PHASE METERS

Phase meters measure the time-domain position of any periodic signal, including electromagnetic waves, with respect to another periodic signal of the same frequency, and then relate the resulting time difference to the period to display it in terms of the phase angle.

Measurement technique applied in phase meters depend upon the frequency of the tested signals. In the range of lower frequencies, below several megahertz, the signals under test are acquired and directly processed to produce the phase reading. Analog or digital time-into-output reading conversion methods may be used.

Application of internally generated phase references improves measurement accuracy. With the recent development of fast real-time data acquisition systems, sampling methods are used to compute wave parameters, like phase shift and magnitude, average value, and others.

In the higher frequency region, above several megahertz, the linear down-conversion of both tested signals is applied to reduce the operating frequency so lower frequency measurement techniques can be used. The frequency down-conversion employs sinusoidal heterodyning, down counting, and coherent or periodic random sampling.

Besides stand-alone phase measuring devices, built-in phase meters are used as parts of impedance meters, power meters, frequency meters, network and waveform analyzers, as well as analog and digital oscilloscopes. Some high-frequency wave analyzers and digital oscilloscopes use coherent or random sampling methods to reconstruct the wave images and display them on the screen before processing. Direct oscilloscope two-channel observation methods and indirect x-y ellipsis display methods are discussed in ***Oscilloscopes***. Typical phase measurement is based on the assumptions that the investigated waves have the same periods and that they are sampled at the same points relative to the cycle start.

Many direct and indirect or conversion phase meters allow for reduction of random errors by accumulating many readings and computing average values.

Microwave six-port network analyzers (1, 2) and homodyne four-port meters (3) form a separate group of phase meter related instruments which use scalar power or voltage readings to compute phase shift and other parameters of the networks.

REVIEW OF THE PHASE MEASUREMENT METHODS

In this section a brief review of the basic methods of phase measurement is presented. More details related to the specific implementation are described in the later parts of the article.

As mentioned before, the oscilloscope x-y method with Lissajous patterns is given in the article entitled ***Oscilloscopes*** in greater detail. The phase shift is determined from the following equation for signals of the same frequency.

$$\mathrm{PH} = \operatorname{arcsine}(\mathrm{A}/\mathrm{B}) \tag{1}$$

where PH is the phase shift, and A and B are as shown in Fig. 1.

The accuracy of this method is limited by the errors of the vertical and horizontal channels and by the error of reading from the oscilloscope screen. The total error may exceed 5%.

Another visual method, which could be digitized, is the sweep method. Two waves are displayed on the screen, as shown in Fig. 2. The phase reading involves measurements of the period and the time delay between the two waves. The following expression is used to determine the phase

$$\mathrm{PH} = 360^\circ \mathrm{T_d}/\mathrm{T} \tag{2}$$

where T_d is the delay between the waves and T is the period.

The visual method leads to the error which could be more than several percent when the phase shift between the waves is small. Additional error is introduced due to channel misalignment and the wave vertical offset. Some analog and digital oscilloscopes have digital signal processing packages which automate the measurement process, so the error of reading from the screen can be significantly reduced.

The wave offset error is compensated in some analog and digital phase meters by the proper technique described in (15). The phase measurement involves the process of conversion of the input waves into standardized rectangular signals, as shown in Fig. 3. The time shift preserved in the front edge difference signal, V_{DD}, is related to the entire period thus resulting in the phase shift. The duration of the difference signal can be measured digitally and referred to the period duration in order to compute the phase shift. The difference signal can be also averaged to provide direct information about the phase shift. Proper calibration of the averaging device provides correct readings. The lead or lag information is indicated by additional logic circuitry described later in this article.

Many waveform analyzers, including more complex digital oscilloscopes, accumulate the signal samples from the tested signals and process them in order to determine various signal parameters. Among them, the phase shift is obtained from the computations.

GENERAL BLOCK DIAGRAMS OF DIRECT PHASE METERS

Figure 4 is a general block diagram of a direct phase meter system without frequency down conversion. Two input waves are applied to the inputs A and B. The waves are converted into trains of pulses of the same lengths and delivered to the processor whose function is to determine the phase difference in an analog or digital fashion. Connection of the frequency down-converters to both inputs greatly expands the frequency range of operation.

The heart of the direct phase meter is a phase-to-output variable converter whose major function is translation of the phase difference of the investigated signals into a quantity like voltage, time ratio, or frequency ratio. Figure 5 illustrates the first type of a converter that changes the input signal phase difference into the output voltage. This volt-

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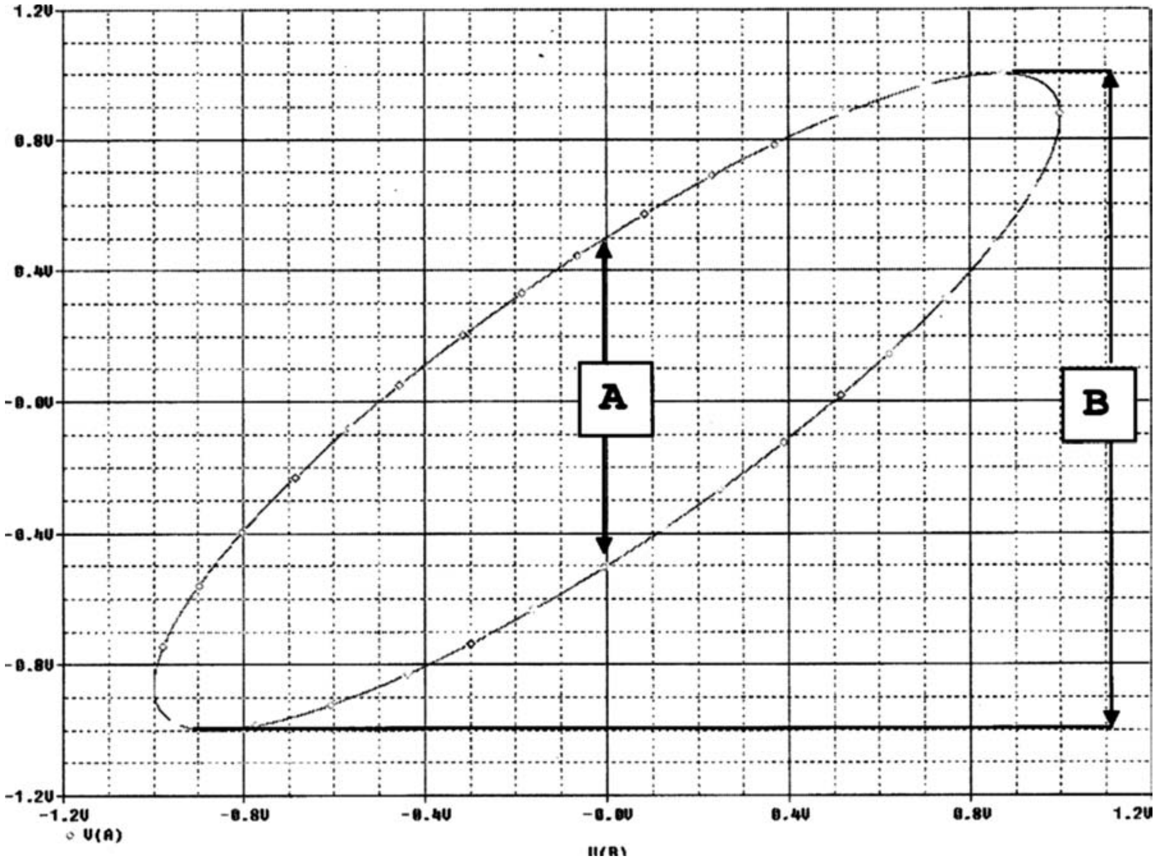


Figure 1. Phase measurement using Lissajous pattern for two signals of the same frequency.

