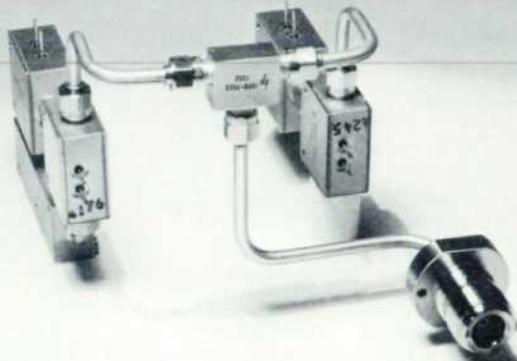


APRIL 1975

# HEWLETT-PACKARD JOURNAL



**10 HZ - 18 GHz**

# A High-Performance Automatic Microwave Counter

*This new counter needs only a single input to measure 10 Hz to 18 GHz, and its sensitivity is many times better than previous counters. It's also systems compatible.*

**By Richard F. Schneider**

**M**EASURING FREQUENCIES FROM LOW AUDIO all the way to microwave has always required many different counters or counter plug-ins, a good deal of range switching and cable changing, and at least  $-7$  dBm (100 mV) of signal.

Not any more. The new Model 5340A Microwave Frequency Counter (Fig. 1) measures frequencies between 10 Hz and 18 GHz using only a single input connector. Measurements are completely automatic, and sensitivity is  $-30$  dBm (7 mV) from 10 Hz to 500 MHz,  $-35$  dBm (4 mV) from 500 MHz to 10 GHz, and  $-25$  dBm (12 mV) from 10 GHz to 18 GHz. Thus measurements may be made where signals are inherently low-level, or where directional couplers or lossy elements reduce the original signal level.

A typical sensitivity curve is shown in Fig. 2. Note that the counter is usable well above 18 GHz and that conservative specifications apply.

Model 5340A gets its high sensitivity and wide bandwidth from the new thin-film samplers used in its front end as harmonic mixers (see article, page 10). A new phase-locked loop design provides not only automatic operation, but also greatly reduced sensitivity to spurious input signals, harmonically related or not. Frequencies from 10 Hz to 250 MHz are counted directly, and frequencies above 250 MHz are measured using an automatic transfer oscillator technique.

Model 5340A is compatible with the new HP bus interface system.<sup>1</sup> The bus system provides for control and communication between instruments up to 51 feet apart. As many as 15 devices can operate on the bus, so the 5340A can be part of an easily implemented automatic measurement system.

Equipped with all of its systems options, Model 5340A can communicate digitally with printers, calculators, card readers, computers, teleprinters, and

other devices. All of its front-panel controls (except power on/off) may be remotely programmed, including resolution, range, reset, and sample mode.

## Controls

There are actually four range selections on the counter: 10 Hz to 18 GHz at  $50\Omega$  input impedance, 250 MHz to 18 GHz at  $50\Omega$  input impedance, 10 Hz to 250 MHz at  $1\text{ M}\Omega$  input impedance, and a time base oscillator check at 10 MHz. A precision type N connector is used on the  $50\Omega$  input and a BNC connector is used on the  $1\text{ M}\Omega$  input.



**Cover:** Behind the type N connector on the front panel of Model 5340A Frequency Counter is the assembly shown here: a power splitter followed by two wide-band thin-film hybrid samplers and other elements of two phase-locked loops. The samplers are the main reason this single input is

the only one needed to measure frequencies from 10 Hz to 18GHz.

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**Fig. 1.** Model 5340A Microwave Frequency Counter can measure 10 Hz to 18 GHz automatically, using only a single input. Eight digits are displayed. Resolution is selectable from 1 Hz to 1 MHz.

Resolution is selectable in decade steps from 1 Hz to 1 MHz, and the normal counter reset and sample rate controls are also on the front panel. Eight digits are displayed along with appropriate annunciators indicating mode of measurement (direct or phase locked) and units of kHz, MHz, or GHz.

### Counter Organization

The general block diagram of the new counter is shown in Fig. 3. An internal programmer checks to see if a directly countable signal is present (by sensing its amplitude and frequency range) and if it is, the frequency is counted and displayed according to the resolution setting.

The internal programmer also checks to see if a phase lockable signal is present. If it is, the automatic transfer oscillator is enabled, the harmonic number is calculated, and the gate time is extended so that the input frequency is displayed automatically according to the resolution selection. Fig. 4 is a simplified flow diagram of the internal program.

If a directly countable signal is present, this signal overrides the automatic transfer oscillator mode. This assures that the fundamental signal will be measured and not a harmonic frequency when the fundamental is below the transfer oscillator range. Also, for multiple frequency inputs where the largest signal is in the 10 MHz to 250 MHz range, this feature assures the correct determination of the

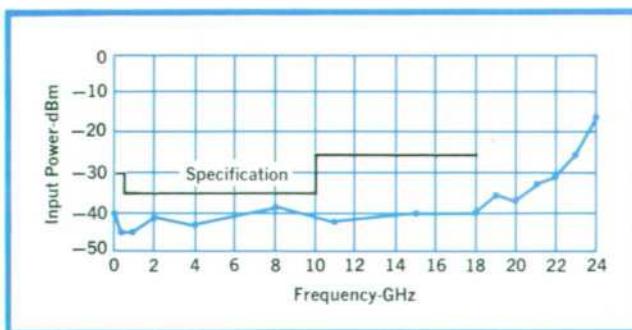
largest component's frequency.

For signals within the transfer oscillator frequency range, automatic amplitude discrimination circuits assure that only the largest signal is measured. If a microwave signal in the transfer oscillator range contains spurious signals, such as power supply residuals, that are within the sensitivity of the direct count range, the range selection of 250 MHz to 18 GHz can be used. This enables only the automatic transfer oscillator, and the automatic amplitude discrimination circuitry then finds the largest signal.

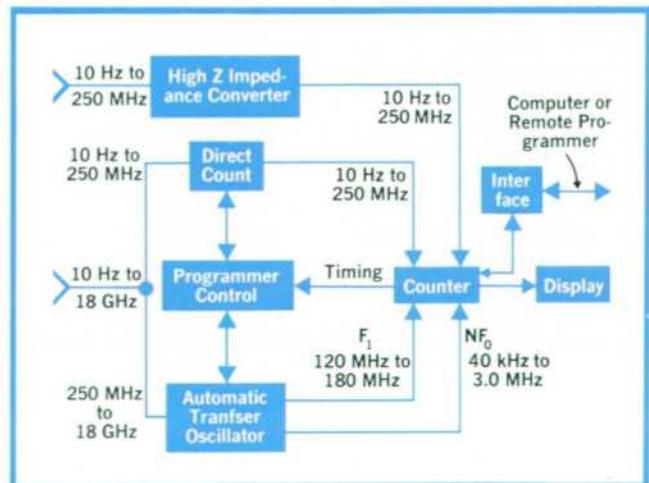
The separate 1 M $\Omega$  input for 10 Hz to 250 MHz uses the same direct counting circuitry as the 50 $\Omega$  input.

### Automatic Transfer Oscillator

The automatic transfer oscillator uses an IF-offset phase-lock loop with the thin-film sampler operating as a mixer. As shown in the accompanying article (page 10), the sampler IF response is very flat from the lowest sampling frequency of 120 MHz



**Fig. 2.** Typical 5340A sensitivity.



**Fig. 3.** Model 5340A measures 10 Hz to 250 MHz directly, and 250 MHz to 18 GHz using an automatic transfer oscillator technique. Internal programming selects the proper mode.

through the 150th harmonic of 18 GHz. This response is fundamental in obtaining the performance

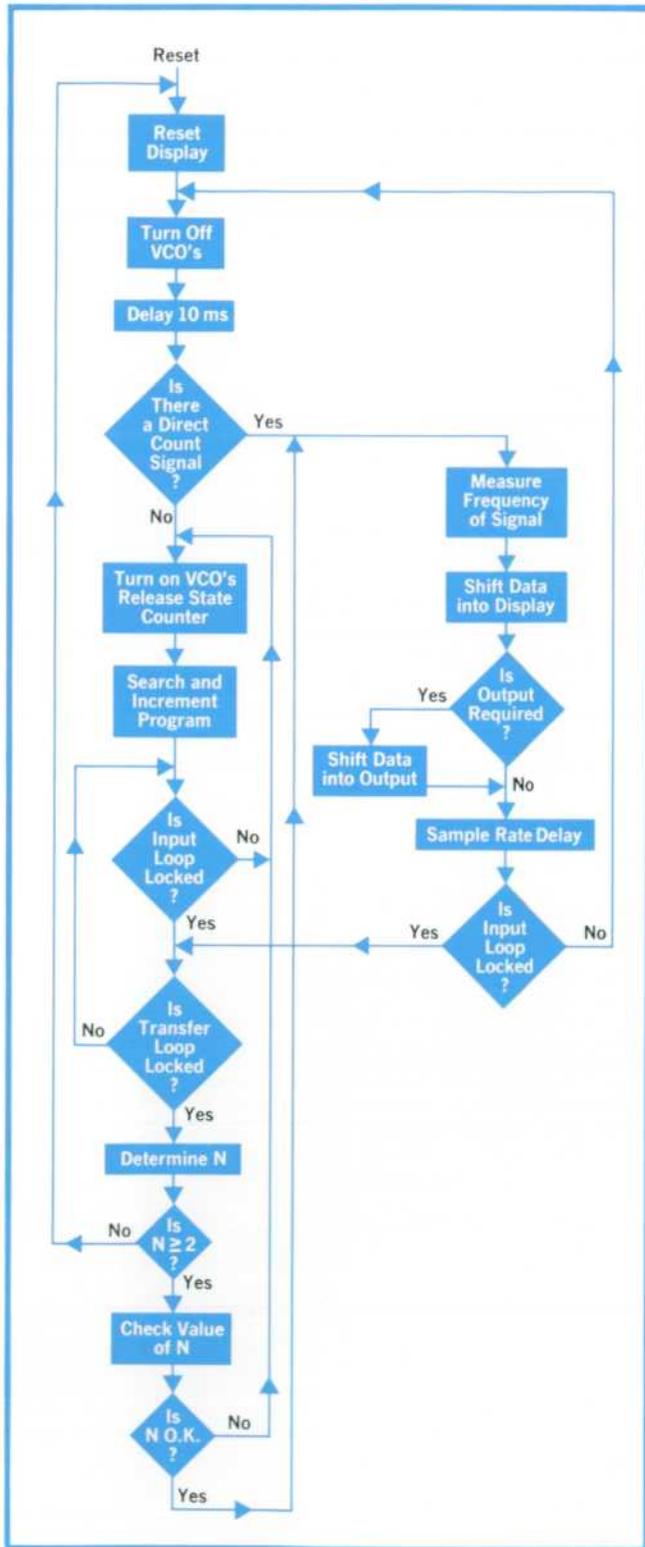


Fig. 4. Simplified flow diagram of 5340A internal programming. Search and increment program automatically optimizes phase-lock loop compensation and bandwidth in the transfer-oscillator mode.

of the counter.

Fig. 5 is a block diagram of the automatic transfer oscillator. The input signal is divided into two equal signals by a resistive power divider. The resulting signals are the inputs to two thin-film samplers, one used in the input phase-lock loop and terminated and the other used to determine the harmonic number. The input signal to the second sampler is fed through to the direct count circuits.

The input phase-lock loop consists of a voltage controlled oscillator (VCO), a sampler, an IF amplifier, a phase detector, and dc gain and control system compensation. The VCO searches over its range until an IF signal equal to the reference frequency of 20 MHz is found. Phase lock occurs when the phase detector output drives the VCO frequency  $F_1$  such that:

$$F_X = NF_1 - F_{IF1} \quad (1)$$

$$\text{where } F_{IF1} = F_{IF REF} = 20 \text{ MHz at phase lock.} \quad (2)$$

A quadrature detector assures that the loop locks only on the lower sideband to satisfy equation 1.

Next the VCO frequency  $F_1$  is translated to a frequency  $F_2$  so that

$$F_2 = F_1 \pm F_0 \quad (3)$$

where the offset frequency  $F_0$  is 20 kHz.

