5345 ELECTRONIC COUNTER

HEWLETT hp PACKARD

MAKING AUTOMATIC PHASE MEASUREMENTS WITH THE 5345A ELECTRONIC COUNTER

This application note describes a calculator based HP Interface Bus System which automatically measures phase from 0° to 360° for frequencies up to 1 MHz. The 5345A Electronic Counter makes the measurement system possible due to its ability to make high resolution non-biased time interval average measurements, its high sensitivity, and its compatibility with the HP Interface Bus. The 5345A's unique time interval capability permits accuracies in the phase measurement to better than .1° and repeatability of .01°. Since measurements are fast and completely automatic, the system is well suited to application areas such as production testing and quality control. The high accuracy recommends the system to laboratory and R&D applications. Use of the HP Interface Bus ensures that the instruments need not be dedicated to this particular configuration. The bus allows instruments to be quickly and easily reconfigured to solve a variety of measurement problems.

APPLICATION NOTE 174-9

INTRODUCTION

The phase difference between two signals of equal frequency may be computed from a time interval measurement and a period measurement according to the equations:

$$\phi\,(\text{deg}) = 360\,\frac{\Delta t}{T}\ ;\quad \phi\,(\text{rad}) = 2\pi\,\frac{\Delta t}{T}$$

where Δt = the time interval between corresponding points on the two waveforms and T = the period as shown in Figure 1.

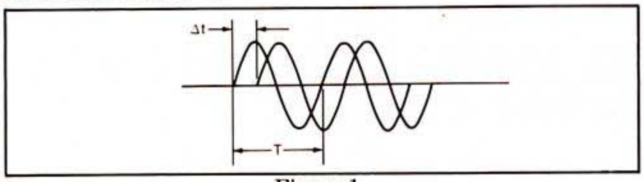

Figure 1

MEASUREMENT SET-UP

The measurement system consists of the 5345A Electronic Counter (opt. 011), the 59303A D-to-A Converter, the 59307A VHF Switch, the 59405A opt. 020/021A HP-IB Calculator Interface, the 11221A Math ROM block, and the 9820/21A Calculator. The instruments are connected to the calculator as shown in Figure 2.

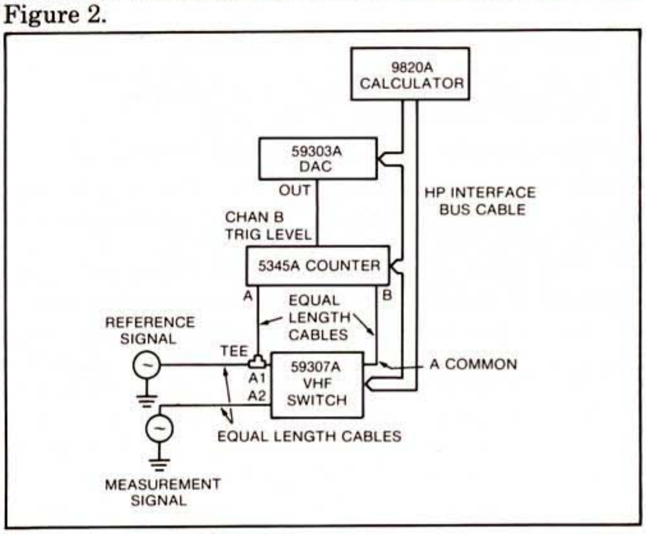

Figure 2

Set the Talk/Listen address switches on the 5345A counter, the 59303A DAC, and the 59307A VHF switch as specified in Table 1. These switches are located on the rear panels of the instruments and must be set as specified so as to agree with the addresses used in the program.

Table 1

	TALK/LISTEN ADDRESSES	MODE SWITCH	A5	A4	A3	A2	A1
5345A Counter	J/*	addressable	0	1	0	1	††
59307A VHF Switch	/>	addressable	1	1	1	1	0
59303A DAC	/9 (program) /8 (data)	addressable	1	1	0	0	††

††not used

Place the Math and PCII ROM blocks into ROM slots 1 and 3 respectively of the 9820A Calculator. To interface the instruments to the calculator, perform the following: plug the ASCII Bus Interface Card into any of the four slots on the rear panel of the 9820A Calculator. Connect ASCII Interface cables (10631A, B, or C) from the interface card of the calculator to the rear panel plugs of the 5345A counter, the 59303A D to A Converter, and the 59307A VHF switch (choose cable lengths such that the total length of ASCII cable does not exceed 24 feet).

