FREQUENCY AND TIME INTERVAL METERS

Frequency and time interval meters are broadly applied to measure frequency, period, and other time-related waveform parameters, including pulse duration, rise and fall times, duty cycle, frequency or period ratio, and also the time relationships between two different signals. The most popular meters, digital meters, measure frequency and time by comparing an unknown quantity to a reference. The reference sources of these meters are usually either built-in or externally applied to control the gate which passes the signal to the counters. The reference sources can work independently of the source of absolute time reference, or they can be synchronized with the absolute time reference to measure the actual time (1, 11). The meters with references provide very accurate readings of frequencies or time intervals, including periods. Less accurate meters with calibrated tuned circuits or frequency-to-voltage converters are applied when less precise frequency or time measurements are required.

The detailed descriptions of the frequency and time standards, frequency stability, frequency transfer, clocks, oscillators, frequency synthesis, phase noise in time and frequency measurements are included in the following articles of this encyclopedia: ***Frequency standards, characterization***; ***Frequency stability***; ***Clocks in telecommunications***; ***Measurement of frequency, phase noise and amplitude noise***.

The frequency and time interval measurements are interrelated, and for higher frequencies, it is more accurate to measure frequency and calculate time parameters. For lower frequencies, the period measurements are more reliable and the frequency is then calculated.

FREQUENCY METERS

Frequency represents the count of the number of events of a repetitive waveform occurring per unit of time. The accepted unit of frequency is hertz (Hz), corresponding to the number of cycles per second. Other, larger units are kilohertz (kHz or 10^3 hertz), megahertz (MHz or 10^6 hertz), gigahertz (GHz or 10^9 hertz), and terahertz (THz or 10^{12} hertz). Smaller units are millihertz (mHz or 10^{-3} hertz) and microhertz (μHz or 10^{-6} hertz).

The simplest frequency meters are passive or active absorption meters, which are applied for periodic signals whose frequencies are within microwave frequencies and also within microwave frequency ranges. As shown in Fig. 1, the meter is composed of an LC resonance circuit, a diode detector, and a meter indicating the maximum reading when the circuit is tuned to the frequency of the radiating source. The frequency ranges are selected by changing the coils. The variable capacitor used to tune the LC circuit is calibrated in frequency or wavelength units. The microwave absorption meters have their resonance circuits constructed as resonating cavities with tunable dimensions.

The other absorption meters, called dip oscillators (2), involve processes of energy absorption from external sources in order to mix them with the internally generated sine wave signals (Fig. 2). When the oscillator frequency is the same as the source frequency, the meter indicates the minimum indication since the differential frequency component is a direct current, which does not pass through the circuit capacitor.

Frequency and time interval measurements can be performed applying an oscilloscope. The distance considered as a period of an observed is computed either visually or by a built-in digital counter (15). The visual reading leads to large errors reaching several percent. The built-in digital meters do not differ from classical frequency counters, which are described later in this text.

The block diagram of a single-channel, low-frequency (below several hundred megahertz) counter is depicted in Fig. 3, and the typical waveforms are shown in Fig. 4. The unknown frequency signal after shaping is applied to the main gate operating like an AND logic gate, which is opened by the main gate control signal for a defined amount of time. The gate timing is selected according to the preferred setting of the time base controlled by the time base generator (clock). The unknown frequency, f_x, is then compared with a built-in standard. Through the open gate the input signal pulses are applied to the digital counter that accumulates the count and displays it according to the measurement cycles programmed in the measurement cycle control unit. The total count on n pulses refers to the main gate control pulse duration, T_{base}, so the unknown frequency is expressed as

$$fx = \frac{n\text{pulses}}{Tbase} \tag{1}$$

Inaccuracy of Eq. (1) is caused by the discrete nature of pulse counting. The error involved is called ±one count quantization error (3). Additional errors are added due to short- and long-term instability of the time base oscillator (clock) and due to the input conditioning unit trigger uncertainty. This error can be reduced by accumulation of many measurements and averaging. The error is then reduced $\sqrt{N}$ times, where N is the number of measurement cycles.

TIME INTERVAL MEASUREMENT

To achieve time interval measurement, we change the frequency counter configuration by swapping the function of the time base with the function of the input signal. The input signal opens the main gate for the pulses applied from the time base oscillator through the time base dividers, as shown in Figs. 5 and 6. The count accumulated in the counter register multiplied by the time base period yields the unknown time interval duration:

$$Tx = nTclk \tag{2}$$

The basic errors are similar to the ones discussed before. More discussion of errors is included later in the article.

A two-channel, start–stop, time interval meter can measure the time between two independent events or it can measure the period or the pulse width of one waveform. When two events are separately measured, the two signals are applied independently to two inputs, A and B. When

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*.

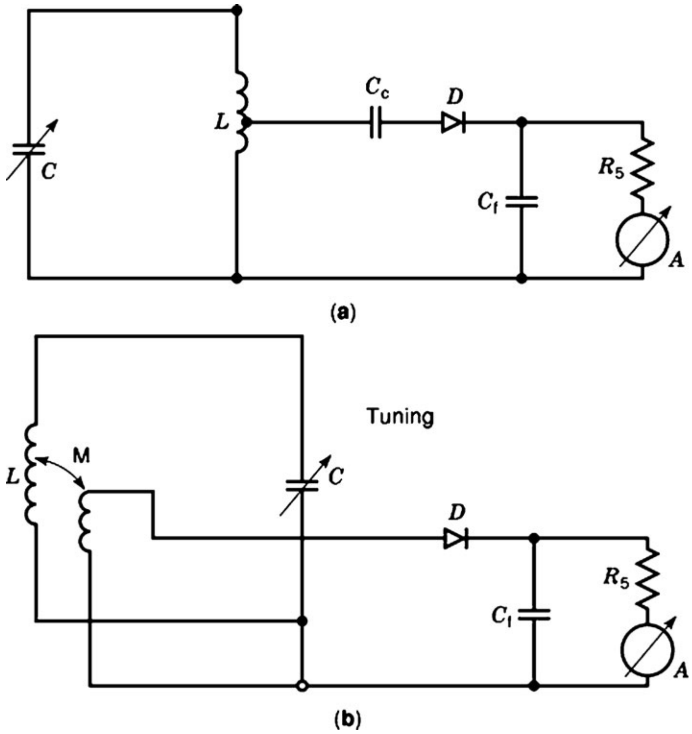

Figure 1. Passive absorption wavemeter. (a) Capacitive-coupled. (b) Transformer-coupled.