This is done in a transfer phase-lock loop. The frequency  $F_2$  drives the second sampler and produces a second IF output  $F_{IF2}$  as follows:

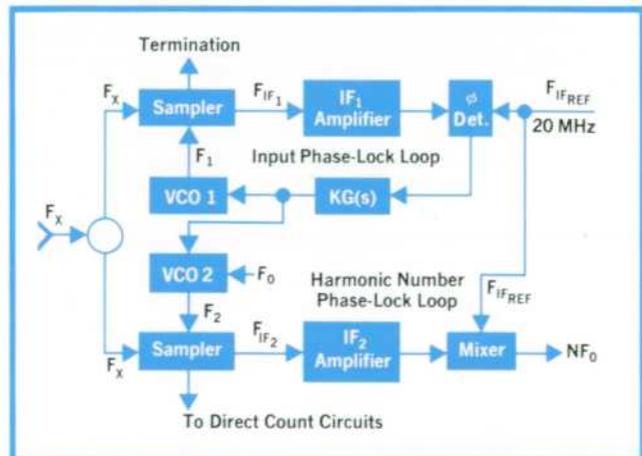


Fig. 5. Wideband thin-film samplers are used as harmonic mixers in the automatic transfer oscillator phase-lock loops. The input loop mixes the signal with a harmonic of the sampling frequency. The second loop determines the harmonic number.

$$F_{IF_2} = NF_2 - F_X \quad (4)$$

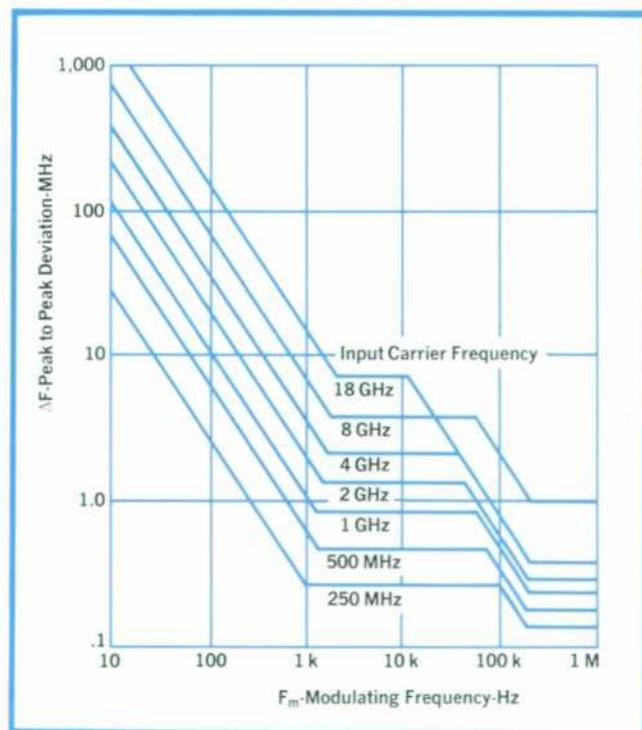
$$= N(F_1 \pm F_0) - (NF_1 - 20 \text{ MHz}) \quad (5)$$

$$= \pm NF_0 + 20 \text{ MHz} \quad (6)$$

By mixing  $F_{IF_2}$  with the 20 MHz reference frequency and rejecting 20 MHz and higher frequencies, the harmonic frequency,  $NF_0$ , is obtained. Counting the number of zero crossings for the period of the offset frequency  $F_0 = 20 \text{ kHz}$  then determines the harmonic number  $N$  of the phase lock loop. The input frequency is then calculated and displayed by presetting into the counter the 20 MHz reference frequency, measuring the VCO frequency of the input phase lock loop, and extending the gate time according to the harmonic number  $N$ .

### Compensation and Acquisition Time

Compensation of the input phase-lock loop is optimized for bandwidth and acquisition time by using the harmonic number information. First, the compensation ranges are divided into octave input-frequency ranges from 250 to 500 MHz, 500 to 1000 MHz, 1 to 2 GHz, 2 to 4 GHz, 4 to 8 GHz and 8 to 18 GHz. Of course, all the ranges overlap so there is continuous input frequency coverage.



**Fig. 6.** Typical 5340A frequency modulation tolerance characteristics for single-tone FM on input signal. Input level is  $-20 \text{ dBm}$ . Carrier frequency will be correctly measured if modulation frequency and peak-to-peak deviation are below curves.

The search ramp rate is then programmed along with the proper octave range compensation. When phase lock occurs, the harmonic number is compared with the allowable numbers for that compensation. If incorrect, the programmer is stepped until the proper combination of harmonic number and compensation is obtained. This procedure is accomplished prior to any counting (see Fig. 4).

The results of this compensation technique are normalization of the input phase-lock loop at maximum bandwidth (200 kHz), optimized compensation for the octave range allowing prescribed FM performance, and minimum acquisition time.

Acquisition time is defined as the time it takes for the phase-lock loops to acquire a signal that is abruptly switched on. Acquisition time is measured in production at input frequencies of 400 MHz, 7 GHz, and 18 GHz. These input frequencies are switched on with a solid-state RF switch, and the HP 5360A Computing Counter is used to measure the time interval between the RF signal and the counter main gate. A mean-time and standard-deviation program in the 5375A Computing Counter Keyboard averages a series of acquisition times to provide the required data.

The acquisition time varies depending on where the programmer is in the cycle with respect to the signal input time, and is found to average 150 ms with a 75 ms standard deviation. This time can be reduced to 50 ms with a 10 ms standard deviation by operating in the octave range programming mode (Opt. 003).

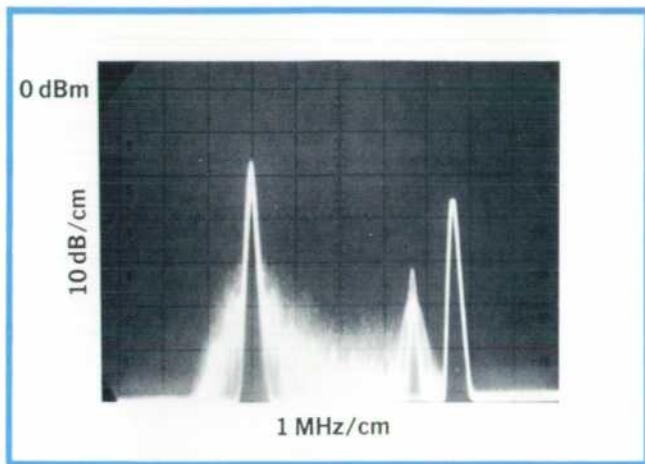
### AM and FM Tolerance

Amplitude modulation tolerance is determined by the sensitivity specification. So long as the minimum voltage in the modulation trough is not less than the sensitivity, an accurate count is obtained. For example, with a  $-10 \text{ dBm}$  input at 10 GHz, 94.5% modulation index will cause the signal to drop to  $-35 \text{ dBm}$  (4 mV) at its lowest amplitude and would be the limit of modulation possible.

FM tolerance characteristics are a function of modulation rate and input frequency. A family of curves describing the FM capability at  $-20 \text{ dBm}$  for six input frequencies is shown in Fig. 6. These curves show, for example, that with an 8 GHz input frequency, residuals due to power supply FM can be tolerated to 100 MHz peak-to-peak deviation at a 100 Hz rate.

These FM tolerance characteristics were obtained using single-tone modulation. Multiple tones will decrease the capability if they are within the phase-lock loop bandwidth.

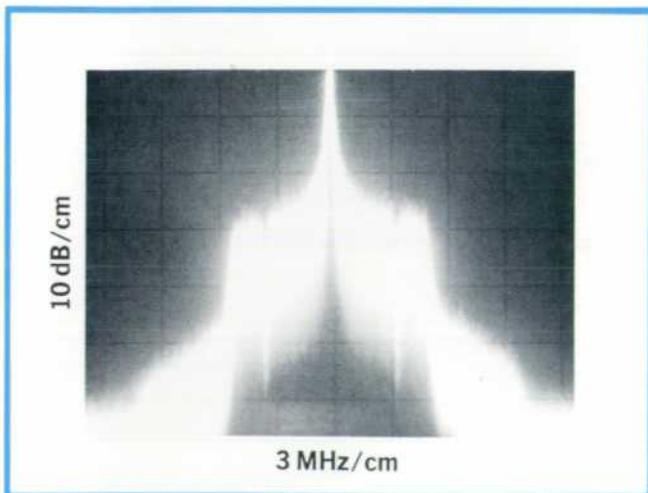
An excellent example of 5340A performance is



**Fig. 7.** Frequency spectrum of a local television station (Channel 36). Model 5340A correctly measured the video carrier frequency (603.25 MHz) with only a UHF antenna connected to its input.

shown in Fig. 7. Here the video carrier frequency of a local UHF television station (channel 36) is measured at 603.25 MHz. The video carrier amplitude modulation, the color subcarrier frequency, and the FM sound carrier and sidebands were automatically disregarded by the counter. This measurement was made on a signal received from a UHF antenna connected directly to the counter input.

The carrier frequency of signals with frequency modulation rates greater than the phase-lock loop bandwidth can also be measured. Since the deviation tolerance increases by at least 6 dB/octave at modulation frequencies above about 1 MHz, these sidebands will be rejected, while those within the bandwidth will be averaged. Broadband noise signals will be processed in the same manner. For

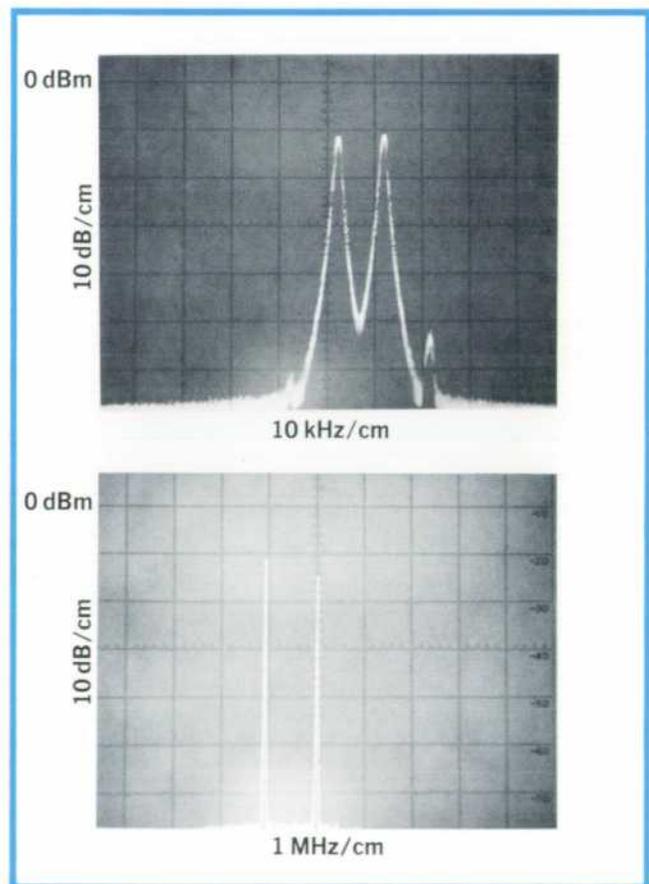


**Fig. 8.** Spectrum of an 8 GHz microwave telephone signal with 2 master groups (1200 channels). Model 5340A correctly measured the carrier frequency.

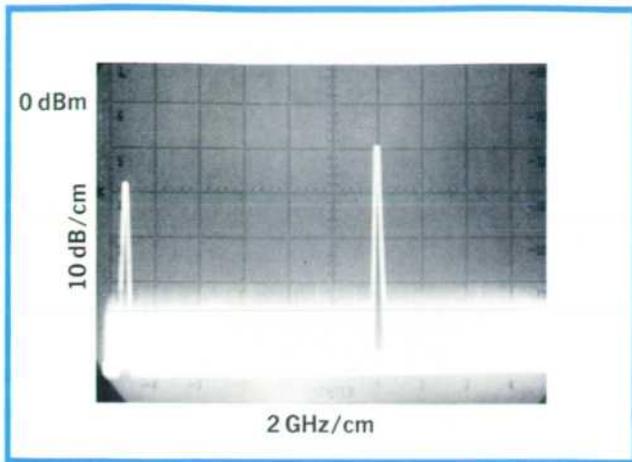
example, the carrier frequency of a microwave telephone relay transmitter signal, about 8 GHz, was correctly measured in the presence of frequency modulation equivalent to two master groups or 1200 telephone channels. Random noise was used to simulate traffic in the telephone channels. Modulation rates ranged from less than 100 kHz to nearly 6 MHz, and frequency deviation was 141 kHz rms per channel. The spectrum of this signal is shown in Fig. 8.

#### Automatic Amplitude Discrimination

The high sensitivity and wide dynamic range (42 dB) of the 5340A present a formidable challenge with regard to spurious signals. For example, if an input signal of +7 dBm has harmonically related components 35 dB down, these signals will be at -28 dBm, well within the instrument's sensitivity. Another important example is that of frequency multiplier or synthesizer chains, where spurious signals can occur anywhere in the input frequency range.



**Fig. 9.** Model 5340A is designed to measure only the largest signal in its passband. Top spectrum is of signals 10 kHz apart and differing in amplitude by 1 dB. In bottom spectrum, signals are 1 MHz apart and differ by 3 dB. The larger signal in each case was measured.



**Fig. 10.** Typical worst-case 5340A amplitude discrimination. Here the signals are at 450 MHz and 12 GHz and an 8 dB amplitude difference was required.

Automatic amplitude discrimination is incorporated in the design of the input phase-lock loop and harmonic frequency circuits. Circuits in the input phase-lock loop simultaneously observe all the signals within the bandwidth and sensitivity of the instrument. Next these signals are amplified by a hard-limiting amplifier and are filtered at the reference frequency. Assuming that the largest signal present is sufficiently large, the filtered output signal contains the frequency of the largest signal, frequency-modulated by the undesired signals. A small-dynamic-range phase detector then allows only the largest signal to phase lock. The signals can be present within or outside the bandwidth of the phase-lock loop; the circuit will respond and lock onto only the signal of largest magnitude.

By using a similar technique of a hard-limiting amplifier in the harmonic frequency circuit, zero crossings are counted only for the largest signal present there also.

The spectrum of two signals within the bandwidth of the input phase-lock loop is shown in Fig. 9. The larger signal was correctly measured, illustrating that at frequencies of 405.500 MHz and 405.501 MHz an amplitude difference of less than 1 dB is required to discriminate between the signals. Also shown are two 400 MHz signals 1 MHz apart; here a 3 dB difference in amplitude was required. Fig. 10 is the spectrum of signals at 450 MHz and 12.0 GHz. Here an 8 dB amplitude difference was required to discriminate between the two signals.

#### Direct Counting System

For frequencies below the second harmonic of the input phase-lock loop, the direct count system

shown in Fig. 11 is automatically activated. The input signal from the main input connector is amplified to a detectable level, then fed to a broadband diode detector and to the triggering circuit in the counter. The threshold of the detector is set to a level just above that required for correct counting. A detector output is required for the control system to display an answer, so only stable, noise-free answers are displayed.

