U. S. Department of Commerce
National Bureau of Standards

New Frequency Calibration Service

A New Frequency Calibration Service of the National Bureau of Standards

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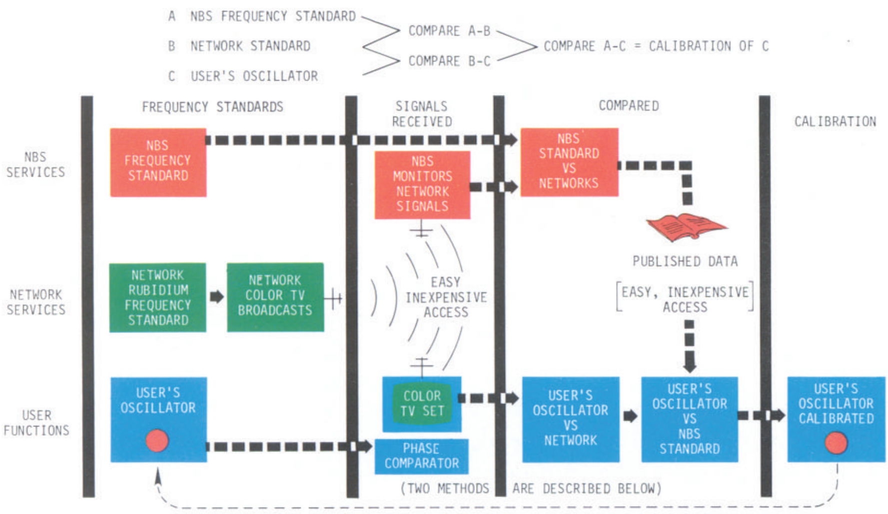
A NEW FREQUENCY CALIBRATION SERVICE

This new service is a way to calibrate oscillators — traceable to NBS — with less cost and effort than with other services now available. The new service gives the user the option of calibrating his oscillator quickly with modest accuracy or of expending more effort for high accuracy.

Existing NBS frequency calibration services involve radio transmissions of signals that are carefully controlled at the transmitter. But when received by the user, these signals can be degraded in quality and hard to locate in the radio band. Using television signals for this new service has several advantages: First, the signals are readily available and usually very strong. Second, television receivers are simple to operate, and the antennas are much easier to install than shortwave radio equipment. This new service lets the person doing the calibration concentrate on the calibration and spend less time fussing to get a useable signal.



Network television signals cover most areas in the 48 states. NBS monitors the frequency of all three commercial networks and publishes "offset" data in a monthly bulletin (available without charge). Users can use this published data to calibrate their oscillators with traceability to NBS.

The NBS frequency calibration service uses network television color signals as a transfer standard. If a user wants to make a calibration, he compares a TV signal coming from the national networks (local signals won't do) with his local oscillator. NBS monitors the same signal, calibrates it, and tells the user what correction to use.

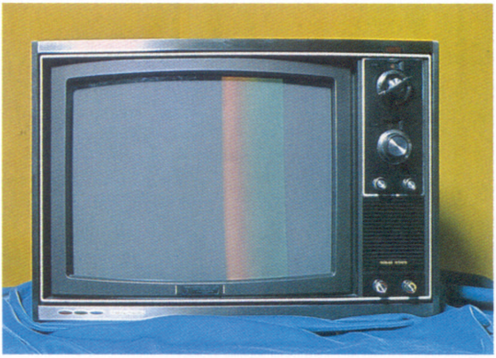
The network color signals change their frequency very slowly and the changes are small. So NBS does not need to recalibrate them very often, and the user needs new correction data at infrequent intervals. NBS checks the networks daily and publishes the corrections once a month. This is often enough. The results obtained by this method of frequency calibration match or exceed any other method available. Anyone desiring a frequency calibration can make one quickly and have confidence in the results.

HOW THIS FITS INTO OTHER NBS SERVICES

NBS operates radio stations WWV, WWVH, and WWVB. This new service complements these radio broadcasts. However, only frequency calibrations are offered using the television signals — time of day, time ticks, and time codes are not included. But the new service, for those users who can get network television, will be faster, easier, and lower in cost than the present radio services. Users who have the equipment and skill necessary to use radio signals will probably want to continue to use them. However, if TV signals are available and the radio services fall short in some respect, then a switch is indicated. Many users can get a good TV signal in their area, but find it difficult to erect a suitable antenna for the NBS radio signals. This new NBS service operates equally well on cable (CATV) systems, the UHF channels, and in areas of Canada and Mexico that receive U.S. network signals. But the receiver must be a color set.

EQUIPMENT NEEDED FOR ACCURATE CALIBRATION

Because this service is new, NBS is cooperating with manufacturers to have them offer the necessary equipment. However, in order to demonstrate the service, NBS has designed prototype equipment for two methods of frequency calibration. These methods are described. The plans for equipment construction are offered without charge to anyone interested in building his own equipment or in manufacturing these instruments commercially.



NBS has developed two prototype pieces of equipment to demonstrate the new frequency calibration service: the Color Bar Comparator, and the nearly automatic digital comparator called the System 358 Frequency Measurement Computer.

Color Bar Comparator Method

One prototype is a simple circuit that can be built into a very small box. It requires only a single connection to a standard color TV receiver. When an oscillator is connected for calibration, a colored vertical bar appears on the TV screen. By timing the changes in color of the bar (or motion across the screen), a user can calibrate his oscillator. The resolution of this method makes it suitable for lower-quality oscillators similar to those used by Hams or as the time base of inexpensive counters.

Digital Comparator Method

NBS also designed a second piece of equipment that is nearly automatic. It computes the offset of the oscillator being calibrated and displays the result as a four-digit number on the TV screen. It automatically displays ten such readings, takes an average of those ten, displays the average, and continues to take additional readings. After filling the screen with data, it starts over again, replacing the old data with new numbers. As an aid to the users, this equipment displays a cursor on the screen. The cursor tells you that the system is working and if your oscillator is high or low in frequency with respect to the network.

"But," you ask, "what does the service cost?" If you already have a color set, the Color Bar Comparator costs very little. It has a parts cost of about $25.

The NBS prototype of the Digital Comparator, called the System 358 Frequency Measurement Computer, is a more complicated version. It costs more, but does much more. As its name suggests, it computes the frequency difference between your oscillator and puts the answer on the TV screen. This makes calibration fast, easy, and accurate.

BASIC PRINCIPLE OF THE TV FREQUENCY CALIBRATION SERVICE

The four major television networks in the U.S. use atomic oscillators to generate their color reference signals. These oscillators are usually rubidium standards and produce the necessary color signal at a frequency of 3.58 MHz (millions of cycles per second). All color television receivers "lock" onto the color subcarrier signal. So, if your color set is tuned to a network program, its internal 3.58 MHz oscillator generates a replica of the atomic oscillator signal back at the network studio.

This happy coincidence allows everyone with a color set to have almost direct access to a number of atomic oscillators for calibrations. And not just any oscillators at that – These are checked by the National Bureau of Standards (NBS) which publishes their offsets.

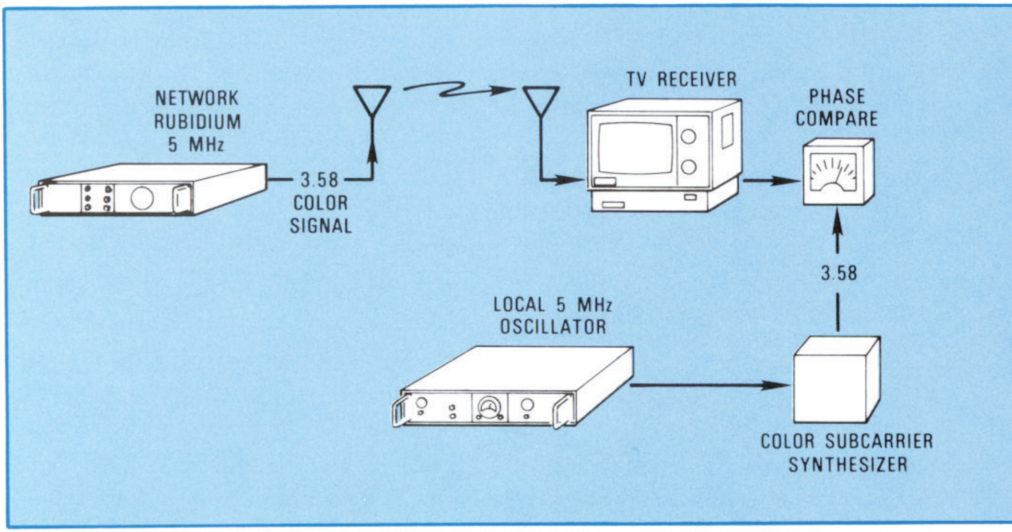
The 3.58 MHZ signal from the color receiver is not a substitute for your own oscillator. It is a calibrating signal that can be used to set your oscillator very accurately. In only 15 minutes, you can match the results of hours or days of data using NBS radio stations WWV and WWVH.

