Time and Frequency Measurements

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ABSTRACT

This paper summarizes the field of time and frequency measurements. It discusses their basics, the underlying technologies, the specifics of commonly-used clock measurement systems and the ways the resulting phase or frequency data is utilized to characterize precision frequency sources.

INTRODUCTION

• Time and Frequency Measurements

Time and frequency are among the fundamental physical parameters that commonly must be measured, often with demanding requirements for precision and accuracy. Those parameters are closely related since frequency is the rate of change of phase (time). There are myriad techniques for performing those measurements, and some of those methods, with an emphasis on the time-domain, are the subject of this paper. See [1-14] for general references for time and frequency measurements.

Most time and frequency measurements today use some form of digital instrumentation to produce readings in numeric form [A]. Those readings may be utilized directly or can serve as data for some form of analysis (e.g., frequency stability). The measurement technique must be appropriate for both the time or frequency source under test and the purpose of the measurement.

All time and frequency measurements require a reference (e.g., a frequency standard), preferably one having higher stability and greater accuracy than the source under test.

The performance of a frequency source can be measured in either the time or frequency domain. While they should produce comparable results, and domain conversions are possible, it is usually found that one or the other domain is most suitable for a particular measurement. Generally this means that time domain measurements are best suited to characterize medium and long-term performance via time series statistical analysis (e.g., Allan deviation), while frequency domain measurements are best suited to short-term performance via phase noise spectral analysis. The traditional separation between these domains has been at an observation time of > 1 second and a sideband frequency > 1 Hz but those bounds are often widened for modern measuring systems.

• Terminology

The field of time and frequency metrology, like most, uses specific terminology, some of which is described below.

A precision *frequency source* often takes the form of an active quartz crystal oscillator (XO), which is usually oven controlled (OCXO) and whose frequency may also be voltage controlled (OCVCXO). Another common type of precision frequency source is a rubidium (Rb) or cesium (Cs) passive atomic *frequency standard* wherein a crystal oscillator is locked to an atomic reference. Any of these devices may be called a *clock*, regardless of whether or not it drives timing circuits [B]. Thus the terms frequency standard and clock are often used interchangeably. A frequency standard typically produces an output at some *standard frequency*, e.g., 10 MHz.

Clock metrology takes the form of either *phase* or *fractional frequency* measurements with respect to the reference device, where their relative phase can be expressed in either angular or time units and fractional frequency is a normalized value equal to the frequency deviation divided by its nominal value. A phase reading is instantaneous (e.g., a timetag) while a fractional frequency reading is the difference between two phase values divided by their interval. Fractional frequency and time are equal, $\Delta f/f = \Delta t/t$, so a frequency offset of 1×10^{-12} is equivalent to a time change of 1 ps per second.

Frequency stability analysis generally applies to equally-spaced phase or frequency measurements taken at a particular *measurement interval* denoted by the lower-case Greek letter *tau* (τ). Other words used for this quantity are *sampling interval*, *measurement time*, *sampling time* or *averaging time*. The measurement and sampling terms are usually associated with the measurement process itself, while the averaging time applies to the analysis. The basic measurement interval is often denoted as τ_0 while the analysis averaging time is simply called τ. Phase data in this context have units of seconds denoted by x, while frequency data are dimensionless fractional frequency denoted by y [15]. A frequency stability analysis often involves calculating the Allan variance (AVAR) or its square root (ADEV).

Aging refers to a slow change in frequency due to internal effects while *drift* describes the change caused by all mechanisms including environmental sensitivities.

• Data Averaging

Data taken at a certain measurement interval τ_0 can be *averaged* to become data at an integer multiple n of the measurement tau, $\tau=n\cdot\tau_0$, and the use of the term *data averaging* can sometimes lead to confusion [16]. Frequency data are averaged to a longer tau by ordinary *algebraic averaging*, while phase data undergo the same transformation by *decimation* (actually *downsampling*, see Figure 1). In other words, to average frequency data, one adds n adjacent frequency points and divides that sum by n, while, to average phase data, one simple uses every nth point by skipping $n-1$ intermediate points, where n is called the *averaging factor*, *AF*. Thus we average frequency data by averaging and we average phase data by decimation. In both cases, we call the process averaging, but it is performed by decimation for phase data.

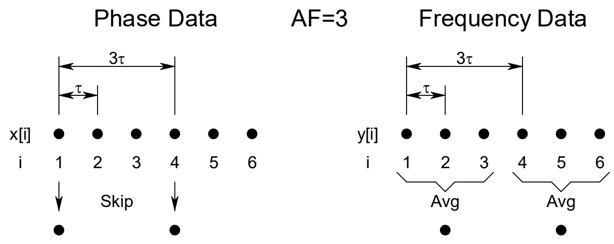

Figure 1. The Averaging of Phase and Frequency Data

• Resolution, Precision, and Accuracy

Resolution refers to the numerical limit imposed on the fineness of the measurement by the digital hardware, e.g., the number of digits captured and the quantization of the readings. *Precision* is a more general term related to the fineness of the measurement and includes its noise, scatter and reproducibility. *Accuracy* refers to the degree which the measurement is correct, e.g., conforms to a standard. One can have varying degrees of both precision and accuracy as shown in Figure 2 [14]. The measuring system resolution and/or noise floor generally sets the former while the latter is determined by the reference.

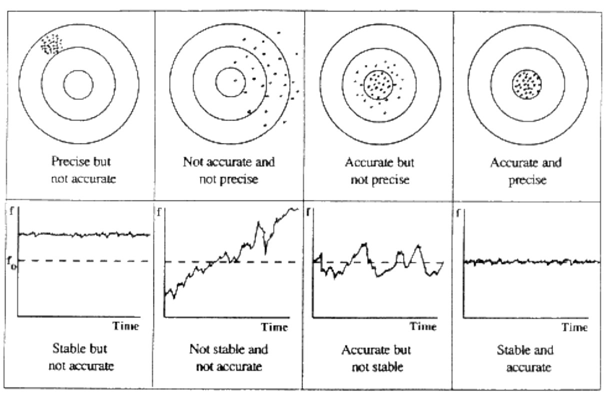

Figure 2. Precision and Accuracy

MEASUREMENT ATTRIBUTES

• RF and Pulse Inputs

Clock measurement systems tend to fall into two categories, those handling RF (e.g., 10 MHz) inputs and those handling pulse (e.g., 1 pps) inputs. While it is quite easy to convert an RF signal into a low rate digital waveform (e.g., a 10^7 divider), the opposite conversion is more difficult.

• Scanned Clock Measurement Systems

A multi-channel clock measurement system can devote measurement hardware to each channel or one set of hardware can be shared with all channels in a scanned system. In the case of scanned frequency measurements, there will be a large (and perhaps variable) dead time between measurements, while scanned phase measurements will maintain continuity but will have wider spaced data points. The tradeoff for potentially lower hardware complexity and cost with a scanned system is therefore fewer lower quality measurements.

Scanned frequency data may be quite adequate for long term aging measurements but is much less satisfactory for a statistical stability analysis. Scanned phase data may be quite satisfactory for all purposes where channels do not need to be measured as often or at the same time.

Scanning can be accomplished with either RF or pulse (e.g., 1 pps) clock signals. The former is appropriate only for frequency measurements, and care must be taken to provide adequate isolation between channels. Pulse switching is generally easier, and can be done for multichannel phase measurements by providing a divider (e.g., 10 MHz to 1 pps) for each channel and switching one signal to a shared time interval counter. This is particularly easy in the case of a source having an internal 1 pps output that can be appropriately disabled.

