NBSIR 73-307

A DUAL CHANNEL, DOUBLE HETERODYNED PHASE SHIFT MEASUREMENT SYSTEM 110 MHz TO 18 GHz

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ARMY/NAVY/AIR FORCE
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U.S. DEPARTMENT OF COMMERCE, Frederick B. Dent, Secretary
NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, Director

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A DUAL CHANNEL, TIME-INTERVAL, PHASE SHIFT MEASUREMENT SYSTEM

This report presents a system description, error analysis and operating procedure for a dual channel phase shift measurement system operable in the frequency range 110 MHz to 18 GHz.

Basic principles of operation include double stage heterodyning from RF and microwave frequencies to 100 kHz, time-interval and period measurements, and automatic conversion to phase in degrees through use of a digital computer.

Key words: Computer; counter; heterodyne; period; phase shift; time-interval.

DATE: April, 1973

OBJECTIVES: Establish or improve the phase measurement capability of calibration laboratories through the development of an appropriate phase measuring system and related standards operating from 110 MHz to 18 GHz.

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

1. Background

Microwave phase shift measurements, in general, use rotary vane phase shifters as transfer standards. Calibration of the transfer standards is performed at a few specific frequencies (usually three or less) using sliding short circuit in precision waveguide section techniques [1].[1] Uncertainties for the calibration of rotary vane phase shifters are usually within the range 0.1 to 1.0°. In turn the calibration of other phase shift devices by comparison with the rotary vane transfer standard has uncertainties which may be in the range 0.2 to 2.0°.

[1]Figures in brackets indicate literature references at the end of this report.

The disadvantages in using sliding short circuit techniques to calibrate the rotary vane phase shifters are:

1. Systematic uncertainties better than 0.05° are difficult if not impossible to achieve.
2. Data reduction is complicated and time consuming.
3. Systems are expensive and must be duplicated for each waveguide size.

Recent efforts at the National Bureau of Standards have been directed toward producing an improved phase shift measurement system to be used in calibrating rotary vane phase shifters or low loss lengths of waveguide transmission line used as phase shift transfer standards.

1.1 Goals

The proposed characteristics of an improved phase shift measurement (PSMS) include the following:

1. Frequency range: 10 MHz - 40 GHz*
2. Phase shift range: 0 - 360°
3. Uncertainty of phase displacement measurements: 0.01°
4. Measurement resolution: 0.001°
5. Readout: direct reading

*The frequency range goal (1) was reduced through mutual agreement between the sponsor and NBS to 110 MHz - 18 GHz which meets immediate needs of the sponsor and conforms with equipment capabilities used in the system.

1.2 Selection of Measurement Method

Three different phase shift measurement techniques were investigated to determine which one would most nearly satisfy the goals. These three techniques involved: 1) A pulse-operated electronic phase shifter, 2) A resolver phase shifter, and 3) A time interval counter.

The pulse operated phase shifter was designed to retard the phase of a synchronous clock by a specified amount over a particular period of time. One of these instruments has been built with a phase shift accuracy of 5 nanoseconds at 100 kHz (0.18°), which was insufficient for the requirements of this project.

The resolver phase shifter operated at 30 MHz and had deviations in repeatability ranging from 0 to 27°. This technique was not pursued further.

The resolution of the time-interval counter was measured using a high stability 100 kHz source and found to be 100 picoseconds which in terms of phase at 100 kHz is equivalent to 0.0072°. (See Section 4.2.1b). In addition, the system could be broadband and direct reading in phase from 0° to 360°; therefore, the time-interval method of phase shift measurements was chosen as the basis of the PSMS.

2. Measurement System Description

2.1 Introduction

The basic operational principles of the PSMS are heterodyning and time-interval measurement. No theory for these techniques will be presented, since these subjects are covered in numerous texts and papers involved in RF and microwave theory.

This description follows a step-by-step explanation of the various signal processing stages from RF input to output phase display. Refer to Figure 1 for a block diagram of the PSMS.

2.2 Overall System

The PSMS has two channels, called test and reference, which accept two coherent RF signals and double heterodynes both signals to two 100 kHz sine waves. These are shaped to square waves from which two quantities are measured by a counter: 1. the period of one complete cycle and 2. the time interval occurring between the zero crossing points of the waveforms of the two 100 kHz square waves. These data are then used to compute (using a digital computer) the phase displacement in degrees between the two 100 kHz signals.

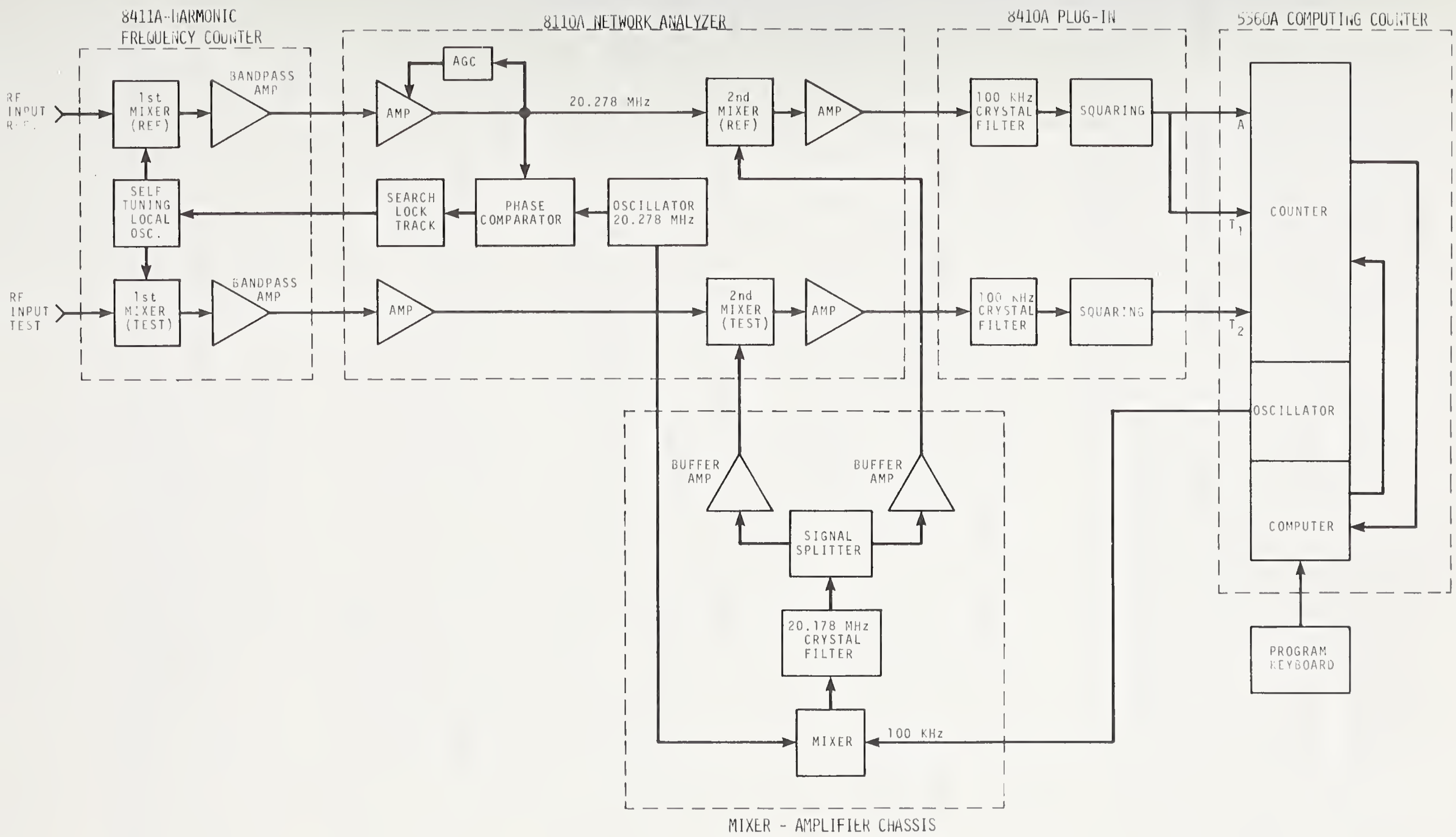

Figure 1. Block diagram of the Phase Shift Measurement System.

2.2.1 First Heterodyne Stage

The technique used in the first heterodyne stage of each channel is referred to as harmonic mixing [2]. At this stage any two input RF signals in the 0.11 to 18 GHz range are converted to two 20.278 MHz IF signals. High frequency harmonics of the self-tuning local oscillator are applied to the first mixers to obtain 20.278 MHz IF difference frequency signals. (See Figure 1.)

The self-tuning local oscillator contains a pulse generator, a voltage tuned oscillator (VTO) and a frequency and phase control system. Signals from the VTO are applied to the pulse generator to obtain harmonics in the 0.12 - 18 GHz range which are mixed with the RF input signals. A harmonic 20.278 MHz above the RF input signal is used to phase lock the VTO to the RF input signal. The phase lock loop supplies tuning control voltages to the VTO to perform the following functions:

1. Initially sweeps the VTO to search for the RF input frequency.
2. Phase locks the reference channel first IF to a 20.278 MHz crystal oscillator reference. [2, Section 3, page 95].

2.2.2 20.178 MHz Signals

A 100 kHz signal derived from the time base oscillator in the counter is mixed (see Appendix B for circuit) with a

20.278 MHz signal from the crystal oscillator reference for the first heterodyne stage. The difference IF frequency, 20.178 MHz, is selected using a very narrow band crystal filter (3 dB bandwidth = 5 kHz) and is split into two channels (test and reference), where each signal is then buffer amplified (Appendix B) and fed to the second heterodyne stage in the test and reference channel.

2.2.3 Second Heterodyne Stage

The two 20.278 MHz signals from the first heterodyne stage are mixed with the two 20.178 MHz signals to obtain two 100 kHz difference frequency signals.

2.2.4 Wave Shaping at 100 kHz

The 100 kHz difference IF signals from the second heterodyne stage are each amplified and filtered in very narrow band crystal filters (3 dB bandwidth = 5 kHz) and sent to squaring circuits (Appendix B) used to obtain square waves having voltage steps which are coincident with the zero crossing of the input sine waves. The rise time of the 100 kHz square waves is less than 10 nanoseconds and rises from -0.5 volts to 4.5 volts.

2.2.5 Time-Interval Measurements

The 100 kHz square waves go to the time-interval counter, where two quantities are measured:

1. The period of the reference channel square wave.
2. The time interval between the positive going steps of the reference channel and test channel 100 kHz square waves.