The direct count amplifier is ac coupled so dc levels may exist on input signals and no external offset adjustment is necessary. Because of the ac coupling, unsymmetrical signals, such as pulse trains, can generally not be tolerated by this input. The measurement of pulses is best accomplished by the high-impedance input. This amplifier is ac coupled also, and requires no external offset adjustment, but it has a special circuit to accommodate pulse trains. The baseline offset characteristic of an unsymmetrical input, such as a pulse train, is automatically corrected for inputs with a duty factor as low as 0.1%. Full sensitivity is thereby maintained, making this input suitable for use with a 10:1 divider oscilloscope probe on such signals as IF responses and logic levels.

#### Digital Input/Output

The digital output is ASCII-coded and TTL or DTL compatible. The output string has the following format:

```
D | L  O | Sp Sp dddddddd E + d Cr Lf
where D = DIRECT
      L = LOCK
      O = OVERFLOW
      Sp = SPACE
      d = DIGIT 0 thru 9
      Cr = CARRIAGE RETURN
      Lf = LINE FEED
```

A manually programmable five-bit address is located on the rear panel along with a local-systems switch. If, for instance, the counter is used with a printer only, the switch would be placed in the local position. If the counter is part of a measurement system, the switch would be placed in the systems position and the counter would respond to the signals on the bus when properly addressed.

The 5340A is remotely programmed by placing its address on the bus, followed by a string of ASCII characters. Programmable functions include resolution, range, octave program, reset, sample mode, sample trigger, output mode, and local-remote codes.

#### Options

The counter is available with a rear-panel connector for the 50Ω input, and with a 10 MHz to 250

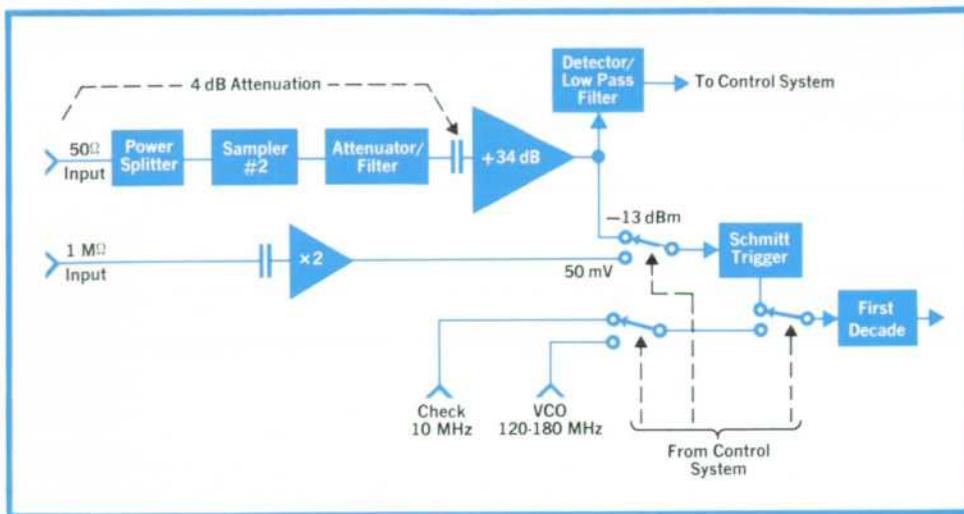


Fig. 11. 5340A direct-count circuitry.

MHz 1M $\Omega$  rear-panel input in parallel with the front-panel input. A 50 $\Omega$  termination is provided so that the front-panel connector may be terminated where the additional capacitance of the cable to the rear panel cannot be tolerated. If the termination is used, the input impedance of the rear-panel input is reduced to 50 $\Omega$ .

An optional oven time-base oscillator is available. It has an aging rate of less than  $5 \times 10^{-10}$ /day.

#### Acknowledgments

Many individuals contributed to the development of the 5340A Counter. The performance at microwave frequencies could not have been realized without the outstanding thin-film sampler developed by Jerry Merkelo and Bob Hall. The design innovations of the input phase-lock loop with automatic amplitude discrimination were developed by Art Bloedorn. Counter, programming, and bus interface design was the responsibility of Al Foster. Rory Van Tuyl provided the design of the sampler driver, the VCO's and the direct count amplifiers. Bob Maldewin was responsible for the power supply design and part of the VCO development. Glen Elsea provided the mechanical design of the instrument and Dick Goo was the engineering aide and technician on the project. Special recognition and credit is deserved by Rory Van Tuyl and Al Foster who provided many ideas, stimulating discussions, and aid to the systems development.

My thanks also to John Dukes, engineering section manager, for his support and to Ron Potter for his technical aid. 🧑

#### Reference

1. G. E. Nelson and D. W. Ricci, "A Practical Interface System for Electronic Instruments," Hewlett-Packard Journal, October 1972.



#### Richard F. Schneider

Dick Schneider was project manager for the 5340A Counter. This was his fourth microwave counter project since joining HP in 1964. The others were the 5260A Frequency Divider, the 5240A Frequency Meter, and the 5257A Transfer Oscillator. Dick received his BS degree in electrical engineering from Case Institute of Technology in 1952 and his MS degree from California State University at San Jose in 1968. Before coming to HP he worked in the aerospace industry on missile and satellite test equipment, microwave amplifiers, telemetering, radar, and receiver systems. He was a Loran specialist in the U.S. Coast Guard. Dick is a member of IEEE.

# SPECIFICATIONS

## HP Model 5340A Frequency Counter

### Signal Input

#### INPUT 1

RANGE: 10 Hz to 18 GHz.  
SYMMETRY: Sine wave or square wave input (40% duty factor, worst case).  
SENSITIVITY: -30 dBm, 10 Hz-500 MHz; -35 dBm, 500 MHz-10 GHz; -25 dBm, 10-18 GHz.  
DYNAMIC RANGE: 37 dB, 10 Hz to 500 MHz; 42 dB, 500 MHz to 10 GHz; 32 dB, 10 GHz to 18 GHz.  
IMPEDANCE: 50 $\Omega$   
VSWR: <2:1, 10 Hz-12.4 GHz; <3:1, 12.4-18 GHz.  
CONNECTOR: Precision Type N.  
COUPLING: dc to load, ac to instrument.  
DAMAGE LEVEL: +30 dBm  $\pm$ 7 V dc (total power not to exceed 1 W).  
ACQUISITION TIME: <150 ms mean typical.

#### INPUT 2

RANGE: 10 Hz-250 MHz direct count.  
SENSITIVITY: 50 mV rms, 150 mV p-p pulses to 0.1% duty factor, minimum pulse width 2 ns.  
IMPEDANCE: 1 M $\Omega$  shunted by <25 pF.  
CONNECTOR: Type BNC female.  
COUPLING: ac.  
MAXIMUM INPUT: 10 Hz to 100 Hz 200 V rms.  
100 Hz to 100 kHz 20 V rms.  
100 kHz to 250 MHz 2 V rms.

**AUTOMATIC AMPLITUDE DISCRIMINATION:** The counter will automatically select the largest of all signals present (250 MHz to 18 GHz phase-lock range), providing that signal is 20 dB (10 dB typical) larger than any other.

**MAXIMUM AM MODULATION:** Any modulation index as long as the minimum voltage of the signal is not less than the sensitivity specification.

### Time Base

**CRYSTAL FREQUENCY:** 10 MHz.

#### STABILITY:

AGING RATE:  $\leq \pm 3 \times 10^{-7}$  per month.  
SHORT TERM:  $\leq 5 \times 10^{-10}$  rms for 1 second averaging time.  
TEMPERATURE:  $\leq \pm 2 \times 10^{-6}$  over the range of -20° to +65°C.  
LINE VARIATION:  $\leq \pm 1 \times 10^{-7}$  for 10% line variation from 110 V or 230 V line.

**OUTPUT FREQUENCY:** 10 MHz  $\geq$  2.4 V square wave (TTL compatible) available from rear panel BNC.

### Optional Time Base (Option 001)

Option 001 provides an oven-controlled crystal oscillator time base with an aging rate near that of a time standard. This option results in better accuracy and longer periods between calibration.

A separate power supply keeps the crystal oven on and up to temperature when the instrument is turned off as long as it remains connected to the power line.

**FREQUENCY:** 10 MHz.

#### STABILITY:

AGING RATE:  $\leq \pm 5 \times 10^{-10}$ /day after 24-hour warm-up\* and  $\leq 1.50 \times 10^{-7}$ /year.

SHORT TERM STABILITY:  $1 \times 10^{-11}$  for 1 s avg. time.  
 $1 \times 10^{-11}$  for 10 s avg. time.  
 $2 \times 10^{-11}$  for 100 s avg. time.

LINE VARIATION:  $\leq \pm 5 \times 10^{-10}$  10% change.\*\*

TEMPERATURE:  $\leq \pm 1 \times 10^{-8}$  frequency change over a -55° to 65°C temperature range.  $\leq \pm 2.5 \times 10^{-9}$  over 0 to 40°C range.

**WARM-UP:** Within  $5 \times 10^{-9}$  of final\*\*\* value 15 minutes after turn-on, at 25°C.

\* For oscillator off-time less than 24 hours.

\*\* 1 minute required for unit to stabilize.

\*\*\* Final value is defined as frequency 24 hours after turn-on.

**FREQUENCY ADJUSTMENT RANGE:**  $> 2 \times 10^{-6}$  ( $> \pm 40$  Hz from 10 MHz) with 18-turn control.

**FREQUENCY ADJUSTMENT:**  $1 \times 10^{-9}$  (0.01 Hz) 18-turn control.

### General

**ACCURACY:**  $\pm 1$  count  $\pm$  time base error.

**RESOLUTION:** Front panel switch selects 1 MHz, 100 kHz, 10 kHz, 1 kHz, 100 Hz, 10 Hz, or 1 Hz.

**DISPLAY:** Eight in-line long-life display tubes with positioned decimal point and appropriate measurement units of kHz, MHz, or GHz.

**SELF CHECK:** Counts and displays 10 MHz for resolution chosen.

**OPERATING TEMPERATURE:** 0° to 50°C.

**POWER:** 115 V or 230 V  $\pm 10\%$ , 50-60 Hz, 100 VA.

**REAR PANEL CONNECTORS (OPTION 002):** This option provides input connectors on the rear panel. Input specifications remain the same. Input 1 (Type N) is on the rear panel in place of installation on the front panel. Input 2 (BNC) is available on the front and rear panels. Input impedance is reduced to 50  $\Omega$ .

**REMOTE PROGRAMMING AND DIGITAL OUTPUT (OPTION 003):** Option 003 adds the capability of digital outputting and remote programming via a 24-pin, series 57, Microribbon connector on the rear panel marked DIGITAL INPUT/OUTPUT. The TTL and DTL compatible, bidirectional bus consists of eight (8) data lines plus 7 status and control lines.

**PRICE IN U.S.A.:** 5340A, \$5,300.00

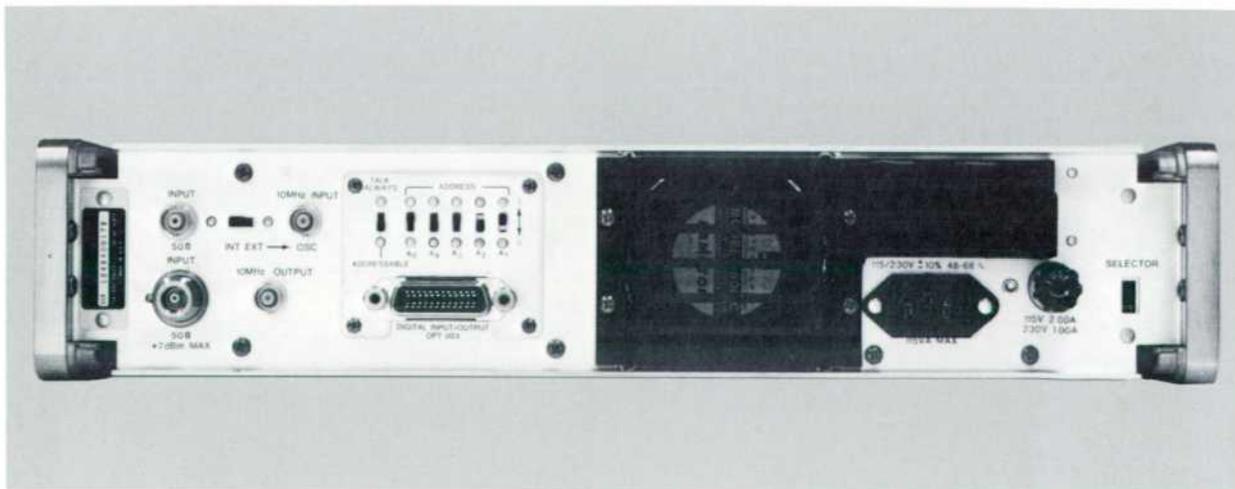
OPTION 001: \$400.00

OPTION 002: \$100.00

OPTION 003: \$350.00

**MANUFACTURING DIVISION:** SANTA CLARA DIVISION

5301 Stevens Creek Boulevard  
Santa Clara, California 95050



# A dc-to-20-GHz Thin-Film Signal Sampler for Microwave Instrumentation

*This rugged, miniature, wideband sampler is responsible for many of the advanced capabilities of the new Model 5340A Microwave Counter.*

By Jerry Merkelo

**E**SCALATING DEMAND FOR HIGH-PERFORMANCE MICROWAVE INSTRUMENTS that meet tougher specifications of bandwidth, sensitivity, standing-wave ratio, and size prompted the development of the improved sampling devices that serve as wideband harmonic mixers in the new Model 5340A Microwave Counter.\* These devices have bandwidths exceeding 20 GHz, very low line reflections (SWR < 1.7 typical), and wide tolerance to drive-pulse shape. They are miniature, simple, and rugged, and their physical configuration makes them adaptable to a variety of uses.