Controller hardware/firmware and a user interface is mandatory for a scanned clock measurement system. It is best that the data rate of each channel be constant regardless of the number of active channels.

• System Hardware, Firmware and Software

A typical clock measuring system contains analog and digital hardware, internal firmware to perform the measurement process and output the data, and external user interface software to control the system and store the data. The hardware can use standard instrumentation (e.g., a commercial counter) or custom circuits. The user interface software generally runs on a dedicated computer via a direct (e.g., USB) or LAN connection.

• Clock and Environmental Monitors

Clock measurements are often accompanied by data logging of clock monitor signals and environmental parameters, particularly during longer term measurement runs and where environmental sensitivity is being observed. These monitor data can be recorded by a data acquisition system (DAQ) and correlated with the clock measurements.

• Aliasing

Aliasing refers to the effect of taking discrete measurements at an insufficient sampling rate to resolve faster changing variations that are thereby downsampled and appear in the data as lower frequency components. One can obviously not expect to observe behavior of the device under test that occurs faster than measurements are made. Indeed, per information theory, two samples per cycle are the minimum required to perform a measurement. But, as a practical matter, it is worse than that because front-end low-pass anti-aliasing filtration is generally not possible and high frequency components (see Interference below) can corrupt time domain measurements.

• Interference

Power line and other such electrical interference can be a problem, especially for time domain measurements where the interference shows up indirectly through aliasing as slow variations related to differences between the AC power line frequency and the measurement tau.

Frequency domain (RF spectrum analyzer and phase noise) measurements often show spectral spikes related to AC power line harmonics and computer clocks. Once identified, they can simply be ignored in many cases. Otherwise, much fiddling may be required to reduce or eliminate them (see below). In extreme cases, one may resort to DC or battery power for all system components or even operate instruments at an alternative AC power frequency to identify the root cause of spurious components.

In general, it is reasonable to say that the best result (the one with least interference) is the correct one unless the interference is internal to the device under test.

• Ground Loops, AC Fields, Power Strips and RF Isolation Transformers

Ground loops are a common cause of interference in time domain frequency stability measurements. Those problems can arise from AC power line currents flowing through interconnecting RF coaxial cables, through instrument chassis grounds, and even because of stray AC power line magnetic fields.

RF isolation transformers can help to reduce or eliminate conducted interference problems, and since they should not ever cause harm themselves, can be a permanent part of a measurement setup [17].

A simple but effective technique is to operate all parts of the measurement system (source, reference and instrumentation) from the same AC power strip thereby avoiding any neutral ground currents.

It is advisable to use linear rather than switching DC power supplies wherever possible for all instrumentation. Ferrite beads and USB isolators can help to reduce or eliminate interference via computer cables.

• Outliers

Time and frequency measurements are subject to anomalies due to either the device under test or the measurement system [18]. When such anomalies occur, it is important to explain all outliers, thereby determining whether they are due to the measurement process or the device under test. An important first step is to correlate the bad point with any external events (e.g. power outages, equipment failures, etc.) that could account for the problem. Failures of the measurement system, frequency reference, or environmental control are often easier to identify if multiple devices are under test. A common gap in all measurement channels points to a failure of the measurement system, while a common change in all measurement readings points to a reference problem. Auxiliary information such as monitor data can be a big help in determining the cause of outliers.

A log of all measurement system events should be kept to facilitate outlier identification. Discrete phase jumps are a particular concern, and, if they are related to the RF carrier frequency period, may indicate a missing cycle or a problem with a digital divider. A phase jump will correspond to a frequency spike with a magnitude equal to the phase change divided by the measurement interval. Such a frequency spike will produce a stability record that appears to have a (large magnitude) white FM noise characteristic, which can be a source of confusion.

• Time (Phase) Versus Frequency Measurements

Only phase measurements can assess the relative phase between the source and reference clocks. Phase measurements are much to be preferred over frequency measurements for most purposes because it implies continuous observation of the device under test. One can confidently use phase data to obtain corresponding frequency data by calculating 1^{st} differences, and can easily down sample the phase data to a longer measurement tau. One can perform the inverse conversion from fractional frequency to phase only by assuming zero dead time and an arbitrary initial phase value, and must use algebraic averaging to a longer tau.

• Phase – Frequency Conversions

Phase data can be converted to frequency data by calculating their 1^{st} differences (numerical differentiation) while fractional frequency data can be converted to phase data by numerical integration. In the latter case, the frequency data must have zero dead time or one must assume that the frequency value correctly represents that of the source over the whole measurement interval.

• Dead Time

Dead time between measurements should be eliminated or minimized both to avoid missing data and to best support subsequent stability analysis. Dead time occurs most often in frequency measurements with an ordinary counter which requires a finite amount of time to reset between measurements, resulting in data with a measurement spacing that is longer than the measurement tau.

While it is perfectly reasonable to collect frequency data at widely-spaced intervals with a much shorter measurement tau for observing frequency aging, that data is unsuited for performing a statistical (ADEV) analysis. For that, zero, or perhaps low, dead time is necessary, which in the later case can use the Barnes B2 ratio to apply a dead time correction [11].

Phase data intrinsically has no dead time and is to be preferred.

• Noise Floor

The most important performance attribute of a clock measuring system is its noise floor, its effective measurement resolution. That property can be assessed by applying low noise coherent inputs to both its signal and reference ports and observing the resulting stability data, which generally takes the form of white PM noise that has an ADEV that decreases with averaging time as τ^{-1}. The noise floor is usually set by either by internal system noise or by data quantization.

An example of a noise floor plot for a clock measurement module is shown in Figure 3 [19].

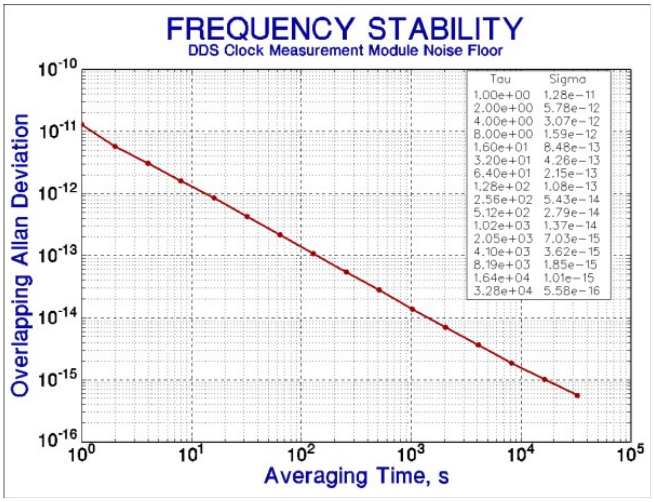

Figure 3. Noise Floor Plot for a Clock Measurement Module

• Data Quantization

Data quantization often sets the useful resolution of a clock measuring system. Quantization can be detected by observing the numeric data, by plotting it, or for better visibility, by displaying it with an lag 1 autocorrelation scatter plot as shown in Figure 4 [20]. Quantization noise has the statistical properties of white noise (e.g., ADEV log slope of -1 for W PM and -½ for W FM noise).