Before examining any of the various circuit implementations, we should look at the basic principle of the service. The rubidium oscillators used by the networks are 5 MHz units modified to include a synthesizer to generate a 3.5795454545 . . . . . MHz (rounded to 3.58 MHz) color subcarrier signal. The 3.58 MHz was synthesized by taking

$$\frac{63}{88} \times 5 \text{ MHz.}$$

If one wishes to adjust the frequency of a 5 MHz oscillator to agree with the network 5 MHz, it can be done by utilizing the phase detector scheme shown. You might ask, why measure *phase* to calibrate *frequency*? As shown by the meter, two frequencies are compared by making a *phase* comparison. In this case, the signals compared are at 3.58 MHz, so the phase meter full scale deflection "reads" one cycle (360°) of that frequency or, using the period of the signal, about 279 nanoseconds full scale. If the local oscillator frequency changes relative to the network color signal, the meter moves. How much does it move? Well, if those two frequencies differed by one cycle per second, the meter would deflect zero to full scale in one second and then start over again in the next second.

Notice, however, that if the crystal oscillator in our example were of rea-



Scheme for comparing local 5 MHz oscillator with network rubidium 5 MHz.

sonable quality, we could expect a slow moving meter. Let's take an example: Assume the crystal oscillator frequency is already set to within one part in 10^{10} of the network rubidium. This is written as 1×10^{-10} – a small number but typical for good crystals! The problem is to figure out how much the meter will move; that is, how many degrees of phase or nanoseconds per second will be accumulated. Set up the problem like this:

$$\frac{\text{Nanoseconds Accumulated}}{\text{1 Second}} = 1 \times 10^{-10}$$

The right side of the equation is a number without dimensions (a numeric), so the left side must match. This means that we multiply the denominator (seconds) by 10^{+9} to get nanoseconds for our units.

quency engineers say fractional frequency and write our example equation as:

$$\frac{\Delta t}{T} = \frac{\Delta f}{f},$$

where the fractional frequency offset, $\Delta f/f$, is our small fraction, 1×10^{-10}.

Both NBS methods described in the following pages are based on this principle of measuring phase to get frequency. The results for both measuring methods give an answer as a frequency offset.

By using the same scheme of synthesizing 3.58 MHz from the local 5 MHz oscillator, the phase of the two 3.58 MHz signals may be compared either on a meter or, for greater accuracy, on a chart recorder. If the meter stands still or the chart recorder draws a straight line, indicating a fixed phase between

SOLVING: Number of nanoseconds accumulated in 10^{+9} nanoseconds (one second) $= 10^{-10} \times 10^{+9} = 10^{-1}$ = one-tenth of a nanosecond in one second.

This says that our meter will take **ten** seconds to move one nanosecond. Or, we can say that our meter will move full scale (279 nanoseconds) in 2790 seconds. This is about 46 minutes.

So, measuring phase *is* the way to go – It is really just another way of saying that we are measuring part of a cycle, or a fraction of a cycle. Time and fre-

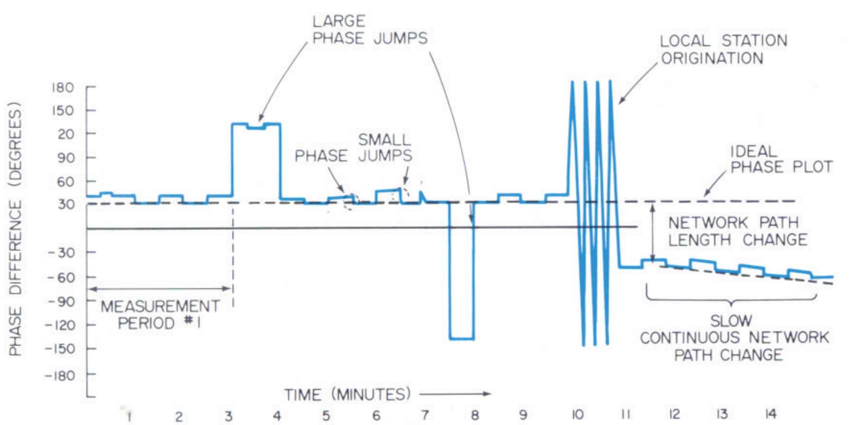
the two 3.58 MHz signals, it follows that the two 5 MHz oscillators agree in frequency.

Of course, in the real world, the meter never stands still and the chart recorder never draws a straight line. Due to instabilities in the propagation path, we will always see small "bumps" or jumps in phase. In addition, the oscillators themselves will impose some ultimate limitation on the straightness of the line.

Phase Instabilities

If the 5 MHz local oscillator were perfectly matched with the network rubidium so that the only instabilities were those introduced by the network path, a phase chart recording of the two signals might look something like this:

There are basically four types of phase instability illustrated: large and small phase jumps, network path length changes, and local station originations. All of these instabilities tend to limit the precision of phase measurement, and hence, the precision with which you can calibrate the frequency of the local oscillator to the network 3.58 MHz. The ideal phase plot is shown as a straight dotted line at +30°, constant phase. The ultimate resolution is limited primarily by the slow continuous net path change illustrated from minutes 11 through 14. In most cases, resolution is



Phase recording of a crystal oscillator as compared to a network TV color signal. Notice the various phase instabilities.

limited to about 10 nanoseconds in 15 minutes. This corresponds to:

$$\text{RESOLUTION} = \frac{\Delta f}{f} = \frac{\Delta t}{T} = \frac{10 \text{ ns}}{15 \text{ min}} = \frac{10 \text{ ns}}{900 \text{ s}} = \frac{10^{-8} \text{s}}{0.9 \times 10^{3} \text{ s}} = 1.1 \times 10^{-11}$$

For measurement times shorter than 15 minutes, the measurement resolution will be reduced roughly in proportion to the reduction in measurement time; i.e., 1×10^{-10} in 1.5 minutes. Note that this resolution represents about the *best* one can hope to achieve. If large and small phase jumps are not taken into account, the result can be *much* worse.

The large phase jumps (up to ± 90° ± 70 ns) are primarily the result of the way the networks operate. Phase jumps are caused by switching from one video tape machine or camera to another, with different lengths of cable being placed in the path. Most large phase jumps are coincident with changes from a program to a commercial and back again. Using TV requires some attention to what is on the screen – one should be alert to sudden phase jumps coincident with commercials.

Small phase jumps are the result of phase distortion in the microwave system used to carry the network programs and to multipath between the local station transmitter and the TV receiver. Differential phase distortion within the TV receiver also contributes. The magnitude of small phase jumps is on the order of 1 to 10 ns, depending on the network and the degree of multipath at the receiving location. For best results, the receiver should use an antenna system that minimizes "ghosts."

During station breaks, the received 3.58 MHz originates from the local television station's 3.58 oscillator. Unless the local station is one of the few that is equipped with a rubidium oscillator, its frequency will probably be no better than 1×10^{-7}, and the phase will change more rapidly, about one full cycle per second. **No precision measurements can be made on local programming.** Many stations record network programs for rebroadcast at a different time. When network programs are "tape delayed," the 3.58 MHz is referenced to the local station's oscillator and is therefore invalid as a precision reference. In any given area of the U.S., a few days of experience will provide a user with a good idea of local program schedules.