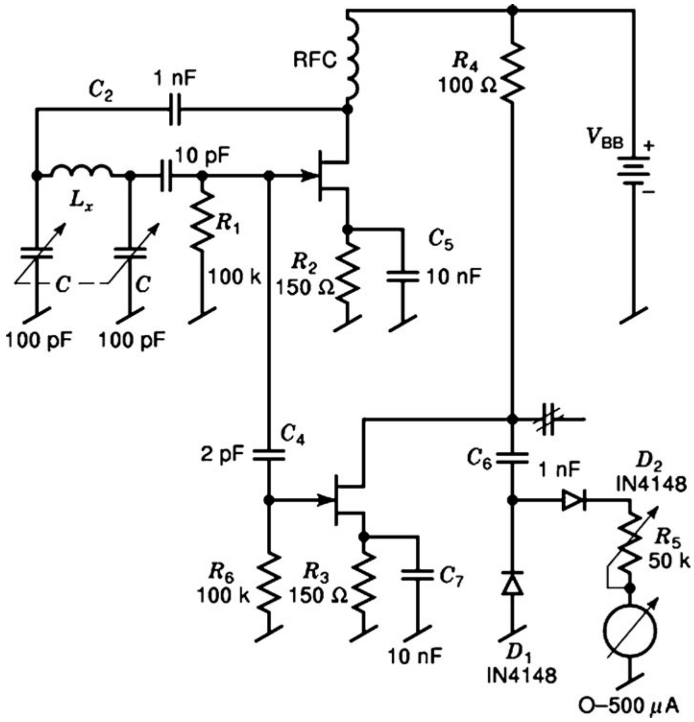

Figure 2. Active absorption wavemeter (dip meter).

a single signal is investigated, the inputs of the meter are connected together or the same signal is applied to both inputs. One input conditioning system is set to one signal slope, and the other system is set to the other slope. The process is carried out the way the previous meter operates (Figs. 7 and 8).

RATIO MEASUREMENT MODE

Two input counter shown in Fig. 9 can be used to find the ratio of two frequencies. One signal is applied to one channel and the other channel is used to gate the first signal. In all cases when the frequencies of the two channels are different, the smaller frequency signal gates the higher frequency signal. The accuracy of measurement is very critical when both frequencies are close one to each other. The

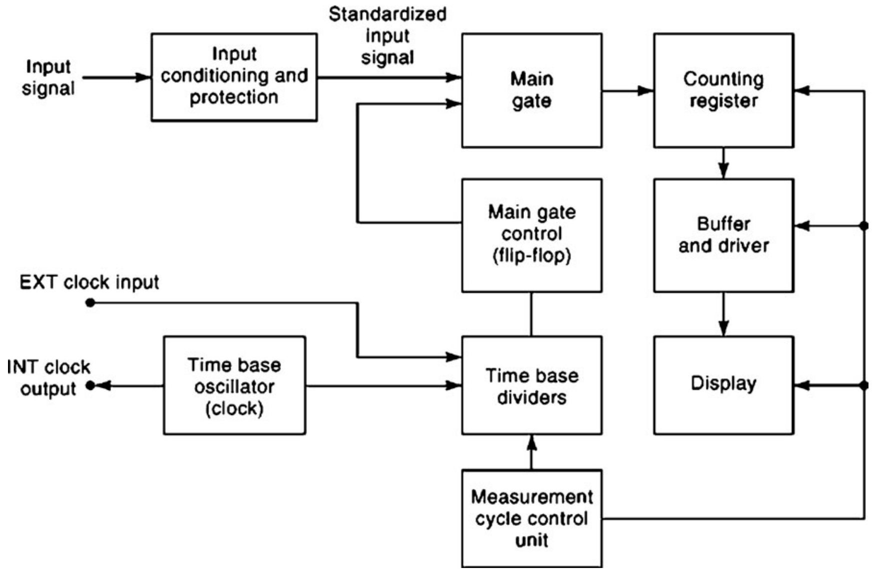

Figure 3. Frequency mode of a counter.

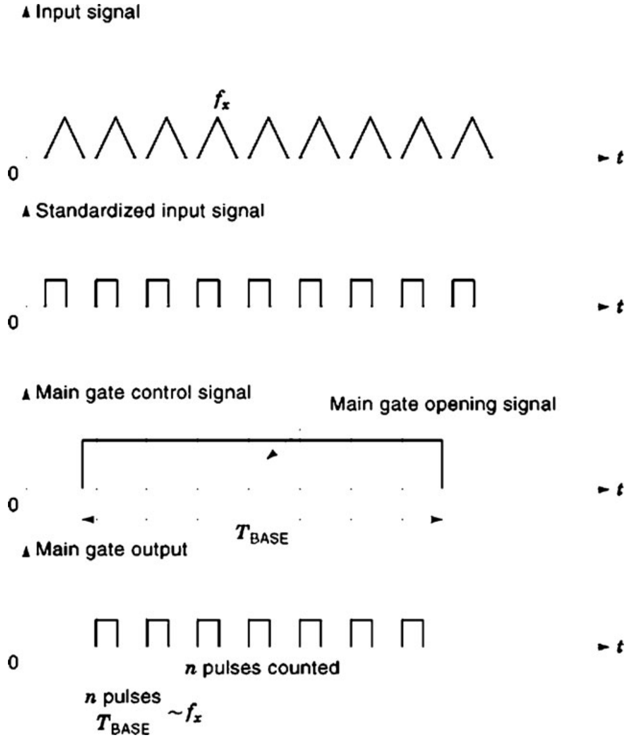

Figure 4. Waves in a frequency counter.

effect of ±1 count becomes then more significant and has to be reduced by averaging.

RECIPROCAL COUNTER

The reciprocal counter measures the period and calculates the frequency from the period. At lower frequencies, the period measurements show smaller effect of the ±1 count error than the frequency measurements. When the signal frequency exceeds the clock frequency, the frequency measurement is more accurate. Some reciprocal counters switch their mode from period to frequency measurement (3).

In the following sections the two major digital counter components are described. The first of them is the input conditioning unit; and the second is the time base oscillator.

INPUT CONDITIONING CIRCUIT

A block diagram of an input conditioning circuit is shown in Fig. 10 and its more detailed version in Fig. 11. The major functions of the circuit is to convert a periodic input signal into a standardized rectangular pulse wave whose pulses can be counted during gating time when the fre-

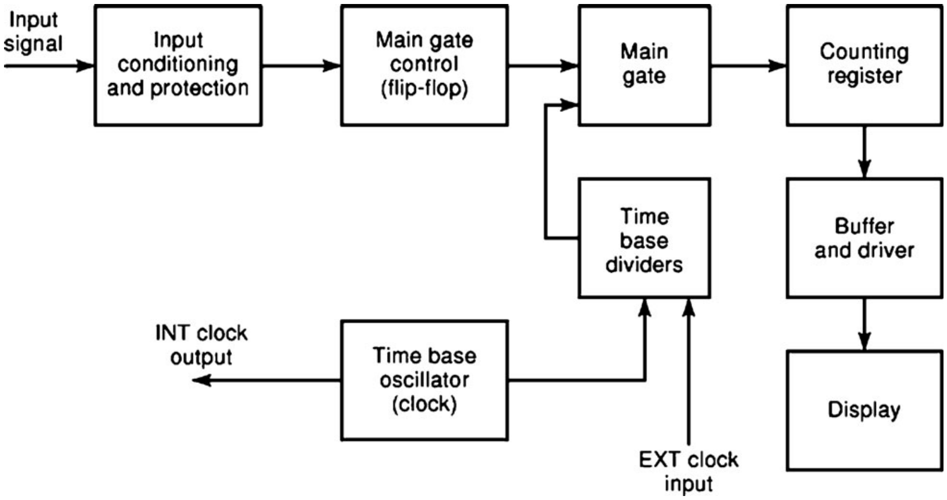

Figure 5. Period measurement mode of a counter.

