T31-6-1

PRECISION FREQUENCY MEASUREMENT
IN THE MEDIUMWAVE AND THE
SHORTWAVE BROADCAST BANDS

By Charles A. Taylor

PHILOSOPHY Precision Frequency Measurement (PFM) has already proven its value to those who use it extensively. Some typical uses for PFM are identifying new (previously unlogged) broadcast stations, identifying old (previously logged) stations, and recognizing facility changes (new transmitters). If the DXer has a list of PFMs at hand, he can quickly determine if the identity of that station that is heard alone or mixed with others, is that of a station which he has logged before or one that he is seeking. While not a certain identifier of the unidentified, under the proper circumstances it approaches 100% certainty.

TECHNIQUES Having passed briefly on the value of PFM, let us address ourselves to a method used to acquire them. In preparing this article, I limited myself to techniques for PFM that are based on usage of the digital frequency counter as the device that measures the frequency indirectly. Specifically excluded are frequency meters (such as the Lampkin 150 or the military BC-221 or LM) as being impractically expensive or incapable of the required resolution, which is on the order one Hertz (one-thousandth of one kilohertz), or about 0.0001%; or better.

The digital frequency counter (hereafter simply "counter") is a versatile instrument which provides a direct, visual readout of whatever frequency is being measured. Briefly, a counter uses an electronic gate which is opened for predetermined, precise periods of time (for our purposes, one second or ten seconds). The unknown frequency that is to be measured is made to pass through this electronic gate. Electronic counting devices then count each and every cycle of the unknown frequency that passes through the gate during the respective period of time, and the count at the end of that period is then displayed on numerical devices as a count readout which is the same as the unknown frequency. The electronic gate is opened and closed by a time base, termed a "clock". This clock is electronic in its operation and is controlled by a very precise crystal oscillator of 1 MHz, 10 MHz, or some other frequency typically between 3 and 5 MHz.

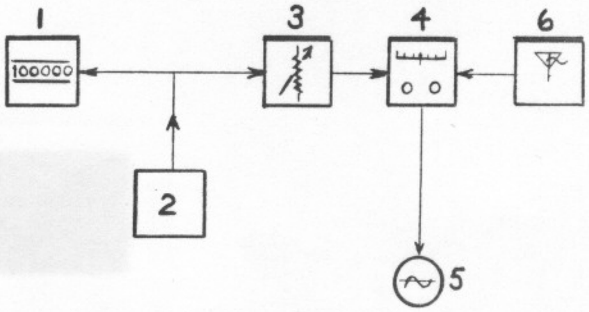
A counter cannot be connected to the unmodified radio receiver in any configuration that would yield frequency measurements of a resolution required for PFM. Assuming a receiver I-F bandpass of 4 kHz, connection of a counter to the receiver IF would merely yield relatively invariable reading centered on 455 kHz—meaningless for PFM.

Connection of a counter to the receiver local oscillator would yield a readout that would bear a relatively constant and accurate relationship to the signal frequency. The drawback is that in receivers designed for mediumwave and shortwave reception, the local oscillator usually "tracks" the signal frequency with an offset equal to the I-F frequency. A counter connected to the local oscillator would read out (assuming an IF of 455 kHz) a frequency 455 kHz above the signal frequency and so necessitate subtraction of 455 kHz from each and every measurement to derive the signal frequency. A further hinderance is the lack of an indicator in the unmodified receiver that it is tuned accurately so that the I-F frequency could be exactly centered in the I-F passband. This would yield a readout accuracy of only plus-or-minus 2 kHz or worse (after subtraction of 455 kHz from the counter readout), depending on the width or shape of the receiver passband.

A counter cannot simply be connected to a radio antenna in order to measure specific radio frequencies, for two reasons: first, the typical counter lacks the high sensitivity necessary to measure the feeble radio signals that arrive after a transoceanic voyage; second, the counter is inherently incapable of distinguishing which of many radio frequencies that are applied to its input is to be counted—and it cannot count them all simultaneously.

The above hinderances to the construction of a workable PFM station by direct connection of the counter to the radio receiver, plus the unwillingness of DXers, even though technically competent, to perform the necessary modifications upon their receivers, have inspired a relative simple solution—the Heterodyne Method.

Heterodyne Method of Frequency Measurement The nearly universal solution to the problem of acquiring PFMs without performing receiver modifications, has been to use the heterodyne frequency measurement system, whose typical components are represented in the following block diagram (the arrows indicate the direction of signal or information flow upon the interconnections between the components):



Blocks, and their descriptions:

1. frequency counter
2. transfer oscillator (abbreviated TO) a variable radio-frequency oscillator, chosen and designed for its frequency stability (a critical quality for PFM applications)
3. variable attenuator a device which attenuates, or reduces, the output of the transfer oscillator in a controllable manner to permit it to be adjusted so that it is approximately equal in strength to that of the unknown signal frequency
4. heterodyne detector a device which detects the difference in frequency between the transfer oscillator and the unknown signal frequency, and which converts this difference to a form usable by the indicating device; while numerous devices will serve as a heterodyne indicator, the single device used by the DXer is a radio receiver
5. indicating device a device which accepts the frequency difference information from the heterodyne detector, and converts it into a audible or visible indication; some indicating devices used are "S"-meters, loudspeakers, oscilloscopes, and strip recorders
6. unknown frequency the signal whose frequency is to be measured, typically as accepted from an antenna

In operation, the counter (block 1) continuously measures the frequency of the transfer oscillator (block 2); the transfer oscillator is made to zero-beat with the unknown signal frequency by observing the combined indications at the output of the heterodyne detector (block 3). Since under conditions of zero-beat, the transfer oscillator assumes a frequency nearly identical to that of the unknown signal frequency, the counter will measure a frequency which is essentially the same as the unknown signal frequency.

Exclusive of the counter, already described, we will describe typical categories of equipment used for each block.

Transfer oscillator Typically, a signal generator or a modified frequency meter is used as a TO. A frequency meter, as modified, is particularly suited for this application for two reasons: first, in consideration of its original purpose as a frequency-measuring device, it is designed for maximized frequency stability; second, it will include a frequency vernier in its complement of controls. Such a control permits the monitor to adjust the frequency of the TO in minute increments—essential for accurate zero-beat (A frequency meter, when used as a TO, is not used directly as a frequency-measuring device; rather, the counter measures its frequency. This eliminates the need for a calibration book and interpolative readout, which is the source of inaccuracy in the use of frequency meters.).