2.2.6 Computation

A digital computer connected to the counter and located in the same chassis utilizes these measured values of period and time interval to compute the phase difference between two 100 kHz square wave signals. The relationship is:

$$\phi = 360 \frac{t}{T} \tag{1}$$

where

ϕ = relative phase difference (degrees)

t = time interval (seconds)

T = period of one cycle at 100 kHz (seconds)

The digital computer is programmed through a keyboard. Random differences in the measurement of time interval and period occurring from one measurement to the next can be reduced by programming the computer to average the results of a number (N) of measurements. The possible selections for N are 1, 10, 100, 1000, and 10,000. The variation in readings is reduced by $1/\sqrt{N}$ [3] if the difference in readings is caused by randomness.

2.2.7 Display

The computed phase difference is displayed on the front panel of the counter in digital form. Eleven digits may be observed; however, only six digits (three to the right of the decimal) have any significance. The duration of the display depends on the number N selected for the measurement and may vary from a few tenths of a second (N = 1) to 50 seconds (N = 10,000).

3. Operating Procedure

3.1 Introduction

The instructions cover setup and use of the PSMS. The order of the instructions is chronological in the sequence which is normally followed, starting with assembly of the system from the major component pieces through control settings to use of the system in a measurement procedure.

The setup procedure refers to certain specific equipment in the PSMS by the model numbers assigned to these items by their manufacturer.* Referral by model number rather than descriptive terms is done to reduce ambiguity in following these instructions. Model numbers are printed on the front panels

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of each major component; therefore, no difficulty is anticipated in identifying each major component by its model number.

3.2 System Setup

3.2.1 Cable Connections for the PSMS

Most of the cables referred to are semi-rigid coaxial cables especially constructed for inter-system connections. These cables have been shaped to fit when the relative rack position of the major components is from top to bottom -- (1) 5360A, (2) 8410A, (3) mixer amplifier chassis.

The following cables should be connected before AC power is turned on.

a. Connect the 8411A to the 8410A, using the cable attached to the 8411A.

b. Connect the reference output on 8410A plug-in to input A of the 5365A module in the 5360A counter, using the semi-rigid coaxial cable with BNC connectors supplied.

c. Connect the reference output on 8410A plug-in to the T_1 input of the 5379A time-interval plug-in, using the semi-rigid coaxial cable with BNC connectors supplied to fit.

d. Connect the test output on the 8410A plug-in to the T_2 input on the 5379A plug-in, using the semi-rigid coaxial cable supplied to fit.

e. Connect the 100 kHz clock output on the rear panel of the 5360A counter to the 100 kHz input on the rear panel of 8410A plug-in, using the semi-rigid coaxial cable with BNC connectors supplied to fit.

f. Connect the 100 kHz output on the rear panel of the 8410A plug-in to the 100 kHz input on the rear panel of the mixer amplifier chassis, using the semi-rigid coaxial cable with SMA connectors supplied to fit.

g. Connect the 100 kHz arming output on the rear panel of the 8410A plug-in to the Ext. Meas. Time input on the rear panel of the 5360A counter, using the semi-rigid coaxial cable with BNC connectors supplied to fit.

h. Connect the cable from the 5375A keyboard to the connector which fits on the rear panel of the 5360A counter.

i. Connect the 20.278 MHz output on the rear panel of the 8410A to the 20.278 MHz input on the rear panel of the mixer-amplifier chassis, using the semi-rigid coaxial cable with SMA connectors supplied to fit.

j. Connect the 20.178 MHz outputs on the rear panel of the mixer-amplifier chassis to the 20.178 MHz inputs on the rear panel of the 8410A, using the two semi-rigid coaxial cables with miniature Sealectro connectors on one end and SMA connectors on the other end which are supplied to fit.

3.2.2 Switch Position for Measurement System

Switch positions and controls on the front panel of the 5360A and the plug-ins 5365A and 5379A are:

a. Push button switch to EXT

b. Measurement time to 1 ms with multiplier to 1

c. 5365A function to period

d. 5365A input to middle position

e. 5365A sensitivity to X1

f. 5365A level controls to preset

g. 5379A time interval T_1 slope to $\uparrow$

h. 5379A time interval T_2 slope to $\uparrow$

i. 5379A T_1 to X1

j. 5379A T_2 to X1

k. 5379A arming to auto

l. 5379A sep-com to sep

Switch positions and controls on the front panel of the 8410A are:

a. Amplitude test channel gain to 69 dB

b. Amplitude vernier control full clockwise

c. Frequency range control set to the frequency of operation

Set the trig-norm switch on the rear panel of the 5360A to norm.

3.2.3 Power Level Setting

Check to see if the AC power cord to the 8410A plug-in unit is connected and turn on AC power to the 5360A, 8410A and mixer-amplifier chassis.

The following sequence is suggested for adjusting the RF signal levels at the inputs to the phase measurement system:

a. Adjust the power levels of the RF signals in both the test channel and the reference channel to minimum.

b. Connect the phase shift measurement system to the external system through the APC-7 (7 mm) connectors. The external reference channel should be connected to the reference input of the 8411A.

c. Bring the power level of the reference channel RF up until the indication on the front panel of the 8410A is at the left edge of the operate region. Then increase the power level by 3 dB. The indicator should be near the left center of the operate region.

d. Reverse the input connections so that the test channel RF signal is entering the reference channel part of the 8411A.

e. Adjust the test channel RF signal so that the indicator on the front panel of the 8410A is at the right edge of the operate region.

f. Reverse the connections again so that the test channel RF enters the test channel of the 8411A and the reference channel RF enters the reference channel of the 8411A.

3.2.4 Computer Program for Phase Measurement

The following program is entered on the 5375A keyboard so that the phase will be displayed in degrees [4]:

a. Set sub-norm-man to norm

b. Select N (Set to 1, 10, 100, 1000, or 10 K)

c. Press: Manual

d. Load: 360

e. Press: C exchange X ($C \leftrightarrows X$)

f. Press: Learn

g. Press: Clear XYZ

h. Press: a exchange with x

i. Press: X for prog

j. Press: Module A

k. Press: b exchange with x

l. Press: Plug-in

m. Press: b→x→y

n. Press: ÷ (divide)

o. Press: c→x→y

p. Press: X (multiply)

q. Press: a→x→y

r. Press: + (add)

s. Press: a exchange with x

t. Press: Repeat

u. Press: a→x→y

v. Press: N→x→y

w. Press: ÷

x. Press: Display X

y. Press: Run

z. Press: Start

3.2.5 Zero Crossing Adjustment

a. Connect an oscilloscope to the Ref output on front panel of the 8410A plug-in.

b. Reduce the power level of the RF input to the reference channel by 26 dB. (This should cause the 8411A and 8410A to lose lock.)

c. Adjust the ref channel pot on rear of 8410A plug-in unit until the output of the ref channel squaring circuits observed on scope is between its upper and lower state. (Output appears noisy.)

d. Return reference channel power to normal operating range.

e. Connect scope to test channel output on front of 8410A plug-in.

f. Reduce RF power level to test channel approximately 40 dB.

g. Adjust test channel pot on rear of plug-in until output appears between its upper and lower states.

h. Return power level of RF input to test channel to normal operating position.

i. Return connections to counter from Blank-Plug-In.

3.3 Measurement Procedure

The system should now be operating and reading phase in degrees. The measurement of phase shift is ready to begin.

With the device under test at its initial starting value record the phase reading observed on the counter. Take several readings to make sure that the system is not drifting. (With normal operation and proper warm-up -- four hours -- the variation from reading to reading should be random and have a standard deviation of about 0.007°.) Next change the phase in the test channel to the desired nominal value of phase shift and observe the phase readings on the counter. Take several readings to see that the readings are repeating. (In most cases, the first reading of phase after a phase shift has occurred will be in error because part of the measurement occurred while the phase was being shifted. Time should be allowed for a full measurement after the phase has been shifted.)

The largest potential error observed in making phase shift measurements is referred to in this report as quadrature error. (Quadrature refers to the measurement technique used to reduce the error.) This error was unanticipated in designing this system and its source is not definitely known at this time. However, the effect of this quadrature error can be reduced (± 0.25° reduced to ± 0.06°) by the following measurement procedure:

1. Make the first measurement of phase shift by recording the phase readings before and after a phase shift has been produced. Record the difference between the phase readings.
2. Insert a 90° phase shift in the reference channel RF signal.
3. Repeat the phase shift measurement as in (1).
4. The phase shift value to be recorded as the measured value is the average of the measurements in (1) and (3).

For added confidence in the measurement of phase shift the measurements should be repeated with the reference channel RF phase shifted by 180° and 270° from its initial value of phase in (1). A comparison of the average of phase shift measurements taken for reference channel RF phase settings of (0° and 90°), (90° and 180°), (180° and 270°), (0° and 270°) or (0°, 90°, 180° and 270°) will give the user a good approximation of the random and systematic changes occurring in the measurement.

If more than one phase shift is to be measured, as in calibrating a rotary vane phase shifter, the phase shifts may be measured successively without changing the reference channel RF phase until the complete string of phase shifts has been recorded. Then the reference channel phase can be changed by 90° and the phase shift readings recorded again.

A suggested procedure for measurement of successive phase shifts -- for example, calibrating a rotary vane phase shifter at increments of 20° through a total range of 720° -- is to record the initial value of phase before and after each incremental value of phase shift. This reduces the effect of drift which may occur in the measurement system and in the external system. If the initial value of phase is not recorded between successive phase shifts, the effect of drift is cumulative.

4. Errors

4.1 Introduction

Errors in the measurement of phase shift result from two main sources:

1. Errors from the PSMS.
2. Errors from the auxiliary equipment. (The auxiliary equipment includes the RF source, signal splitting components and the phase shift device under test. Appendix A includes a more complete description of a typical auxiliary system and the treatment of errors associated with that system.)

This error analysis considers all predictable sources of random error in the PSMS. The quadrature error previously mentioned is not included in the theoretical analysis, since it is systematic and its source has not yet been determined; thus no theoretical limits can be assigned. However, the experimental evaluations (Section 5) indicate the extent of reduction of quadrature error from the quadrature averaging measurement procedure.

4.2 Theoretical Error Analysis

Specifically, the errors in the PSMS result from:

1. Frequency instability of the HP 5360 reference oscillator (ε_1).
2. Time-interval measurement uncertainty (ε_2).
3. Cross-channel leakage (ε_3).
4. Environmental effects (ε_4).
5. Errors caused by amplitude variations of the input signal (ε_5).
6. Error caused by trigger instability (ε_6).