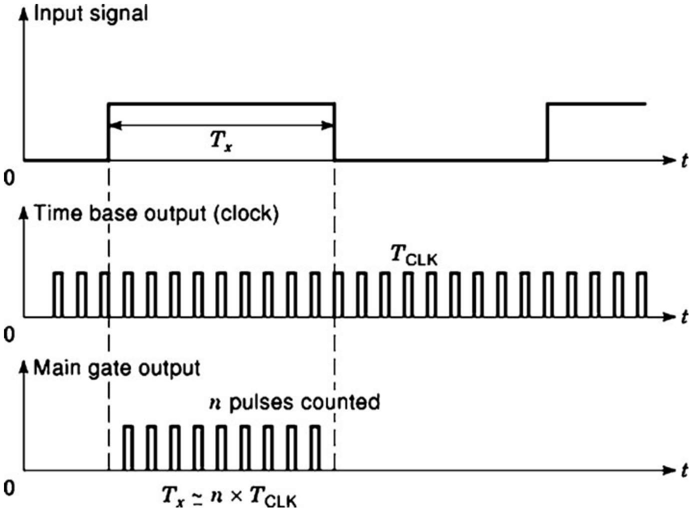

Figure 6. Waves in period meter.

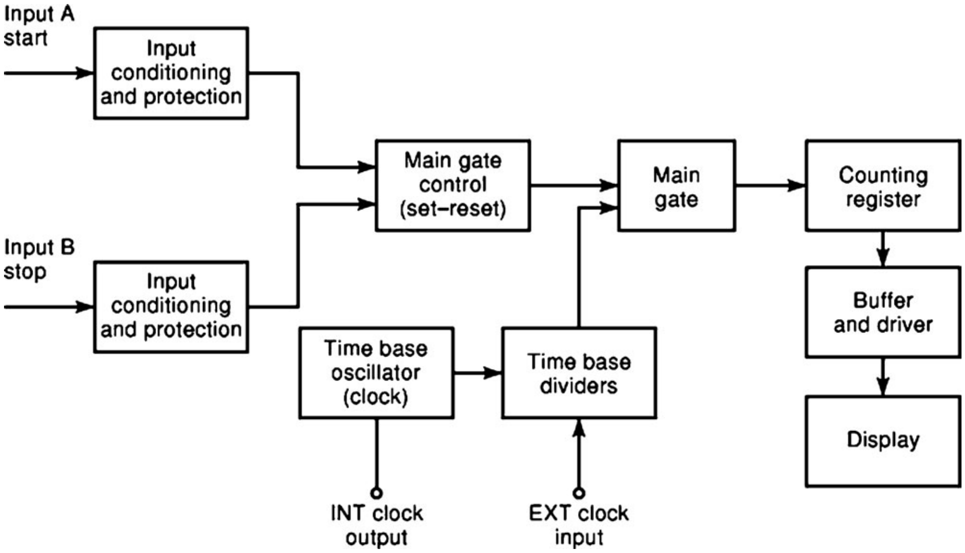

Figure 7. Time interval measurement mode.

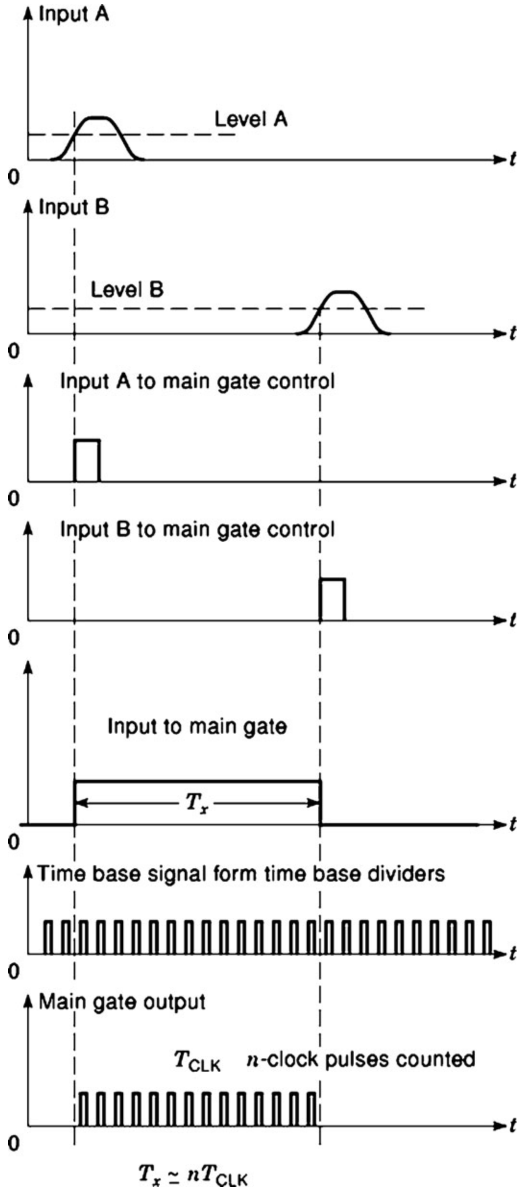

Figure 8. Waves in the time interval meter.

quency is measured. When the period or the time interval is measured, the pulses from the gating signals are counted during the interval defined by the input signal. The input conditioning circuit, especially the trigger amplifier and the comparator with hysteresis, provides proper shaping of the input signals of various amplitudes, shapes, and speeds in order to drive digital circuits of the meter. At the same time, the effects of the input signal impurities, noise, and interference are also minimized by the trigger and comparator circuits. An amplitude limiter and sometimes an additional fuse protect the internal circuits when the input signal levels exceed the dynamic capability of the circuit.

DIGITAL CIRCUITS OF THE COUNTERS

Typical digital parts of a modern frequency or time interval meter include specialized integrated circuits. Each of them has a high frequency oscillator, main gate, time base counter, multidecade data counter, latches, seven-segment decoders, digit multiplexers, and multidigit multiplexed *LED*-display drivers. The circuits require very few external components, like crystal, several resistors, capacitors, display, switches, and power supply to operate. Circuits like these are capable of measuring frequency, period, and time interval, counting pulses, and determining frequency ratio. Maximum frequency range for direct count does not exceed several tenths of MHz. Additional prescaler circuits can extend the range of operation well above 1 GHz.

The details of design and analysis of various circuits, including flip-flops, counters, analog and digital comparators, analog and digital phase-locked-loop circuits are given in other articles of the encyclopedia. The related articles are: ***Asynchronous circuits***; ***Asynchronous sequential circuits***; ***Comparator circuits***; ***Counting circuits***; ***Phase-***

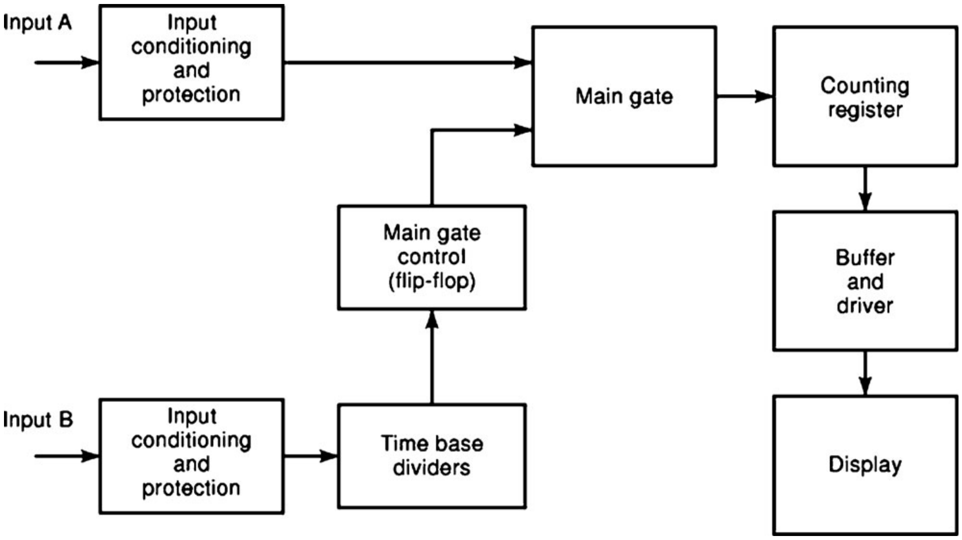

Figure 9. Ratio measurement mode of a counter.