Set the following 5345A controls: impedance (channel A and B) to 1 MΩ, slope (channel A and B) to +, trigger level (channel A and B) to preset, attenuation (channel A and B) to X1, coupling (channel A and B) to DC, and the SEP/COM switch to separate. Since the calculator remotely controls all other front panel controls of the counter and all the controls of the VHF switch and DAC, there is no need to set these controls to any particular position.

THEORY OF OPERATION

The measurement system depicted in Figure 2 is set up to make a phase measurement on a differential basis. This means that to find the time interval corresponding to the phase difference between the two signals, two time intervals are measured and the difference is taken. The advantage to this method is the fact that systematic errors are cancelled and the overall accuracy of the measurement is improved as compared to a single measurement. The reference time interval measurement is made with the A1 input of the VHF Switch connected to A common and the trigger level of channel B (controlled by the DAC) adjusted to obtain a time interval greater than 10 nsec (the counter cannot measure time intervals less than 10 nsec). The second time interval measurement is made with the A2 input of the VHF switch connected to A common. These two measurements are represented in Figure 3. Since τ is common to both measurements, when the two measurements are subtracted, the resultant time interval corresponds precisely to the phase difference between the signals.

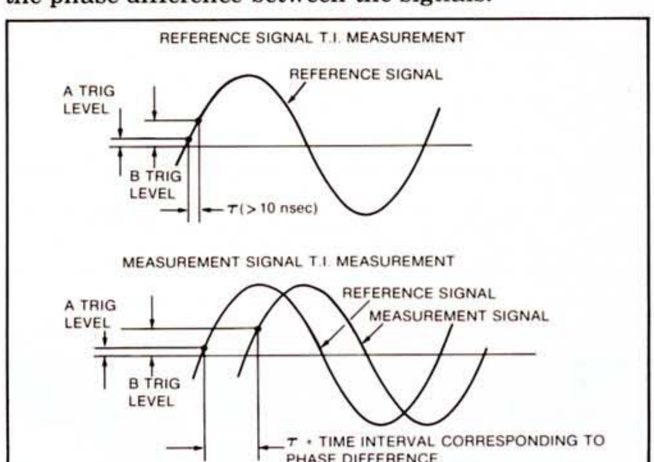

Figure 3

PROGRAM OPERATION

Key into the calculator the program listed on the back of this application note. The program will require the user to respond to the following:

"NO. IN AVE" — The user should enter the desired number of time intervals over which the time interval average measurement is to be made.

The flow diagram of Figure 4 diagrams the program operation. With the counter gate time in MIN., the program measures the reference signal time interval (input A1 of the VHF switch connected to Common A) and the measurement signal time interval (A2 connected to Common A). By knowing the two

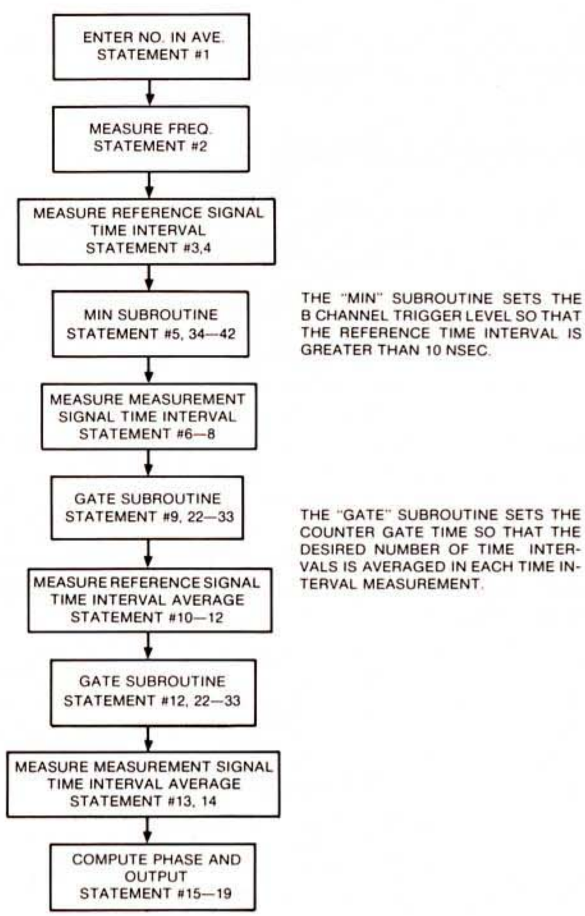

Figure 4. Program Flow Diagram

time intervals and the desired "NO. IN AVE", the program can select the appropriate counter gate times for the average by calling the subroutine "GATE". This subroutine selects a gate time such that the desired number of time intervals will be averaged in the reference signal or the measurement signal time interval measurements.