However, ready availability has encouraged the use of signal generators of varying manufacture as a TO. Most signal generators of the continuously variable-

T31-8-2

frequency variety are not optimized for this application, but nevertheless are of almost universal utility as-is for use as a TO. Few signal generators include a frequency vernier control for incremental frequency adjustment, but the alert operator will discover that operation of the variable attenuator will have a small effect on the signal generator frequency output.[1] In my experience, even laboratory-grade signal generators of the continuously-variable frequency variety display this unintentional, albeit useful, quirk of behavior.

Another shortcoming associated with signal generators, especially those of consumer-grade quality, is short-term frequency instability which manifests itself as difficulty in maintaining zero-beat with the signal of unknown frequency. This shortcoming becomes progressively more acute at SW frequencies, perhaps rendering the signal generator worthless at these frequencies unless modified. A solution for this problem will be related later in this article.

Fortunately, optimization of a signal generator for use as a TO is not difficult for the DXer of medium competence to accomplish. What is required is the addition of a frequency vernier control (a small, air-variable trimmer capacitor or a voltage-variable-capacitance diode and potentiometer combination) to the frequency-determining elements of the signal generator, and addition of voltage regulation to the signal generator power supply.

Variable attenuator A degree of attenuation is necessary in introducing the TO output into the heterodyne detector, when performing a PFM upon all but the strongest local signals. This is necessary because, in order to achieve a zero-beat of maximum clarity and definition, both the TO output and the unknown signal must be of approximately equal intensity. A serious unbalance of intensity between the two would allow the stronger to "swamp" the weaker, rendering the zero-beat inaudible. Placing an attenuator in the output of the TO is necessary because its maximum output may well be one million times more intense than the signal whose frequency is to be measured.

The variable attenuator which is included as one of the controls of a signal generator, has some limitations which must be taken into account in PFM usage. First, in the typical signal generator, the variable attenuator intervenes between the instrument's internal oscillator and its output jack. If the signal generator were connected directly to the counter input jack, the wide range of adjustment of the variable attenuator could not be used. This is the case, because in adjusting the variable attenuator in order to reduce the signal generator output to an intensity which would be equal to that of a relatively weak signal, it would probably be found that the output would be so reduced as to fall below the sensitivity threshold of the counter, which would then cease to count the signal generator frequency. In order to avoid this difficulty, a logical solution would be to modify the signal generator to permit connection of the counter in the signal path before the variable attenuator, such that the counter would "see" the unattenuated output of the signal generator internal oscillator, uneffected by the variable attenuator.

An alternate solution would be to buy or construct an outboard variable attenuator whose input would be connected to the signal generator output jack, along with the counter input, and whose output would be connected to the heterodyne detector (the signal generator internal attenuator would be set for maximum signal generator output). In both alternatives, manipulation respectively of the signal generator internal variable attenuator or of the outboard variable attenuator would have relatively little affect upon the intensity of the signal applied to the counter input.

Unfortunately, while logically valid, both alternatives have related pitfalls. These will be discussed later.

Heterodyne detector As indicated earlier, the single device used as a heterodyne detector by the DXer, is a radio receiver. The DXer's own receiver is the logical candidate for this function. Part of the versatility of the PFM technique depends on the receiver used by the DXer. In order to measure a signal's frequency, it must obviously be audible on the receiver that is used as a heterodyne detector, indicating that sensitivity is an important factor. Another important factor is selectivity, in order to separate the signal of interest from other, undesired signals on adjacent frequencies.

Generally, the more elaborate the receiver, the more useful it will be in this function.

The output of block three, the variable attenuator, may be connected to the antenna connection of block four, the heterodyne detector (radio receiver), through a medium-value resistor (1 kilohm), through a small-value capacitor (10 picofarads), or it may be radiated to the receiving antenna by a small radiator antenna (such as a whip antenna of some 3 feet). The alternatives have difficulties of likely encounter, which will be discussed later.

OPERATION To illustrate the operation of a PFM station, and to acquaint the reader with some of the difficulties involved with typical equipment, we will consider the measurement of an unknown frequency.

Assuming that the monitor has tuned the receiver to a signal whose frequency is to be measured, with the receiver BFO off, the TO is tuned to the same frequency. Since, by the process of locating the unknown signal frequency on the dial of the receiver, a coarse frequency measurement has been performed; tuning the TO would be a matter of approaching the signal frequency until an audible heterodyne is noted in the loudspeaker or headset (Unless a strong signal has been tuned in on the receiver, the variable attenuator should be set for a medium-to-low TO output in order to prevent the generation of spurious responses due to overload of the receiver that may be mistaken for the TO frequency itself.).

When the heterodyne is heard, the variable attenuator is adjusted for maximum loudness of the heterodyne (without disturbing the TO frequency). When this condition is achieved, the TO output has been adjusted such that it is of approximately equal strength as the unknown signal. (Alternatively, assuming that the TO frequency has been adjusted such that a subaudible heterodyne (i.e. a carrier beat), or SAH, is generated with the unknown signal, adjust the TO variable attenuator for maximum "swing" of the receiver carrier or S-meter. This condition likewise indicates that the TO output is approximately equal in strength to that of the unknown signal.)

The next step is to adjust the TO frequency to bring it to zero-beat with the unknown radio frequency. Of the entire procedure, this is perhaps the most elusive step to the apprentice monitor. Zero-beat will be located at the midpoint where the heterodyne drops in pitch and begins to rise again, as the TO frequency is adjusted.

Approximate zero-beat will be identified when the frequency of the TO has been so adjusted that an SAH is set up with the unknown frequency, and that by minutely adjusting TO frequency vernier control, the rapidity of the SAH can be varied and controlled. Assuming that approximate zero-beat has been acquired, the TO frequency vernier control should be minutely adjusted such that the SAH, as evidenced by the regular, periodic swing of the receiver S-meter, slows down and stops. This condition should persist for at least 5 seconds, before the TO frequency drifts to an extent that it must be readjusted for exact zero-beat.

