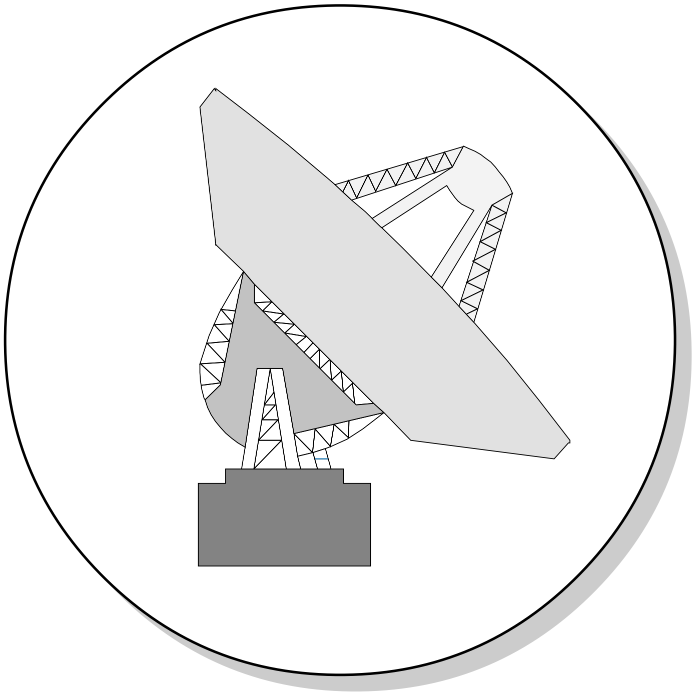
Fundamentals of Microwave Frequency Counters

Application Note 200-1

Electronic Counters Series



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Down-Conversion Techniques for Automatic Microwave Frequency Counters

A frequency counter, being a digital instrument, is limited in its frequency range by the speed of its logic circuitry. Today the state of the art in high-speed logic allows the construction of counters with a frequency range of around 500 MHz. Continuing advances in IC technology should extend this range beyond 1 GHz in the not-too-distant future.

The designer of an automatic microwave counter must look to some form of down-conversion in order to extend frequency measurement beyond 500 MHz. Four techniques are available today to provide this down-conversion:

1. Prescaling, with a range of 1.5 GHz;
2. Heterodyne Converter, allowing measurements as high as 20 GHz;
3. Transfer Oscillator, used in counters with ranges to 23 GHz;
4. Harmonic Heterodyne Converter, a new technique which can provide measurements to 40 GHz.

Prescaling

Prescaling involves simple division of the input frequency resulting in a lower frequency signal which can be counted in digital circuitry. The frequency measured by the counter section is related to the input simply by the integer N. A display of the correct frequency is accomplished either by multiplying the counter's contents by N or by increasing the counter's gate time by a factor of N. Typically, N ranges from 2 to 16.

Figure 1 shows the block diagram of a high frequency counter using prescaling as its down-conversion technique. The input signal is conditioned to interact correctly with the prescaling circuit, and then it is divided by N before entering the main gate. Beyond this point the block diagram looks like a conventional counter, with the main gate being opened and closed (by the main gate flip-flop) in timing precisely determined by the crystal time base of the instrument. The decade counting assembly (DCA) now accumulates the under-500 MHz frequency measurement, which is multiplied by N and transmitted to the display.

Modern frequency counters using this technique are capable of measuring above 1.0 GHz. Recent developments in solid-state technology promise to extend this range into the low microwave range within a few years.

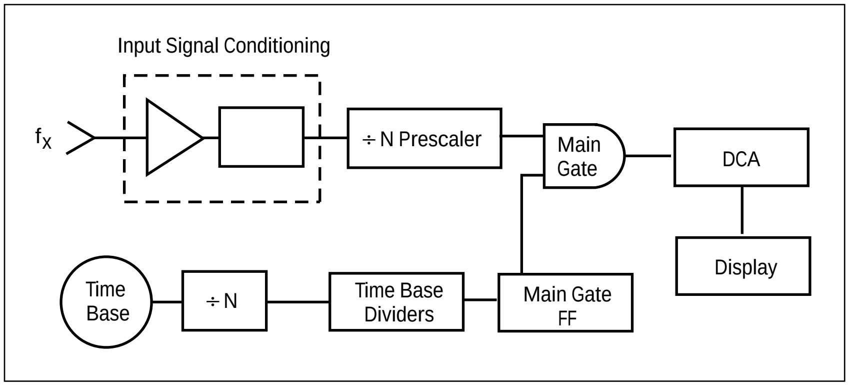


Figure 1. Block diagram of a high-frequency counter using the prescale down-conversion technique.

Heterodyne Converter

Heterodyne down-conversion centers about a mixer which beats the incoming microwave frequency against a high-stability local oscillator signal, resulting in a difference frequency which is within the conventional counter’s 500 MHz bandwidth.

Figure 2 is the block diagram of an automatic microwave counter using the heterodyne down-conversion technique. The down-converter section is enclosed by the dotted line. Outside the dotted line is the block diagram of a conventional counter, with the addition of a new block called the processor. The decision-making capability of a processor is necessary here in order to lead the counter through its measurement algorithm. The high stability local oscillator of Figure 2 is generated by first digitally multiplying the frequency of the instrument’s time base to a convenient fundamental frequency (designated f_{in}), typically 100 to 500 MHz. This f_{in} is directed to a harmonic generator which produces a “comb line” of frequencies spaced at f_{in} extending to the full frequency range of the counter. One line of this comb, designated Kf_{in}, is then selected by the microwave filter and directed to the mixer. Emerging from the mixer is a video frequency equal to $f_x – Kf_{in}$. This video frequency is amplified and sent to the counter. The display contains the sum of the video frequency and Kf_{in}, which is provided by the processor. (The processor stores the value of K, since it is in control of the microwave filter.)

The signal detector block in Figure 2 is necessary for determining the correct K value. In practice, the processor will begin with K=1 and will “walk” the value of K through the comb line until the signal detector determines that a video frequency is present. At this point the acquisition routine is terminated and measurement can begin.