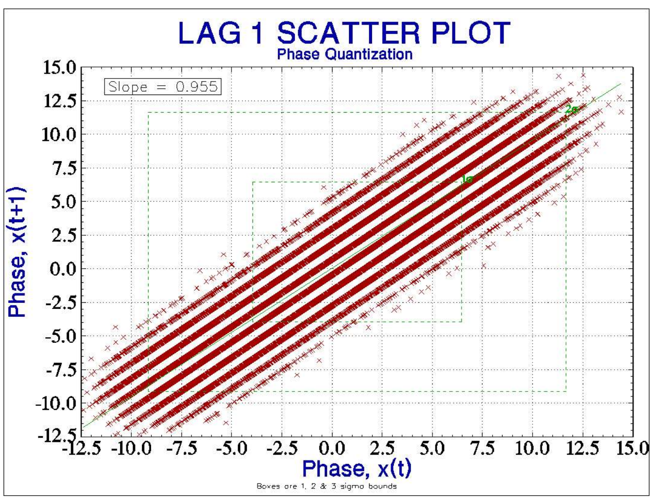

Figure 4. Lag 1 Scatter Plot Showing Phase Quantization

• 3-Cornered Hat

It often occurs that the reference stability is not greater than that of the source being measured, and one must adjust the results accordingly. This situation can exist over all or a portion of the averaging times under observation. In the case of two assumed identical sources, one can estimate their individual ADEV stabilities by dividing the results by √2. If three sources are available, it is possible to estimate their individual stabilities by measuring them as three pairs and using the so-called 3-corned hat method [C, 21-29].

MEASUREMENT METHODS

• Oscilloscope

An oscilloscope can serve as a low-precision way to perform a time comparison between two waveforms and to make an estimate of the frequency of a signal. Modern digital oscilloscopes often include a numeric readout of these quantities. Although that increases the measurement resolution it is still only suitable to obtain approximate values. Such estimates can be improved by watching the slew rate between two signals: At a frequency offset of $1x10^{-9}$, a 10 MHz signal will slew 1 period in 100 seconds.

In a frequency standards laboratory, an oscilloscope is most useful for troubleshooting, determining nominal frequency, as well as signal amplitude, waveform, distortion and general cleanliness, often with a 50 Ω input termination.

• Frequency Counters

The most common instrument for making time and frequency measurements is the frequency counter, a generic term for a device that uses digital techniques to count pulses over a certain time interval.

In its simplest form, a frequency counter displays the frequency in hertz of an input waveform as the count of the zero crossings over a 1 second interval derived from its reference. The measurement precision is limited by the number of input frequency cycles, the measurement time, and the noise of the counter's input circuits (see Sine to Digital Conversion below), and can be enhanced as described below (see Reciprocation and Interpolation).

Similarly, a period meter displays the count of reference zero crossings during one or multiple cycles of the input signal. The time resolution is the reference clock period divided by the number of periods averaged.

The term "universal counter" is often used for an instrument that implements frequency, period and time interval (and perhaps other) counter modes [30-31]. Counters come in a wide variety of types and resolutions, and are available as plug-in boards, modules and complete instruments. A popular example of the later is the Stanford Research Systems SR620 Time Interval/Frequency Counter with $1x10^{-11}$/s resolution shown in Figure 5.

Figure 5. Stanford Research Systems SR620 Counter

Some modern counters operate by time tagging events and displaying frequency, period or time interval based on those values (see Timestamping below).

The Time Interval Analyzer (TIA) is advanced form of counter capable of doing high resolution timetagging of events at a very high rate, but it is also suitable for making frequency, period and time interval measurements [32]. Figure 6 shows the GuideTech GT668 which has 0.9 ps resolution when driven with fast, low jitter pulses.

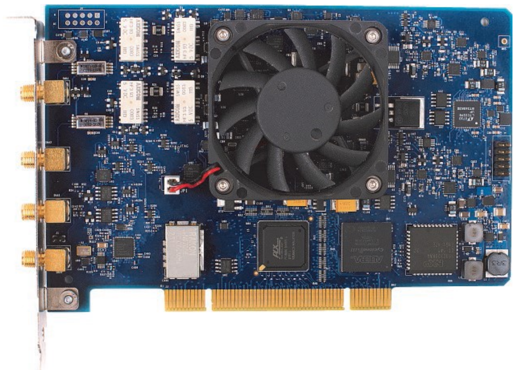

Figure 6. GuideTech GT668 Time Interval Analyzer

• Reciprocation

Modern frequency counters generally obtain the best frequency resolution by making period measurements using a higher frequency internal clock and mathematically converting (reciprocating) the result.

• Interpolation

The digital resolution of a counter, generally equal to the clock period, is often enhanced by analog interpolation. That process, which can take the form of linearly charging a capacitor between the input and clock zero crossings and reading the resulting voltage, can improve the resolution by a significant factor (e.g., up to say x1000).

• Timestamping

Alternately, a frequency counter can operate by time stamping the zero crossings of the input waveform versus the reference. The input period is the average of the difference between adjacent timestamps, while the input frequency is the reciprocal of that value.

Other timestamping instruments use quite sophisticated signal processing, e.g., linear regression [33], to obtain high resolution and low noise, with the caveat that that can change the statistics of the resulting data [D].

• Time Interval Counters

A time interval counter measures the difference between a pair of start and stop signals, by either counting clock pulses during that interval or by time tagging the start and stop events, with respect to a reference clock [12, 34-36].

An example of a low cost 60 ps resolution time interval counter suitable for measuring a pair of 1 pps signals is the TAPR TICC shown in Figure 7 which is a daughter board for an Arduino computer E, 37-42].

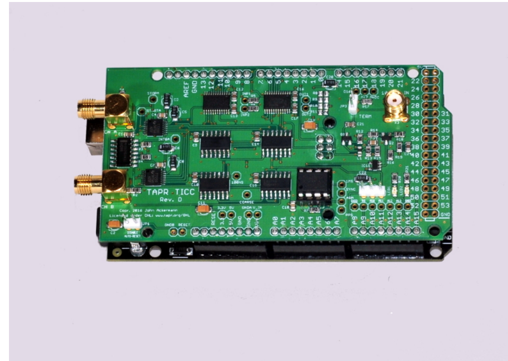

Figure 7. TAPR TICC Timestamping Time Interval Counter

A block diagram of a time interval clock measuring system is shown in Figure 8. It can be an excellent choice.

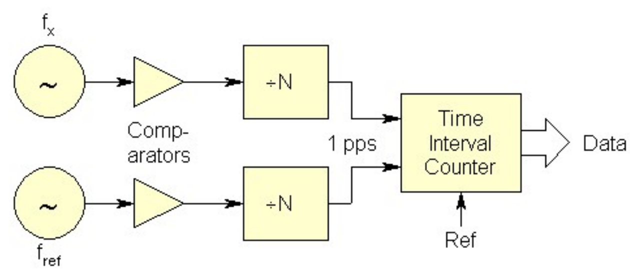

Figure 8. Block Diagram of a Time Interval Measuring System

• Sine to Digital Conversion & Zero-Crossing Detectors

RF and audio sinewave to digital conversion (zero crossing detection) is critical for achieving a low noise floor in clock measuring devices, particularly for the beat note in a heterodyne or dual mixer time difference system [43-46]. This low frequency signal (e.g., 1 kHz) which conveys the phase information has modest amplitude (e.g., 0.5 V) and a relatively low slope (e.g., 3 V/ms) that must be amplified and zero crossing detected with minimal noise. The usual technique is to use several cascaded stages of amplification with gradually increasing bandwidth. Discrete bipolar transistor differential amplifiers [47], low noise op amps followed by fast comparators, and specialized ICs, e.g., LTC6957, [48-49], have been used for this purpose.

Minimal hysteresis should be used so as to avoid offsetting the triggering point from zero.

Counter input circuits are sub-optimum as zero crossing detectors because they necessarily have a wide input bandwidth, and may also be located in a somewhat noisy digital environment.

