm", "F0S0M1R7T1E"; fmt 4x,
     e10.0; red "vm", pl; ret pl.
```

Other HP-IB voltmeters of at least 4-digit resolution may be used by making suitable changes.



Flow diagram of the Power Sensor Calibration Program.

```
0: "POWER SENSOR CALIBRATION PROGRAM;780718;rev B":
1:
2: "INITIALIZATION":time 5000;rem 7;cli 7;clr 7;lcl 7
3: dev "pm1",713,"pm2",712,"pm3",729,"sg",719,"vm",722
4: dim C$[4,11],A[18,11],K$[6],L$[11],D$[16],A$[11]
5: dim S[41],C[41],K[41],R[41],Q[41],T[41]
6: cfg ;0→r0→r1→S ——————————————————————————— Clear Flags; Reset Designators
7: ent "TODAY'S DATE",D$
8: ent "FILE # OF CALIBRATION DATA?",X
9: ldf X,C$,A[*] ————————————————————————————————————— Load Calibration Data
10:
11: "FREQS":2000→E;18→V
12: ent "START FREQ(MHz)?",E
13: if flg13;sfg 1;gto "CALSHORT" —————— If No Value is Entered, Use Standard Freqs.
14: ent "STOP FREQ(MHz)?",H;if H<E;gto "FREQS"
15: ent "FREQ STEP(MHz)?",Q
16: int((H-E)/Q)+1→V ————————————————————————— Calculate Number of Test Freqs.
17: if V>41;gto "FREQS" ——————————————————————— If >41 Freqs., Re-enter Freqs.
18:
19: "CALSHORT":
20: dsp "SHORT TO COUP. OUTPUT";stp
21: 0→L;1→r0;cll 'startup' ———————————————— Set-up Power Meters, Freq. & Level
22: for N=1 to V ——————————————————————————————————————————————— Freq. Loop
23: cll 'sgf'('freq');cll 'level'(-22,1) —— Set Freq.; Adjust Level for −22 dBm to Incident P.M.
24: 'rpm'-'ipm'→S[N] ————————————————————————————— Store Indicated Return Loss
25: next N
26:
27: "next sensor":0→S;cll 'pause';beep
28: ent "SENSOR UNDER TEST MODEL #?",K$;cap(K$)→K$
29: if K$="478A";1→S  )
30: if K$="8478B";2→S |
31: if K$="8481A";3→S }———————————————————————————— Define Model # Designator
32: if K$="8481H";4→S |
33: if K$="8484A";5→S )
34: if S=0;gto "next sensor"
35: ent "SENSOR UNDER TEST SERIAL #?",L$
36: if S=5;ent "SER # OF 30dB 11708A ATTEN.",A$ ——————— If 8484A, 30 dB Attn Needed
37: if S=r1;if S#0;gto "CALOK"                 )          { Skip Calibration with Standard
38: if S+r1=3;if abs(S-r1)=1;gto "CALOK"       }——————————{ Sensor if Previous Calibration
39: if S+r1=8;if abs(S-r1)=2;gto "CALOK"       )          { Is Valid.
40: if S>2;gto "8481std"
41:
42: "CALIBRATION WITH STD. SENSOR":
43: dsp "STD 8478B TO 432A POWER METER!";stp
44: dsp "8478B TO COUP. VIA SPECIAL ATTN";stp
45: dsp "ZERO 432A-CHECK DRIFT";stp
46: dsp "SET 432A TO 0.1mW RANGE";stp ;gto "CALRUN"
47: "8481std":dsp "STD 8481A TO TEST POWER METER!";stp
48: dsp "ZERO-SET & CALIBRATE TO 1mW";stp
49: if S=4;dsp "STD 8481A TO COUP. DIRECT";stp ;gto "CALWAIT"
50: dsp "STD 8481A TO COUP VIA SPEC. ATTN";stp
51: "CALWAIT":for N=1 to 4;dsp "WAITING 2 MIN FOR TEMP STABILITY";wait 30000
52: next N;dsp ""
53: "CALRUN":2→r0;0→L;cll 'startup' ———————————— Set-up Power Meters, Freq. & Level
54: -12→D;if S=4;-2→D ——————————— Desired Test P.M. Reading of −12 dBm (−2 dBm for 8481H)
55: for N=1 to V ——————————————————————————————————————————————— Freq. Loop
56: cll 'sgf'('freq');cll 'level'(D,3) ——————— Set Freq.; Adjust for Proper Test P.M. Level
57: 'tpm'-'ipm'→C[N] ————————————————————————————————— Store Result (in dB)
58: next N
```

Annotated listing of the Power Sensor Calibration Program (1 of 4).

```
59:
60: "MEASURE C.F. OF DUT":
61: S→r1;beep
62: "CALOK":cll 'pause'
63: if S>2;gto "8480 test"
64: if S=1;dsp "CONNECT 478A TO 432A POWER METER";stp ;gto +2
65: dsp "TEST 8478B TO 432A POWER METER!";stp
66: dsp "TEST SENSOR TO COUP. VIA ATTN.";stp
67: dsp "ZERO 432A-CHECK DRIFT";stp
68: dsp "SET 432A TO 0.1mW RANGE";stp ;gto  KRUN"
69: "8480 test":dsp "TEST SENSOR TO TEST POWER METER";stp
70: if S<5;dsp "ZERO-SET AND CALIBRATE TO 1mW";stp ;gto "CONNECT" —{ If Not 8484A,
                                                                    { Use 1 mW
71: dsp "8484A TO PWR REF OUT VIA #11708A";stp )
72: dsp "ZERO-SET AND CALIBRATE TO 1uW";stp    }———————————— If 8484A Use 1 μW
73: dsp "REMOVE #11708A FROM 8484A";stp        )
74: "CONNECT":if S#4;dsp "TEST SENSOR TO COUP. VIA ATTN";stp ;gto "WAIT"
75: dsp "8481H TO COUP. DIRECT";stp ———————————————— If Not 8481H, Use 10 dB Attn.