The remaining block in Figure 2 which has not been discussed is the automatic gain control (AGC) circuit. This circuit provides a degree of noise immunity by desensitizing the video amplifier such that only the strongest frequency components of the video signal will enter the Schmitt trigger and be counted.

A key ingredient in automating the heterodyne down-conversion process is the microwave filter. Two filters used for this purpose are (1) a YIG filter, and (2) an array of thin-film filters which are selected by PIN diode switches.

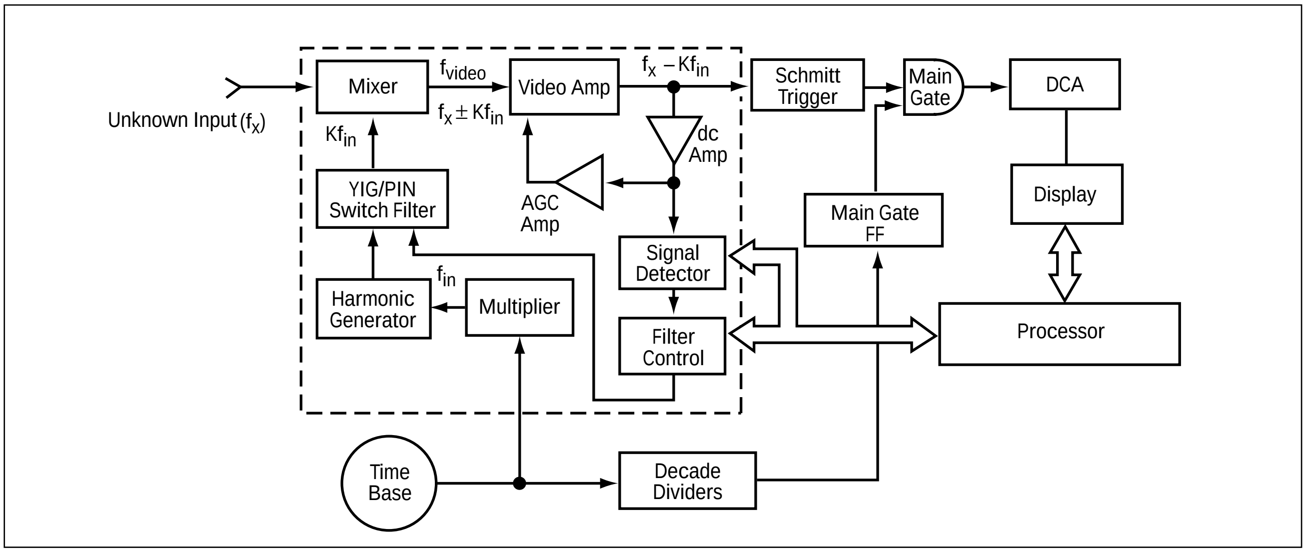


Figure 2. Block diagram of the heterodyne down-conversion technique.

Transfer Oscillator

The transfer oscillator uses the technique of phase locking a low frequency oscillator to the microwave input signal. The low frequency oscillator can then be measured in a conventional counter, and all that remains to be accomplished is to determine the harmonic relationship between that frequency and the input.

Figure 3 is the block diagram of a microwave counter using the transfer oscillator technique. Once again, the down-conversion circuitry is contained within the dotted line. A processor is not necessarily included in the block diagram, although some decision-making ability is necessary in the acquisition process, just as with the heterodyne converter above.

In Figure 3 the input signal is shown being phase locked to a voltage controlled oscillator (VCO #1) in the upper portion of the converter section. Once phase lock is achieved, the relationship between the input and the VCO frequency is f_x=N_f, where N is an integer. The remainder of the down-converter circuitry is devoted to the task of determining N. The counter can now measure f_1, (typically 100–200 MHz) and multiply by N for a display of the microwave frequency. As in the case of prescaling above, this multiplication is usually accomplished by extending the gate time of the counter by a factor of N (which takes values from 1 to 200).

The quadrature detector in the phase lock loop of the automatic transfer oscillator insures that the output of VCO #1 bears the correct phase relationship with respect to the input signal.

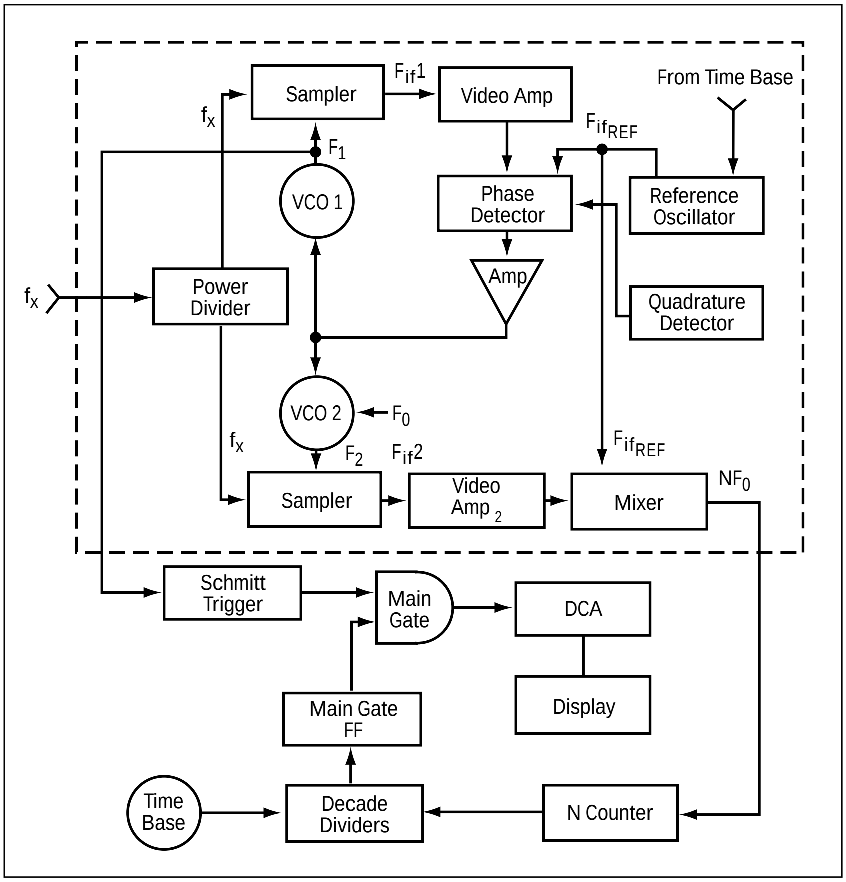


Figure 3. Block diagram of the transfer oscillator down-conversion technique.