Assuming that the SAH frequency has been brought to essentially zero, such that the receiver S-meter remains in a relatively fixed position, the TO frequency will be equal to that of the unknown signal. The frequency read-out of the counter, along with the date of measurement, can then be recorded. It would be wise to make at least three consecutive frequency measurements of this sort, each time readjusting the TO frequency vernier control for an exact zero-beat before making the measurement. The several measurements may then be averaged and any fraction of a Hertz appearing in the average should be rounded off to the nearest Hertz.

CAVEAT While the foregoing procedure may appear on its face to be simple of execution, it may well be difficult until experience refines one's techniques. Some of the pitfalls that may be encountered will be

T31-8-3

pointed out so that the apprentice monitor may avoid a multitude of erroneous measurements.

Beware, in adjusting the TO frequency initially to that of the unknown frequency, that the TO output has not been adjusted to such a level that it generates false, spurious responses in the receiver. If in doubt, the output of the TO should be adjusted to near minimum initially. The approximate frequency of the unknown signal may be estimated by its position on the receiver dial and in relation to the frequencies of known, adjacent signals. The TO may be adjusted to this approximate frequency by alternately observing the TO frequency on the counter and the TO frequency dial calibration. When satisfied that the TO frequency is near the approximate signal frequency, the TO frequency may be "rocked", or swept back and forth across this approximate frequency while simultaneously increasing the TO output until a heterodyne is observed.

Care is necessary in initially adjusting the TO output, as previously emphasized, to avoid generating spurious responses by overloading in the receiver. A simple method that will assist in determination whether or not the heterodyne observed in the preceding steps, is a true response or a spurious one, is to carefully "rock" the receiver across the combined two signals. If the heterodyne frequency between the pair changes, the response is almost certainly a spurious one. If, however, the heterodyne frequency remains constant, the response is more likely to be a true one.

A true response may be mimicked by a beat between the TO frequency and another strong MW or SW signal. In this instance, the heterodyne frequency between the apparent TO signal and the unknown may remain constant when the receiver is rocked across the combination, but the modulation of the signal with which the TO signal is combining, may appear to ride in on the TO signal. A true response can also be mimicked by heterodyning a harmonic of the TO against the unknown. While this is not strictly speaking a true response (since a TO harmonic is classifiably a spurious radiation), it has its uses. A harmonic of the TO frequency would be recognized when the counter and the dial of the TO display a frequency which is one-half, one-third, one-fourth, et al., of the approximate unknown frequency.

To gain valuable experience, it would be of advantage for the apprentice monitor to measure the frequency of stations whose frequencies are known positively. Also, measurement of such frequencies over a period of time, besides providing experience, will allow the apprentice monitor to observe frequency fluctuations of these familiar frequencies and to acquaint himself with the limitations of his own equipment.

LIMITATIONS AND DIFFICULTIES Some brief references have been made to limitations and difficulties that relate to the TO and its operation. We will now address our attention to some other equipment limitations and attendant difficulties of likely encounter.

Counter and TO direct radiation In attempting to perform PFMs on any but the strongest MW and SW signals, it may be found that the signals of unknown frequency are "swamped" by the TO output—even though the variable attenuator has been adjusted for minimal TO output. This is a manifestation of direct radiation from the TO or counter, situation in which radio-frequency energy is being radiated from the TO or counter power line cords, interconnecting cables, chassis, or chassis openings, to the receiver antenna.

Two solutions immediately present themselves. First, efforts toward perfecting the shielding and filtering of TO and counter chassis and leads; additional bypassing of power line cords, using ceramic disc or mica capacitors of moderate capacitance (about 1000 pF) plus series inductances of several microhenries, inserted in each lead of the power cords (this filtering being accomplished within the TO and counter enclosures); and use of coaxial cable interconnections between the TO and the counter, will serve to reduce the "floor" of direct radiation. Second, it would be helpful to locate the monitor station at some mimimal distance from the receiving antenna, using a coaxial feedline to interconnect the two.

The first solution has been found to be of limited effectivity in the author's own situation. It was found that the greater portion of the direct radiation emanated from the readout apperture of the author's counter (a Heath IB-1101). Use of a shield fashioned from copper screen and fastened within the readout apperture and bonded to the counter chassis, may be effective. The author's desire to avoid modification of the counter ruled out this alternative however, so no experience can be related. However, even the Hewlett-Packard 5245L frequency counter has been observed to radiate radio-frequency energy via the readout apperture, so it is thought that such a solution may only be partly effective (Likewise, laboratory grade signal generators have been found to be "leaky" of radio-frequency energy.)

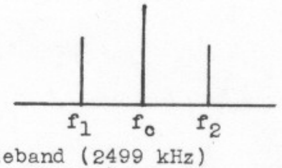
The second solution will probably be effective in limiting the level of stray radiation that reaches the receiver, assuming a separation of several meters between the monitor station and the receiving antenna. In the author's own experience, this solution was completely effective with a separation of three meters between the monitor station and receiving antenna. The difficulty with this solution is that it does not relate to the minimal distance likely to be encountered between the monitor station and a loop antenna. A Space Magnet may be relatively insensitive to stray radiation, as it is designed to respond only to the magnetic component of a passing radio wave while ignoring the electrostatic field—mode by which the stray radiation is probably radiated.

USES Other typical uses for the PFM monitor station follow.

TT frequency measurement It is simple to determine the unknown frequency of a test tone that is being transmitted by a broadcast station. This is accomplished by measuring first the station carrier frequency, recording that quantity, and then measuring the frequency of either sideband. The difference in frequency between either sideband and the carrier is equal to the frequency of the test tone.