Numbers from the Network

In all of the preceding discussions, it has been assumed that the goal is to calibrate a local oscillator and to make it agree with the frequency of the network rubidium. This is *not* what we want. For reasons that need not concern us here, the network rubidiums are "offset" from the NBS frequency standard by *about* **minus 3000 parts in 10^{11}** (-3000×10^{-11}). The exact offset is measured by the National Bureau of Standards and published in the monthly **NBS Time and Frequency Services Bulletin**. This publication can be obtained, free of charge, by writing the Time & Frequency Services Section, NBS, Boulder, Colorado 80302.

The average offset for the three commercial networks, with respect to the NBS frequency standard, for the week February 24 - 28, 1975, was:

EAST COAST

NBC: -3014.0×10^{-11}
CBS: -2961.2×10^{-11}
ABC: -3006.2×10^{-11}

WEST COAST

NBC: -3011.8×10^{-11}
CBS: -3001.4×10^{-11}
ABC: -3008.7×10^{-11}

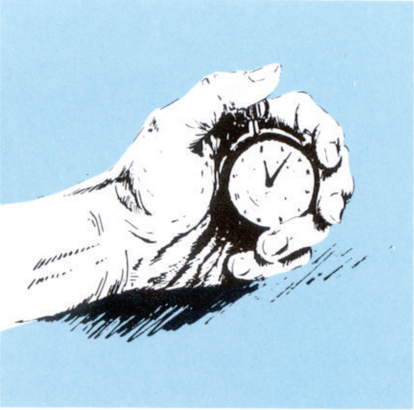
The minus sign preceding the offset indicates that the network subcarrier signal is low compared to the NBS frequency standard.

You might ask why there are two sets of data. Network programs in the Eastern, Central, and Mountain Time Zones originate from New York City. However, in the Pacific Time Zone, network programs originate from Los Angeles. The National Bureau of Standards monitors the rubidium standards at the networks on *both* coasts. Therefore, if you live in the Eastern, Central, or Mountain Time Zone, you should use the data published for the East Coast. The West Coast data is only for those users who live in the Pacific Time Zone.

SUMMARY

A person who wants to calibrate his oscillator can use the television network subcarrier to do so. This is possible because NBS checks the network frequencies and publishes the "offset" (or error) of the network rubidiums with respect to the NBS standard. A user would know two things: (1) the differ-

ence between his oscillator and the network rubidium (by measurement), and (2) the difference between the network and NBS (by publication). With this information, he can compute the difference between his oscillator and NBS. Thus, his calibration is traceable to NBS.



9.31 seconds is the number you would read on your stopwatch using equipment like that described. In one method, you are timing a color change; in the other method, a vertical bar or "cursor" moves across the TV screen.

How to Measure the Frequency Offset

As we have shown earlier, you can measure frequency offset by measuring accumulated phase differences between two signals. In the case of the color subcarrier with an offset of -3000×10^{-11}, it is convenient to measure the time, T (period of the beat note), required to accumulate one cycle of phase difference (Δt) at 3.58 MHz.

$$\text{But: } \Delta t = \frac{1}{f} = \frac{1}{3.57954 \times 10^6} = 27936 \times 10^{-11} \text{ seconds.}$$

$$\text{OFFSET} = \frac{\Delta t}{T} = \frac{\text{How much it moves}}{\text{How long it takes}} = \frac{\text{1 period of the 3.58}}{\text{1 period of beat note}}$$

We know the offset for the U.S. TV networks is nominally -3000×10^{-11}. So we can solve for:

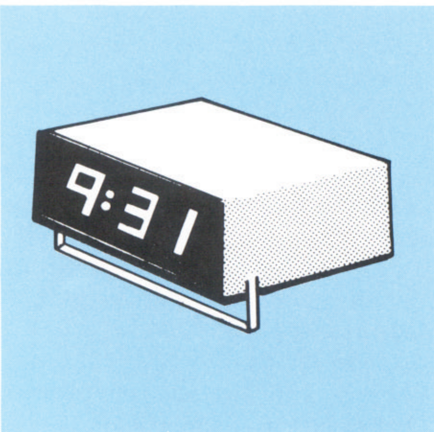
$$T = \frac{\Delta t}{\text{OFFSET}} = \frac{27936 \times 10^{-11}}{3000 \times 10^{-11}} = 9.31 \text{ seconds.}$$

as the period of the beat note. This means that if the network subcarrier oscillator were offset exactly -3000×10^{-11}, the network 3.58 signal would lose one cycle with respect to an NBS-controlled (or zero offset) 3.58 oscillator in 9.31 seconds.

For example, if the network offset were reported to be -3010×10^{-11}, the period of the beat note would change and be shortened to:

$$T = \frac{27936 \times 10^{-11}}{3010 \times 10^{-11}} = 9.28 \text{ seconds.}$$

Let's look at this example more closely. A network frequency change of 10 parts in 10^{11} results in a beat note period change of 0.03 second. But if we make a measurement error in the calibration setup we use, how does this change the answer? Following the example, if our timing measurement is in error by 0.03 second, the frequency measurement will be in error by **ten parts in 10^{11}** (10×10^{-11}).



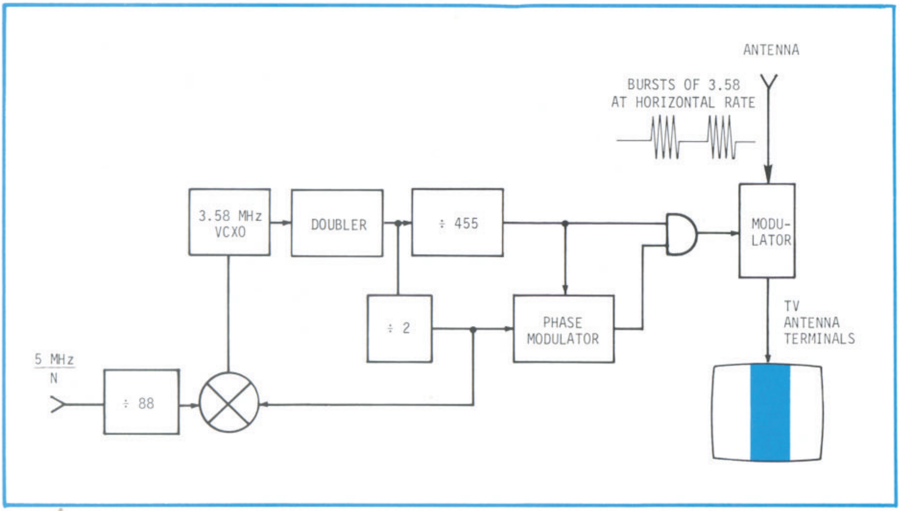
There is also something else we should notice. A digital circuit to measure the beat note period only needs three digits; i.e., for the digits in a number like the 9.31 or 9.28 used in our examples. If you recalculate the math from the example above, you can show that ± 1 count (± 0.01 second) in such a digital circuit for the period measurement results in only a 3×10^{-11} variation in frequency measurement. So we have very high resolution in our measurement technique and low cost because digits cost money

We will now examine some methods of implementing the beat note period measurement as used in the prototype equipment.

METHOD 1: COLOR BAR COMPARATOR

One simple method devised by NBS to compare a local frequency source with the network rubidiums is to use a color bar comparator. This is a small, low-cost circuit that can be added to any color TV receiver. It is shown in block form and schematically.

As shown on the block diagram, the circuit connects only to the TV receiver antenna terminals. However, better results can be obtained (see schematic) if the receiver is modified with an input connector that feeds the color bar signal directly to the color processing (Chroma) circuit in the set. This modifi-



cation does not affect normal operation of the receiver.

