

Calibrating crystal oscillators with TV color-reference signals

Phase-comparison with networks' rubidium standards yields resolution in minutes that would require days of checking against WWV or WWVH; National Bureau of Standards has designed simple measurement circuitry

by Dick D. Davis, *National Bureau of Standards, Boulder, Colo.*

□ A crystal oscillator can be calibrated accurately in about 15 minutes by comparing its phase to that of the color-reference signals broadcast by the four major television networks. It would take days of comparing the frequencies of the oscillator to those of the signals broadcast by National Bureau of Standards radio stations WWV and WWVH to achieve accuracy of that order.

And since NBS monitors network signals and publishes offsets with respect to its standards, oscillator calibrations by such phase comparisons can be traced to NBS. What's more, NBS has applied for patents on a number of circuits that make phase comparison with color-TV subcarriers relatively simple. Among them are the color-bar comparator, the digital-subcarrier comparator, and the frequency-measurement computer, which are described in this article.

A TV receiver tuned to a network color program is a highly accurate reference because ABC, CBS, NBC, and PBS all use rubidium oscillators to generate 3.58-megahertz signals, and every color-TV set phase-locks to those references. A scheme for comparing the phases of the two signals is shown in Fig. 1.

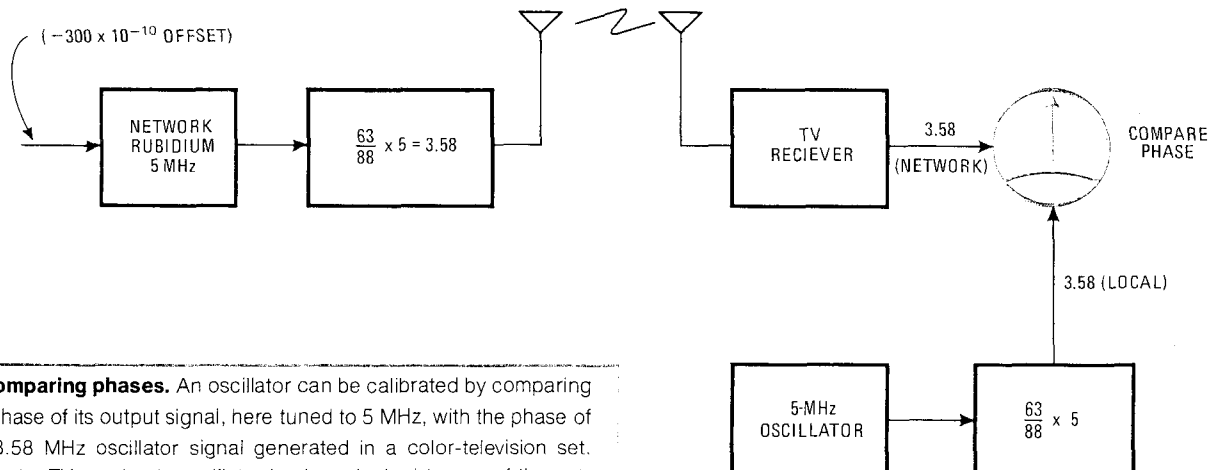
If the frequency of the reference signal is 3.58 MHz, the full-scale reading on the phase meter, one 360° cycle, is about 279 nanoseconds. If the oscillator's fre-

quency differs from the reference, the phase difference varies with time. For example, if the two frequencies differ by one cycle per second, the meter would deflect from zero to full scale in one second, return to zero, and start over again in the next second.