76: "WAIT":for N=1 to 4;dsp "WAITING 2 MIN FOR TEMP STABILITY";wait 30000
77: next N;dsp ""
78: "KRUN":3→r0;0→L;if S=5;-20→L ——————————— Set Level to 0 dBm (—20 dBm for 8484A)
79: cll 'startup' —————————————————————————————— Set-up Power Meters, Freq. & Level
80: for N=1 to V;-12→D;if S=5;-32→D ———— Freq. Loop; —12 dBm Desired (—32 for 8484A)
81: if S=4;-2→D ——————————————————————————————————————————— (—2 dBm for 8481H)
82: cll 'sgf'('freq');cll 'level'(D,3);if S=5;'ipm'→X ———— Set Freq.; Adjust Level
83: 'tpm'-'ipm'→K[N];cll 'test478' ——————————— Store Result (in dB); Check if 478A
84: next N
85:
86: "MEASURE RHO":if S=4;cll 'sgf'(E);gto "RHOREADY"
87: cll 'pause'
88: dsp "TEST SENSOR TO COUP. DIRECT";beep;stp
89: if S<3;dsp "SET 432A TO 10mW RANGE";stp
90: "RHOREADY":4→r0;0→L;cll 'startup' ———————— Set-up Power Meters, Freq. & Level
91: for N=1 to V ——————————————————————————————————————————————————— Freq. Loop
92: cll 'sgf'('freq');cll 'level'(-22,1);'rpm'→X ————————— Set Freq.; Adjust Level
93: 'rpm'-'ipm'→R[N];cll 'test478' ——————————— Store Result (in dB); Check if 478A
94: next N
95: cll 'pause'
```

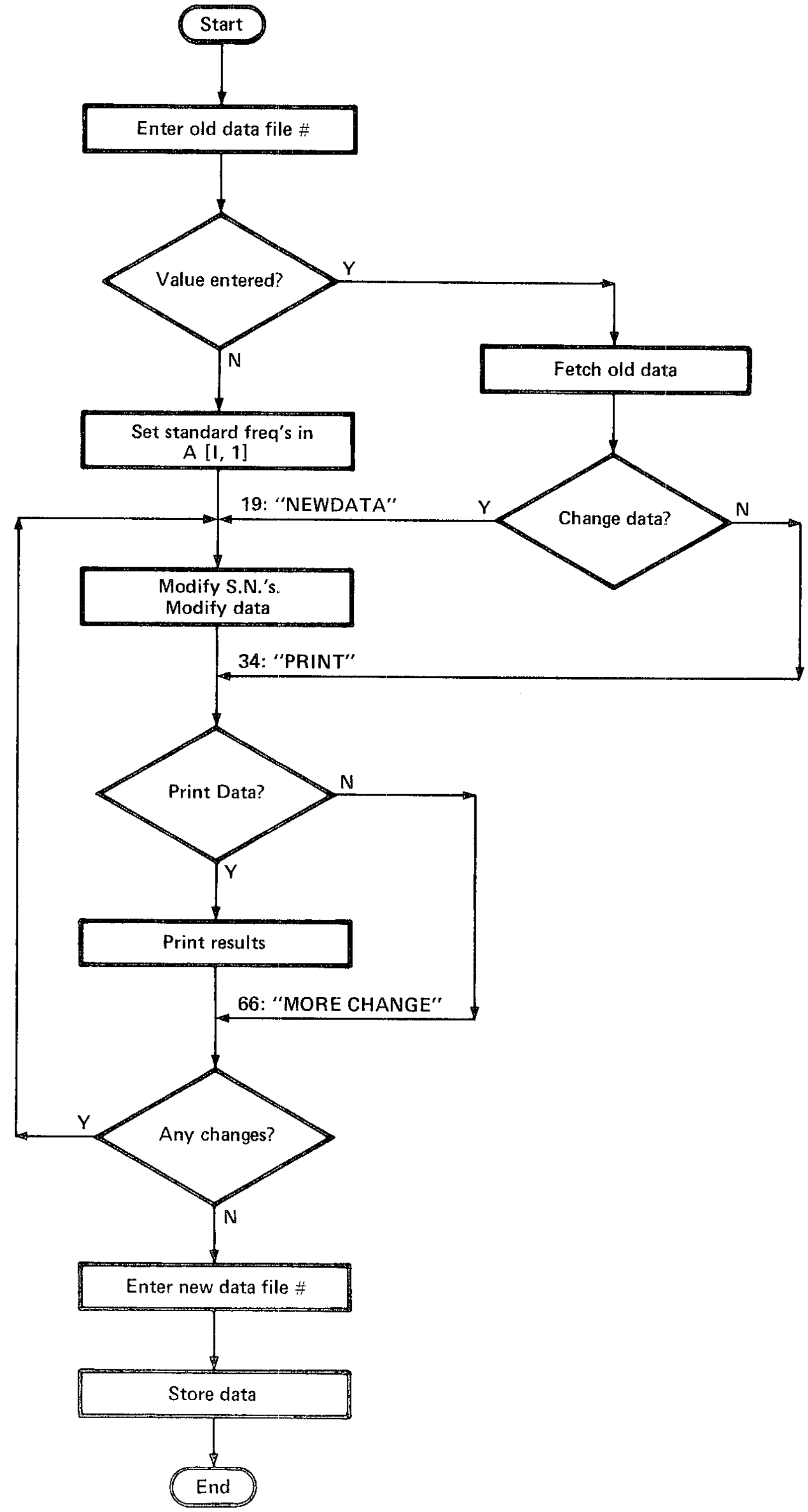
Annotated listing of the Power Sensor Calibration Program (2 of 4).