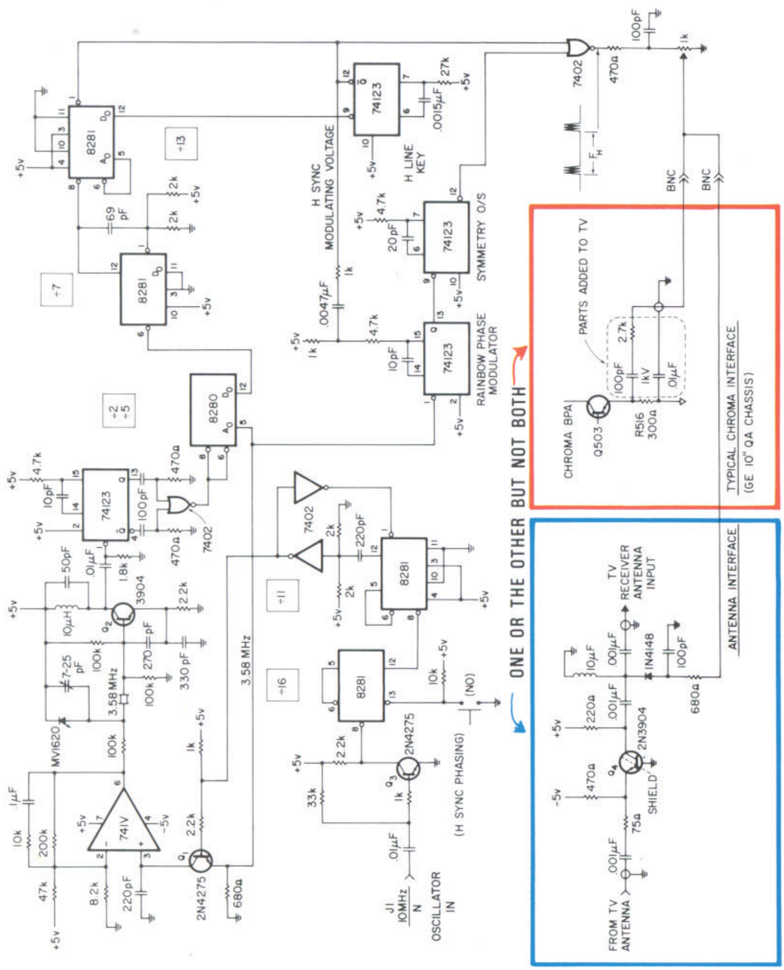
The schematic has enough detail so that the circuit can be constructed and used. Let's look at how it works. On the left, the input jack J1 accepts the local frequency source at a frequency of 10 MHz or at an integer submultiple; that is, 10 MHz divided by "N," where N = 1, 2, 3 . . up to 100. This lets you compare frequency sources of many different frequencies if you wish (one at a time, of course).

The input signal from J1 is divided by 16 and then by 11 for a total of 176 and is used to drive the base of Q1 which is a phase lock loop comparator. The 741 operational amplifier (connected as an RC integrator) drives the voltage-controlled crystal oscillator (VCXO) operating at the color subcarrier frequency of 3.58 MHz. The other input to the comparator comes to Q1 emitter from the loop output circuit.

The VCXO output signal drives a 74123 one-shot circuit for pulse shaping of the oscillator output. Two signals are taken from the one-shot and the positive-going transitions are coupled through a 7402 NOR frequency doubler to divide by 2 (part of the 8280) and fed back to Q1 for phase lock. The result of the phase lock is that we have a crystal oscillator operating at the subcarrier frequency phase locked to a local standard! This permits us to inject a signal into a television receiver and compare it to the network color subcarrier.

Part of the 8280 that divided by 2 for us is used to divide by 5. Subsequent dividers at ratios of 7 and 13 provide a total (5 X 7 X 13) division ratio of 455. The resultant frequency is that of the horizontal oscillator in

TV Color Bar Comparator with both antenna and video connections.



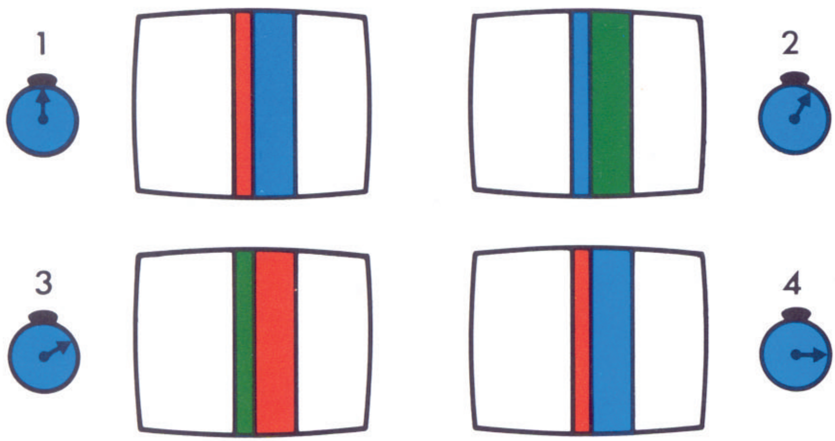
the TV receiver. This will cause the pattern on the screen to be a stationare vertical bar. This horizontal rate signal is used, with the output of the modulator, to drive the receiver.

We have shown two options on the schematic: the antenna TV interface circuit and also a video TV interface circuit for one model of receiver. No matter how the signal gets into the receiver, it will be processed just as if it were normal picture information. The beat of the local crystal oscillator with the network signal forms a vertical "rainbow" bar. The color of the bar changes with respect to the network rubidium. Our problem then becomes that of using a stopwatch to measure how long it takes this color change to occur. The stopwatch reading is equal to the period of the beat note.

To use the color bar system for oscillator calibration, tune the receiver to a network color program, and set the oscillator to be calibrated so that the rainbow appears to move across the bar from right to left in about 10 seconds. If the frequency of your oscillator is far off, the colors in the rainbow pattern will change very rapidly and the entire bar will move in the direction of the color changes. The bar can be positioned to the middle of the screen by the pushbutton labeled "Horizontal Sync Phasing."

With the rainbow repeating colors in about 10 seconds, carefully adjust the crystal oscillator until the period is:

$$T = \frac{27936 \times 10^{-11}}{\text{NBS published offset for network being viewed}} \text{ seconds.}$$



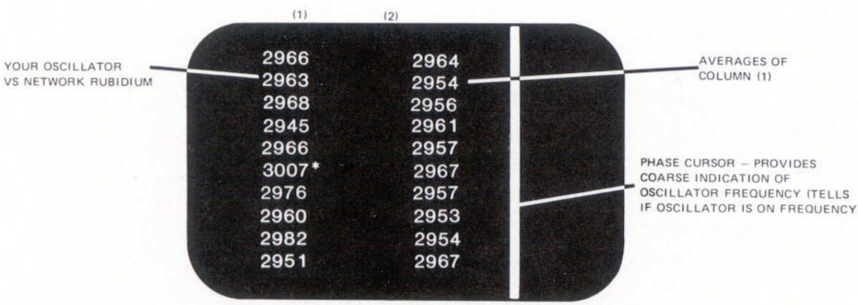
If possible, check more than one network to increase the confidence in calibration. Also, by measuring over ten beat note periods, the effect of reaction time with the stopwatch will be reduced. Recall that for 1 period, an error of 0.3 second corresponds to a frequency error of 10 parts in 10^{11}. For ten periods, a measurement error of 0.03 second will result in a frequency error of 10 parts in 10^{11}.

As mentioned before, the rainbow will be of higher quality if the signal is connected into the receiver as a video signal. The improvement is due to the fact that antenna injection also modulates the received *audio* carrier. This results in a visible beat note that constantly changes with the audio content of the program. The other example circuit shown connects the signal directly into the Chroma bandpass amplifier. The rainbow is then nearly perfect. **Exercise extreme caution when connecting signals to receivers that have the chassis at one side of the AC line.**

METHOD 2: NBS SYSTEM 358 FREQUENCY MEASUREMENT COMPUTER

For those users who require accuracies approaching 1 part in 10^{11}, another calibration method is available. The System 358 Frequency Measurement Computer (FMC) computes and displays the oscillator offset directly on the TV screen. The user simply turns on the unit and waits for 15 minutes. He then comes back, reads off 10 computed offsets, and averages them to obtain an accuracy approaching 1 part in 10^{11}.

The FMC automatically performs the operation of measuring the period of the 3.58 MHz beat note, T, computing



*INDICATES LARGE PHASE JUMP – NUMBER WILL NOT BE INCORPORATED INTO AVERAGES SHOWN IN COLUMN (2).

