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## In this Issue:



40 GHz stands for 40 gigahertz, which is the scientific way to say 40,000,000,000 cycles per second. That's a high frequency, 500 times higher than VHF television broadcast frequencies, but still 10,000 times lower than visible light. Equipment that operates in the 4-to-40-GHz range includes police speed detection radars, military and commercial aircraft radars, line-of-sight communications systems, and satellite up and down links. Even higher frequencies are in use, too. There's equipment in current production that operates up to 60 GHz, developmental systems that go up to 110 GHz or so, and experimental devices in the 2-300 GHz range. Two atmospheric windows at 34 and 94 GHz are of particular interest—these are frequencies at which the earth's atmosphere appears much more transparent than it does at other frequencies.

This month's issue and cover photo are devoted to some new high-performance microwave counter products that help test this high-frequency equipment. The system described in the articles on pages 3 and 14 measures frequencies as high as 40 GHz, whether the microwave energy is continuous or in the form of short bursts or pulses. The counter described in the article on page 20 measures the frequencies of continuous microwave signals up to 26.5 GHz.

Here's a question for designers of microprocessor-based equipment. What do you do when you find you have more read-only memory than you need to microprogram all the functions your equipment is supposed to have? Why, you add more functions, of course. Many a product has been upgraded in capability for very little added cost by using extra ROM space. But on page 25 you'll find another suggestion for using that spare ROM. If you save it for corrections to the basic ROM, you'll be able to order masked chips much earlier for all of your ROM except the chip that contains the corrections. That one can be an erasable ROM until all of the microcode is final. It's a simple way to get into production faster.

-R. P. Dolan

Editor, Richard P. Dolan • Contributing Editor, Howard L. Roberts • Art Director, Photographer, Arvid A. Danielson  
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# Microwave CW and Pulse Frequency Measurements to 40 GHz

*A new harmonic heterodyne frequency converter plug-in adds automatic 40-GHz frequency measurements to the universal capabilities of HP's top counter.*

by Richard F. Schneider, Ronald E. Felsenstein, and Robert W. Offermann

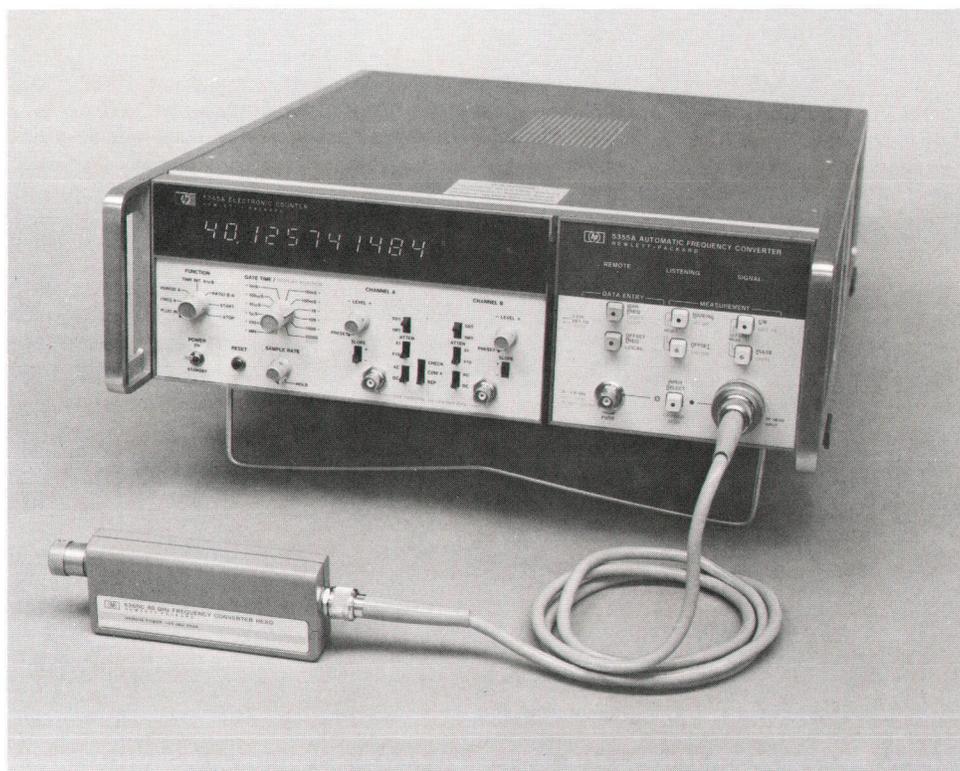
**T**O BE USEFUL in the widest possible range of applications, a microwave counter should be capable of measuring the carrier frequencies of pulsed or CW signals, and for pulsed signals, should also provide for time interval or frequency measurement of the pulse modulation. The design should be optimized with wide IF bandwidths for narrow pulses and wide FM deviations, and should have high sensitivity. Cost-effective frequency range selection and automatic operation are essential.

A new system that operates as a plug-in to the HP 5345A 500-MHz Universal Counter<sup>1</sup> is designed to meet these requirements over a carrier frequency range of 0.4 to 40 GHz. The system, which consists of the 5355A Automatic Frequency Converter and the 5356A/B/C Frequency Converter Heads, is shown in Fig. 1. It provides an effective alternative to the complex specially assembled systems that formerly were the only way to measure up to 40 GHz.

The 5356A/B/C Frequency Converter Heads eliminate the

need for microwave transmission lines to connect the measured source to the counter. Coaxial cables, while convenient, cannot always be used, since two-metre coaxial lines typically have about 10 dB loss at 18 GHz and get worse at higher frequencies. To circumvent this, hybrid microwave circuits in the heads down-convert incoming frequencies to intermediate frequencies (IF) that are easily transmitted over a 1.7-metre miniature coaxial cable to the 5355A Automatic Frequency Converter Plug-in. This eliminates the transmission line loss and effectively improves system sensitivity by that amount. Heads with various coaxial or waveguide connectors can be selected to meet the measurement requirement (see article, page 14).

Microprocessor control in the plug-in makes operation automatic in either pulse or CW mode. The new system uses the single-sampler harmonic heterodyne technique.<sup>2</sup> The microprocessor computes the input frequency according to the desired resolution set on the 5345A Counter front panel



**Fig. 1.** Model 5355A Automatic Frequency Converter plug-in for Model 5345A Counter measures the frequencies of CW or pulsed signals up to 40 GHz. Down-conversion of the input frequency takes place in the interchangeable 5356A/B/C Frequency Converter Heads, eliminating the need for high-frequency transmission lines between the source and the counter. External gating makes it possible to measure the frequency profile within a pulse.

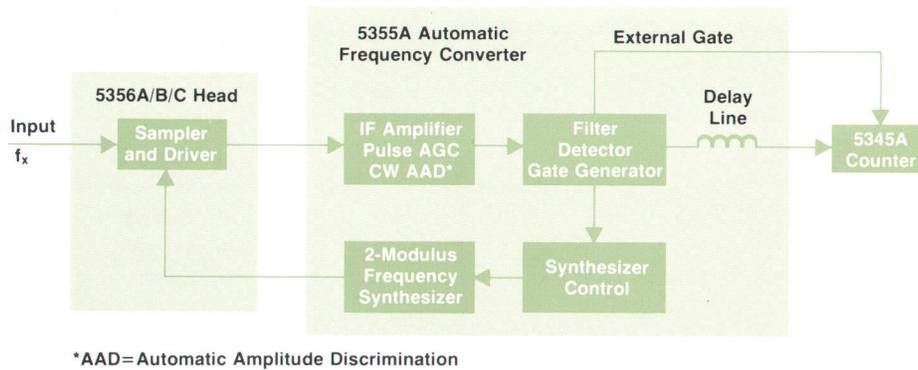


Fig. 2. Simplified block diagram of the harmonic heterodyne frequency conversion technique for CW and pulsed signals.

and displays the frequency on the counter's eleven-digit display.

The 5355A plug-in has a simplified keyboard that allows the user to select automatic or manual CW or pulse operation, to specify frequency offsets or multiplication of the measured frequency by a constant, to display frequency deviation, and to select the prescaler built into the plug-in. The prescaler divides the input frequency by eight. It is used to measure frequencies from 0.4 to 1.6 GHz; no frequency converter head is needed in this range. The prescaler has its own fused front-panel connector.

Pulse repetition frequency measurements and time interval measurements such as pulse width, pulse repetition interval, pulse repetition period, and pulse-to-pulse spacing are made by the reciprocal-taking 5345A Counter, using the detected IF from the 5355A Converter plug-in. The counter mainframe also measures frequencies from 50  $\mu$ Hz to 500 MHz. The counter has a maximum time interval resolution of two nanoseconds for single-shot intervals and two picoseconds for time interval average measurements.

The complete microwave counter system consisting of the 5345A Counter with the 5355A Frequency Converter and the 5356A/B/C Heads measures any frequency from 50  $\mu$ Hz to 40 GHz. Its sensitivity with the 5356A/B Heads is -20 dBm from 1.5 to 12.4 GHz and -15 dBm from 12.4 to 26.5 GHz. With the 5356C Head, sensitivity is 5 dB better up to 26.5 GHz and decreases to -10 dBm at 40 GHz. Prescaler sensitivity is -15 dBm from 400 MHz to 1.6 GHz.

In the automatic mode, the system measures the frequencies of RF pulses from 100 ns to 20 ms wide at pulse repetition frequencies of 50 Hz to 2 MHz. In manual mode, pulses as narrow as 60 ns can be measured, and external gates as narrow as 20 ns may be applied to the counter for applications such as measuring the frequency profile within a pulse.

For pulsed RF-signals, the FM tolerance is 50 MHz peak-to-peak for a 100-ns pulse in the automatic mode, and 80 MHz p-p for a 60-ns pulse in the manual mode. Automatic calibration of the 5345A mainframe assures accuracy to 3 kHz in pulsed carrier frequency measurements. Resolution is selectable to as fine as 100 Hz by frequency averaging. For example, a 26.5-GHz pulse radar with a 1- $\mu$ s wide pulse could be measured with a 10-ms gate time to a resolution of 10.3 kHz and an accuracy of 43 kHz or about 2 parts in  $10^6$  (assuming no time-base error).

For CW (continuous) signals, the maximum resolution is 0.1 Hz up to 10 GHz and 1 Hz from 10 to 40 GHz. The FM tolerance is 15 MHz p-p in the normal mode and 60 MHz p-p in the special FM mode.

## Harmonic Heterodyne System

The harmonic heterodyne technique has been described in previous articles.<sup>2</sup> Basically, a microwave sampler is driven at programmed synthesized frequencies, as shown in Fig. 2, until a signal occurs in the passband of the IF amplifier, indicating that some harmonic of the sampling frequency is mixing with the incoming microwave signal to produce a countable IF. The microprocessor then executes an algorithm to identify the harmonic number  $N$  and the sign of the IF (sum or difference), and solves for the input frequency, according to the equation:

$$f_x = Nf_s \pm IF \quad (1)$$

where  $f_x$  is the input frequency,  $N$  is the harmonic number, and  $f_s$  is the programmed synthesized frequency.

The harmonic number is determined by changing the synthesized frequency slightly and measuring the change in the IF frequency.

$$N = \frac{f_{IF1} - f_{IF3}}{f_1 - f_3} \quad (2)$$

$$\text{where } f_{IF1} = IF \text{ when } f_s = f_1$$

$$f_{IF3} = IF \text{ when } f_s = f_3$$

The sign of the IF in equation 1 is determined by whether  $f_{IF3}$  is larger or smaller than  $f_{IF1}$ .

## Pulse Mode

The basic design parameters of the system were derived from the pulse requirements and the mainframe counter's capabilities. Linear programming<sup>3</sup> was used to optimize the system. Seven equations in five variables were solved subject to various boundary conditions, including the minimum input frequency, the IF bandwidth, the IF guard band, the maximum harmonic number, and the minimum synthesizer frequency. The linear programming equations were entered into the computer and families of solutions were obtained for the five variables. Tradeoffs were then made to minimize the tuning range of the synthesizer oscillator and optimize the IF bandwidth. Finally, a separate computer program was derived to determine the minimum number of frequencies required to obtain complete frequency coverage. The result is a set of frequency tables, one for each frequency converter head. For example, with the 18-GHz Model 5356A head, only 13 synthesizer frequencies are required.

In the search routine the synthesizer is stepped instead of swept. The synthesizer frequency tables are stored in a ROM, and the synthesizer is stepped to the next frequency in the table after waiting the longest specified pulse repetition interval of 20 ms. This is repeated until a signal appears in the IF passband of 157 to 330 MHz. Next the synthesizer frequency is digitally incremented 4 MHz and the IF passband is tested. If the incremented-synthesizer IF falls outside the passband, the search routine proceeds to the next frequency in the table. If the IFs for both synthesizer settings are within the passband, the calculation of N and

the sign of the IF can proceed.

After the initial acquisition in the IF passband of 157 to 330 MHz, the IF can shift into the IF guard band without affecting the measurement. The guard band extends down to 78 MHz and up to 375 MHz, as shown in Fig. 3. If the IF moves out of the guard band, the 5355A reacquires the input and discards the results of any measurement in progress.

Automatic gain control of the IF amplifier in the pulse mode minimizes the required input signal on/off ratio and maintains the signal-to-noise ratio. An IF detector and a

## A 400-to-1600-MHz $\div 8$ Prescaler

by Hans J. Jekat

Behind the 0.4-to-1.6-GHz input on the front panel of the 5355A Automatic Frequency Converter is a prescaler that divides the input frequency by eight to bring it within the range of the 5345A Counter mainframe. The prescaler operates in both the CW and pulsed RF modes. An arming circuit senses marginal signals to keep the counter from miscounting. The prescaler input is protected by a fuse that is accessible from the front panel.

Fig. 1 is a block diagram of the prescaler. The latest state-of-the-art technology has been applied in the design of the attenuator, amplifier, and binary circuits.

### AGC Attenuator

The attenuator and the AGC (automatic gain control) circuit (see Fig. 1) are used in both CW and pulsed RF modes. AGC is very important in the pulsed RF mode, since unwanted signal during the off condition of the pulse signal could cause the pulse detector to delay its gate closing. Therefore, the AGC is set to a level where the RF pulse can be counted, and the off portion of the pulse is then

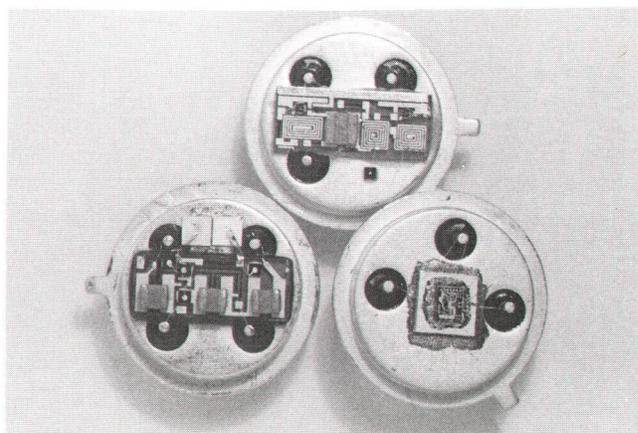


Fig. 2. Attenuator (l.), amplifier, and binary (r.) are housed in TO-12 packages.

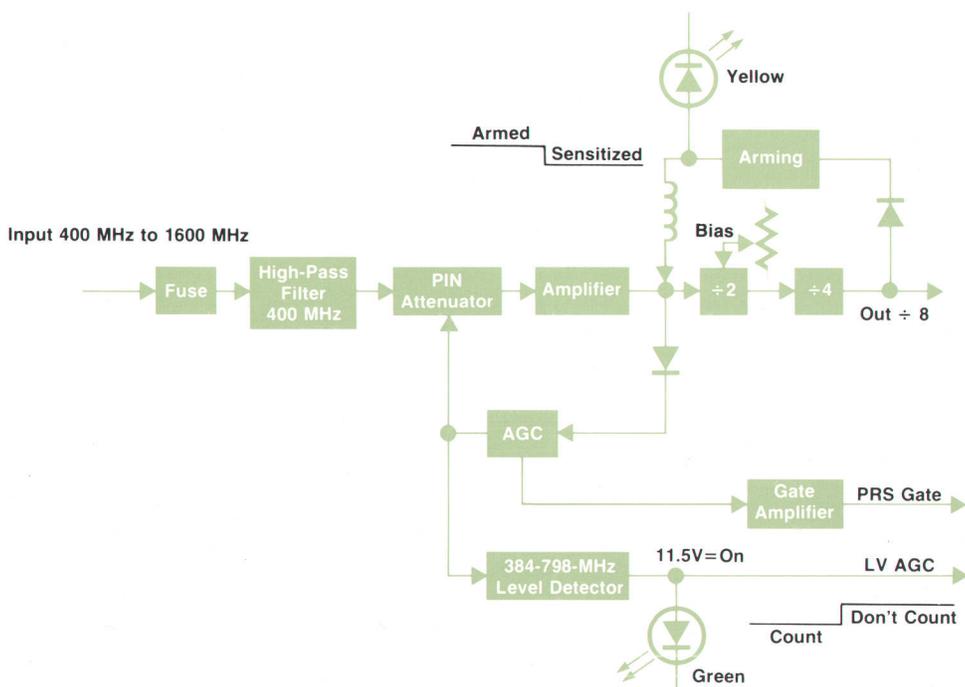
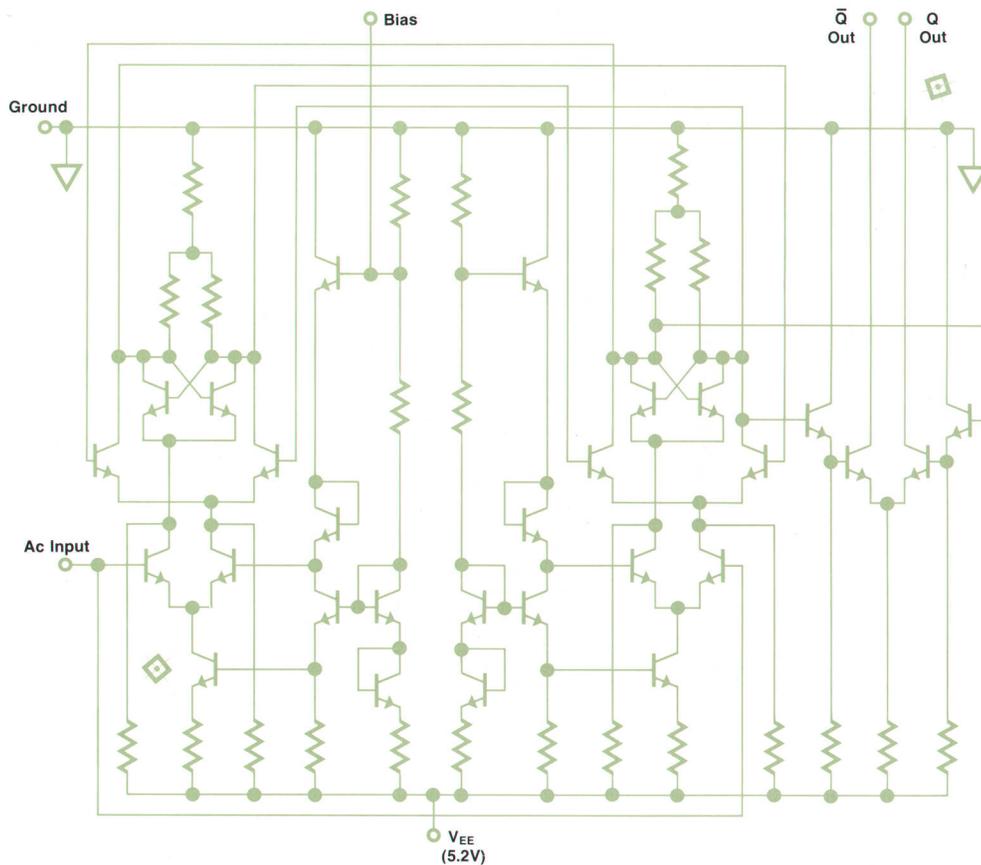


Fig. 1. Block diagram of the 400-1600 MHz  $\div 8$  prescaler in the 5355A Automatic Frequency Converter.