The MIN subroutine is called to set the channel B trigger level by programming the DAC such that the reference signal time interval is greater than 10 nsec. This is necessary since the counter is not able to measure time intervals less than 10 nsec. A 10 nsec delay could have been introduced by inserting a length of cable between the A and B channels but, as is discussed under Measurement Considerations, the difference in capacitance due to differences in length of the cables introduces significant errors in the phase measurement.

With the appropriate gate times selected, the reference signal time interval and the measurement signal time interval are measured. A period measurement is then made. The phase is then computed by the equation

$$\phi\,(\text{deg}) = 360 * \frac{(\text{T.I.}_{\text{meas.}} - \text{T.I.}_{\text{ref.}})}{\text{period}}$$

The phase in degrees and radians is output on the calculator printer in the following output format:

```
PHASE (DEG)=
        181.14
PHASE (RAD)=
         3.161
```

Figure 5

MEASUREMENT CONSIDERATIONS

1. ACCURACY: The measurement procedure used in this application note can be described as a difference technique where two measurements are made, the difference in which gives the actual time interval corresponding to the phase difference in the signals. This has a number of advantages, two major ones being: systematic errors are reduced to zero; and, for equal amplitude signals, no error is introduced by having Channel A and Channel B trigger at points other than the zero crossing. The following will discuss the contribution to the total measurement error due to trigger error, error due to difference in amplitudes between the signal and the reference, and the error due to unequal lengths of cable in the measurement signal and reference signal paths which, depending upon the impedance of the sources, causes an actual shift in phase.

   The accuracy of the phase measurement is determined by the relative accuracy of the two time interval measurements. The rms error in a time interval measurement may be written as

$$\pm \frac{\text{trigger error} \pm 2 \text{ nsec}}{\sqrt{\text{intervals averaged}}} \pm .7 \text{ nsec} \pm \text{time base accuracy}$$

   The ± .7 nsec error and the time base error will be subtracted out when the difference is taken.

The trigger error for a time interval measurement on a 10 mV rms signal with noise voltage less than 100 μV rms (40 dB S/N) is given as ±.3% of the time interval reading. As the signal voltage is increased (assuming the noise remains below 100 μV rms), the trigger error is decreased due to the increased slope through the hysteresis window of the counter. The trigger error for a signal with level ν volts rms is approximately

$$\pm \frac{3 \times 10^{-5}}{\nu} * \text{T.I. reading (for noise } < 100\ \mu\text{Vrms and attenuator X1)}$$

For a reference signal level of ν_1 volts rms and a measurement signal level of ν_2 volts rms, the trigger error in the reference time interval measurement is

$$\epsilon_1 = \pm \frac{3 \times 10^{-5}}{\nu_1} * \text{T.I.}_{\text{ref}} * \frac{1}{\sqrt{N}}$$

and the trigger error in the measurement signal time interval is

$$\epsilon_2 = \pm \frac{1.5 \times 10^{-5}(\nu_1 + \nu_2)}{\nu_1 \nu_2} * \text{T.I.}_{\text{meas}} * \frac{1}{\sqrt{N}}$$

where N = number of time intervals averaged.

The trigger error in time interval translates to an error in phase as follows:

$$\phi \text{ (degrees)} = \frac{360}{T} \left[(\Delta t_2 \pm \epsilon_2) - (\Delta t_1 \pm \epsilon_1)\right]$$

where Δt_2 = measurement signal time interval

Δt_1 = reference signal time interval

T = period

$$= \frac{360}{T} (\Delta t_2 - \Delta t_1) \pm \frac{360}{T} (\epsilon_2 + \epsilon_1)$$

So the error in phase $\delta\phi$ may be written as

$$\delta\phi = \pm \frac{360}{T} (\epsilon_2 + \epsilon_1)$$

$$= \pm \frac{360}{T\sqrt{N}} \left[\frac{1.5 \times 10^{-5} (\nu_1 + \nu_2)}{\nu_1 \nu_2} \cdot \text{T.I.}_{\text{meas}} + \frac{3 \times 10^{-5}}{\nu_1} \cdot \text{T.I.}_{\text{ref}}\right] \qquad \text{Eq. [1]}$$

