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A Simple Precision System for Measuring CW and Pulsed Frequencies Up to 12,400 MC

WHEN it is necessary to measure high frequencies to better than wavemeter accuracy, it is usual practice to custom-build a system which frequently becomes bulky, expensive, and inconvenient to use. This problem has now been significantly simplified by a new transfer oscillator which permits such measurements to be made with the *-hp-* high-speed frequency counters*. Measurements can be made with this transfer oscillator-frequency counter combination from 0 cps to at least 12,400 megacycles at an accuracy approaching 1 part per million. Not only does the system permit measurement of c-w frequencies, but it will also enable the carrier frequency of pulsed or frequency-modulated waves to be measured. The system is simple and sufficiently rapid that it is suited to production-line use.

How the system measures high frequencies can be described by reference to Fig. 2. The transfer oscillator generates a stable signal, adjustable in frequency from 100 to 220 mc, which is continuously monitored to 1 part per million accuracy by the frequency counter. Harmonics of the transfer oscillator are then compared in a mixer with the frequency to be measured, using the oscilloscope contained in the transfer oscillator to observe the difference frequency. By suitably adjusting the transfer oscillator frequency, a zero beat can be obtained between a transfer oscillator harmonic and any unknown frequency from 100 to 12,400 megacycles.† When the zero beat is obtained, the unknown is determined merely by multiplying the reading on the frequency counter by the proper harmonic number. If the proper number is unknown, it can be found by the simple system described later.

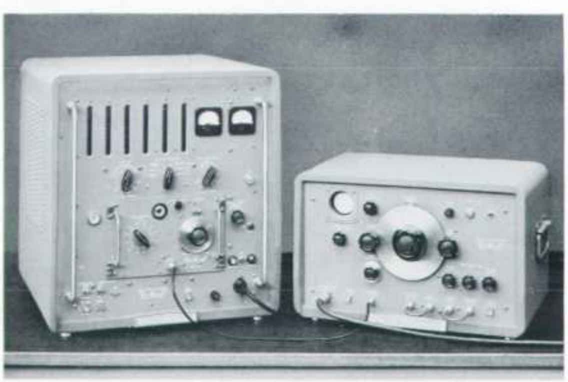


Fig. 1. New -hp- Model 540A Transfer Oscillator (right) operates with -hp- 524B High Speed Counter and 525B Converter to form precision measuring system capable of operation from 0 cps to 12,400 megacycles.

C-w frequencies below the convenient lower frequency operating range of the transfer oscillator can be measured by connecting them to the frequency counter where the answer will be presented directly on the counter's display system. By this means frequencies down to 0 cps can be measured.

C-W MEASUREMENTS

If an ideally stable c-w signal were being measured, the operator would adjust the frequency of the transfer oscillator while observing the difference frequency as plotted by the self-contained oscilloscope's 60-cps sweep. The first presentation usually recognized will be similar to Fig. 3(a) where a low (but significant) difference frequency is displayed. As the operator continued tuning (Fig. 3(b)), the pattern would collapse to a

*Alan S. Bagley, Dexter Hartke, and Wm. D. Myers, "Frequency and Time Measurements with the New -hp- High Speed Counter," Hewlett-Packard Journal, Vol. 5, No. 7-8, Mar.-April, 1954.

†Frequencies from 10 to 100 megacycles can also be measured by using a harmonic of the measured frequency and the fundamental of the oscillator.

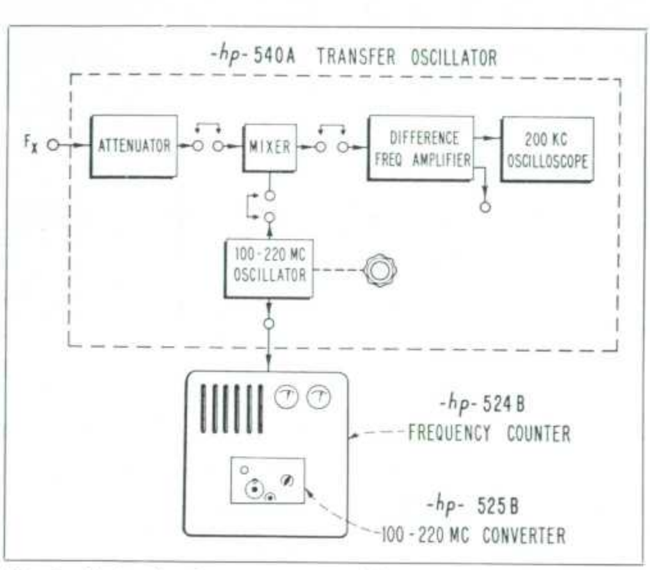


Fig. 2. *Basic circuit arrangement of frequency counter-transfer oscillator measuring system. Main components of transfer oscillator are shown within dashed line.*