Harmonic Heterodyne Converter

The harmonic heterodyne converter, as its name implies, is a hybrid of the previous two techniques. A counter using this block diagram (Figure 4) will acquire the input microwave frequency in the manner of the transfer oscillator, but it will then make frequency measurements like a heterodyne converter.

Figure 4 shows the input f_x being directed to a sampler, with the resulting down-converted video signal $f_{if} = f_x – Nf_s$ amplified and sent to the counter. The sampling frequency f_s is created by a processor-controlled synthesizer.

The acquisition routine for this down-converter consists of tuning the synthesizer f_s until the signal detector finds a video signal f_{if} of the appropriate frequency range (defined by the band-pass filter). Next, the harmonic number N must be determined, as in the transfer oscillator. One method of finding N is to use a second sampler loop, as with the transfer oscillator (Figure 3), or similar technique. A second method is to step the synthesizer back and forth between two closely-spaced frequencies and observe the differences in counter readings; it is then a simple task for the processor to calculate N.

A frequency measurement is accomplished by the processor's multiplying the known synthesizer frequency f_s by N, adding the result to the video frequency f_{if} measured in the DCA, and displaying the answer: $f_x=Nf_s+f_{if}$. In this process the harmonic heterodyne converter resembles the heterodyne converter, since the sampler is effectively mixing the Nth harmonic of a very stable source with the input to produce a video difference frequency.

The harmonic heterodyne converter has the potential to be constructed at a lower cost than the previous two techniques because it can be designed with just one microwave component (the sampler) and the control, decisions, and calculations can be performed by a low-cost microprocessor.

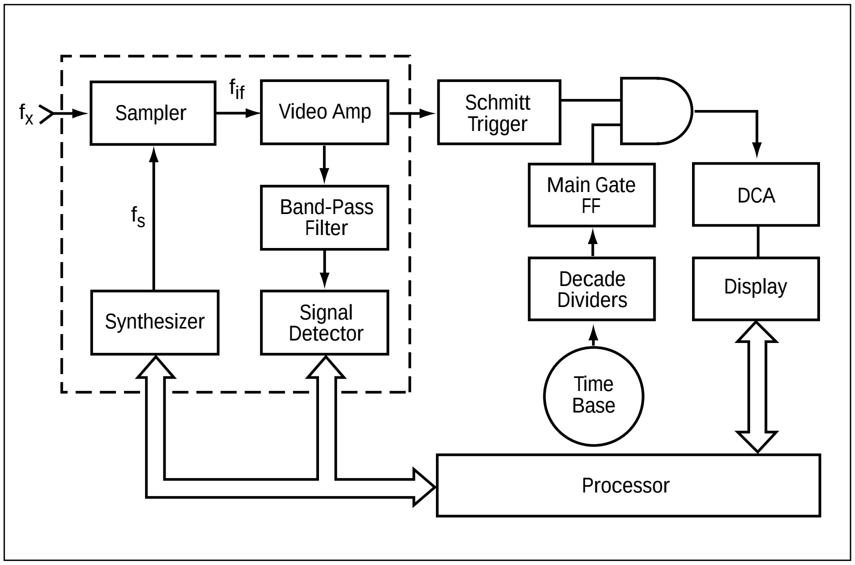


Figure 4. Block diagram of the harmonic heterodyne down-conversion technique

Comparing the Principal Microwave Down-Conversion Techniques

In this chapter we will examine the performance trade-offs between the three down-conversion techniques which allow measurements over 1.5 GHz: heterodyne converter, transfer oscillator, and harmonic heterodyne converter.

Measurement Speed

The time required for a microwave counter to perform a measurement may be divided into two parts:

1. Acquisition — The time necessary for the counter to detect a microwave signal and prepare to make a measurement; and
2. Gate Time — The duration of the counter's gate required to measure to a given resolution.

Each of the three down-conversion techniques we have discussed offers trade-offs in the area of measurement speed.

The heterodyne converter, using the YIG filter, has an acquisition time ranging from 40 milliseconds to over 200 milliseconds. A design using thin film filters has an impressively short acquisition time of less than 1 millisecond. The gate time for heterodyne converter counters is 1/R, where R is the desired resolution in Hertz.

A microwave counter using the transfer oscillator technique will typically have an acquisition time of about 150 milliseconds, which is comparable to the heterodyne converter. Gate times for the transfer oscillator are longer since, as with the prescaler, they must be set to N/R in order to effectively multiply the counter's contents by N. This factor of N can cause the transfer oscillator counter to measure much more slowly than the heterodyne converter for high resolution (100 Hz or less) measurements of microwave frequencies. For typical measurements with resolution 1 kHz or greater, the difference in measurement speed between the three techniques will not be noticed by the operator.

The harmonic heterodyne converter has an acquisition time of 350 to 500 milliseconds, the slowest of the three techniques. Gate time can range from 1/R to 4/R, much better than the transfer oscillator technique and close to the heterodyne technique.

Accuracy

The accuracy of microwave counter measurements is limited by two factors:

1. The plus/minus one-count quantization error; and
2. Time base errors.

Time base errors may further be looked at in two different ways: short-term stability, which generally limits the repeatability from one measurement to the next; and long-term stability, which limits the absolute accuracy of a measurement.

It should be noted that, in a typical user environment, a counter's accuracy capabilities will be masked by the effects of temperature fluctuations on the time base. Depending on the crystal oscillator used, these fluctuations will generally limit both repeatability and absolute accuracy to at least parts in 10^9 and perhaps as much as parts in 10^6. It is best to carefully examine temperature stability specifications before attempting high-precision measurements with a microwave counter.