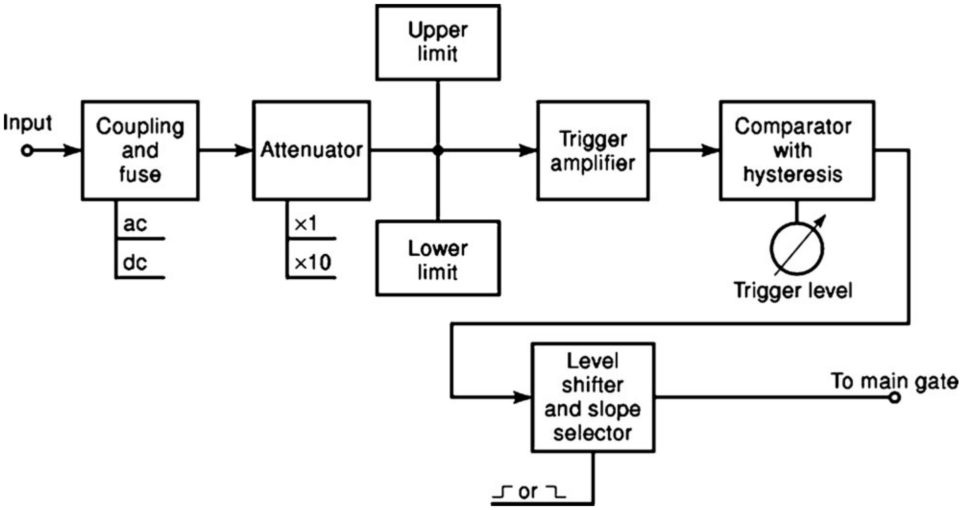

Figure 10. Block diagram of an input circuit.

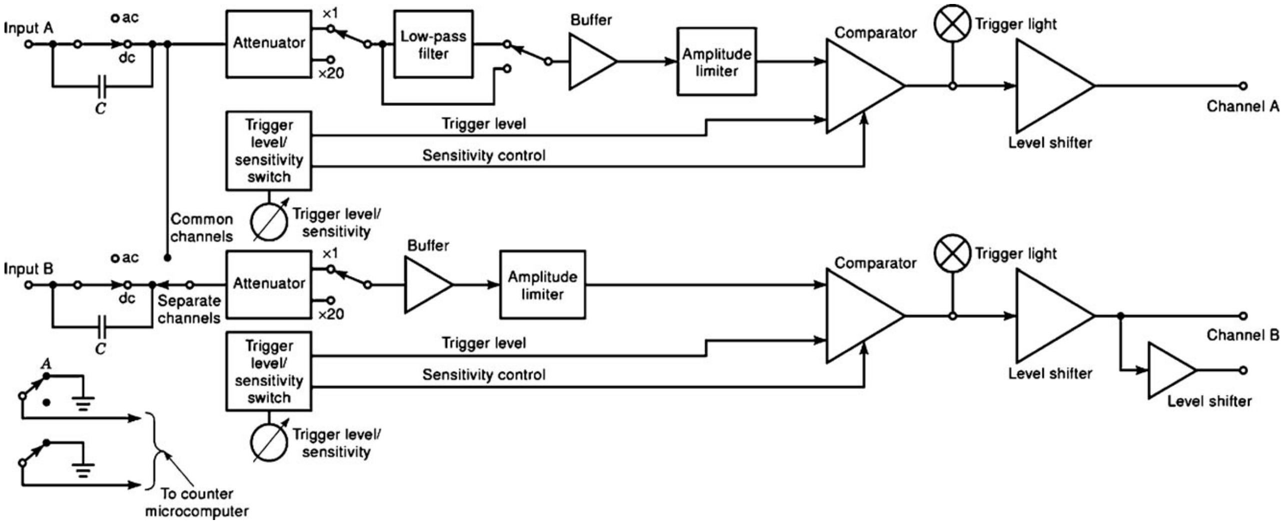

Figure 11. Input circuit of the HP 5315 counter.

locked loops; ***Synchronous Sequential circuits***; and ***Multivibrators***.

TIME BASE OSCILLATORS

The standard oscillators are discussed in ***Frequency stability***. Here, only a short introduction is included to review the limitations. The time base oscillators are usually high-stability, high-accuracy crystal oscillators. In more expensive and complex solution, the crystal oscillator is mounted in an oven to maintain constant temperature during regular operation so the temperature effects on the oscillator frequency can be minimized. This guarantees relative inaccuracies close to 1×10^{-8} while nonstabilized oscillators, even if they are temperature-compensated [temperature-controlled crystal oscillators (*TCXO*)], show errors at least two orders of magnitude higher. The rubidium frequency reference oscillators have much better accuracy expressed as an error close to 10^{-10} (4). Much more expensive, cesium beam frequency standards have their inaccuracies on the order of 10^{-11}. The most complex, maser oscillators, mostly used as frequency standards, reach the level of error close to 10^{-15}. The accuracy figures cited here are related to one-year change (5). Due to the cost and weight, the majority of counters employ various crystal oscillators. Many of them have temperature-stabilized ovens for better stability [oven-controlled crystal oscillators (*OCXO*)]. The most popular frequencies of the time base oscillators are 1 MHz and 10 MHz, which allows for establishing very convenient meter frequency ranges. High precision crystals can be produced for fundamental mode of operation up to about 300 MHz (9). Two examples of block diagrams of the crystal oscillators are shown in Fig. 12. In the first circuit [Fig. 12(a)] the quartz operates as an inductor with a high-quality factor that maintains very good frequency stability. The second circuit [Fig. 12(b)] oscillates when the quartz impedance reaches its minimum, which occurs at the frequency of series resonance. The transistor solutions are shown in Fig. 13. Lower frequency signals necessary to control the counter main gate are obtained from the frequency dividers. A typical time base divider unit is shown in Fig. 14 for both modes of operation, frequency measurement and time interval (or period) measurement.

ERRORS IN DIGITAL FREQUENCY AND TIME INTERVAL METERS

An electronic counter measuring frequency or time interval involves generation of signals by a reference oscillator or a clock and a discrete counting of pulses within certain amount of time defined by the gating process. The types of measurement errors include the following:

- Time base errors result from inaccuracy and from short- and long-term instability of the time base oscillator.
- Trigger error, of random character, is caused by the noise. The error is a result of random instability of the gate pulse width caused by the noise of different thresholds.