straight horizontal sweep line when a true zero beat were obtained (Fig. 3(c)) on a stable signal.

In practice, however, few high-frequency signals are sufficiently stable that a simple zero beat can be obtained. Instead, the signal to be measured usually has enough short-time instability that beat frequency patterns like those in Figs. 4(a) and (b) are somewhat more typical, at least at kilomegacycle frequencies. These patterns are those of frequencies passing through zero beat as displayed by the internal oscilloscope's 60-cycle sweep. Notice that the zero beat point is where the cycles in the patterns become expanded horizontally and reverse their slope before reaching full amplitude. Notice further that, not only can the zero point be determined, but by adjusting the frequency of the transfer oscillator, the zero beat can be positioned at the two edges of the pattern (Figs. 5(a) and (b)) or at any other desired point. This means that the limits between which the signal is varying, whether due to instability or to frequency modulation, can be measured. For example, an 11,000 megacycle c-w signal with 150 kc deviation caused by power supply ripple can be measured in such a way that the 150 kc of deviation can be determined. Information of this character at high frequencies is difficult to obtain with other systems.* The ability to make deviation measurements and the fact that an oscilloscopic display presents considerable information about the nature of the signal being measured are two of the reasons for incorporating an oscilloscope in the transfer oscillator instead of using a simple aural detector. The choice of a line frequency sweep is also of considerable value, because much of the deviation in typical signals is related to the line frequency.

ACCURACY OF C-W MEASUREMENTS

The error involved in measuring a c-w frequency can be divided into two parts. First is the error of the frequency counter in measuring the frequency of the transfer oscillator. Second is the error involved in comparing the transfer oscillator frequency with the frequency to be measured.

If the counter is being operated from its internal standard, it will measure the frequency of the transfer oscillator to within ±1 part per million. The counter is also arranged, however, to operate from an external standard. If it is so operated, it will measure the transfer oscillator frequency to the accuracy of that standard up to the limit of the error of comparison.

The second error, the error of comparison, is typically in the order of ±2 parts in 10^7 but involves several factors. One factor is the short-time stability of the transfer oscillator (about ±1 part in 10^7). Another factor is the setability of the oscillator (about ±1 part in 10^7) which also involves to some extent the skill of the operator. These factors are perhaps best summed up in the histogram of Fig. 7. This histogram shows the distribution of the error of comparison of 250 measurements made by five operators. Precautions were taken in the set-up to eliminate all but the error of comparison. The rms value of this distribution is well within ±1 part in 10^7.

All of these errors assume that the signal being measured is significantly more stable than the error of comparison. If the signal has an instability of the same magnitude or

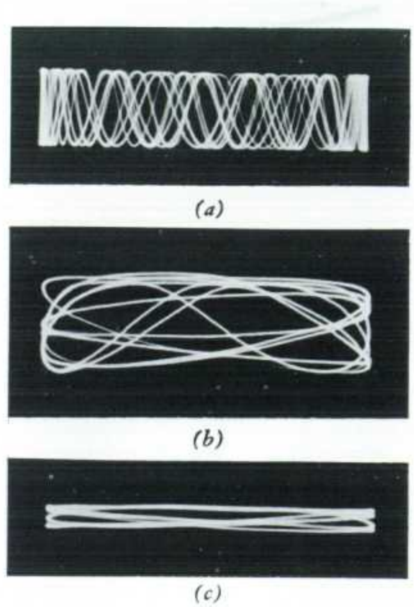


Fig. 3. *Typical sequence of patterns obtained on transfer oscillator's scope as difference frequency is reduced to zero on a stable signal. Note that internal scope uses a 60-cycle sweep.*