Assuming that a stable temperature environment exists, let us compare the short-term stability (repeatability) of microwave measurements for each of the three down-conversion techniques. Figure 5 illustrates this comparison. For a gate time of one second, it is clear that the transfer oscillator is limited to about 1×10^{-8} resolution. The heterodyne and harmonic heterodyne converters are limited to about 1×10^{-9}, where short-term instabilities of common crystal oscillators become the limiting factor. With the high stability of an oven oscillator, these two converters are capable of resolving 1×10^{-10} at microwave frequencies.

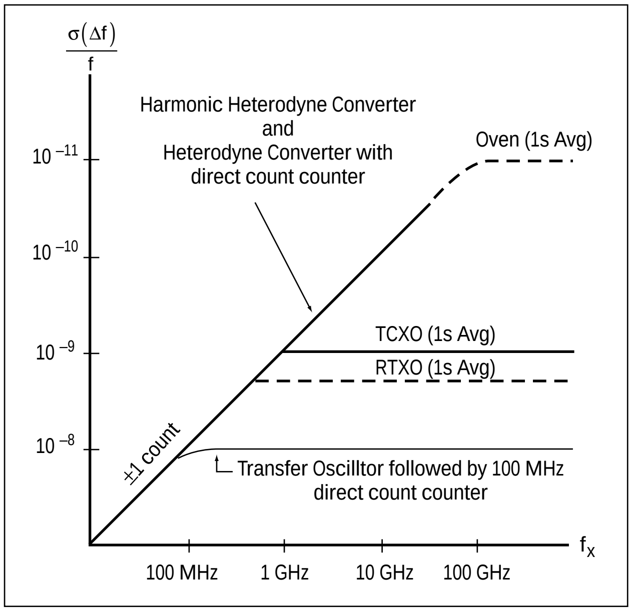


Figure 5. Short-term stability: Resolution limits of the three down-conversion techniques for a measurement with 1-second gate time. Three types of crystal oscillator are considered. Room temperature (RTXO), temperature compensated (TCXO), and high-stability ovenized ("oven").

Of considerably more importance to the user, however, are the long-term effects which limit the accuracy of microwave counter measurements. Figure 6 graphs the combined effects of inaccuracies due to time base aging and the ±1 count uncertainty. In this figure it is assumed that the time base was calibrated to a high degree of accuracy one month ago. Clearly, even with the best time bases available, the long-term instability of the time base becomes the accuracy limitation, no matter which down-conversion technique is used. It may therefore be concluded that accuracy is not a consideration in choosing between microwave down-conversion techniques for a particular application.

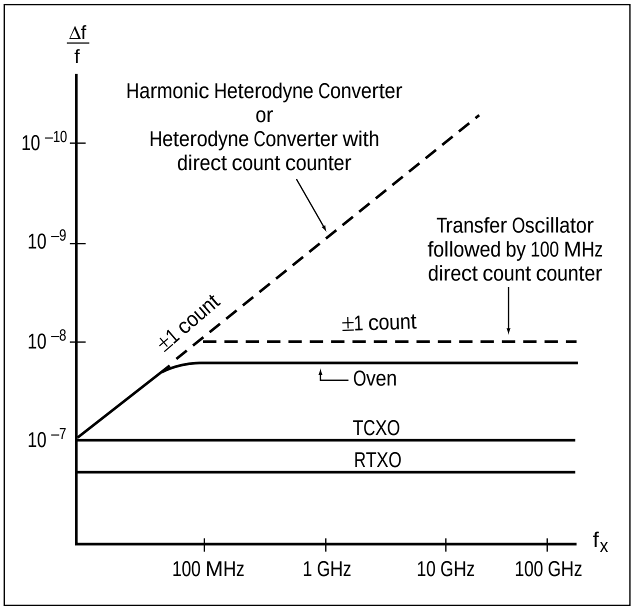


Figure 6. Long-term stability: Accuracy limits of microwave counters for a 1-second gate time, assuming one month since last calibration.

Sensitivity and Dynamic Range

As illustrated in Figure 7, there is little difference in sensitivity specifications among the three down-conversion techniques. A good microwave counter will have sensitivity of about –25 dBm for most measurements.

The lower dashed line in Figure 7 indicates the true sensitivity of a typical HP 5340A Frequency Counter, which uses the transfer oscillator technique. The transfer oscillator is capable of exceptional sensitivity since the input signal into the down-converter enters a narrow-band (about 200 kHz) phase lock loop. The counter is therefore relatively insensitive to noise on the input and may be designed for high sensitivity without too much concern for triggering on low-level noise. The harmonic heterodyne converter, with a relatively narrow input bandwidth, also has the potential of outstanding sensitivity. The heterodyne converter, on the other hand, has an effective input bandwidth of 200 to 500 MHz; great care must be exercised in the design of these counters to avoid false readings due to broadband noise.

The dynamic range of a microwave counter is a measure of the separation of the sensitivity specification and the highest level input signal which can be counted reliably. A typical value for this upper level is +7 dBm, which is also graphed in Figure 7. It should be noted that some microwave counters allow measurements of inputs to +20 dBm and beyond; for example, the HP 5341A (Heterodyne Converter) and the HP 5342A Option 003 (Harmonic Heterodyne Converter) both measure +20 dBm inputs.