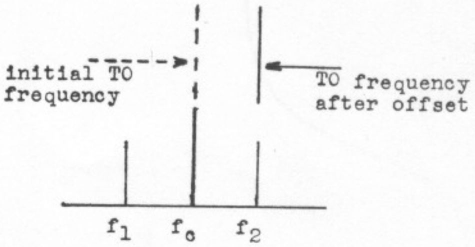
To measure the frequency of either sideband, it is possible to take one of three approaches. The first is to zero-beat the TO with either sideband: After measuring the carrier frequency, and without altering the variable attenuator setting, carefully increase or decrease the TO frequency until it is found to cause an SAH with either sideband. This will occur when the TO frequency is offset from the carrier frequency by an amount equal to the test-tone frequency (typically 400, 500 or 1000 Hz). To illustrate, consider a typical case of a station operating on 2500 kHz, which is transmitting a test tone of 1000 Hz:

fig. 1



f_1 lower sideband (2499 kHz)
f_c carrier (2500 kHz)
f_2 upper sideband (2501 kHz)

fig. 2



f_1 lower sideband (2499 kHz)
f_c carrier (2500 kHz)
f_2 upper sideband (2501 kHz)

Two sidebands, 2499 kHz and 2501 kHz, are generated by the modulation process and transmitted along with the carrier, as illustrated in fig. 1. In fig. 2, the TO is brought to zero-beat with the station carrier, as shown. At this juncture, the counter should read out 2500.000 kHz. Then the TO frequency is varied upwards until it is approximately equal to the frequency of the upper sideband, at which time there would appear an SAH on the receiver carrier meter. The TO frequency vernier would be minutely adjusted to bring this SAH to zero, at which time the counter would read out 2501.000 kHz. To determine the test-tone frequency, subtract the carrier frequency from the upper sideband frequency, i.e. 2501.000- 2500.000= 1.000 kHz, or the test-tone frequency.

The second approach is to measure the carrier frequency as in the first approach, and then, while listening to the frequency of the heterodyne that is introduced by detuning the TO from zero-beat with the station carrier, adjust the TO frequency until the heterodyne formed by the TO and the carrier is heard to be equal in frequency (or pitch) to that of the test tone. At this instant, an SAH will be produced which can be be brought to zero-beat by minutely adjusting the TO frequency vernier. The TO frequency thereby becomes equal to whichever sideband is zero-beat.

The third approach requires a highly selective receiver for accomplishment. Invoking the receiver's maximum selectivity, return the receiver to either sideband at which time the test tone will become inaudible and the sideband selected alone will be apparent. The sideband may then be measured in frequency in the normal manner. Then tune the receiver to the carrier and measure its frequency. As before, the test-tone frequency is equal to the difference in frequency between either sideband and the carrier.

All three approaches require recognition that sideband frequencies that are generated in the A-M modulation process are discrete r-f energies that are transmitted simultaneously with the carrier, and that each sideband is individually measureable in frequency.

Frequency Check measurements With a carefully calibrated PFM station, the experienced MW monitor can accurately measure the frequency of a MW station, as can a frequency-monitoring service. Frequently, when faced with with severe cochannel interference, a frequency monitoring service will measure the frequencies of both sidebands of a broadcasting station which is modulating with test tone, and average the two to determine the carrier frequency. Such an option is available to the MW monitor. Correct measurement of test-tone modulation frequency and of the carrier frequency of a broadcast station which is conducting a frequency-check transmission, may be sufficient evidence for a cooperative chief engineer to issue a verification.

A similar opportunity may be available to both the MW and the SW monitor in recording the frequency error of a particular transmitter over a period of time (e. g. several days), for submission as evidence of reception for correlation with the records available to a chief engineer; for the issuance of a verification. The author recently received an unsolicited (but very much welcomed) verification for submission of a record of several days' measurements.

Heterodyne frequency measurement Measurement of the frequency of a heterodyne is identical to measurement of a test-tone frequency, save that a heterodyne is created by the beating of two radio frequencies while test-tone modulation produces three frequencies (two sidebands and a carrier). If the monitor's receiver lacks sufficient selectivity to determine whether a particular tone on a broadcast channel is the result of modulation by some station or of an audible frequency difference between two station carriers, it can be determined by measuring frequencies that exists in the immediate vicinity of the channel. A test-tone broadcast would yield three related frequencies while a heterodyne would yield only two frequencies.

Receiver frequency spotting The PFM equipment can be used as a most useful adjunct to a receiver with mediocre dial frequency calibration. In this application, the TO is set at a frequency which the monitor wishes to tune; and the receiver is tuned until the TO output is audible, thus tuning the receiver to the desired frequency exactly.

While using the PFM equipment in this function. it is necessary for the monitor to become acquainted somewhat with overload characteristics of the receiver and the degrees of output produced by the TO at various settings of the TO variable attenuator. This is necessary because in setting the TO variable attenuator for an excessively high output, spurious responses may be generated in the receiver which could be mistaken for the TO output frequency; likewise, an insufficiently low setting of the TO variable attenuator may render the TO output obscure or inaudible. Experience is of value in determining the optimum TO variable attenuator setting for frequency-spotting applications.

Some TOs have facilities for amplitude-modulating the TO output with a test tone of some frequency, typically 400 Hz or 1000 Hz. So modulated, a TO output frequency will become more conspicuous for frequency-spotting purposes.

When modulating a TO for frequency spotting, increase the percentage of modulation of the TO incrementally to maximum while observing the counter readout; at some high degree of modulation, it will probably be found that the counter readout will become erratic and unstable. Note or record this degree of modulation and avoid advancing the modulation control to this setting. Avoid using the modulation function of the TO while making frequency measurements.

ERRORS INHERENT IN PFM There are certain sources of error inherent in the PFM process. If the sources of these errors are recognized and understood, they can be minimized.

Time-Base Error Reviewing the brief description of a digital frequency counter presented in the beginning of this article, it will be remembered that the time base determines the period of time that the electronic gate is open. In a hypothetical case, the electronic gate is opened for a precise period of one second. If an input of exactly one megahertz (one megacycle per second) were applied to the input of the counter, then exactly one million cycles would transit the gate, to be counted by the electronic counting devices, and displayed on the counter readout as a count of 1,000,000 Hz (or 1,000.000 kHz, depending on the placement of the decimal point). If the gate period is changed to precisely 10 seconds, then exactly ten million cycles would transit the gate to be counted and displayed as 10,000,000. Depending on the placement of the decimal point, this would be read as 1,000,000.0 Hz, or as 1,000.0000 kHz, with the least significant digit (the digit to the extreme right, abbreviated LSD) representing tenths of a Hertz (the LSD represents one-Hertz units in the case of a one-second gate period).