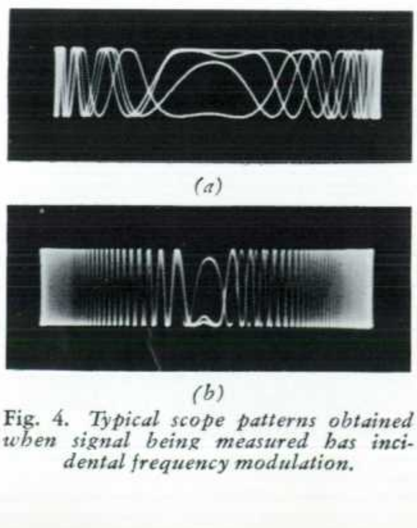
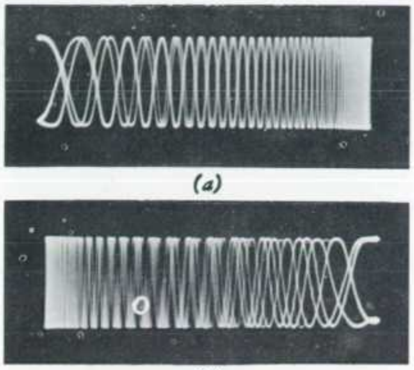


Fig. 4. *Typical scope patterns obtained when signal being measured has incidental frequency modulation.*

*The versatility and accuracy of deviation measurements can be increased by adding to the system a new electronic frequency meter which will be described in an early issue.



(a)

(b)

Fig. 5. *Typical scope patterns obtained when zero beat is adjusted to occur at limit of excursion of signal being measured.*

greater than the error of comparison, the accuracy of the comparison will of course be reduced accordingly.

To sum up the error of the counter with the error of comparison, the data in Fig. 7, although they involve only the error of comparison, can also be considered to represent the present limit of the system using an appropriately stable signal and an appropriately accurate external frequency standard. If the internal standard is used, measurements can be made on an appropriately stable signal to within approximately 1 part in 10^6 including the error of comparison. Obviously, the system is suited to most of the precise present-day frequency measurements.

IDENTIFYING THE BEATING HARMONIC

When the zero beat is obtained, the unknown frequency will be equal to the frequency of the transfer oscillator multiplied by the order number of the harmonic causing the beat. The proper harmonic number will usually be known at once, because the approximate value of a frequency to be measured is usually known. Even if the approximate value is completely unknown, however, it can still be obtained quickly by making two short measurements. If a frequency of 10,000 megacycles were being measured, for example, a measurement could be made by tuning the transfer oscillator to 200 megacycles where the zero beat would be caused by the 50th harmonic of 200 megacycles. The fundamental frequency, 200 mc, will be known because it is indicated directly by the counter. By now setting the oscillator to the next lower frequency that causes a zero beat (196.078 mc), we know that the zero beat is caused by the next higher harmonic. That is,

$$(\text{Harmonic no.}) \times 200 \text{ mc} = (\text{Harmonic no.} + 1) \times 196.078 \text{ mc}$$

or,

$$\text{Harmonic no.} = 50.$$

The measurement can and should be cross-checked by tuning the oscillator to the next higher frequency (204.082 mc) that causes a zero beat. This beat will be caused by the next lower harmonic (49th). By this simple system the harmonic causing the zero beat can be uniquely identified*.

PULSE MEASUREMENTS

Another attractive feature of the transfer oscillator-frequency counter system is that it can be used to measure to high accuracies the carrier frequency of r-f pulses.† To make pulse measurements, an external oscilloscope suitable for viewing video pulses and with a linear sweep should be used in place of the simple internal oscilloscope which cuts off at about 200 kc. An output from the difference frequency amplifier is provided for presentation on the vertical system of an external oscilloscope. The high frequency cutoff of the difference frequency amplifier is a little above 2 mc. An output can also be obtained directly from the mixer for use with a suitable external amplifier.

*For frequencies lying in or near the fundamental range of the transfer oscillator, a variation of this technique may be required.

†Alan Bagley and Dexter Hartke, "Measurement of the Carrier Frequency of RF Pulses," presented at 4th Conference on High Frequency Measurements, Wash., D.C., Jan. 19, 1955 and at 7th Regional Conference, Phoenix, Ariz., Apr. 27, 1955.

