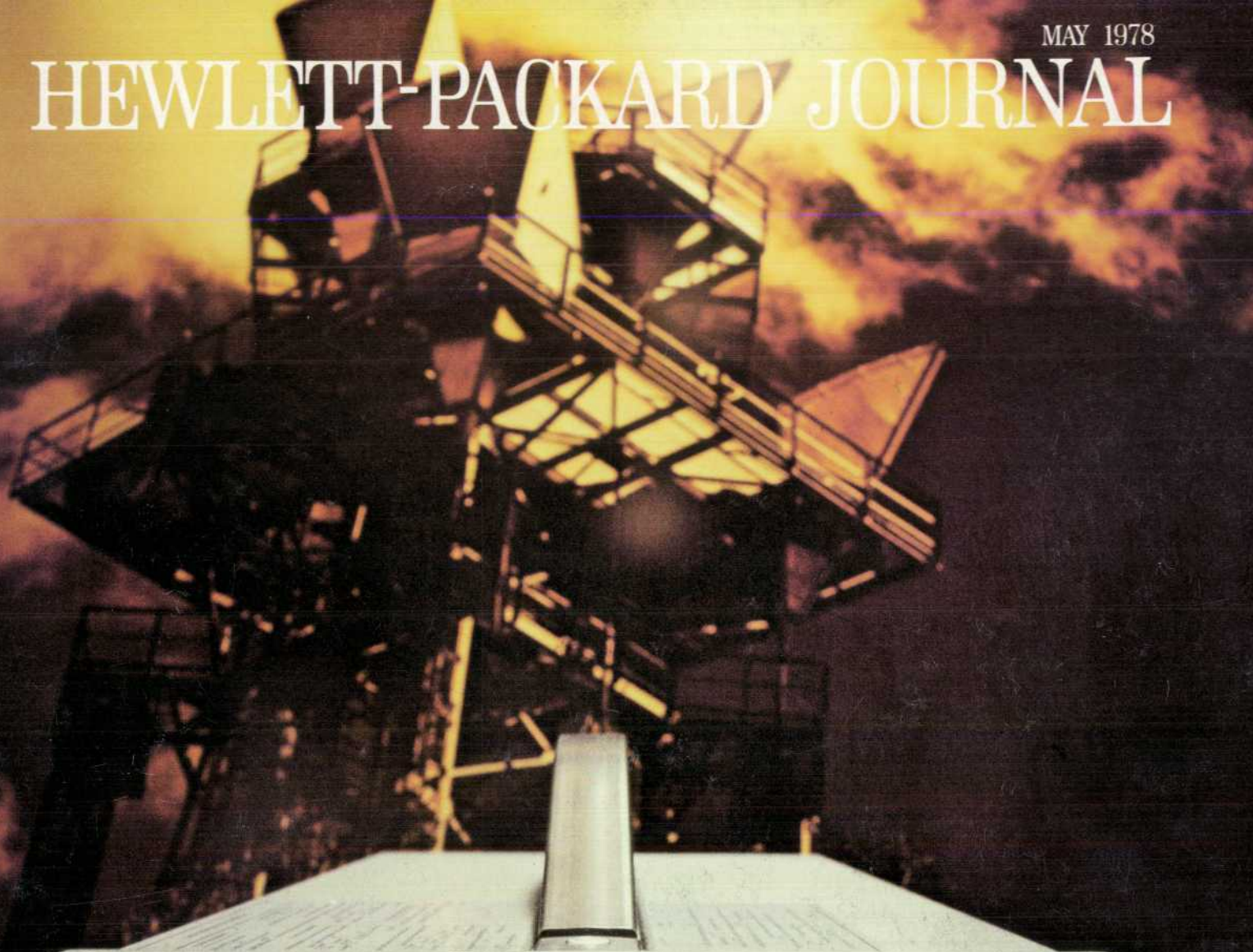


HEWLETT-PACKARD JOURNAL



5342A MICROWAVE FREQUENCY COUNTER
HEWLETT · PACKARD

17 952 000 000

— GHz — — MHz — — KHz — — Hz — *

FREQ
 AUTO MAN (MHz)

RESET SET RECALL

AMPL OFS dB OFS MHz

CHS

STBY LINE ON

RESOLUTION
 10KHz 100KHz 1MHz
 10Hz 100Hz 1KHz
 1Hz

CHECK

7 8 9
 4 5 6
 1 2 3
 0 . ENTER

SAMPLE RATE

GATE REMOTE

HOLD

50Ω 1MΩ 10Hz - 500MHz 500MHz - 18GHz

DL 3.5V MAX FUSED DL 1

Microprocessor-Controlled Harmonic Heterodyne Microwave Counter also Measures Amplitudes

The new harmonic heterodyne frequency measuring technique provides wide FM tolerance, high sensitivity, and automatic amplitude discrimination. Simultaneous measurement of input amplitude is optional.

by Ali Bologlu and Vernon A. Barber

AUTOMATIC MICROWAVE FREQUENCY measurements to 18 GHz and beyond have generally been done using one of two frequency down-conversion techniques, the transfer oscillator or the heterodyne converter (see box, page 5). In a new microwave counter, Model 5342A (Fig. 1), a new down-conversion technique, called harmonic heterodyne conversion, provides many of the advantages of both traditional methods while significantly reducing cost. Among these advantages are wide FM tolerance, high input sensitivity, and automatic amplitude discrimination.

The new technique requires only one microwave component, a sampler, and relies on a microprocessor to perform the required computations, thereby eliminating a good deal of digital hardware and its associated expense. The microprocessor also adds to the counter's power and versatility by making it possible to manipulate the measured data. An easy-to-use keyboard permits the operator to define frequency offsets or measure frequency deviations. An amplitude measurement option provides simultaneous measurements of input signal level and input frequency for the first time in a microwave counter.

Model 5342A measures frequency from 10 Hz to 18 GHz with a resolution of 1 Hz. It has an 11-digit display. With the amplitude measurement option, the user can see input level displayed in dBm with 0.1-dB resolution and ± 1.5 -dB accuracy, and frequency can be displayed simultaneously with 1-MHz resolution.

Harmonic Heterodyne Conversion

Fig. 2 is a simplified block diagram of the harmonic heterodyne technique. All of the harmonics of an internal oscillator are simultaneously mixed with the unknown signal by the sampler. The output of the sampler consists of sum and difference frequencies produced by each harmonic of the internal oscillator mixing with the unknown. The internal oscillator, a

programmable frequency synthesizer locked to the counter's time base, is incremented in frequency until one of the outputs of the sampler is in the counting range of the low-frequency counter. The IF detector detects when the IF (intermediate frequency) is in the range of the low-frequency counter and sends a signal that causes the synthesizer control to stop incrementing the frequency of the synthesizer. The IF is then counted by the low-frequency counter. The unknown frequency can be determined from the relation:

$$f_x = Nf_1 \pm f_{IF1}$$



Cover: An easy-to-use keyboard puts the microprocessor-based Model 5342A Microwave Frequency Counter through its paces. This new counter measures frequencies and (optionally) amplitudes, with or without offsets, up to 18 GHz, and has extensive built-in self-test facilities.

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Swept-Frequency Measurements of High Levels of Attenuation at Microwave Frequencies



Fig. 1. Model 5342A Microwave Frequency Counter measures frequencies from 10 Hz to 18 GHz. With its amplitude measurement option, it can simultaneously measure and display frequency and amplitude. Keyboard control and microprocessor architecture provide ease of operation and data manipulation features.

- where f_x = unknown frequency
 N = harmonic of frequency synthesizer
 f_1 = programmed frequency of synthesizer
 f_{IF1} = IF produced by Nf_1 mixing with f_x .

The frequency f_1 of the programmable synthesizer is known, since it is known where the indexing of the

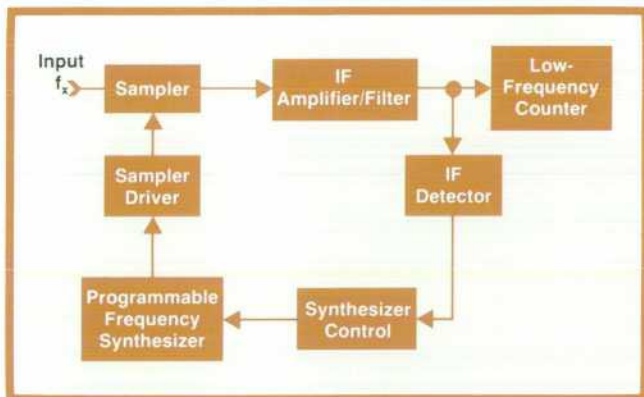


Fig. 2. Simplified block diagram of the harmonic heterodyne frequency conversion technique used in the 5342A Counter. All harmonics of a frequency synthesizer are simultaneously mixed with the unknown in a sampler. The synthesizer frequency is incremented until one of the sampler outputs is in the range of the low-frequency counter. The system measures this output, determines which synthesizer harmonic produced it, and adds the measured value to the known harmonic frequency. A microprocessor controls the synthesizer and does the computations.

synthesizer was stopped. f_{IF1} is known, since it is counted by the low-frequency counter. Still to be determined are N and the sign (\pm) of the IF. This is done by making one more IF measurement with the synthesizer frequency offset from its previous value by a known amount Δf . Thus $f_2 = f_1 - \Delta f$. This produces an IF, f_{IF2} , that is counted by the low-frequency counter. The offset Δf is much smaller than the IF, so if f_x is less than Nf_1 , then f_{IF1} produced by mixing Nf_1 with f_x will be greater than f_{IF2} . Conversely, if f_x is greater than Nf_1 then f_{IF1} will be less than f_{IF2} . This is shown in Fig. 3. N is then determined as follows:

$$f_{IF1} = Nf_1 - f_x \quad (Nf_1 > f_x)$$

$$f_{IF2} = Nf_2 - f_x \quad (Nf_2 > f_x)$$

$$N = \frac{f_{IF1} - f_{IF2}}{f_1 - f_2}$$

or, if f_x is greater than Nf_1 ,

$$f_{IF1} = f_x - Nf_1 \quad (Nf_1 < f_x)$$

$$f_{IF2} = f_x - Nf_2 \quad (Nf_2 < f_x)$$

$$N = \frac{f_{IF2} - f_{IF1}}{f_1 - f_2}$$

The unknown frequency is then computed as follows:

$$f_x = Nf_1 - f_{IF1} \quad (f_{IF2} < f_{IF1})$$

$$f_x = Nf_1 + f_{IF1} \quad (f_{IF2} \geq f_{IF1})$$

Since the frequency of the synthesizer is known to the accuracy of the counter's time base and the IF is measured to the accuracy of the counter's time base the accuracy of the microwave measurement is determined by the time base error and the ± 1 -count error inherent in any counter.

Automatic Amplitude Discrimination

The bandwidth and gain characteristics of the IF provide automatic amplitude discrimination. This means that the counter will measure the frequency of the highest-level signal in the presence of a multitude of signals at different frequencies, provided that the desired signal is larger than any other by a certain minimum number of dB. The specified minimum separation for the 5342A is 6 dB for signals within 500 MHz of the desired signal and 20 dB for signals farther away. Typical values are lower.

FM Considerations

The discussion up to now has dealt with the ideal case in which the counter is measuring input signals with little or no FM. However, many signals in the microwave region, particularly those from microwave radios, have significant modulation on them. To prevent this modulation from causing incorrect computation of the harmonic number N , the harmonic heterodyne technique is implemented as shown in Fig. 4. There are two synthesizers offset by precisely 500 kHz, two counters, and a pseudorandom sequence generator that controls a multiplexer and the two counters synchronously.

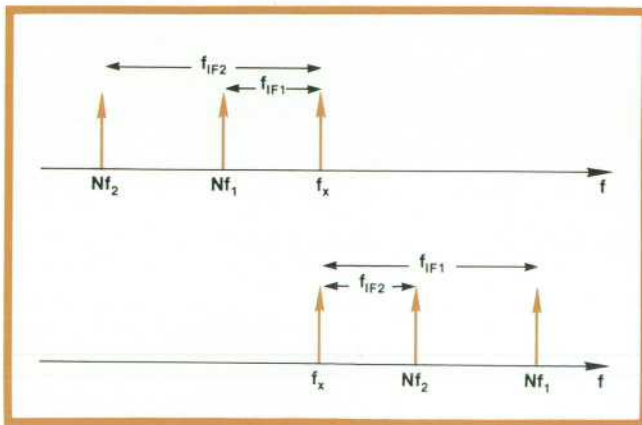


Fig. 3. To determine the number, N , of the synthesizer harmonic that produced the sampler output at intermediate frequency f_{IF1} , the counter makes a second measurement with the synthesizer frequency f_1 changed to $f_2 = f_1 - \Delta f$, where $\Delta f \ll f_{IF1}$. If $f_x < Nf_1$ then $f_{IF2} < f_{IF1}$, and if $f_x > Nf_1$ then $f_{IF2} > f_{IF1}$, as shown here. Then $N = |f_{IF1} - f_{IF2}| \div \Delta f$.

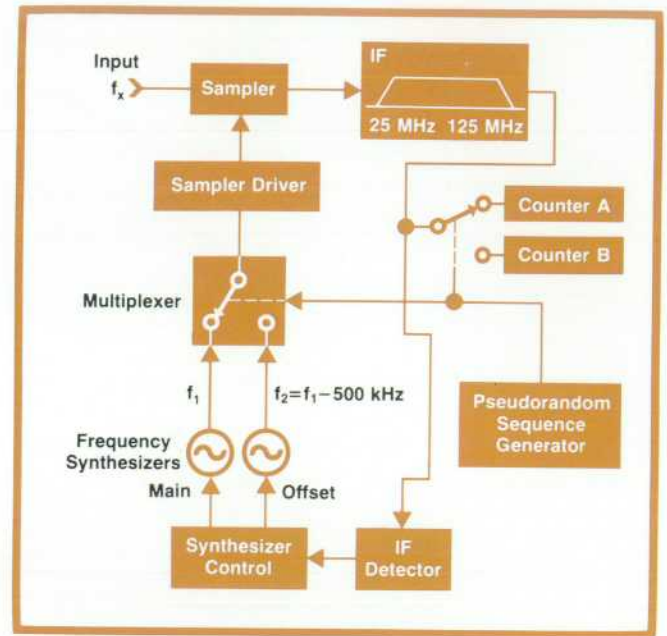


Fig. 4. The harmonic heterodyne technique is implemented in the 5342A Counter with two synthesizers and two counters, as shown here, to prevent frequency modulation on the unknown signal from causing an incorrect computation of the harmonic number N . A pseudorandom sequence generator switches between the two synthesizers and the two counters. Pseudorandom switching avoids any coherence between the switching rate and the modulation rate of the FM on the unknown.