If the gate period were not exactly one second in duration, the number of cycles passed to the counting devices would not be exactly one million. Since the gate period is controlled by the time base, an error in the time-base frequency will cause an error in the number of cycles counted. The error in the count (as averaged over a number of counts) will be proportional to the error in the time-base frequency. Obviously then, the time-base frequency must be a very closely controlled quantity. Generally it is, but beware of the counter whose time base is controlled by the 60-Hz, power-mains frequency; the short-term stability of which is much too poor for our purposes. Counters to be reviewed later in this article will not possess this class of time base.

In order to be able to perform PFMs of an accuracy approaching 1 Hertz in the mediumwave band, and 5 Hertz in the shortwave bands; the stability of the time base must be about twice to ten times the desired readout accuracy. Since an average of 1 Hz at 1 MHz in the mediumwave band is the goal (stated as one part per million, or 1 p.p.m as abbreviated), then a time-base stability of 0.1 p.p.m. (or restated as one part in ten million) is indicated. Fortunately, such a stability is achieved by the time bases of even some of the simplest counters. In order to achieve approximately 1-Hz accuracy in the 11-meter shortwave band, a time-base stability of one part in 300 million (or 0.003 p.p.m.) is indicated. Unfortunately, a counter whose time base can achieve this stability would be expensive; the monitor would have to be contented with impaired accuracy at those frequencies. An accuracy of 50 Hertz in the 11 m.b. might be considered a worst-case figure. Experience indicates that an accuracy of about 10 Hertz is feasible in that region.

Time-base error is minimized by careful calibration of the time base and by a counter warm-up period of at least one-half hour before use. Since most counters either have a time base whose frequency is 1 MHz, or have a calibration output of 1 MHz; calibration is facilitated by observing the beat frequency between the harmonic of the time base and one of the frequencies transmitted by WWV, WWVH, JJY, et al. In using a time and frequency standard station for calibration, select the highest standard station frequency that is audible consistently in your area (usually 10 MHz during the winter and 15 or 20 MHz during the summer) and adjust the time base of the counter for slowest SAH against the standard station (when calibrating a counter time base, a warmup period of at least one hour prior to calibration is necessary).

Digitalization Error Beside an error in time-base frequency which over several counts will cause a proportional error in the counter readout, another source of error inherent to digital counters is digitalization error. Digital counters are on/off devices which only respond to a specific point on an input waveform. Since the counter gate may open at a random time in relationship to the frequency that is to pass through it (remember that the gate is only required to remain open for a specific period of time), there is an uncertainty as to which portion of the waveform of the incoming frequency will first appear when the gate is first opened; and so whether or not the specific portion of the waveform that triggers the counting devices will have already passed.

To illustrate, assume that the counting devices only respond to that portion of the incoming waveform (the square waveform is the appearance that the TO waveform will have after passing through the counter input preconditioning circuitry) that is marked "A" in the following figures 3 through 5:

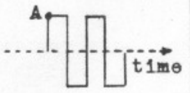


Fig. 3

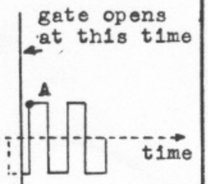


Fig. 4

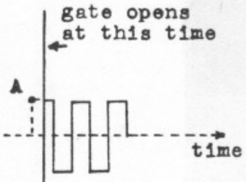


Fig. 5

If, as in figure 4, point "A" of the first cycle of the incoming waveform just passed by the gate, has yet to arrive, the counting devices will be able to count it as it passes. If, as in figure 5, point "A" has already passed when the gate opens, the counting devices will be unable to count it. The result is that, to take the example of a 1-MHz input frequency, the counting devices may count 999,999 Hertz; 1,000,000 Hertz; or 1,000,001 Hz. This uncertainty in the LSD (the digit to the extreme right) is a manifestation of the digitalization error. There will always be this ± 1-count uncertainty inherent in any counter that lacks a synchronized gate (the case with most of the counters that the DXer is likely to acquire). Since plus-or-minus one count out of a frequency of 100,000 Hz is a greater percentage of that frequency (0.001%) than it is of 1,000,000 Hz (0.0001%), or of 10,000,000 Hz (0.00001%); this error is of greater consequence at a lower frequency than it is at a higher frequency. In this respect, a counter's accuracy increases with frequency (disregarding time-base error and assuming that we do not exceed the counter's cut-off frequency, i.e. that frequency above which the counter ceases to count). In order to reduce the percentage of the digitalization error at lower frequencies, we can increase the gate period (for example, from one second to ten seconds, or even to one hundred seconds) and so minimize the digitalization error as a percentage of the total number of cycles counted. Likewise, we can make a series of independent measurements and rely on statistical probability to average out the error. For mediumwave PFMs, unless a counter with a ten-second gate (and a TO of correspondingly greater stability) is available, we must rely on making several measurements and averaging the individual results. For shortwave PFMs, the digitalization error is about proportional to the frequency to be measured; at 10 MHz, it becomes nearly negligible.

Synchronization Error Also termable zero-beat error, this error is caused by the lack of a perfect zero-beat between the TO frequency and the signal of unknown frequency. While a perfect zero-beat, i.e. a perfect synchronization in frequency between the TO and the unknown frequency, is a practical impossibility; an error of 0.1 to 0.25 Hz is an easily attained minimum at mediumwave frequencies. The error at shortwave frequencies is apt to be greater, perhaps 0.5-1.0 Hz without especial care. This is true because the relatively rapid fade characteristics of SW signals, especially those that have been propagated via a polar or near-polar path, tend to obscure the zero-beat.

Lacking an oscilloscope with long-term luminescent phosphor or a strip recorder for use as an indicating device (block 5 of the basic heterodyne frequency measurement system), one must depend on experience and multiple measurements to reduce synchronization error to a reasonable minimum (about 0.25 Hz, mediumwave; 0.75 Hz, shortwave).