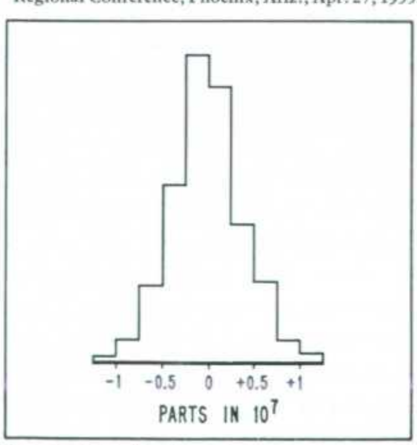
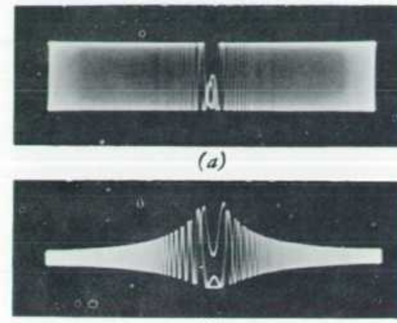


Fig. 7. *Distribution of error of comparison in 250 measurements made by five operators.*



(a)

(b)

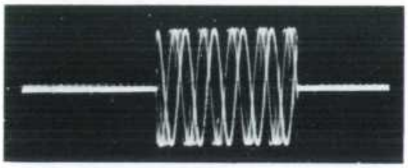
Fig. 6. *Typical scope patterns obtained when (a) signal has wide excursions and (b) when excursions are so wide that display is limited by system bandwidth.*

When the oscillator is tuned for a zero beat with a pulsed r-f wave applied to the system, the first presentation usually recognized on the oscilloscope will be similar to that in Fig. 8(a). This is a plot of the difference frequency as modulated by the r-f pulse envelope. About five cycles of difference frequency are occurring for each r-f pulse width. If the pulse width is 10 microseconds, the difference frequency will be about 500 kc. As the oscillator is more closely tuned to zero beat, the number of difference-frequency cycles per pulse will decrease and finally become less than one cycle. When the beat frequency is much less than one cycle, a pattern like that in Fig. 8(b) will be obtained. Each of the horizontal lines is now a segment of a sine wave, and the lowest beat frequency is obtained when the pattern becomes a family of traces all having the same shape, as in Fig. 8(b). In Fig. 8(b) the beat frequency is about one one-hundreth of a cycle per pulse width.

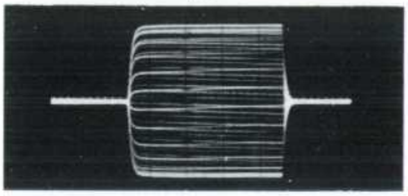
The magnitude of frequency shifts that may occur during a pulse can also be measured by using a variation of this technique.

ALTERNATE PULSE PRESENTATION

While the above-described method is a basic method for measuring



(a)



(b)

Fig. 8. *Typical scope patterns obtained in pulsed r-f measurement as (a) zero beat is first approached and (b) when beat frequency has been made very small.*

pulsed carriers, another slight variation will usually permit the measurement to be made faster. This modified technique gives about the same accuracy of measurement on a stable pulsed carrier but is easier to use.

The modification consists of increasing the low-frequency cutoff of the difference-frequency amplifier in the instrument. If the low-frequency cutoff is made sufficiently high, the pulsed difference frequency will be differentiated by the time constant of the amplifier. The presentation obtained on the oscilloscope will then be as indicated in Figs. 9(a) through (c). When the difference frequency is relatively large, a notch will be seen in the oscilloscope pattern as in Fig. 9(a). As the difference frequency is reduced, the pattern will begin to converge as in Fig. 9(b). When the difference frequency is reduced to its lowest value, the presentation will appear as in Fig. 9(c). This presentation is the same as that in Fig. 8(b) except that it is differentiated.

To facilitate these sawtooth presentations, a panel control is provided for adjusting the low-frequency cutoff of the difference-frequency amplifier. This cutoff, normally below 100 cps for c-w measurements, can be switched with the control to be 10 kc and is then continuously adjustable to above 400 kc. When a suitable cutoff is used, almost complete convergence of the presentation as in Fig. 9(c) can be obtained for pulses as short as 1 microsecond. Although use of too low or too high a cutoff will reduce the accuracy of the measurement, this selection is not critical since in a practical case no absolute optimum exists. It has been found that an amplifier time-constant of about one-fourth the pulse width is satisfactory. Such a time constant was used in Fig. 9(c). The fact that the trailing edge of the pulse is also differentiated by the amplifier makes it easy to select the proper value of time constants. If the carrier frequency is unusually unstable during the pulse, the degree of convergence shown in Fig. 9(c) will not be obtained. With typical amounts of instability, however, the convergence will still be highly defined.