The operating algorithm is as follows. With the multiplexer having selected the main oscillator output, the main oscillator frequency f_1 is swept from 350 MHz to 300 MHz in 100-kHz steps. The offset oscillator frequency f_2 is maintained at $f_1 - 500$ kHz by a phase-locked loop. When the IF detector indicates the presence of an IF signal in the range of 50 MHz to 100 MHz, the synthesizer stops its sweep and the counter starts the harmonic number (N) determination. The pseudorandom sequence output switches between the main oscillator and the offset oscillator and between counter A and counter B so that counter A accumulates f_{IF1} (produced by Nf_1 mixing with f_x) and counter B accumulates f_{IF2} (produced by Nf_2 mixing with f_x). The pseudorandom switching prevents any coherence between the switching rate of the multiplexer and the modulation rate of the FM that might produce an incorrect computation of N . N and the sign of the IF are computed as previously described, since counter A accumulates f_{IF1} , and counter B accumulates f_{IF2} . The pseudorandom sequence is then disabled, the main oscillator is selected, and the frequency of f_{IF1} is measured in counter A to the selected resolution.

The counter's FM tolerance is related to the length of the pseudorandom sequence. As shown in the box on page 13, the maximum error in the determina-

Down-Conversion Techniques for Microwave Frequency Measurements

A frequency counter is limited in its direct-counting frequency range by the speed of its logic circuitry. Today the state of the art in high-speed logic allows the construction of counters with a frequency range of around 500 MHz. Continuing advances in IC technology should extend this range beyond 1 GHz in the not-too-distant future.

The designer of an automatic microwave counter must look to some form of down-conversion to extend frequency measurement beyond 500 MHz. Four techniques are available today to provide this down-conversion:¹

- Prescaling, or simply dividing the input frequency, with a range of only about 1.5 GHz;
- Heterodyne converter, allowing measurements as high as 20 GHz;
- Transfer oscillator, used in counters with ranges to 23 GHz;
- Harmonic heterodyne converter, a new technique that can provide measurements to 40 GHz, and is used in the new Model 5342A Microwave Frequency Counter to measure up to 18 GHz.

Heterodyne Converter

In a heterodyne converter, the incoming microwave signal is mixed with a high-stability local oscillator signal of known frequency, resulting in a difference frequency within the range of a conventional counter (see Fig. 1). The high-stability local oscillator signal is generated by first digitally multiplying the frequency of the instrument's time base to a convenient fundamental frequency, f_{in} , typically 100 to 500 MHz. This f_{in} is directed to a harmonic generator that produces a comb line of frequencies spaced at f_{in} extending to the full frequency range of the counter. One line of this comb, Kf_{in} , is then selected by a microwave filter and directed to the mixer. Emerging from the mixer is an intermediate frequency equal to $f_x - Kf_{in}$. This frequency is amplified and sent to the counter. The display contains the sum of the intermediate frequency and Kf_{in} .

In practice, the system begins with $K=1$ and steps the microwave filter through the comb line until a detector indicates that an intermediate frequency in the proper range is present. The microwave filter may be a YIG filter or an array of thin-film filters that are selected by PIN diode switches.

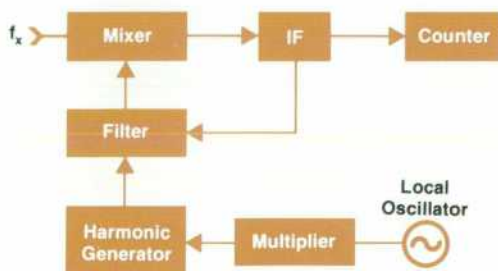


Fig. 1. Heterodyne converter.

Transfer Oscillator

The transfer oscillator (Fig. 2) uses the technique of phase locking a low-frequency voltage-controlled oscillator (VCO) to the microwave input signal. The VCO frequency f_1 can then be measured in a conventional counter, and all that remains is to determine the harmonic relationship between that frequency and the input. A second VCO is often used to help determine the

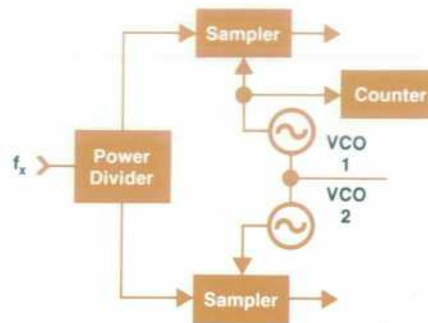


Fig. 2. Transfer oscillator.

harmonic member N . The counter then measures f_1 , multiplies by N (usually by extending its gate time) and displays the result.

Harmonic Heterodyne Converter

The harmonic heterodyne converter, as its name implies, is a hybrid of the previous two techniques. Fig. 2 on page 3 is a simplified diagram of a counter that uses harmonic heterodyne conversion. The input f_x is directed to a sampler, with the resulting down-converted video signal $f_{IF} = f_x - Nf_1$ amplified and sent to the counter. The sampling frequency f_1 is created by a processor-controlled synthesizer.

The acquisition routine for this down-converter consists of tuning the synthesizer frequency f_1 until the signal detector finds a video signal f_{IF} of the appropriate frequency range (defined by the bandpass filter). Next, the harmonic number N must be determined, as in the transfer oscillator. One method of finding N is to use a second sampler loop or similar technique. A second method is to step the synthesizer back and forth between two closely-spaced frequencies and observe the differences in counter readings; it is then a simple task for the processor to calculate N .

A frequency measurement is accomplished by the processor's multiplying the known synthesizer frequency f_1 by N , adding the result to the frequency f_{IF} measured by the counter, and displaying the answer: $f_x = Nf_1 + f_{IF}$.

The harmonic heterodyne converter has the potential to be constructed at a lower cost than the previous two techniques because it can be designed with just one microwave component, the sampler, and the control, decisions, and calculations can be performed by a low-cost microprocessor.

Comparison

The table below compares the three major down-conversion techniques.

Characteristic	Heterodyne Converter	Transfer Oscillator	Harmonic Heterodyne Converter
Frequency Range	20 GHz	23 GHz	40 GHz
Measurement Speed	150 ms Acquisition 1/R Gate	150 ms Acquisition N/R Gate	350 ms Acquisition 1/R Gate
Accuracy	Time-Base Limited	Time-Base Limited	Time-Base Limited
Sensitivity/ Dynamic Range	-30 dBm/35-50 dB	-35 dBm/40 dB	-30 dBm/35-50 dB
Signal-to-Noise Ratio	40 dB	20 dB	20 dB
FM Tolerance	30-40 MHz peak-peak	1-10 MHz peak-peak	10-50 MHz peak-peak
AM Tolerance	Less than 50%	Greater than 90%	Greater than 90%
Amplitude Discrimination	4-30 dB	2-10 dB	2-10 dB

Reference

1. "Fundamentals of Microwave Frequency Counters," HP Application Note 200-1.

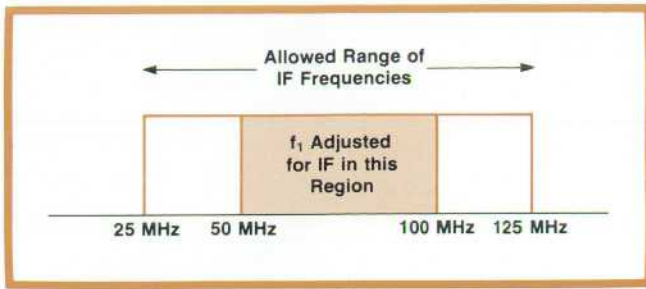


Fig. 5. 5342A Counter's FM tolerance is determined by the IF bandwidth, which is 25 to 125 MHz. The IF detector stops the sweep when the IF is between 50 and 100 MHz. Thus the allowable FM is 50 MHz peak to peak.

tion of the harmonic number N is

$$\epsilon_{\max} < \frac{\Delta f_x}{\sqrt{P\Delta f}}$$

where P is the length of the pseudorandom sequence in clock periods, Δf_x is the peak frequency deviation of the unknown, and Δf is the frequency offset between the two synthesizers. For example, if $P = 2^{15} - 1$, $\Delta f_x = 5$ MHz, and $\Delta f = 500$ kHz, $\epsilon_{\max} < 0.2209$. As long as $\epsilon_{\max} < 0.5$, N is correctly determined.

The length of the pseudorandom sequence also affects the counter's measurement time, which con-

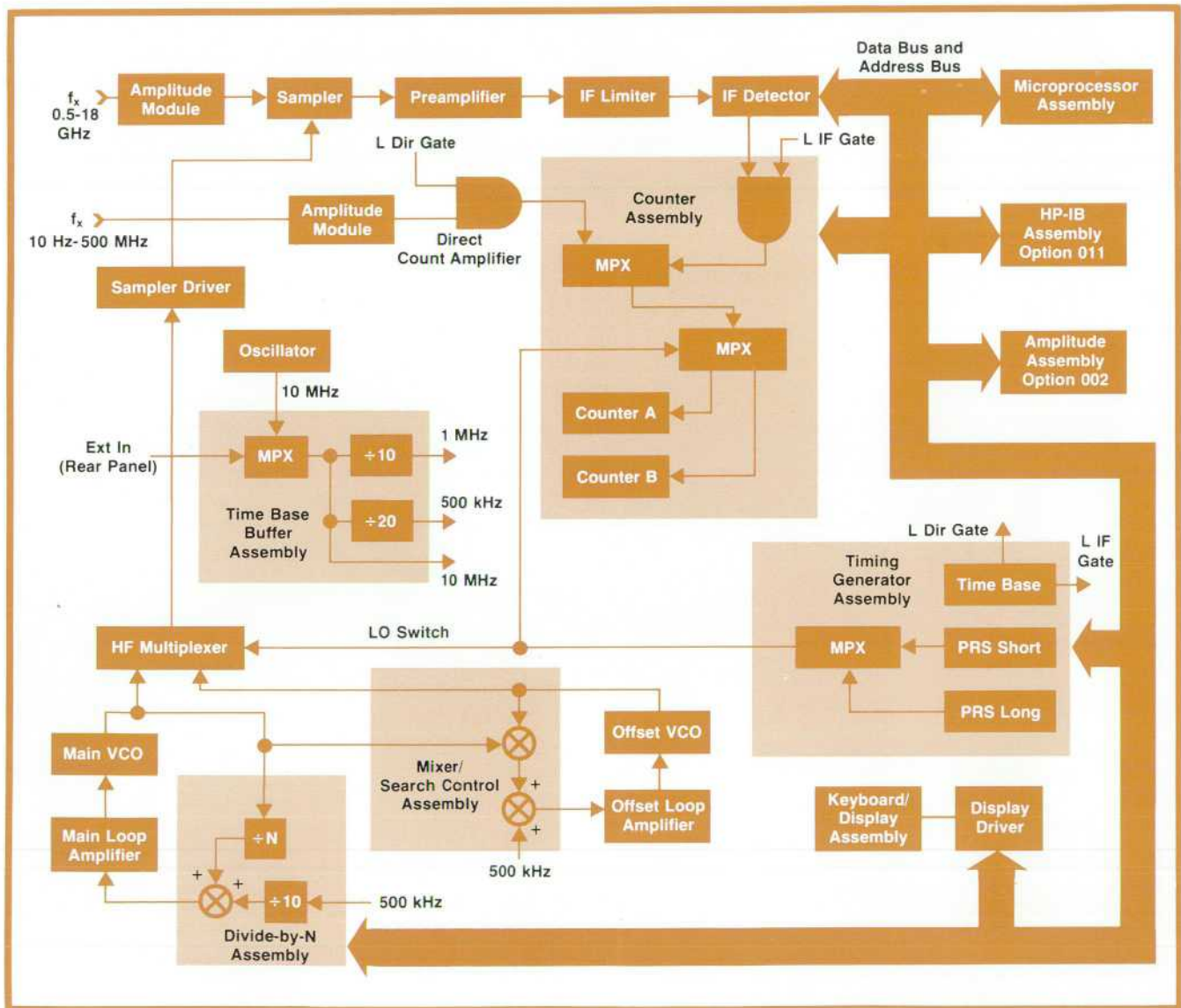


Fig. 6. 5342A block diagram. Only one microwave component, the sampler, is needed. This helps reduce cost.

sists of three components: sweep time, N determination time, and gate time. The sweep time is 150 milliseconds or less and the gate time for 1-Hz resolution is one second. In normal operation the pseudorandom sequence length is 360 milliseconds, so the total measurement time is about 1½ seconds. Under these conditions the counter can tolerate 20 MHz peak-to-peak frequency deviation on the unknown. This corresponds to the bandwidth of most telecommunications channels.

The counter's maximum FM tolerance is determined by the bandwidth of the IF amplifier. As Fig. 5 shows, the allowable range of intermediate frequencies is 25 to 125 MHz. The IF detector is adjusted to stop the sweep when the IF is in the range 50 to 100 MHz. Therefore, a maximum of 50 MHz peak-to-peak frequency deviation on the unknown can be tolerated. A switch on the rear panel of the 5342A selects either the 20-MHz or the 50-MHz FM mode. In the wide FM mode the pseudorandom sequence length is 2096 milliseconds, so the acquisition time is significantly increased over the normal mode.

Counter Design

The overall 5342A block diagram is shown in Fig. 6. The product design not only decreases assembly costs but also yields significant RFI performance improvements. As can be seen in Fig. 7, the entire counter is built into one die casting. The boards that constitute the individual assemblies plug into one multilayer motherboard, thereby eliminating all

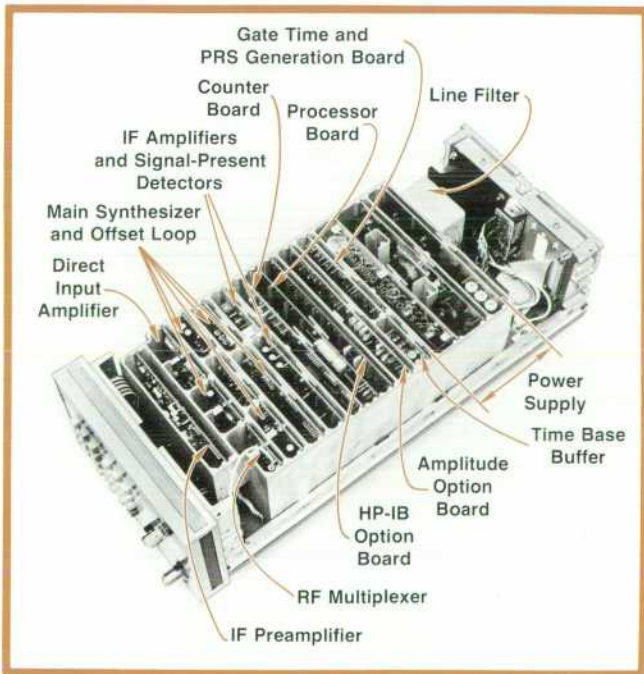


Fig. 7. Product design minimizes assembly costs and improves RFI performance. A single casting houses all assemblies, which plug into a single multilayer motherboard.