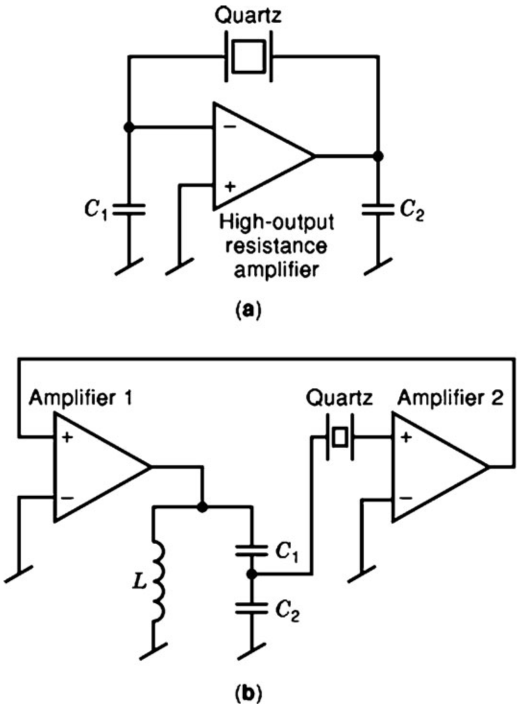

Figure 12. Block diagrams of crystal oscillators. (a) Collpits oscillator. (b) Crystal oscillator with quartz coupling two stages.

- The systematic error, effecting only time interval measurements, originates in any differences between the start and stop trigger levels caused by hysteresis of the internal comparator, differences in delays, and the signal slew rate (3, 7).
- The plus/minus count error is due to lack of synchronization of the gating pulses and the counted pulses.

The numerical values of different error components strongly depend upon the quality of the reference oscillator. The inaccuracies of the various clock circuits are between 10^{-8} and 10^{-6}.

The trigger error, important in the period and the time measurements, can be expressed in terms of the noise voltage levels and the triggering signal speed as follows (3):

$$e_t = \frac{\sqrt{2(e_i^2 + e_m)^2}}{\frac{dV_{in}}{dT}} \tag{3}$$

where

e_i is the root mean square (*rms*) voltage noise of the instrument input circuits,

e_m is the rms voltage noise of the signal source limited by the counter bandwidth,

$\frac{dV_{in}}{dT}$ is the slew rate of the input signal at the trigger point.

The level of the noise component can reach several hundred microvolts. The slew rate of the pulses vary from several volts per nanosecond to several volts per microsecond or less, which leads to the error values between 1 ps and 1 ns.

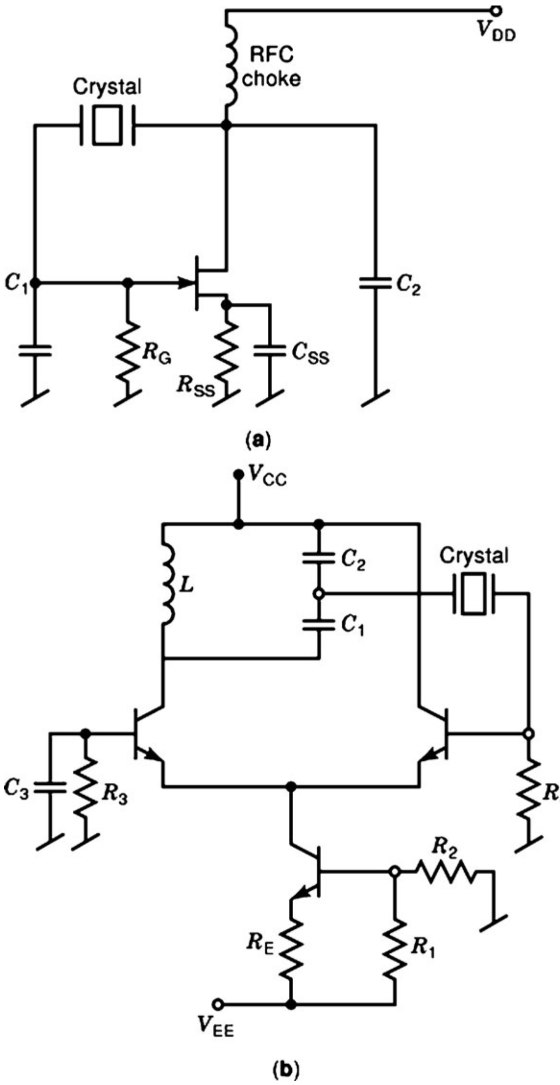

Figure 13. Circuit implementation of crystal oscillators. (a) Collpits oscillator. (b) Crystal oscillator circuit with quartz coupling two stages.

The systematic error, which strongly depends on the differences in delays the trigger level settings, affects the time interval measurements when short pulses are measured. This error is usually minimized through careful design and calibration.

The ±one count error, which is random in nature, becomes critical when a small number of pulses are counted within the frame of the gating pulse. Then a missing or additional pulse creates a relative error of great significance. These error effects can be summarized as follows:

$$\frac{\Delta f}{f} = \pm \frac{1}{f_{in} T_{GATE}} \tag{4}$$

for frequency measurements and

$$\frac{\Delta T}{T} = \pm \frac{T_{clk}}{T_{in}} \tag{5}$$

for period measurements, where f_{in} and T_{in} are frequency and period of the signal under test, T_{clk} is the time base period, and T_{GATE} is the length of the counter gating pulse.

If f_{clk} = 10 MHz and f_{in} = 10 kHz, then the frequency error equals $\pm\ 10^{-7}$ and $\frac{\Delta T}{T} = \pm\ 10^{-3}$ for 1 s gating pulse.

HIGH-FREQUENCY METERS

Direct measurement of frequency is now available to the frequencies close to 1 GHz. Higher-frequency measurements above 1 GHz are achieved by means of frequency down-conversion using prescaling with frequency dividers (Fig. 15), transfer oscillators (Fig. 16), and frequency translation by mixing (Figs. 17 and 18). The frequency prescaling involves a process of frequency division in the fast digital counters. Then a classical low-frequency counter measures the input signal frequency. Typical division ratios are 2 to 16. The maximum frequency divided in a stable manner can reach several gigahertz (HP 5386A). Frequencies of signals reaching 25 GHz can be measured with help of transfer oscillators. The down-conversion, which based on the heterodyne conversion, is applied to provide measurements within the frequency ranges comparable with the previous method, although the harmonic conversion extends the frequency to millimeter wave region (10).

In the following sections, the transfer oscillator and frequency translation methods are discussed.

TRANSFER OSCILLATOR

The transfer oscillator provides the down-conversion to extend the frequency measurement range by means of phase locking a low-frequency oscillator to the high-frequency

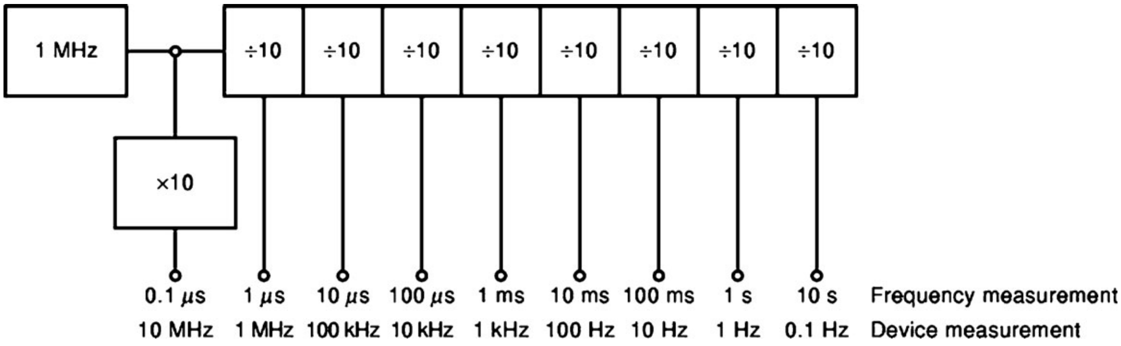

Figure 14. Time base divider unit.