$\Delta t/T$, scaling the result for readout in parts in 10^{11}, and displaying the one- and ten-period averages on the TV screen. This method involves a more complex instrument and all of the details are not shown in this booklet. Photos, design diagrams, and schematics are available from NBS. For information, write to the **Time & Frequency Services Section, NBS, Boulder, Colorado 80302.** These prototype instruments are only intended to serve as examples to manufacturers and individuals. Parts lists, detailed mechanical drawings, and adjustment procedures are not available.

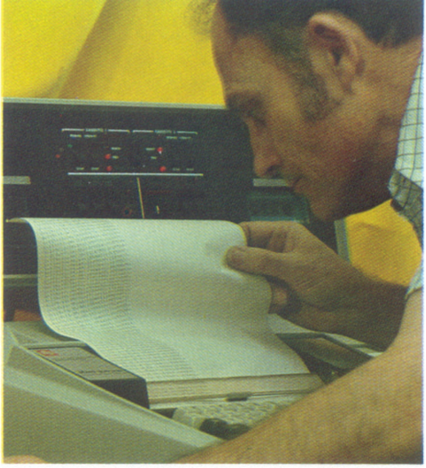
The FMC provides a means for comparing an oscillator with the TV network's 3.58 MHz subcarrier. Readout is a series of 4-digit numbers, representing the frequency offset between the oscillator being calibrated and the atomically controlled color subcarrier. By referring to network offsets published monthly in the NBS Time and Frequecy Services Bulletin, a user of the FMC can set his oscillator to agree with the NBS standard to better than 1 part in 10^{10} in five minutes and 3 parts in 10^{11} in fifteen minutes. Radio methods of calibrating oscillators traceable to NBS require several days of "averaging" to achieve this resolution.

When making network offset comparisons, the FMC will accept as input any oscillator whose frequency is 10 MHz/N, where "N" is any integer from 1 to 100.

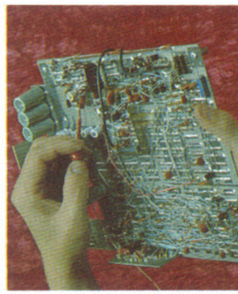
NOTE: **The highest available frequency should be used when there is a choice. For example, if an oscillator frequency of 100 kHz is used, the data sampling rate is 568 Hz. This results in aliasing frequencies that are displaced by only 1.6 parts in 10^4 from the nominal 100 kHz. When 5 MHz is used as the input, the first aliasing frequency is displaced by 7.4 parts in 10^3.**

The FMC can also be used to compare two oscillators with each other with a resolution of 2 parts in 10^{11} in twenty minutes. In this mode, oscillator "A" frequency can be 10 MHz/N (N = 1 to 100) and oscillator "B" input frequency can be 5 MHz/N (N = 1 to 10). For example, oscillator "A" could be 10 MHz, 5 MHz, 2.5 MHz, 1.25 MHz. . . . . 100 kHz; and oscillator "B" could be 5 MHz, 2.5 MHz, 1.25 MHz . . . .500 kHz.

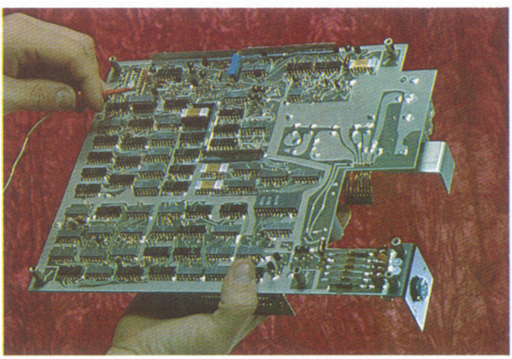
The FMC consists of a 5-inch color TV receiver with an additional electronics package mounted to its base. Readout for the FMC is on the TV screen, with two columns of ten 4-digit numbers, and an additional analog "phase cursor."

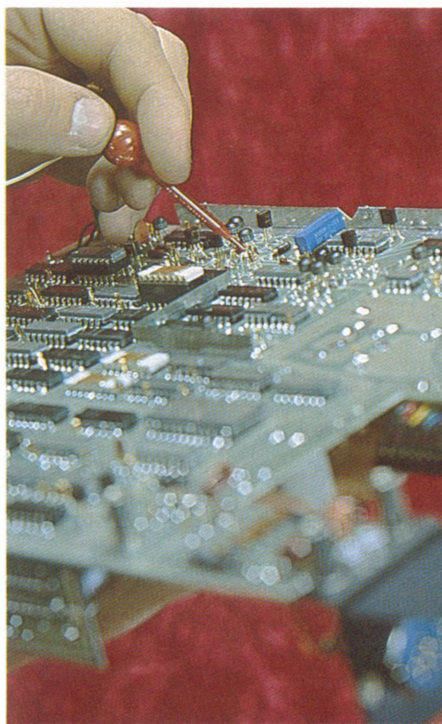


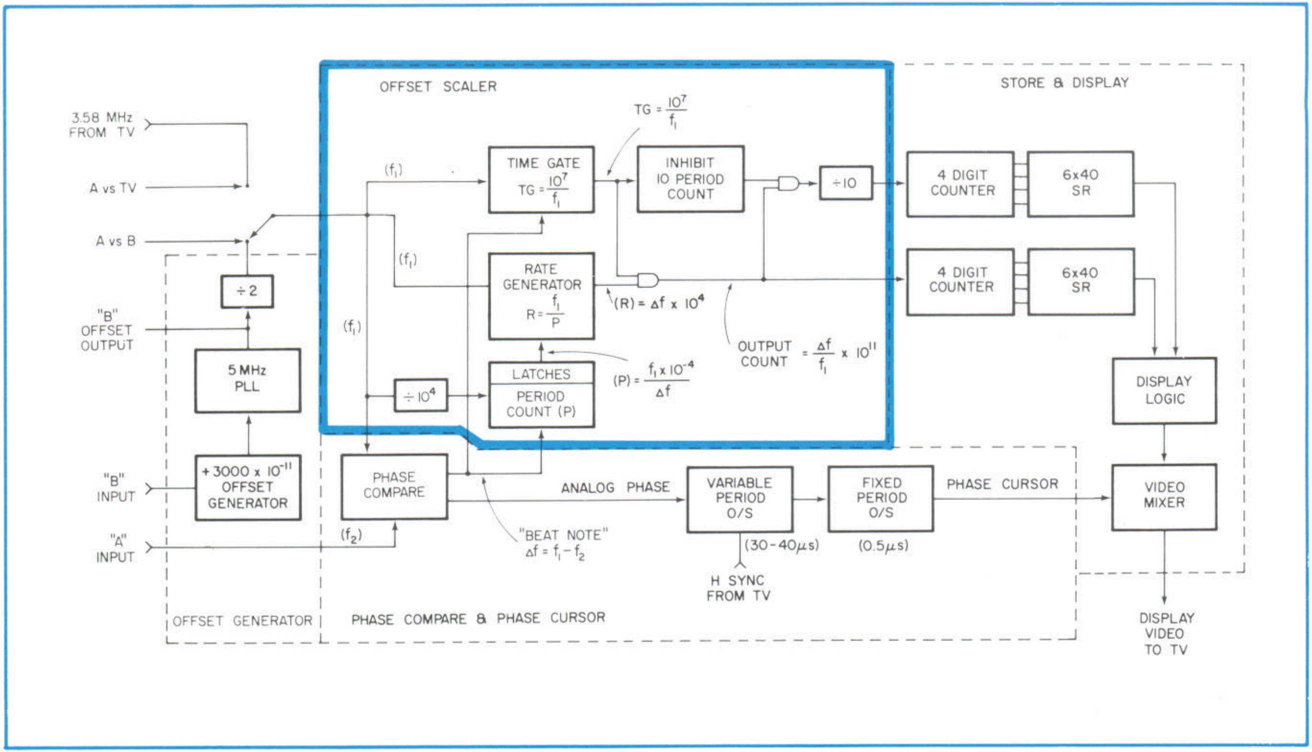
West Coast data are derived from a telephone-synch-transfer link at the ABC/Los Angeles network center.



Although the circuitry for the Frequency Measurement Computer is complex, calibrations are fast, easy and accurate.