The design of these new sampling devices is based on proven design concepts developed by Grove<sup>1,2</sup> and Cohn<sup>3</sup>, but uses up-to-date thin-film quartz-substrate technology and advanced solid-state devices. The design breaks new ground in several ways:

- Beam-lead diode chips improve balance, minimize parasitic reactances, and increase diode burnout power level.
- A double microstrip structure with slot-line coupling is used.
- Circuit geometry is naturally balanced. Filter embedding of active circuits maximizes bandwidth.
- The drive line is terminated to ease gate-pulse-generator design.

## Sampler Design

Conceptually, the basic design of the new sam-

pling device is illustrated by Fig. 9 of reference 1, which is reproduced here as Fig. 1. This design calls for the ground plane to be split to form a transmission line with shorted ends. The leading edge of the gate pulse turns on the sampling diodes, travels down the transmission line, is reflected at the shorted ends, and arrives back at the diodes with inverted phase, turning them off. Thus the diodes are turned on and off within a few picoseconds to form a very short sampling pulse. The diodes are capacitively coupled to the gate pulse

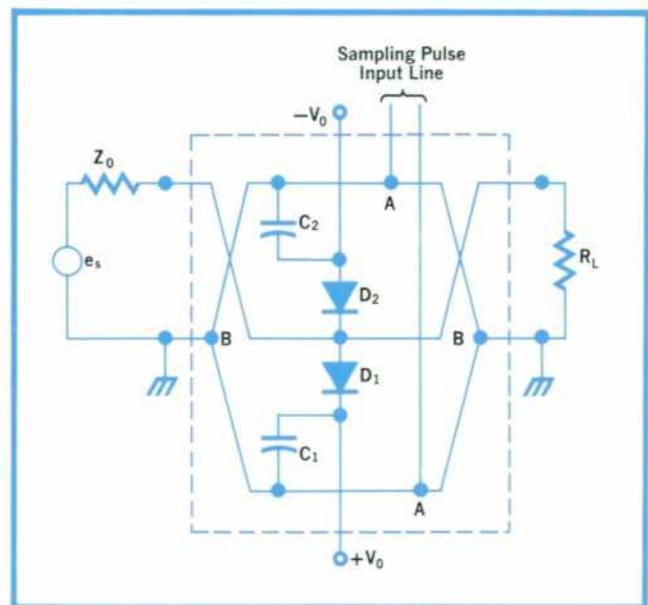


Fig. 1. Sampler equivalent circuit. Design is based on a split ground plane, which acts as a transmission line.

\* See article, page 2.

through  $C_1$  and  $C_2$  and the sampled output appears across the diodes.

The signal voltage developed across each diode, neglecting nonlinear effects, is (Eq. 12, ref. 1):

$$V_s = \frac{e_{in} \left( \frac{1}{LC} \right)}{s^2 + s \left( \frac{R + Z_o/2}{L} \right) + \frac{1}{LC}}$$

The central role of the diode inductance  $L$ , capacitance  $C$ , and resistance  $R$  is apparent in this equation. The diode circuit is series-resonant and shunts the signal line, so the resonant frequency must be moved above the band of interest by reducing  $L$  and  $C$ . To obtain the minimum  $LC$  product, beam-lead diodes may be used. Such diodes are manufactured from the same wafer and inherently have identical characteristics. The additional benefit of good diode matching improves symmetry and therefore improves balance and decoupling in the sampler.

A central concept in the design is the balancing of the gate pulse with respect to the signal line as shown in Fig. 1. The slot line, introduced by S. Cohn<sup>3</sup>, provides a natural circuit topology for this purpose. A slot line consists of a narrow gap in a conductive coating on one side of a dielectric substrate, the other side of the substrate normally being bare. Slot line can be used alone, or with microstrip line on the other side of the substrate as it is in the new thin-film sampler.

Experimental slot transmission lines coupled to microstrip lines were constructed, characterized by  $s$ -parameter measurements over a wide frequency range, and modeled. A slot parallel to and beneath a microstrip transmission line is not coupled to the line and raises the line impedance slightly. This can be compensated by increasing the microstrip line width over the length of the slot. A short slot transverse to the microstrip line can be accurately modeled as a parallel resonant line or tank circuit.

The design takes advantage of these properties by using two microstrip lines on opposite sides of a substrate with a slot in their common ground plane. The slot is parallel to and beneath the signal line, and transverse and symmetrical below the gate-pulse drive line. See Fig. 2 for details. A fast-rising voltage on the drive line develops a pulse across the slot but is not coupled to the signal line. The beam-lead diode pair is connected across the slot through capacitors and the node between the two diodes is connected to the signal line through a plated hole in the substrate at the center of the slot. This construction fits the simplified representation shown in Fig. 1.

## Construction

Fig. 2 shows the actual sampler layout with the ground plane slot and drive transmission line. The other side of the substrate supports the signal filter structure. The details of construction are determined by the requirement to minimize stray reactances, especially the inductance which appears in the sampling diode circuit. This inductance includes the diode beam leads and the plated-through hole in the substrate which connects to the signal transmission line.

The substrate thickness is a compromise between

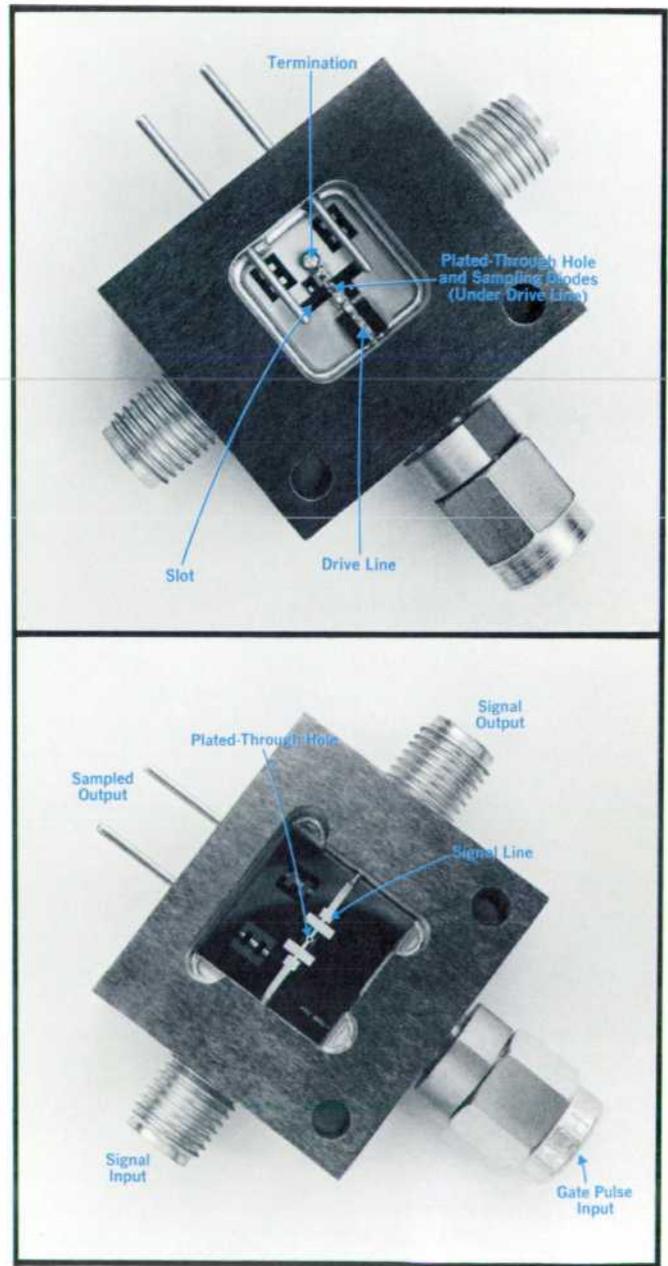


Fig. 2. New thin-film 20 GHz sampler has a double-microstrip structure with slot-line coupling. The two sampling diodes are on beam-lead chips.

minimizing inductance and substrate fragility. For a thin substrate, quartz is used to minimize dielectric constant and line losses and obtain the widest signal transmission line for a characteristic impedance of 50 ohms.

With these choices, the sampling series inductance is about 250 pH and the diode capacitance must be about 0.1 pF to obtain a resonance above 30 GHz. With these values for the central element, three- to seven-section low-pass filters were designed using empirical methods to reduce signal line reflections. Table 1 shows the final results of optimized signal-line VSWR for a 20-GHz-cutoff filter design. VSWR is less than 1.7 over the entire bandwidth.

The drive pulse enters a piggyback microstrip line attached to the ground plane side of the substrate. A ribbon connection in air is made from the end of this substrate across the sampling slot to a terminating load resistor. The input pulse is capacitively coupled to the diodes and the remaining energy dissipates in this internal load. Output is taken from the two sampling capacitors through resistors and a bias circuit. The entire device is mounted in a metal package with three miniature coaxial connectors.

### Operation and Experimental Results

Fig. 3 shows a typical circuit used for testing sampler operation. In normal operation, the sampler is driven by a source of fast-risetime signals which may approximate step or pulse waveforms.

A source of repetitive signal waveforms is connected to either end of the signal transmission line which is terminated at the other end in a load. An amplifier with two inputs is connected to the two sampling capacitors. These inputs are dc-coupled

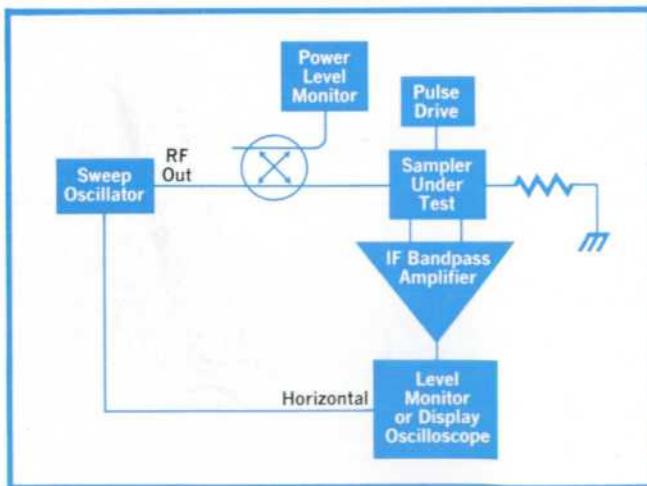


Fig. 3. Typical circuit used for testing sampler operation (conversion efficiency, IF response, etc.).

Table I: Typical Sampler Characteristics

TASK? 2

CONN DEVICE TEST SAMPLE

FREQ	REFL	VSWR	RTN LS	ANG
2000.000	.127	1.291	17.9	145.0
2400.000	.147	1.346	16.6	110.7
2800.000	.162	1.387	15.8	74.6
3200.000	.169	1.408	15.4	36.9
3600.000	.171	1.414	15.3	-.9
4000.000	.171	1.413	15.3	-36.9
4400.000	.162	1.387	15.8	-69.6
4800.000	.155	1.368	16.2	-94.5
5200.000	.167	1.400	15.6	-113.1
5600.000	.194	1.482	14.2	-134.7
6000.000	.225	1.582	12.9	-161.0
6400.000	.245	1.648	12.2	169.4
6800.000	.242	1.638	12.3	137.2
7200.000	.210	1.532	13.6	103.5
7600.000	.151	1.355	16.4	68.6
8000.000	.072	1.155	22.8	32.3
8400.000	.008	1.016	42.1	-168.5
8800.000	.073	1.158	22.7	143.1
9200.000	.111	1.249	19.1	106.3
9600.000	.115	1.260	18.8	70.9
10000.000	.089	1.197	21.0	35.9
10400.000	.045	1.093	27.0	2.4
10800.000	.004	1.009	47.1	134.9
11200.000	.044	1.091	27.2	119.6
11600.000	.071	1.154	22.9	98.5
12000.000	.117	1.265	18.6	70.3
12400.000	.087	1.191	21.2	56.5
12800.000	.127	1.290	18.0	40.3
13200.000	.161	1.384	15.9	9.8
13600.000	.179	1.436	14.9	-29.3
14000.000	.168	1.404	15.5	-72.5
14400.000	.148	1.347	16.6	-121.3
14800.000	.123	1.281	18.2	175.3
15200.000	.120	1.273	18.4	100.0
15600.000	.144	1.337	16.8	30.8
16000.000	.178	1.434	15.0	-25.2
16400.000	.206	1.519	13.7	-70.7
16800.000	.208	1.526	13.6	-109.6
17200.000	.212	1.537	13.5	-132.9
17600.000	.215	1.548	13.4	-155.0
17999.996	.252	1.673	12.0	-170.6

to a bias circuit and ac-coupled to the amplifier stages. Bias may be adjusted to effect a good compromise between maximum bandwidth (maximum bias) and maximum output (minimum bias). The amplifier may have a normal IF bandpass characteristic and be followed by a detector feeding an oscilloscope display.

Samplers have been built and tested as illustrated in Fig. 3. Fig. 4 shows the relative conversion efficiency, normalized to unity at low frequencies. The seven-element low-pass filter structure designed for 20 GHz cuts off sharply at this frequency and maintains a VSWR of less than 1.7 in the frequency band.