• Phase Spillovers

Time interval measurements will spill over when the phase difference passes between zero and its maximum value, the signal period, at a rate determined by the frequency offset between the two inputs. This is a major reason (besides setting the measurement tau) that RF signals are divided down to (say) 1 pps rates before undergoing time interval measurements. It is awkward (but not impossible) to correct for these phase spillovers (see Figure 9), especially if they oscillate back and forth at the transition.

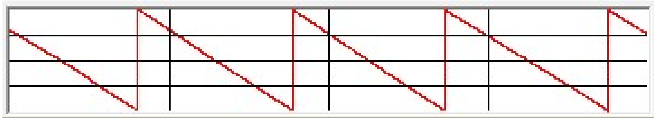

Figure 9A. Phase Data with Spillovers

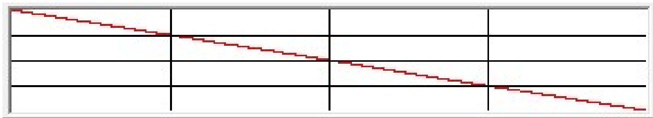

Figure 9B. Phase Data with Spillovers Removed

• Heterodyne Techniques

Heterodyne techniques (frequency mixing and downconversion) are often used to enhance the resolution of a frequency measurement. By subtracting a local oscillator (LO) reference frequency that is near that of the signal under test, a counter can measure the period of the resulting small difference frequency (beat note) with greater resolution as shown in Figure 10 [F].

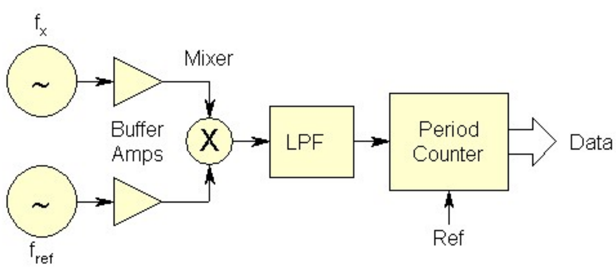

Figure 10. Block Diagram of Heterodyne Frequency Measuring System

Phase information is preserved through a frequency mixing process, and downconversion to a lower frequency allows subsequent measurement hardware (e.g., period counter) to achieve higher resolution.

In most cases, the IF frequency after downconversion is much lower than the RF frequency of the source under test; this provides a large heterodyne factor to enhance the period meter resolution. The counter resolution is set by its digital clock rate and interpolation factor (if any); a lower beat note frequency will increase the heterodyne factor and overall measurement resolution at the expense of a narrower nominal source frequency range and longer minimum measurement tau. A lower beat frequency also make low noise sine to digital conversion more difficult.

For example, consider a heterodyne frequency measuring system for a 10 MHz source and a 100 Hz beat note (reference offset) making a 1 second measurement using a 100 period average with a traditional non-interpolated period meter having a 100 MHz clock. The fractional period meter resolution is therefore 10 ns / 1 second or 10^{-8} and the heterodyne factor is 10 MHz / 100 Hz or 10^5, thereby providing an overall fractional frequency resolution of 10^{-8} / 10^5 or 10^{-13}.

As an alternative to making a digital period measurement of the beat frequency, it can be estimated using the FFT or by a sine fitting algorithm. The latter has also been used after direct sampling at 10 MHz [50].

The principal disadvantage of this heterodyne arrangement is that it only supports frequency measurements and that it provides no indication of the sense of the frequency difference between the RF and LO signals. In also requires the generation of a low noise offset LO as its reference, and the system is therefore limited to a single nominal frequency.

Even though a period counter making a time measurement is used, it is still measuring the beat note frequency (not the source phase). With a classic multiple-period counter, the measurement tau is set by the beat note rate; the tau actually varies slightly with the frequency noise, but that is not a cause for concern. The bigger concern is dead time; for a classic period counter, even one that reciprocates the result and/or uses interpolation, there is a small but finite delay between measurements. That is normally not a problem either, and complicated approaches (such as an alternating pair of counters) are rarely necessary. Dead time is avoided completely in a counter that captures timestamps.

• Dual Mixer Time Difference Configuration

Dual Mixer Time Difference (DMTD) clock measuring systems combines the resolution enhancement of heterodyning with a dual channel arrangement that allows for phase measurements to be made between the reference and device under test with a time interval counter (TIC) as shown in Figure 11 [51-59]. This arrangement has the further advantage of using a common offset LO whose noise contribution tends to cancel out, particularly when the inputs to the TIC are nearly coincident.

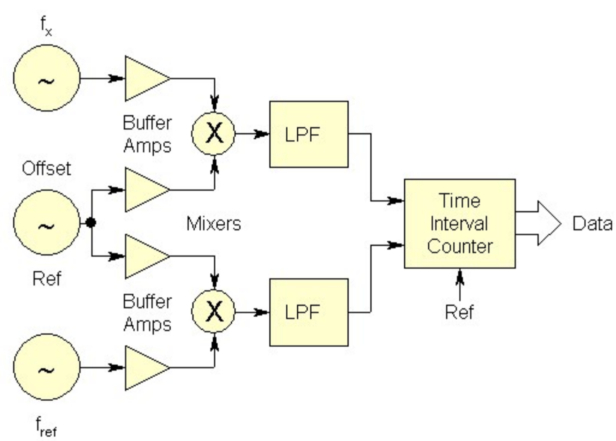

Figure 11. Block Diagram of Dual Mixer Time Difference Clock Measuring System

The DMTD hardware comprises buffer amplifiers for the RF and offset LO signals to provide isolation and input termination, dual analog frequency mixers, low pass filters for the beat notes, and a time interval counter. The TIC has low noise zero crossing detectors at its start and stop inputs, and generates time difference or timetag data using a reference clock. The offset LO is typically implemented with a frequency synthesizer (e.g., DDS) or low-noise crystal oscillator, not necessarily coherent with the reference.

The DMTD concept is widely applied for making low noise, high resolution clock measurements, and can be effectively configured for multichannel systems [61]. Like the simple heterodyne arrangement, it is usually limited to a single nominal frequency. Digital implementations are possible [62-63].

The Microsemi Multi-Channel Measurement System (MMS) is an example of a classic analog DMTD clock measuring system (see Figure 12), which achieves a 10 MHz noise floor of < 5e-13 @ 1s. It is available with a database system for data storage and retrieval.

Figure 12. Microsemi Multi-Channel Measurement System

• Tight PLL and ADC

A low noise oven controlled voltage controlled crystal oscillator (OCVCXO) in a tight (fast, wide bandwidth) phase lock loop (PLL) can be used to measure the frequency stability of its "reference" source, and the analog control voltage values digitized by an analog to digital converter (ADC) to provide numeric readings (see Figure 13) [64]. The tight PLL allows the OCVCXO tuning voltage to follow the frequency fluctuations of the applied reference within the PLL bandwidth, thus demodulating those variations with a scale factor equal to the OCVCXO tuning sensitivity. That voltage can then be digitized to provide the desired frequency data output.