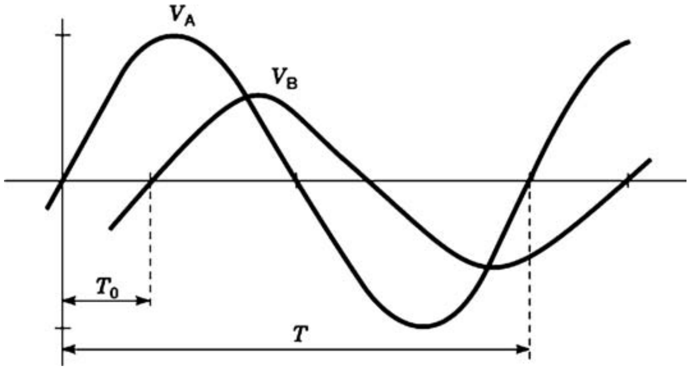


Figure 2. Phase measurement using sweep method.

age can be measured directly by a voltmeter or converted into the current and measured by an ammeter. Analog-to-digital converter added to the converter of Fig. 5 changes it into a simple digital phase meter. The way the results are displayed depends upon the type of applied phase detector. Phase meters with two-quadrant, digital or unipolar type of the phase detector produce the results in terms of phase magnitude and lead/lag indication. Meters with four-quadrant phase detectors deliver bipolar readings thus indication negative or positive phase shift when the positions of both waves are shifted more or less than 90°. Figure 6a shows a two-quadrant phase detector with Exclusive-NOR gate whose inputs are controlled by the two binary signals formed from the input signal under test and the reference signal. The gate output signal is filtered to yield the DC level proportional to the phase shift. The static transfer characteristic shown in Fig 6b illustrates the relationship between the output voltage level and the phase difference between the input signals. The detector registers only the phase magnitude. Additional circuitry is necessary to indicate the phase polarity.

The four-quadrant phase detector of Fig. 7a includes two clocked D flip-flops. The binary input signals shifted in phase are applied to the clock inputs while D inputs are high. The two output signals from the flip-flops are subtracted in a bipolar analog subtractor and then filtered by a low-pass filter. The detector exhibits inconsistent readings near $-180°$ and $180°$ which is shown in terms of sudden changes in the transfer characteristic of Fig. 7b.

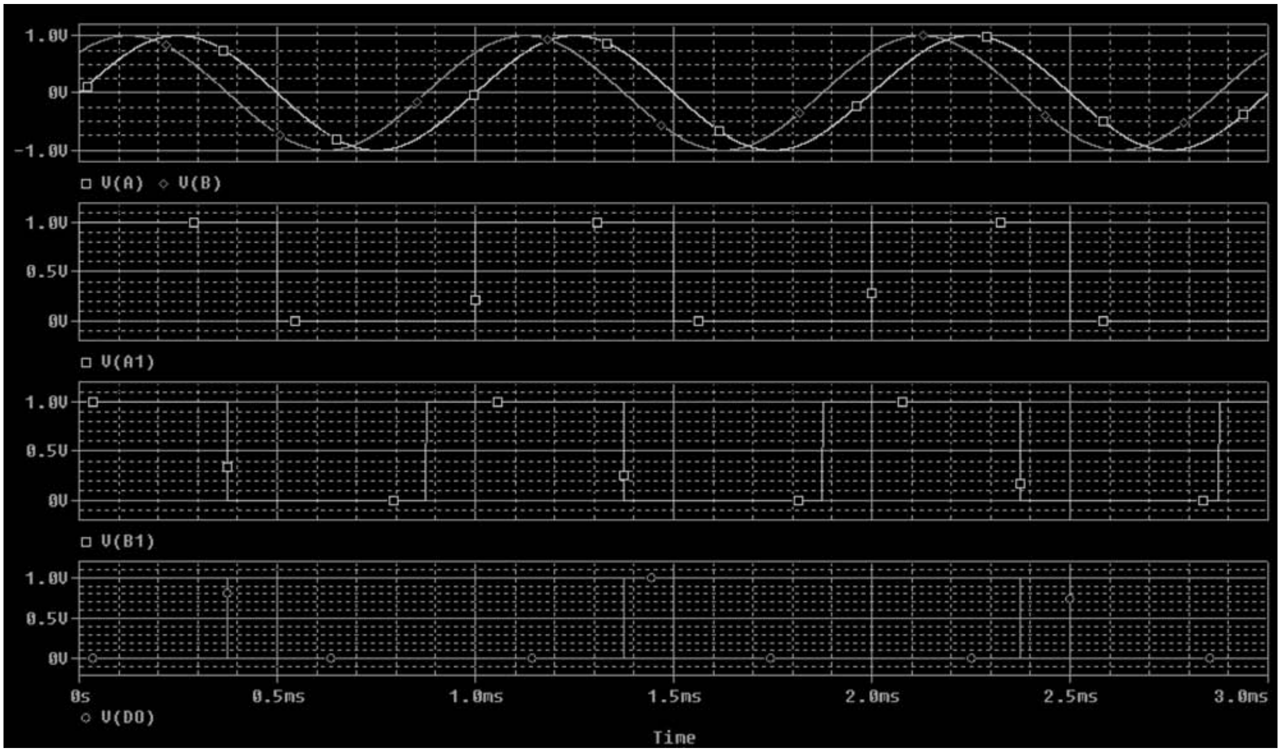


Figure 3. Phase measurement using wave amplitude standardization (for both analog and digital measurements).

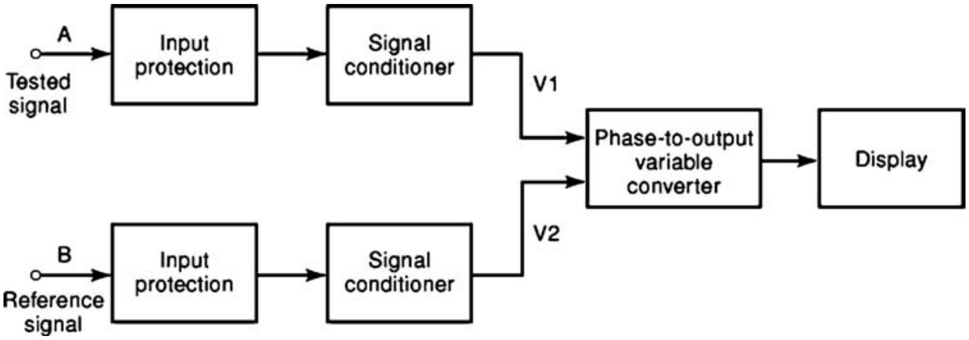


Figure 4. General block diagram of a phase meter.

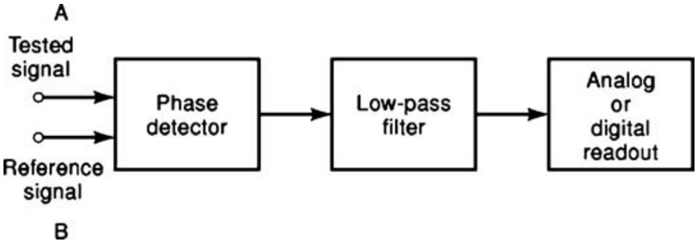


Figure 5. Phase-to-output variable converter with phase detectors.

Another four-quadrant product type of a detector and its static transfer characteristic are shown in Fig. 8. This type of a detector is often used in phase-lock-loop systems.

A classical digital phase meter shown in Fig. 9 uses two channel time interval measurement that combines the time shift between the waves and the period measurements. The meter could be a stand-alone unit or it could be a part of a frequency counter or an oscilloscope.

In some digital meters, the time shift between the waves can be initially converted into gate pulses whose duration is measured by a single channel time interval meter. The reading related to the period constitutes the measure of the phase shift (4). Figure 10 shows a phase-to-output variable converter in which an internal counter locks in to the input signal frequency producing a multiple frequency of the external signal. An internal counter counts the multiple-frequency pulses, and if the multiplication

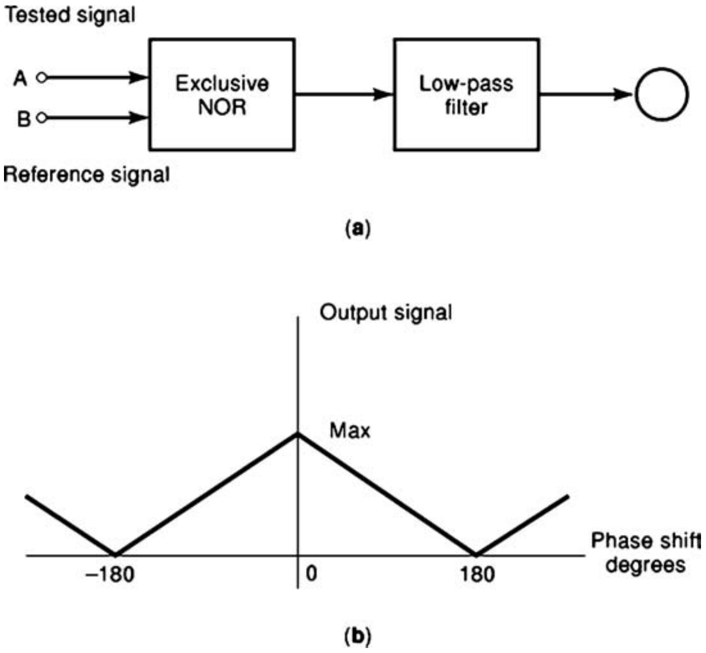


Figure 6. Two-quadrant phase detector. (a) Diagram. (b) Static transfer characteristic.

factor is 360 with the resolution of one degree, the phase shift is given directly in degrees. Larger multiplication factors, like 3600, offer better resolution. Application of the high-frequency clock whose frequency is much greater than the input signal repetition frequency requires compatible high-frequency counters (5).