These errors will be discussed individually.

From (1) Section 2.2.6 the equation for the conversion of time-interval and period measurement to phase in degrees is:

$$\phi = 360 \left(\frac{t}{T}\right) \text{ (degrees)} \tag{1}$$

since

$$f = \frac{1}{T} \text{ (hertz)} .$$

Then:

$$\phi = 360\, tf \text{ (degrees)}. \tag{2}$$

The derivatives of (1) and (2) will be used in the discussions of ε_1 and ε_2.

4.2.1 Frequency Instability of the HP 5360 Reference Oscillator (ε_1)

The derivative of equation (2) with respect to the frequency (f) gives

$$d\phi = (360\ t)\ df,$$

letting

$$\varepsilon_1 = |\Delta\phi| = 360\ t\ |\Delta f|. \tag{3}$$

The reference oscillator frequency is 5 MHz, and its stability is given as less than 5 parts in 10^{10} per twenty-four hours [3, p.2]. A divide-by-5 and a divide-by-10 network in the 5360A provides the required 100 kHz reference signal. The stability after frequency division is no worse than 2.5 parts in 10^7. Inspection of (3) shows that the error (ε_1) increases with t and is maximum for $t = T = 10^{-5}$ seconds. Substituting in (3) we get

$$\varepsilon_1 = 9 \times 10^{-7} \text{ degrees.}$$

This error is not significant with respect to other errors to be discussed.

4.2.2 Time Interval Measurement Uncertainty (ε_2)

This error can be determined from the partial derivative of (1) with respect to the time interval (t) and the period (T).

$$d\phi = \frac{\partial \phi}{\partial t} dt + \frac{\partial \phi}{\partial T} dT$$

$$\Delta\phi = \frac{360}{T} \Delta t - \frac{360t}{T^2} \Delta T.$$

The maximum error ε_2 occurs for $t = T$ and $\Delta t = \Delta T$ which gives:

$$\varepsilon_2 = \frac{720}{T} |\Delta T|.$$

The result of an experiment to determine ΔT using a high stability 100 kHz source (short term stability equal to 2×10^{-10}) is $\Delta T = 100 \times 10^{-12}$ seconds, i.e., repetitive readings of period measurements differed by no more than 100×10^{-12} seconds.

Using $\Delta T = 100 \times 10^{-12}$ seconds the value for (ε_2) is

$$\varepsilon_2 = 0.0072°$$

4.2.3 Cross Channel Leakage

A signal that reaches the test channel from the reference channel input is a cross-channel leakage signal. A leakage signal of any magnitude may introduce a measurement uncertainty. In general, leakage signals are treated as random error sources because it is an extremely difficult task to completely characterize them in terms of their magnitude and phase.

The maximum error generated by a leakage signal can be estimated from [5, Section 8, p.12]:

$$\varepsilon_{3max} = 104.6 \frac{|E_L|}{|E_T|} \text{ degrees,} \qquad (4)$$

where $|E_L|$ is the magnitude of the leakage signal and $|E_T|$ is the magnitude of the test signal and $|E_L| << |E_L|$.

Measurements of cross-channel leakage in the 8411A and 8410A indicated a maximum leakage of -74 dB occurring in the frequency range 11 - 16 GHz. The resulting phase error from (4) is

$$\varepsilon_{3max} = 0.020°.$$

4.2.4 Environmental Effects

Even though the environment within many calibration laboratories is closely controlled, inhomogeneous temperature variations can still easily occur. It would be an extremely difficult task to attempt a theoretical determination of the magnitude of the error introduced by changes in the environment. The experimental approach is the most practical way of evaluating this random error (ε_4).

The error resulting from environmental changes is observed as drift during a measurement. To minimize drift, sufficient warm-up time -- four hours -- must be allowed. Stabilities within 0.015° have been attained for periods of two hours after warm-up, however, most phase shift measurements can be accomplished in thirty minutes or less. Furthermore, the drift time per measurement can be reduced to approximately two minutes by rechecking the zero reference point prior to each calibration point. Using this technique the estimated limit of error (ε_4) from environmental changes is less than 0.005°.

$$\varepsilon_4 = 0.005°.$$

4.2.5 Amplitude Errors

The measured time interval is the time displacement between the reference and test channel signals. If the amplitude of the test channel signal remains constant as the microwave device under test is adjusted, the start trigger level of the squaring circuits can be set at any arbitrary value. But the amplitude of the test channel signal may vary a finite amount during a measurement; thus the zero crossing point is used to minimize counter degradation caused by amplitude variations in the microwave test signal. Further, the greatest trigger resolution is obtained at the zero crossing point.

Triggering the squaring circuit at the zero crossing of the 100 kHz sine wave can be accomplished only within a certain tolerance. Triggering no longer occurs if the amplitude of the test signal is reduced to -30 dB below the normal operating level. At -30 dB however, it was possible to adjust the level control so that the displayed phase was within 2.0° of that displayed at 0 dB. Thus the error caused by amplitude changes in the test channel can be determined as:

$$\varepsilon_5 = \frac{2.0|\Delta L|}{30} \text{ degrees,}$$

where ΔL is the change in the insertion loss of the microwave device under test.

Typically, a rotary vane phase shifter produces an insertion loss change of less than 0.1 dB for any setting on the dial. For a rotary vane phase shifter calibration, the error becomes

$$\varepsilon_{5max} = 0.007°.$$

4.2.6 Instability of the Preset Trigger Level in the Time-Interval Plug-In

This error (ε_6) can be determined as

$$\varepsilon_6 = \frac{360}{T}\left(\frac{4\Delta E}{R}\right) = \frac{1140\ \Delta E}{TR} \text{ degrees,}$$

where ΔE is the instability of the trigger level; T is the period of the input signal and R is the rise rate of the input signal; and the factor (4) is due to the start/stop trigger points in measuring both time interval and period. It has been experimentally determined that $R = 4 \times 10^8$ volts/sec. The manufacturer specifies that the trigger level in the time interval plug-in can be adjusted within 0.005 volts [7, Section 5-3].

Thus, the error becomes

$$\varepsilon_6 = 0.002°.$$

4.2.7 Error Summation in the PSMS

The total maximum theoretical error is determined by simple addition of the magnitudes of the individual theoretical errors.

a. Frequency instability of the reference oscillator:

$$\varepsilon_1 = \text{not sufficient}$$

b. Time-interval measurement uncertainty:

$$\varepsilon_2 = 0.007°$$

c. Cross-channel leakage:

$$\varepsilon_3 = 0.020°$$

d. Environmental effects:

$$\varepsilon_4 = 0.005°$$

e. Amplitude changes:

$$\varepsilon_5 = 0.007°$$

f. Trigger instability:

$$\underline{\varepsilon_6 = 0.002°}$$

Total error: $\varepsilon_{total} = 0.041°$

5. Experimental Evaluation

5.1 Introduction

Systematic uncertainties in measurements using the PSMS are due to residual quadrature errors. The magnitude of these errors cannot be predicted theoretically; however, experimental measurements can be performed to determine the limits of systematic error. In addition random error limits can be experimentally verified.

Systematic errors can affect the measurement results of the PSMS in two ways: 1. as bias errors producing an offset of measured values from the true value and 2. errors contributing to the spread between measured values. Normally differences between measured values of the same phase shift are caused by random errors. However, because of the measurement procedure, successive measured values of the same phase shift are not from the same population; hence, differences in the measured values cannot be considered random.

To determine the limits of systematic error and verify the random error limits given in (4) three separate groups of phase shift measurements were performed. For each group of measurements the initial phase setting was zero degrees; the increments were 20 degrees (two groups) and 24 degrees; and the final phase setting was nominally 360 degrees.

The measurement procedure described in section 3.3 was used in all the measurements, and the results were determined from averages of quadrature related sets. The results for each group of measurements are shown in the form of correction curves; where the difference between measured values and dial reading (or calculated value) is plotted along the ordinate, and the dial reading or calculated value of phase shift is plotted along the abscissa.

The measurements were made at 10.23 GHz and at 17.0 GHz.

5.2 Measurements at 10.23 GHz

5.2.1 Phase Shifts Produced by a Rotary Vane Phase Shifter

A system was set up, using WR-90 waveguide with two channels (test and reference) having a microwave signal in each channel derived from a reflex klystron -- frequency locked at 10.23 GHz to a crystal controlled reference oscillator. See figure 2.

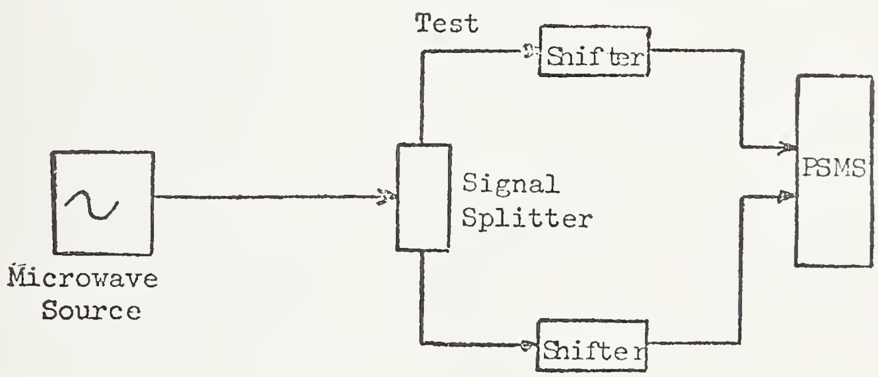

Figure 2. Simplified block diagram of a test set-up in WR-90 waveguide using a rotary vane phase shifter.

The phase shifter used in the test channel is a WR-90 rotary vane phase shifter with a precision dial such that phase position (on the dial) can be reset within ± 0.02 degrees. The phase shifter in the reference channel was used to obtain 90-degree phase shifts for quadrature averaging.