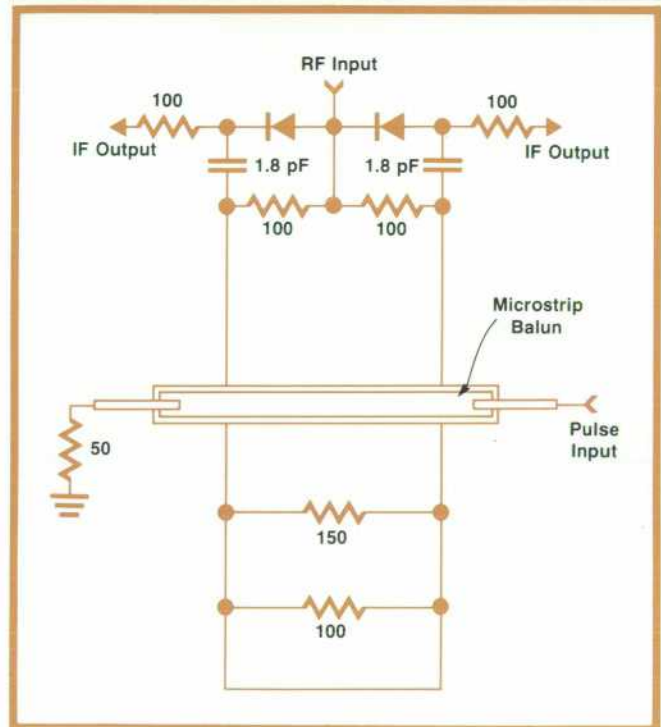
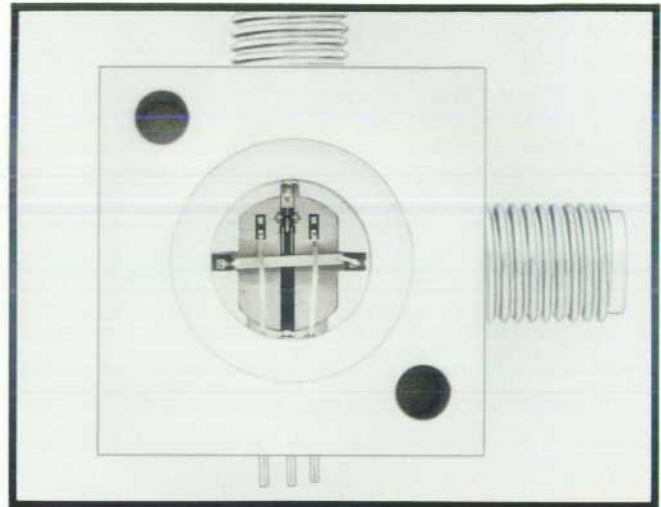


Fig. 8. Sampler is a thin-film hybrid circuit. The sampling pulse couples to the slotted line through a balun that generates two opposite-polarity pulses to drive the Schottky diodes.

wiring except for the rear-panel power connections.

The power supply is of the switching regulator type. The power supply boards are also inside the casting, but in a separate compartment, so the switching spikes are contained and are not permitted to interfere with the rest of the circuitry. On the front panel a fine metallic mesh covers the LED display and attenuates emissions from this area. These precautions have resulted in improved RFI performance with respect to past instruments.

The casting is also the main structural element of the instrument. The side rails of the box are attached to it, and the front and rear panel assemblies are

Signature Analysis in the 5342A

Incorporating microprocessor control into the 5342A Microwave Frequency Counter made it possible to develop a powerful measuring instrument at a substantial reduction in cost. Besides providing many operational benefits, such as keyboard entry of frequency and amplitude offsets, resolution selection, and offset recall, microprocessor control enhances the serviceability of the 5342A by providing powerful diagnostic routines, also selectable from the front-panel keyboard, that aid the service person in fault isolation and instrument verification (see Fig. 1). Other microprocessor routines, exercised every time the instrument is turned on, check the health of ROMs and RAM and display error codes if all is not well.

Despite the diagnostic aids provided by the microprocessor, placing a microcomputer inside a sophisticated measuring instrument also introduces some serviceability problems. After the first prototype was constructed, we discovered it was impossible to isolate certain failures to a particular assembly using traditional troubleshooting equipment and techniques.

Failures involving the microprocessor assembly and the individual assemblies that interface to the microprocessor assembly were extremely difficult to troubleshoot. Even after hours of troubleshooting, it was uncertain whether the fault was a control failure originating on the microprocessor assembly, an interface failure originating on an assembly's interface with the microprocessor, or a failure in some other part of the instrument, causing the measurement algorithm to hang up or branch to an incorrect program segment. We needed a quick way to verify proper operation of the microprocessor control assembly.

Fortunately, there was a solution which, even though the instrument had advanced to the prototype stage, was inexpensive to implement and permitted microprocessor verification and fault isolation to the component level. This technique, called signature analysis, relies on a relatively inexpensive troubleshooting instrument—the 5004A Signature Analyzer.¹

Signature Analysis

Signature analysis, as implemented in the 5004A Signature Analyzer, employs a data compression technique to reduce long, complex data streams at circuit nodes to four-digit hexadecimal signatures. By taking the signature of a suspected circuit node and comparing it to the correct signature, which is empirically determined and documented in the operating and service manual, proper circuit operation is quickly verified. By probing designated nodes, observing good and bad signatures, and then tracing back along the signal flow from outputs to inputs, the cause of an incorrect signature may be discovered and corrected.

In operation, four signals must be supplied to the signature analyzer. A START signal initiates the measurement window. During this time window, DATA from a circuit node is clocked into the signature analyzer. A CLOCK signal synchronizes the data. A STOP signal terminates the measurement window.

There are two ways to implement signature analysis and meet the requirements just mentioned in a microprocessor-based product: free running and software driven. In the free running method, the microprocessor is forced into an operating mode in which it cycles continuously through its entire address field. START/STOP signals are derived from the address bus lines. In software driven signature analysis, a stimulus program is stored in ROM. The stimulus program generates START/STOP signals and can also write repeatable DATA streams onto the data bus for testing other assemblies connected to the microprocessor. Free running signature analysis has the advantage of not requiring



Fig. 1. Nine diagnostic modes are available with the counter in AUTO mode. The SET key is pushed twice and is followed by the appropriate digit key.

SET, SET, 0: Indicates that the main synthesizer is sweeping (SP) and that the signal has been placed in the IF (23) and finally that the harmonic determination has been made (Hd). This display is shown in the photograph.

SET, SET, 1: Displays the main synthesizer frequency, the location of the harmonic comb line (e.g., if $-$, harmonic is below f_x so must add IF result), and the harmonic number N.

SET, SET, 2: Displays results of counter A accumulation during acquisition.

SET, SET, 3: Displays results of counter B accumulation during acquisition.

SET, SET, 4: Displays intermediate frequency being counted.

SET, SET, 5: If Option 002, amplitude measurement, is installed, a single corrected amplitude measurement is made and held.

SET, SET, 6: If Option 002, amplitude measurement is installed, a continuous measure of uncorrected amplitude is displayed.

SET, SET, 7: When the signal is removed from the microwave port, the main synthesizer sweeps over its full range in 100-kHz steps.

SET, SET, 8: This mode is a keyboard check.

any ROM space for storing the stimulus program. Software driven signature analysis has the advantage of being able to exercise a greater portion of the instrument's circuitry. For thorough testing, both techniques could be implemented in the same instrument.

In the 5342A, lack of ROM space ruled out the software driven implementation. To implement the free running approach in the 5342A, all that was required was the addition of some switches and pull-up resistors to the microprocessor assembly. Fig. 9 on page 9 shows a block diagram of the 5342A microprocessor assembly. The shaded area contains the components added to the assembly to implement free running signature analysis.

To check out the microprocessor assembly, the microprocessor is forced into a free run mode by opening the data bus switches S1 (this prevents data out of the ROMs from altering the forced free run instruction) and grounding the free

run switch S2. When S2 is grounded, a clear B instruction is presented to the microprocessor data input (clear B was chosen to minimize the number of diodes needed). This causes the B accumulator to be cleared and the address to be incremented by 1. Consequently, the address lines from the microprocessor repeatedly cycle over the entire address field of the microprocessor from 0000 to FFFF. By using the most significant address line as both START and STOP for the 5004A, and one phase of the microprocessor clock as the 5004A CLOCK input, repeatable, stable signatures are obtained for the microprocessor address lines, ROM outputs, device select outputs, and most circuit nodes on the microprocessor assembly. By check-

ing the assembly's outputs for correct signatures (documented in the manual), it is possible to verify with a high degree of confidence that the assembly is functioning properly. If a signature is incorrect, then signatures are checked back along the signal flow paths, from outputs to inputs. When a device is found where the output signature is bad but the input signatures are good; that device is replaced.

Reference

1. A.Y. Chan, "Easy-to-Use Signature Analyzer Accurately Troubleshoots Complex Logic Circuits," Hewlett-Packard Journal, May 1977.

-Martin Neil

bolted onto the side rails.

The only microwave component required to make the frequency measurements is the sampler, Fig. 8. This consists of a thin-film hybrid mounted in an aluminum package that is manufactured by a hobbing die. This technique is similar to coin minting and results in relatively low piece costs.

Operation of the sampler is similar to that of

samplers used in previous HP microwave counters.¹ On the hybrid are two Schottky diodes placed across a slotted line. The sampling pulse couples to the slotted line through a stripline balun that generates two opposite-polarity pulses to drive the diodes. The down-converted signal is taken from two isolated resistors to the preamplifier. Resistors across the slot are used to absorb secondary reflections introduced

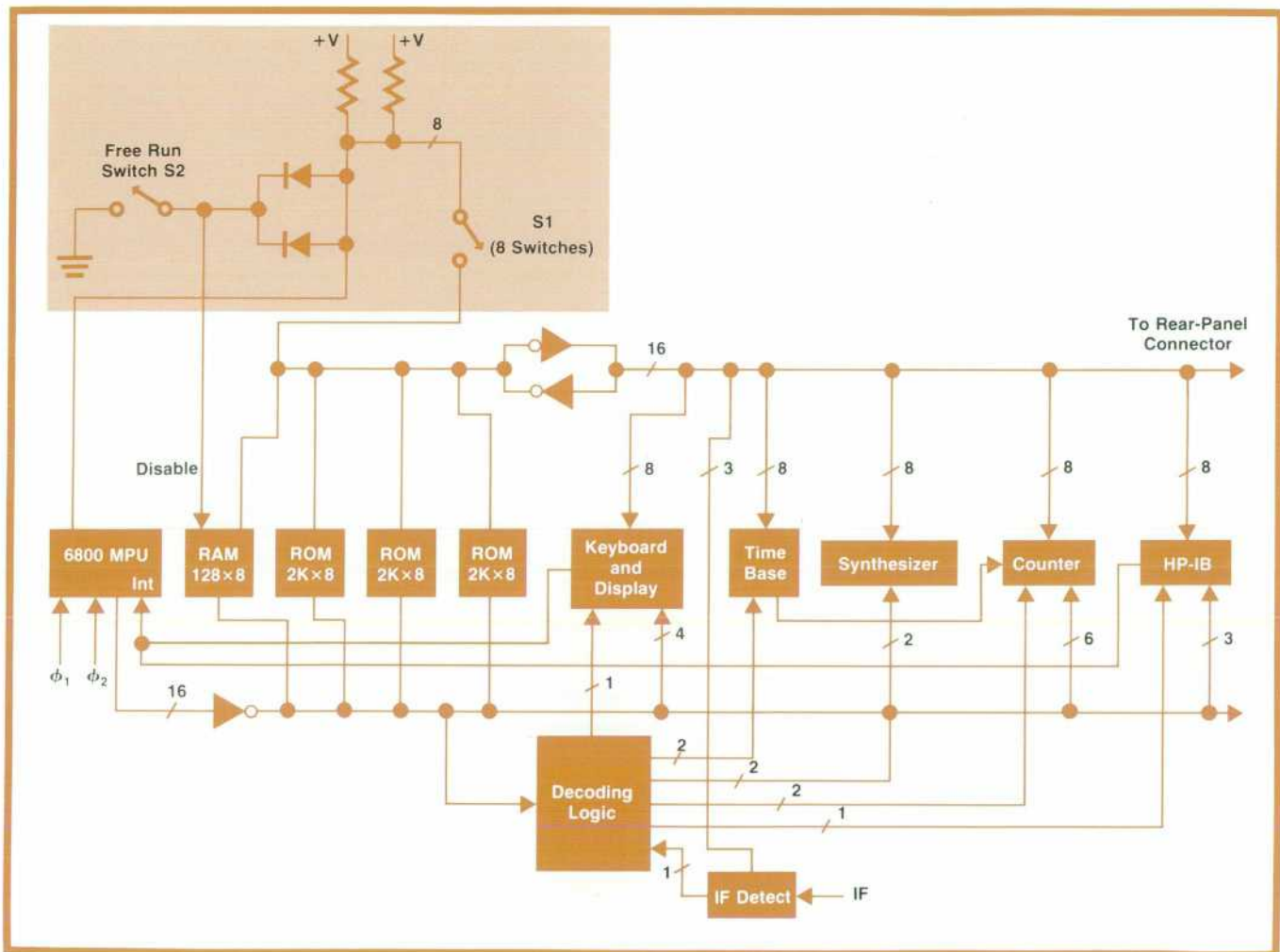


Fig. 9. 5342A microprocessor assembly. Components in the shaded area were added for troubleshooting by signature analysis. Only a few switches and pull-up resistors were required.

by the sampling pulse.

Microprocessor Architecture

Measurement, control, and system coordination of the 5342A are implemented by a 6800 microprocessor. The microprocessing unit (MPU) handles interfacing to the analog circuits, the power-up routine, display control, keyboard manipulation and control, frequency and amplitude measurements, arithmetic calculations, and diagnostics (Figs. 9, 10, 11). The MPU consists of one 6800 chip, 128 bytes of RAM (random-access memory), and three 2K-byte ROMs (read-only memories) that store the MPU programs. Decoder/drivers for peripheral circuit interfaces and diagnostic switches to facilitate signature analysis for trouble shooting are also located on the processor board. A ribbon cable transports the address, data,

and necessary control lines to the rear panel for interfacing to external devices. During the power-on cycle, the 6800 first does a RAM exercise by doing a READ/WRITE for each memory location using four different patterns. In hexadecimal code the four patterns are FF, 00, AA, and 55. Should a particular location not pass, the front-panel display shows all "E"s. After the RAM test the 6800 goes through a ROM checksum routine. A defective ROM results in a display of 1, 2, or 3 on the front panel, indicating the failed ROM. Successful completion of the above steps causes the instrument to light up all display segments and front-panel LEDs, giving the user a visual check. The instrument then comes on in the auto mode, with 1-Hz resolution and the HP-IB interface cleared.