**Fig. 3.** 1.6-GHz binary (+2 circuit) consists of two cross-coupled current-mode flip-flops in a master-slave configuration.

compressed to a point below the input sensitivity, thereby preventing noise counting and gate jitter. The attenuator contains four PIN diodes connected in a  $\pi$  configuration. There are two PIN diodes in the transmission line compared to the one that is commonly used in a  $\pi$  attenuator. The advantage is that the off capacitance is only half as great and therefore, the attenuation in the off condition is higher. The tradeoff is a slightly higher input VSWR. To get good high-frequency attenuation, the bypass capacitors are parallel-plated capacitors with an extremely low profile of 0.13 mm. Parallel resonances and inductive reactances are not discernible. The attenuator is packaged in a TO-12 four-lead package (see Fig. 2).

### 2-to-1600-MHz Amplifier

The amplifier used in the prescaler is constructed on a sapphire substrate measuring 2.5 by 6.4 mm. Only two transistors and one chip capacitor have to be mounted on the sapphire substrate. The rest of the circuitry consists of thin-film resistors and thin-film inductors. The low parts count in the amplifier yields a very high reliability. The amplifier has  $\pm 1$  dB flatness and 24 dB gain, and is housed in a TO-12 package (Fig. 2), which uses little space on the prescaler printed circuit board.

### 1.6-GHz Binary

The 1.6-GHz binary (+2 circuit) is a monolithic high-frequency divider circuit (see Fig. 3). Two current-mode flip-flops are cross-coupled in a master-slave configuration. Second-level current switches control updating and latching of the flip-flops. Two input bias lines to the master flip-flop second-level current switch control self-oscillation and bandwidth by prebiasing the data transistors. This makes them switch faster, since they do not have to wait for the total output swing of the slave flip-flop. This technique requires a larger voltage swing for lower frequencies, and since the voltage swing is limited, the low-frequency response is degraded. In other

words, we are trading off low-frequency toggle speed for high-frequency toggle speed.

By controlling the clock input bias, the binary can be pushed into self-oscillation around 1200 MHz. At this point, the binary is in its most sensitive region over the entire bandwidth. The binary stops oscillating and begins dividing when an RF pulse appears at the prescaler input. In CW mode, the 1.6-GHz binary is biased to a point of no self-oscillation. This sacrifices some sensitivity but assures that the counter will not respond to noise. In pulsed RF mode, the binary can be biased in the more sensitive oscillating mode since the gate signal dictates which signal is counted.

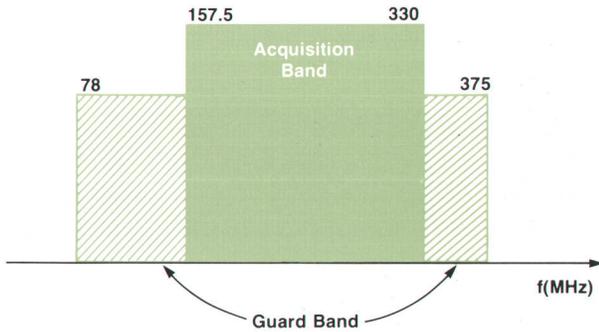
The binary is packaged in a four-lead TO-12 package (see Fig. 2) and the casting of the prescaler acts as a heat sink for it.

### Hans J. Jekat



Hans Jekat is an electrical engineering graduate of the Technische Hochschule in Munich. He moved to the U.S.A. in 1958, and since 1964 has been with HP's Santa Clara Division. He served as project leader for the 5300 Measuring System and designed the 5300A mainframe, the 5305A/B Counters, several of the MOS/LSI circuits used in the 5300 system and other instruments, and the prescaler and IF amplifier for the 5355A Frequency Converter. His counter work has resulted in several patents. Hans is married, has two sons, and lives in Redwood City, California. For many years a trainer of show horses, he also enjoys soccer and skiing.

For many years a trainer of show horses, he also enjoys soccer and skiing.



**Fig. 3.** 5355A IF passband extends from 157.5 to 330 MHz for the down-converted carrier frequency. The guard band allows for worst-case FM on the carrier of 45 MHz peak. The specification is 80 MHz peak-to-peak for pulsed signals.

gate generator provide the 5345A Counter with an external gate signal about 30 ns shorter than the pulse burst and centered on the burst to eliminate measurement of the rise and fall frequency transients.

### Calibration

The main gate circuits in the 5345A Counter have an asymmetry that causes a small difference between the time it takes for the gate to open and the time it takes for the gate to close. This difference, typically about 300 picoseconds, becomes significant when the gate is opened and closed many times for a single measurement on narrow pulses. The error is proportional to the intermediate frequency and inversely proportional to the input pulse width.

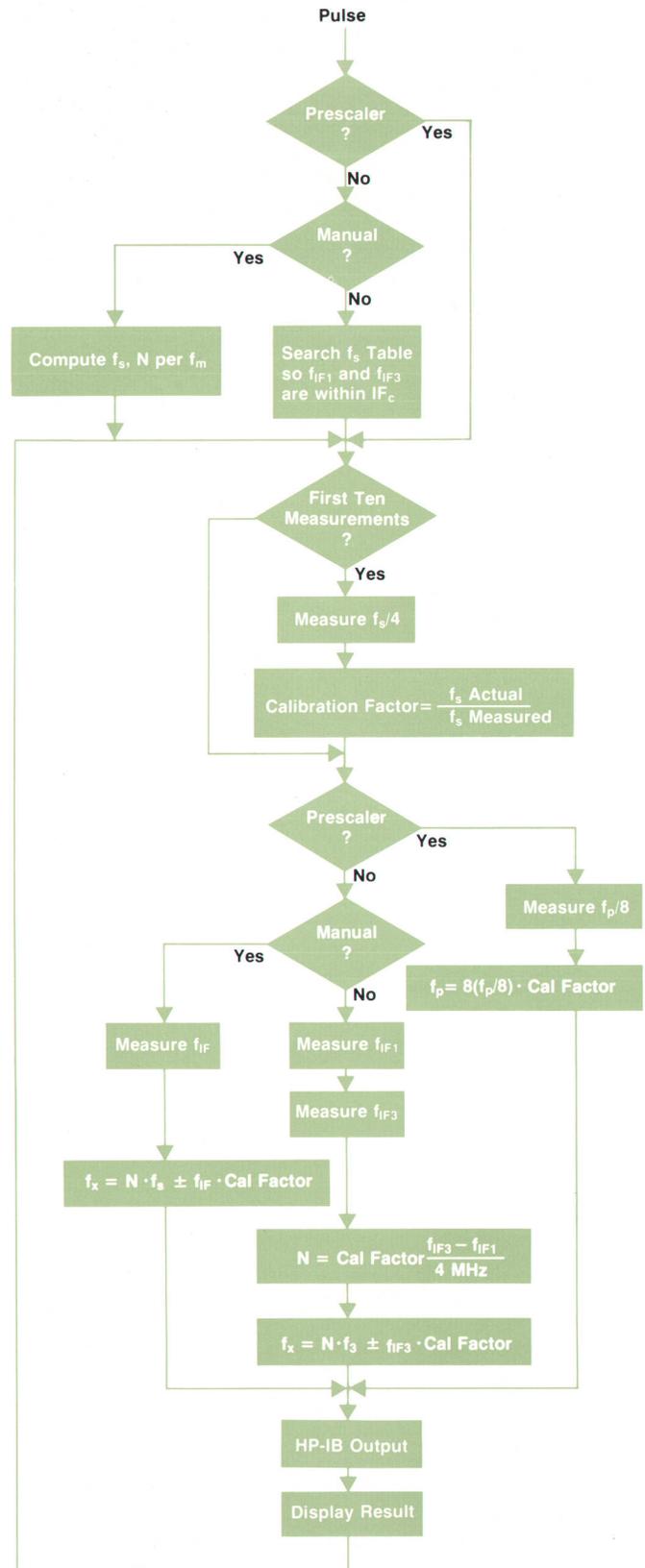
To minimize the effect of this error, an automatic calibration routine in the 5355A is used whenever pulse bursts narrower than 100  $\mu$ s are measured. The calibration routine uses the synthesizer signal for a reference frequency by switching this signal into the IF after dividing by four. Using the gate derived from the input signal, this reference signal is measured, and the ratio of the actual synthesizer frequency to that measured is computed and used as a calibration factor. To improve the accuracy of the calibration factor, it is averaged for the first ten measurements after the signal is acquired. The letter **C** is displayed in the left-most position of the 5345A display during these ten measurements to indicate that calibration is taking place.

A change in the input pulse width of more than 12%, or loss and reacquisition of the input, will cause a new calibration cycle to take place. A special operating mode disables the calibration scheme for relative frequency measurements where absolute accuracy is not required.

### Pulse Algorithm

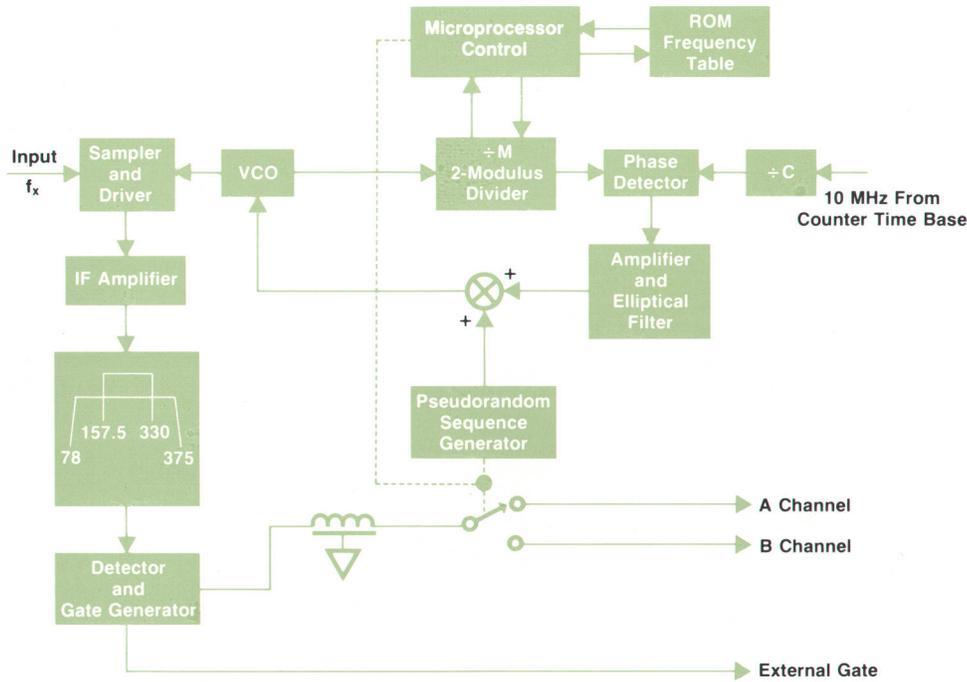
The flow diagram shown in Fig. 4 outlines the search, acquisition, calibration, computation, and measurement cycles of the pulse algorithm. The harmonic number determination is made with a 100- $\mu$ s minimum gate time. A normal pulsed frequency measurement is made of  $f_{IF1}$  and  $f_{IF3}$  for synthesizer frequencies  $f_1$  and  $f_3$ , respectively. The harmonic number  $N$  is then computed as follows:

$$N = \frac{f_{IF3} - f_{IF1}}{4 \text{ MHz}} \times \text{Calibration Factor}$$



Definition of Symbols: See Fig. 6, page 9

**Fig. 4.** Search, acquisition, calibration, computation, and measurement algorithm for pulse measurements.



**Fig. 5.** In CW mode, a pseudorandom sequence generator modulates the VCO frequency. A and B counters measure the two VCO frequencies and the corresponding intermediate frequencies. This information makes it possible to identify which harmonic of the VCO is mixing with the input to produce the IF. The length of the pseudorandom sequence determines the allowable FM in the CW mode.

N is continually measured during an automatic measurement.

For a 100- $\mu$ s gate time, the time required for a pulse frequency measurement is  $2 \times 100 \mu\text{s}$  divided by the duty factor of the pulse signal. Since the duty factor is the gate width multiplied by the pulse repetition frequency, a 1- $\mu$ s wide pulse with a 1-kHz repetition rate requires 200 ms to measure.

### CW Mode

Harmonic number determination in the CW mode uses a pseudorandom sequence technique described previously<sup>4</sup> to improve tolerance to FM. The counter's FM tolerance of 15 MHz p-p is related to the length of the sequence, which is normally set for 22 ms. A special mode lengthens the sequence to 360 ms for 60 MHz p-p FM tolerance.

The pseudorandom sequence is applied to the frequency synthesizer at the VCO (voltage-controlled oscillator) input, as shown in Fig. 5, at a rate outside the phase-locked-loop bandwidth. The loop remains locked, but the pseudorandom sequence modulates the VCO frequency about 4 MHz peak-to-peak. The harmonic number and the sign of the IF are determined by switching the counter between the A and B channel inputs synchronously with the 4 MHz modulation step. The pseudorandom sequence is activated twice, once to measure the synthesizer frequency change and once to measure the corresponding IF change. In each case the frequency change is the difference between the A and B counts. To determine N the IF change is divided by the synthesizer change and the result is rounded to the nearest integer (see next section). With this technique, only one synthesizer is needed (many systems switch between two synthesizers to determine N). The CW frequency resolution, a measure of the synthesizer noise spectral density, is typically less than  $\pm 2$  Hz at 18 GHz with a one-second gate time.

Automatic amplitude discrimination is provided in the CW mode by using a limiting IF amplifier and providing an IF bandwidth that is greater than half the sampling rate. This tends to make the average zero-crossing rate equal to the frequency of the highest-level signal present. The counter will measure this frequency, provided that this signal is more than 8 dB greater than signals within 500 MHz and 20 dB greater than other signals within the frequency range of the 5356A and 5356B Heads.

### CW Algorithm

The CW algorithm is shown in Fig. 6. Note that the synthesizer deviation is measured as well as the IF deviation. This is required to determine the synthesizer deviation accurately, since the modulation sensitivity of the VCO is not perfectly linear. The harmonic number N is then computed as follows:

$$N = \frac{\Delta f_{IF}}{\Delta f_2}$$

The harmonic number is checked every ten gate times to make sure it is correct.

### Synthesizer

The divide-by-M frequency synthesizer is phase-locked to the 10-MHz time base of the 5345A mainframe. It operates from 885.2 to 1056 MHz. A two-modulus divider, controlled by the microprocessor according to the frequency table stored in the ROM, sets the frequency as shown in Fig. 7. Each converter head is coded so that when it is plugged into the 5355A, the proper frequency table is accessed. The VCO steps through the frequencies in a nonlinear manner. The minimum change is 400 kHz.

The VCO output is amplified and sent to the 5356A/B/C

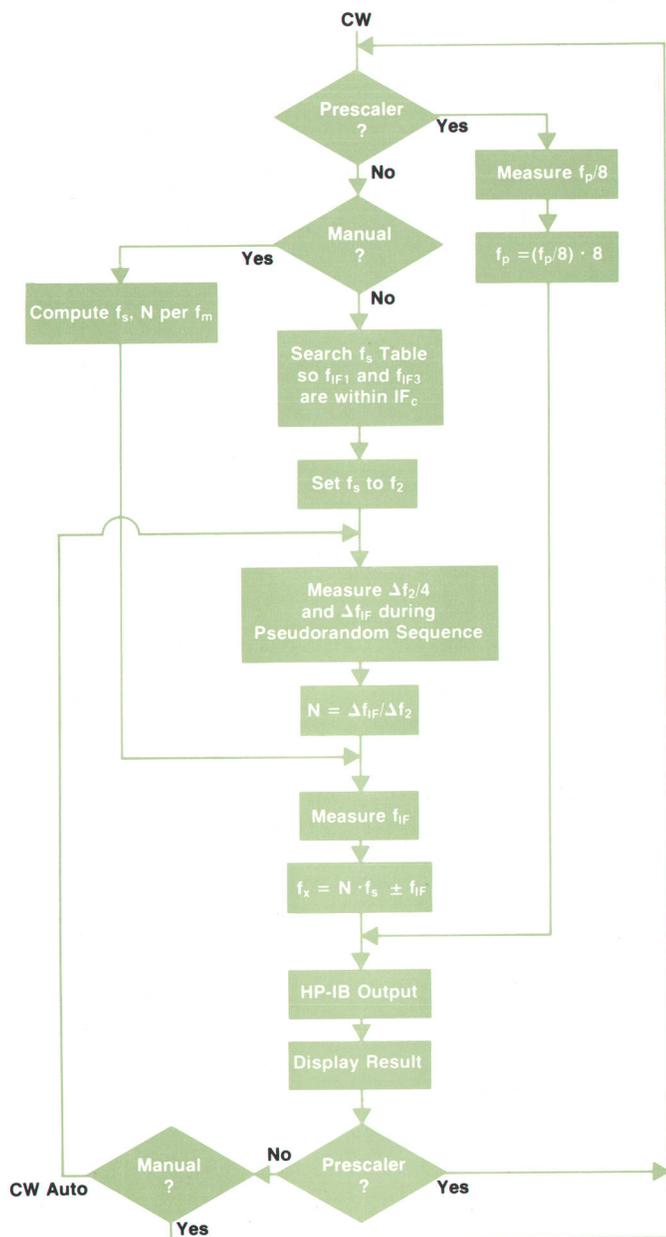


Fig. 6. CW measurement algorithm.