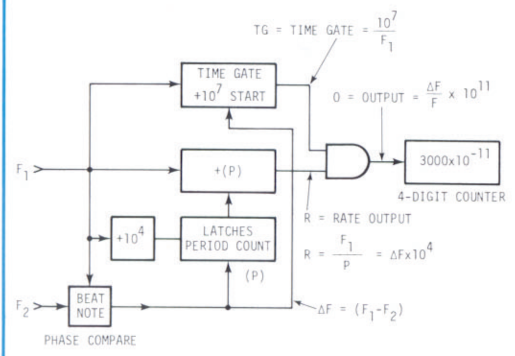
Block Diagram, System 358 Frequency Measurement Computer.

Block Diagram Overview

The FMC is divided into four main functional parts: offset scaler; beat note phase comparator and cursor generator; data store and display; and offset generator.

The offset scaler processes the beat note and 3.58 MHz signals to generate an output count proportional to offset $\times 10^{-11}$. This output count is applied directly to the single-period 4-digit counter. A new measurement is stored in the 6×40 single-period shift register (SR) for readout. The output count of the offset scaler is also applied to the 4-digit ten-period counter through an inhibit gate and a ÷10 prescaler. The ten-period counter therefore accumulates 1/10 of its total count on each single-period measurement.

Theory of the Offset Scaler. The offset scaler accepts the beat note and the color subcarrier frequency, f_1, from the TV. The variable divider generates output pulses at the rate $R = \Delta f \times 10^4$; that is, 10,000 times the beat note frequency. These rate pulses are gated on for a time equal to $10^7/f_1$. The count output to the data store counters is therefore:



The objective is to obtain a reading on a 4-digit counter at the output such that each accumulated count is equal to 1 part in 10^{11} offset between f_1 and f_2. That this has been accomplished can be verified by the following analysis. First, frequency offset is defined as:

$$\text{OFFSET} = \frac{f_1 - f_2}{f_1} = \frac{\Delta f}{f_1}$$

The beat note phase comparator generates $f_1 - f_2 = \Delta f$. The beat note frequency, Δf, is applied as a start-stop gate to the period counter, "P." The total count accumulated in "P" in one cycle of Δf can be expressed as:

$$\text{"P"} = \frac{f_1 \times 10^4}{\Delta f}$$

$$\frac{\Delta f}{f} \times 10^{11} \ (\text{count} = R \times TG = \Delta f \times 10^4 \times \frac{10^7}{f_1}).$$

For each cycle of Δf, the period count is latched and applied to the rate generator, where the output rate is

$$R = \frac{f_1}{P}$$

The rate of output pulses from divider (÷P) is:

$$R = \frac{f_1}{P} = \frac{f_1}{\frac{f_1 \times 10^{-4}}{\Delta f}} = \frac{\Delta f}{10^{-4}} = \Delta f \times 10^4.$$

This rate output is accumulated in the 4-digit counter for a period of time determined by time gate TG which enables the "and" gate preceding the counter. The total output count for each measurement cycle can be expressed as:

$$\text{OUTPUT COUNT} = R \times TG = \Delta f \times 10^4 \times \frac{10^7}{f_1} = \frac{\Delta f}{f_1} \times 10^{11}.$$

Therefore, if $\Delta f/f_1 = 3000 \times 10^{-11}$, the output count accumulated will be

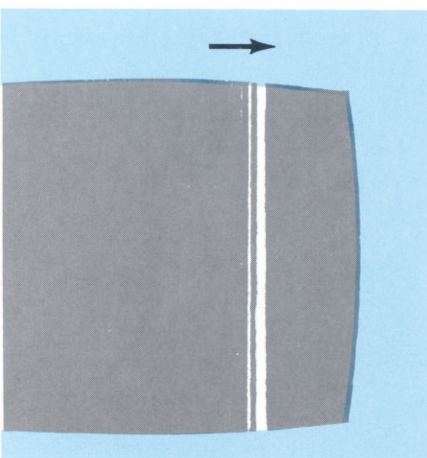
$$\frac{\Delta f}{f_1} \times 10^{11} = [3000 \times 10^{-11}] = 10^{11} = 3000 \times 10^0 = 3000 \text{ counts.}$$

The scaling factor for the output is the product of the 10^4 divider and 10^7 time gate. These two factors may be partitioned in other ways – for example, 10^5 and 10^6 or 10^3 and 10^8; however, the partitioning used is optimum for the nominal 3000 parts in 10^{11} offset to be measured.

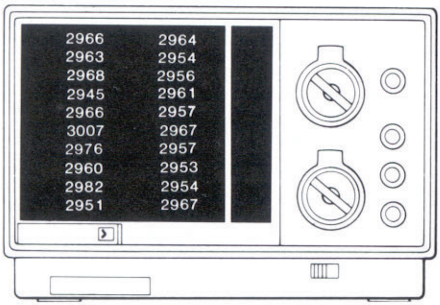
With the partitioning used, and an offset of 3000 parts in 10^{11}, the period count will be 3,333 and the time gate, TG, will be on for 0.3 of the beat note period. The maximum offset that can be measured is 10,000 parts in 10^{11}, in which case the time gate is on continuously, and simultaneously, the 4-digit counter overflows. The minimum offset that can be measured is determined by overflow of the 16-bit period counter, P. This occurs at an offset of approximately 150 parts in 10^{11}.

Neither the 3.58 MHz color subcarrier nor the 10 MHz/N input to be compared with it has been mentioned in the preceding discussion. Normally, f_1 is the 3.58 MHz input and f_2 is the harmonically related 10 MHz/N input. However, the unit will work equally well with any frequencies that have harmonically related offsets in the range of 150 to 10,000 parts in 10^{11}. We take advantage of this property in measuring the relative offsets of two oscillators in the "A" *vs* "B" mode.

Beat Note Phase Comparator and Phase Cursor Generator. The phase comparator section compares the phase of each 126th cycle of 3.58 MHz from the TV receiver with each 176th cycle of the "A" input. This circuit performs



the same harmonic synthesis function as the network rubidium frequency standards which generate 3.5795454 . . . MHz by taking 63/88 × 5 MHz. The analog voltage resulting from this phase comparison is stored in a sample and hold integrator. The analog "beat note" is further processed through two paths, the phase cursor path for a visual



indication of the beat note and a Schmitt trigger to condition the signal for the TTL offset scaler input.

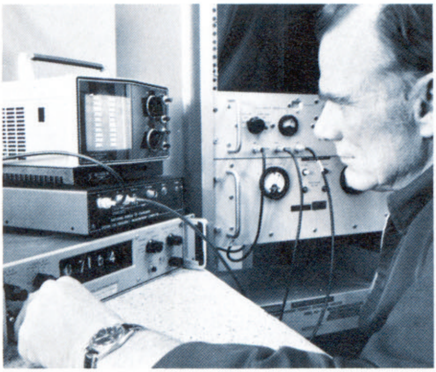
Data Store and Display. The gated frequency from the offset scaler is accumulated in the two 4-digit counters in the data store and display section. After each beat note measurement cycle, the single-period counter is gated on for 2.79 seconds. The accumulated single-period count is then dumped to the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

The readout data is presented as two columns of ten 4-digit numbers (see figure, page 17). The left column represents single-period offset readouts and the right column represents ten-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.

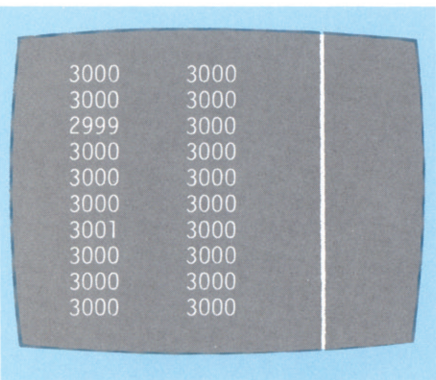
At the end of approximately 13 seconds, the first single-period measurement is completed and the data is loaded into the top 4 digits in the left column. The second 4 digits in the left column will now be intensified. On each following 10-second interval, data is loaded into succeeding positions in the left column until ten single-period averages have been accumulated. At this time, the first 10-period average will be loaded. This process continues until all ten 10-period averages have been loaded.