For large phase differences where $\text{T.I.}_{\text{meas}} >> \text{T.I.}_{\text{ref}}$, the error becomes

$$\delta\phi \simeq \pm \frac{360}{T\sqrt{N}} \cdot \frac{1.5 \times 10^{-5} (\nu_1 + \nu_2)}{\nu_1 \nu_2} \text{T.I.}_{\text{meas}}$$

$$\simeq \frac{1}{\sqrt{N}} \cdot \frac{1.5 \times 10^{-5} (\nu_1 + \nu_2)}{\nu_1 \nu_2} \cdot \phi$$

The graph in Figure 6 presents the percentage error in phase as a function of the larger signal voltage (the difference in voltage level is assumed less than 6 dB) for the case where the measurement time interval is much greater than the reference time interval (e.g., large phase difference). Otherwise, the error must be computed according to equation [1].

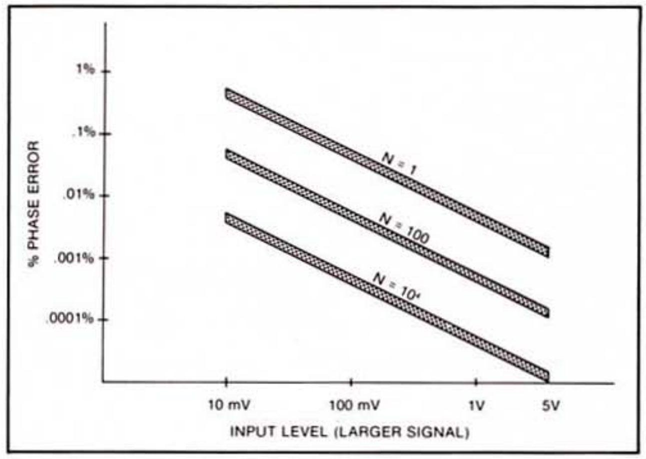

Figure 6

Additional error occurs when the amplitudes, ν_1 and ν_2, are not equal. This error is evident from Figure 7.

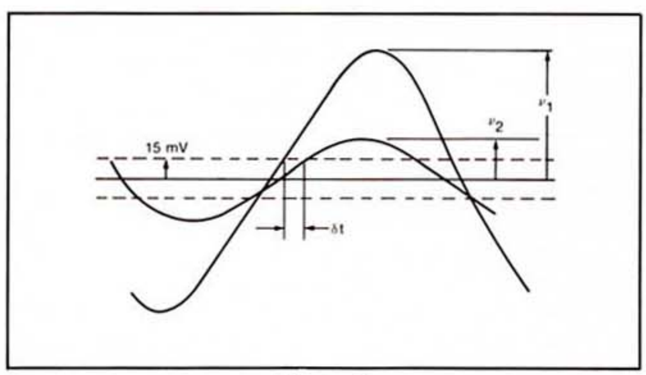

Figure 7

In this case, the trigger controls are set to preset and in + slope so that triggering occurs, as a worst case, 15 mV above ground (typically, 7 mV above ground). The error produced in the time interval difference may be expressed, assuming ν_1 and $\nu_2 >> 15$ mV, as

$$\delta t = \pm \frac{.015}{2\pi f} \frac{\Delta\nu}{\nu_1 \nu_2}$$

where ν_1 = peak voltage of reference
ν_2 = peak voltage of signal
f = frequency
$\Delta\nu = | \nu_1 - \nu_2 |$

In terms of phase error, this becomes

$$\delta\phi \text{ (deg)} = 360 \cdot f \cdot \delta t \cong .86^* \frac{\Delta\nu}{\nu_1 \nu_2}$$

Other errors include a 2 nsec resolution limit which is decreased by $\sqrt{N}$ for N time interval averages and a ±10 psec mismatch between delays through the VHF switch.

An expression for total error in the measurement becomes

$$\delta\phi \text{(deg)} \cong \pm .86 \frac{\Delta\nu}{\nu_1\nu_2} \pm \frac{360 * f * 2 \text{ nsec}}{\sqrt{N}} \pm 360 * f * 10 \text{ psec}$$

$$\pm \frac{1}{\sqrt{N}} \left(\frac{1.5\text{x}10^{-5}(\nu_1 + \nu_2)}{\nu_1 \nu_2} \right) * \phi$$

The last term was plotted in Figure 6. Figure 8 plots the first three terms as a function of frequency, peak voltage level, and N. To find the total error, add the contributions from Figures 6 and 8.