Real-time sampling technique which is applied in modern data acquisition systems allows computations of the phase shift between two signals. The two signals are applied to the samplers through ant-aliasing filters. The sampled signals are then converted by analog-to-digital converters and stored in processor memory for further processing. The phase shift is calculated from the samples located near zero-crossings for both signals. Basic phase error is related to uncertainty of these samples (6).

Bridges measuring complex impedances and complex transmission coefficients also measure phase shift with the help of precision phase shifters. In the impedance meters, phase measurements are accomplished with reference to the calibrated phase shifter by adjusting and comparing the phase shifter and the system attenuator readings for unknown impedance by setting the output of a video detector to null. In the transmission coefficient measuring bridges, the signal is applied to the device under test and to the variable phase shifter. A general block diagram of such a meter is shown in Fig. 11, and a simplified diagram of a millimeter wave transmission coefficient bridge is shown in Fig. 12 (7).

DOWN-CONVERSION TECHNIQUES USED IN PHASE METERS

Phase-to-Output Variable Converters previously described are limited in their operation frequency range by the speed of the input circuits, logic circuits in a counter, and circuits of a phase detector. Although the frequency counters can directly measure frequencies of signals reaching far more than several megahertz, time interval measurements are affected by large errors which reduce operating frequencies for phase measurements.

In order to extend the phase meter operating frequency range the following techniques are used:

1. Down counting (8)
2. Sinusoidal heterodyne conversion (5, 9)
3. Coherent sampling (10)
4. Random repetitive sampling (11–13)

All methods involve acquisition of many periods of the signal under test.

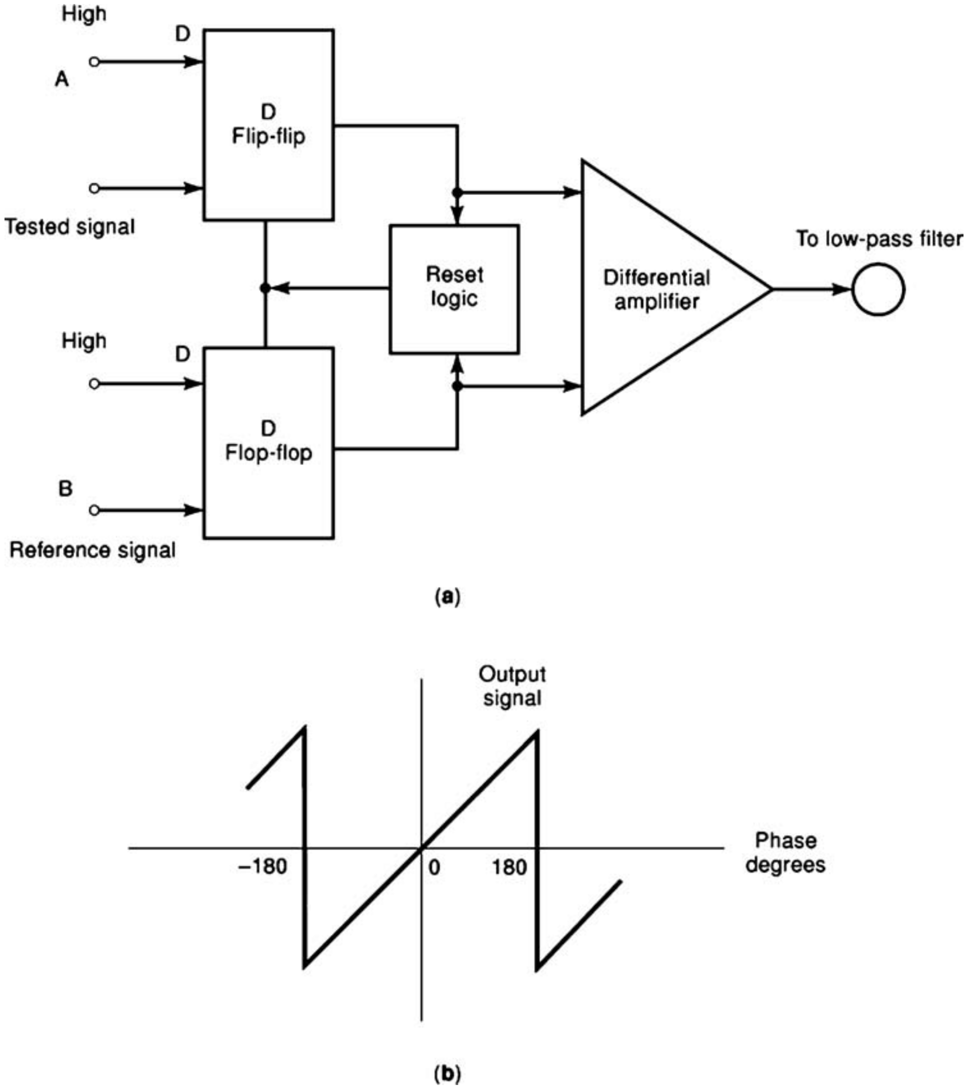
Application of the down-conversion technique in signal and network analyzers, impedance meters, and multichannel microwave receivers increases the frequency range of phase measurements to millimeter waves. The most critical issue in high-frequency tests related to wave separation is solved with the aid of directional couplers and hybrid-tee connectors.

Down Counting

Two input signals, the signal under test and the reference signal, are applied to two identical frequency dividers. As a result, lower frequency signals are measured in analog or digital circuits previously described. This method has found applications in high-speed frequency counters which also have the capability of time interval measurements leading to phase determination.

Sinusoidal Heterodyne Conversion

The heterodyne, single or double down-conversion process reduces the frequency of the tested signals by mixing so they can be acquired and directly processed by lower frequency phase meters. The block diagram of a typical heterodyne phase meter is shown in Fig. 13. The system is



(a)

(b)

Figure 7. Four-quadrant phase detector. (a) Diagram. (b) Static transfer characteristic.

designed to lock-in the voltage controlled oscillator to the incoming signal frequency of the reference channel so a signal of fixed intermediate frequency is produced. The voltage controlled oscillator also mixes with the other signal to reduce its frequency to the same intermediate frequency as that of the reference signal. Intermediate frequency signals are then processed by a classical low-frequency phase meter.

Coherent Sampling

The phase meter uses a fast sampling technique to down convert periodic high frequency signals to intermediate frequency signals. Initially, the internally generated sampling pulses are swept automatically until their frequency is locked to produce the intermediate frequency signals, as in Fig. 14. Two high-frequency input signals are sampled in the sampling gates which are switched on by very short sampling pulses. The samples are stored in analog memories (capacitors of sample-and-hold circuits). The sampling rate is automatically adjusted so each sample occurs at an earlier relative point on the waves during a subsequent recurrence of the waves. The reconstructed waveforms after sampling resemble the original waves but they have much lower frequencies. The sampling pulse frequency is controlled by a phase-locked-loop system which maintains the desired intermediate frequency at the sampler unit. The method is applied in vector voltmeters, network analyzers, and impedance meters to measure phase shift and magnitude of two different signals.