If a large phase jump occurs at any time in the sequence, the corresponding single-period offset will be read out, but that measurement *will not be* incorporated into the 10-period average. On the next measurement cycle, the single-period average will be rewritten and the count incremented. As each measurement is completed, the TV speaker "beeps" as a reminder to the operator.

The Offset Generator is an added feature that allows the comparison of two oscillators with each other. It does not use a network TV signal. A reference oscillator connected to input "A" is compared with a +3000 parts in 10^{11} offset replica of input "B." If both "A" and "B" have no offset with respect to each other, the readout will be 3000. If "B" is offset by some amount with respect to "A," the amount will be indicated in the readout by its deviation from a reading of 3000. For example: If "B" is offset +15 parts in 10^{11} with respect to "A," the readout will be 3015. Readout accuracy is 1 part in 10^{11} for 22 minutes of data. (Twenty-two minutes represents ten 10-period readouts at the sampling frequency of 2.5 MHz, with 3000 parts in 10^{11} offset.)



When the offset computer is used in the "A" *vs* "B" (Offset) mode, the two frequencies, "A" and "B," do not have to be the same. For example, "A" could be 10, 5, 2.5 1.25, or 1 MHz, or 500, 250, 125 or 100 kHz (i.e., 10 MHz/N), while "B" could be 5 MHZ, 2.5 MHz, 1.25 MHz, or 1 MHz. Performance is somewhat degraded for "B" less than 1 MHz.



The offset generator also provides a self-check function. If both "A" and "B" inputs are connected to the same oscillator, the readout should be 3000, providing an easy check of the offset computer logic.

Getting the Best Results.

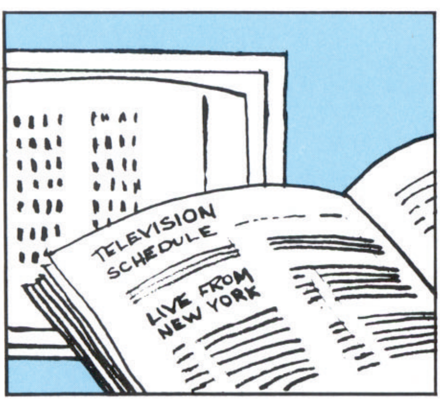
Although the frequency measurement computer reduces the labor of calibrating an oscillator, it does not relieve the user of the responsibility of verifying that "good" data is actually being processed. The user must be sure that the station being used is actually transmitting network-originated programs.

At the present time, data for three networks are available from NBS. The easiest thing to do is to take successive readings, if possible, on all three networks for 1.5 minutes each and verify that they are offset relative to each other by approximately the correct amount. Nominally, ABC and NBC operate at -3000 parts in 10^{11} and CBS at -2950 parts in 10^{11}.

Assume readings were taken with the following correct results:

ABC: -3131×10^{-11}
NBC: -3120×10^{-11}
CBS: -3082×10^{-11}

Note that the readings for ABC and NBC agree to 15 parts in 10^{11}, and CBS is lower by about 50 parts in 10^{11}.



Since all readings are higher than they should be by about 130 parts in 10^{11}, the reference oscillator should be lowered in frequency by this amount and measurements taken for accurate setting.

If one of the three offsets had differed radically from its correct *relative* value, we could assume that the station involved was on local programming. For example, if the relative offset for NBC were -2460, then the NBC station would not be used at that time.

The user may become somewhat dis-

ACTUAL READOUT DATA
USING SYSTEM 358 FREQUENCY MEASUREMENT COMPUTER

	NBC			CBS			ABC		
	3006	3010	3011	2961	2958	2981	3000	3001	3001
	3027	3009	3013	2964	2962	2960	3003	3000	3004
	0302	3011	3014	0296	2957	2962	0298	3002	3001
	3011	3015	3008	2960	2957	2962	3001	3004	2999
	3004	3011	3008	2964	2975	2957	3003	3001	3001
	3018	3012	3018	2951	2955	2957	3001	3001	3001
	3007	3007	3009	2970	2970	2963	3001	3002	3002
	3004	3013	3011	2961	2958	2958	3003	3282	3282
	3020	3014	3012	2960	2959	2962	3003	3000	3001
	3012	3025	3027	2960	2964	2960	3000	2998	3001
10-PER. AVERAGE	3010.3	3011.3	3011.6	2961.2	2960.0	2960.1	3001.7	3001.0	3001.2
OVERALL AVERAGE	3011.1			2960.4			3001.3		

In some cases, the logout scanner gets an electrical transient that causes a short count. However, this does not affect the accuracy of the data.

Circled values are outliers that were disregarded when computing averages. All averages are in parts in 10^{11}. Average fractional frequency offsets for the period were as follows:

NBC: -3010.9×10^{-11}
CBS: -2960.2×10^{-11}
ABC: -3002.0×10^{-11}

COMPUTATION WORKSHEET TO DETERMINE FREQUENCY OFFSET

DATE:____________________

NBC START TIME:	CBS START TIME:	ABC START TIME:

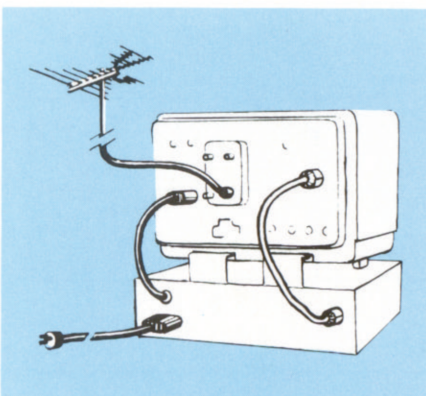
____________	____________	____________
10-PER. AVERAGE	10-PER. AVERAGE	10-PER. AVERAGE

The user may become somewhat discouraged at this point, but the situation is not as bad as it may seem. Network stations in the Eastern, Central, and Pacific time zones typically carry 10 to 14 hours of network-originated programs per day. You should be really discouraged only if you live in the Mountain time zone where network programming is typically four hours per day.

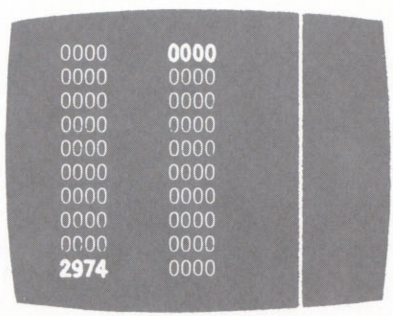
The best choices are the daytime "soaps" and quiz shows. These are usually daily programs and originate from the New York and/or Los Angeles network centers. Weekly evening programs are usually network-originated except in the Mountain time zone. Once the programming schedule in any given city is identified, a log can be made up to indicate when measurements should be made.

First-Time Operation

1. Connect power cable to FMC. Connect jumper cables between FMC and TV (1 power 9-pin Amphenol cable). Allow system to warm up for best results.
2. Connect TV antenna. If in high signal area, whip antenna may be used; however, better results will probably be obtained with outside antenna oriented to minimize "ghosts."

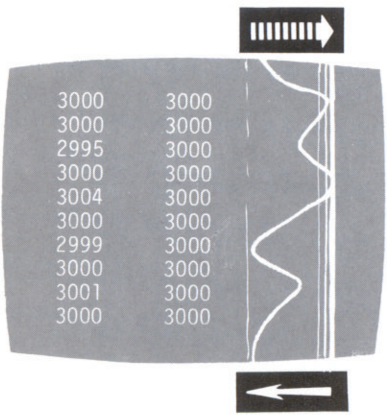


3. Turn on power to TV and FMC.
4. Observe TV screen. The TV should be displaying 2 columns of ten 4-digit numbers. The phase cursor should be visible as a vertical line on the right half or near the center of the screen.
5. Press the reset button. The screen should be displaying all zeros with the bottom 4-digit number in the left column (single-period average) and the top 4-digit number in the right (ten-period average) intensified.