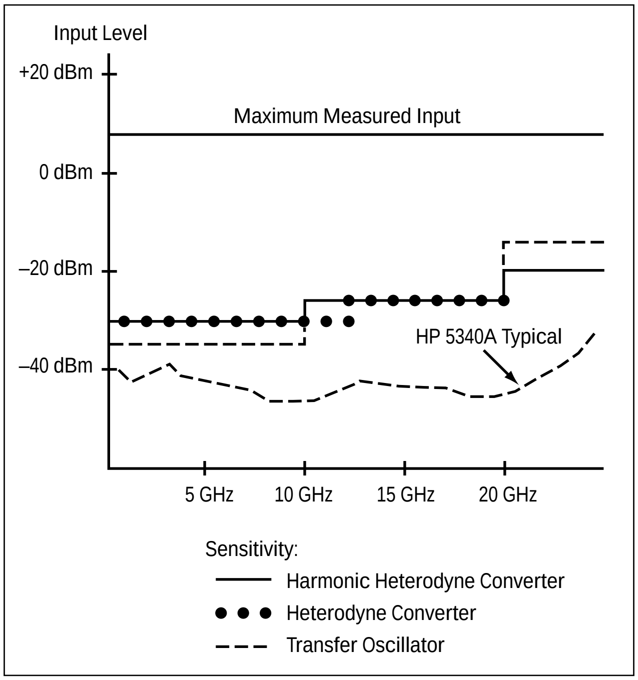


Figure 7. Available microwave counter sensitivity specifications. Maximum measured input (regardless of down-conversion technique) is typically +7 dBm, although many counters allow measurements to +20 dBm.

Signal-to-Noise Ratio

An important consideration in choosing a microwave counter is the signal-to-noise environment of the measurement. As mentioned in the above paragraph, the apparent amplifier bandwidth at the counter's input limits the amount of noise which the counter can tolerate on the measured signal.

Consider a microwave frequency to be measured which has a good deal of noise surrounding the carrier. Such a situation is illustrated in Figure 8a. A transfer oscillator or harmonic heterodyne converter counter will be capable of measuring the signal if the peak carrier exceeds the noise floor by 20 dB. A typical heterodyne converter counter, however, will require 40 dB or greater separation to allow accurate measurement.

A common situation wherein broadband noise surrounds a signal to be measured is in the monitoring of solid state microwave sources. Figure 8b shows the typical output of a solid state sweeper. With this type of spectrum to be measured, a transfer oscillator or harmonic heterodyne converter will provide reliable readings up to the maximum sweeper output power (about +10 dBm). The typical heterodyne converter counter will encounter noise interference at sweeper output levels near –10 dBm.

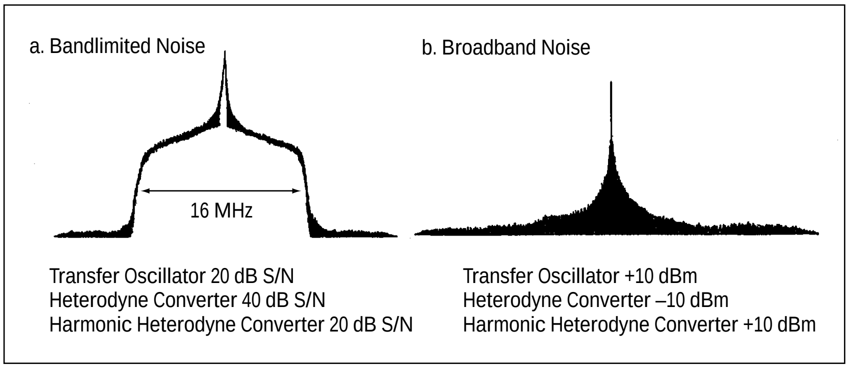


Figure 8. Spectral display of tests on microwave counters to determine signal-to-noise requirements. Tests included (a) band-limited AM noise, and (b) broadband noise generated at the output of a solid-state microwave sweeper.

FM Tolerance

All modern microwave counters are capable of measuring today's microwave sources with their inherent incidental frequency modulation. There are applications, however, in which it is desired to measure a microwave communications carrier with frequency modulation present. In these cases the FM tolerance of microwave counters becomes a consideration for choosing the appropriate instrument.

A heterodyne converter may be thought of as dividing microwave frequency space into distinct bands, of a width equal to the comb line spacing. The design of these instruments is such that the video counting capability of the conventional counter is somewhat greater than the comb line spacing. It is this resulting overlap between adjacent bands that is the measure of the FM tolerance of the counter. Figure 9 illustrates the FM tolerance of the HP 5341A Frequency Counter. In this counter the comb line spacing is 500 MHz, but the video bandwidth of the counter is 530 MHz. (As seen in Figure 9a, a frequency measurement band begins 15 MHz above the comb line and ends 45 MHz above the next comb line.) As Figure 9b indicates, the FM tolerance of this particular design is over 500 MHz with the carrier located mid-band, and diminishes to 30 MHz at band edges. These are typical values for the heterodyne converter technique.

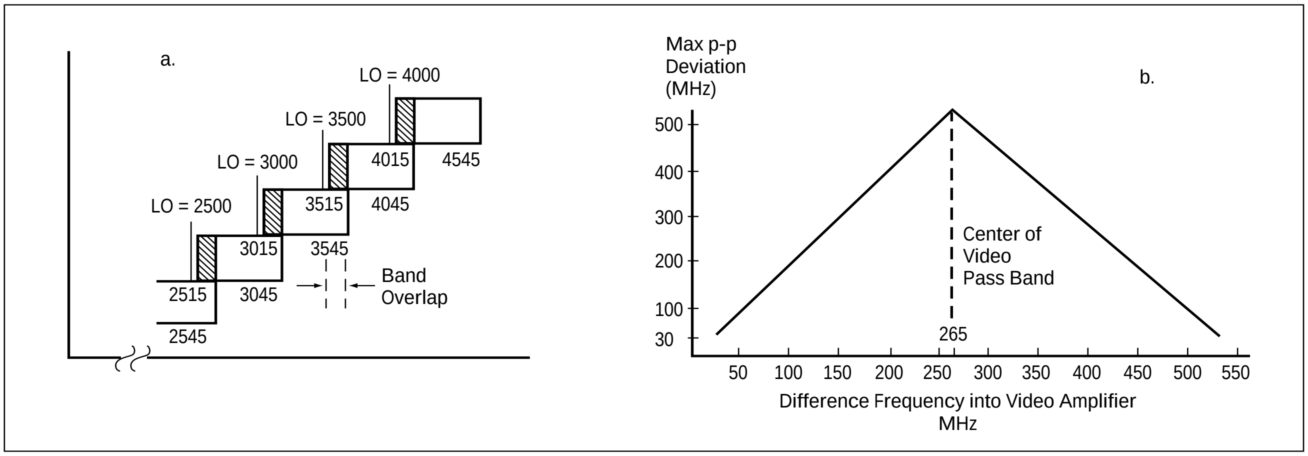


Figure 9. Analysis of the FM tolerance of the heterodyne down-conversion technique. The HP 5341A Frequency Counter is used as an example.