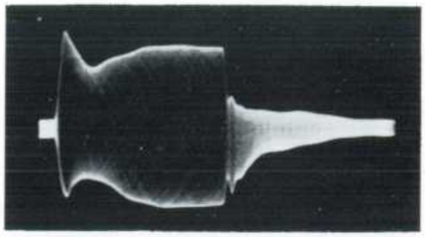
The fact that the amplifier time-constant is adjustable also permits the equipment to be used to measure carriers modulated with non-rectangular pulses such as gaussian pulses.

ACCURACY OF PULSE MEASUREMENTS

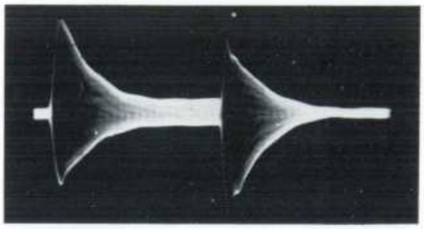
The accuracy with which a pulsed carrier can be compared with a tranfer oscillator harmonic is in the order of one one-hundredth of a cycle per pulse width. Pulse width enters into the accuracy of measurement at a given r-f frequency because the accuracy with which either a beat frequency or convergence of a sawtooth can be discerned becomes less as the pulse width becomes shorter.

OPERATION ABOVE 5 KMC

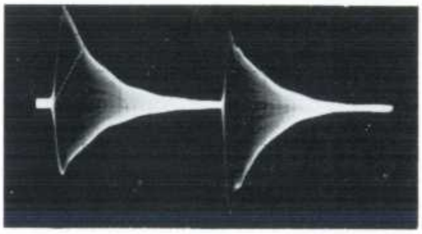
The mixer in the transfer oscillator is a broadband design which operates from low frequencies to more than 5 kilomegacycles. As higher and higher frequencies are measured, however, the efficiency of the mixer falls off with an accompanying loss in sensitivity. As a result, when frequencies above 5 kmc are to be measured, it is desirable to use an *-hp-* Model 440A Detector Mount either as an external tuned mixer or as a local oscillator harmonic generator. The detector mount contains a 1N21B silicon crystal with a tuning stub. The difference frequency amplifier and the internal oscillator in the instrument are provided with ex-



(a)



(b)



(c)

Fig. 9. *Typical sequence of scope patterns obtained with sawtooth presentation as zero beat is approached (a) and (c) when beat frequency has been reduced to low value.*

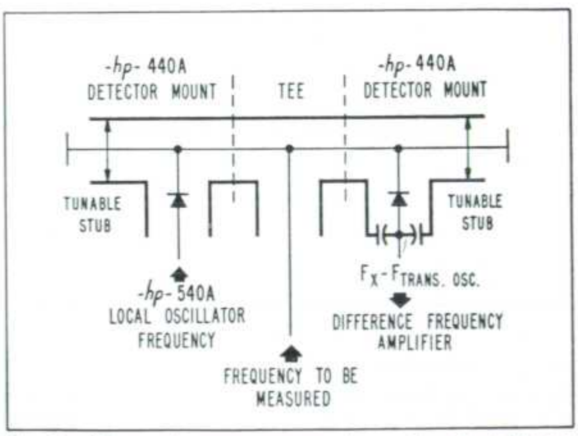


Fig. 10. *Schematic arrangement of two -hp- Model 440A Detector Mounts as used to increase sensitivity of measurements in range above 5 kmc.*

ternal terminals to accommodate use of an external mixer or external harmonic generator.

Although only one detector mount is needed for measurements in the 5,000 to 12,400 mc range, better sensitivity and lower noise will be obtained if the harmonic generating process is isolated from the mixing process. This isolation is obtained by using a second 440A detector for harmonic generation alone. Both the crystal used for harmonic generation and that used for mixing thus become tuned. As a result, the currents through the mixing crystal are to some extent limited to those of the unknown and of the proper harmonic. An increase in output and discrimination against unrelated frequencies are therefore obtained. A schematic diagram of the arrangement using two detector mounts is shown in Fig. 10.