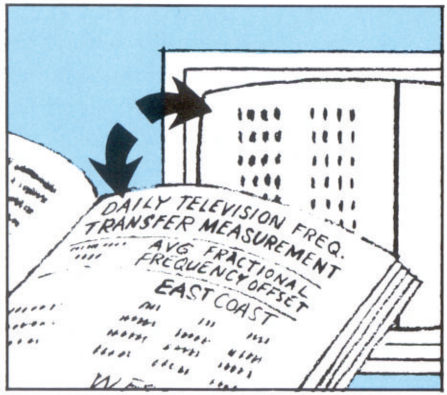
6. Connect oscillator to be calibrated to input "A" and verify that selector switch is set to "A" *vs* TV.

7. Observe movement of cursor. If the oscillator to be calibrated is on frequency, the cursor will move slowly left to right and fly back right to left. The period of the cursor movement will be approximately 10 seconds. If the indication of the cursor is not correct, adjust the oscillator.



8. Each time the cursor moves across and back, the speaker will emit a "beep" and a computed value of offset will be entered in the intensified 4-digit space in the left (single-period) column. (NOTE: Volume control must be turned up to hear "beep."

9. Observe the value of computed offset being entered. If the computed offset is higher than the published value, lower the frequency of the oscillator being calibrated. If the computed offset is lower, increase the oscillator frequency.



10. After observing about one minute of data, you can estimate whether your oscillator is approximately correct (to at least 2 parts in 10^{11}).

11. At this point, sample the other two networks to insure that the data are consistent. (Verify that you are tuned to a network program.)

12. Settle on a network with the least scatter in single-period averages. Let several readings be entered, then press reset button and hold for approximately one second, immediately after a "beep." All data should be erased and the top 4 digits of both the single- and ten-period columns should be intensified.

NOTE: The error reject circuit is activated any time a reading is more than 300 parts in 10^{11} from a

nominal 3000 offset. For example, if the single-period readout is 2600 or 3400, the value will be entered in the single-period column but will not be averaged into the 10-period column. When the error reject circuit is activated, the single-period column is reset to intensify the last 4-digit number in the column rather than the first. Normally, the intensified 4-digit number blinks at a 1.4 Hz rate. If data is rejected, the intensified number does not blink. The error reject is deactivated when two consecutive "good" readings are obtained. The error reject circuit is inhibited when measuring "A" *vs* "B" (offset).

13. Allow the FMC to accumulate several 10-period averages (maximum of 10) and discard all obvious "outliers." Take the average of the remaining readings. Compare this average with the published offset for the network being used. For example, the average of ten readings on ABC is 3015. The published offset of ABC is 3006 (February 1975 value). Your oscillator is high in frequency by +9 parts in 10^{11} (±3 parts in 10^{11}).

14. To verify, repeat measurements on the other networks. For example, measurement on CBS is 2968, published offset is 2961. Error is +7 parts in 10^{11}, verifying ABC reading to within 2 parts in 10^{11}. NBC measurement is 3022, published offset is 3014.

15. If oscillator being calibrated is within required tolerance (in this case, it is approximately +10 parts in 10^{11} high), you are finished. Otherwise, adjust oscillator and recheck.

    NOTE: Since most oscillators will exhibit some hysteresis, especially when large changes are made in frequency, it is wise to check the oscillator several hours after making a change in frequency. A little experience with the particular oscillator being calibrated is invaluable.

Comparing Oscillators with Each Other

1. Connect reference oscillator to input "A" and oscillator to be checked to input "B."

2. Place selector switch to "A" *vs* "B" (offset). An offset generator within the FMC will offset the "B" input by +3000 parts in 10^{11}.

3. Observe the cursor. It should move right to left and fly back left to right, with a period of 13.3 seconds. If the oscillator to be checked is far off frequency, adjust until the above is true.

4. If "B" and "A" have no relative offset, the readout will be 3000. If "B"

is high in frequency, the readout will be above 3000.

5. After adjusting "B," allow the unit to accumulate ten 10-period averages for maximum accuracy. Measurement is good to at least 2 parts in 10^{11} for ten 10-period averages (22 minutes).

FMC Self-Check

1. Connect an oscillator of reasonable quality (stability better than 1 part in 10^7/day) to *both* "A" and "B" inputs. Place selector switch to "A" *vs* "B" offset. FMC self-check should be made after 30-minute warmup.
2. The FMC will now compare the "A" input against a +3000 parts in 10^{11} offset version of "A." The readout for 10-period averages should be 3000 ± 1 count. If the readout differs drastically from 3000, it indicates a failure of some portion of the count logic.

Use of FMC with Zero Offset Color Subcarrier

Color subcarriers may be stabilized with zero offset (such as WTTG-TV in Washington, D. C., stabilized with a cesium reference by the U. S. Naval Observatory). To calibrate oscillators against zero offset subcarriers, proceed as follows:

1. Connect oscillator to be calibrated to input "B."
2. Connect "B" offset to input "A."
3. Proceed as with other subcarrier measurements.

NOTE: A larger scatter in data can be expected in this mode of operation. The scatter is very dependent on precise adjustment of the offset generator. For an improperly adjusted offset generator, the scatter can exceed 10 parts in 10^{11} for a 15-minute average. Under ideal conditions, the scatter will be on the order of 4 parts in 10^{11}.

Use of FMC with Unstable Crystals

The FMC is primarily intended to calibrate oscillators with stability of better than 1 part in 10^7/day. In fact, if the oscillator being calibrated will not hold still to better than 1 part in 10^7 (± 10,000 parts in 10^{11}), the digital readout cannot be used. About the best one can do with a really poor-quality oscillator is make the cursor "stand still" momentarily.

If the cursor moves less than one cycle each three seconds, then the oscillator is within 1 part in 10^7 of the color subcarrier. By switching between networks, one can obtain a "concensus;" however, there is no way to really verify if the subcarrier is originating from a network, as can be done when checking a good oscillator.

The FCC requires all stations to maintain 3.579545 . . . . .MHz ± 10 Hz on their subcarriers, so by comparing with several stations, one is assured of being within 3 parts in 10^6. If the oscillator being calibrated is stable to 0.001% (1 part in 10^5), it is close enough.

SPECIFICATIONS FOR PROTOTYPE NBS FREQUENCY MEASUREMENT COMPUTER

This section gives the performance specifications obtained by using the NBS-designed circuits. Other designs by individuals or manufacturers may give different results. These specifications are listed as one example of what can be achieved with a modest investment. Please note that other versions of this type of equipment would not necessarily include all of these features.

Inputs:	1. Level:	1 V (rms) (Min.)	
	Frequency:	10 MHz/N (N = 1 to 100)	
	Use:	TV compare, "A" *vs* "B" compare	
	2. Level:	1 V (rms) (Min.)	
	Frequency:	5 MHz/N (N = 1 to 10)	
	Use:	"A" *vs* "B" compare	
Outputs:	"B" Offset:	+3000 parts in 10^{11}	
	Level:	TV (rms) (unterminated cable not to exceed 3 ft. length)	
Linearity:	Phase variation not more than ±5 ns from best fit from 30 ns/s linear phase change		
Power:	115V AC, 60 Hz, 50W (including 5" color TV)		
Controls:	"A" *vs* TV, "A" *vs* "B" offset:		
		Switch:	2-way toggle
		Reset:	push button
		Power:	switch, 2-way toggle
Accuracy:	"A" *vs* TV:	Dependent on stability of TV 3.58. Typically ±10 parts in 10^{11} for 93 s, ±2 parts in 10^{11} for 15 min (3σ)	
	"A" *vs* "B"	±20 parts in 10^{11} for 133 s 10-period average; ±2 parts in 10^{11} for 22 min average (typical)	

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Readout Resolution:	Single-period:	1 part in 10^{11} when offset is +3000 parts in 10^{11}. Resolution decreases to 3 parts in 10^{11} for offset of 9000 parts in 10^{11}.
	Ten-period:	Round off to nearest 1 part in 10^{11}, so at +3000 parts is 10^{11}, error is 0.5 parts in 10^{11}. Error increases as offset deviates from +3000 parts in 10^{11}. At 9000 parts in 10^{11}, maximum error is 1.5 parts in 10^{11}. By averaging ten 10-period readings, the resolution is increased to 1.5 parts in 10^{12}. In most cases, the readout resolution is about an order of magnitude greater than the stability of the signal being measured.

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