Another solution, shown in Fig. 15, involves a regular subsequent process of sampling typically used in sampling wave analyzers and oscilloscopes. Two input signals are sampled in sampling gates by very narrow sampling pulses whose timing is coherently triggered by the waves of lower frequencies which are synchronous submultiples of the input signal frequencies. Subsequent samples are automatically delayed so the output waves look like time-transformed input signals. The sampling rates do not exceed several hundred KHz while the input signal frequencies could reach more than 20 GHz. The time-domain transformation factors are very high. For instance, if 10 GHz

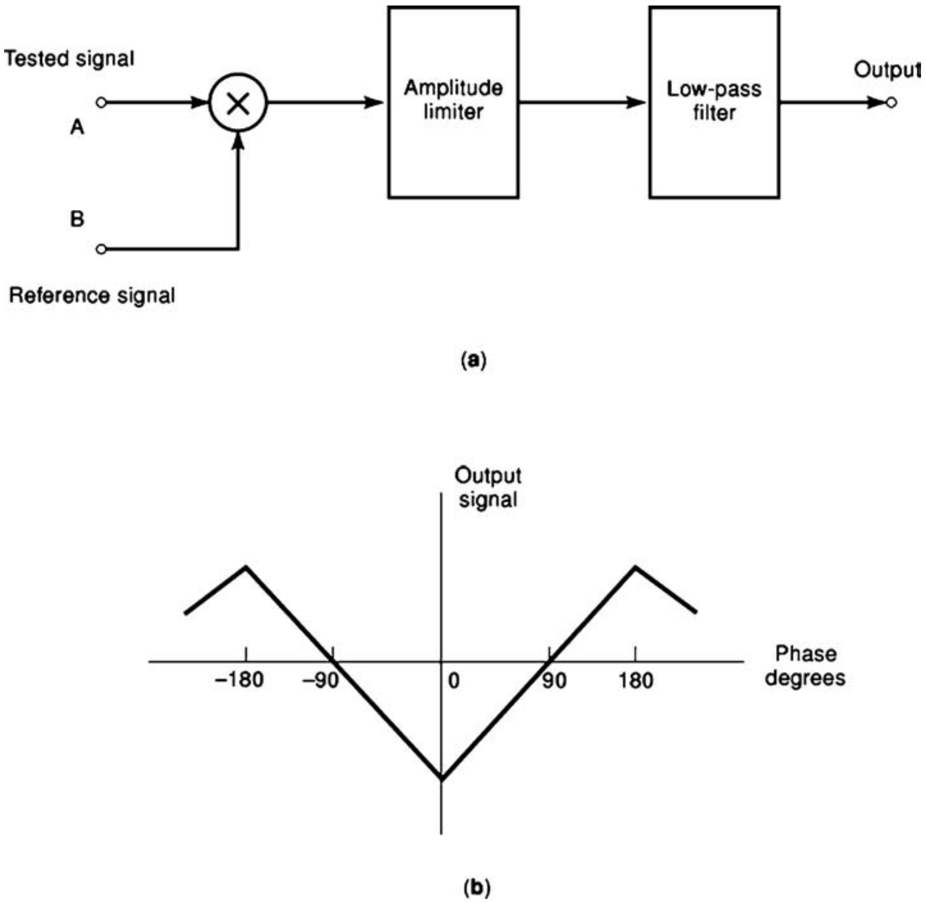


Figure 8. Four-quadrant analog phase detector. (a) Diagram. (b) Static transfer characteristic.

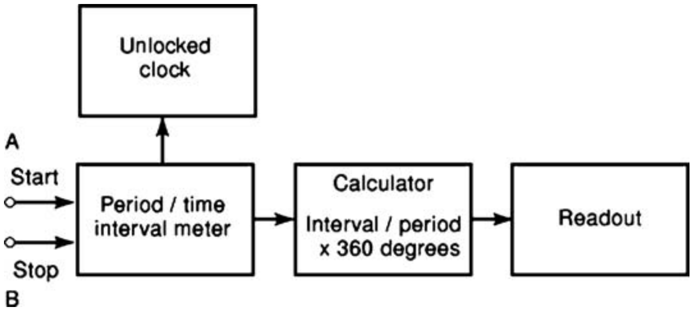


Figure 9. Phase-to-output variable converter with time interval meter.

waves are tested and 1000 samples are taken to reconstruct a period, with the samples located 10 μ apart, then the time transformation factor is 10^8. This allows determining the phase using a low frequency processor calculating signal parameters or a direct phase meter (14).

Random Repetitive Sampling

Random repetitive sampling is applied in modern digital scopes which can also measure time intervals and phase shifts. A typical block diagram of major parts of such a scope is shown in Fig. 16. Two analog signals applied to the inputs are converted into corresponding digital signals. The sampling process in analog-to-digital converters, including sample-and-hold blocks, is controlled by and acquisition processor. The analog signals are used to trigger the time base of the acquisition processor. The samples are not collected in a sequential order, and the processor determines their proper location in relation to the trigger signals synchronized with the input waves. The voltage and time coordinates of individual samples are stored in the processor memory. The waves can be displayed on the scope screen and all information about the waves is also available for further processing. The phase shift between the two tested signals is measured with measurement/storage modules, such as HP 54657A, HP 54658A, and HP 54659B.

The measurement requires the display of a minimum of one cycle of the reference signal. The data acquisition time necessary to capture one period is usually larger than in coherent sampling units. The internal computer, together with the measurement/storage unit, can produce the calculated result of the phase shift. In automatic measurement mode, the phase is referred to as 50% of the transition level. A wave processor, also shown in Fig. 16, reconstructs the waves and displays them at its own rate. Processes of ac-

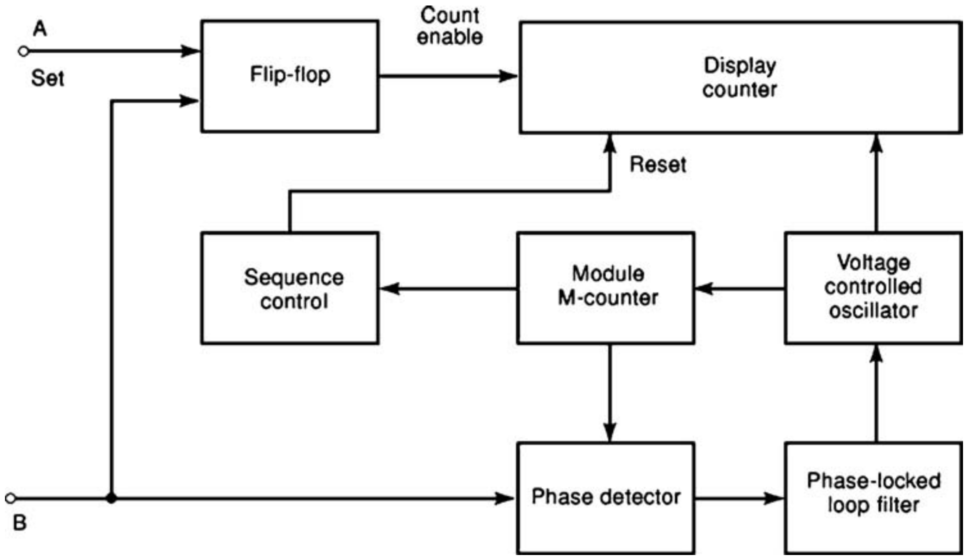


Figure 10. Counting phase-to-output variable converter with a frequency multiplier.

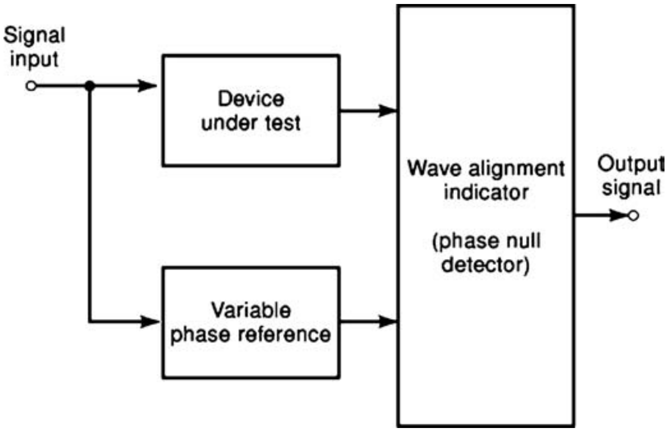


Figure 11. General block diagram of a referred direct phase meter.