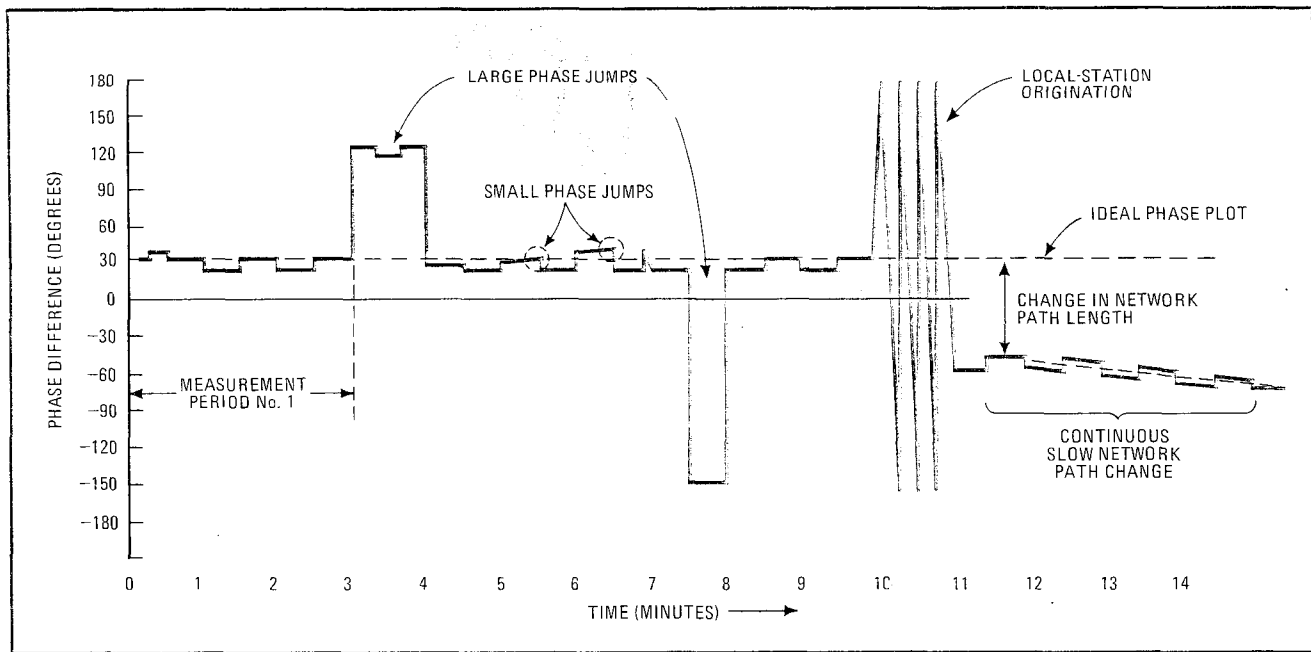
If the crystal oscillator is set to within one part in 10^{10} , or 1×10^{-10} , of the 3.58-MHz reference frequency, the phase meter will accumulate 1×10^{-10} nanoseconds of phase difference after 1 ns of observation time, or 0.1 ns per second of observation time. Since the meter will move full-scale, or 279 ns, in 2,790 seconds, a high measurement resolution is possible. For example, if the 2,790-second period is measured with an uncertainty of $\pm 10\%$ —279 seconds—the resolution is $\pm 10\%$ of 1×10^{-10} , or $\pm 1 \times 10^{-11}$.

Taking advantage of offsets

Several years ago, the networks began using rubidium atomic oscillators to increase the stability of their color subcarriers. These were standard 5-MHz rubidium oscillators with added circuitry that synthesized 3.5795454... MHz by multiplying 5 MHz. by 63/88. Some time after these units were put into service, the international standard of frequency, the reference tracked by NBS, was changed by $+300 \times 10^{-10}$. The network



1. Comparing phases. An oscillator can be calibrated by comparing the phase of its output signal, here tuned to 5 MHz, with the phase of the 3.58 MHz oscillator signal generated in a color-television set. Since the TV receiver's oscillator is phase-locked to one of the networks' highly stable and accurate rubidium oscillators, it provides an accurate, stable, and convenient reference.



2. Phase plot. The phase difference between signals from an oscillator under test and the network's color subcarrier is never constant for more than a brief period. This must be considered when calibrating an oscillator to a TV color-subcarrier reference.

rubidium oscillators are therefore offset with respect to these standards.

Thanks to the offset of the networks' oscillators with respect to NBS standards, a crystal oscillator can be checked for accuracy in less than 10 seconds with resolutions in the range of a few parts in 10^{10} . The time required to accumulate 360° of phase shift in these network standards is

$$P = T/Q$$

where T is the period of the reference signal and Q is the offset of the unknown. With a 3.58-MHz reference and 3×10^{-8} offset, the period of the beat note is 9.31 seconds.