Keyboard input is connected to the MPU interrupt line. When a key is pushed the MPU consults a key table, branches to the proper key sequence routine, and displays a prompt. If the sequence is not completed, some of the key lights will be kept blinking, indicating that the routine is waiting for more key depressions to complete the sequence. If an unexpected key is pushed it may be ignored or an error indication may be displayed, depending on the situa-

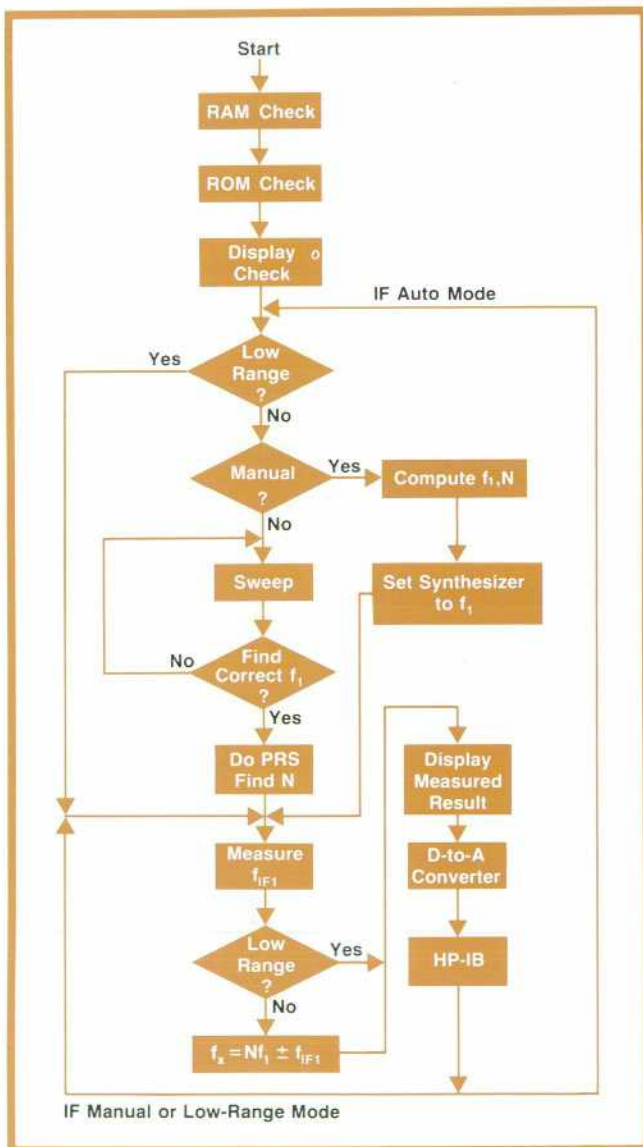


Fig. 10. Simplified 5342A system flow chart.

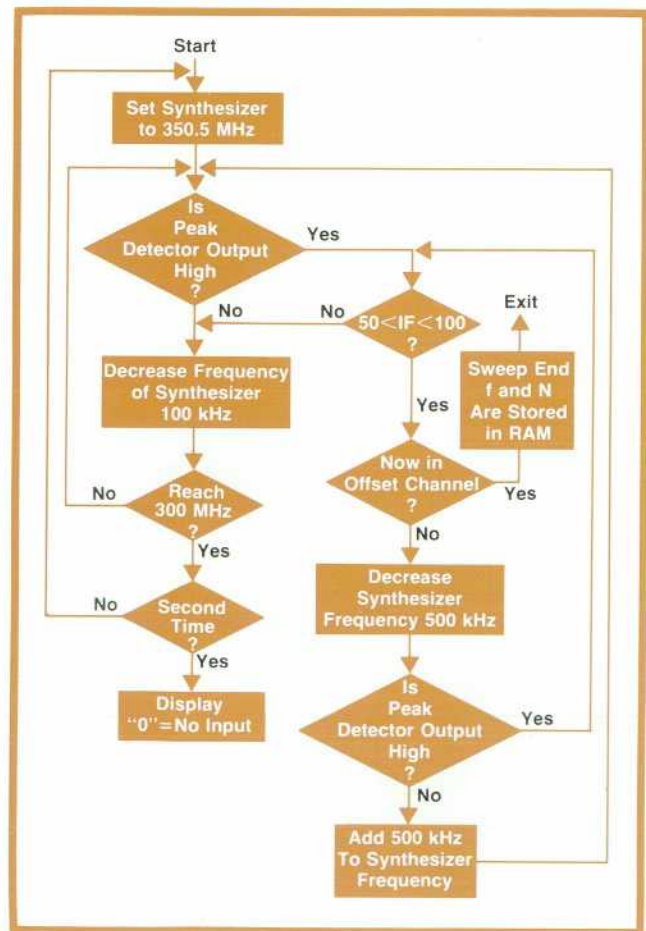


Fig. 11. 5342A sweep flow chart.

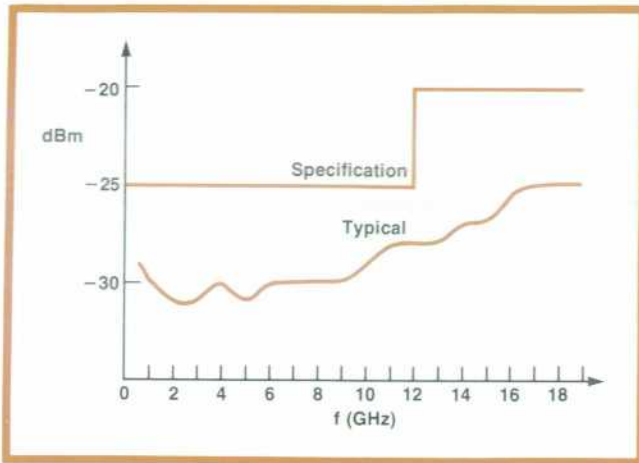


Fig. 12. Specified and typical 5342A input sensitivity.

tion. Software diagnostic routines are built in as a service aid, enabling the user to diagnose problems to the subassembly level. Digital board troubleshooting can be done to the component level using signature analysis (see page 8).

Front-Panel Inputs and Controls

The 5342A has two inputs, one going from 10 Hz to 520 MHz, and the other from 500 MHz to 18 GHz. Sensitivity of the microwave input is shown in Fig. 12. The right-hand side of the front panel deals with input signal channel selection and sample rate control of the measurement. The left-hand side of the front panel enables the user to do data manipulation by keyboard control of the processor. Instructions on how to do this are on a label (Fig. 13) that is affixed to the instrument top.

The panel layout is in algebraic notation. Panel operation closely resembles remote programming via the HP interface bus (HP-IB). When the machine powers up it is in the auto mode with 1-Hz resolution. As the user selects other resolutions, insignificant zeros are truncated. Display digits are in groups of three to facilitate reading.

In case the user wants to bypass the acquisition cycle of the algorithm, a manual mode of operation is available. In this mode, the user should know the unknown frequency within 50 MHz and enter it via the keyboard. The counter then acts like a receiver making frequency measurements.

Offsets can be specified from the front panel. Any frequency offset can either be subtracted from or added to the measured frequency. In the auto offset mode of operation the counter holds the initial measurement and then displays all succeeding measurements as deviations about the initial reading.

Amplitude Measurements

Equipped with the amplitude measurement option,

the 5342A is alone among microwave counters in its ability to make simultaneous amplitude and frequency measurements. Incoming signal amplitude is measured to 0.1-dB resolution with a specified accuracy of ± 1.5 dB. Amplitude offsets can be entered from the front panel in the same way as frequency offsets.

The most fundamental decision involved in designing an amplitude measuring system was what element to use to sense amplitude. Ideally, we wanted a system that is RMS-responding from -30 to $+20$ dBm, makes measurements rapidly, has stable calibration, is burnout resistant, and has low input SWR. One choice might have been to use the counter's sampler and measure its output level. Unfortunately, this IF level is also a function of the input frequency, of the intermediate frequency, and of the sampler drive pulse amplitude and frequency, and begins to saturate at about -10 dBm. Some sort of switchable attenuator ahead of the sampler to increase dynamic range would have resulted in an input SWR greater than three at low levels. Among other alternatives, thermistors are subject to drift and easy burnout, and while thermocouples do not suffer these problems, their sensitivity is low, necessitating a narrow video bandwidth and consequent slow response at low levels. Point-contact diodes are sensitive, wideband, and have the low origin resistance necessary for driving an operational amplifier without biasing, but they are not very rugged, mechanically and electrically, nor are they stable over long periods. Planar Schottky diodes have recently been built, however, with low barrier height, so they are usable without bias. These

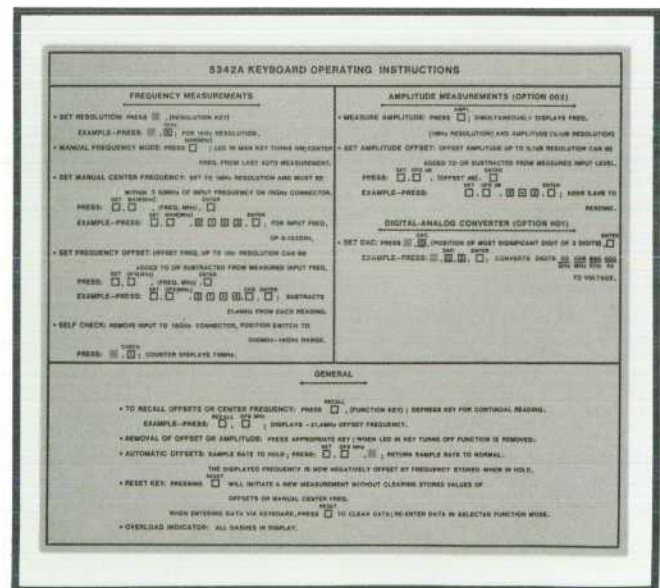


Fig. 13. Instructions for using the front-panel keyboard are attached to each instrument. Frequency and amplitude offsets are easily specified.

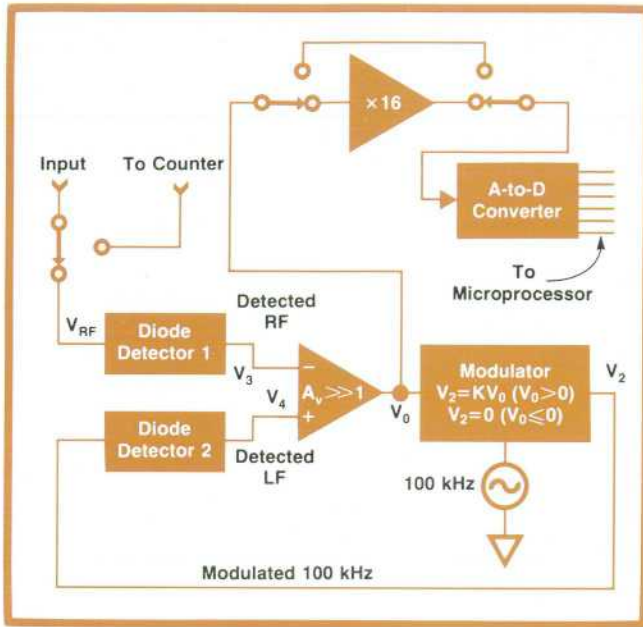


Fig. 14. Planar Schottky diode detectors are used in the optional amplitude measurement system. Two detectors are used to compensate for temperature variations. The dc output voltage V_0 is proportional to the RF sine wave voltage as long as the detectors are matched, and is independent of temperature as long as the detectors are at the same temperature.

devices are like point-contact diodes, but have the stability and ruggedness of ordinary Schottky diodes. These diodes are now in use in several HP applications.^{2,3} They meet all of our requirements except that they are not RMS-responding at levels above about -20 dBm. Thus we actually measure voltage but make the instrument read out in units of power, and it is accurate as long as the signal does not contain much amplitude modulation.

The diode output voltage is a function of temperature and must be compensated. The circuit that does this (see Fig. 14) also provides another advantage. For A_v sufficiently large, $V_3 = V_4$. Since the detector outputs are equal, their inputs must be equal if the detec-

tors are identical and their outputs are independent of frequency. Therefore

$$V_{RF} = V_2 = KV_0$$

Thus V_0 , the dc output voltage, is proportional to the RF sine wave voltage regardless of the transfer function of the detectors, as long as the detectors are matched. The output is also independent of temperature if the diodes are at the same temperature.

The detector output voltage at -30 dBm input is about 0.5 mV, so the dc characteristics of the differential amplifier are very important. The amplifier is a hybrid, laser-trimmed for low offset voltage and drift. The low origin resistance of the detector diodes allows the amplifier bias current to be drawn through the reverse direction of the diodes without introducing appreciable offset.

To display amplitude in dBm, we need the logarithm of V . The availability of monolithic integrating converters of 13-bit accuracy allows this function to be performed by the instrument's microprocessor instead of the usual logarithmic amplifier. The dynamic range is further increased by a switchable dc amplifier ahead of the analog-to-digital converter. This combination allows better than 0.03 -dB resolution at all levels and avoids the drift problems of a log amplifier. Once the processor has logged and scaled the result it uses the frequency information obtained in a previous measurement to correct the result according to a calibration table stored in memory (more about this later).

Thin-Film Hybrid

All of the microwave components are contained in a thin-film assembly (Figs. 15 and 16). The dc blocking capacitors and all resistors are integrated on two sapphire substrates, one for the microwave detector, CR3, and the other for the low-frequency detector, CR4. CR1 and CR2 are PIN diodes used to route the input signal either to the counter or to the detector.

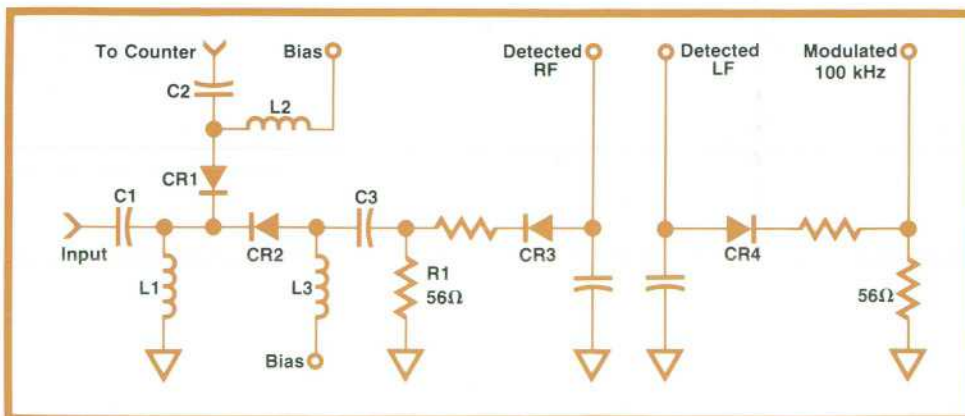


Fig. 15. All of the microwave components of the amplitude measurement system are contained in a thin-film assembly. Detectors CR3 and CR4 are planar low-barrier Schottky diodes manufactured by HP.

A Technique that Is Insensitive to FM for Determining Harmonic Number and Sideband

by Luiz Peregrino

The basic principle of a heterodyne microwave counter is the use of a sampler or harmonic mixer to convert the high-frequency signal to a low intermediate frequency (IF) that can be counted directly. Before the frequency of the microwave signal can be computed from the measured IF the harmonic number and the sideband must somehow be determined.

One way to determine the harmonic and sideband is to use two microwave receivers with local oscillators offset by Δf . The difference between the two IF frequencies is proportional to the harmonic number and the sign of the difference determines the sideband:

$$N = \left| \frac{f_{IF1} - f_{IF2}}{\Delta f} \right|$$

The main disadvantage with this technique is the cost of the two high-frequency receivers.

An alternate solution is to vary the local-oscillator frequency, for instance switching regularly between two values. It can be shown that this technique would be very sensitive to FM present in the microwave signal.^{1,2}

Another possibility is to apply random modulation to the local oscillator and correlate the applied modulation to the resultant modulation in the IF. If there is crosscorrelation between the applied modulation and the FM in the microwave signal, there will be an error in the determination of the harmonic number, but if this error is less than 0.5, it can be completely eliminated, because the harmonic number is an integer.