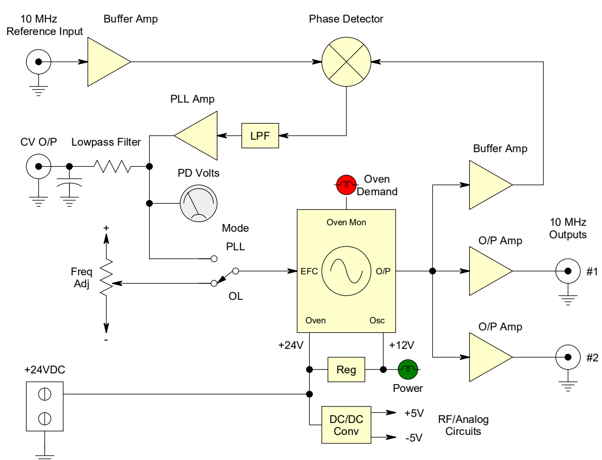

Figure 13A. Block Diagram of PLL Module

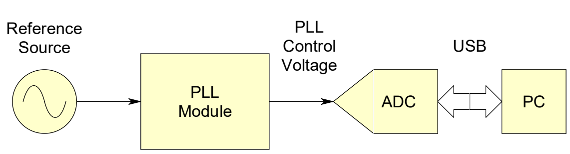

Figure 13B. Block Diagram of PLL System

• Loose PLL and ADC

A loose (slow, narrowband) PLL can be used in a classic phase noise demodulation configuration where the loop keeps the mixer (e.g., diode DBM) inputs at quadrature for best phase detector sensitivity. A simple modification of this arrangement using a single coherent input can be used to make static phase measurements on a device (e.g., amplifier, filter) inserted in one line, for example, for temperature coefficient of phase measurements (the DDS phase measurement method discussed below is an alternative for this that requires no quadrature adjustment). The phase detector sensitivity in V/rad is equal to the peak amplitude of the low frequency beat note when the PLL is unlocked.

• Delay Line Discriminator

Another related technique is the delay line discriminator [65-66]. A single source is split into two paths feeding the mixer (phase detector), with a delay line (a length of coaxial cable) inserted into one leg. The delay line has the effect of converting frequency variations into phase variations. Quadrature conditions are established by using a quarter wave delay line with delay $\tau=1/(4f_0)$ seconds, where f_0 is the carrier frequency in Hz. The sensitivity of the discriminator to source frequency fluctuations in V/Hz is equal to $K_d = K_\phi \cdot 2\pi \cdot \tau$, where K_ϕ is the phase detector sensitivity in V/rad [G]. This sensitivity is too low for measuring precision frequency sources but has found to be useful for making VCO phase noise measurements far from the carrier. Frequency detection can be an advantage when there is a high level of phase noise near the carrier. The delay line discriminator method is fast and wideband.

• Radio Receivers

Radio receivers can be employed for phase and frequency measurements, including direct conversion, heterodyne and software defined radio (SDR) technology along with internal coherency. In an analog receiver, after downconversion, the baseband or low frequency IF signal may be processed using FFT techniques to extract phase and frequency information. Similarly, an SDR receiver using digital downconversion and IQ processing can obtain that information. Specialized clock measurement hardware based on SDR receiver digital processing is becoming available at reasonable cost, offering both time and frequency domain measurements with very high performance.

Off-the-air frequency measurements to perform a local calibration or to measure a remote signal can be done quite easily with a receiver having a coherent frequency plan and an external frequency reference. After reading the nominal received frequency, an audio spectrum analyzer can be used to determine the baseband frequency to a small fraction of a Hz (after prior calibration of its sampling clock). SDR radios can perform a similar frequency determination even easier. These measurements can achieve accuracies on the order of $1x10^{-7}$, limited mainly by HF propagation.

The frequency readout of a modern synthesized receiver in the CW mode displays the frequency of the actual received signal when the baseband audio tone is equal to its nominal value.

A fast and easy way to perform a moderately accurate receiver frequency calibration on a transceiver that has both CW and CW Reverse functions (e.g., upper and lower sidebands) that can be quickly switched between is to tune in a standard frequency broadcast (e.g., WWV or CHU) and adjust it for equal tones between those two modes. This can generally be done by ear to within a few Hz.

Figure 14 shows the audio output from a receiver tuned to CHU at 7.850000 MHz, first in normal and then reversed CW mode. The peak detected beat note frequency changes from about 600.5 Hz to 599.5 Hz, offsets of about $\pm 6x10^{-8}$ respectively [67].

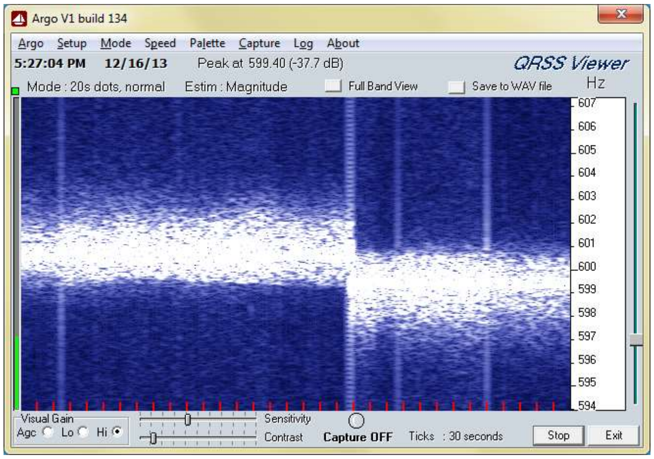

Figure 14. 7.850000 MHz CHU Received Spectral Display in CW and CW Reverse Modes

• RF Spectrum Analyzers

An RF spectrum analyzer operates like a radio receiver. It can not only show a spectral display of the signal but can also show the frequency of a particular component much like a frequency counter. Like an ordinary radio receiver, this can be especially useful for weak signals in the presence of (possible stronger) others. No data is generally externally available, however, for stability analysis.

• Direct RF and IF Signal Digitization

Phase and frequency measurements can be made by using an analog to digital converter (ADC) to digitize either the clock RF signal or the IF signal from a heterodyne measuring system [68-75]. The Microsemi Model TSC 5120A Phase Noise Test Set is an example of the use of direct RF digitization for both time and frequency domain measurements, while JPL [76] and AMSAT [77] have developed special purpose time and frequency domain measurement systems using digitization of the IF signal, the latter employing a PC sound card. Those techniques use digital signal processing (DSP) to estimate the phase of the sampled beat signal.

The Microsemi Model 5120A uses direct RF 1-30 MHz sampling and digital signal processing and has a complete user interface (see Figure 15) [78-79]). The signal and reference input are sampled with a high speed ADC much like in a SDR and all the subsequent processing (downconversion, decimation and phase detection) is done digitally with the help of a DDS [80]. Dual signal and reference channels support cross correlation to reduce the noise floor. Baseband computation includes both time (ADEV) and frequency (FFT) domain processing, and the device achieves a very low < 3e-15 @ 1s and -145 dBc/Hz @ 1 Hz floor. The Microsemi 5125A is a similar device that covers 10-400 MHz.

Figure 15. Microsemi 5120A Phase Noise Test Set

The Microsemi 3120A Phase Noise Test Probe is a similar lower cost device with a PC virtual user interface that has a < 1e-13 @ 1s noise floor (see Figure 16).

Figure 16. Microsemi 3120A Phase Noise Test Probe

• Frequency Multiplication

Frequency multiplication is a basic way to manipulate an RF signal. After multiplication, small phase and frequency variations of the RF carrier are increased by the same factor as the nominal frequency. If the nominal frequency, f, is multiplied by N (e.g., 10), the PM modulation index, m, is also increased by a factor of N, as are the small phase, $\Delta\phi$, (radian or seconds) and frequency, Δf, (Hz) deviations, while the fractional frequency deviation $\Delta f/f$ remains the same. In the frequency domain, the PM sideband level is raised by 20 $\log_{10}(N)$ dB (e.g., 20 dB/decade).