**Definition of Symbols for Figs. 4 and 6**

- $f_p$  Unknown prescaler frequency input
- $f_s$  Synthesizer frequency
- $f_x$  Unknown RF head frequency input
- $f_{IF}$  Down-converted IF (intermediate frequency)
- $N$  Harmonic of  $f_s$  that, mixed with  $f_x$ , produces  $f_{IF}$
- $f_m$  Keyboard-entered manual frequency
- $IF_c$  IF center passband 157.5 to 330 MHz
- $f_1$  Value for  $f_s$  from a synthesizer table
- $f_2$   $f_1 + 2$  MHz
- $f_3$   $f_1 + 4$  MHz
- $f_{IF1}$  Down-converted IF when  $f_s = f_1$
- $f_{IF3}$  Down-converted IF when  $f_s = f_3$

Head and to the phase-locked loop buffer amplifier. This signal is then divided by four and applied to the microprocessor-controlled  $\div M$  two-modulus divider. The two-modulus divider permits the setting of frequencies other than the normal integer values by switching between  $\div 40$  and  $\div 41$  division factors. The phase detector has a reference frequency input of 100 kHz derived from the 10-MHz counter time base.

In the CW mode, the harmonic number is determined by applying the pseudorandom sequence to the VCO input. The pseudorandom rate is outside the loop bandwidth so that the center frequency of the synthesizer is not perturbed. A high-and-low-gain amplifier is used to optimize the system performance for both frequency measurement and  $N$  determination. Low gain is used during harmonic number determination so the maximum peak-to-peak deviation is obtained, while high gain is used during the frequency measurement to obtain the best spectral purity.

Elliptical filtering is used to minimize the 100-kHz sidebands that are caused by noise on the 100-kHz reference signal feeding through and modulating the VCO. Another operational amplifier is used to condition a tuning signal that goes to a filter in the IF amplifier. This filter tracks the synthesizer tuning and maintains the IF amplifier cutoff frequency at about one-half the sampling frequency (synthesizer frequency) to minimize spurious responses.

Special precautions were taken to reduce the power-line sidebands in the synthesizer spectrum. It was necessary to wrap the elliptical filter inductor with a mu-metal shield and place a sheet of transformer steel alongside the printed circuit board casting to obtain the specified resolution.

**IF Filter/Detector/Gate Generator**

The various IF bands are determined by three analog filters followed by level detectors as shown in Fig. 8. The edges of the acquisition band have individual filters and detectors, while the guard band is determined by cascaded high-pass and low-pass filters followed by a single detector. All filters are five-pole Chebyshev type and all detectors consist of a low-barrier Schottky diode and a capacitor.

The IF input is limited and has constant amplitude. The detected level on each capacitor is compared to a reference voltage by a high-speed voltage comparator, the output of which gives a digital indication of the presence of a signal in the passband of the associated filter. By designing the filter so that the band edge frequency is several dB into the filter's stopband, the exact cutoff frequency can be set by a simple adjustment of the reference voltage. This allows precise determination of the band edges without precision trimming of the filters themselves. The outputs of the three comparators are combined by logic that produces four data lines from which the microprocessor can determine when a CW or pulse signal is present in the acquisition or guard bands.

The detection scheme is fast enough to detect the presence of a valid IF signal from a single 60-ns wide burst. This not only minimizes acquisition time in the pulse mode, but also allows these same circuits to be used for generation of a signal to gate the 5345A for pulse measurements. When a pulsed-RF signal is present in the passband of one of the filters, the output of the associated comparator approxi-

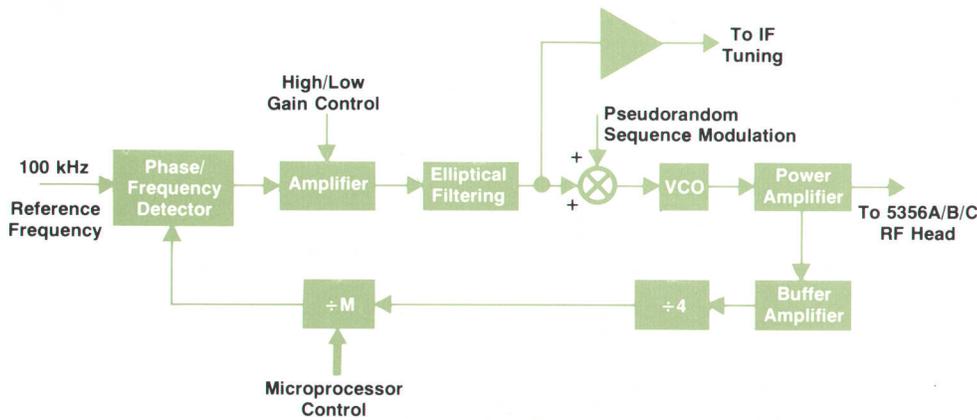


Fig. 7. The 5355A's frequency synthesizer generates the local oscillator signal to down-convert the input signal in the 5356A/B/C Frequency Converter Head.

mates the modulation envelope of the input RF signal. By using the comparator following the 78-to-375-MHz bandpass filter, a gate will be obtained whenever there is a countable signal present. However, it is not desirable to use this detected envelope directly as a gate. This is because pulse modulators commonly introduce a significant amount of phase distortion in the process of turning the RF signal on and off. Also, if the gate signal is the same width as the burst to be counted, the timing of the gate relative to the burst becomes extremely critical. For these reasons it is desirable to make the gate signal narrower than the burst to be counted, thus avoiding miscounts due to both turn-on and turn-off distortion and to incorrect alignment between the gate and the RF burst. This is done by using a comparator in the detector that has two outputs, each with an independent enable. One output is delayed and then used to enable the other output, thus causing the leading edge of the second output to be delayed. However, when the RF burst ends, both outputs return to the no-signal state simultaneously. The result is a pulse on the second output that is narrower than the input pulse by the amount of the delay, which in this case is 30 ns. This output is translated to the

proper levels and routed to the "gate out" connector on the 5355A's rear panel. From there, it is connected to the gate control input on the 5345A using the cable supplied with each 5355A. The IF signal is internally routed to the 5345A via a delay line of the proper length so that the gate pulse is centered in the IF burst at the 5345A's main gate flip-flop. This timing relationship is shown in Fig. 9.

### Front Panel

The 5355A has two inputs, one with a range of 400 to 1600 MHz, and the other for the removable high-frequency RF head. A simple seven-pushbutton keyboard handles all the measurement and diagnostic functions. Most of the user applications are handled by three of the keys. The two right-hand keys determine a PULSE or CW measurement, and the bottom key selects the appropriate input.

The four remaining keys are used for more sophisticated measurements, such as manual or offset measurements. These measurements require keyboard-entered frequencies. To enter a manual frequency, the gold MAN FREQ key is pushed to place the 5355A in gold data entry mode. In this mode, the gold legends on the front panel apply. By using

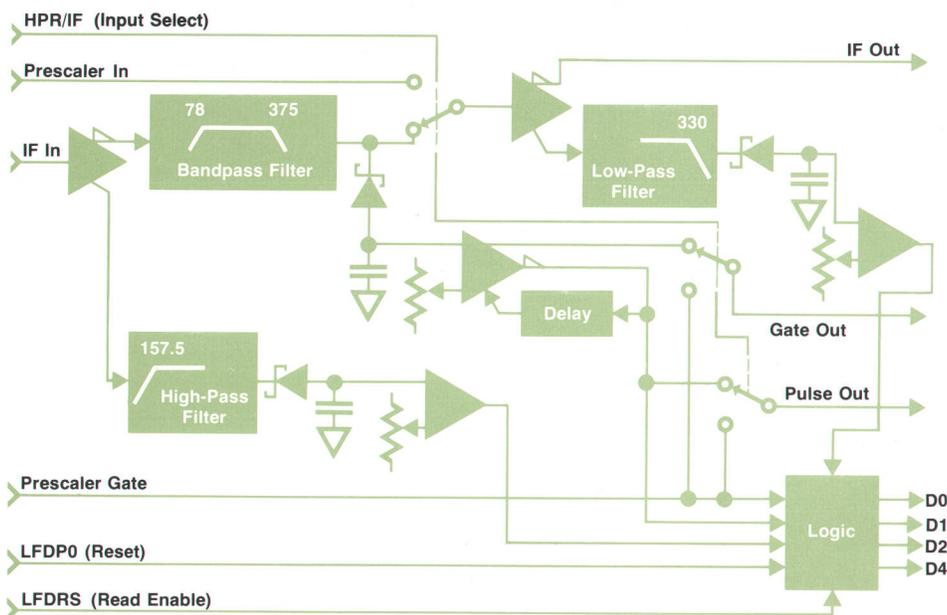
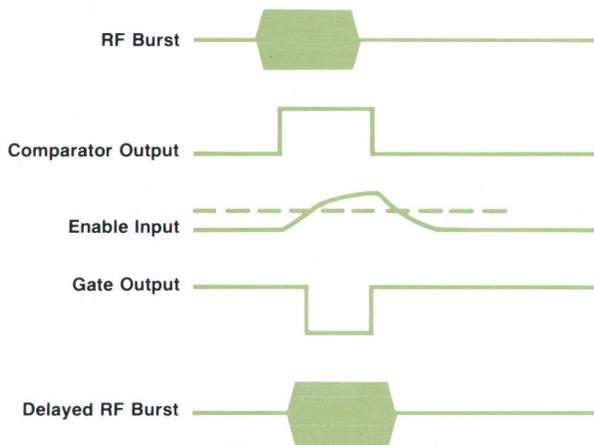


Fig. 8. IF filter, detector, and gate generation circuits.



**Fig. 9.** 5355A gate timing. The gate signal is shorter than the detected RF pulse and centered on it. This eliminates miscounts due to turn-on and turn-off distortion.

the two keys labeled UP and DOWN, the desired manual frequency can be entered. For a manual measurement the frequency entered must be within 50 MHz of the input frequency. Pushing the gold key again restores the 5355A to its previous measurement mode.

To enter an offset frequency, the blue OFFSET FREQ key is pushed to place the 5355A in blue data entry mode. In this mode, the blue legends apply. Using these keys, the sign, mantissa, decimal point, and units of the offset frequency can be entered. Pushing the blue key again restores the 5355A to its previous measurement mode.

Diagnostics and special functions are engaged by pushing two keys simultaneously. Pushing CW and PULSE activates one of two specialized measurement modes. When the 5355A is in CW mode, a long pseudorandom sequence is activated so that more FM can be tolerated at the input. When the 5355A is in pulse mode, the calibration factor is computed continuously (normally it is computed on only the first ten measurements).

Pushing the blue and gold keys simultaneously engages various diagnostics and specialized modes. Each time these two keys are pushed, two digits centered between equals signs are displayed in the 5345A mainframe for one second. The digits identify which mode is being activated. A total of 21 modes are available. Presently, 17 have been assigned.

All of the front-panel functions are remotely programmable via the HP-IB.\* The programming resembles pushbutton operation for all measurements, diagnostics, and specialized modes. For data entry of manual and offset frequencies, a floating-point input format is used.

### Resolution and Accuracy

The resolution of a frequency measurement is directly proportional to the gate time. For example, a 1- $\mu$ s gate time provides a resolution of 1 MHz. To improve the resolution on CW or repetitive pulsed RF signals, frequency averaging is used. Averaging improves the resolution by  $\sqrt{n}$ , where  $n$  is the number of samples averaged.<sup>5</sup> For a 1- $\mu$ s external gate signal and a 5345A gate time setting of 10 ms,  $10^4$  external gates are required to complete one measurement and im-

\*Compatible with IEEE 488-1978.

prove the resolution to 10 kHz. By frequency averaging, resolution may be increased to 100 Hz, depending upon the total measurement time, as shown in Fig. 10.

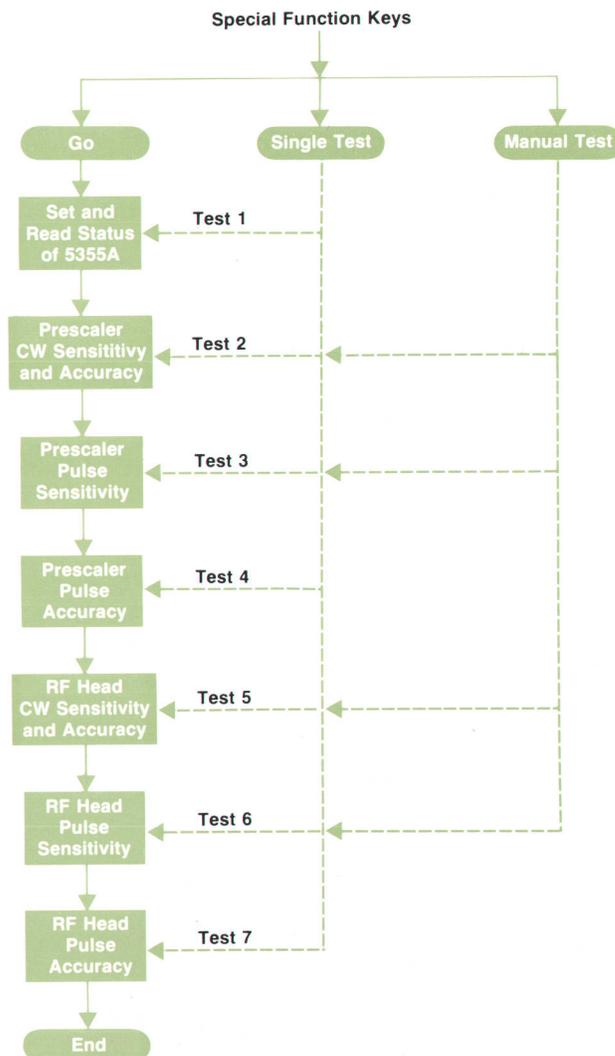
Gating errors in the 5345A, described previously in the calibration section, cause frequency errors inversely pro-

## An Automatic Microwave Frequency Counter Test System to 40 GHz

by Larry L. Koepke

Testing the 5343A Microwave Frequency Counter, the 5355A Automatic Frequency Converter, and the 5356A/B/C Frequency Converter Heads for conformity to all of their specifications over their entire frequency ranges is not a trivial task. To handle this formidable job, a special automatic test system had to be devised. Some of its features are:

1. The software programs are structured to allow the operator to run a full set of tests automatically (without operator assistance), to select a single test to run, or to select frequencies and power levels manually (see Fig. 1).



**Fig. 1.** Test program structure and special function key assignments in the Microwave Counter Test System.

2. The system can make numerous repetitive frequency measurements at different power levels automatically, freeing the test technician to align and/or repair instruments that have failed the automatic tests.
3. The system provides failure reports to help the test technician locate instrument failures.
4. In the data log mode the system provides a printout of the complete test.
5. The operator is made aware of a failure or the end of a test by an audible signal.

The Microwave Counter Test System is controlled by an HP 9825A Desktop Computer using HP-IB\* signal sources (HP 3330B, HP8660C, HP 8672A) to derive the frequencies of 10 Hz to 40 GHz. Frequencies of 18.5 GHz to 26.5 GHz are derived by doubling the 8672A frequencies of 9.25 GHz to 13.25 GHz. Frequencies of 26.5 GHz to 40 GHz are derived by quadrupling the 8672A frequencies of 6.625 GHz to 10 GHz.

The system is capable of supplying CW or pulsed RF to the instruments under test. A 5359A Time Synthesizer is used to generate pulses to modulate the CW signal generator outputs. HP 33311B/C Coaxial Switches used for signal switching and an HP 8495K 10-dB Step Attenuator are controlled via the HP-IB by three HP 59306A Relay Actuators. Two HP 436A Power Meters controlled via the HP-IB and one HP 432C Power Meter controlled via an HP 98032A 16-bit I/O Interface make the required power measurements. Frequency measurements on the combined 5355A Converter (listen only) and 5356A/B/C Heads are made by the 5345A Counter and output via the HP-IB to the 9825A Desktop Computer. 5343A Microwave Frequency Counter frequency measurements are output directly via the HP-IB to the 9825A. A separate HP 98034A HP-IB I/O interface was used for

the instruments under test (5343A or 5355A), so that an HP-IB failure in one of these instruments would not affect the system instruments under HP-IB control, which are on another 98034A HP-IB I/O Interface. Fig. 2 is the system block diagram.

The instrument test programs, associated data files, and special function keys are stored on the HP 9885M Flexible Disc. When the system is first powered up the 9825A Computer automatically loads track 0, file 0; the Start program loads the special function keys from the flexible disc and displays *PRESS S.F. KEY FOR DESIRED UNIT*. The operator presses the special function key on the 9825A corresponding to the instrument being tested, and the instrument test program selected by the operator is loaded from the 9885M Flexible Disc into the 9825A memory and executed from line 0. The operator now answers questions asked by the 9825A: do you wish to data log? yes or no; if yes enter the date; enter the instrument serial number. The complete test is then executed.

### Larry L. Koepke



Larry Koepke has been a test and electronic tooling technician with HP since 1959. Born in Rockford, Iowa, he learned his electronics in the U.S. Army. He assembled the test system and wrote the test programs for the 5355A Frequency Converter, the 5356A/B/C Heads, and the 5343A Microwave Counter. A resident of San Jose, California, Larry is married, has two daughters and one grandson, and likes to ride horses and bicycles.

\*Compatible with IEEE 488-1978.

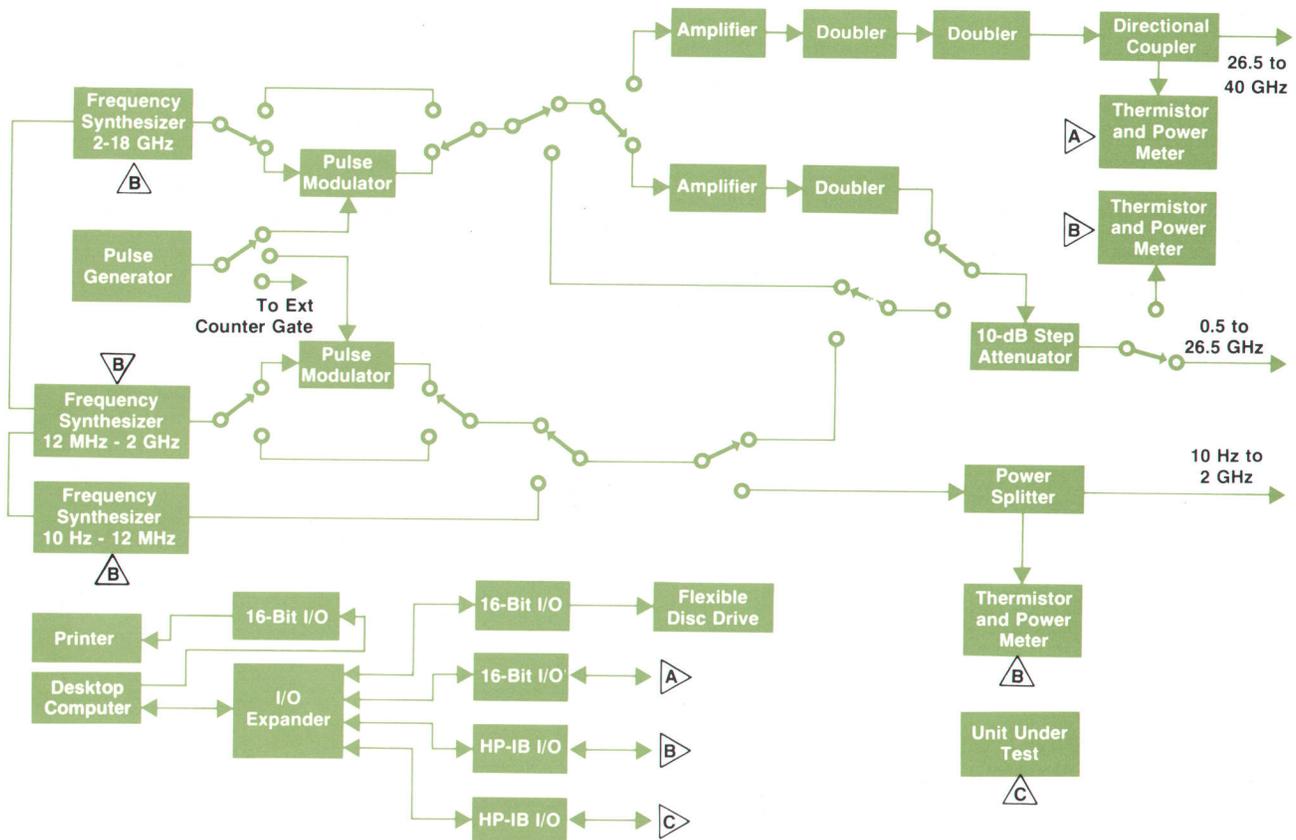


Fig. 2. Block diagram of the Microwave Counter Test System.