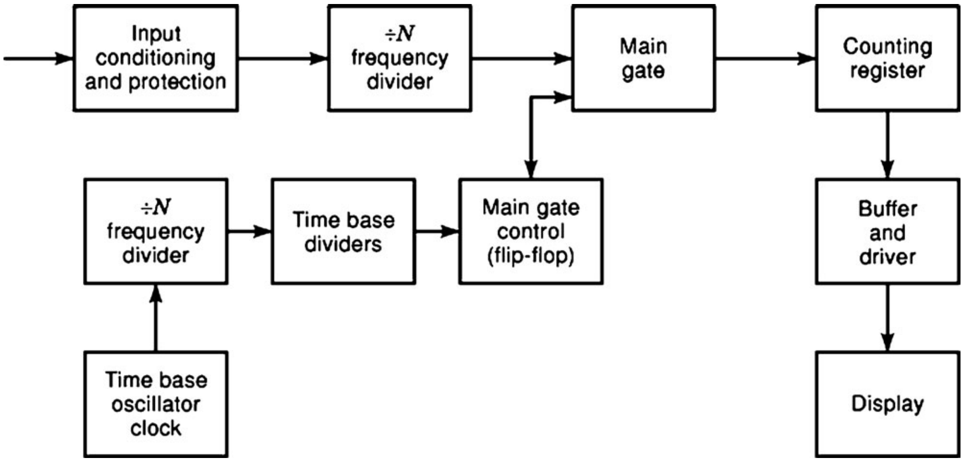

Figure 15. High-frequency counter with down conversion.

repetitive input wave. The high-frequency signal of the frequency f_x is sampled every n-th period at a rate adjusted by the low-frequency oscillator of the frequency f_1, as in coherent sampling scopes. The low frequency and the number n are computed to find the high frequency (3, 10).

Figure 16 shows the block diagram and basic waves illustrating operation of a transfer oscillator. The upper part includes the phase-locked-loop system composed of a voltage-controlled oscillator, VCO_u, producing narrow sampling pulses; sampling gate; video amplifier, acting as a low-pass filter; phase detector, comparing phases of a reference oscillator signal with a signal filtered by the video amplifier. The lower part has the same sampling gate and video amplifier as the upper channel. Additionally, the channel includes a frequency mixer with a filter, and a low-frequency counter measuring frequency and frequency ratio.

When the loop is in lock, the input signal of frequency f_x is sampled by the narrow pulses at frequency f_1 established by the voltage-controlled oscillator $\mathrm{VCO_u}$. The frequency f_1 is much lower than f_x, and is adjusted automatically in the loop.

The output signal of the sampler is composed of the train of samples whose amplitudes vary like the input signal amplitude but at a much lower rate (f_{u1}). This signal, filtered by the video amplifier, has the frequency close to the reference frequency oscillator f_{ur}. The signal frequencies in the lock-in conditions follow the equation

$$f_x = n\ f_1 - \ f_{u\,f} = n\ f_1 - \ f_{ur} \tag{6}$$

where f_1 is the sampling pulse frequency, f_x is the unknown frequency, f_{ur} is the reference frequency, which in lock equals f_{u1}, n is an integer number. Typically, $f_{ur} < nf_1$, so nf_1 is close to f_x. The upper channel sends the signal of frequency f_1 to the low-frequency counter shown at the bottom of Fig. 16. The counter also determines the frequency transfer coefficient, n, and finally the product of n and f_1. The lower channel involves the same sampling processes as the upper channel but the sampling frequency is offset to $f_1 + f_0$, where f_0 is a constant frequency much lower than f_1. By offsetting the frequency f_1, the unknown integer number n is transferred to the frequency f_0. The rate of the signal variations after sampling and filtering by the lower channel video amplifier is determined by the frequency f_{If}. The frequency relations for the lower channel are as follows:

$$f_{I\,f} = n(\ f_1 + \ f_0) - \ f_x \tag{7}$$

since

$$f_2 = \ f_1 + \ f_0 \tag{8}$$

hence

$$f_{I\,f} = n\ f_0 + \ fu\ f = n\ f_0 + \ f_{ur} \tag{9}$$

The signal of frequency f_u is mixed with the signal of frequency f_{ur} and later filtered to pass only the signal of frequency nf_0. The low frequency counter measures the frequency ratio of nf_0 and f_0 to determine the number n, and this number determines the length of the time base to measure the frequency nf_1. In this way all components are available to find the frequency f_x, which is expressed as

$$f_x = n\ f_1 - \ f_{ur} \tag{10}$$

In practice, $f_{ur} < nf_1$ and $f_x = nf_1$.

FREQUENCY TRANSLATION

Frequency translation or heterodyne down-conversion system is shown in Fig. 17. The conversion involves mixing the input signal of unknown frequency with a harmonic of the reference source. The harmonic number, k, is adjusted automatically by the processor, which registers the signal from the signal detector and tunes the YIG/PIN switch filter until harmonic frequency of f_1 from the comb generator (generator of many harmonic signals) produces a noticeable detector signal. The comb generator is controlled through the frequency by the clock reference signal of high stability. The multiplier output signal frequency is typically 100 MHz to 500 MHz. The flowchart of Fig. 18 illustrates the system operation.

A combination of both previously described methods is applied in harmonic heterodyne counters to extend the measurement range to millimeter and submillimeter waves.