The transfer oscillator's tolerance of frequency modulation is more complex. As seen in Figure 10a, the maximum allowable peak-to-peak deviation is a function of modulating frequency and carrier frequency. In general, this tolerance is at a minimum at the point where modulating frequency is equal to the bandwidth of the input phase lock loop. If more than one tone modulates the carrier simultaneously (as in the case of the multichannel communication modulation), the analysis of Figure 10a is no longer applicable. A typical response to multichannel FM is shown in Figure 10b; this is a graph illustrating the capabilities of the HP 5340A Frequency Counter. On this chart tolerance of FM is indicated by the number of voice channels which are modulated onto the carrier. It can be seen that the FM tolerance of the transfer oscillator is in this case dependent upon carrier frequency and the per-channel loading of the radio. Since most microwave radios operate between 86 kHz rms and 140 kHz rms per-channel loading, it can be seen that a transfer oscillator like the HP 5340A is capable of measuring just about all fully loaded microwave communications carriers in use today.

The FM tolerance of the harmonic heterodyne converter is much easier to analyze. Since the down-converter automatically centers the video frequency f_{if} in the video amplifier's passband (see Figure 4), then the bandwidth of the video amplifier determines the FM tolerance. In the case of the HP 5342A Microwave Frequency Counter, FM tolerance is equal to or better than 50 MHz peak-to-peak.

In summary, although the transfer oscillator is capable of measuring microwave frequencies with all common forms of FM modulation, the heterodyne converter and harmonic heterodyne converter have a clear advantage in the area of FM tolerance.

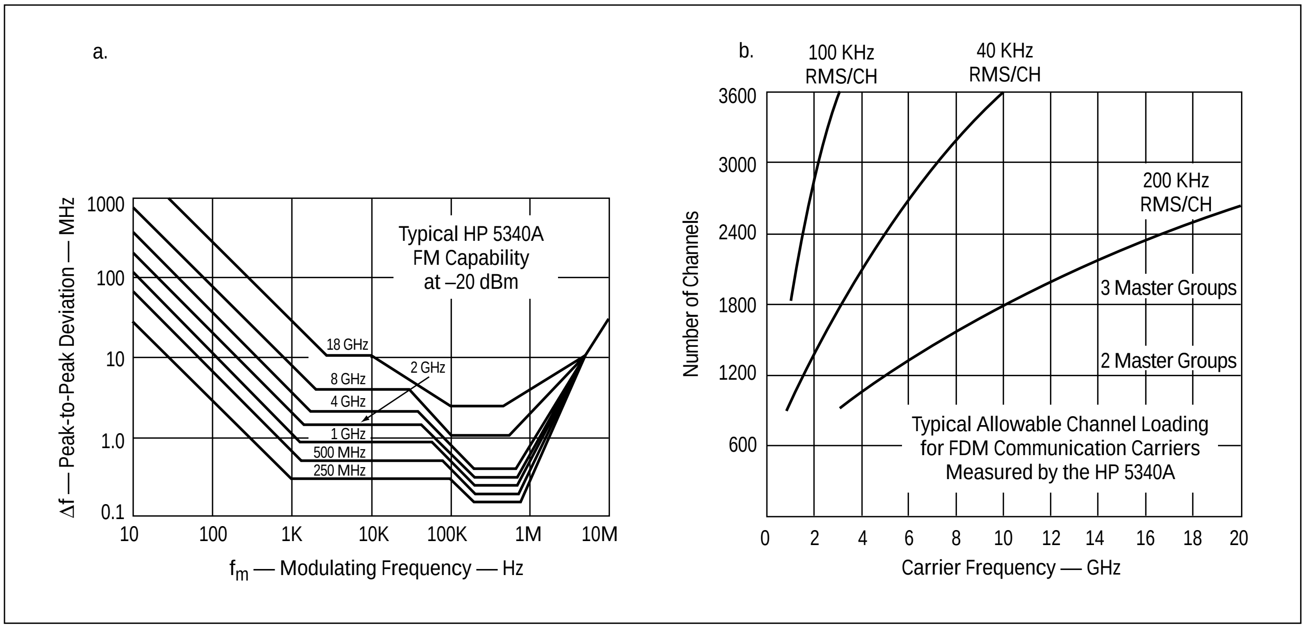


Figure 10. Graphical representation of the FM tolerance of a transfer oscillator counter — the HP 5340A Frequency Counter.

AM Tolerance

A second form of modulation encountered during microwave measurements is amplitude modulation. Few microwave radios use AM for communications transmissions, but nearly all microwave sources provide signals with incidental AM. Also, in many R&D and maintenance environments a time-varying attenuation of the signal is commonly encountered.

The heterodyne converter's tolerance to amplitude modulation is limited by its AGC circuitry when such a circuit is employed in the counter design. In Figure 2 we saw that the AGC circuit is used to provide a variable attenuation of the input according to the signal strength entering the counter. If the signal amplitude at the input varies due to AM, it is possible that the AGC circuitry will be unable to track the changing level and will prevent operation of the counter. A practical limitation of AM tolerance for the heterodyne converter is less than 50% AM.

The transfer oscillator and harmonic heterodyne converter suffer no such limitations with respect to AM. Essentially the only requirement of these down-converters when measuring an amplitude modulated signal is that the lowest amplitude point of the waveform be strong enough that the counter can continue to measure. For example, the HP 5340A or HP 5342A can easily measure a carrier at a level of –10 dBm with 95% AM.

Amplitude Discrimination

Frequently a microwave counter will be called upon to measure a signal in the presence of other lower level signals. The ability to perform this measurement directly is referred to as amplitude discrimination.