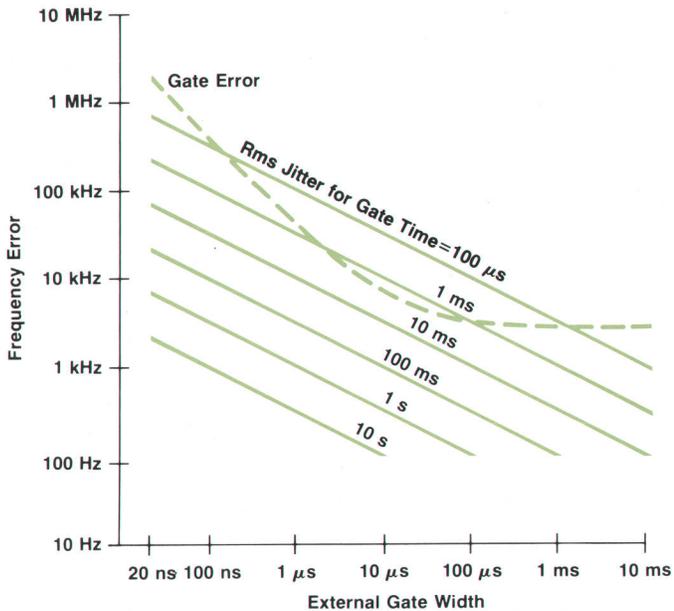


Fig. 10. Gate error and resolution of frequency average measurements as a function of gate width.

portional to external gate width. The calibration routine improves the accuracy about one order of magnitude. The residual gate error, shown in Fig. 10, is independent of gate time and may be decreased to 3 kHz for external gate widths from about  $4\mu\text{s}$  to  $100\mu\text{s}$ . Since the resolution of the calibration factor is not zero and secondary 5345A main gate errors are present, 3 kHz is the accuracy limit. However, calibration is not used for external gate widths greater than  $100\mu\text{s}$ , so the accuracy is the same as the 5345A Counter in this region.

Since no pulse burst standard exists, pulse accuracy measurements are made with a CW source with the mainframe counter externally gated. Actual pulse measurements using the test equipment described on page 11 typically are more accurate than the specification. Fig. 11 shows the results of typical pulse measurements on an 18-GHz synthesizer as a function of pulse width.

Pulse modulation of a source causes phase modulation of the carrier, especially during the rise and fall times of the pulse. This can be a result of direct FM or  $\Phi\text{M}$ , AM-to-FM conversion, or frequency pulling of the source. A video signal (feedthrough of the pulse modulation) may also be present along with the modulated carrier, further distorting the waveshape. Although the 5355A's adaptive gate generator removes about 15 ns from the leading and trailing edges of the pulse, some phase modulation may remain, especially for short pulses. Therefore, frequency accuracy for burst measurements depends on input signal purity; any phase perturbations that cannot be removed by the 5355A will cause errors.

A typical CW statistical measurement of a synthesized 18-GHz source with the source and counter time bases tied together using a 1-s gate time had a standard deviation (one sigma) of 0.57 Hz and a mean difference of  $-0.08$  Hz for 1000 measurements.

### Self Check

The 5355A can perform six measurements, two using the prescaler input and four using the RF head input. With the prescaler, either pulse or CW mode can be selected. With the RF head, pulse auto, CW auto, pulse manual, or CW manual can be selected.

The 6800 microprocessor executes these complex algorithms using 12K bytes of ROM and 1K bytes of RAM. With the flexibility the microprocessor allows, it was easy to implement special self-check routines that execute whenever the instrument is turned on. In the 5355A, the two RAM integrated circuits are verified for data-pattern read/write and addressability. Then the two ROM integrated circuits are tested via a checksum. Following RAM and ROM tests, the synthesizer is programmed to three known frequencies and performs three  $100\text{-}\mu\text{s}$  measurements to verify each setting. Should any of these power-on tests fail, the operator gets a unique ten-second warning display per failure. Thereafter, the 5355A will attempt to follow the measurement algorithm specified by the user.

### Acknowledgments

The team that developed the 5355A and the 5356A/B/C was as follows: Luiz Peregrino did most of the initial investigation, systems analysis, and synthesizer design. The MPU/HP-IB hardware was developed by John Shing. Mohamed Sayed was responsible for the 5356A/B/C heads. He developed the 40-GHz sampler, VCO, sampler driver, high-pass filter, and power amplifier hybrids, and provided the integration and testing of the heads. The prescaler channel was the responsibility of Hans Jekat, who also designed the IF amplifiers and provided many solutions to systems problems. The mechanical designer of the 5355A was Dick Goo, and of the 5356A/B/C was Keith Leslie. Tool design was by Jerry Curran. Martin Neil provided the initial

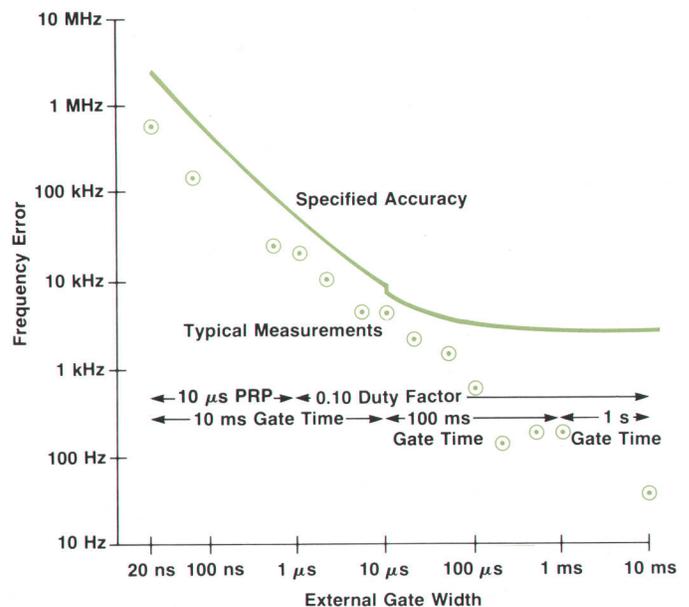


Fig. 11. Typical measurements on an 18-GHz pulsed source. Peak pulse power is  $-10$  dBm. Each point is the average of 100 measurements.

marketing introduction, and Larry Johnson completed that assignment. Randy Goodner was the service engineer, and Larry Koepke built the microwave counter test system and wrote the software. Quality assurance was under the surveillance of Joe Bourdet. Alex Campista and Ron Harter were the pilot run technicians. Ian Band was the lab engineering manager and Roger Smith the microwave counter section head. Many thanks to all of the people above and to all of the others that contributed to the production of these instruments.

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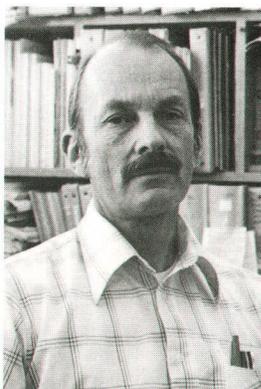
#### Robert W. Offermann

Bob Offermann received his BS degree in electrical engineering from California Institute of Technology in 1971, and for the next two years combined circuit design work at the U.S. Naval Undersea R&D Center with graduate studies at Caltech. He received his MS degree in 1973 and joined HP shortly thereafter. Bob has contributed to the design of the 5363A Time Interval Probes, done investigations on time interval measurements, designed the IF and gating circuits for the 5355A Frequency Converter, and served as the first 5355A production engineer. A native of Stockton, California, he now lives in Saratoga, California. He's married and enjoys swimming, sailing, ballroom dancing, and theater.



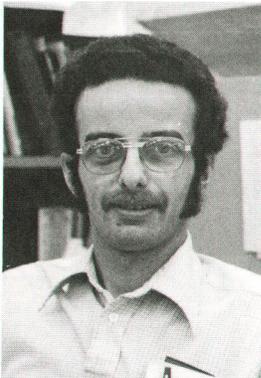
#### Richard F. Schneider

Dick Schneider is project manager for the 5355A Frequency Converter and the 5356A/B Frequency Converter Heads. With HP since 1964, he's contributed to the design of the 5240A, 5260A, and 5257A counter products, developed several microwave counter and phase-lock systems, and served as project manager for the 5340A Counter. A native of Cleveland, Ohio, he graduated from Case Institute of Technology with a BSEE degree in 1952 and spent several years designing missile and satellite test equipment, microwave amplifiers, and telemetering, radar, and receiving systems before joining HP. He also served in the U.S. Coast Guard as a Loran specialist. Dick is a member of IEEE and holds an MSEE degree from California State University at San Jose, received in 1968. He's married, has two sons, and relaxes with tennis and woodworking.



#### Ronald E. Felsenstein

With HP since 1969, Ron Felsenstein designed the processor for the 5345A Counter, served for a year as a laser and logic production engineer, and was responsible for the 6800 firmware and the digital interface design for the 5355A Frequency Converter. Born in Montevideo, Uruguay, he received his SB degree in electrical engineering from Massachusetts Institute of Technology in 1969. Now a resident of Santa Clara, California, Ron and his family (he's married and has two children) enjoy winter camping in their recently acquired motorhome. Ron collects U.S. stamps and coins and is a dedicated do-it-yourselfer when it comes to car and home repairs.

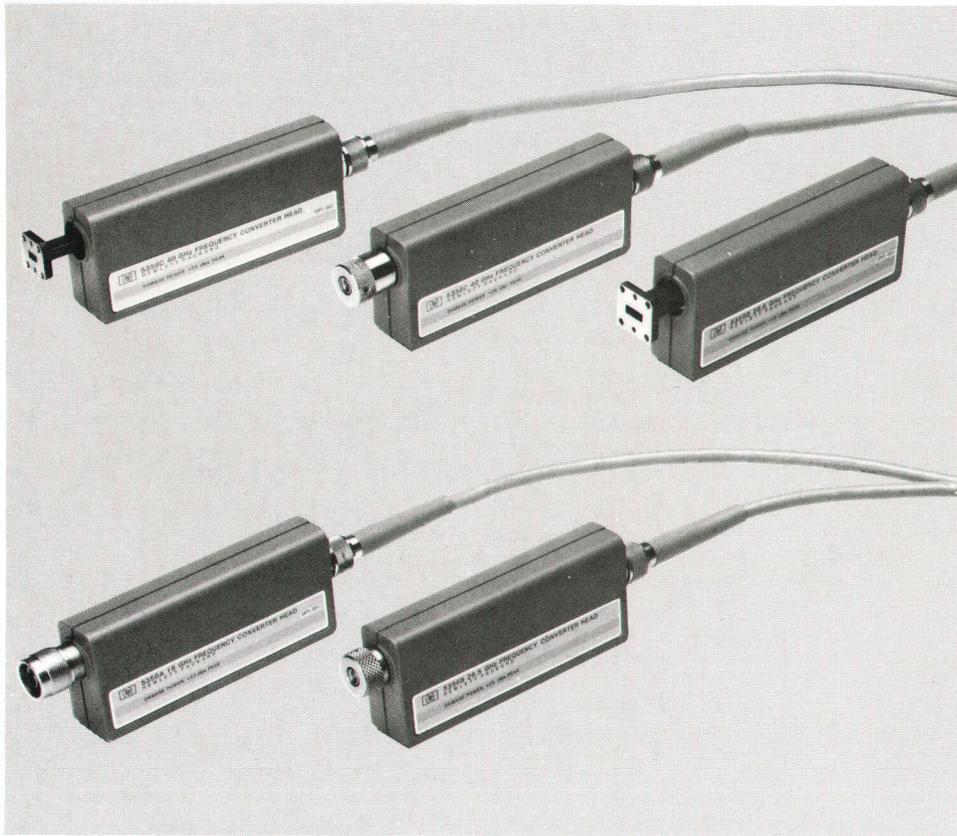


## 40-GHz Frequency Converter Heads

by Mohamed M. Sayed

**T**HERE IS AN UPPER LIMIT to the frequencies at which automatic microwave frequency measurements may be made simply by connecting a coaxial cable between the source and the counter. This is because

the cable's losses are generally greater for higher frequencies, thus demanding more sensitivity from the counter, while microwave counters become less and less sensitive at higher frequencies. Thus a frequency is reached where not



**Fig. 1.** Model 5356A/B/C Frequency Converter Heads offer a choice of input connectors and frequency ranges for microwave frequency counting up to 40 GHz.

enough signal reaches the counter to trigger it properly. These conditions dictate using a waveguide instead of a coaxial cable. However, waveguides are suitable only for certain frequency bands, e.g., K-band (18-26.5 GHz) or R-band (26.5-40 GHz). Moreover, they are expensive and lack the mechanical flexibility of the coaxial cable.

Frequency Converter Heads Models 5356A/B/C, Fig. 1, combine the convenience of coaxial cables with the broad frequency band of a microwave counter (1.5-40 GHz), and can be used for either CW or pulse measurements. These heads convert microwave frequencies to intermediate frequencies (IF) using the sampling technique. The sampling frequency input to the head and the IF output from it are connected by a 1.68-metre cable to the 5355A Automatic Frequency Converter (see article, page 3). The microwave input frequency to the head is calculated from measurements of the IF and the answer is displayed on the 5345A Counter (the 5355A is a plug-in for the 5345A). The down-

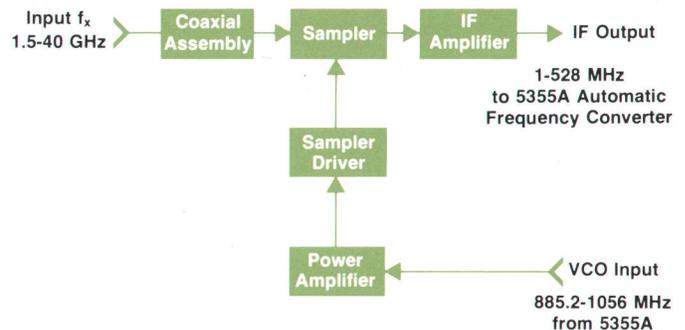
conversion is performed completely in the head and only the IF is connected to the 5355A.

To cover the frequency band up to 40 GHz, four different connectors are available: N, SMA, APC-3.5 and waveguide. Three models and two options are available to suit various applications. Table 1 shows the frequency ranges of the five heads.

The heads have male connectors because sources generally have female connectors. The 5356A has an N-type connector and is useful up to 18 GHz. The 5356B has an SMA connector, and can be used up to 26.5 GHz. To strengthen the SMA male connector, a special collar was designed to protect it. The collar also makes it easier for the customer to connect it to the source. Some customers prefer using a K-band waveguide from 18 to 26.5 GHz; the 5356B Option 001 has a WR-42 connector to meet this need. The

**Table 1**  
Frequency Ranges and Connectors of  
Model 5356A/B/C Frequency Converter Heads

FREQUENCY	HEAD	CONNECTOR	HEAD CODE
1.5-18 GHz	5356A	N	0
1.5-26.5 GHz	5356B	SMA	1
18-26.5 GHz	5356B Opt. 001	Waveguide (WR-42)	2
1.5-40 GHz	5356C	APC-3.5	4
26.5-40 GHz	5356C Opt. 001	Waveguide (WR-28)	5



**Fig. 2.** Simplified block diagram of the 5356A/B/C Frequency Converter Heads.

# 40-GHz Synthesizer Tests Frequency Converter Heads

by Mohamed M. Sayed

To test the accuracy of the 5356/5355 system in CW and pulse modes, a synthesized source is needed, especially to check for  $\pm 1$ -count accuracy with a one-second gate time. Both synthesizers and pulse modulators are commercially available up to 18 GHz, and these are used in the 5356/5355 test system. To cover the 18-to-26.5-GHz band, an amplifier and a K-band doubler are used. The input frequencies to the doubler are 9 to 13.25 GHz and the output frequencies are 18 to 26.5 GHz as shown in Fig. 1.

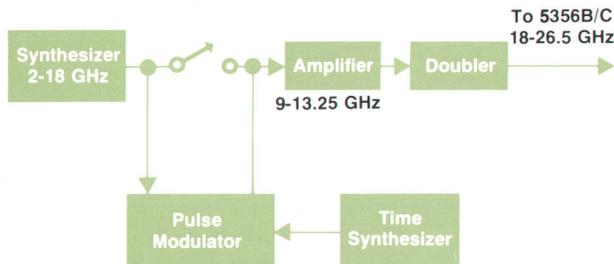


Fig. 1. Generation of an 18-to-26.5-GHz signal to test the 5356B/C Heads.

In the 26.5-to-40-GHz range an R-band doubler can be used, with the primary synthesizer operating from 13.25 to 20 GHz. This means that the synthesizer, the pulse modulator, and the amplifier must also operate up to 20 GHz. Since most of the instruments operate only up to 18 GHz, major modifications would have been needed.

The simpler method that is actually used to generate a synthesized signal to 40 GHz is to use an amplifier and two doublers in cascade. The first stage is an amplifier-doubler, and the second stage is another doubler. The primary synthesizer, the pulse modulator, and the amplifier operate in the frequency range 6.625 to 10 GHz. Fig. 2 shows a block diagram of the 26.5-to-40-GHz synthesizer.