In Fig. 5, the oscillators are used in their swept mode, showing a response at  $IF_n = NF_d \pm F_s$  where  $IF_n$  is the output frequency of the bandpass ampli-

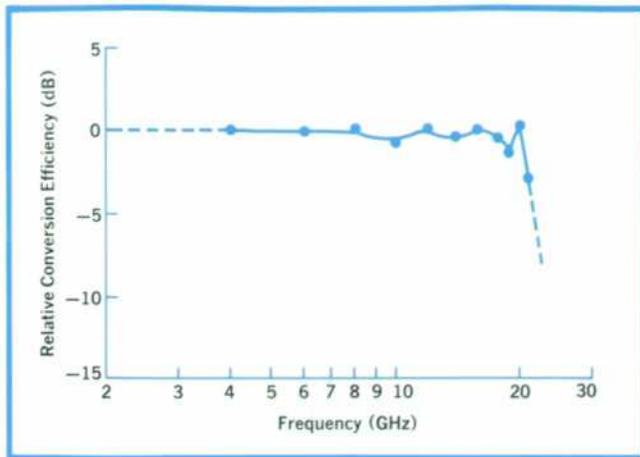
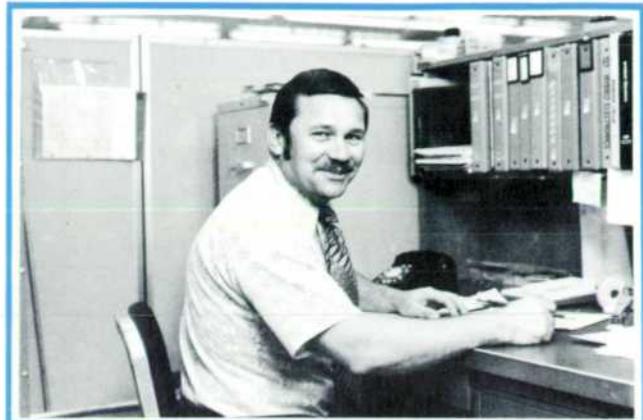


Fig. 4. Relative conversion efficiency of thin-film sampler.

fier,  $F_s$  is the sampled signal frequency, and  $NF_d$  is the drive pulse repetition rate multiplied by the harmonic number. A response is obtained whenever  $IF_n$  is in the IF amplifier passband. Note that the responses are nearly equal in amplitude at all frequencies.

#### Acknowledgments

I would like to express my appreciation for continuous and patient support from R. W. Anderson and Dexter Hartke, engineering managers at Hewlett-Packard's Santa Clara Division. My thanks also go to other members of the Hewlett-Packard team: to Merrill Brooksby for helpful suggestions, to John Dukes for guidance, and to all members of the thin-film laboratory and secretarial staff for patient and irreplaceable cooperation. Members of HPA Division deserve special recognition for patient and continuous effort in device-parameter definition.



#### Jerry Merkelo

Jerry Merkelo was born in the Ukraine. Displaced by World War II, he received his early education in France, where he worked as an electrician for a year before coming to the United States in 1956. After a short drafting career, he spent two years in the U.S. Army, then entered the University of Illinois and received his BS and MS degrees in electrical engineering in 1965 and 1966. He joined HP in 1966. Jerry has worked on microwave components for synthesizers and high-frequency counters, and in the thin-film area has developed special mixers, agc amplifiers, microwave filters, and the thin-film samplers. He's now hybrids line manager with HP's Santa Clara Division.

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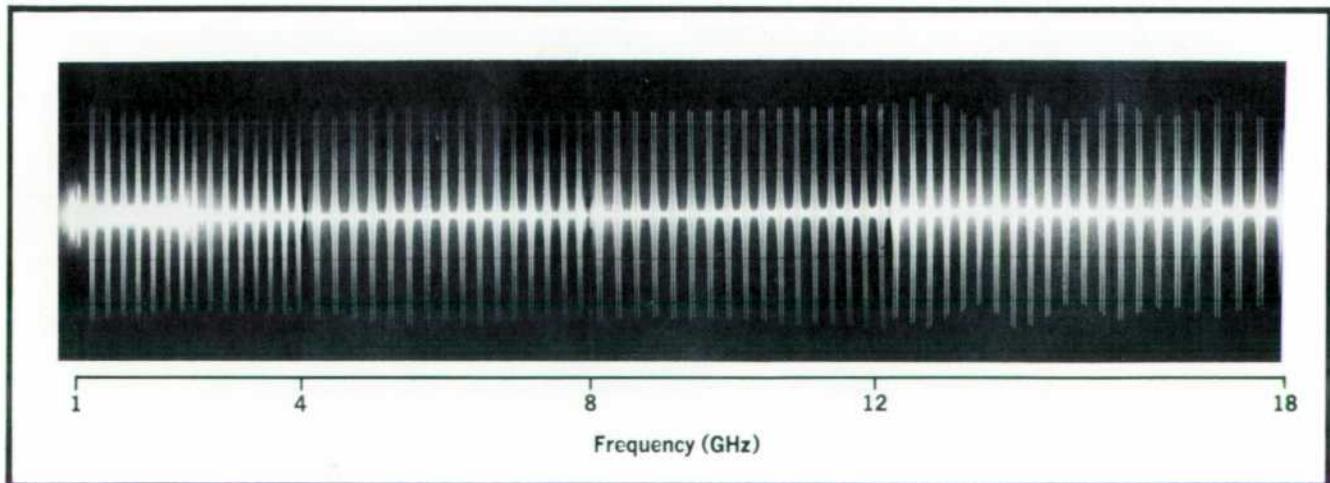


Fig. 5. In swept tests, the sampler produces a response whenever its output frequency is in the passband of the IF amplifier shown in Fig. 3. Note uniformity of responses.

# Automating the Calibration Laboratory

*This new family of systems, combining standard and specially developed hardware and software, greatly reduces instrument calibration times without sacrificing precision or thoroughness.*

by E. Robert Aikin and John L. Minck

**C**OMPUTER-BASED AUTOMATIC TEST STATIONS have been around for a number of years. They found their earliest uses in production areas, where throughput is high, and in engineering, where they provide increased technical performance that's impossible to achieve in other ways. In many cases the complexity of tests, such as a communications satellite, simply make manual measurements hopelessly slow, and so an automatic system has been installed.

Instrument calibration, on the other hand, has so far proved resistant to automation. Automated testing is most successful and most easily implemented where little human intervention is required, while instrument calibration, test, and repair have always called for the highest of skill levels and considerable manual manipulation.

Now, however, it's likely that even the calibration laboratory will begin to turn to automation as the most cost-effective solution to its needs.<sup>1</sup> Instruments are becoming substantially more complex in design and sophisticated in operation. Training loads are increasing as instrument types proliferate. Instrument circuitry is becoming more digital, making tests more difficult manually, but matching computerized systems better. Corporations are focusing increased attention on the accuracy of their production testing to document compliance with new product liability responsibilities. New federal laws concerning worker safety will mean procedures, instrumentation, and training may have to be reexamined for safety considerations. All these factors tend to increase the pressures on the calibration laboratory.

At the same time, instrument manufacturers are beginning to design their products with automatic testing in mind. The computer-testable instrument is becoming an increasingly large part of the calibration laboratory's workload.

## Prototype Leads to New Calibration Systems

To study the impact of computer-assisted instrument calibration, HP has operated a prototype system in its Customer Service Center in Mountain View, California, for several years. This system is used in the calibration of a wide variety of electronic meters, digital voltmeters, oscilloscopes, plug-ins, counters, and oscillators. The Service Center handles a diverse workload and hence very much resembles a typical industry calibration and repair shop.

The CSC system has served as the forerunner of a new family of systems specifically designed to match many of the requirements of industry calibration laboratories. 9550 Instrument Calibration Systems, Fig. 1, are modular systems that can be specialized for selective workloads or expanded to test a broader range of instruments. The systems use a software operating executive well oriented to a calibration laboratory.

9550 systems will be provided with a library of calibration programs for many instruments in common use. For instruments not included in the library, test technicians can quickly learn to write special programs. The computer language is ATSBASIC, an instrumentation version of the easy-to-learn language BASIC. Test programs now being written by HP are primarily for performance test and alignment. Repair and diagnostics are being reserved for a later phase.

## What Automation Saves

Calibrations with these automatic systems have proved three to five times faster than manual techniques. For instance, a performance test of the HP 412A Multimeter runs in 6 minutes, the HP 400E Voltmeter in 4 minutes, the HP 200CD Oscillator in 5 minutes, and the HP 180A Oscilloscope mainframe in about 10-15 minutes.



**Fig. 1.** 9550 Instrument Calibration Systems are modular computer-controlled dedicated systems designed to help solve calibration laboratory problems of work overload, personnel training, and laboratory management. Large and small systems are available. Calibration-quality stimulus and measuring instruments, plus computer-applied corrections, assure that automated calibrations equal or exceed manual methods.

This experience, along with comprehensive data gathered from many calibration laboratories, has been used in a detailed analysis of the time and cost savings to be expected from automated instrument calibration.<sup>2</sup> This analysis is much too detailed to attempt even to summarize it here. It does show, however, that with experienced technicians, automation can save 5–25 dollars per calibration, based on the time saved just in performance test, alignment, and overhead functions.

Not considered in this detailed analysis, but also very important, is that automation permits routine calibrations to be done by less experienced personnel. It thereby frees the experienced technician to perform more challenging tasks, such as repairing defective instruments and writing test programs for newly acquired instruments.

#### Stimulus Subsystems

9550 systems use calibration-quality stimulus and measuring instruments recognized by calibration laboratory managers for their accuracy and stability. A complete list appears on page 24.

Low-frequency ac stimulus to 1100 volts rms is obtained from the HP 745/746 AC Calibrator. The HP 3320B Synthesizer provides frequencies up to 13 MHz, and RF stimulus to 1300 MHz comes from the HP 8660A/86602A Synthesized Signal Generator.

Dc calibrations to  $\pm 1100$  volts and to  $\pm 110$  milliamperes are done with a Fluke 3330B. An HP 6263B Power Supply provides up to 5 amperes dc.

Pulses for testing oscilloscopes are provided by an HP 8004A Pulse Generator and an HP 211B Square-Wave Generator.

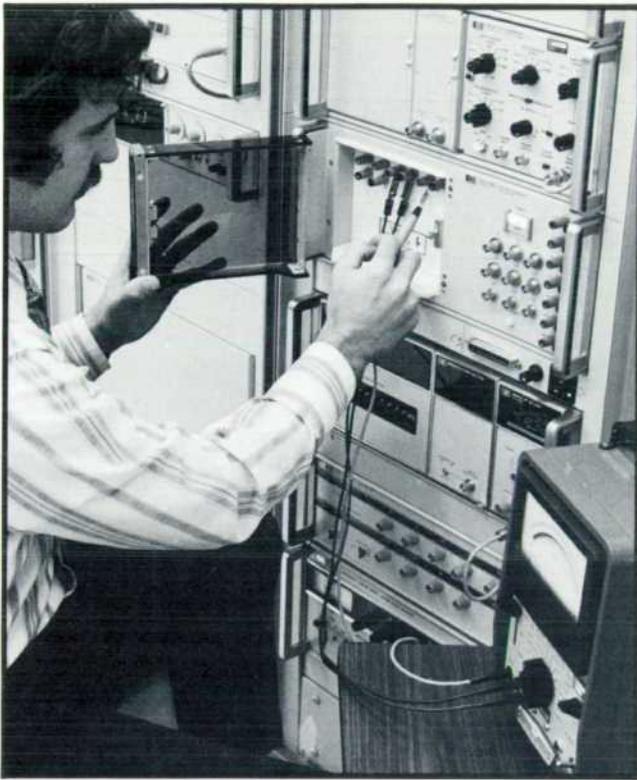
In addition to these stimulus instruments, a programmable line regulator (GR 1592A) controls ac line power to the unit under test so line sensitivity tests can be run under software control.

Operator safety was a prime design objective in 9550 systems, since lethal voltages must be used in many calibrations. In computer systems high voltages can appear without the operator's turning a knob or switch, so special hardware and software interlocks are provided and warnings to the operator are displayed before high voltage is applied.

Most of the stimulus signals are routed through a special switching and safety panel. All dc and ac voltages over 100 volts must be connected behind a transparent protective door on the systems interface panel (Fig. 2). The door is arranged to accept typical instrument probes inside its access space. This door is hardware interlocked to the high-voltage supplies so they will remove all high voltage if the door is opened while high voltage is applied to any terminals behind it. Before voltages are actually applied to the terminals behind the closed interlocked door, the software instructions ask for a response from the operator to alert him that lethal voltages are coming.

WARNING — HIGH VOLTAGES NOW BEING  
APPLIED DO NOT TOUCH OUTPUT  
CONNECTIONS  
DO YOU UNDERSTAND? YES

Other interlocks, both hardware and software, prevent switching high voltages through unexpected paths to terminals outside the protective door. This applies not only to high stimulus volt-



**Fig. 2.** High voltages in 9550 Systems appear behind this interlocked safety door. Hardware and software interlocks are provided.

ages applied by the system, but also to external high voltages being measured by the system.

### Measurement Subsystems

The primary measuring subsystem in 9550 systems is the HP 3480B/3484A Digital Voltmeter which makes up to 1000 dc measurements per second and provides track-and-hold for ramp and waveform sampling. Also, its true-rms detector provides accurate ac readings up to 10 MHz. Moderate accuracy resistance measurements are also possible.

Waveform and signal analysis can be performed with a manually operated oscilloscope, an HP 180D/1801A/1820C.