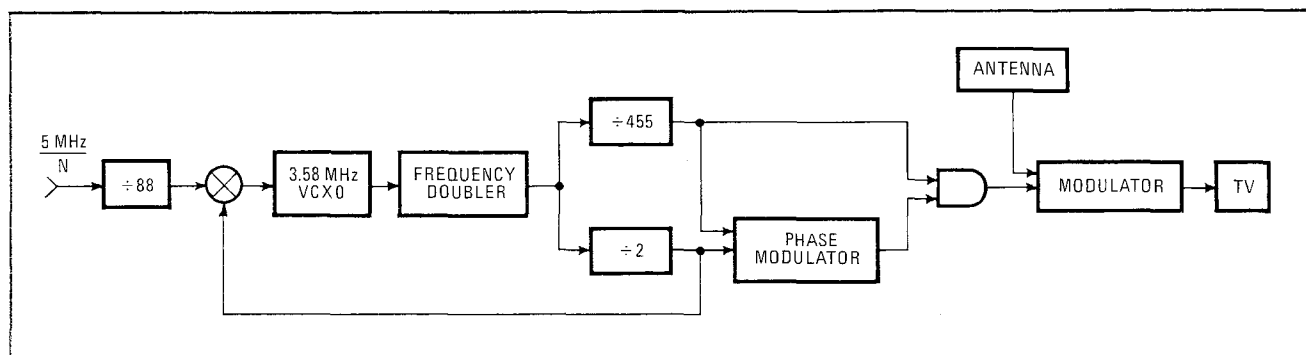
If the offset were 3.01×10^{-8} , the period of this beat note would be 9.28 seconds, a change of 0.03 second. Conversely, an error of 0.03 second in making a period measurement yields an error in the frequency measurement of only one part in 10^{10} . What's more, the measurement has only three digits—the 9.31- and 9.28-second intervals of these examples. A measurement error of ± 1 digit (± 0.01 second) results in a frequency-meas-

urement error of only $\pm 3 \times 10^{-11}$.

The ultimate resolution of this measurement technique is limited by a slow continuous net change in the path length the signal travels between the network's standard and the receiver (Fig. 2). In most cases, resolution is limited to about 10 ns in 15 minutes, which corresponds to a resolution of 1.1×10^{-11} .

Figure 2 also illustrates three types of phase instabilities that must be considered: large and small phase jumps and local station originations. Large phase jumps are caused by switching from one video-tape machine or camera to another, as different lengths of cable are inserted in the path. Small phase jumps result from phase distortion in the microwave system that carries network programs and from multipath between the local station's transmitter and the receiver, as well as differential phase distortion in the receiver.

Most large phase jumps coincide with changes from a program to a commercial and back again. During station breaks, the 3.58-MHz reference originates from the local station, rather than the network. Since few local stations are equipped with rubidium oscillators, their



3. Comparator. The output of a crystal oscillator, operating at the frequency of the color subcarrier and phase-locked to an oscillator under test, is combined with the signal entering a TV set so that the phases of the two signals can be compared.

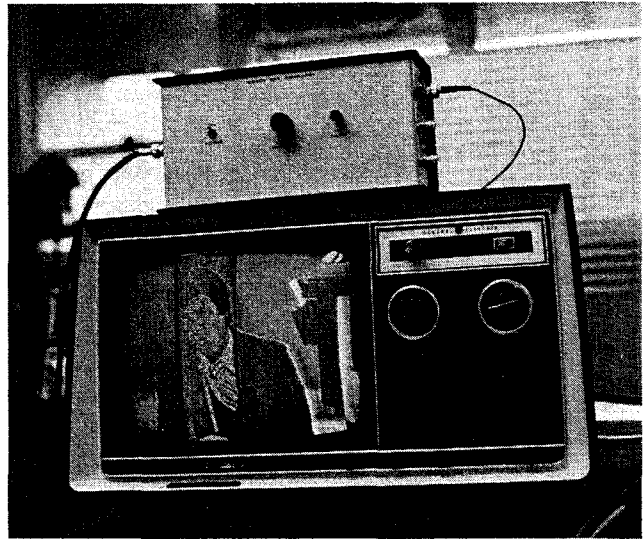
references cannot be used for calibration to the same accuracy as with network signals because they are often offset by 1×10^{-7} or more.