All modern microwave counters incorporate amplitude discrimination in their designs. This capability is one of the key features of the transfer oscillator and harmonic heterodyne converter. These counters are typically capable of always finding the most prominent component of the spectrum, provided that it is at least 2 dB above nearby signals and at least 10 dB above signals at the far end of the counter's frequency range. Figure 11 is an illustration of these measurement capabilities.

The heterodyne converter is somewhat more difficult to analyze. Although this technique allows amplitude discrimination of widely separated signals (through the use of a variable attenuator), the questions remains: What happens when two significant frequency components are within the same band? The answer to this situation is that the AGC circuitry (see Figure 2) must be able to differentiate between the two signals. Typical AGC circuits found in heterodyne converters provide discrimination between signals which lie from 4 dB to 30 dB apart, located in the same band.

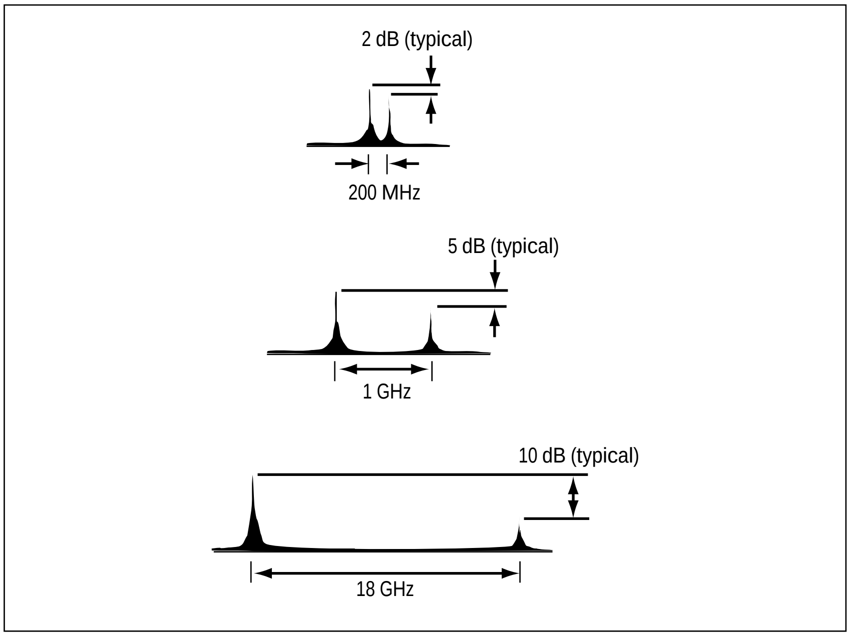


Figure 11. Amplitude discrimination capabilities of the transfer oscillator and harmonic heterodyne converter. Each drawing indicates the required level separation in order for the counter to distinguish the greater signal

Summary of the Comparison

Thus far in this note we have examined the performance trade-offs among the three down-conversion techniques used in microwave counters. A summary of these trade-offs is listed in Figure 12. Bold type indicates that the technique enjoys a significant performance advantage. It should be noted that these comparisons are made on the basis of typical specifications; a comparison of individual instruments may produce different results in some categories.

Characteristic	Heterodyne Converter	Transfer Oscillator	Harmonic Heterodyne Converter
Frequency Range	20 GHz	23 GHz	40 GHz
Measurement Speed	**150 ms acquisition 1/R gate**	**150 ms acquisition N/R gate**	**350 ms acquisition 4/R gate**
Accuracy	Time base limited	Time base limited	Time base limited
Sensitivity/ Dynamic Range	–30 dBm/35–50 dB	–35 dBm/40 dB	–30 dBm/35–50 dB
Signal-to-Noise Ratio	40 dB	**20 dB**	**20 dB**
FM Tolerance	**30–40 MHz peak-peak**	1–10 MHz peak-peak	**10–50 MHz peak-peak**
AM Tolerance	Less than 50%	**Greater than 90%**	**Greater than 90%**
Amplitude Discrimination	4–30 dB	**2 –10 dB**	**2 –10 dB**

Figure 12. Summary of the performance of the three principal microwave counter down-conversion techniques.

Additional Considerations in Choosing a Microwave Counter

Signal Inputs

The first check of the inputs to a microwave counter is to insure that the frequency ranges covered by the various input connectors satisfy the requirements of the application. At times, it can be burdensome to be continually changing the input connector from one spigot to another. Of course, the ideal situation in a systems application is for one connector to cover the full frequency range of the counter.

A consideration of great importance in microwave counters is that of damage level limitations on the input signal level. Most microwave counters today can tolerate up to +25 dBm inputs without damage. An overload indicator which warns of an input signal level approaching the damage level can also be very useful; most modern microwave counters incorporate such a feature.

Systems Interface

A feature of great importance in microwave counters is systems compatibility. Specifying an input/output interface compatible with IEEE Standard 488-1975 insures that the counter will be able to interact readily with printers, computers, and desk-top controllers in a well-defined fashion. The Hewlett-Packard Interface Bus, which is HP’s implementation of IEEE-488, provides data output and programming of all front panel controls of microwave counters using the ASCII code via an 8-bit bidirectional bus.

IF Offsets

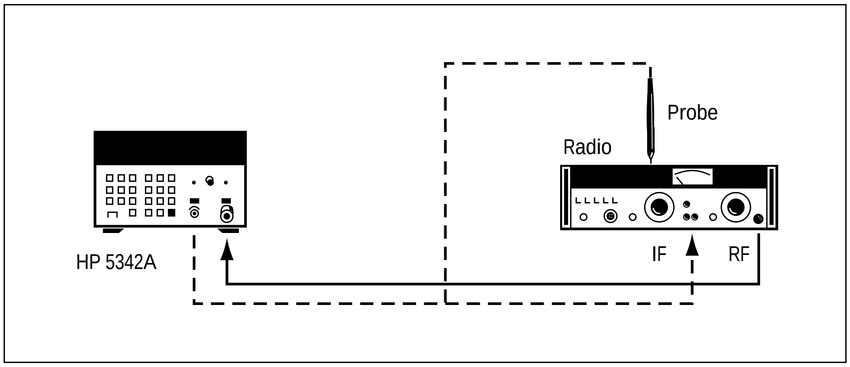
In some communications applications of microwave counters, it is convenient to have the counter’s display offset by some constant. This is a feature which is available in most microwave counters today. The most elegant provision for offsets is found in the HP 5342A, which allows arbitrary offsets (to a resolution of 1 Hz) to be entered via a front panel keyboard; this feature is made possible by the use of a microprocessor in the instrument.