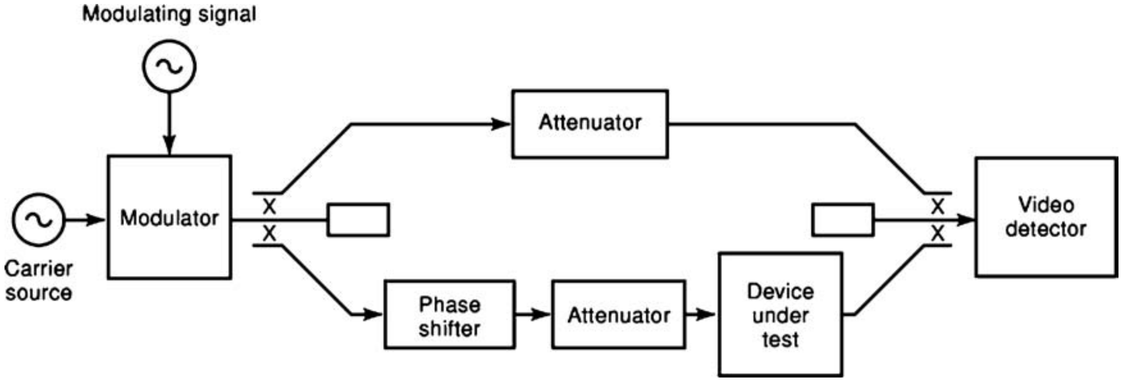


Figure 12. Simplified diagram of a referred complex transmission coefficient bridge.

quisition and wave reconstruction take a long time, but the enhanced signal processing capability of the system allows for automation of the phase shift measurements and other signal parameters.

EXAMPLES OF PHASE METERS AND OTHER PHASE MEASUREMENT UNITS

In this section, several examples of commercial phase measuring devices are discussed. Two typical stand-alone phase meters, a phase meter of a more advanced network analyzer, and a phase meter applied in a high-frequency

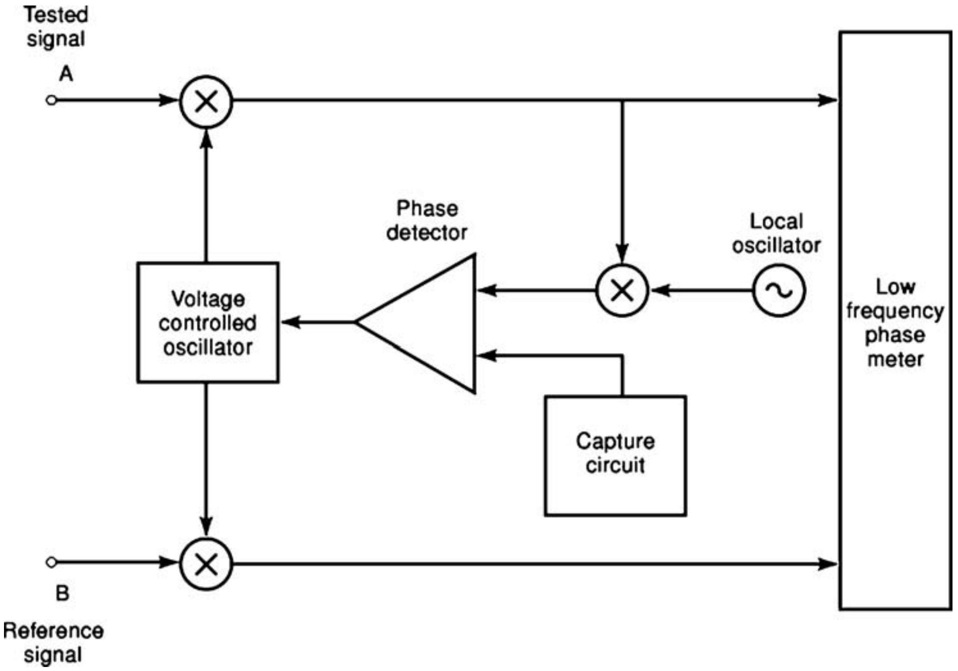


Figure 13. Simplified block diagram of a heterodyne phase meter.

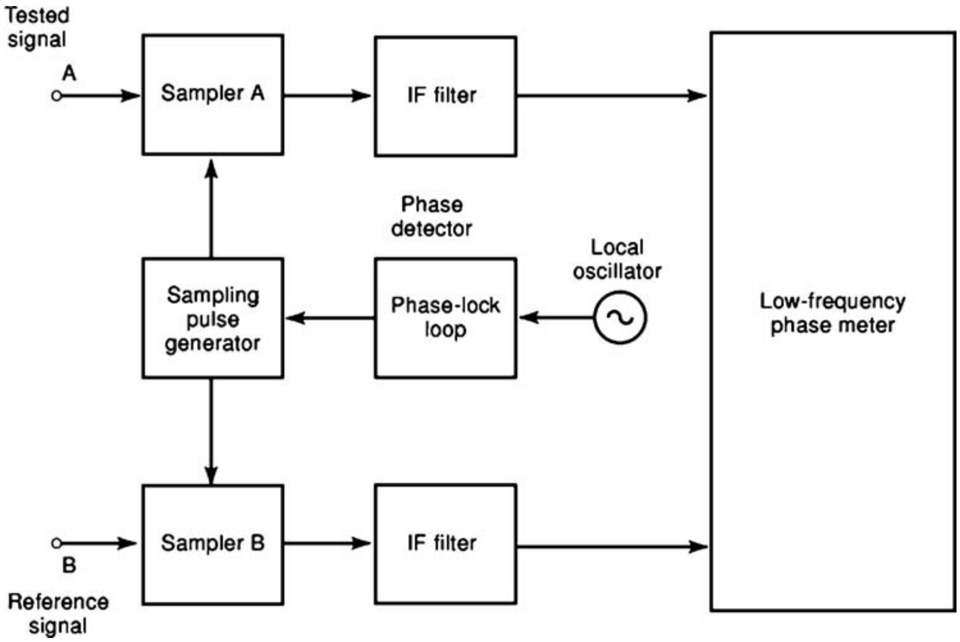


Figure 14. Simplified block diagram of a phase meter with a phase-lock loop coherent sampler.

impedance meter are included.

Example of Low-Frequency Direct Phase Meters

The first two units shown in Figs. 17 and 18 are two classical stand-alone phase meters designed by Feedback Instruments, Inc. (UK) (15). Both analog and digital meters have the same analog signal processors. In the analog meter the processor output signal, which is proportional to the phase shift between the input signals under test, is filtered and directly measured by a DC meter. In the digital meter, the processor output signal is converted into its digital equivalent form and displayed. The meters use a smart compensation technique to correct errors due to input comparator or input wave offsets which are critical when the input signals have different amplitudes. The mark/space ration-adjusting circuit fulfills this function. The analog meter operates up to 1 MHz, with a resolution of 1° and inaccuracy less than 2°. The digital meter operating within the same frequency range has a resolution and mid-frequency error of 0.1°.

Example of a Phase Meter Applied in Network Analyzers

Figure 19 shows the simplified block diagram of a typical network analyzer. The analyzer measures magnitude and phase responses of high-frequency networks. The signals can be acquired by three receivers which have double fre-