In the new 5342A Microwave Frequency Counter, a pseudorandom signal^{3,4} is used to change the local oscillator frequency between the values f_1 and f_2 and gate the resultant f_{IF1} and f_{IF2} into two low-frequency counters. This reduces the problem to determining the proper pseudorandom sequence length to give the desired FM tolerance.

Let $g(t)$ represent a period of the pseudorandom sequence (see Fig. 1). When $g = +1$ the local oscillator frequency is set to f_1 and f_{IF1} is gated into counter 1. When $g = -1$ the local oscillator frequency is changed to f_2 and f_{IF2} is gated into counter 2. At the end of the sequence, $t=T$, the difference of the numbers accumulated by both counters is used to determine the harmonic number.

The number $M(t)$ accumulated by a counter is given by the integral of the frequency during the time the counter is gated on.¹ Let $M_1(t)$ and $M_2(t)$ represent the numbers accumulated by counter 1 and 2, respectively.

$$\begin{aligned} M_1(t) &= \int_0^{t_1} f_{IF1}(t) dt + \int_{t_2}^{t_3} f_{IF1}(t) dt + \dots \\ &= \int_0^T f_{IF1}(t) dt \Big|_{g=+1} \end{aligned}$$

$$\begin{aligned} M_2(t) &= \int_{t_1}^{t_2} f_{IF2}(t) dt + \int_{t_3}^{t_4} f_{IF2}(t) dt + \dots \\ &= \int_0^T f_{IF2}(t) dt \Big|_{g=-1} \end{aligned}$$

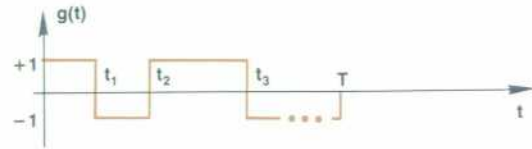


Fig. 1.

We will consider only the upper sideband case. The lower sideband case is identical except for a change in sign. Let f_x represent the unknown frequency and N the harmonic number. By proper selection of IF amplifier bandwidth and local oscillator frequencies, we can guarantee that the harmonic and sideband will be the same for both oscillator frequencies. With that in mind, we have:

$$f_{IF1}(t) = f_x(t) - Nf_1$$

$$f_{IF2}(t) = f_x(t) - Nf_2$$

$$M_1(t) = \int_0^T f_x(t) dt \Big|_{g=+1} - Nf_1 \int_0^T dt \Big|_{g=+1}$$

$$M_2(t) = \int_0^T f_x(t) dt \Big|_{g=-1} - Nf_2 \int_0^T dt \Big|_{g=-1}$$

$$M_1(t) - M_2(t) = \int_0^T g(t) f_x(t) dt - N(f_1 T_1 - f_2 T_2)$$

where T_1 is the length of time for which $g = +1$ and T_2 is the length of time for which $g = -1$. Then

$$N = \frac{M_2 - M_1}{T_1 f_1 - T_2 f_2} + \frac{\int_0^T g(t) f_x(t) dt}{T_1 f_1 - T_2 f_2} = N_c + \epsilon$$

The value of the integral is not available, so the second term appears as an error in the calculated harmonic number N_c .

For a pseudorandom sequence we have $T_1 - T_2 = T_c$, where T_c is the sequence clock period.^{3,4} This difference can be made zero by a small modification of the sequence circuit, or it can be disregarded if the sequence is long enough. Then we have:

$$T_1 = T_2 = T/2$$

$$f_1 - f_2 = \Delta f$$

$$N = \frac{2(M_2 - M_1)}{T \Delta f} - \frac{2}{T \Delta f} \int_0^T g(t) f_x(t) dt.$$

Let us consider the error term as function of time and take the Fourier transform. Using the shifting theorem we have:

$$E(j\omega) = \frac{2}{T} \left[\frac{1 - e^{-j\omega t_1}}{j\omega} - \frac{e^{-j\omega t_1} - e^{-j\omega t_2}}{j\omega} + \dots \right] \frac{F_x(j\omega)}{\Delta f}$$

Upper-case letters are used to represent Fourier transforms. The term in brackets can be recognized as the Fourier transform of the pseudorandom sequence. The term $F_x(j\omega)/\Delta f$ can be considered as the input to a linear system and $E(j\omega)$ as the output.¹ The transfer function of this system is:

$$H(j\omega) = \frac{2}{T} \left[\frac{1 - e^{-j\omega t_1}}{j\omega} - \frac{e^{-j\omega t_1} - e^{-j\omega t_2}}{j\omega} + \dots \right]$$

To determine the counter's sensitivity to sine wave modulation present in $f_x(t)$ we only need to know $|H(j\omega)|$. This can be easily found at frequencies that are multiples of $f_0 = 1/T$ by taking the square root of the power spectrum for the repetitive sequence.⁴

$$|H(jn2\pi f_0)| = 2 \frac{\sqrt{P+1}}{P} \left| \frac{\sin \frac{\pi n}{P}}{\frac{n\pi}{P}} \right|, n > 0$$

where P is the sequence length in clock periods:

$$P = \frac{T}{T_c}$$

We can use a safety factor of 2 to take care of the actual value of $|H(f)|$ for frequencies not multiples of f_0 . The worst case occurs for frequencies of the order of f_0 . For large P , we have:

$$\epsilon_{\max} \approx \frac{4}{\sqrt{P}} \frac{\Delta f_x}{\Delta f} \approx \frac{1}{2}$$

$$P \geq 64 \left(\frac{\Delta f_x}{\Delta f} \right)^2$$

where Δf_x is the peak deviation of the unknown signal.

Thus if we want the counter to tolerate 10 MHz peak FM on the input signal, and $\Delta f = 500$ kHz,

$$P > 25,600.$$

Since $P = 2^m - 1$, where m is the number of shift-register stages in the pseudorandom sequence generator, a 15-stage shift register would be needed to generate this sequence.

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2. R.A. Baugh, "Frequency Modulation Analysis with Hadamard Variance," Proceedings of the Frequency Control Symposium, April 1971, pp. 222-225.
3. S.W. Golomb, "Shift Registers," Holden-Day Inc.
4. S.W. Golomb et al., "Digital Communications with Space Applications," Prentice-Hall, 1964.

Luiz Peregrino

Luiz Peregrino received the degree Engenheiro de Eletronica from the Instituto Tecnol6gico da Aeronautica in Sao Paulo, Brazil in 1959. In 1960 he joined HP's marketing organization for a brief period, then spent three years with other companies as a development engineer and field engineer before rejoining HP in 1964. Luiz has been involved in production, research, and development for many HP products. He originated the random modulation concept for harmonic determination used



in the 5342A. He's a member of IEEE. He enjoys skiing and swimming, and is a home computer enthusiast.

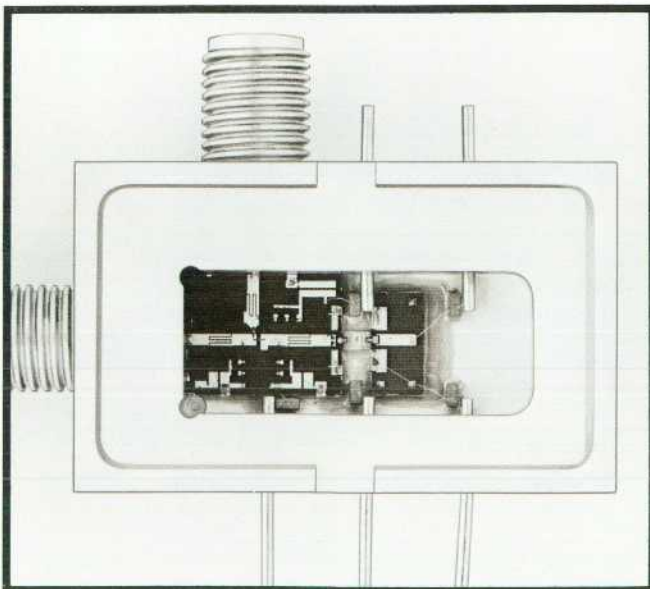


Fig. 16. Thin-film amplitude measurement assembly.

Inductors L1 to L3 act as RF chokes at high frequencies and as part of a 500-MHz high-pass filter with the capacitors C1 to C3 at lower frequencies. This represents an almost lossless method of injecting bias into a broadband, planar circuit.

Detectors CR3 and CR4, as mentioned above, are planar, low-barrier Schottky diodes manufactured by HP. They are mounted with their bypass capacitors on a common metal substrate for close thermal matching.

Since low SWR is important for an amplitude measurement, careful attention was paid to parasitic reactances and impedance matching. Fig. 17 shows typical SWR in amplitude mode, including the front-panel input connector.

The amplitude measurement circuit is made to serve as an attenuator by biasing PIN diode CR2 with high current and PIN diode CR1 with only about 0.4 mA. Most input energy is dissipated in the termination, R1, and input SWR is low. CR1, however looks

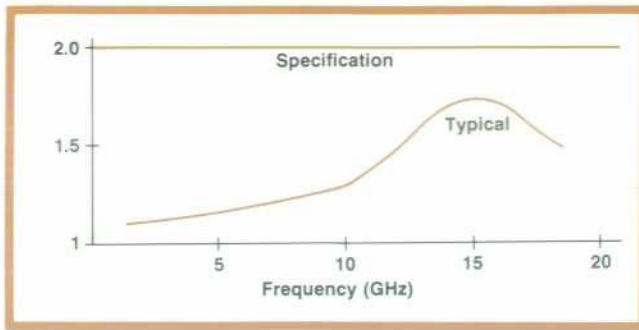


Fig. 17. Model 5342A input SWR in amplitude mode, including the front-panel connector.

like about 250 ohms and a small amount of energy (approximately -15 dB) goes to the sampler. This function is controlled by the converted signal level in the IF. With this technique, dynamic range is increased to $+20$ dBm with no danger of overloading the input sampler.

Amplitude Error Correction

A feature of Model 5342A is its ability to correct for known errors according to a stored calibration table before display. Since the microprocessor knows the frequency and measured amplitude of the input signal, it is possible to correct not only for the frequency response of the detector and the insertion loss of the input connector and switch but also for amplitude related errors such as mistracking between detectors. Typical errors to be corrected are shown in Fig. 18. Measurements such as this are made on every unit before installation and the data is stored in a PROM in much the same format as shown in Fig. 18. Curve A is stored to eight-bit resolution in 0.25-GHz increments and curve B also to eight-bit resolution in 4-dB increments and every 0.5 GHz. The processor uses the frequency and uncorrected amplitude of the input signal to look up the values of correction in each table and to interpolate for intermediate values. Since Table B is normalized to the level used in Table A, the correction values are simply added together and applied to the result.

The system that collects the data to calibrate each amplitude module consists of two signal sources and four TWT (traveling wave tube) amplifiers multiplexed together, with attenuators and an output directional coupler and power meter under the control of an HP 9825A Desktop Computer via the HP-IB. This system drives the module under test with all frequencies and amplitudes in its range, and with low source SWR and accurately known amplitude. The error in the response of the module is then measured and stored in the calibration PROM.

Amplitude Accuracy

Many factors affect the accuracy of an amplitude measurement in the 5342A. For traceability of our standards to NBS and their application to individual instruments in production we allow 0.4 dB. There can be up to 0.1 dB error in all the digital processes. Analog errors, such as op amp offset, modulator linearity, noise, and A-to-D converter accuracy can add a maximum of 0.3 dB. While drift with temperature is typically less than 0.2 dB from 0° to 50°C , we allow a maximum of 0.4 dB. The worst-case uncertainty for all these variables together is thus ± 1.2 dB. These errors although not random, are independent and will rarely add to this value. The root-sum-of-the-squares⁴ uncertainty, a more realistic value of expected error, is less than 0.6 dB. To this value must be added mismatch uncertainty, which depends upon the SWR of both the source and load. Reference 4 contains a good discussion of this.

Low-loss cables are recommended for routing signals to the front panel of the 5342A. Flexible cable with repeatable insertion loss less than semi-rigid coax has recently become available⁵ and is very convenient to use.

Acknowledgments

Many individuals made significant contributions to the 5342A. The single-sampler concept was first suggested by John Dukes. Tom Coates provided microprocessor support software and other user aids that got the project off to a running start. The sampler was the result of Jeff Wolfington's ingenious efforts. The power supply was done by John Gliever. We were fortunate to have Yoh Narimatsu working on the synthesizers. Art Bloedorn did the IF preamps and the direct input channel and also took production engineering responsibility for the product. Digital design was initiated by Chuck Howey. When Chuck

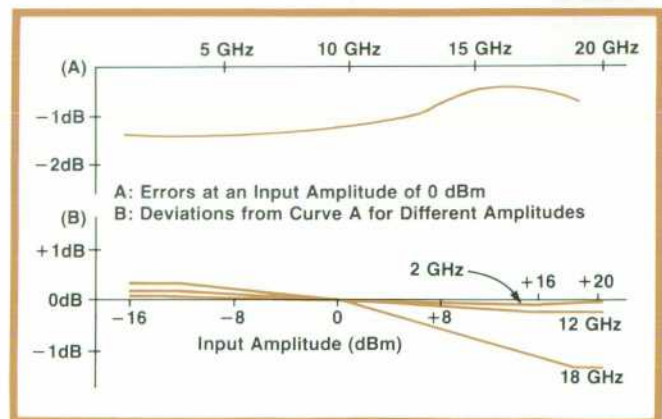


Fig. 18. Each 5342A amplitude measurement system is calibrated before installation. Systematic errors are stored in a PROM and the microprocessor corrects each measurement before display.

opted for a farming career, John Shing stepped in and was responsible for digital design and firmware. Special thanks are due Al Foster who designed an HP-IB interface to the 6800 processor. For the amplitude-measurement option, Steve Upshinsky worked on the low frequency analog circuitry and Art Lange did all the digital work, including programming of the calibration system. Thanks also go to Karl Ishoy for help with hybrid circuit production. 5342A product design was effectively done by Keith Leslie. Martin Neil, support engineer, contributed significantly in troubleshooting concepts and manual preparation. Product introduction was by Craig Artherholt. The product was designed and put into production under the

lab management of Ian Band and Roger Smith. 

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Ali Bologlu



Ali Bologlu has been with HP for fifteen years and has been project manager for microwave counters since 1970. He's contributed to the design of many HP frequency synthesizers and microwave counters, most recently the 5342A. Ali received BS and MS degrees in electrical engineering in 1962 and 1963 from Michigan State University and the degree of Electrical Engineer from Stanford University in 1965. Born in Istanbul, Turkey, he's married, has three children, and now lives in

Mountain View, California. He plays tennis, enjoys water sports, and coaches a youth soccer team.

Vernon A. Barber



Al Barber has been designing HP microwave counters for ten years. His latest project was the amplitude measurement option for the 5342A. Al was born in Chicago and grew up in Fairbanks, Alaska. He received his BSEE degree from the University of Washington in 1967 and his MSEE from Stanford University in 1970. He's a member of IEEE. Al's tastes in recreation run to mountain climbing and classical music. He's climbed in the Sierra Nevada, the Rocky Mountains, the Alaska Range, the

Alps, and the Himalaya, and he's now learning piano. He's married and lives in San Jose, California.