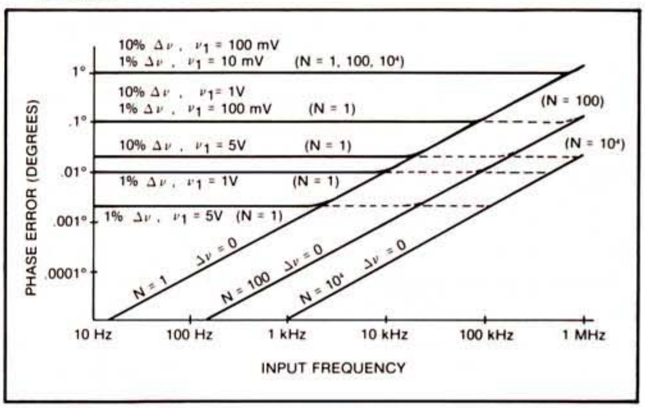

Figure 8

Another source of error arises from an actual phase shift which occurs in the reference signal and measurement signal paths. Figure 9 shows the simplified circuit when measuring the measurement signal time interval (input A2 of the VHF switch is connected to A common). The capacitance in each case is the sum of distributed cable capacitance and the input capacitance of the counter input channel (<30 pf). The signal at each input to the counter will undergo a phase shift equal to

$$-\tan^{-1}\left(\frac{2\pi f C_{total} \cdot 1.E6 \cdot R_s}{1.E6 + R_s}\right)$$

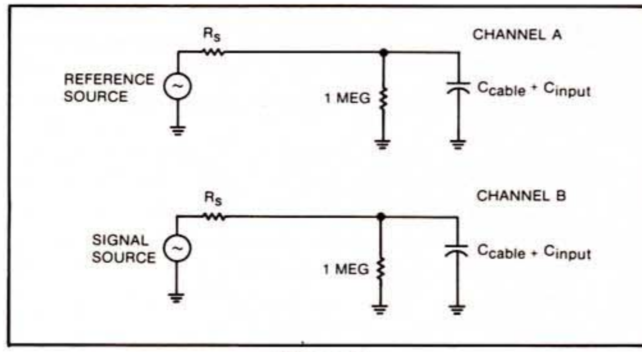

Figure 9

The difference in phase shift between the reference and measurement paths, assuming equal source impedances and equal input impedances for channel A and B, is

$$-\tan^{-1}\left(\frac{2\pi f C_{meas} * 1.E6 * R_s}{1.E6 + R_s}\right)$$

$$+ \tan^{-1}\left(\frac{2\pi f C_{ref} * 1.E6 * R_s}{1.E6 + R_s}\right)$$

Figures 10, 11 and 12 show the error for various source impedances and differences in capacitance. The total capacitance (for either path) used in the calculations was 300 pf.

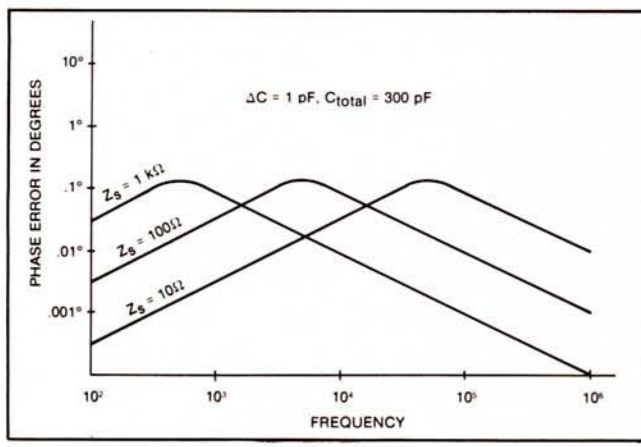

Figure 10

2. For lower frequencies (less than 100 Hz), the time required to make a phase measurement becomes noticeably longer due to the long times required to obtain an average if N is greater than 1. Aside from this time consideration, the phase of frequencies much less than 100 Hz can be measured.