```
96:
97:  "CALCULATIONS":
98:  1→I;2→J;if S<3;5→J ———— Set Pointers: Row 1; Column 2 for 8480 Series, Column 5 for Thermistors
99:  "Coupler transmission":.99→T ———— Max. Possible Transmission
100: for N=1 to V ———— Freq. Loop
101: 'freq'→F;cfg 3 ———— Calculate Freq.; Clear Interpolation Flag
102: "STANDARD C.F.":if A[I,1]=F;A[I,J]→K;gto "Calc CF"               }
103: if A[I,1]>F;gto "interpolate"                                     }   Find Standard Cal
104: if I#18;I+1→I;gto "STANDARD C.F."                                 }—— Factor (Interpolate
105: "interpolate":sfg 3;if I=1;A[I,J]→K;gto "Calc CF"                 }   if Necessary)
106: A[I,J]+(F-A[I,1])(A[I,J]-A[I-1,J])/(A[I,1]-A[I-1,1])→K            }
107: "Calc CF":Ktn↑((K[N]-C[N])/10)→K[N]                               }
108: "rho":tn↑((R[N]-S[N])/20)→R[N] ———— Return Loss to RHO
109: "delta rho":if flg3;100000→Q[N];gto "gamma source" —— Big Uncertainty for Interpolation
110: "directivity":.0316→D;if F>8000;.0631→D ———— Data Sheet Spec for D
111: D/T→A;A[I,8]+Ttn↑(-A[I,9]/20)→C }
112: A+(A+C)R[N]+CR[N]R[N]→Q[N]       }———— Calculate Error Coefficients for Δρ
113: "gamma source":if flg3;100000→T[N];gto "Calculations done" ——{ Big Uncertainty
                                                                   { for Interpolation
114: .0909→U;if F>8000;.1304→U;if F>12400;.2→U ———— S11 of Attn. (Data Sheet Spec)
115: A[I,10]+tn↑(-A[I,11]/10)C/(1-UC)→G ———— Source Reflection Coefficient
116: if S=4;C→G ———— For 8481H, No 10 dB Attn.
117: "mismatch unc":(1+(R[N]+Q[N])G)/(1-A[I,J+2]G)→M;MM→M ———— Equation (3-13)
118: "Power meter unc":1.01953→W;if S>2;1.01531→W;if S>3;1.02447→W }
119: if S>4;1.02306→W                                               }—— Figure (3-5)
120: "worst case unc":100((A[I,J+1]/100+1)MW-1)→T[N] ———— Equation (3-12)
121: "Calculations done":cll 'test478';next N
122:
123: "ADJUST REF CAL FACTOR":                       }            If Any Cal. Factor >100%,
124: max(K[*])→A;max(A,100)→A;int(10000/A)/100→A   }———— Renormalize
125: for N=1 to V;AK[N]→K[N];next N                 }            100 A = 50 MHz Cal  Factor
126:
127: "OUTPUT":spc ;prt D$;spc                                             }
128: prt "CALIBRATION DATA";prt "FOR POWER SENSOR"                        }
129: fmt "HP MODEL#",c6;wrt 16,K$                                         }
130: fmt "SER#",c11;wrt 16,L$                                             }
131: prt "USING STANDARD";if S>2;gto "8481A Std"                          }
132: prt "8478B SENSOR";wrt 16,C$[2];spc ;gto "FORMAT"                    }
133: "8481A Std":prt "8481A SENSOR";wrt 16,C$[1];spc                      }   Headings,
134: prt "REF. CAL FACTOR";fmt "@ 50MHz=",f4.0,"%";wrt 16,100A            }—— Serial Numbers,
135: if S=5;prt "WITH 30dB ATTEN";fmt "SER#",c11;wrt 16,A$                }   and Formats
136: spc                                                                  }
137: "FORMAT":fmt 1,"FREQ";fmt 2,f4.1,x,f5.1,2x,f4.1                      }
138: fmt 3,"GHz     CF%  %UNC"                                            }
139: fmt 4,"GHz     EE%  %UNC"                                            }
140: fmt 5,6x,"REF";fmt 7,"FREQ COEFF DELTA"                              }
141: fmt 8,"GHz   RHO   RHO"                                              }
142: fmt 9,f4.1,x,f5.3,x,f5.3                                             }
143: "print CF":wrt 16.1;wrt 16.3    }
144: for N=1 to V                    }———— Print Cal. Factor Results
145: wrt 16.2,'freq'/1000,K[N],T[N]  }
146: cll 'test478';next N            }
147: "print EE":spc ;wrt 16.1;wrt 16.4                                   }
148: for N=1 to V                                                        }  Print Effective
149: 100((T[N]/100+1)(1-R[N]R[N])/(1-(R[N]+Q[N])(R[N]+Q[N]))-1)→X       }  Efficiency
150: wrt 16.2,'freq'/1000,K[N]/(1-R[N]R[N]),X                            }  Results
151: cll 'test478';next N                                                }
152: "print RHO":spc ;wrt 16.5;wrt 16.7;wrt 16.8 }
153: for N=1 to V                                }———— Print RHO Results
154: wrt 16.9,'freq'/1000,R[N],Q[N]              }
155: cll 'test478';next N                        }
156: spc 5;gto "next sensor" ———— Return for Another Power Sensor
157: end
```

Annotated listing of the Power Sensor Calibration Program (3 of 4).