SENSITIVITY

The minimum signal level with which measurements can be made varies with frequency and with the method of measurement. A guide to representative minimum usable signal levels for c-w, pulse or f-m measurements is shown in Fig. 11. The data for these curves were obtained by averaging six measurements using the lowest possible harmonic of the transfer oscillator (i.e., highest possible oscillator frequency). The plotted values further represent the signal level necessary to obtain an output at the difference-frequency amplifier output terminal which is 6 db above the noise level. This output corresponds to that which will produce a usable vertical deflection of the internal oscilloscope.

The curve at the upper left in Fig. 11 shows representative minimum usable signal levels in the range from 400 to 5,000 megacycles when a measurement is made by connecting the unknown directly to the input attenuator of the instrument. This attenuator is useful when the unknown is relatively large in amplitude because it enables the input level to be adjusted to the level which will give most effective action in the mixer. This is particularly true for pulse measurements.

Since the attenuator is a piston type, however, it has an insertion loss which in this case is approximately 20 db at the lower frequencies. An increase in sensitivity can therefore be obtained by not using the attenuator and by connecting the unknown directly to the internal mixer. An input terminal for the mixer is provided on the panel. This arrangement will give the sensitivity shown by the middle curve in Fig. 11.

The right-hand curve shows typical sensitivity using two Model 440A Detector Mounts for external harmonic generation and mixing, as discussed previously.

In the range from 220-100 mc, the minimum usable signal is in the order of 200 microvolts. From 100 to

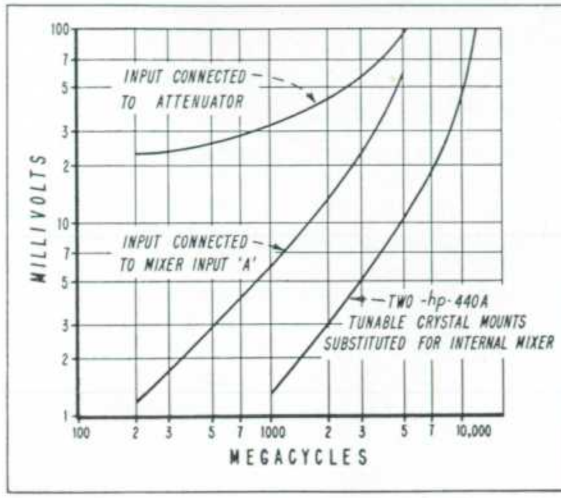
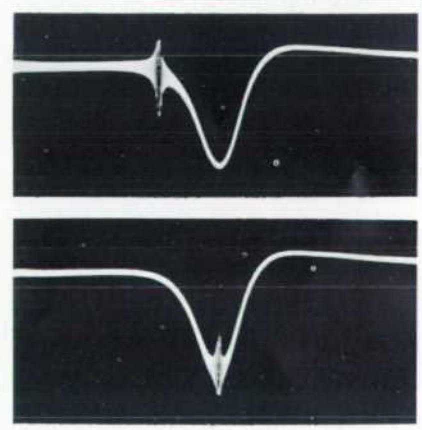


Fig. 11. *Representative minimum signal levels on which measurements can be made. Curves are average of six responses using lowest possible harmonics of transfer oscillator. Curves show input required to produce at difference frequency output terminal a response 6 db above noise level.*

WAVEMETER CALIBRATION



Much interest has been shown by visitors in the use of the transfer oscillator-frequency counter system in the *-hp-* plant for calibrating cavity wavemeters up to 18 kmc. The accompanying oscillograms show the presentation the operator sees when measuring a wavemeter setting. In the upper oscillogram a "birdie" from the transfer oscillator has been adjusted to be near the notch caused by the reaction type wavemeter. In the lower oscillogram the transfer oscillator has been adjusted so that the birdie coincides with the center frequency of the wavemeter. Effects of temperature and mechanical tolerances in the wavemeter can easily be measured with the arrangement.