3. The measurement of phase between pulses in a 50Ω system can be made by switching impedance on channel A and B to 50Ω (this will cause the amplitude to vary between the measurement signal and reference signal measurements but this will not affect the accuracy), adding slightly more than 10 nsec's worth of cable at the channel B input (i.e., between the A common of the VHF switch and channel B input of the counter), and

adjusting channel A and B trigger levels for reliable triggering. Trigger error and error due to amplitude differences may be neglected. The error would be reduced to approximately:

$$\delta\phi\,(\text{deg}) \approx \pm \frac{360 * f * 2\text{nsec}}{\sqrt{N}} \pm 360 * f * 10\ \text{psec}$$

4. The measurement of phase difference between sinusoidal signals in a 50Ω environment may be made as explained in (3) above except that A and B trigger levels should be in preset. The accuracy considerations discussed in (1) and (2) also apply for the 50Ω case with the exception that differences in cable lengths of the two signal paths have no effect.

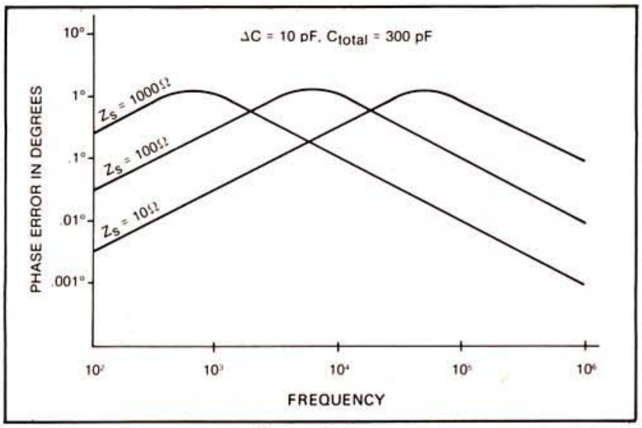

Figure 11

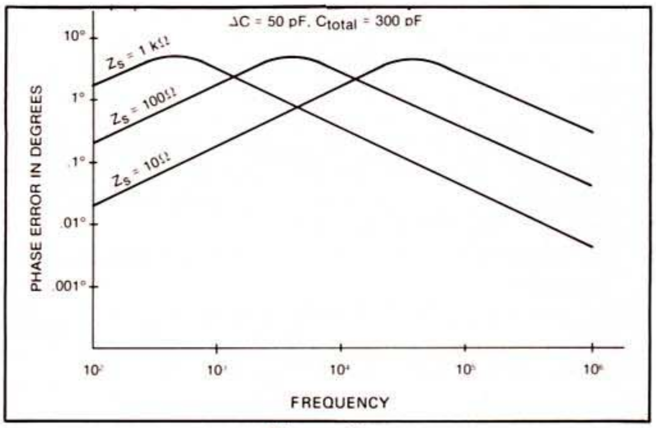

Figure 12

9820/21A Program Listing

```
0:
DSP "PHASE";DSP
;DSP ;DSP ;TBL 4
;TBL 5⊢
1:
ENT "NO. IN AVE"
,A⊢
2:
CMD "?U*","I2E89
:I1","?J";DSP ;
CMD "?U*","J1";
CMD "?J5";FMT *;
RED 13,R6;1/R6→R
3⊢
3:
CMD "?U>","A1";
DSP "  ";DSP ⊢
4:
CMD "?U*","I2F3G
5E89:I1","?J";
DSP "   ";CMD "
?U9","E0","?U8";
FMT "2";WRT 13⊢
5:
CMD "?U*","J1";
CMD "?J5";FMT *;
RED 13,B;B→R5;
GSB "MIN"⊢
6:
CMD "?U>","A2";
DSP "  ";DSP ;R5
→B⊢
7:
CMD "?U*","J1","
?J5"⊢
8:
FMT *;RED 13,R9⊢
9:
GSB "GATE"⊢
10:
CMD "?U>","A1";
DSP "  ";DSP ⊢
11:
CMD "?U*","J1","
?J5";FMT *;RED 1
3,R1⊢
12:
CMD "?U>","A2";
DSP "  ";DSP ;R9
→B;GSB "GATE"⊢
13:
CMD "?U*","J1","
?J5"⊢
14:
FMT *;RED 13,R2⊢
15:
360*(R2-R1)/R3→X
⊢
16:
2*π*(R2-R1)/R3→Y
⊢
17:
FXD 2;CMD "?"⊢
18:
PRT "PHASE (DEG)
=",X⊢
19:
FXD 3;PRT "PHASE
 (RAD)=",Y⊢
20:
PRT "          "
;STP ⊢
21:
GTO 0⊢
22:
"GATE";A*B→C⊢
23:
IF C≤1.E-6;58→Z;
GTO "W"⊢
24:
IF C≤1.E-5;59→Z;
GTO "W"⊢
25:
IF C≤1.E-4;60→Z;
GTO "W"⊢
26:
IF C≤1.E-3;61→Z;
GTO "W"⊢
27:
IF C≤1.E-2;62→Z;
GTO "W"⊢
28:
IF C≤1.E-1;63→Z;
GTO "W"⊢
```