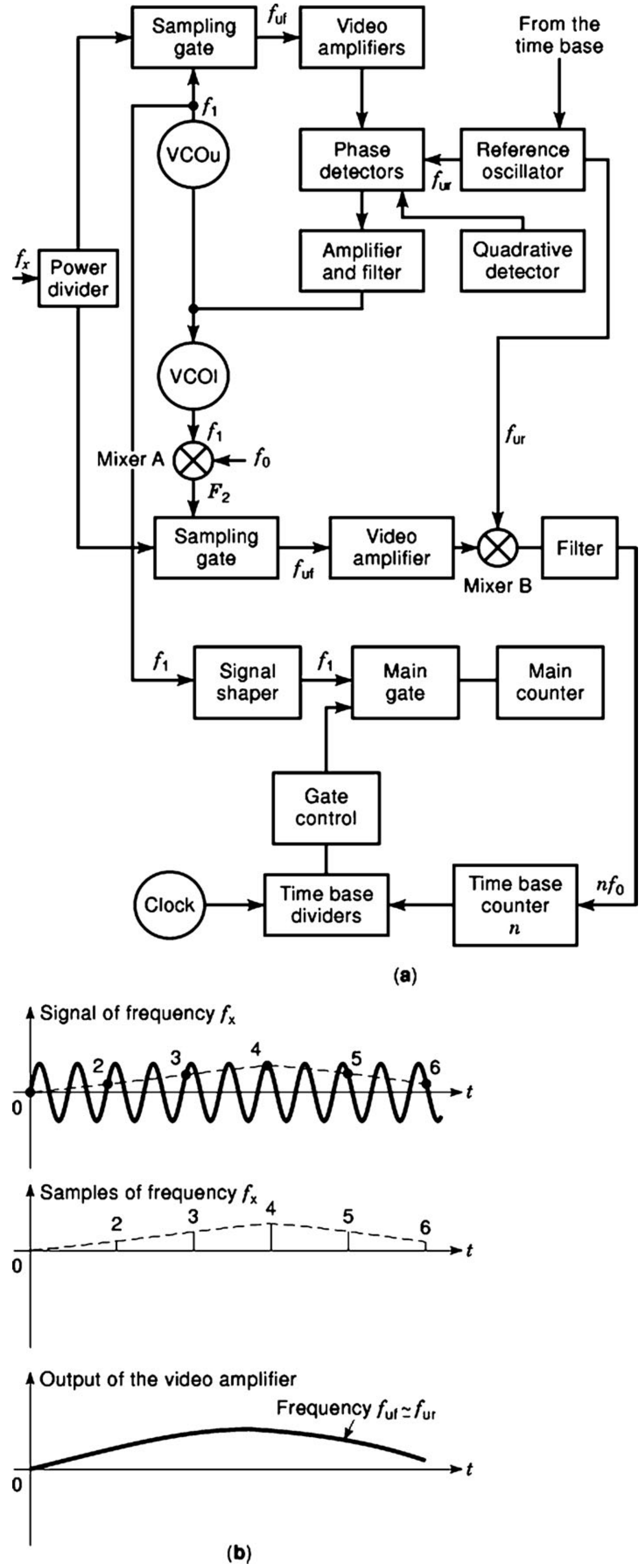

Figure 16. Transfer oscillator. (a) Block diagram. (b) Time waves in the upper part of the circuit.

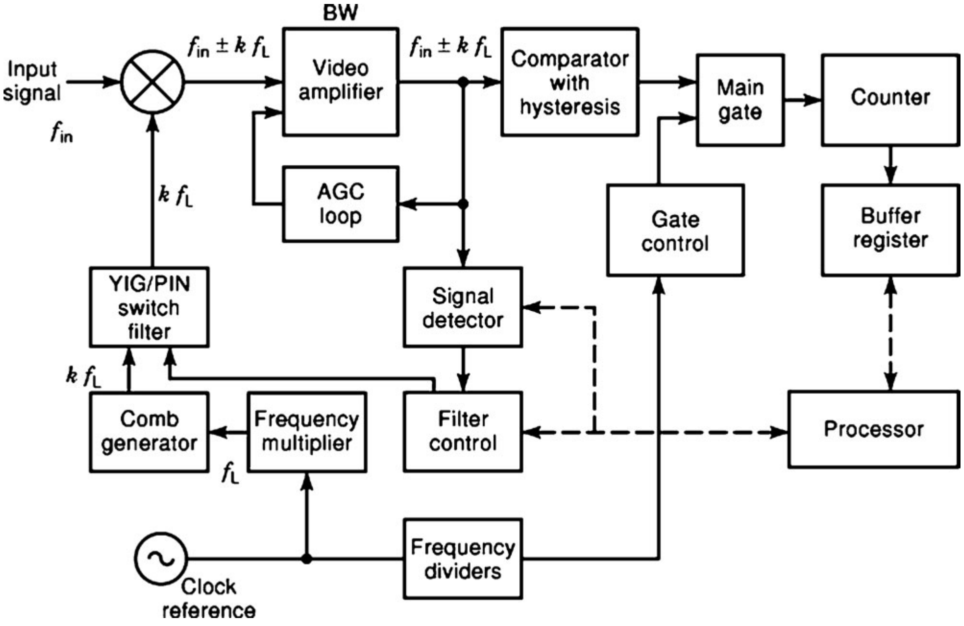

Figure 17. High-frequency counter with frequency translation (heterodyning).

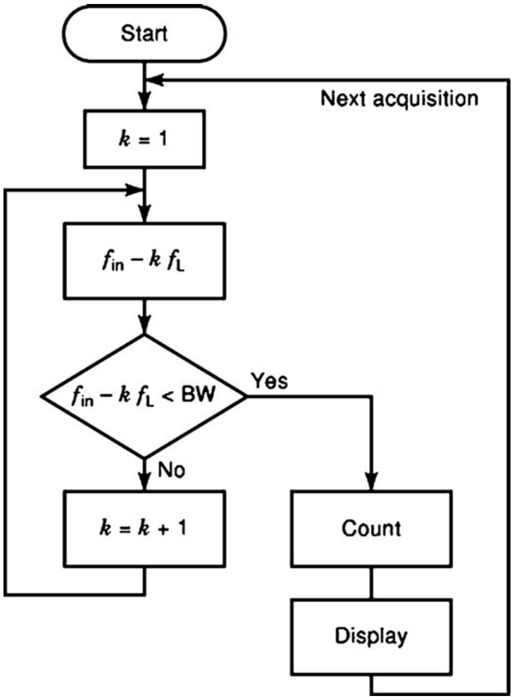

Figure 18. Flowchart illustrating operation of a high-frequency counter with frequency translation.

Table 1. Summary of the performance of the three basic microwave counter down-conversion techniques.

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-to-peak	1–10 MHz peak-to-peak	10–50 MHz peak-to-peak
AM Tolerance	Less than 50 %	Greater than 90 %	Greater than 90 %
Amplitude Discrimination	4–30 dB	2–10 dB	3–10 dB

Similar techniques are used in optical measurements, although all operations are performed on optical signals.

Table 1 compares the basic parameters of the three types of microwave counters discussed before.

LOW-FREQUENCY METERS

A classical digital frequency counter can measure signal frequencies by determining periods. The frequencies are then computed from the periods. Another method to measure low frequencies is applied in the counters, which have frequency multipliers. Figure 19 shows the frequency multiplier with the phase-locked-loop system. The loop is in lock when the subharmonic frequency of the voltage-controlled oscillator is adjusted to satisfy the phase condition which is imposed by the phase detector. The phase difference between the detector input signals must be confined between 0° and 180°, with the center of 90°; or for some detectors the range of 180° is centered at 0° in order to produce a stable dc output to control the voltage-controlled oscillator. When the frequencies are not correctly aligned, the loop is not in lock, and the output voltage of the low-pass filter oscillates. If both frequencies are closer together, the oscillating frequency falls within the low-pass filter bandwidth, and the loop "captures" the input signal to lock it. The voltage-controlled oscillator is tuned automatically by the negative feedback loop of the system.

Another interesting method is applied in low-frequency measurements of rotating objects. This method is called a stroboscopic method. The low-frequency stroboscopic method involves high-intensity flashes of light, whose frequency can be controlled by a source of very stable but adjustable frequency signals. The light is directed on the mark on the rotating object whose frequency is to be measured. For the proper frequency of the flashlight, full synchronization of the light pulses with a rotating object produces a single motionless image of the marker. The synchronization can be also achieved at the rotational speeds, which are multiples or submultiples of the actual speed of the rotating object. Figure 20 shows the basic measuring configuration with a stroboscopic device and the most basic patterns observed for various speeds. More complex synchronization patterns are described in Ref. 7.

The high-frequency stroboscopic method is applied in sampling oscilloscopes described in ***Oscilloscopes***. The sampling scopes were also called the stroboscopic oscilloscopes during very early stages of the development of this technique.