In order to display the wavemeter notch, the signal source is frequency modulated. The amount of modulation deviation and the bandwidth used for the difference frequency amplifier determine the apparent width of the birdie. By reducing the amplifier bandwidth, the birdie can be made narrower than that shown. Normally, sine wave modulation is used for the source and the same modulating waveform is used for horizontal deflection of the oscilloscope. For clarity of illustration in the above oscillograms, however, a linear sweep was used.

The set-up used to measure the wavemeter frequency is that which uses two detector mounts as described in the accompanying article. The mounts are slightly modified to enhance their operation above their 12.4 kmc rated limit.

The arrangement used is an outgrowth of the arrangement described by W. D. Myers in the article "Simplified Microwave Frequency Measurements Using the 10 Mc Frequency Counter," *Hewlett-Packard Journal*, Vol. 3, No. 5-6, Jan.-Feb., 1952.

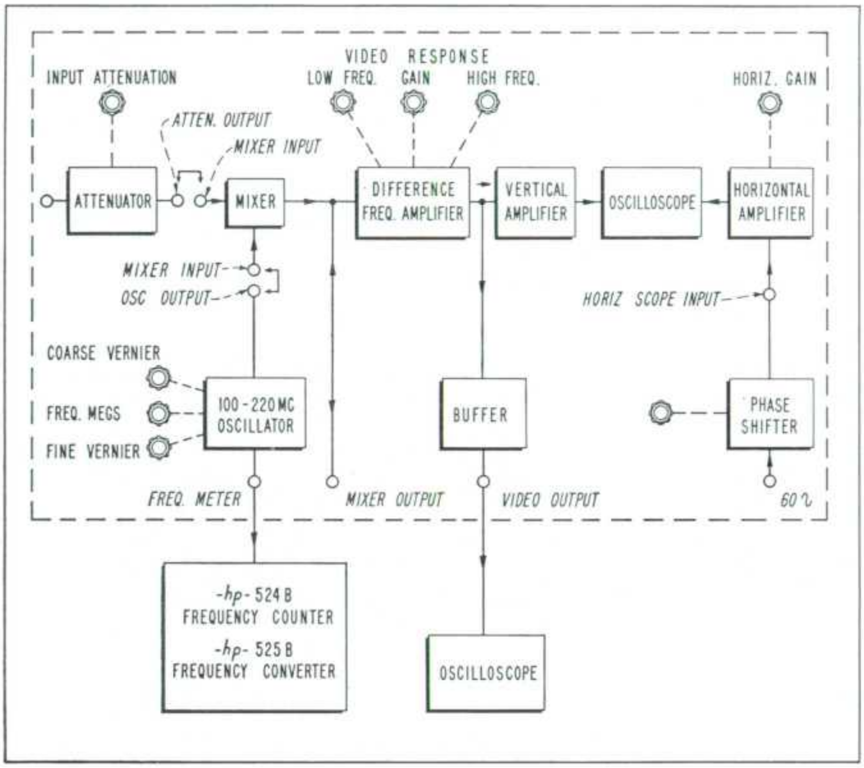


Fig. 12. *Detailed block diagram of transfer oscillator circuitry.*

10 mc, if harmonics of the signal are used for the measurement, the minimum usable signal varies from about 1 millivolt at 100 mc to 1 volt at 10 mc. Below 10 mc it is 1 volt, the sensitivity of the *-hp-* 524B Frequency Counter.

In the range from 100 to 10 mc the *-hp-* 525A Frequency Converter can be used for c-w measurements. In this case the minimum usable signal will be 10 millivolts.

CIRCUIT ARRANGEMENT

Fig. 12 shows the arrangement of the major circuitry of the 540A Transfer Oscillator. At the front end is an isolated piston attenuator which can be used to attenuate high level signals to a level suitable for the crystal mixer. No direct connection is made from the attenuator to the mixer, since in some applications it is desirable to bypass the attenuator. The attenuator output can be connected to the mixer by means of a short coaxial patch cord.

The mixer is provided with two inputs, A and B, which are available at panel terminals. This arrangement permits the external signal to be connected directly to the internal mixer so as to avoid the insertion loss of the input attenuator if desired. Mixer input B is provided for connecting the internal oscillator with a coaxial patch cord.

Connections to the mixer and local oscillator are made externally, because with this arrangement external tuners can be used to enhance measurements of frequencies above 5 kmc as described previously.