9820/21A Program Listing

```
29:
48→Z⊢
30:
"W";CMD "?U*";
FMT Y2,Z;WRT 13⊢
31:
WTB 13,71;WTB 13
,Z⊢
32:
CMD "?U*","I1","
?J";DSP "  "⊢
33:
RET ⊢
34:
"MIN";IF B>10.E-
9;IF B≤R3/2;RET
⊢
35:
-4→X⊢
36:
"LP";CMD "?U8";
FMT FXD *.0;WRT
13,X;DSP "    "⊢
37:
X+1→X⊢
38:
CMD "?U*","J1","
?J5"⊢
39:
FMT *;RED 13,R5⊢
40:
IF R5>10.E-9;IF
R5≤R3/2;RET ⊢
41:
IF X>25;FXD 0;
PRT "B TRIG (MV)
=",X⊢
42:
GTO "LP"⊢
43:
END ⊢
R304
```

USING THE 9830A CALCULATOR

The 9830A Calculator may be used in place of the 9820/21A Calculator with system operation remaining essentially unchanged. The following sections list the necessary equipment for operation with the 9830A Calculator, discuss any differences in program operation, and present the complete program listing of the 9830A software.

MEASUREMENT SET-UP

The 9830A measurement system consists of the 5345A Electronic Counter (opt. 011), the 59303A Digital to Analog Converter, the 59307A VHF Switch, the 59405A opt. 030 HP-IB Calculator Interface, the 9830A Calculator, the 11274B String Variables ROM, and the 9866A Calculator Printer. Place the extended I/O ROM and the String Variables ROM in any of the Calculator ROM slots. The instruments are configured in precisely the same manner as in the case when the 9820A Calculator is the controller.

SYSTEM OPERATION

The system with the 9830A Calculator as the controller operates in the same manner as the system with the 9820A Calculator as the controller. The program requests the user to respond to the following:

"NUMBER IN AVERAGE" — enter the desired number of time intervals over which each time interval average measurement is to be made.

Figure 13 is a flow diagram of the 9830A software.