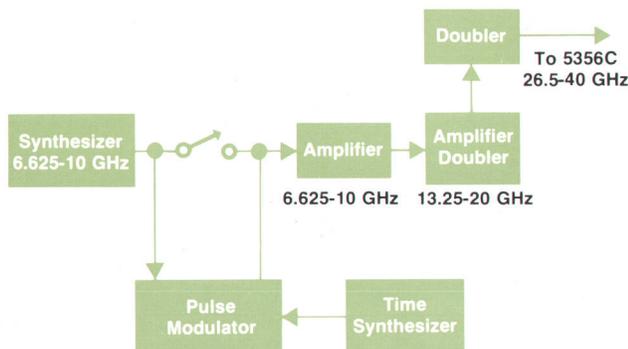


Fig. 2. Generation of a 26.5-to-40-GHz signal to test the 5356C.

### Acknowledgments

Special thanks are due Roger Stancliff of the HP Santa Rosa Division for his help in designing the amplifier doubler.

APC-3.5 connector, which is mode-free to 34 GHz,<sup>1</sup> is used up to 40 GHz in the 5356C. The effect of this connector's moding between 34 and 40 GHz is taken into account by reducing the specified sensitivity by 5 dB in this region. A special collar was designed for the APC-3.5 connector to strengthen it and to protect it from damage. Waveguide connector WR-28 is also offered, for customers using only R-band (26.5 to 40 GHz).

### Frequency Converter Head Design

Fig. 2 shows the block diagram of the 5356A/B/C. The input voltage-controlled oscillator (VCO) frequency to the 5356A/B/C varies from 885.2 MHz to 1056 MHz and the output IF to the 5355A varies from 1 MHz to 528 MHz. The IF output is proportional to the RF input within the 5356A/B/C's dynamic range. All of the components in the head are built in thin-film microcircuit configurations.

The coaxial assembly shown in Fig. 2 is replaced by a high-pass filter for the 5356A Option 001. Since the 5356/5355 is a pulse counter, the input pulse may contain a video signal. This signal may be so large that it overloads the counter, especially since the IF gain is about 80 dB. To attenuate such video signals, Model 5356A option 001 has a high-pass filter between the input connector and the sampler. The filter's maximum insertion loss from 1.5 to 18 GHz

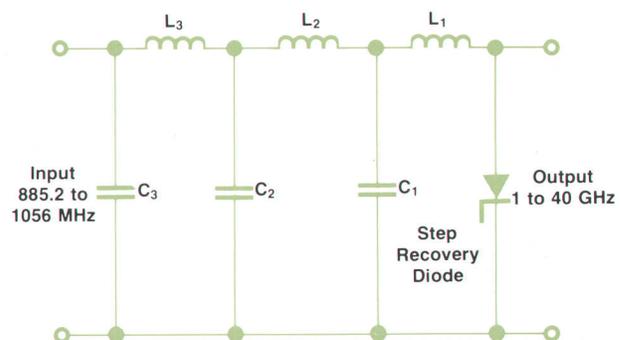
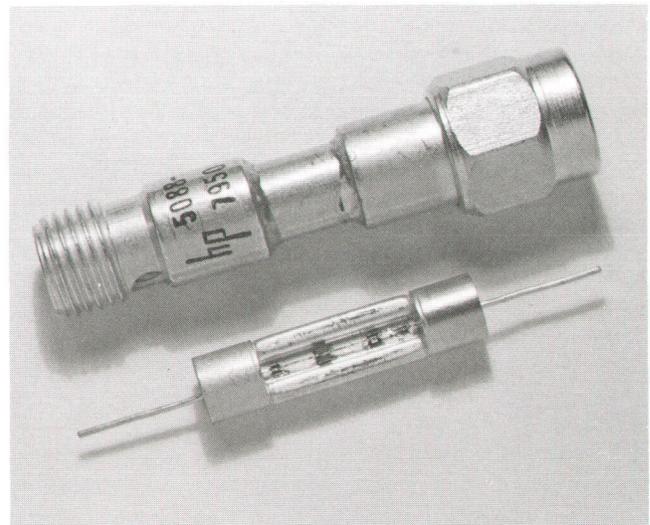
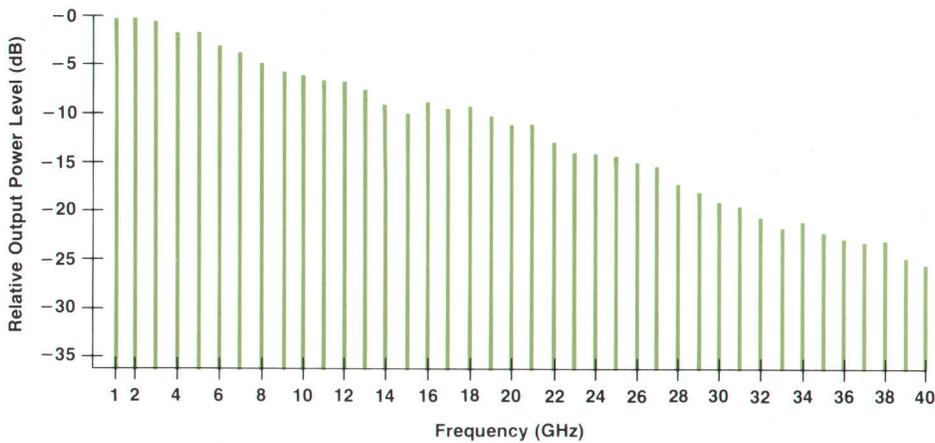


Fig. 3. Photo and schematic of the 5356A/B/C sampler driver.  $L_1$  is drive inductance and  $C_1$  is tuning capacitance.  $L_2$ ,  $C_2$ ,  $L_3$ , and  $C_3$  form a matching network to match the impedance seen at  $C_1$  to 50  $\Omega$ .



**Fig. 4.** Spectrum of the sampler driver output shows comb lines to 40 GHz. The input frequency is 1 GHz.

is 1 dB, and its minimum insertion loss below 100 MHz is more than 35 dB.

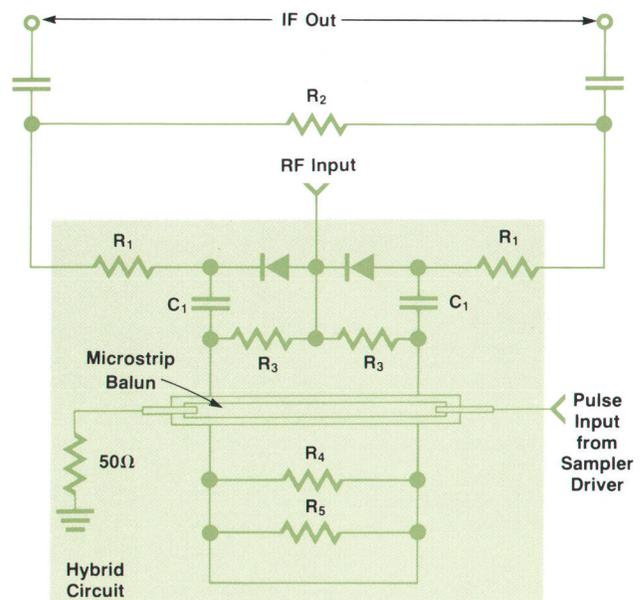
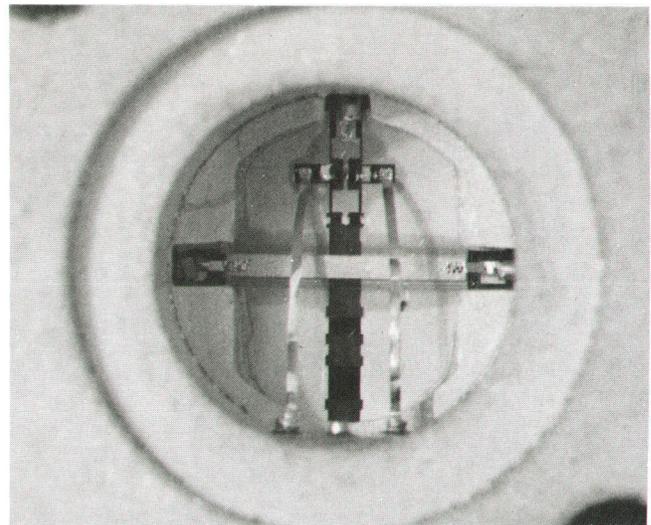
The power amplifier is housed in a TO-8 package using a thin-film alumina substrate. It consists of two stages, a gain stage and a power stage. The amplifier is driven to saturation so that its output is insensitive to input variations. The IF amplifier is housed in a TO-12 package using a thin-film sapphire substrate. It also consists of two stages.

The head casting consists of an upper half and a lower half. The sampler and the two printed circuit boards are mounted on the lower half. Heat sink materials are attached to the upper half to dissipate the heat from the power amplifier and the IF amplifier. There is also a heat sink on the lower half for the power amplifier. As a result, the temperature rise is less than 9°C. The heat sink materials also serve as shock absorbers for mechanical vibrations. The casting is designed to accept the different input connectors: N, SMA, APC-3.5, waveguide WR-42, and waveguide WR-28. The casting is also designed for improved EMI (electromagnetic interference) performance. All of the parts inside the head can be disassembled easily, using a screwdriver and an SMA wrench. As a result, the 5356A/B/C is easy to troubleshoot.

### Sampler Driver

The heart of the frequency converter head is the sampler driver. Fig. 3 shows a schematic diagram. The driver is built in a coaxial package. The step-recovery diode has a very fast rise time that generates a comb of harmonics of the VCO frequency. One of the comb frequencies is heterodyned with the input microwave frequency to produce an IF output in the proper range.

When time domain measurements were used to test the sampler driver, the test parameters were very sensitive to operator error and test equipment limitations. Therefore, frequency domain measurements are used. Since a 1-to-40-GHz spectrum analyzer (without external mixer) wasn't commercially available, an in-house 40-GHz spectrum analyzer was designed. Fig. 4 shows typical comb lines up to 40 GHz for a 1-GHz VCO. A 40-GHz test fixture was also designed to test the driver and to adjust the tuning element before sealing it. The input VCO frequency is varied from 885 MHz to 1056 MHz and the 38 comb lines are adjusted to meet the required counter sensitivity. The input to the



**Fig. 5.** 40-GHz sampler used in the 5356C Head is a thin-film hybrid circuit.  $R_1$  and  $R_2$  are chosen to optimize bandwidth and dynamic range.

sampler driver is almost constant since the power amplifier is working in the saturation region. Therefore, the comb lines are insensitive to power amplifier variations and temperature.

### Sampler

Fig. 5 shows a schematic diagram of the sampler. It consists of a thin-film hybrid mounted in an aluminum package. Two versions of the sampler are used. The 5356A/B sampler is the same as the one in the 5343A Counter without the thin-film buffer amplifier.<sup>2,3,4</sup> The 5356C 40-GHz sampler is the same basic design with slightly different component values. For the 5356C,  $R_1$  and  $R_2$  are chosen to maximize the sampler's dynamic range up to 40 GHz.

In both versions of the sampler, two beam-lead Schottky-barrier diodes are placed on the hybrid across the slotted line. This type of diode provides a low, easily controlled inductance and is easy to mount on the thin-film substrate by the thermocompression bonding technique.

To work up to 40 GHz, the diodes are chosen for minimum series resistance, junction capacitance, and stray capacitance. The diode capacitance is incorporated in a low-pass filter that has a cutoff frequency of 41 GHz. The circuit is optimized for low SWR up to 40 GHz using an in-house OPSNAP computer program. Fig. 6 shows the relative sampler conversion efficiency up to 40 GHz, and Fig. 7 shows the return loss up to 40 GHz. Four experimental setups were used for these measurements: 1.5-2.4 GHz, 2-18 GHz, 18-26.5 GHz and 26.5-40 GHz.

The sampler's IF output is designed to be insensitive to sampler driver variations. The minimum output from the sampler driver is enough to drive the sampler into saturation. Therefore the IF output is also insensitive to temperature variations.

### 5355A Compatibility

The design goal was to make any 5356A/B/C work with any 5355A. The interface between these two instruments is analog, since the VCO signal comes from the 5355A to drive the power amplifier in the 5356A/B/C, and the IF comes from the 5356A/B/C to drive the IF amplifier in the 5355A. To guarantee complete compatibility the following conditions were established.

- The IF output from the 5356A/B/C is insensitive to the level of the VCO input from the 5355A. The lowest VCO input power level at any frequency is sufficient to drive

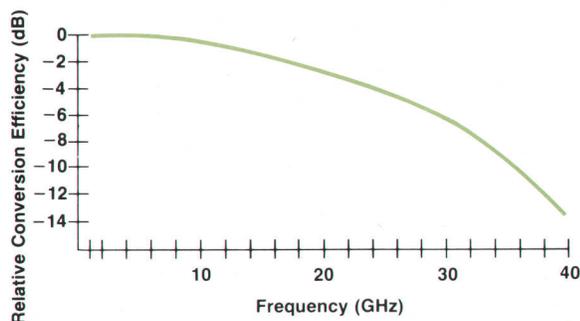


Fig. 6. Relative conversion efficiency of the 40 GHz sampler. The IF is 300 MHz and the VCO frequency from the 5355A is 1 GHz.

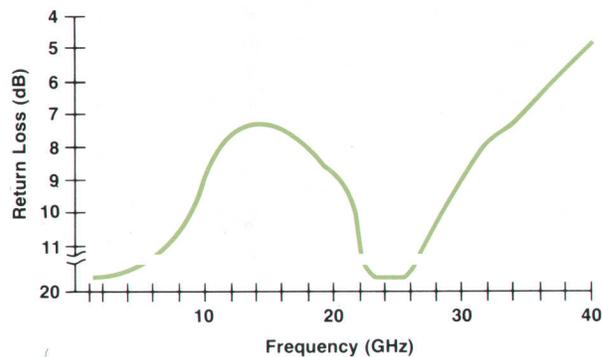


Fig. 7. Return loss of the 40 GHz sampler.

the power amplifier to saturation. Thus the output of the sampler driver is insensitive to the 5355A VCO level.

- The IF output from the 5356A/B/C to the 5355A is sufficient to guarantee the minimum sensitivity of the combined system. The counter sensitivity is defined as the 5356A/B/C conversion efficiency (RF to IF) plus the 5355A IF sensitivity. The 5355A IF sensitivity is adjusted to meet the required specifications and the 5356A/B/C conversion efficiency is tested from 1.5 to 40 GHz to assure that it meets the necessary levels.
- The input of the 5355A is unconditionally stable so that it will not oscillate with any 5356A/B/C. Also, the output of the 5356A/B/C is unconditionally stable with any 5355A. This is especially important since the IF gain of the combined system can exceed 80 dB.

### Sensitivity, Flatness, and Distortion

Since the 5356C is so broadband, there were trade-offs to be made among sensitivity, frequency response flatness, and distortion caused by sampler overload. The bias resistor  $R_2$  between the sampler IF output terminals (Fig. 5) was chosen to maximize the dynamic range of the combined 5356C and 5355A up to 40 GHz.

Dynamic range is a function of frequency. For the 5356C it ranges from  $-25$  dBm to  $+5$  dBm below 12.4 GHz and from  $-20$  dBm to  $+15$  dBm above 12.4 GHz for full accuracy ( $\pm 1$  count). However, the harmonic number is correctly

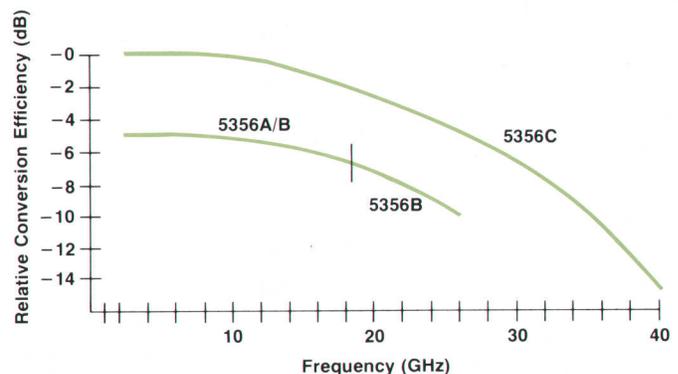
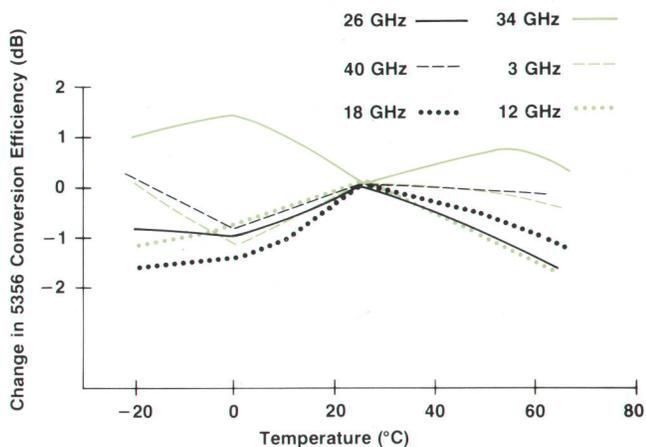


Fig. 8. Relative conversion efficiency of the 5356A/B/C up to 40 GHz. The IF is 100 MHz and the VCO frequency is 1055 MHz. Note the higher sensitivity of the 5356C.

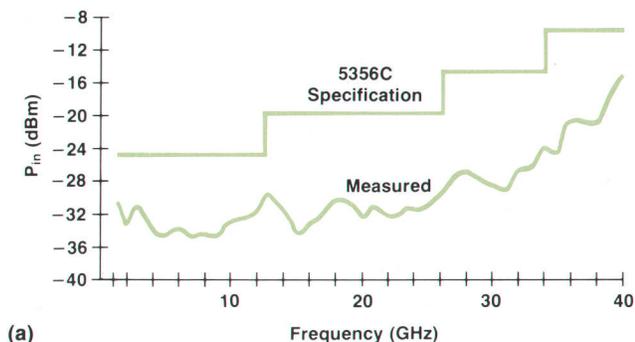


**Fig. 9.** Relative change of 5356A/B/C conversion efficiency with temperature. The IF is 100 MHz and the VCO frequency is 1055 MHz.

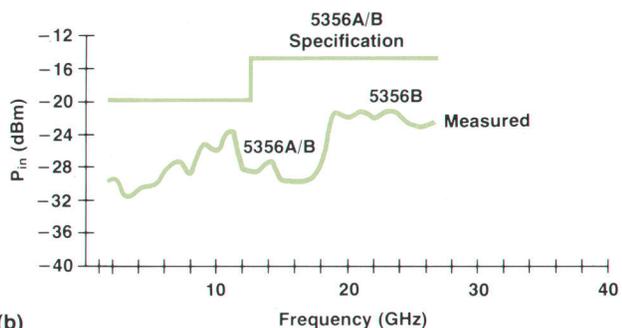
determined for a wider range of input signal levels: -30 to +8 dBm below 12.4 GHz and -25 to +18 dBm above 12.4 GHz.

The dynamic range of the 5356A can be shifted by using one of the HP 8493B-Series Attenuators to replace the coaxial assembly (see Fig. 2). For example, the 8493B Option 010 will make the dynamic range -10 to +15 dBm instead of -20 to +5 dBm. The damage level will change from +25 dBm to +33 dBm CW and +35 dBm pulse.