```
158:
159: "SUBROUTINES":
160: "freq":if flg1;A[N,1]→p1;ret p1 ——— If Standard Freqs., Read From A[*];
161: E+(N-1)Q→p1;ret p1 ——— Else Calculate Freq.
162:
163: "level":if p2=1;'ipm'→p3;'ipm'→p3;gto "check" )
164: if p2=2;'rpm'→p3;'rpm'→p3;gto "check"          }  Read Desired Power Meter,
165: 'tpm'→p3;if S=4;if r0=3;wait 10000             }——If 8481H Sensor, Wait
166: 'tpm'→p3                                       )  10 Seconds
167: "check":p3-p1→p3;if abs(p3)<1;ret ——— Actual – Desired → p3; If <1 dB, OK and Return
168: int(p3+.5)→p3 ——— Calculate Level Change Needed
169: if p3<0;if bit(2,'checkgen');gto "warning" ——— If Necessary, Check If Increase Is Possible
170: L-p3→L;cll 'sgl';gto "level" ——— Change Power Level and Check Again
171: "warning":fmt 1,"LOW LEVEL AT";fmt 2,f4.1,"GHz" }——— Warning If Max. Power
172: wrt 16.1;wrt 16.2,'freq'/1000;ret                }    Is Too Low
173:
174:
175: "pause":cll 'sgf'(E);lcl 7;rem 7;cll 'off';ret ——— Power Meters to Local; Turn Off RF
176:
177: "startup":rem 7;cll 'off';cll 'pmz&t';cll 'sgl';ret ——— { Zero Power Meters,
178:                                                           { Initialize Level
179: "test478":if S=1;if flg1;if N=9;V→N }
180: ret                                 }——— If Standard Freqs. & If 478A, Stop at 10 GHz
181:
182: "POWER METER SUBROUTINES":
183: "pmz&t":fmt ;wrt "pm1","Z1I";wrt "pm2","Z1I";if S>2;wrt "pm3","Z1I" { Zero
184: fmt 4x,f4.0;red "pm1",p1;red "pm2",p2;if S>2;red "pm3",p3 —Read      { P.M.'s
                                                                   P.M.'s Mantissa
185: if p1>2 or p2>2;jmp -2 }
186: if S>2;if p3>2;jmp -3  }——— If Not Within 2 Counts of Zero, Zero Again
187: wrt "pm1","9D+I";wrt "pm2","9D+I";if S>2;wrt "pm3","9D+I" ——— Set to dBm
188: gto -1;if rdb("pm1")<84;if rdb("pm2")<84;gto +2 }——— If Power Meters Are Still
189: if S>2;gto -2;if rdb("pm3")<84;gto +1            }    Zero-Setting, Keep Reading
190: ret
191:
192: "ipm":fmt 3x,e9.0;wrt "pm1","T";red "pm1",p1;ret p1 ——— Read Incident Power Meter
193: "rpm":fmt 3x,e9.0;wrt "pm2","T";red "pm2",p1;ret p1 ——— Read Reflected Power Meter
194: "tpm":if S>2;fmt 3x,e9.0;wrt "pm3","T";red "pm3",p1;ret p1 {If 8480 Series, Read
195: 'dvm'→p1;if p1<=0;-70→p1;ret p1                             {Test P.M., Else Read
196: 10log(.1p1)→p1;ret p1                                       {Voltmeter and
197:                                                             {Convert to dBm
198: "dvm":fmt ;wrt "vm","F1R7M3A1H0D0T1";fmt f.0;red "vm",p1;ret p1 ——— Read
199:                                                                     Voltmeter
200: "SIG GEN SUBROUTINES":
201: "off":fmt ;wrt "sg","K;=070";ret ——— Turn RF Power OFF
202: "sgl":fmt "K",2b,"07",b;if L>13;13→L ——— Set Generator Level; Max. Level Is +13 dBm
203: if L<-120;wrt "sg",59,61,48;ret ——— Min. Level Is —120 dBm
204: if L>3;wrt "sg",48,61-L,51;ret                   }
205: int(abs(L/10))→p1;wrt "sg",p1+48,51-10p1-L,49;ret }——— Send Level on Bus
206: "sgf":if p1<2000;gto "FREQERR" }
207: if p1>18000;gto "FREQERR"      }——— Set Generator Freq.; If Out of Range, Print Error
208: fmt "P",fz9.3,"Z9";wrt "sg",p1;ret ——— Send Freq. on Bus
209: "FREQERR":fmt f5.0,"MHz OUT OF RANGE" }
210: wrt 0,p1;beep;stp                     }——— Freq. Error Message
211: "checkgen":rdb("sg")→p1;ret p1 ——— Read Generator Status
*6478
```

Annotated listing of the Power Sensor Calibration Program (4 of 4).



Flow diagram of the Power Sensor Data File Construction Program.