Audio Imaging A possible source of error, especially for the inexperienced monitor, is audio imaging. Audio images are most likely to occur when attempting to PFM the frequencies of two stations which are heterodyning one another with a resultant carrier beat in the audio-frequency range. This is best explained through the aid of illustrations:

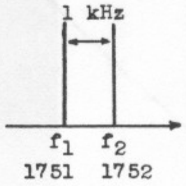


Fig. 6

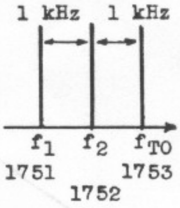


Fig. 7

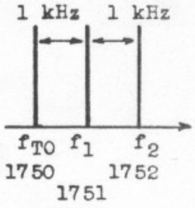


Fig. 8

In figure 6, two stations, one on 1751 kHz, and the other on 1752 kHz, are heterodyning one another. Since they are on frequencies 1 kHz separated, the heterodyne is 1 kHz. In figure 7, the TO frequency (1753 kHz) has been brought into the vicinity of the pair. Since the frequency of the TO (f_{TO}) has been brought to 1 kHz of 1752 kHz (f_2), there will also be set up a heterodyne of 1 kHz between f_{TO} and f_2. In addition, an audible beatnote will be generated by the difference in frequency between the first 1-kHz heterodyne (between f_1 and f_2) and the second 1-kHz heterodyne (between f_2 and f_{TO}). In figure 8, the same situation exists, the only difference is that the additional 1-kHz heterodyne is generated by f_{TO} (on 1750 kHz) and f_1 (on 1751 kHz). Here again, the two 1-kHz heterodynes will interact to generate a second beat. In either case, the audible beat between heterodynes can be brought to zero; however, in both cases, the TO frequency will be offset from either station frequency by an amount equal to the difference in frequency between the two initial, heterodyning signals.

In this condition, the TO frequency forms a mirror image of the alternate frequency (with respect to the middle frequency, i.e the frequency between the mirror-image frequencies). In figure 7, f_{TO} is the image frequency of f_1; in figure 8, f_{TO} is the image frequency of f_2.

See those paragraphs entitled "TT frequency measurements" and "heterodyne frequency measurement" for advice on avoiding errors due to audio imaging. Also refer to the following paragraph for further advice on avoidance of errors. An additional aid in this circumstance is to observe the indicating device (block 5). It will be found that the indicating device will register an SAH when the TO is brought within about 10 Hz of either 1751 kHz or 1752, but an SAH will be relatively weak or lacking entirely when an audio image occurs.

SAH Obscuration An additional problem in PFM is that of SAH obscuration. In this situation, an SAH or SAHs already exist on a channel as the result of interaction between carriers. Attempting to zero-beat the TO frequency with any of the interfering carriers will be impeded by the pre-existing SAH(s).

At mediumwave frequencies, it is possible to separate SAHing signals on a frequency by use of a directional antenna, usually a loop antenna. Another approach is to quickly PFM one of the frequencies as the other fades, and vice-versa. This approach is more feasible at mediumwave frequencies where the fading period is longer and the relatively lengthy fadeout of one of the carriers facilitates PFMing the other.

TYPICAL EQUIPMENT

Counters There are several models of counter currently available new at intermediate prices. It is perhaps Heath that first offered counters in kit form in a price range that made them feasible purchases for the non-professional. While competitive models have narrowed the price range, Heath counters are to be reckoned with first. Used Heath counters are becoming available at price reductions; nevertheless, the apprentice monitor may consider construction of a new kit in order to acquire some familiarity with the instrument.

The simplest Heath counter that has been available is the IB-101. The IB-101 has a cutoff frequency of 15 MHz, meaning that the counter will be unable to measure an input frequency in excess of 15 MHz. This is quite sufficient for mediumwave PFM, but is too low for direct shortwave PFM. At room temperature (25°C), the IB-101 has been observed by Ronald F. Schatz[1] to maintain a stability of 0.1 p.p.m. (or 1 Hz at 10 MHz) or better. The author's Heath IB-1101 (with a 100-MHz cutoff frequency) has a time-base stability equal to that of the IB-101. The Heath IB-1102 and IB-1103 have a temperature-compensated crystal oscillator (TCXO) time base, for somewhat greater stability. Both the IB-101 and the IB-1101 have 5 readout digits (of the gaseous discharge tube type, called "nixies"). The IB-1102 and IB-1103 both have 8 readout nixies. The Heath IM-4001, which is the third-generation version of the IB-1100 and the elder IB-101, has 5 digits of the newer light-emitting diode type readout (abbreviated LED).

The Weston 1252 and the Spectronics SC-30 are listed in the brief equipment review as they appear suitable for PFM use; however, no experience has been had with them.

Digital Readouts and Scaler Switching Typical counters of lower price have 5 or 6-digit readouts, while frequencies to be measured typically have 7 or 8 significant digits. Counters are capable of reading out such frequencies by utilizing different scalers, which generate gate-time periods from the time-base frequency. If a gate-time period of 1 millisecond (abbreviated ms, meaning one-thousandth of one second) is used, the gate will be opened for one millisecond. In the case of a 1-MHz frequency which is to be measured, one thousand cycles would be passed and counted during that period and the readout would be 01.000. This would be interpreted as 1.000 MHz (and the scaler selector switch would probably be labelled "MHz" for this gating period). In the case of a frequency of exactly 1750 kHz, to measure this frequency the scaler selector switch would first be set to "1 ms" (or "MHz", depending on the switch label). In this range, the counter would read 01.750, to be interpreted as 1.750 MHz. Then, the scaler selector switch would be set to "1 sec" (or "kHz", depending on the switch label), and the readout would change to 50.000 kHz; the two most significant digits (abbreviated MSD, the digits to the extreme left) 17 having been suppressed. On a counter with 8 digits (such as the Heath IB-1102 or IB-1103), the scaler selector switch could be set immediately to "kHz", and this hypothetical 1750 kHz frequency would read out as 01750.000 kHz, to be interpreted as 1750.000 kHz.

Incidentally, some counters such as the Weston 1252 possess a feature known as leading zero blanking, meaning that the redundant zero to the extreme left in the readout 01.750 would be blanked, leaving the readout 1.750. None of the Heath counters possess this feature, and it is unnecessary once the monitor becomes accustomed to ignoring the redundant zero.

Transfer Oscillator Only three specific signal generators have been listed in the brief equipment review. Doubtless other types would serve, but these are types that are known definitely to be suitable for use as a TO.

A signal generator, for use as a TO, must have sufficient output to drive the selected counter. A signal generator which has voltage regulation incorporated into its power supply is inherently much more suitable because it will possess improved frequency stability. Likewise, a signal generator which includes a frequency vernier among its complement of controls is much more suitable for use as a TO because it will be more easily zero-beat against the signal of unknown frequency. If the prospective monitor decides to add voltage regulation to a signal generator that lacks it, sufficient tolerance should be allowed for resultant reduction in output. Otherwise, especially for use at shortwave frequencies, a signal generator will probably have to be optimized.