Frequency multiplication can therefore be used to enhance the level of discrete or noise PM sidebands for RF spectral analysis. The multiplier hardware can be a harmonic multiplier or multiplier chain, perhaps using diode, active or SRD devices, or a PLL multiplier (PLOM) with sufficient loop bandwidth for the sideband frequencies of interest. It is even feasible to (safely) overload the input mixer of an RF spectrum analyzer to generate harmonics for observation.

• Cross Correlation Techniques

Cross correlation using a pair of independent phase measurements can be used to reduce the noise of the measurement system [81-83]. This technique can be used to reduce the noise floor of both time and frequency domain measurements.

• Frequency Error Multiplication

Frequency error multiplication (FEM) is a classic but underutilized method for improving the resolution of a phase or frequency measurement 84-85]. The resolution can be increased by a process of error multiplication whereby the unknown and reference frequencies are multiplied by factors of N and N-1 respectively and then mixed to obtain the original nominal unknown frequency with its frequency difference increased by a factor N as shown for N=10 in Figure 17.

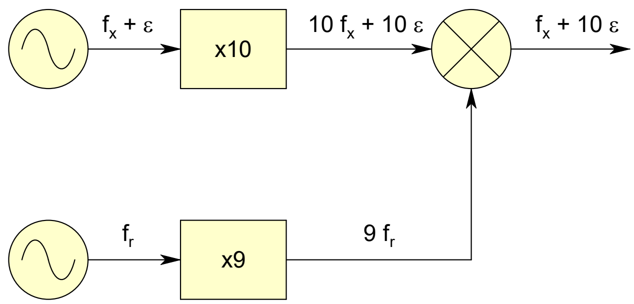

Figure 17. Block Diagram of x10 Frequency Error Multiplier

This technique can be applied multiple times to any of the time and frequency domain measurement methods, including the direct use of a frequency counter or RF spectrum analyzer. It is generally limited to a single carrier frequency, and the results depend critically on the noise of the multipliers, the RF filtration, isolation and shielding, and the crosstalk between the signals. Narrowband filtration limits the range of useful sideband frequencies. Resolution enhancements of 10^4 are possible with careful implementation.

• Comparison Between Systems

A comparison of the relative advantages and disadvantages of these methods is shown in Table I.

Table I

Comparison of Time and Frequency Measurement Methods

Method	Advantages	Disadvantages
Divider and Time Interval Counter	Provides phase data Covers wide range of carrier frequencies Easily expandable at low cost	Modest resolution Not suitable for short τ
Mixer and Period Counter	Resolution enhanced by heterodyne factor Provides direct frequency data Usable for short τ Expandable at reasonable cost	No phase data No frequency sense Requires offset reference Single carrier frequency
Dual Mixer Time Difference	High resolution, low noise Provides phase data Offset reference noise and inaccuracy cancels No fixed reference channel	Single carrier frequency Relatively complex
Radio Receiver	Quasi-standard instrument Wide frequency range Quite good resolution possible	Useful for weak signals Frequency data mostly
RF and IF Signal Digitization	Flexibility, automation	More complex
RF Spectrum Analyzer	Standard instrument	Useful for weak signals Limited resolution Frequency data only
Tight PLL	Quite simple hardware Good resolution	Single carrier frequency Analog scale factor Frequency data only Requires low noise OCVCXO at measurement frequency
DDS Phase Control	Provides phase data Covers range of frequencies Quite simple hardware High resolution Relatively high measurement rate	Unfamiliar method
Crosscorrelation	Lower noise floor	More complex
Error Multiplication	Higher resolution	Narrowband

• RF Notch Filtration

The dynamic range of RF spectral analysis used to measure noise or spurious components away from the carrier can be enhanced by notching the RF carrier itself, allowing the gain of the spectrum analyzer to be increased without overload. A quartz crystal notch filter is most suitable for this. A correction may be needed for the (small) attenuation of the filter at the sideband frequency.

• Direct Digital Synthesis

A direct digital synthesizer (DDS) is an increasingly-popular means for generating a coherent frequency from an applied reference. It is a high speed digital device that adds the contents of a tuning register to a phase accumulator at each clock cycle, thereby generating a sawtooth phase ramp which addresses a sine lookup table to produce a digital word that represents the output waveform. That word is then converted to analog form and, after lowpass filtration, produces the desired RF output. A DDS has the advantages of 1-chip implementation, high frequency operation, fast phase continuous tuning, very fine frequency resolution, phase programmability, rather low power and reasonable cost. An example of a DDS device (an Analog Devices AD9951) is shown in Figure 18.

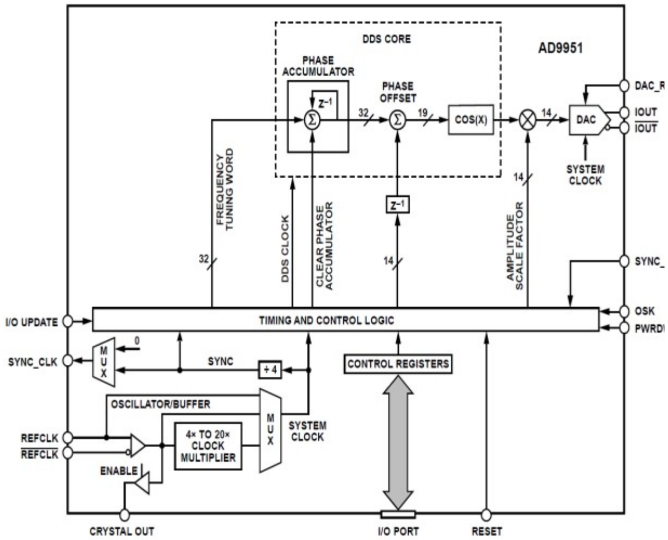

Figure 18. Block Diagram of DDS Frequency Synthesizer

One DDS application for clock measurements is to generate the offset LO signal for a dual mixer time difference system. Another, less common, application is described below.

• DDS Phase Measurements

A DDS can be utilized to make high-resolution phase measurements by means of a microprocessor-controlled phase tracking loop [19]. The technique compares the phase of the signal under test against a reference signal from the DDS at the same nominal frequency in an analog phase detector. The sense of the phase detector output is detected by an analog comparator whose 1-bit output steers the phase of the DDS via the microprocessor. The phase tracking loop keeps the phase detector centered at quadrature and uses the DDS phase word to produce an output phase data stream. The phase comparator information is also used to make DDS frequency adjustments as required to maintain phase tracking.

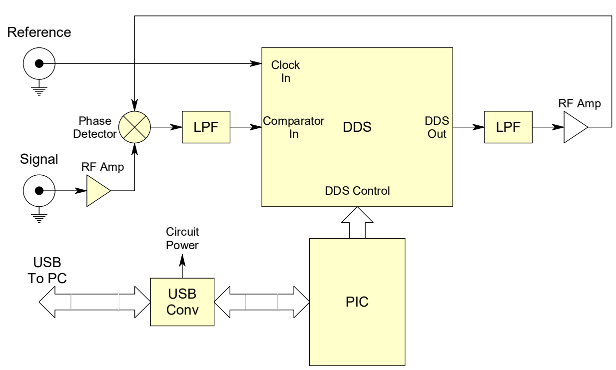

Figure 19. Block Diagram of DDS Clock Measurement Module

A photograph of a PicoPak DDS clock measurement module is shown in Figure 20.