```
0: "POWER SENSOR DATA FILE CONSTRUCTION PROGRAM":
1:
2: "INITIALIZATION":
3: dim C$[4,11],A[18,11],K$[15],B$[3]
4: ent "OLD CALIBRATION DATA FILE#=?",X
5: if flg13;gto "ALLNEW"
6: ldf X,C$,A[*]
7: ""→B$;ent "CHANGE DATA (Y or N)?",B$
8: if cap(B$[1])="N";gto "PRINT"
9: if cap(B$[1])#"Y";gto -2
10: gto "NEWDATA"
11:
12: "ALLNEW":
13: for I=1 to 18
14: 1000I→A[I,1]
15: if I<12;1000(I+1)→A[I,1]
16: if I=12;12400→A[I,1]
17: next I
18:
19: "NEWDATA":dsp "SN OF 8481A; now=",C$[1];ent "",C$[1]
20: dsp "SN of 8478B; now=",C$[2];ent "",C$[2]
21: dsp "SN of COUPLER; now=",C$[3];ent "",C$[3]
22: dsp "SN of 10dB PAD; now=",C$[4];ent "",C$[4]
23: 1→J;"K(%) for 8481A@"→K$;cll 'COLUMN'
24: "DEL K(%)-8481A@"→K$;cll 'COLUMN'
25: "RHO  for 8481A@"→K$;cll 'COLUMN'
26: "K(%) for 8478B@"→K$;cll 'COLUMN'
27: "DEL K(%)-8478B@"→K$;cll 'COLUMN'
28: "RHO  for 8478B@"→K$;cll 'COLUMN'
29: "COUPLER   RHO @"→K$;cll 'COLUMN'
30: "COUPL. DIR(dB)@"→K$;cll 'COLUMN'
31: "PAD RHO       @"→K$;cll 'COLUMN'
32: "PAD ATTEN (dB)@"→K$;cll 'COLUMN'
33:
```

If No Old Data, Go Set-up Freqs.

Load Old Data

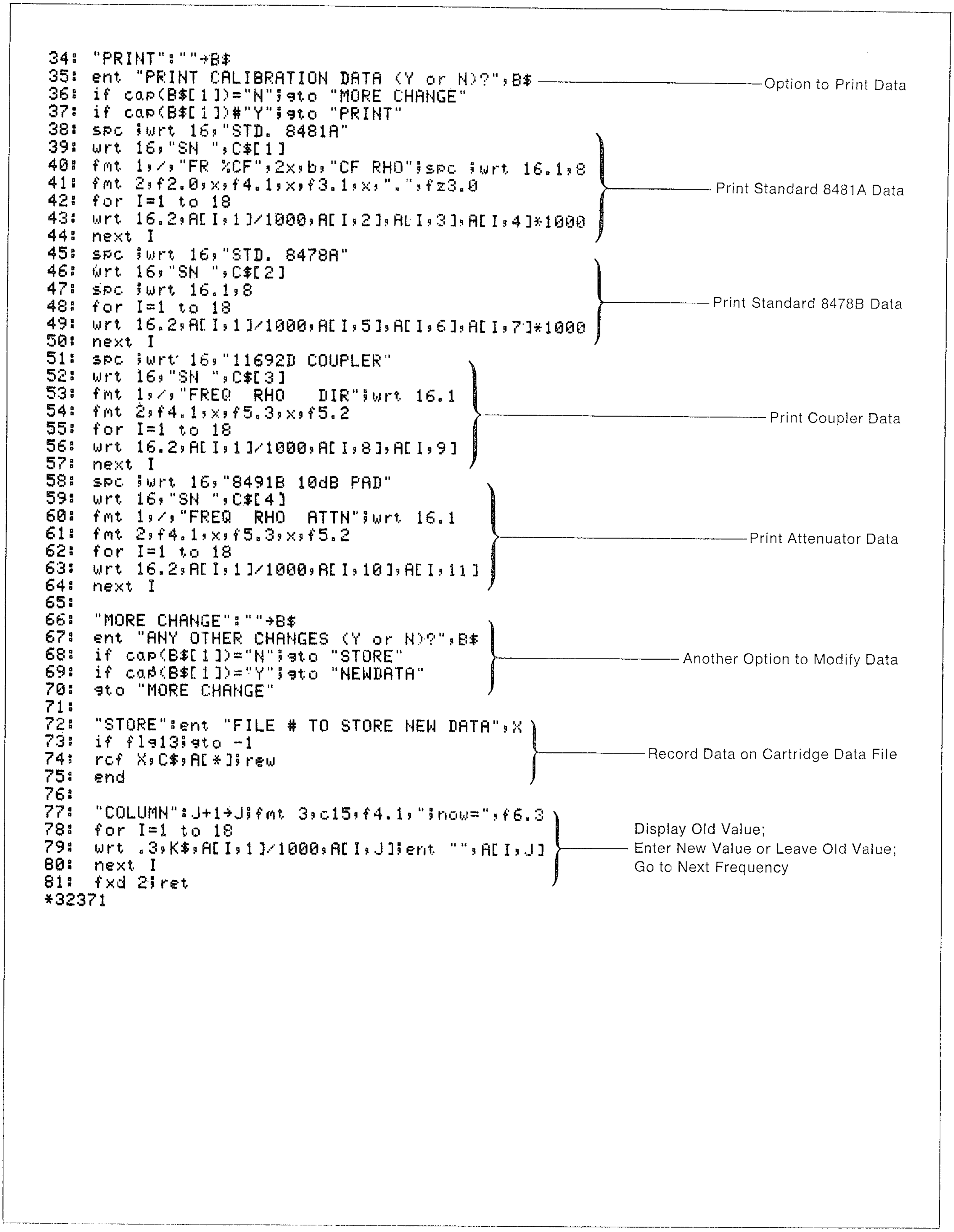
Option to Change Data

Set-up Standard Freqs.

Input, Modify
or Leave
Serial Numbers

Display Prompts for Each
Column (Question Is in
Subroutine "COLUMN")

Annotated listing of the Power Sensor Data File Construction Program (1 of 2).