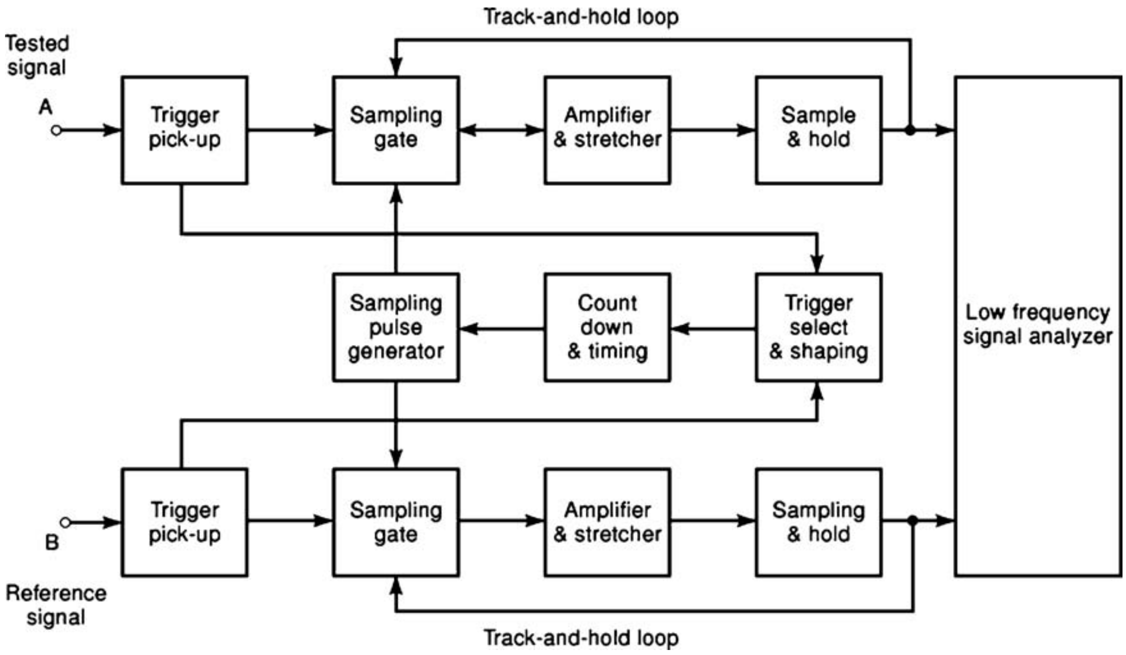


Figure 15. Simplified block diagram of a coherent sampler with a time base.

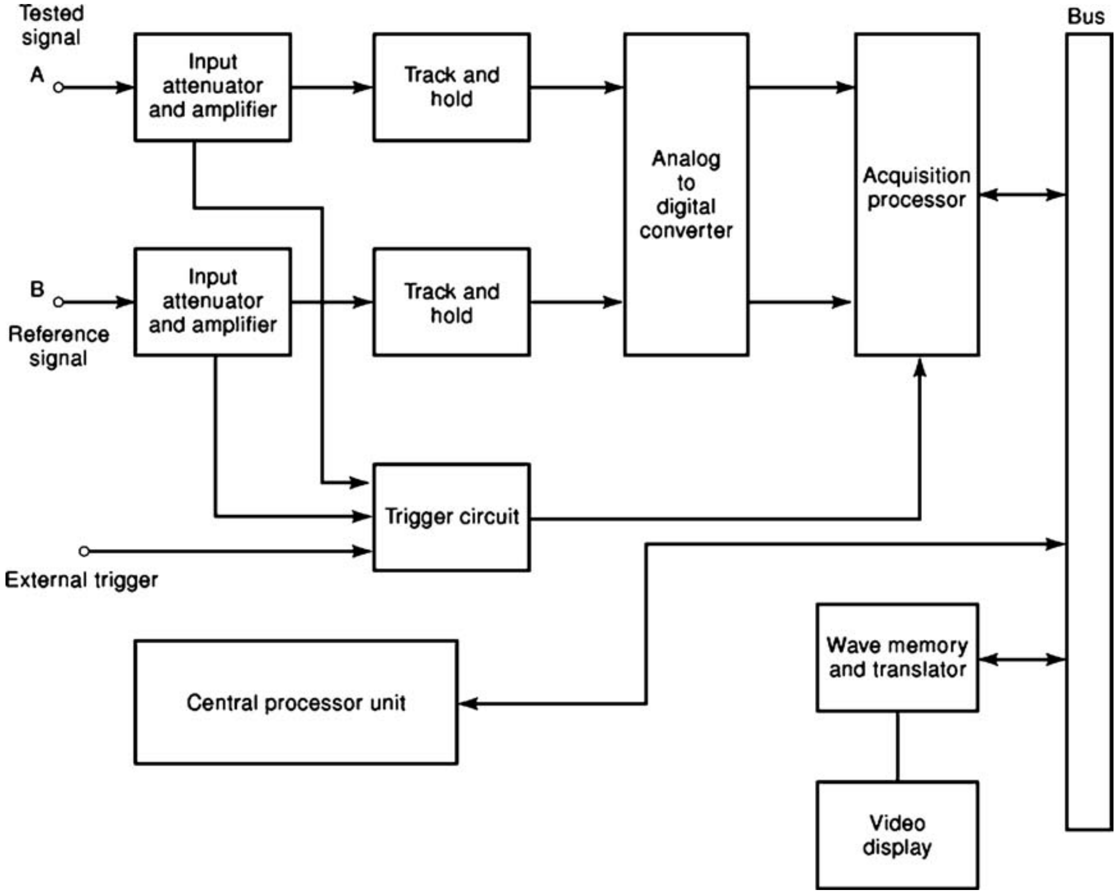


Figure 16. Simplified block diagram of a random repetitive sampling scope.

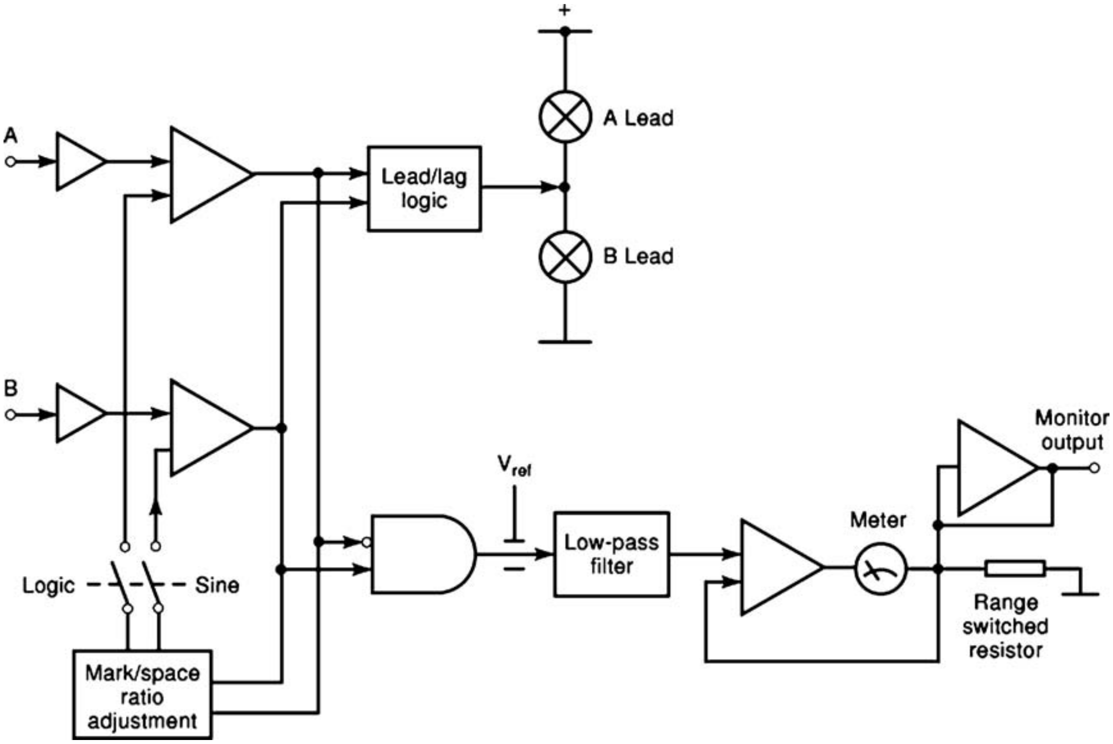


Figure 17. Simplified block diagram of Feedback Instruments Limited analog phase meter, APM 612 (Courtesy Feedback Instruments Incorporated).

quency down conversion. After conversion, the signals can be processed by analog quadrature detectors and split into real and imaginary parts to calculate phases and magnitudes after analog to digital conversion (Fig. 20). In some other solutions the signals can be sampled after frequency down-conversion, and then converted from analog to their digital equivalents. The output signals of the analog-to-digital converters contain both amplitude and phase information. In the receivers, digital quadrature detectors are used to generate real and imaginary parts of the converted input signals (9, 21). The signals are then filtered and processed by the fast math processor to yield magnitude and phase (Fig. 21).

Example of Phase Meters Applied in Wave Analyzers

Many wave analyzers, including some modern digital oscilloscopes, combine features of coherent samplers and digital signal processors. Figure 22 shows a two-channel signal analyzer in which time transformed waves in an analog part of the analyzer are converted into digital signals and then processed in the digital processor. The results of processing, in terms of wave parameters, like phase, magnitude, average value, and others are displayed. This type of circuit is used in the HP 71500A Microwave Transition Analyzer (16), and it is also applied in sampling digitizing oscilloscopes (13).