Using the color-bar comparator

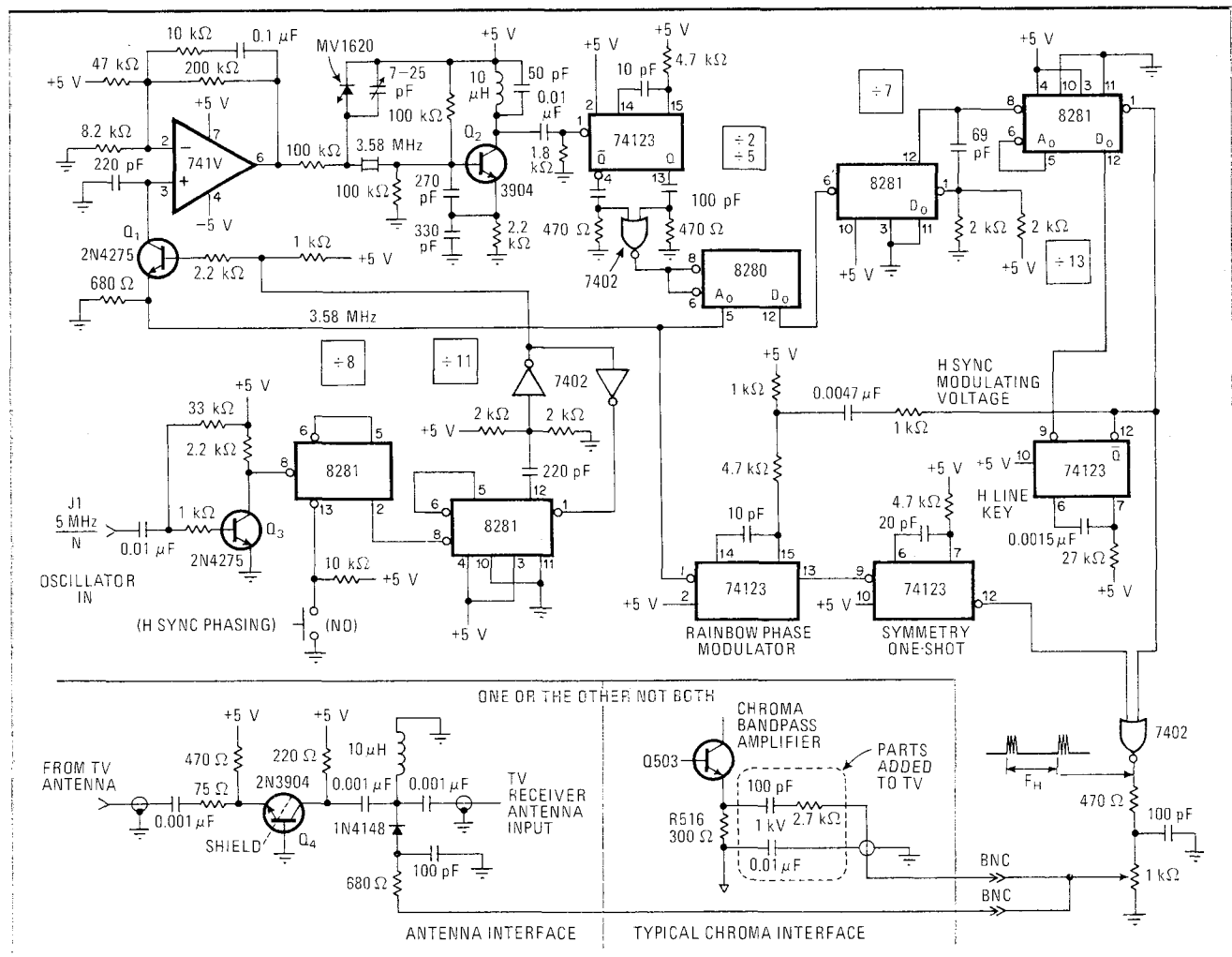
The simplest NBS circuit, the color-bar comparator, is shown in block-diagram form in Fig. 3. The input signal, at a frequency of 5 MHz or an integer submultiple, is divided by 88. This divided-down signal drives a 3.58-MHz voltage-controlled oscillator. The 3.58-MHz output is doubled, then divided by two to provide a phase-locking feedback signal. The frequency-doubled signal is also divided by 455, which provides a signal at the TV receiver's horizontal-oscillator frequency. That signal ultimately generates a stationary vertical bar on the screen (Fig. 4).

The color of the vertical bar changes as the phase relationship changes between the network rubidium and the oscillator under test. The phase modulator changes the color of the bar across its width so that times between these color changes can be measured. For example, the time between one solid red bar and the next can be measured.