```
34: "PRINT":""→B$
35: ent "PRINT CALIBRATION DATA (Y or N)?",B$
36: if cap(B$[1])="N";gto "MORE CHANGE"
37: if cap(B$[1])#"Y";gto "PRINT"
38: spc ;wrt 16,"STD. 8481A"
39: wrt 16,"SN ",C$[1]
40: fmt 1,/,"FR %CF",2x,b,"CF RHO";spc ;wrt 16.1,8
41: fmt 2,f2.0,x,f4.1,x,f3.1,x,".",fz3.0
42: for I=1 to 18
43: wrt 16.2,A[I,1]/1000,A[I,2],A[I,3],A[I,4]*1000
44: next I
45: spc ;wrt 16,"STD. 8478A"
46: wrt 16,"SN ",C$[2]
47: spc ;wrt 16.1,8
48: for I=1 to 18
49: wrt 16.2,A[I,1]/1000,A[I,5],A[I,6],A[I,7]*1000
50: next I
51: spc ;wrt 16,"11692D COUPLER"
52: wrt 16,"SN ",C$[3]
53: fmt 1,/,"FREQ  RHO   DIR";wrt 16.1
54: fmt 2,f4.1,x,f5.3,x,f5.2
55: for I=1 to 18
56: wrt 16.2,A[I,1]/1000,A[I,8],A[I,9]
57: next I
58: spc ;wrt 16,"8491B 10dB PAD"
59: wrt 16,"SN ",C$[4]
60: fmt 1,/,"FREQ  RHO  ATTN";wrt 16.1
61: fmt 2,f4.1,x,f5.3,x,f5.2
62: for I=1 to 18
63: wrt 16.2,A[I,1]/1000,A[I,10],A[I,11]
64: next I
65:
66: "MORE CHANGE":""→B$
67: ent "ANY OTHER CHANGES (Y or N)?",B$
68: if cap(B$[1])="N";gto "STORE"
69: if cap(B$[1])="Y";gto "NEWDATA"
70: gto "MORE CHANGE"
71:
72: "STORE":ent "FILE # TO STORE NEW DATA",X
73: if flg13;gto -1
74: rcf X,C$,A[*];rew
75: end
76:
77: "COLUMN":J+1→J;fmt 3,c15,f4.1,";now=",f6.3
78: for I=1 to 18
79: wrt .3,K$,A[I,1]/1000,A[I,J];ent "",A[I,J]
80: next I
81: fxd 2;ret
*32371
```

Annotated listing of the Power Sensor Data File Construction Program (2 of 2).

Appendix A

The purpose of this appendix is to develop an expression for the wave incident upon the *standard power sensor* or *sensor under test* in terms of *incident power meter* reading. The system schematic (**Figure 3-3**) contains two directional couplers which are normally packaged as one dual-directional coupler. The signal-flow graph for the system of **Figure 3-3** is shown in **Figure A-1**(a). For a background in signal-flow graph analysis, consult the references by Mason, Kuhn, and Hunton.

The signal-flow graph for the dual-directional coupler part of **Figure A-1**(a) must be simplified to develop manageable equations. The first step is to delete those branches leading from the auxiliary arms back toward the primary line as in **Figure A-1**(b). The signals along those branches are lower than those already existing on the main line by several orders of magnitude. From **Figure A-1**(b) it is apparent that the signals in the reflected auxiliary arm of the coupler have no effect on the primary line output or the incident arm output. The branches associated with the reflected arm can therefore be deleted for this derivation.

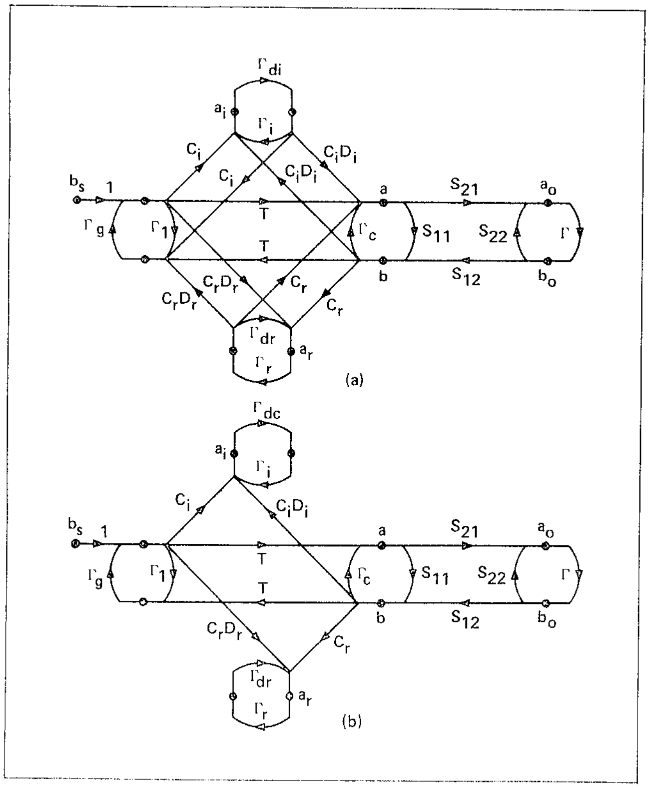


Figure A-1. Signal-flow graphs for the calibration factor measurement system shown in **Figure 3-3**. (a) The complete signal-flow graph. (b) The simplified signal-flow graph formed by deleting branches from the auxiliary line to the mainline of the coupler.