Fig. 8 shows the relative conversion efficiency of the 5356A up to 18 GHz, the 5356B up to 26.5 GHz, and the 5356C up to 40 GHz. These curves are for 25°C. Fig. 9 shows



(a)



(b)

**Fig. 10.** (a) Sensitivity of the 5356C/5355A system. (b) Sensitivity of the 5356A/5355A and 5356B/5355A systems. In all cases the 5355A is a worst-case unit.

the variation of the conversion efficiency with temperature.

A 5355A that has the lowest IF sensitivity within the system specifications is used to test each 5356A/B/C. Fig. 10 shows the combined sensitivity for CW and pulses.

### Acknowledgments

The author would like to thank all members of the hybrid department of the HP Santa Clara Division, especially Kathy Luiz, who assembled the original thin-film circuits. The 5356 product design was accomplished very effectively by Keith Leslie. Special thanks are due Jeff Wolfington and Al Barber for their constructive criticism during the course of this project. Many individuals from the HP Santa Rosa, Stanford Park, and Microwave Semiconductor Divisions deserve credit for their help and constructive discussion, especially Young Dae Kim of Stanford Park for his help in designing the high-pass filter for the 5356A Option 001. The product introduction of the 5356A/B was handled by Martin Neil, and of the 5356C by Larry Johnson and Doug Nichols. Service engineers were Randy Goodner for the 5356A/B and Joe Dore for the 5356C. Production engineers were Bob Offermann for the 5356A/B and Art Bloedorn for the 5356C. Special thanks are due to Luiz Peregrino for his continuing encouragement. The author would like to express his appreciation to Roger Smith, microwave section manager and Ian Band, engineering lab manager, for their support and interest in this project.

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2. J. Merkelo, "A dc-to-20-GHz Thin-Film Signal Sampler for Microwave Instrumentation," Hewlett-Packard Journal, April 1973.
3. A. Bologlu and V.A. Barber, "Microprocessor-Controlled Harmonic Heterodyne Microwave Counter also Measures Amplitudes," Hewlett-Packard Journal, May 1978.
4. A. Bologlu, this issue, p. 20.

### Mohamed M. Sayed



Mohamed Sayed joined HP's Microwave Technology Center in 1973. After working on microwave silicon and GaAs FET transistors for two years, he joined HP's Santa Clara Division, and since that time has worked on microwave counters. Born in Egypt, he received his BSEE and MSEE degrees from Cairo University and his PhD from Johns Hopkins University in Baltimore, Maryland. He has taught at Cairo, Johns Hopkins, and Howard Universities, and is currently teaching at San Jose State University. Before joining HP, he spent a year doing research on

solar cells at the University of Delaware. He has published papers in the field of microwave measurements, microwave transistors, and solar energy. He's a member of IEEE and is active in the National Alumni Schools Committee of Johns Hopkins University. Mohamed is married, has a daughter, and lives in Cupertino, California. He is currently attending Santa Clara University to obtain his Master's degree in engineering management. In his spare time he likes to read and travel.

# A 26.5-GHz Automatic Frequency Counter with Enhanced Dynamic Range

A new sampler provides higher frequency coverage and 10 dB greater sensitivity than previous designs.

by Ali Bologlu

**D**IRECT-COUNTING FREQUENCY COUNTERS are restricted by the speed of today's logic circuitry to maximum frequencies of 500 MHz or so. Consequently, automatic microwave counters must employ some method of down-conversion to extend counting into the gigahertz range. Traditional techniques, such as the transfer oscillator and heterodyne techniques, were supplemented by the harmonic heterodyne technique with the introduction of the HP 5342A in the spring of 1978.<sup>1</sup> The advent of the microprocessor made this technique possible along with a significant reduction in instrument cost.

A new microwave frequency counter, Model 5343A, makes its own contribution by extending the frequency range to 26.5 GHz and improving sensitivity and dynamic range by about 10 dB across the band. Furthermore, features have been added, making the instrument more system-oriented.

## System Architecture

The block diagram of the 5343A is very similar to that of the 5342A (see reference 1). Besides software, the major changes are in the sampler area, which will be dealt with in detail later in this article. The operating algorithm is as follows. The multiplexer selects the main oscillator output and the main oscillator frequency  $f_1$  is swept from 350 MHz

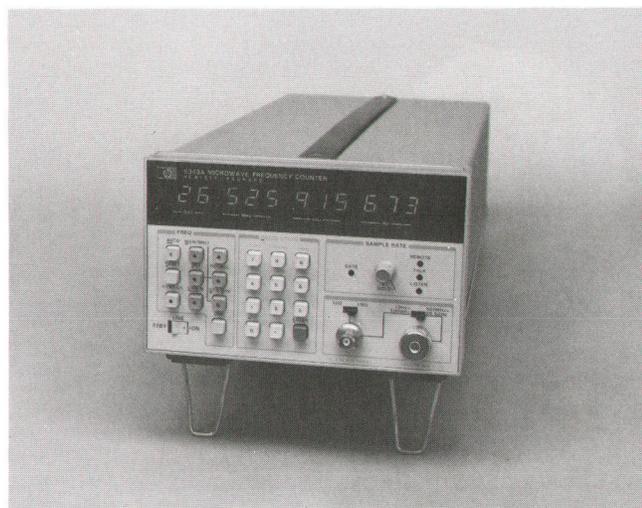
to 300 MHz in 100-kHz steps. The offset oscillator frequency  $f_2$  is maintained at  $f_1 - 500$  kHz by a phase-locked loop. When the IF detector indicates the presence of an IF signal in the range of 50 MHz to 100 MHz the synthesizer stops its sweep and the counter starts its determination of the harmonic number  $N$ . The pseudorandom sequence output switches between the main oscillator and the offset oscillator and between counters A and B. 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  $f_1$  is measured by counter A to the selected resolution. The pseudorandom sequence prevents any coherence between the switching rate of the multiplexer and the modulation rate of the FM that might be present on the input signal. Such coherence might produce an incorrect computation of  $N$ . Finally, the harmonic number and the sign of the IF are computed and the input frequency  $f_x$  is computed as follows:

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

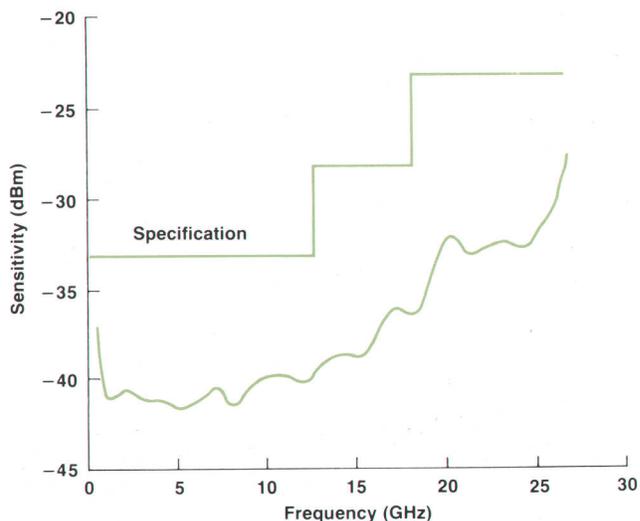
$$f_x = Nf_1 + f_{IF1} \quad (f_{IF2} > f_{IF1})$$

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

It has been shown<sup>2</sup> that the length of the pseudorandom



**Fig. 1.** Model 5343A Microwave Frequency Counter provides high sensitivity and automatic amplitude discrimination in CW frequency measurements to 26.5 GHz. Offsets and scale factors can be entered via the front panel.

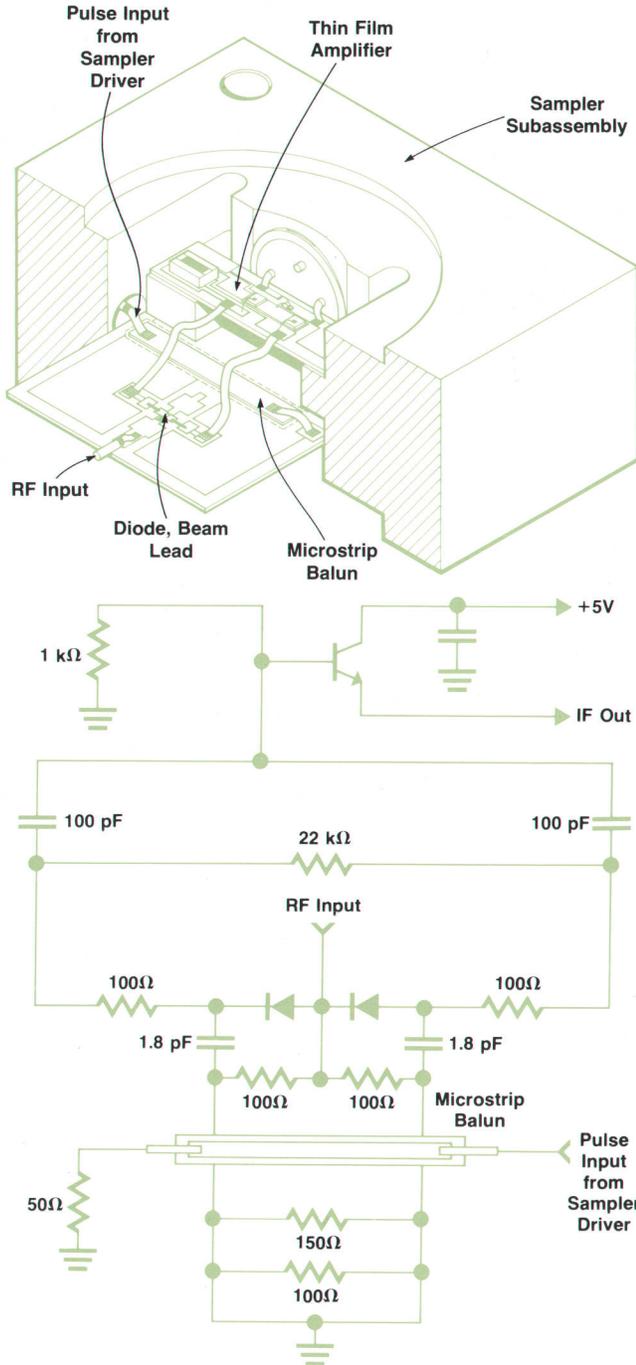


**Fig. 2.** 5343A sensitivity.

sequence required to tolerate frequency modulation on the input signal is given by the expression

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

Thus to allow the counter to tolerate 10 MHz peak FM on



**Fig. 3.** The principal design contribution in the 5343A Microwave Counter is this new sampler, a refined version of previous designs. A thin-film buffer amplifier improves the impedance match between the sampler output and the first IF amplifier.

the input signal with  $\Delta f = 500$  kHz, the  $P$  value should exceed 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. It is obvious from the expression for  $P$  that the more FM one wants to tolerate the longer the sequence has to be, which in turn affects the counter's measurement time.

The 5343A has three different sequence lengths of 22 ms, 360 ms, and 2.2 s. The corresponding FM deviations the instrument tolerates in the automatic mode are 6 MHz, 20 MHz, and 50 MHz peak to peak, respectively. These limits in fact only apply when the modulation rate is synchronous with the pseudorandom sequence. Since the modulation in microwave communication systems is usually either data or voice, the probability of synchronization is very remote. Consequently, although the deviation may be large, the signals may often be measured by the 5343A using the short sequence length, thereby making acquisition times faster.

### New Sampler Improves Sensitivity

5343A sensitivity is shown in Fig. 2. The main contributor to this improved sensitivity is a new microwave sampler, which is the only microwave component in the instrument. Operation of the sampler is similar to the sampler used in the 5342A,<sup>1</sup> the main difference being the use of a thin-film buffer amplifier to provide a better impedance match between the output of the sampler and the first IF.

In this sampler structure (Fig. 3), the sampling pulse couples to the slotted line through a microstrip balun that generates two opposite-polarity pulses to drive the sampling diodes. The down-converted signal is taken from two isolated resistors to the second substrate in the structure, which is the buffer amplifier. Resistors across the slot are used to absorb secondary reflections introduced by the sampling pulse. The input structure forms the essence of a low-pass filter with an effective cut-off greater than 26.5 GHz. This structure provides an input return loss as shown in Fig. 4.

### Front-Panel Inputs and Controls

The 5343A has two inputs, one going from 10 Hz to 520 MHz and the other from 500 MHz to 26.5 GHz. 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 for doing this are on a label that is affixed to the instrument top.

The panel layout is in algebraic notation, thereby making panel operation closely resemble remote programming via the HP Interface Bus (HP-IB\*). When the instrument 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 fre-

\*Compatible with ANSI/IEEE 488-1978.

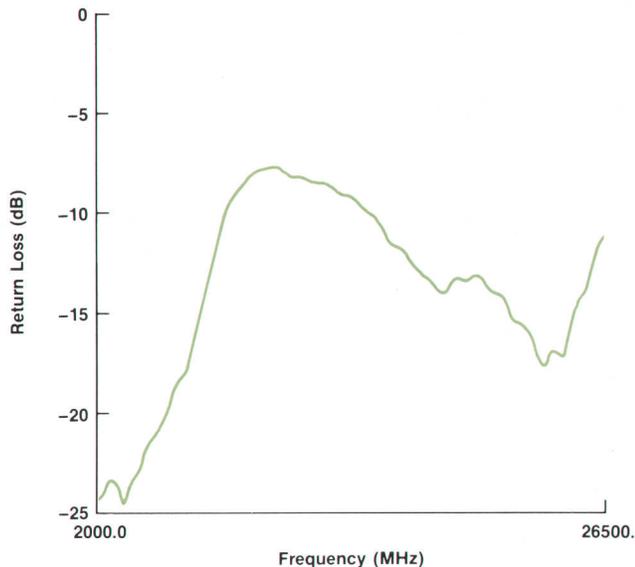


Fig. 4. Return loss of the 5343A sampler.

quency 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. Frequency readings may also be multiplied by integers and offsets then added to the product, in effect solving the equation

$$y = mx + b$$



### 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 5343A. 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.

where  $m$  is the multiplying integer,  $x$  the measured frequency and  $b$  the offset.

### Acknowledgments

I would like to acknowledge the efforts of John Shing, Jeff Wolfington, and Keith Leslie for their important and timely contributions to the 5343A.

### References

1. A. Bologlu and V.A. Barber, "Microprocessor-Controlled Harmonic Heterodyne Microwave Counter also Measures Amplitudes," Hewlett-Packard Journal, May 1978.
2. L. Peregrino, "A Technique that Is Insensitive to FM for Determining Harmonic Number and Sideband," Hewlett-Packard Journal, May 1978.

## SPECIFICATIONS

### HP Model 5343A Microwave Frequency Counter

#### Input 1

FREQUENCY RANGE: 500 MHz-26.5 GHz.

#### SENSITIVITY:

500 MHz-12.4 GHz -33 dBm  
12.4 GHz-18.0 GHz -28 dBm  
18.0 GHz-26.5 GHz -23 dBm

MAXIMUM INPUT: +7 dBm.

#### DYNAMIC RANGE:

500 MHz-12.4 GHz 40 dB  
12.4 GHz-18.0 GHz 35 dB  
18.0 GHz-26.5 GHz 30 dB

DAMAGE LEVEL: +25 dBm, peak.

IMPEDANCE: 50 ohms, nominal.

CONNECTOR: APC-3.5 male with collar (SMA compatible).

#### SWR:

500 MHz-10 GHz <2.1 typical  
10 GHz-18 GHz <3.1 typical  
18 GHz-26.5 GHz <3.1 typical

COUPLING: dc to load, ac to instrument.

FM TOLERANCE: switch selectable on rear panel. For modulation rates from dc to 10 MHz.

WIDE: 50 MHz p-p worst case.

NORMAL: 20 MHz p-p worst case.

NARROW: 6 MHz p-p worst case.

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

#### MODES OF OPERATION:

AUTOMATIC: Counter automatically acquires and displays highest level signal within sensitivity range.

MANUAL: Center frequency entered to within  $\pm 50$  MHz of true value.

#### ACQUISITION TIME:

AUTOMATIC MODE: Narrow FM: 200 ms worst case.  
Normal FM: 530 ms worst case.

Wide FM: 2.4 s worst case.

MANUAL MODE: 80 ms after frequency entered.

#### AUTOMATIC AMPLITUDE DISCRIMINATION:

Automatically measures the largest of all signals present, providing that signal is: 6 dB (typical) above any signal within 500 MHz; 20 dB above any signal, 500 MHz-26.5 GHz.

#### Input 2

FREQUENCY RANGE: 10 Hz to 520 MHz Direct Count.

SENSITIVITY: 50 $\Omega$  10 Hz to 520 MHz 25 mV rms; 1 M $\Omega$  10 Hz to 25 MHz 50 mV rms.

IMPEDANCE: Selectable: 1 M $\Omega$ , <50 pF or 50 $\Omega$  nominal.

COUPLING: ac.

CONNECTOR: Type BNC female.

MAXIMUM INPUT: 50 $\Omega$  3.5 Vrms (+24 dBm) 5 Vdc fuse protected; 1 M $\Omega$  200 Vdc + 5.0 Vrms.

#### Time Base

CRYSTAL FREQUENCY: 10 MHz.

#### STABILITY:

AGING RATE: <1 $\times 10^{-7}$  per month.

SHORT TERM: <1 $\times 10^{-9}$  for 1 s avg. time.

TEMPERATURE: <1 $\times 10^{-9}$  over the range 0°C to 50°C.

LINE VARIATION: <1 $\times 10^{-7}$  for 10% change from nominal.

OUTPUT FREQUENCY: 10 MHz,  $\pm 2.4$ V square wave (TTL compatible); 1.5V peak-to-peak into 50 $\Omega$  available from rear panel BNC.

EXTERNAL TIME BASE: Requires 10 MHz, 2.0V peak-to-peak sine wave or square wave into 1 k $\Omega$  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 (see separate data sheet), that results in better accuracy and longer periods between calibration.

CRYSTAL FREQUENCY: 10 MHz.

#### STABILITY:

AGING RATE: <5 $\times 10^{-10}$ /day after 24-hour warm-up.

SHORT TERM: <1 $\times 10^{-10}$  for 1 s avg. time.

TEMPERATURE: <7 $\times 10^{-9}$  over the range 0°C to 50°C.

LINE VARIATION: <1 $\times 10^{-10}$  for 10% change from nominal.

WARM-UP: <5 $\times 10^{-9}$  of final value 20 minutes after turn-on, at 25°C.

#### Digital-to-Analog Converter

##### Option 004

Option 004 provides the ability to convert any three consecutive displayed digits into an analog voltage output. A display of 000 produces 0V output; 999 produces 9.99V full scale.

ACCURACY:  $\pm 5$  mV  $\pm 0.3$  mV/°C (from 25°C).