EXAMPLES OF CALIBRATION OF FREQUENCY AND TIME INTERVAL METERS

The processes of calibration are usually done by comparison of time or frequency of the internal time bases of the meters with available, more accurate standards whose parameters are traceable to national or international references. The standard frequencies and time standards are accessible directly through radio, TV, and satellite signals, including GPS (1, 11). The inaccuracy of atomic standards used to deliver reference signals reaches the level of 10^{-13}. Commercially available built-in standards (4) have their accuracy close to 10^{10}. The external sources serve to either introduce automatic frequency corrections or establish the error bands. The frequency comparison can be done by means of the vector voltmeters, the linear phase comparators, oscilloscopes, and frequency counters measuring the differential frequency. Figures 21 through 23 show a few examples of the measurement setups in which the frequency of the counter time base are compared with the applied reference. The oscilloscope Lissajous patterns are described in ***Oscilloscopes***. Figure 21 illustrates another oscilloscope method that registers the frequency drift of an oscillator under test in relation to the oscillator of high stability. The rate of movement of the observed wave indicates the drift. If the wave displayed on the screen moves to the left, the tested frequency is higher than the frequency of the standard. If the wave moves right, the counter frequency is lower. Frequency error can be calculated from the speed of motion of the wave. If a 1 MHz wave is displayed using a 100 KHz reference signal for triggering and the observed drift is one full cycle per 10 s, then the frequency error 0.1 cycle per second related to 1 MHz gives 10^{-7} relative error due to the drift. The vector voltmeter method is illustrated in Fig. 22. The phases of the reference and tested signals are compared instead of frequencies. Frequency difference is calculated from the phase change $\Delta\Phi$ over a predetermined amount of time Δt_f according to the definition of the frequency:

$$\frac{\Delta f}{f} = \frac{\Delta\phi}{2\pi\Delta t\, f} \tag{11}$$

where. The factor 2π can be replaced with 360° when the phase is expressed in degrees.

In Fig. 23, the frequency counter is used to compare the frequency of the unit under test with the frequency of the standard source frequency. The standard source clocks the frequency counter that measures the frequency counter under test.

Precision time and frequency transfer procedure at a remote site by means of the *GPS* system is described in (8, 11, and 13). A site clock can be compared with the universal time coordinated (*UTC* at *NIST*) anywhere in common view of the GPS satellite with NIST branch located in Boulder, Colorado. *GPS* signal availability and introduction of *GPS* disciplined oscillators (*GPSDO*) have added new references for frequency calibration (11). The *GPSDO* delivers typical signals of 5 MHz and/or 10 MHz, and they can be also a convenient source of 1.544 MHz or 2.048 MHz.

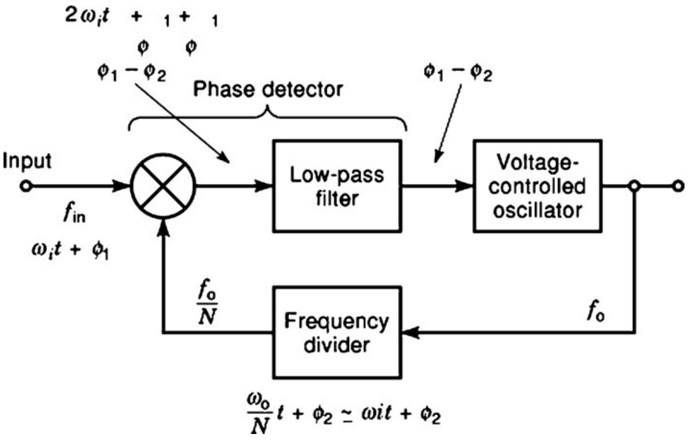

Figure 19. Frequency multiplier applied in low-frequency counters.

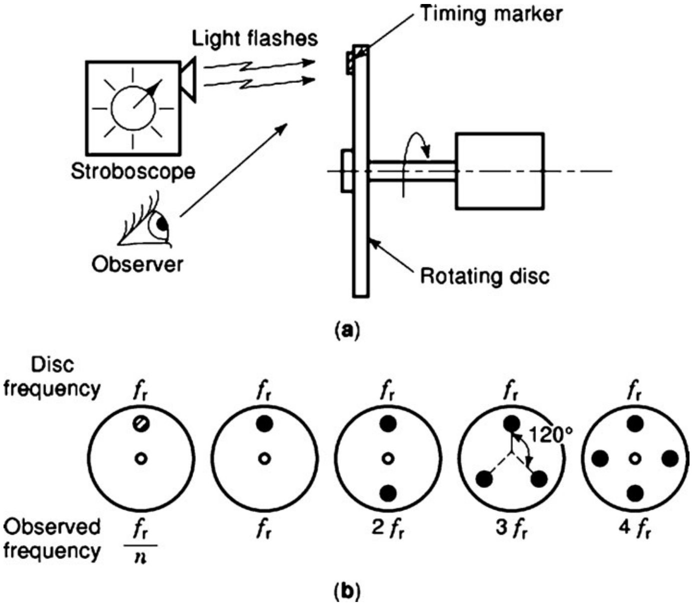

Figure 20. A stroboscope. (a) Measurement setup. (b) Stroboscopic patterns.

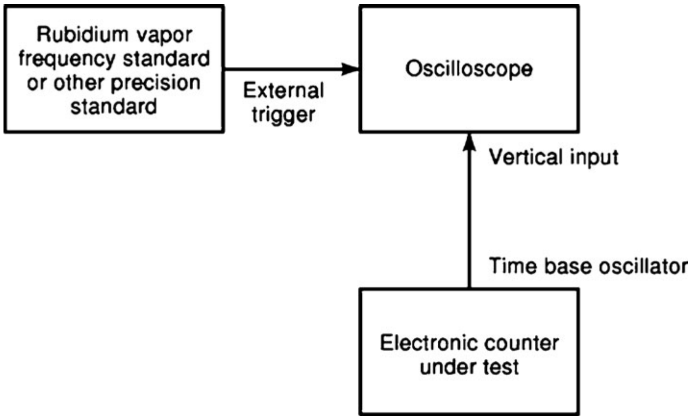

Figure 21. Oscilloscope tests of the frequency drift.

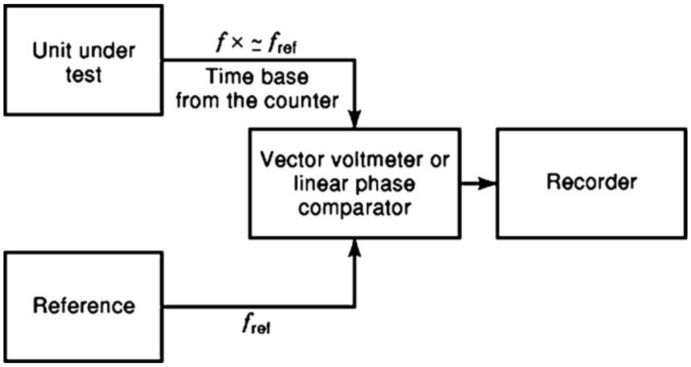

Figure 22. Frequency comparison testing circuit with a vector voltmeter or a phase comparator.

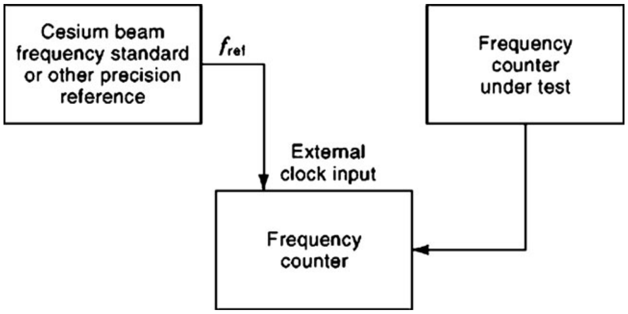

Figure 23. Frequency comparison with a counter.

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ANDREW RUSEK
Oakland University, Rochester, MI