Acquisition of a BC-221 or LM frequency meter for use as a TO is probably more desirable, especially when the price of a new signal generator is weighed against that of a surplus BC-221 or LM (about $35 to $50). The BC-221 and the LM are built with r-f tight integrity as their variable attenuator must be the only access to the outside world, in order to maintain absolute control over the signal generated within. Once connected to a counter, however, a frequency meter's r-f tight integrity can be destroyed because the counter may unintentionally radiate the meter's signal uncontrollably. No modification that can be made to the frequency meter will overcome this difficulty. A sidestep module (SSM), to be discussed in the next chapter, will provide a satisfactory solution to the problem of counter radiation.

The following is a brief review of some equipment that would be of interest to the prospective monitor:

EQUIPMENT REVIEW

COUNTERS

Manufacturer and Model	sensitivity of counter (mV)	cutoff frequency (MHz)	number of digits in readout	timebase short-term stability (Hz)	temperature range over which short-term stability defined (°C)	long-term stability (p.p.m.) per period of time	price (does not include shipping and insurance)
Heath							
IB-101	100	15	5	3	22-37	3/1 mo	unk
IB-1100	100	30	5	3	22-37	3/1 mo	$150
IB-1101	50	100	5	3	17-32	1/1 mo	$200
IB-1102	50	120	8	1	15-50	1/1 yr	$280
IB-1103	50	180	8	1	15-40	1/1 yr	$350
IM-4001	15	30	5	10	0-50	n.s.	$130
Hewlett-Packard							
5318A	25	80	7	n.s.	n.s.	n.s.	$250
Miida							
Digipet-60	50	60	5	40	0-40	1/1 yr	$300
Weston							
1252	10	30	6	10	0-40	7.5/yr	$296
Spectronics							
SC-30	100	30	5	n.s.	n.s.	n.s.	$170

SIGNAL GENERATORS

Manufactures & Model	maximum output(mV)	internal modulation	price (minus shipping and insurance)
EICO 330	300	400 Hz	$63 kit $95 wired
Heath IG-102	100	400 Hz	$45 kit
IG-42	100	n.s.	$98 kit

T31-8-7

Addresses:

EICO
283 Malta Street
Brooklyn, NY 11207

Heath Company
Benton Harbor, MI 49022

Hewlett-Packard
1501 Page Mill Road
Palo Alto, CA 94304

Miida (via T.R.I. Corp.
505 West Olive Avenue
Sunnyvale, CA 94086)

Spectronics
1491 East 28th
Signal Hill, CA 90806

Weston (via Newark Electronics
500 North Pulaski Road
Chicago, IL 60624)

Listing of equipment types does not constitute an endorsement of any sort. It is suggested that a catalog be acquired from above companies to ascertain current price plus shipping information.

SIDESTEP MODULE

The Sidestep Module (SSM) was conceived as a solution to deteriorating TO stability at shortwave frequencies and to problems associated with leakage of r-f energy from counter and TO apertures and interconnections.

The SSM accepts two inputs, one from the TO and one from a source of frequency-stable, 1-MHz fundamental and harmonics (called a 1-MHz spectrum). In the SSM, the TO variable frequency is mixed with the 1-MHz spectrum to synthesize a virtual variable-frequency TO signal which interpolates between the 1-MHz spectrum points. This virtual TO signal has essentially the stability of the TO frequency, so that if a low-band TO signal is accepted as the TO input, the virtual TO signal will have essentially that stability to 30 MHz and beyond.

The SSM and its theory will be explained more fully in the following paragraphs. See the following Figure 9 for the block diagram of the SSM:

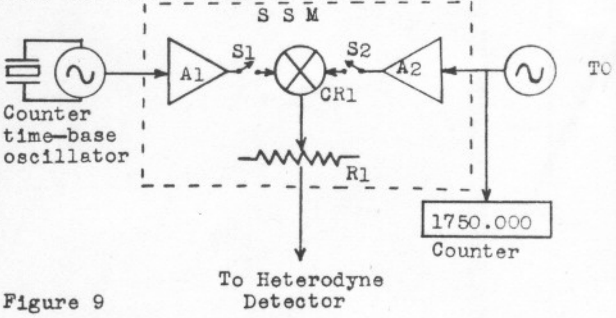


Figure 9

A1 radio-frequency amplifier for 1-MHz spectrum
A2 radio-frequency amplifier for TO output
CR1 SSM radio-frequency mixer
R1 SSM variable attenuator (used in lieu of TO variable attenuator, which is left at maximum)
S1 1-MHz cutout switch (when off, output of SSM is TO frequency only)
S2 TO cutout switch (when off, output of SSM is 1-MHz spectrum only, for calibration of time base)

SSM Block Diagram The SSM has two inputs, one from the counter time-base oscillator, and one from the TO (It should be understood that accepting an output from the counter time-base oscillator has no influence on the operation of the counter. This frequency-stable 1-MHz source fortunately exists within the counter; however, a 1-MHz output from any other frequency-stable source could be used.). In the SSM, the 1-MHz spectrum is amplified by radio-frequency amp. A1 and applied to mixer CR1. Also, the output of the TO is amplified by radio-frequency amplifier A2, after which it is applied to mixer CR1, along with the amplified 1-MHz spectrum. The 1-MHz spectrum possess harmonics of 1 MHz up to and beyond 30 MHz. The output of CR1 is a combination of frequencies: the original TO signal, the 1-MHz spectrum, and the sum-and-difference combinations of the TO frequency and allthe harmonics of the 1-MHz spectrum. For example, if the TO has been set to 100 kHz, the output of CR1 is the original input frequencies, plus the sums and differences of all these frequencies:

(TO = 100 kHz) 1000 kHz ± 100 kHz = 1100 kHz, 900 kHz
(1000-kHz spectrum fundamental, 100-kHz TO frequency)
2000 kHz ± 100 kHz = 2100 kHz, 1900 kHz
(2000-kHz harmonic, 100-kHz TO frequency)
3000 kHz ± 100 kHz = 3100 kHz, 2900 kHz
(3000-kHz harmonic, etc.)
4000 kHz ± 100 kHz = 4100 kHz, 3900 kHz
(4000-kHz harmonic, etc.)
and so on;