CONVERSION SPEED:  $\sim 50$   $\mu$ s to  $\pm 0.01\%$  of full scale reading.

RESOLUTION: 10 mV.

OUTPUT: 5 mA, Impedance <1.0 ohm.

CONNECTOR: Type BNC female on rear panel.

#### General

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

RESOLUTION: Front-panel pushbutton select 1 Hz to 1 MHz.

RESIDUAL STABILITY: When counter and source use common timebase or counter uses external higher-stability timebase <4 $\times 10^{-11}$  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.

MULTIPLY ROUTINE: Selected from front-panel pushbuttons. Measured frequency is multiplied by any integer up to 99. Then offset can be added or subtracted for  $y = mx \pm b$  result.

TOTALIZE: Input 2 can totalize at rate up to 520 MHz. Readout on the fly is controlled by front panel or HP-IB.

EXTERNAL TRIGGER: TTL type low-level or contact closure to ground  $>50$   $\mu$ s typical at rear-panel connector A initiates measurements when in sweep mode.

SWEEP MODE: Selected from front-panel pushbutton. Allows interface to appropriate sweeper for start, stop, and marker frequency measurements.

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.

ACCESSORIES FURNISHED: Power cord, 229 cm 7 $\frac{1}{2}$  ft.

SIZE: 133 mm H  $\times$  213 mm W  $\times$  498 mm D (5 $\frac{1}{4}$   $\times$  8 $\frac{3}{8}$   $\times$  19 $\frac{1}{2}$  in).

WEIGHT: Net 9.1 kg (20 lb). Shipping 12.7 kg (28 lb).

PRICES IN U.S.A.: 5343A Microwave Frequency Counter, \$5,200. Option 001 High

Stability Time Base, \$500. Option 004 Digital-to-Analog Converter, \$250. Option

011 Digital Input/Output (HP-IB), \$350.

MANUFACTURING DIVISION: SANTA CLARA DIVISION  
5301 Stevens Creek Boulevard  
Santa Clara, California 95050 U.S.A.

# Microwave Counter Measurements

by Richard F. Schneider

FOR CONVENTIONAL PULSE RADARS, the major parameters that must be measured are the average burst frequency, the pulse repetition frequency (PRF), the pulse repetition period (PRP), the pulse repetition interval (PRI), and the pulse width. These measurements are automatically made by connecting the equipment as shown in Fig. 1. To measure the average burst frequency, the user need only assure that the peak pulse power is within the counter system specifications. Usually a test port is available in the form of a directional coupler built into the radar system, or a test horn can be connected to the 5356A/B/C Head for measurements after the radar system has been "buttoned up", such as on the flight line. Since the gating signal for the 5345A Counter is generated by the 5355A Converter, no auxiliary equipment is required. This gate signal, as described in the article on page 3, is about 30 ns shorter than the RF burst to avoid turn-on and turn-off transients. The measurement is made by selecting the plug-in and external gate functions of the 5345A Counter and the pulse mode of the 5355A Converter. The average burst frequency is then displayed on the 5345A Counter.

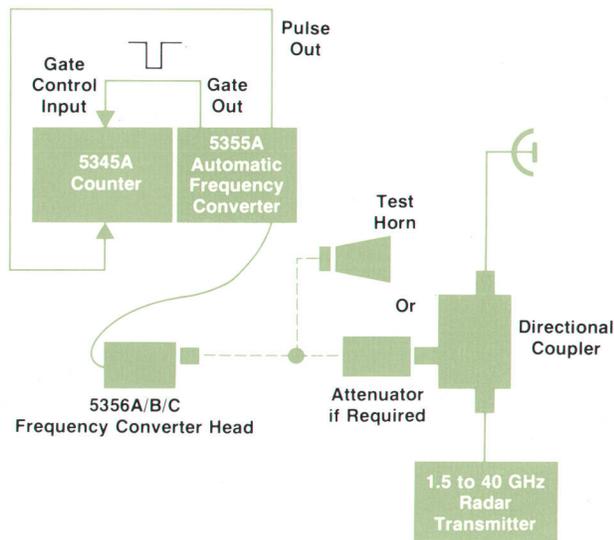


Fig. 1. Test setup for conventional radar measurements (average burst frequency, pulse repetition frequency, pulse repetition period, pulse repetition interval, pulse width).

Since the IF is detected in the 5355A Converter plug-in and is available on the rear panel PULSE OUT connector, this signal can be used to make the other measurements. PRF is measured by setting the 5345A Counter function switch to **FREQ A** after adjusting Channel A to the proper levels. PRP is measured by simply setting the 5345A Counter function switch to **PERIOD A**. Pulse width is measured by setting the function switch to **TIME INT A TO B**, the input to **COMMON**, channel A slope to **-**, and channel B slope to **+**. PRI is measured by reversing the A and B channel slope polarities.

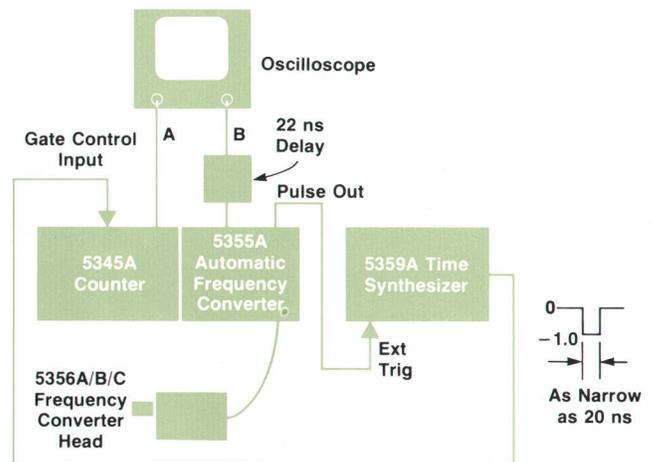


Fig. 2. Test setup for frequency profiling of an RF burst.

Since the IF is limited before detection, pulse width measurement accuracy is dependent on the rise time and the pulse width. For slow rise times, the pulse out (and the measured width) will probably be longer than the width defined by the time interval between actual 50% points, while for fast rise times it will be within 3% of the actual pulse width. This occurs since the pulse out signal starts and stops when the input RF level exceeds the system sensitivity. Jitter can also occur in the pulse width measurement if the pulse modulation is not coherent with the carrier. This can cause the IF envelope to vary by one period of the IF, or in the worst case, as much as  $\pm 10$  ns. However, this jitter is automatically averaged out if time interval averaging is used.

## Frequency Profiling and CW Measurements

Frequency profiling of an RF burst is done using a time synthesizer such as the HP 5359A, as shown in Fig. 2. Here the 5359A Time Synthesizer is triggered by the pulse output signal from the 5355A Converter plug-in. The 5359A's delayed output pulse, a  $-1.0$ -volt signal, is used to enable the 5345A Counter's gate control input. The width of this external gate signal determines the gate time of the 5345A. The delay is incremented after each measurement so that measurements are made at successively later times within the RF burst. Fig. 3 shows the frequency profile and spectrum of a 250-ns wide chirp pulse. The chirp has a bandwidth of 200 MHz; it was generated by ramping a voltage-controlled oscillator (VCO) and synchronously pulse modulating its output. For chirp radar applications, the linearity of the ramp is paramount, while Doppler radars require minimal FM on the burst. These measurements can be made to 100-Hz resolution with external gates as narrow as 20 ns.

For CW measurements, such as on a CW radar, a STALO (stabilized local oscillator), or a COHO (coherent oscillator),

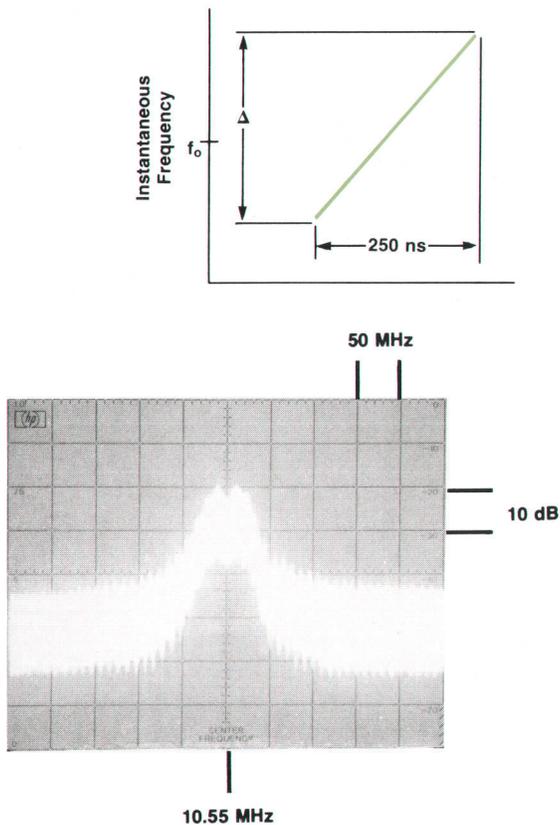


Fig. 3. Frequency profile and spectrum of a 250-ns chirp pulse. Profile can be measured using a 20-ns gate.

frequencies are measured to 1-Hz resolution in one second. Also, the average frequency of a fully loaded microwave carrier with traffic can be measured, since the counter system's specified FM tolerance is 15 MHz p-p (80 MHz p-p in the special FM mode).

### VCO Measurements

Transient measurements needed to evaluate a VCO are settling time and post-tuning drift, as shown in Fig. 4. The settling time is the time ( $t_{st}$ ) required for the output frequency to enter and stay within a specified error band ( $\pm f_{st}$ ) centered around a reference frequency ( $f$ ) after application of a set input voltage. Post-tuning drift is the maximum change in frequency ( $\pm f_{ptd}$ ) during the time interval  $t_1$  to  $t_2$ , where  $t_1$  is a specified time after  $t_0$ , the start of the step input voltage. These measurements may be made with the equipment shown in Fig. 5.

In this measurement, the tuning voltage pulse generator is set to the necessary step voltage levels to drive the VCO. This generator also provides an external trigger to the 5359A Time Synthesizer, which synchronizes the 5345A Counter by generating a gate control input signal. The time ( $t_r$ ) that it takes the VCO to reach the reference frequency is then set into the time synthesizer as a delay, and the width of the synthesizer output pulse is set to an appropriate gate width for the measurement. Then selecting the automatic or manual pulse mode of the 5355A Converter plug-in causes the counter to display the VCO reference frequency.

The start of the reference frequency step may also be

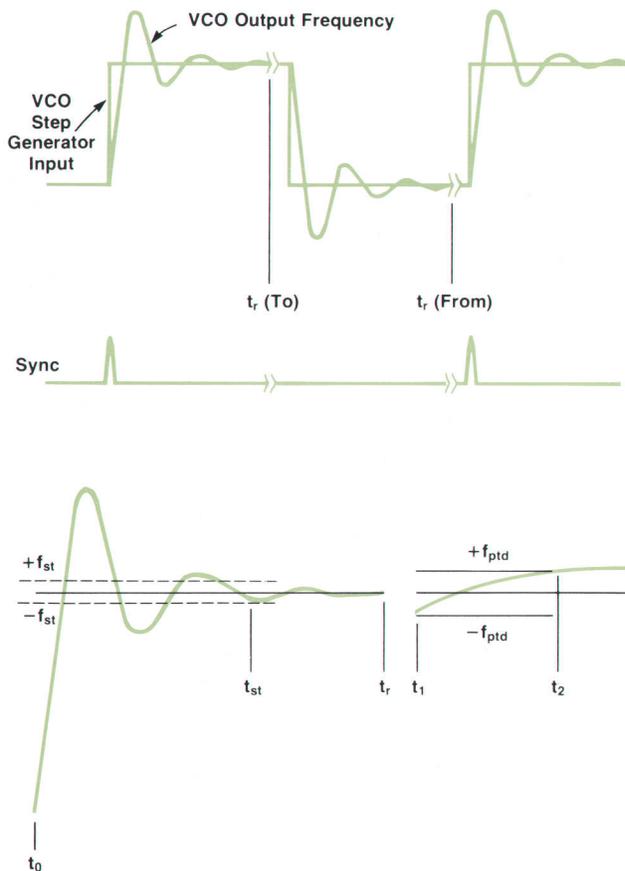


Fig. 4. Transient measurements needed to evaluate a voltage-controlled oscillator (VCO) are settling time and post-tuning drift.

observed by stepping the time synthesizer delay by one-half the step generator period. In this manner, the absolute levels of the VCO step generator may be adjusted to set the initial and final reference frequencies. Next, the delay is decreased until the displayed counter frequency exceeds the specified error band ( $\pm f_{st}$ ). This delay defines the settling time. In a similar manner, the post-tuning drift may be measured by observing the change in frequency from delay time  $t_1$  to time  $t_2$ . In both measurements, changes of frequency may be easily observed by setting the counter to

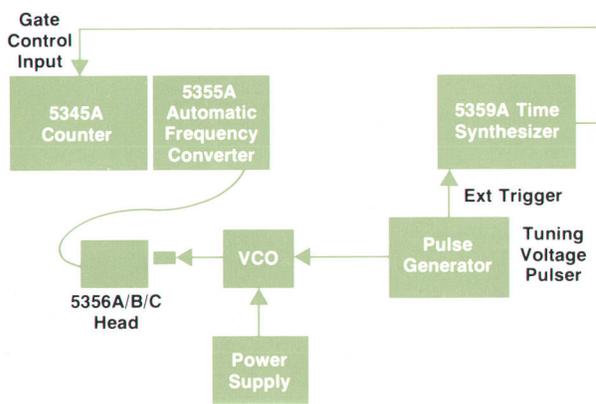


Fig. 5. Test setup for VCO measurements shown in Fig. 4.

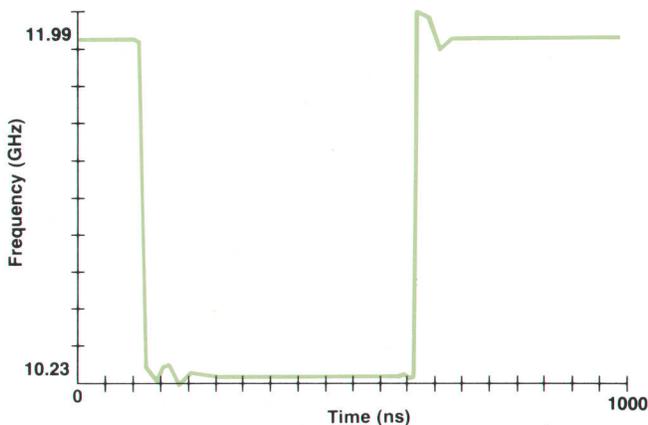


Fig. 6. Settling time measurement on a VCO.

display deviations from the reference frequency. This is done by subtracting the reference frequency by entering the last measurement into the 5355A Converter as a frequency offset.

For large frequency steps, the 5355A Converter will have to reacquire the signal when changing from the initial to the final frequencies. This can be prevented if the initial and final frequencies fall within the 5355A IF bandwidth for two harmonics of the 5355A synthesizer frequency that is used to down-convert the microwave input signal (see article, page 3). For instance, if the VCO is stepped from 8 to 12 GHz, a synthesizer frequency may be found to satisfy both of

these frequencies. By using the 5355A's diagnostic mode 9, the synthesizer frequency may be set to 1025.2 MHz. The 8th harmonic is 8201.6 MHz, and the IF frequency is 201.6 MHz. The 12th harmonic is 12.3024 GHz and the IF frequency is 302.4 MHz, which is still within the limits of the IF bandwidth. The actual IF can be observed in diagnostic mode 10.

By adjusting the synthesizer frequency and the initial or final VCO frequency, it is possible to nearly center both IFs so maximum deviations can be measured. It is possible then to observe frequency transients whose excursions are less than one-half the IF bandwidth. The size of the step from initial to final VCO frequencies is ultimately limited by the bandwidth of the 5356A/B/C Frequency Converter Head being used.

A settling time measurement of a VCO is shown in Fig. 6. Fully automatic measurements can be configured using the HP-IB to control the time synthesizer (delay generator), plotter, tuning voltage pulser, and digital voltmeter. Other VCO measurements, such as frequency accuracy, frequency range, frequency linearity, pushing and pulling factors, modulation sensitivity, hysteresis, and warm-up frequency drift may be easily made in the CW mode.

#### CORRECTION

Here is the caption that was missing from page 31 of our March issue:

**Fig. 7.** Calibration oscillator. The LC tank circuit alternately turns off each transistor so the output power is restricted to  $I_o^2 R/4$ .  $I_o$  and  $R$  were chosen to make this equal to  $-10$  dBm.

## Laboratory Notebook

### A Flexible Software Development Technique

A common problem in the development of microprocessor-based instruments is that there comes a time when the software has to be committed to firmware in the form of read-only memories (ROMs). Generally the software development engineer delays committing to masked ROMs as long as possible to avoid the costly mask changes that would be required should "bugs" or necessary modifications appear in the future. The software development technique used for the 5355A Automatic Frequency Converter (see article, page 3) is flexible enough to allow an early commitment to ROMs without being penalized for changes later on. This technique can be used in any instrument where the ROMs are not coded to full capacity.

The technique also offers advantages once the instrument is in production. Generally, it is possible to implement a relatively complex software modification by changing one correction ROM instead of all ROMs. If the correction ROM can be replaced with an EROM (erasable ROM), then the production change can be implemented without incurring a long lead time for a new masked ROM.

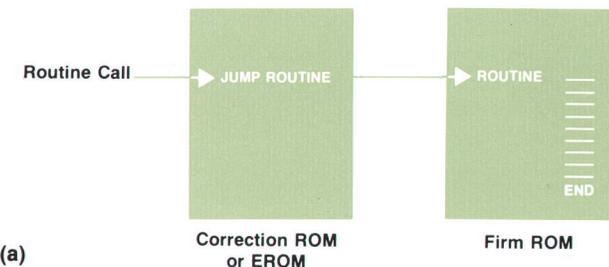
To explain the technique, the 5355A can be used as a case history. Approximately one year before product release, it was evident that it would take 9K to 10K bytes of microcode to complete the 5355A. Our microprocessor board had two 24-pin sockets to accommodate ROMs. With the ROMs available at the time, the microcode could have been programmed into 8K×8 and 2K×8 ROMs, thus filling up both ROMs. For a slight incremental cost, the 2K×8 ROM was replaced with a 4K×8 ROM, making the total available microcode space 12K bytes. The extra 2K bytes of ROM became valuable space to accommodate corrections for the 8K×8 ROM microcode.

Unlike the 4K×8 ROM, the 8K×8 ROM could not be simulated with a single pin-for-pin-compatible EROM. It was therefore necessary to order a masked ROM eight months before product release. In anticipation of future microcode corrections, any software routine larger than 250 bytes was partitioned into relocatable sectors with coding taking up 250 bytes or less.