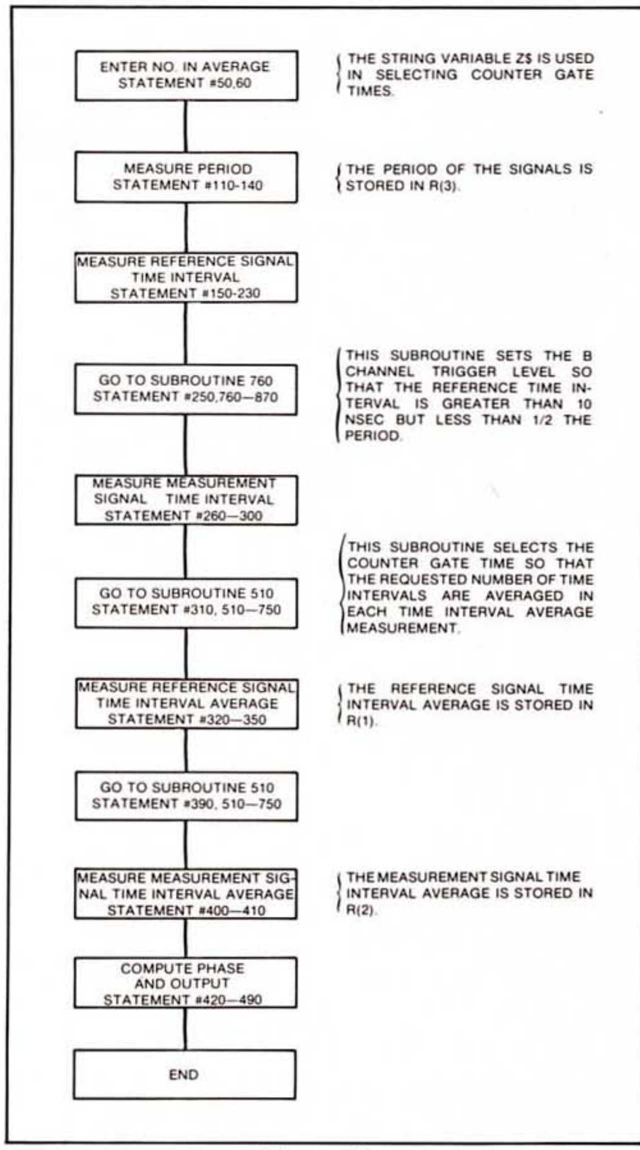

Figure 13

9830A Program Listing

```
10 DIM R[20],Z$[4]
20 Z$="G I1"
30 DISP "AN174-9:  PHASE"
40 WAIT 1000
50 DISP "NUMBER IN AVERAGE";
60 INPUT A
70 CMD "?U*","I2E8I1","?J"
80 WAIT 100
90 CMD "?J5"
100 ENTER (13,*)R[6]
110 CMD "?U*","F1G0I1","?J"
120 WAIT 100
130 CMD "?J5"
140 ENTER (13,*)R[3]
150 CMD "?U>","A1"
160 WAIT 100
170 CMD "?U*",
    "I2F3G5E8:9I1","?J"
180 WAIT 100
190 CMD "?U9","E0","?U8"
200 OUTPUT (13,*)"2"
210 WAIT 100
220 CMD "?U*","J1","?J5"
230 ENTER (13,*)B
240 R[5]=B
250 GOSUB 760
260 CMD "?U>","A2"
270 WAIT 100
280 B=R[5]
290 CMD "?U*","J1","?J5"
300 ENTER (13,*)R[9]
310 GOSUB 510
320 CMD "?U>","A1"
330 WAIT 100
340 CMD "?U*","J1","?J5"
350 ENTER (13,*)R[1]
360 CMD "?U>","A2"
370 WAIT 100
380 B=R[9]
390 GOSUB 510
400 CMD "?U*","J1","?J5"
410 ENTER (13,*)R[2]
420 X=360*(R[2]-R[1])/R[3]
430 Y=2*PI*(R[2]-R[1])/R[3]
440 CMD "?"
450 FIXED 2
460 PRINT "PHASE(DEG)=  ",X
470 FIXED 3
480 PRINT "PHASE(RAD)=   ",Y
490 PRINT
500 GOTO 10
510 C=A*B
520 IF C>1E-06 THEN 550
530 Z$[2,2]=":"
540 GOTO 710
550 IF C>1E-05 THEN 580
560 Z$[2,2]=";"
570 GOTO 710
580 IF C>1E-04 THEN 610
590 Z$[2,2]="<"
600 GOTO 710
610 IF C>1E-03 THEN 640
620 Z$[2,2]="="
630 GOTO 710
640 IF C>1E-02 THEN 670
650 Z$[2,2]=">"
660 GOTO 710
670 IF C>1E-01 THEN 700
680 Z$[2,2]="?"
690 GOTO 710
700 Z$[2,2]="0"
710 CMD "?U*"
720 OUTPUT (13,*)Z$
730 CMD "?U*","I1","?J"
740 WAIT 100
750 RETURN
760 IF B>1E-08 AND B
    <= R[3]/2 THEN 870
770 J=-4
780 CMD "?U8"
790 OUTPUT (13,*)J
800 J=J+1
810 CMD "?U*","J1","?J5"
820 ENTER (13,*)R[5]
830 IF R[5]>1E-08 AND R[5]
    <= R[3]/2 THEN 870
840 IF J<25 THEN 780
850 FIXED 3
860 PRINT "B TRIG LEVEL
    (MV)= ",J
870 RETURN
880 END
```

For more information, call your local HP Sales Office or East (201) 265-5000 • Midwest (312) 677-0400 • South (404) 436-6181 • West (213) 877-1282. Or, write: Hewlett-Packard, 1501 Page Mill Road, Palo Alto, California 94304. In Europe, Post Office Box 85, CH-1217 Meyrin 2, Geneva, Switzerland. In Japan, Yokogawa-Hewlett-Packard, 1-59-1, Yoyogi, Shibuya-Ku, Tokyo, 151.

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