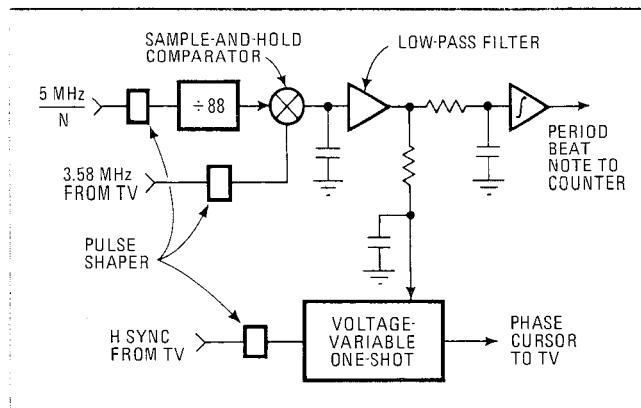
Without the modulator, the entire bar would change



4. Display. The color-bar comparator generates a vertical bar on a television screen, and colors move across the bar. By timing one complete cycle—from solid red to solid red, for example—the frequency offset of the oscillator under test from the National Bureau of Standards oscillator can be determined.



5. Generator. After division by 88, the signal from an oscillator under test phase-locks a crystal oscillator. The output of the color-bar generator can be interfaced to a color-TV receiver, either through the antenna terminals or directly into the chroma circuit.



6. Alternate. A sample-and-hold circuit can compare the phase of the 3.58-MHz color-subcarrier standard with the phase of the signal from the oscillator under test every 88 cycles of the test input.

color at one time, making it difficult to tell exactly when a given change takes place. It would also be difficult to tell whether the frequency of the test signal is higher or lower than that of the reference signal because it would be necessary to remember in what order the colors change.

In the schematic of the color-bar comparator (Fig. 5), the input signal is divided by 8 and then by 11 in the two 8281 input dividers. The output of the second 8281 drives the base of Q_1 , a phase-locked-loop comparator. A 741 operational amplifier connected as an RC integrator tunes the voltage-controlled crystal oscillator at the color-subcarrier frequency of 3.58 MHz.

The VCXO's output signal drives a 74123 one-shot circuit that shapes the pulse. Two signals are taken from the one-shot, and the positive-going transitions are coupled through a 7402 NOR frequency doubler to a divide-by-two (part of an 8280) and fed back to Q_1 for phase lock. The crystal oscillator, operating at the color-subcarrier's frequency and phase-locked to the oscillator under test, is required because the necessary 3.58-MHz signal cannot easily be synthesized from the input signal. Part of the 8280, which divides by two, also divides by five. Subsequent dividers at ratios of 7 and 13 provide a total division ratio of 455 ($5 \times 7 \times 13$).

Making the presentation clear

Although this system can be used without access to the inside of the TV set, the rainbow will be of higher quality if the signal is injected into the receiver's video circuits. This eliminates modulation of the receiver's audio carrier, which causes a beat note that varies with the audio content of the program. An example of the circuitry required to inject the signal directly into the chroma-bandpass amplifier is shown in the schematic.

After an oscillator is connected to the color-bar generator and the color-bar generator is connected to a television set, the oscillator is adjusted so that the rainbow appears to move across the bar from right to left in about 10 seconds. If the oscillator frequency is far off, the colors in the rainbow pattern will change rapidly, and the entire bar will move in the direction of the color change.

Since the period of the beat note equals the period of

the reference divided by the offset, the frequency of the color comparator output signal is

$$f = 1/PQ$$

where P is the period of the beat note and Q is the offset of the network signal as published by NBS.

When the oscillator under test is adjusted for an output of 5 MHz, the frequency of the color-comparator's output is 3.58 MHz. The period of the beat note in seconds is then approximately $279/Q$, where Q is expressed as parts in 10^{-9} .

Measuring the subcarrier digitally

The digital subcarrier comparator shown in the block diagram of Fig. 6 and schematically in Fig. 7 allows measurement of the period of a beat note to ± 0.01 second. To obtain a measurement precision of $\pm 1 \times 10^{-10}$, an average of at least 10 readings, representing about 90 seconds of data, must be taken. A measurement to this precision using the 60-kHz transmission of WWVB would require two to eight hours under stable conditions. To improve the subcarrier-comparator measurement to $\pm 2 \times 10^{-11}$ would require averaging 100 sample-period measurements—about 15 minutes of data recording.

The digital subcarrier comparator provides an analog readout of phase on the screen in the form of a narrow vertical line that moves slowly from left to right, then retraces rapidly right to left when the local oscillator is high in frequency. This sawtooth response allows positive setting of the local oscillator because, if the local oscillator is low in frequency, the cursor line will move right to left and fly back from left to right.