SPECIFICATIONS

HP Model 5342A Microwave Frequency Counter

Input Characteristics

INPUT 1:

FREQUENCY RANGE: 500 MHz to 18 GHz
 SENSITIVITY: 500 MHz to 12.4 GHz, -25 dBm
 12.4 GHz to 18 GHz, -20 dBm
 MAXIMUM INPUT: +5 dBm (see Option 002, 003 for higher level)
 DYNAMIC RANGE: 500 MHz to 12.4 GHz, 30 dB
 12.4 GHz to 18 GHz, 25 dB

IMPEDANCE: 50 ohms, nominal
 CONNECTOR: Precision Type N female
 DAMAGE LEVEL: +25 dBm
 OVERLOAD INDICATION: Displays dashes when input level exceeds +5 dBm nominal
 COUPLING: dc to load, ac to instrument
 SWR: <2:1, 500 MHz - 10 GHz
 <3:1, 10 GHz - 18 GHz

FM TOLERANCE: Switch selectable (rear panel)

FM (wide): 50 MHz p-p worst case

CW (normal): 20 MHz p-p worst case

For modulation rates from dc to 10 MHz

AM TOLERANCE: Any modulation index provided the minimum signal level is not less than the sensitivity specification.

AUTOMATIC AMPLITUDE DISCRIMINATION: Automatically measures the largest of all signals present, providing that signal is 6 dB above any signal within 500 MHz, 20 dB above any signal, 500 MHz-18 GHz.

MODES OF OPERATION: Automatic: Counter automatically acquires and displays highest level signal within sensitivity range. Manual: Center frequency entered to within ±50 MHz of true value.

ACQUISITION TIME: Automatic mode: normal FM 530 ms worst case, wide FM 2.4 s worst case, Manual mode: 5 ms after frequency entered.

INPUT 2:

FREQUENCY RANGE: 10 Hz to 520 MHz Direct Count
 SENSITIVITY: 500L, 10 Hz to 520 MHz, 25 mV rms
 1 MΩ, 10 Hz to 25 MHz, 50 mV rms
 IMPEDANCE: Selectable: 1 MΩ, <50 pF or 50Ω nominal
 COUPLING: ac
 CONNECTOR: Type BNC female
 MAXIMUM INPUT: 500L, 3.5Vrms (+24 dBm) or 5Vdc fuse protected; 1 MΩ, 200 Vdc = 5.0 Vrms

TIME BASE:

CRYSTAL FREQUENCY: 10 MHz
 STABILITY: Aging rate: <1 × 10⁻⁷ per month
 Short term: <1 × 10⁻⁹ for 1 second avg. time
 Temperature: <1 × 10⁻⁹ over the range 0°C to 50°C
 Line variation: <±1 × 10⁻⁷ for 10% change from nominal.

OUTPUT FREQUENCY: 10 MHz, ±2.4V square wave (TTL compatible), 1.5V peak-to-peak into 50Ω available from rear panel BNC.
 EXTERNAL TIME BASE: Requires 10 MHz, 1.5V peak-to-peak sine wave or square wave into 1 kΩ via rear-panel BNC connector. Switch selects either internal or external time base.

Optional Time Base (Option 001)

Option 001 provides an oven-controlled crystal oscillator time base, 10544A, that results in better accuracy and longer periods between calibration.

CRYSTAL FREQUENCY: 10 MHz

Aging rate: <5 × 10⁻¹⁰/day after 24-hour warm-up
 Short term: <1 × 10⁻¹¹ for 1 second avg. time
 Temperature: <7 × 10⁻⁹ over the range 0°C to 50°C
 Line variation: <1 × 10⁻¹⁰ for 10% change from nominal
 Warm-up: <5 × 10⁻⁹ of final value 20 minutes after turn-on, at 25°C

Amplitude Measurement (Option 002)

Option 002 provides the capability of measuring the amplitude of the incoming sine wave signal, and simultaneously displaying its frequency (MHz) and level (dBm). The maximum operating level and the top end of the dynamic range are increased to +20 dBm. Amplitude offset to 0.1 dB resolution may be selected from front-panel pushbuttons.

INPUT 1:

FREQUENCY RANGE: 500 MHz-18 GHz
 DYNAMIC RANGE (FREQUENCY AND LEVEL):
 -22 dBm to +20 dBm, 500 MHz to 12.4 GHz
 -15 dBm to +20 dBm, 12.4 GHz to 18 GHz
 MAXIMUM OPERATING LEVEL: +20 dBm
 DAMAGE LEVEL: +25 dBm
 OVERLOAD INDICATION: Displays dashes when input level exceeds +20 dBm nominal
 RESOLUTION: 0.1 dB
 ACCURACY: ±1.5 dB (excluding mismatch uncertainty)
 SWR: <2:1 (amplitude measurement)
 <5:1 (frequency measurement)
 MEASUREMENT TIME: 100 ms + frequency measurement time
 DISPLAY: Simultaneously displays frequency to 1 MHz resolution and input level. (Option 011 provides full frequency resolution on HP-IB output)

INPUT 2: (50Ω impedance only)

FREQUENCY RANGE: 10 MHz-520 MHz
 DYNAMIC RANGE (FREQUENCY AND LEVEL): -17 dBm to +20 dBm

DAMAGE LEVEL: +24 dBm
 RESOLUTION: 0.1 dB
 ACCURACY: ±1.5 dB (excluding mismatch uncertainty)
 SWR: <1.8:1
 MEASUREMENT TIME: 100 ms + frequency measurement time
 DISPLAY: Simultaneously displays frequency to 1 MHz resolution and input level.

Extended Dynamic Range (Option 003)

Option 003 provides an attenuator that automatically extends the dynamic range of operation for input 1.

INPUT 1:

FREQUENCY RANGE: 500 MHz to 18 GHz
 SENSITIVITY: 500 MHz to 12.4 GHz, -22 dBm
 12.4 GHz to 18 GHz, -15 dBm
 DYNAMIC RANGE: 500 MHz to 12.4 GHz, 42 dB
 12.4 GHz to 18 GHz, 35 dB
 DAMAGE LEVEL: +25 dBm
 SWR: <5:1

General

ACCURACY: ±1 count ± time base error.
 RESOLUTION: Front-panel pushbuttons select 1 Hz to 1 MHz.
 RESIDUAL STABILITY: When counter and source use common time base or counter uses external higher stability time base, <4 × 10⁻¹¹ rms typical.

DISPLAY: 11-digit LED display, sectionalized to read GHz, MHz, kHz, and Hz.
 SELF CHECK: Selected from front-panel pushbuttons. Measures 75 MHz for resolution chosen.

FREQUENCY OFFSET: Selected from front-panel pushbuttons. Displayed frequency is offset by entered value to 1-Hz resolution.
 SAMPLE RATE: Variable from less than 20 ms between measurements to HOLD which holds display indefinitely.

IF OUT: Rear panel BNC connector provides 25 MHz to 125 MHz output of down-converted microwave signal.

OPERATING TEMPERATURE: 0°C to 50°C
 POWER REQUIREMENTS: 100/120/220/240 Vrms, ±5%, -10%, 48-66 Hz; 100 VA max

SIZE: 133 mm H × 213 mm W × 498 mm D (5¼ × 8¼ × 19½ in)
 WEIGHT: Net 9.1 kg (20 lb), Shipping 12.7 kg (28 lbs).

PRICES IN U.S.A.: 5342A, \$4500. Options: 001, \$500. 002, \$1000. 003, \$375.
 MANUFACTURING DIVISION: SANTA CLARA DIVISION
 5301 Stevens Creek Boulevard
 Santa Clara, California 95050 U.S.A.

Generating High-Speed CRT Displays from Digital Data

A new graphics translator converts information received from a digital system by way of the HP interface bus into the analog signals needed for tracing vectors and characters on high-resolution CRT displays.

by Arnot L. Ellsworth and Kunio Hasebe

GRAPHICAL DISPLAY of digital data is generally easier to interpret than long columns of numbers. Trends, curve shapes, maxima, and minima are much easier to perceive when data is presented in graphical form.

X-Y plotters are widely used for converting digital data to graphics, giving accurate, permanent records that encompass large amounts of data with fine detail. There are times, however, when a plotter may be too slow. In applications that require many plots to be made in getting to the desired result, such as adjusting a circuit for a desired response, not only is a lot of paper wasted but the time required to make all those plots may be inordinately long.

Storage CRTs provide a means of presenting graphical data more quickly than X-Y plotters. They too can present a great amount of data at one time, the amount being limited only by the resolution of the CRT. However, if only part of the stored display needs to be updated, the entire display must be erased and all the data retransmitted to the display.

Directed-beam CRT displays, on the other hand, use a refresh memory, any part of which can be updated without erasing data in the rest of the memory. Hence, updating is fast, enabling a high degree of operator interaction with the digital system. Furthermore, refreshed directed-beam displays are significantly brighter than storage-tube displays.

Unfortunately, there has been a major stumbling block to the use of directed-beam displays: the need for the user to provide interfacing to the digital system. This can be especially troublesome when design and production resources needed for the interfacing are limited.

A Ready-Made Interface

The new HP Model 1350A Graphics Translator, Fig. 1, represents a general solution to the interface problem. It accepts data supplied by way of the HP interface bus, stores the data, and repetitively generates the analog signals needed for tracing the specified vectors and characters (Fig. 2).

All that is necessary to implement a display system with the new graphics translator is to connect its outputs to a directed-beam display and its input to an HP-IB interface for the system calculator or computer (Fig. 3). The display needs to have full-scale deflection factors of one volt and at least 2-MHz response on the X and Y axes and 10-MHz response on the Z axis. The system controller may already have an HP-IB interface since so many instrumentation systems are now being designed around the HP interface bus.*

Programming is straightforward. Vectors are traced by specifying the coordinates of the vector end points. Characters are drawn by specifying each character by a single ASCII code (lower or upper case) and the starting position of the character string.

Fast Results

The principal advantage of using the new graphics

*Hewlett-Packard's implementation of IEEE standard 488-1975, ANSI Standard MC 1.1, and BUS CEI.

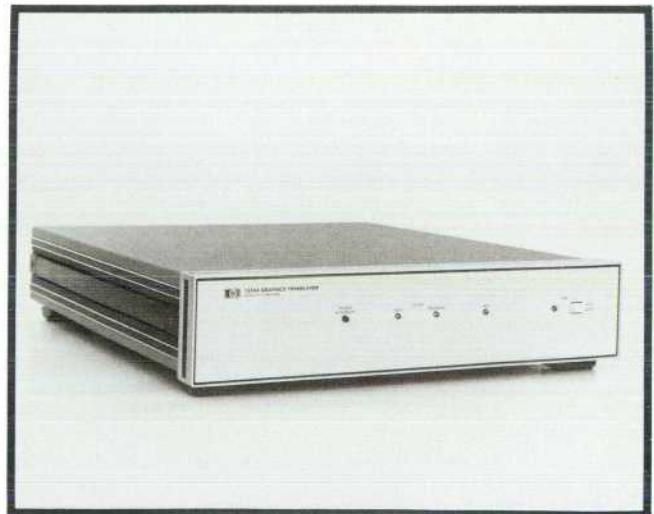


Fig. 1. The new Model 1350A Graphics Translator converts outputs from digital systems to analog outputs for driving high-resolution, directed-beam CRT displays. It will be particularly useful for systems involving engineering design, statistics, medicine, process control, radar, and any others requiring high-resolution graphics display.

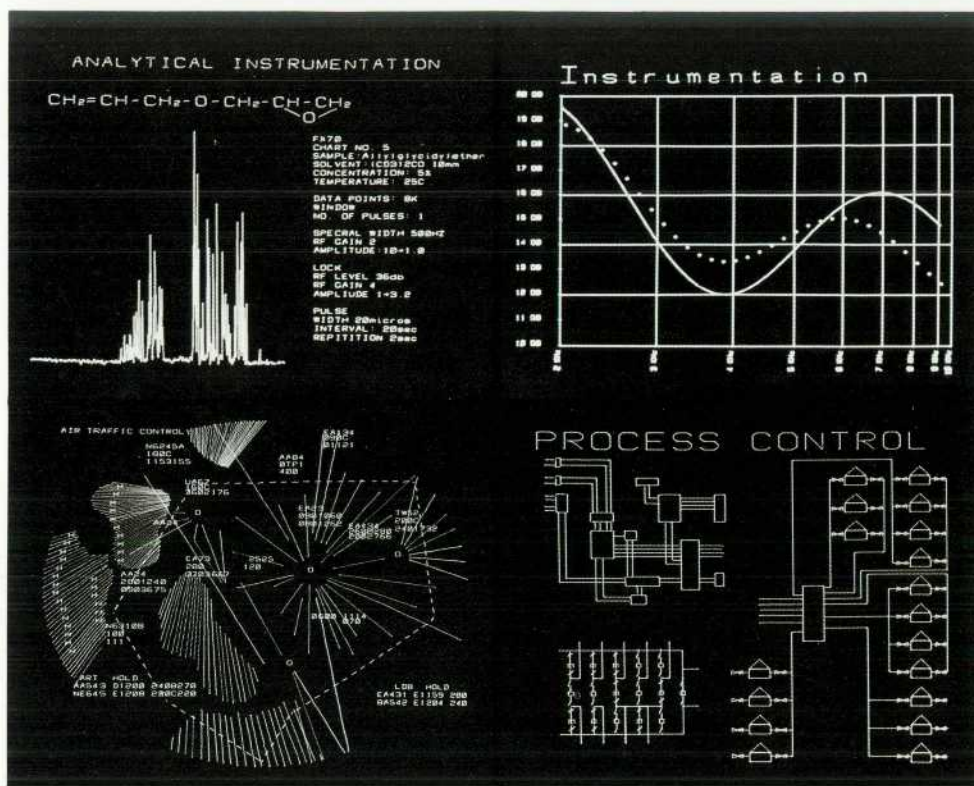


Fig. 2. Displays generated by a digital system using the Model 1350A Graphics Translator. Hewlett-Packard offers a variety of CRT displays suitable for use with the new graphics translator, with viewing areas ranging from 8 × 10 cm to 30 × 35 cm.

translator and a directed-beam display is the increased system throughput rate. Where changes are being made in the data to be displayed, the effects of changes are immediately apparent. Curve fitting, for example, can be done much more quickly than with other display devices. When the system user has to make decisions related to scale factors, data limits, and so on, the interactivity and speed of response of the graphic display system shorten the time needed to configure the display parameters so the data is presented in the optimum form. Once the data presentation is optimized, an X-Y plotter connected to the HP-IB can give a permanent record of the displayed data.

The internal 2K-word refresh memory of the new graphics translator can be partitioned into 32 files. The data displayed from any of these files can be blanked, unblanked, or erased individually, permitting selective erasure, an especially useful feature if standard data is to be retained for comparison with later data. Windowing, expansion, highlighting by blinking selected areas of the display, and the use of cursors are also possible.