An equivalent flow graph for the left end of **Figure A-1(b)** (with the reflected arm deleted) may be found by first calculating a_i and a in terms of b_s and b. This effectively considers the coupler and signal source without the attenuator. The non-touching loop rule yields

$$a_i = \frac{b_s}{\Delta} C_i + \frac{b}{\Delta} C_i D_i (1 - \Gamma_g \Gamma_1) + \frac{b}{\Delta} T \Gamma_g C_i \qquad \text{(A-1)}$$

$$a = \frac{b_s}{\Delta} T (1 - \Gamma_i \Gamma_{di}) + \frac{b}{\Delta} \Gamma_c (1 - \Gamma_i \Gamma_{di})(1 - \Gamma_g \Gamma_1) + \frac{b}{\Delta} T^2 \Gamma_g (1 - \Gamma_i \Gamma_{di}) \qquad \text{(A-2)}$$

where Δ is the system determinant given by

$$\Delta = (1 - \Gamma_i \Gamma_{di})(1 - \Gamma_g \Gamma_1) \qquad \text{(A-3)}$$

Equation (A-1) can be solved for b_s/Δ and the result substituted into (A-2). The result is

$$a = a_i \frac{T}{C_i} (1 - \Gamma_i \Gamma_{di}) + b(\Gamma_c - TD_i) \qquad \text{(A-4)}$$

Now a signal-flow graph can be formed that gives a in terms a_i and b to agree with equation (A-4). This is done for the flow-graph shown in **Figure A-2**(a).

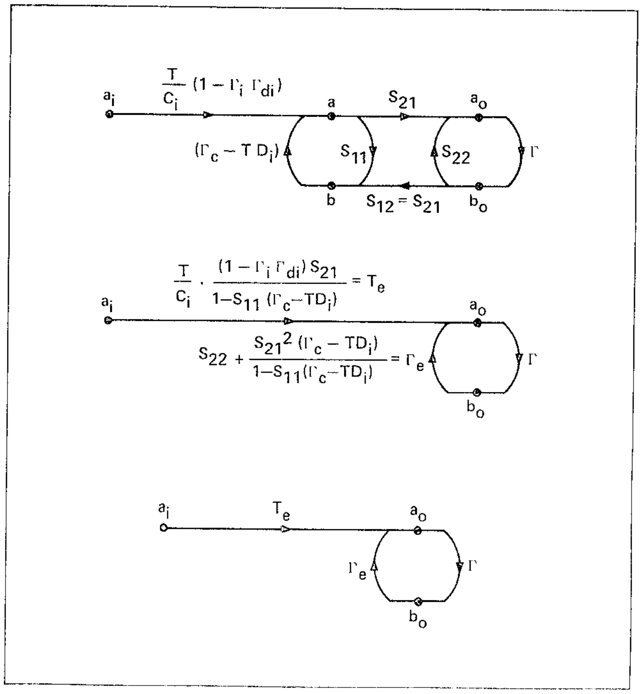


Figure A-2. Simplification of the signal-flow graph for the measurement of K_b. The goal is to find a_o in terms of a_i.

The next step is to use the signal-flow graph of **Figure A-2**(a) to find the mainline output wave a_0 in terms of a_i. Using the non-touching loop rule on **Figure A-2**(a)

$$a_0 = a_i \frac{T}{C_i} \cdot \frac{(1 - \Gamma_i \Gamma_{di})\, S_{21}}{1 - S_{11}\,(\Gamma_c - TD_i}$$

$$+\, b_0 \left[S_{22} + \frac{S_{21}{}^2\,(\Gamma_c - TD_i)}{1 - S_{11}\,(\Gamma_c - TD_i)} \right] \qquad \text{(A-5)}$$

This is also the equation of the signal-flow graph shown in **Figure A-2(b)**. Thus **Figure A-2(b)** can be considered as equivalent to **Figure A-2(a)**. From **Figure A-2(b)**, the equivalent source reflection coefficient Γ_e, seen by a load placed on the test port, is

$$\Gamma_e = S_{22} + \frac{S_{21}{}^2\,(\Gamma_c - TD_i)}{1 - S_{11}\,(\Gamma_c - TD_i)} \qquad \text{(A-6)}$$

The equivalent transmission from a_i to a_0 is given by

$$T_e = \frac{T\,(1 - \Gamma_i \Gamma_{di})\, S_{21}}{C_i\,(1 - S_{11}\,(\Gamma_c - TD_i)\,)} \qquad \text{(A-7)}$$

If load Γ is connected to the test port, the output wave is

$$a_0 = a_i \frac{T_e}{1 - \Gamma \Gamma_e} \qquad \text{(A-8)}$$

Thus the output wave, a_0, is found in terms of the wave incident upon the sensor of the *incident power meter,* a_i.

Appendix B

The purpose of this appendix is to develop expressions for the measurement of reflection coefficient. A dual-directional coupler is used to separate the forward and reverse traveling waves. **Figure B-1** is a simplified signal-flow graph of the system. Branches leading from the auxiliary arms back toward the primary line have been dropped to simplify the analysis. The signals along those branches are lower than the signals existing on the main line by several orders of magnitude.

The incident waves upon each of the detectors in the auxiliary arms can be found using the non-touching-loop rule for signal-flow graphs.