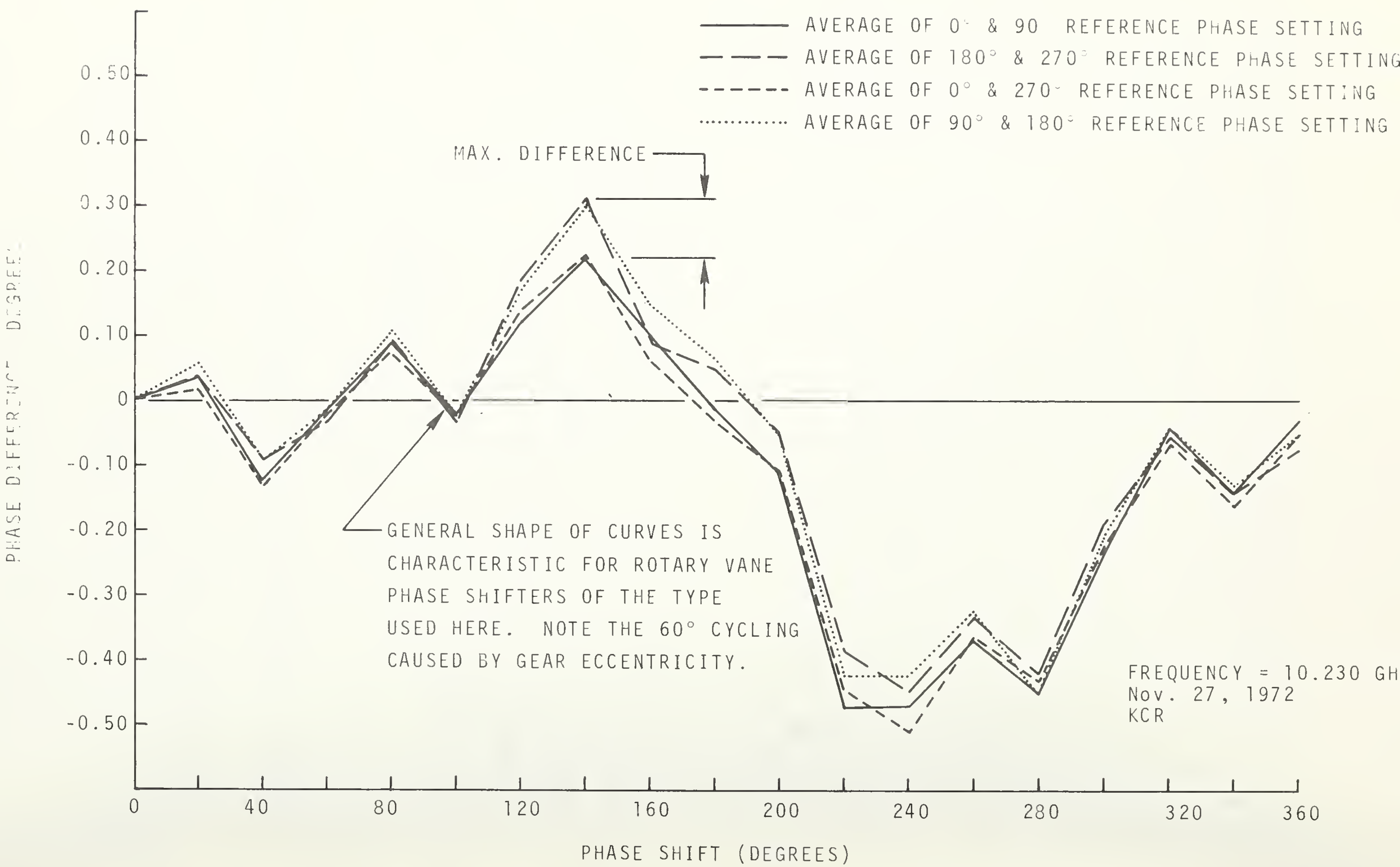

Figure 3. Results of measurements of phase shift produced by a rotary vane phase shifter at 10.230 GHz.

Results from this group of measurements are shown in figure 3. The major deviations of the correction curves from the zero degree difference line are characteristic for a rotary vane phase shifter. Phase shifts from rotary vane phase shifters will differ from the dial readings, depending upon the orientation of the vane in the waveguide, the gearing eccentricity and the mismatch [6] at the insertion point. These deviations from zero will typically vary by as much as 0.5 degrees.

Systematic errors cannot be evaluated from these results since the phase shifts are not well known; but since they are repeatable, the difference (spread) between curves is of interest in verifying the random error limits given in section 4. The random errors producing spread between the curves are:

1. Errors from resettability of the rotary vane phase shifter (includes an initial and a final phase setting) = ± 0.030 degrees
2. Environmental effects on the waveguide system (temperature) = ± 0.005 degrees
3. Frequency and power instability of the microwave source = ± 0.005 degrees
4. Random error from the PSMS = ± 0.041 degrees

The maximum expected variation in phase shift measurements determined by the square root of the sum of the squares of the contributing random errors is ± 0.051 degrees. The maximum observed phase shift measurement error is ± 0.045 degrees, which is within the theoretical limit; and the conclusion is that the PSMS random error limit = ± 0.041 degrees is valid

The following group of measurements provides some information about systematic errors.

5.2.2 Phase Shifts Produced by a Sliding Short Circuit in a Precision Waveguide Section

The waveguide system described in Section 5.2.1 was modified so that the test channel phase shifter was a sliding short circuit in a precision waveguide section. (See Figure 4.)

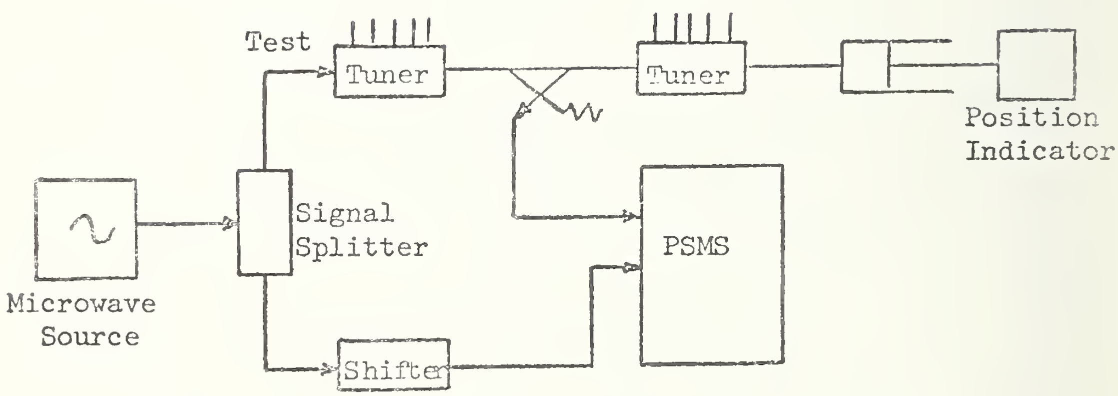

Figure 4. Simplified block diagram of a sliding short phase shift test system using WR-90 waveguide.

The phase shifts resulting from movement of the sliding short circuit are calculable with uncertainties of ± 0.
(The uncertainties were calculated using equations given

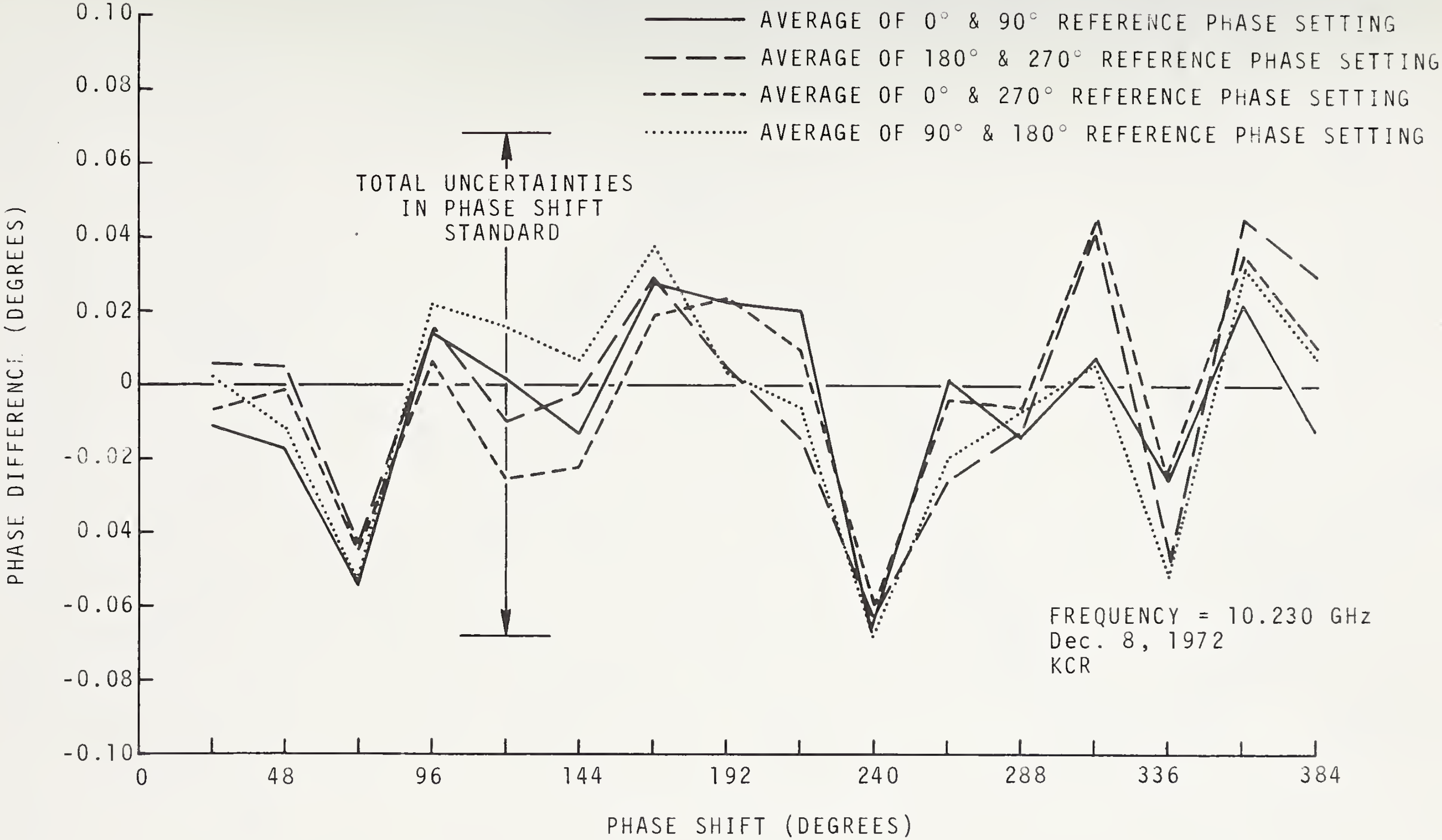

Figure 5. Results of phase shift measurements at 10.23 GHz. Phase shifts produced by a sliding short circuit technique.