Microwave Power Measurements

A common microwave instrument application is the measurement of frequency and signal level in the same set-up. A microwave counter which has the ability to measure and display signal level along with frequency can be quite convenient in these situations. The HP 5342A has an amplitude measurement option for just this purpose.

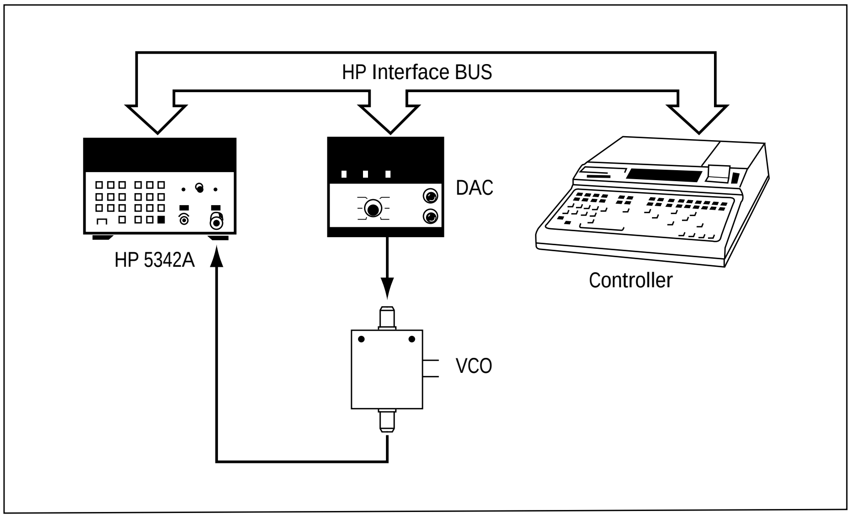
Some Applications of the HP 5342A Microwave Frequency Counter

1. Problem: A maintenance technician needs to measure the local oscillator of a microwave radio receiver. This L.O. is 70 MHz less than the 3850 MHz transmitted frequency, but for convenience he wishes to reference his measurement to the transmitted frequency.



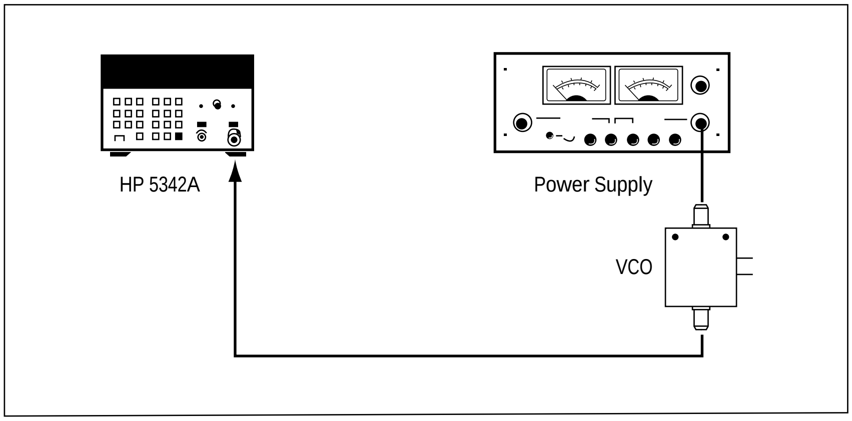
Solution: Measure the L.O. in the HP 5342A's high-frequency input with an offset of +70 MHz entered on the keyboard. The display will read 70 + 3780 = 3850 MHz. Note that the 70 MHz IF oscillator can be measured in the low-frequency input of the HP 5342A. If an output connector for the IF is not available, an oscilloscope probe can be used to probe the interior of the radio.

2. Problem: A simple, automated test set-up is needed to measure the tuning linearity of microwave VCOs in a production area.



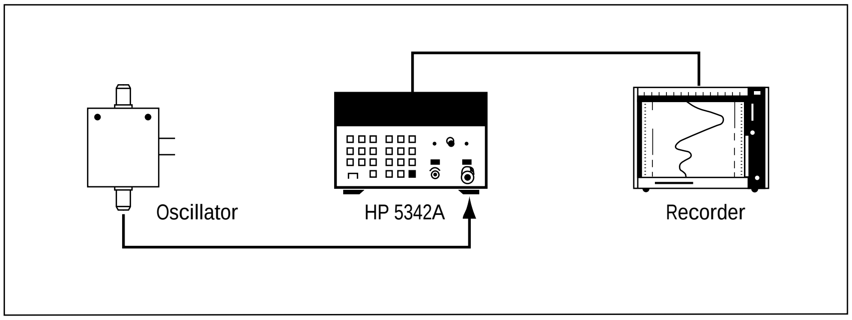
Solution: Construct a small system using the HP Interface Bus, with a desktop computing controller such as the HP 9825A. A programmable Digital-Analog Converter such as the HP 59303A provides the voltage stimulus, and the HP 5342A provides the high-accuracy frequency measurement. The computing controller can print the results, or it can be configured to graph the output on an XY plotter.

3. Problem: A microwave R&D engineer needs to measure the effect of small frequency changes on the output power of a microwave VCO.



Solution: The HP 5342A with Option 002 measures both parameters simultaneously. The engineer can fine tune the VCO's output frequency with a power supply and observe amplitude changes with frequency on the HP 5342A's display.

4. Problem: A researcher needs to characterize the drift of a microwave oscillator over a long time.



Solution: The HP 5342A with Option H01 provides analog output of operator-selected digits in the HP 5342A's display. With the HP 5342A measuring the oscillator's output, connect the analog output from the HP 5342A's rear panel to a strip chart recorder for an unattended set-up.

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