This comparator is somewhat different from the color-bar comparator in that it does not synthesize 3.58 MHz from the oscillator under test. Instead, a sample-and-hold circuit compares the phase of the 3.58-MHz standard with the phase of the signal from the oscillator under test, which is at a frequency of $5 \text{ MHz}/N$, once every 88 cycles of the input. If $N = 1$, the comparison rate is approximately 56.8 kHz, and the phase of each 88th cycle of the 5-MHz signal is compared with the phase of each 63rd cycle of the 3.5-MHz television signal.

The effect is the same as if $63/88 \times 5 \text{ MHz}$ were synthesized and compared with the TV receiver's 3.5 MHz. The sample-and-hold comparator output passes through a low-pass filter to eliminate sampling and other high-frequency noise from the beat note.

The beat note is processed through a Schmitt trigger to provide a start-stop signal for a digital counter. If difficulty is experienced in adjusting the counter start-stop circuits to trigger on the same slope (both positive or both negative), a flip-flop may be added to the Schmitt-trigger output. This will give a symmetrical square-wave output, and each half cycle will be equal to one cycle of the beat note.

The steps in calibrating an oscillator with the digital comparator are the same as for the color bar. The phase cursor is used to make a coarse adjustment of the oscillator, and then the oscillator is adjusted to the period computed from the offset published by NBS until the readout equals this period.

Another version of the digital-subcarrier comparator

computes the offsets corresponding to 10 10-period averages and displays them directly on the TV screen. By averaging 10 of these 10-period averages, accuracies approaching $\pm 1 \times 10^{-11}$ can be achieved.

The frequency-measurement computer determines the period of the 3.58-MHz beat note, computes the offsets, scales the results for 4-digit readout in parts in 10^{11} , and displays the one- and 10-period averages. A block diagram of the instrument is shown in Fig. 8.

The phase-comparator-and-cursor-generator section is equivalent to the digital-subcarrier comparator. It compares the 3.58-MHz TV signal with the signal under test and generates a beat note and a cursor. The offset scaler accepts the beat and the 3.58-MHz reference signal, f_1 . The rate generator provides pulses at $R = \Delta f \times 10^4$, which is 10,000 times the beat frequency. These rate pulses are gated on for a time T_G equal to $10^7/f_1$. The count output to the data-store counters is therefore

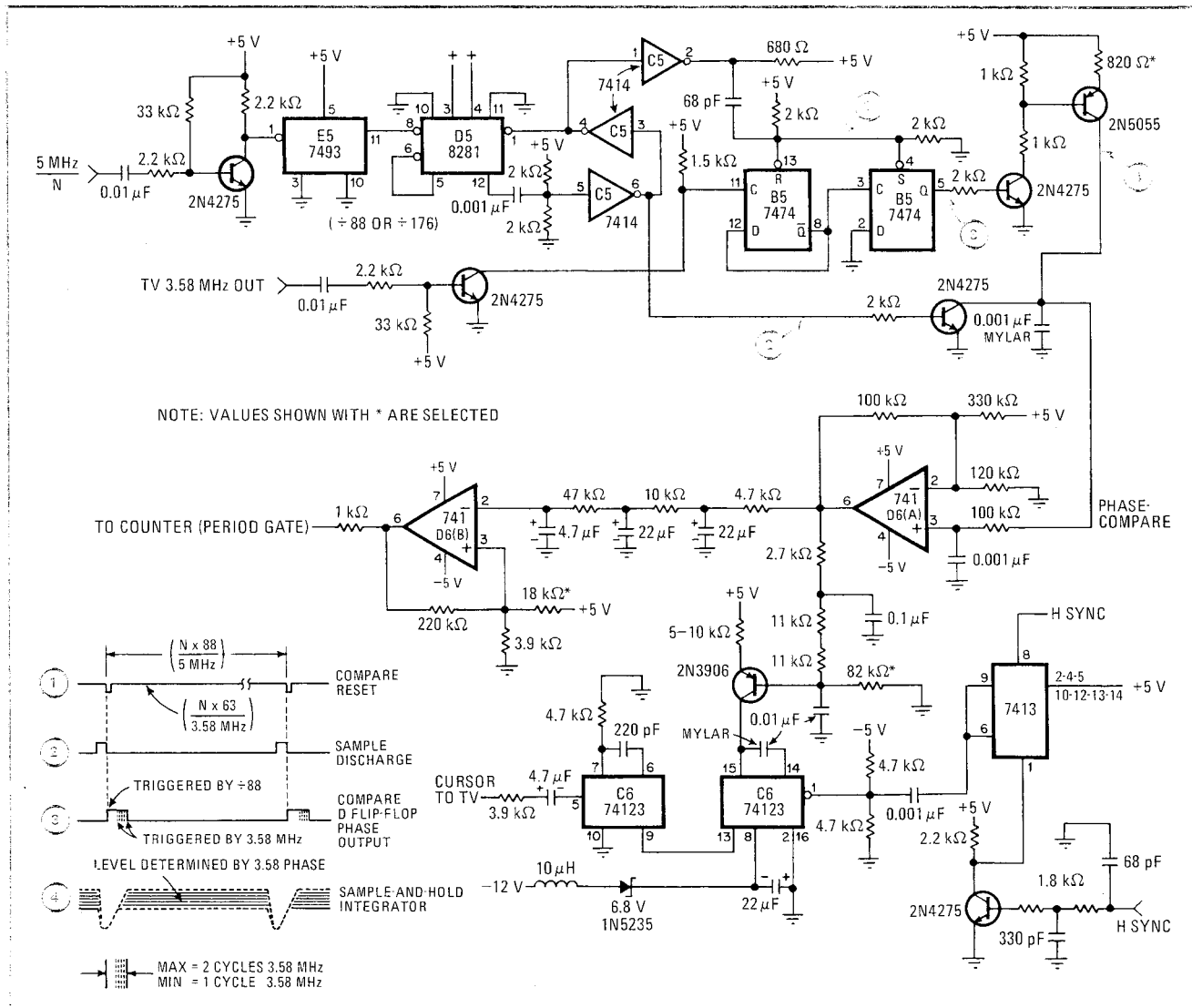
$$R \times T_G = \Delta f \times 10^4 \times (10^7/f_1) = (\Delta f/f_1) \times 10^{11}$$