[1] resulting from non-perfect tuning of Γ_{2i} and S_{31}, waveguide dimensional variations, motional resettability of the short circuit, cross channel leakage, frequency instability, and environmental temperature effects.)

The results from quadrature averaged measurements are shown in Figure 5, where the difference between the measured value and the calculated value of phase shift is plotted against the total phase shift.

The differences between the measured and calculated values of phase shift are well within the total uncertainties assigned to the calculated values; however, no technique has been developed to separate the uncertainties of the PSMS from those of the sliding short circuit system used to produce the phase shifts. Therefore, the limit of systematic uncertainty of the PSMS is taken as the worst case difference between the measured and calculated phase shifts. From the data the worst case difference is 0.064°, and the systematic uncertainty ($\varepsilon_{systematic}$) is given as:

$$\varepsilon_{systematic} = \pm\ 0.064°.$$

5.3 Measurements at 17.0 GHz

These measurements were performed to verify that the error limits (systematic and random) observed at 10.23 GHz are also valid at 17.0 GHz.

For these measurements a system was set up using WR-62 waveguide with a rotary vane phase shifter as a transfer

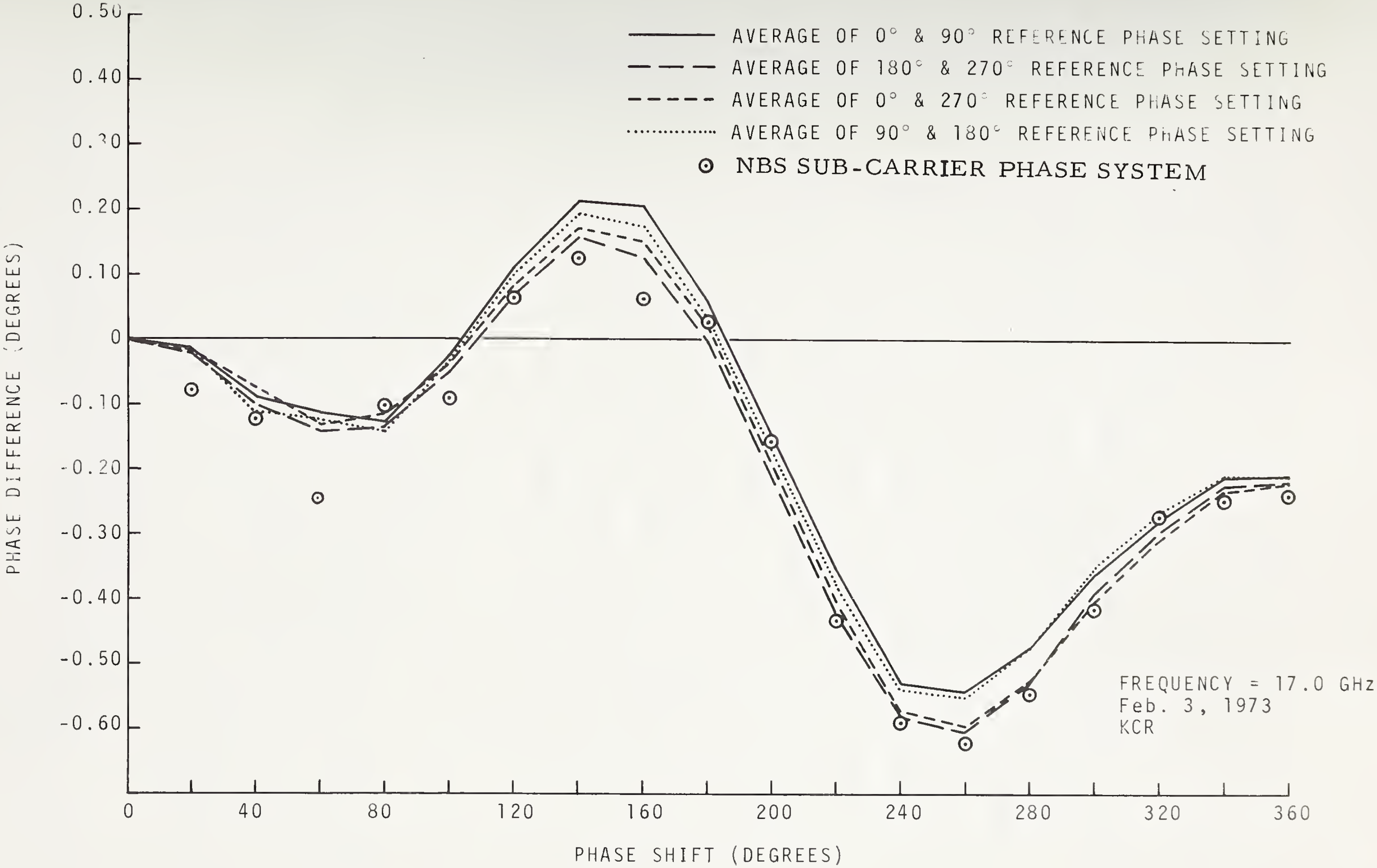

Figure 6. Results of phase shift measurements at 17.0 GHz.

standard. Phase shifts produced using the transfer standard were measured with the PSMS and the NBS sub-carrier phase shift measurement system. (SC/MS) Results of measurements from both systems are shown in figure 6.

An analysis of the data from the two different systems gives a mean difference of 0.031 degrees between the PSMS measurements and the SC/MS measurements with a two sided 95 percent confidence interval between 0.049 degrees and 0.012 degrees. These 95% confidence intervals are well within the systematic uncertainty limits of 0.08 degree and (3S) random uncertainty limits of 0.129 degree established for the SC/MS.

No definite conclusions concerning systematic and random error limits for the PSMS can be drawn. However, these results (figure 7) are definitely similar to the results obtained at 10.23 GHz (figure 4), and the errors are no worse at 17.0 GHz than at 10.23 GHz.

6. Conclusions

Phase shift measurements using the PSMS can be within the systematic uncertainty limits of 0.064 degrees and a random uncertainty of 0.041 degrees if the quadrature averaging procedure is used.

7. Recommendations

Accurate phase shift measurements require consideration for the following:

1. Auxiliary system--see Appendix A for a description of requirements and a discussion of the errors from the auxiliary system.
2. Operating procedure--Without quadrature averaging errors as large as 0.25 degrees will occur.
3. Frequency range--The manufacturer's specification for operation of the 8411A is 110 MHz to 18 GHz. This specification has not been verified; however, no difficulty has been encountered in operation at frequencies selected at random within this range. In addition, successful operation at 18 GHz was achieved during developmental stages. None of the circuits developed at NBS (see Appendix B) or modifications of commercial equipment (see Appendix C) will affect the frequency range specification given by the manufacturer.
4. Power range--The safe levels of RF and microwave power input are given in section 3.2.3, and operation within this range is recommended. In addition, variations of power level during the measurement will affect the uncertainty of the results. This error, listed in section 4.2.5, will be increased if the phase shift measurements are accompanied by power level changes greater than 0.1 dB.

Appendix A. Auxiliary Equipment

1. Function

Shown in figure 7 is a block diagram of a system used successfully at NBS as an auxiliary system to the phase shift measurement system. The functions of the auxiliary system are:

1. Generate an RF signal which is stable in power and frequency.
2. Split the RF signal into two channels (test and reference) with cross channel leakage less than 80 dB below the signal level in either channel.
3. Provide the insertion point in the test channel for the phase shift device under test.
4. Have phase shift capability in the reference channel of at least 90 degrees.

2. Requirements

2.1 RF Source

The RF source should be frequency controlled so that frequency variations will be less than 1×10^{-7} in a thirty-minute period. In addition, fluctuations in power level should be less than 0.1 dB in a thirty-minute period.

2.2 Signal Splitter and Isolators

The RF signal should be split approximately equally into two channels in such a way that the leakage from either channel to the other is less than -80 dB. With uniconductor waveguide

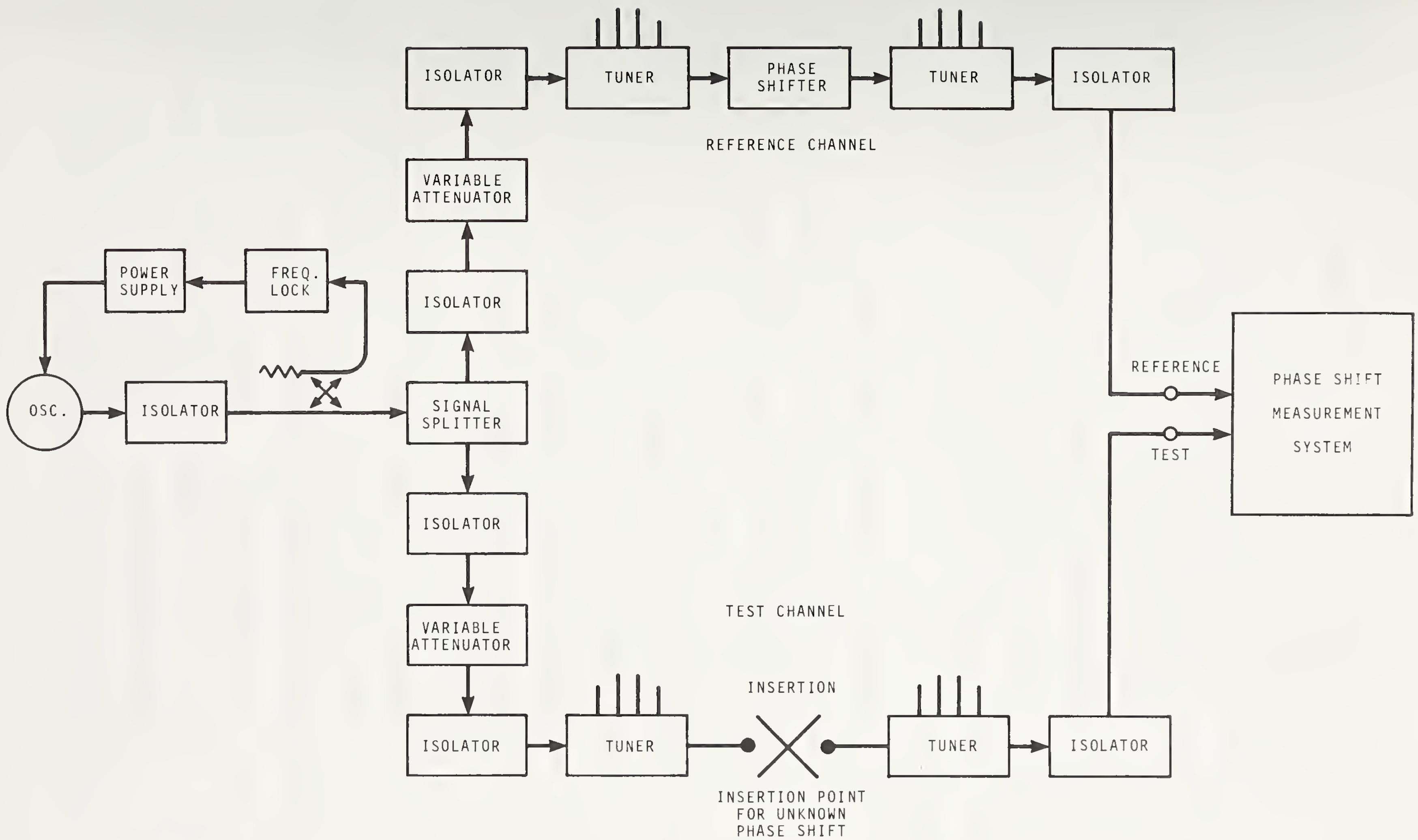

Figure 7. Block diagram at an auxiliary system used in conjunction with the PSMS for phase shift measurements.

magic tees or hybrid tees will work,and in coaxial systems power splitters with 30 dB isolation between channels will work. In coaxial or waveguide systems additional isolation should be used so that the leakage is reduced.