The details of another solution applied in wave analyzers and vector voltmeters involves the sampling techniques and is described in Coherent Sampling in this article can be found in (10).

Example of a Phase Meter Applied in an Impedance Meter

Figure 23 shows a block diagram of a vector impedance meter. Two high-frequency signals, one proportional to the voltage across impedance, the other proportional to the current of the impedance, are converted to lower, intermediate frequency by means of coherent sampling. The coherent sampling process is controlled by a phase-locked-loop circuit supported by a search loop, which acts when the phase-locked-loop is not locked. The intermediate-frequency signals are processed by a low-frequency pulse phase detector to determine the phase. A voltage magnitude signal, after demodulation, defines the impedance magnitude.

ERRORS IN PHASE METERS

The errors affecting the accuracy of direct phase measurements originate in analog and digital parts of different phase measuring devices described before. The phase measuring devices have two or more channels. Misalignment of the channels, threshold levels, gains, differences in hysteresis loops of comparators, and noise introduce major errors. If analog readout is used the reading error is added to the previous errors. In digital time interval meter errors also involve the time base uncertainty and the count error [17,18,19]. Frequency down-conversion introduces additional phase errors due to differences in converter channels. Low-frequency digital phase meters operating without built-in references can have their maximum errors below 0.1° (17).

Calibration of low-frequency phase meters requires application of high precision, digitally synthesized variable

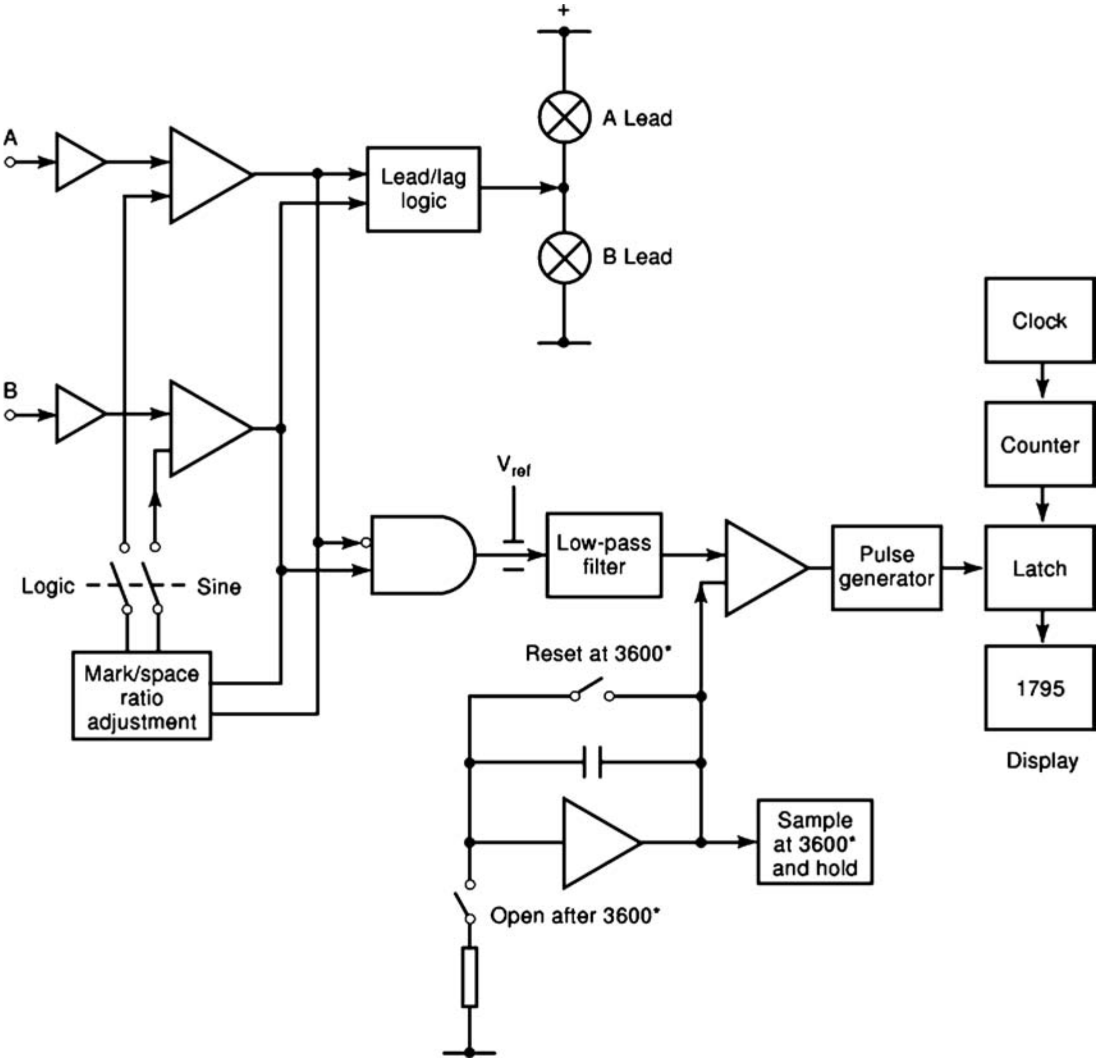


Figure 18. Simplified block diagram of Feedback Instruments Limited digital phase meter, DPM 609 (Courtesy Feedback Instruments Incorporated).

phase generators whose estimated uncertainties do not exceed 20 millidegrees (20). In microwave and millimeter wave regions, air-filled transmission lines of calibrated lengths help achieve significant accuracy. The length of such lines can be measured with laser interferometers yielding errors below 0.01° (17).