The 50Ω X, Y, and Z analog outputs can drive several displays in parallel with the same information. However, four separate blanking outputs are provided so four different blanking signals can be obtained. These override the Z-axis signal generated for the displays. Thus, information intended only for certain displays in a multiple-display set-up can be blanked from the others. These blanking signals in

effect “steer” the data to the appropriate displays.

Compared to the less-expensive raster display systems, directed-beam displays have higher resolution because vectors are traced in any direction with continuous lines and also because the addressing scheme enables the beam to be positioned with greater precision. For example, the 10-bit addresses used by the new graphics translator permit the beam to be positioned to any of the more than one million positions in the 1023 × 1024-point display area. Furthermore, updating is faster because only the vector end points need to be known—the system does not have to take time to calculate intermediate points. This speed

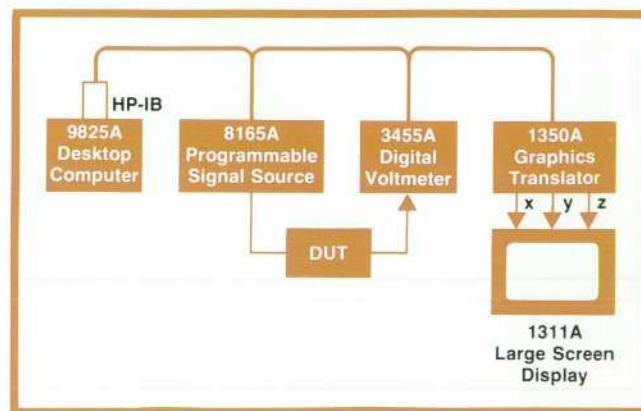


Fig. 3. Typical of the kind of systems that can use the new graphics translator advantageously is this automatic system for measuring filter response in a production environment (DUT=device under test).

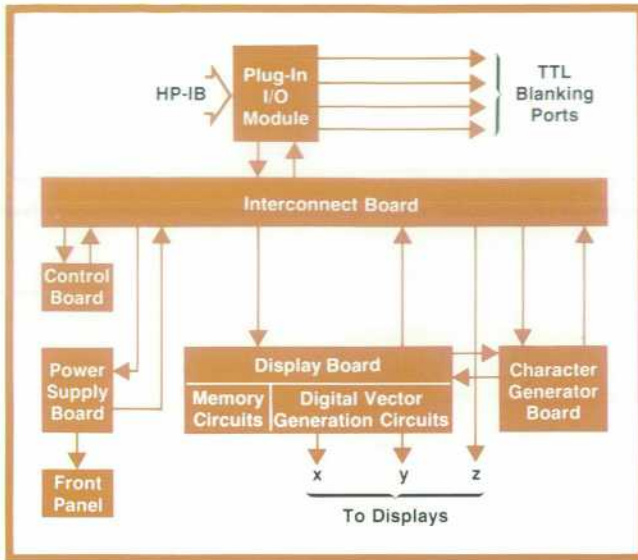


Fig. 4. Basic block diagram of the Model 1350A Graphics Translator. The character generator and I/O module are designed to be easily replaced if special characters are needed and/or if the I/O format needs to be modified.

enables simulated motion studies.

How It's Organized

The internal organization of the Model 1350A Graphics Translator is shown in the block diagram of Fig. 4. The refresh memory contains the data to be displayed. It can store up to 2048 vectors and/or characters and, as mentioned before, can be partitioned into 32 files of any length, as long as the total file contents do not exceed the memory.

A separate character generator is included so a complete character can be generated in response to a single ASCII code. It is a separate subassembly with its own control circuitry so it can control the instrument to some extent while drawing characters. This enables it to scale or rotate the characters. It is implemented such that the character set can be changed for special applications.

The I/O module for the input and output of data is also a separate subassembly, allowing easy modification of the I/O format. This module was designed almost completely with TTL technology to allow very fast data transfer ($<2 \mu\text{s}/\text{character}$ or $<20 \mu\text{s}/\text{point}$). Much of the TTL circuitry could have been replaced with a less-expensive microprocessor system but this would have slowed the data transfer rate significantly.

Vector Generation

Among other requirements, there is an important one that the design of the vector generator had to meet: the CRT beam should be moved at the same constant rate for all vectors regardless of length and

angle so the beam intensity will be uniform everywhere on the display.

This is difficult to do at the speeds required for a refreshed, directed-beam display. Consequently the vector generator approximates the ideal situation by using one of six tracing times and one of 32 intensity levels for each vector according to its length. This gives $6 \times 32 = 192$ combinations of tracing times and intensity levels to approximate the ideal constant tracing rate.

A block diagram of the vector generator is shown in Fig. 5. To assure long-term stability, digital techniques are used right up to the line-driver amplifiers. This has resulted in very good temperature stability, as well as good, demonstrated reliability.

Operation is as follows. The coordinates for the next vector endpoints are latched in the NEXT X,Y latches. When the system finishes tracing the present vector, the arithmetic units subtract the present X-Y position coordinates from the next position coordinates. The results are the Δx and Δy components of the next vector.

The Δx component is right-shifted until a comparator indicates that the five left-most bit positions are filled with zeros. The number of shifts required is a gross indication of the length of the Δx component. The same operation occurs with the Δy component, and the control circuits then select the larger of the two shifts as the designator of tracing time. Vector length determines tracing time as follows:

Vector length	Tracing time
1 > length > 1/2 of full screen	$\approx 48 \mu\text{s}$
1/2 > length > 1/4	$\approx 24 \mu\text{s}$
1/4 > length > 1/8	$\approx 12 \mu\text{s}$
1/8 > length > 1/16	$\approx 6 \mu\text{s}$
1/16 > length > 1/32	$\approx 3 \mu\text{s}$
1/32 > length > 0	$\approx 1.5 \mu\text{s}$

The upper four bits of Δx and Δy are summed to obtain a five-bit number for control of the intensity level. The shifted Δx and Δy components are applied to rate multipliers that divide down the input clock rate according to the magnitudes of Δx and Δy . The divided-down clocks increment or decrement the X and Y position counters and the D-to-A converters generate analog signals proportional to the counters' instantaneous contents, moving the CRT beam through a series of microsteps to arrive at the next position (three-pole low-pass filters in the drive amplifiers smooth the microstep transitions). When the control circuits determine that the correct number of clocks have occurred, the rate multipliers are stopped.

Operation with the character generator is similar

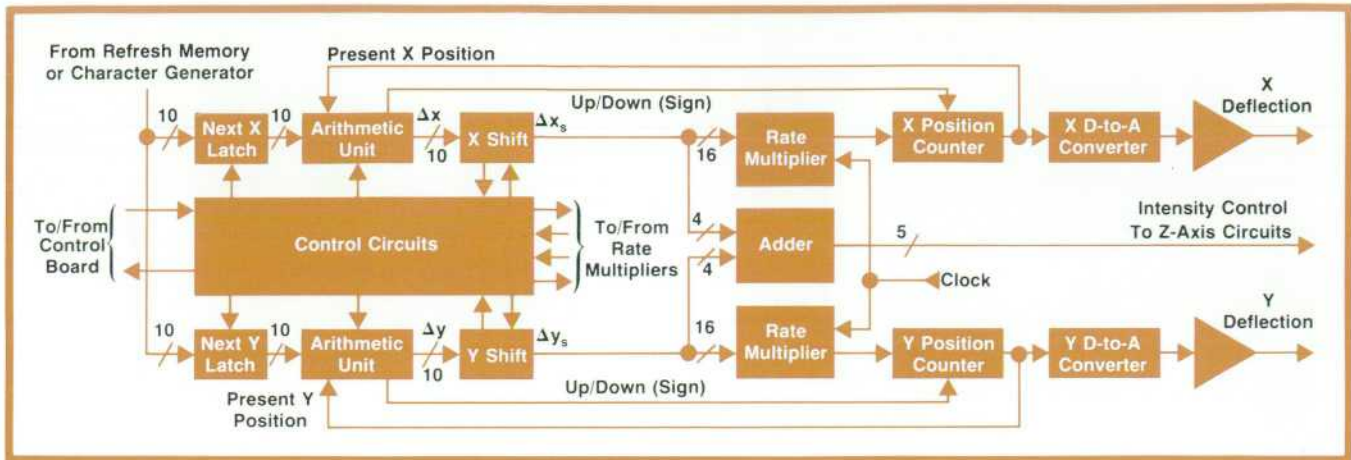


Fig. 5. Simplified block diagram of the vector generator. All processing is performed digitally to eliminate drift. The coordinates of the instantaneous CRT beam position are held in counters, and the counter contents are converted to analog signals for driving the X-Y inputs to the CRT display.

except that the arithmetic units act as pass-throughs since the character generator has already computed Δx and Δy . Also, switching circuits (not shown) can modify the arithmetic signs and interchange Δx and Δy so the characters can be rotated.

The character generator is a conventional ROM-controlled algorithmic state machine that uses a look-up table to find the end points of short vectors for tracing each character. Scaling factors can be applied to the algorithms so the character size can be magnified ($\times 1$, $\times 2$, $\times 4$, $\times 8$). The Δx - Δy coordinate information for each vector end point is sent to the vector generator.

Refresh Rate

The refresh rate depends upon the number of vectors and characters to be drawn and the number of blanked movements of the CRT beam. Each normal-size character requires $15 \mu s$ to trace. The vector trace time is according to the list on page 19 and the time for blanked movements is the same as for vector movements. As an example, consider a presentation that has 50 characters, a graticule of 21 vertical and 21 horizontal lines, 40 tick marks on the graticule, 60 blanked movements to trace the graticule and tick marks, 24 blanked movements to position the characters, and 200 data points joined by short vectors. Total trace time is then approximately:

50 characters at $15 \mu s$	$\approx 750 \mu s$
42 lines at $48 \mu s$	$\approx 2016 \mu s$
40 tick marks at $4.5 \mu s$	$\approx 180 \mu s$
60 short blanked movements at $6 \mu s$	$\approx 360 \mu s$
24 blanked movements at $12 \mu s$	$\approx 288 \mu s$
200 data points at $1.5 \mu s$	$\approx 300 \mu s$
	<u>$\approx 3894 \mu s$</u>

$$1/3894 \mu s \approx 250 \text{ Hz}$$

Hence, the refresh rate for this data display is well above the flicker level.

Processing the Data

The data path from the input to the refresh memory is outlined in Fig. 6. ASCII-coded data written in the graphics translator machine language is accepted through the HP-IB interface in the following format:

NN xxxx, yyyy;

followed by a colon (:), carriage return (CR), or line feed (LF). The first two letters (NN) are a mnemonic for the instruction command (see Table I), and can be either upper or lower case. The parameters xxxx and yyyy are four-digit decimal numbers. For example, the instruction "pa 200, 500:;" moves the CRT beam to $x = 200$, $y = 500$ on the 1023×1024 matrix ("pa" is the mnemonic for "plot absolute"). xxxx and yyyy may not be used with some instruction commands.

The system is initialized when the decoder ROM (see Fig. 6) detects CR, LF, or a colon (:). The instruction counter is then reset to 0, the system is put into the "listen program" mode, and the BCD data shift register is cleared. When the system is in this mode, the next two alphanumeric characters received through the interface buffer are interpreted by the decoder ROM as an instruction. (If through some error these two alphanumeric characters are not one of the instruction commands listed in Table I, the system goes into a "sleep" mode and does nothing until another CR, LF, or : is received.)

After the instruction counter counts the two alphanumeric characters, the system goes into the "listen data" mode and the numeric data is clocked into the BCD data shift register. When a parameter terminator ("," or ";") occurs, the register contents are converted to

Table I. Graphics Translator Instructions

Vector Group	File Group	Auxiliary Display Group	Memory Group
pa- plot absolute (x,y)	nf- name file	wx- write auxiliary for	em- erase memory
pe- pen (0=up, 1=down)	pf- blank file	display (0,1,2...15)	um- unblank memory
cs- character size and	uf- unblank file	sx- stop writing auxiliary for	fl- find memory location
rotation	sn- stop naming file	display (0,1,2...15)	
tx- text mode	ff- find file	ex- erase auxiliary display	
	en- erase file names		

binary and transferred through the multiplexers to the register designated by the decoder ROM according to the instruction command. When the next CR, LF, or : is detected by the decoder ROM, the data is loaded into the next address in memory and a new instruction cycle is initiated.

An exception to the above occurs with the plot absolute (pa) command, which causes data to be loaded into memory each time a semicolon (;) appears. This allows several coordinates to be transmitted in one statement. For example, the single statement "pa 100, 100; 350, 900; 600, 100; 100, 100;" draws a triangle.

The instruction command "tx" causes the system to

go into the text mode. The 7-bit ASCII code following tx is then loaded into the 10-bit Y coordinate register. Character size and angle of rotation fill out the remaining three bits. The X coordinate register is filled with 1's and loaded into memory at the same time as the information in Y. During readout of the memory, the ten 1's in X indicate to the display circuits that the information in Y is to be sent to the character generator.

The system remains in the text mode until receipt of the end-of-text character (binary 3).

Each of the 32-bit words stored in the refresh memory contains the following:

X coordinate (or text-mode code) 10 bits

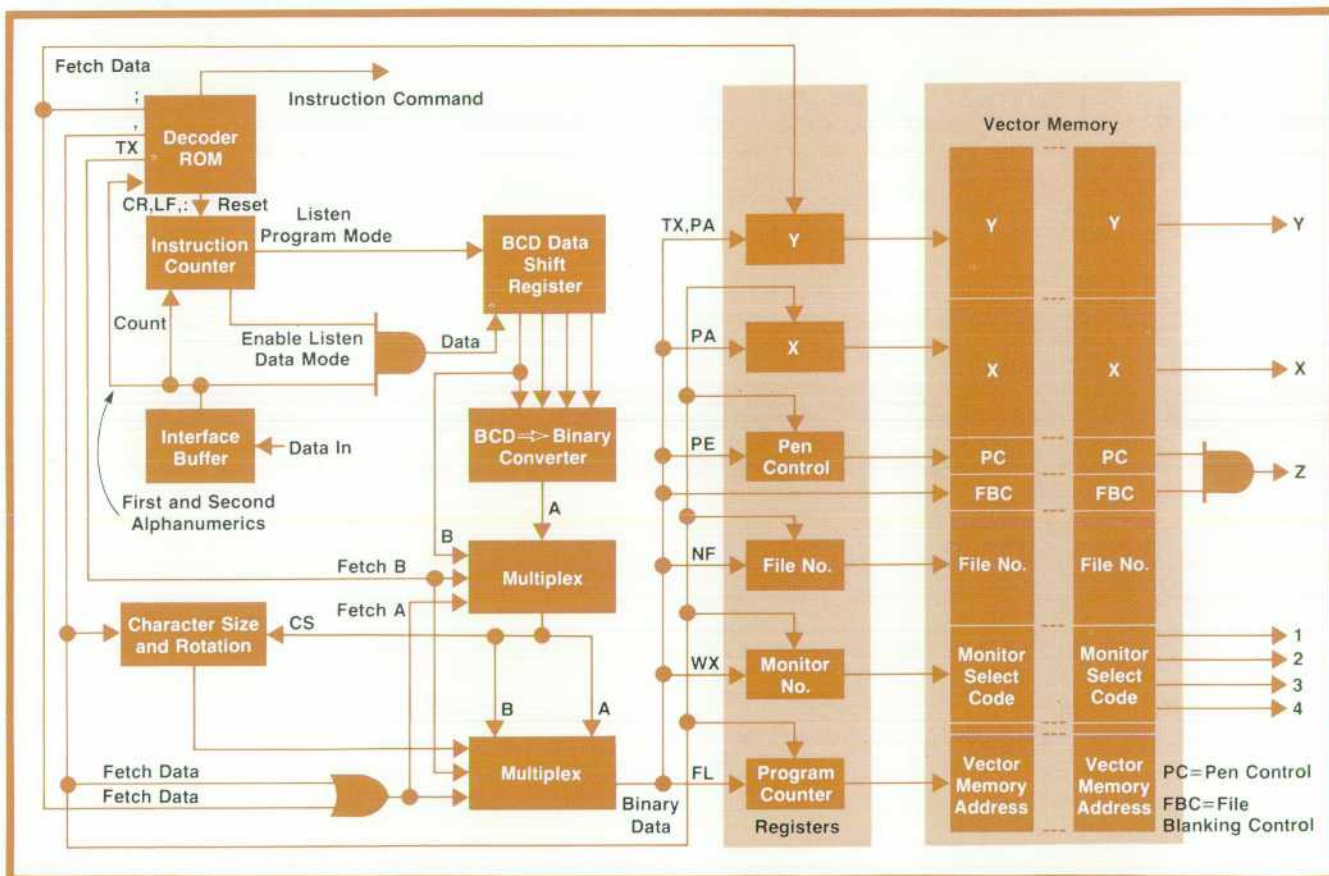


Fig. 6. Block diagram of the data processing circuits.