Expanded versions of the 9550 family include additional measuring subsystems under computer control. The HP 3450B DVM provides higher accuracy and resolution in dc measurements. The HP 432C Microwave Power Meter measures RF power up to 3 GHz (to 18 GHz with optional thermistor mounts). The HP 5327B Counter measures frequencies up to 550 MHz. The HP 334A Distortion Analyzer makes measurements on oscillators and sources up to 100 kHz.

Most of the measurement subsystems are connected to the unit under test through the switching-

interface panel. This panel provides high-voltage scanning, the ability to monitor frequencies with the counter and other capabilities.

Among the other functions provided by the switching/interface panel, standard fixed resistors from 1 ohm to 1.0 megohm are switched under computer control to a front-panel jack so ohmmeters may be checked or currents measured. A special data scanning function is used for interfacing the system to instrument data outputs such as printer outputs on DVMs and counters. Called "BCD scanning" and described on page 19, this function offers a flexible method of reading a wide variety of logic levels and codes used in different instruments from different manufacturers.

In the future, instruments are expected to become more programmable. Therefore, 9550 systems have a programming connector that permits computer control of 48 contact closures to exercise programmable test units and further reduce the need for human intervention.

### Computer and Peripherals

9550 Instrument Calibration Systems are dedicated, "stand-alone" systems. A 16K word mini-computer, the HP 2100A, operates with a mass memory disc, the HP 7900A. The disc drive has one fixed disc and one replaceable disc pack for a total of 2.5 million words of storage. The disc serves as mass storage for a variety of instrument programs. Thus the system can be calibrating voltmeters and within seconds call up programs to calibrate oscilloscopes as the new workload comes in.

A standard line of peripherals is available for various needs. A medium-speed tape punch is used in program writing and to generate master record tapes for archive storage or mailing. Various hard-copy peripherals, such as teleprinters and line printers, provide program listings and permanent copies of test reports. A typical test report printout is shown in Fig. 3.

The system is under the control of a special system control panel. On the panel is a key-operated switch that selects either operator or supervisor mode. In supervisor mode, on-line debugging and program writing are possible. In operator mode, the programs can be run by the operator but cannot be modified by him. A CRT/keyboard unit acts as the principal interface between the operator and the system.

### Human Engineering

Considerable attention was given to the human engineering of the system, since a substantial amount of human intervention is still needed in calibrating any manual piece of test equipment. A

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DC OUTPUT METER CORRELATION AND LINEARITY #1V

INPUT VS DC OUTPUT CORRELATION

METER READING	OUTPUT READING	% ERROR(FS)
.2	.202	.05
.4	.405	.12
.5	.507	.14
.6	.608	.16
.8	.808	.19
1	1.007	.0

INPUT VS METER READING CORRELATION

INPUT VOLTAGE	METER READING	% ERROR(FS)
.2	.2	.0
.402	.4	.2
.503	.5	.15
.604	.6	.4
.803	.8	.3
1.002	1	.2

SEGMENT NO. 3 TEST PERFORMED--FAILED

VOLTAGE RANGE ACCURACY # FULL SCALE

RANGE	OUTPUT	% ERROR (FS)
1 MV	1.001	.12
3 MV	1.001	.07
10 MV	.997	-1.25
30 MV	.999	-.07
100 MV	1.001	.07
300 MV	1	-.04
1 V	.999	-.14
3 V	1	-.04
10 V	.997	-.3
30 V	.999	-.15
100 V	.999	-.08
300 V	.998	-.23
1000 V	.997	-.27

SEGMENT NO. 4 TEST PERFORMED--FAILED

CURRENT RANGE ACCURACY

RANGE	OUTPUT	% ERROR (FS)
.001 MILLIAMPS	1.011	1.14
.003 MILLIAMPS	.995	-.5
.01 MILLIAMPS	.994	-.62
.03 MILLIAMPS	.995	-.49
.1 MILLIAMPS	.994	-.65
.3 MILLIAMPS	.993	-.74
1 MILLIAMPS	.994	-.55
3 MILLIAMPS	.989	-1.07
10 MILLIAMPS	.986	-1.38
30 MILLIAMPS	.987	-1.33
100 MILLIAMPS	.978	-2.16
300 MILLIAMPS	.991	-.88
1000 MILLIAMPS	1.002	.22

RESISTANCE RANGE ACCURACY

RANGE	MEASURED	ERROR
1 OHMS	1.04	4.1
10 OHMS	9.93	-.67
100 OHMS	99.24	-.76
1000 OHMS	1003.51	.35
10000 OHMS	9953.5	-.47
100000 OHMS	99452.3	-.54
1.00000E+06 OHMS	988712	-1.13
1.00000E+07 OHMS	9.92298E+06	-.77
1.00000E+08 OHMS	9.65722E+07	-3.43

STANDARDS USED: 3330R 3480R RESISTANCE STANDARD

TEST TIME: 0 HOUR 6 MIN 28 SEC

## Some Definitions for Calibration Laboratory Work

**Performance Check**—Primarily a front panel electrical certification with no alignment performed. Might allow for internal checks such as power supply voltages. Generally includes adjustment of controls accessible without removing covers.

**Alignment**—Adjustment of mostly internal controls which set range sensitivities, frequency response, etc.; may be electrical or mechanical. Very minor repairs permitted such as changing a starred resistor value. In general, if a control reaches the end of its travel and must be replaced, it is considered a repair.

**Repair**—Diagnosis and replacement of defective components and modules of the instrument under test.

**Preventive Maintenance**—Routine service procedures, such as air filter cleaning, vacuuming up paper particles, or oiling sliding parts.

**Mechanical Inspection**—Cleanup and touchup procedures such as window polishing, cabinet paint touchup, knob tightening, etc.

CRT, and answering DONE, YES, or NO with the hand-held remote control unit in the other hand. The remote control unit has a long cord so the operator can move conveniently.

A novel approach to assist alignments and adjustments is a three-light cluster on the remote control unit. These can be used for a number of purposes, but one example is as follows. The three lights are labeled "HIGH," "PASS" and "LOW." As an operator is making an adjustment on an in-

Text continued on page 20.

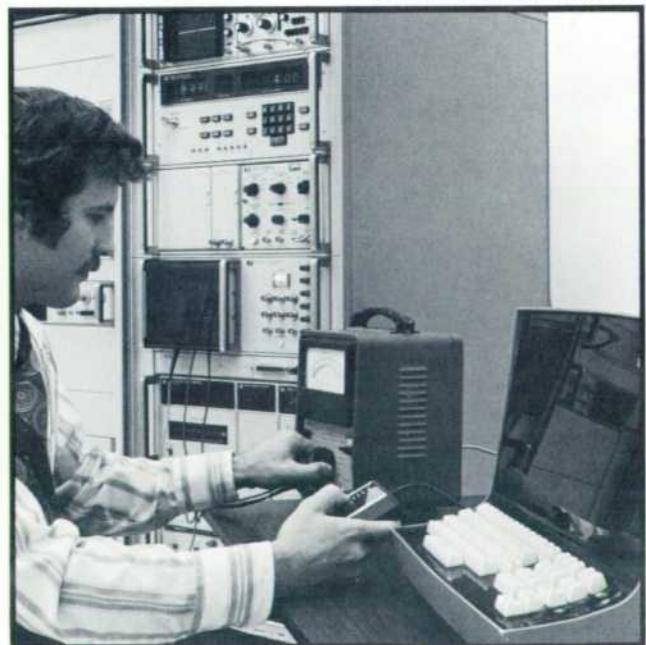


Fig. 4. A hand-held remote control unit with lights and buttons for operator/system communication is useful in many procedures.

small hand-held operator keyboard (see Fig. 4) was designed to allow the operator to communicate with the computer. This remote control unit is especially valuable when the operator is switching ranges with one hand, watching for the instructions on the

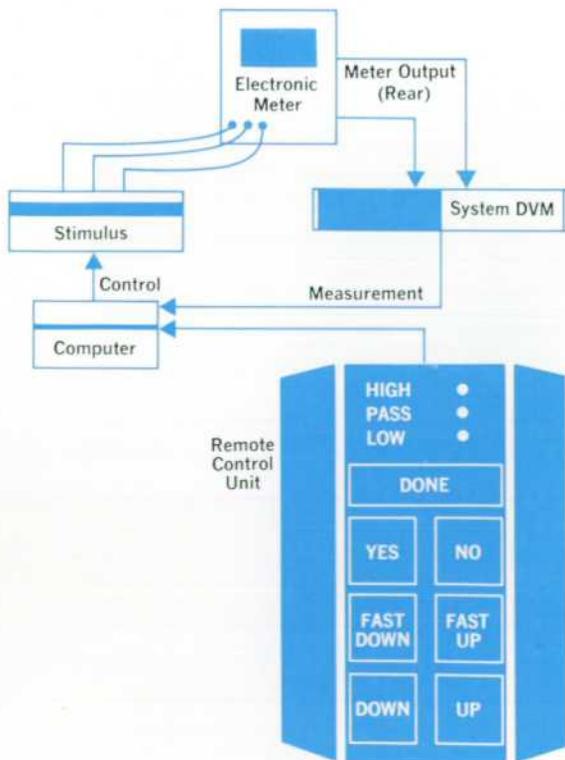
## Novel Procedures Speed Automatic Calibrations

The design of 9550 Instrument Calibration Systems represents an effort to strike an optimum balance between hardware and software systems, with due consideration given to human factors and the nature of the unit under test. To automate a test, it's not enough to transcribe the manual test procedures onto the computer or simply to record all of the instructions out of the service procedure. Instead, it's important to step back from manual procedures and look at the fundamental purpose of each test before starting to program an instrument for automatic test. A few examples will give a better perception of this technique.

### Electronic Meter Calibration

In calibrating an electronic meter, much of the time (and error) is associated with the operator's visually reading the meter movement. On a multifunction meter, such as the HP 412A, the operator must switch through 13 range positions for the three different functions of volts, milliamperes and ohms, a total of 39 switch positions. At each position he must interpret the full-scale indication and decide whether the instrument is within specifications. He must also run a meter movement linearity test on one range to make sure that the meter movement is linear. Here's how the 9550 does it (see diagram).

First, the system programs the stimulus to a nominal 10% of full scale (0.1 volt) and the needle deflects to approximately 10% of full scale. The operator holds the remote control box, with its "UP/DOWN" buttons, in his hand.



System setup for calibration of electronic meter.

Watching the needle deflection, he presses the appropriate button to provide more or less stimulus voltage and quickly adjusts the stimulus so the needle deflection is exactly over the 0.1 cardinal point. He then presses the "DONE" button on the remote controller. The system measures and records the voltage at the 412A meter output jack (proportional to meter deflection).\* The system also records the true dc voltage required at the input of the instrument to deflect the needle to the 0.1 point.

The system next applies a nominal 20% FS signal and the sequence is repeated. And so it goes, through each of the cardinal points as the operator adjusts the stimulus and aligns the needle to the exact cardinal point. At each of these points, the system is characterizing the meter movement in terms of the electrical output required to get a particular mechanical deflection. The whole process typically takes 30 seconds. The data is stored in a correction table in memory.

The system immediately determines whether the meter movement is linear from the recorded stimulus required for the series of cardinal point deflections.

The real time-saving impact now occurs as the operator tests all three functions in each of the 13 different range positions. The system instructs him to set the range to 1 millivolt and, with one hand on the range switch, he clicks over to the bottom range. In his other hand he presses the "DONE" button and the system immediately applies one millivolt. The operator no longer has to look at the meter movement because the electrical output and the previously characterized meter data tells the system whether the needle is deflected to precisely full scale. The system quickly takes its data and then issues a new instruction for the operator to switch the range to 3 millivolts. He again presses the "DONE" button and the system electrically reads the meter deflection. The meter face might as well be covered with a mask since the operator no longer pays any attention to the meter deflection.

Once the voltage function test is completed, the milli-ampere function and then the ohms function are checked with much the same speed, again without any need for the operator to watch the meter scale. The operator's total attention is on the CRT viewing screen; he keeps one hand on the range switch and the remote control box in the other hand. The entire performance test takes only 6 minutes.

### Oscilloscope Time Base

Another unconventional technique can be applied to oscilloscope time base calibrations. Using the traditional techniques and a time mark generator, and checking each range of the time base plug-in for sweep accuracy, most of the time is spent checking the very long sweeps. For instance, the longest sweep at 5 s/cm would typically take 50 seconds. It's necessary for the operator to wait all the way through each sweep to see how the last time mark comes out. Minutes of waiting time are consumed on the slow sweeps. Worse yet, when adjustments are needed, the operator must wait for the sweep retrace and start a whole new run to see whether his time adjustment was accurate.

\*Some older instruments don't have a meter output jack and the cover must be removed to gain access to this voltage.

With an automatic system, time base calibrations can be much faster. First, the system digital voltmeter with high input impedance is attached to the horizontal deflection plates of the oscilloscope (usually through some isolation resistance). Then the CRT instructs the operator to adjust the beam manually to zero centimeters and the system measures the voltage required to deflect the spot to that position. The operator adjusts the beam to the 5-centimeter graticule and then to 10 cm, and the system records the voltage required for those deflections. After a quick computation of the volts per centimeter sensitivity of the CRT tube, the system instructs the operator to start the sweep. So far what has happened is equivalent to the meter characterization already described.

The system digital voltmeter has a track-and-hold option that can determine a voltage at a precisely known time. Using this capability, the system quickly measures two voltages at an accurately timed interval and computes the sweep voltage slope in volts/second. After comparing that number with the precalibration in volts/cm, the system easily determines whether the slope of the CRT ramp is adequately calibrated. It is not necessary to wait for the entire sweep to occur since the slope over a small segment is adequate for the computer to make a go/no-go decision.