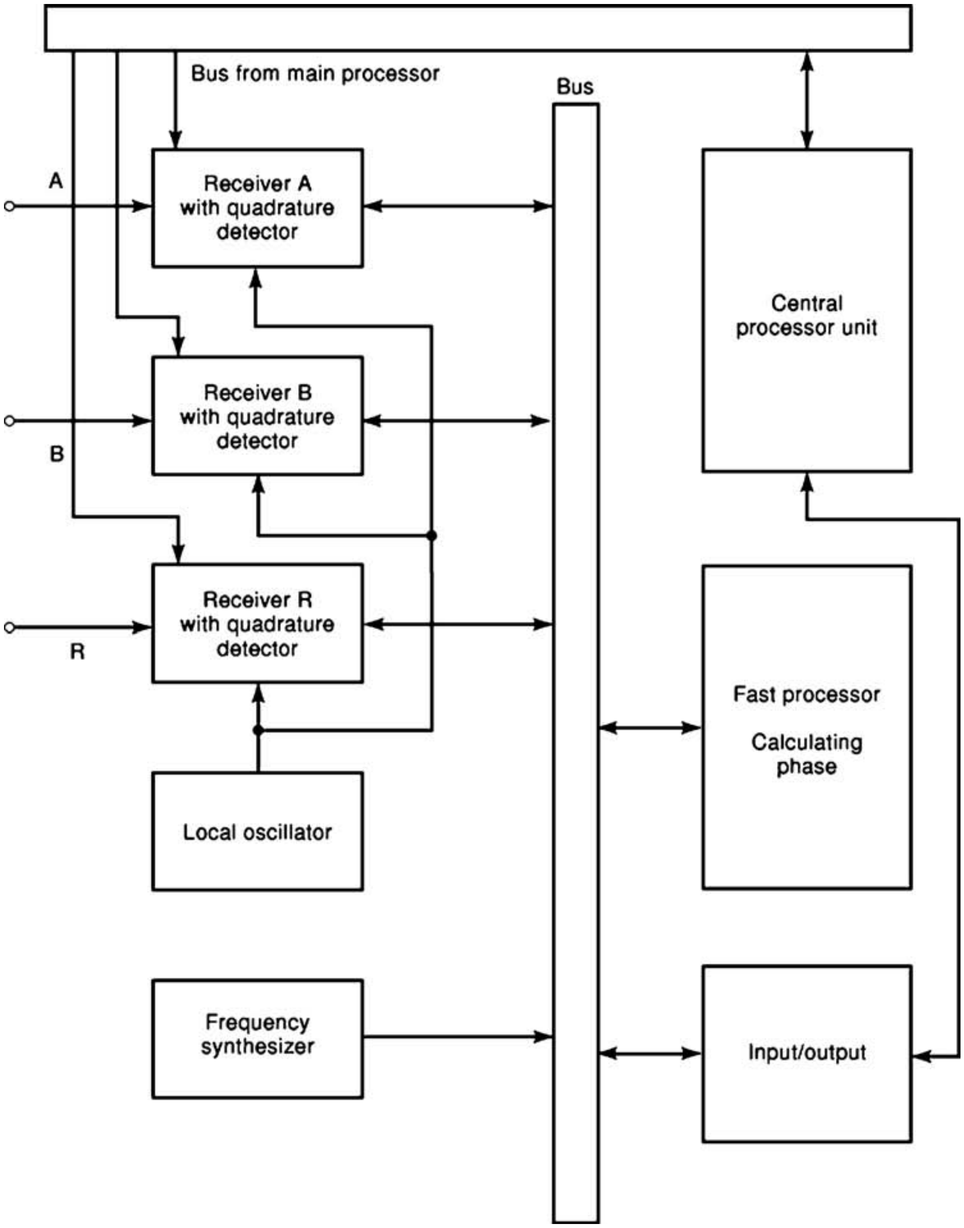


Figure 19. Simplified block diagram of a network analyzer with receivers and quadrature detectors.

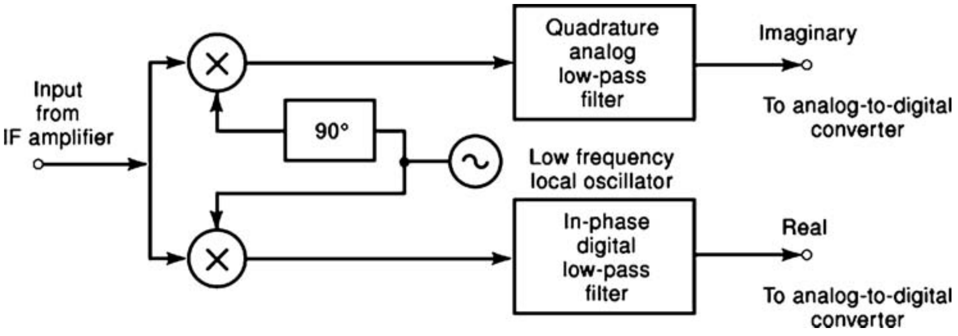


Figure 20. Quadrature analog detector recovering real and imaginary signal components.

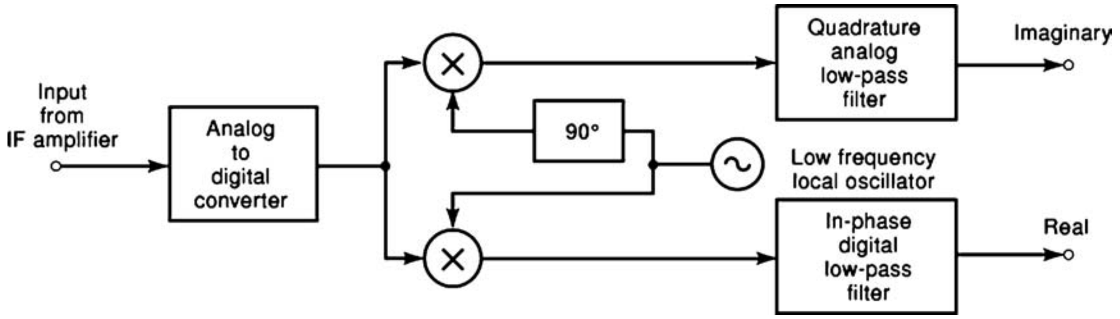


Figure 21. Quadrature digital detector recovering real and imaginary signal components.

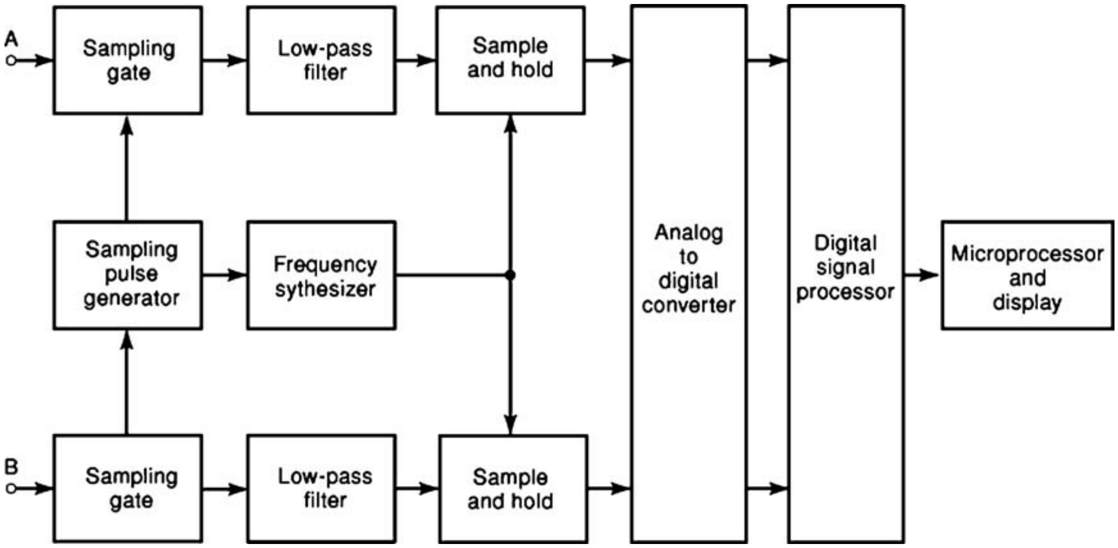


Figure 22. Simplified block diagram of a transition wave analyzer.

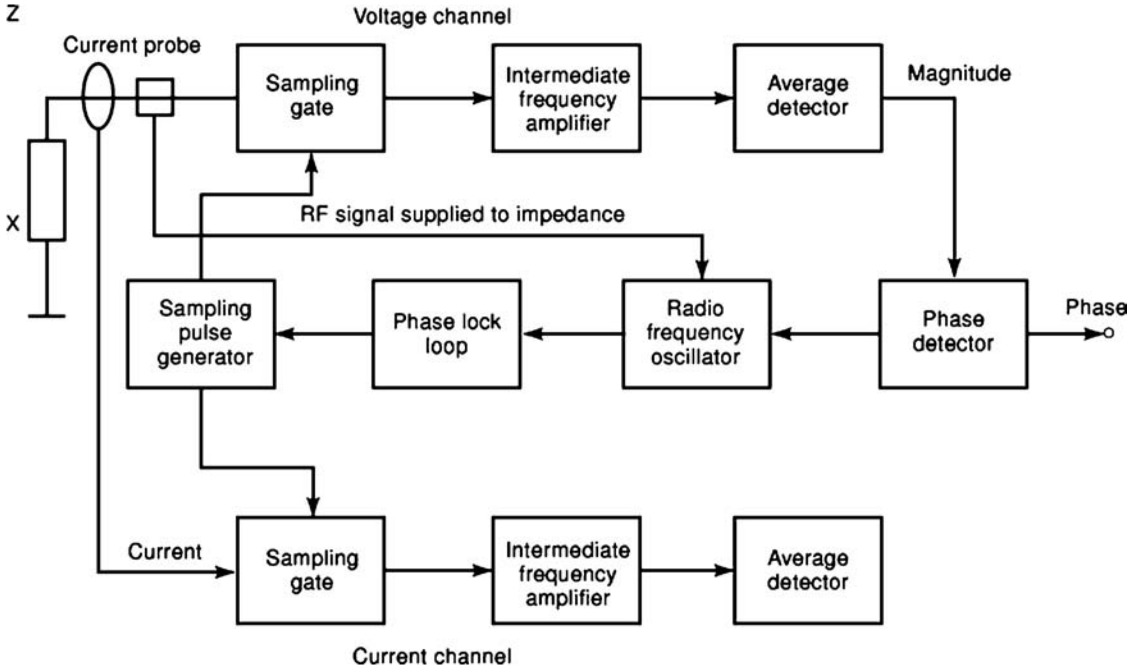


Figure 23. Simplified block diagram of an impedance meter with a phase meter unit.

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