The gated frequency from the offset scaler is accumu-

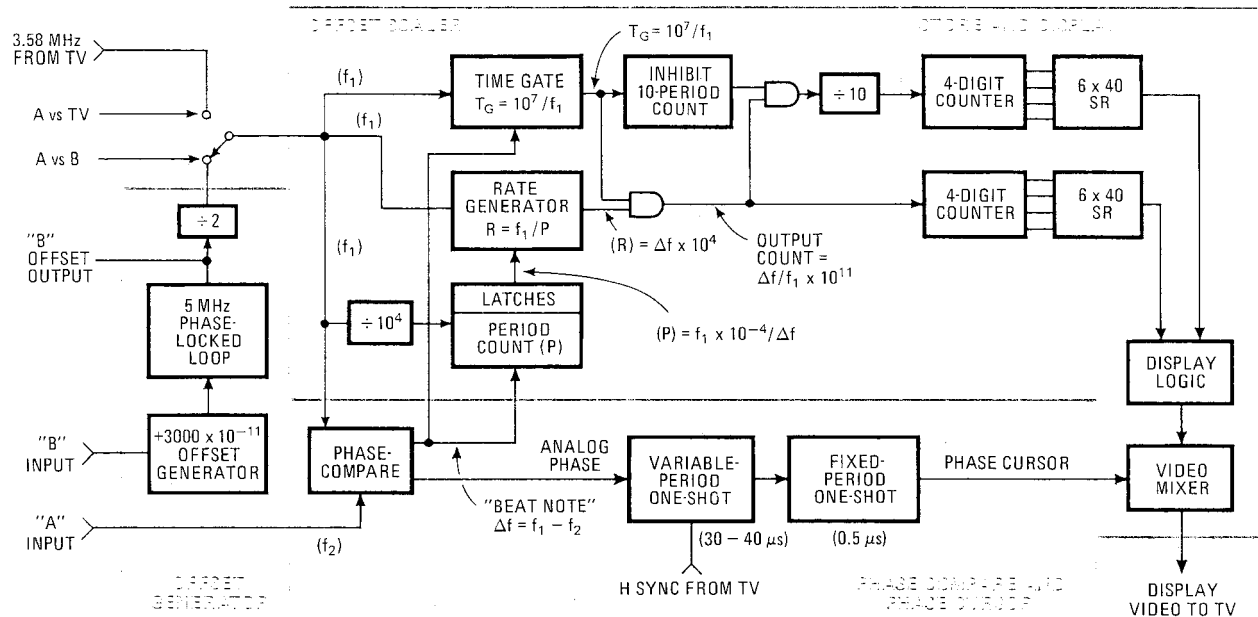
lated in the two 4-digit counters in the data-store-and-display section. After each cycle of beat-note measurement, the single-period counter is gated on for 2.79 seconds. The accumulated single-period count is then dumped to the single-period store for readout. The 10-period 4-digit counter is preceded by a divide-by-10, so from each single-period average, it accumulates 1/10 of its total count. At the end of 10 one-period averages, contents of the 10-period counter are dumped to the 10-period store for readout.