(TO = 600 kHz) 1000 kHz ± 600 kHz = 1600 kHz, 400 kHz
2000 kHz ± 600 kHz = 2600 kHz, 1400 kHz
3000 kHz ± 600 kHz = 3600 kHz, 2400 kHz
4000 kHz ± 600 kHz = 4600 kHz, 3400 kHz
5000 kHz ± 600 kHz = 5600 kHz, 4400 kHz
and so on;
(TO=433.3 kHz)1000 kHz±433.3 kHz=1433.3 kHz,566.7 kHz
2000 kHz±433.3 kHz=2433.3 kHz,1566.7kHz
3000 kHz±433.3 kHz=3433.3 kHz,2566.7kHz
4000 kHz±433.3 kHz=4433.3 kHz,3566.7kHz
5000 kHz±433.3 kHz=5433.3 kHz,4566.7kHz
and so on.

In a typical situation, the sum frequencies (e.g. 4000 kHz + 433.3 kHz = 4433.3 kHz) would more likely be used as the relation to the TO frequency would be the most obvious.

Additionally, the SSM provides a sidestep function (from which the module takes its name). In this function, the virtual TO frequency (which is zero-beat with the signal of unknown frequency) "sidesteps" the direct TO output, whose amplitude is relatively uncontrollable, by a factor of 1 MHz or a multiple thereof.

For example, if the monitor desires to measure a frequency of 1575 kHz; a TO frequency of 575 kHz or 2575 kHz may be used with the SSM to synthesize this 1575 kHz frequency. In both cases, the unknown frequency is sidestepped by the direct TO frequency, to avoid difficulties of swamping. Since the virtual TO frequency is synthesized solely within the SSM itself, the degree of leakage is much more controllable.

TO Stability Suppose on a particular signal generator used as a TO, the first frequency band extends from 100 to 300 kHz; the second from 300 to 1200 kHz; the third from 1200 to 3500 kHz; the fourth from 3500 to 10000 kHz, and so on. Also suppose that five full revolutions of the TO frequency control knob are necessary to cover each of these bands. The total frequency change per frequency control knob revolution would be 40 kHz on band 1; 180 kHz on band 2; 460 kHz on band 3; and 1300 kHz on band 4. It can be seen that the rate of frequency change per frequency control revolution is lowest on the first two bands. Also, the absolute frequency stability of the TO output would be greatest on these first two bands. Consequently, these same first two bands would be the most useful for making accurate PFMs because it would be easier to zero-beat the TO output with the signal of unknown frequency and to maintain that zero-beat using those two bands.

SSM OPERATION Suppose that an unidentified station, whose frequency is about 11.5 MHz, is to be PFMed. First, S1 is turned off so that the 1-MHz spectrum from the counter time base is removed, along with all the sum-and-difference frequency products of the 1-MHz spectrum and the TO frequency; leaving only the TO frequency at the output of the SSM. The TO is roughly zero-beat with the unknown frequency, and its frequency readout on the counter is recorded (assume 11,560 kHz). The TO is then set to band 1 or 2, S1 is turned on, and some combination of TO frequency and 1-MHz spectrum is mentally calculated to reach that frequency. Two options are immediately evident: the TO can be set to 560 kHz where its output will add to the 11th harmonic of the 1-MHz spectrum, to produce 11,560 kHz (11,000 kHz + 560 kHz = 11,560 kHz); or the TO can be set to 1560 kHz, where its output will add to the 10th harmonic of the 1-MHz spectrum, to produce 11,560 kHz (10,000 kHz + 1,560 kHz = 11,560 kHz). The counter, which reads out the TO frequency only, will read out 560 kHz and 1560 kHz respectively. It remains for the monitor to mentally or manually add the TO frequency to the appropriate 1-MHz harmonic

(Note that other combinations are possible, e.g. 2560 + 9000 kHz; 3560 + 8000 kHz; 4560 + 7000 kHz; 12560—1000 kHz; 13560—2000 kHz; et al. But the combinations that use the lowest TO frequency are preferred.). Continuing with the example, the TO is adjusted for an accurate zero-beat with the frequency that is being measured, and the exact frequency is read out. Suppose that the counter reads out 560.056 kHz. This is mentally or manually added to 11,000.000 kHz (the 11th harmonic of 1 MHz), for 11,560,056 kHz, the exact frequency in question. This is recorded, along with the date.

CONCLUSION More specifics and comments are available concerning the circuitry and variations thereupon of an SSM, from the author. It is expected that others who are interested in applications of PFM or in assembling a PFM station, will have questions. Such questions are invited and are to be answered en masse in a sequel to this article at the earliest possible date. For more specifics concerning the SSM, send 45¢ and an SASE; likewise, questions for the projected sequel are to be sent to 939 Eastern Avenue, Indianapolis, IN 46201, U.S.A.

The author wishes to thank the IRCA's Seattle Publishing Committee, and especially Jerry Lineback of NASWA's SWC, for seeing this article into print. It is hoped that this article will arouse interest in PFM which is, after all, a tool that is useful only when used.

Notes:

[1] Precision Frequency Measurement by Ronald F. Schatz (see Bibliography below)

Bibliography The following articles are recommended for further reading, especially the article Yes, SAH by Glenn Hauser, which might be considered as minimal basic reading:

A. Yes, SAH Glenn Hauser. Describes sub-audible heterodynes, how to detect them and how to use them. (1 p.) IRCA Reprint No. T7

B. Precision Frequency Measurement Ronald F. Schatz. Describes methods of determining the exact frequency of a station with a Heathkit IB-1101 frequency counter (2 pp.) IRCA Reprint No. T5

C. Precision Frequency Analysis for the Mediumwave DXer Ronald F. Schatz. Describes some methods of performing Precision Frequency Measurements, and analysing the results. (2 pp.) IRCA No T27

Items A and B & C above are available to non-IRCA members at 10¢ per page and an SASE, from IRCA Reprints, P.O. Box 17088, Seattle, WA 98107, U.S.A. When ordering, it is suggested that an additional 32¢ be enclosed for IRCA Reprint List No. PM-5 (6 pp.) which lists many reprints of specific or general interest to the shortwave DXer.