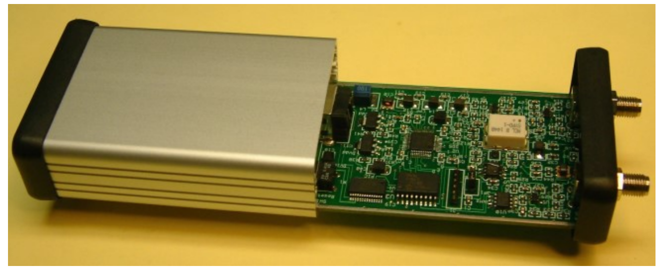

Figure 20. PicoPak DDS Clock Measurement Module

• Clock Measuring System Specifications

The specifications for a time domain clock measurement system will typically include the items shown in Table II.

Table II
Typical Clock Measurement System Specifications

Parameter	Example	Remarks
Mesaurand	Phase	Preferred vs. freq
Resolution	10-12 @ 1 s	Varies significantly
Noise Floor	10-11 @ 1 s	Varies significantly
Frequency Range	5 – 15 MHz	Varies significantly
Reference	10 MHz	Standard
Measurement Tau	1 second	Some ≤10 ms
Measurement Rate	1/second	Some ≥100/s
# Channels	1	Some have many
Data Format	ASCII 1/line	Varies
Timetags	MJD	Preferred
RF Inputs SWR	1.5:1	>14 dB RL
RF Inputs Level	+7 dBm	Near standard
Phase TC	±5 ps/°C	Can be critical
Software	User Interface	S/B Included
Interface	USB	Or Ethernet, etc.
Physical	Small module	Appropriate size
Power	+5V via USB	Varies

OTHER SYSTEM COMPONENTS

• Time and Frequency References

The criteria for a suitable reference source depend on the parameters being measured. For a frequency domain measurement, phase noise is paramount, and, for many test setups, it is advantageous that the nominal reference frequency be the same as that of the device under test. For a time domain measurement, Allan deviation stability over the range of averaging times of interest is paramount, and 10 MHz is often the preferred nominal frequency. Similarly, reference frequency accuracy must be consistent with the measurement objective. For a time comparison, the reference must be synchronized with respect to a suitable external clock. For long term measurements, reference reliability is essential. In many cases, a GPS-synchronized and syntonized OCVCXO or rubidium oscillator can serve as a reference for most measurements. For the most demanding measurements, an active hydrogen maser is the reference of choice. Regardless of the type of reference device, its reliability is paramount to maintain measurement system operation, and redundant references are recommended, particularly for a multichannel system.

• Distribution Amplifiers

Distribution amplifiers are often used in a clock measuring system, particularly to supply coherent reference signals to measurement devices. These amplifiers should have low noise and distortion, have low phase temperature sensitivity, and be of high quality and reliability.

• Coax Cable Phase TC

Coaxial cable phase temperature coefficient (TC) of phase is an often ignored but potentially problematic aspect of a clock measurement facility. Any long (>30m) cables subject to wider than laboratory temperature variations should have specified low TC of phase to avoid phase change and pseudo frequency offset. Foamed polyethylene dielectric is greatly to be preferred over Teflon.

• Coaxial Cables, Connectors and SWR

Coaxial cables and connections are subject to phase changes due to mechanical stress; this is particularly true of inherently loose BNC connectors. Properly torqued SMA or Type N connectors are preferred. Coaxial jumper cables are especially prone to becoming erratic, and a suspect cable should be immediately marked, repaired or discarded. SMA connectors should be inspected for tiny metal debris before every insertion. Cable leakage is generally not a problem, but double shielded or semi-rigid cables are recommended.

Transmission line reflections due to improperly terminated coaxial cables can cause unwanted amplitude and phase changes. AM/PM conversion in a subsequent zero crossing detector can result in additional phase sensitivity. All frequency measuring system devices should have their input SWR or return loss specified; values better than 1.5:1 and 14 dB are recommended. Rise time and wave shape can affect the transmission of pulse signals [86].

• Low Pass Filter Phase TC

Low pass filters (LPF) are often present in the output amplifiers of frequency sources and distribution amplifiers. The phase transfer function of these filters necessarily has some temperature sensitivity depending on their complexity, cutoff frequency and component TC. This phase TC can affect phase measurements and its rate of change can produce a pseudo frequency offset. RF amplifiers and filters used in frequency sources should have their phase TC specified; a sensitivity of a few ps/°C is typical for a well-designed device.

• Harmonic Distortion

Harmonic distortion components on the source waveform can, in some cases depending on their phasing, reduce its zero crossing slope and thereby add input circuit noise via AM/PM conversion. This can be avoided by the use of an appropriate low pass filter (LPF) at the input of the sine to digital converter. Care must be taken however regarding LPF TC of phase.

• AM/PM Conversion

Amplitude stability per se is seldom an issue for time and frequency systems, but AM to PM conversion in devices such as zero crossing detectors can be a problem. In principle, AM noise can be removed by limiters and amplitude variations removed by level control loops, but those means are seldom needed or used. Gross amplitude changes are often experienced because of loose connections.

• Active and Passive Devices Under Test

Most frequency measurements are made on active sources, but passive devices (e.g., quartz crystal resonators) can be measured using test oscillators, RF bridges and other such means [87].

• Multichannel Systems

Multichannel time and frequency measuring systems are often required to handle several or even many clocks and oscillators. Those systems can take different forms depending on the number of channels, multiple nominal source frequencies, resolution, noise floor, measurement rates and other parameters. These can be bought as turnkey systems, assembled from standard instruments or custom-made, and supported with a variety of user interface, data storage and analysis software.

Some systems include means for making simultaneous measurements for all channels, perhaps by adjusting the data between channels having a phase offset between their zero crossings. That feature is especially important for an absolute time standard ensemble.

Crosstalk can become an issue for multichannel systems (as it can for any clock test facility with multiple sources at the same frequency). RF switch scanners are an obvious concern. Low frequency beats and cyclic disturbances can be hard to track down. Injection locking can occur between two sources at nearly the same frequency and phase, particularly via an inadequately-isolated mixer.

• Data Interfaces

There are multiple hardware arrangements and protocols for instrument data interfaces, some obsolescent (e.g., PC parallel) or nearly so (e.g., PC serial, GPIB) and others currently popular (e.g., USB, Ethernet, Wi-Fi). All can handle most frequency measurement system data rates. USB is widely supported, can supply low-power instruments. Ethernet offers easy networking, and like USB, is easily multiplexed. Wi-Fi offers especially easy connectivity, especially for small systems, and ground isolators are available. High speed TIA boards use PXI-type interfaces.

• Data Format

There is no standard format for clock measurements, but two common choices are plain frequency values in Hz for simple frequency measurements and MJD timetagged phase values in seconds for phase data. These formats should use ordinary ASCII characters, one line per datum, and have sufficient dynamic range and resolution. Data files may include an optional header that describes the measurement and identifies the source and reference clocks. A data format that includes units like nanoseconds and microseconds that changes between lines can be hard to parse.

• Timetags

Timetags are recommended for inclusion in all clock data files. MJD timetags are particularly recommended as these have been widely accepted and proven to be easy to use. Along with that, it is further recommended that the computer or system applying these timetags be operated on UTC time.

• Databases

The use of a formal relational database is recommended for the storage, archiving, backup and retrieval of clock data, along with any associated measurement information and monitor readings [88].

• UPS and Backups

It goes without saying that all elements of a time and frequency of measuring system must operate continuously, and thus be assured of uninterruptable power. That requirement includes the sources under test, the references and their distribution, all measurement devices and controllers, monitor DAQ devices, and all data handling equipment (LAN switches, database servers, etc.). For critical applications, a facility-wide UPS backed up by a generator is recommended. The analysis workstations are generally not as critical.