The readout data is presented as two columns of 10 4-digit numbers (Fig. 9). The left column represents single-period offset readouts, and the right column represents 10-period offset readouts. To start a measurement sequence, the user pushes the reset button. All readouts are reset to zero, and the top 4 digits in each column are intensified, indicating that data will be loaded in these positions.

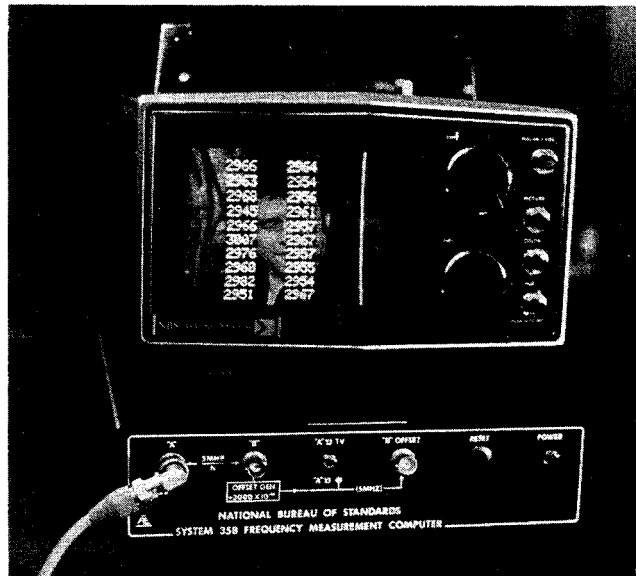
At the end of approximately 13 seconds, the first single-period measurement is completed, and the data is loaded into the top 4 digits in the left column. The



7. Digital comparator. One output from the sample-and-hold comparator can generate a cursor on a television screen while a second output feeds a counter for digital readout of offset. Waveforms at four points in the circuitry are also shown here.



8. Signal flow. A signal of unknown frequency (A) can be compared with either the color-subcarrier 3.58-MHz signal or another reference signal (B) for on-screen display. The B-input offset generator provides the offset necessary to make accurate measurements quickly, a self-check capability for the computer, or a means to make comparisons to a zero-offset color subcarrier.



9. Computer. Frequency offsets and averages of 10 offset readings can be computed. The values can be displayed, along with a phase cursor, on a television screen.

second 4 digits in the left column are then intensified. On each following 10-second interval, data is loaded into succeeding positions in the left column until 10 single-period averages have been accumulated. The first 10-period average is then loaded. The process continues until all 10 10-period averages have been loaded.

Adding refinements

One feature added to the frequency-time computer in use at the National Bureau of Standards permits the user to leave the instrument unattended during its 15-

minute run. A circuit compares the result of the latest single-period measurement with the expected value and, if there is a significant difference, ignores the measurement. This compensates for large phase jumps that may occur in the broadcast signal if, for example, the broadcast switches between network and local origin.

The frequency-time computer also contains circuitry that allows the comparison of two oscillators with each other. A reference oscillator connected to one input is compared with a +3,000 x 10⁻¹¹ offset replica of the second input. If the two signals have no offset with respect to each other, the on-screen readout will be 3,000. Readout accuracy is within $\pm 1 \times 10^{-11}$ for 22 minutes of data, which represents 10 10-period readouts at a sampling frequency of 2.5 MHz, with 3,000 x 10⁻¹¹ offset. This mode is also useful for comparing oscillators against zero-offset color subcarriers. WTTG-TV in Washington, D.C., for example, uses an oscillator stabilized with a cesium reference by the U.S. Naval Observatory.

If the offset and direct inputs are connected to the same oscillator, the readout should be 3,000. This provides a simple check of the frequency-time computer's circuitry. □

Closing the loop

The author will answer questions about this article at the National Bureau of Standards booth at IEEE Intercon. He will also answer calls on April 22 at (303) 499-1000, Ext. 3639. His address is National Bureau of Standards, MS 277.06, Boulder, Colo. 80302. Manufacturers interested in producing phase-comparator circuits should also call or write NBS.