Finally, the operator is instructed to switch through all of the sweep's speeds and before the trace moves more than about one-third of the total sweep, each sweep's accuracy can be assured. The sweep is permitted to go completely through one full sweep so sweep linearity can be assured for the entire distance, but it is generally not necessary to do this step in every range position.

Naturally, it isn't possible to use this technique on faster sweeps. The technique is changed at about five milliseconds per centimeter due to the sampling rate and time resolution of the DVM, and high-frequency loading of the CRT. However, as mentioned before, the fast sweeps are not the time consuming part of the calibration.

A useful byproduct of this technique comes into play when adjustments are required on the sweep time. The *slope* readout of the system indicates whether the adjustment made is correct. Thus it is not necessary for the operator to wait for the entire sweep.

Validation tests have been run on this technique and correlations within 0.5 percent of traditional time-mark techniques have been achieved repeatedly. The same basic technique can be used on the vertical attenuators and amplifiers by characterizing the vertical CRT sensitivity at midfrequency ranges in volts/centimeter. Traditional high-frequency response and pulse response tests are still performed.

The automatic system also provides benefits when calibrating the faster sweeps. Using conventional time-mark techniques the operator must *estimate* the number of centimeters of error by observing the position of a time mark relative to a major graticule mark. His viewing accuracy is typically one-half minor division or 0.1 cm. In 9550 systems the precise HP 3320B Synthesizer triggers the HP 8004A Pulse Generator to serve as a programmable time mark generator. The operator uses the remote control unit to vary the synthesizer frequency UP or DOWN to align the leading edge of the time mark pulse exactly under a major graticule mark. He then presses DONE and the system reads the frequency of the oscillator and converts the reading to time per centimeter. Thus operator error is eliminated,

resulting in a more accurate calibration.

### BCD Scanning for Counters and DVMs

In calibrating a typical digital voltmeter, an operator needs to see every numerical value of every display digit to check for dead spots. He must also check range accuracy and linearity and, at the same time, look at the binary-coded decimal data coming from the printer output connector on the rear. By considering this group of functional tests from scratch, it is possible to reorder them into an extremely fast sequence, making use of the power of the computer.

First, there is a severe interface problem in dealing with a variety of manufacturers' BCD standards. A BCD code can be weighted  $\pm 1224$  or  $\pm 1248$ , and levels may have any of the following combinations of values as well as others.

Logic 0 :	0V	-24V	-8V	-28V	...
Logic 1 :	+5V	-1V	+18V	-2V	...

This is just for one manufacturer. Other manufacturers use their own logic levels, and some older counters and instruments use staircases for digital output.

Instead of requiring an individual interface card for each combination of logic codes and levels, 9550 systems use an interface technique that relies on the very fast dc sampling of the system digital voltmeter. The four-line BCD groups from the unit under test appear on a scanner switch that is gated to the fast-sampling system digital voltmeter. The DVM reads the voltage on each of the BCD lines, and the system software decides the logic level and logic weighting of the instrument under test.

First, the system applies 0 volt stimulus and the operator adjusts the zero adjust until the display reads all zeros. When he presses the "DONE" button, the system scans across all 16 BCD output lines. Assuming a logic code of +1248 and logic levels of -8 and +18 volts, the system DVM would see -8 volts on all the BCD lines.

The system then programs a nominal 1.111 from the dc stimulus and the operator is instructed to adjust the "UP/DOWN" button until all ones appear in the display. When he presses the "DONE" button, the system scans across all 16 lines and sees the voltages appear as follows: +18, -8, -8, -8, +18, -8, -8, -8, etc.

The system then programs 2.222 and again the operator makes adjustments to the stimulus until all the display digits are 2's. Again the system scans the electric outputs and sees -8, +18, -8, -8, etc.

Repeating this process for 0.000 through 9.999, the operator sees every number in every digit position and at the same time the system looks at every electrical output combination.

The advantage of the technique, however, is that the operator doesn't have to read the display when other functional tests are to be performed, such as ohms, or mA. The system has already compared inputs, visual readouts, and BCD outputs. In effect, the system can now "read" the unit under test. The operator has already seen that there are no dead spots. So in one fast run through ten positions, the linearity, the display and the BCD outputs are all checked in less than one minute.

strument, the system may be monitoring, for example, the voltage of a power supply.

If the voltage is out of tolerance and on the high side, only the "HIGH" light will turn on. The system may even tell the operator which direction to turn the adjustment, and, as he moves down into the in-tolerance region, the "HIGH" light will stay lighted and the "PASS" light will turn on. Finally, as he moves through the center of the tolerance band the "HIGH" light will switch to "LOW" with the "PASS" light remaining on. Subsequently, the "PASS" light will go out when the voltage is below the tolerance band.

Thus a very precise center-of-range indication is provided to the operator. Since the box is movable, it can be placed close to the operator's field of view as he makes his adjustments. This can be a major safety feature if adjustments are being made on very high voltage supplies. The operator does not have to look over to the system panels.

### Software Operating System

The software operating system is a disc-based executive called TODS (Test Oriented Disc System). TODS is designed to eliminate restrictions on the size and scope of software programs that might otherwise be limited by the available computer core memory. It provides for segmenting of programs on the disc and easy access to the various segments via program and subroutine linking. HP ATSBASIC, FORTRAN, and HP Assembly Language are all compatible with TODS.

TODS also provides editing routines that can automatically delete or change source programs on the disc. This is important when new programs are being written and debugged.

Another important feature of TODS is the catalog and librarian system. As the system stores programs on the disc it catalogs their locations so they can easily be accessed by instrument test routines. On command, the librarian will print out a list of the programs stored on any selected portion of the disc. It will also print the amount of space remaining on the disc.

In addition to programs, the disc also provides data storage for test results. Test data is normally stored in data files using a standardized system format that allows easy access for printed test records or other more permanent files.

### Calibration Programs

A widely used rule of thumb for system planners is if entirely new applications software must be generated, costs can easily run between one and three times the cost of the hardware in the system. Therefore, careful concern must be given to plan-

ning for these software costs which accrue not only at the installation of a system but involve a continuing expense during its useful lifetime.

There is substantial advantage in having the instrument manufacturer generate test programs. Internal knowledge of the instrument under test as evidenced in a program written by technicians experienced with the instrument can offer subtle improvements over a test program merely transcribed from the instrument manual by a professional programmer.

Therefore, HP has planned a user interchange library starting with a group of HP-furnished programs to allow early cost-effectiveness for installed systems. The early programs will cover high population instruments typical of many calibration laboratories. Fig. 5 is a list of these programs.

These application programs include performance tests plus alignment and adjustment procedures. For HP instruments, the program content is at least equal in capability to the calibration techniques described in the service manuals, and frequently includes tests and techniques learned in years of instrument test experience (see page 18).

Of course, it will be impossible for HP to provide test programs for all instruments that require periodic calibration, so most users will at some time write programs of their own. Because instrument testing has many common aspects regardless of where it is done, there is substantial advantage in standardizing instrument calibration programs and operating systems. With suitable standards, there can be general compatibility and interchange of programs among dozens and perhaps even hundreds of users for better efficiency.

It is often surprising even to experienced programmers what degree of conformity is required and how detailed standards must be to guarantee compatibility. To assure compatibility among calibration programs written not only by HP but also by different users, relatively strict standards have

METERS		OSCILLOSCOPES		OTHER
Simpson 260	HP 428B	HP 120A	TEK 422A	HP 200AB
HP 400D	HP 430C	HP 120B	TEK 454A	HP 200CD
HP 400E/EL	HP 431B	HP 130B	TEK 545A	HP 205AG
HP 400H	HP 431C	HP 130C	TEK 561A	
HP 400L	HP 432A	HP 140A	TEK 564A	HP 8690A
HP 410B	HP 3400A	HP 180A	TEK B	
HP 410C	HP 3439A	HP 1401A	TEK CA	HP 5212A
HP 412A	HP 3440A	HP 1421A	TEK D	HP 5245L
		HP 1801A	TEK 1A1	
		HP 1821A	TEK 3A6	
			TEK 3B3	

Fig. 5. HP will supply performance test and alignment programs for many instruments, starting with these. A users' group is being established so user-written programs can also be shared.

TEST PROGRAM FORMAT	
1	Titles Program Descriptions Data Reserve Hardware & Software Initialization
999	
1000	Program Mainflow
5799	
5800	Data Statements Ranges & Tolerances
5999	
6000	Exit Controls
6199	
6200	
	Standard Subroutines
8999	
9000	Special Subroutines
9999	

**Typical Program Mainflow**

```

1000 REM
1001 REM PROGRAM MAINFLOW
1002 REM *****
1003 REM
1010 REM * SET SWITCH PATHS
1020 SWIC(0,23)
1030 REM * OPERATOR INSTRUCTIONS
1040 GOSUB 8500
1050 DISPLAY "SET 410 RANGE SWITCH TO THE FOLLOWING SETTINGS"
1060 DISPLAY "DEPRESS DONE WHEN COMPLETED"
1070 DISPLAY
1080 REM * GET EXPECTED & TOLERANCE VALUES
1090 READ V,T
1100 FOR I=1 TO 13
1110 REM * GET RANGE & FULL SCALE VALUES
1120 READ R(I),P(I)
1130 REM * SAVE EXPECTED & TOLERANCE VALUES
1140 LET V(I)=V
1150 LET T(I)=T
1160 REM * DISPLAY RANGE REQUIRED
1170 IF I=7 DISPLAY R(I)/1000;"TAB(0)";"U"
1180 IF I=6 DISPLAY R(I);"TAB(0)";"U"
1190 REM * DONE?
1200 GOSUB 7300
1210 IF NOT P(I) GOTO 1160
1220 REM * IF RANGE > 10 MV GOTO 1500
1230 IF I>3 GOTO 1500
1240 REM * APPLY CURRENT ACROSS 1 OHM RESISTOR J 17
1250 REM * CLOSE APPROPRIATE CURRENT PROGRAMMING SWITCHES
1270 SWIC(5,31)
1280 SWIC(37,41)
1300 REM * EXPRESS CURRENT IN MA
1310 LET P(I)=1000*P(I)
1320 REM * APPLY VOLTAGE
1330 GOSUB 7800
1340 WAIT 200
1350 GOTO 2000
1500 REM * SET SWITCHING FOR VOLTAGE PROGRAMMING

```

**Typical Subroutine for Entering Ranges and Tolerances**

```

5800 REM ----- DATA STATEMENTS -----
5810 REM * EXPECTED VALUE & FULL SCALE TOLERANCE
5820 DATA 1,.01
5830 REM * RANGE (MV) & FULL SCALE VOLTAGE (V)
5840 DATA 1,.001,3,.00316,10,.01,30,.0316,100,.1,300,.316
5850 REM * RANGE (V) & FULL SCALE VOLTAGE (V)
5860 DATA 1,1,3,3.16,10,10,30,31.6,100,100,300,316,1000,1000

```

**Typical Measurement Subroutine**

```

9600 REM ----- METER DC OUTPUT MEAS -----
9605 REM *
9610 DVMSU(1,1,2)
9620 FOR K=1 TO 20
9630 DVMM(10,P(I),400)
9640 REM * SETTLED TO .1% ?
9650 IF ABS(P(I)-P(I))<.001*P(I) GOTO 9680
9660 REM * SETTLED TO 2 MILLIVOLTS ON SCALES * .5
9665 IF P(I)<.5 AND ABS(P(I)-P(I))<.002 GOTO 9680
9670 NEXT K
9680 REM * PASS VOLTAGE READ
9685 LET P(I)=(P(I)+P(I))/2
9690 REM * PASS RESPONSE TIME
9695 LET P(I)=K/2
9699 RETURN

```

Fig. 6. Strict standards will help assure compatibility of HP and user-written programs. Program format is fixed, and REM statements are used liberally in programs to enable others to understand them. Language is ATSBASIC, an instrumentation version of the easy-to-learn language, BASIC.

been established. Fig. 6 shows the required test program format and some typical program segments. Notice that REM (remark) statements are used extensively to communicate the function of each section of the program.

### Executive Sequence Control

As common and standardized as instrument calibrations are (a 400D is calibrated much the same in all calibration laboratories), it is still true that most laboratories have their own special test philosophies and operating rules. Based on experience with the Customer Service Center system and other work, Hewlett-Packard has developed a special executive sequence control for 9550 Instrument Calibration Systems. This operating executive serves as a central traffic director for the ongoing technical tests.

Generally, most of the tests made on an instrument are divided into technical test segments as shown in Fig. 7. The HP 412A test program, for instance, consists of a test directory, five technical test segments, a test record segment, and an alignment segment. In this case, the sequence control handles the entry into each test segment and provides for an orderly sequence through the test segments. At the same time, it is controlling the disposition of data and keeping track of the status and sequence of test segments.

The sequence control is needed because various things happen in a typical calibration sequence that require operator intervention, and these events must be made compatible with a computerized system. For example, if a probe falls off the interface panel during a test, the operator must halt the program and return to some point from which he can proceed forward again. In 9550 systems, a "bailout" button is provided. Pressing this button turns off stimulus and clears switching in an orderly way, returns to the sequence control, displays the test directory (Fig. 7), preserves the previous data, and asks the operator where to restart.