2.3 Tuners

The device under test in the test channel should have minimum mismatch at its input and output ports. The effect of mismatch on phase measurements is covered in Section 3 of this Appendix.

2.4 Reference Channel Phase Shifters

The measurement procedure given in Section 3 requires a 90° phase shift in the reference channel RF signal.

3. Errors in Auxiliary System

The following errors contribute significantly to the total error related to a specific measurement.

1. Frequency instability of the microwave signal source.

A simple analysis shows this error to be dependent upon the frequency instability of the microwave oscillator and the differential length between the reference and test channels from oscillator to the 8411 input. This error can be minimized in two ways. First, the frequency stability of the microwave oscillator can be minimized; and second, the differential length (ideally thought of as the differential electrical length) of the reference and test channels should be minimized.

A sample result given on p. 8-13, [5], is repeated here. Assume the differential physical length of a waveguide system operating at 10 GHz to be 10 ft. and the microwave frequency instability to be 10 kHz. The maximum error caused by these two uncertainties becomes 0.036 degrees. Frequency dependence of the components would increase this error. The best way to evaluate this error in a given laboratory setup is to change the microwave frequency in known, finite amounts, and measure the corresponding phase shifts. From a plot of these data and a knowledge of the frequency instability of the microwave oscillator, the maximum error for the specific equipment arrangement can be determined quite accurately.

2. Mismatch of the Device Under Test.

This error is a function of reflections from the device under test and the system containing the insertion point terminals. In the analysis [6] the coefficients Γ_g and Γ_L represent the reflection coefficients of the generator and load, respectively, as seen at the insertion point terminals.

The VSWR at the input to the HP 8411A is specified by the manufacturer as less than 1.5 up to 8 GHz and less than 2.0 at higher frequencies. The effect of such a mismatch shows up in the error calculation in the coefficient Γ_L. Suppose, for example, that the device under test is a rotary vane phase shifter (VSWR = 1.3), and it is connected with a waveguide to coaxial adapter to the input of the HP 8411. The maximum phase error caused by mismatch is 11.0 degrees. This error can be reduced with tuners and/or isolators at the insertion point terminals. For example, the rotary vane phase shifter (VSWR = 1.3) connected to a tuned insertion point where $\Gamma_g = \Gamma_L = 0.0005$ will have a maximum phase error of 0.02 degrees [6, p. 620].

More typically the same rotary vane phase shifter with insertion point mismatch $\Gamma_g = \Gamma_L = 0.015$ would have a maximum phase error of 0.4 degrees.

3. Cross Channel Leakage

This error has been discussed in [5, p. 8-11]. RF leakage must be measured in each microwave system used. In general an error of 0.012 degrees corresponds to a cross-channel leakage signal of -80 dB.

4. Environmental Effects

This error has also been discussed in [5, p. 8-11]. When operating in a controlled laboratory environment the phase error from this source is small unless the differential path length between the reference and test channels is large (20 wavelengths). For small differential path lengths (less than five wavelengths) and temperature variations less than 0.1°C during the measurement period the phase error is 0.007 degrees.

For a 1 foot differential path length at 10 GHz and mismatch at the insertion point of $\Gamma_g = \Gamma_L = 0.015$, typical errors from the auxiliary system are:

1. Frequency instabilities of RF source $\varepsilon_f = 0.004$
2. Mismatch at insertion point $\varepsilon_m = 0.40$
3. Environmental effects on components $\varepsilon_T = 0.007$

The total maximum possible error is $\varepsilon_{max} = 0.41°$

The treatment of errors from an auxiliary system will be different for each system used. The example above is given to show that errors from sources other than the PSMS must be considered in phase shift measurements.

Appendix B. Circuit Schematics of Non-Commercial Equipment

This appendix contains circuit schematics for non-commercial equipment developed at NBS to perform particular functions in the PSMS which are described in Section 2 of the report. These circuits and their functions are:

1. Mixer-amplifier--Produces a 20.178 MHz signal from mixing 20.278 MHz with 100 kHz.
2. Squaring circuit--Produces a 100 kHz square wave from a 100 kHz sine wave. The rise time is less than 10 nanoseconds and can be triggered at the zero crossing point of the input sine wave.
3. Buffer amplifier--Provides between 30 and 40 dB amplification of the low level 20.178 MHz signal from the power splitter. See figure 1.
4. 100 kHz amplifier--This circuit provides a 100 kHz sine wave from a distorted 100 kHz signal from the counter oscillator of the 5360A.

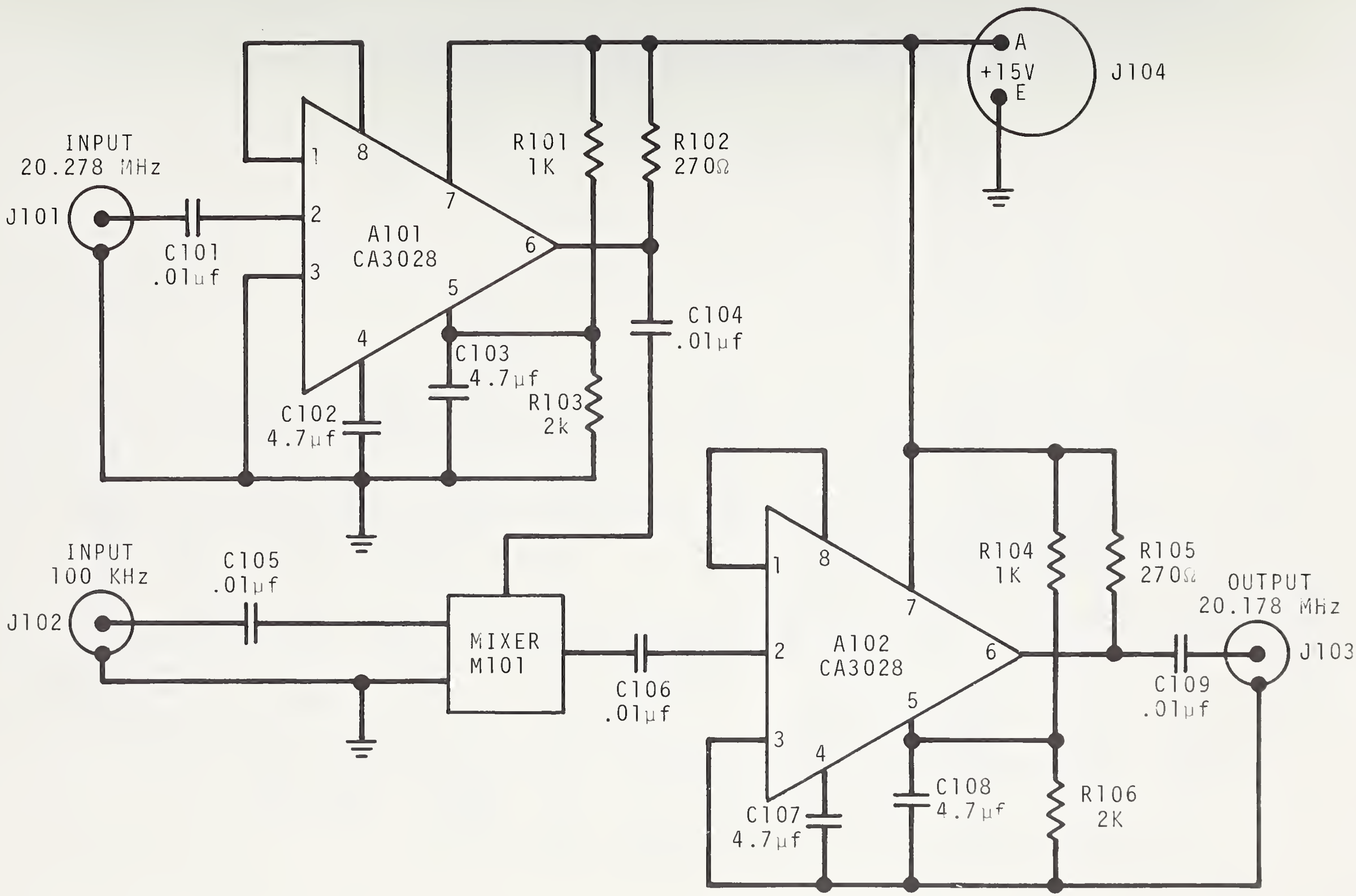

Figure 8. Circuit schematic of Mixer Amplifier.