The difference frequency produced in the mixer is applied to a 40 db amplifier. An input terminal for this amplifier is available on the panel for use when an external mixer is used. The amplifier is provided with a gain control and with controls that adjust its low and high frequency response. The response controls are useful when measuring pulsed carriers and when excessive noise is combined with the frequency to be measured.

The output of the amplifier is available for connection to an external oscilloscope or, alternatively, the internal oscilloscope can be used. The internal oscilloscope has a response from 100 cps to 200 kc and a gain of 40 db which, together with the gain of the difference-frequency amplifier, gives an overall difference-frequency gain of 80 db.

—Dexter Hartke

SPECIFICATIONS
-hp-
MODEL 540A TRANSFER OSCILLATOR

GENERAL

FREQUENCY MEASUREMENT RANGE: 10 mc to 5,000 mc with internal mixer, or to 12,400 mc with external -hp- Model 440A Detector Mount.

TYPE INPUT SIGNAL: C-w, A-M, or pulse.

INPUT SIGNAL LEVEL: 50 millivolts to 5,000 megacycles (see curves in text). Max. equiv. c-w power ½ w at 50Ω.

ACCURACY: Depends on stability of unknown signal and pulse length—see text.

AUXILIARY EQUIPMENT: (1) -hp- Model 524B Electronic Counter. (2) -hp- Model 525B Frequency Converter Unit. (3) Oscillosynchroscope (for pulse measurements). (4) 1 or 2 -hp- Model 440A Detector Mounts.

OSCILLATOR

FUNDAMENTAL FREQUENCY RANGE: 100 mc to 220 mc.

HARMONIC FREQUENCY RANGE: To above 12,400 mc.

STABILITY: Less than 0.002% change per minute after 30-minute warmup.

DIAL: Six inch diameter, calibrated in 1 mc increments. Accuracy ±½%.

VERNIER CONTROLS: Mechanical: 9:1 reduction drive. Electrical: Permits trimming oscillator frequency by approximately ±125 ppm maximum.

OUTPUT: Approximately 2 volts min. across 50Ω over frequency range.

ATTENUATOR

RANGE: Continuously adjustable from approximately 20 to 80 or more db at 1 kmc.

INPUT IMPEDANCE: 50 ohms. VSWR: 1.5 max. at 1 kmc; 3 max. at 5 kmc.

AMPLIFIER

GAIN: Adjustable; 40 db max.

BANDWIDTH: High-frequency 3 db point adjustable from below 1 kc to above 2 mc; low-frequency 3 db point adjustable from below 10 kc to above 400 kc.

MAX. UNDISTORTED OUTPUT: 1 volt rms across 1,000Ω.

OSCILLOSCOPE: (Self-Contained 2 in. C-R tube.)

VERTICAL DEFLECTION SENSITIVITY: 5 millivolts rms per inch.

BANDWIDTH: 100 cps to 200 kc. High frequency control adjusts 3 db point from below 1 kc to above 200 kc.

HORIZONTAL SWEEP: Internal power frequency sine wave sweep with phase control, or externally applied signal without phase control.

HORIZONTAL DEFLECTION SENSITIVITY: 1 volt/inch, 20 cps to 5 kc.

MISCELLANEOUS

CONNECTORS: Attenuator Input: Female type N; all others female type BNC.

SIZE: Cabinet Mount: 20¾" wide, 12½" high, 14¾" deep. Rack Mount: 19" wide, 10½" high, 12¾" deep.

WEIGHT: Cabinet Mount: 35 lbs.; shipping weight 85 lbs. Rack Mount: 25 lbs.; shipping weight 75 lbs.

POWER: 115/230 v rms ±10%, 50-1000 cps, approx. 75 watts.

AUXILIARY EQUIPMENT: -hp- Model 440A Detector Mount, $85.00. -hp- Model 524B Electronic Counter, cabinet mount, $2150.00. -hp- Model 524BR Electronic Counter, rack mount, $2125.00. -hp- Model 525B Frequency Converter Unit, 100-220 mc, $250.00.

PRICE: -hp- Model 540A Transfer Oscillator, cabinet mount, $615.00. -hp- Model 540AR Transfer Oscillator, rack mount, $600.00.

All prices f.o.b Palo Alto, California.
Data subject to change without notice.