Another example: an internal malfunction causes an instrument to start smoking when a high voltage, such as 1000 volts, is applied to it during a normal test cycle. In some systems, stopping the program simply halts the computer, leaving all switches closed and 1000 volts still applied to the instrument. In 9550 systems, pressing the bailout button starts an orderly shutdown sequence which opens all switches and turns off the high voltage. Then the sequence control places the test directory back on the screen to inform the operator of the present status of the test sequence.

Another function of the sequence control is to

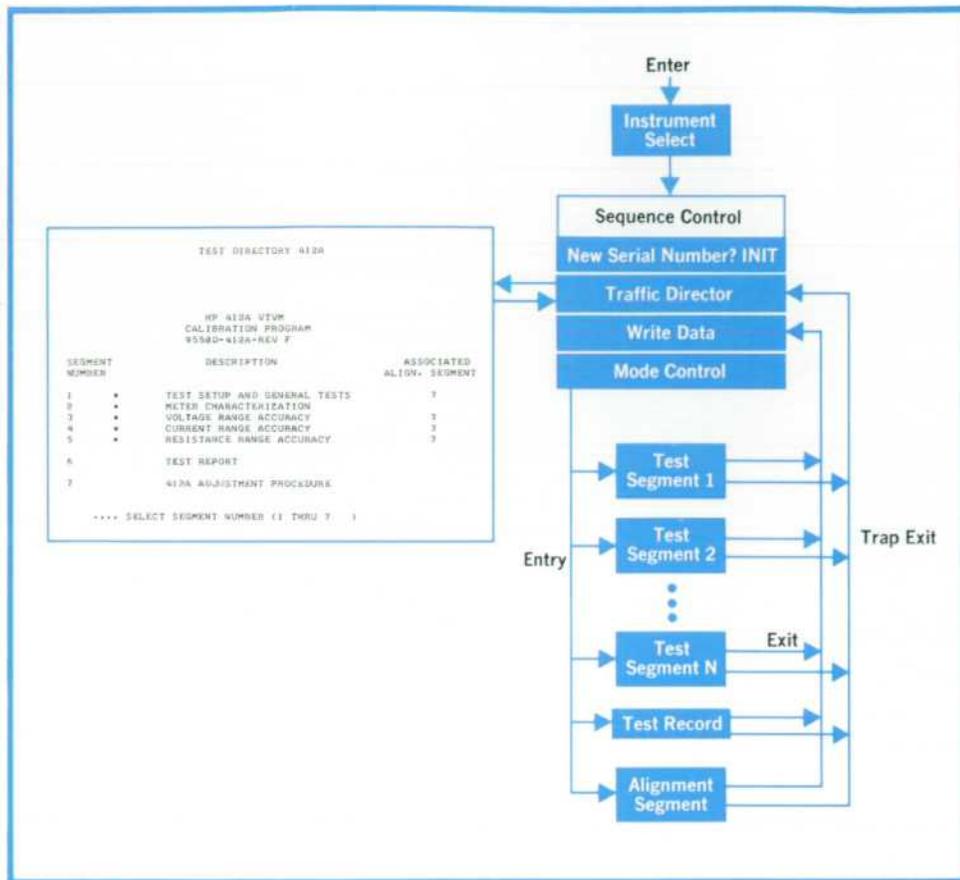


Fig. 7. Executive sequence control adapts sophisticated 9550 software to the calibration laboratory environment. A normal sequence proceeds automatically, but test interruptions and decision points cause the test directory to appear on the CRT so the operator can select what to do next.

provide for operator alignment or adjustment sequences after any performance test. If a particular test segment fails, the operator gets a "segment fail" indication and may then choose an associated alignment test segment to adjust the instrument within specification.

Probably the most important feature of the sequence control is that it is written in the same ATS BASIC language as all test segments. Thus, although HP personnel have written the executive with their best ideas of proper sequence and test philosophies, it is easy for the local calibration laboratory to add its own administrative procedures and test philosophies to the basic control. If the local laboratory needs to enter technician badge numbers or output special instructions to the operator, it can easily insert them. If the local laboratory doesn't want an operator to perform alignment or adjustment segments, it takes only a few ATS-BASIC statements to implement this capability. The great advantage is that a change need only be made in the sequence control and it is automatically incorporated in all test programs without modifying the test programs.

#### Better than Manual Accuracy

The power of the computer offers a chance to get

substantial improvements in instrument accuracies by means of computer-stored correction routines. Correction factors and cable losses as well as instrument calibration factors can all be worked into the programs so that substantially better accuracies can be achieved than with any one of the instruments themselves. Hence automated calibration gives up nothing in precision compared to manual techniques; in fact the opposite is true.

#### Acknowledgments

The HP Customer Service Center in Mountain View, California, provided the early impetus for automatic instrument calibration. Neil Neilson planned and built the prototype system to test concepts and cost effectiveness with the management support of John Walling, Jim Hodel, and Chuck Ernst. Mark Sayer contributed greatly to system configuration and software.

On the 9550 project, Chuck Martin designed the special switching interface, Larry Lim did the mechanical design, Bob Valentine assisted with high accuracy measuring techniques, and Steve Harper developed system self-check procedures. Homer Tsuda designed the sequence control architecture. The entire project was aided by the management insight of Dale Ewy. The project manager is now

## Observations from an Operating System

The following observations from the operating system in the HP Customer Service Center in Mountain View may be appropriate.

Automatic calibration systems must keep busy. Running time for a typical station is worth about \$1 per minute, depending how overhead is assigned. This means that the system must have instruments available in a warmup mode in front of the system before they actually reach the test position. For instance, if six or eight meters can run per hour and a given meter requires a one-hour warmup, eight or ten warmup positions must be provided.

It is especially important to provide adequate interface switching rather than rely on an operator to cable and uncable interconnections. A given connection absorbs about 30 seconds of running time, including the time it takes to read an instruction, to understand it, to connect, to check the connection, and an average time to correct mistakes. Thus specialized switching is quite cost-effective.

The combination of the computer system and an innovative programmer knowledgeable in metrology techniques is hard to overestimate. Experience with a typical program writing cycle for the HP 412A Multimeter is instructive. On the first pass, the HP 412A sequence ran about 11 minutes. Multiple probe changes were required and a number of techniques were quite clumsy. By changing switching and providing faster and novel measuring techniques, the time was reduced to 9 minutes, and finally to 6 minutes.

Don Lawrence and Ron Gould is in charge of production engineering.

We feel it's also important to acknowledge the active interest in automatic instrument calibration of the U.S. Army's Metrology Engineering Center at Huntsville, Alabama. Mr. Fred Seeley, Mr. William Barron and Mr. Malcolm Shelton contributed much in concept, vision, and encouragement during the project.

Finally, many system safety concepts were introduced to protect the system operators by Ernie Harper, who heads HP Automatic Measurement Division efforts to develop design concepts for system safety to meet IEC and other standards. 

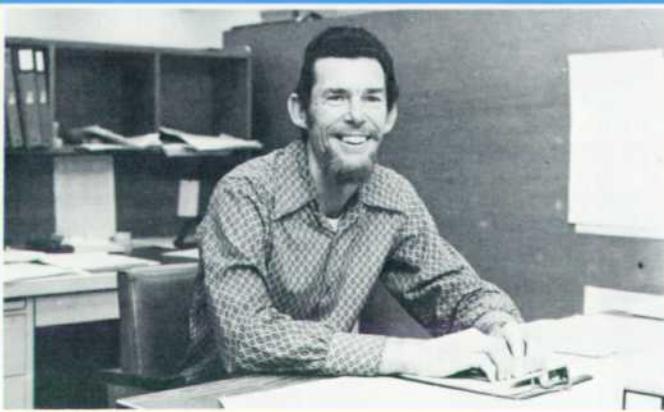
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### John L. Minck

John Minck is Market Manager for Instrument Calibration Systems at HP's Automatic Measurement Division. A member of the Precision Measurement Association and the American Society for Quality Control, he also serves as Region 12 Coordinator for the National Conference of Standards Laboratories. He's the author of several articles in technical publications and co-editor of a textbook on microwave measurements. John received his BSEE degree in 1952 from the University of Notre Dame and his MSEE-Administration degree from Stanford University in 1956. He joined HP in 1958 as a sales and applications engineer and later served as regional sales manager. In 1964 he became marketing manager of the Microwave Division, and five years later, manager of the Solid State Display Department. He assumed his present position in 1971.



### E. Robert Aikin

After serving in the U.S. Navy, Bob Aikin attended the University of Colorado, graduating with a BSEE degree in 1952. He came to HP the same year. Since then, he's been assistant service manager, applications engineer, field service engineering manager, program manager, and engineering project manager, his latest project being the 9550 Instrument Calibration System. Bob and his wife have an unusual family; besides one child of their own they have four adopted ones—two from Korea, one from Greece, and one from California. Bob serves on the board of directors of the local area association and favors outdoor recreational pursuits, including sailing, backpacking, and skiing.

## SYSTEM INFORMATION

### HP 9550 Instrument Calibration Systems

#### Stimulus

##### AC CALIBRATION SOURCE

HP 745A-H18/746A-H17 AC Calibrator  
Frequency Range: 10 Hz to 110 kHz  
Voltage Range: 1 mv to 110 V rms (745A) to 1100 V rms (746A)

##### AC SOURCE

HP 3320B 13 MHz Synthesizer  
Frequency Range: .001 Hz to 13 MHz  
Output Level: -73 dBm to +26.99 dBm (5 V rms into 50  $\Omega$ )

##### RF SOURCE

HP 8660A/86602A 1300 MHz Synthesizer  
Frequency Range: 1 MHz to 1300 MHz  
Output Level: -146 dBm to 13 dBm (1.0 V rms into 50  $\Omega$ )

##### DC CALIBRATION SOURCE

Fluke 3330 B DC Calibrator  
Voltage Range: 0 to  $\pm 1100$  Vdc  
Current Range: 0 to  $\pm 110$  mA

##### PULSE SOURCE

HP 8004A Pulse Generator (Manual Operation, Rate Programmed)  
Repetition Rate: 100 Hz to 10 MHz  
Transition Times: < 1.5 ns  
Pulse Amplitude:  $\pm 0.05$  V to  $\pm 5$  V peak (into 50  $\Omega$ )  
Pulse Width: 0 to 1 ms

##### SQUARE WAVE SOURCE

HP 211B Square Wave Generator  
Frequency Range: 1 Hz to 10 MHz  
Output Voltage: 0 to 5 V, 50  $\Omega$   
0 to 60 V, Open Circuit

##### HIGH CURRENT SOURCE

HP 6263B High Current Source  
Current Range: 0 to 5 A  
Voltage Range: 0 to 5 V

##### AC LINE POWER SOURCE

GR 1592 AC Line Regulator  
Output Voltage: 102, 115, 125 V rms  
Output Current: 0 to 10 A  
Input Voltage: 100 to 130 V rms

##### RESISTANCE SOURCE (Programmable)

Fixed Values: 1  $\Omega$ , 10  $\Omega$ , 100  $\Omega$ , 1 k $\Omega$ ,  
10 k $\Omega$ , 100 k $\Omega$ , 1 M $\Omega$

#### Measurement

##### DC VOLTAGE

HP 3480B/3484A Multifunction DVM  
Voltage Range: 100 mV to 1000 V, F.S.

##### AC VOLTAGE

HP 3480B/3484A Multifunction DVM  
Frequency Range: 1 Hz to 10 MHz  
Voltage Range: 100 mV to 1000 V, F.S.

##### RESISTANCE

HP 3480B/3484A Multifunction DVM  
Ohms Range: 100  $\Omega$  to 10 M $\Omega$ , F.S.

##### WAVEFORM

HP 180D/1801A/1820A 50 MHz Dual-Channel Oscilloscope  
(Manual Operation)

##### HIGH RESOLUTION DC VOLTAGE

HP 3450A Digital Voltmeter  
Voltage Range: 100 mV to 1000 V, F.S.

##### FREQUENCY

HP 5327B Timer/Counter  
Frequency Range: 0 to 550 MHz  
Period Range: 0 to 10 MHz, 1 to 10<sup>8</sup> periods  
Time Interval: 0.1  $\mu$ s to 10<sup>8</sup> sec

##### DISTORTION

HP 334A-H15 Distortion Analyzer  
Fundamental Range: 50 Hz to 100 kHz  
Distortion Range: 0.1 to 100%

##### RF POWER

HP 432C/478A Power Meter  
Frequency Range: 1 MHz to 3 GHz (18 GHz optional)  
Power Range: 10  $\mu$ W to 10 mW, F.S. (beyond 10 mW with  
calibrated attenuators)

##### HIGH VOLTAGE AND SWITCHING

HP 09551-60002 Signal Switching Interface and  
High Voltage Safety Interlock Panel

#### Computer and Peripherals

HP 2100 A Computer, 16K Core Memory  
HP 2752A Teleprinter  
HP 2748A Photo Reader  
HP 9403A System Control Panel  
HP 7900A Dual Disc Memory (one disc pack replaceable)  
HP 2600A Keyboard/Display  
HP 9404A Control Unit  
HP 2155A Input/Output Extender  
HP 12539B Time Base Clock

#### Options

HP 2895A Medium Speed Punch  
HP 2767A Line Printer  
HP 2754B Heavy Duty Teleprinter  
HP 11163A Worktable

#### General

**SIZE:** 3-bay or 4-bay Cabinet  
64.25 inches (1632 mm), overall height  
**POWER:** 3-Phase, 20 A per phase  
**PRICE IN USA:** \$125,000 to \$175,000 depending upon capability  
and options.

**MANUFACTURING DIVISION:** AUTOMATIC MEASUREMENT DIVISION  
974 East Arques Avenue  
Sunnyvale, California 94086

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