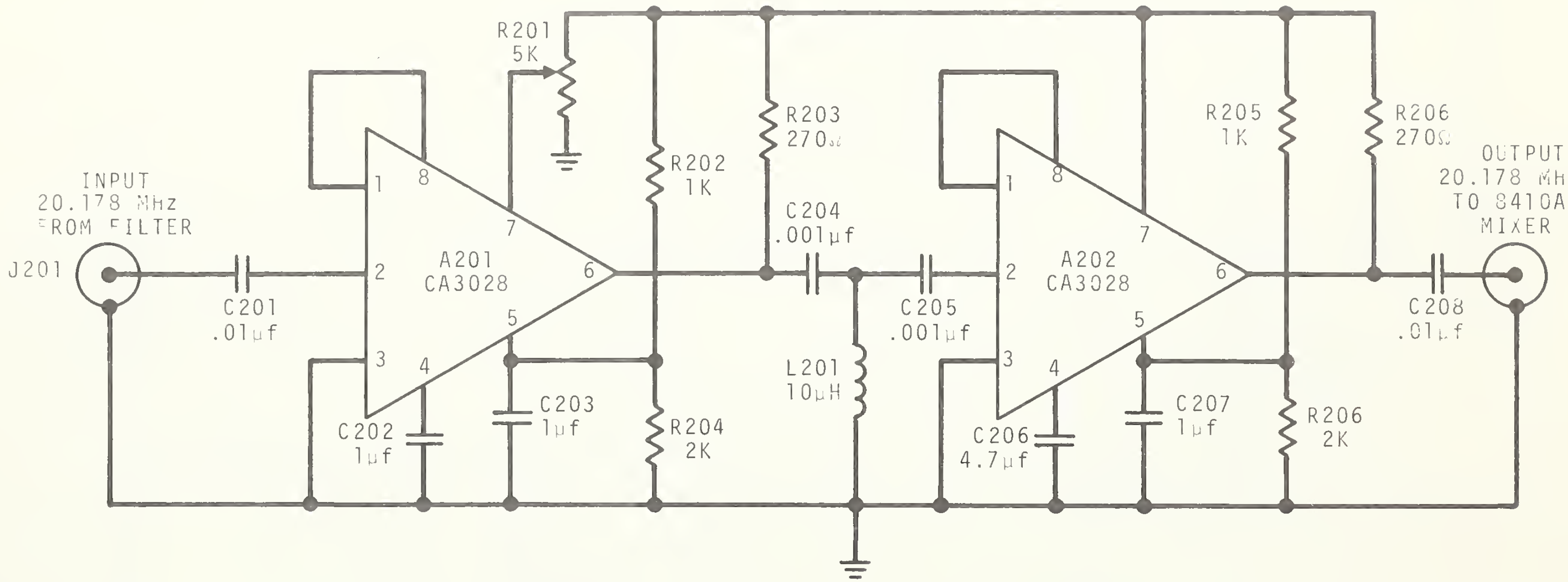

Figure 9. Circuit schematic of 20.178 MHz Buffer Amplifier.

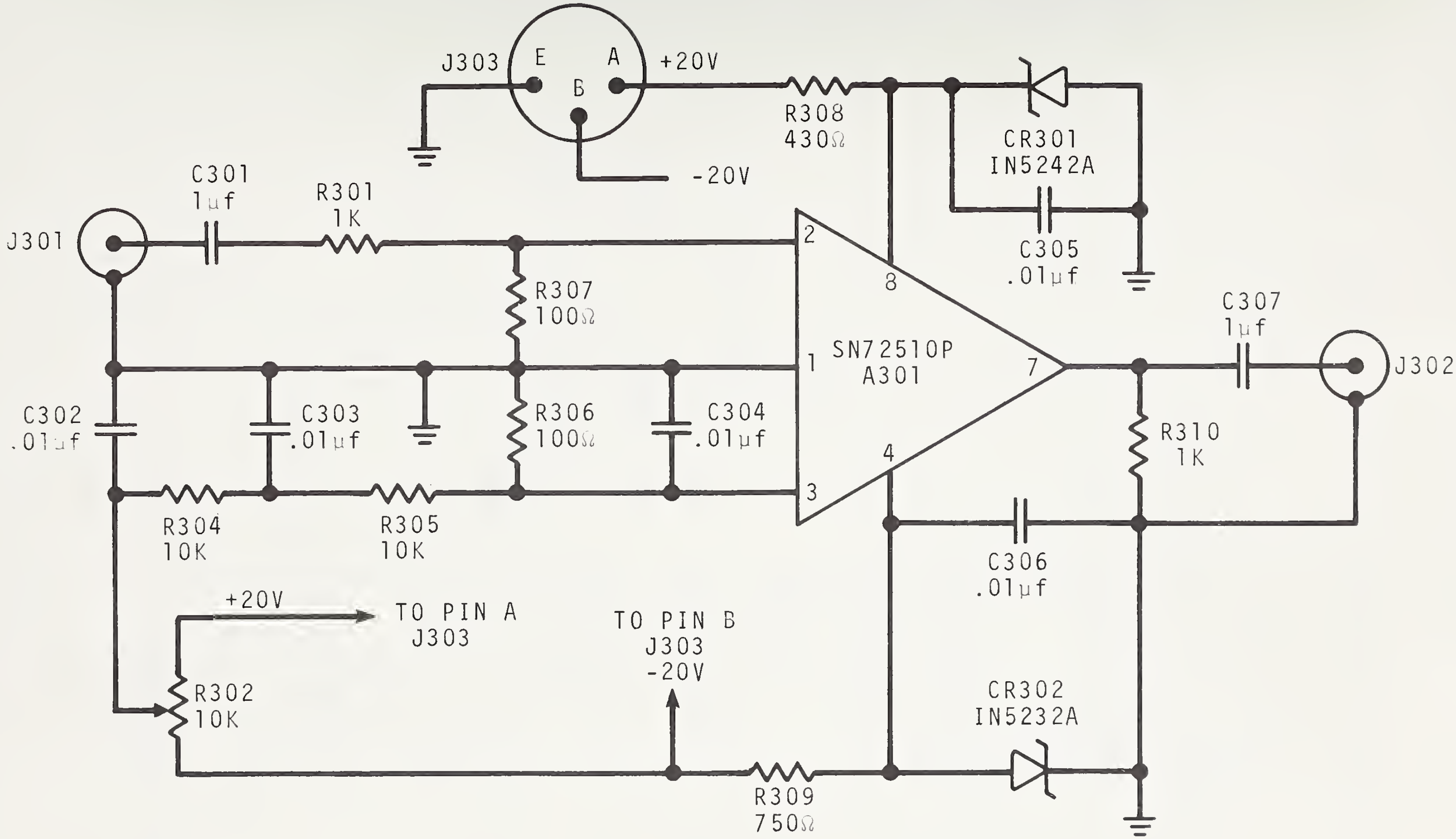

Figure 10. Circuit schematic of Squaring Circuits.

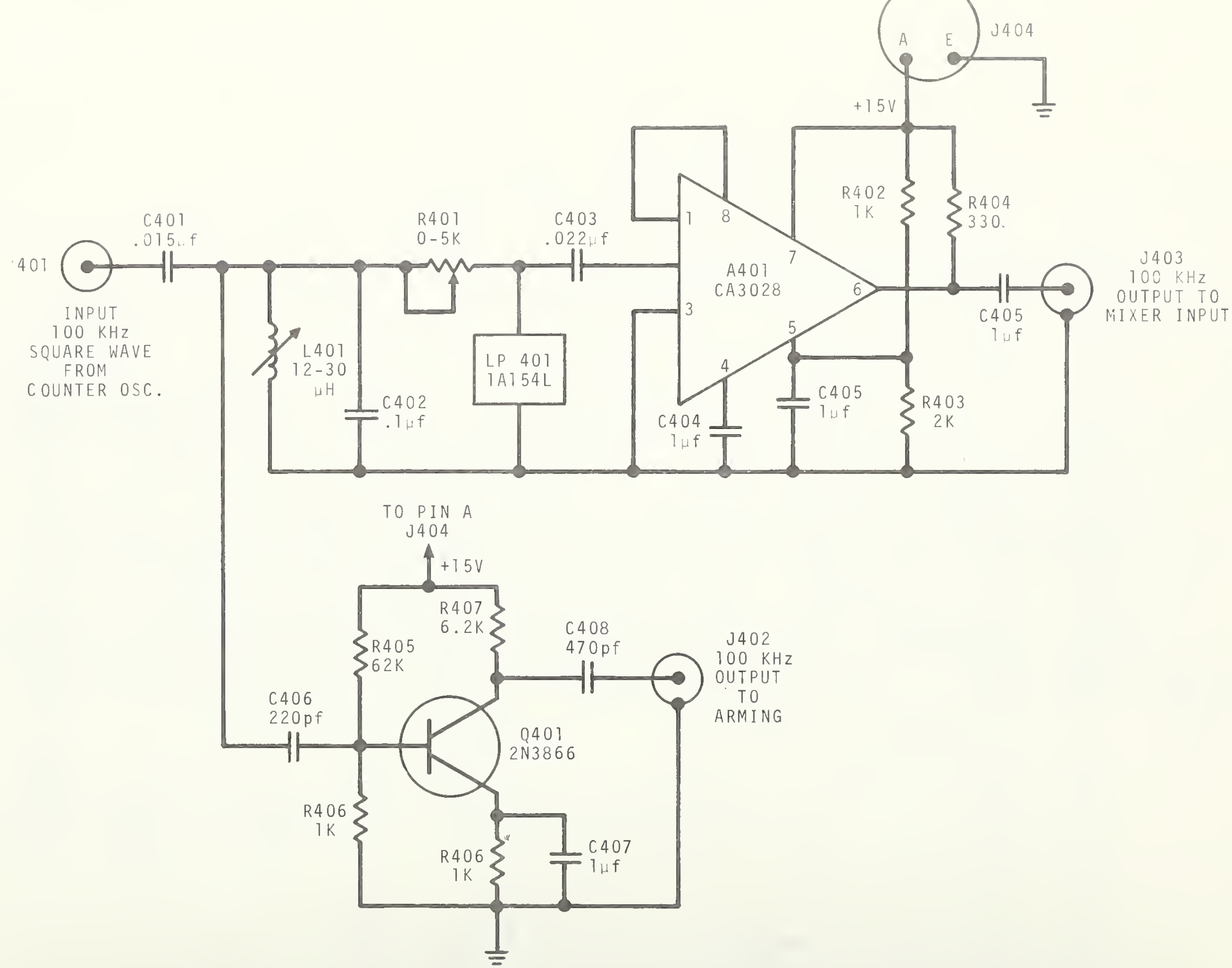

Figure 11. Circuit schematic of 100 kHz Distribution Amplifier.

Appendix C. Modifications of Commercial Equipment

1. Modifications

1.1 General

The components of the PSMS include certain commercially available equipment. Some parts of the 8410A have been modified to improve performance and/or to make the equipment compatible with system design.

The modifications include component changes in circuits shown in Reference 2 schematic diagram 08410-90016 and are referred to in terms A6 through A16, which are identifiable in the reference.