$$a_i = \frac{b_s}{\Delta}\Big[C_i\,(1-\Gamma_r\Gamma_{dr})\,(1-\Gamma_c\Gamma) + \Gamma T C_i D_i\,(1-\Gamma_r\Gamma_{dr})\Big] \qquad \text{(B-1)}$$

$$a_r = \frac{b_s}{\Delta}\Big[C_r T\Gamma(1-\Gamma_i\Gamma_{di}) + C_r D_r\,(1-\Gamma_i\Gamma_{di})\,(1-\Gamma\Gamma_c)\Big] \qquad \text{(B-2)}$$

where Δ is the system determinant. The ratio of a_r to a_i found from these two expressions is

$$\frac{a_r}{a_i} = \frac{C_r\,(1-\Gamma_i\Gamma_{di})}{C_i\,(1-\Gamma_r\Gamma_{dr})}\cdot\frac{D_r+\Gamma\,(T-D_r\Gamma_c)}{1-\Gamma\,(\Gamma_c-TD_i)} \qquad \text{(B-3)}$$

$$= \frac{C_r\,(1-\Gamma_i\Gamma_{di})}{C_i\,(1-\Gamma_r\Gamma_{dr})}\cdot\left[D_r+\frac{\Gamma T\,(1-D_iD_r)}{1-\Gamma\,(\Gamma_c-TD_i)}\right]$$

The measurement procedure is to measure the magnitude of the ratio of (B-3) twice: first for a short circuit ($\Gamma = -1$) connected and then for the *sensor under test.* The complex ratio of those two measurements is

$$R = \frac{\dfrac{a_r}{a_i}}{\left.\dfrac{a_r}{a_i}\right|_{\Gamma=-1}} = \frac{D_r + \dfrac{\Gamma T\,(1-D_iD_r)}{1-\Gamma\,(\Gamma_c-TD_i)}}{\dfrac{D_r-T+D_r\Gamma_c}{1+\Gamma_c-TD_i}} \qquad \text{(B-4)}$$

where the first form of (B-3) is used for the denominator and the second form for the numerator. A first step in simplifying (B-4) is to expand the fraction of the numerator by long division to give

$$R = \left[\frac{1+\Gamma_c-TD_i}{D_r-T+D_r\Gamma_c}\right]\Big[D_r+\Gamma T\,(1-D_iD_r)\,(1+\Gamma(\Gamma_c-TD_i)+\Gamma^2(\Gamma_c-TD_i)^2+\ldots)\Big] \qquad \text{(B-5)}$$

Equation (B-5) is approximated by dropping terms in the numerator and denominator which contain second and higher order products of Γ_c, D_i, and D_r. The result is

$$R \approx \frac{1}{1-\dfrac{D_r}{T}}\left[-\frac{D_r}{T}-\Gamma\,(1+\Gamma_c-TD_i) - \Gamma^2\,(\Gamma_c-TD_i)\right] \qquad \text{(B-6)}$$

But $(1 - D_r/T)^{-1}$ can be approximated by $(1 + D_r/T)$. Then the second order terms are again dropped and the result is

$$R \approx -\frac{D_r}{T} - \Gamma\left(1+\Gamma_c-TD_i+\frac{D_r}{T}\right) - \Gamma^2\,(\Gamma_c-TD_i) \qquad \text{(B-7)}$$

The magnitude of R is considered to be the measured value of the reflection coefficient magnitude.

The worst-case error, $\Delta\rho_{max}$, is, considering $\rho = |\Gamma|$ and $\rho_c = |\Gamma_c|$,

$$\begin{aligned}\Delta\rho_{max} &= |R|_{max} - \rho \\ &= \left|\frac{D_r}{T}\right| + \rho\left(\rho_c + |TD_i| + \left|\frac{D_r}{T}\right|\right) + \rho^2\,(\rho_c + |TD_i|) \qquad \text{(B-8)} \\ &= A + B\rho + C\rho^2\end{aligned}$$

where A, B, and C are defined by

$$A = \left|\frac{D_r}{T}\right|$$

$$B = \rho_c + |TD_i| + \left|\frac{D_r}{T}\right| \qquad \text{(B-9)}$$

$$C = \rho_c + |TD_i|$$

Note that B = A + C.

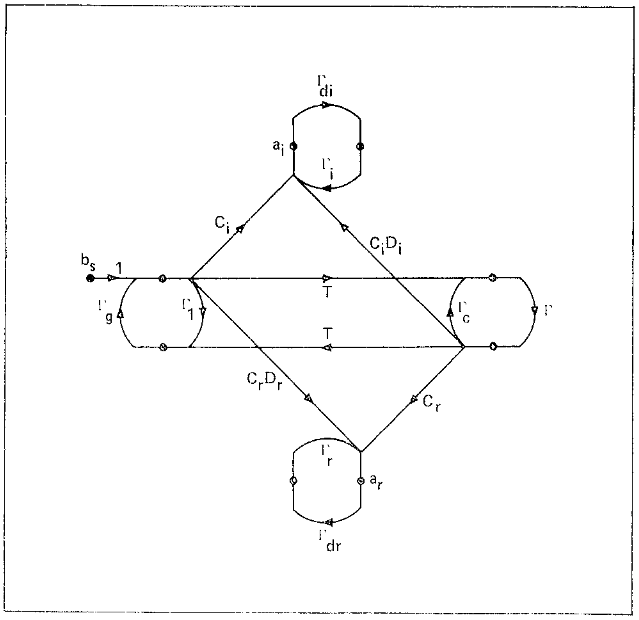


Figure B-1. Signal-flow graph for the reflection coefficient measurement system shown in **Figure 3-4.**

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Hunton, J. K. "Analysis of Microwave Measurement Technique by Means of Signal Flow Graphs," *Trans IRE,* Vol MTT-8 (Mar., 1960) 206-212.

Kuhn, N. J. "Simplified Signal Flow Graph Analysis," *Microwave Journal,* Vol. 6, No. 10 (Nov., 1963) 59-66.

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