Y coordinate (or ASCII character)	10 bits
File number	5 bits
Monitor select code	4 bits
Pen control (blank or unblank)	1 bit
File blanking control	1 bit
Unassigned	1 bit

Pre-Programmed Subroutines

To simplify the programming of the graphics translator, a number of graphics utility subroutines for use with several different host computers have been prepared. The graphics command statements in the higher-level languages used with these programs were selected to be easy to understand and, if possible, to be already familiar to the user. For example, one of these routines, the 10184A Softcopy Graphics Library designed to run on the Model 9825A Desktop Computer, supports the Models 9862A and 9872A Plotters as well as the graphics translator. This routine has graphics command statements and parameter meanings for the translator that for the most part are identical to the plotter command statements. Hence, the user does not have to learn the graphics translator machine language (GTML).

The "hdcpy" statement in this subroutine indicates to the desktop computer that the data is to be sent to the plotter for a hard-copy output. Whenever the user gives a graphics command statement, the graphics subroutine first looks for the "hdcpy" flag. If the flag is clear, the system speaks GTML to the graphics translator via the HP-IB and the CRT display is updated. If the flag is set, it speaks the HP graphics language (HPGL) to the plotter and the user obtains a hard copy of the graphics information.

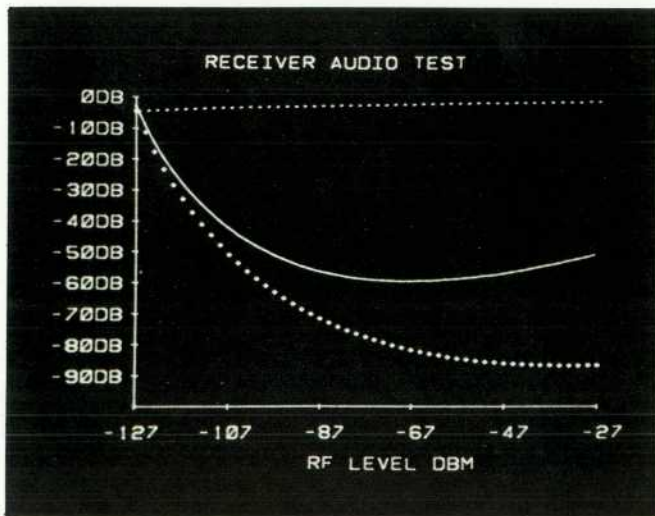


Fig. 7. Display resulting from the program described in the text. The bottom trace is the noise level at a receiver's output as a function of the RF input level. The middle trace is the level of the combined noise and distortion and the top trace is the signal plus noise and distortion.

Some of the Softcopy Graphics statements are:

plt x,y	draw a line to x,y
scl x ₁ , x ₂ , y ₁ , y ₂	establish the scale range
ofst x,y	offset the origin
file x	designate a file number
bfile x,x,...	blank these files.
vfile x,x,....	view these files.
flsh x,y,y...	flash this file (x) on these monitors (y,y,...).
mon x,x,	display subsequent data on these monitors.
bmon x,y,....,y	blank these files (y,y,...) from this monitor (x).
vmon x,y,....,y	view these files on this monitor.

Because the cartridge tape on which the Softcopy Graphics Library is supplied, is written in the Model 9825A's machine language and includes the compiler, there is no need to use the "call" statement to execute the graphics command statements.

An example of a program written with Softcopy Graphics statements is shown below followed by an explanation of the program steps. This program traces the display shown in Fig. 7, the result of a radio receiver test, and illustrates the relative simplicity of creating graphic displays with the Model 1350A using a Model 9825A Desktop Computer as a controller and the Softcopy Graphics Library.

```

0: pclr;fxd 0;csiz 3
1: scl -145,-20,-120,20
2: yax -127,10,-100,1
3: xax -100,20,-127,-26
4: plt -110,10,1;lbl "RECEIVER AUDIO TEST"
5: plt -90,-120,1;lbl "RF LEVEL DBM"
6: for Y=-90 to 0 by 10
7: plt -145,Y-2,1;if Y>=0;lbl " "
8: lbl Y,"DB";next Y
9: for X=-127 to -25 by 20
10: plt X-7,-110,1;lbl X;next X
11: 1→D;qsb "read data";if F=1;plt X,Y,1;lbl "#";jmp 0
12: 2→D;qsb "read data";if F=1;plt X,Y;jmp 0
13: 3→D;qsb "read data";if F=1;plt X,Y,1;lbl "*";jmp 0
14: stp
15: hdcpy 1;atc 0
16: end
17: "read data":

```

Explanation of the program:

- Line 0 Clears the picture on the CRT screen, sets the fixed point format, and establishes the size of characters to be used.
- Line 1 Establishes the user's scale range for the plotting area.
- Line 2 Draws the Y-axis.
- Line 3 Draws the X-axis.
- Lines 4 & 5 Writes titles.
- Lines 6-8 Writes labels on the Y-axis tick mark location.
- Lines 9-10 Writes labels on the X-axis tick mark location.
- Lines 11-13 Reads the DVM measured values and plots data. "F" is a flag that indicates another reading is to be taken. 1→D, 2→D, 3→D set switches in the test set-



Fig. 8. Graphics workstation uses the Model 1350A Graphics Translator with the Model 9825A Desktop Computer. Vectors and characters for all the displays shown here are stored in Model 1350A's files at the same time and directed to individual displays by Model 1350A's blanking signals.

up to supply the indicated inputs to the DVM.

- Line 14 Stops the program execution.
- Line 15 Sets hard copy flag and continues the program from line 0.
- Line 17 Beginning of the subroutine to make measurements and to set F=0 if the measurement cycle is complete.

Acknowledgments

Tom Bohley and Bill Mason developed the vector generator. Bill also contributed to the character generator and the power supply. Mechanical design was by Bill Smith. Many thanks are also due Ed Scholtzhauer of the Loveland Instrument Division



Kunio Hasebe

Kunio Hasebe joined HP's intercontinental operations in 1973 as a staff engineer, a position that involved a considerable amount of travel in the far east. He later became the intercontinental specialist on the HP interface bus, logic analysis, and digital signal analysis. Wishing to get involved in R and D, Kunio transferred to the Colorado Springs Division in 1976, where he did some of the programming and I/O design for the 1350A Graphics Translator. Kunio was born in Japan but when he

was 13 his family moved to Hawaii. There, he obtained both BSEE and MSEE degrees from the University of Hawaii in 1971 and 1972. Fond of driving, Kunio likes to unwind by winding around Colorado's mountain roads in his aging BMW.

SPECIFICATIONS
HP Model 1350A Graphics Translator

INPUT INTERFACE: HP-IB listener only that conforms to IEEE 488-1975. Data acceptance rate is 2 μ s per character.
X, Y, ANALOG OUTPUT: +0.2 Vdc to +1.2 Vdc into 50 Ω . X, Y, analog vectors, between addressable points. Positive up and to the right.
Z ANALOG OUTPUT: 0 to 1 V unblanked, -1 V blanked, into 50 Ω .
ADDRESSABLE RESOLUTION: 1000 \times 1000 points.
MEMORY: 2048 Vectors or characters.
32 ADDRESSABLE FILES: may be of any length that does not exceed memory size. Files can be erased or blanked.
ADDRESSABLE WRITE POINTER: allows new data to be written from that address forward.
CHARACTER GENERATOR: 8 \times 12 resolution stroke characters. Modified full ASCII set (compatible with HP 9825A keyboard). Character strokes are stored in plug-in ROM's.
4 PROGRAMMABLE SIZES: 1 \times , 2 \times , 4 \times , 8 \times , 80 characters per line and 51 lines (not to exceed memory size) at 1 \times character size.
2 PROGRAMMABLE ORIENTATIONS: 0 $^\circ$ and 90 $^\circ$.
INPUT CONNECTOR: rear panel, conforms to IEEE 488-1975.
OUTPUT CONNECTORS: three rear panel BNC's for X, Y, and Z axes with shields grounded. Four rear panel BNC auxiliary outputs for TTL blanking of displays.
FRONT PANEL INDICATOR LIGHTS: power interrupt, listen data, listen program, power on.
OPERATING ENVIRONMENT
TEMPERATURE: (operating) 0 $^\circ$ C to +55 $^\circ$ C (+32 $^\circ$ F to +130 $^\circ$ F); (non-operating) -40 $^\circ$ C to +70 $^\circ$ C (-40 $^\circ$ F to +158 $^\circ$ F).
HUMIDITY: to 95% relative humidity at +40 $^\circ$ C (+104 $^\circ$ F).
ALTITUDE: (operating) to 4600 m (15 000 ft); (non-operating) to 7600 m (25 000 ft).
SHOCK: 30 g level with 11 ms duration and 1/2 sine wave shape.
VIBRATION: vibrated in three planes for 15 min. each with 0.25 mm (0.010 in) excursion, 10 to 55 Hz.
POWER: selectable 100, 120, 220 or 240 Vac, +5%, -10%, 48 Hz to 440 Hz maximum power 100 VA approximately 80 W). Average power dissipation at 60 Hz and 120 V without any options is approximately 74W.
SIZE: 98 mm H \times 426 mm W \times 511 mm D (3.875 \times 18.937 \times 20.125 in).
WEIGHT: 4.5 kg (2 lb).
PRICE IN U.S.A.: Model 1350A Graphics Translator, \$3450.
MANUFACTURING DIVISION: COLORADO SPRINGS DIVISION
 1900 Garden of the Gods Road
 P.O. Box 2197
 Colorado Spring, Colorado 80901 U.S.A.

who provided much help in the development of the Softcopy Graphics Library, and to new-product planning managers Dave Wilson and Bob Bell who helped define the instrument. 🍷



Arnot L. Ellsworth

Fresh out of the U.S. Navy, Arnie Ellsworth joined HP's Colorado Springs Division in 1969 as a production-line technician. He also started engineering studies part-time at the University of Colorado. In 1972, he transferred to the R and D labs, eventually assuming project leadership of the 1317A and 1321A CRT displays before becoming project leader on the 1350A. Arnie earned his BSEE degree at UC in 1974 and his ME degree in 1977. Work and school has left little spare time but

weekends are devoted to his family (wife, boy 5, girl 7) and church work. Arnie's a Corvette buff and he also joins his daughter in learning stunt roller skating.

Laboratory Notebook

Swept-Frequency Measurements of High Levels of Attenuation at Microwave Frequencies

A major difficulty facing anyone measuring high attenuation levels at microwave frequencies is getting adequate power to the measuring instrument's detector. One way around this problem is provided by the setup shown in the diagram.

Microwave power from the sweep oscillator is split off through a series of couplers and supplied directly to the measuring instrument's detector. The remaining power passes through a microwave amplifier and an amplitude modulator then through the attenuator under test before being coupled to the direct power path prior to detection.

The path containing the attenuator under test was made many wavelengths longer than the direct path so while the frequency is swept, the microwave power from the two paths at the detector goes rapidly in and out of phase. The resulting display on the CRT of the frequency response test set is thus a closely-spaced series of peaks, as shown in the photo, with the envelope of the peaks delineating

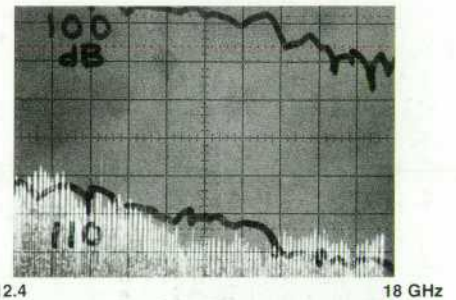
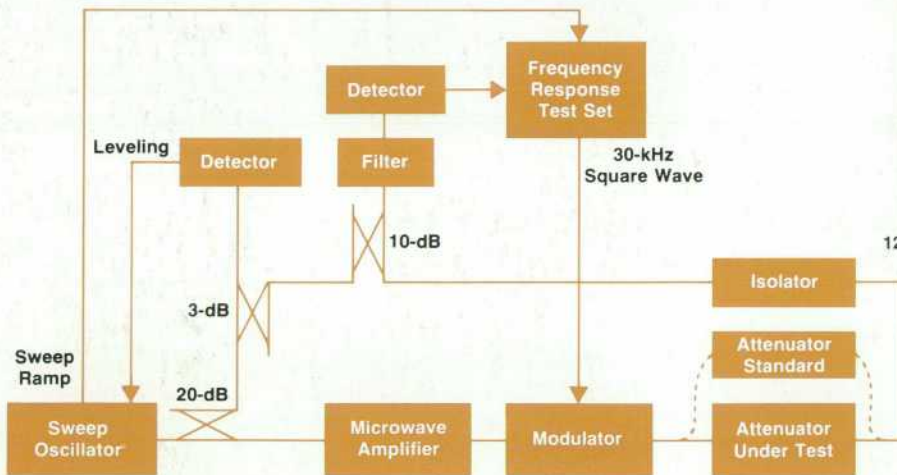
the attenuation-vs-frequency characteristics of the attenuator under test.

The advantage of this setup is that the power in the direct path causes the detector to operate as a linear detector, as long as the signal from the attenuator path is much smaller than the direct path. Much greater measurement sensitivity is thus obtained. This system, which is used for production-line testing of the Model 8496BH Step Attenuators,* has a dynamic range of 120 dB.

Much helpful advice was provided by Bob Kirkpatrick in the design of this system.

Robert Jacobsen
Stanford Park Division

* See "Economical Precision Step Attenuators for RF and Microwaves," by G.R. Kirkpatrick and D.R. Veteran, Hewlett-Packard Journal, May 1974.



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