The modifications are:

1. Circuit board A6 -- The output from collector of Q3 is sent through a 2 K ohm resistor in series with a 1 μf capacitor to a coaxial Rg 174 cable to the RF output jack on the rear panel of the 8410A chassis.
2. Circuit board A12 -- The 20.178 MHz signal to this circuit board arrives via an Rg 174 coaxial cable from the rear panel of the 8410A. Also, the base of Q7 has been fixed biased through a 20 K ohm resistor between test point 5 and the base and a 2 K ohm resistor to ground. The AGC signal has been disconnected.
3. Circuit board A11 -- Capacitor C4 (470 pf) has been changed to .059 μf.

4. Circuit board A16 -- Capacitor C8 (8200 pf) has been changed to 0.067 μf.
5. Circuit board A13 -- This board has been removed, since a 20 MHz signal is not required.
6. Circuit board A14 -- The 20.178 MHz signal to this circuit board is input through an Rg 17coaxial cable from the rear panel of the 8410A.

Appendix D. Parts Lists

The PSMS includes commercial and non-commercial equipment. The parts list for the commercial equipment is included in references 2, 3, and 7. This appendix includes a listing of all major components and a minor component list for the non-commercial equipment. The minor component list refers to the circuit schematics in Appendix B.

Table 1. Major Components of the PSMS

Description	Manufacturer
Computing Counter Model 5360A option H-14	Hewlett-Packard
Plug-In Time Interval Model 5379A	Hewlett-Packard
Harmonic Frequency Converter Model 8411A, option H-10	Hewlett-Packard
Network Analyzer Model 8410A option H0-7	Hewlett-Packard
Blank Plug-In Model 8410-K13	Hewlett-Packard
Keyboard Model 5375A	Hewlett-Packard
Filter 100 kHz, 3 dB Bandwidth ± 3 kHz	McCoy Electronics
Filter 20.178 MHz, 3 dB Bandwidth ± 5 kHz	McCoy Electronics
Power Supply Model LZS-11	Lambda Electronics
Cabinet Rack Series 2000, Model E-2024	Bud Radio Inc.
Signal Splitter, Model PdM-20-55	Merrimac Industries Inc.

Table 2. Parts Information for Mixer Amplifier Circuit

Part No.	Description
A101	Integrated Circuit Amplifier CA3028
A102	Integrated Circuit Amplifier CA3028
M101	Mixer
J101	Coaxial Connector Female SMA
J102	Coaxial Connector Female SMA
J103	Coaxial Connector Female SMA
C101	Capacitor Dipped Mica .01 μf 100 Volts
C102	Capacitor Tantalum Electrolytic 4.7 μf 35 Volts
C103	Capacitor Tantalum Electrolytic 4.7 μf 35 Volts
C104	Capacitor Dipped Mica .01 μf 100 Volts
C105	Capacitor Dipped Mica .01 μf 100 Volts
C106	Capacitor Dipped Mica .01 μf 100 Volts
C107	Capacitor Tantalum Electrolytic 4.7 μf 35 Volts
C108	Capacitor Tantalum Electrolytic 4.7 μf 35 Volts
C109	Capacitor Dipped Mica .01 μf 100 Volts
R101	Resistor 1 KΩ Carbon .25 Watt
R102	Resistor 270 Ω Carbon .25 Watt
R103	Resistor 2 KΩ Carbon .25 Watt
R104	Resistor 1 KΩ Carbon .25 Watt
R105	Resistor 270 Ω Carbon .25 Watt
R106	Resistor 2 KΩ Carbon .25 Watt

Table 3. Parts Information for 20.178 MHz Amplifiers

Part No.	Description
A201	Integrated Circuit, Linear Amplifier, CA3028
A202	Integrated Circuit, Linear Amplifier, CA3028
C201	Capacitor, Fixed, Mica, .01 μf, 100 Volts
C202	Capacitor, Fixed, Tantalum Electrolytic, 1 μf, 35 Volts
C203	Capacitor, Fixed, Tantalum Electrolytic, 1 μf, 35 Volts
C204	Capacitor, Fixed, Mica, 0.001 μf, 100 Volts
C205	Capacitor, Fixed, Mica, 0.001 μf, 100 Volts
C206	Capacitor, Fixed, Tantalum Electrolytic, 4.7 μf 25 Volts
C207	Capacitor, Fixed, Tantalum Electrolytic, 1 μf, 35 Volts
C208	Capacitor, Fixed, Mica, .01 μf, 100 Volts
J201	Coaxial Connector, Bulkhead, Female, SMA
J202	Coaxial Connector, Bulkhead, Female, SMA
J203	Jack, 5 Pin Connector, Female
R201	Resistor, Variable 0-5 K, ½ Watt, 1 turn
R202	Resistor, Fixed, Carbon, 1K ± 10%, ¼ watt
R203	Resistor, Fixed, Carbon, 270 ± 10%, ¼ watt
R204	Resistor, Fixed, Carbon, 2K ± 10%, ¼watt
R205	Resistor, Fixed, Carbon, 1K ± 10%, ¼ watt
R206	Resistor, Fixed, Carbon, 2K ± 10%, ¼ watt
L201	Inductor, Fixed, 10 μh ± 20%, 150 ma

Table 4. Parts Information for Squaring Circuits

Part No.	Description
A301	Integrated Circuit Differential Voltage Comparator SN72510P
C301	Capacitor Mica 1 μf 100 Volts
C302	Capacitor Mica .01 μf 100 Volts
C304	Capacitor Mica .01 μf 100 Volts
C305	Capacitor Mica .01 μf 100 Volts
C306	Capacitor Mica .01 μf 100 Volts
C307	Capacitor Mica .01 μf 100 Volts
J301	Coaxial Connector Bulkhead Female SMA
J302	Coaxial Connector Bulkhead Female SMA
R301	Resistor Carbon 1 KΩ ± 10%
R302	Resistor Variable Wirewound 0-10K 15 Turn ½ watt
R304	Resistor Carbon 10K ± 10% ¼ watt
R305	Resistor Carbon 10K ± 10% ¼ watt
R306	Resistor Carbon 100 Ω ± 10% 1/8 watt
R307	Resistor Carbon 100 Ω ± 10% 1/8 watt
R308	Resistor Carbon 430 Ω ± 10% 1 watt
R309	Resistor Carbon 750 Ω ± 10% 1 watt
R310	Resistor Carbon 1K ± 10% ¼ watt

Table 5. Parts List for 100 kHz Distribution Amplifier

Part No.	Description
A401	Integrated Circuit Linear Amplifier CA3028
C401	Capacitor, Fixed, Plastic Molded, .015 μf, 100 Volts
C402	Capacitor, Fixed, Plastic Molded, .1 μf, 100 Volts
C403	Capacitor, Fixed, Plastic Molded, .022 μf, 100 Volts
C404	Capacitor, Fixed, Tantalum Electrolytic, 1 μf, 35 Volt
C405	Capacitor, Fixed High-K Monolytic, 1 μf, 25 Volts
C406	Capacitor, Fixed Dipped Mica, 220 pf, 500 Volts
C407	Capacitor, Fixed, High-K Monolytic, 1 μf, 25 Volts
C408	Capacitor, Fixed Dipped Mica, 470 pf, 500 Volts
J401	Coaxial Connector, Bulkhead, Female, SMA
J402	Coaxial Connector, Bulkhead, Female, SMA
J403	Coaxial Connector, Bulkhead, Female, SMA
J404	5 pin miniature Socket, Female, Amphenol 126-218
L401	Variable Inductor, Delevan Series 4000, 15-44 μh
L-P401	Filter, Fixed, Low Pass, Cutoff 150 kHz, Kappa 1A 154L
Q401	Transistor, Medium Power, 2N3866
R401	Variable Resistor, 0-5KΩ, 0.5 watt
R402	Resistor, Fixed, 1KΩ, ¼ watt, Carbon
R403	Resistor, Fixed, 2KΩ, ¼ watt, Carbon
R404	Resistor, Fixed 330 Ω, ¼ watt, Carbon
R405	Resistor, Fixed, 62KΩ, ¼ watt, Carbon

Part No.	Description
R406	Resistor, Fixed, 16KΩ, ¼ watt, Carbon
R407	Resistor, Fixed, 6.2KΩ, ¼ watt, Carbon
R408	Resistor, Fixed, 1KΩ, ¼ watt, Carbon

Appendix E. Sample Data Sheet for Phase Shift Measurements

A sample data sheet is included as an example for those intending to make phase shift measurements using the PSMS.

The data sheet was setup to allow for recording at least five measurements at each phase shift setting.

Reference Phase	TEST CHANNEL PHASE SETTING													
	0	20	40	60	80	100	120	140	160	180	200	220	240	26
0														
90														
180														
270														

REFERENCES

[1] G.E. Schafer, R.W. Beatty, Error Analysis of a Standard Microwave Phase Shifter, Journal of Research of the National Bureau of Standards--C, Engineering and Instrumentation, Vol. 64C, No. 4, October-December 1960, pages 261-265.

[2] ________________, Operating and Service Manual Network Analyzer 8410A, Harmonic Frequency Converter 8411A, published March 1970, copyright Hewlett-Packard Co.

[3] ________________, Service Manual--Computing Counter 5360A and Input Module 5365A, published July 1970, copyright Hewlett-Packard Co.

[4] ________________, Phase Measurement in Degrees or Radians, Computing Counter Applications Library, Number 2, Hewlett-Packard Co.

[5] R.W. Beatty, D.A. Ellerbruch, D.H. Russell, G.E. Schafer, R.S. Turgell, J.P. Wakefield, and T.L. Zapf, "Lecture Notes for the Phase Shift Measurements Seminar," June 1967, Unpublished NBS Report. 8-1 to 8-15.

[6] G.E. Schafer, Mismatch Errors in Microwave Phase Shift Measurements, IRE Transactions on Microwave Theory and Techniques, November 1960, 617-622.

[7] ________________, Operating and Service Manual Time Interval Plug-In 5379A, copyright Hewlett-Packard Company, March 1970.

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

This report presents a system description, error analysis, and operating procedure for a dual channel phase shift measurement system operable in the frequency range 110 MHz to 18 GHz.

Basic principles of operation include double stage heterodyning from RF and microwave frequencies to 100 kHz, time-interval and period measurements, and automatic conversion to phase in degrees through use of a digital computer.

17. KEY WORDS (Alphabetical order, separated by semicolons)

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