To make a sector relocatable, one or more jump instructions were required. The jump instructions have a fixed location within the

4K×8 address space. Thus, whenever a correction and/or modification was needed, the operand address code of the appropriate jump instructions was changed from one pointing to the 8K×8 ROM to one pointing to some unused address space within the 4K×8 EROM (see example in Figs. 1 and 2 on line 15). If necessary, an entire sector can be redone. On the average, however, a correction will be needed half-way into a sector. Following the corrected code, an extra jump instruction is added to get back to the usable part of the sector in the original 8K×8 ROM (see Fig. 2 line 24). Assuming 2K bytes of correction space and 250-byte relocatable sectors, one can expect 16 corrections (125 bytes on the average) before the memory is filled. In the case of the 5355A, many routines were much smaller than 250 bytes. Therefore, the 2K-byte correction space was adequate for more than 16 corrections.

With this technique only one version of the 8K×8 masked ROM was needed. When the time came to produce the instrument, the 4K bytes of software code could be implemented and shipped in either a 4K×8 EROM or a 4K×8 ROM. The choice between the two was determined by 1) how "final" the software appeared to be, and 2) the cost tradeoff between the higher EROM unit price and the mask charge of the ROM. For the 5355A, the break-even point between EROMs and ROMs was one production run. It was therefore decided to build the first two production runs initially with EROMs. Masked ROMs were ordered with sufficient lead time to allow a last-minute replacement before shipping the instruments.



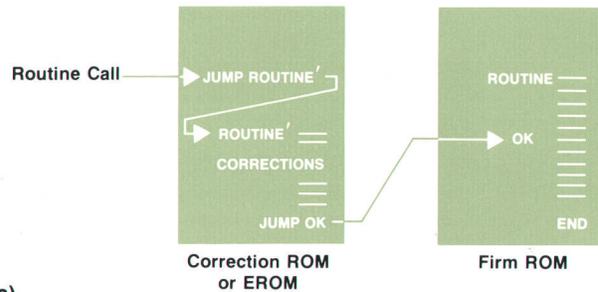
```
(a)
0001 * 08-12-79 FILE NAME: AREA
0002 *
0003 * AREA OF CIRCLE CALCULATION
0004 * USES MATH PACK SIMILAR TO H-P POCKET CALCULATOR
0005 *
0006 * SUBROUTINE CALL: JSR CIRCLE
0007 * ENTRY REQUIREMENTS: RADIUS INITIALIZED
0008 * EXIT STATUS: XX REGISTER CONTAINS RESULT
0009 *
0010 0160 RADIUS EQU #160 RADIUS VARIABLE RAM ADDRESS
0011 6080 PI EQU #6080 PI CONSTANT ROM ADDRESS
0012 *
0013 *
0014 5441 CIRCLE ORG #5441 FIXED ADDRESS WITHIN 4K BYTE EROM
0015 5441 7E CIRCLE JMP START
0016 5442 73
0017 5443 28
0018 *
0019 7328 BD START ORG #7328 ADDRESS WITHIN 8K BYTE ROM
0020 7329 50 JSR FCLR CLEAR ALL MATH REGISTERS
0021 732A 21
0022 732B CE LDX #RADIUS
0023 732C 01
0024 732D 60
0025 732E BD JSR FRCL XX←RADIUS
0026 732F 50
0027 7330 00 JSR FRCL XX←RADIUS, YY←RADIUS
0028 7331 BD
0029 7332 50
0030 7333 00 JSR FMULT XX←RADIUS*RADIUS
0031 7334 BD
0032 7335 50
0033 7336 15 LDX #PI
0034 7337 CE
0035 7338 60 JSR FRCL XX←PI, YY←RADIUS*RADIUS
0036 7339 80
0037 733A BD JSR FMULT XX←2*PI*RADIUS
0038 733B 50
0039 733C 00
0040 733D 00 JSR FMULT XX←PI*RADIUS*RADIUS
0041 733E BD
0042 733F 50
0043 7340 39 RTS RETURN: END OF ROUTINE
0044 7341 END
```

Fig. 1. (a) Relationship of the correction ROM to the firm ROM for routines that have not been corrected. (b) An example in 6800 microcode.

Should software bugs be discovered in the future, a new 4K×8 ROM would be ordered. In the event that the 4K×8 ROM runs out of correction space, then the complete set of ROMs will be required. At that time, it will be beneficial to clean out the correction space in the 4K ROM by changing the jump operand addresses back to the 8K ROM. Note that the example in Fig. 2 has been amply annotated so that a correction can be spotted easily. Removing the special corrections months or years later is therefore a simple task.

Figs. 1 and 2 show an example of a correction in 6800 micro-processor code. The 4K×8 correction EROM is assigned addresses \$5000 to \$5FFF and the 8K ROM is assigned addresses \$6000 to \$7FFF. Note that the correction penalty here is 12 bytes in the 4K×8 EROM plus about five microseconds for the jump instruction at the end of the correction. Redoing the entire routine would have required 26 bytes.

-Ronald E. Felsenstein



```
(a)
0001 * 11-13-79 FILE NAME: CIRC MF
0002 *
0003 * CIRCUMFERENCE OF CIRCLE CALCULATION
0004 * USES MATH PACK SIMILAR TO H-P POCKET CALCULATOR
0005 *
0006 * SUBROUTINE CALL: JSR CIRCLE
0007 * ENTRY REQUIREMENTS: RADIUS INITIALIZED
0008 * EXIT STATUS: XX REGISTER CONTAINS RESULT
0009 *
0010 0160 RADIUS EQU #160 RADIUS VARIABLE RAM ADDRESS
0011 6080 PI EQU #6080 PI CONSTANT ROM ADDRESS
0012 *
0013 *
0014 5441 CIRCLE ORG #5441 FIXED ADDRESS WITHIN 4K BYTE EROM
0015 5441 7E CIRCLE JMP START
0016 5442 58
0017 5443 50
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Fig. 2. (a) Relationship of the correction ROM to the firm ROM for a routine that has been corrected. (b) 6800 microcode example.

# SPECIFICATIONS

## HP Model 5355A Automatic Frequency Converter and HP Models 5356A/B/C Frequency Converter Heads

### Input Specifications CW and Pulse Modes

	5356A	5356B	5356B Opt. 001	5356C	5356C Opt. 001
<b>SENSITIVITY:</b>					
1.5-12.4 GHz	-20 dBm	-20 dBm		-25 dBm	
12.4-18 GHz	-15 dBm	-15 dBm		-20 dBm	
18-26.5 GHz		-15 dBm	-15 dBm	-20 dBm	
26.5-34 GHz				-15 dBm	-15 dBm
34-40 GHz				-10 dBm	-10 dBm
<b>MAXIMUM INPUT:</b>					
1.5-12.4 GHz	+5 dBm	+5 dBm		+5 dBm	
12.4-18 GHz	+5 dBm	+5 dBm		+15 dBm	
18-26.5 GHz		+5 dBm	+5 dBm	+15 dBm	
26.5-40 GHz				+15 dBm	+15 dBm
<b>DYNAMIC RANGE:</b>					
1.5-12.4 GHz	25 dB	25 dB		30 dB	
12.4-18 GHz	20 dB	20 dB		35 dB	
18-26.5 GHz		20 dB	20 dB	35 dB	
26.5-34 GHz				30 dB	30 dB
34-40 GHz				25 dB	25 dB
<b>DAMAGE LEVEL:</b>					
	+25 dBm peak	+25 dBm peak	+25 dBm peak	+25 dBm peak	+25 dBm peak
<b>IMPEDANCE:</b>					
	50Ω nominal	50Ω nominal		50Ω nominal	
<b>SWR (TYPICAL):</b>					
1.5-10 GHz	<2:1	<2:1		<2:1	
10-18 GHz	<3:1	<3:1		<3:1	
18-26.5 GHz		<3:1	<3:1	<3:1	
26.5-34 GHz				<3:1	<3:1
34-40 GHz				<5:1	<5:1
<b>CONNECTOR:</b>					
	N Male	SMA Male with collar	WG WR-42	APC-3.5 Male with collar	WG WR-28

#### 5355A 0.4-1.6 GHz Input:

SENSITIVITY: -15 dBm.  
 MAXIMUM INPUT: +5 dBm.  
 DYNAMIC RANGE: 20 dBm.  
 DAMAGE LEVEL: +24 dBm (Fuse in BNC Connector).  
 IMPEDANCE: 50Ω nominal.  
 SWR: <2.5: 1 typical.  
 CONNECTOR: BNC.

#### 5356A OPTION 001 HIGH-PASS FILTER:

INSERTION LOSS: <1 dB from 1.5 to 18 GHz.  
 INSERTION LOSS BELOW 100 MHz: >35 dB.

### General

**IF OUT:** Down converted signal in range of 80-375 MHz available at 5355 rear panel IF OUT connector. 0 dBm nominal level.

**GATE OUT:** 0 to -1 volt detected IF signal used to drive 5345A external gate control input.

Width of gate out is approximately 30 ns less than rf burst width.

**PULSE OUT:** Detected IF signal: TTL levels; TTL low indicates signal present; +1 to 0V typical into 50Ω.

**OPERATING TEMPERATURE:** 0° to 55°C.

#### WEIGHT:

5355A: 3.75 kg (8 lb, 4 oz) net.

5356A/B/C: 0.54 kg (1 lb, 3 oz) net.

**5356A/B/C DIMENSIONS:** 27.4 mm × 138 mm × 56.5 mm (1.08 × 5.43 × 2.23 in). Cable length: 1.68 metres (66 in).

**PRICES IN U.S.A.:** 5355A Automatic Frequency Converter Plug-In (HP-IB Standard), \$4150.

5356A 18 GHz Frequency Converter Head, \$1300.

Option 001 High Pass Filter, add \$125.

5356B 26.5 GHz Frequency Converter Head, \$1800.

Option 001 18-26.5 GHz Waveguide Input, add \$600.

5356C 40 GHz Frequency Converter Head, \$2400.

Option 001 26.5-40 GHz Waveguide Input, add \$500.

5345A Electronic Counter, \$4900.

Option 011 HP-IB, add \$800.

Option 012 HP-IB (includes Programmable Trigger Level), add \$1450.

**MANUFACTURING DIVISION:** SANTA CLARA DIVISION

5301 Stevens Creek Boulevard

Santa Clara, California 95050 U.S.A.

### Operating Mode Specifications

#### CW Mode

	5356A/B Input Auto Mode	5356A/B Input Man Mode	5355A 0.4-1.6 GHz Input	5356C Input Auto Mode	5356C Input Man Mode
<b>FM TOLERANCE:</b>	15 MHz p-p (60 MHz p-p in special FM mode). Rate: dc-10 MHz	80 MHz p-p Rate: dc-10 MHz	Instantaneous frequency must not exceed 0.4-1.6 GHz range.	60 MHz p-p Rate: dc-10 MHz	80 MHz p-p Rate: dc-10 MHz
<b>AM TOLERANCE:</b>	Any modulation index provided the minimum signal level is greater than the counter sensitivity.				
<b>MULTIPLE SIGNAL DISCRIMINATION:</b> (typical)	Automatic Amplitude Discrimination (AAD). Automatically measures largest signal provided signal is 8 dB (typical) greater than any signal within 500 MHz and 20 dB (typical) greater than any signal over range 1.5-26.5 GHz.			8 dB within 500 MHz range, 20 dB within 1.5-26.5 GHz, 15 dB within 26.5-40 GHz (Option 001: 20 dB within 26.5-40 GHz)	8 dB within 500 MHz range
<b>ACQUISITION TIME:</b> (typical)	400 ms (1.1 s in special FM mode)	15 ms	<1 ms (Freq ≥800 MHz) 5345A Gate Time + 45 ms (Freq <800 MHz)	1.4 s (Option 001: 1.1 s)	15 ms
<b>MEASUREMENT TIME:</b>	Acquisition time + 4×5345A Gate Time + 5345A Sample Rate + 125 ms (Gate Time ≤100 ms) Acquisition time + 5345A Gate Time + 5345A Sample Rate + 35 ms (Gate Time ≥1 s)		Acquisition time + 5345A Gate Time + 5345A Sample Rate + 35 ms	Gate Time ≤100 ms: Acquisition time + 4×Gate Time + 5345A Sample Rate + 125 ms Gate Time >100 ms: Acquisition time + 5345A Gate Time + 5345A Sample Rate + 35 ms	
<b>LSD DISPLAYED:</b>	1 Hz 5345A Gate Time			1 Hz 5345A Gate Time	
<b>RESOLUTION:</b>	±2×LSD ± 1×10 <sup>-10</sup> rms × Freq		±5 × LSD	±2×LSD ± 1×10 <sup>-10</sup> rms × Freq	
<b>ACCURACY:</b> (after 1 minute warmup)	±2×LSD ± 1×10 <sup>-10</sup> rms × Freq ± Time Base Error × Freq		±5 × LSD ± Time Base Error × Freq	Resolution ± Time Base Error × Freq	

Specifications describe the instrument's warranted performance. Typical or nominal performance characteristics provide useful application information but are not warranted.

**Pulse Mode**

	5356A/B Input Auto Mode	5356A/B Input Man Mode	5355A** 0.4-1.6 GHz Input	5356C Input Auto Mode	5356C Input Man Mode
<b>FM TOLERANCE:</b> (typical)	50 MHz p-p chirp	80 MHz p-p chirp	Instantaneous frequency must not exceed 0.4-1.6 GHz range	50 MHz p-p chirp	80 MHz p-p chirp
<b>ACQUISITION TIME:</b> (typical)	$\frac{100 \mu s}{\text{Ext. Gate Width} \times \text{PRF}} + 650 \text{ ms}$ (Ext. Gate $\leq 100 \mu s$ )  $\frac{2}{\text{PRF}} + 650 \text{ ms}$ (Ext. Gate $> 100 \mu s$ )	0	0 (Freq. $\geq 800 \text{ MHz}$ )  $\frac{5345A \text{ Gate Time}}{\text{Ext. Gate Width} \times \text{PRF}} + 45 \text{ ms}$ (Freq. $< 800 \text{ MHz}$ )	Ext. Gate $\leq 100 \mu s$ : 8 (Option 001: 7)/PRF +1.55 s (Option 001: 1.25 s) +100 $\mu s$ /(Ext. Gate Width $\times$ PRF) Ext. Gate $> 100 \mu s$ : 10 (Option 001:9)/PRF +1.55 s (Option 001: 1.25 s)	0
<b>CALIBRATION TIME:</b>	$\frac{5345A \text{ Gate Time}}{\text{Ext. Gate Width} \times \text{PRF}} + 75 \text{ ms}$ Performed during 10 consecutive measurements when pulse mode is selected, after any front panel change, or when the external gate width changes by more than 12%. Only calibrates if external gate is $< 100 \mu s$ .				
<b>MEASUREMENT TIME:</b> (typical)	$\frac{\text{Acquisition Time} + \text{Calibration Time} + 5345A \text{ Sample Rate} + 5345A \text{ Gate Time or } 100 \mu s \dagger}{\text{Ext. Gate Width} \times \text{PRF}} + 100 \text{ ms}$  †whichever is greater	$\frac{\text{Acquisition Time} + \text{Calibration Time} + 5345A \text{ Sample Rate} + 1 \mu s}{\text{Ext. Gate Width} \times \text{PRF}} + \frac{5345A \text{ Gate Time}}{\text{Ext. Gate Width} \times \text{PRF}} + 60 \text{ ms}$		$\frac{\text{Acquisition Time} + \text{Calibration Time} + 5345A \text{ Sample Rate} + 100 \text{ ms} + 5345A \text{ Gate Time or } 100 \mu s \dagger}{\text{Ext. Gate Width} \times \text{PRF}}$  †whichever is greater	$\frac{\text{Acquisition Time} + \text{Calibration Time} + 5345A \text{ Sample Rate} + 60 \text{ ms} + (1 \mu s + \text{Gate Time})}{\text{Ext. Gate Width} \times \text{PRF}}$
<b>PULSE WIDTH</b> MINIMUM: MAXIMUM:	100 ns 20 ms	60 ns 20 ms	100 ns 1 s	100 ns 20 ms	60 ns 20 ms
<b>PULSE REPETITION FREQUENCY</b> MINIMUM: MAXIMUM:	50 Hz 2 MHz	50 Hz 2 MHz	100 Hz 2 MHz	50 Hz 2 MHz	
<b>MINIMUM ON/OFF RATIO:</b>	25 dB typical			25 dB typical	
<b>MAXIMUM VIDEO FEEDTHROUGH:</b>	15 mV p-p typical for RF burst rise and fall times $\geq 10 \text{ ns}$			15 mV p-p typical for RF burst rise and fall times $\geq 10 \text{ ns}$	
<b>MINIMUM EXT. GATE WIDTH:</b> (5345A)	60 ns	20 ns	40 ns	60 ns	20 ns
<b>LSD DISPLAYED:</b>	$\frac{1 \text{ Hz}}{5345A \text{ Gate Time}}$			$\frac{1 \text{ Hz}}{5345A \text{ Gate Time}}$	
<b>RESOLUTION:</b>	$\pm 2 \times \text{LSD} \pm \text{rms jitter}^*$		$\pm 10 \times \text{LSD} \pm 5 \times \text{rms jitter}^*$	$\pm 2 \times \text{LSD} \pm \text{rms jitter}^*$	
<b>ACCURACY:</b> (after 1 minute warmup)	$\pm 2 \times \text{LSD} \pm \text{rms jitter}^* \pm \frac{.04}{\text{Ext. Gate Width}} \pm 3 \text{ kHz} \pm \text{Time Base Error} \times \text{Freq}$		$\pm 16 \times \text{LSD} \pm 5 \times \text{rms jitter}^* \pm \frac{.08}{\text{Ext. Gate Width}} \pm 24 \text{ kHz} \pm \text{Time Base Error} \times \text{Freq}$	$\pm 2 \times \text{LSD} \pm \text{rms jitter}^* \pm \text{Time Base Error} \times \text{Freq} \pm 3 \text{ kHz} \pm \frac{.04}{\text{Ext. Gate Width}}$	

\*rms jitter = (5345A Gate Time  $\times$  Ext. Gate Width)<sup>-1/2</sup> + 100 Hz  
\*\*Specifications apply only to external gating of 5345/5355.

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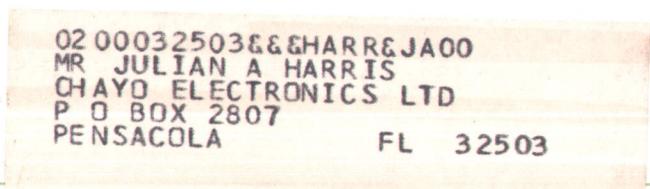
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APRIL 1980 Volume 31 • Number 4

Technical Information from the Laboratories of  
Hewlett-Packard Company

Hewlett-Packard Company, 1501 Page Mill Road  
Palo Alto, California 94304 U.S.A.  
Hewlett-Packard Central Mailing Department  
Van Heuven Goedhartlaan 121  
1180 AM Amstelveen The Netherlands  
Yokogawa-Hewlett-Packard Ltd., Suginami-Ku  
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