Frequency reference continuity is particularly important. A backup reference should be in place and being measured at all times so that it can be used immediately instead of the primary reference whenever necessary.

Clock data must be backed up and archived on a regular basis, preferably using a formal database.

• System Maintenance

Clock measuring system maintenance requirements are primarily associated with the environment and supporting equipment rather than the clocks or measuring system itself. UPS batteries and backup generator maintenance is critical so they are available when needed as is routine facilities housekeeping chores. Computers and databases require backup and software updates on a regular basis, and instrumentation must receive periodic recalibration including frequency reference traceability. Normal system use generally detects measurement problems such as jumps or increased noise.

• Test Facility Considerations

It also goes without saying that the environment conditions of a clock measuring system should be consistent with the other requirements. Temperature fluctuations can cause phase shifts and pseudo frequency offsets. Mechanical noise and vibration can map over to measurement noise, especially when crystal oscillators are involved because of their relatively high acceleration sensitivity. Mechanical disturbances can cause phase jumps and even intermittent operation. Occasional test area environmental disturbances can be exploited to observe device sensitivities.

It is quite common for a clock test facility to have a Helmholtz coil pair for DC and low frequency AC magnetic field testing. A small electromagnetic shaker can be needed to measure quartz crystal oscillator dynamic acceleration sensitivity.

Only rarely is it necessary to provide DC magnetic shielding in a clock test facility, and an AC/RF field screen room, while sometimes needed for sensitive phase noise or spurious component measurements, is seldom provided. Clock conducted interference and susceptibility testing can be done locally, but a full-fledged EMI test facility is usually needed for checking radiated emissions/susceptibility. The problem then arises (as it may for mechanical shock and vibration, flash X-ray, etc.) as to how to provide the necessary clock instrumentation at a remote facility.

One consideration forgotten with occasional large impact is to assure that critical equipment is protected against water damage due to a leaky pipe, A/C condensate or fire sprinklers.

Physical security may or may not be an issue; it is particularly advisable to limit access to facility frequency reference vaults. Disturbance of ongoing measurements can be especially costly when long term runs are involved.

• Date and Time

It is important that all elements of the clock measuring system have the same (correct) date and time for their timestamps. The use of NTP or a network time server is recommended.

• Timekeeping

Timekeeping is hard, and at a precise level is most certainly not for the faint of heart, requiring far more effort than is needed to make the clock measurements described herein. An independent timing laboratory needs a primary (absolute) frequency standard as its clock source, and preferably a number of them deployed as a time scale ensemble. Reliability is of the essence, as is a well-controlled environment with redundant utilities. Along with such a facility, means are needed for precise time transfer to and from other such laboratories. Fortunately, independent timing is not a requisite to make clock stability measurements.

• Documentation and Training

All aspects of the time and frequency measuring system should be well-documented, particularly test procedures and any custom hardware or software used. A log should be kept of all relevant system events (configuration changes, outages, etc.). It must be possible to trace all such events when preparing reports on or reviewing test results.

Clock measurements are a unique endeavor that requires specialized training and experience, knowledge that is needed by anyone working in the time and frequency field. That know-how is gained by reading the relevant technical literature, working with experienced people and attending training sessions, conferences and tutorials. One of the best such training opportunity is the annual T&F Seminar at NIST [I].

• Analysis

The analysis methods and level of detail applied to the data from a clock measurement depends mainly on the objective of test. Plotting the data is often a way to gain insight into clock behavior. Specialized software is available for frequency stability analysis [89-90].

• Reporting

The results of a clock evaluation may need to be reported formally. The contents and format of this report will vary with the circumstances, but should always include the date and purpose of the test, the sources, the measurement methodology, and the results and conclusions. If possible, a reference to the raw data should be included. It can be advantageous to draft the test report during the measurement process.

• Clock Measuring System Selection

The choice of a clock measuring system depends on the sources under test and the test objectives. Simple frequency measurements can be made with an ordinary counter, and modern high-resolution instruments can handle all but the most precise measurements. When higher resolution is needed, heterodyne techniques, including DMTD and direct digital methods are available. The highest performance clock measurement instruments now use RF sampling and digital signal processing, and the highest performance counters use timestamping techniques. Nevertheless, traditional analog methodology can also provide excellent performance along with intrinsic simplicity and transparency.

Phase measurements are preferred in many cases, and time interval counters are often used, either alone or as part of a more complex system. Other considerations include nominal frequency, RF/pulse inputs, measurement rate, scanning, number of channels, data storage and cost. In all cases, the frequency reference must have adequate stability and accuracy, often using an ovenized crystal or Rb oscillator syntonized to GPS. Custom software may be needed even with commercial systems. Complete systems can be bought commercially, assembled from available instruments or custom-built.

CREDITS, NOTES AND REFERENCES

• Credits

Instrument photographs are from the web sites and literature of their respective manufacturers.

• Notes

[A] Analog frequency measurement techniques include wavemeters (e.g., HP 536A), heterodyne frequency meters (e.g., GR 620A, BC-221) and pulse count discriminators (e.g., GR 1142A). A wavemeter is simply a calibrated narrowband filter. A heterodyne frequency meter is essentially a calibrated RF oscillator that is zero-beat with the unknown frequency. A pulse count discriminator indicates frequency as the average value of a constant duration pulse train. An OCVCXO in a tight PLL can serve as an effective way to measure frequency stability. In the simplest form, a double balanced mixer or the integrated output of a S-R flip-flop can provide a useful measure of phase difference.

[B] An ordinary clock can be thought of as a device to integrate its frequency source to obtain a phase or time value.

[C] The term "3-cornered hat" was coined by J.E. Gray of NIST.

[D] A classical or so-called Π counter (conventional, reciprocating or interpolating) makes a frequency measurement averaged over the measurement interval, equivalent to two phase samples at the beginning and end, a Δ counter makes multiple phase measurements at overlapping samples over the measurement interval, and a Ω counter uses a linear regression applied to multiple phase samples. The Greek letter names resemble the shapes of their respective phase sampling functions. They have Allan (AVAR), Modified (MVAR) and Quadratic (QVAR) variance responses at their basic measurement intervals.

[E] The TAPR TICC uses a pair of TDC7200 Time-to-Digital Converter chips. It has a resolution of about 60 ps and a 1s ADEV of about $7x10^{-11}$, and can operate at a rate up to 100 measurements per second. It can be used in time interval mode to compare two 1 pps signals, as the time interval counter in a DMTD system, or in timestamp mode in a heterodyne system as a period meter using the difference between adjacent timestamps, all without dead time. In heterodyne or DMTD systems, the noise floor will likely be set by the offset LO and/or zero crossing detector.

[F] In principle, one could process the beat note in the frequency domain, extracting its frequency with an FFT or numerical sine fit. In practice, this does not work as well as using a zero crossing detector and time interval counter.

[G] This expression ignores the sinc term that applies to longer tau. The delay line discriminator will probably require a means for calibration.

[H] The Quartzlock A7 Frequency and Phase Comparator uses the frequency error multiplier technique [91].

[I] NIST Time and Frequency Division's annual seminar covers clocks, oscillators, atomic frequency standards, rf and optical synchronization, optical oscillators, quantum information, optical cooling and heating; making precise frequency, time, phase-noise, and jitter measurements; and establishing measurement accuracy and traceability. This 4-day course is the most comprehensive available.

[J] Please note that there is a typo in SP1065 Eq. 28 for TTOTVAR on p. 26: The tau exponent should be 2, not 3.

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